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TECHNOLOGY PLATFORM FOR THE FABRICATION OF MICRO-INDUCTORS ON SILICON FOR DC-DC CONVERSION

(MAGNETICS ON SILICON)

A Dissertation presented to the academic faculty

By

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In Partial Fulfilment of the Requirement for the Degree of Doctor of
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University College Cork, Ireland
Coláiste na hOllscoile Corcaigh



Tyndall National Institute, National University of Ireland, Cork
2018

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Ask, and it shall be given to you; seek, and ye shall find; knock, and it shall be opened unto you.

- *Matthew 7:7*

To my family.

This thesis was written entirely by the author, except where stated otherwise. The source of any material not created by the author has been clearly referenced.

Ricky Anthony

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List of Acronyms

SoC	System on Chip
PwrSiP	Power Supply in Package
PwrSoC	Power Supply on Chip
PMIC	Power Management IC
PLiS	Power Inductors in Silicon
SEM	Scanning Electron Microscopy
EDX / EDS	Energy-dispersive X-ray spectroscopy
XRD	X-ray Diffraction
TEM	Transmission electron microscopy
XPS	X-ray photoelectron spectroscopy

Units

Different unit systems are in used mainly, International System/System International d'Unites (SI) or meter-kilogram-second system (MKS) and Gaussian system or centimetre-gram-second (CGS). The CGS system is commonly used in the USA and Asian countries whereas SI system is widely used in Europe. These units can be converted from one unit system to another by a conversion factor. Below are the conversion factors between these units. The units used in this thesis is SI.

Quantity	Symbol	CGS	Conversion factor	SI
Magnetic flux density	B	Gauss (G)	10^{-4}	Tesla (T)
Magnetic field strength	H	Oersted (Oe)	$10^3/4\pi$	A/m
Magnetic flux	ϕ	Maxwell (Mx)	10^{-8}	Weber
Magnetization	$4\pi M$	Gauss (G)	$10^3/4\pi$	A/m
Magnetic moment	m	emu	10^{-3}	A-m ²
Permeability	μ	dimensionless	$4\pi * 10^{-7}$	H/m
Relative permeability	μ_r	undefined	-	dimensionless
Demagnetization factor	D	dimensionless	$1/4\pi$	dimensionless

emu = electromagnetic unit

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Abstract

Power conversion circuitry is an integral part of electronic devices such as in hand-held mobile devices and laptops. With the on-going trend towards miniaturization of electronic components, a significant challenge will be to deliver high efficiency power management solutions. Switch mode DC-DC power supplies (SMPS) in particular are highly efficient and have high power density. The power passive components in SMPS such as inductors which take up almost 30% of the designed power conversion circuitry are usually bulky, discrete and off the shelf components which have to be miniaturized further for possible integration with power management ICs for high-frequency applications without compromising on its efficiency.

In recent years, an increase in switching frequencies (> 10 MHz) and with soft magnetic core technology, these magnetic components have been miniaturized below 2 mm^2 . These inductors can now be integrated in-package (PwrSiP) with power ICs with the ultimate aim to increase integration and reliability by realizing a monolithically integrated power supply on chip (PwrSoC). This has led to substantial interest in the area, from both industry and academia. Although there have been significant developments in component design to achieve efficient and miniaturized micro-inductors, on-silicon CMOS compatible process technology requires further development for miniaturization and losses remain a significant roadblock. This dissertation focusses on process solutions to the challenges by providing new fabrication routes that reduce the inductor losses, increase batch yield, integration and reliability. The processes developed are integrated to realize the first closed core solenoid micro-inductor.

Firstly, to reduce DC winding losses, a high resolution ($\sim 5 \text{ }\mu\text{m}$) and high aspect ratio (17:1) single-spin metal moulding technology has been developed. Thick copper air-core inductor micro-windings ($\sim 80 \text{ }\mu\text{m}$) with varying winding width ($5 \text{ }\mu\text{m}$ to $25 \text{ }\mu\text{m}$) and footprint (0.36 mm^2 - 1.9 mm^2) were fabricated. The $80 \text{ }\mu\text{m}$ thick windings and $5 \text{ }\mu\text{m}$ spacing (0.39 mm^2) suggested $\sim 42 \%$ reduction in resistance (from $273 \text{ m}\Omega$ to $159 \text{ m}\Omega$) compared to $50 \text{ }\mu\text{m}$ thick windings and $10 \text{ }\mu\text{m}$ spacing (0.45 mm^2). This is a cost-effective process for miniaturization and reducing DC winding losses by comparison with multi-spin, low resolution and low aspect ratio processes.

Secondly, to reduce magnetic core loss, a borane based variable composition (Permalloy $\text{Ni}_{80}\text{Fe}_{20}$ to Invar $\text{Ni}_{37}\text{Fe}_{63}$) electroless bath has been developed. This has been shown to give greater selection of the core in terms of magnetic (96 A/m for $\text{Ni}_{37}\text{Fe}_{63}$ - 26.6 A/m for $\text{Ni}_{81}\text{Fe}_{19}$) and electrical resistivity (26 $\mu\text{Ohm-cm}$ for $\text{Ni}_{81}\text{Fe}_{19}$ - 62 $\mu\text{Ohm-cm}$ for $\text{Ni}_{37}\text{Fe}_{63}$). In-parallel, an electrochemical post-processed ultra-soft magnetic film material has been developed with coercivity < 5 A/m, anisotropy field > 900 A/m, saturation flux density ~ 1.4 T and resistivity > 65 $\mu\text{Ohm-cm}$. The post-processed film showed a reduction of the as-deposited coercivity from 30 A/m to 1.5 A/m whereas the anisotropy field improved from 735 A/m to 954 A/m along the hard-axis. The high frequency real permeability response of 1.65 μm thick film at zero bias suggested an initial permeability > 550 with a cut-off frequency ~ 120 MHz.

Both sputter and electrochemical deposition routes have been explored to laminate the magnetic films which could restrict the eddy current losses at high frequencies. A site-selective metallization process on dielectrics (such as SU-8, BCB and parylene-C) without sputtered blanket seed layers through cost-effective electrochemical route has been developed as a route to core-laminations. Sputtered spacer films (Ta(N)) with Permalloy have been shown to improve anisotropy and high-frequency properties.

Finally a first closed core solenoid micro-inductor prototype has been fabricated. The device was FEM simulated, analytically designed and micro-fabricated in a 3-D closed-core solenoid inductor. The top windings of the device were realized by integrating the HAR photoresist process developed. The Ni-Fe (45/55) core was realized using an in-house developed electroplating process. The closed core design suggested a two-fold increase in inductance compared to an open core design. The fabricated 3-D closed core micro-inductor has an inductance of ~ 54 nH with winding DC resistance of ~ 220 m Ω and saturation current of ~ 500 mA. The device has a footprint area of ~ 0.75 mm² and an inductance density of 72 nH/mm². This miniaturized and high inductance device would be ideal for integration with power management ICs for high-frequency power conversion applications. Compared to FEM simulated air-core and open core designs, inductance can be further increased by a factor of 12.4 and 1.95 respectively, with the closed core design. The inductance densities for the air-core, open-core and closed core designs are 5.6 nH/mm², 36 nH/mm² and 68 nH/mm² respectively.

Chapter 1

Introduction

Portable and wireless electronic devices such as smart-phones, GPS (global positioning system), electronic notebooks are witnessing continuous shrinking in size and cost. Simultaneously there is a need for increase in functionality along with efficient power management systems. High density electronic circuits coupled with high power efficiency have been the essence of the electronics revolution over the decades. The International Technology Roadmap for Semiconductors (ITRS 2014) has predicted a rise in ‘*more than Moore*’ phenomenon in the coming years aided by continuous miniaturization of silicon feature sizes with the advancements in CMOS technology, which will support this high density integration and functionality [1.1].

Recent years indicate an on-going trend towards very compact low-power (100 mW–1 W) and low voltage (1 V–80 V) dc-dc converters mainly for battery-operated applications [1.2]. While the semiconductor industries have achieved significant progress in the past decade in terms of miniaturization and switching frequency, the dc-dc power converter technology which is an inevitable building block of any electronic gadget has shown a rather slow progress. This is because the power supply circuitry has energy storing passive components (inductors, capacitors etc.). An increase in converter switching frequencies (> 10 MHz) been shown to enable reduction in inductance requirement and footprint of inductors. But they still lag behind in comparison to other passive components such as the resistor and capacitor. High efficiency ($> 90\%$) of the micro-inductors within miniaturized dimensions (< 2 mm²) is a challenge, especially at very-high frequencies (30 MHz – 300 MHz).

This thesis focuses on miniaturization of integrated magnetic components, primarily with respect to current carrying micro-inductors for power conversion applications. It investigates the micro-inductor device losses in the conductor windings and the magnetic cores and develops novel solutions for high-frequency integrated magnetic technologies with the aim to advance and develop the existing microfabrication processes. The challenge is to develop processes for the fabrication

of high frequency (> 30 MHz) integrated on-silicon micro-inductors which would achieve high efficiency ($> 90\%$) within a low footprint ($< 2 \text{ mm}^2$) and high yield, appropriate for mass fabrication. The thesis focusses on developing processes and integrating the processes developed to realize a new closed core solenoid micro-inductor on silicon.

1.1.High Frequency dc-dc Converters

dc-dc converters are an essential part of any portable electronic device today. These devices derive their power primarily from the batteries. The voltage levels required for different sub-circuitry can vary from the supplied battery voltage. The dc-dc converters are used to change one dc voltage to another. It can be broadly classified into three types: *linear*, *switching capacitive* and *switching inductive converters*.

Linear converters can be fully integrated on chip. They are small and low cost. They have active devices, where the output voltage is kept steady by changing the regulator resistance. The access power is dissipated, usually as heat. However, they exhibit poor efficiency and density and cannot be used for step-up power conversion.

Capacitive dc-dc converters on the other hand do not need the inductive components and have higher efficiency compared to linear converters. But there always remains a trade-off between the accuracy in terms of the output voltage efficiency. Unlike linear converters they can be used for step-up conversion.

The switching inductive converters would ideally have 100% conversion efficiency or zero power loss. They have the ability to buck (step-down converter) and boost (step-up converter) and show excellent transient performance.

Figure 1.1 illustrates a point-of-load (POL) inductive dc-dc switched mode power supply (SMPS) on-chip where the inductor is completely integrated with switches, control and drive. The basic SMPS buck converter consists of a switching network and a low-pass filter. The switch opens and closes periodically to generate a waveform with a duty cycle. This duty cycle is the fraction of time during which the switch is closed. The frequency (or the *switching frequency*) is inversely proportional to the time-period. In addition to the desired DC voltage, the input also consists of undesired harmonics which are then filtered with a low-pass filter.

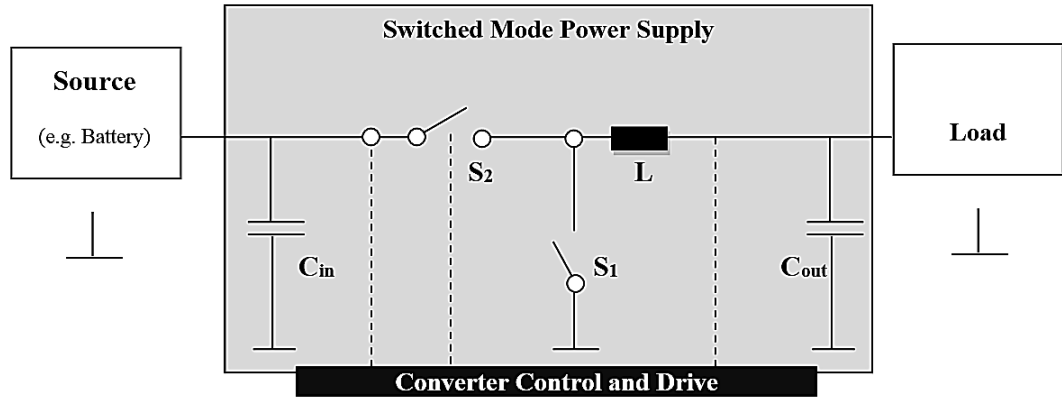


Figure 1.1. A dc-dc switched mode power supply [1.3].

A major bottleneck in further miniaturization of the circuit without compromising on efficiency, accuracy and loss is faced from the passive components such as the inductors and capacitors. The increase in the converter switching frequency can reduce component values and the footprint area of the passives. Micro-fabrication of these components on silicon is therefore of interest. These miniaturized micro-fabricated inductors can then be stacked with power management ICs (PMICs) and capacitors to realize a power supply on chip (PwrSoC) concept (Figure 1.2).

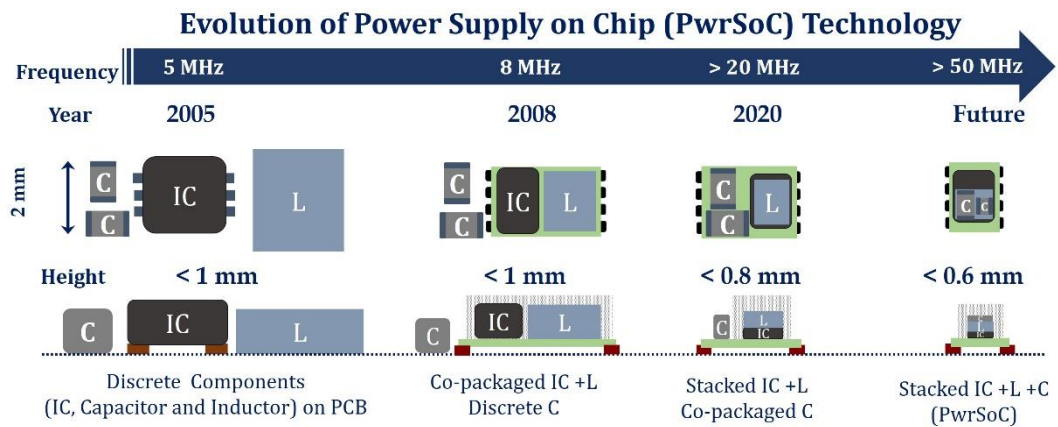


Figure 1.2. A Roadmap for evolution of power-supply-on-chip technology [1.3].

1.2. Research Challenges and Objective

Power supplies are often seen as an off-the-shelf component for electronic manufacturers even though power supplies could take up $\sim 40\%$ of the volume of the circuitry. Moreover, most of the power supply area is taken up by passive components such as inductors and capacitors. State of the art dc-dc converters in commercial devices operate from 1 MHz to 20 MHz with inductance values from 270 nH to 1 μ H. There are still considerable challenges involved for very high frequency (>100 MHz)

components in industry which require research and development. Ideal power inductors should have the following properties:

- *High efficiency*
- *Low Cost*
- *Low footprint*
- *Low EMI*

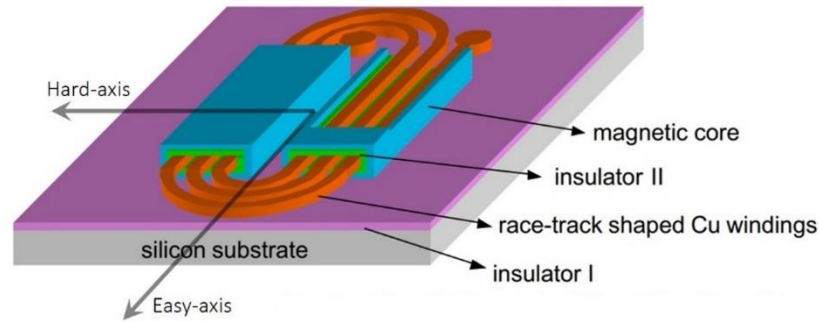


Figure 1.3. A racetrack inductor with magnetic core [1.4].

The overall objective of this work was to advance the fabrication processes technology of micro-magnetics with the focus on electrochemical processes. This has been addressed with the aim of low cost fabrication processing to develop miniaturized high energy density micro-inductor prototype. The governing equations and definitions of inductors and soft magnetic materials in given in details in appendix-I [1.5-1.10].

1.3.Scope of the Thesis

The past two decades have seen the emergence of new integrated power micro-inductors with advanced design and fabrication processes. Improvements in integrated magnetics not only requires novel design approaches for better efficiency, but also new processes or process development to fabricate new complex designs with high yield. These processes must reduce the losses associated with such miniaturized devices and increase the overall efficiency. The thesis presents literature review in the beginning of each chapter and outlines the challenges and proposes the solutions to each of them.

Chapter 2 presents on power inductors for dc-dc conversion reported in the literature. It highlights the recent developments in power supply on chip (PwrSoC) and in package (PwrSiP) from industry and academia. It then focusses on different

inductor designs and details the technology reported for each of them to draw a comprehensive comparison.

Chapter 3 focuses on reducing the winding losses by providing a thick high aspect ratio winding photoresist process in a single spin. Three different classes of photoresists were tested. A negative tone acrylic based resist, THB-151N has shown excellent adhesion, large process margin and lower resolution compared to some of the existing photoresists used in the industry today. A detailed analysis and optimization in terms of UV exposure, bake time, side-wall profile, development margin and overall yield has been provided for the photoresist. The new photoresist and plating process reduced dc resistances by 42 % in comparison to previously reported technology with AZ 9260 within a footprint area of 0.4 mm^2 . The limitations of optical lithography process as a roadblock to miniaturization (as mentioned in ITRS 2014, Whitepaper: More Moore [1.1]) have also been discussed. The second part of the *Chapter 3* discusses the issues associated with the wet etching process of the top magnetic core with existing thick and permanent SU-8 resist. As an alternative, a process was developed with a new resist which reduced the core undercut by 40% compared to the previous process, thereby increasing the wet etch process margin and increasing the wafer yield to 80-85 %.

Chapter 4 examines the soft magnetic material deposition their lamination techniques through sputtering and electrochemical processes to reduce the core eddy current losses. Electroless deposition of soft magnetic films was pursued for uniform deposition, higher deposition rate and the possibility of electroless deposition on dielectrics. Highly anisotropic Ni-Fe deposition in an external magnetic field, using borane based electroless plating solutions, is discussed. The deposition temperature was reduced below 60°C with increased borane concentration resulting in preferred Fe deposition. Deposition of wide range of Ni and Fe alloy compositions were possible with this process.

In the second parallel aspect of the work, a novel room temperature electrochemical post-processing is demonstrated for soft magnetic material ($\text{Ni}_{45}\text{Fe}_{55}$) to achieve films with ultra-soft magnetic properties (coercivity $< 5 \text{ A/m}$) by an-hydrous oxidation along with higher resistivity ($\sim 70 \text{ }\mu\text{Ohm-cm}$). With limited soft magnetic alloy compositions available for electrochemical deposition, this post-processing technique

could open areas of research in which the crystallinity of an as-deposited material can be significantly altered to improve the soft-magnetic properties.

In *Chapter- 5*, sputtered $\text{Ni}_{81}\text{Fe}_{19}$, with a thickness of 550 nm showed out of plane anisotropy which increased the in-plane coercivity > 1360 A/m. Samples at different process pressure and voltages were deposited and optimized conditions were established to reduce the coercivity below 25 A/m. With these conditions at hand, a lamination study was pursued by nitrogen-doped tantalum Ta(N) as spacer layer to achieve uniform permeability spectra (up to 500 MHz) while maintaining a coercivity < 32 A/m.

In the second section of *Chapter-5*, a self-assembled monolayer growth process has been developed, whereby it is possible to deposit conductive magnetic films such as Ni-Fe alloys on dielectrics like silicon dioxide and SU-8 polymer. This method has been successfully integrated with the micro-inductor fabrication processes.

This thesis takes special interest in realizing the process for a novel closed core micro-inductor on silicon. A detailed design study in *Chapter-6* of this new structure has been undertaken. The integrated inductor has a double layer metal winding completely surrounded by an electroplated $\text{Ni}_{45}\text{Fe}_{55}$ core. The top windings are realized by integrating the thick resist process described in *Chapter 3*. The chapter discusses the process challenges confronted during the fabrication and methods pursued to overcome these challenges.

Finally the thesis concludes with discussions and future work in *Chapter-7*. The processes, materials and devices developed in the thesis will find applications in next-generation power magnetics and MEMS in general. The future progress based on this thesis is discussed in detail.

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Chapter 2

State-of-the-Art: Power Inductors for dc-dc Conversion

2.1. Introduction

The scaling of devices has seen increased integration, from a transistor density of 0.2 billion per cm^2 in 2006 to almost 6.4 billion per cm^2 anticipated in 2017-18 [ITRS 2015]. Efficient energy consumption and delivery to microprocessors and systems-on-chip is a major constraint in power electronics. It requires better integration and significant miniaturization. The roadmap described by Huljak et. al. [2.1] in 2000 predicted the use of power converters within a chip by 2010. It also predicted that an isolated converter with input voltages of 12 V with dimensions of 0.1" x 0.4" x 1" and power density of 1000 W/in³ may be in use (Figure 2.1). However, these goals are yet to be achieved as the realization of such an integrated module requires multi-faceted research and development in terms of packaging, circuit topography, magnetics, and control and switches. Figure 2.2 shows the predicted technological advancements needed with the increase in frequency [2.1]. A converter efficiency of over 90% and an output of 0.5 V would be needed at 10 MHz for further scaling.

The system level miniaturization has been aided with advances in Micro-Electro-Mechanical Systems (MEMS) and packaging, where process technologies are developed and integrated for micron and sub-micron scale devices. However, new processes have to be developed to realize high efficiency and miniaturized micro-components.

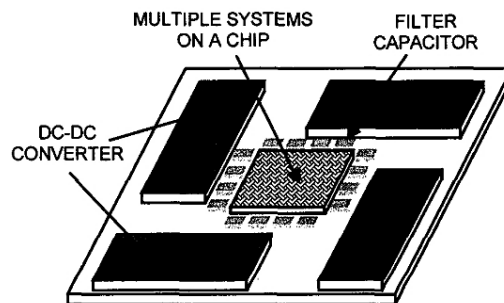


Figure 2.1. An integrated microprocessor and power converter proposed by Huljak et. al. [2.1].

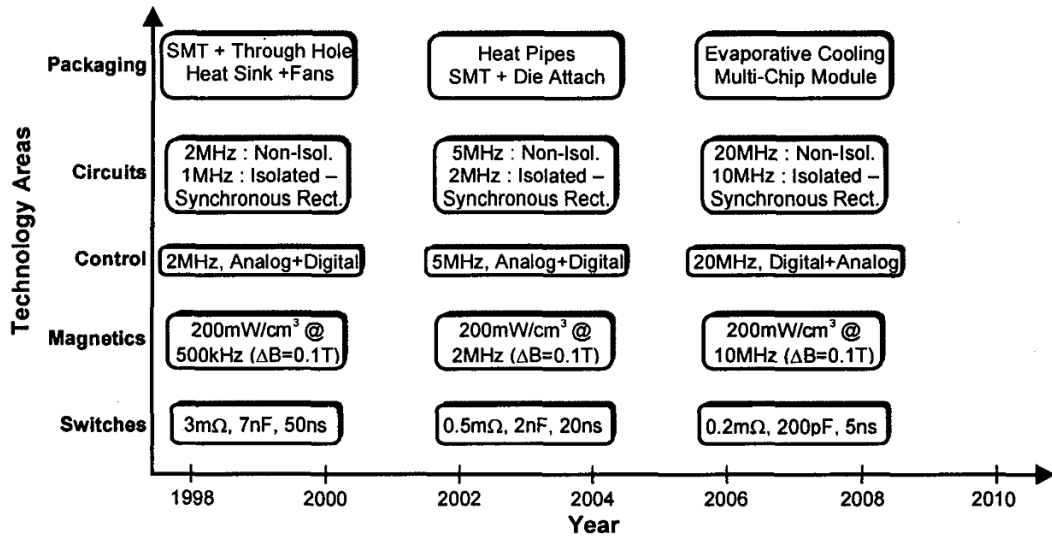


Figure 2.2 Technology developments for reducing size by increasing operating frequency [2.1].

In recent years researchers have reviewed and proposed the future trends in power magnetics (PwrSiP and PwrSoC) [2.2-2.10] and power semiconductors [2.11]. The focus of this thesis is advancing magnetics technology for miniaturization, better integration and reduced losses without compromising on efficiency. The development of process technology with simultaneous advancements in design and magnetic core technology is essential for the success of integrated magnetics [2.12]. Figure 2.3 shows the development ‘pillars’ of integrated magnetics.

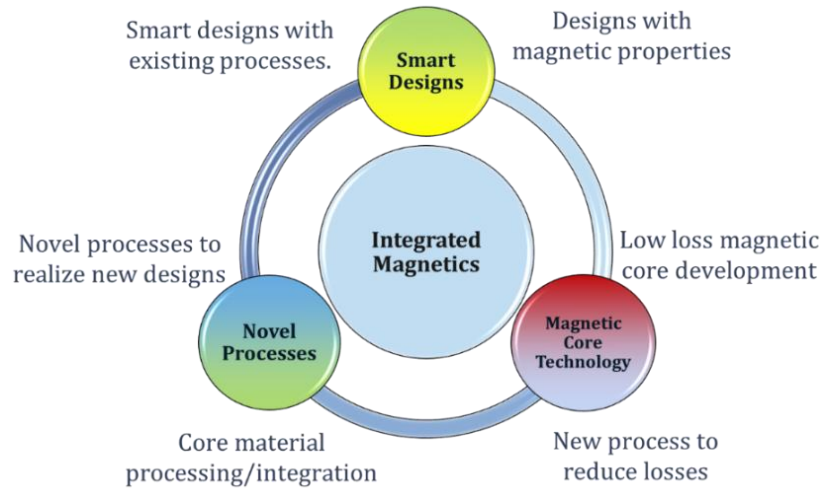


Figure 2.3. The development ‘pillars’ of integrated magnetics and their inter-dependence for its success.

In the next sections, integrated power inductors realised with MEMS based processes will be described. The inductor designs are discussed in detail and compared to outline the merits and demerits in each of the designs. This will be followed by a

brief outline of industrial and academic developments in PwrSiP and PwrSoC technology.

2.2. State of the Art

On-silicon inductors are usually CMOS compatible and can be smaller in size due to sub-micron fabrication techniques. The next section will review the magnetic micro-inductors developed for PwrSiP and PwrSoC. The section is divided in terms of inductor designs and finally a comparison between these designs is outlined. Micro-inductors can be conventionally divided into *air-core* and *magnetic core devices*.

2.2.1. Air-Core Inductors

Air-core inductors do not have a core magnetic material. The windings are in planar or 3-D geometry (such as spiral, solenoidal and toroidal) as shown in Figure 2.4 and Figure 2.5. However, packaging and reliability of such bulk-micromachined [2.13-2.14] and free standing windings [2.15] is a challenge. Compared to magnetic core inductors, where the high-frequency response is limited by the core material, air-core devices show high Q-values and a constant inductance over a large frequency range. Air-core inductors have certain disadvantages compared to magnetic core inductors. They require a high number of turns for significant inductance enhancement, thus increasing footprint and the winding resistance losses become significant on increasing the number of turns. In addition, EMI are higher compared to magnetic core. However air-core inductors are easier to fabricate with fewer fabrication steps and are more cost effective.

Kim et. al. [2.16] reported a toroidal air-core inductor prototype (Figure 2.5). The vias were fabricated with copper plated on SU-8 micro-structures (metal encapsulation process). At high frequencies, the higher current density at the surface of the windings would reduce restrict ac winding losses. But such a process would require excellent step coverage across SU-8 micro-pillars and reliability of SU-8 at high temperatures. Inductances of 76 nH and 200 nH, DC resistance $\sim 0.2 \Omega$ and 1Ω with Q-factor ~ 35 and 24 at 100 MHz were measured, respectively [2.16].

Similar fabrication approaches have been exploited to fabricate flexible inductors (shown in Figure 2.6) on parylene substrate [2.17] with and without magnetic core. Inductors on flexible substrates offer better packaging. This allows the devices to be larger in area compared to on-silicon inductors. However, the bending of the flexible substrate will elongate the metal windings. In case of magnetic cores on flexible

inductor, the bending would increase the core length and change the core magnetic properties. Moreover, the reliability and performance of the devices under stress needs to be studied.

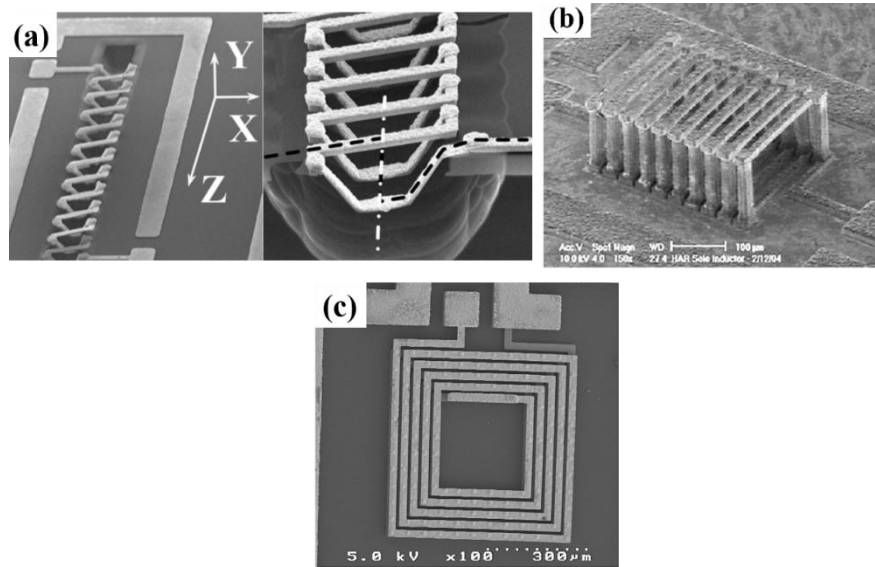


Figure 2.4. Some of the air-core inductors (a) and (b) solenoidal (c) spiral [2.13-2.15].

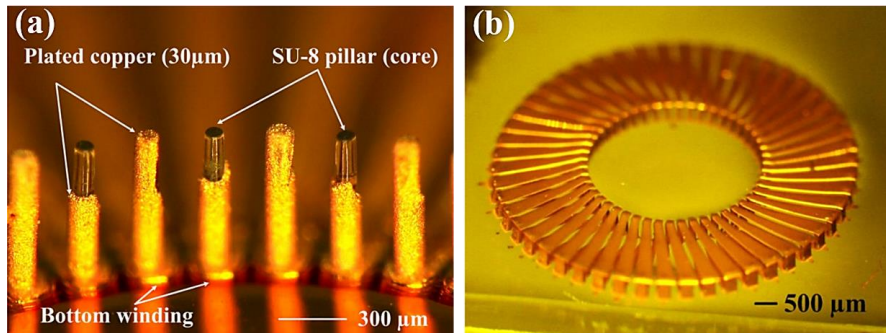


Figure 2.5. Air-core toroidal inductors with encapsulated windings [2.16].

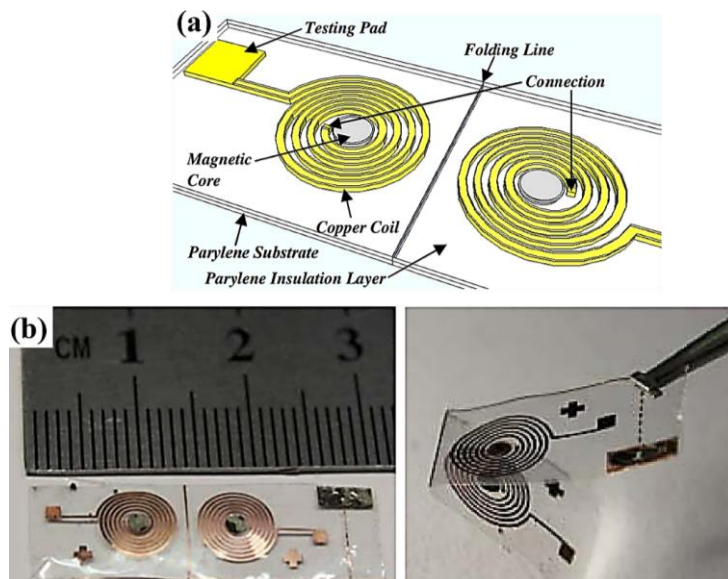


Figure 2.6. (a) Spiral inductors design on parylene and (b) multi-layer spiral on parylene [2.17].

2.2.2. Magnetic Core Inductors

(a) Planar / Spiral Micro-inductors:

Planar magnetic core micro-inductors have been realized by fabricating micro-windings on silicon with magnetic material wrapped around the windings. A high Q-value, low DC resistance and high inductance densities can be achieved with this design. Having the magnetic material surround lowers the EMI losses. Anisotropy in the magnetic core can be achieved by having a racetrack design with a stretched-out core along the easy-axis [2.18-2.21]. Figure 2.7 shows a racetrack inductor with magnetic core. These inductors can be scaled down below 1 mm^2 and are ideal for wide frequency (10 MHz-100 MHz) and inductance ranges (10 nH-200 nH). An anisotropic core can be developed by depositing the core in presence of external magnetic field with flux orientation along the hard-axis. This significantly improves the frequency response, increases saturation current and lowers the coercivity losses from the core.

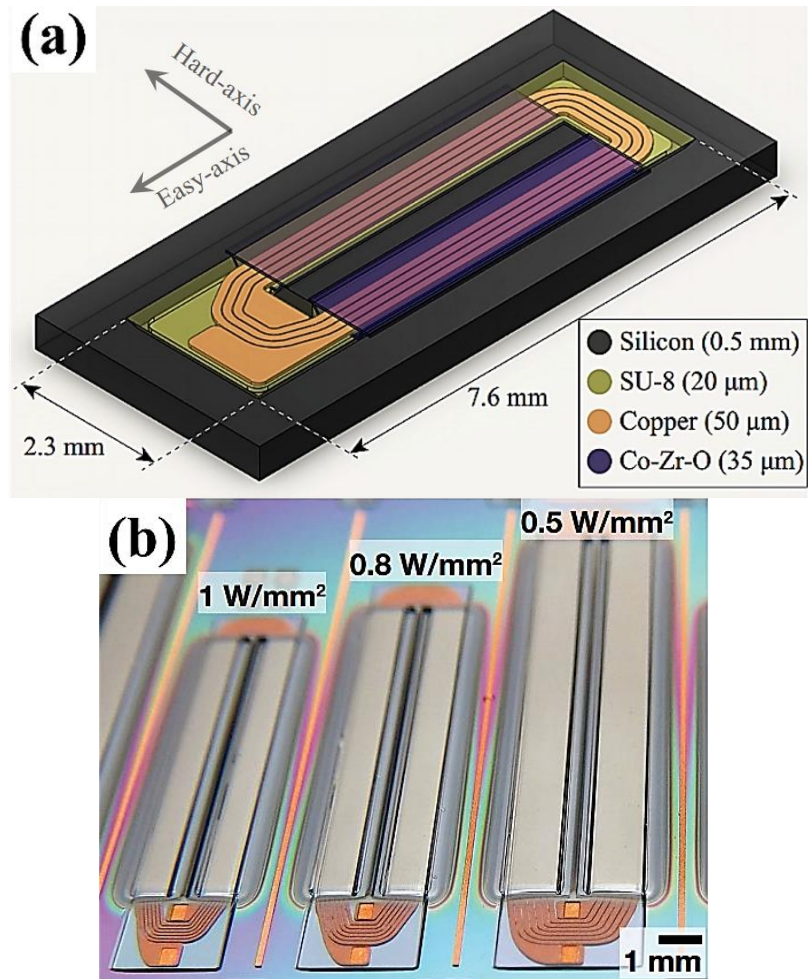


Figure 2.7. (a) Schematic of racetrack micro-inductor and (b) scaled micro-inductors [2.20-2.21].

(b) Stripline Inductors:

Stripline micro-inductors have a single winding with a magnetic material round it. Figure 2.8 shows a V-groove stripline inductor reported by researchers at Dartmouth College, USA. It has Co-Zr-O nano-granular core material all around a thick copper winding isolated from the silicon substrate insulated with oxide layer [2.22-2.23]. These designs are ideal for high frequencies (> 50 MHz), where reasonable inductances are needed (< 50 nH). Also, the current handling capacity of the designs can be improved (150 mA to 1 A) using dc flux cancellation with coupled inductor designs [2.22]. These designs are easier to fabricate, however achieving high inductances remains a challenge. Morrow et. al. [2.24] from Intel Corporation reported a stripline coupled inductor with self-inductance of ~ 22 nH and coupling coefficient of 0.9 (Figure 2.9).

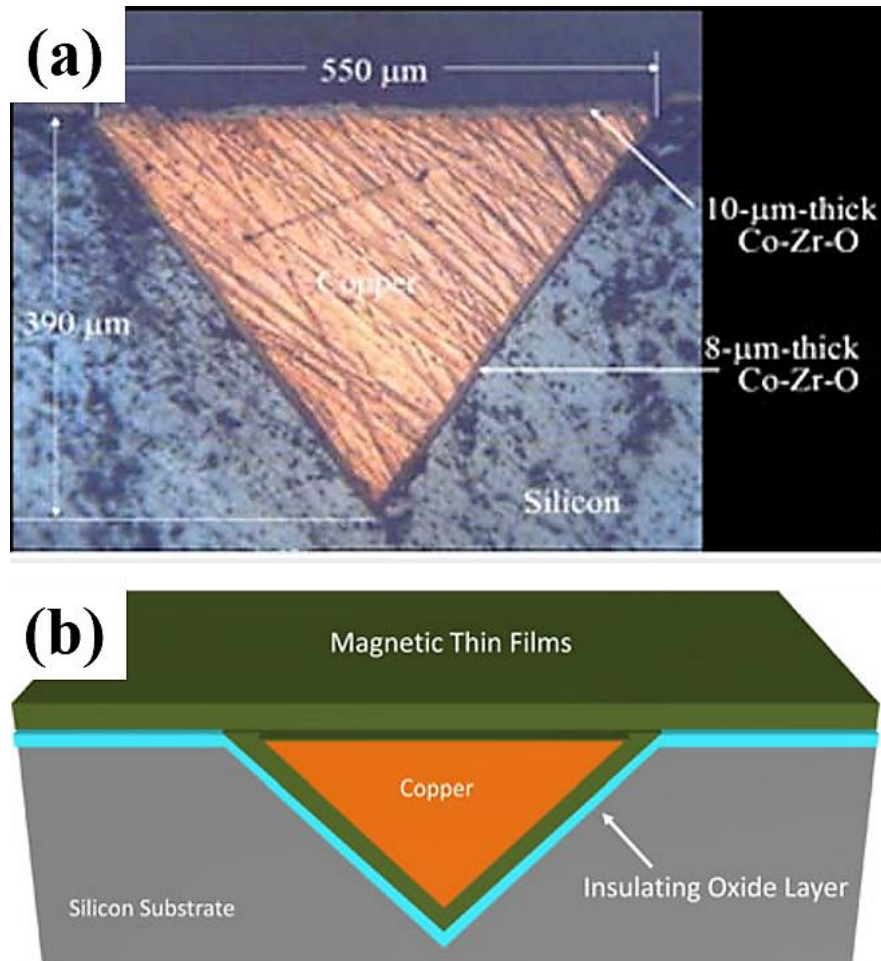


Figure 2.8. V-groove stripline micro-inductors (a) Fabricated cross-section and (b) Schematic [2.22].

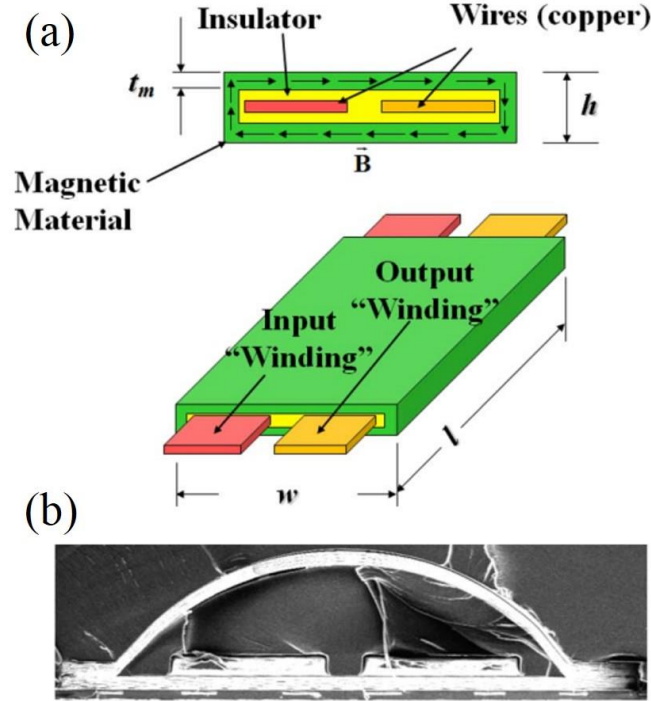
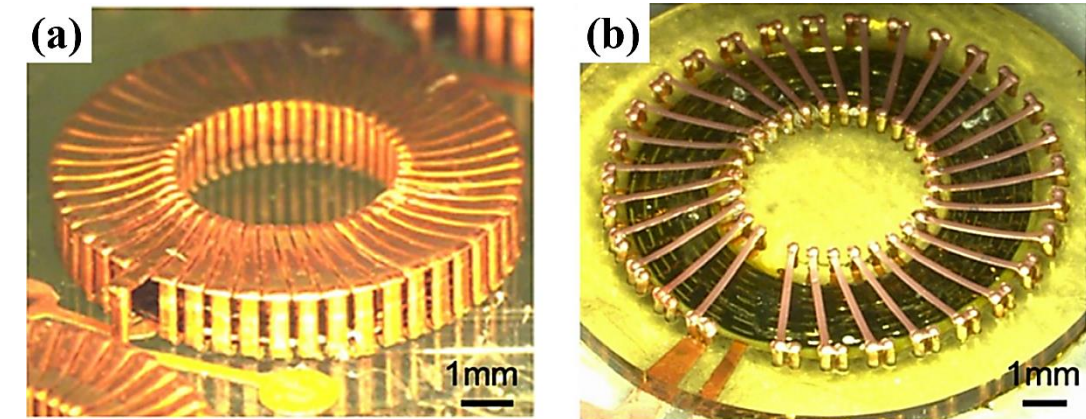


Figure 2.9. (a) Schematic of a coupled stripline inductor and (b) cross-section SEM image of the stripline coupled inductor reported by Intel Corp.[2.24].

(c) Toroidal Micro-inductors:

Toroidal inductors have a closed magnetic core around which the metal windings are wrapped. Ahn et. al. have previously reported toroidal-meander type inductors with multilevel meander Permalloy core, a footprint of 4 mm^2 and inductance density of 30 nH/mm^2 at 5 MHz [2.25]. Researchers at Georgia Institute of Technology have reported toroidal inductors (Figure 2.10) with co-packaged CoNiFe laminated core with $1 \text{ }\mu\text{H}$ inductance at 30 MHz and Q-factor of ~ 20 at 5 MHz [2.26]. High inductance densities and laminated core are under development. Moreover, integrated magnetic cores with anisotropic cores remains a challenge due to the winding geometry. Moreover, the core have to be co-packaged with the microfabricated



windings.

Figure 2.10. Toroidal microinductors (a) Air-core and (b) with packaged core [2.26].

(d) *Solenoidal Micro-inductors:*

A solenoid inductor has a bar-shaped core around which the windings are wrapped. Figure 2.11 shows a solenoidal inductor with thin CoTaZr as magnetic core. Researchers at Stanford University [2.27-2.28] have reported an inductance over 70 nH, dc resistance (DCR) below 1 Ω and a footprint $\sim 1 \text{ mm}^2$. The device was found to be well scalable and an inductance density of 219 nH/mm² could be achieved on scaling [2.27]. One of the advantages of a solenoid structure is the ease by which uniaxial anisotropy can be induced in the magnetic core structure. However, the winding structures need via connections and additional related process steps and cost compared to spiral microinductors.

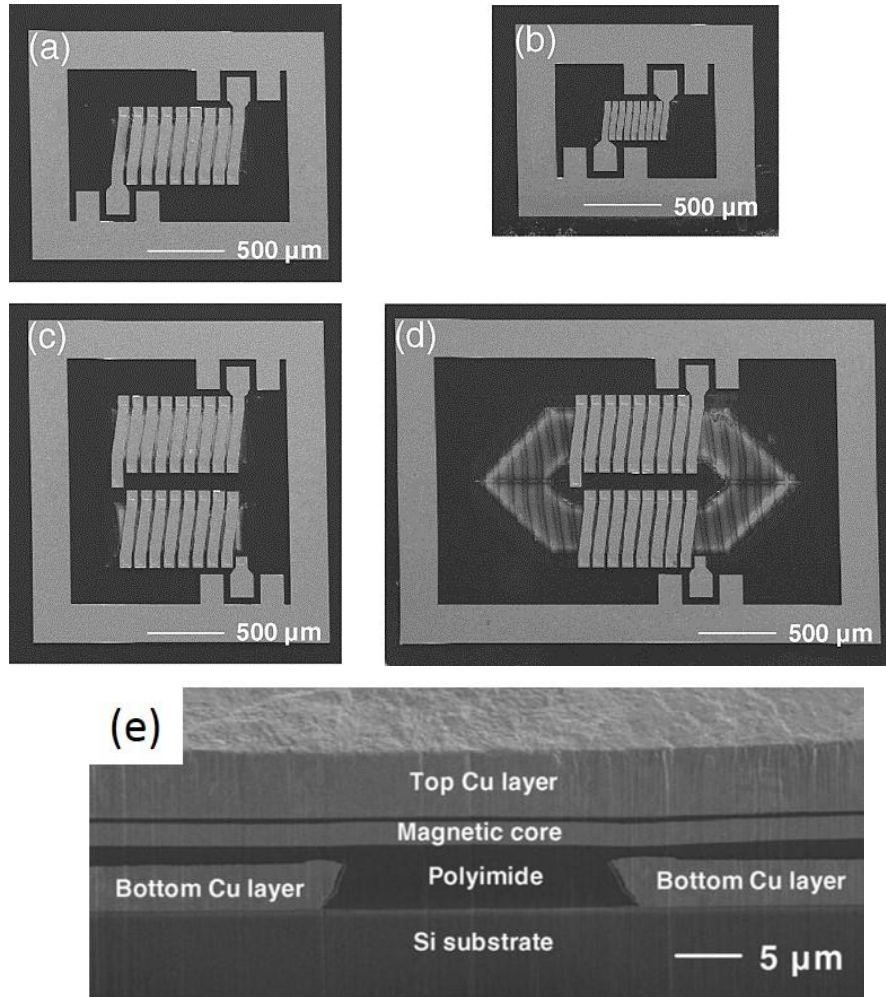


Figure 2.11. SEM images of solenoid inductor (a) before scaling (b) after scaling (c) series solenoid and (d) series solenoid with magnetic core and (e) the cross-sectional SEM image of the solenoid device [2.27].

Table- 2.1 compares the different inductor designs in terms of performance, process and losses.

Table-2.1. Micro-inductor design comparison [2.5]

Micro-Inductor Designs	Advantages	Disadvantages
Stripline	○ High inductance density. ○ Low dc resistance. ○ Magnetic core anisotropy. ○ High frequency of operation. ○ Windings are easy to fabricate.	○ Difficult to achieve high inductances (limited by footprint area). ○ Core lamination and deposition difficult.
Spiral / Planar	○ Windings can be fabricated easily. ○ High inductance density possible.	○ High EMI losses. ○ High dc resistance. ○ Core deposition and lamination difficult. ○ Uniaxial anisotropy difficult to realize.
Solenoid	○ High inductance density possible. ○ Lower substrate capacitive effects as top winding and substrate gaps are more. ○ Uniaxial anisotropy easier to realize. ○ Easy to deposit and laminate core.	○ Multi-step fabrication process (with via and two layer windings). ○ Difficult to achieve a completely integrated laminated closed core compared to stripline. ○ High dc resistance.
Toroidal	○ Lower EMI (electro-magnetic interferences). ○ High saturation current. ○ Easy to deposit and laminate core. ○ High inductance density possible.	○ Uniaxial anisotropy difficult to realize. ○ Complex fabrication process. ○ High dc resistance.

2.3. Power Supply in Package (PwrSiP) and Power Supply on Chip (PwrSoC)

Off-the-shelf power inductors are co-packaged with the *PMICs* and the other converter components to realize a packaged power converter solution, termed as *Power-Supply-in-Package (PwrSiP)*. The passive components can either be assembled along side or stacked on the ICs. Figures 2.12, 2.13 and 2.15 show some of the researched and commercially available PwrSiP platforms. In general, PwrSiP have a profile of < 1.2 mm and have higher power density compared to conventional power modules. Most of the demonstrators reported so far have air-core inductors [2.29-2.35], while some have integrated thin-film magnetic inductors [2.36-2.42]. However, the air-core inductors in these demonstrators occupy the majority of the footprint.

Although PwrSiP has been developed commercially, no PwrSoC demonstrators have been reported commercially so far. Wens et. al. (Figure 2.12) reported a fully integrated 800 mW dc-dc buck converter (26 V to 1.2 V) with four-phase (3.9 nH for

each air-core inductors) with a peak efficiency of 58% [2.32]. Switched-mode dc-dc converters (100 MHz to 233 MHz) have also been reported with an efficiency of up to 80%-87% [2.37, 2.42] by NXP Semiconductors and Intel. This compared to SC (switched-capacitors) regulators, which have 60% to 80% efficiency, provides high level of integration. Switched-mode dc-dc converters have higher efficiency, however achieving efficiency $> 90\%$ still remains a challenge.

Ni et. al. [2.34], reported a 1.2 V to 3.3 V dc-dc converter with 130 nm CMOS technology with an efficiency of 80.5%, by implementing an on-chip, high-Q air-core inductor design [Figure 2.12]. Sturcken et. al., reported a complete 2.5D chip stack, where the IC is flip chip mounted onto an interposer which holds the fabricated coupled inductors (3.2 mm^2) [2.43]. With a peak efficiency of 74%, switching frequency of 75 MHz and load current of 3 A, the 1.8V to 1.1 V converter is a step forward for $> 50 \text{ MHz}$ PwrSiP [Figure 2.13]. Commercially, Enpirion [2.45], Texas Instruments [2.46] and Panasonic [2.47] have developed PwrSiP solutions with air-core inductors.

On the other hand *Power-Supply-on-Chip (PwrSoC)* is a monolithic integration of passives onto the PMIC. To realize such a monolithic power converter solution, the inductors must be efficient and small enough for complete integration. Magnetic core inductors have high inductance density, lower electromagnetic interference (EMI) and high efficiency. However, at frequencies $> 30 \text{ MHz}$ such inductor will need laminated core for constant inductance. Hence, there is an opportunity to improve high-frequency performance of magnetic core inductors. The use of laminated magnetic cores further improves the inductance density [2.27-2.28] and restricts core eddy current losses.

No PwrSoC solutions exist to meet the tight market requirements and such inductors are suited only to $< 10 \text{ A}$ output current. Hence, PwrSoC is presently undergoing significant research and requires some key developments such as an increase in operating frequency, further miniaturization, and better integration while maintaining high efficiency for commercial success.

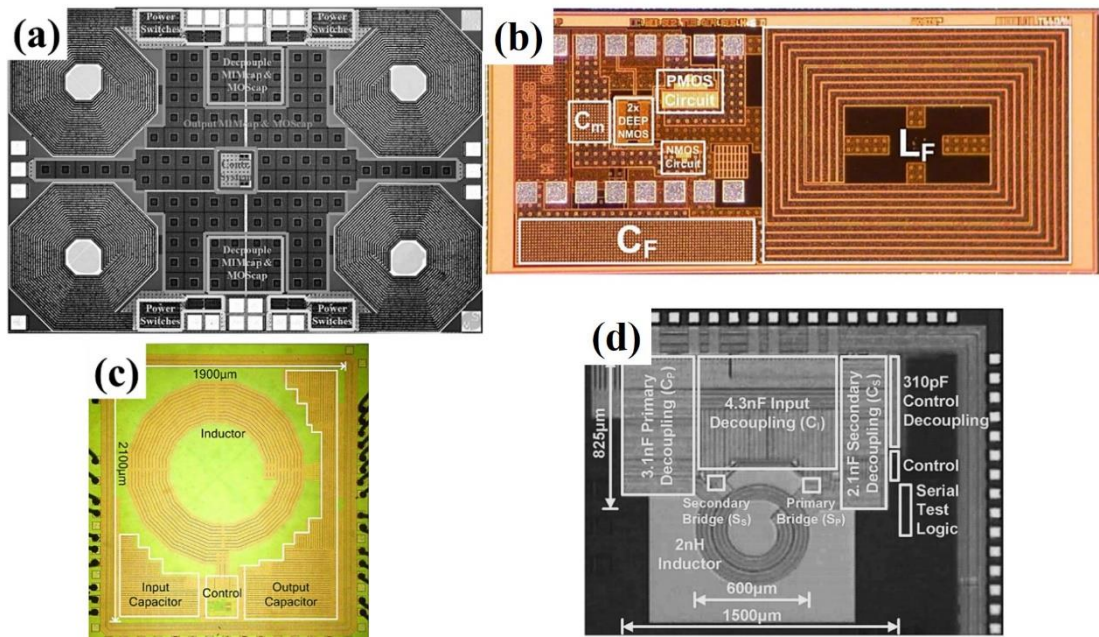


Figure 2.12. Some of the PwrSoC solutions proposed in research (a) Wens et.al., [2.32] (b) Alimadadi et. al. [2.33], (c) Ni et. al. [2.34] and (d) Musunuri et. al. [2.35].

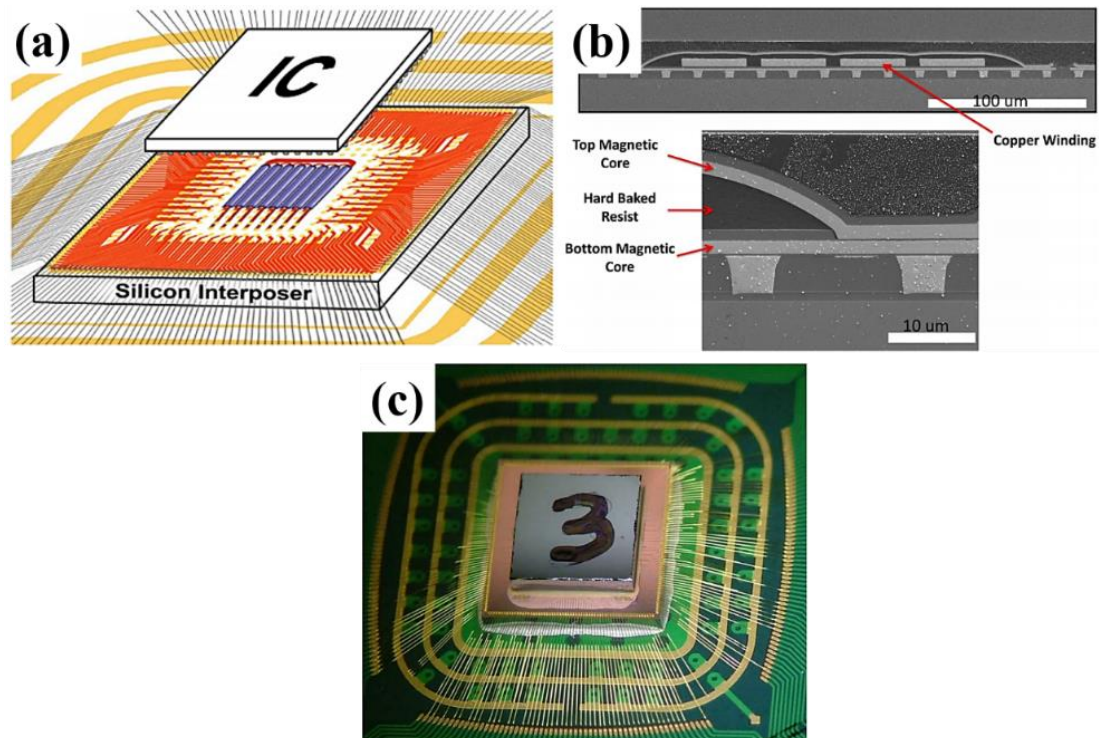


Figure 2.13. 2.5D multi-phase buck converter (a) Schematic, (b) Inductor structure and (c) packaged 2.5D integrated voltage regulator chip stack from IBM [2.43]

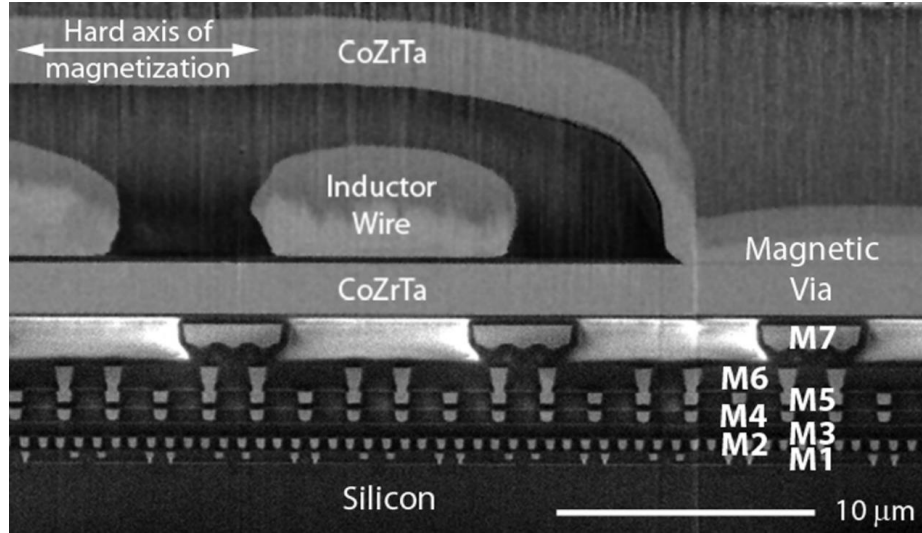


Figure 2.14. Inductor structure with CoZrTa core on top of a 90 nm 7-metal level CMOS process from Intel [2.44]

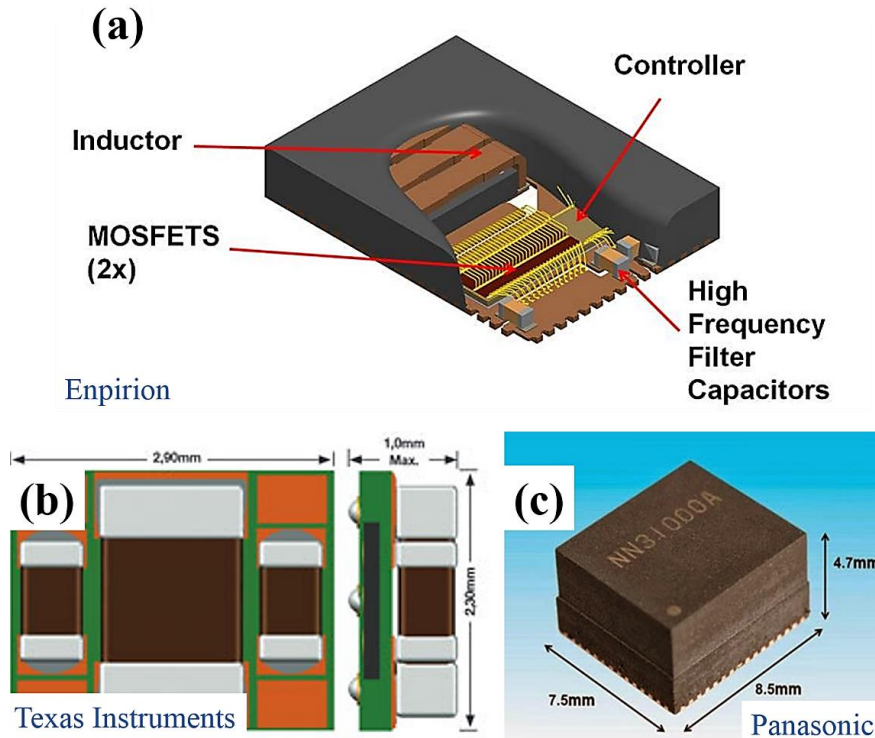


Figure 2.15. Commercially available PwrSiP modules (a) Enpirion [2.45] (b) Texas Instruments [2.46] and (c) Panasonic [2.47].

2.4. Trade-offs and Challenges

To understand the design trade-offs for integrated inductors, table-2.2 lists the parameters for an ideal inductor. An ideal inductor should have very high efficiency along with small footprint. However, this will not be possible if significant inductance is needed. To achieve significant inductances, the number of windings or the core thickness have to be increased. Increasing the turns would also increase winding losses

and footprint, while increasing core thickness beyond the skin depth would increase core losses. Figure 2.16 shows the design trade-offs for the integrated micro-inductors. The use of magnetic core material increases the inductance and inductance density (reduces footprint for required inductance), but high permeability of the material also limits the current handling capability as the core saturates more quickly. This thesis aims to address these challenges and in *Chapter 6*, a high inductance density closed core solenoid micro-inductor prototype is described.

Table-2.2 Parameters of an ideal integrated inductor

Integrated magnetic inductor parameters	Ideal characteristics
Inductance density	High
Saturation Current	High
Efficiency	High
Core losses	Low
Winding losses	Low
Footprint	Low

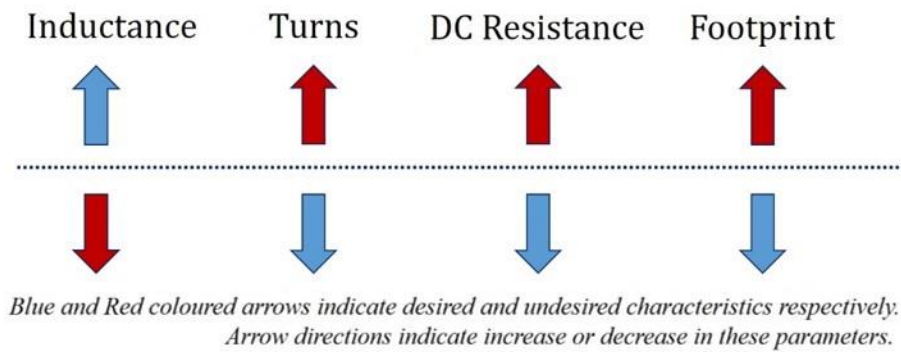


Figure 2.16. Trade-offs for designing integrated magnetic inductors with high inductance values.

2.5. Inductor Figure of Merit

Inductors can be compared in terms of their dc or ac performance [2.5]. Inductance per unit dc resistance (L/R_{dc}) is a widely used dc figure of merit (FOM). This can be improved by reducing the dc resistance by depositing thick micro-windings (discussed in chapter 3). Alternatively an increase in inductance of the device can be achieved by increasing the magnetic core thickness. This however, is often limited by the skin depth if the core material is electrically conductive. Hence, developing a high resistive magnetic core could be an alternative method of increasing L/R_{dc} . This FOM is not applicable for strip-line inductors, as the L/R_{dc} can be increased by reducing the length (therefore R_{dc}) of the strip-line. In dc-dc converters, this ratio can be expressed

in terms of the duty cycle (D), the output voltage (V_o), the output current (i_o) and ripple current (i_r) and frequency (f) :

$$\frac{L}{R_{dc}} = \frac{V_o*(1-D)}{f*i_o*i_r*R_{dc}} \quad (2.1)$$

An alternative FOM can also be expressed in terms of energy density (E : energy stored in the core of the device per unit footprint area) of the device:

$$E = \frac{Li^2}{2A_r} \quad (2.2)$$

Where, ' L ' is the inductance, ' i ' is the current and ' A_r ' is the footprint area. In this case, FOM could be increased by reducing the footprint area of the device without reducing the inductance or by increasing inductance (L) without increasing the footprint area (A_r). Both of these approaches are possible by increasing the winding density which reduces the footprint area of the inductor or by accommodating additional turns within the same footprint area. Introducing low permeability core magnetic material increases the saturation current (i), however the inductance becomes smaller. However, this FOM does not take into account the ac performance of the device in terms of ac resistance of the winding, and frequency of operation etc..

A more suitable Q -factor which considers the ac performance of micro-inductors, is a frequency, inductance and ac resistance (R_{ac}) dependent factor. It is given by:

$$Q = \frac{2\pi fL}{R_{ac}} \quad (2.3)$$

The thesis has used the above mentioned FOM for the closed core solenoid micro-inductor in *Chapter 6*, while for literature review, equation (1.3) has been used for comparison.

Table-2.3 lists some of the micro-inductors reported in the literature so far. As observed from the table, electroplating and sputter deposition remain the preferred deposition process. While, spiral/planar design is the most reported due to ease in fabrication.

Table-2.3 State of the art- Thin film micro-inductors.

‘-’ indicates data not reported

Literature	Inductor structure	Core deposition	Footprint Area (mm ²)	L (nH)	R_{DC} (Ω)	I_{Sat} (mA)	Inductor structure	Maximum Q at frequency (MHz)	Q-factor	Inductance density (nH/mm ²)	Energy density (nJ/mm ²)	L / R _{dc} * A _r (nH/ Ω -mm ²)
Brandon'03 [2.48]	Spiral	Electroplated	1	12.8	2800	5.9	25	1	1.34	218.7	0.068	37
Ahn'98 [2.49]			1	9	11700	50.4	-	1	0.25	1300	-	25.8
Walker '13 [2.50]			-	-	298.4 and 428.3	1.60 and 3.14	-	-	-	-	-	186 and 136
Panda '13 [2.51]			20	-	60	-	-	-	-	-	-	-
Sadler ' 97 [2.52]			0.1	16	1500	3	-	1000	1.25	93	-	-
Gao '05 [2.53]			0.001	1.35	424	1.6	-	1	1.7	314	-	196
Katayama'00 [2.54]		Sputtered	3	25	960	0.9	450	3	3	38.4	3.89	42.6
Nakazawa'00 [2.41]			3	16	960	0.9	450	3	3	60	6.08	66.6
Sasaki'00 [2.55]			5	12.3	400	0.4	-	5	8	32.5	-	81.3
Sato'00 [2.56]			7	21.9	360	0.45	300	7	15	16.4	0.74	36.5
Kim'02 [2.57]			8	25	1000	1	300	8	5	40	1.8	40
Harburg'13 [2.58]			4	50	1000	1.096	-	4	15	20	-	18.2
Strucken '13 [2.43]			150-200	0.245	8 x 12.5	0.27	-	-	-	51	-	46.3
Kowase'05 [2.59]		Screen-printed	4	225	140	0.015	10000	4	30	0.622	31.1	41.4
Fukuda'03 [2.60]			5	36	1500	0.67	100	5	70	41.6	0.2	62.1
Mano'05 [2.61]			5	36	1250	0.079	890	5	25	34.7	13.7	439.52

Literature	Inductor structure	Core deposition	Footprint Area (mm ²)	L (nH)	R_{dc} (Ω)	I_{Sat} (mA)	Inductor structure	Maximum Q at frequency (MHz)	Q-factor	Inductance density (nH/mm ²)	Energy density (nJ/mm ²)	L / R_{dc} * A_r (nH/ Ω -mm ²)
Mandal '13 [2.62]	Spiral	Pulsed laser deposition	< 1	15.4	500 - 1000	-	-	-	1.6	65	-	-
Uchiyama '13 [2.63]		Air-core	30	-	69 and 205	2 and 11	-	-	-	-	-	34.5 and 18.6
Pan '05 [2.64]			< 150	-	2000	-	-	30-40	60	-	-	-
Kifle '15 [2.65]			4500	-	3.86	1.46	-	3500	14.8	2.65	-	-
Yang '10 [2.66]			1000	-	1.8	-	-	15000	15	-	-	-
Han '13 [2.67]			2400	-	6.8	-	-	5000	29.3	-	-	-
Kratt '10 [2.68]			400	2.25	41	2.25	-	400	50	18	-	8
Woytasik '06 [2.69]			-	-	1000	-	-	120	20	-	-	-
Wibben'08 [2.31]			170	0.283	2	0.5	0.19	-	4.6	7	0.128	14
Wens'11 [2.32]			225	0.532	3.9	1	0.6	-	24	7.3	1.32	7.3
Alimadadi'09 [33]			660	1.8	4.38	0.7	0.05	-	10	2.4	0.003	3.5
Ni '09 [2.34]			180	1.6	10.5	1.2	0.17	-	14	6.5	0.095	5.4
Musuruni'05 [2.35]			10	16	72	2	0.3	-	-	4.5	0.2	2.25
Sun '05 [2.70]			< 6500	-	20	-	-	3000	7	-	-	-
Wang'05 [2.18]	Racetrack	Electroplated	10	6.4	140	0.13	700	4	6	21.8	5.36	168
Wang'08 [2.71]			20	11.5	440	0.5	700	5.5	11.7	38.2	9.38	76
Meere '09 [2.19]			30	2.5	144	0.4	500	9	8	57.6	7.2	144
Gardner'08 [2.72]		Sputtered	20	0.13	160	3.3	54	100	-	1230	1.8	373

Literature	Inductor structure	Core deposition	Footprint Area (mm ²)	L (nH)	R_{dc} (Ω)	I_{Sat} (mA)	Inductor structure	Maximum Q at frequency (MHz)	Q-factor	Inductance density (nH/mm ²)	Energy density (nJ/mm ²)	L / R_{dc} * A_r (nH/ Ω -mm ²)
Prabhakaran'05 [2.73]	Stripline	Sputtered	5	9.02	2.6	0.074	10000	5	10.9	0.29	14.4	411.78
Gardner'09 [2.44]			40	0.022	3.7	0.04	30	100	-	165.1	0.074	4129.5
Yao'11 [2.22-2.23]			100	0.424	3.4	0.004	1000	100	66	8	4	2093.7
DiBene'10 [2.26]			82	0.12	17	-	75	10	-	141.7	0.4	-
Morrow'11 [2.24]			50	0.12	17	0.02	75	10	3.3	141.7	0.398	-
Lu'07 [2.74]	Toroidal	Sputtered	30	113	470	-	3500	30	67	4.16	25.48	-
Orlando'06 [2.75]		PVD	10	31.4	500	0.095	180	10	20.9	16	0.26	167.6
Y. Y. Park'99 [2.76]		Electroplated	5	3.36	800	1.95	100	5	8.1	238	1.19	122.11
D. Flynn'06 [2.77]			1	10	1240	0.05	112	1	1.73	124	0.78	2480
Lei'07 [2.78]	Solenoid	Electroplated	5	16	1610	-	-	5	1.42	100.6	-	-
J W Park'03 [2.79]			3	65.55	2300	0.15	200	3	9.2	35	0.7	233.9
J Y Park'00 [2.80]			0.001	4	670	0.3	10	0.3	1.7	167.5	0.008	558.3
Ahn'98 [2.81]			1	4	400	0.308	-	1	1.5	100	-	324.6
Kim'15 [2.82]			< 10	27	600	-	-	4	20	22	-	-
Lee'08 [2.28]		Sputtered	30	0.88	70	0.67	200	30	6	79.5	1.59	118.7

Comprehensive plots from the data in table 2.2 (both air and magnetic core) are shown in Figure 2.17 to Figure 2.21. Spiral and solenoid/toroidal inductors with operating frequency > 10 MHz have been reported, while stripline inductors have shown high inductance density and are found to be ideal for < 10 MHz frequencies (Figure 2.17). Intel [2.24] have reported > 100 MHz stripline inductors with laminate core. The study indicates that spiral inductors could ideal choice for high inductance density for high frequency operation.

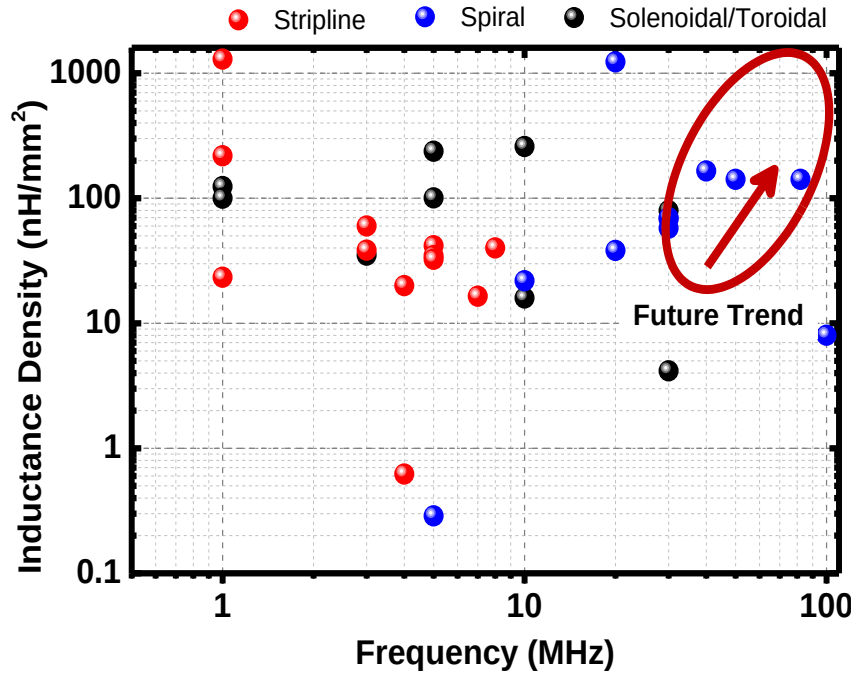


Figure 2.17. Inductance density vs. frequency for different integrated inductor designs (obtained from table-2.2).

Stripline inductors have lower DCR and high inductance density (but limited inductances) due to a single strip of winding, while solenoid and spiral can have moderate DCR values with high inductance densities (Figure 2.18). Spiral designs reported have higher Q-factor < 10 MHz, while solenoid designs could have moderate Q-value > 10 MHz with significantly higher inductances. This is limited by the core material properties and remains a major challenge. Hence, stripline design could be ideal choice for low inductance requirements. However, high inductance requirements could be fulfilled by spiral and solenoid designs.

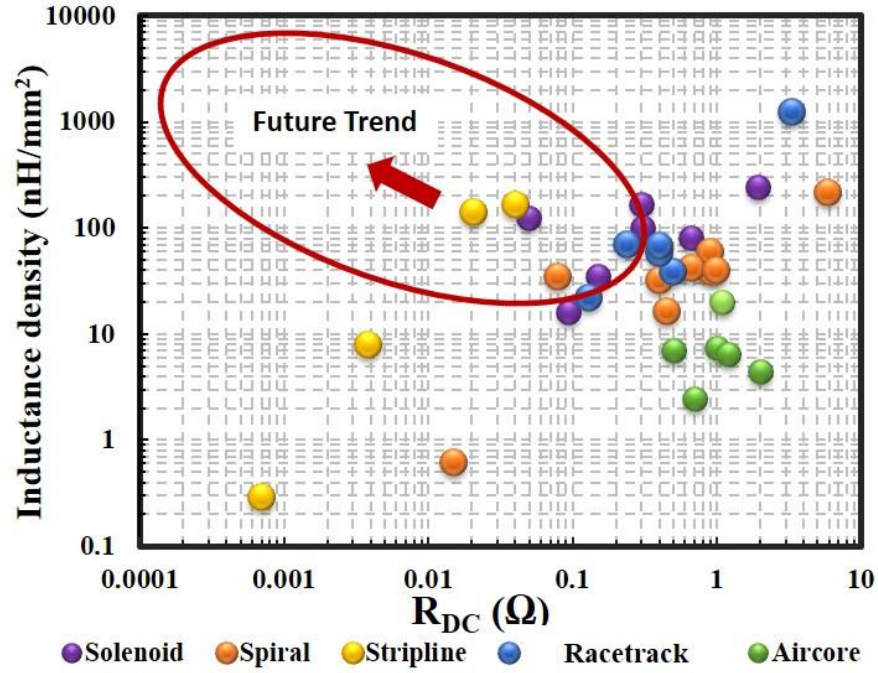


Figure 2.18. Inductance density vs. DCR for different integrated inductor designs (obtained from table-2.2).

At high frequencies (> 100 MHz), air-core inductors have constant inductance (Figure 2.19). However, the absence of magnetic core limits the inductance. Stripline inductors could provide high energy density at frequencies (< 100 MHz), while air-core inductors have much lower energy densities but are acceptable > 100 MHz (Figure 2.20).

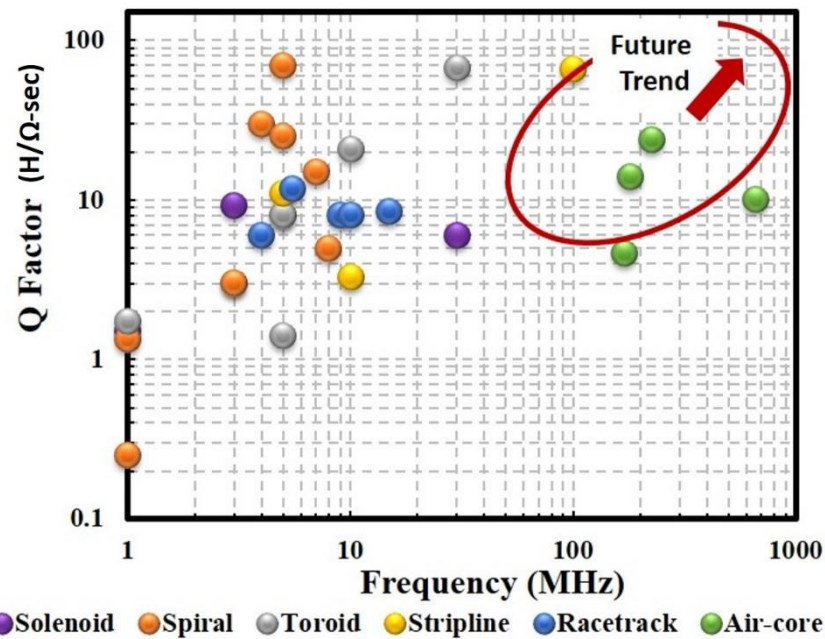


Figure 2.19. Q-factor vs. frequency for different integrated inductor designs (obtained from table-2.2).

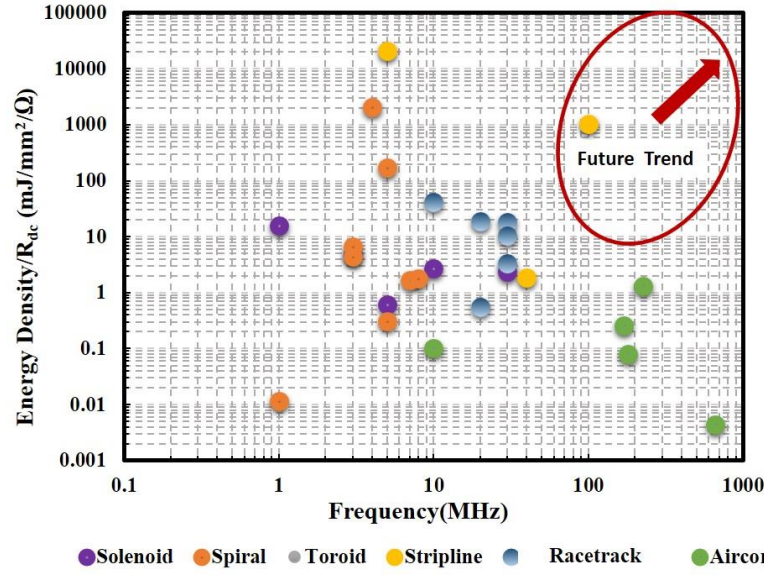


Figure 2.20. Energy density vs. frequency for different integrated inductor designs (obtained from table-2.2).

Reported solenoid and spiral inductors have high L/R_{DC} , while spiral inductors show higher inductance density (Figure 2.21). Solenoid inductors have shown moderate energy density with high L/R_{DC} ratio.

In this thesis a closed core solenoid inductor have been demonstrated to achieve moderate inductance and high L/R_{DC} values as an alternative to stripline inductors for < 30 MHz operation.

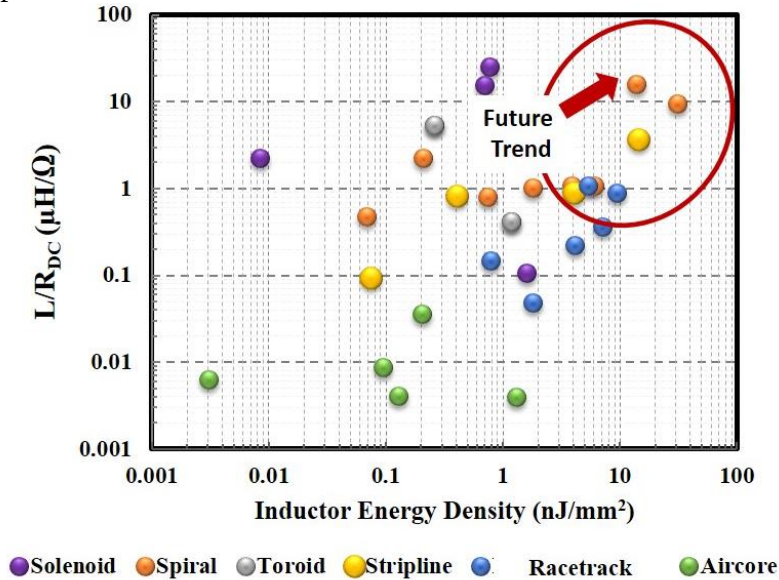


Figure 2.21. Inductance per DCR vs. inductor energy density for different integrated inductor designs (obtained from table-2.2).

2.6. Conclusions

This chapter focusses on the state of the art in micro-inductors technology developed for PwrSiP and PwrSoC solutions. Unlike air-core, magnetic core inductors have lower component footprint area and high efficiency. Hence, magnetic core inductors are essential in realizing compact, high density and efficient PwrSoC solutions. The literature survey undertaken suggests significant work has been done in developing magnetic core inductors (spiral, toroidal, solenoid etc.). However, compared to air-core inductors, magnetic core eddy current losses dominate at high frequencies. In the next few chapters, this thesis will propose solutions to reduce winding and core losses. It will then explore methods to achieve electrochemical and sputter laminated cores for restricting high frequency eddy current losses. Then closed core inductor will be designed, micro-fabricated on silicon and tested.

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Chapter 3

Micro-Winding Process Technology

3.1. Introduction

This chapter presents the importance of high-aspect-ratio (HAR) and high-resolution (i.e. minimum photoresist feature size) photoresist in reducing winding losses and device footprint area by electroplating compact windings respectively for high-frequency inductors on-silicon. Detailed analysis is included on the influence of windings losses on the device efficiency and reduction of device footprint. To overcome the winding losses, high-aspect-ratio MEMS based photoresist processes, both negative and positive tones were investigated and the limitations of the optical photolithography and the photoresists have been described.

The photoresists were shortlisted depending on the following properties:

- Excellent adhesion to most surfaces, especially copper surface for plated copper windings.
- High resolution ($< 10 \mu\text{m}$) and HAR (> 10) with moderate thickness $< 100 \mu\text{m}$.
- Wide process margin.
- High photoresist sensitivity to broad-band exposure.
- Stable in acidic electrochemical baths.
- Easy stripping.

Apart from the above mentioned properties, a photoresist with good adhesion to Ni-Fe surface is explored as an etch mask and compared to traditionally used SU-8 photoresist for top core patterning. Figure 3.1 (a) and (b) shows the Ni-Fe core wet etched through a photoresist mask. The edges of the patterns show over-etched core. This would also reduce the core over-etch and improve wafer yield. This chapter will also investigate the influence of winding thickness and spacing on reducing AC and dc winding resistance. As a solution to these requirements, a new process is developed with negative tone THB-151N photoresist for fabrication of HAR ($\sim 17:1$) micro-windings and as a wet etch mask for core etching.

The process developed has been integrated to realize the top windings in a closed-core solenoid micro-inductor structure proposed in chapter 6.

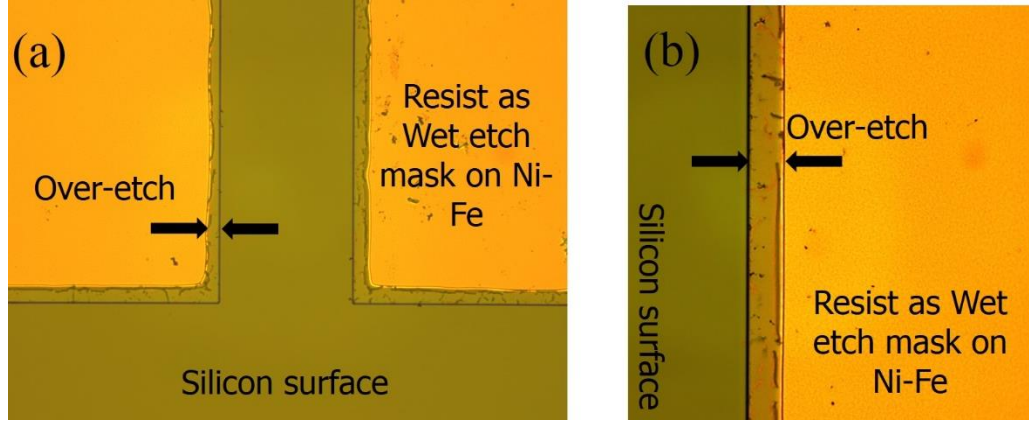


Figure 3.1. Over-etch observed on bottom core wet etching with AZ9260 wet etch mask.

3.2. Winding Loss Study

Reducing the size of the thin film micro-inductors for industry scale packaging will only be possible by reducing the inductor feature sizes and increasing packaging density of the windings [3.1]. However, miniaturization has shown an increase in DC winding loss contribution to the overall inductor loss [3.2]. Also, metal moulding processes for fabricating inductor micro-windings are presently limited by low resolution photoresist processes. This has restricted the efficiency of the micro-inductor device and the net efficiency of the dc-dc converter circuitry. It is therefore, important to understand the role of winding losses on net device efficiency and how it impacts the inductor performance as the device footprint is reduced. In an ideal situation, inductor efficiency (η) will be 100%. Considering only losses from the inductor, the inductor efficiency (η) as a FOM is expressed in terms of converter power output ($P_{\text{Converter Output}}$) and input ($P_{\text{Converter Input}}$) as:

$$\eta = \frac{P_{\text{Converter Output}}}{P_{\text{Converter Output}} + P_{\text{Inductor losses}}} \quad (3.1)$$

Where,

$$P_{\text{Inductor losses}} = P_{\text{Winding losses}} + P_{\text{Core losses}} \quad (3.2)$$

And,

$$P_{\text{Winding losses}} = P_{\text{dc losses}} + P_{\text{ac losses}} \quad (3.3)$$

The AC losses can be divided into proximity losses and skin effect in the windings. These effects become prominent at high frequencies. The performance indicative parameter of these devices is the Q -factor which is dependent on the resistance (R) and inductance (L) of the windings at a frequency (f) and is given by:

$$Q = 2\pi fL / R_{ac} \quad (3.4)$$

The winding losses due to skin effect and proximity effect vary with frequency and so will the inductor Q factor. In order to achieve high performance characteristics, it is apparent that the winding resistance has to be reduced for a designed inductance and frequency within a designated footprint. This is only feasible with a high AR and high resolution moulding photoresist process. Thick micro-windings will decrease DC resistance [3.3].

It is important to note that at high frequencies, due to skin effect, there is current crowding at the surface of the conductor. As a result, the effective current carrying area decreases, thereby increasing the resistance of the windings at high frequencies. Apart from skin depth losses, reducing the winding spacing increases proximity losses, i.e. the increment in the resistance of a winding caused by nearby alternating current carrying conductor. It is hence important to study the limitations of a thick winding at high frequencies. Figure 3.2 shows the Ansoft Maxwell 3D simulation of 4-turn copper winding (50 μm thick and separated by 5 μm spacing) at 100 MHz and 0.5 A current with skin effect. Figure 3.2 shows that the current density is higher at the surface of the copper windings due to skin effect.

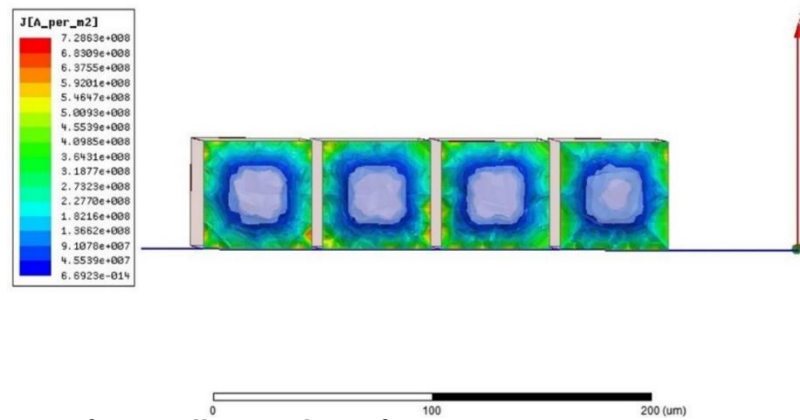


Figure 3.2. Ansoft Maxwell 3D analysis of 0.5 A current carrying copper windings at 100 MHz depicting skin effect.

Figure 3.3 depicts the analytically obtained [3.4], highest efficiency (considering AC and DC winding losses) achievable in a 120 nH racetrack inductor operating at 20 MHz switching frequency at different footprint areas (2 mm^2 to 15 mm^2) for $35 \text{ }\mu\text{m}$ thick winding and varying winding spacing. For smaller footprint, there is 4 % efficiency fall from the ideal case, because of $\sim 26\%$ increase in DC resistance contribution. This effect is not very prominent for larger footprint inductors. It is apparent that the percentage of device footprint occupied by the spacing becomes less significant for larger footprint area, which in turn makes the device performance less sensitive to the spacing.

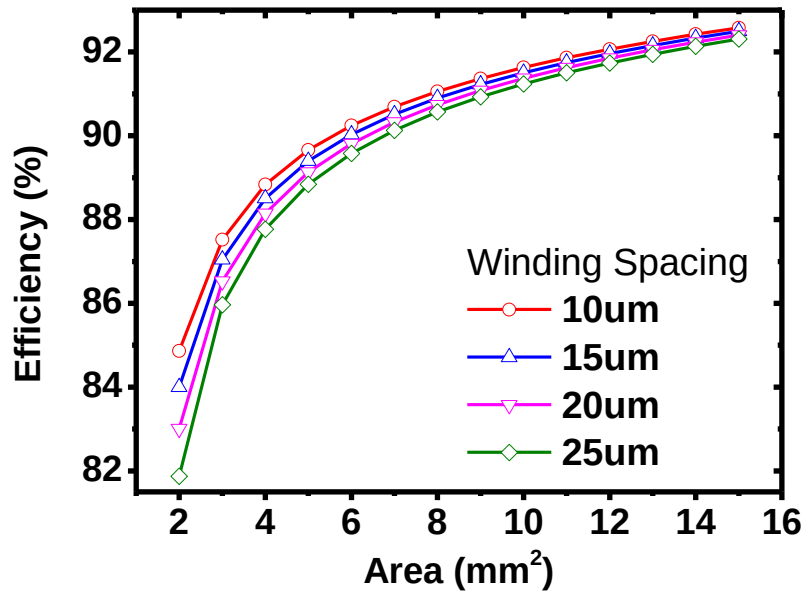


Figure 3.3. Design Study: efficiency dependence on inductor footprint for varying winding spacing. ($L=120 \text{ nH}$, winding thickness= $35 \text{ }\mu\text{m}$, frequency= 20 MHz)

In this study of the influence of winding width and spacing on inductor efficiency, the loss contributions from the core and device geometry (except winding width and spacing) are kept fixed. The footprint (0.5 mm^2), device geometry, frequency (20 MHz) and core losses have been fixed to explicitly study the influence of winding losses due to variation in winding geometry on inductor efficiency. A magnetic core (Ni-Fe 45/55) with a thickness of $4.5 \text{ }\mu\text{m}$ is considered for the study. The inductance varies only with the winding cross-sectional area.

Figure 3.4 (a) and 3.4 (b) depicts the inductor schematic and the calculated efficiency (computed from equation 3.1) of the micro-inductors designed with varying windings spacing and width for 50 μm and 80 μm thick Cu windings (4 turn) with a magnetic core. With fixed core dimensions, footprint (1.5 mm^2) losses from the core (hysteresis and eddy currents) are kept constant. The variation of efficiency with winding spacing's and width is completely due to winding losses. Increasing winding width at the expense of winding spacing improves device efficiency. The efficiency of the device can be further improved by reducing the DC winding losses by increasing the winding thickness. Brunet et. al. [3.5], have previously reported a multistep process for thick (91 μm) AZ 9260 with an aspect ratio and minimum feature size of 6:1 and 14 μm , respectively for fabricating micro-windings. However, limited thickness in single spin ($\sim 10 \mu\text{m}$) and the resulting need for multi-step coating increases the processing time. Additionally, process optimization becomes difficult as multiple soft bakes have to be included, which means the first coated photoresist layers is often overbaked.

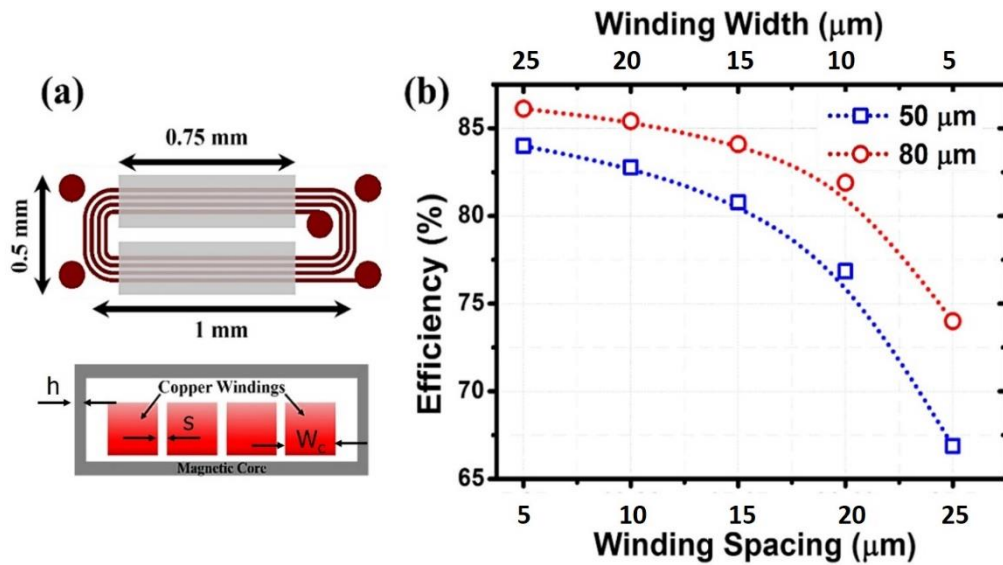


Figure 3.4. (a) Schematic representation of a magnetic core micro-inductor and its cross-section. (b) Influence of winding thickness and width on micro-inductor efficiency (0.5 mm^2 footprint area).

The resolution of the photolithography process often restricts the minimum winding spacing that can be achieved. Moreover, the thickness of the photoresist also limits the minimum photoresist width which becomes the winding spacing. Hence, a trade-off is needed between HAR and high-resolution photoresist process such that thick windings are realized to reduce DC winding losses while keeping the footprint to a minimum.

The core-width of the device is determined by the winding width (W_c), number of turns (n), spacing (s) and the thickness of the core (h) as shown in Figure 3.3 (a).

$$\text{Core width} = 2[n(s + W_c) + s + h] \quad (3.5)$$

It essentially means that the core width depends on the winding width and the spacing (parameters limited by micro-winding fabrication processes). In other words, to reduce the core - width we have to reduce ' W_c ', ' h ' and ' s ' or at least one of them. As reducing winding width will increase the DC winding losses and reduce device efficiency, the only other way to reduce the micro-inductor footprint without increasing the DC winding losses is by reducing the winding spacing. This ascertains the need for a high resolution and aspect ratio metal moulding process. Hence, simply a HAR process would not satisfy the need for miniaturization of the device. Essentially the new process must yield both high resolution for reducing footprint and HAR for reducing DC winding losses.

It is important to note that at high frequencies, due to skin effect, there is current crowding at the surface of the conductor. As a result, the effective current carrying area decreases, thereby increasing the resistance of the windings at high frequencies. Apart from skin depth losses, reducing the winding spacing increases proximity losses. It is hence important to study the limitations of a thick winding at high frequencies. Figure 3.4 shows the Ansoft Maxwell 3D simulation of 4-turn copper winding (50 μm thick and separated by 5 μm spacing) at 100 MHz and 0.5 A current without (Figure 3.4 (a)) and with (Figure 3.4 (b)) the proximity effect taken into account in the simulations. This has been done by considering a region of analysis around the inductor during the simulation for including proximity effect. Figure 3.4(a) shows that the current density is higher at the surface of the copper windings due to skin effect. However, on taking into consideration a vacuum region around the windings for the proximity study (Figure 3.4 (b)), we observe that the flux from the adjacent current carrying winding links with the adjacent windings, thereby increasing the current density at the surface of the windings.

3.3. State of the Art: Metal Moulding Technology

In recent years, miniaturization of micro-electromechanical systems (MEMS) and advances in chip level packaging have been supported by developments in

technologies such as photoresists for patterning via electroplating and wet-etching. Furthermore, the need for efficient alternatives to existing MEMS processes especially for selective wet-etching of thick metal patterns, moulds in micromachining processes and solder bump-bonding requires thick and strippable photoresist process development. One of the challenges is to develop a high resolution and HAR removable metal moulding photoresist process. X-Ray-LIGA (*Lithographie, Galvanoformung, Abformung*) has been used to achieve high resolution and structure density [3.6]. However, UV-LIGA methods are more attractive being more cost-effective and capable of processing at the dimensions ideal for a wide range of MEMS applications. For an industrial scale development, the process must be repeatable with an acceptable process margin and low cost.

a. Ultra-Thick SU-8 and KMPR photoresist:

Ultrahigh thickness > 1 mm [3.8] and HAR > 18 in a single spin [3.9] have already been reported with SU-8 [3.7] (Figure 3.5(a)). However, internal stress, low resolution and in some cases poor substrate adhesion [3.10] are major drawbacks. Moreover, SU-8 swelling during the development step can result in device failure and may be followed by complete delamination [3.11]. This is often compensated for with adhesion promoters (such as OmniCoat) or additives. However, processing to improve the adhesion can lead to difficulties in stripping the resist after polymerization which can damage micro-structures.

Other chemically amplified ultra-thick photoresists [3.12] such as KMPR, have shown similar drawbacks [3.13-3.14]. At low-micron levels (< 10 μm) it becomes more challenging to develop the patterns without damaging them.

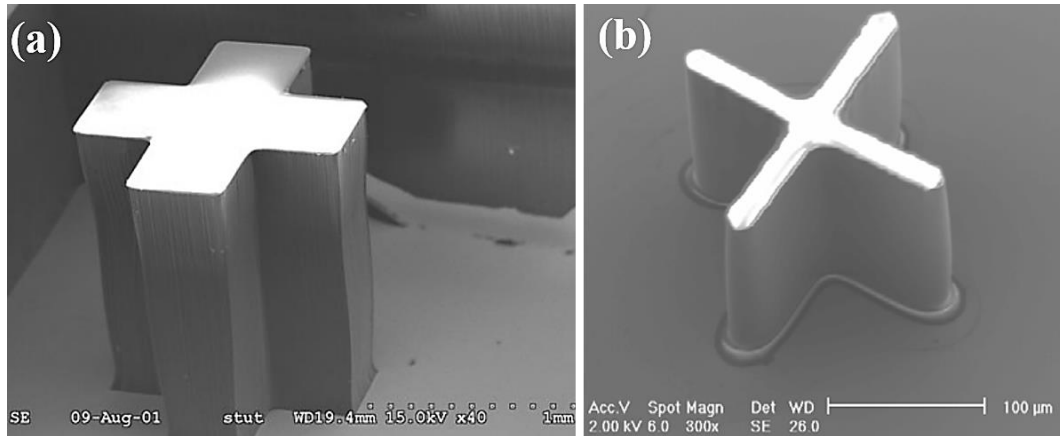


Figure 3.5. (a) 1.5 mm thick ultra-thick SU-8 structures [3.8]. (b) 180 μm thick and HAR (18:1) KMPR structure [3.12]

b. Next generation thick photoresists:

Figure 3.6 (a) shows the micro-winding structure electroplated through traditionally used AZ 9260. Recently, Rao et al. [3.15] have demonstrated 130 μm thick THB-151N resist molds with an aspect ratio of 2.6:1 and minimum feature width of 50 μm (Figure 3.6 (b)). Other thicker negative tone variations in the AZ series (AZ 125 nXT) [3.16] have also been reported to have 18:1 aspect ratio with 20 μm as minimum feature size (Figure 3.6 (c)). Bourrier et al. [3.17], have shown significant improvement with BPN-100 compared to the supplier data sheet by reporting a process for 500 μm thick with 17:1 aspect ratio and 30 μm wide resist molds (Figure 3.6 (d)).

Table 3.1 lists the thick photoresist processes used for metal moulding applications and compares the process parameters from the literature. Positive tone resists require multiple spins [3.5] to attain $> 50 \mu\text{m}$ thickness thus increasing the process time to > 420 minutes. On the other hand, most negative tone resists require significant pre and post exposure bake. Some earlier works have shown encouraging resist thickness in single spin processing, however poor resolution deems them impractical for miniaturized MEMS fabrication. The focus of this work was to achieve a thick metal moulding photoresist process along with a high resolution (i.e. minimum photoresist feature size which is also the winding spacing).

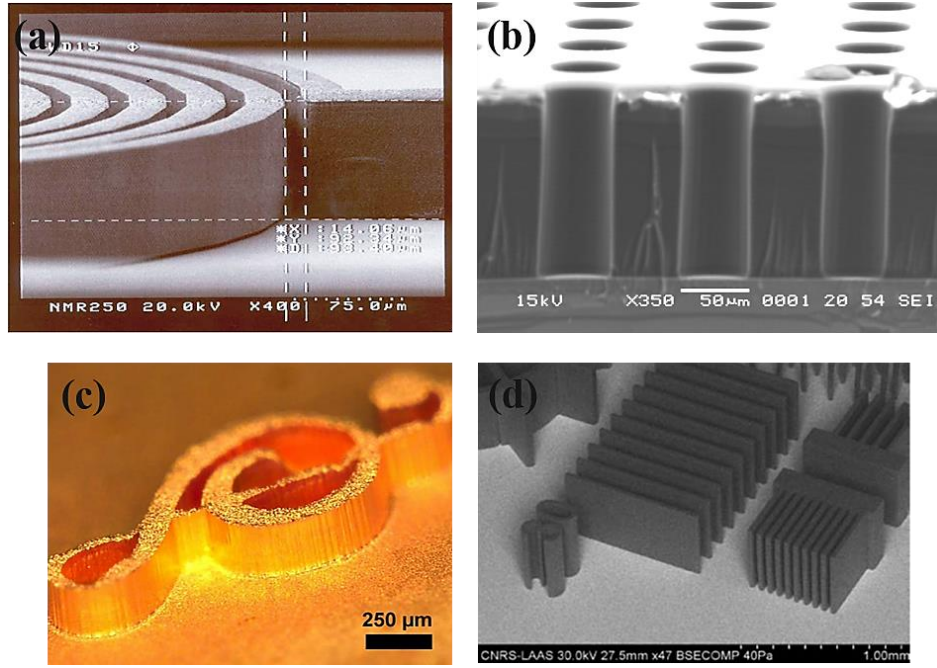


Figure 3.6. (a) Micro-winding structures with AZ 9260 [3.5], (b) micro-pillars with THB-151N [3.15], (c) ultra-thick AZ 125 nXT micro-structure [3.16] and (d) 500 μm thick test patterns with BPN-100 [3.17].

Table 3.1. Temporary photoresists for thick micro-metallic moulds

'-' indicates data not reported

'NA' indicates not needed

Photoresist	Photoresist Type	Maximum Thickness (μm)/ Number of spins	Resolution (μm)	Pre & Post Bake Time (min)	Aspect ratio
AZ 9260 [3.5]	Positive tone	81 / 4	14	150 / NA	6
BPR 100 [3.18]	Negative tone	100 / 1	60	40 / 20	1.5
BPN 100 [3.17]	Negative tone	500 / -	30	425 / NA	17
NR2-20000P [3.19]	Negative tone	120 / -	-	-	3
THB-151N [3.15]	Negative tone	130 / 2	50	15 / NA	2.6
AZ 125XT [3.16]	Negative tone	1800 / -	90	-	< 20

3.4. Theoretical Limitations

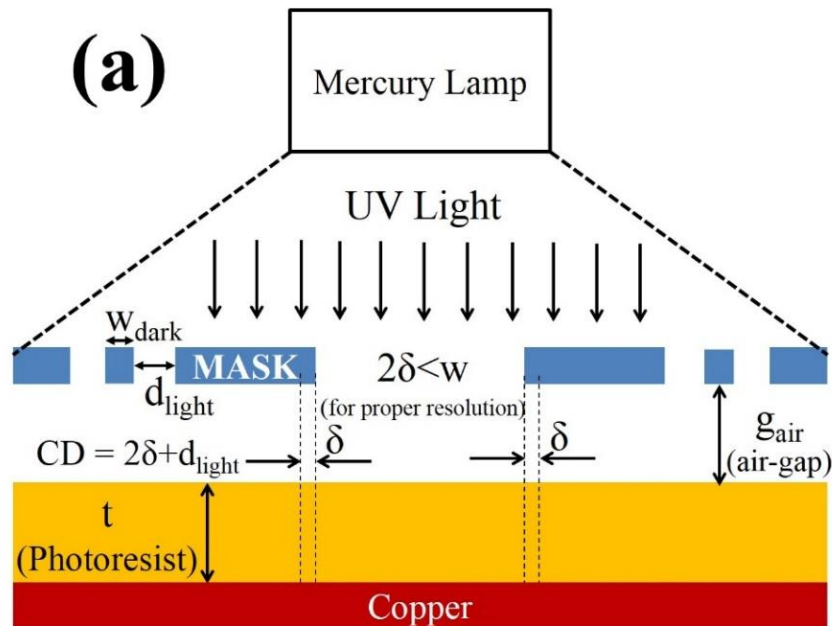
In shadow exposure mode, UV exposure plays a crucial role in determining the minimum resolution (the *critical dimension* (CD)) that can be developed faithfully. The CD is dependent on UV wavelength (λ), the gap between the mask and photoresist (g_{air}) and photoresist thickness (t) and given by the equation [3.20]:

$$\text{Critical Dimension} = \frac{3}{2} \sqrt{\lambda \left(g_{\text{air}} + \frac{t}{2} \right)} \quad (3.6)$$

Figure 3.7 (a) is a schematic depiction of edge broadening observed on UV exposure in hard-contact mode ($g_{\text{air}}=0$). Considering the photoresist to be more responsive to i-line, the optimum λ is considered to be 365 nm. In the case of a negative

tone photoresist, the broadening of exposed regions would mean an increase in exposed resist width by 2δ . This means that the minimum width of the dark region (w) should be $> 2\delta$ to avoid bulk exposure. After exposure, the negative tone resist will broaden to $2\delta + d_{light}$ where ' d_{light} ' is the actual width of the feature size in the mask. The situation can worsen in the presence of edge beads which creates an unavoidable air-gap from mask to resist even in hard-contact mode and with thicker photoresists.

Figure 3.7 (b) shows minimum resolution and maximum AR achievable in hard-contact mode on UV exposure with photoresist thickness (calculated from equation 3.6). The AR is calculated by the ratio of photoresist thickness and width by considering the CD as the minimum resist width (for negative tone photoresist). As expected the CD increases with the thickness of the photoresist, but it is interesting to note that the maximum achievable AR also increases with photoresist thickness. For ultra-thick resists (such as SU-8), an AR of 35:1 is possible with 500 μm thickness. The AR reduces to 2:1 when thickness approaches $\sim 10 \mu\text{m}$. It is apparent that thick resist processes are preferable for HAR. As mentioned earlier, an increase in thickness also increases the CD significantly as observed from the figure. In case of winding process, this increase in width will translate into the winding spacing which will increase the footprint of the inductor. It is therefore obvious, that a trade-off exists and must be addressed to ensure a specified footprint is maintained by opting for an appropriate photoresist thickness.



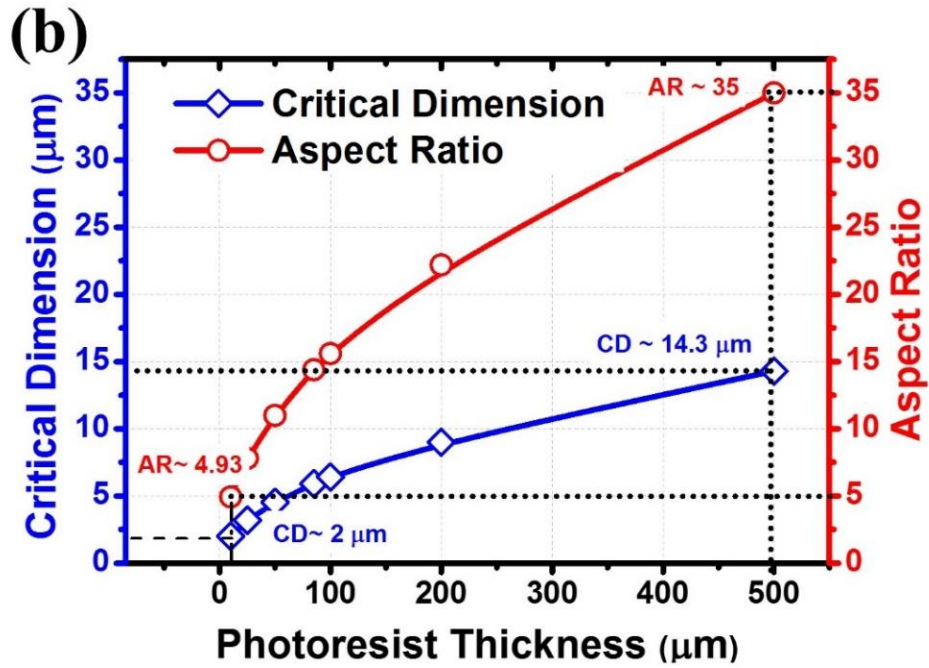


Figure 3.7. (a) Schematic diagram of thick negative tone photoresist exposed by UV light through a photo mask and (b) calculated critical dimension and maximum aspect ratio calculated with respect to photoresist thickness.

3.5. Microfabrication Process

The following section will describe fabrication of air-core racetrack inductors on silicon with HAR metal moulding photoresists. The table 3.2 lists the photoresists reported in the literature for HAR MEMS metal moulding with the required specifications for micro-winding fabrication on a Cu surface. These commercially available photoresists were tested to fabricate air-core microinductors on a wafer scale. Each of these resists have their own advantages and disadvantages.

Table 3.2. Temporary photoresists selected for thick micro-metallic plating.

Resist	Tone Type	Resist Chemistry	Single spin thickness (μm)	Adhesion to Copper
THB 151N (JSR Micro)	Negative	Acrylic	<100	Excellent
NR22-20000P (Futurrex)	Negative	Epoxy	<100	Marginal
AZ 40XT (Microchemicals)	Positive	Acrylic	~ 45	Excellent

a. Seed deposition

Thermally oxidized (~2 μm thick in Thermco thermal oxidation chamber) silicon wafers were selected as starting material to form high-quality electrical insulator of dielectric isolation. This native oxide acts as a barrier material from diffusion and electrical isolation from the top seed layers.

This is followed by DC sputtering (Nordiko) of 20 nm Titanium (Ti) / 100 nm Copper (Cu) seed layer as shown in fig 3.8 (a).

b. Photoresist Spin Coating

For spin coating, a Laurell spinner (Model-WS-400P-6NPP/LITE/AS) was used and substrates baked on a standard hotplate. The resists were exposed on an optical mask aligner (Canon PLA-501 FA for low intensity and high time exposure duration and Karl Suss MA6 system for high intensity and low exposure duration) through a chrome patterned glass mask (from Compugraphics Ltd., UK) in hard contact mode (Figure 3.8 (b)).

c. Photoresist Development

The resist was then developed by manual agitation (Figure 3.8 (c) and 3.8 (d)). For positive tone photoresist, the exposed region becomes soluble in the developer, revealing a positive sloped (acute angled) pattern (Figure 3.8 (c)). With negative tone photoresists, the diffracted regions results in cross-linking reactions in the photoresist. Thus the exposed regions remain insoluble in developer, resulting in a negative slope profile (obtuse angled) (Figure 3.8 (d)). The resist thickness was measured using a Tencor P-10 α -step profilometer.

d. Micro-winding electroplating

The wafer was briefly dipped in an acid-based solution to remove cuprous oxide formed from Cu seed exposure to the atmosphere and improve wettability prior to electroplating of copper. That was followed by a brief O₂ plasma treatment for 2 minutes at 100 W to remove any organic residue. The wafer was then electroplated in an automated wafer plating system (Digital Matrix (SA/1b) system) and commercially available sulphuric acid based acidic Cu plating solution (Schlötter Ltd) at a pH of 0 and room temperature. The deposit thickness was controlled and maintained at each stage to avoid over-plating.

e. Photoresist removal

After electroplating, the photoresist was removed by gently agitating the stripping solution for resist removal.

f. seed etching

The Ti/Cu seed layers were etched in hydrofluoric acid (HF) and ammonium persulphate solutions, respectively (Figure 3.8 (e) and 3.8 (f)). The Cu thickness was measured on a profilometer and Quanta FEG-650 SEM (scanning electron

microscope). The Cu plating follows the resist patterns and shows either an acute or obtuse side-wall profile with positive and negative photoresist respectively.

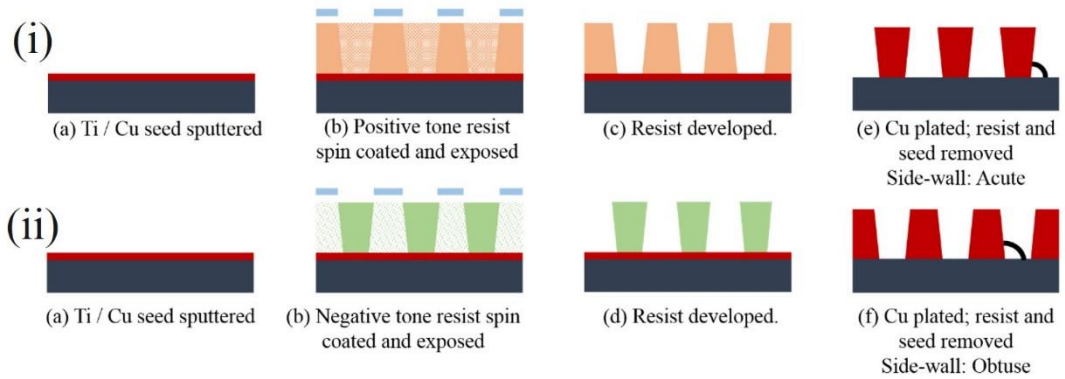


Figure 3.8. Schematic diagram of micro-winding fabrication process with (i) positive and (ii) negative tone photoresist.

3.5.1. NR22-20000P [3.19]

NR22-20000P (from Futurrex Ltd., USA) is an epoxy based negative tone photoresist. It is viscous and semi-transparent with a characteristic fruity odour for thick film applications and is compatible with UV exposure at 365 nm wavelength. The datasheet suggests that it can achieve $>100\ \mu\text{m}$ thickness in a single spin, has excellent resistance to plating baths, superior resolution and easy stripping. Table-3.3 lists the process steps for $30\ \mu\text{m}$ to $75\ \mu\text{m}$ thickness developed in this work.

Table 3.3. Process conditions for NR22-20000P photoresist on 100 mm wafers.

Parameters	30 μm Thick	50 μm Thick	75 μm Thick
Main spin speed (rpm) /sec	1815 /40	1000 / 40	735 / 40
Multi-step soft bake ($^{\circ}\text{C}/\text{secs}$) ramped mode	130/1200 and 150/360	130 /1200 and 150 / 1800	130/1200 and 150/120
Cooling Time (sec)	900	1800	1800
Exposure (mJ/cm^2) dose (recommended – increased)	315-1200	710-3000	1850-3000
Post Exposure bake ($^{\circ}\text{C}/\text{secs}$)	80/300	80/300	80/300
Development time (secs)	120	210	420

Initial trials, however, showed resist loss on development (RD6 developer). Although the recommended process step ($\sim 315\ \text{mJ}/\text{cm}^2$ for $30\ \mu\text{m}$ thickness) was followed for the work, a thickness of only $20\ \mu\text{m}$ was measured due to severe resist loss on development (Figure 3.9 (a-b)). This is attributed to the under-exposed state of the photoresist. During photoresist illumination, absorption is rarely the only optical phenomenon taking place. As the light reaches the base of the resists, it is reflected back. This reflected ray then interferes with the light travelling down and produces standing waves. This reduces the net intensity which results in cross-linking of the

resists and results in the resist loss. In the development stage, this under-exposed resist becomes soluble to the developer resulting in thinner photoresist thickness. Increasing the exposure dose four fold (1200 mJ/cm^2) compensates for the standing-wave issue and no resist loss is observed on development. On increasing the bake time to 1200 secs, the resist adhesion improved as the additional solvent content in the resist evaporated. An overall thickness of $30 \mu\text{m}$ was obtained on development.

Although considerable improvements were observed on optimizing exposure dose and bake conditions, adhesion and poor resist resolution ($< 35 \mu\text{m}$) still remained. This is observed with $30 \mu\text{m}$ to $75 \mu\text{m}$ thick patterns (Figure 3.10 (a-e)). The resist widths were found to be $\sim 20\%$ smaller than on the mask patterns. Moreover, the resist widths $< 35 \mu\text{m}$ were completely destroyed.

It was found that almost 80% of the devices were realized, while the remainder of the 20% came off during scotch-tape adhesion test. It was thus confirmed that the resist has poor adhesion to Cu surfaces and was deemed unsuitable for realizing high-density micro-windings.

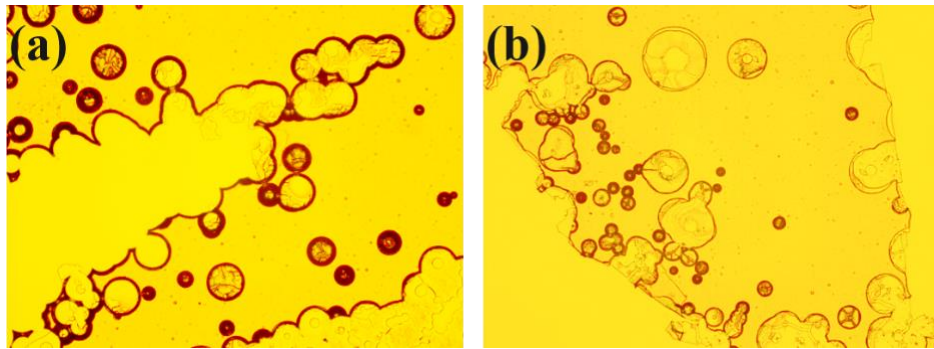


Figure 3.9. (a-b) Photoresist showing resist loss on Cu surface after development with recommended $30 \mu\text{m}$ thick resist process.

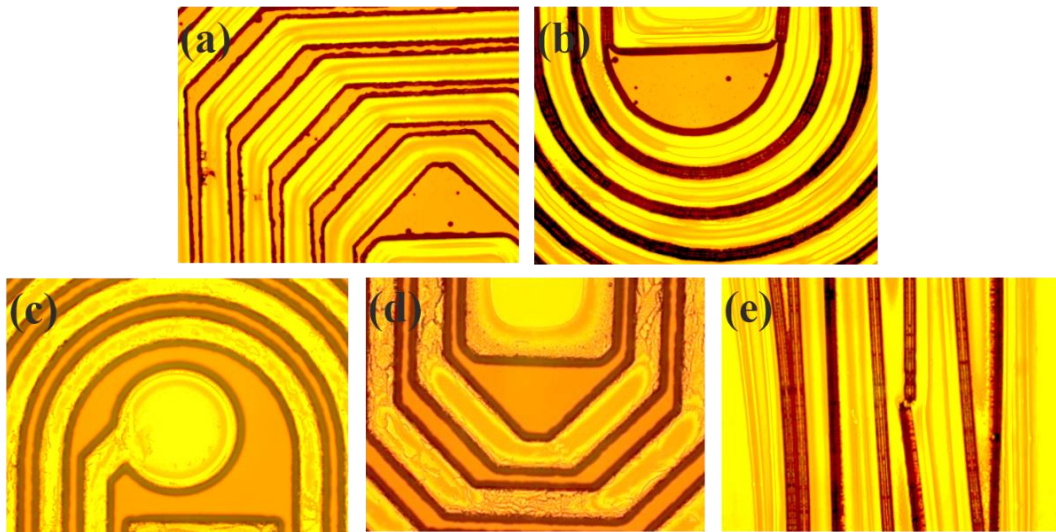


Figure 3.10. (a) $30 \mu\text{m}$ thick photoresist patterns. (b) $55 \mu\text{m}$ thick photoresist patterns. (c-d) $75 \mu\text{m}$ thick photoresist patterns and (e) one of the collapsed structures on development.

3.5.2. AZ 40XT (AZ Series) [3.5]

The other thick metal moulding photoresist, AZ 40XT (MicroChem) is an acrylic chemistry based, positive tone, chemically amplified photoresist. The resist can achieve a maximum thickness of $\sim 100\ \mu\text{m}$ in a single spin (aspect ratio: 4:1) and moderate exposure dose (g-, h- and i-line sensitive). For initial tests, a $40\ \mu\text{m}$ process was developed. On soft baking the resist showed a degassing issue resulting in bubble formation. This was avoided by optimizing the exposure dose, including implementing wait times between process steps to allow natural degassing.

Table 3.4 lists the process details for AZ 40XT. Poor resolution was observed for resist spacing $< 35\ \mu\text{m}$, while wider spacing ($> 50\ \mu\text{m}$) were cleanly developed (Figure 3.11 (a-c)). As mentioned earlier, for devices with $< 0.5\ \text{mm}^2$ footprint, we need a high resolution photoresist process which would reduce the width of the windings and along with HAR processing, minimize DC winding losses. Hence, this resist was also judged unsuitable.

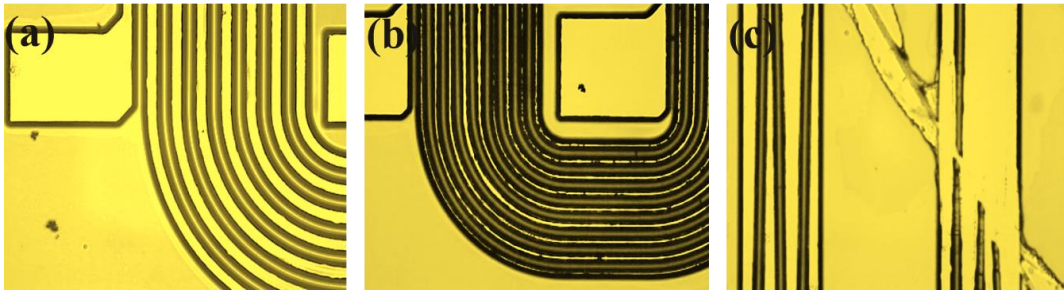


Figure 3.11. (a) $45\ \mu\text{m}$ thick AZ 40XT patterns and $50\ \mu\text{m}$ wide. (b) Patterns with $35\ \mu\text{m}$ resist width. (c) Collapsed $20\ \mu\text{m}$ wide resist structures.

Table 3.4. Process conditions for AZ 40XT on 100 mm wafer substrates

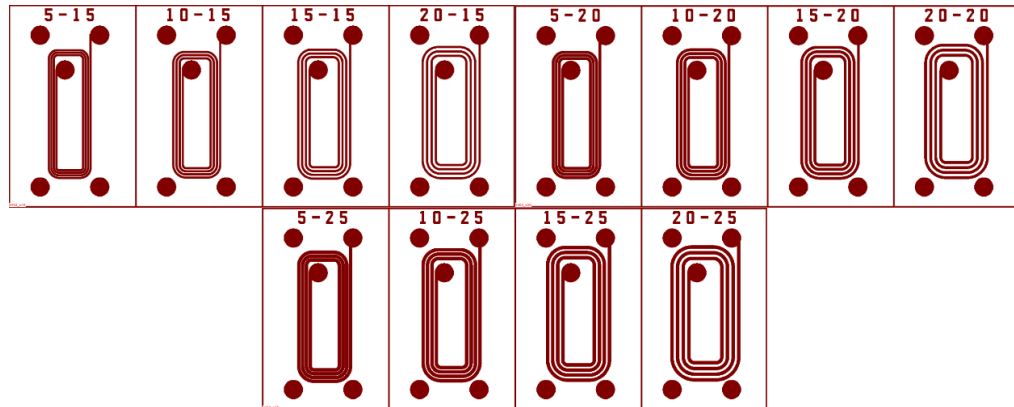
Parameters	45 μm Thickness
Main spin speed (rpm) /sec	1750 / 30
Soft bake ($^{\circ}\text{C}/\text{secs}$) ramped mode	125 / 420
Cooling Time (sec)	600
Exposure (mJ/cm^2) dose	420
Post Exposure bake ($^{\circ}\text{C}/\text{secs}$)	105 $^{\circ}\text{C}$ / 180
Development time (secs)	600

3.5.3. THB-151N [3.21]

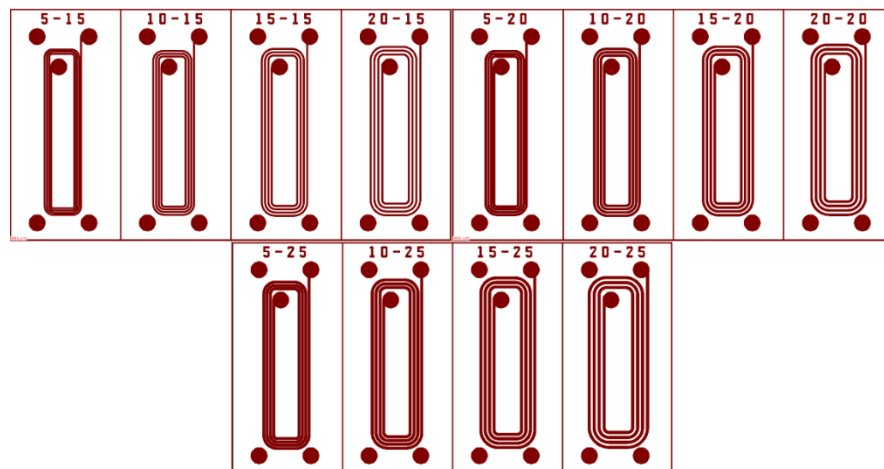
a. Resist chemistry and winding patterns

THB-151N (from JSR Micro Inc.) is a semi-transparent (clear yellow) viscous ($3900\ \text{cP}$ at 25°C) solution. The datasheet obtained from the manufacturer suggests 7.25 as the highest AR that could be obtained. The resist is sensitive to broadband UV wavelengths, with peak sensitivity to i-line wavelength ($365\ \text{nm}$) and compatible with

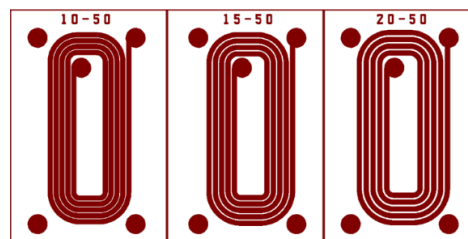
typical Cu electroplating solutions. It can also be re-flowed to achieve dome like topography by standard baking after development. Prior to spin coating, the resist is allowed to warm to room temperature and is then exposed to the air briefly (600 secs) to assist natural out-gassing of the photosensitizer often trapped in the solvent. This step reduces the air-bubbles often observed during the spin coating step. A test chrome glass mask design with winding widths varying from 15 μm to 50 μm and windings gaps (or resist width) ranging from 5 μm to 25 μm has been used (Figure 3.12).



(a)



(b)



(c)

Figure 3.12. Mask layouts of different package sizes with varied windings and gaps (a) 0402, (b) 0603 and (c) 0805.

b. Optimization

The AR mentioned for walls on the JSR datasheet of 7.25 is for a 150 mm diameter Cu coated wafer. On repeating the process recommended by JSR for 80 μm resist thickness (spin coating: 300 rpm/10 sec to 950 rpm/20 secs) on 100 mm Cu coated wafers, an aspect ratio of ~ 6.5 and resist thickness of 65 μm was achieved. Also, following the same bake times, the solvent content was found to be high, which made the wafer stick to the chrome mask on hard exposure. This required photoresist process optimization on 100 mm diameter wafers. In the following sections, the optimization of spin profile, exposure and bake conditions of the photoresist THB-151N on 100 mm diameter wafers have been described in details.

The experimentally optimized resist thickness in terms of main spin speed is shown in Figure 3.13 (a). The main speed step determines the uniformity and the final resist thickness. To achieve thickness $> 75 \mu\text{m}$, the main spin speed was reduced to 650 rpm for 30 s. The second relaxation time (600 s) between pre-spin and main spin allows the resist to re-flow again towards the centre from the wafer edges. Decreasing spin speeds further did not yield any increase in thickness but instead resulted in non-uniformity across the wafer.

Figure 3.13 (b) shows the experimentally optimized spin profile for different photoresist thicknesses. However, the high solvent content at 650 rpm (main speed) reduced resist resolution, result in resist loss during development and resulted in the wafer sticking to the chrome mask during exposure. Hence, the pre-exposure bake time was also optimized. Another 600 s relaxation time after the spin process and before pre-exposure bake was included. A low temperature bake ($< 80^\circ\text{C}$) showed a resist loss during the development step. Hence, the wafer was soft-baked (pre-bake) on a standard hotplate by ramping up to 130°C for 600 s (for 85 μm resist thickness) from room temperature before ramping back down to room temperature. Unlike the process described in the datasheet, the ramped prebake mode ensured no bubbles were formed.

The wafer was then exposed (exposure dose: $1100 \text{ mJ}/\text{cm}^2$) in a high intensity (32 mW/cm^2) UV broadband (i-g and h-line mercury lamp) optical mask aligner (Karl Suss MA6 system) through a chrome patterned glass mask in hard contact mode.

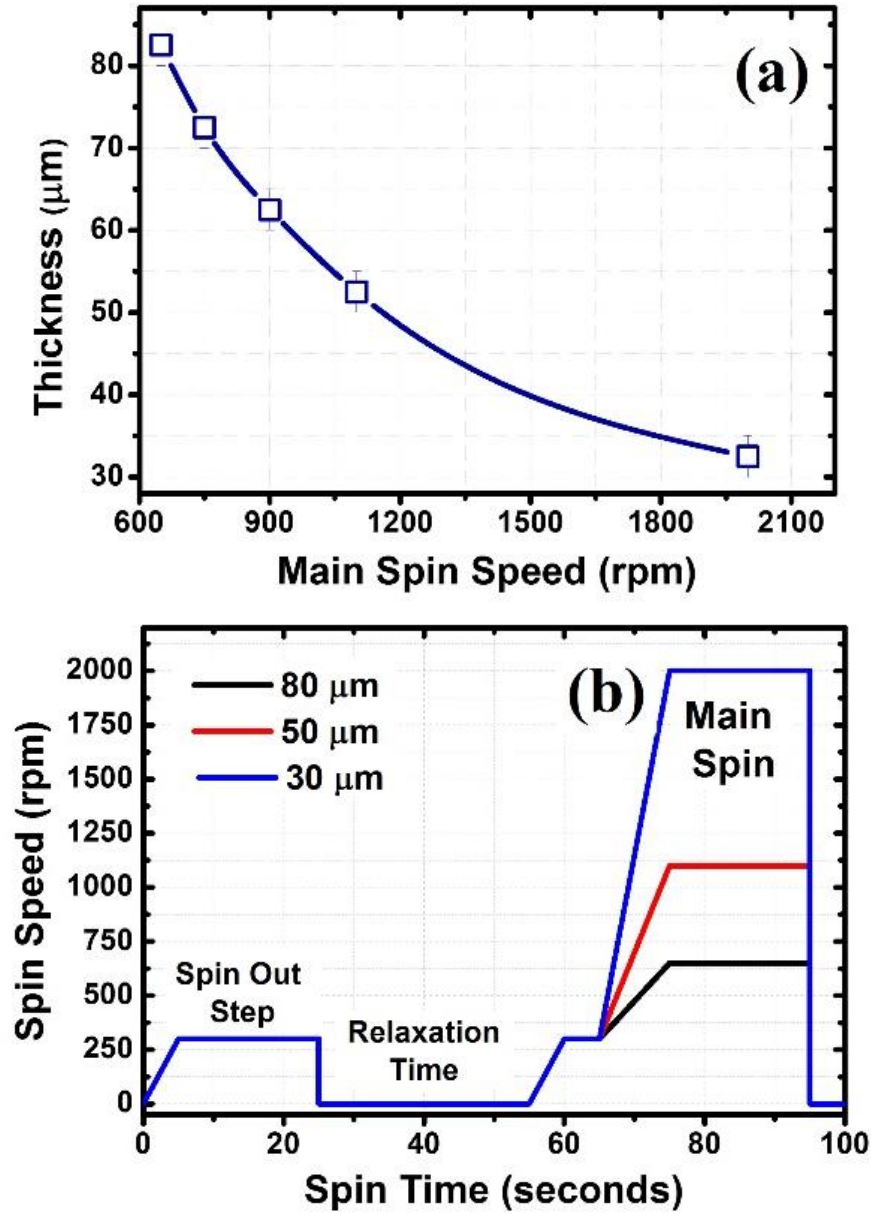


Figure 3.13. Experimentally determined optimized (a) spin speeds (main) and (b) spin profile for different thickness of THB-151N.

Figure 3.14 shows the exposure matrix for the resist on Cu surface for 35 μm , 55 μm and 75 μm thicknesses with experimentally optimized exposure doses of 620 mJ/cm^2 , 800 mJ/cm^2 , 1100 mJ/cm^2 , respectively. At higher exposure doses the diffraction from the edges of the chrome mask patterns becomes severe. As previously discussed in section 3.4, this results in poor resolution.

No post-baking was found to be needed for THB-151N. The exposed wafer was then developed by manual agitation in the commercial TMA238WA solution (from JSR Micro) at room temperature. It is a metal-ion free (MIF) transparent solution with

2.38% strength by weight alkali tetramethylammonium hydroxide (TMAOH). The wafer was nitrogen dried completely.

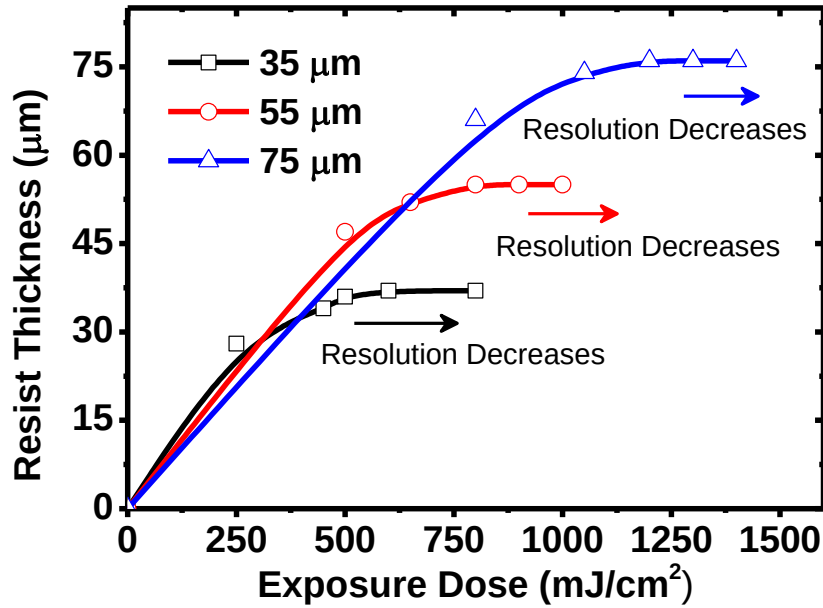


Figure 3.14. Experimentally optimized exposure matrix for 55 μm , 35 μm and 75 μm resist thickness.

c. Resist Characterization

The thick resist structures showed no deformity or collapse on drying, indicating excellent adhesion between the photoresist and Cu surface. Figure 3.15 (a) shows the uniformity measured across a 100 mm (4 inch) wafer with THB-151N. Edge beads were avoided by removing the edge resist prior to soft-bake and exposure. This improved the resist uniformity achieving a 3.5 % variation across the wafer. Figure 3.15 (b) shows an 85 μm thick single spin resist coated wafer with different windings patterns.

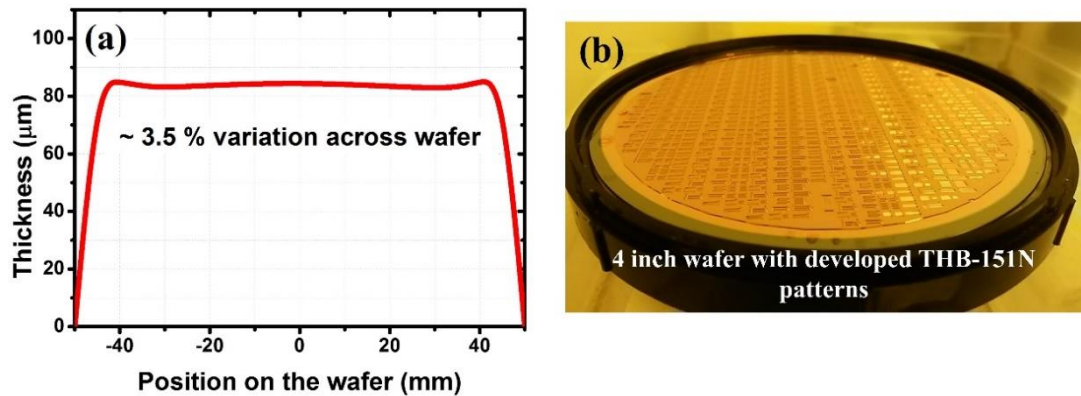


Figure 3.15. (a) Photoresist thickness measured across a 100 mm diameter wafer and (b) Wafer with thick (85 μm) resist with different winding patterns.

Figure 3.16 shows the SEM images of cleanly developed patterns with varying widths and spacing. It was observed that high exposure doses for a short durations improved the resolution significantly. This is attributed to Fresnel diffraction from the mask pattern which degrades resolution during extended exposure. On increasing the exposure time these edges absorb enough light to remain undeveloped. The resist was exposed in hard contact mode. It is also important to note that some features develop earlier than others. This is attributed to the fact that it is difficult to dissolve and remove finer spaced features with the developer solution. However, the relatively large development margin allowed all of the patterns to be developed cleanly. Even though the resist shows some swelling before removal during the development, unlike some resists (such as SU-8), it did not deform nearby microstructures.

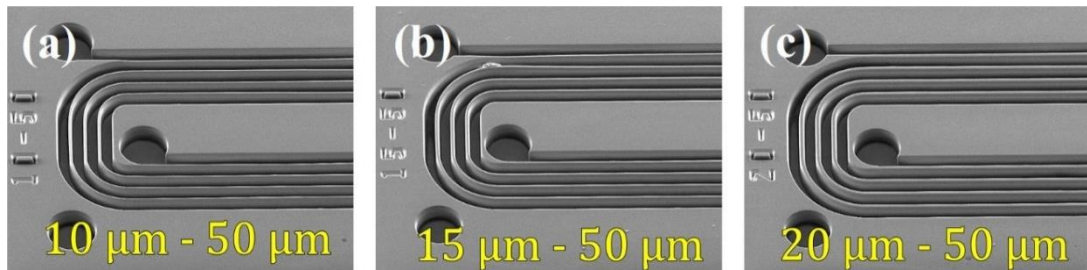


Figure 3.16 SEM micrographs of 85 μm thick and 50 μm wide open photoresist patterns: (a) 10 μm resist wall width (b) 15 μm resist wall width and (c) 20 μm resist wall width.

Figure 3.17 shows SEM images of 85 μm thick THB-151N resist. Figure 3.17 (a) shows the 5 μm resist line-width winding patterns with 50 μm resist spacing. As observed the resist is cleanly developed confirming optimized development conditions. No delamination or peeling is observed which confirms excellent adhesion between the Cu seed and the resist. Moreover, the tilted image shows a near vertical side-wall profile which was later confirmed with cross-section analysis of electroplated windings. It is important to note that, under-exposure can cause resist loss during the development step while over-exposure results in a negatively sloped side-wall profiles. A 17:1 AR with a resist width of 5 μm was achieved (Figure 3.17 (b)). Moreover, the resist width of 5 μm is comparable to 5.91 μm resolution determined by CD calculations of the same resist thickness (85 μm).

In addition to the wavelength and numerical aperture of the exposure tool, the intensity and duration of exposure also plays a crucial role in determining the diffraction intensity from mask patterns. A high intensity for short exposure duration increases the resolution compared to low intensity for high exposure duration. This

permits a clean photoresist development to achieve high resolution patterns. Lower resolution ($\geq 10 \mu\text{m}$ resist width) was observed on high exposure duration with low intensity compared to high intensity and short exposure duration ($\geq 5 \mu\text{m}$). Figure 3.17 (c) shows the SEM micrograph of $85 \mu\text{m}$ thick and $10 \mu\text{m}$ wide resist patterns confirming the near vertical side-wall profile ($\sim 90^\circ$).

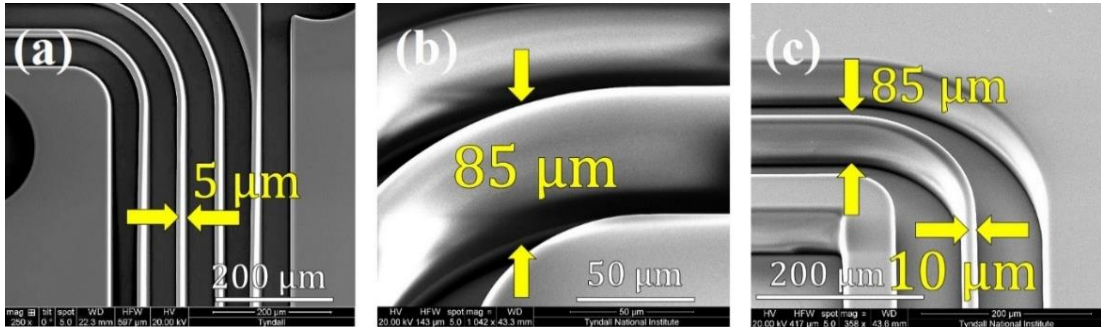


Fig 3.17. SEM micrographs of $\sim 85 \mu\text{m}$ thick and $50 \mu\text{m}$ wide photoresist patterns: (a) $5 \mu\text{m}$ resist width (b) $85 \mu\text{m}$ thick resist side-wall and (c) $10 \mu\text{m}$ resist width resist pattern.

Figure 3.18 depicts the SEM images of $80 \mu\text{m}$ thick electroplated Cu windings with 16:1 aspect ratio via resist mould. It is often experienced that electroplating via inclined resist mould, changes the plating rate as the conductive area increases. This results in over-plating. As observed from Figure 3.18 (a-b), the windings are uniformly plated. This can be attributed to uniform width of the resist and near vertical size-walls. Moreover, $5 \mu\text{m}$ spacing in-between Cu windings demonstrates a clean stripping of the resist in 20 mins. None of the Cu microstructures were damaged during the process. This is confirmed with $\sim 80 \mu\text{m}$ thick vertical features and $\sim 5 \mu\text{m}$ gap (as shown in fig 3.18 (c-d)). The side-wall of electroplated Cu structures is almost 91° . Advantages of the process developed include lower UV exposure energies, shorter baking times, and excellent adhesion to metal surfaces, near vertical side-wall profiles and easy resist removal which make THB-151N ideal for micro-coil processing for MEMS applications such as described here.

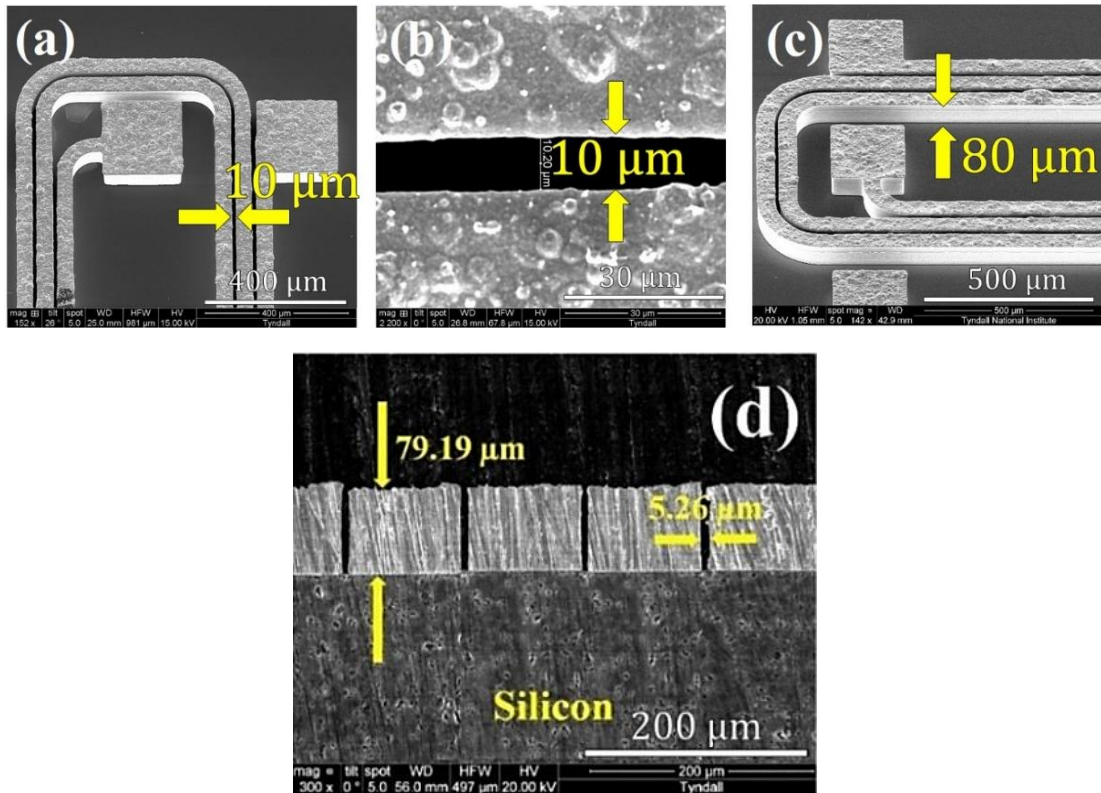


Figure 3.18. SEM micrographs of electroplated Cu windings depicting: (a-b) 10 μm winding gap and (c-d) 80 μm thick Cu pads and $\sim 91^\circ$ side-wall profile and 5 μm winding gaps.

The process developed with THB-151N in this work will be integrated with the rest of the fabrication process. There are three important aspects of this process necessary for integration:

- **Removal of fine resist features through Cu windings:** After electroplating the densely spaced Cu windings, the photoresist is removed. The resist lifts off first and then gets dissolved without damaging the plated windings. The development for finer features requires continuous agitation for longer durations and the remover (THB S17) needs to be replenished.
- **Seed etching:** As discussed before, the wet etchant (ammonium persulfate solution) seep into the spacing, between the Cu windings and reacts with the seed to form soluble copper sulphate. This reaction is instantaneous and the narrow spacing does not hinder the etching process.
- **Filling of windings with SU-8:** The developed copper windings are insulated from the top magnetic core by a permanent insulating polymer. For such thick structures, SU-8 is used as the inter-metal dielectric in this work. For narrow winding spacing

and HAR micro-structures, the thick ($> 100 \mu\text{m}$) SU-8 photoresist will cover the windings completely.

d. Air-core inductors

Table-3.5 lists the 12 nH air-core micro-inductors fabricated at wafer-scale with the footprint area and the measured small-signal resistances (75 kHz-30 MHz, HP 4285 LCR meter). The winding resistances were simulated with finite element analysis (Ansoft Maxwell). On comparing with previous reported process [3.21] of 50 μm thick windings and 10 μm spacing (0.45 mm^2 footprint area), with the new 80 μm thick windings and 5 μm spacing (0.39 mm^2 footprint area) suggests a 42 % reduction in winding resistance at 75 kHz (Figure 3.19 (a)). This is attributed to the increase in winding cross-sectional area which varies inversely with resistance.

At lower frequencies (such as 75 kHz), the effective cross-sectional area determined by skin depth ($\sim 238 \mu\text{m}$) is larger than the winding cross-section. Hence, AC losses are negligible $< 1 \text{ MHz}$ (as observed from Figure 3.19 (a)). However, at high frequencies the winding resistance increases due to reduced effective area (due to skin effect) and proximity effects due to nearby windings. The proximity effect can be reduced by increasing the winding spacing but that would also increase the device footprint. Nevertheless, as a trade-off the footprint area can be reduced further with the new process by decreasing winding spacing with a small increase in resistance (Figure 3.19 (b)) at high frequency.

Another advantage of the high resolution achieved in a single spin with this process is to increase the number of turns per footprint area, thereby increasing the inductance density. Such compact MEMS devices could easily be integrated on-chip. Moreover, such high AR photoresist processing could also be applicable in the fabrication of various other MEMS and micro interconnect applications. It is one of the highest AR achieved for moulding photoresist (that is readily removable) with such high resolution.

Table 3.5. Footprint and measured resistances of 12 nH and 80 μm thick 4-turn air-core inductors.

Package Size	Footprint Area (mm^2)				Resistance (Ω)			
	Winding width (μm)	Winding Gap (μm)			Winding width (μm)	Winding Gap (μm)		
0402	15	0.36	0.39	0.45	15	0.20	0.22	0.23
	20	0.39	0.45	0.50	20	0.16	0.17	0.18
	25	0.45	0.55	0.60	25	0.134	0.15	0.16
0603	15	0.53	0.58	0.65	15	0.237	0.25	0.26
	20	0.58	0.65	0.74	20	0.193	0.20	0.21
	25	0.65	0.74	0.82	25	0.16	0.17	0.18
0805	50	1.68	1.78	1.9	50	0.14	0.146	0.154

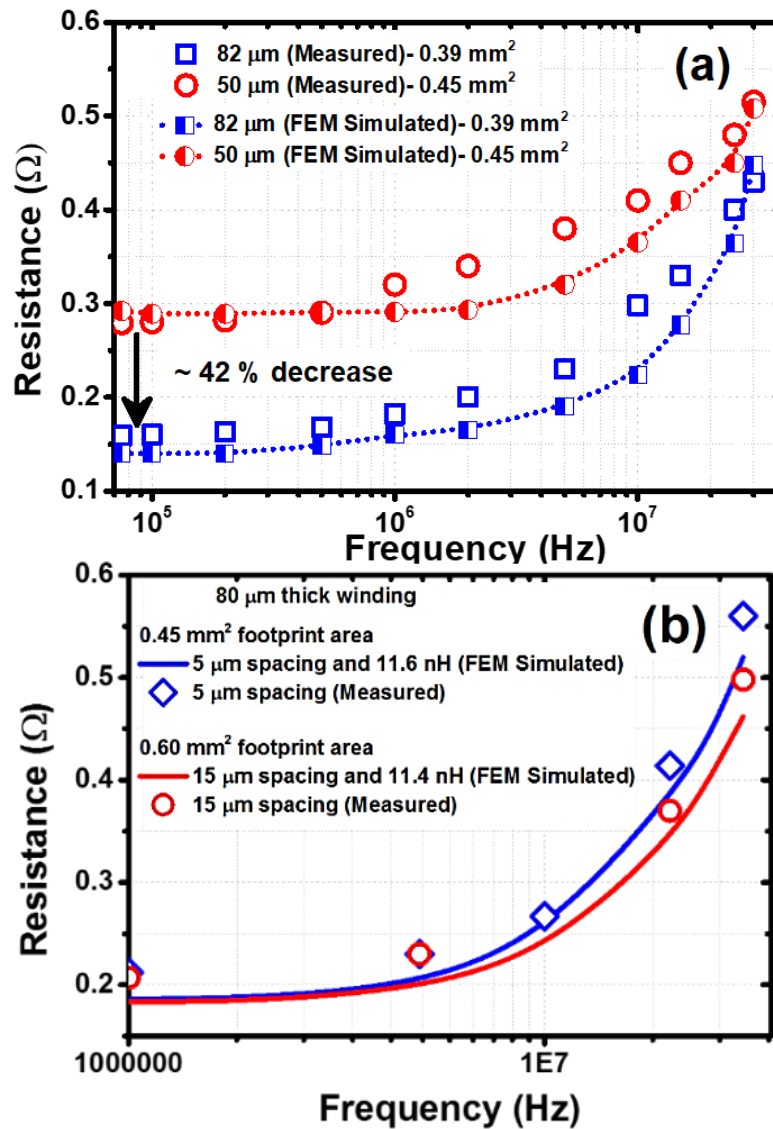


Figure 3.19. Winding resistance vs. frequency comparisons between 50 μm and 80 μm single-spin THB-151N process: (a) Increase in winding thickness (from 50 to 82 μm) and reducing footprint (from 0.45 to 0.39 mm^2) by reducing winding spacing. (b) Reduction of device footprint (from 0.60 to 0.45 mm^2) with new high resolution resist process without significant increase in resistance.

3.6. Conclusions from HAR photoresist processes

Figure 3.20 compares the photoresist process developed with reported metal moulding resists in terms of AR and minimum resist feature. Table 3.6 lists the key conclusions drawn from the photoresists tested for fabricating thick and densely spaced micro-windings.

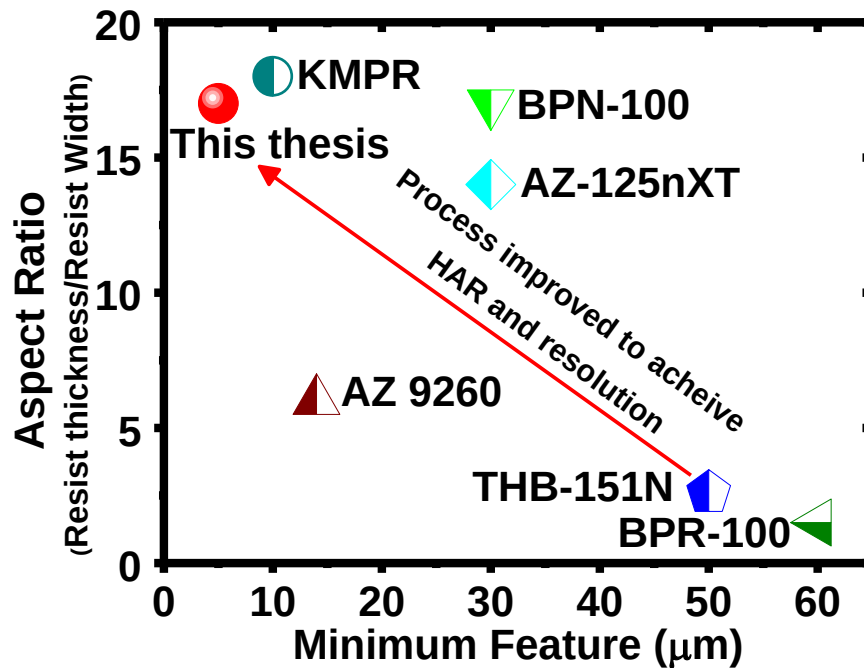


Figure 3.20. High-aspect-ratio metal moulding photoresists comparison with THB-151N process developed.

Table 3.6. Conclusions from temporary photoresists tests for fabricating windings.

Photoresists		
NR2-20000P	AZ 40xT	THB-151N
○ Requires high exposure dose to compensate resist loss.	○ No resist loss observed with recommended exposure dose.	○ No resist loss observed with recommended exposure dose.
○ < 35 μm thick resist patterns collapse / delaminate on development.	○ < 35 μm resist patterns collapse / delaminate on development.	○ 5 μm resist patterns faithfully developed.
○ Low development margin. Delamination observed.	○ High development margin. No delamination observed.	○ High development margin. No delamination observed.
○ Poor adhesion to Cu.	○ Good adhesion to Cu.	○ Good adhesion to Cu.
○ Maximum single spin thickness: 75 μm	○ Maximum single spin thickness: 75 μm	○ Maximum single spin thickness: 75 μm

3.7. Photoresist as etch mask

The fabrication process of a magnetic core micro-inductor requires a resist step to wet etch the planar (bottom) and patterned (top) core. Low cost and time effective wet processes have always been a preferred etch process in 3D MEMS structures to etch most materials. But, this becomes challenging in case of poor adhesion between the resist and the magnetic material. In such cases, etchant seep in between the magnetic material and the photoresist resulting in lateral etch or over-etch of the magnetic core.

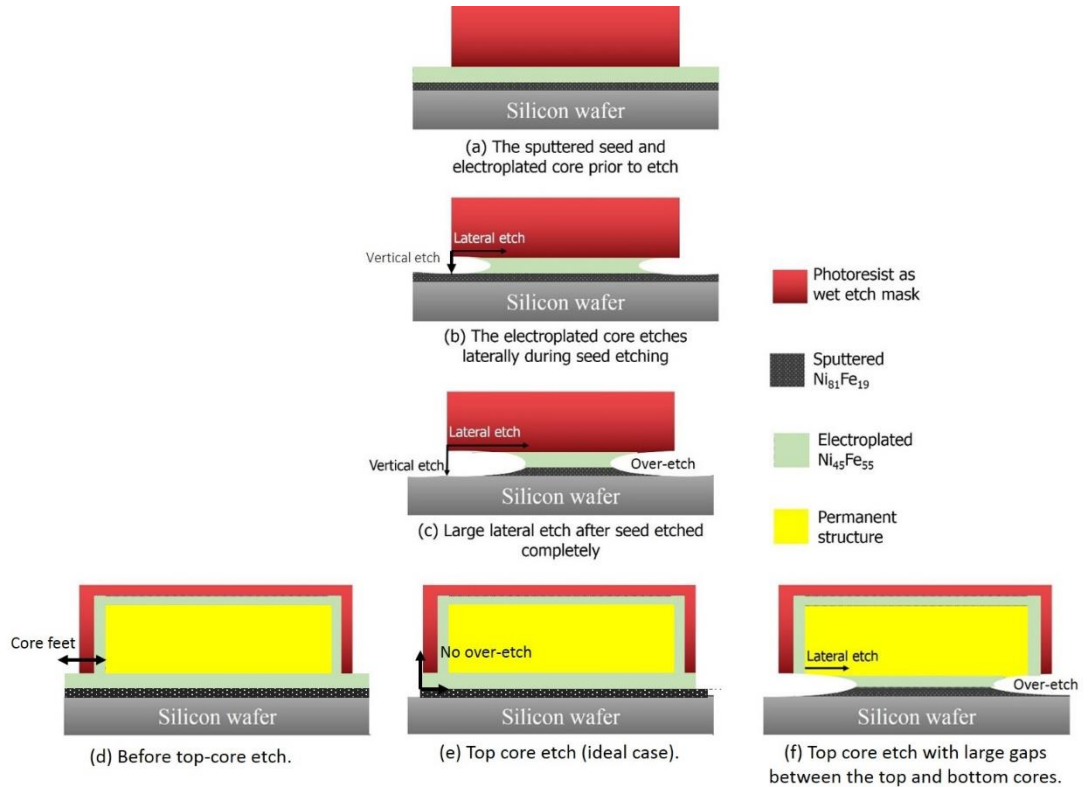


Figure 3.21. Schematic of: (a) bottom core without etch, (b) lateral-etch with seed remaining, (c) over-etch as seed is completely removed, (d) top core with core feet (e) top core after ideal etch and (f) Top core etching (realistic case).

Figure 3.21 (a-f) shows a schematic of the top and bottom core with and without etch. The $\text{Ni}_{45}\text{Fe}_{55}$ core is electroplated on sputtered $\text{Ni}_{81}\text{Fe}_{19}$ seed (Figure 3.21 (a)). The seed and the core are patterned with DI: HNO_3 (2:1) solution through a wet etch mask. Initially the core etch both vertically and laterally. But as the etchant starts to etch the dense sputtered $\text{Ni}_{81}\text{Fe}_{19}$ seed vertically at a slower etch rate, the lateral etch rate of electroplated $\text{Ni}_{45}\text{Fe}_{55}$ is significantly higher (Figure 3.21 (b)). By the time the sputtered seed is completely etched, the core is left with substantial over-etch (Figure 3.21 (c)).

Figure 3.21 (d) shows the top core before etching. During top core etch, ideally there should not be any over-etch (Figure 3.21 (e)). In worse case it can result in an air-gap between the top and bottom core (Figure 3.21 (f)), reducing inductances substantially as the air-gap increases reluctance. This may also result in fringing flux from the core opening resulting in EMI.

SU-8 is a widely used etch mask for thick MEMS patterning. However, it has high internal stress and low resistance to humidity. This sometimes results in cracks and de-lamination [3.8]. Moreover, SU-8 acts as a permanent structure in some devices and cannot be stripped off. Figure 3.22 (a) shows one such case where the SU-8 residue in-between the core, resulting in core shorting. Fig 3.22 (b) shows the cracks and de-lamination of SU-8 resist mask, exposing the copper winding underneath.

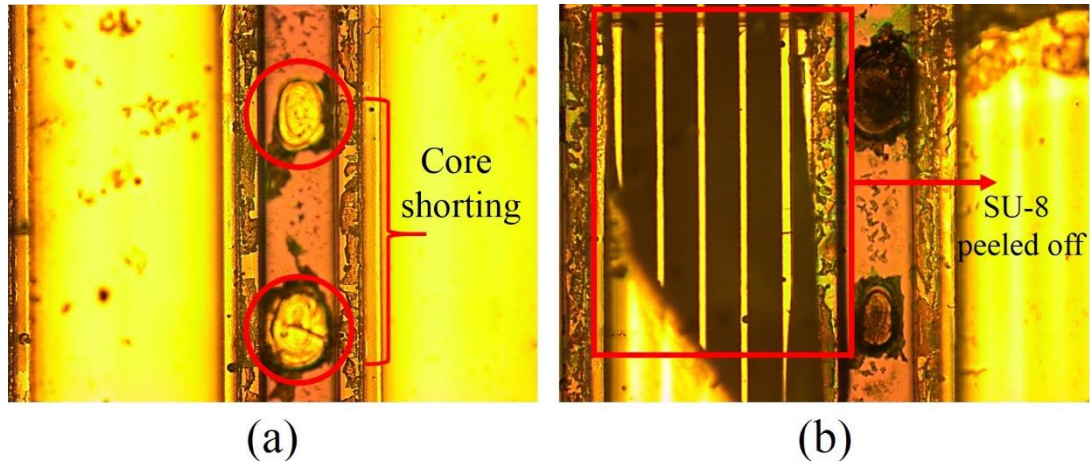


Figure 3.22. Microscopic images of the top view of the core etched through SU-8 wet etch mask: (a) core shorted due to remaining SU-8 residue and (b) cracks and delaminated SU-8 exposing Cu windings underneath.

In previous section, development of a thick THB-151N resist process which can be readily removed was discussed. It is selected as temporary wet etch mask for core etching. SU-8 has poor adhesion to most metallic surfaces [3.22-3.23]. Initial experiments showed that SU-8 peels off easily on scotch tape pull test, while THB-151N showed excellent adhesion and survived the tape test. Unlike SU-8 it could be readily removed in commercially available THB-S17 remover with manual agitation in 20 minutes without damaging the micro-structures.

For the comparison, a 70 μm SU-8 and THB-151N was targeted in a single spin on 1.8 μm thick $\text{Ni}_{45}\text{Fe}_{55}$ electroplated core and 100 nm / 10 nm of $\text{Ni}_{81}\text{Fe}_{19}$ / Ti sputtered seed. Electrodeposited cores and sputtered $\text{Ni}_{81}\text{Fe}_{19}$ seed were etched in nitric acid (> 69% from Sigma Aldrich) diluted with DI water in 1:2 ratio at room temperature

followed by hydrofluoric acid (HF) for Ti adhesion layer etch. The patterns have a core-feet of 100 μm . At different etch durations the core over-etch was observed.

a. SU-8 as wet etch mask:

The wet etch is progressed till the core in the exposed regions is completely etched. Figure 3.23 (a) shows that significant lateral etch (over-etch) with SU-8 after the core material from the exposed regions are etched. This results from poor adhesion between Ni-Fe core and SU-8. On continuing the wet-etch, top and bottom core are isolated and top core wet etches (Figure 3.23 (b)). This is avoided by partial etching of the wafer, hence compromising the wafer yield. Figure 3.23 (c) shows an over etch of 50.3 μm of the core-feet in 8 mins of etch duration.

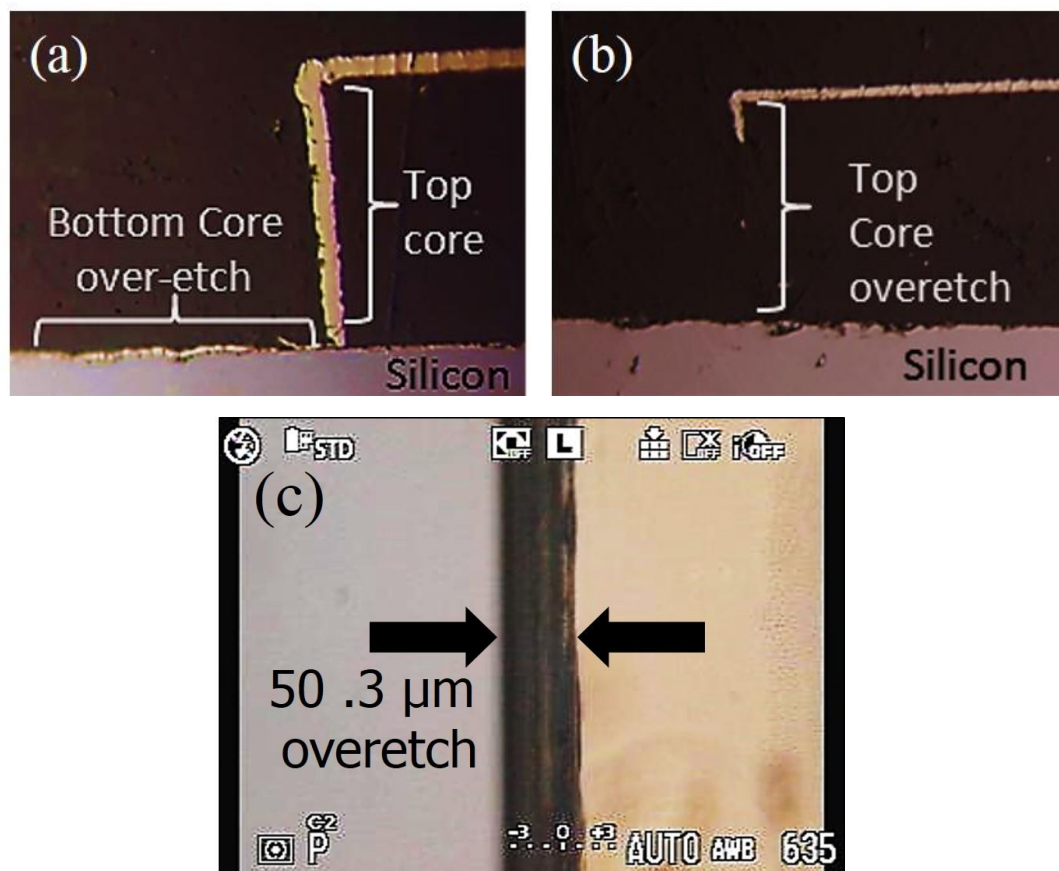


Figure 3.23. Cross-sectional images of over-etched (a) bottom and (b) top core with SU-8 as etch mask and (c) plane view of the over-etched pattern.

b. THB-151N as wet etch mask:

Figure 3.24, shows that overetch observed with THB-151N. The over-etch measured with THB-151N was 28.3 μm for 8 min of duration; while with SU-8 50.3 μm of the core-feet was etched for the same duration of etching. Hence, with this THB-151N process core-etch can be reduced by almost 44%.

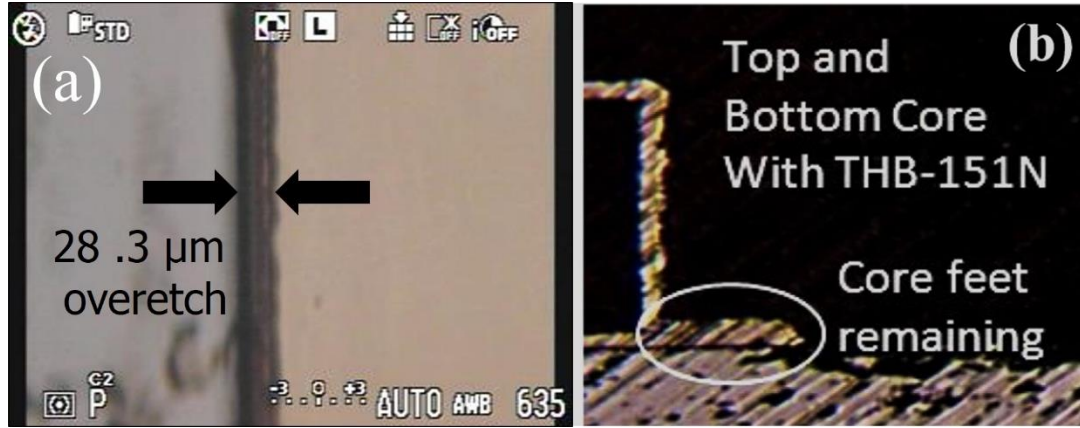


Figure 3.24. (a) Plane image and (b) cross-sectional image of over-etched $\text{Ni}_{45}\text{Fe}_{55}$ with THB-151N as etch mask.

3.8. Conclusions

This chapter focussed on developing HAR and high resolution temporary photoresist processes to realize thick and densely spaced micro windings which would reduce DC resistance and minimize inductor footprint. For this purpose, three temporary photoresists were tested, namely NR22-20000P, AZ 40xT and THB-151N. Compared to NR22-20000P and AZ 40xT, THB-151N showed good adhesion to Cu surface and high aspect ratio (17:1) with resist feature down to $\sim 5 \mu\text{m}$.

The THB-151N photoresist was optimized for 35 μm , 55 μm and 85 μm resist thicknesses. Air-core inductors (12 nH) with thick copper micro-windings ($\sim 80 \mu\text{m}$) with varying winding width (5 μm to 25 μm) and footprint (0.36 mm^2 - 1.9 mm^2) were fabricated with the 85 μm thick resist process for integrated power magnetic devices (such as micro-inductors and micro-transformers). The resistance of 80 μm thick windings and 5 μm spacing (0.39 mm^2) showed $\sim 42\%$ reduction in DC resistance (from 273 m Ω to 159 m Ω) compared to 50 μm thick windings and 10 μm spacing (0.45 mm^2). This process increased the L/R_{dc} ratio 43 nH/ Ω to 75 nH/ Ω . The high resolution process ensures further reduction in winding pitch and device footprint without significant concessions on efficiency. The near-vertical side-wall profile ($\sim 91^\circ$) assists the control of the copper electroplating rate.

Moreover, the THB-151N resist shows excellent adhesion which has been successfully exploited to pattern magnetic core with reduced ($\sim 44\%$) core over-etch compared to SU-8. Unlike ultra-thick photoresists such as SU-8, this photoresist can be easily removed after exposure. Higher single spin thickness by comparison with positive tones photoresists reduces processing time while increasing process margin

and resolution. This resist process is appropriate for applications in MEMS for micro-fabrication of high AR and low loss micro-windings.

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Chapter 4

Magnetic Core Technology: Soft to Ultra-soft Magnetic Material

4.1.Introduction

Apart from winding losses discussed in the previous chapter, reducing magnetic core losses are a significant challenge, which must be addressed. Low-loss soft magnetic materials are integrated as magnetic core in the fabrication of on-silicon micro-inductor and transformers to enhance inductance and power density.

A material is categorized as a soft magnetic material “if in a weak field (< 1000 A/m), the magnetization process occurs, this includes domain wall motion and domain magnetization rotation”. Soft-magnetic materials have been widely researched from naturally existing ferromagnetic elements such as Ni, Co and Fe. Although these materials are well reported and a mature area of research, in recent years they have received renewed interest due to their potential as core material for the realization of integrated thin film passive components unlike bulk magnetic materials. Excellent soft magnetic properties can be achieved depending on the alloy composition, deposition conditions and its processing.

There are two important aspects of the magnetic core research: advancements in magnetic material deposition processes and improvement in soft magnetic properties. To address the first aspect of magnetic core research, electroless deposition has been investigated. Compared to electroplating, electroless deposition deposits on deeply recessed regions, does not require an external power supply, and overcomes excessive build-ups on the wafer edges and non-uniformity associated with electroplating. An electroless deposition process of Ni-Fe alloys with different alloy compositions has been developed. These Ni-Fe alloys provide a wide range of magnetic (coercivity and anisotropy field) and electrical resistivities. To address the second aspect of the magnetic core research, a new electrochemical method to develop ultra-soft magnetic properties in as-deposited $\text{Ni}_{45}\text{Fe}_{55}$ has been reported.

4.2. Magnetic Core Losses and Properties

Soft magnetic materials are used in micro-inductor/transformers to offer enhanced performance over air-core inductors. The fundamental magnetic properties have been described in the chapter.

The net core losses in terms of power loss ($P_{Core\ Loss}$) can be expressed as:

$$P_{Core\ losses} = P_{Hysteresis} + P_{Eddy} + P_{anomalous} \quad (4.1)$$

Where, the core loss is a sum of hysteresis ($P_{Hysteresis}$), eddy current (P_{Eddy}), and residual loss components (also known as anomalous loss- $P_{anomalous}$). This allows each of the loss mechanisms to be treated separately, as if they are independent of each other. The growing need for smaller and more efficient micro-inductors has presently shifted the focus on developing low loss and high saturation soft magnetic materials.

One of the key challenges is to reduce all these losses simultaneously. The key parameters that determine the performance of magnetic core materials are:

(a) Saturation flux density (B_{Sat})

The magnetic material should have a high value of saturation magnetization. This would enhance the current handling capability of the device without saturating the core. In addition, a high B_{Sat} increases the permeability ($B = \mu H$) and reduces the device footprint needed to meet the desired inductance.

(b) Coercivity (H_C)

The material must have a very low coercivity to keep the hysteresis losses low, especially at high frequencies (as $Hysteresis\ loss \propto frequency$).

(c) Relative real Permeability (μ_r')

The magnetic material should have a high real magnetic permeability over a wide frequency range. This increases inductance density. However, the device must be designed to keep the core below its peak saturation.

(d) Anisotropy Field (H_K)

The anisotropy field is the force related to the crystal anisotropy forces in the material along the easy-axis. On application of external magnetic field along other axes, the anisotropy tends to hold the magnetization along the easy-axis. This field,

needed to magnetize the material in other axes, is called the anisotropy field. The material should have high anisotropy field along the hard axis (HA). This increases the ferromagnetic resonance frequency. Although the permeability would be reduced ($\mu_r \propto \frac{1}{H_K}$).

(e) Electrical Resistivity (ρ)

The core magnetic material should have a high resistivity. This minimises core eddy current losses and allows the increase of the device operation frequency. In addition, this facilitates a thicker core to be deposited, with little magnetic field variation across the film. This could potentially increase the inductance density depending on other parameters.

(f) Deposition and Integration process:

The developed material must be integratable in a CMOS based on-silicon device fabrication process. Hence, it is essential that the material is compatible with the rest of the fabrication process and can be deposited with existing thin film deposition processes (sputtering, electrochemical deposition etc.).

In this chapter, methods to develop soft to ultra-soft magnetic films with the target properties listed in table 4.1 were investigated.

Table 4.1. Properties of an ideal core material

Material properties	Specifications
Coercivity	< 10 A/m
Resistivity	> 70 $\mu\Omega$ -cm
Saturation flux density	> 1 T
Anisotropy field	> 700 A/m
Relative permeability	> 500
Cut-off frequency	> 100 MHz

4.3.State of the Art

Magnetic materials can be broadly classified as soft (coercivity < 1000 A/m) and hard magnetic (coercivity > 10000 A/m). Figure 4.1 shows some of the widely reported soft and hard magnetic materials [4.1]. Soft magnetic materials are an ideal choice for integrated power magnetic applications due to their low coercivities, high flux densities and permeability. This section will focus on the development of soft-magnetic materials for high frequency magnetic applications and lay the foundation for the development of ultra-soft magnetic films later in section 4.6.

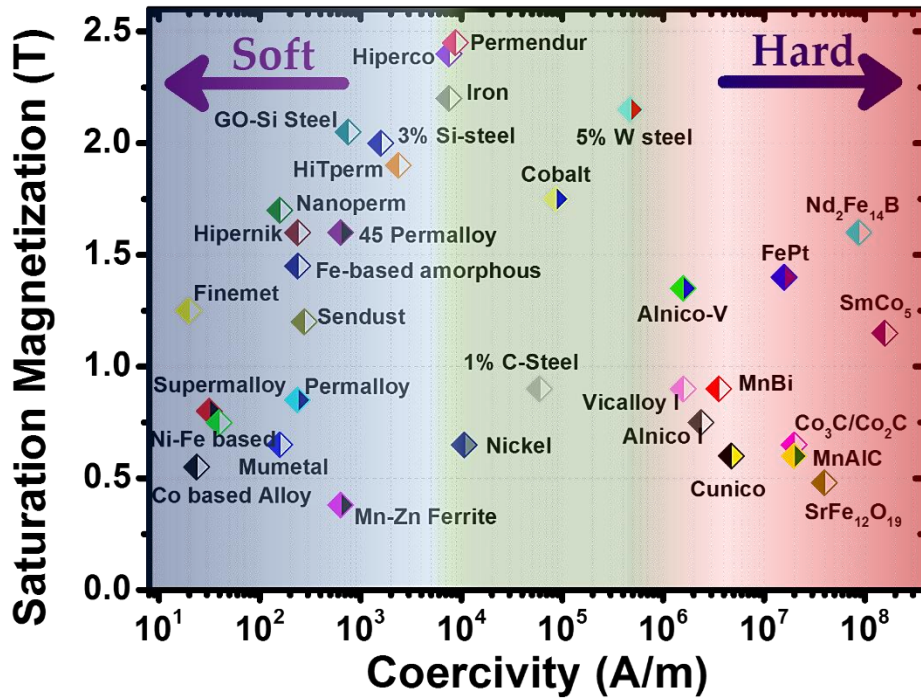


Figure 4.1. Saturation magnetization vs coercivity of commercially available soft and hard magnetic materials [4.1].

Conventional soft magnetic materials can be further classified as nano-crystalline, amorphous, metal-alloys and ferrite.

Ferrites (Ni-Zn, Mn-Zn based etc.) are ceramics used as core material and are developed with ferrite oxides of constituent materials. The base materials (such as Ni, Zn and Cu) are weighed into the correct proportions, calcined and milled to make a powder. The milling step determines the particle size. The powder is pressed at high pressure before sintering. The sintered ferrite core attains the required magnetic properties that are influenced by these processes [4.2]. The processes also make ferrites unsuitable for integration with silicon magnetics processing.

Ni-Zn ferrites are an important group of high permeability materials with uniform permeability up to several MHz and resistivity as high as $10^5 \Omega\cdot\text{m}$ to $10^8 \Omega\cdot\text{m}$. Compared to Mn-Zn ferrites which are ideal for < 2 MHz applications, Ni-Zn ferrites have higher permeability and a functional frequency range from 1 MHz to a maximum of 30 MHz.

The inclusion of CuO compounds prior to the sintering process can increase the operation frequencies to ~ 100 MHz. This makes Ni-Cu-Zn based ferrites an excellent alternative to Ni and Co based nano-crystalline magnetic films that have very low resistivity. Ferrites can be manufactured on a large scale with low-cost processing and

have the desirable very high resistivities ($> 10^6 \mu\Omega\text{-cm}$). However, a low saturation magnetization ($< 0.5 \text{ T}$), poor coercivities ($> 100 \text{ A/m}$), challenges in integration and the need for high temperature sinter processing are significant disadvantages. This roadblock has been addressed by pulse laser deposition (PLD) [4.3] and screen-printing techniques [4.4-4.6]. However, poor film quality (grain and strain non-uniformity in the film) and the resulting inferior film properties remain.

Amorphous soft magnetic materials are metal alloys which are non-crystalline in nature and have atomic species randomly oriented. Such materials are typically Co, Ni or Fe based. They are fabricated into amorphous ribbons, wires and solid core structures by rapid solidification from the melt at high quenching rate. For e.g., Finemet precursors are amorphous ribbons obtained from molten metals of Fe, Si, B and traces of Cu and Nb by rapid quenching at $1 \times 10^6 \text{ }^\circ\text{C/sec}$. The ribbons are then cut into core shapes for discrete components. Finemet can also be sputter deposited from amorphous ribbon targets, but requires high temperature annealing ($> 500 \text{ }^\circ\text{C}$) for nano-crystallisation for reducing coercivity ($< 10 \text{ A/m}$). Such high temperature processing makes it unsuitable for on-silicon integration.

Other CMOS compatible high saturation flux density ($> 1.5 \text{ T}$) Co based amorphous materials such as Co-Zr-Ta (CZT) or Co-Zr-Ta-B (CZTB) are sputter deposited and can be rendered magnetically anisotropic by application of a magnetic field during annealing or deposition [4.7-4.8].

Nano-crystalline soft magnetic films are rapidly replacing ferrite cores. Properties such as high saturation flux density, low coercivities, high temperature stability and ease of deposition make them an ideal core material for high frequency integrated magnetic applications. Crystallization of amorphous precursor material through rapid quenching such as Finemet (Fe-Si-B containing small amounts of Nb-Cu) develops grains $< 15 \text{ nm}$ in dimensions. This nano-crystalline nature improves the soft-magnetic properties significantly [4.9-4.10]. The composition of a soft magnetic nano-crystalline alloy is represented as $TL_{1-x-y-z}TE_xM_yNM_z$, where TL , represents a late ferromagnetic transition-metal element such as Co, Ni and Fe, while TE , M and NM represents early transition-metal element (such as Zr, Nb, Hf etc.), a metalloid (such as B, P, Si etc.) and a noble metal, respectively [4.11].

These materials can be classified into two types: single-phase ferromagnetic alloys and a two phase (nano-crystalline and amorphous) with grain boundaries. These

materials can be easily integrated in device fabrication processes. Figure 4.2 shows the dependence of coercivity with grain size (also known as Herzer's plot) for soft-magnetic materials [4.12]. The grain-size (D) is an essential parameter determining the coercivity of a ferromagnetic material. The $1/D$ dependence of coercivity for large grain-sizes ($> 100 \mu\text{m}$) shows that good soft magnetic properties are possible in this regime (multi-domain). This is because as the grain sizes increases, the demagnetization field increases and above a critical size, the demagnetizing energy becomes energetically favourable over exchange interaction (which favours the single domain), resulting in a multi-domain. Again, for $< 20 \text{ nm}$, grain-size coercivity varies as D^6 with grain-size. In this regime (Super-paramagnetic regime), the domains appear as small ferromagnetic nanoparticles). During magnetization, these domains can readily flip without incurring loss. **Magnetic metal alloy films** such as $\text{Ni}_{81}\text{Fe}_{19}$ [4.13-4.14], $\text{Ni}_{45}\text{Fe}_{55}$ [4.15] and CoNiFe [4.16-4.19] have shown nano-crystalline phases. These films have low stress and are easy to deposit electrochemically [4.20-4.21]. In addition, the magnetic and electrical resistivities are dependent on alloy composition and deposition processes.

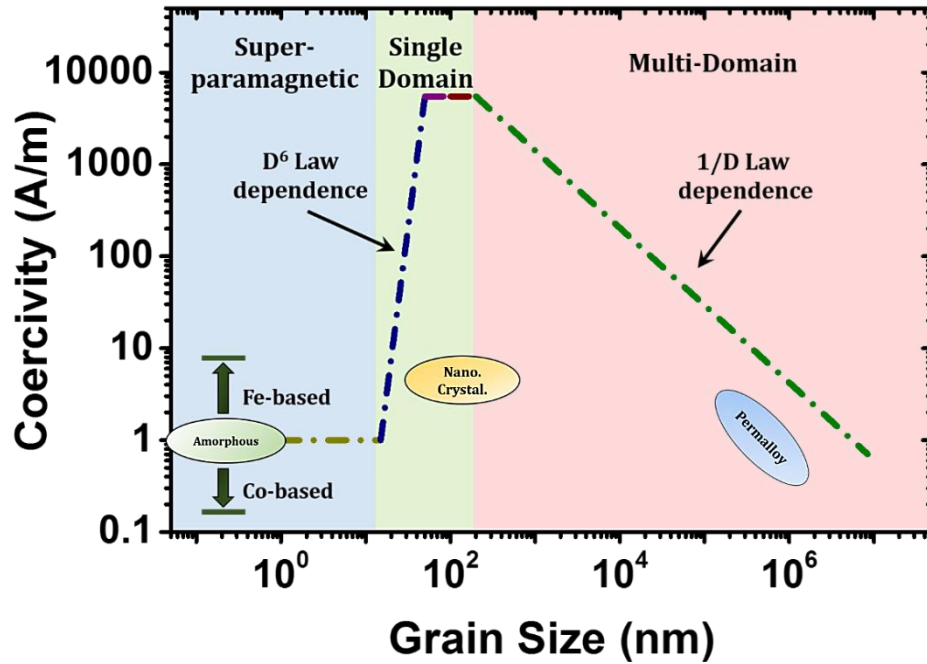


Figure 4.2. Herzer's plot: Coercivity and grain size relationship in soft-magnetic alloys [4.12].

Table 4.2 lists a selection of conventional soft-magnetic materials reported. It can be noted that only CZT has shown ultra-soft magnetic properties. Moreover, the failure to deposit ultra-soft magnetic films with low-cost electrochemical processes remains a major roadblock.

Figure 4.3 shows the B_{Sat} vs. permeability of different soft-magnetic materials. The diagonal separation indicates the limitations with conventional magnetic materials. They either are restricted in terms of B_{Sat} or μ_i values (depending on alloy compositions). New commercial materials such as Nanomet (Fe-Co-Si-B-P-Cu) and hetero-amorphous soft magnetic films have broken this limit and have shown $B_{Sat} > 1.5$ T.

Table 4.2. Conventional soft-magnetic materials and their properties

' - ' indicates data not reported

Type	Material	Process	B_{Sat} (T)	H_c (A/m)	ρ ($\mu\Omega$ -cm)	μ_r	FMR (GHz)	Thick- ness (μm)
Metal Alloys	Ni ₈₁ Fe ₁₉ [4.22]	Sputtering	1.3	-	20	2000	0.64	4
	Ni ₈₀ Fe ₂₀ [4.23]	Electroplated	0.79	-	20	2200	-	10-20
	Ni ₄₅ Fe ₅₅ [4.24]	Electroplated	1.5	102	45	300	> 0.1	3.5
	CoNiFe [4.25]	Electroplated	1.9	16	24	-	-	-
	NiFeMo [4.25]	Electroplated	0.8	57	60	2500	-	-
	CoZrTa [4.22]	Sputtering	1.52	1.2	>100	1100	1.4	-
	FeBN [4.26]	Sputtering	1.95	2400	100	4500	-	3
	CoFeCu [4.23]	Electroplated	1.4	80	18	300	-	10
	NiFe (Cu ²⁺) [4.27]	Electroplated	1.65	<10	-	-	-	-
	CoHfTaP d [4.28]	Sputtering	1	40	170	-	-	9
Ferrites	CoFeB [4.29]	Sputtering	0.8	5.6	10 ⁴	50	3	0.5
	Mn-Zn [4.30]	Screen printing	0.2	3200	3 x 10 ⁸	6	> 0.01	-
	Ni-Zn [4.31]	Screen printing	0.25	-	10 ¹²	25	> 0.01	-
	Ni-Zn [4.6]	Screen printing	0.46	26400	10 ⁸	120	> 0.01	100
Oxides	Ni-Zn [4.32]	Screen printing	0.8	5600	10 ⁸	60	-	55
	CoZrO [4.33]	Sputtering	1.3	80	600	80	3	20

	CoFeHfO [4.34]	Sputtering	1.02	32 -80	1500 - 1700	200- 220	-	0.4-8
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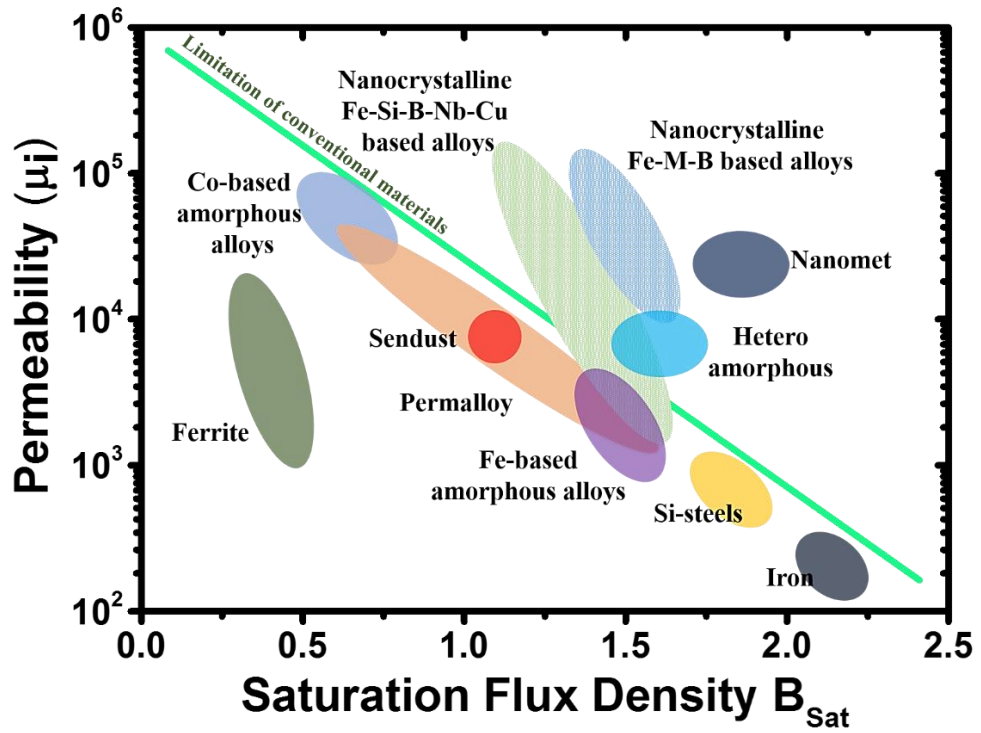


Figure 4.3. Permeability vs saturation flux density of different soft magnetic materials. The Co, Fe based amorphous alloys, nano-crystalline and Ni-Fe based metallic alloys are ideal choice for thin film magnetics.

Soft-magnetic materials have found applications in transformers, inductors, flux detectors, sensors, electro-magnetic (EM) shields etc. Table 4.3 lists the applications of soft magnetic materials from 1 Hz to beyond 1 GHz. The magnetic flux in a pulse transformer does not vary between positive and negative values like power transformers. Rather, the pulse transformer operates in a “unipolar” mode. Both these transformers need low-loss high permeability materials. Current transformers used as signal isolation and measurement need similar core properties for faithful replication of the primary current in the secondary circuit. Soft magnetic materials are used as EM shields to protect data stored in RFID chips [4.3]. They also find applications in magnetic write heads, where the data is stored as magnetized bits by passing current through inductive write heads. In recent years, magnetic sensors have been developed [4.35] where changes in the flux within sensitive soft magnetic cores can be exploited for position or magnetic field detection. Hence, it is important to develop high

frequency soft magnetic materials to improve their performance over a wide-range of applications.

Table 4.3. Conventional soft-magnetic materials and their applications [4.1]

Frequency	Material	Applications
Static < 1 Hz	Soft iron, Co-Fe, Ni-Fe etc.	Electromagnets, relays
Low Frequency 1 Hz- 1 kHz	Si steel, permalloy finemet, magnetic glasses	Transformers, motors, generators
Audio-frequency 100 Hz - 100 kHz	Permalloy foils, finemet, magnetic glasses, Fe-Si-Al powder (sendust), Mn-Zn ferrite	Inductors, transformers for switched mode power supplies, TV flyback transformers
Radio-frequency 0.1-1000 MHz	Mn-Zn ferrite, Ni-Zn ferrite, Ni-Fe	Micro-inductors/Transformers, antenna rods
Microwave > 1 GHz	YIG, Li ferrite	Microwave isolators, circulators phase shifters, filters

4.4. Electrochemical Deposition

Sputter and electrochemical deposition processes have been widely researched for depositing soft magnetic films. Compared to electrochemical deposition, sputter deposition has some disadvantages, such as: low sputter rates (< 500 nm/min), and expensive targets which make it is a costly method for depositing thick films. The deposition flux can be non-uniform requiring rigorous optimization. The sputtering targets can be expensive and a heat up during deposition which may result in material stress. Moreover, the target material is blanket deposited on the chamber walls; this contributes to material wastage and potential contamination in the sputtering of other targets materials.

Electrochemical deposition is a lower-cost alternative to sputtering with higher deposition rates. It is broadly defined as the process of coating a material (metal, oxide or salt) onto the surface of a conducting surface in an electrolysis solution. Over the years, soft magnetic films have been successfully deposited on conductive surfaces. Figure 4.4 compares the saturation flux density and coercivity of electrochemically deposited soft magnetic materials. Co-Fe based soft magnetic films have shown higher flux (~ 2.4 T) densities and anisotropy fields (~ 1000 A/m) (Figure 4.5). However, developing electrochemical baths with consistent film composition remains a challenge. Use of phosphorus or borane based materials in electrochemical baths have also shown some improvement for increasing resistivity of the otherwise rather conductive magnetic films (Figure 4.6).

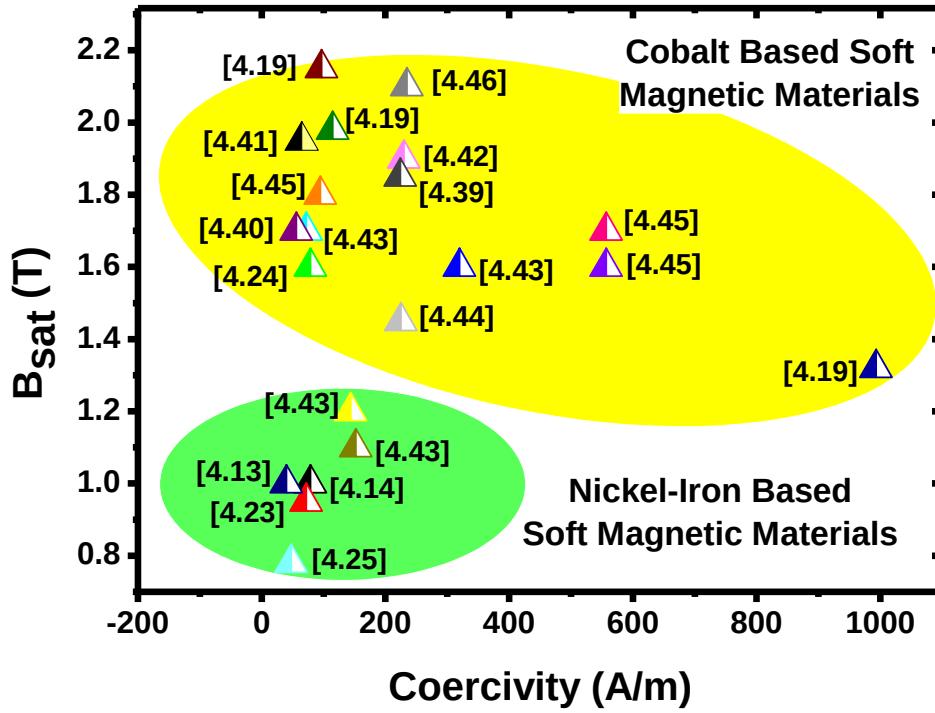


Figure 4.4. Saturation flux density and coercivity (hard-axis) of electrochemically deposited soft magnetic materials.

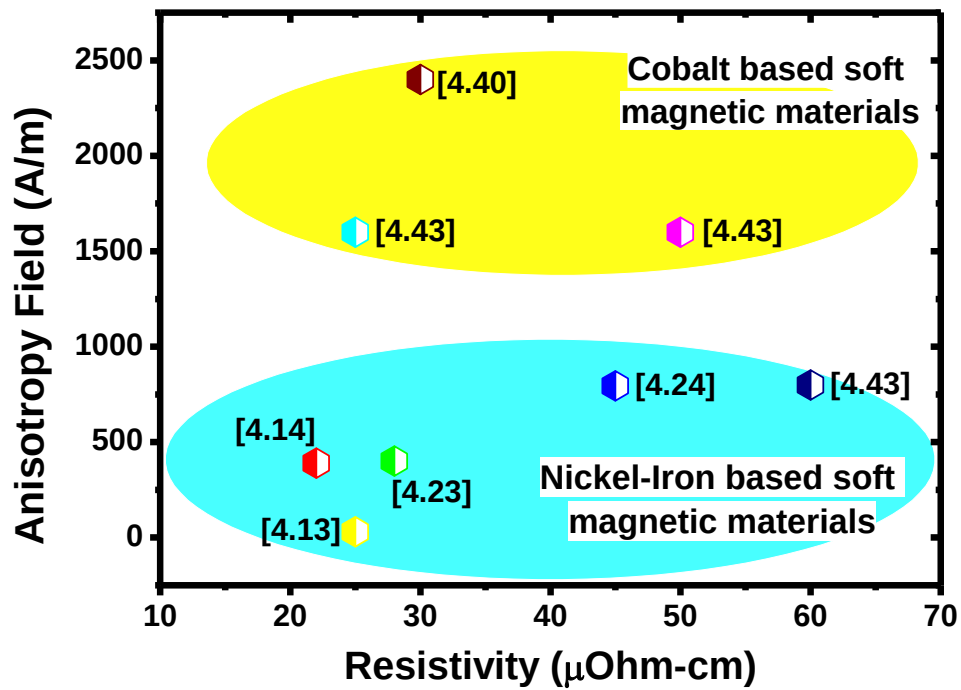


Figure 4.5. Anisotropy field (HA) and electrical resistivity of electrochemically deposited soft magnetic materials.

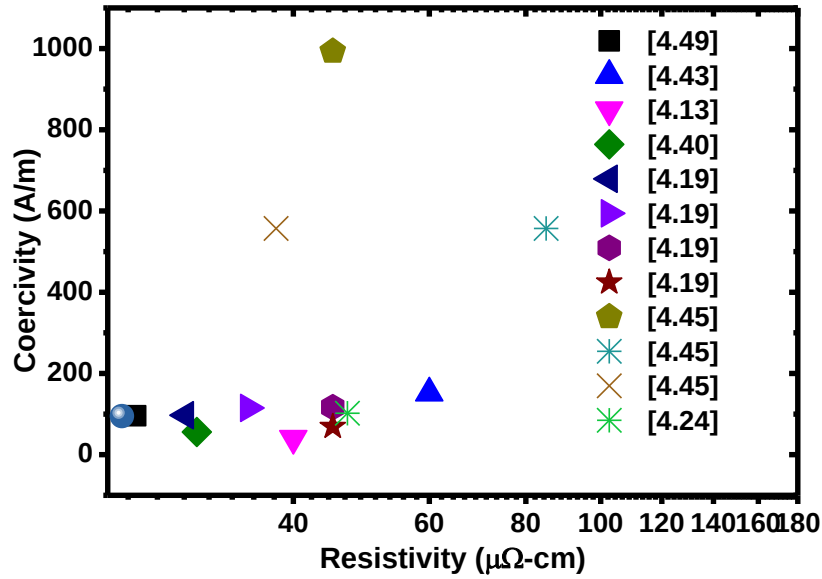


Figure 4.6. Electrical resistivity and coercivity of electrochemically deposited soft magnetic materials.

Electroless Deposition

In the case of electroplated deposition, thicker deposition at the edge of the wafer closer to the electrical contact, compared to the centre can result. This can increase the losses and reduce the overall efficiency of the devices in that region. Special arrangements are needed to overcome the non-uniform deposits.

Electroless deposition is a thermally activated autocatalytic process for depositing films without the use of an external power supply. Table 4.4 lists the general composition of electroless bath. Figure 4.8 depicts the electroless deposition process. The electrolyte solution contains a dissolved or in-situ chemical reducing agent (RA). This reducing agent is oxidized, providing the electrons needed to reduce the metal ions in the solution (Me^{n+}) to its metallic state (Me) at the substrate surface, thereby depositing a film. The reduced metal then acts as a seed for further deposition.

The films are uniformly deposited on the substrates immersed within the bath. Electroless processing has a number of advantages by comparison with electrolytic deposition. Conformal homogeneous deposits can be formed with high yield in high aspect ratio structures and over three-dimensional topologies, without the need for a full or highly conducting seed layer [4.48]. This process is ideal for nanowires growth [4.49-4.51], deposition through silicon vias [4.52] and can result in less porous films [4.53] than those achieved with electrolytic deposition. The tertiary current

distribution characteristic is another issue leading to non-uniformity in electrolytic films [4.54] that can require complex and costly anode placement. The absence of power sources overcomes the non-uniformity observed in electroplated films due to irregularities in current density distribution observed (*terminal effects*) [4.55-4.56]. Di-methylamine borane as reducing agent in water has high solubility, stability at room temperature and high catalytic activity for anodic oxidation for Ni. Hence, DMAB used as reducing agent for the Ni-Fe variable alloy development.

Table 4.4. General composition of electroless plating bath

Component	Purpose
Metal salt	Source of metal deposit
Reducing agent	Reduction of metal ion
pH adjuster	pH adjustment
Complexing agent	To form metal complex
Additives	To improve bath stability

(a)

4 A	5 A	6 A	7 A	8		1 B	2 B	3 B	4 B	5 B	
								 B	C	 N	
								Al	Si	P	
Ti	 V	 Cr	 Mn	 Fe	 Co	 Ni	 Cu	 Zn	Ga	Ge	As
Zr	Nb	 Mo	Tc	 Ru	 Rh	 Pd	 Ag	 Cd	 In	 Sn	 Sb
Hf	Ta	 W	 Re	Os	Ir	 Pt	 Au	Hg	 Tl	 Pb	 Bi

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● Autocatalytic ▲ Co-deposition with Ni & Co ■ Galvanic displacement

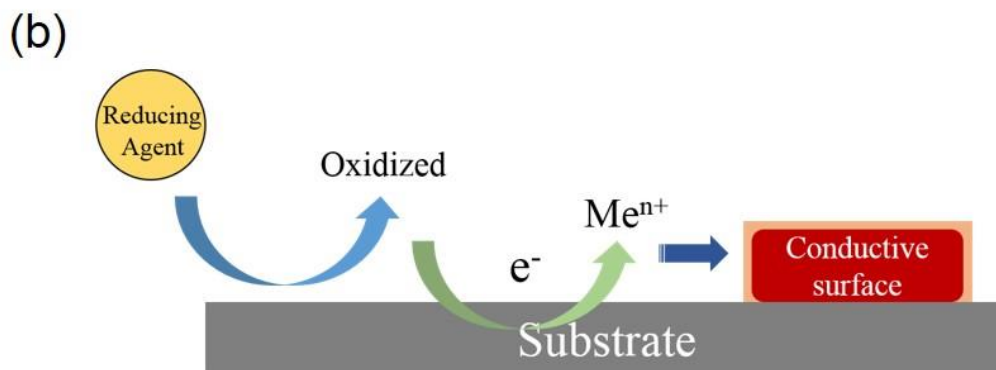


Figure 4.7 (a) Periodic table of the elements showing the metals and their alloys which can be deposited in absence of external voltage source.

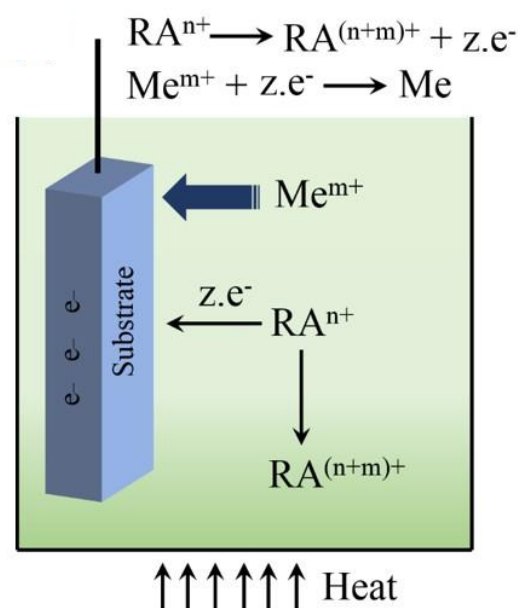


Figure 4.8 Schematic of the electroless deposition process.

4.5. Soft Electroless Ni-Fe Magnetic Films with Variable Magnetic and Electrical Properties

In the following sections, an electroless method of depositing Ni-Fe alloy films with different alloy compositions have been described. The objective of the work was to achieve high quality magnetic films with variable soft magnetic and electrical properties. In this work dimethylamine borane complex (DMAB) was used as a reducing agent for electrolessly depositing Ni-Fe alloy material. The deposition was performed in the presence of an external magnetic field to achieve high anisotropy through preferential orientation of the magnetic dipoles during deposition. It is observed that high dimethylamine borane complex concentration leads to preferable Fe deposition at lower deposition temperatures, when other parameters are kept constant. This contributes to an increase in resistivity with excellent magnetic properties.

4.5.1. Experimental procedure:

The aim of the experiment is to deposit Ni-Fe alloys in presence of external magnetic field. All the solutions were prepared from de-ionized (DI) water of resistivity 18 MΩ-cm. The chemicals used were purchased from Sigma-Aldrich and used as received. The electroless process was performed in glass beakers. The temperature of the electroless bath was maintained with an Ikamag RCT stirring

hotplate and IKA H60 temperature probe. The pH was monitored with an OAKTON pH 6 (Acorn series) and adjusted with ammonium hydroxide solution. Silicon (100) wafers were sputtered with 20 nm Ti for adhesion followed by 100 nm Cu in a Nordiko DC magnetron sputtering system. Commercially available positive tone photoresist AZ9260 (Microchemicals GmbH) is used to pattern the wafers.

The morphology and composition of the electroless deposits were analysed with a Quanta FEG600 scanning electron microscope (SEM) with energy dispersive X-rays (EDX). Intensity correction for trace elements was performed. Film thickness was confirmed with a Tencor (P-10) surface profilometer. The static magnetic properties were analysed with a BH loop tracer (MESA HF200P, SHB instruments). The coercivity (H_c), saturation flux density (B_{sat}) and anisotropy field (H_c) values were obtained from the BH loops of the samples. Complex permeability characterization at room temperature was performed with a wide-band (1 MHz to 9 GHz) permeameter (PMM 9G, Ryowa Electronics). The electrical resistivities of the samples were measured with a four-point probe system. The currents (I) and voltages (V) across the sample were measured with an Agilent DC multimeter and the resistivity calculated as: $\rho = K(V * T/I)$, where K is correction factor (~ 4.53 for semi-infinite thin sheet) and T is thickness of the plated material [4.19]. Microstructural X-ray diffraction (XRD) analyses of $Ni_{81}Fe_{19}$ (permalloy) and $Ni_{37}Fe_{63}$ films were performed on a PANalytical X'Pert PRO MPD XRD system equipped with a Cu K-alpha radiation (1.5405 Å) source and goniometer resolution of 0.001°. Grain sizes and lattice orientation were determined from the XRD results obtained.

4.5.2. Results and discussions

$Ni_{81}Fe_{19}$ films were deposited electrolessly in the presence of a magnetic field. Table 4.5 lists the bath compositions to achieve different composition of Ni-Fe alloys. The pH of the bath was adjusted to 6.5 with diluted ammonium hydroxide, while the deposition temperature was maintained as listed in the table. All the bath constituents were solubilised before adding dimethylamine borane complex (reducing agent). The reducing agent in the solution reduces the metal ions to metal state. Bath-I and Bath-II are the composition for uniform Permalloy deposition. No significant change in composition is observed on increasing dimethylamine borane complex concentration from 0.017 mol-dm⁻³ to 0.034 mol-dm⁻³. Bath-II was selected for $Ni_{81}Fe_{19}$ for its lower temperature deposition compared to Bath-I.

Table-4.5: Borane based Nickel-Iron baths. Concentrations are in mol dm⁻³.

Bath Contents	Bath-I	Bath-II	Bath-III	Bath-IV	Bath-V
Di-ammonium Citrate	0.027	0.027	0.027	0.027	0.027
Lactic Acid	0.22	0.22	0.22	0.22	0.22
NiSO ₄ . 6H ₂ O	0.060	0.060	0.060	0.060	0.060
FeSO ₄ .7H ₂ O	0.058	0.058	0.058	0.058	0.058
DMAB Content	0.017	0.034	0.068	0.102	0.136
pH	6.5	6.5	6.5	6.5	6.5
Temperature (°C)	85	75	65	60	58
Ni and Fe atomic composition (%) $\pm 3\%$	Ni: 81 Fe: 19	Ni: 81 Fe: 19	Ni: 74 Fe: 26	Ni: 55 Fe: 45	Ni: 37 Fe: 63

a. Influence of bath constituents: Figure 4.9 (a) shows the deposition rate of Permalloy films electrolessly deposited under these conditions. The initial plating rate was found to be 6.6 $\mu\text{m/hr}$ (DMAB concentration: 0.034 mol-dm⁻³), however, after 10 minutes of plating the deposition rate decreased gradually stabilizes to 3.1 $\mu\text{m/hr}$. The Ni and Fe atomic percentage were found to be 78 % - 81 % and 22 % - 19 % respectively by EDX, with negligible boron content (co-deposited from borane based bath) measured (< 1%) in all the deposited films. All the deposition processes are repeatable.

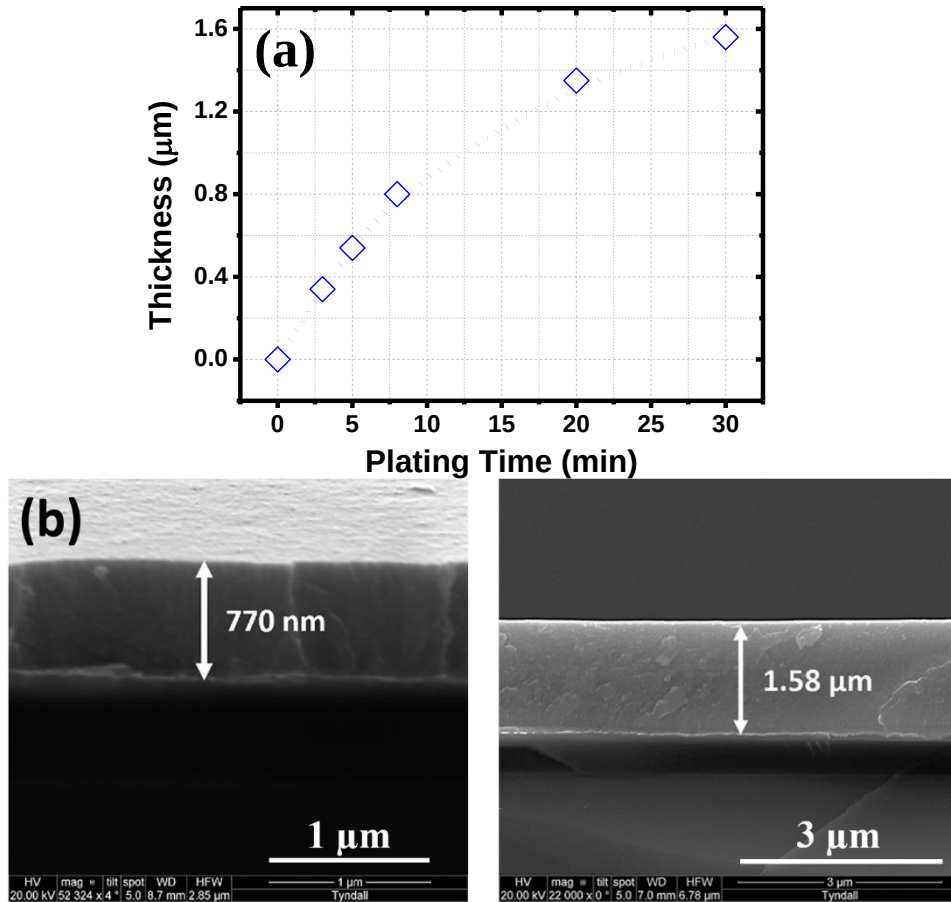


Figure 4.9. (a) Thickness of Permalloy films electroless deposited at different plating times. (b) SEM images of $\text{Ni}_{81}\text{Fe}_{19}$ films with thicknesses 770 nm and 1.58 μm .

Figure 4.9 (b) depicts the SEM cross-section micrographs of uniform films 770 nm and 1.58 μm in thickness. All the films were deposited in the presence of NdFeB magnets with magnetic field (~ 24000 A/m) along in-plane direction of the wafer during deposition to induce anisotropy in the deposited films. The distance between the magnet and the substrate was maintained at 15 cm from the outer edge to keep the magnetic properties consistent without disturbing the magnetic stirrer. Deposition in magnetic field has been reported for electroless CoNiFe films [4.57-4.58], but no comprehensive study has been done on electroless Ni-Fe alloy deposition in magnetic field.

Further investigation were done with increased Ni and Fe ion content while maintaining their ratio at 1:1 and the other constituents unchanged. Figure 4.10 shows that higher Ni and Fe content in the bath increases the deposition rate. However, as observed from the Figure, this increase in deposition rate reaches a plateau as the Ni salt concentration increases above 0.12 mol-dm^{-3} . This suggests increase in Ni concentration does not increase deposition rate any further. There is no significant change in composition on increasing the metal ion concentration with deposits in the range Ni (74-81) and Fe (26-19) at. wt. %. This increase in deposition rate may be attributed to higher catalytic activity which is due to the increase in Ni ions by the oxidation reaction of DMAB. This is consistent with electrolessly deposited Ni-Co alloys reported in the literature [4.17, 4.19 and 4.59]. For the remainder of the processing a Ni content of 0.06 mol-dm^{-3} was utilised to keep a consistent deposition rate of 110 nm/min and smooth film surface.

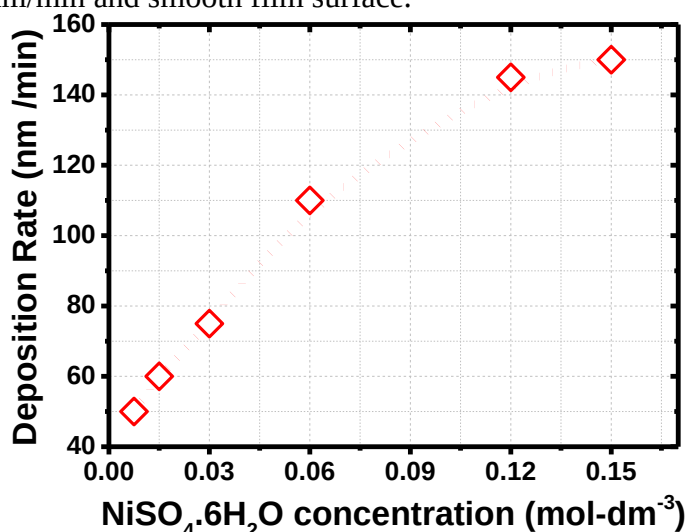


Figure 4.10. Influence of increase in Ni concentration (keeping $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$: $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ salt same by weight) in film deposition rate.

Electroless deposition of Ni-Fe alloys [4.60-4.62] from hypophosphite baths has also been reported previously. These baths can provide up to 25 % Fe composition [4.59]. Wang et al [4.62] reported deposition of Ni-Fe-P amorphous films from boric acid and sodium citrate baths to achieve 38 % Fe and 3 % P (rest is Ni). The film quality and grain size strongly depends on the complexing additives and reducing agent. In this work, di-ammonium citrate and lactic acid were employed as complexing agents and DMAB was used as reducing agent as similar bath compositions previously investigated at Tyndall have shown excellent nano-crystalline electroless CoNiFe-B thin films [4.19].

A higher Fe content offers an increase in resistivity and saturation flux density with increased coercivity. Hence, a trade-off is required in terms of the magnetic and electrical properties of the Ni-Fe alloy films, which can be probed by varying the Ni and Fe compositions. Higher DMAB content can increase Fe content relative to Co in CoNiFe-B deposits [4.18]. This behaviour is attributable to the increase in catalytic activity of the deposits for the anodic oxidation of DMAB, since iron becomes more active for this reaction than nickel with DMAB. To achieve this in Ni-Fe alloys, the DMAB concentration was increased from 0.017 to 0.136 mol-dm⁻³.

DMAB concentration can be increased to reduce temperature at which deposition starts. Figure 4.11 shows the influence of DMAB content on this temperature. Figure 4.12 shows the SEM images of the surface of the deposited films at 0.017, 0.034, 0.102 and 0.136 mol-dm⁻³ DMAB concentrations. The deposition of the samples started at temperatures: 85 °C, 75 °C, 65 °C and 58 °C respectively. The films deposited in high temperature (85°C, bath-I) showed poor morphology due to local deformation due to excessive heating while deposits from high DMAB concentration (0.136 mol-dm⁻³, bath-V) showed poor morphology and increased particle size. Moreover, the bath-V is found to be unstable for long duration depositions. The films deposited at 75 °C and 65 °C showed excellent morphology.

Figure 4.13 shows that the deposited Ni-Fe alloy composition can be varied by changing the DMAB concentration in the solution. On increasing the DMAB concentration from 0.017 mol-dm⁻³ to 0.136 mol-dm⁻³, the Ni-Fe alloy composition can be varied from Ni₈₁Fe₁₉ to Ni₃₇Fe₆₃. The magnetic core thickness (770 nm - 1.58 µm) in micro-inductors and transformers is chosen based on the frequency of operation (20 -100 MHz) such that, the eddy current losses can be kept to a minimum.

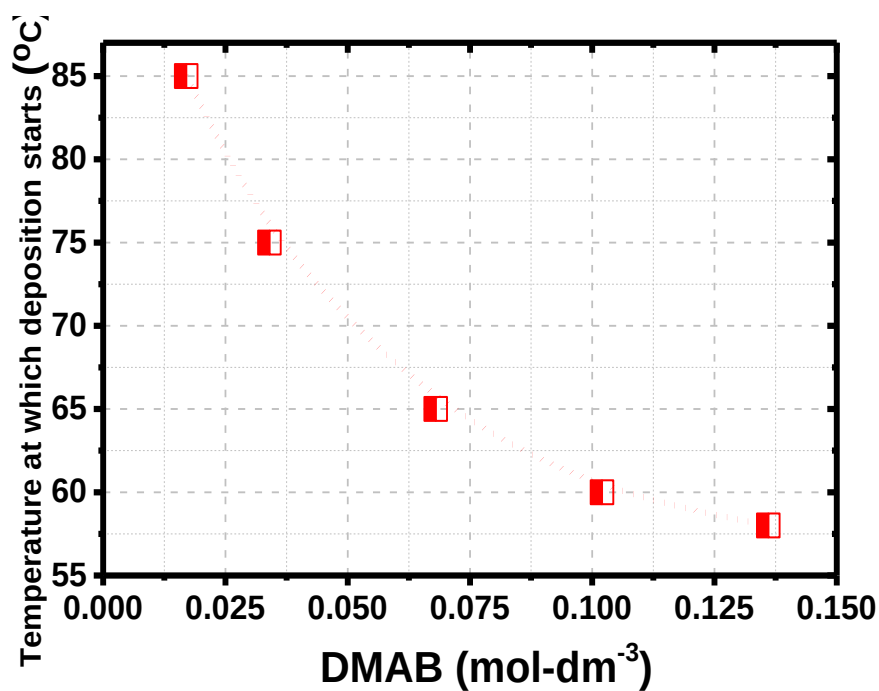


Figure 4.11. Influence of DMAB concentration on starting deposition temperature.

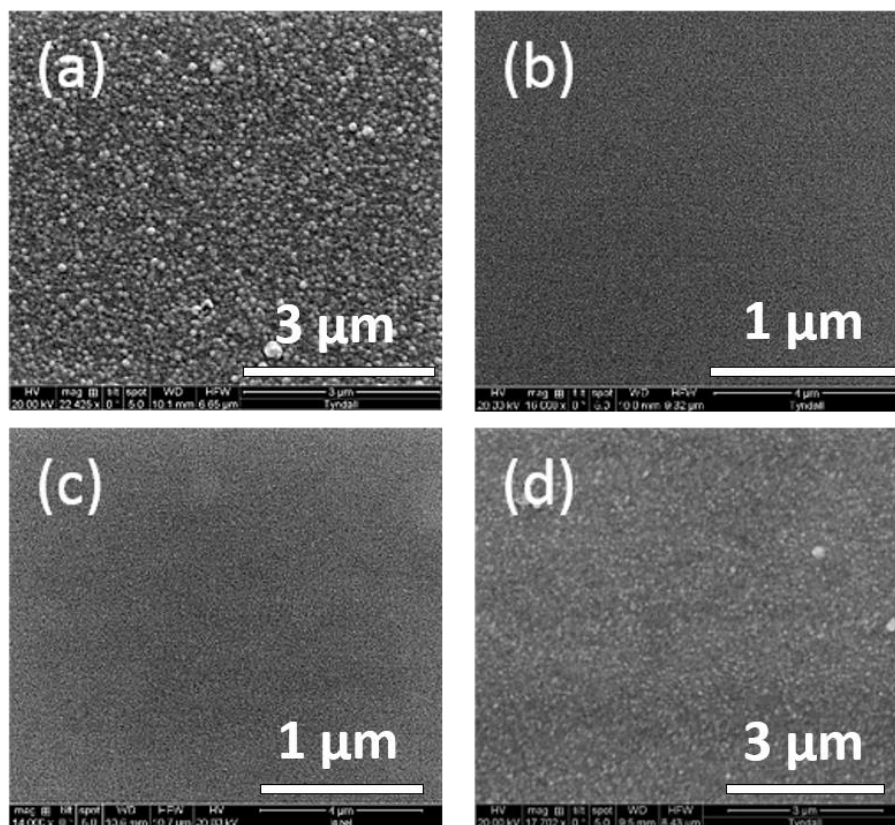


Figure 4.12. SEM micrographs of electrolessly deposited samples in baths with varying DMAB concentration and temperature: (a) 0.017 mol-dm⁻³ at 85 °C. (b) 0.034 mol-dm⁻³ at 75 °C. (c) 0.102 mol-dm⁻³ at 65 °C. (d) 0.136 mol-dm⁻³ at 58 °C.

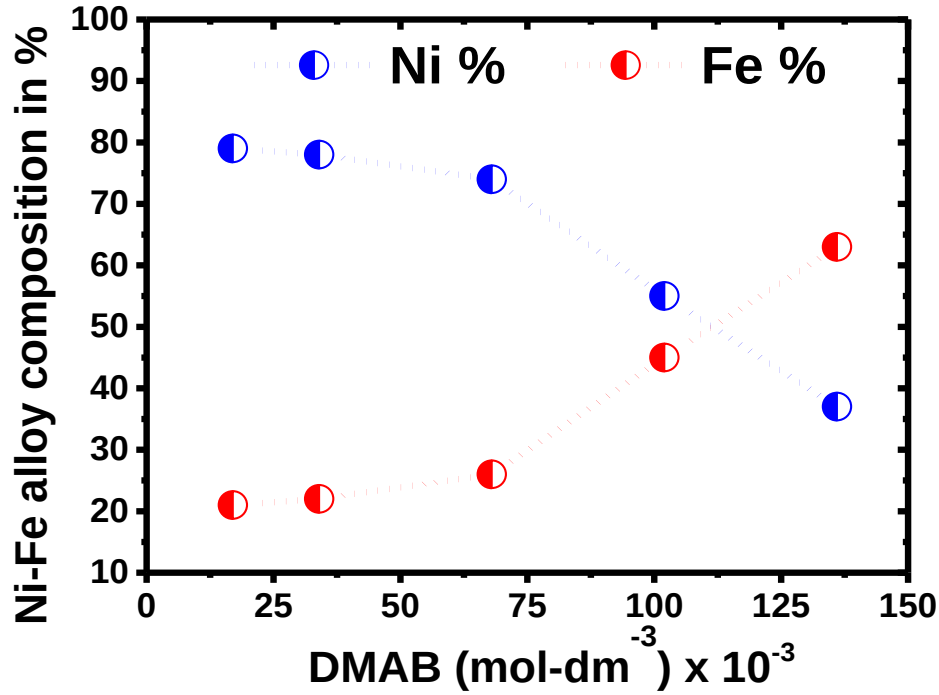


Figure 4.13. Influence of di-methylamine borane concentration on Ni-Fe alloy composition of the film.

b. Magnetic Characterization: The deposited films were investigated for their magnetic properties using a BH loop tracer. More than 8000 A/m field was applied to completely saturate the sample during the measurement. Figure 4.14 (a) shows the normalized hysteresis loops of the easy-axis and hard-axis of the electrolessly deposited Permalloy film (Ni₈₁Fe₁₉) of bath I. The saturation flux density was measured to be ~1 T. The H_k values for the permalloy films increased from 960 A/m to 1120 A/m depending on thickness deposited while the hard-axis coercivity decreased with thickness and the coercivity values were always below 38.4 A/m with 29 A/m being the minimum measured coercivity (shown in Figure 4.14 (a)). Figure 4.14 (b) shows the normalized hysteresis loops of the easy-axis and hard-axis of a Ni₃₇Fe₆₃ sample deposited in the external magnetic field. The sample exhibited a high saturation flux density of ~1.7 T with the high coercivity value ~96 A/m. This can be attributed to the Fe rich Ni-Fe alloy. The composition to be used is based on the trade-off in performance and is therefore determined by the application. It is possible to achieve various Fe compositions (between 19-63%) by keeping the same electroless bath composition and changing di-methylamine borane concentration only.

Figure 4.15 shows the anisotropy field and coercivity values obtained versus film thickness. The coercivity decreases with an increase in thickness (d). This is in

accordance with the Néel equation [4.64]: H_c (coercivity) = Ld^{-n} , where L and n are constants depending on magnetization of the films, energy wall domain, structure, thickness uniformity and surface geometry. The anisotropy in the films increase with thickness, which is well-established [4.65]. This is also influenced by the external magnetic field during deposition and roughness in the films. The externally induced magnetic field forces the domains to align along the magnetic field. This is an energetically favourable direction of spontaneous magnetization (easy-axis). The increase in surface roughness increases coercivity, by alignment of the domains in such a way that the magnetic coupling between the domains is energetically unfavourable.

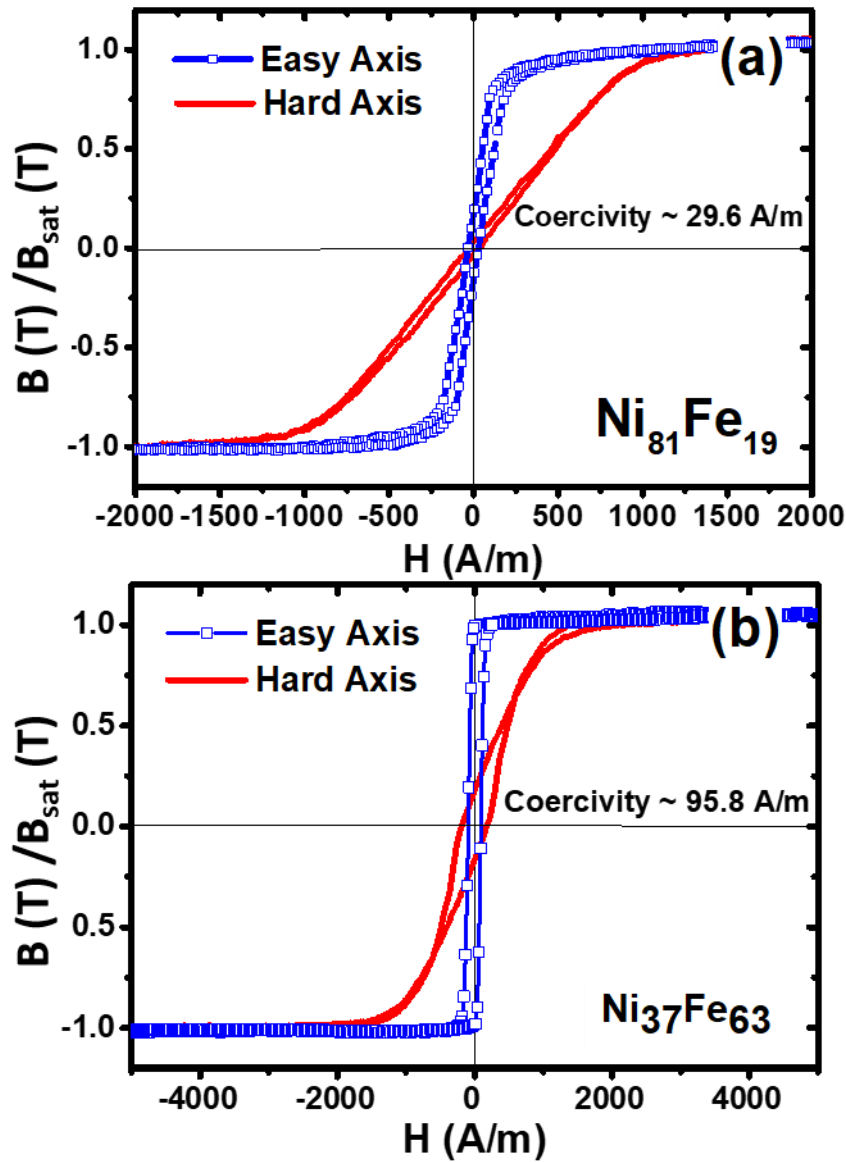


Figure 4.14. Normalized hysteresis loops of (a) $\text{Ni}_{81}\text{Fe}_{19}$ and (b) $\text{Ni}_{37}\text{Fe}_{63}$ films.

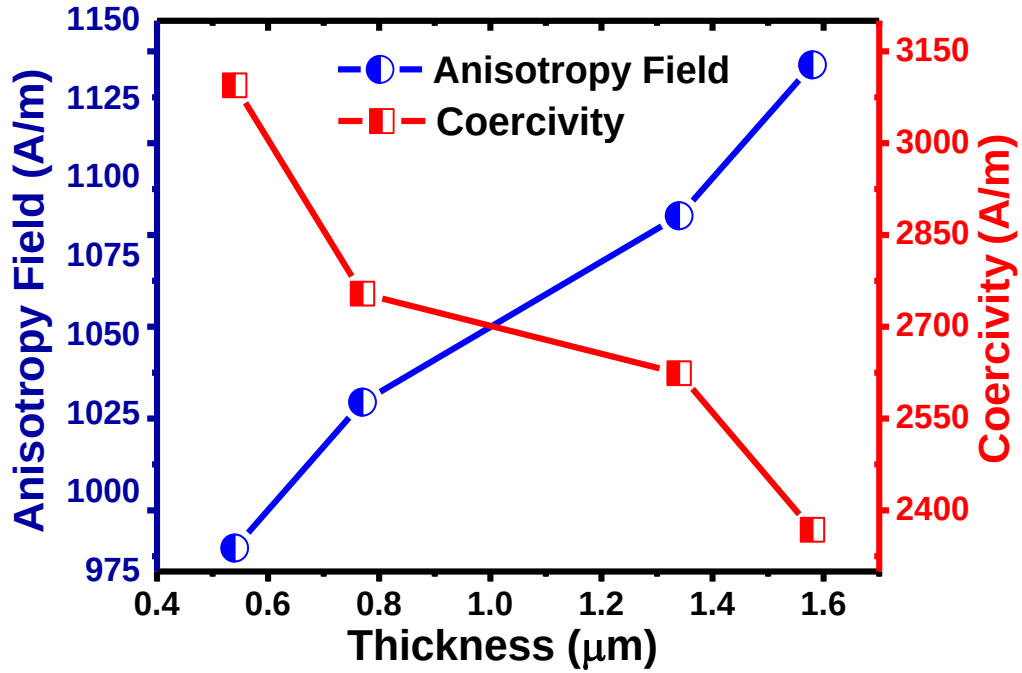


Figure 4.15. Anisotropy field and coercivity of $\text{Ni}_{81}\text{Fe}_{19}$ films deposited in presence of magnetic field.

There have been very few reports on high frequency characteristics of electroless magnetic materials and in particular, Ni-Fe alloys. Hence, it is important to assess the high frequency response of electroless Ni-Fe alloys for their applicability in high frequency integrated magnetics. Figures 4.16 (a) and 4.16 (b) depict the real and imaginary part of the permeability spectra of $\text{Ni}_{81}\text{Fe}_{19}$ films of different thickness at 1600 A/m external bias measured with high-frequency permeameter system. As observed from the Figure, the real part of the permeability is stable beyond 100 MHz and has a roll-off frequency of ~ 200 MHz with a significant increase in the cut-off frequency for the $1.58 \mu\text{m}$ thick deposit compared to 540 nm thick film. This can be attributed to the high anisotropy ($\sim 1120 \text{ A/m}$) of the deposited film, which may have resulted from the stress developed in thicker films. The decrease in initial permeability with thickness is in accordance with previously reported works [4.66], where the relative permeability (μ_r) relates to the thickness (t) of the magnetic films as, $\mu_r \propto t^{-0.5}$. The imaginary permeability (Figure 4.16 (b)) is a measure of loss in the material. It can also be seen that the film has high ferromagnetic resonance frequencies for thicker deposits, showing the contribution to large anisotropy of increasing film thickness.

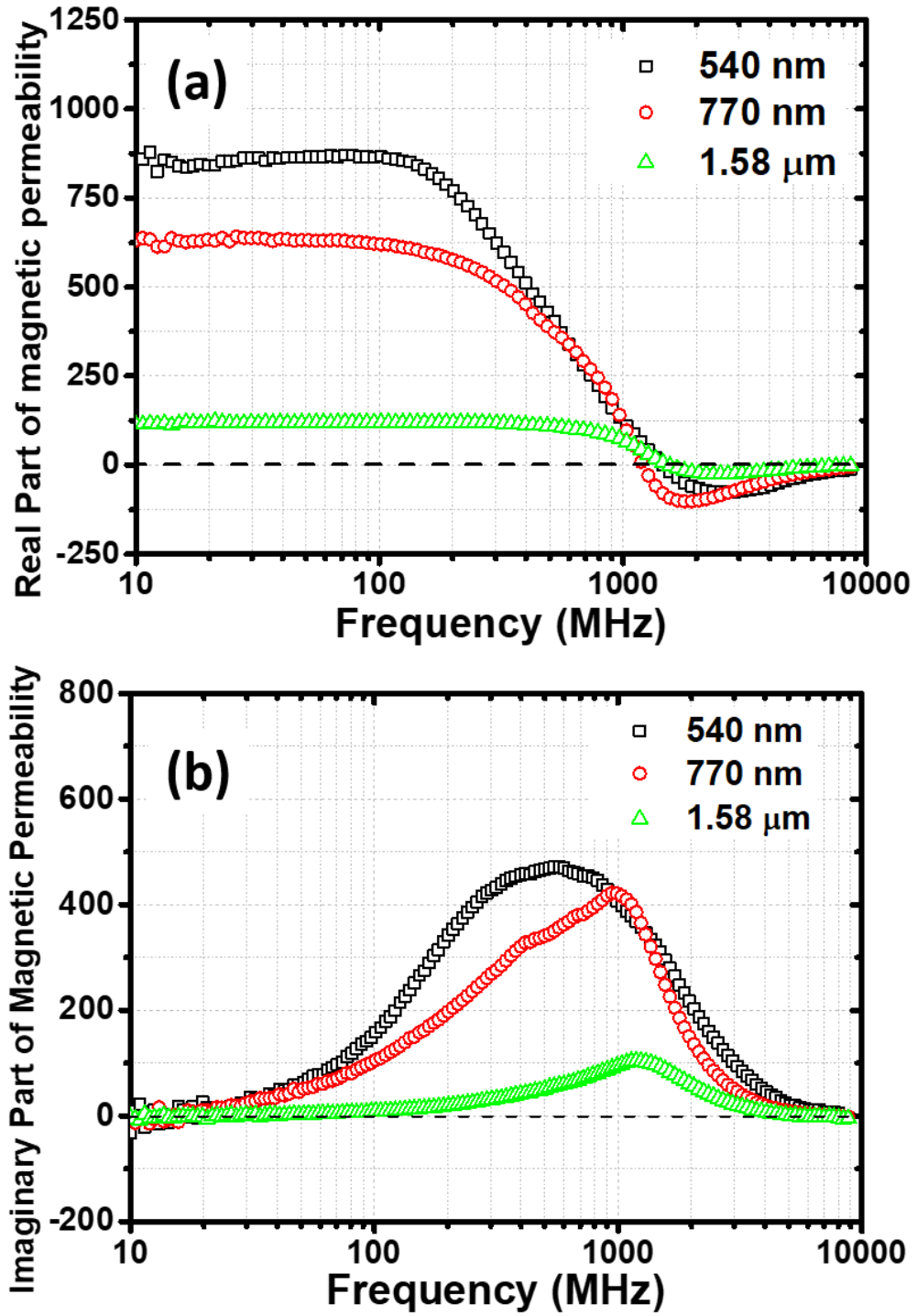


Figure 4.16. Permeability a) (real part) of $\text{Ni}_{81}\text{Fe}_{19}$ films and b) imaginary part of 540 nm, 770 nm and 1.58 μm thick films at 1600 A/m external bias field.

c. Crystallinity and Resistivity: The electrical resistivity of the material is a significant parameter on which the critical thickness of the magnetic core is based. This thickness is estimated from the skin depth equation:

$$d = \sqrt{\frac{\rho}{f \cdot \mu_0 \mu_r \pi}} \quad (4.2)$$

Where, ρ , $\mu_0 \mu_r$ and f are the resistivity, permeability of the film and the frequency of operation, respectively. For core thicknesses above its skin depth, the eddy currents contribute to the core losses. Thicker cores on the other hand allow better flux confinement in the cores, which in turn increases the inductance density. Hence, it is desirable to have highly resistive magnetic films without degrading the magnetic properties. In this work di-methyamine borane complex baths were preferred over hypophosphite for lower coercivity. Hence, the resistivity of the deposits increased with Ni content gradually decreasing (Permalloy: 81% Ni to Invar: 37% Ni) and Fe content increasing (Permalloy: 19% to Invar: 63%) by varying di-methyamine borane complex in the bath (as listed in Table 4.5) to achieve a higher Fe content.

Figure 4.17, shows the increase in resistivity from 26 $\mu\Omega\text{-cm}$ to 63 $\mu\Omega\text{-cm}$ with changing alloy composition from $\text{Ni}_{81}\text{Fe}_{19}$ (Bath-II) to $\text{Ni}_{37}\text{Fe}_{63}$ films (bath-V). This increase is attributed to the Fe rich alloy. Compared to $\text{Ni}_{81}\text{Fe}_{19}$, the resistive soft $\text{Ni}_{37}\text{Fe}_{63}$ magnetic alloy would reduce the eddy-current losses, however the high coercive (96 A/m) nature of the films will be a limiting factor. Hence, a trade-off is required in terms of the magnetic and electrical characteristics of the films.

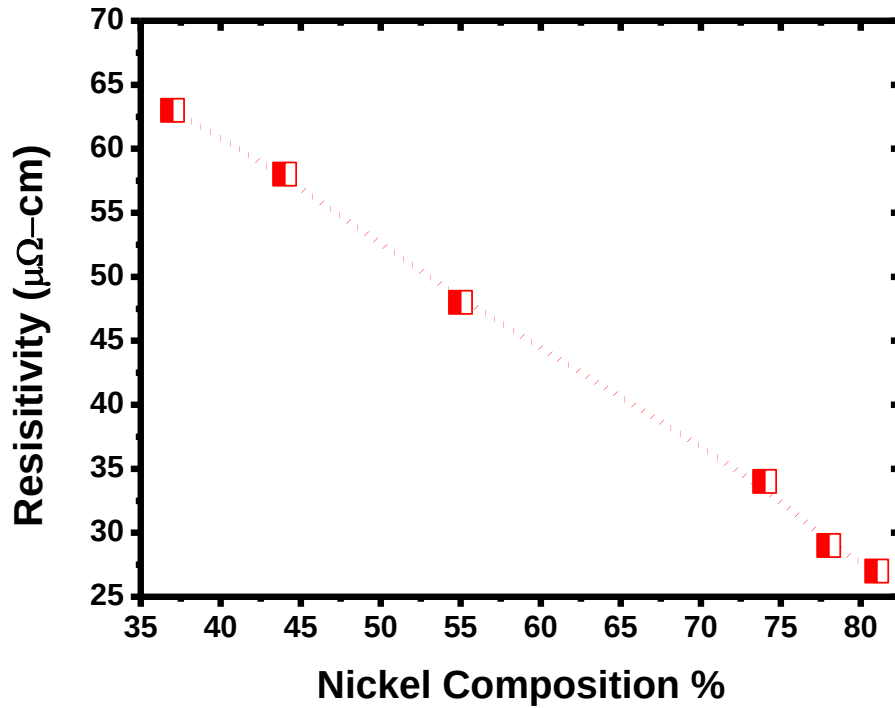


Figure 4.17. Resistivity of thin films with varying Ni-Fe alloy composition (~300 nm).

X-ray diffraction peak analysed with High-score software (Figure 4.18) suggested a BCC rich phase ($\text{Ni}_{81}\text{Fe}_{19}$) at peak 43.45° and BCC ($\text{Ni}_{37}\text{Fe}_{63}$) phase along with some FCC phase at peak 43.35° . The grain sizes calculated for polycrystalline $\text{Ni}_{37}\text{Fe}_{63}$ and $\text{Ni}_{81}\text{Fe}_{19}$ films using the well-established Debye-Scherrer's formula indicates grain sizes of 30 nm and 32.4 nm, respectively suggesting a nano-crystalline phase in the material. In accordance to the Herzer's plot, this accounts for the low coercivity (< 100 A/m) measured for both the film compositions ($\text{Ni}_{37}\text{Fe}_{63}$ and $\text{Ni}_{81}\text{Fe}_{19}$). Table 4.6 lists the properties of Ni-Fe alloy composition and their respective magnetic and electrical properties.

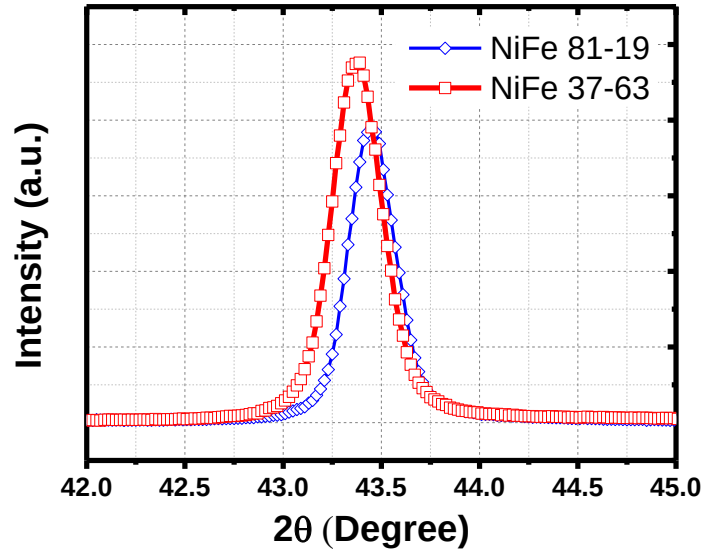


Figure 4.18. XRD peaks of $\text{Ni}_{81}\text{Fe}_{19}$ and $\text{Ni}_{37}\text{Fe}_{63}$.

Table-4.6: Ni-Fe alloy compositions and the respective magnetic and electrical properties.

Ni-Fe composition (with traces $\leq 1\%$ of B) & Variation in Ni %	Coercivity (A/m)	Anisotropy field (A/m)	Resistivity ($\mu\Omega\text{-cm}$)
$\text{Ni}_{78}\text{Fe}_{22} \pm 4\%$	29.6	960	26
$\text{Ni}_{54}\text{Fe}_{46} \pm 2\%$	43.2	880	49
$\text{Ni}_{45}\text{Fe}_{55} \pm 3\%$	52	720	57
$\text{Ni}_{36}\text{Fe}_{64} \pm 2\%$	96	600	62

4.6.Ultra-Soft Magnetic Material Development

In the previous section, a wide range of Ni-Fe alloys were developed with varied magnetic and resistivities. However, none of the alloys have shown ultra-soft magnetic (< 10 A/m coercivity) properties. Hence, development of a low loss magnetic film is essential for efficient high-frequency magnetics applications. Such a magnetic material would reduce the inherent core losses and improve device efficiency.

Vapour deposited Co-Zr-Ta-B [4.36], Fe-Cu-Nb-Si-B [4.66] have shown excellent magnetic properties ($H_c < 10$ A/m). However, these materials are sputter deposited (slow deposition rates) or require high-temperature processing to modify the crystallinity of the material. Moreover, selective patterning and a high temperature post-process means the vapour-based processes may not always be compatible with the existing on-silicon device processing.

Electroplating on the other hand, is now a conventional low-cost metallization process in the micro-fabrication industry. Advantages such as the possibility of depositing with low-energy and high deposition rates has made it widely accepted as a thin film deposition method. Electroplated magnetic films such as Co-Fe alloys [4.19, 4.67] have shown high saturation flux density (B_{Sat} : 2.0 T - 2.45 T) and low coercivities ($H_c < 160$ A/m), respectively. However, electroplated ultra-soft magnetic materials ($H_c < 10$ A/m) along with high electrical resistive ($\rho > 70 \mu\Omega\text{-cm}$) properties are yet to be reported. Attempts have been made with patterned magnetic films to improve soft-magnetic properties [4.68]. However, such methods require rigorous optimization no significant improvements in coercivity ($H_c < 10$ A/m).

Ni and Fe alloys based alloys have been known as active oxygen evolution reaction catalysts. They have been used form OER electrolysis for water splitting and rechargeable metal-air batteries. Instead of developing a new magnetic alloy, which is limited naturally existing magnetic materials, the properties of as deposited films to develop low-loss ultra-soft material has been changed by this method.

To develop aforementioned ultra-soft magnetic properties, the next section focuses on an electrochemical post-processing technique to change the crystalline properties of as-deposited $\text{Ni}_{45}\text{Fe}_{55}$. The experimental procedure used is a modification of one developed to generate thick hydrated oxide layers on the surface of polycrystalline nickel and iron electrodes. Potential cycling in alkaline solution allows the surface oxide layer to be extended considerably beyond the monolayer level resulting in a coating that can be significantly porous and hydrated. The high Fe content in $\text{Ni}_{45}\text{Fe}_{55}$ alloy could be turned in to hydro-oxides, which may change the magnetic and electrical resistivity of the film. The aim was to develop a resistive ($> 70 \mu\Omega\text{-cm}$) and ultra-soft magnetic material ($H_c < 10$ A/m) from an as-deposited material this method. This process will expand the research presently limited by available soft-magnetic

materials and be exploited in a wide-range of soft-magnetic films to develop ultra-low coercivities.

4.6.1. Experimental procedure

Step I: Pulse Reverse plating $\text{Ni}_{45}\text{Fe}_{55}$ film

The first step of the process is depositing $\text{Ni}_{45}\text{Fe}_{55}$ in-house developed plating system and solution. A 100 mm diameter Si wafer (thermally oxidized and sputtered with Ti (20 nm) / Permalloy (100 nm seed)) was pulse-reverse-plated (PRP) method using an in-house developed bath (shown in table-4.7) at a current density of 1 A/dm^2 in the presence of an external magnetic field (300 mT at the centre of the wafer) at room temperature and pH of 2.5. The external magnetic field aligned the domains along the applied external field, thus resulting in a magnetically anisotropic film (with distinct easy and hard axis). The hard-axis will have higher anisotropy field and lower coercivity than the easy axis. The core flux is oriented along this direction to minimize hysteresis losses. The optimized plating parameters are given as: I_{forward} : 550 mA; T_{forward} : 18.4 m-sec; T_{off} : 0.5 m-sec; I_{reverse} : 3.85 A; T_{reverse} : 0.6 m-sec and T_{off} : 0.5 m-secs. Figure 4.19 shows the pulsed current waveform. The positive cycle for T_{forward} duration represents plating time, while the short negative duration represents the removal/etching duration. This gives a dendrite-free and uniform composition with small grain sizes ($\sim 33 \text{ nm}$). The plating rate is $0.05 \mu\text{m/min}$ and the wafer is rotated at regular intervals by 180° to ensure uniform deposition.

Table-4.7: Bath constituents for electroplating Ni-Fe (45/55).

Constituents	Quantity
DI Water	2.7 L
$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ (Sigma Aldrich)	450 grams (0.70 M)
$\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ (Sigma Aldrich)	26 grams (0.05 M)
Boric acid (Sigma Aldrich)	75 grams (0.45 M)
Saccharin (Sigma Aldrich)	15 grams (0.030 M)
1, 3, 6 - Naphthalene Trisulphonic acid (Sigma Aldrich)	12 grams (4.5 grams/L)
Sulfosalicylic acid (Sigma Aldrich)	15 grams (5.5 grams/L)
Triton X (Sigma Aldrich)	1.5 grams (0.5gms/L)

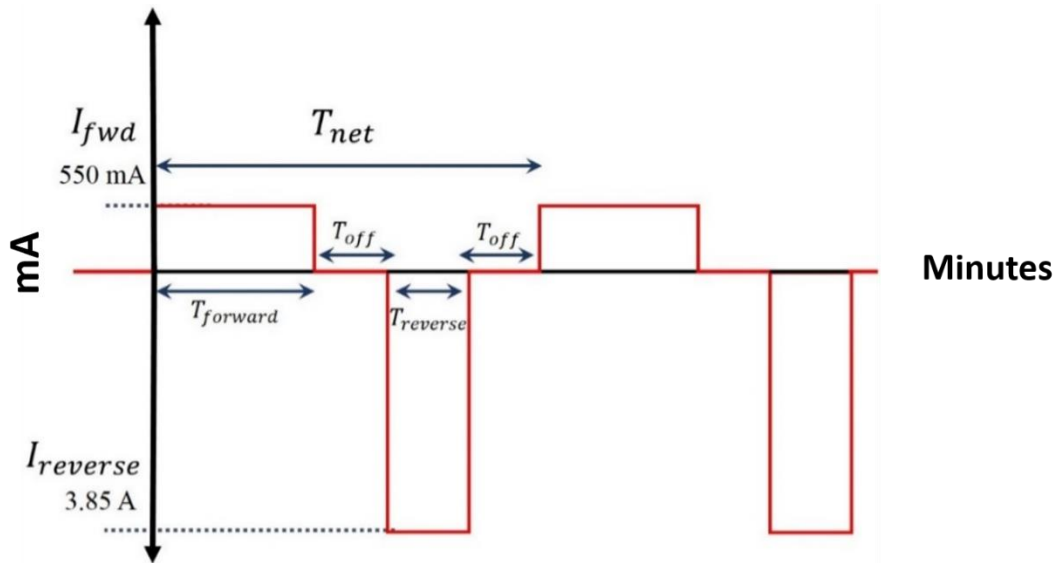


Figure 4.19. Pulse current waveform.

Step II: Anodizing as-deposited $\text{Ni}_{45}\text{Fe}_{55}$ film

The second step is a cyclic voltammetry (C-V) treatment at 1 M NaOH solution (pH: 12) between the potential limits of 0.65 V and 1.5 V versus a calomel (Hg_2Cl_2) reference electrode. Scan rates (from 50 mV/s to 200 mV/s) and number of cycles (100-300 cycles) were varied to examine the influence of cyclic time and rates on the deposit characteristics. Figure 4.20 shows the cyclic voltammetry curves of cycles at 50 mV/s.

These processes are facilitated by the potential cycling procedure and the extent of hydrous oxide growth is largely dependent on the upper and lower potential limits, composition, substrate type and pH [4.69-4.71]. Briefly, the upper limit must be sufficiently anodic that compact oxide formation significantly exceeds the single monolayer level so that on subsequent reduction a disturbed, highly disordered layer of metal atoms is produced at the working electrode surface ($\text{Ni}_{45}\text{Fe}_{55}$). Often the optimum lower limit will occur at or just below the monolayer oxide reduction peak potential.

On subsequent re-oxidation the disrupted layer of metal atoms is converted to hydrated, or partially hydrated, oxide (complete hydration under these conditions may involve several redox cycles) and a fresh inner compact layer is regenerated at the metal surface on each anodic sweep. On repetitive cycling the porous outer layer increases in thickness at the expense of the underlying metal.

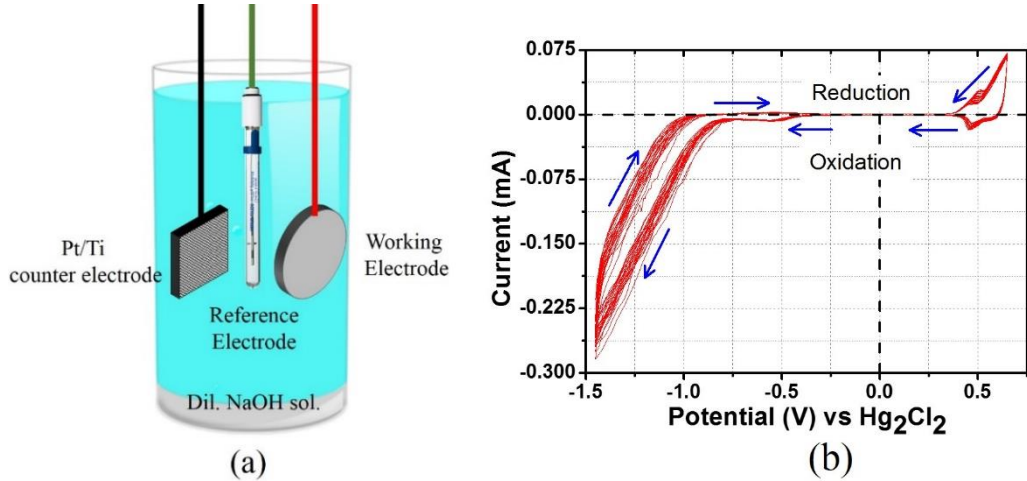
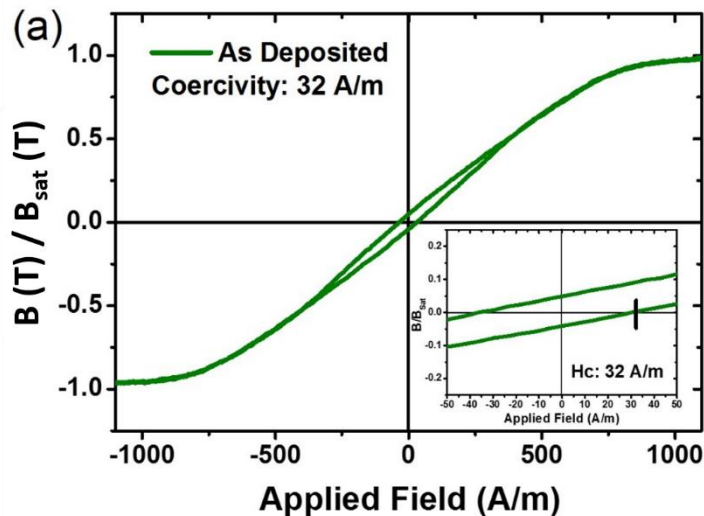


Figure 4.20. (a) Anodization setup and (b) anodic cycling curves showing cathodic and anodic current peaks.

4.6.2. Results and discussions

a. BH loop analysis: To optimize the scan conditions, wafer scale samples were prepared with different scan speeds (200 mV/s to 50 mV/s) and measured by BH loop tracer. Figure 4.21 (a) shows the measured hysteresis loop of as-deposited sample. The coercivity measured along the hard-axis is ~ 32 A/m. Figure 4.21 (b) shows the hysteresis loops along hard-axis with 300 cycles of slow (50 mV/s) and fast scan speeds (200 mV/s) for the post processing oxidation. As observed from the Figure, no reduction in coercivity compared to as-deposited sample could be observed with faster scan rates while with slower scan rates, the coercivity reduced to $\sim 1/15^{\text{th}}$ of the original value. This can be attributed to sequential oxidation with faster scans (confirmed with EDX and XPS analysis later). Moreover, a considerable increase in anisotropy is observed for films processed at lower scan rates, which also drives the reduction in coercivity.



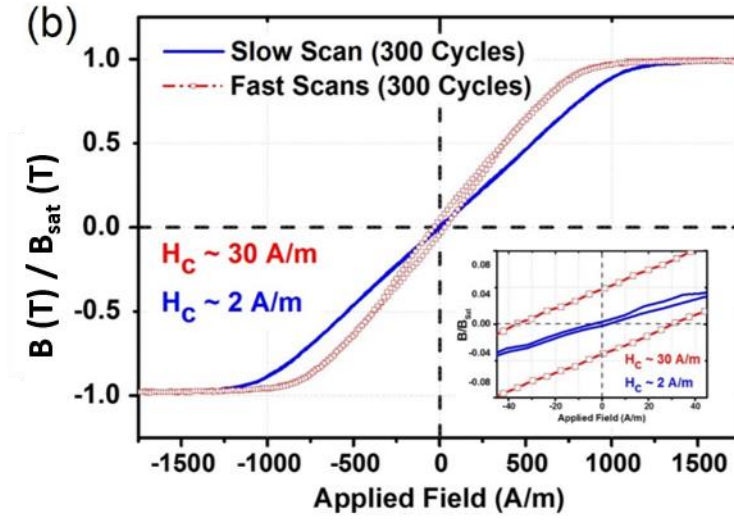


Figure 4.21. Hysteresis loop of (a) As –deposited and (b) post processed samples with 300 slow and fast cycles.

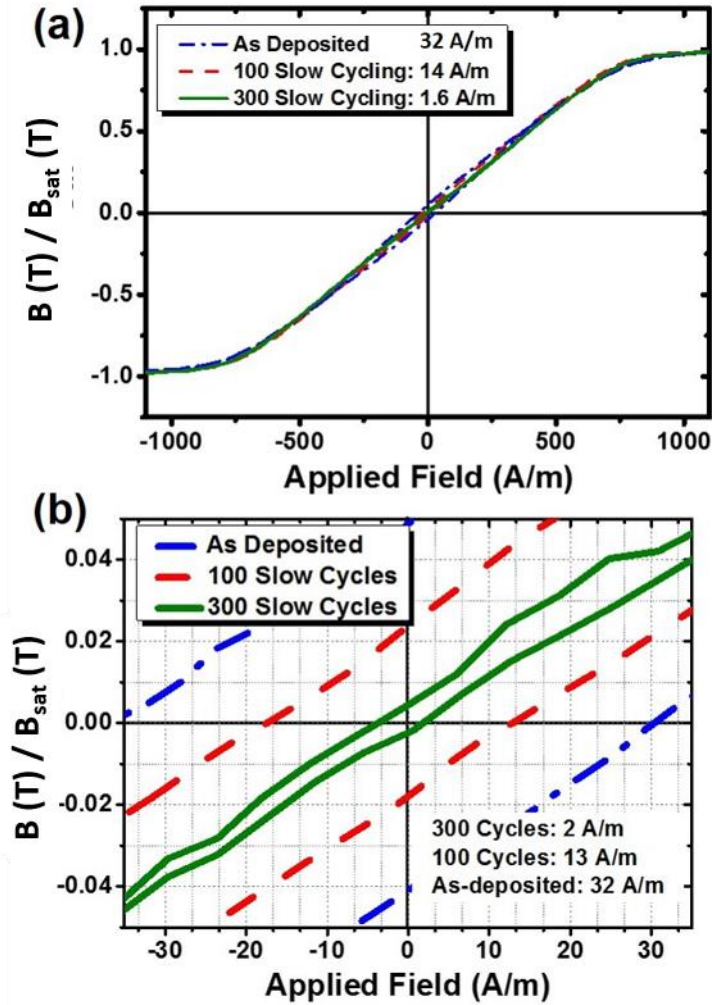


Figure 4.22. (a) and (b) Hysteresis loop of post processed samples with 100 and 300 slow cycles in comparison to as-deposited film (100 mm diameter wafer scale) of $1.87 \mu\text{m}$ thickness.

To understand the influence of number of scans, the total number of scans are changed (from 100 cycles to 300 cycles) with the optimized scan rate (50 mV/s). Figure 4.22 shows the hysteresis loop at different stages of this processing. A gradual decrease in coercivity with number of scans is observed. To ensure process repeatability and characterization, multiple samples (4 samples of 2 x 2 cm² area and a 100 mm diameter wafer scale) were developed under identical conditions and multiple BH loops were recorded. In all the cases, the coercivity remained < 5 A/m while an anisotropy field > 900 A/m was measured. All the samples showed a similar reduction in coercivity (< 5 A/m) as the number of anodization cycles increased. There was no significant change in saturation flux density (B_{sat}) before (saturation flux: 248 nWb) and after (saturation flux: 258 nWb) the post-processing in the wafer-scale samples of 1.87 μm thick Ni₄₅Fe₅₅ and in 2 cm x 2 cm samples (saturation flux before: 58 nWb and saturation flux after: 61 nWb) of 1.65 μm thick Ni₄₅Fe₅₅.

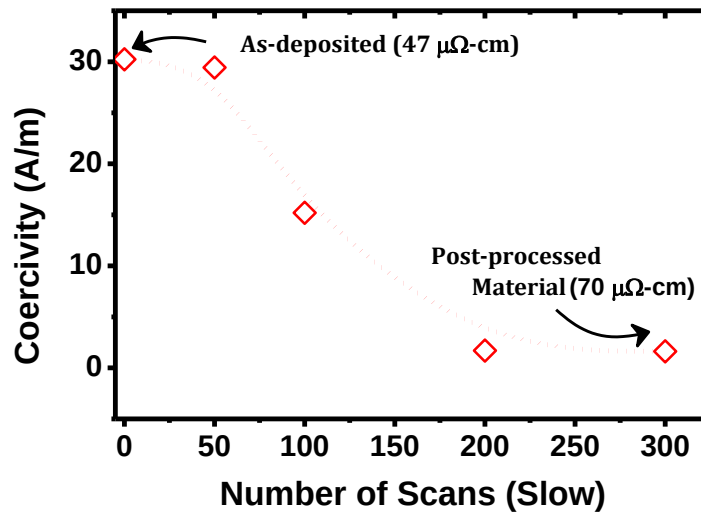


Figure 4.23. Coercivities at different stages of post-processing at 50 mV/s scan rate.

The coercivities were also measured after equal intervals of scanning at 50 mV/s scan speeds. Figure 4.23 shows the coercivity of the material with number of scans and the resistivities measured before and after the post-processing. Initially no significant change in coercivity was measured ($H_c \sim 32$ A/m). It was observed that the coercivity reduced gradually as the number of scans were increased. This could be attributed to the slow oxidation of the material. As the oxidation of the material picked up, the coercivity started to reduce. The oxidation of the material also increased the resistivity of the film increased from 47 $\mu\Omega\text{-cm}$ to 70 $\mu\Omega\text{-cm}$. The anodic cycling was

stopped once the coercivity were decreased to 2 A/m as no further reduction in coercivity was measured.

Figure 4.24 shows the coercivity of the material with number of scans for thickness of magnetic film between 1 μm – 6 μm . As observed before, initially no significant change in coercivity was measured. The coercivities reduced gradually as the number of scans increased. The Ni and Fe anhydrous-oxidation of the films reduce the grain size significantly. Further analysis were done to understand the changes in structural, oxidation and high frequency characteristics of the on post-processed films.

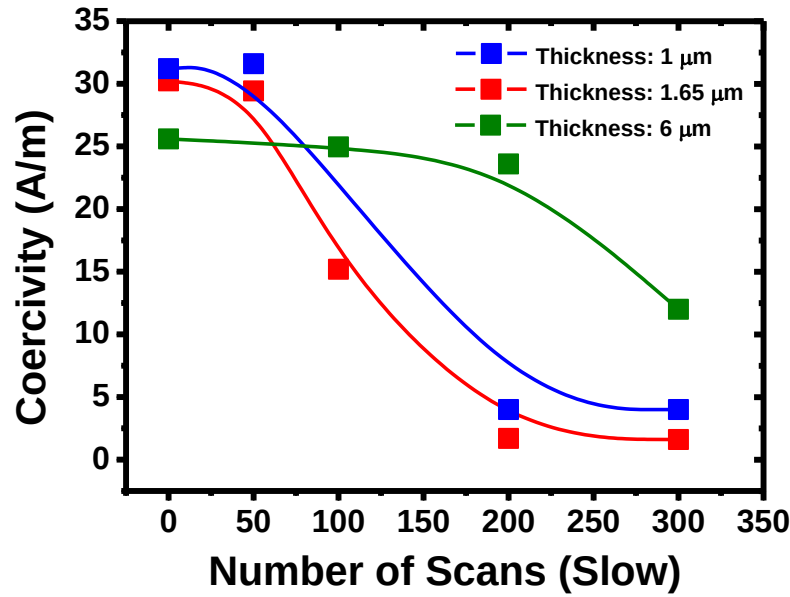


Figure 4.24. Coercivities measured at different stages of post-processing (slow cycles) for different film thicknesses.

b. SEM / EDX Analysis: Figure 4.25 depicts the SEM micrograph of the surface of the film, before (Figure 4.25 (a-b)) and after (Figure 4.25 (c-d)) cyclic treatment. As observed from the images, the nano-crystalline $\text{Ni}_{45}\text{Fe}_{55}$ shows the porous nature after post-processing (Figure 4.26 (e)). The composition changes in the films (before and after post-processing) were determined by electron-dispersive x-ray (EDX) spectra (Figure 4.26). A significant increase in Ni and Fe $K\alpha$ peaks and substantial reduction in Ni and Fe $L\alpha$ (7.48 and 6.4 KeV respectively) peaks suggest change in composition and oxidation after post-processing (Ni: 42% / Fe: 43.8% / O: 14.2%) compared to as-deposited material ((Ni: 47% / Fe: 53%). It is interesting to note that the presence of a new oxide peak ($K\alpha$ at 0.52 KeV) on post-processing which indicates some oxidation of Ni and Fe. This compositional change played a crucial role in reducing coercivity (< 5 A/m) and increasing resistivity (> 70 $\mu\Omega\text{-cm}$).

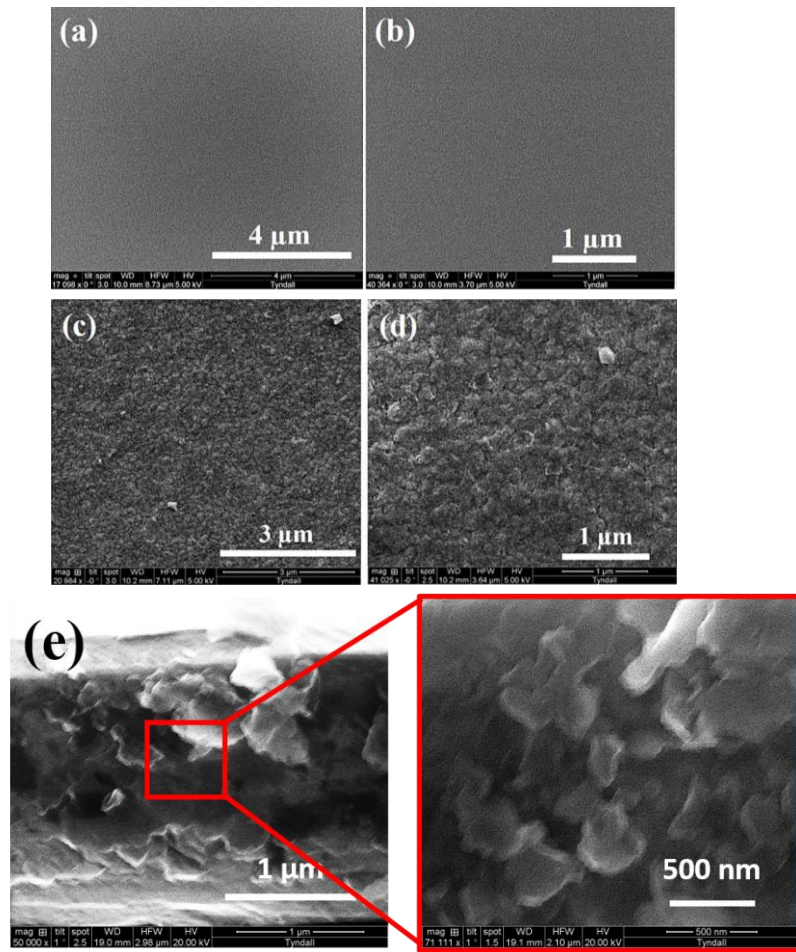


Figure 4.25. Influence of post-processing on $\text{Ni}_{45}\text{Fe}_{55}$ film surface (SEM micrograph) before (a-b) and after (c-d) post-processing. (e) Cross-sectional image of the porous film.

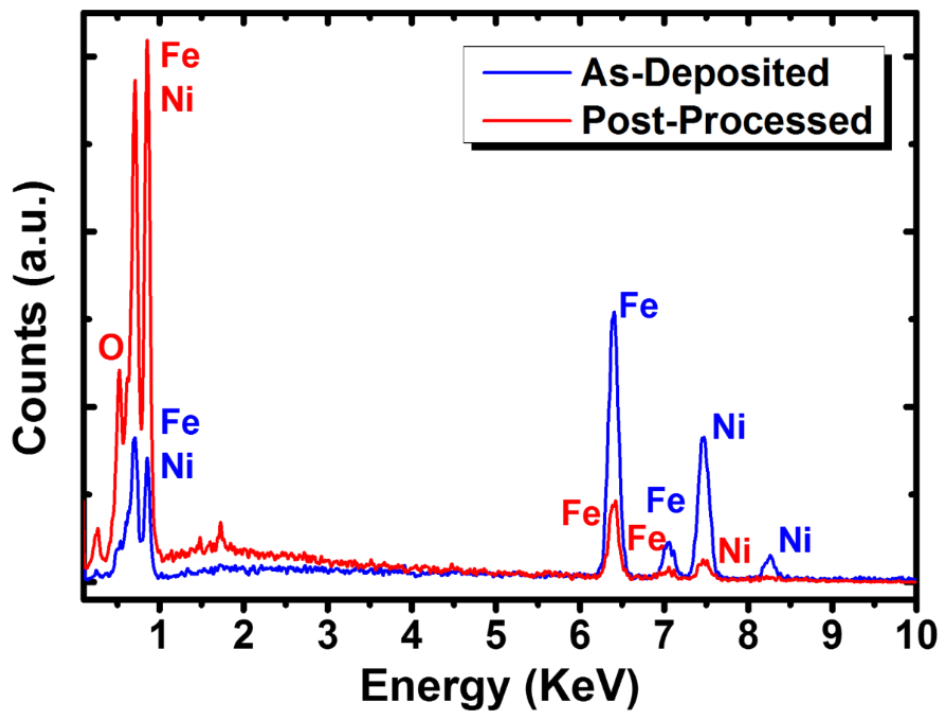
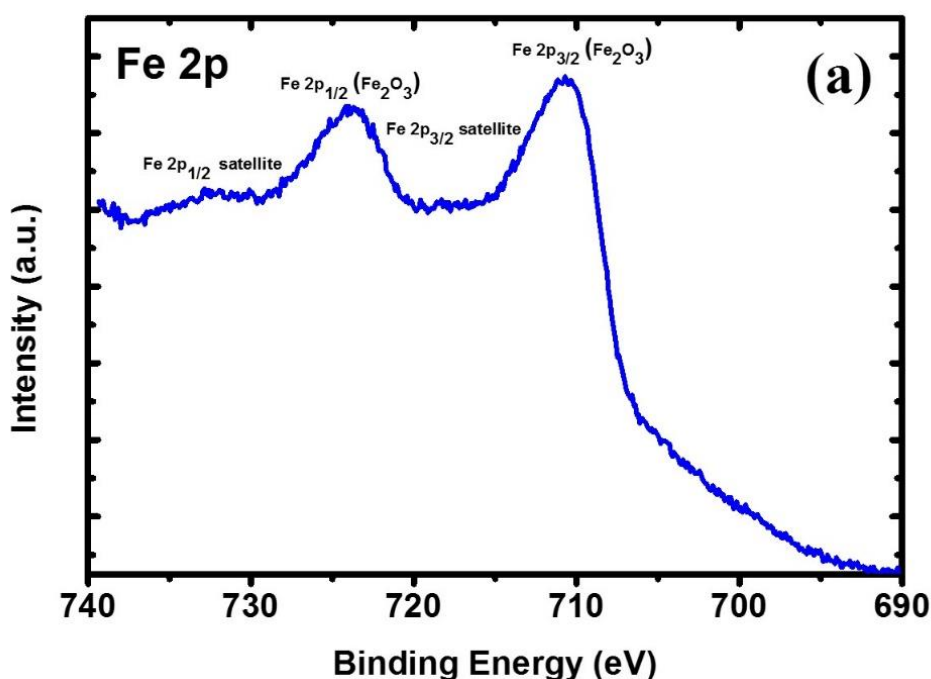


Figure 4.26. EDX spectra as-deposited and post-processing.

c. XPS Analysis: To determine the oxidation states of Ni and Fe, XPS (X-ray photoelectron spectroscopy) studies were utilized. Figure 4.27 (a-b) shows the XPS of Ni 2p and Fe 2p core-level scans (along with their components) of the film after processing along with its components or chemical states. The Fe 2p spectrum (Figure 4.27 (a)) shows evidence of strong Fe oxidation between 705 eV and 740 eV with two primary peaks (Fe 2p_{1/2} and Fe 2p_{3/2}). The satellite peaks confirm the oxidation state to be Fe (III) while the primary peaks implies a clean and pristine surface after post-processing. The primary peak at 711 eV and 724 eV binding energies is consistent with reported values in literature [4.72]. Figure 4.27 (b) shows the Ni 2p spectra of the post-processed film. The primary peaks at 853 eV and 873 eV confirm Ni (II) oxidation states with composition of the Ni (OH)₂ (which could be α -Ni(OH)₂ or β -Ni(OH)₂). The electrochemical treatment in NaOH solution oxidized the Ni to Ni (II) state. The redox reaction as mentioned before shows the chemical transition of the material. This film is expected to have a three-dimensional layered double hydroxide (LDH) structure (Figure 4.28) as reported by Diogini and Strasser [4.71].



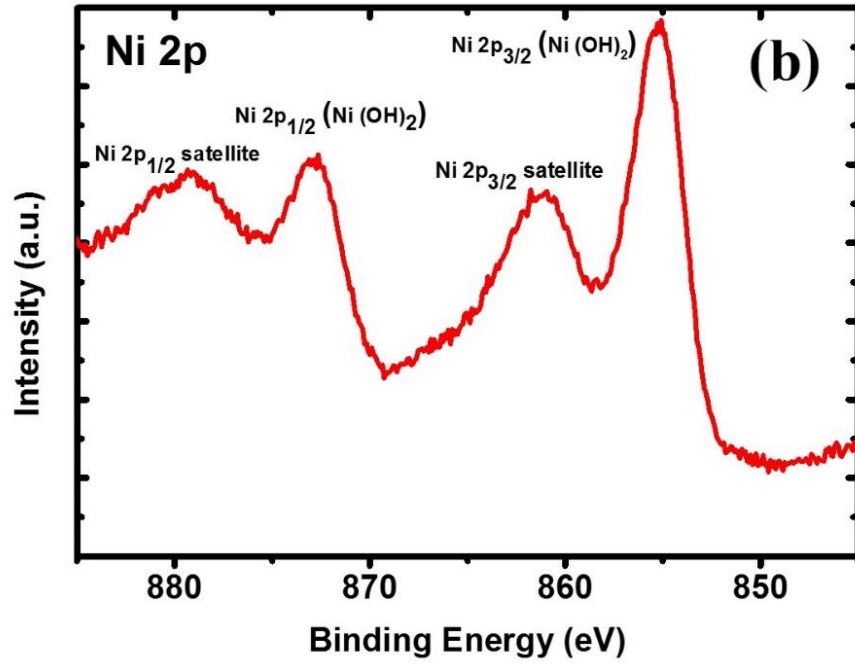


Figure 4.27. XPS peaks of (a) Fe 2p and (b) Ni 2p from the post-processed Ni-Fe (45/55) sample suggesting Fe (III) and Ni (II) oxidation states with respective satellite peaks.

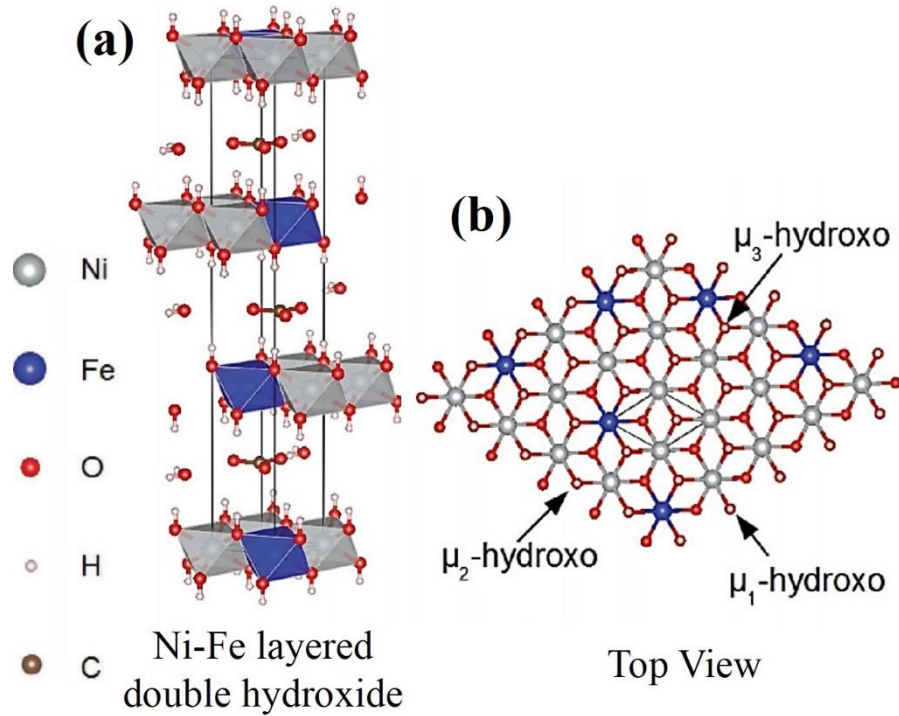


Figure 4.28. Crystal structure of Ni-Fe double-layered hydroxide (LDH) as proposed by Diogini et. al. [4.71].

d. XRD Analysis: Figure 4.29 shows the X-ray diffraction (XRD) peaks of the as-deposited and post-processed films. As observed, there is a distinct change in the crystallinity of the material upon cyclic treatment. The post-processed film shows an

amorphous nature. The grain size (D) is estimated from XRD data with Scherrer's equation ($D = \frac{0.94 \cdot \lambda}{\beta_{1/2} \cos \theta}$). The grain size estimated is 33 nm for the as-deposited film prior to its transformation to nano-needle like nature on post-processing.

It is known that with increasing grain size ' D ', coercivity steeply increases following a D^6 -power law up to 50 nm [4.12]. Hence, the decrease in H_C maybe attributed to the fall in grain-size (Figure 4.30). A H_C of ~ 2 A/m is obtained from the D^6 -power law equation for the post-processed film. This is in-line with the H_C obtained from the hysteresis loops.

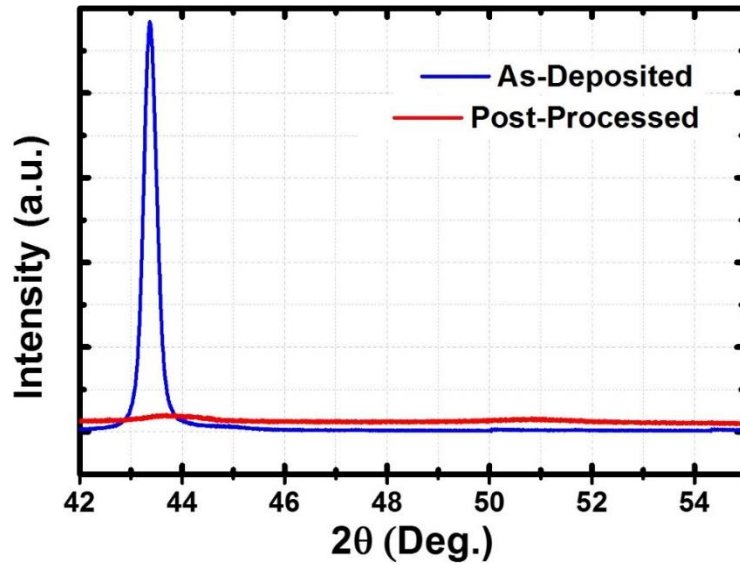


Figure 4.29. XRD peaks of as-deposited and post-processed sample.

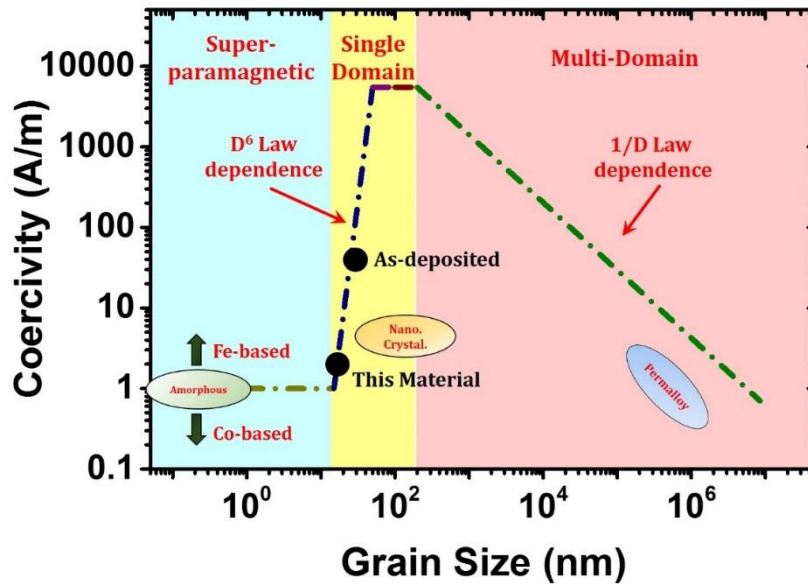


Figure 4.30. Herzer's Plot: Influence of grain size on coercivity [4.12].

e. Raman Spectroscopy: Figure 4.31 depicts the Raman spectra of the as-deposited and post-processed $\text{Ni}_{45}\text{Fe}_{55}$ material. As observed, there is a distinct difference in Raman peaks. The Raman spectra of as-deposited $\text{Ni}_{45}\text{Fe}_{55}$ correlate well with the literature [4.73]. The peaks at 523 cm^{-1} and 694 cm^{-1} relate to the anhydrous oxidation of Ni and Fe after post-processing.

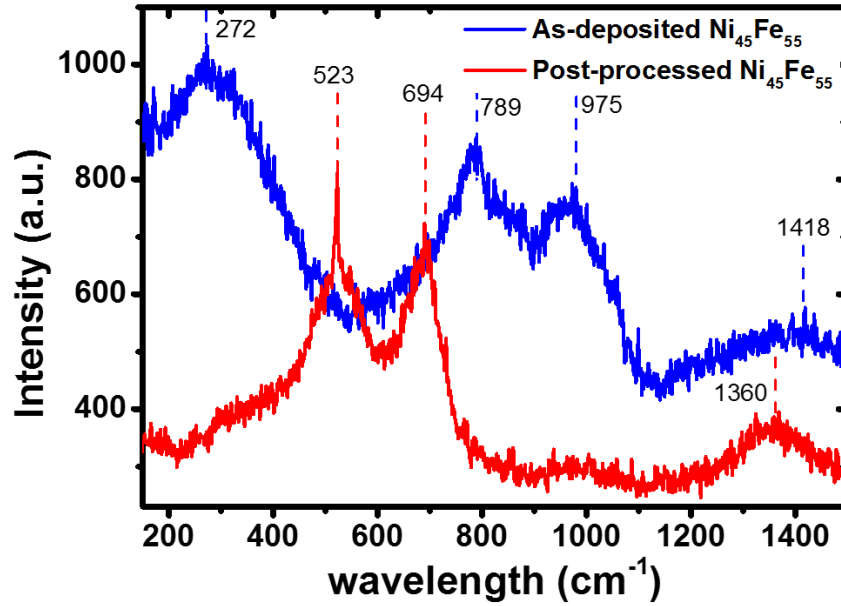


Figure 4.31. Raman spectra of as-deposited and post-processed material.

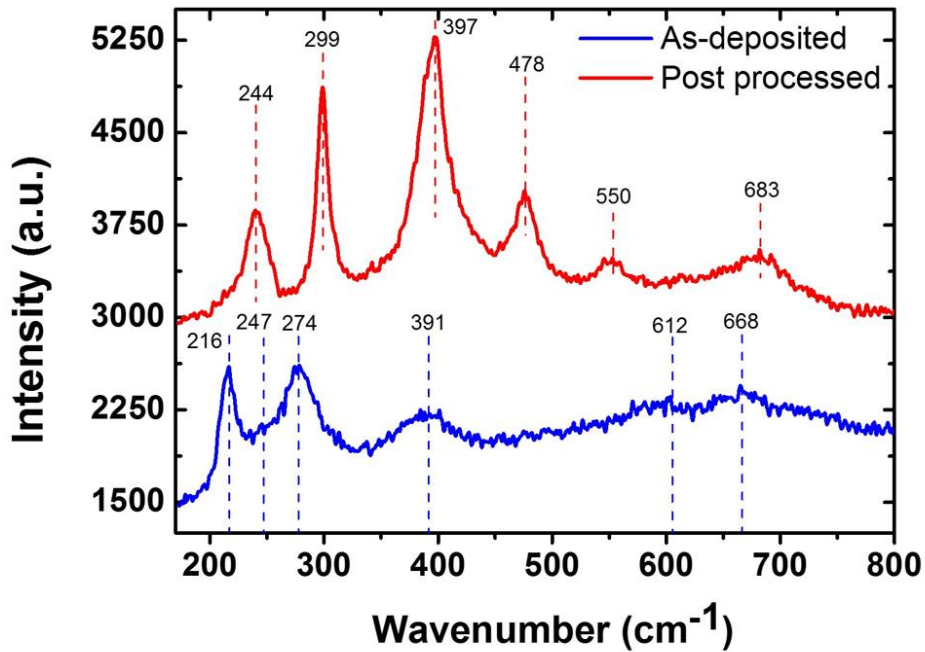


Figure 4.32. Raman spectra of $\text{Ni}_{45}\text{Fe}_{55}$ sample before and after the process.

To ascertain the Fe (III) state of the material, Raman spectra of $\text{Ni}_{45}\text{Fe}_{55}$ sample were recorded before and after the anodization process (Figure 4.32). The TEM image of electroplated Fe after post-processing showed distinctive change in structure, from granular to distinctive needle like shape (Figure 4.33). This vindicates the change in grain size determined from the XRD plot. This also attributes to the decrease in coercivity in accordance to Herzer's plot.

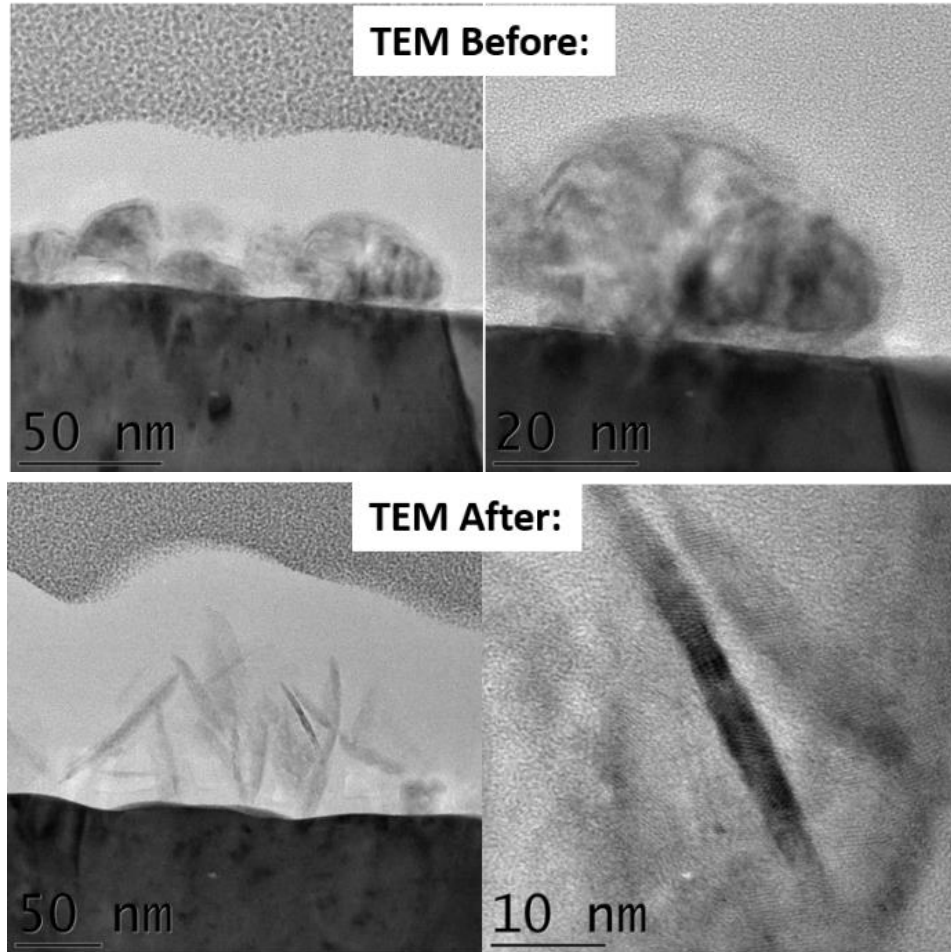


Figure 4.33. TEM images of the Fe sample with structural changes observed from before and after the anodization process.

f. High-frequency permeability: The post-processed film was diced in 3.5 mm x 3.5 mm area sizes and the high frequency permeability response of the material was measured with Wide-Band Complex Permeameter (1 MHz – 9 GHz), PMM 9G, Ryowa Electronics, Japan. Figure 4.34 shows the high frequency permeability response of the films before and after the anodization process at zero bias field. The 1.65 μm thick film shows an initial real permeability of ~ 550 , with a calculated cut-off frequency (f_c) of 120 MHz compared to 67 MHz for as-deposited film. Where, the

cut-frequency is dependent on the resistivity (ρ), material thickness (t) and permeability ($\mu_r\mu_o$) as [4.15] :

$$f_c = \rho / t^2 \mu_r \mu_o \pi \quad (4.5)$$

The measured real initial permeability of pulse-reverse-plated Ni₄₅Fe₅₅ is 650 for 1.65 μm thickness. The improvement in cut-off frequency with the post-processed films is due to the increase in resistivity of the film (from 47 $\mu\Omega\text{-cm}$ to 70 $\mu\Omega\text{-cm}$) and reduced initial relative permeability (650 to 550) compared to as-deposited Ni₄₅Fe₅₅. Table 4.8 lists the properties of as-deposited and post-processed films.

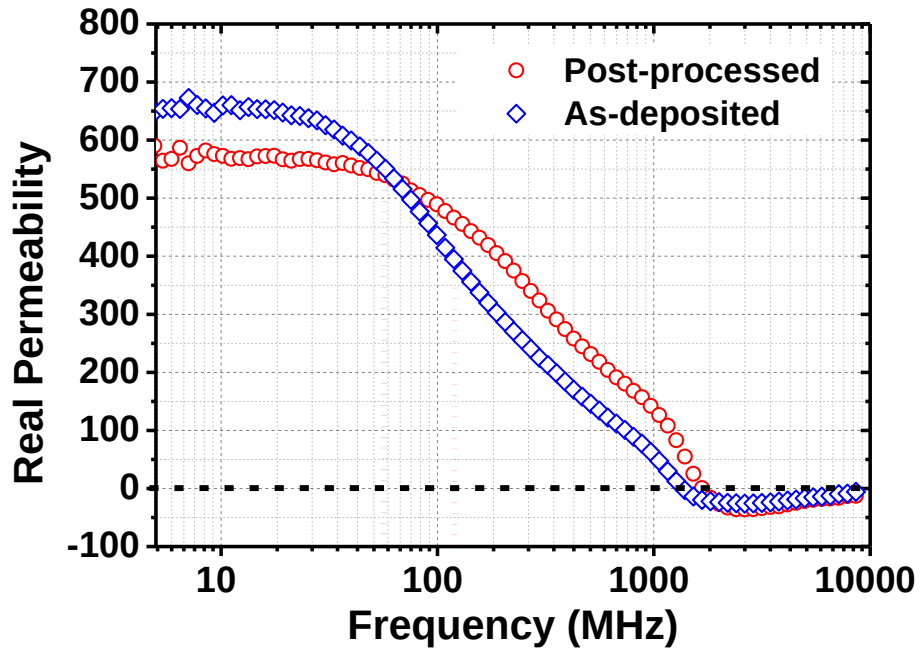


Figure 4.34. Measured real permeability vs frequency of 1.65 μm thick post-processed and as-deposited film depicting the calculated cut-off frequency at null bias.

Table 4.8. Comparison of as-deposited and post-processed Ni₄₅Fe₅₅.

Material properties	As-deposited	Post-processed (300 cycles & Scan rate: 50 mV/sec)
Thickness	1.65 μm	1.65 μm
Coercivity	32 A/m (0.4 Oe)	2 A/m (0.04 Oe)
Resistivity	47 $\mu\Omega\text{cm}$	70 $\mu\Omega\text{cm}$
Saturation flux density	1.4 T	1.4 T
Anisotropy field	735 A/m	900 A/m
Initial Relative permeability	650	550
Cut-off frequency (calculated)	67 MHz	120 MHz

4.6.3. Process Repeatability

To investigate the process repeatability, two samples of 2 cm x 2 cm sizes with $\text{Ni}_{45}\text{Fe}_{55}$ of 1.65 μm thickness were electroplated and post-processed under the same conditions (300 cycles at 50 mV/sec). The BH loops were traced 10 times with BH loop tracer. In all cases, the hard-axis coercivities measured for the samples were < 5 A/m and anisotropy field ~ 900 A/m. The samples showed a similar reduction in coercivity with number of anodization cycles. Figure 4.35 (a) and 4.35 (b) shows the hysteresis loops measured of the two samples and their respective anisotropy field and coercivities.

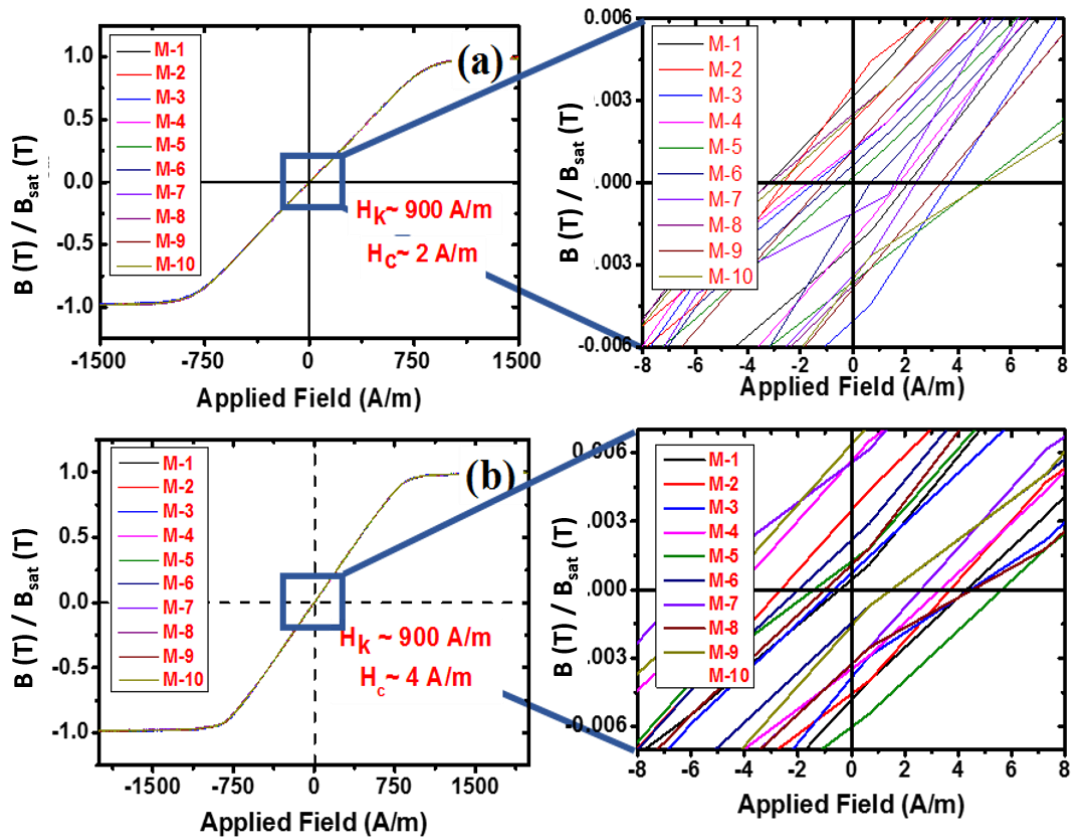


Figure 4.35. BH loops of two post-processed samples of same thicknesses (a) Sample-A and (b) Sample-B.

The post-processed sample was also measured at room temperature in a SQUID magnetometer (MPMS XL5, Quantum Design, USA) to re-confirm the low coercive properties of the material. This system has a high-sensitivity of 0.1% [4.74] compared to SHB systems, which has a sensitivity of 1 % [4.75]. Figure 4.36 shows the hysteresis plots of post-processed material. As observed from the plots, the post-processed material has a coercivity of ~ 5 A/m along the hard axis, with an anisotropy field of

~ 1000 A/m. This confirms that an ultra-low loss material has been achieved with this process.

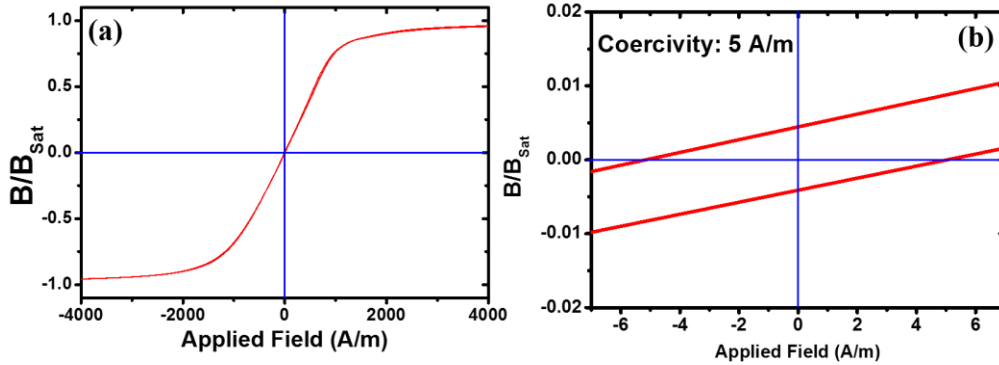


Figure 4.36. Hysteresis plots of the post-processed material measured in SQUID magnetometer: (a) Complete BH loop and (b) zoomed-in plot depicting the coercivity.

Compared to sputtered ultra-soft magnetic materials (such as CZTB or Finemet), electrochemically developed material has some distinct advantages:

- This method of developing ultra-soft magnetic material is a low cost alternative to sputtering.
- Unlike sputter process, electroplated material has higher deposition rate and thicker cores can be deposited.
- The electrochemical process (such as electroless) is independent of substrate sizes and can deposit in recessed regions. Hence, this process can be an ideal method for depositing ultra-soft magnetic cores on non-traditional substrates of variable sizes such as PCBs, 3D printed and flexible substrates.
- The process developed in this chapter for $\text{Ni}_{45}\text{Fe}_{55}$ can be built on to develop other ultra-soft magnetic materials. This extends the research towards developing new ultra-soft magnetic materials, often limited by availability of sputter targets.
- Finemet requires high temperature (> 500 °C) annealing for developing ultra-soft magnetic properties. This could damage the permanent structures in the device. This makes this material unsuitable as core for on-silicon microfabrication process. The room-temperature electrochemical post-processing makes this process ideal for integration with micro-fabrication process of magnetic passives.

4.7. Conclusions

An electroless nickel-iron alloy deposition process utilising an external magnetic field has been described to achieve varying nickel and iron compositions for the high

frequency applications (> 30 MHz). High anisotropy (960 A/m), low coercivity (29.6 A/m) and high saturation flux density (1.7 T) values were achieved which show significant improvements appropriate for high frequency magnetics on silicon applications. It has been shown that higher Fe content films (from Permalloy: 19 % to Invar: 63%) can be achieved by increasing the di-methylamine borane complex concentration in the electroless bath. The magnetic, electrical and structural characteristics of these application specific metal alloy films with different Ni and Fe content were reported. The coercivity values ranging from 29 A/m to 96 A/m, saturation flux density from 1 T to 1.7 T and resistivity values from $28 \mu\Omega\text{-cm}$ to $63 \mu\Omega\text{-cm}$ were which obtained are controllable by varying the film composition.

The increased resistivity of the films reduces the eddy current losses whereas the permeability studies suggests high frequency applicability (>100 MHz) of the thin films as core material in magnetics on Si applications. The micro-structural analyses suggested that the deposits have nano-crystalline phase with grain sizes below ~ 33 nm resulting in low coercivity values in the films. The pH value (~ 6.5) of the bath ensures it is compatible with standard photoresists (e.g. AZ9260, SU-8, THB-151N) used in silicon based micro-fabrication processes. In conclusion, the electroless Ni-Fe alloy deposition process developed provides a range of magnetic and electrical properties that can be employed as core materials in the fabrication of on-silicon magnetics depending on design requirements.

However, electrochemically ultra-soft magnetic materials are yet to be developed. Hence, in this chapter an electrochemical process is reported to develop a new ultra-soft magnetic material. The microstructure of as-deposited, pulse-reverse-plated (PRP), $\text{Ni}_{45}\text{Fe}_{55}$ alloy was changed by electrochemically post-processing the film in an in-house prepared basic solution at room temperature. The typical hysteresis curve of the material along its hard-axis before and after post-processing was determined using a BH loop tracer and a SQUID magnetometer.

The post-processed film shows a reduction in coercivity of as-deposited Ni-Fe film (47% Ni and 53% Fe) from 30 A/m to < 5 A/m whereas the anisotropy field (H_k) improved from 735 A/m to 900 A/m along hard-axis. By comparison, the coercivities of electrodeposited Fe-Co-Ni alloys are restricted to 30 A/m – 400 A/m (depending on composition). The anhydrous oxidation of the film after processing is confirmed by estimating the oxidation states observed in x-ray photoelectron (XPS) analysis. The

real and imaginary permeability along the hard-axis of the post-processed material was also measured using wide-band permeameter up to 9 GHz. The high frequency permeability response suggested an initial real permeability of 550 with a cut-off frequency (f_c) $\sim$ 120 MHz. The f_c achieved with the process is higher than 67 MHz for the as-deposited Ni₄₅Fe₅₅ of same thickness (1.65 μ m) [4.15]. This new material could be a promising candidate as a low-loss magnetic core for highly miniaturized and efficient micro-magnetic devices for high frequency applications.

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Chapter 5

Magnetic Core Lamination: Sputter and Electrochemical Deposition Routes

5.1. Introduction

There are two approaches to reduce the eddy current losses and increase the inductance [5.1]:

(a) **Increasing the resistivity of the core (ρ):** A resistive core material increases the skin depth of the material, thus the magnetic flux density distribution in the core is uniform. This could be accomplished by alloying the magnetic material. However, the magnetic properties of the materials such as coercivity and anisotropy field need to be optimized along with its electrical resistivity, as discussed in Chapter 3 for high frequency applications.

(b) **Magnetic laminations:** The core can be divided into thin slices, separated by electrically resistive and non-magnetic insulator. Such insulated sheets are known as a *lamination*. The insulator isolates the conductive magnetic films electrically and the non-magnetic nature of the insulator restricts the magnetic interaction between the magnetic layers.

This chapter will investigate core lamination technologies and their influence on micro-inductor performance. The chapter describes core lamination processes by both sputter and electrochemical deposition routes explored as part of the thesis. In particular, electroless deposition processing is investigated as a method for metalizing on insulating surfaces without a sputtered seed. The technique also allows metallization of recessed regions.

5.2. State of the Art- Core Lamination Technology

In order to eliminate the influence of core eddy current losses, the thickness of the core has to be restricted to the skin depth for a designed frequency of operation. This in turn limits the flux confined in the core and limits the inductance density. Laminations are used to reduce the eddy current losses and improve inductance

density. Previous reports include laterally and vertically laminated structures [5.6-5.7], thermal oxidation of magnetic films to form insulators [5.13, 5.30], sequential sputtering of dielectric and magnetic films [5.2-5.3, 5.5-5.10, 5.12-5.18, 5.21, and 5.23-5.33] and sequential plating of magnetic material and copper followed by selective copper etching [5.14-5.19]. Electroless metallization based on surface catalyzation with the co-deposition of electrophoretic resist and Pd ions have also been explored [5.22]. Although these processes have shown improvements in the device operation, the complexity, cost and process inefficiencies remain a challenge.

Table 5.1 lists the lamination method reported in the literature. The insulator properties and the magnetic properties reported are listed in Table 5.2. As a conclusion from the works given in table 5.1, we understand that:

- Reported work show inductance density can be increased between 9 and 28 times ($1.3 \mu\text{H}/\text{mm}^2$ to $36 \mu\text{H}/\text{mm}^2$) compared to core without lamination.
- Above certain thickness of the insulating spacer, the grain size of the magnetic layer increases. This determines the coercivity of the laminated core above this thickness (apart from defects).
- This critical thickness of the spacer is dependent on the spacer material.

For e.g.:

Al_2O_3 : 2 nm

SiO_2 : 10 Å – 60 Å

Tantalum: No effect

- The coercivity can be reduced as much as 10 times when spacer thicknesses are below the above-mentioned critical thicknesses.
- However, a strong exchange and coupling interaction between the magnetic layers is observed when spacer thicknesses are very small ($< 2 \text{ nm}$ for Al_2O_3 and $< 10 \text{ Å}$ for SiO_2). This again results in poor soft magnetic properties.

Table-5.1 Magnetic multilayers and their deposition process: A Review.

‘-’ indicates data not reported

Type of deposition	Research / Industrial Organization	Magnetic Material	No. of magnetic layers (n)	Deposition Method	Insulation / Spacer	Insulator or Spacer Thickness	Comments / Observations
Sputter Deposition	IBM, 2008 [5.2]	Ni ₈₁ Fe ₁₉	2	RF sputtered and E-Beam evaporation	Si, Ti, Au and SiO ₂	20 Å -100 Å	Coercivity reduced by a factor 10 with a simple bi-layer regardless of the spacer material used provided the spacer thickness is below a critical value (10 Å -15 Å)
	Philips, 1998 [5.3]	Ni ₈₁ Fe ₁₉	-	Sputtering	Mo	100 nm Mo / 150 Å Ni ₈₁ Fe ₁₉	For Molybdenum layers above 1000 Å the effect of lamination on coercivity decreases.
	Stanford University, 1994 [5.6]	Ni ₈₁ Fe ₁₉	7	RF Reactive sputtering	FeAlN	0.24 µm	Compared to un-laminated cores, smaller coercivity of 1 Oe was achieved in the FeAlN / NiFe laminated films, similar to Fe(Al)N/SiO ₂ , and FeN/NiFe multilayers.
	UC Berkley, 1996 [5.7]	Ni ₈₁ Fe ₁₉	10	RF Sputtering	SiO ₂ and AlO ₂	3 µm	High power density with a 10-layer core (1000 W/cm ²) at 80% efficiency, and 95% efficiency at (60 W/cm ²) micro-transformer reported.
	Bakers Process System, 1998 [5.8]	Ni ₈₁ Fe ₁₉	10 and 48	RF Sputtering	FeAl(N)	100 nm of NiFe with 900 nm of FeAlN	The multilayers display an improved anisotropic behaviour and smaller H_C and magnetostriction compared to single Ni ₈₁ Fe ₁₉ .
	CNRS, 2002 [5.33]	Ni ₈₁ Fe ₁₉	2	Sputtering	SiO ₂	10 Å -100 Å	A strong exchange and coupling interaction between the magnetic layers depends on SiO ₂ insulation thickness. Coercivity increases below 10 Å.

Type of deposition	Research / Industrial Organization	Magnetic Material	No. of magnetic layers (n)	Deposition Method	Insulation / Spacer	Insulator or Spacer Thickness	Comments / Observations
Sputter Deposition	Carnegie Mellon University , 1998 [5.10]	Ni ₈₁ Fe ₁₉ and FeAlN	32	RF Sputtering	Ni ₈₁ Fe ₁₉ /FeAlN and FeAlN/SiN _x	-	The permeability roll off frequency of 2 μm thick patterned FeAlN films increased from 20 to 200 MHz when laminated into 32 layers separated by 25 Å thick SiN interlayers.
	IBM, 2001 [5.12]	Ni ₈₁ Fe ₁₉	3 and 4	Magnetron Sputtering	Al ₂ O ₃	0.6 nm and 2.4 nm Al ₂ O ₃	Laminating permalloy with a moderate (0.5 -2 nm) Al ₂ O ₃ thickness leads to a regular domain pattern. Above 2 nm the magnetization is disturbed and the coercivity increases.
	Ins. of Solid State & Materials Research Dresden, 2001 [5.13]	Ni ₈₁ Fe ₁₉	2	DC Magnetron sputtering and Thermally Oxide	NiFe ₂ O ₄ (through oxidation) below 300°C	0.6 μm	Oxidation of the sputtered permalloy thin films in air occurs from about 300 °C. Fe concentration reduces as it gets oxidized more. The magnetostriction shifts from negative to positive values and the electrical resistivity decreases during annealing, as Fe is oxidized more.
	Siemens, Infineon and Unaxis, 2002 [5.16]	FeAlN, Ni ₈₁ Fe ₁₉ and CoFeBi	-	Sputtering	SiO ₂ and Al ₂ O ₃	0.2 nm -10 nm	The cut-off frequency for the investigated material systems differs significantly from the FMR frequency. Structural effects play a major role in damping behaviour at high frequency and high biasing fields.

Type of deposition	Research / Industrial Organization	Magnetic Material	No. of magnetic layers (n)	Deposition Method	Insulation / Spacer	Insulator or Spacer Thickness	Comments / Observations
Sputter Deposition	ReadRite Corporation, 2001 [5.17]	Ni ₈₁ Fe ₁₉	7	Reactive sputtering	FeRhN	50 nm	It is believed that the modification of FeRhN microstructure by NiFe under-layer plays a more important role in improving the soft magnetic properties than the exchange coupling between the FeRhN and NiFe layers.
	Uaxis, Seagate, Max Planck and IPHT, 2002 [5.18]	Ni ₈₁ Fe ₁₉	12 and 16	RF Sputtering	Al ₂ O ₃ / FeAlN and Ni ₈₁ Fe ₁₉ / FeAlN	10 nm Ni ₈₁ Fe ₁₉ / 30 nm FeAlN & 2 nm Al ₂ O ₃ / 30 nm-300 nm FeAlN	- A minimal Ni-Fe spacer and Fe-Al-N thickness is 10 nm and 15 nm respectively. Below this Ni-Fe thickness, the Fe-Al-N shows columnar grains (poor magnetic properties). - For Al₂O₃ the optimal thickness is 2 nm. Above this thickness, Fe-Al-N shows columnar grains and poor magnetic properties. Optimized H_c in both cases < 0.5 Oe
	Veeco Instruments and McGill Univ., 2005 [5.21]	Ni ₈₁ Fe ₁₉ and CoFe	1 to 8	DC Sputtering	Ni ₈₁ Fe ₁₉ with CoFe	2000 Å CoFe / 5 Å - 15 Å Ni ₈₁ Fe ₁₉	$B_s > 2.4$ T and hard-axis $H_c \sim 3$ Oe achieved on deposition minimized. The Magnetostriction remains at $4 \cdot 10^{-6}$ and the stress was further optimized by applying substrate bias of 50 V without sacrificing film magnetic softness.

Type of deposition	Research / Industrial Organization	Magnetic Material	No. of magnetic layers (n)	Deposition Method	Insulation / Spacer	Insulator or Spacer Thickness	Comments / Observations
Sputter Deposition	Univ. Elect. Sci. Techn., China, Chengdu, 2007[5.23]	Ni ₈₁ Fe ₁₉ and FeAlN	20	Magnetron Sputtering Method	Ni ₈₁ Fe ₁₉ and Cu laminating FeAlN	10 nm of Cu and Ni-Fe.	Magneto impedance (MI) ratio is measured. The MI ratio of the laminating FeAlN film with ferromagnetic Permalloy layer is enhanced by 50% more than that with non-ferromagnetic copper due to exchange induced ripple reduction mechanism
	Univ. Elect. Sci. Tech. of China, Chengdu, 2007 [5.27]	Ni ₈₁ Fe ₁₉	100, 20,10 and 5	Magnetron Sputtering	FeAlN	10 nm, 50 nm and 200 nm	The dispersion of induced anisotropy in multilayers is suppressed due to the exchange coupling between NiFe and FeAlN sublayer.
	Arizona State University, 2010 [5.28]	Ni ₈₁ Fe ₁₉	20 and 10	DC magnetron sputtering	Cr	Ni ₈₁ Fe ₁₉ : 50 nm and 100 nm	Permeability increased from 170 to 650 by reducing NiFe thicknesses from 100 to 50 nm. It was attributed to the presence of stripe domains. Core with thinner NiFe layers with on-chip spiral inductors increase inductance by 6 times.
	Univ. of York, 2007 [5.25]	CoFe	3	Sputtering	Al ₂ O ₃	15Å	The choice of the correct seed layer is an important factor in reducing coercivity. NiFe and Ru seed reduce grain diameter and improve magnetic properties, while Ta seed has no effect. Lamination reduces the coercivity because it reduces the grain volume.

Type of deposition	Research / Industrial Organization	Magnetic Material	No. of magnetic layers (n)	Deposition Method	Insulation / Spacer	Insulator or Spacer Thickness	Comments / Observations
Sputter Deposition	Intel, 2008 [5.26]	CoZrTa	4	DC Magnetron sputtering	CoO with some Co ₃ O ₄ and Co ₂ O ₃	7 nm	28 times increase in inductance as compared to identical transmission lines without magnetic material and a 16 times increase in quality factor.
	Columbia University, 2013 [5.32]	Ni ₈₁ Fe ₁₉ and CoZrTa	3	RF Sputtering	SiO ₂	4 nm - 40 nm SiO ₂	Reducing DC magnetron sputtering voltage reduces easy-axis coercivity (0.17 Oe for CZTB and 0.4 Oe for NiFe).
	Sojo Univ., Delta Works AND Tohoku University, 2002 [5.5]	CoFeB	-	RF Magnetron Sputtering	SiO ₂	10-20 nm	Each magnetic particle in the presented films hold magnetic softness even if the insulator cuts off the exchange interaction between the films, leading to an ultra-high resistivity without losing magnetic softness.
	Columbia University, 2012 [5.29]	CoZrTa (CZT)	3	DC Magnetron Sputtering	SiO ₂	10 nm	Reducing DC magnetron sputtering voltage reduces easy-axis coercivity (0.17 Oe for CZTB and 0.4 Oe for NiFe). Dipolar coupling between the two FM layers observed for CZT system. This was absent in NiFe system.
	Arizona Univ., Intel, 2012 [5.30]	Co-Zr-Ta-B	5	Sputtering and Oxidation	CoO	2 nm-5 nm CoO	With laminations, an up to 9.1 X inductance increase with frequency response up to 2 GHz can be achieved.

Type of deposition	Research / Industrial Organization	Magnetic Material	No. of magnetic layers (n)	Deposition Method	Insulation / Spacer	Insulator or Spacer Thickness	Comments / Observations
Sputter Deposition	Stanford, Veeco Ins. and Intel, 2007 [5.24]	CoZrTa	3	Physical vapour deposition	AlN	0.1 μm	The permeability spectra of CZT films can be improved at the low-frequency range, and multiple magnetic resonance peaks can be suppressed by lamination.
Electro-chemical Process	NMRC / Tyndall, 2006 [5.22]	Ni ₈₁ Fe ₁₉	2	Spin coated and electroplated	Eagle Photoresist	6 μm	Photoresist Electrodeposited with Pd to form an insulation layer. Ni electrolessly deposited as seed and Ni-Fe as core is electroplated.
	Georgia Institute of Technology, 2003 [5.19]	Ni ₈₁ Fe ₁₉	4 to 72	Electroplating and sacrificial etch	Air gap	6 μm (Cu etched away)	Three different fabrication technologies for integration of RF inductors: on-chip, in the chip-to-board interconnect layer and in-package.
	Georgia Institute of Technology, 2002 [5.14]	Ni ₈₁ Fe ₁₉	3	Electroplating and sacrificial etch	Air gap	6 μm air (left after Cu etching)	A sacrificial etching technique to develop highly laminated core has been described.
	Georgia Institute of Technology, 2013 [5.31]	Ni ₈₁ Fe ₁₉	100	Electroplating	Air gap	-	Toroidal inductors with nano-laminated cores showed negligible eddy-current loss. Buck power converter (1–2 MHz) has power conversion efficiency > 85%, peak operating flux density of 0.3–0.5 T and converter output power level exceeding 5 W.

Type of deposition	Research / Industrial Organization	Magnetic Material	No. of magnetic layers (n)	Deposition Method	Insulation / Spacer	Insulator or Spacer Thickness	Comments / Observations
Other methods of deposition	Georgia Institute of Technology, 1999 [5.11]	NiFeMo and Ni ₈₁ Fe ₁₉	2	Spin coated and hard cured	Polyimide thin film	5 µm	Integrated inductors with easy axis cores have better performance than hard axis core devices <100 kHz, while the hard axis core devices have better performance than easy axis core > 100 kHz. The single layer of supermalloy by electroplating is limited (around 5 nm), in part due to its high stress.
	Georgia Institute of Technology, 2002 [5.15]	Ni ₈₁ Fe ₁₉ foils 50 µm thick	3	Hot press method	Co-Netic AA Coated with polyimide	12.5 µm	Mechanical lamination and electro-deposition of copper windings by means of LIGA-like lithography through thick epoxy photoresists is reported.
	Hitachi Ltd., 1991 [5.4]	Ni ₈₁ Fe ₁₉	-	Thermal Oxidation	Oxide (NiFe ₂ O ₄)	2 nm	The film coercivity decreases linearly with increasing layer numbers due to grain growth suppression and magnetic separation by oxide film of permalloy layer. The saturation magnetization and magneto-resistivity decrease as the number of layers increase.
	Georgia Inst. of Technology and MIT, 2003 [5.20]	Ni ₈₁ Fe ₁₉ and CoNiFe	2	PECVD	SiO ₂	-	Embedded electroplated materials (Cu, Ni ₈₀ Fe ₂₀ , CoNiFe) within etched and fusion-bonded silicon to form the micro-machined structure.

Table-5.2 Properties of the insulation and the magnetic properties of the lamination.

‘-’ indicates data not reported

Magnetic material	B_{Sat} (T)	H_C (A/m)	Relative permeability (μ_r)	Insulators	n	CTE (ppm/°C)	$\rho_{insulator}$ (Ω -cm)	Insulator / Spacer Thickness (nm)
CoZrTa [5.29]	1.2	24	2000	SiO ₂	> 2	0.55	10^{14} - 10^{16}	10 - 20
CoFe [5.21, 5.25]	2.4	8-240	200	Al ₂ O ₃	> 2	5.4	$20.e^{-06}$, 10^{14}	1 - 1.5
CoZrTa and Ni ₈₁ Fe ₁₉ [5.24]	-	8, 120	1500	AlN	> 2	4.5	$>10^{17}$	7 - 10
-	-	-	-	Parylene-C	~ 2	7	$\sim 10^{14}$	> 200
CoZrTa [5.30]	-	36.2	-	CoO	> 3	-	-	2-2.5
Ni ₈₁ Fe ₁₉ and CoZrTa [5.31]	1.2	120, 36	300	Air gap	> 2	0.0035	$\sim 10^{16}$	2000 -5000

Figure 5.1 shows sputter laminated CZT films with spacer of SiO₂. A Tantalum layer is deposited prior to SiO₂ deposition to smoothen the surface. The spacing between magnetic laminations is kept consistent at 10 nm, to avoid formation of domain walls so that the path of magnetic flux is easily closed between adjacent layers and also avoiding the formation of pin-holes in the insulating spacer layer [5.29]. The proposed simulated inductor with the laminated core has an inductance density of 200 nH/mm². The sputter process allows the CZT, Ta and SiO₂ to be deposited in a multi-target sputter system without breaking the vacuum.

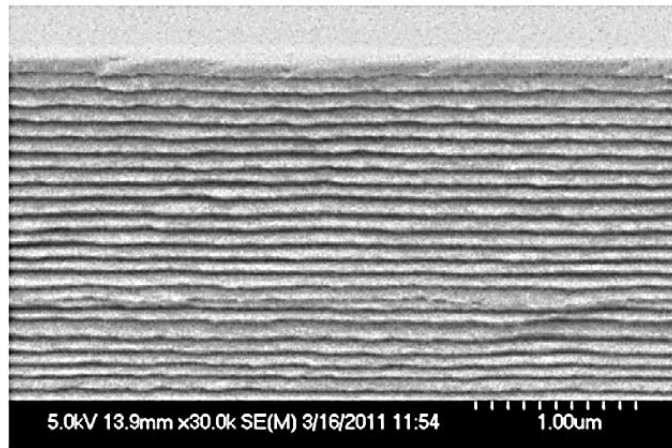


Figure 5.1. SEM image of magnetic lamination (anisotropic Co_{91.5}Zr_{4.0}Ta_{4.5} separated by SiO₂ and Ta) [5.29].

Georgia Ins. Tech. reported a process that involves electroplating magnetic films and Cu sequentially with an automated robotic system and selectively etching the Cu layer to reveal air gaps that are filled with PDMS or SU-8 as shown in Figure 5.2 [5.14, 5.19, 5.31 and 5.34]. This process requires automated and time-consuming plating process. The selective etching of Cu to reveal air-gaps would essentially affect the structural strength of the core. Moreover, the core has to be co-packaged with the windings. Also from Georgia Tech., Herrault et. al. reported laminated Permalloy (electroplated) through oxidized and DRIE etched silicon substrates (Figure 5.3) as insulation [5.35]. This method provides structural strength to the core. Such silicon embedded core structure is only applicable to solenoid and toroidal designs. Additionally, the automated sequential plating of the magnetic material and Cu is time consuming.

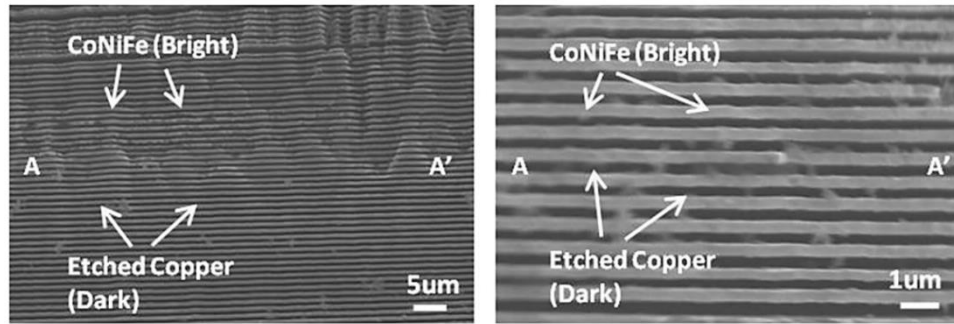


Figure 5.2. Images of nano-laminated CoNiFe cores [5.34].

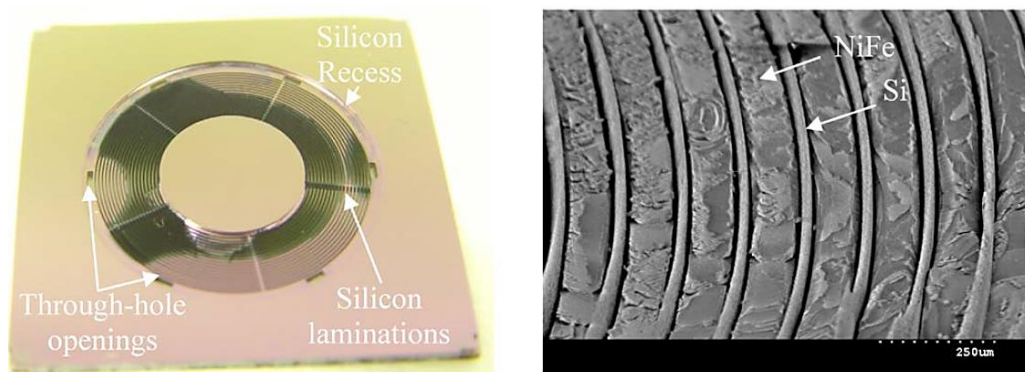


Figure 5.3. Images of laminated Permalloy core developed by electroplating through oxidized and etched Si substrate [5.35].

Tyndall / NMRC's Brunet et. al. [5.22], (Figure 5.4) proposed an electrochemical lamination technique, whereby EAGLE 2100 ED photoresist (Shipley's electro-deposited photoresist) was deposited in an electrochemical bath containing Palladium Chloride (PdCl_2) catalyst material followed by Nickel (Ni) / Ni-Fe deposition. This process requires sequential electroless deposition of Ni seed followed by Ni-Fe magnetic layer. This increases the process duration and the conductive Ni seed ($7 \mu\Omega\text{-cm}$) would contribute to core eddy current losses. In addition, prior to each electroless Ni deposition step, Pd used with the photoresist is lost. This increases the cost of the overall process.

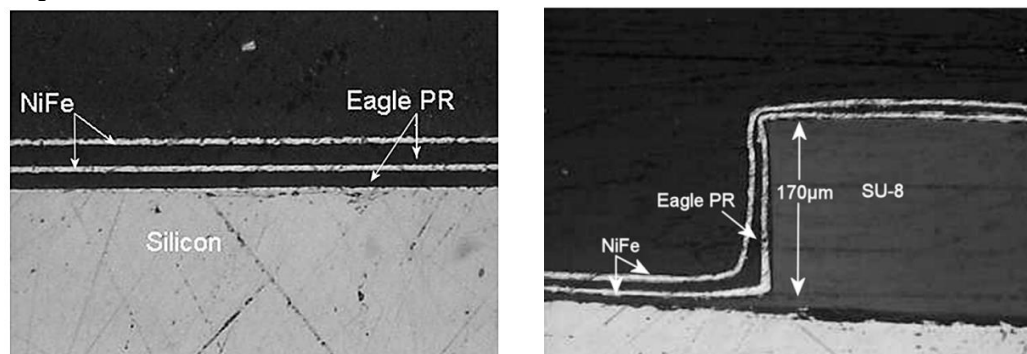


Figure 5.4. Cross-section of laminated core with EAGLE ED 2100 [5.22].

Morrow et. al. [5.36] from Intel, showed sputter laminated coupled inductors (Figure 5.5) by layering eight Permalloy layers with insulating material between them. Sputtering is alternated between Permalloy (400 nm thick) and insulating layers (10 nm thick) in-situ, to produce an eight layer laminated stack with total thickness of 3.4 μm [5.36]. The top-core is isolated from the copper windings by a photo-definable photoresist, which gives a dome shaped arch on thermal reflow. The 3.4 μm thick, 8-layer laminated Permalloy films showed an initial relative permeability of ~ 1050 and a cut-off of ~ 30 MHz. Three different laminated inductors with core widths, 50 μm (20 nH), 100 μm (16 nH) and 150 μm (13 nH) were fabricated. The low current inductance level decreases with the width of the inductor. As observed from the Figure 5.5, top and bottom core laminates are not closed at the core-feet. Moreover, the etching of Permalloy and the dielectric in wet etch process will be challenging and will require a dry etch alternative. This increases the cost and process time.

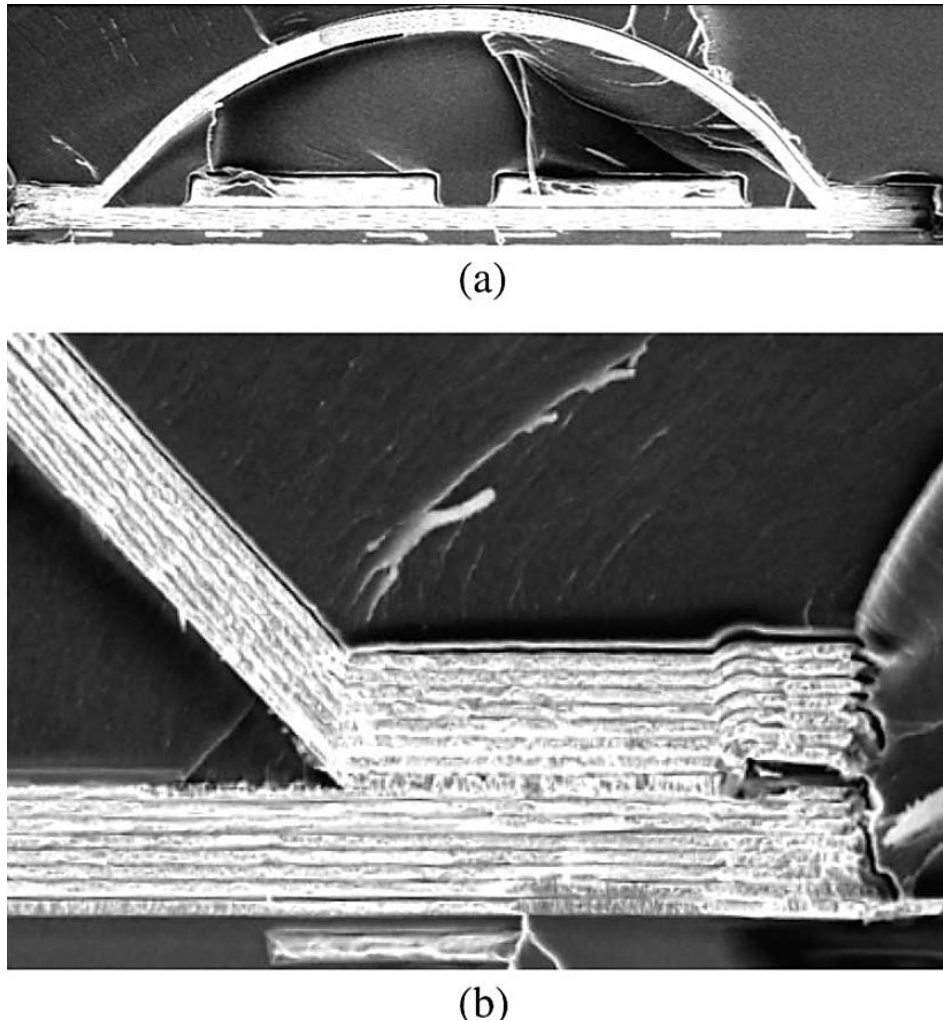


Figure 5.5. Cross-section of coupled micro-inductors (a) complete structure (b) eight laminated Permalloy core [5.36].

The magnetic laminations have to be optimized in terms of saturation flux density (B_{Sat}), hard-axis coercivity (H_C) and resistivity (ρ). Figure 5.6 shows the B_{Sat} , H_C and ρ of sputtered 200 nm CoFe with 5 Å and 15 Å Ni-Fe under-layer [5.21] for write pole applications. There is linear increase in resistivity with number of laminates and decrease in B_{Sat} from 2.43 T to 2.32 T. Figure 5.7 shows the hysteresis loops of single layer and four layer laminations and dependence of easy-axis coercivity of Permalloy with Al_2O_3 spacer thickness [5.12]. Similar investigation on permeability by keeping net core thickness to 1 μm and varying individual Ni-Fe laminate thickness separated by 5 nm Cr spacer has been reported by Xu et.al. [5.37]. The permeability reduces in the 1 μm thick as the individual Ni-Fe thicknesses are reduces and number of laminations increases (Figure 5.8).

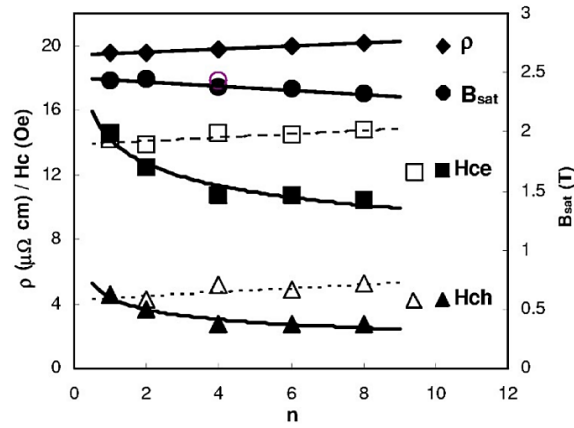


Figure 5.6. Magnetic properties of laminated CoFe with 5 Å (open symbol) and (closed symbols) 15 Å Ni-Fe [5.21].

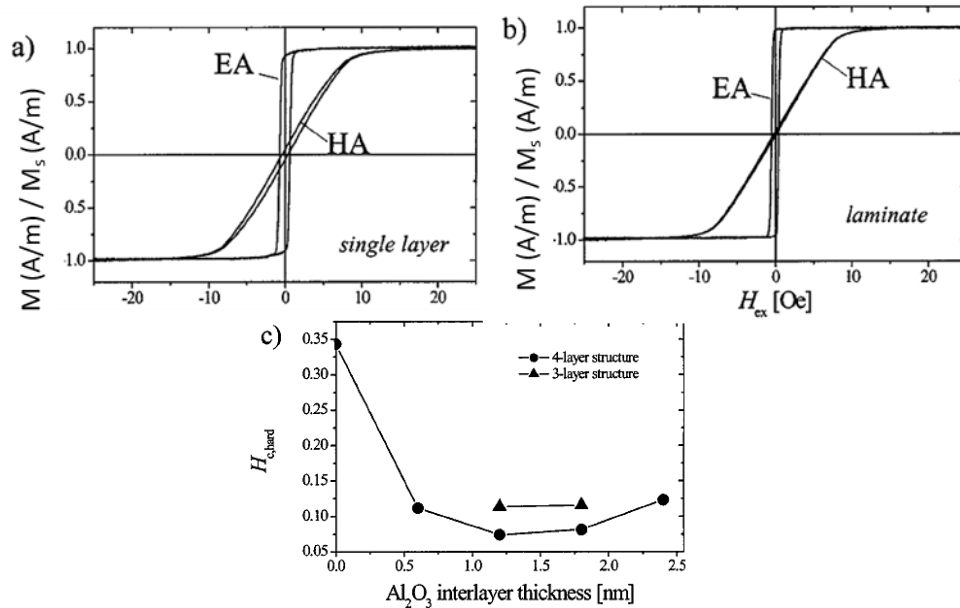


Figure 5.7. Magnetic properties of (a) un-laminated Permalloy and (b) laminated Ni-Fe with Al_2O_3 [5.21] (c) Easy axis coercivity variation with number of laminations.

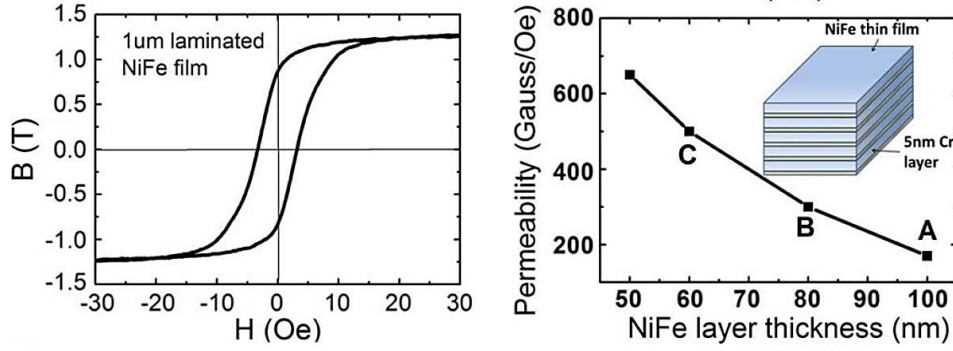


Figure 5.8. Hysteresis loop of un-laminated 1 μm thick NiFe film and permeability of laminated NiFe films (net thickness: 1 μm) with varying individual thicknesses [W. Xu, S. Sinha et.al., 2011, 5.37].

The next section details a theoretical investigation of the current density and magnetic intensity distribution within the magnetic films and how they can be improved by laminations.

5.3. Magnetic Laminations: Theoretical Framework

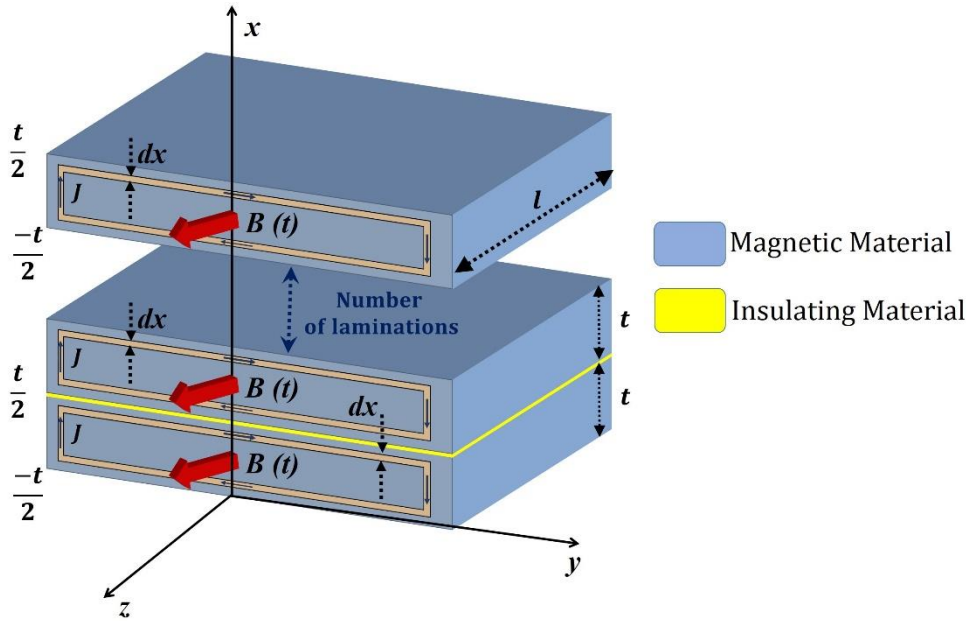


Figure 5.9. Cross-section of laminations with a thickness ' t ' separated by thin insulator.

Let us consider a laminated core [5.1] as shown in Figure 5.9. Assuming that the magnetic field intensity H is uniformly distributed along the x-axis ($\delta \gg t$). Where, δ is the skin depth of the material.

The magnetic field intensity and current density across a single lamination are derived in the appendix section. The magnitude of the magnetic field intensity across the lamination can be expressed as:

$$|H_z(x)| = H_z \left(\frac{t}{2} \right) \sqrt{\frac{\cosh\left(\frac{2x}{\delta}\right) + \cos\left(\frac{2x}{\delta}\right)}{\cosh\left(\frac{t}{\delta}\right) + \cos\left(\frac{t}{\delta}\right)}} \quad (5.1)$$

The normalized field intensity across the laminations is:

$$||H_z(x)|/H_z \left(\frac{t}{2} \right) = \sqrt{\frac{\cosh\left(\frac{2x}{\delta}\right) + \cos\left(\frac{2x}{\delta}\right)}{\cosh\left(\frac{t}{\delta}\right) + \cos\left(\frac{t}{\delta}\right)}} \quad (5.2)$$

The current density is:

$$J(x) = J(y) = -\frac{dH_z(x)}{dx} = -\frac{1+j}{\delta} H_z \left(\frac{t}{2} \right) \frac{\sinh\left(\frac{x}{\delta} + j\frac{x}{\delta}\right)}{\cosh\left(\frac{t}{2\delta} + j\frac{t}{2\delta}\right)} \quad (5.3)$$

The normalized magnitude is:

$$|J(x)| * \delta / H_z \left(\frac{t}{2} \right) = \sqrt{\frac{2[\cosh\left(\frac{2x}{\delta}\right) - \cos\left(\frac{2x}{\delta}\right)]}{\cosh\left(\frac{t}{\delta}\right) + \cos\left(\frac{t}{\delta}\right)}} \quad (5.4)$$

5.3.1. Magnetic field intensity and current density distribution in the core with varying net thickness

The equations (5.1-5.4) are solved in MATLAB 2010 and plotted. Figure 5.10 (a) and (b) shows the magnitude of magnetic field intensity and the current density across the magnetic core for different widths of the lamination. The plots show the magnetic field or current distribution across the normalized single core width from the centre of the core ($x/t=0$) towards edges. The core width has been from ' δ ', i.e. equal to the skin depth to 10δ , i.e. 10 times thicker than the skin depth of the magnetic material.

From Figure 5.10 (a) and (b), when the core thickness (t) equals 10δ , the magnetic field intensity and current density is almost zero at the centre and gradually increases as we approach the edges of the core. This reduces the flux distribution across the core at high frequency and contributes to eddy currents, as the current density is higher at the edges. As the thickness of the core is reduced and approaches the skin depth of the magnetic material, the magnetic field intensity and the current density are well distributed within the magnetic film. This reduces the core eddy current loss.

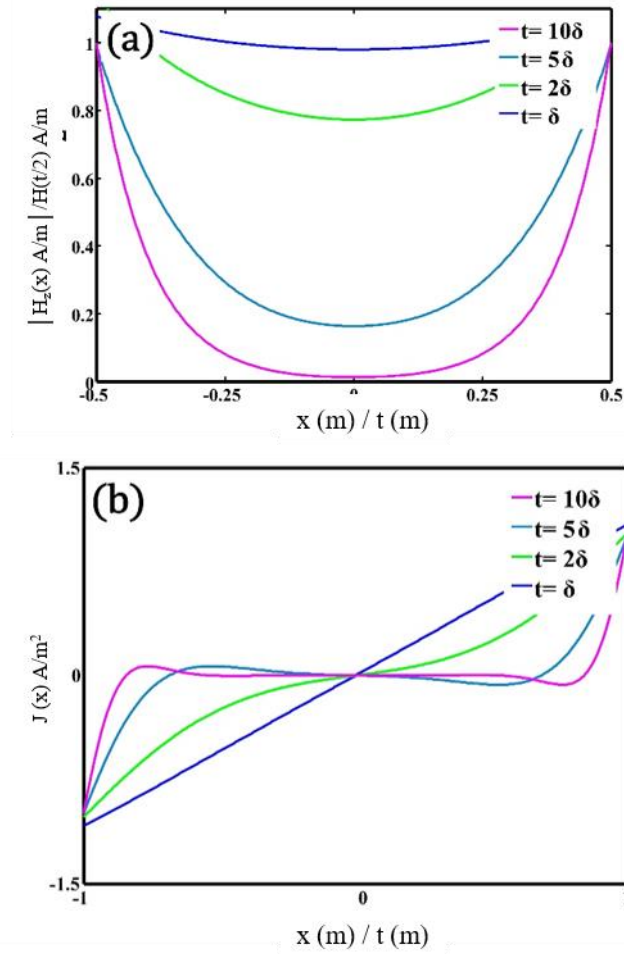


Figure 5.10. (a) Field distribution and (b) current density distribution for different widths of the lamination.

5.3.2. Magnetic field intensity and current density distribution in laminations

Figure 5.11 (a) and (b) shows the magnitude of magnetic field intensity and the current density across the magnetic lamination with thickness $(t) = 10\delta$. In this case, the core thickness is 10 times thicker than its skin depth. Although ideally there should be no change at high-frequency in inductance density of the inductor with 10δ thick core compared to a core with thickness $= \delta$, the eddy-currents due to non-uniform current density will reduce the inductance. It is hence important to divide the core into thicknesses equal to its skin depth. This way, the operation frequency of the inductor can be increased (depending on individual magnetic layer thickness) without increasing the core eddy current losses. In other words, theoretically the inductance density can be increased by adding more laminations with each lamination thickness below or equal to the skin depth (δ).

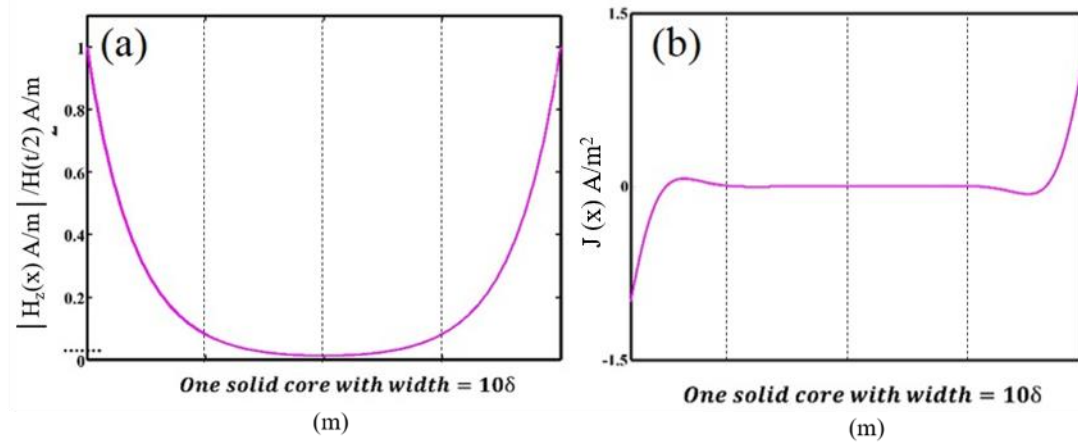


Figure 5.11. (a) Normalized field and (b) current density distribution in a solid core with 10δ width.

This section describes how: *dividing the core into thin laminations and increasing the number of laminations influences the magnetic intensity and current density within the laminated films.*

Let us consider that the solid core (thickness: 10δ) as discussed in the previous section is now divided into 2 and 5 equal sections with individual laminates of thicknesses 5δ and 2δ , respectively.

(a) 2-Laminations:

The core divided into two laminates shows some increase in the magnetic field intensity and the current density at the centres of the individual laminations. This marginal increase reduces the core eddy current loss (Figure 5.12 and 5.13). However, this may not be sufficient. Hence, it is apparent that the number of laminations have to increase further.

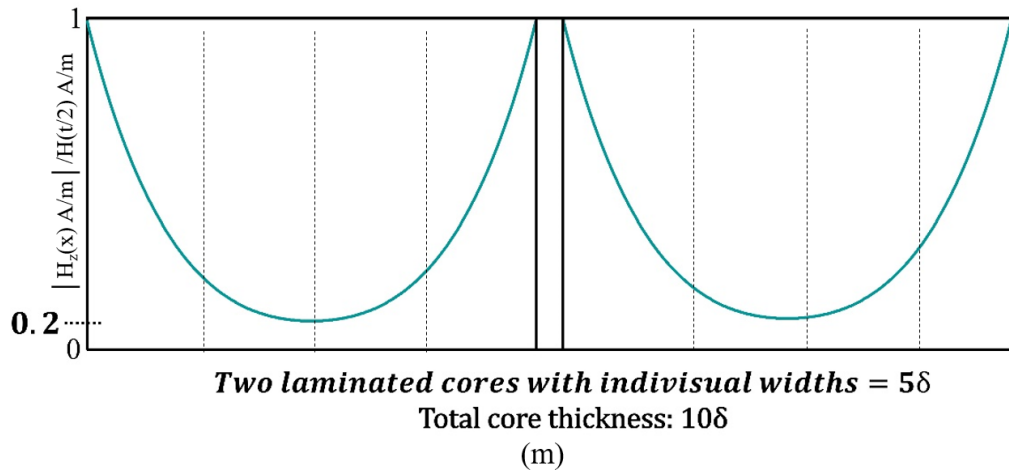


Figure 5.12. Normalized field distribution in a core with two laminations with individual widths of 5δ (net width: 10δ).

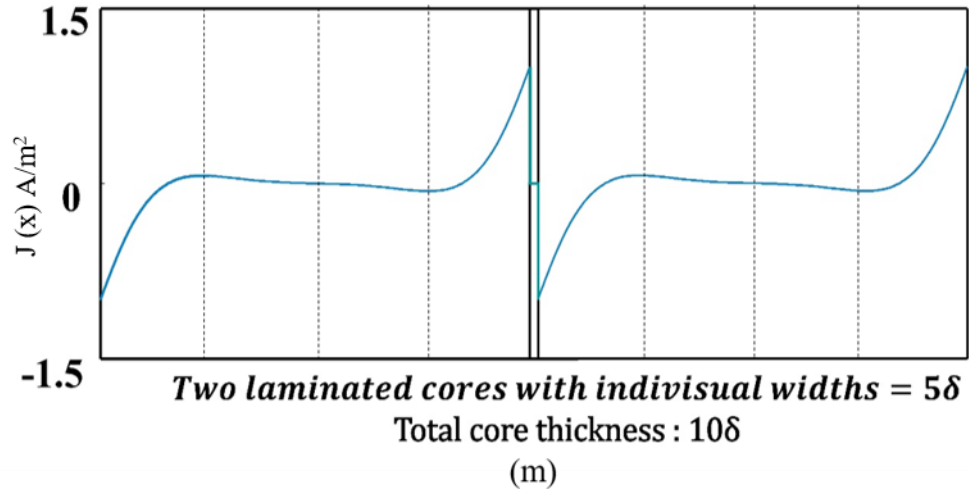


Figure 5.13. Current density distribution in a core with two laminations with individual widths of 5δ (net width: 10δ).

(b) 5-Laminations:

On increasing the number of laminations to 5, it is observed that the magnetic field intensity and the current density is more uniformly distributed within each of the laminates (Figure 5.14 and 5.15). This increases the magnetic flux uniformity within the core and a uniform current density distribution reduces eddy current losses significantly compared to a single solid core.

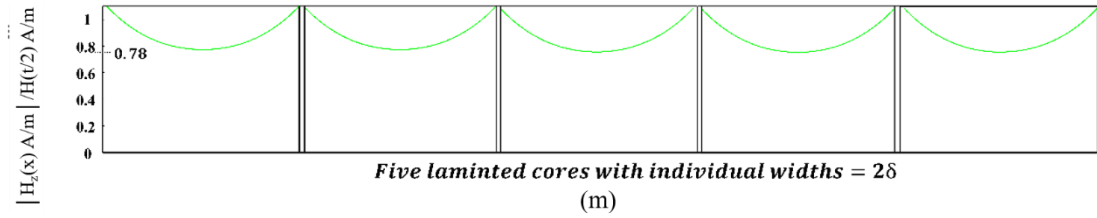


Figure 5.14. Normalized field distribution in a core with five laminations with individual widths of 2δ (net width: 10δ).

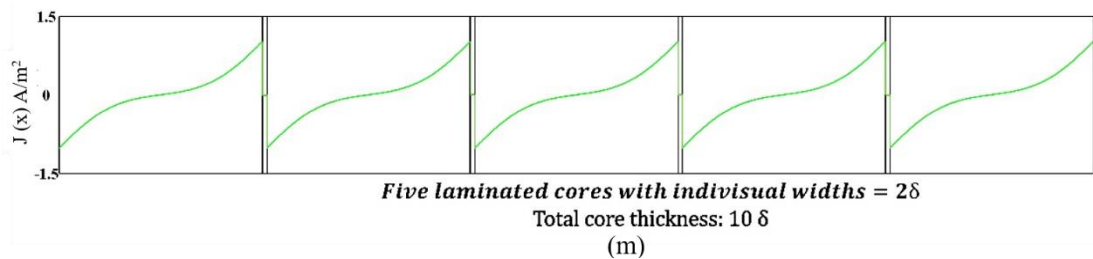


Figure 5.15. Current density distribution in a core with five laminations with individual widths of 2δ (net width: 10δ).

The following conclusions can be drawn from the above study:

- The current density and field distribution across the core becomes almost zero at the centre and increases gradually resulting in core eddy-current losses as we approach the edges of the core.
- Introducing laminations, by dividing the core equally into smaller sections of thickness equal to the skin depth will result in a more uniform current density distribution.
- Increasing the number of laminations, by keeping each laminate thickness equal to skin depth will theoretically increase inductance density. In reality, the capacitive coupling between the magnetic films would restrict the increase in inductance.

The above analysis has considered an ideal insulator that allows no magnetic coupling between the magnetic layers and provides complete electrical insulation between the cores. If the insulation fails to provide magnetic isolation (i.e., no magnetic coupling between the magnetic layers), the core flux density will be distributed across all the laminates. This will result in strong exchange and magnetic coupling resulting in increased coercivity [5.33]. Whereas, failure to isolate the core electrically will increase eddy current losses.

In the next section two methods to achieve magnetic laminations will be explored. In the first section, DC magnetron sputter deposition conditions for Permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) and magnetic laminations Permalloy along with high resistive nitrogen doped Tantalum (Ta) will be investigated. In addition, a novel electroless route will be explored by development of a metallization process on polymer insulations such as SU-8.

5.4. Magnetic Core Laminations using Physical Vapour Deposition (Sputtering)

Sputter deposition has some distinct advantages such as batch deposition of alternate magnetic and insulating films. Also, sputtering systems are also compatible with *in-vacuo* surface treatment and *in-situ* analysis. Apart from film thickness and deposition rate, the stress in the film is largely dependent on the deposition process, substrate type and its temperature during deposition [5.47].

In this section, multilayers of $\text{Ni}_{81}\text{Fe}_{19}$ are studied with a thin Ta(N) spacer layer, in order to understand how thick cores can be deposited with sputtering with excellent in-plane soft magnetic properties and frequency response.

5.4.1. Sputter deposition optimization of $\text{Ni}_{81}\text{Fe}_{19}$:

Permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) was sputter deposited in DC magnetron sputtering system. The deposition conditions of the sputter deposited $\text{Ni}_{81}\text{Fe}_{19}$ films were optimized in terms of deposition pressure, power and substrate temperature as shown in table 5.3. The magnetic properties were measured with the BH loop tracer.

Figure 5.16 depicts a schematic of the desirable nano-laminate $\text{Ni}_{81}\text{Fe}_{19}$ with in-plane easy and hard-axis separated by ultra-thin spacer films, respectively. The sputtered permalloy films without lamination have shown spin re-orientation from in-plane to the out-of-plane (perpendicular) direction as film thickness increases above a certain thickness known as ‘the critical thickness (t_{critical})’. At low pressures the films are under compressive stress, while at high pressures a columnar growth develops in the film (Figure 5.16 (b)). This is often attributed to the self-shadowing of the incident atoms by the atoms already deposited [5.44]. The columnar Permalloy film growth produces a characteristic out-of-plane anisotropy property where the magnetization direction is along the length of the column, resulting in poor in-plane magneto-crystalline anisotropy. On the other hand, thick electroplated Ni-Fe films ($\sim 9 \mu\text{m}$) can be deposited without columnar deposition. The growth conditions such as the sputtering pressure and the substrate temperature also influence the out-of-plane anisotropy [5.44].

In the experiments, out-of-plane anisotropy was observed in Permalloy films greater than 500 nm in thickness (Figure 5.17 (b)). Sample-12 was selected based on coercivity as the optimized condition for depositing $\text{Ni}_{81}\text{Fe}_{19}$ films. Figure 5.17 shows the hysteresis loops of sputtered $\text{Ni}_{81}\text{Fe}_{19}$ magnetic films for different deposition conditions (power, pressure, DC/RF and with and without external magnetic field). As observed from the measured hysteresis loops, the coercivity along hard-axis is minimum for 117 nm thick sputtered $\text{Ni}_{81}\text{Fe}_{19}$ (57.6 A/m). This optimized condition and thickness of $\text{Ni}_{81}\text{Fe}_{19}$ was used to develop sputtered laminations.

Table-5.3 Measured magnetic properties of $\text{Ni}_{81}\text{Fe}_{19}$ films are different deposition conditions.

No.	Type	With or Without Magnetic field	t (nm)	Power & Pressure (W / mTorr)	Measured Results							
					Hard Axis (HA)				Easy Axis (EA)			
					nWb		A/m		nWb		A/m	
					B_S	B_r	H_c	H_k	B_S	B_r	H_c	H_k
S-1	DC	✓	121	500 / 5.83	4.7	3.2	175	72	11.6	10	160	312
S-7	RF	x	700	1000 / 5.83	15	6.9	1360	3360	46.6	21	1360	2936
S-8	RF	✓	700	1000	26	25	1432	434	26.6	26	1432	560
S-9	DC	✓	87	RF Etch 1 KW + 500 / 5.83	5.8	0.5	307	2320	6.9	6.6	710	480
S-10	DC	✓	81.6	RF etch: 1 kW. 500 / 5.83	6.9	0.7	71.2	1072	6.6	6.3	400	61
S-11	DC	✓	34.3	100 / 1.12	1.8	0.06	91.2	1696	1.9	2.0	683	186
S-12	DC	✓	117	100 / 1	7.7	0.7	57.6	707	8.2	7.9	290	41
S-13	DC	✓	197	500 / 1.09	20	5.4	143	440	2	19	220	67
S-14	DC	✓	546	500 / 1	58	23	1367	4926	5	24	1324	4742

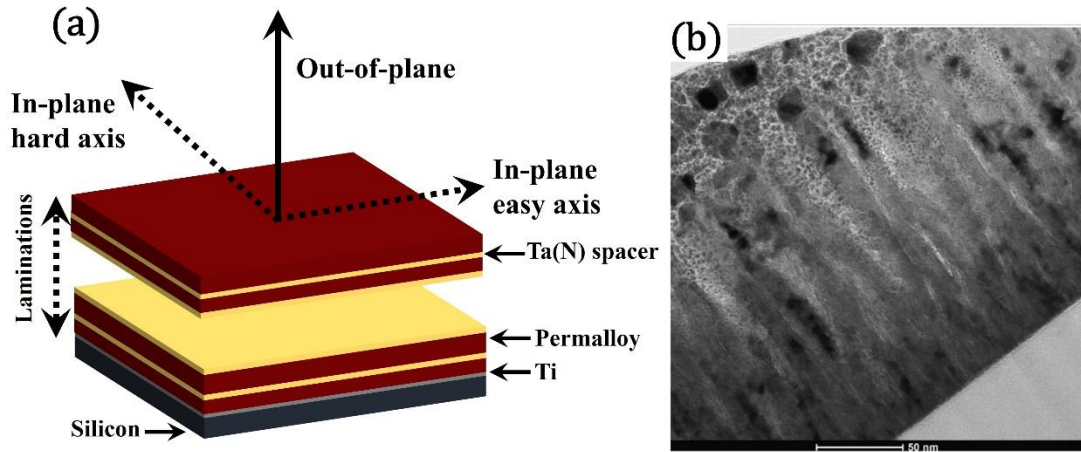


Figure 5.16. (a) Schematic of magnetic multilayers with insulators and (b) TEM image of Ni-Fe films with columnar and porous structure [5.44].

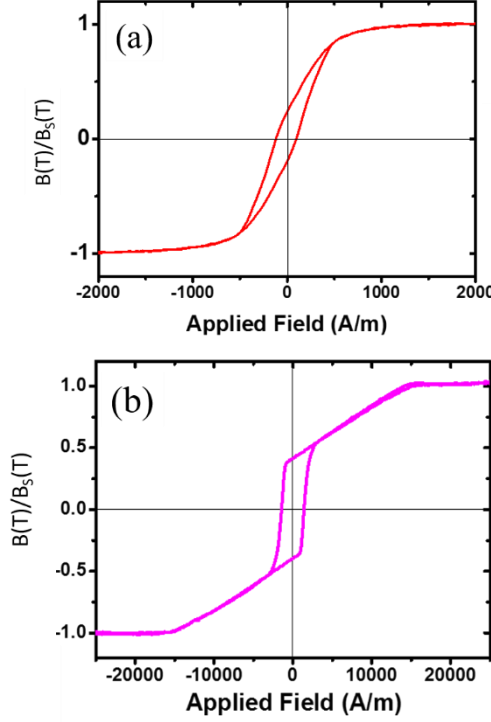


Figure 5.17. (a) Sample-13 (197 nm), H_c : 143 A/m and (b) Sample-14 (550 nm), H_c : 1367 A/m.

In the next section, deposition and characterization of multilayers of permalloy with Ta(N) spacer layers have been discussed. The direction of anisotropy in the film gradually changes with thickness of the sputtered $\text{Ni}_{81}\text{Fe}_{19}$ film. This change in anisotropy from in-plane to out-of-plane with increasing film thickness results in poor in-plane soft magnetic properties. It is evident from the hysteresis loops (Figure 5.17 (b)). Figure 5.17 (b) shows the stepped hysteresis loop with out-of-plane anisotropy.

From the literature we know that the total effective anisotropy (K_{Total}) of a film of thickness ' t ' expressed as $K_{Vol} + \frac{2 \cdot K_{Surf}}{t}$ [5.41], is thickness dependent [5.42], where, K_{Vol} and K_{Surf} are the anisotropy constants representing the bulk/volume and surface (interface in case of multilayers) anisotropy terms, respectively. For thin Permalloy films (where usually $K_{Surf} < 0$ and $K_{Vol} > 0$), the magnetization shifts from in-plane to out-of-plane as the film thickness increases. The thickness ($t_{critical}$) of the film at which the in-plane spin orientation shifts to out-of-plane is proportional to the ratio of K_{Surf} and K_{Vol} as $\frac{2 \cdot K_{Surf}}{K_{Vol}}$. The surface anisotropy is independent of the film thickness and arises out of the reduced local magnetic symmetry of the surface atoms [5.43-5.44]. The $1/t$ net surface anisotropy contributing term tends to reduce with thickness while, the K_{Vol} (which represents the contributions from the shape $(-\frac{N_d \mu_0 \cdot M_s^2}{2})$), the

magneto-elastic anisotropy (K_{me}) and the magneto-crystalline anisotropy (K_{mc})), where M_s and N_d are saturation magnetization and demagnetizing coefficient respectively), reaches its maximum as the thickness approaches $t_{critical}$ [5.45].

At lower Permalloy ($Ni_{81}Fe_{19}$) thickness values (40 – 100 nm), there is a negligible contribution from the magneto-elastic anisotropy (K_{me}) [5.46]. Competition between the magneto-crystalline anisotropy (K_{mc}) and shape anisotropy ($-\frac{N_d\mu_0 M_s^2}{2}$) determines the direction of magnetization since there is no significant contribution from K_{me} . The shape demagnetizing factor favours in-plane anisotropy, while K_{mc} promotes the out-of-plane anisotropy.

5.4.2. Sputter deposition $Ni_{81}Fe_{19}$ / Ta(N) multilayers

Figure 5.18 depicts the SEM cross-section of the nano-laminated Permalloy separated by ultra-thin (~ 20 nm) Ta(N) films, respectively. The Permalloy films thickness was uniformly deposited (each layer thickness 115 nm - 110 nm) using the optimized sputter conditions described above. The four-point probe electrical resistivity measurement suggested a Permalloy resistivity of about 25 $\mu\Omega$ -cm. The electron dispersive spectroscopy (EDS) measurements indicated a Ni: 82% and Fe: 18% Permalloy composition. The measured Ta(N) resistivity of about 3200 $\mu\Omega$ -cm depends on the Ta(N) composition and the deposition conditions.

In this case, the individual Permalloy thickness is kept well below the critical thickness. Three different samples were prepared with 1, 2, and 4 layers of 20 nm thick Ta(N) sandwiched between 2, 3, and 5 Permalloy layers of 110 nm thickness each (with net thickness of 240 nm, 370 nm, and 630 nm, respectively). Measurement of 2 Permalloy layers (Figure 5.19 (a)) had a coercivity of 29.45 A/m (as shown in the inset) and anisotropy field of 160 A/m. The reduction in H_c values diminishes with additional multilayers (figs. 5.19(a), (b) and (c)). However, a substantial increase in anisotropy field (H_k), from 180 A/m to 660 A/m was observed with additional multilayers (3 and 5 layers of $Ni_{81}Fe_{19}$). This increase in H_k can be attributed to the magneto-elastic anisotropy with each Ta(N) inter-layer influencing the two adjacent $Ni_{81}Fe_{19}$ layers [5.49].

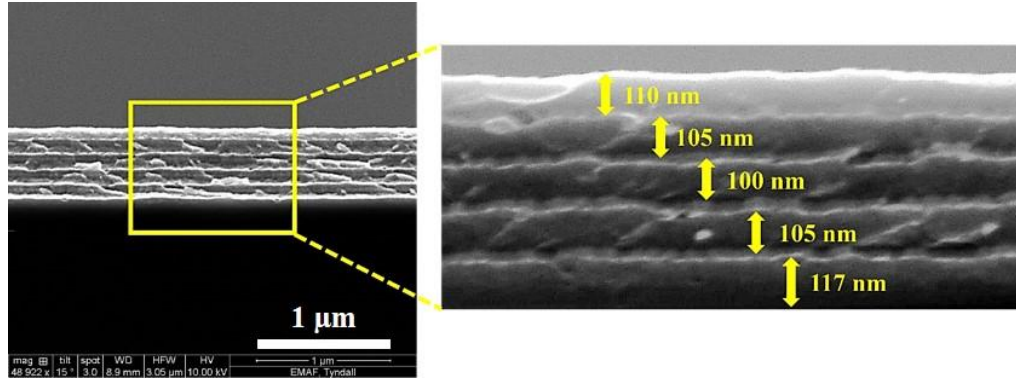
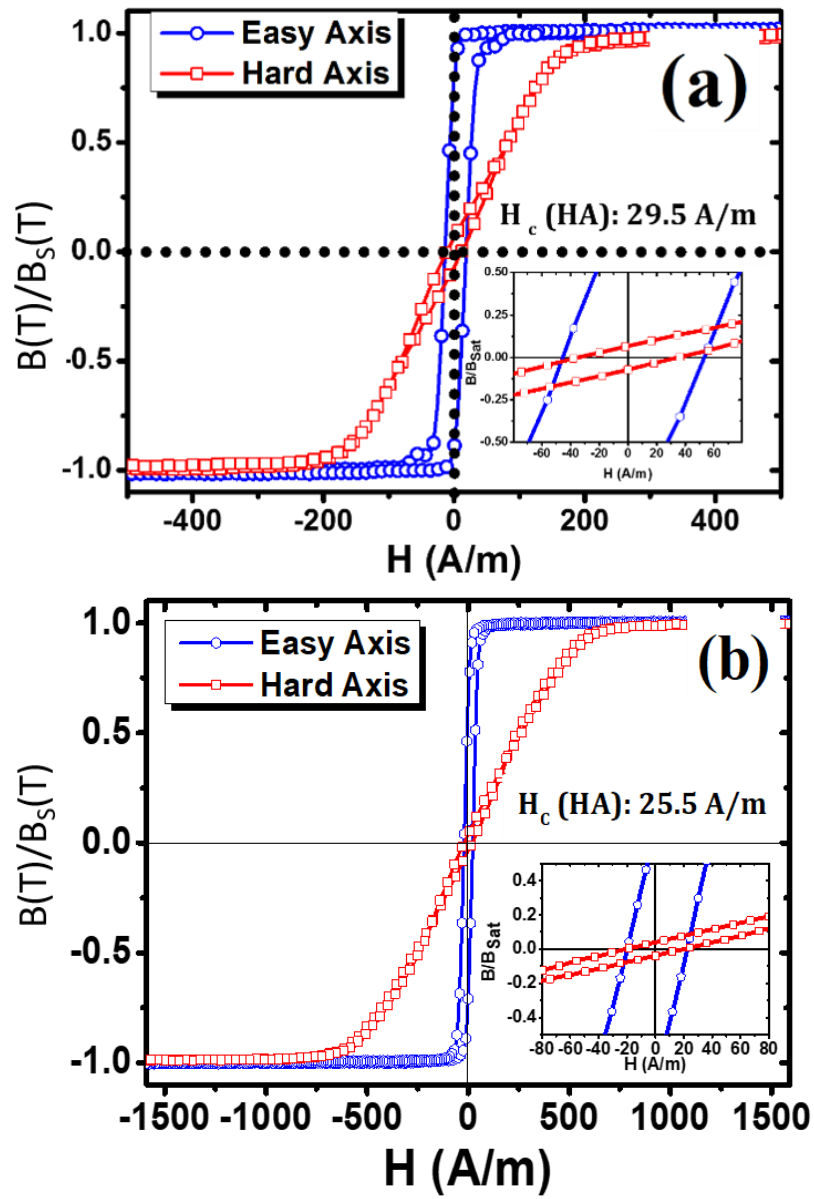


Figure 5.18. Scanning electron microscopic images of 5 permalloy layers separated by thin Ta(N) spacers.



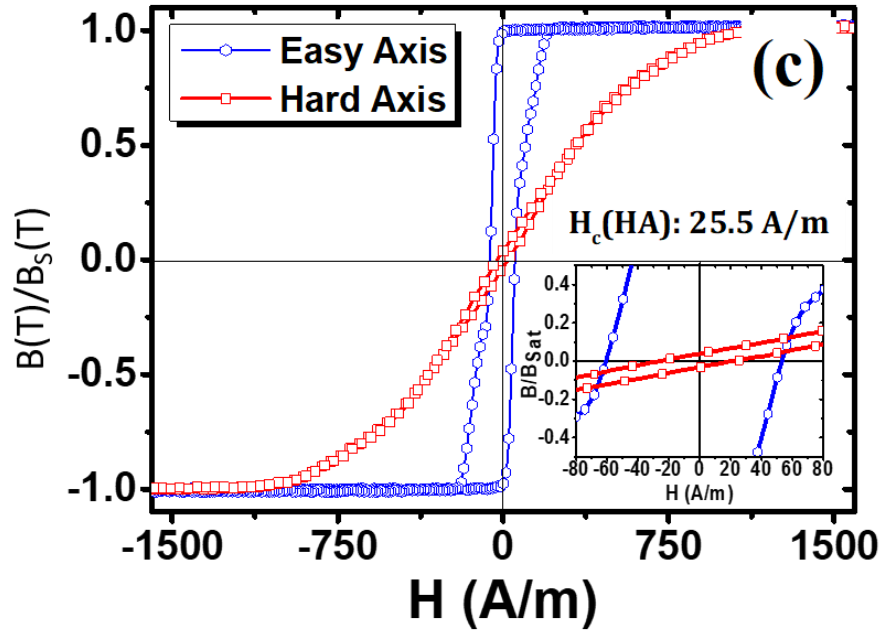


Figure 5.19. Hysteresis loops of (a) 2 Permalloy layers (net thickness: 240 nm); (b) 3 Permalloy layers (net thickness: 370 nm) and (c) 5 Permalloy layers (net thickness: 630 nm) separated by Ta(N) films.

The saturation fields and coercivities of the laminated multilayers were measured at different in-plane angles. These measurements were made to understand how the directional stress (if any) in the wafer influences the in-plane magnetic properties with increased number of laminations. The wafers were rotated manually to specific angles marked on a wafer holder to measure the saturation field and coercivity in the BH loop tracer.

Figures 5.20 (a) and 5.20 (b) show the H_k and H_c change with the direction of applied field respectively. It is interesting to note that even though H_k along the hard-axis in the 5 Permalloy layer laminate shows significantly higher H_k (~ 660 A/m) compared to 3 and 2 Permalloy layers, the H_c is almost the same for 3 and 2 Permalloy layers. The 2 Permalloy layer films show that there is significant in-plane anisotropy (Figure 5.20(a)) and hard-axis coercivity (Figure 5.20 (b)). This was also observed with 3 and 5 Permalloy layers, where the inclusion of successive Ta(N) layers increases in-plane anisotropy (Figure 5.20 (a)). Although anisotropy increases with the number of Permalloy films, the hard axis coercivity of all the films shows a no reduction (Figure 5.20 (b)).

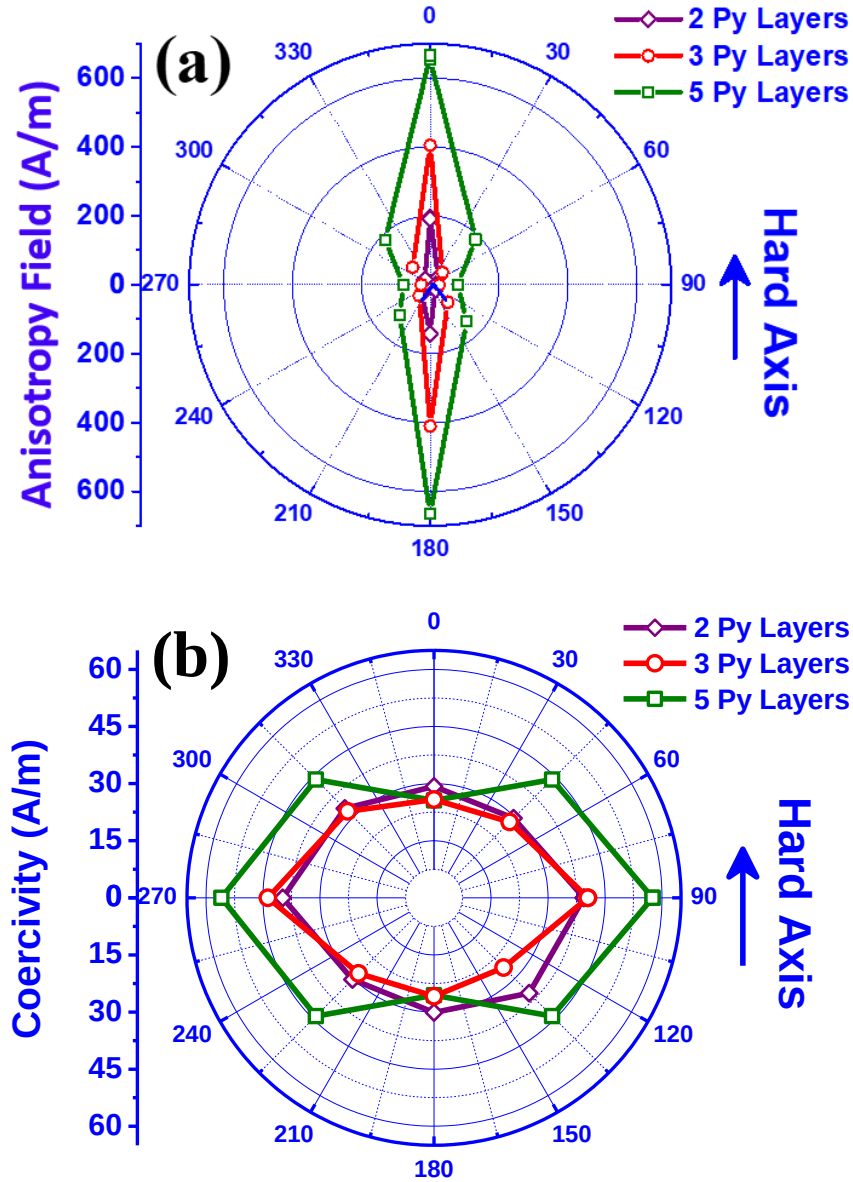


Figure 5.20. Directional dependence of (a) anisotropy field and (b) coercivity (H_c) measured in-plane for nano-laminated films measured with BH loop tracer.

It is known that the permeability response of non-laminated Permalloy films show high eddy current losses beyond 100 MHz. The imaginary part of the permeability increases due to eddy current losses [5.51]. This restricts the use of Permalloy as the magnetic core to applications below 100 MHz. Moreover, the FMR frequency is well below 1 GHz as predicted by the Landau-Lifschitz-Gilbert model. The cut-off frequency (f_c) in terms of film permeability is expressed as $\frac{\rho}{t^2 \mu_o \mu_r \pi}$. Where, the film thickness, bulk resistivity and relative permeability are represented as t , ρ and μ_r , respectively. The permeability of the magnetic material is proportional to $1/\sqrt{t}$ [5.51].

Figures 5.21 (a) and 5.21 (b) show the real and imaginary parts of the permeability of the laminated Permalloy films versus frequency. It is clear that the permeability response is flat up to 200 MHz (2 laminations) and 440 MHz (3 laminations). The laminated films reduce the eddy current losses and increase in the anisotropy increases the FMR frequency. However, the capacitive coupling increasing laminations would reduce the cut-off frequency [5.52]. The net effect of increase in anisotropy and capacitive coupling determines the high-frequency response of the films.

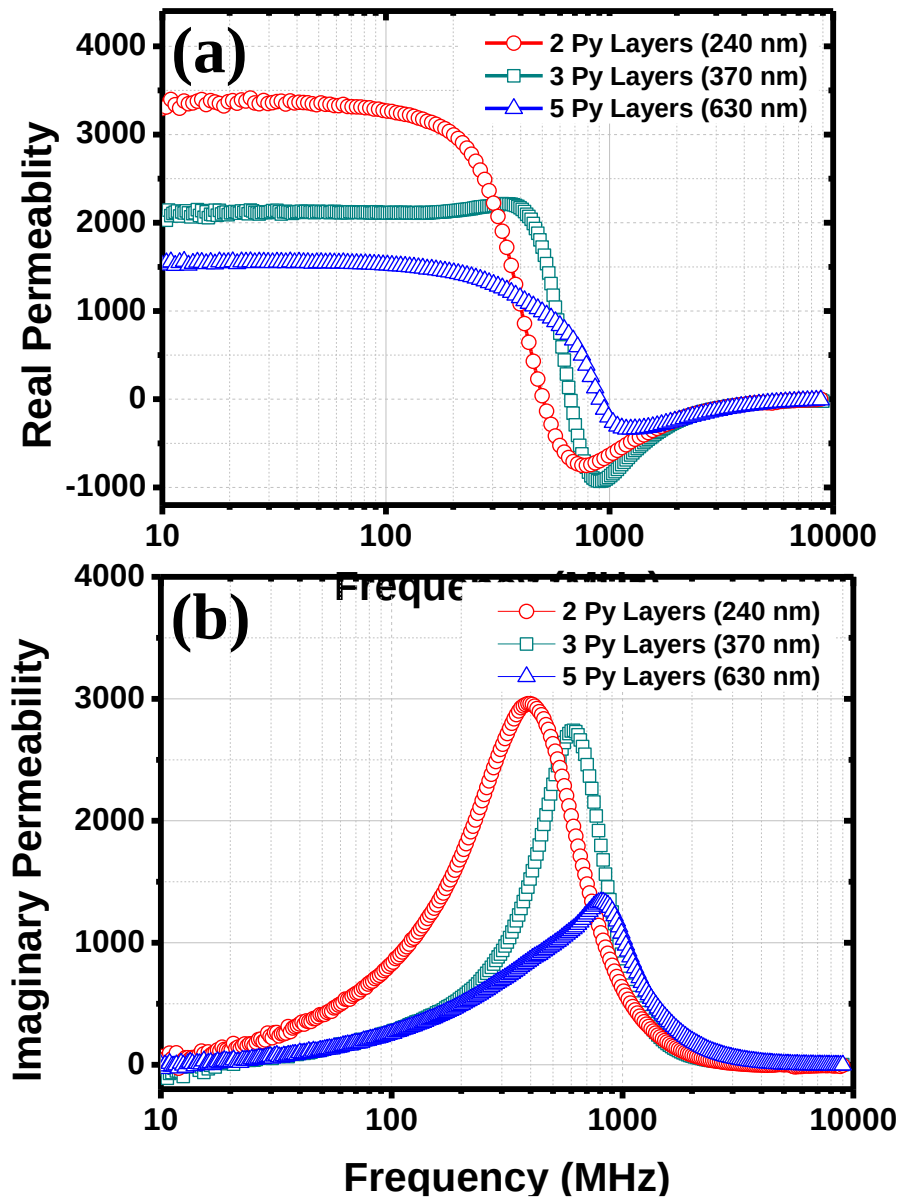


Figure 5.21. Relative permeability: (a) Real and (b) Imaginary spectra of TaN/Permalloy/Ta(N) films measured at zero bias.

In this section of the thesis, sputter lamination of $\text{Ni}_{81}\text{Fe}_{19}$ with Ta(N) spacers have been investigated for high-frequency magnetics applications. The laminated cores were found to be applicable for < 200 MHz operation. It is important to note that, apart from the film stress (magnetostriction), the core shape and device geometry plays a crucial role in the magnetic properties of the core. As a low-cost alternative to the sputter lamination process, an electrochemical route has also been investigated. To develop a method which eliminates the need for a sputter seed, the next section will first demonstrate an electroless metallization process without sputtered seed and then this process will be further exploited to develop a lamination step using polymer spacer layer.

5.5. Electrochemical Lamination Route Through Electroless Deposition:

The next section of the thesis, describes a novel process of metallization with Permalloy of insulating surface with surface activation and electroless deposition. The first section describes the process on silicon dioxide surface. The process is an alternative method of depositing magnetic core on Si wafers without sputtered seed. The process is further explored for depositing Permalloy on insulating polymer (SU-8) to develop magnetic core laminations with the SU-8 polymer as insulating spacer.

5.5.1. Activation and Metallization of Silicon dioxide surface

The first step to develop an electrochemical lamination process was to develop an electrochemical magnetic material deposition process without sputtered seed. Silicon wafers $<100>$ were pre-cleaned in acetone, iso-propyl alcohol (IPA) and DI water. This was followed by plasma treatment in a March Plasmod, GCM-200, system in an oxygen atmosphere at 100 W for 5 mins. The samples were immersed 3-Aminopropyl)triethoxysilane (APTES) solution for 30 mins. The solution measured a pH OF 5.0. The ethoxy groups of the APTES molecules get hydrolyzed. The hydrolyses process is catalysed by water, resulting in the formation of silanols. These silanols form a monolayer of APTES via covalent bonds by condensing on to the surface of the substrate and the APTES molecules cross link laterally to form a siloxane network of self-assembled monolayers (SAM). The amino groups of these siloxanes are orientated away from the substrates surfaces as shown in Figure 5.22. The excess SAM layer is removed from the surface of the substrate by sonication resulting in a SAM [5.53-5.54].

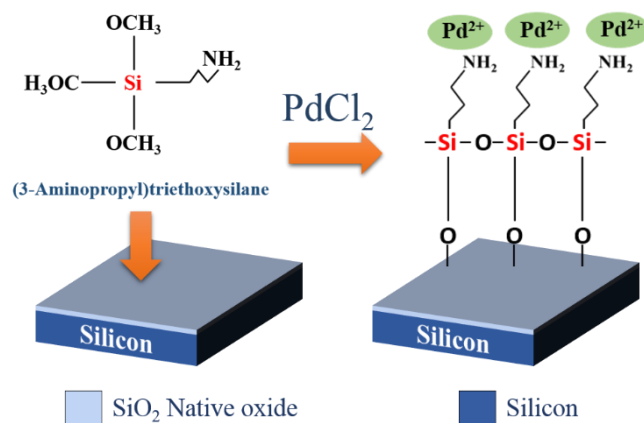


Figure 5.22. Schematics of self-assembled monolayer deposition process and Pd^{2+} deposition as catalyst layer.

At this stage, the samples were heated at 65 °C in an in-house prepared palladium solution to form a thin catalytic layer. This leads to the formation of thin Pd^{2+} on the sample substrate through the amine bonds. It is important to note that SAMs adhere to the thin, naturally oxidized layer, on silicon. The Pd acts as nucleation centres for subsequent electroless metal deposition. At this stage, the sample is ready for Permalloy deposition. The samples were cleaned in DI and dried with nitrogen gas.

An in-house borane based bath developed for electroless Permalloy deposition has been described earlier in chapter-4. This bath composition has been optimized to achieve a uniform film on Cu. Permalloy films were electrolessly deposited using bath conditions (pH ~ 6.5 and temperature ~ 75 °C) in absence of applied external magnetic field. The deposit thickness was recorded versus time using a surface profilometer (Tencor Alpha-step 200). Deposit thicknesses up to ~1 μm could be obtained in 900 seconds of deposition. In the previous chapter, Fe preferentially deposited for lower coercivities (< 78 A/m) and higher resistivities (> 45 $\mu\Omega\text{-cm}$) by altering the DMAB content of the bath. The high Fe content reduces the hysteresis losses, whereas the high resistivity of the film will allow thicker core to be deposited without increasing core eddy-current losses. However, the film deposited on Si surface have shown stress resulting in cracks with thicker deposits (> 300 nm).

Figure 5.23 illustrates the deposition thickness of the film achieved with immersion time. The deposition rate increases initially and a thickness ~ 1 μm could be achieved with the deposition process. Thicker deposits (> 1 μm) have shown delamination of the films.

Scanning electron microscope (SEM) images of the Permalloy deposits with and without oxygen plasma treatment were obtained. As shown in Figure 5.24 (a-b), the deposits without oxygen plasma exhibited fractal growth. This type of dendritic growth mechanism is often attributed to directional growth preference due to local thermodynamic in-equilibria [5.55]. Deposits with 15 minutes oxygen plasma (150 W) preclean led to smooth growth (Figure 5.24 (c)). This can be attributed to the surface oxidation, which improves hydrophilicity of the SiO_2 substrate for forming bonds with APTES molecules in the solution. The amine groups are then available for Pd^{2+} ion interaction, which forms the activation layer for subsequent electroless magnetic material deposition. This process could also be relevant for depositing metals on insulating surfaces for MEMS applications.

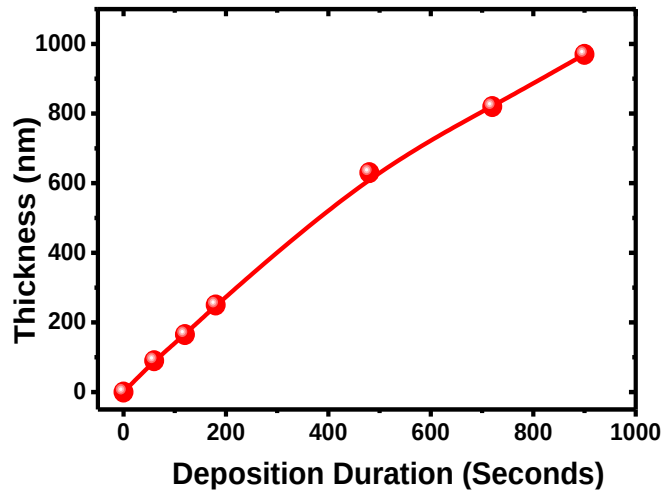


Figure 5.23. Thickness of Permalloy deposits on SiO_2 surface.

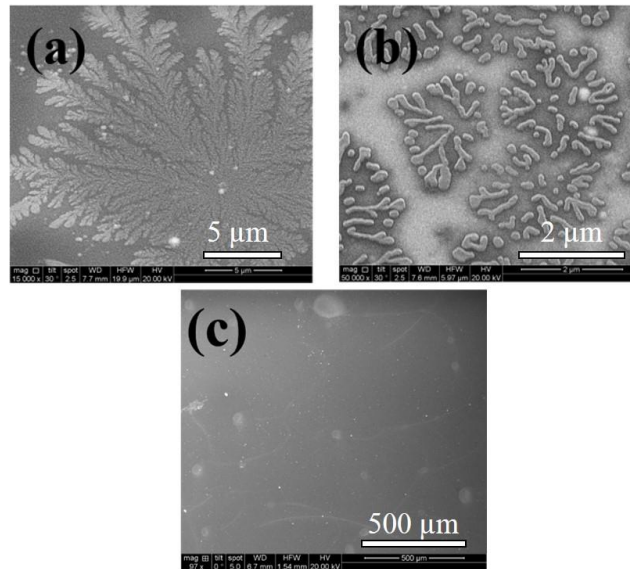


Figure 5.24. SEM micrograph of: (a-b) Fractal Permalloy growth observed on Si surface without oxygen plasma treatment and (c) Smooth Permalloy deposition after plasma treatment.

The energy dispersive x-ray (EDX) analysis was performed at different stages of the magnetic seed deposition process. Figure 5.25 (a) shows the EDX of palladium activated sample prior to metallization. It confirms the presence of palladium prior to Permalloy deposition. Figure 5.25 (c) depicts the EDX results of the sample with electrolessly deposited Ni-Fe which exhibited distinct Ni and Fe peaks with suggested Ni ($78 \% \pm 3 \%$) and Fe ($22 \% \pm 3 \%$) composition. It is important to note that the nature of nucleation and layer growth plays a critical role in determining the magnetic properties. The resistivity of the films were found to be $25 \mu\text{Ohm-cm}$ - $30 \mu\text{Ohm-cm}$, which is higher than that for PVD or electroplated Permalloy films ($\sim 20 \mu\text{Ohm-cm}$). Literature have shown that small % of boron is co-deposited in electroless process. This increases the resistivity of the deposited films in DMAB based electroless baths. Light element like boron with low photon energies cannot be detected in the EDX spectrum [5.56].

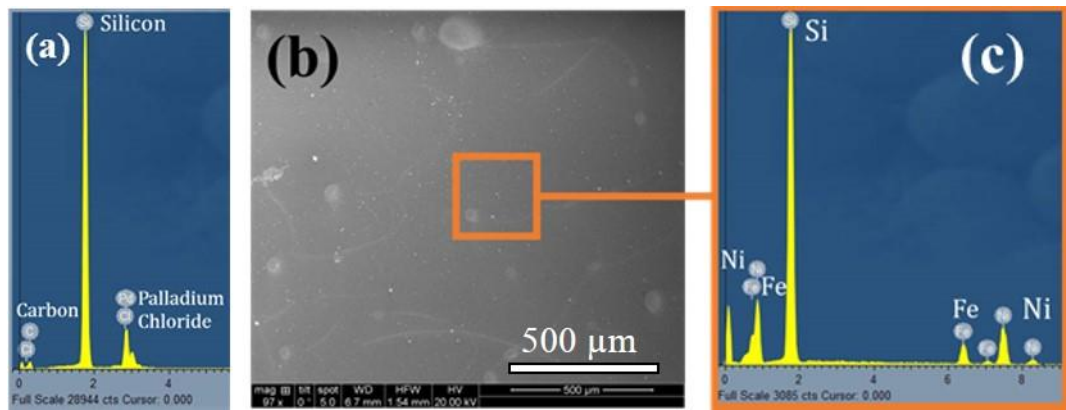


Figure 5.25. (a) EDX spectrum of Pd catalyst on Silicon surface and (b) SEM micrograph after electroless Permalloy deposited on palladium catalyst with corresponding EDX spectrum (c).

The deposits were tested in a BH loop tracer (SHB instruments, Model: MESA 200 HF) up to 250 Oe (2 kA/m) external magnetic field. Figure 5.26 depicts the isotropic hysteresis loop along two directions along in-plane but perpendicular to each other for 100 nm thin Permalloy film on Si. A coercivity of ~ 4.5 Oe (360 A/m) and saturation flux density of ~ 0.95 T was obtained from the BH loop tracer. This film has acceptable coercivity as a seed layer. There is no sputtered seed layer deposited prior to electroless Permalloy deposition. The higher resistivity of the electroless film compared to usually sputtered seed films (such as Permalloy, Cu or Ti) will restrict the core eddy current losses. Moreover, DMAB concentration in the bath could be changed for deposit iron rich Ni-Fe alloys, as discussed in Chapter 4. The change in alloy

composition gives a wide range of coercivities (29 A/m to 96 A/m), saturation flux densities (1 T to 1.7 T) and resistivities (28 $\mu\Omega\text{-cm}$ to 63 $\mu\Omega\text{-cm}$) of the films, as described in *Chapter 4*.

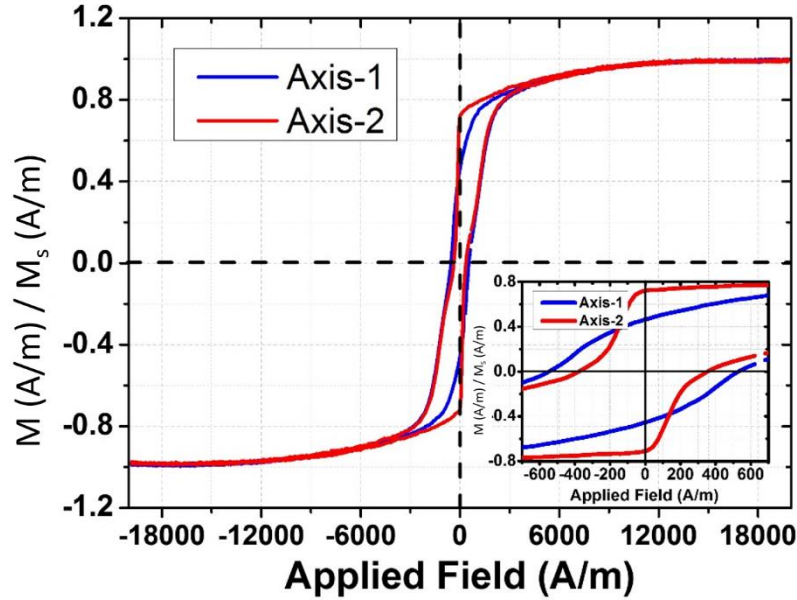


Figure 5.26. Hysteresis curve of 100 nm Permalloy deposit.

5.5.2. Activation and Metallization on SU-8 Photoresist:

SU-8 is widely used as inter-layer dielectric, isolating the windings from the top-core. Hence, a new process sequence is needed to metallize the SU-8 to form the top core. This process is depicted in Figure 5.27. SU-8 (from MicroChem Inc., USA) was spin coated on spin coater (Laurell, Model: WS-400B-6NPP/LITE/AS) at 2000 rpm / 30 secs and 1800 RPM / 30 secs main speed to achieve 70 μm and 100 μm on silicon wafer. This was followed by exposure on an optical mask aligner (Cannon PLA 501FA, Japan) and puddle mode developed in propylene glycol methyl ether acetate (PGMEA) solvent (Rohm and Haas Elec. Mat., UK) to reveal clear SU-8 patterns. Resist thickness of $\sim 120 \mu\text{m}$ was measured on a profilometer (Tencor Instruments, Alpha step 2000). The sample was plasma treated for 5 mins at 300 W power in oxygen plasma (March Plasmod GCM 200). This step assists in activating the oxygen bonds at the surface of the photoresist making it hydrophilic. Plasma being present everywhere activates the recessed regions of SU-8 as well. No loss of resist was measured in profilometer. A SAM is deposited on the SU-8 sample by immersing in (3-aminopropyl)triethoxysilane (APTES) solution prepared in-house followed by sonication to remove the excess SAM layers. This was followed by activation of the

sample in an in-house developed palladium chloride (Sigma Aldrich) solution. This results in Pd^{2+} binding with amino group NH_2 (as shown in Figure 5.28 (b)). The palladium acts a thin conductive layer which strongly binds with NH_2 group. During the experiments non-conductive plastic tweezers were used as conductive tweezers could be metallized in the electroless bath.

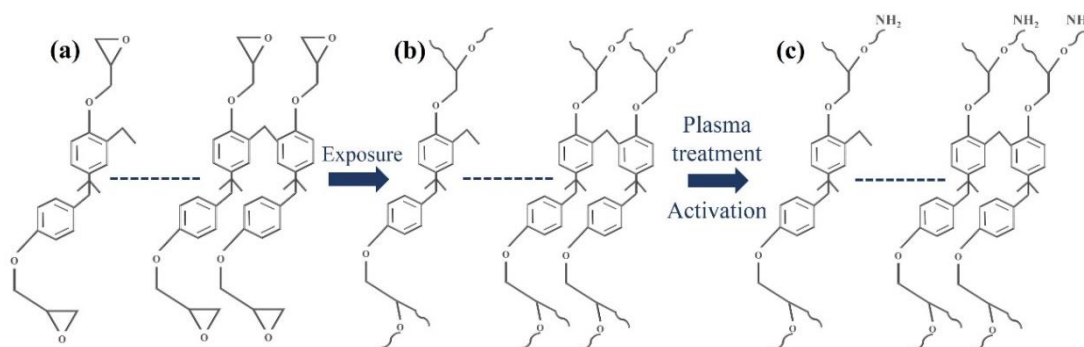


Figure 5.27. Surface activation process of SU-8 surface. (a) SU-8 molecules before exposure. (b) SU-8 cross-linking after exposure and bake. (c) Plasma treatment and activation with SAM resulting in amine bonds with open oxygen sites.

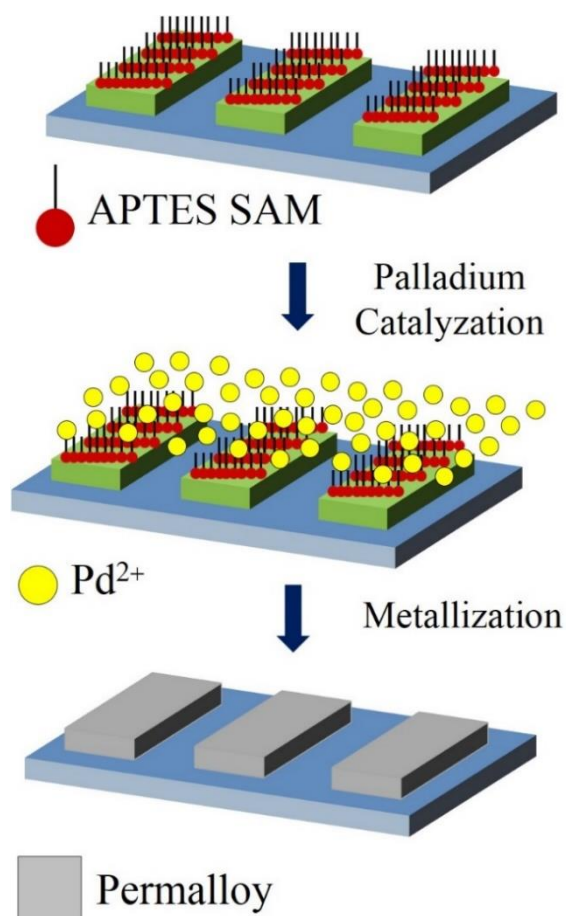


Figure 5.28. Self-assembled monolayer deposition and Pd^{2+} activation on SU-8 surface. (a) Silicon patterned with SU-8 50. (b) SU-8 molecule before and after exposure. (c) Isotropic treatment of SU-8. (d) APTES monolayer deposition on SU-8 surface. (e) Palladium (Pd^{2+}) activated on SU-8 surface.

An in-house developed borane based bath ($0.034 \text{ mol-dm}^{-3}$ Dimethylamine borane as reducing agent) was prepared with di-ammonium citrate ($0.027 \text{ mol-dm}^{-3}$ as complexing agent) and lactic acid (0.22 mol-dm^{-3}) as surfactant to deposit permalloy on the activated SU-8 samples (details of the process were discussed in Chapter 4). All the chemicals were used as obtained from Sigma Aldrich. The temperature and bath pH were well controlled at 75°C and 6.5 respectively to give optimized results. The samples were deposited in the presence of an external magnetic field to ensure anisotropy in the films. The in-house arrangement includes two attracting NdFeB magnets being placed across the beaker containing the sample with field of $\sim 250 \text{ Oe}$, a magnetic stirrer rotating at 250 rpm and Ikamag RCT hotplate with IKA H 60 thermometer probe. The deposition thickness was measured at regular intervals with surface profiler to acquire the deposition rate. Table 5.4 lists the thermal and electrical properties of the insulators that have also been activated with this process. The surface of THB-151N could not be activated. This is because in the APTES solution (containing ethanol), the THB-151N shows resist loss.

Table-5.4. Thermal and electrical properties of the insulators activation and metallization investigated.

Insulating Photoresists	Activated and metallized	Properties			
		Dielectric Constant (K)	Volume Resistivity	CTE (ppm/ $^\circ\text{C}$)	Thermal Conductivity (W/m $^\circ\text{K}$)
SU-8 50 (Microchem)	Yes	3-4	$\sim 10^{16}$	52	0.2-0.3
BCB (Dow Chemicals)	Yes	2.49-2.65	$\sim 10^{19}$	52	0.29
Parylene-C (ParaTech)	Yes	3.1	$\sim 10^{16}$	38	0.084
THB -151N	No	3-4	$\sim 10^{18}$	-	-

Figure 5.29 (a) is an optical image of the site selective Permalloy deposits on a patterned substrate. As observed from the image, the metal is deposited only on the SU-8 patterns. Selective deposition with feature separations of 0.3 mm has been successfully achieved, which is typically the core separation distance in integrated micro-inductors/transformers. Electron dispersive X-ray (EDX) analysis established the material composition to be Ni: $79 \pm 2\%$ and Fe: $20 \pm 2\%$. Small traces of Pd can also be observed on the EDX spectra (Figure 5.29 (b)).

Figure 5.30 (a) is a scanning electron microscopic (SEM) image of the Ni-Fe alloy cross-section on a planar SU-8 surface. The thickness uniformity of deposition on the

planar surfaces is confirmed from the cross-section of the film. The cross-section image of a 65 μm thick patterned SU-8 (Figure 5.30 (b)) acquired by mechanically polishing the cross section confirms the uniformity of deposition on patterned structures with the inset depicting the SU-8 side-wall completely covered with permalloy.

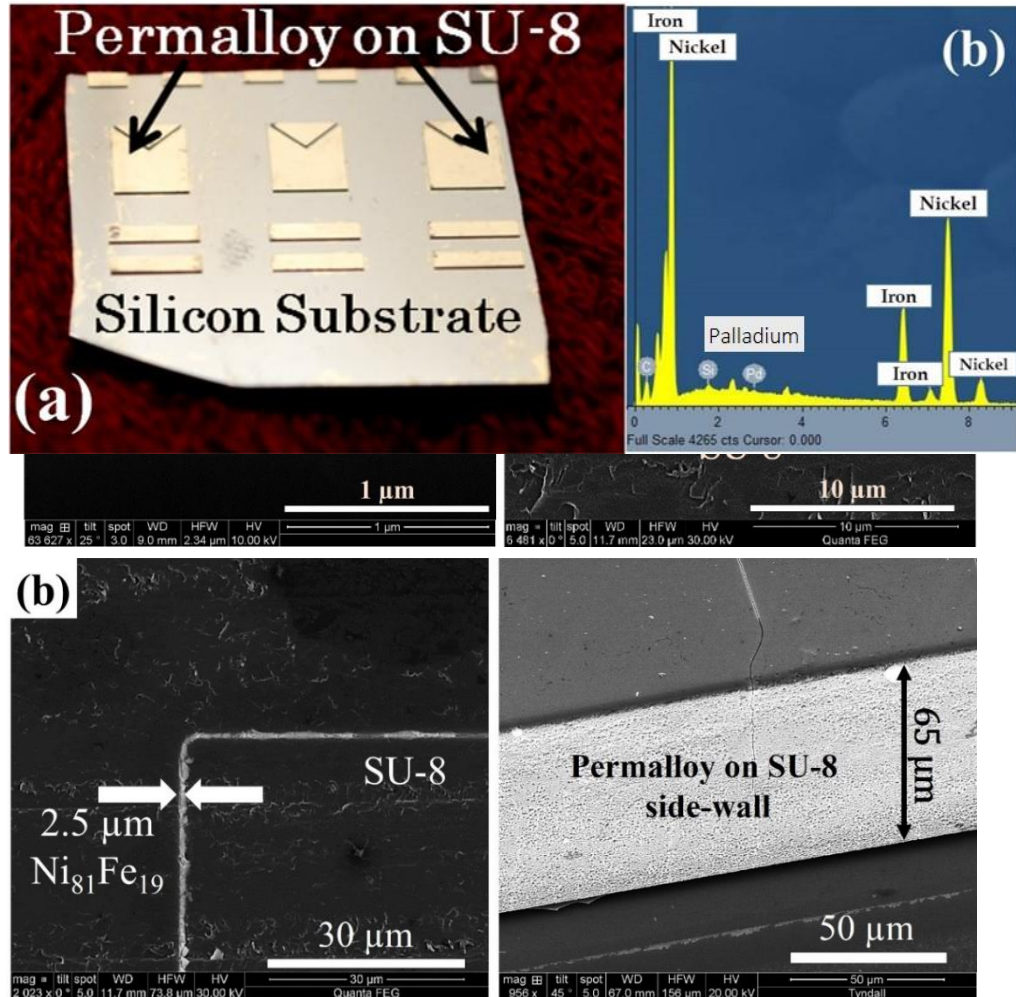


Figure 5.29. (a) Selective Permalloy deposited on 65 μm thick SU-8 and (b) EDX spectra of the deposited Permalloy film on 65 μm thick patterned SU-8.

Figure 5.30. Uniform Permalloy deposited on SU-8 without seed layer: (a) on planar SU-8 resist with thicker deposits. (b) Cross-section of 65 μm thick patterned SU-8 with $\sim 1.4 \mu\text{m}$ thick Permalloy deposit and depicting 45° tilted image of uniformly deposited Permalloy around 65 μm thick sidewall.

5.5.3. Process Integration for laminations:

A passivation process is required with SU-8 for top core patterning and device protection. This layer, if thin enough, can act as an insulating spacer in magnetic laminations. In this section, the site-selective metallization process is exploited to form a laminated top magnetic core. Compared to Brunet et. al. [5.22], this is a three step

process, for depositing magnetic core electrochemically (Figure 5.31 (b)). This process does not require an additional Ni electroless seed as required on Figure 5.31 (a). Moreover, no electro-depositable photoresist is required and the Pd solution is reusable as the process requires only immersion into the solution.

Figure 5.32 depicts a cross-sectional schematic of the process developed to activate the final SU-8 passivation layer. It is important to note that the exposed copper windings (as shown in Figure 5.32) were concealed with thick temporary resist (such as THB-151N), which cannot be activated with APTES and protects the windings from subsequent steps. The devices were plasma treated and immersed in the SAM solution as described earlier (Figure 5.33 (a)). Ultra-sonic cleaning in acetone, IPA and DI, followed this step. The devices were then catalysed in PdCl_2 solution (Figure 5.33 (b)) followed by electroless deposition of Permalloy ($\sim 2 \mu\text{m}$) (as shown in Figure 5.33 (c)). The magnetic film thickness and uniformity of the process was confirmed with SEM analysis.

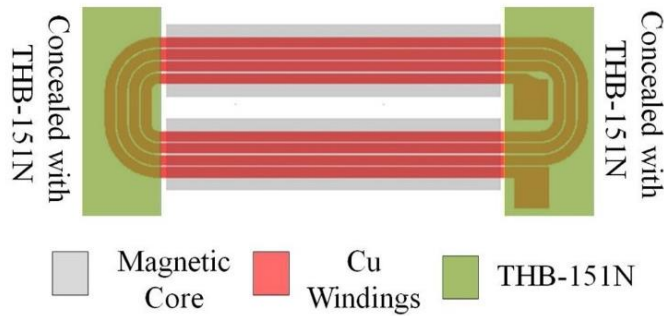


Figure 5.31. (a) Previously reported five step seed deposition process [5.22] and (b) Three step core magnetic material deposition process developed in this work.

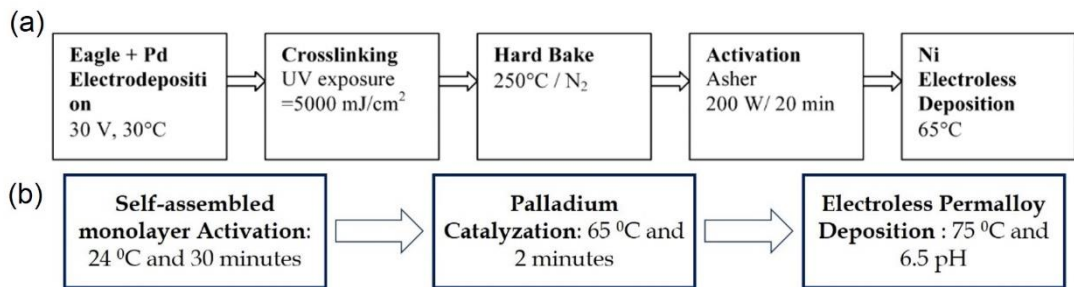


Figure 5.32. Top view of a racetrack inductor with concealed Cu coils with THB-151N.

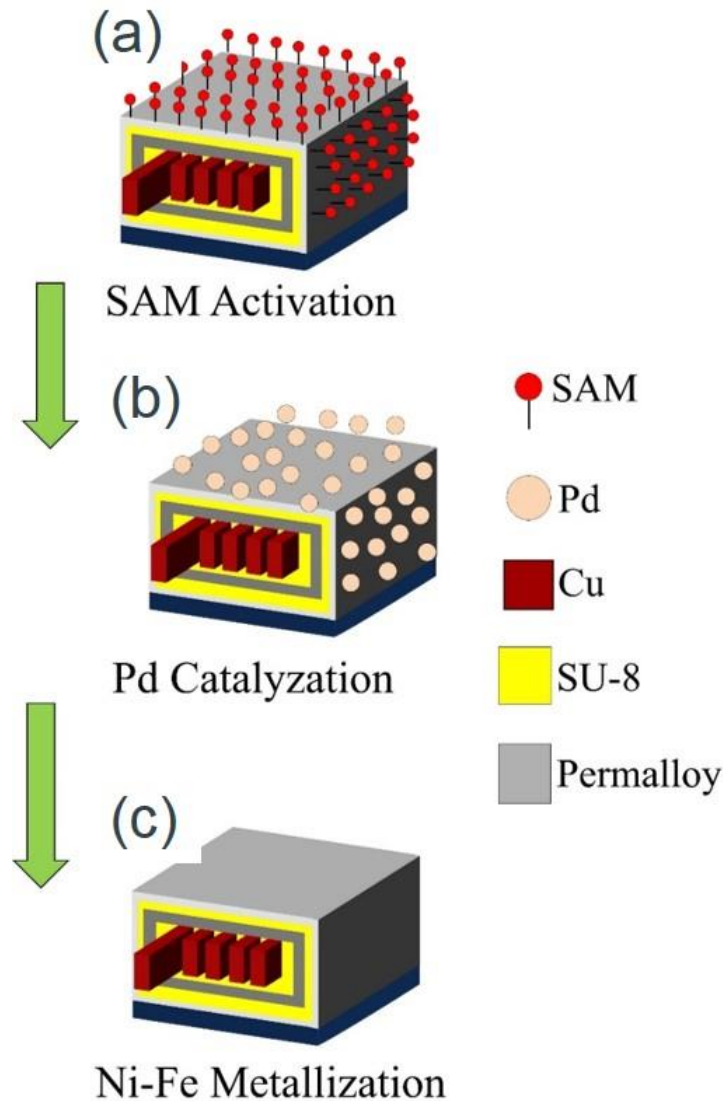


Figure 5.33. Electrochemical lamination process: (a) SU-8 passivation layer activated with SAM. (b) Pd catalyzation and (c) Electroless Permalloy deposition.

The established process was then integrated with a CMOS compatible micro-inductor fabrication process. Figure 5.34 (a) depicts the top core fabricated with on 160 μm thick SU-8 with Permalloy without sputtered seed. A Permalloy thickness of $\sim 2.5 \mu\text{m}$ was deposited on activated outer-most SU-8 patterns corresponding to the material skin depth for $\sim 20 \text{ MHz}$ operation (considering resistivity and relative permeability of $25 \mu\text{Ohm-cm}$ and 500 respectively for electroless Permalloy). The uniformity of the deposits is well maintained at the resist sidewalls. Moreover, the conformal solution based electrochemical nature of the process eliminates poor step coverage, which is challenging for PVD deposited seed layer [5.26] in deep or recessed structures. This is further demonstrated in the undercut regions beneath the SU-8 (Figure 5.34 (b)), where thick uniform Permalloy is deposited without a metal seed

layer. Although such undercut regions are not desirable for lamination, the deposition in such recessed regions demonstrates the ability to metallise recessed structures applicable to the wider MEMS fabrication community.

SU-8 is a widely used passivation layer [27-28] in micro and nanofabricated devices being relatively immune to atmospheric and temperature/humidity changes. Figure 5.34 (c) shows a cross-section of a fabricated micro-inductor with an outer protective SU-8 layer. The thickness of deposited Permalloy is uniform all across the surface of 70 μm thick outer SU-8 layer.

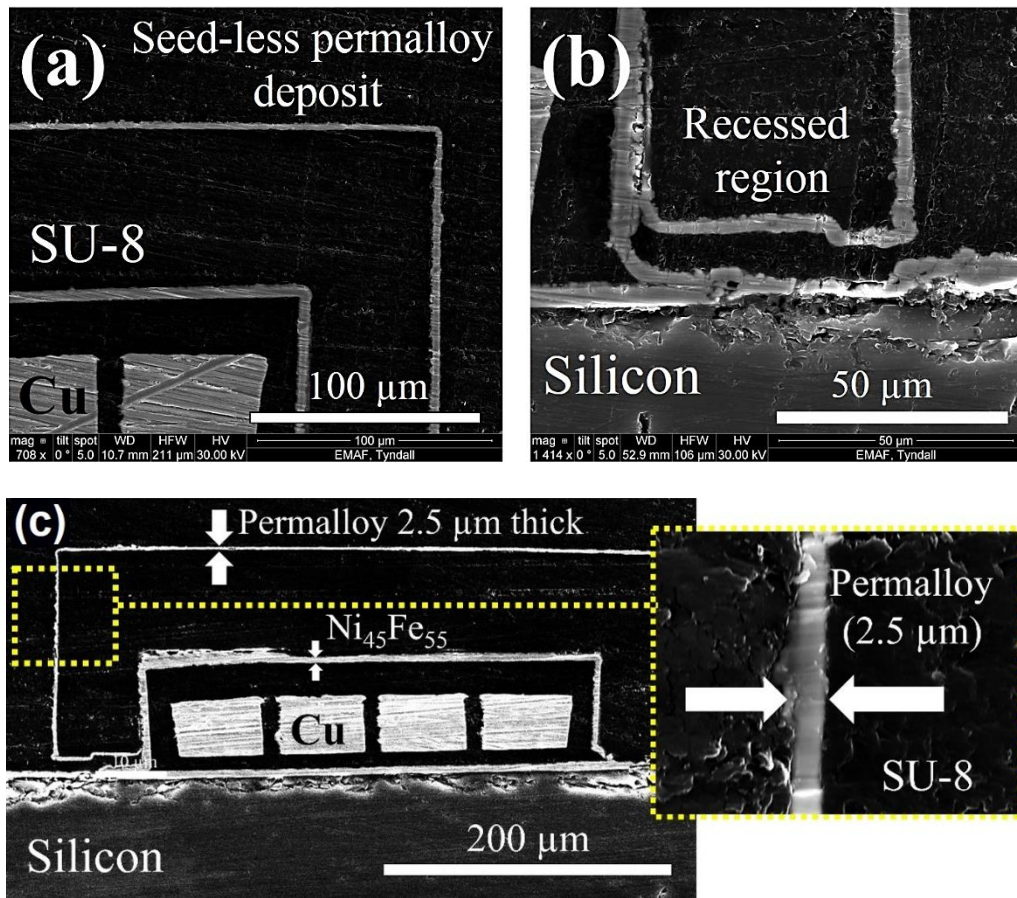


Figure 5.34. SEM micrograph of the device cross-section with integrated process. (a) Uniform $\sim 2.5 \mu\text{m}$ thick Permalloy outer-layer deposit on SU-8 including (b) recessed regions underneath SU-8 (not possible with PVD dependent processes) (c) Complete device cross-section with process integrated to laminate top core.

In this section the magnetic, structural and electrical characterization of a Permalloy electroless deposition process has been reported [5.19]. Anisotropic films have been deposited in the presence of an external magnetic field. Moreover, the static hysteresis loop and permeability spectra suggested excellent soft magnetic properties.

5.6. Electroless Ni-Fe as seed layer:

As discussed in *chapter 3*, wet etching of the magnetic core results in over-etch (Figure 5.35 (a)). The dense sputtered permalloy seed etches slowly compared to the electroplated $\text{Ni}_{45}\text{Fe}_{55}$ core material. This results in significant over-etch and reduces wafer yield. To reduce this over-etch, photoresist with good adhesion with the core material has been explored in *Chapter 3*. Another method of reducing the over-etch could be by replacing the sputtered $\text{Ni}_{81}\text{Fe}_{19}$ seed with an electrolessly deposited $\text{Ni}_{81}\text{Fe}_{19}$ seed. An investigation was carried out with sputtered and electrolessly deposited seed. Two 100 nm thick $\text{Ni}_{81}\text{Fe}_{19}$ samples (sputtered and electrolessly deposited) were prepared and deposited with 2 μm plated $\text{Ni}_{45}\text{Fe}_{55}$. It was then patterned with $\sim 9 \mu\text{m}$ AZ 9260 on a Cannon PLA-501 FA (g-h-i broad-band) mask aligner. Diluted HNO_3 etchant was prepared with 1:2 DI water and cooled down to room temperature. The accessible core material was etched in puddle mode to remove Permalloy (electroless and sputtered) completely from the patterned regions.

As observed from microscopic images in Figure 5.35 (b-d), some seed material may remain between the cores, thereby resulting in core shorting, so etching was continued. Nearly $\sim 2 \mu\text{m}$ (Figure 5.35 (d)) over-etch were measured with electroless seed on core etch. In comparison, traditionally used sputtered seed measured an over-etch of with 12 - 15 μm (Figure 5.35 (c)).

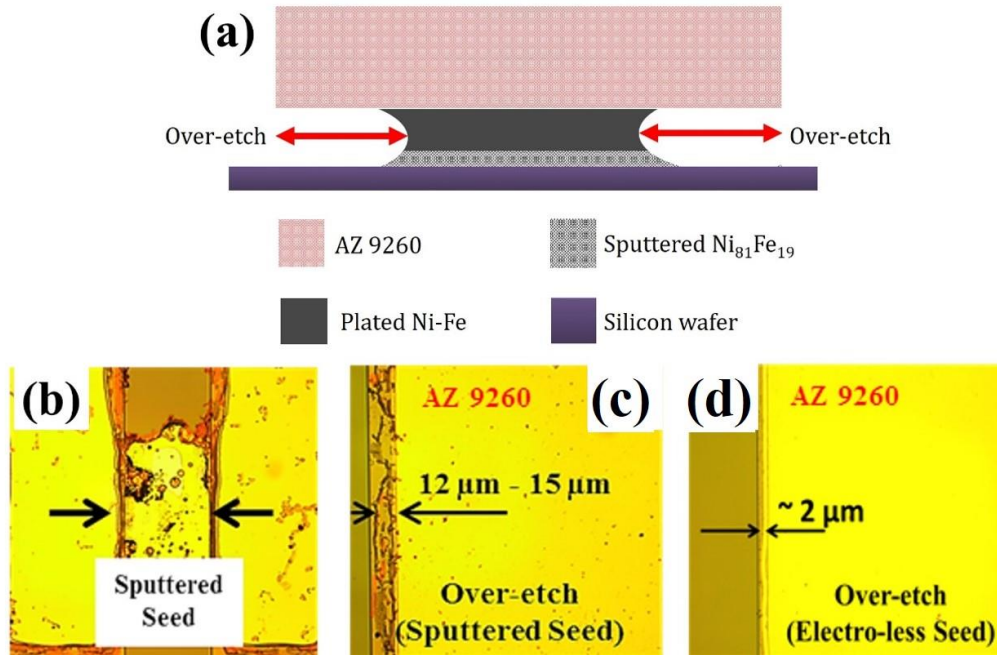


Figure 5.35. (a) Schematic illustration depicting the over-etch of the magnetic core. (b) Sputtered seed remaining while etching in some regions. (c) Over-etch with sputtered and (d) electroless Permalloy.

5.7. Conclusions

This chapter focussed on developing a lamination process for the magnetic core. Two different deposition approaches have been investigated, namely sputter and electrochemical deposition. Sputtered Ta(N) as insulating spacer layer has been explored with Permalloy films to develop Permalloy /Ta(N) laminates. Secondly, a new activation-catalyzation-activation method has been explored for magnetic material deposition on insulators such as SU-8. Both the methods have their own advantages and disadvantages.

The sputtered Permalloy material thickness of 117 nm is optimized to achieve a coercivity of ~ 57.6 A/m. This thickness is used to deposit 2, 3 and 5 laminations of Permalloy with Ta(N) as insulating spacer. The anisotropy shows significant improvement in anisotropy from 180 A/m to 660 A/m with increasing laminations from 2 layers to 5 layers. The coercivity remained well below 30 A/m for all the laminated samples. The cut-off frequency increased from 200 MHz to 440 MHz on increasing the laminations from 2 layers to 5 layers. The sputter deposition method has its advantages such as availability of various insulating and magnetic materials, multiple layer deposition without breaking the vacuum that gives certain flexibility over electrochemical methods.

Electrochemical lamination on the other hand is a low cost alternative. Compared to sputtered films, thicker magnetic films can be deposited with high deposition rates and can be wet patterned. In this chapter, an electroless lamination process has been developed as an alternative to sputtered lamination technique by activating and metallizing 170 μm thick SU-8 polymer surface with ~ 2.4 μm thick Permalloy. The process is ideal for metallizing insulating surfaces and recessed regions.

In conclusion, magnetic lamination are essential for high frequencies > 10 MHz to reduce eddy current losses. Although successful sputter and electrochemical laminations have been reported so far, more research is needed to understand and develop efficient magnetic lamination processes with repetitive properties especially using electrochemical options as a low cost alternative.

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Chapter 6

Closed Core Solenoid Micro-Inductors

6.1. Introduction

In the last few chapters the thesis developed new fabrication processes for efficient micro-inductors. A number of winding geometries have already been investigated including spiral [6.1-6.5], meander [6.6], toroidal [6.7-6.8] and solenoid types [6.9-6.20] and reported works have been discussed in *Chapter 2*. Solenoid designs in particular have low stray capacitive and magnetic losses compared to planar designs, as only the bottom windings occupy the areas of the substrate reducing the substrate capacitive effect. Also, high inductance density and quality factor can be achieved by increasing the number of turns with a relatively small increase in footprint area [6.12]. However, this increases R_{dc} . In this chapter, the thick resist process was integrated to realize a new solenoid inductor structure with low R_{dc} .

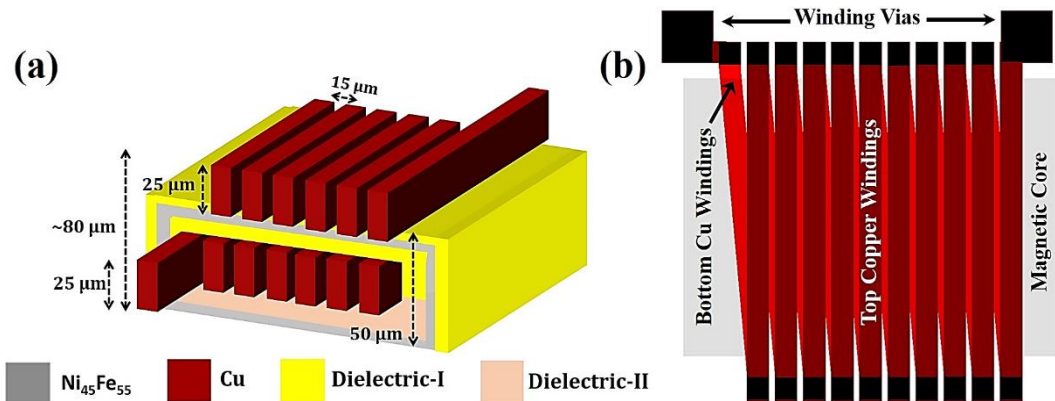


Figure 6.1 (a) Schematic illustration of the closed core micro-inductor cross-section and (b) top view of the mark layout depicting copper windings, Vias and the magnetic core.

The present work investigated the fabrication of solenoid inductors with closed magnetic cores (Figure 6.1). This approach has two advantages: firstly, the closed core further enhances the inductance density compared to the standard open magnetic core structure. Secondly, it is expected to have lower fringing magnetic field compared to the open magnetic core structure as the flux is well confined in the closed core. The fringing magnetic field of the open solenoid magnetic core device can cause serious

electro-magnetic interference with neighbouring circuitry. In this study, we present the first closed core solenoid micro-inductor device to be reported.

6.2. Modelling and Design

Figure 6.1 (a) and 6.1 (b) depict the schematic of the side and top view of the proposed closed core solenoid inductor device, respectively. An analytical model of the closed-core solenoid was developed and verified with Ansoft Maxwell FEM (2D and 3D) simulations which was validated by the fabricated device. Table 6.1 lists symbols used to represent the geometrical parameters of the device. The closed core solenoid structure is realized with double layer metal (DLM) processes, where the final winding was realized with a new high-aspect-ratio (HAR) and high resolution negative tone moulding photoresist process for the windings. It was found that the new design can be reliably designed and fabricated for power conversion applications for portable electronics.

Table 6.1: Geometrical parameters of the device.

Symbol	Description
L	Inductance of the micro-inductor
μ_o	Permeability in free space
μ_r	Relative permeability of the magnetic core
t_m	Thickness of the magnetic core
W_C	Width of the Cu windings
W_G	Gap between two successive Cu windings
$T_{D1,2}$	Thickness of dielectric-I and II
T_{Cu}	Thickness of Cu windings
B_{Sat}	Saturation flux density in the core
ρ_{Cu}	Resistivity of copper windings

The inductance (L) of the closed core inductor with ‘ N ’ number of turns is expressed as:

$$L = \frac{\mu_o \mu_r t_m N^2 \text{Corewidth}}{2(\text{Corelength} + T_{D1} + T_{D2})} \quad (6.1)$$

Where, the core-length and core-width can be calculated from the contribution from the winding width and gaps:

$$\text{Corelength} = (N + 1)W_C + W_G N \quad (6.2)$$

$$\text{Corewidth} = \frac{\text{Footprint}}{\text{Corelength}} - 2T_{Cu} - 2W_G \quad (6.3)$$

The core saturation flux density (B) for current ‘ I ’ is expressed as:

$$B_{Sat} = \frac{\mu_o \mu_r N I}{\text{Corelength}} \quad (6.4)$$

The DC resistance (DCR) of the device is given by:

$$R_{DC} = \frac{2 * \rho_{Cu} * N * (Corelength + 2W_G + t_m + T_{D1} + T_{D2} + T_{Cu})}{W_C * T_{Cu}} \quad (6.5)$$

These equations were solved in Wolfram Mathematica software suite. The solenoid inductor analytical design was validated with 2-D and 3-D Ansoft Maxwell finite element method (FEM) simulations.

6.2.1. Validation

Figure 6.2 (a) and 6.2 (b) shows the inductance variation with number of turns with insets depicting the calculated B_{Sat} at 100 mA. The core and winding geometries obtained from the analytical model have been used in the simulations. The parameters of the device is given in table 6.2. As observed from the figure, the analytical model developed and FEM simulations are well matched. The inductance curve asserts a squared dependence on the number of turns (N^2), also vindicated by the second order polynomial fit (Figure 6.2 (b)). The miniaturized 10 turn device investigated in this study has a $\sim 0.5 \text{ mm}^2$ footprint. This device gives a DC resistance of $0.147 \text{ } \Omega$ (Analytical) and $0.156 \text{ } \Omega$ (FEM simulated). The inductance obtained from the analytical model and FEM simulated are 39 nH (inductance density: 86.7 nH/mm^2) and 43.4 nH (Inductance density: 96.4 nH/mm^2), respectively. This difference in resistance from the analytical model could be attributed to the proximity between the windings in the FEM simulated model. It is important to note that, the device geometry plays a crucial role in its integration. The device core geometry has been kept symmetrical (device-length / device width ~ 1) to keep the influence of the core shape on anisotropy to a minimum. The permeability along the hard-axis is dependent on the anisotropy along the hard-axis. Keeping the shape of the core symmetrical gives a permeability of 280-300, as used in the designs.

Table 6.2: Specifications of the simulated device.

Parameter	Values
Winding Width	$50 \text{ } \mu\text{m}$
Winding Thickness	$25 \text{ } \mu\text{m}$
Winding Spacing	$15 \text{ } \mu\text{m}$
Core thickness	$3.5 \text{ } \mu\text{m}$
Footprint	0.5 mm^2

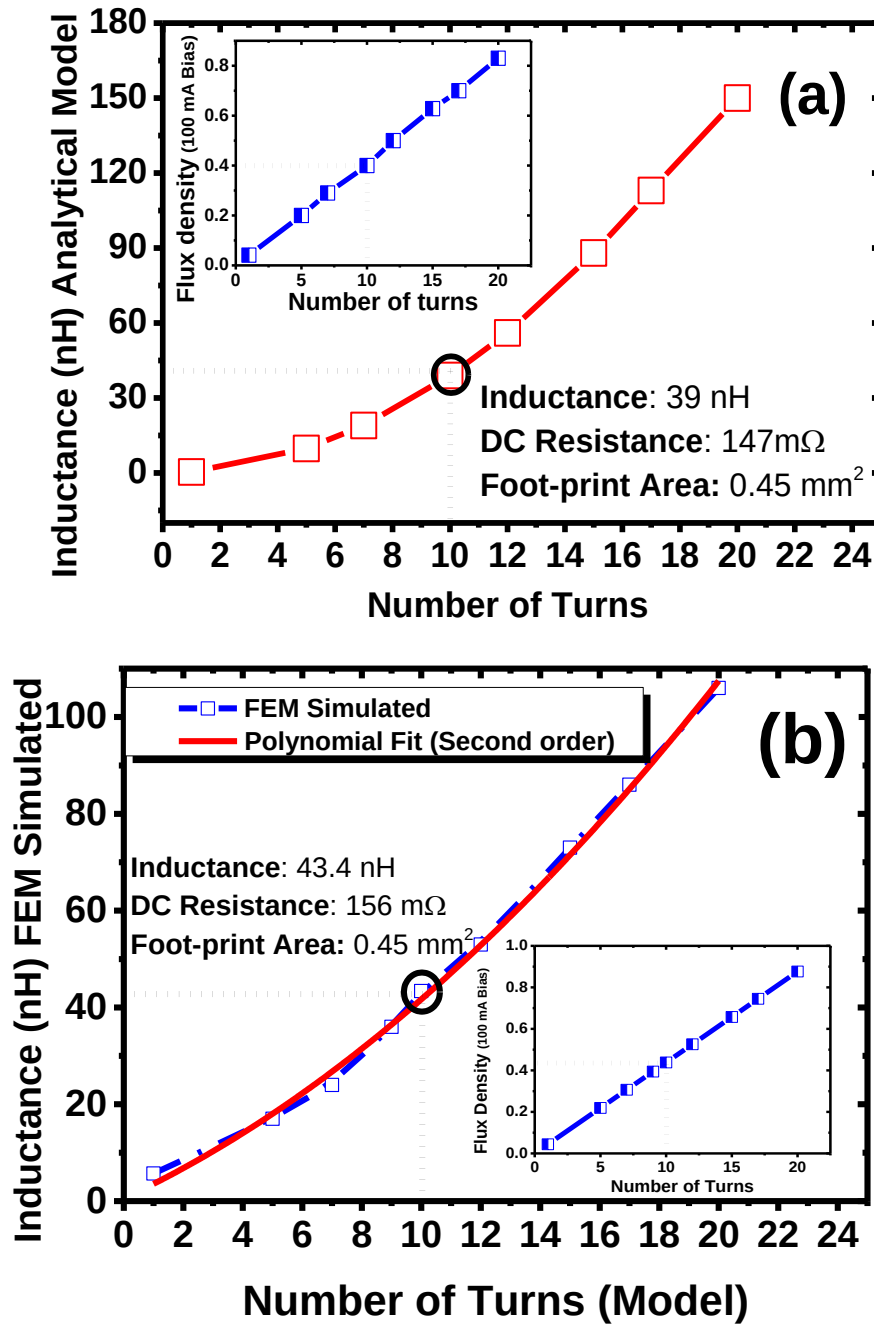


Figure 6.2. Validating (a) analytical model with (b) FEM simulated model of closed core solenoid inductors (0.5 mm²) for $W_C = 50 \mu\text{m}$ and $T_{Cu} = 25 \mu\text{m}$ with inset showing B_{Sat} variation with N .

Figure 6.3 (a) shows the winding width optimization curve for a constant 0.5 mm² footprint device in terms of DC resistance, device geometry and $\omega L / R_{dc}$ ratio (depicted in the inset) at 1 MHz. The winding width is gradually increased while keeping the device footprint constant (0.5 mm²). This is kept constant by varying device length / device width ratio. Also winding thickness of 50 μm for 10 turn

solenoid is kept fixed. This length / device width ratio of 1.13 has been selected as optimum as it gives a core permeability of 280. The inset shows device performance ($\omega L/R_{dc}$) at 1 MHz with the optimized winding width. Figure 6.3 (b) depicts the FEM investigation of winding resistance at high frequency for the optimized winding width ($\sim 50 \mu\text{m}$). As the frequency increases $> 1 \text{ MHz}$, there is significant increase in AC resistance which is attributed to the current crowding at the surface of the winding (skin effect and proximity effect $> 1 \text{ MHz}$) thereby reducing the effective cross-sectional area of the winding. It is to be noted that at high frequencies, core eddy losses also contribute to the overall device losses along with winding losses.

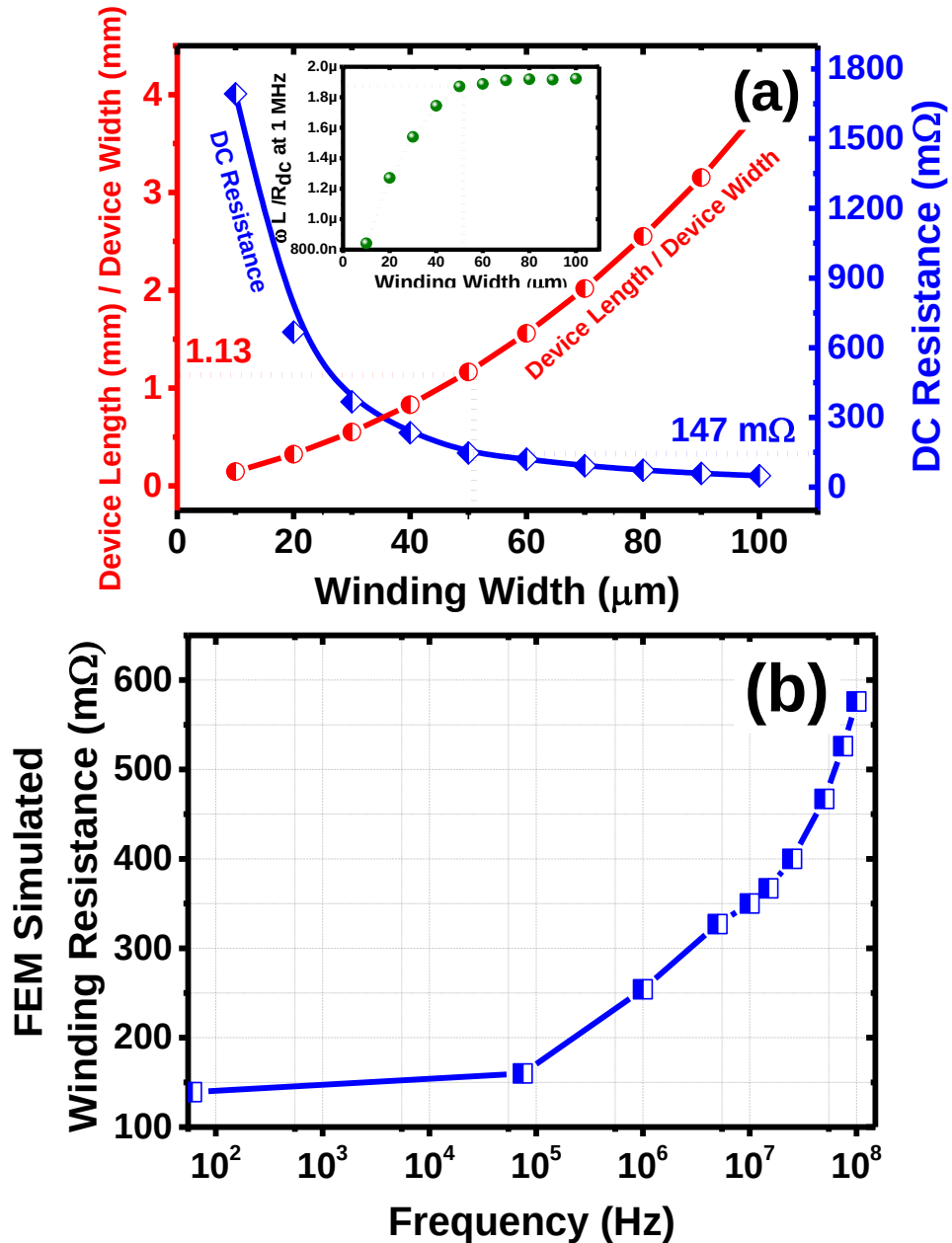


Figure 6.3. (a) Winding width optimization (analytical) curve for 0.5 mm^2 foot-print device in terms of DC resistance, device geometry and $\omega L/R_{dc}$ (depicted in the inset). (b) FEM simulated winding resistance with frequency for $W_C = 50 \mu\text{m}$ and $T_{Cu} = 25 \mu\text{m}$.

6.2.2. Comparison with open core

To understand the advantage of a closed core solenoid geometry over an open core, we FEM simulated the flux orientation in both designs. Figure 6.4 (a) and 6.4 (b) depicts the flux orientation at 30 MHz and 100 mA current bias. The open core design shows significant flux fringing, in the vertical direction. The closed magnetic path confines the magnetic flux within the core, unlike open core device, where there is substantial fringing flux at the open core edges. The fringing magnetic field of the open magnetic core solenoid device may cause electro-magnetic interference (EMI) to neighboring circuits. This could also increase losses within the conductive structures of the nearby circuits and devices. The flux fringing is significantly reduced on closing the magnetic path, as observed in closed core micro-inductors. The flux remains confined within the magnetic core, thereby reducing EMI losses and increasing inductance density.

The core flux density (B) at 100 mA and 30 MHz are shown in Figure 6.5 (c-d). As observed (Figure 6.4 (b) and 6.4 (d)), flux density is much higher at the top core compared to the bottom core. This is attributed to the flux directions (according to right-hand-rule) from the top and bottom current carrying windings converging at the top core. On the other hand, the flux fringing effect in the open core design (Figure 6.4 (a) and 6.4 (c)) reduces the flux density (Figure 6.4 (a)) thereby lowering flux density (~ 0.15 T). It is thus important to take into account the saturation flux density of the core material (1.5 T for $\text{Ni}_{45}\text{Fe}_{55}$) during the design. The peak magnetic flux density of the core should always be below 1.5 T.

The figure 6.5 shows the same device structure scaled down to 0.75 mm^2 footprint device simulated with Ansoft Maxwell 3D. As observed from the figure 6.5 (b), the core remains well below the saturation flux density ($B_{\text{Sat}} \sim 0.9$ T) for 500 mA current and at 30 MHz.

Most of the flux remains confined within the magnetic core which would reduce the EMI losses from compared to open core. However, reducing the EMI further would be a challenge considering the auxiliary field- H from the windings of the device could be cause of EMI with the circuitry around the region (figure. 6.6 (a) and 6.6 (b)).

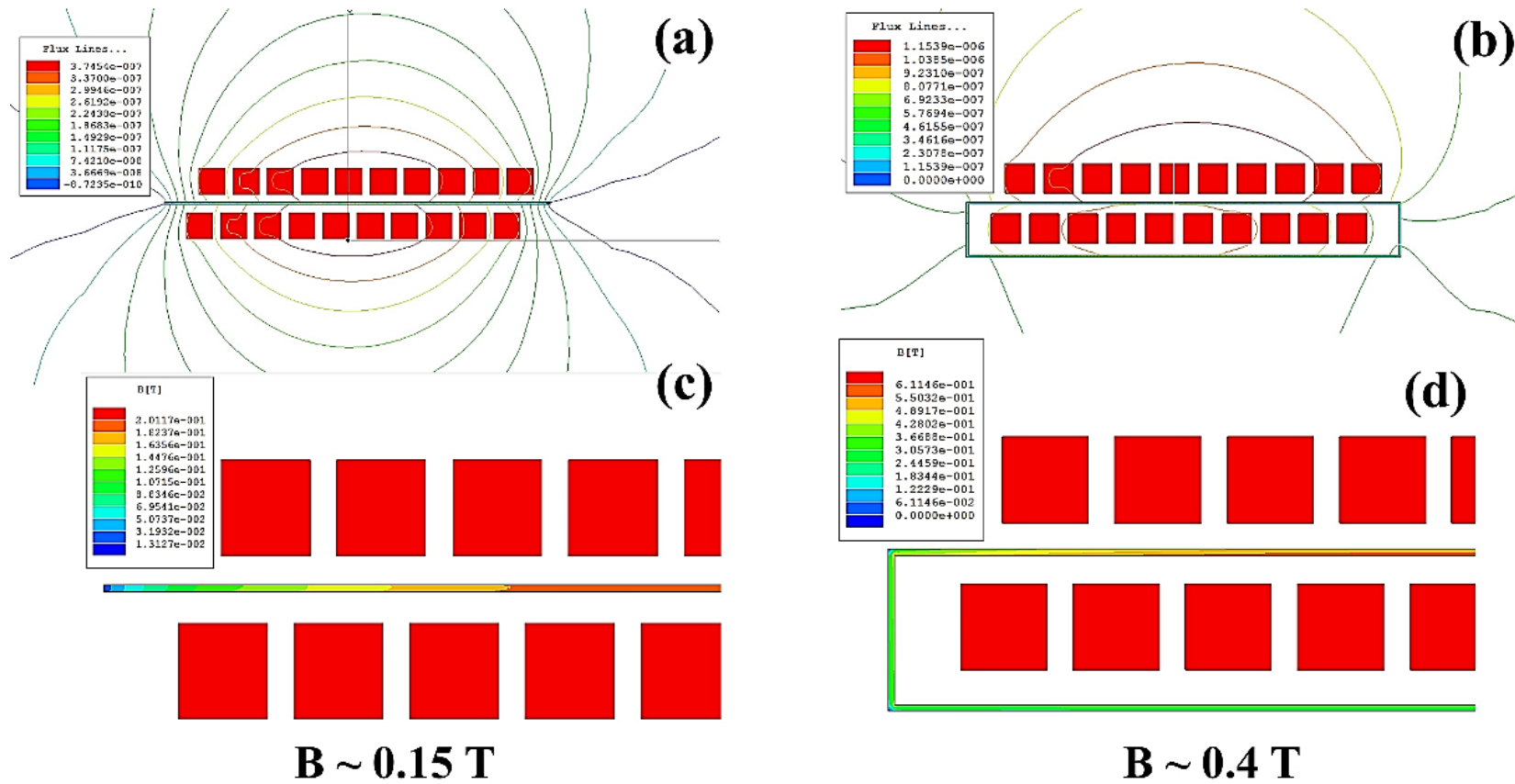


Figure 6.4 FEM (Ansoft Maxwell 2D) simulated: flux orientation in (a) open core (high flux fringing) and (b) closed core solenoid micro-inductors and zoomed in image of the flux density (c) open-core and (d) closed-core microinductors at 30 MHz.

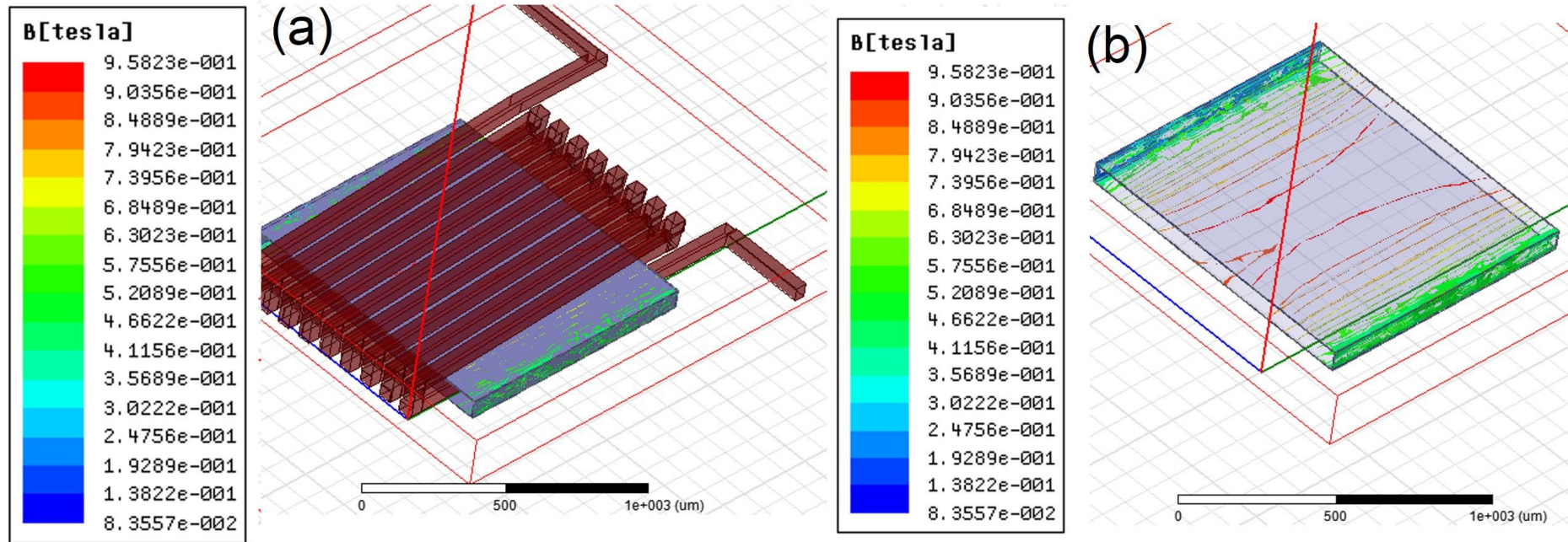


Figure 6.5. Ansoft Maxwell 3D simulated: (a) Closed core solenoid micro-inductor model (b) Core flux density (< 1 T) at 30 MHz (0.75 mm^2).

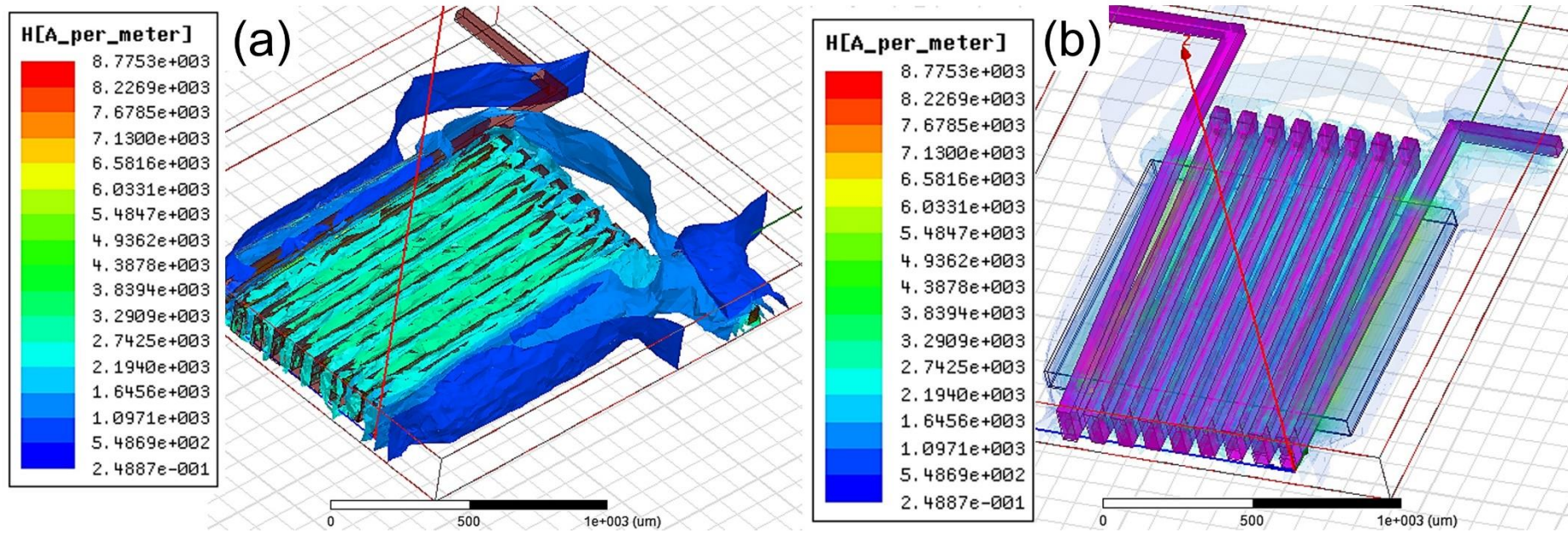


Figure 6.6 Ansoft Maxwell 3D simulated: H -field around the micro-inductor (a) without and (b) with the device winding structure at 30 MHz (0.75 mm^2).

Figure 6.7 (a) depicts the FEM comparison between 10 turn open and closed core solenoid micro-inductors with winding thickness, width and spacing of 15 μm , 25 μm and 50 μm . The simulations show a more than two fold increase in inductance density, with the same DC resistance and footprint (0.5 mm^2) when using a closed core design. This is because the closed magnetic core gives a closed flux path which increases flux density in the core and inductance density of the device. The high frequency response (Figure 6.7 (b)) of the closed core device shows uniform inductance up to 30 MHz for both FEM simulated and the analytical study of the device with a smaller device scaled up to 2 mm^2 footprint. The core thickness has been reduced in the analytical simulations above 30 MHz depending on the skin-depth to take into account the flux crowding at the core surfaces in real-case scenario. This results in sharp lowering of inductance at $> 30 \text{ MHz}$.

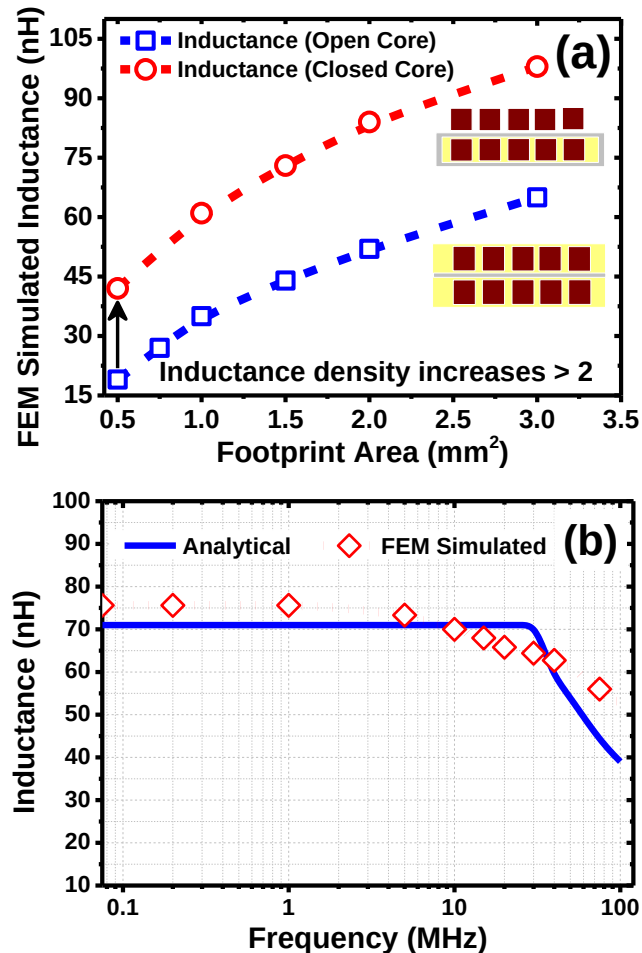


Figure 6.7 (a) FEM simulated inductance of open and closed core solenoid micro-inductors
 (b) Inductance vs frequency curve for FEM simulated and analytically developed model.
 (Assuming core-width = core-length; footprint area = 1.96 mm^2 ; $W_C = 50 \mu\text{m}$, $T_{Cu} = 25 \mu\text{m}$ and $N = 10$).

6.3. Micro-fabrication Process

6.3.1. Process Challenges

As discussed in the previous section, solenoid inductors have certain advantages over other designs (e.g. stripline, planar/spiral and toroid). Furthermore, a closed core design has higher inductance density compared to an open core solenoid design. However, the foremost challenge in the micro-fabrication of the closed core design comes from the realizing the top windings. As observed from the Figure 6.8, to fabricate top windings, thick ($> 80 \mu\text{m}$) photoresist process is needed. This resist should be thicker than the SU-8 polymer (inter-metal dielectric) as shown in the figure 6.8 (a) and should be removed after plating the windings. In *Chapter 3*, a new thick ($\sim 85 \mu\text{m}$) and high-aspect-ratio photoresist (17:1) has been developed with THB-151N photoresist for plating Cu windings with low DC resistance. This process has been integrated to realize the top windings in the closed core inductor.

Table 6.3 reviews the fabrication process of reported solenoid micro-inductors with CMOS compatible processes. The reported magnetic core solenoid micro-inductors have an open core [6.11-6.14, 6.18 and 6.21-6.22]. The maximum winding thickness achieved so far has been $80 \mu\text{m}$ thick [6.14, 6.21].

The next section, will focus on the MEMS based micro-fabrication process to realize the designs discussed in section 6.2 and develop the *first reported closed-core solenoid micro-inductor prototype*.

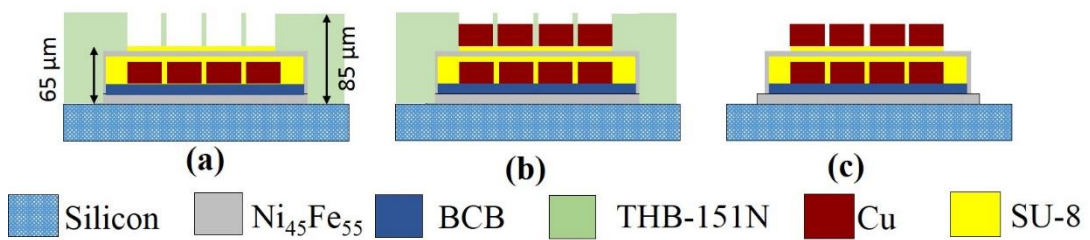


Figure 6.8. Schematic of the closed core solenoid inductor cross-section. (a) $85 \mu\text{m}$ thick photoresist process (b) Top Cu windings electroplated and (c) The temporary photoresist is removal.

Table 6.3: Technology review of reported solenoid micro-inductors*'-' indicates data not reported*

Author	University	L (nH)	N	Substrate	Core Type	Core Material	Core Deposition	Area (mm ²)	Metal Moulding Resist	Windings Thickness and Spacing (μm)
This work	Tyndall	54	10	Silicon	Magnetic	Ni₄₅Fe₅₅	Electroplated	0.75	THB-151N	15-25
[6.9] Sarkar et. al. (2005)	Univ. of Waterloo	10-40	10	Pyrex glass	Magnetic	Ni ₈₁ Fe ₁₉ and Co _{83.2} B _{3.3} Si _{5.9} Mn _{7.6}	Composite with Magnetic nanoparticles	-	SU-8	-
[6.10] Yoon et.al., (1999)	KAIST	2.67, 2.4	6	Silicon & glass	Air-core	-	-	-	-	10 and 20
[6.11] Ahn et. al. (1993)	Georgia Inst. Tech.	200	17, 26	Silicon	Magnetic	Ni ₈₁ Fe ₁₉	Electroplated	-	Polyimide	-
[6.12] Kim et. al. (1998)	Georgia Inst. Tech.	2-20	-	Alumina	Air-core	-	-	-	Polyimide	20 and 50
[6.13] Park e. al. (1999)	Georgia Inst. Tech	600- 1800	14- 32	Silicon	Magnetic	Ni ₈₁ Fe ₁₉ and NiFeMo	Electroplated	1.65- 3.36	SJR 5740	15 and 20
[6.14] Yoon et. al. (1998)	KAIST	2.5, 10	20, 80	Silicon	Magnetic	Ni ₈₁ Fe ₁₉	Electroplated	-	AZ 9262	80 (Thickness)
[6.15] Yoon et. al. (2001)	Georgia Inst. Tech.	2.5, 10	20, 80	Silicon	Air-core	-	-	-	NR9-8000	20 and 80

Author	University	L (nH)	N	Substrate	Core Type	Core Material	Core Deposition	Area (mm ²)	Metal Moulding Resist	Windings Thickness and Spacing (μm)
[6.16] Yoon et. al. (2002)	KAIST	1.17	6	Silicon	Air-core	-	-	-	SU-8	-
[6.17] Lin et. al. (2005)	National Cheng-Kung University	2.5	20	Silicon	Air-core	-	-	0.160	-	0.18 μm (TiW-Al-TiW)
[6.18] Lee et. al. (2008)	Stanford	70	8.5	Silicon	Magnetic	CoZrTa	Sputtered	< 1	Polyimide PI-2611	72 and 24
[6.19] Kim et. al. (2008)	Namseoul University	1-4	7, 12	Silicon	Air-core	-	Sputtered	0.4	-	27 (Thickness)
[6.20] Fang et. al. (2007)	Shanghai Jiao Tong University	1.78	7	Silicon	Air-core	-	-	0.305	AZ P4903	45 and 50
[6.21] Park et. al. (2003)	Georgia Inst. Tech.	2300	-	Silicon	Magnetic	Ni	Electroplated	-	AZ 9262	80 (Thickness)
[6.22] Ahn et. al. (1998)	Georgia Inst. Tech.	400	33	Silicon	Magnetic	NiFe	Electroplated	-	-	-

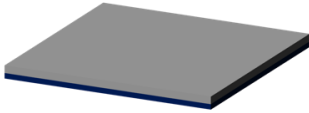
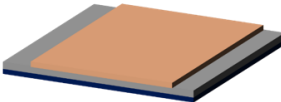
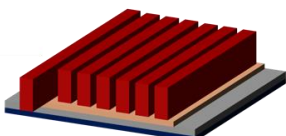
6.3.2. Closed Core Solenoid Fabrication Process

Table-6.4 lists the specifications of the fabricated device and the properties of the materials used for the analytical and FEM simulations. The device fabrication steps are listed sequentially in table-6.5.

Table 6.4- Device parameters

Parameters	Values
Magnetic Material	Ni-Fe (45/55)
Thickness	3.5 μm
Resistivity	47 $\mu\text{Ohm-cm}$
Permeability	280
Coercivity	39 A/m
Saturation flux density	1.5 T
Winding Material	Copper
Winding Resistivity	1.7 $\mu\text{Ohm-cm}$
Thickness (Via)	35 μm
Winding spacing	20 μm
Winding thickness	15 μm and 30 μm
Winding width	53 μm
Dielectric-I thickness	$\sim 10\mu\text{m}$
Dielectric-II thickness	35 μm and 55 μm

Table 6.5: 3-D Closed core solenoid fabrication process steps

Process Schematic	Process Steps
 Bottom core electroplated	- P-type silicon wafers with (100) orientation are thermally oxidized to grow 1 μm thick SiO_2. - Zero-levels are plasma etched (5 μm deep in Si) through OiR 908-35 photoresist. - Ti (20 nm) and $\text{Ni}_{81}\text{Fe}_{19}$ (200 nm) seed is sputter deposited. - $\text{Ni}_{45}\text{Fe}_{55}$ is electroplated to realize the bottom magnetic core.
 Dielectric-I spin-coated and patterned	- 9 μm thick AZ 9260 photoresist is spin coated as etch mask. - The electroplated $\text{Ni}_{45}\text{Fe}_{55}$ from exposed areas is wet-etched and AZ9260 is removed. - BCB is spin coated, exposed and developed to form the inter-layer dielectric/Dielectric-I ($\sim 12 \mu\text{m}$).
 Bottom Cu windings electroplated	- Ti (20 nm) and Cu (200 nm) seed is sputtered. - 35 μm thick AZ9260 is spin coated and developed as metal moulding photoresist. - Cu is electroplated (15 μm) in an automated Cu electroplating system.

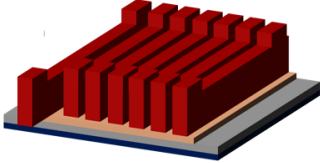
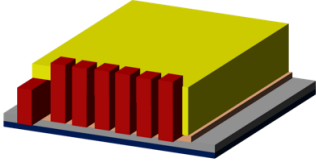
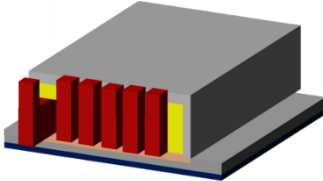
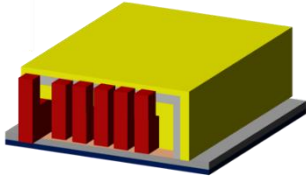
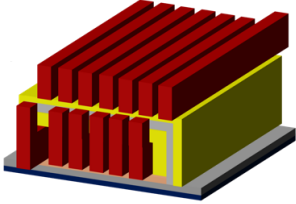
 Cu Via electroplated	- The AZ9260 photoresist is removed. - The seed is not etched. - A multiple spin AZ9260 photoresist (38 μm thick) is spin coated, exposed and developed to form the metal moulds for the vias. - Vias are electroplated in an automated Cu electroplating system. - Ti / Cu seed is wet-etched.
 Dielectric-II spin coated and patterned	- SU-8 is spin coated, exposed and developed to form the inter-metal dielectric (dielectric-II) - This photoresist remains as a permanent structure for isolating the top and bottom windings and cores.
 Top Core electroplated	- The Ti (20 nm) / $\text{Ni}_{81}\text{Fe}_{19}$ (200 nm) is sputter blank deposited for the deposition of top winding. - The top $\text{Ni}_{45}\text{Fe}_{55}$ magnetic core is electroplated covering all of the wafer. - The magnetic layer is electroplated in external magnetic field to induce anisotropy in the film.
 Top Core Patterned through Dielectric-II	- A second layer of dielectric (SU-8) is spin coated-exposed and developed. - This SU-8 pattern acts as core wet-etch mask for the top core. - The top core $\text{Ni}_{45}\text{Fe}_{55}$ is wet-etched completely from exposed regions. - The SU-8 remains as inter-metal dielectric, isolating the top winding from the top core.
 Top Cu windings electroplated	- The new THB-151N photoresist process is assimilated to form the metal moulding process for plating the top Cu windings. - Ti (20 nm) / Cu (200nm) seed is sputter deposited. - Negative-tone THB-151N photoresist ($\sim 90 \mu\text{m}$) is spin-coated, exposed and developed. - The top Cu windings are electroplated in automated Cu plating system to realise the close windings. - The Ti / Cu seed is wet-etched.

Figure 6.9 (a) shows the microscopic image of the bottom winding deposited on ILD with exposed bottom-core feet. The bottom windings are isolated with IMD and copper vias are electroplated. Figure 6.9 (b) and 6.9 (c) depict the top core etched and dielectric deposited prior to top winding deposition. The Cu winding deposition process in the automated plating system is given in appendix-I.

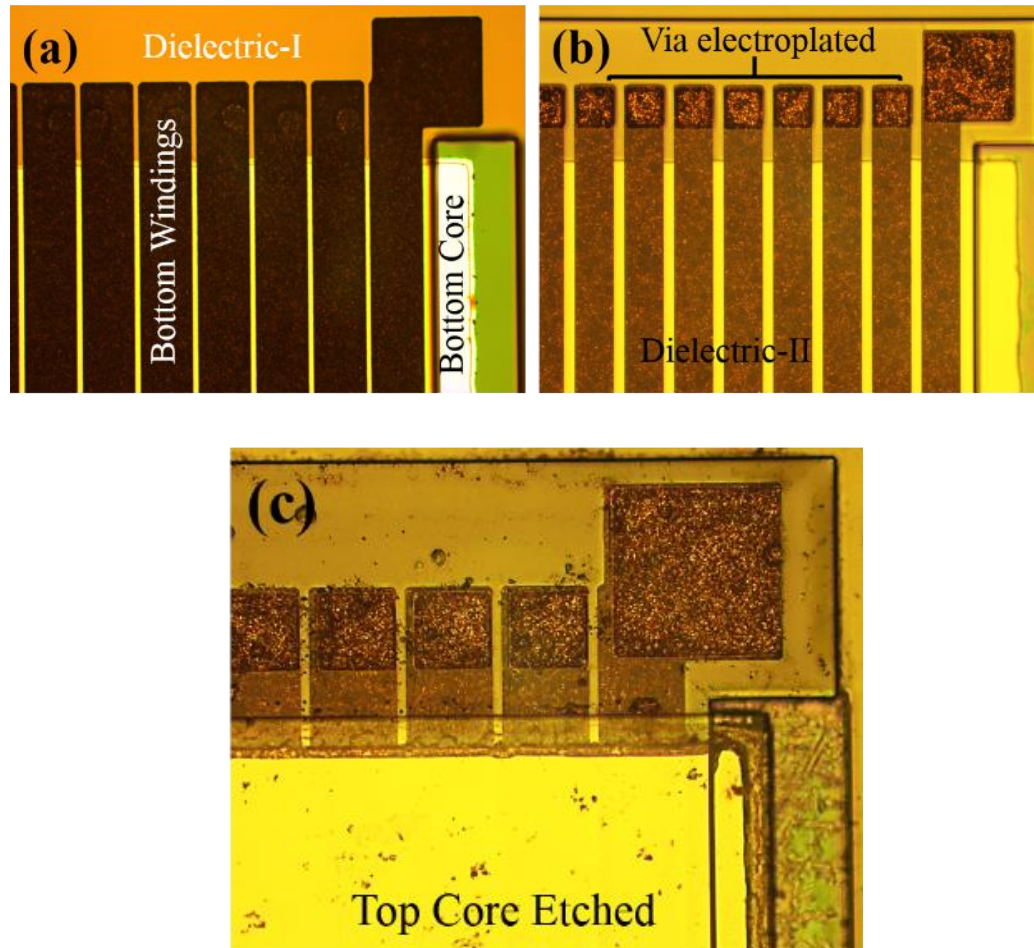


Figure 6.9 Microscopic images of (a) bottom windings on BCB. (b) Electroplated copper via and (c) Top core electroplated and top windings isolating SU-8 layer.

The top windings were realized with $\sim 85 \mu\text{m}$ thick HAR THB-151N photoresist process as developed in Chapter 3 [6.12]. Figure 6.10 (a-c) show the SEM images of patterned photoresist process depicting 0.75 mm^2 device along with $\sim 2 \text{ mm}^2$ winding patterns. The resist pattern was electroplated in the automated Cu plating system (Digital Matrix SA/1b), as shown in Figure 6.10 (d-e).

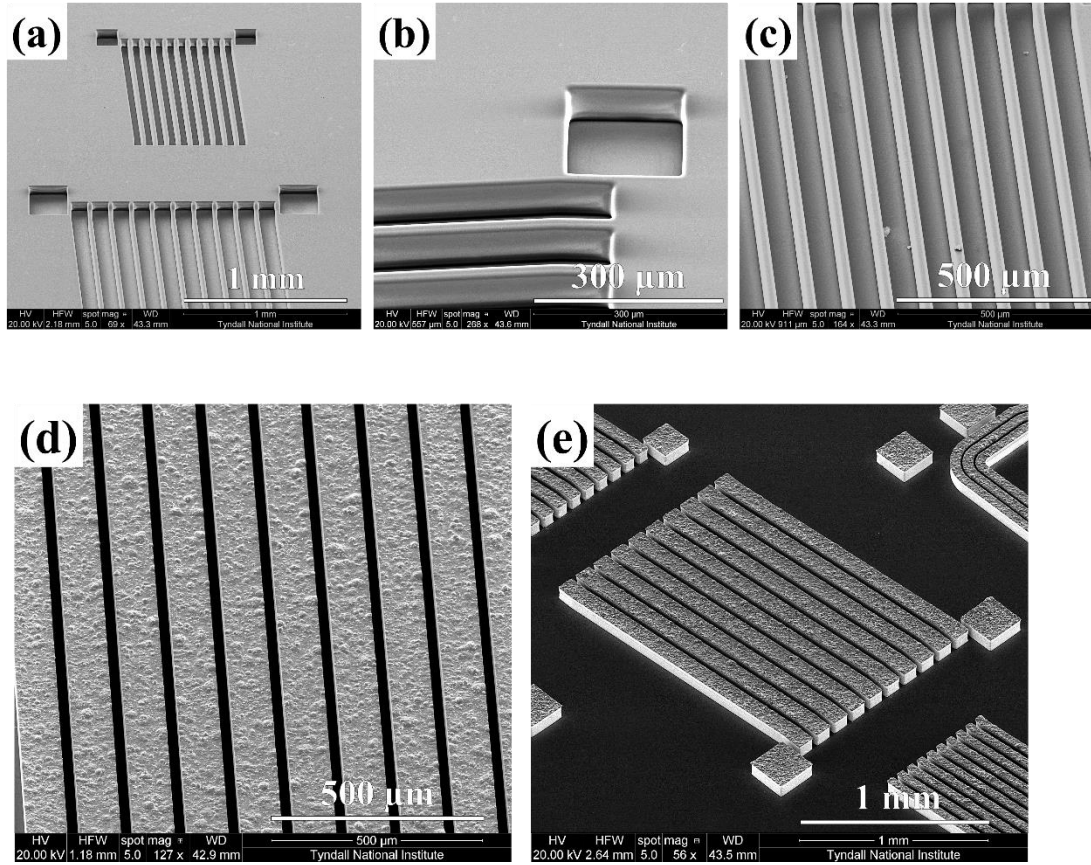


Figure 6.10. (a-c) The metal moulding photoresist for electroplating thick Cu windings. (d-e) Electroplated Cu windings demonstrating thick Cu micro-structures.

Figure 6.11 (a) and 6.11 (b) show the SEM images of the device after the electroplating the via. The bottom and the top windings were completely isolated from the top core. The via is electroplated through the metal moulding resist (AZ 9260) and exposed through SU-8 photoresist. The exposed vias act as connect to the top windings during plating of top winding plating.

As observed from the figure 6.11 (a), the core-feet of the bottom cores were exposed forms the closed core structure when the top core was electroplated. The measured exposed core-feet was 142 μm wide. This image corresponds to the ‘dielectric-II spin coating and patterned’ step in Table 6.5. It is essential to etch the bottom windings thoroughly before proceeding with top core plating to ensure no shorting of the windings with the core.

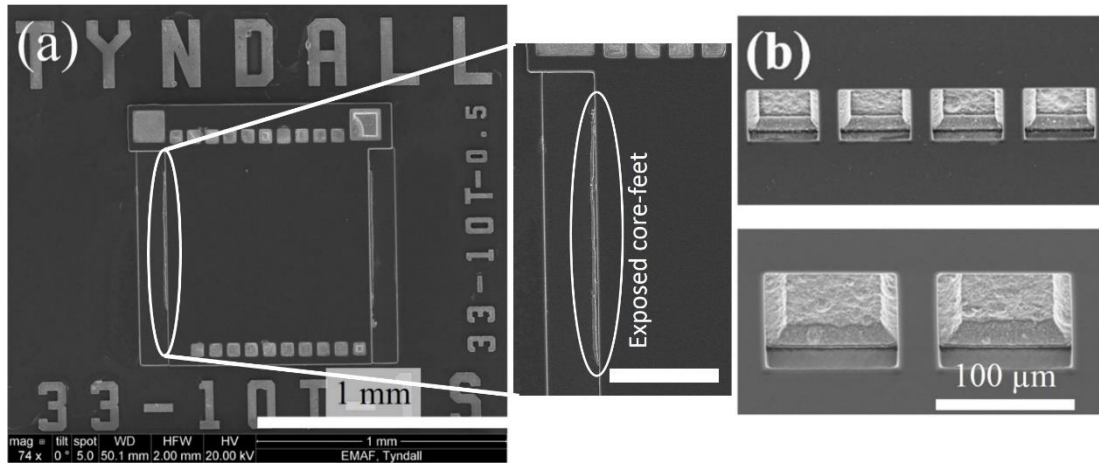


Figure 6.11 (a) Device top view before electroplating the top windings. (b) The exposed vias which connect to the top winding.

Figure 6.12 (a) and 6.12 (b) show 3D X-ray images (Nordson Dage, XD7600NT) of the 0.75 mm^2 complete winding pattern and cross-section, respectively. As observed from the figure, the top and bottom windings are well connected through the Cu via. The images reveal no shorting between the winding patterns and indicates a clean Cu deposition. It is important to note that the background noise distorted the images when thin $\text{Ni}_{45}\text{Fe}_{55}$ core was detected; hence, the core was eliminated to avoid background noise during post-analysis.

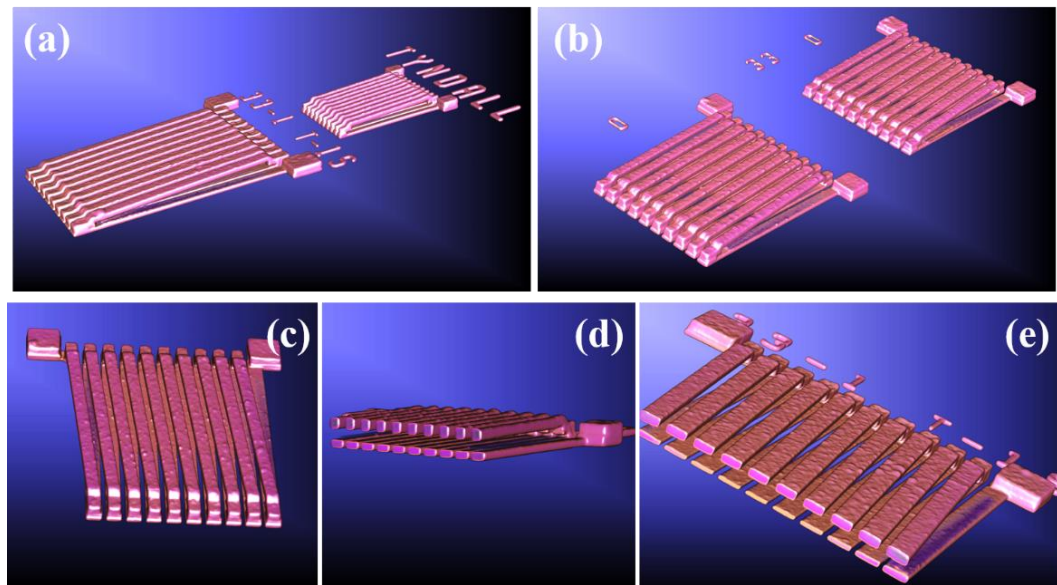


Figure 6.12 3D X-ray images of fabricated (a-c) double metal layer coils of the devices (d-e) cross-section of the electroplated Cu coils for process check.

Process observation and improvements

The fabricated devices were observed under the SEM to check the process outcomes. One of the challenges involved via isolation from the top core while electroplating (Figure 6.13 (a)). Although the SU-8 dielectric layer isolates the core from the via, in the case of insufficient etching, the electroplated top core was seen to have shorted with the via. The connected the via electrically as observed in Figure 6.13 (b). This issue was detected by measuring the resistances between the top winding and the top core. This was eliminated by increasing the top core etch time, which confirmed that the cores remained completely isolated from the via. This kept the via isolated from each other.

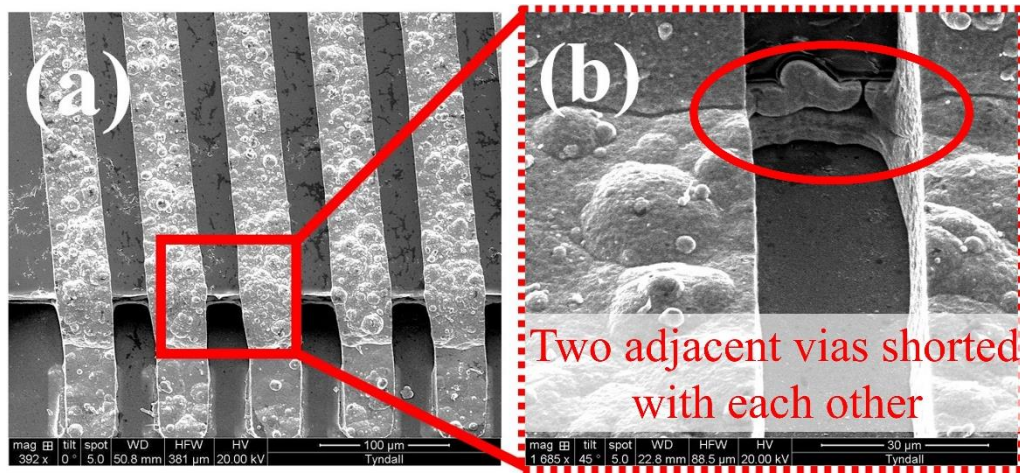


Figure 6.13 Shorting of core with top windings (a) The via are connected to each other with the top-core (b) Electroplated top core connect the two adjacent vias.

Figure 6.14 (a) and 6.14 (b) shows the SEM images of the device with electroplated top windings. The top winding were uniformly deposited with $\pm 1.3 \mu\text{m}$ variation in thickness across the wafer (measured with surface profiler). A contact resistance of $\sim 0.2 \Omega$ is measured which confirmed that the vias are well connected with top windings. The dielectric-I isolates the top windings from the top core.

Figure 6.14 (c) shows the cross-sectional area of the micro-fabricated closed core micro-inductor. The inset shows the device parameters measured with SEM. The top winding gaps are increased to $25 \mu\text{m}$ to ensure the HAR photoresist is well exposed and stripped. The core thickness of $\sim 3.5 \mu\text{m}$ is in accordance to the design. In this process, the over-etch observed with sputtered seed, as investigated in Chapter 5 has been compensated by keeping the core-feets $\sim 200 \mu\text{m}$ wide.

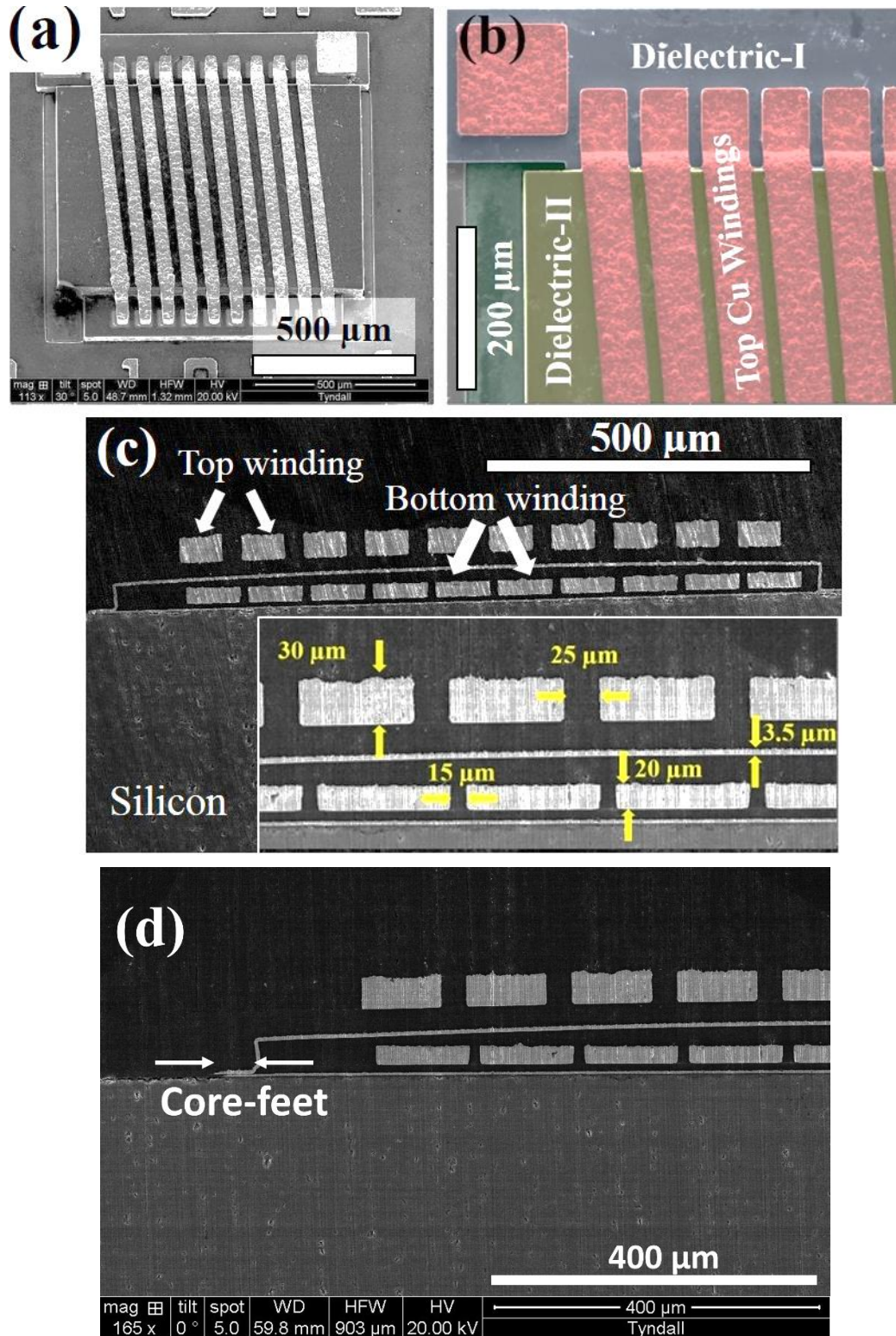


Figure 6.14 (a) SEM images of 10 turn micro-fabricated micro-inductors. (b) Colour differential SEM image depicting the top windings along with dielectric-I and dielectric-II. (c) Cross-sectional image of a closed core solenoid device ($\sim 1.75 \text{ mm}^2$ design) with inset showing the device specifications (d) The core-feet of the closed-core solenoid inductor.

6.4. Device Characterization

The small-signal inductance measurement of the 5 fabricated devices with a footprint of 0.75 mm^2 were performed with a HP 4285 LCR meter (75 KHz-30 MHz). The measured frequency response (Figure 6.15) was compared with analytical and FEM simulated designs with the same device geometry and material specifications as listed in table 6.4. As observed, the measured inductance shows a uniform response up to 20 MHz and starts to fall off $> 30 \text{ MHz}$. The analytical and FEM simulations suggest initial inductances of $\sim 48 \text{ nH}$ and 51 nH respectively. The measured device shows $\sim 12.5 \%$ increase (54 nH) compared to simulated designs. The fabricated core shape induces shape anisotropy. The increases the relative permeability along the hard-axis to ~ 400 . This is reflected in the increase in measured inductance compared to the designed and analytically simulated model. The shape of the core also reduces anisotropy field along the hard-axis ($\sim 560 \text{ A/m}$) as compared to $> 720 \text{ A/m}$. This results in the drop in inductance $> 20 \text{ MHz}$ compared to FEM and analytical simulated models.

Figure 6.16 shows the DC saturation characteristics of the inductor. As the DC current increases above 500 mA , the core starts to saturate. As a result, the core gradually behaves like an air-core, resulting in a gradual fall in inductance. Compared to the simulated open core device, the lower reluctance of closed core 3-D structure decreases the saturation current. This limitation could be overcome by introducing a high saturation flux density ($> 2 \text{ T}$) core material, such as $\text{Co}_{35}\text{Fe}_{65}$ (2.45 T) [6.30-6.31].

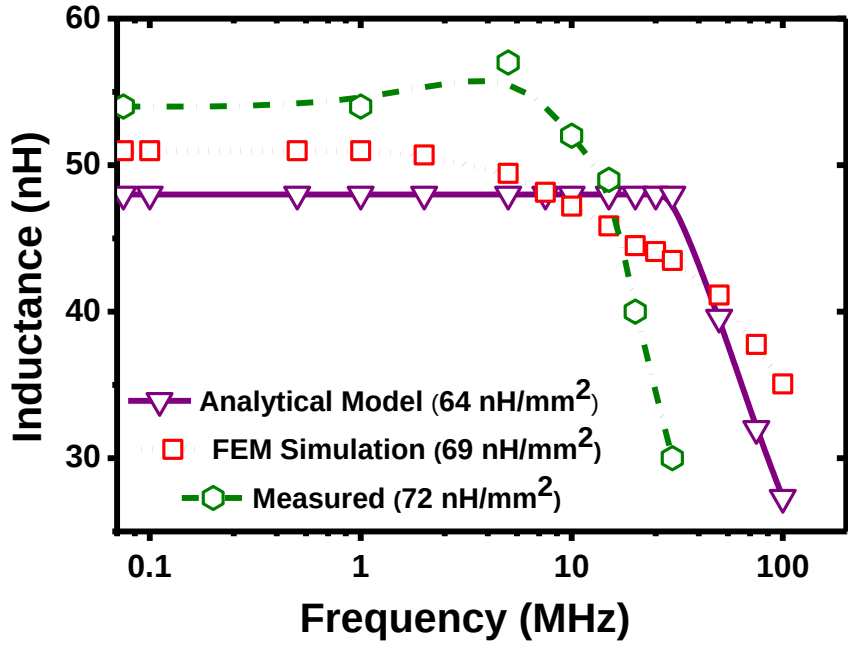


Figure 6.15 Inductance vs Frequency of the designed and measured device.

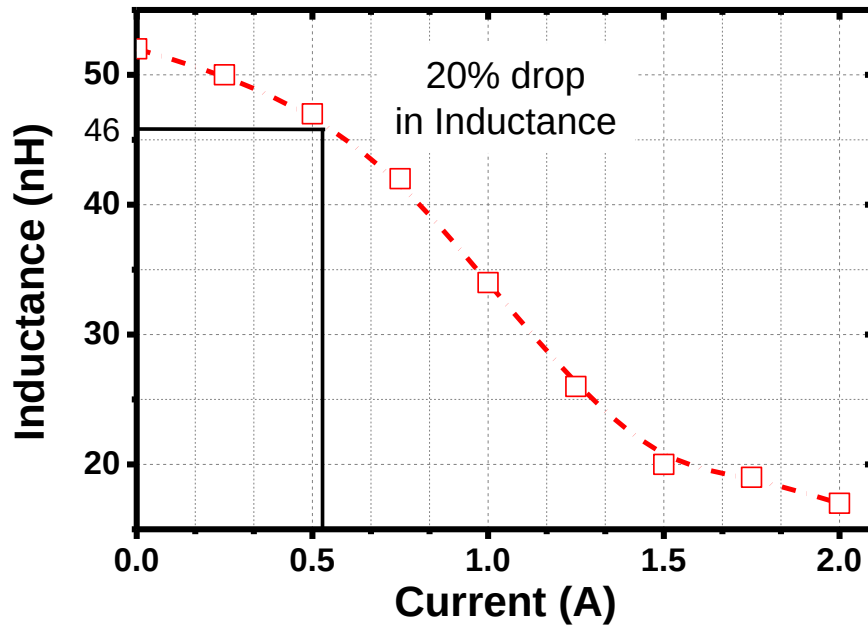
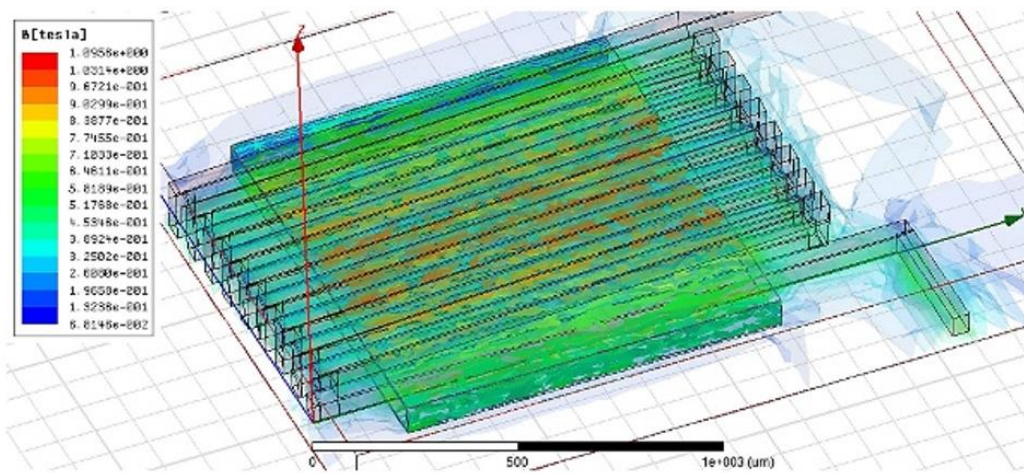


Figure 6.16 Measured DC saturation current characteristics of the device.

This was verified with 3D Ansoft Maxwell analysis at 30 MHz and varying currents from 0.5 A to 3.0 A. The central region shows the regions with peak flux density. This is because the winding density at the centre of the core is greater than the edges. The core flux density gradually decreases with current and reaches below the $\text{Ni}_{45}\text{Fe}_{55}$ saturation flux density (1.5 T) where the peak flux density is 1.02 T for ~ 500 mA of current at 30 MHz (Figure 6.17 (d)). Hence, the core at ~ 500 mA is well below (at $\sim$

1.1 T) its peak saturation flux density of 1.5 T and is the saturation current of the device. This confirms the measured DC saturation current characteristics.

Figure 6.18 (a) and (b) shows the core flux density direction and gradient at 500 mA and 30 MHz. The flux directions converge at the top core, where the dense windings are present. The flux density in this region is ~ 0.96 T. At the edges of the core, the flux density drops sharply. The flux density in this region is ~ 0.55 T. Figure 6.19 shows the Q-value and resistance measured up to 30 MHz. The device has a peak Q-value of 9.82 at 15 MHz. Compared to simulated DC resistance of ~ 196 m Ω , the measured DC resistance of the device is ~ 220 m Ω . Further optimization in terms of core design and laminations could increase the device Q-value further by at least two times.



1.02 T

Figure 6.17 Ansoft Maxwell 3D analysis of peak core flux density of 1 T at 30 MHz. for 0.5.

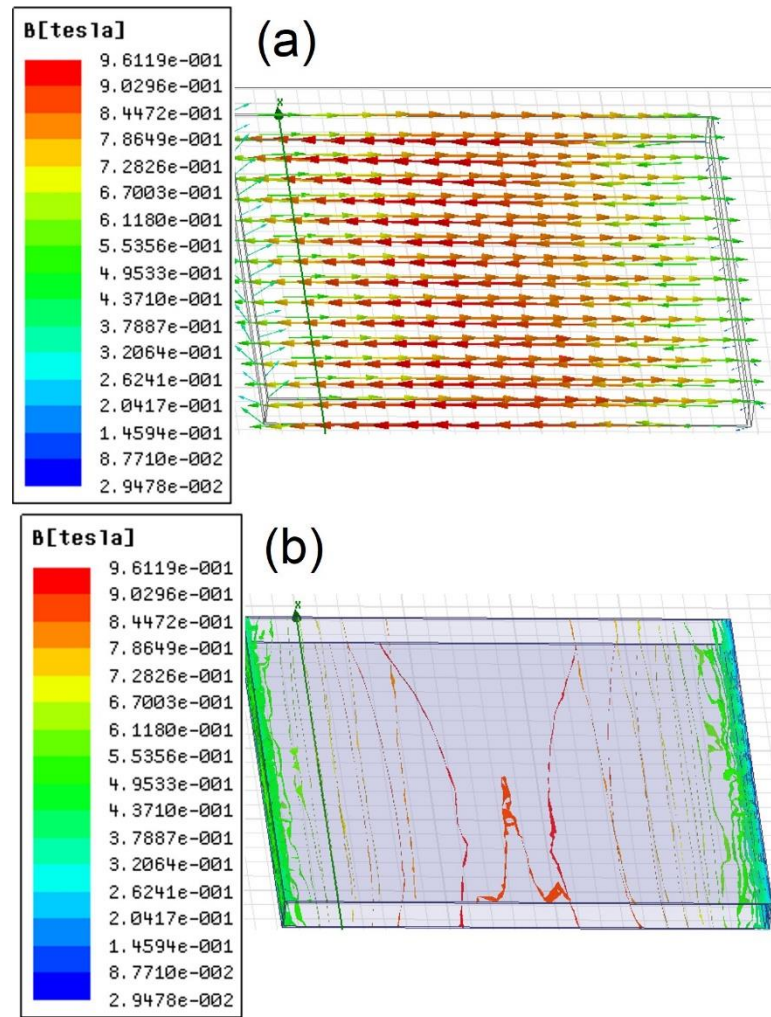


Figure 6.18 Ansoft Maxwell 3D analysis of the (a) flux direction and (b) Core flux density (~ 1.1 T) at 30 MHz and 500 mA curve.

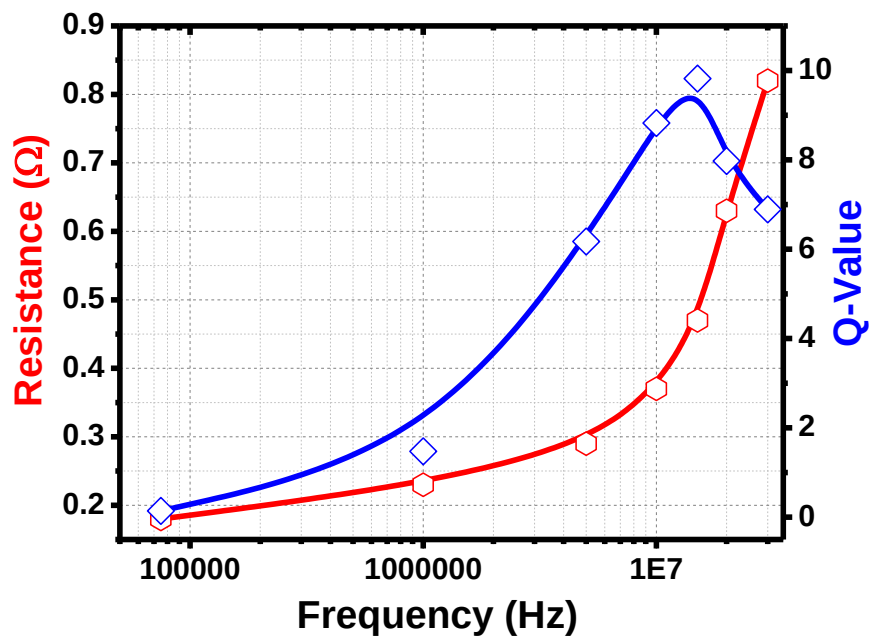


Figure 6.19 Q-values and winding resistance of the device with frequency.

6.5. Comparison with Air-core, open-core solenoid device and SoA

Closed-core inductor has a higher inductance density compared to open and air-core device. Figure 6.20 depicts a graphical comparison between the simulated air-core, open core and closed core inductors in terms of inductance and inductance density. The design parameters are listed before in Table 6.4. Compared to the air-core design (3.2 nH), the open core has an inductance density ~ 27 nH. This is an enhancement by a factor of 8.4 from 4.2 nH of the air-core design. Compared to air-core and open core design, inductance can be further increased by a factor of 12.4 and 1.95 respectively, with the closed core design. The inductance densities for the air-core, open-core and closed core designs are 5.6 nH/mm², 36 nH/mm² and 68 nH/mm² respectively. In the fabricated closed-core design, an inductance density of 72 nH/mm² is achieved. Although there is additional complexity and cost involved in the fabrication of closed core solenoid inductors compared to air-core and open core solenoid inductors, the high inductance density in small footprint makes it worthwhile as an alternative to traditional solenoid inductors.

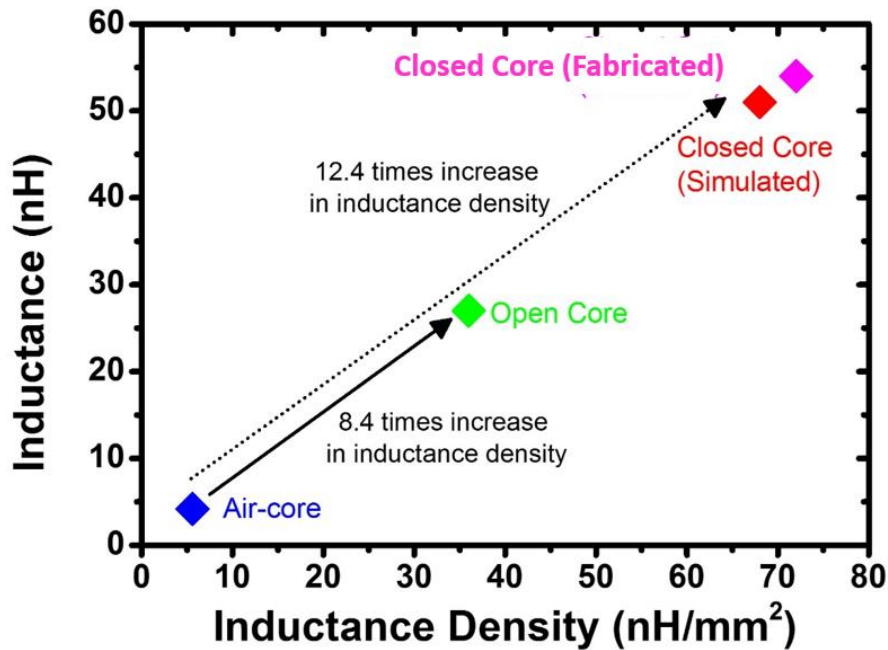


Figure 6.20 Inductance density and inductance comparison between air-core, open-core and closed core designs.

In comparison to solenoid microinductors reported in the literature (Figure 6.21 (a) and 6.21 (b)), the device reported in this chapter is one of the highest inductance densities below 1 mm² footprint with adequate saturation current (> 0.5 A) for low power applications. Park et. al. [6.13] and Ahn et.al. [6.22] have shown higher

inductance densities with laminated core but with footprints $> 2 \text{ mm}^2$. Lee et. al. [6.18] have reported the highest inductance density ($\sim 80 \text{ nH/mm}^2$) and L/R_{dc} below 1 mm^2 footprint. This is attributed to the high relative permeability (~ 600) and saturation flux density ($\sim 2 \text{ T}$) of the CoZrTa was used as the magnetic core material in the open core solenoid design. The future work will involve further design optimization, inclusion of ultra-low loss and high saturation core materials and laminations to increase the inductance density ($> 100 \text{ nH/mm}^2$) frequency of operation $> 30 \text{ MHz}$.

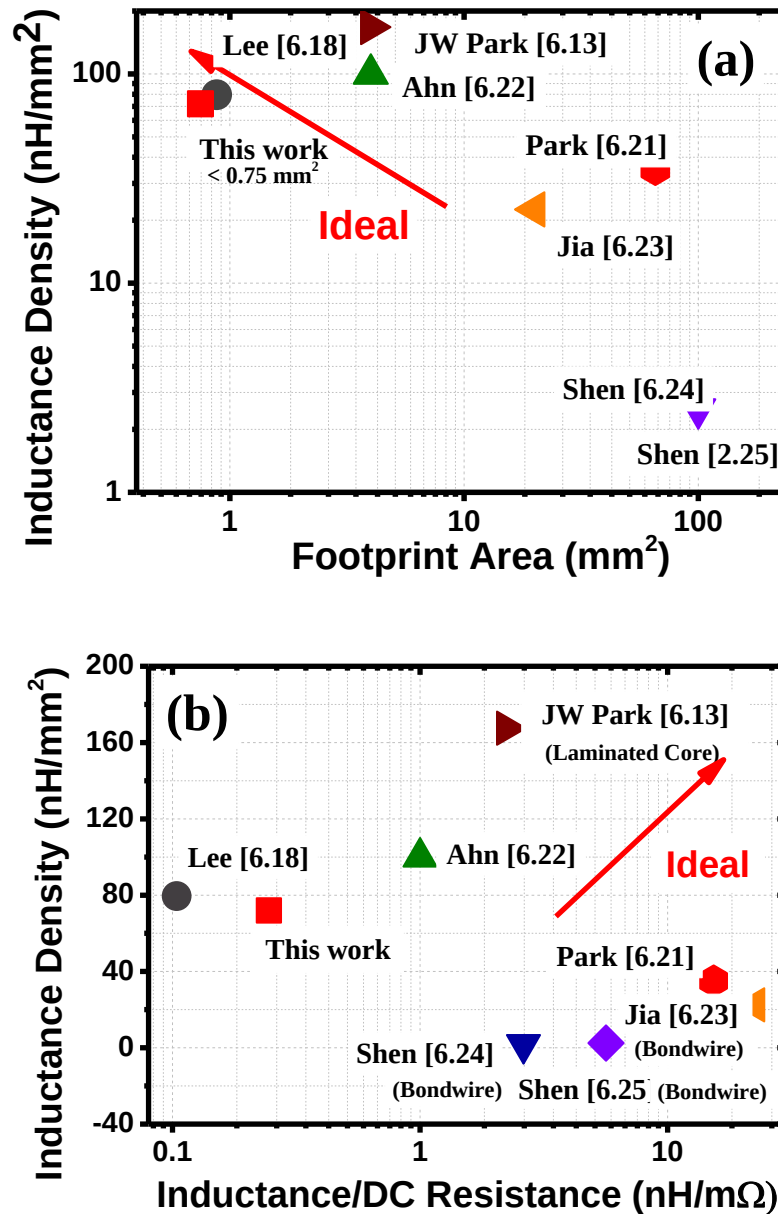


Figure 6.21 Solenoid inductors: State of the art. (a) Inductance density vs Inductance / DCR. (b) Inductance density vs device footprint area.

6.6. Conclusion

In this Chapter, first closed-core solenoid inductor has been FEM simulated, analytically designed and micro-fabricated on silicon. In the first section, a closed core inductor model has been mathematically. The developed analytical model are match well with the FEM simulated results. The analytical simulation of the device has an inductance of ~ 39 nH and a DC resistance of 147 m Ω . This is in close match with FEM simulated device, which has inductance of 43.4 nH and DC resistance of 156 m Ω . The FEM simulations of the closed core inductor has demonstrated higher flux confinement in the core compared to open-core inductor.

Based on the developed analytical model, a closed-core inductance device with a footprint of 0.75 mm² were realized by integrating a thick photoresist process developed in *Chapter 3*. The Ni₄₅Fe₅₅ closed core were realized by in-house developed electroplating process. The closed core design suggested nearly two-fold increase in inductance density (72 nH/mm²) in comparison to an open core design (36 nH/mm²). The fabricated closed core micro-inductor has inductance of 54 nH, DC resistance of 220 m Ω , saturation current of ~ 500 mA and a Q-value of 9.82 at 15 MHz. The simulated device has an inductance of 51 nH and DC resistance of 196 m Ω . The core has demonstrated a peak flux density of 1.02 T at 500 mA and 30 MHz. This value of flux density is below the saturation flux density (1.5 T) of the core material. This miniaturized and high inductance device would be ideal for integration with power management ICs for high-frequency power conversion applications.

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Chapter 7

Summary and Future Work

7.1. Summary

This thesis focused on development of micro-fabrication processes for high-efficiency, low-loss and miniaturization of wafer-scale micro-inductors on silicon for power conversion (PSiP and PwrSoC) applications. To achieve this, new processes for windings and magnetic core material and laminations were investigated. Finally a high inductance density closed-core solenoid micro-inductor prototype is designed, micro-fabricated with CMOS compatible MEMS processes and characterized.

Chapter 1 describes high frequency dc-dc converters and focusses on inductive dc-dc converters. The roadmap for evolution of PwrSoC suggests an increase in switching frequency > 20 MHz with the inductor co-packaged with the power management IC. It is concluded that to achieve this high level of integration, the challenge is to reduce the footprint of the bulky inductors $< 2 \text{ mm}^2$, without compromising on its efficiency.

Chapter-2 highlighted the inductor designs and their limitations reported in literature. The air-core and magnetic core designs are compared. It is concluded that magnetic cores are essential for reducing the device footprint and increasing inductance density. Also, different magnetic core structures (e.g., stripline, planar, solenoid and toroid designs) have also been compared. It is concluded that solenoid designs have high inductance density, lower substrate capacitive effects and can have uniaxial anisotropic magnetic core.

In *Chapter-3*, a theoretical investigation of the windings and its influence on device footprint and efficiency shows high-aspect-ratio Cu windings can reduce DCR significantly. This however is limited by the photolithographic process and photoresist chemistry. Hence, a high-aspect-ratio (17:1) and high resolution single-spin photoresist process with THB-151N has been developed with a thickness of $\sim 85 \text{ }\mu\text{m}$, with resist widths close to the theoretical limit of $5 \text{ }\mu\text{m}$. This is the resist highest aspect ratio to be reported so far for metal moulding process with such high density. The

DCR of micro-fabricated air-core inductors has been reduced by 42%, with a footprint of just 0.39 mm^2 by reducing the winding pitch, while keeping the same number of turns. This thick temporary resist when used as wet-etch mask for etching thick core patterns showed 44% reduction in over-etch as compared to traditionally used SU-8 polymer. This reduces the width of the core-feet included in the mask design for compensating the over etch and increases the wafer yield.

The next chapter (*Chapter-4*) focussed on developing new soft magnetic core materials. The thesis presented an electroless deposition process whereby Ni-Fe magnetic films with variable composition by altering the di-methylamine borane constituent in the bath has been developed. A wide range of magnetic and electrical properties (Table 7.1) of the materials presented in the chapter will find application in broad-scale energy storage and conversion applications.

Table 7.1: Ni-Fe alloy compositions and the respective magnetic and electrical properties.

Ni-Fe composition (with traces $\leq$ 1% of B) & Variation in Ni %	Coercivity (A/m)	Anisotropy field (A/m)	Resistivity ($\mu\Omega\text{-cm}$)
$\text{Ni}_{78}\text{Fe}_{22} \pm 4\%$	29.6	960	26
$\text{Ni}_{54}\text{Fe}_{46} \pm 2\%$	43.2	880	49
$\text{Ni}_{45}\text{Fe}_{55} \pm 3\%$	52	720	57
$\text{Ni}_{36}\text{Fe}_{64} \pm 2\%$	96	600	62

The next section of the *Chapter-4* presents the development of a new ultra-soft ($H_C < 5 \text{ A/m}$) magnetic material (an-hydrous $\text{Ni}_{45}\text{-Fe}_{55}$) based on a room-temperature electrochemical post-processing technique of $\text{Ni}_{45}\text{Fe}_{55}$. The method has been previously reported for hydrogen evolution applications with Ni and Fe thin films. This method has been utilized to post-process the as-deposited $\text{Ni}_{45}\text{Fe}_{55}$ alloy. On post-processing, the coercivity of as-deposited film is reduced to $< 5 \text{ A/m}$ from 32 A/m and increases the resistivity of the film from $47 \mu\Omega\text{-cm}$ to $70 \mu\Omega\text{-cm}$. This is first report on developing a high-resistive ultra-soft magnetic material with an electrochemical method. This unique method of improving the magnetic and electrical properties of as-deposited materials opens a new area of research of already limited core materials.

In *Chapter-5*, two distinct routes (sputter and electrochemical) have been explored to achieve laminated core structures. An optimized, sputtered permalloy films ($\rho_{Py} \sim 25 \mu\Omega\text{-cm}$) nano-laminated with thin (20 nm) Ta(N) with high resistivity ($\rho_{Ta(N)} \sim 3200 \mu\Omega\text{-cm}$) has shown significant improvement in terms of uniformity up to high frequencies of $\sim 500 \text{ MHz}$ and hard-axis anisotropy ($H_k \sim 660 \text{ A/m}$). An electroless

metallization process on insulating surfaces (such as SU-8, BCB and parylene-C) was developed. In addition, a metallization of SU-8 layer ($\rho_{SU-8} \sim 10^{19} \mu\Omega\text{-cm}$) with Ni-Fe alloys (up to 2.4 μm) for lamination has been studied. The process is successfully integrated with CMOS compatible MEMS fabrication process to realize a single laminated top core. Unlike line-of-sight deposition methods, the feasibility of metallization of recessed regions with this process paves the way for the micro-fabrication of novel MEMS designs.

In *Chapter-6*, a first reported closed-core solenoid prototype inductor has been micro-fabricated by integrating the processes developed in *chapter 3*. The closed-core solenoid is analytically designed (54 nH $\sim L$ and footprint $\sim 0.75 \text{ mm}^2$ at 30 MHz) and FEM simulated, wafer-scale microfabricated and characterized. The top windings were realized with the new metal moulding technique (90 μm thick). The key process steps, such as core $\text{Ni}_{45}\text{Fe}_{55}$ electroplating, etching, BCB inter-layer-dielectric, SU-8 inter-metal-dielectric ($\sim 38 \mu\text{m}$) and passivation ($\sim 50 \mu\text{m}$) have been described. The core geometry effects have also been studied in detail and process challenges have been highlighted. The realization of winding through a closed core can be challenging as the adjacent via could short. This has been overcome by additional wet etching. The micro-fabricated device has: $L = 54 \text{ nH}$; $Q = 10$ at 10 MHz and $I_{\text{sat}} \sim 500 \text{ mA}$ with footprint of 0.75 mm^2 . Compared to air-core and open core design, inductance can be further increased by a factor of 12.4 and 1.95 respectively, with the closed core design. The inductance densities for the air-core, open-core and closed core designs are 5.6 nH/mm², 36 nH/mm² and 68 nH/mm² respectively. In the fabricated closed-core design, an inductance density of 72 nH/mm² is achieved.

7.2. Future Work

This section will outline the future work proposed based on the foundation laid by this thesis. It is divided into *design, materials, reliability, packaging* and finally *power converters*.

7.2.1. Efficient Designs

Design is the first step in realizing the micro-inductor device. Following are the key areas where designs can play a crucial role.

(a) Core and winding design

In previous chapters, an elaborate discussion on core losses has been presented. Although new magnetic materials and laminations could restrict eddy current losses and hysteresis losses, one aspect that needs to be looked into is the core design, i.e. the geometry of magnetic core: Core orientation and anisotropy considerations.

Untill now the traditional core designs (E-core, U/C core or pot core) have been explored more often due to limitation in the existing MEMS processes. E-core is a widely implemented core geometry as anisotropic cores can be deposited with flux along the hard-axis. However, in developing anisotropic cores in toroidal designs are challenging. Hence, it is plausible that new alternative core and winding designs have to be explored, taking process limitations into consideration. With advent of 3D printing and the metallization process on insulations reported in this thesis, novel core designs (manipulating the shape anisotropy and efficiently use the magnetic material) can be explored for as discrete components. Also, the influence of core shape on magnetic nano-laminations and the coupling interaction between the magnetic and spacer requires more research.

(b) Electromagnetic Interferences loss and Stray Capacitance Reduction

Electro-magnetic interferences (EMI) is one of the key parasitic parameters which have to be taken into account for real-world applications. Magnetic devices, such as the inductor radiates and absorbs the electromagnetic energy which could cause EMI to or from the circuits and the components in its vicinity. The EMI gets severe at high-frequencies. The application of conductive magnetic materials (such as Ni-Fe) as core act as EMI shields to reduce the radiation by reducing flux leakage and confining the flux. The leakage flux causes coupling with nearby circuits and components resulting in a non-ideal micro-inductor behaviour i.e., the inductance is no longer simply related to the number of turns. However, significant flux leakage still exists. Stray or parasitic capacitances determine the self-resonance-frequency (SRF) which affects the inductor operation range and the Q-factor. The future work should also focus on reducing stray capacitances between the turns and between the turns and the substrate.

7.2.2. Magnetic Material Development

Continuous development of magnetic materials is essential as all the material developed have their merits and demerits. Also, the choice of magnetic materials is

determined by the application of the component. For integrated high-frequency micro-inductors/micro-transformers, reducing core losses is critical.

(a) Electrochemical ultra-soft magnetics

In the thesis, a post-processing technology is developed to achieve an ultra-low loss material. Although it has been successful with $\text{Ni}_{45}\text{Fe}_{55}$, high iron content magnetic alloys (both sputter and electrodeposited) of Co, Fe and Ni could be explored to achieve an ultra-low loss magnetic film with high saturation flux density ($> 2 \text{ T}$) (such as $\text{Co}_{35}\text{Fe}_{65}$ or CoFeHfO). The as-deposited core can be post-processed without affecting the rest of the fabrication processes. Based on the reported work, the coercivity ($\sim 120 \text{ A/m}$) of high resistive as-deposited CoFeHfO films ($\rho_c > 3500 \mu\Omega\text{-cm}$) can be reduced further with the post-processing method. This high resistivity will allow thick resistive cores to be deposited for eliminating the need of magnetic laminations for reducing eddy currents at high frequencies.

(b) Core laminations

In this thesis, efforts have been made to understand and investigate the use of magnetic laminations. Two different approaches (sputter and electrochemical) have been explored. Magnetic laminations will be critical in next-generation high-frequency power magnetic components and the promising results in this thesis have shed-light in developing low-cost repeatable alternatives to existing processes. More research needs to be done to integrate the process in a complete device fabrication process flow. Also, at frequencies $> 100 \text{ MHz}$ laminated cores would be beneficial in terms of inductance density, EMI and flux reduction in comparison to air-core solutions.

Figure 7.1 depicts the permeability spectrum of 3 layer laminated permalloy film ($1 \text{ mm} \times 3 \text{ mm}$) with SU-8 (measured in PMM 9G, Ryowa Electronics, USA). The magnetic film has been deposited in the absence of external magnetic field. Although shape contributes to the permeability response; operating frequency can be increased $> 500 \text{ MHz}$ for UHF applications while non-laminated permalloy films with same dimensions show uniform permeability up to 100 MHz . This approach could be further adapted to achieve laminated solenoid or toroidal micro-inductors with co-packaged laminated cores

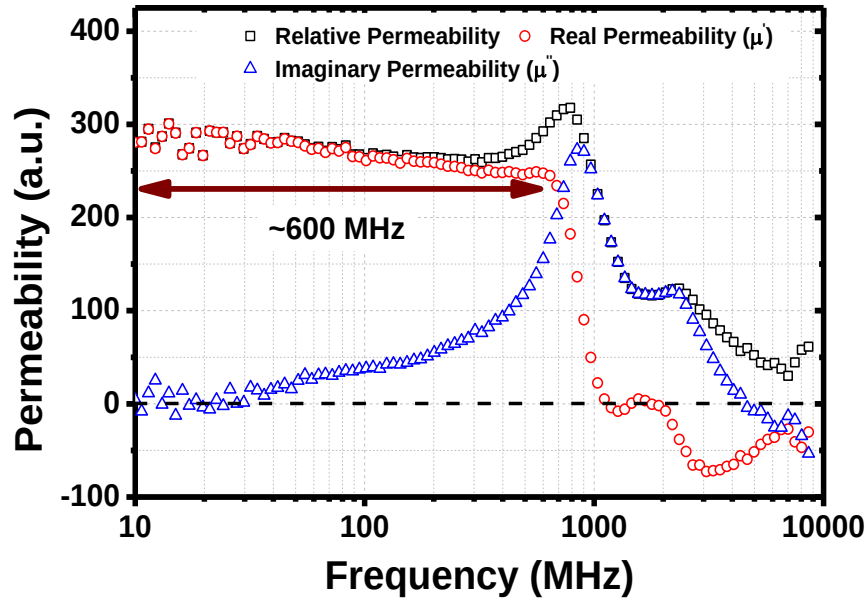


Figure 7.1. Permeability vs frequency of laminated film (1 mm x 3 mm): three layers of permalloy ($\sim 3 \mu\text{m}$ each) separated by thinner variety of SU-8 ($\sim 1 \mu\text{m}$) at null bias.

(c) Magnetic material ageing

The magnetic properties of ferromagnetic materials deteriorates over time with the changes in domain and crystal structures. The domain changes in structure with external factors such as magnetic fields, mechanical vibrations, shock/stress, radiation, temperature fluctuations and high-frequency. Re-magnetization can restore the magnetization. However, when the crystalline structure of the magnetic material changes from a metastable state to an equilibrium state due to physicochemical processes, *irreversible ageing* occurs. During this process, redistribution of foreign inclusions, impurities and defects present in the material occurs. This is often accelerated by increase in temperature. The core magnetic material over time will fail to magnetize completely, resulting in poor saturation magnetization and increased coercivity. It is hence essential to study and control magnetic core ageing to increase the life-time of the micro-magnetic inductors/ transformers which are integral to PSiPs and PwrSoCs. Introducing magnetic materials which are close to their equilibrium state after deposition could slow and reduce the effects of magnetic ageing.

(d) Low / Zero magnetostrictive materials

Ferromagnetic soft magnetic materials such as Ni-Fe alloys are highly magnetostrictive, i.e. the magnetic domains change dimensions when subjected to stress. High stress during fabrication process would result in stress-induced anisotropy which will change the permeability from the design values and hence the inductance density. Materials such as CZTB have shown zero magnetostriction (λ_s). Table 7.2

lists the mechanical properties of soft magnetic properties. Although materials such as $\text{Ni}_{77}\text{Fe}_{15}\text{MoCuTiNb}$ and $(\text{Co}, \text{Fe}, \text{Mo})_{73}(\text{B}, \text{Si})_{27}$ have very low coercivity, as observed from the table, the CZTB has lowest magnetostriction, high saturation flux density and ultra-low coercivity.

Table 7.2 Magnetostrictive properties of some soft-magnetic materials [7.1].

'-' indicates data not reported

Type	Alloy	$\lambda_s \cdot 10^{-6}$	H_c (Oe)	Saturation flux density (T)
Crystalline	$\text{Co}_{50}\text{Fe}_{50}$	70	1.4	2.35
	$\text{Ni}_{50}\text{Fe}_{50}$	25	0.05	1.55
	$\text{Fe}_{97}\text{Si}_3$	9	0.1	2.0
	$\text{Ni}_{77}\text{Fe}_{15}\text{MoCu}$	1	0.01	0.8
	$\text{Ni}_{77}\text{Fe}_{15}\text{MoCuTiNb}$	~ 0.5	0.025	0.5
Amorphous	$\text{Fe}_{80}\text{B}_{14}\text{Si}_6$	30	0.04	1.5
	$\text{Fe}_{40}\text{Ni}_{38}(\text{Mo}, \text{Si}, \text{B})_{22}$	8	0.03	0.8
	$(\text{Co}, \text{Fe}, \text{Mo})_{73}(\text{B}, \text{Si})_{27}$	-0.2	0.003	0.55
	$\text{Co}_{75}\text{Si}_{15}\text{B}_{10}$	-3.5	0.025	0.7
	$\text{Co}_{68}\text{Ni}_{10}\text{B}_{14}\text{Si}_8$	-8	-	0.85
	CZTB	~ 0	0.1	~ 2

Reproduced from 'Sensors-A comprehensive survey', vol. 5, pp. 103, chapter-4, 1989.

7.2.3. Device Reliability

The reliability of micro-inductor devices remains crucial and more often limits the performance of the overall power management circuitry. Once such aspect is the stability of the core material which has been discussed in previous section. Some of the other aspects are as follows:

(a) Thermal reliability

As discussed before, high temperatures accelerates irreversible ageing of the core material. Apart from the magnetic core, high temperature fluctuation also negatively effects the reliability of the device. The inductors / transformers components are found to be most susceptible to thermal failure in the converter circuitry. These devices have permanent structures such as the SU-8 dielectric, BCB, the magnetic films and the windings. The differences in the coefficient of thermal expansion (CTE) of these materials could damage the device and excessive stress especially in SU-8 could result in delamination. Hence, it is essential that low-stress alternatives with matching CTE are explored and their stability tested over thermal cycles.

(b) Mechanical reliability

Mechanical / shock results in the stress in the device which could result in cracks, and delamination. New designs and additional reinforcement process steps could be a possible method of improving the mechanical stability.

7.2.4. Substrate Technology

With on-going miniaturization, high density and functionality of consumer electronics (such as hand-held devices, portable sensors etc.), there is a need for research to develop passives on flexible substrates (such as polyimide, PEEK, polyester or PCBs) for improved packaging. Also need for ‘environmental friendly electronics’ also termed as ‘*green electronics*’ which will reduce electronic waste (*e-waste*). 3D printable bio-degradable polyesters and biocompatible polymers such as PLA (Poly (lactic acid)) and ABS plastic (acrylonitrile butadiene styrene) could be ideal for such developments. The thesis has presented a viable way to deposit magnetic material on insulating surfaces. Such a metallization process will be useful in broader applications in other areas of science and technology.

7.2.5. Packaging

In PwrSiP technology, components are constructed on the lead-frame. The surface technologies such as Quad-Flat-No-Lead (QFN) and ball-grid-arrays (BGA) have also been explored. QFN has better thermal performance due to the inclusion of thermal pads, while BGA rely on ball contacts for heat removal. The packaging of the inductors with capacitors to realize LC interposer is another challenging area to be explored.

7.3. Conclusions

This thesis has developed a key building blocks or process modules for the fabrication of low loss micro-inductors. The process developed for reducing the winding and core hysteresis losses on integration with the device process flow would provide a highly efficient micro-inductor. This will benefit in the on-going progress in power supply in package (PwrSiP) technology and will contribute to the eventual realization of commercially viable Power Supply on Chip (PwrSOC) solution.

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I. Appendix

Fundamentals of Inductors

This section outlines some of the fundamental laws and properties of soft magnetic materials required for inductor design. Table-1.2 lists the symbols to be used to represent these properties.

Table-1.2. Symbols and properties	
Symbols	Properties
μ	Net permeability
μ_0	Permeability in free space
μ_r	Relative permeability
μ'_r	Real part of relative permeability
μ''_r	Imaginary part of relative permeability
L	Inductance
N	Number of turns
ϕ	Magnetic flux
ρ	Resistivity
δ	Skin depth
χ	Magnetic susceptibility
A_c	Cross-section of the magnetic path
A_{B-H}	Area enclosed by hysteresis at frequency f
B	Flux density
B_p	Peak flux density in the core
B_s	Saturation flux density
f	Operation frequency
H	Applied magnetic field
I_{AC}	ac component of inductor current
I_{DC}	dc component of inductor current
l_{mag}	Length of magnetic path
$R_{Air-gap}$	Reluctance due to air-gap in the core
R	Reluctance
R_{mag}	Reluctance due to magnetic core

An inductor is a passive component which stores energy in the form of a magnetic field. It has a core which can comprise either air, non-magnetic or magnetic material. The rate of change of current in a conductor winding induces a change in the magnetic field. The changing magnetic field induces an electromotive force which opposes the change in the current. The inductance (L_S) for a static current is given as:

$$L_S = \frac{N\Phi}{I} \quad (1)$$

where, Φ is the magnetic flux and I is the current flowing through the core. The rate of change of flux caused by changes in the current which induces an electro-motive force (e.m.f.) is given by:

$$\varepsilon = \frac{d\Phi}{dt} = \frac{d\Phi}{dI} \frac{dI}{dt} = L \frac{dI}{dt} \quad (2)$$

where,

$$\text{Inductance } (L) = \frac{d\Phi}{dI} \quad (3)$$

Fundamental Laws:

Ampere's Law

Ampere's law (1826) states that a time varying current induces a time varying magnetic field around a closed path (figure 1). In other words, the closed line integral of a magnetic field H around a closed path is equal to the net current I_{net} passing through the surface enclosed by the path.

$$\oint H(t)dl = I(t) \quad (4)$$

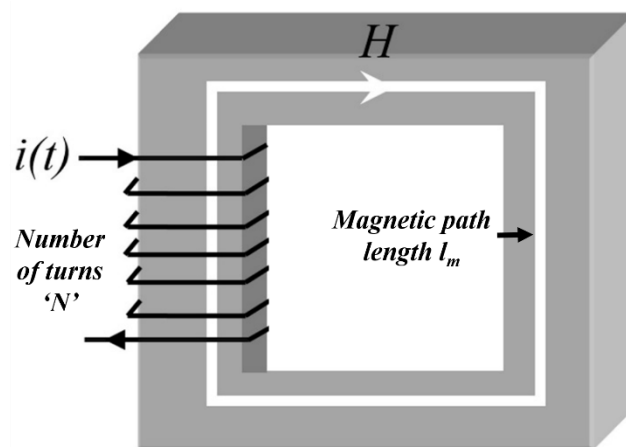


Figure 1. An inductor magnetic core and a winding.

For current flowing through a length l_m (as shown in figure 1.2) with ' N ' number of turns,

$$H(t) \cdot l_m = I(t) = Ni(t) \quad (5)$$

Faraday's Law

Faraday's law (1831) states that time-varying magnetic flux $\Phi(t)$ passing through a closed loop induces a voltage in the loop (figure 2). For a coil carrying current $i(t)$ with ' N ' being number of turns, Faraday's law can be mathematically expressed by:

$$v(t) = \frac{d(N\Phi)}{dt} = NA \frac{dB}{dt} \quad (6)$$

It can also be expressed as (and ' $\mathfrak{R}$ ' being the reluctance):

$$v(t) = \frac{d(N\Phi)}{dt} = N \frac{d\phi}{dt} = N \frac{d}{dt} \left(\frac{Ni}{\mathfrak{R}} \right) = \frac{N^2}{\mathfrak{R}} \frac{di}{dt} = L \frac{di}{dt} \quad (7)$$

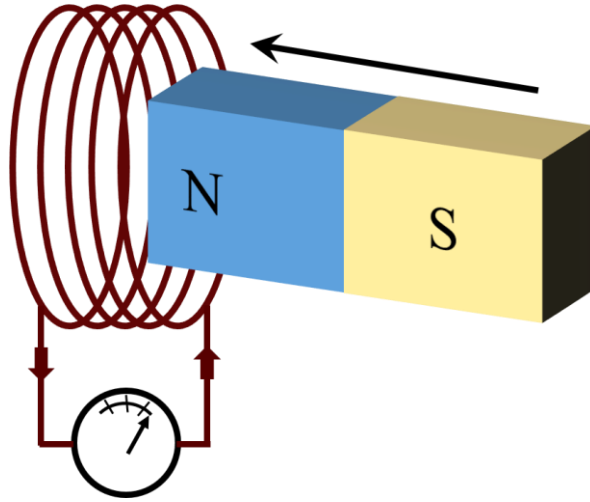


Figure 2. Changing magnetic flux through the closed loops inducing voltage (Faraday's law).

Lenz's Law

Heinrich Lenz (1834) postulated that the induced e.m.f. produced by the change in applied magnetic flux (ϕ_a) has a polarity which induces a current with the magnetic flux (ϕ_b), which in turn tends to oppose the change in applied flux (ϕ_a).

Magnetic Material Properties

Soft magnetic materials have been used in power electronic applications as magnetic cores. The magnetic core reduces reluctance and confines the flux within the core. This reduces the electromagnetic interferences and the leakage inductance significantly. These materials can be easily magnetized or demagnetized so that they can transfer or store magnetic energy. Figure 3 shows a chronological summary of

major developments in soft magnetic materials. In this section, some of the important magnetic properties essential for micro-inductor design will be discussed.

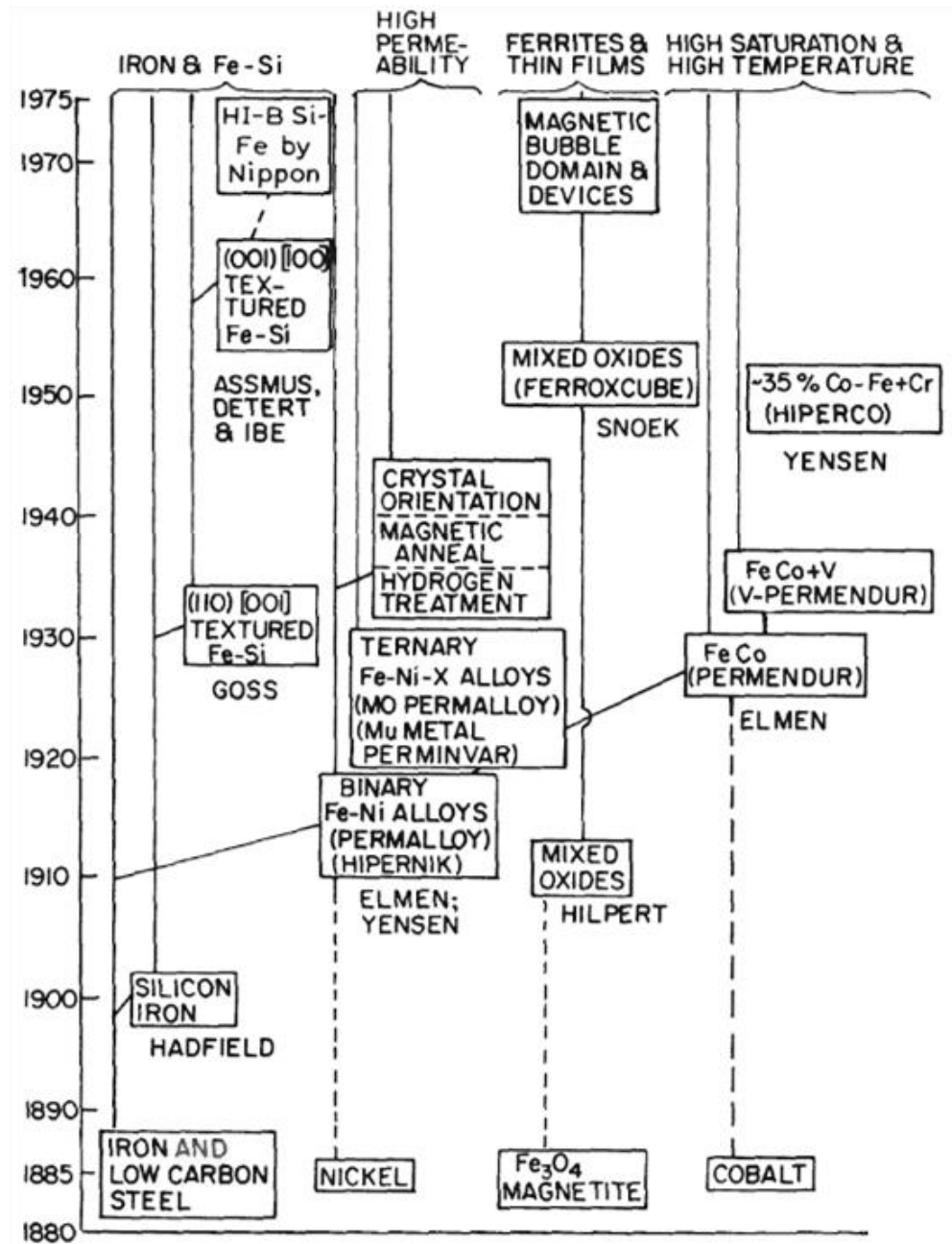


Figure 3. Chronological summary of major developments of soft magnetic materials (Bechtold and Wiener [1.3]).

Magnetic Hysteresis Curve:

A complete magnetization and demagnetization curve of a material is called its *hysteresis loop*. Unlike other materials, ferromagnetic materials (both *soft* and *hard magnetic materials*) have a memory because they retain some of domain orientations even when the magnetic field intensity has been reduced to zero. Unlike hard magnetic materials which require high applied field to magnetize and demagnetize, soft

magnetic materials can be easily magnetized and demagnetized. Figure 4 shows a hysteresis curve of a ferromagnetic magnetic material. The slope represents the permeability of the material. In the presence of an external applied magnetic field (H), the magnetic material responds with a spontaneous magnetization (M). The total magnetic flux (B) density is given by:

$$B = \mu_o(H + M) \quad (8)$$

For soft ferromagnetic materials M readily follows the applied field, i.e.

$$M = \chi H \quad (9)$$

where ' χ ' denotes the magnetic susceptibility.

$$B = \mu_o(1 + \chi)H = \frac{\mu_o(1+\chi)M}{\chi} = \mu_o M \quad (10)$$

(For soft-magnetic materials, $\chi \approx \chi + 1$)

$$B = \mu_r \mu_o H \quad (11)$$

$$\mu_r = (1 + \chi) \quad (12)$$

The area under the loop shows the energy that a magnetic core consumes per unit volume in each cycle which is termed as *hysteresis loss*. For power inductor applications it is necessary to have a small B-H area and a small retentivity with a high core magnetization saturation. *Retentivity* (B_r) is the residual flux density that remains after removing the induced or applied field (shown with red dots). *Coercivity* (H_c) is the magnetic field needed to demagnetize a completely magnetized specimen (shown with red dots). A small area signifies that less energy is required for domain realignment, while a small retentivity value means efficient realignment of the domains. Higher core magnetization saturation on the other hand is required for greater flux density.

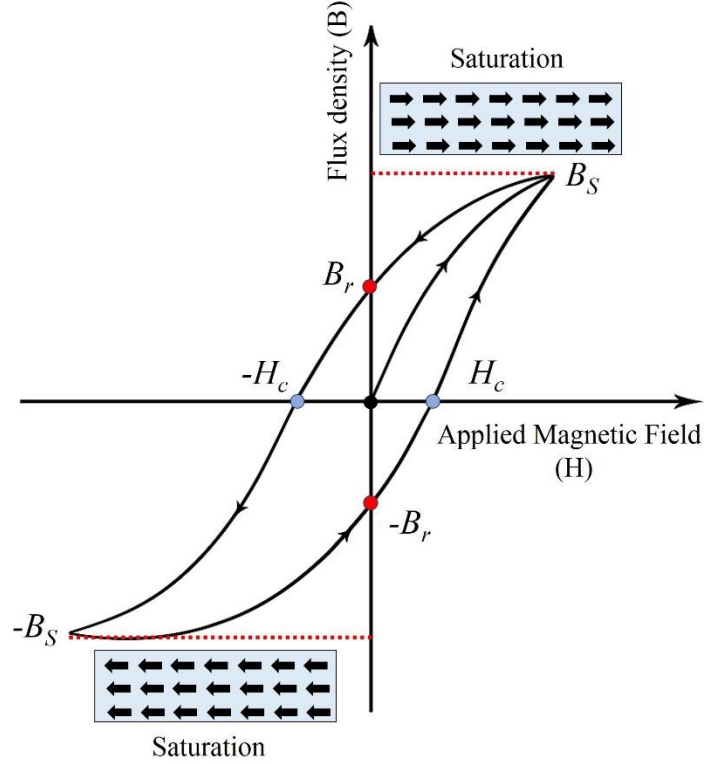


Figure 4. Hysteresis loop of a ferromagnetic material.

Core Saturation

For ferromagnetic materials, the relationship between B and H is non-linear as the relative permeability changes with the magnetic field H . For flux density (B) below B_s , the slope (μ_r) of the B - H curve is high. As the core saturates ($> B_s$), the relative permeability of the core approaches 1 (i.e., the slope B/H attains unity). In this case, the core is unable to confine the flux and acts as if no magnetic core is present. A saturated magnetic core inductor thus acts as an air-core inductor. Hence the peak magnetic flux density B_p should be less than the saturation flux density B_s of the core material. The peak magnetic flux density is dependent on dc and ac components (I_{DC} and I_{AC}) of the inductor current [1.1, 1.4]:

$$B_s \geq B_p (= B_{AC} + B_{DC}) \quad (13)$$

$$B_p = \frac{\mu_0 \mu_r N (I_{AC} + I_{DC})}{l_{mag}} \quad (14)$$

Reluctance

The reluctance (R) is defined as the resistance of the core to the flow of the magnetic flux. The magnetic flux intensity $H(t)$ and magnetic flux density $B(t)$ is given by:

$$B(t) = \mu H(t) \quad (15)$$

where ' μ ' denotes the net permeability of the magnetic material ($\mu_r \mu_o$). On replacing equation (15) to equation (7), we have:

$$v(t) = \frac{d(N\Phi)}{dt} = NA\mu \frac{dH(t)}{dt} = \frac{N^2 A \mu}{l_m} \frac{di(t)}{dt} \quad (16)$$

including equation (7) into (16), hence,

$$L = \frac{N^2 A \mu}{l_m} = \frac{N^2}{\frac{l_m}{A \mu}} = \frac{N^2}{R_{Mag}} \quad (17)$$

where,

$$Reluctance (R_{Mag}) = \frac{l_m}{\mu A_C} = \frac{l_m}{\mu_o \mu_r A_C} \quad (18)$$

The inductance is expressed as magnetic core reluctance:

$$L = \frac{N^2}{R_{Mag}} \quad (19)$$

The inductance of a magnetic core inductor with air-gap is calculated as:

$$L = \frac{N^2}{R_{Mag} + R_{Air Gap}} \quad (20)$$

$$L = \frac{N^2}{\frac{l_m}{\mu_o \mu_r A_C} + \frac{l_{gap}}{\mu_o A_C}} \quad (21)$$

Anisotropy field

The directional dependence of the magnetic properties of a material is known as *magnetic anisotropy*. There are several kinds of anisotropy:

- Magneto-crystalline/crystal anisotropy: This is an intrinsic property of the material. The magnetization process varies with the crystallographic orientation in an applied magnetic field. As a result the energy needed to magnetize the material varies with the direction of applied field.

- Shape anisotropy: The *shape anisotropy* arises from the demagnetization field produced by the material on magnetization due to the shape of the material. This demagnetization field opposes the magnetic field.
- Stress anisotropy: When a material is subjected to magnetic field, its dimension change. This effects is known as *magnetostriction*. This means a material under mechanical stress can alter its domain structure and result in anisotropy known as *stress anisotropy*.
- Induced anisotropy: The anisotropy created by externally influencing (by annealing, applying stress, irradiation etc.) the magnetic material is known as *induced anisotropy*. In the strictest sense, with the exception of magneto-crystalline anisotropy, all other anisotropies could be associated as induced.
- Exchange anisotropy: In bilayer films of anti-ferromagnetic and ferromagnetic materials, the hard magnetization of the anti-ferromagnetic film shifts the magnetization curve of the soft-ferromagnetic material.

Relative Permeability

Relative permeability is the ease with which a magnetic material can be magnetized. It is analogous to the electrical conductivity. It is often expressed as a complex number to describe the ferromagnetic and loss properties of the material at high frequencies. At low frequencies, the applied field and the flux density vary linearly. However, at a high frequency these have a lag time between them. At high frequencies, the applied field and flux density can be expressed as:

$$H = H_o e^{j\omega t} \quad (22)$$

$$B = B_o e^{j(\omega t - d)} \quad (23)$$

Where ‘*d*’ is the phase delay. The magnetic permeability at high frequencies can be expressed as:

$$\mu = \mu_o \mu_r = \frac{B_o e^{j(\omega t - d)}}{H_o e^{j\omega t}} = \frac{B_o e^{-jd}}{H_o} = \frac{B_o (\cos d - j \sin d)}{H_o} = \mu' - j\mu'' \quad (24)$$

$$\mu' = \mu_o \cos d \text{ and } \mu'' = j\mu_o \sin d \quad (25)$$

Skin effect

Direct current through a conductor distributes itself uniformly over the entire cross-section of the conductor. The current density remains constant on moving from the centre of the conductor towards the periphery. On the other hand, alternating currents, due to the inductance effects of the conductor gather at the peripheries. This effect is known as *skin effect*. This results in a power loss also known as *eddy current loss* due to the increase in conductor resistance. The skin depth is the characteristic length within which the alternating current travels:

$$\delta = \sqrt{\frac{\rho}{\pi\mu f}} \quad (26)$$

Where ρ is the resistivity of the conductor carrying alternating current at frequency ' f ' with net material permeability ' μ '.

Inductor Power Losses:

Ideal loss-less inductors would have a 100% efficiency. However, this is cannot be realized because of several loss mechanisms involved. Figure 5 shows a schematic of Tyndall's racetrack micro-inductor. This design has a magnetic core wrapped around the Cu windings.

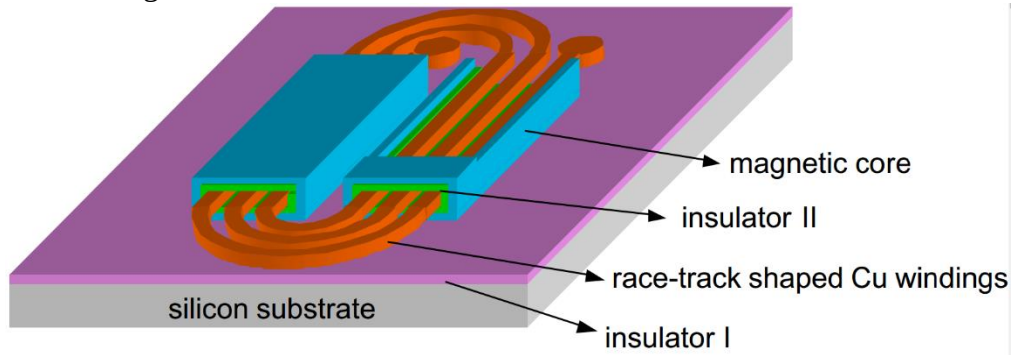


Figure 5. A schematic of Tyndall racetrack micro-inductor.

The losses associated with the design and other such magnetic core micro-inductors are can be separated as:

- a. *Winding losses*
 - dc losses (also known as RI^2 losses)
 - ac losses
- b. *Hysteresis loss (Core)*
- c. *Eddy current loss (Core)*
- d. *Anomalous loss (Core)*

(a) Winding Losses

The dc Conducting Losses:

The dc conducting losses are the largest contributing factor in an inductor. These losses are attributed to the rise in temperature of the device on continued use, causing power to be dissipated in the form of heat. It is given by:

$$P_{DC} = R_{DC}(I_{Lrms})^2 \quad (27)$$

where P_{DC} is power loss due to the dc resistance R_{DC} and I_{Lrms} is the rms current at the load.

AC Conducting losses:

For AC conduction, there is a non-uniform distribution of current within a conductor. This is also known as *skin effect*. The current density is higher on the surface of a conductor up to a thickness known as *skin depth*. Hence, it is apparent that conductors thicker than skin depth cause AC losses. Also, apart from AC conducting losses, there is also a *proximity effect*. At high frequencies, the AC resistance of an adjacent conductor is increased by a nearby current carrying conductor. This happens because, as the AC current changes in a conductor it produces alternating magnetic field which interferes with the current flowing in a nearby conductor. This causes the eddy currents to develop in the nearby conductor, as a result of which currents are accumulated in the furthest regions from the centre of the conductor. For example, the skin depth for Permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) at 1 MHz is 5.03 μm and at 100 MHz it is 0.71 μm . This restricts the core thickness that can be used in inductors at high frequencies. The flux cannot be confined properly in such thin cores, thus reducing the overall inductance density. Table-I lists the skin depth of $\text{Ni}_{81}\text{Fe}_{19}$ (Rel. permeability: 2000 & resistivity: 20 $\mu\Omega\text{cm}$) and Copper (Rel. permeability: 1 & resistivity: 1.69 $\mu\Omega\text{cm}$) at high frequencies:

Table-I Skin depths of $\text{Ni}_{81}\text{Fe}_{19}$ and Copper

Frequency	$\text{Ni}_{81}\text{Fe}_{19}$	Copper
	Skin depth (μm)	Skin depth (μm)
100 KHz	15.91	206.9
1 MHz	5.03	65.42
10 MHz	1.59	20.69
100 MHz	0.50	6.54
1000 MHz	0.16	2.06

Figure 6 shows the current distribution in the cross-section of a solid Cu wire. For dc current, the distribution is uniform across the cross-section of the winding (figure 6 (a)). But the AC current density gradually decreases from the surface of the material towards the centre as the frequency increases (figure 6 (a) and (b)).

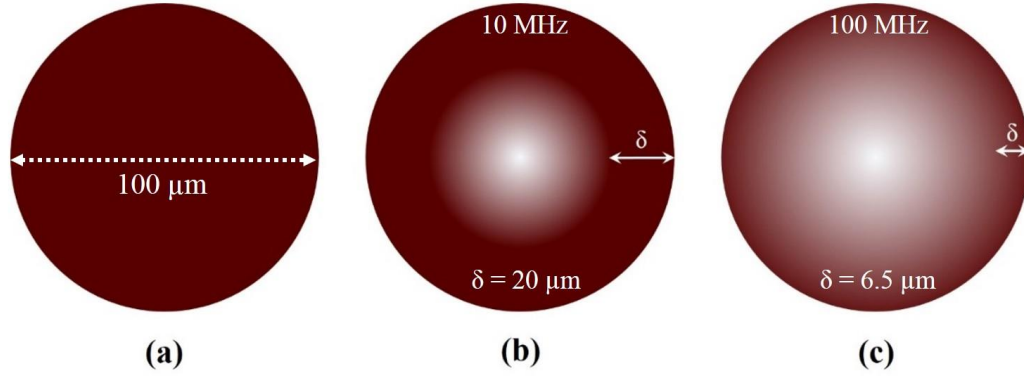


Figure 6. Current distribution over the cross-section of copper wire: (a) At dc (0 Hz) (b) AC at moderate frequencies and (c) ac at high frequencies.

Chapter 3 will investigate the high resolution and aspect-ratio photoresist processes to fabricate dense micro-windings and reduce winding losses.

(b) Hysteresis Losses

Magnetic core inductors are magnetised for operation at high frequencies. However, the energy required to do so is not retained. As observed from the figure 1.6, the path of magnetization is not retained on reducing the applied field to zero. This energy is lost in the form of heat. The area under the curve is proportional to the hysteresis loss. If we consider an ‘N’ turn inductor, then the net energy flowing into the inductor (or the energy delivered to an inductor containing ferromagnetic core during one transverse of the hysteresis curve) is given by:

$$W = AN \oint i dB = l_m A \oint H dB \quad (28)$$

$l_m * A = V$ is the volume of the core magnetic material. The hysteresis loss over one cycle is given by:

$$P_{Hys} = W * f \quad (29)$$

$$P_{Hys} = f * l_m A \oint H dB \quad (30)$$

$$P_{hyst \text{ loss density}} (P_{Hys}/V) = 4f * A_{B-H} \quad (31)$$

where, ‘ A_{B-H} ’ is the area enclosed by the B-H loop at the frequency f .

The hysteresis losses contribution becomes a prominent factor at frequencies beyond 1 MHz. It is apparent that to reduce the inductor losses, soft magnetic materials with high permeability and low coercivity would be ideal. However, the process and cost effectiveness should also be taken into consideration.

(c) *Eddy Current Losses*

Conductors carrying AC currents will generate a changing magnetic flux (in accordance with Lenz's law). This change in magnetic flux will induce an AC voltage which in turn will produce an opposing AC current with the conductor. The opposing current will result in the reduction of the overall current flowing in the conductor. These losses also result in heating of the device. It is given by:

$$P_{Eddy} = I_{Eddy}^2(t)R \quad (32)$$

Many of the magnetic core materials are electrically conductive. In AC conditions, the changing flux generated by the current carrying windings results in a current within the conductive core (*eddy-currents*) which create a flux opposing the original flux. This results in I^2R type loss with the flux gradually decreasing from the surface of the core towards the centre. This loss is dependent on the induced current path. One of the ways to reduce this resistive loss is to laminate the magnetic core. Figure 7 shows the current paths with the laminated core (where ' n ' is number of laminations). The induced voltage and the resistance in the solid core are expressed as V_C and R_C . In case of a laminated core, the resistance of one lamination is $n * R_C$ and the induced voltage per lamination is V_C/n . The power loss per lamination ($P_{laminated}/n$) is:

$$P_{laminated}/n = \frac{\frac{V_C^2}{n^2}}{nR_C} = \frac{V_C^2}{n^3R_C} \quad (33)$$

$$P_{laminated} = \frac{V_C^2}{n^2R_C} \quad (34)$$

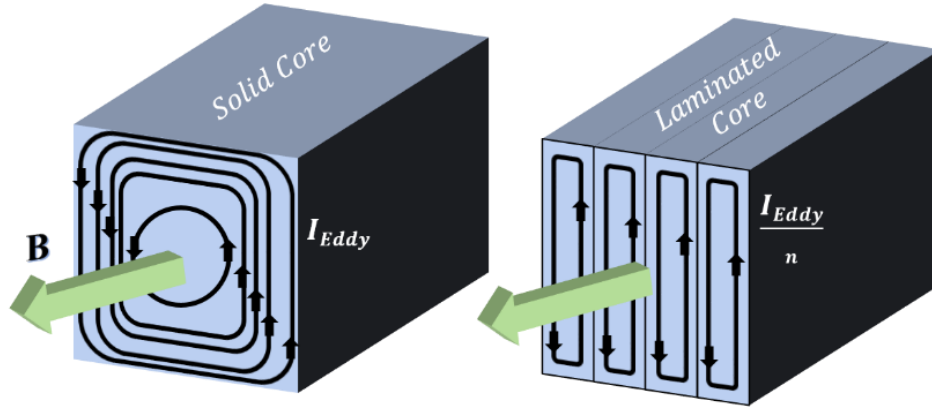


Figure 7. Eddy current loss in conductive soft-magnetic core.

For ‘ n ’ number of laminations, the total loss is reduced by $1/n^2$ times the loss for the solid core. In *Chapter-5* a detailed theoretical framework behind magnetic laminations and the routes to sputter and electrochemical laminated magnetic cores is described.

(d) *Anomalous Loss:*

Anomalous loss accounts for the additional losses left after hysteresis and eddy current losses and often associated as excess eddy current losses. These losses arise due to domain wall motion, non-uniform samples and non-uniform magnetization. The broadening of the hysteresis loop with frequency is associated with anomalous loss [1.5].

Steinmetz Core Loss Equation

The total core loss under sinusoidal excitation is given by a time averaged core loss [1.8]:

$$P_{core\ loss} = K_c f^\alpha B_{max}^\beta \quad (35)$$

β (Steinmetz coefficient) and K_c (hysteresis coefficient) are material dependent constants obtained from curve fitting and usually provided with manufacturer’s data sheets. The Steinmetz coefficient for most of the magnetic materials is ~ 2 . The hysteresis coefficient can be obtained from area of the B-H loop as hysteresis loss per cycle in unit volume material (joules/m³ cycle).

II. Appendix

Switch Mode Power Supply

The source of electrical power can be an ac source (e.g. mains) or dc source (e.g. battery). In case of mains-operated consumer electronics, the power supply usually consists of an ac-dc converter. This is performed by a rectifier circuit. The resulting dc voltage is fed in a dc-dc step-down converter to lower to the desired voltage and isolated from the output voltage. This converter has the control circuit which controls the switched of the dc-dc converter such that the output voltage remains at the desired level. The other part of this dc-dc converter circuit has the switches and passives which steps down the voltage. The mains-operated SMPS have output power in W to kW range, which cannot be achieved with battery-operated dc-dc converters.

In battery-operated dc-dc converters, the battery provides a stable dc voltage output. Hence no rectifying unite is needed. It has a dc-dc control system unit and switches and passives which step-down the voltage to a desired level. In case of step-up converters, the part of the circuit which requires higher voltage is directly connected to the dc-dc converter output, whereas the circuit requiring lower voltage is directly connected to the battery. Unlike mains-operated SMPS, no galvanic isolation is needed and the output voltage is often limited.

The thesis focuses inductor technology for low-power inductive dc-dc buck converter. The ideal circuit of inductive buck converter is shown in Figure 8 below. The converter can operate in continuous conduction mode (CCD) and discontinuous conduction mode (DCM). In this section, the continuous conduction mode has been elaborated.

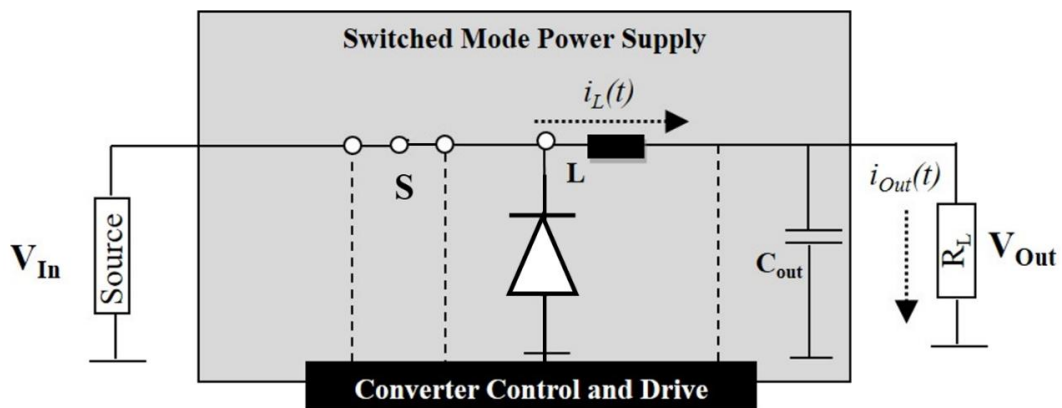


Figure 8. A typical SMPS (Buck converter) schematic.

In continuous conduction mode, the current ($i_L(t)$) through the inductor 'L' is always positive. For a constant time period 'T', the average value of the output voltage (V_{out}) can be calculated as:

$$\frac{T_{ON}}{T} = D \quad (1)$$

where, 'D' is the duty cycle. The frequency (f) is $1/T$.

When the switch S_1 is switched ON, the current through the inductor keeps on rising. The inductor voltage is given by,

$$V_L = L * \frac{di_L}{dt} = V_{in} - V_{out} \quad (2)$$

During the next time interval (T_{OFF}), the switch S is open. The inductor starts discharging into C and R_L . The output voltage is given by:

$$V_L = L \frac{di_L}{dt} = -V_{out} \quad (3)$$

The current through L cannot fall instantaneously but falls off gradually through a return part (usually a diode).

The peak-to-peak current ripple is during the ON state:

$$\Delta I(on) = \int_0^{t_{on}} \frac{V_L}{L} dt = T_{ON} \left(\frac{V_{in} - V_{out}}{L} \right) \quad (4)$$

ii

Similarly, during the OFF state, the decrease in current is given by:

$$\Delta I(off) = \int_{t_{on}}^{t_{on}+t_{off}} \frac{V_L}{L} dt = T_{OFF} \left(\frac{-V_{out}}{L} \right) \quad (5)$$

So, in steady state condition, we have:

$$\Delta I(on) + \Delta I(off) = 0 \quad (6)$$

$$T_{ON} \left(\frac{V_{in} - V_{out}}{L} \right) + T_{OFF} \left(\frac{-V_{out}}{L} \right) = 0 \quad (7)$$

Using equation (1), equation (7) gives:

$$D = \frac{V_o}{V_i} \quad (8)$$

As the duty ratio is always < 1 , the output voltage is always less than the input voltage (as observed from equation (1)). Figure 8 shows the switching states.

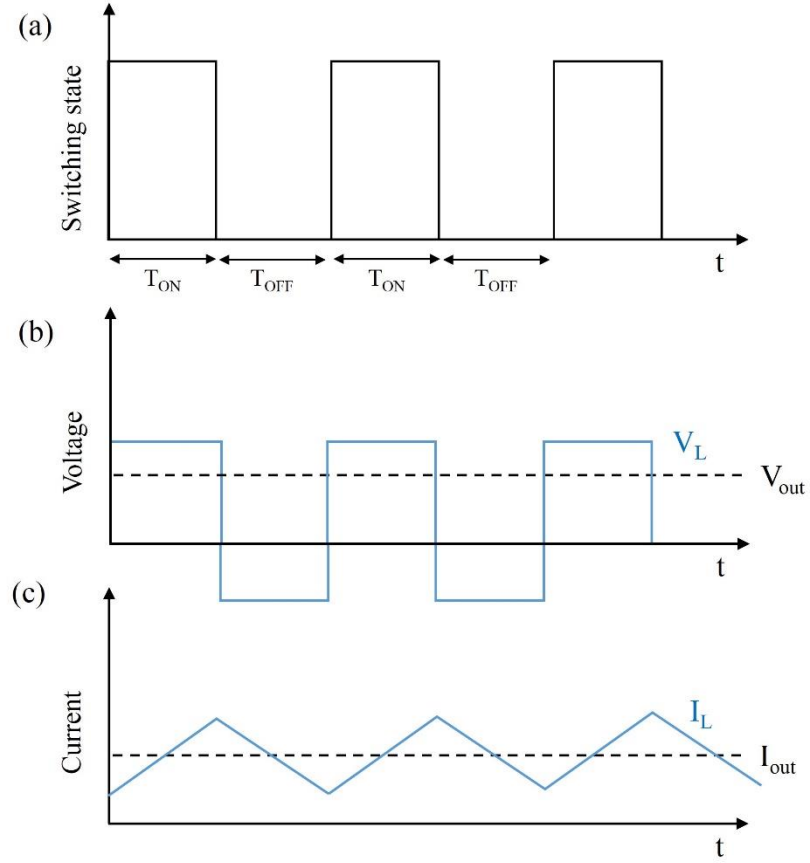


Figure 8. (a) Switching state (b) Output voltage waveform (c) Inductor current in continuous conduction mode.

III. Appendix

Magnetic Laminations: Theoretical Framework

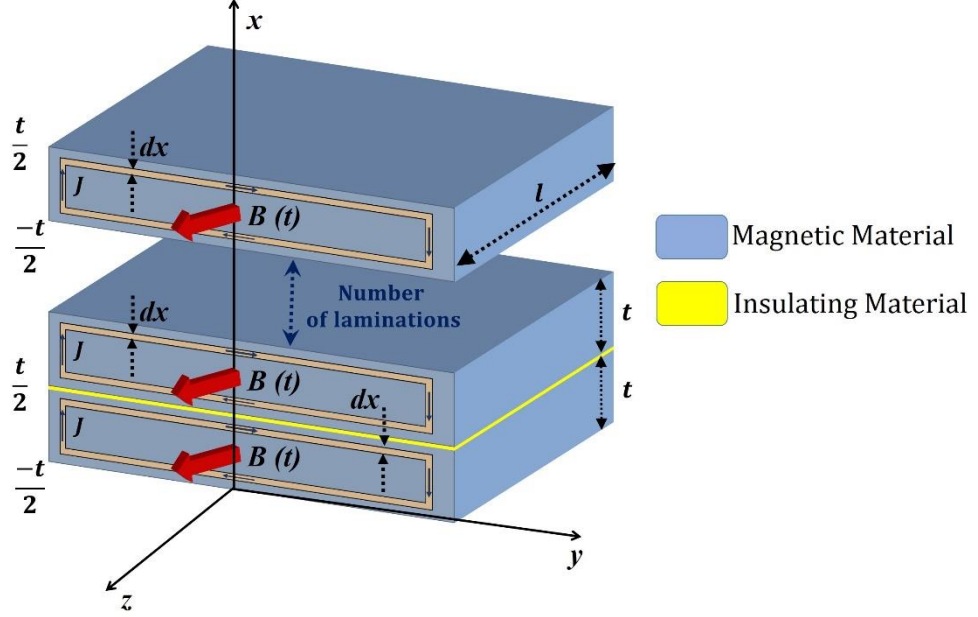


Figure 9. Cross-section of laminations with a thickness 't' separated by thin insulator

Let us consider a laminated core as shown in figure 9. Assuming that the magnetic field intensity H is uniformly distributed along the x-axis ($\delta \gg t$).

where, δ denotes the skin depth of the material.

The sinusoidal current carrying ($i(t) = I_m \sin(\omega t)$) through the inductor windings results in the magnetic flux density:

$$B(t) = B_m \sin(\omega t) \quad (1)$$

The magnetic field intensity within the laminated core can be expressed by the Helmholtz equation:

$$\frac{d^2 H_z(x)}{dx^2} = \gamma^2 H_z(x) \quad (2)$$

where, γ is given as:

$$\gamma^2 = j\omega\sigma\mu = j\delta \quad \text{Or, } \gamma = \frac{1+j}{\delta} \quad (3)$$

Where, ' ω ' is the angular frequency associated with the frequency ' f ' and ' μ ' and ' σ ' are the permeability and conductivity of the magnetic material.

The general solution to equation (2) is given by:

$$H_z(x) = H_1 e^{j\omega\sigma\mu x} + H_2 e^{-j\omega\sigma\mu x} \quad (4)$$

On applying the boundary conditions at the two extremes of the lamination, we have:

$$H_z\left(\frac{t}{2}\right) = H_1 \frac{e^{j\omega\sigma\mu t}}{2} + H_2 \frac{e^{-j\omega\sigma\mu t}}{2} \quad (5)$$

$$H_z\left(\frac{-t}{2}\right) = H_1 \frac{e^{-j\omega\sigma\mu t}}{2} + H_2 \frac{e^{j\omega\sigma\mu t}}{2} \quad (6)$$

On solving for H_1 and H_2 we have:

$$H_1 = H_2 = \frac{H_z\left(\frac{t}{2}\right)}{2\cosh\left(\frac{\gamma t}{2}\right)} \quad (7)$$

And, $H_z(x) = H_1(e^{j\omega\sigma\mu x} + e^{-j\omega\sigma\mu x}) = 2H_1 \cosh(\gamma x)$ (8)

Replacing equation (7) and (3) in (8), we have:

$$H_z(x) = \frac{2H_z\left(\frac{t}{2}\right)\cosh(\gamma x)}{2\cosh\left(\frac{\gamma t}{2}\right)} = H_z\left(\frac{w}{2}\right) \frac{\cosh\left(\frac{x}{\delta} + j\frac{x}{\delta}\right)}{\cosh\left(\frac{t}{2\delta} + j\frac{xt}{2\delta}\right)} \quad (9)$$

$$B_z(x) = \mu \frac{2H_z\left(\frac{t}{2}\right)\cosh(\gamma x)}{2\cosh\left(\frac{\gamma t}{2}\right)} = \mu H_z\left(\frac{w}{2}\right) \frac{\cosh\left(\frac{x}{\delta} + j\frac{x}{\delta}\right)}{\cosh\left(\frac{t}{2\delta} + j\frac{xt}{2\delta}\right)} \quad (10)$$

The magnitude of the magnetic field intensity across the lamination can be expressed as:

$$|H_z(x)| = H_z\left(\frac{t}{2}\right) \sqrt{\frac{\cosh\left(\frac{2x}{\delta}\right) + \cos\left(\frac{2x}{\delta}\right)}{\cosh\left(\frac{t}{\delta}\right) + \cos\left(\frac{t}{\delta}\right)}} \quad (11)$$

The normalized field intensity across is:

$$|H_z(x)|/H_z\left(\frac{t}{2}\right) = \sqrt{\frac{\cosh\left(\frac{2x}{\delta}\right) + \cos\left(\frac{2x}{\delta}\right)}{\cosh\left(\frac{t}{\delta}\right) + \cos\left(\frac{t}{\delta}\right)}} \quad (12)$$

The current density is:

$$J(x) = J(y) = -\frac{dH_z(x)}{dx} = -\frac{1+j}{\delta} H_z\left(\frac{t}{2}\right) \frac{\sinh\left(\frac{x}{\delta} + j\frac{x}{\delta}\right)}{\cosh\left(\frac{t}{2\delta} + j\frac{xt}{2\delta}\right)} \quad (13)$$

The normalized magnitude is:

$$|J(x)| * \delta / H_z\left(\frac{t}{2}\right) = \sqrt{\frac{2[\cosh\left(\frac{2x}{\delta}\right) - \cos\left(\frac{2x}{\delta}\right)]}{\cosh\left(\frac{t}{\delta}\right) + \cos\left(\frac{t}{\delta}\right)}} \quad (14)$$

IV. Appendix

a. Closed Core Solenoid Fabrication steps

Process Description	System Description	Procedure	Process Outcome
RCA clean	RCA clean beakers	Silicon wafer rinse in IPA (50°C) for 1 min. HF dip in 10:1 HF for 2 mins. Perform RCA 1 beaker clean DI / H ₂ O ₂ / NH ₄ OH 6:1:1 at 75 °C for 10 mins. Perform RCA 2 beaker clean DI / H ₂ O ₂ / HCL 6:1:1 at 75 °C for 10 mins. Hot Methanol treatment for 1 min (40°C). Bake wafer in YES oven at 160°C for 1 hour.	-
Thermal Oxidation	Horizontal, atmospheric furnace system	Load at 80 °C in 5 L N ₂ , boat in speed 20 cm/min, stabilise at 800 °C for 20 min in N ₂ , ramp to 1000°C at 10 °C/min in 5 L N ₂ /min; at 1100 °C, N ₂ off, O ₂ ON at 3.7 L/min wait 1 min then H ₂ on at 6L/min, delay for 140 mins, then O ₂ and H ₂ off, N ₂ on at 5 L/min, delay 20 min then cool to 800°C at 5 °C/min in 5L N ₂ /min, boat out at 10 cm/min, unload Oxygen Flow, N ₂ Flow, drive in speed, loading, etc.	1 µm thick oxide
Ti seed deposition	Magnetron sputtering (Hybrid Nordiko advanced energy NDX system)	Ti 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step at 1 kW for 1 min. Deposition at 0.3 kW for 4.5 min.	20 nm thick (44 - 46 Å / min)
Ni₈₁Fe₁₉ seed deposition	Magnetron sputtering (Hybrid Nordiko advanced energy NDX system)	Ni ₈₁ Fe ₁₉ 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step at 1 kW for 1 min. Deposition at 1 kW for 4 min.	100 nm thick (233-245 Å / min)
Ni₄₅Fe₅₅ deposition	In-house electroplating system	Details given in appendix-B.	3.5 µm (550 Å/min)
AZ9260 metal	Spin coating (DNS /Screen-track)	Apply PR Clariant AZ 9260. 2400 rpm for 60 sec. then prebake at 110 °C for 165 sec on a hotplate.	9 µm thick

moulding resist	Exposure (EV 420 aligner)	Exposure energy of 340 mJ/cm ²	
	Development	Puddle develop in AZ 400K at 3:1 (DI: Developer) for 4-6 mins.	
Ni₈₁Fe₁₉ etching	Wet bench (Puddle mode)	Details of etchant given in appendix-B.	Lateral etch: 10-15 µm (max.).
Ti etch	Wet bench (Puddle mode)	Etching done in BOE solution. Etch time <10 secs.	2 nm /sec
AZ9260 removed	Wet bench (Puddle mode)	Resist strip in acetone & Rinse in IPA to clear acetone.	-
Adhesion promoter- AP3000	Spin coating	Spin-dry at 2000 rpm for 30 sec.	-
BCB (ILD)	Spin coating	BCB4026-46 layer puddle for 30 sec. Spin at 2500 rpm for 30 sec. EBR using T1100. Pre-expose bake at 85 °C for 90 sec.	12 - 14 µm
	Exposure (EV 420 aligner)	Exposure energy of 798 mJ/cm ² (Hard contact mode).	
	Development	Pre-develop bake at 75°C for 30 secs. Multi develop cycle may be needed using DS2100 developer.	
	Cure (Vacuum Oven)	Post Develop bake 75 °C for 30secs.	
Ti seed deposition	Magnetron sputtering (Hybrid Nordiko advanced energy NDX system)	Ti 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step at 1 kW for 1 min. Deposition at 0.3 kW for 4.5 min.	20 nm thick (44 - 46 Å / min)
Cu seed deposition	Magnetron sputtering	Cu 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step @ 1	200 nm

	(Hybrid Nordiko advanced energy NDX system)	kW for 1 min. Deposition at 1 kW for 3.7 min.	(444-446 Å/min)
AZ9260 metal moulding resist	Spin coating (DNS /Screen-track)	Apply PR Clariant AZ 9260 -Layer 1 Spin 1000 rpm-30 sec – leave wafer on a flat surface for 10 min - Hotplate bake: 110°C for 100 sec – delay 10 min to rehydrate. Spin layer 2: same spin program as for layer-1, delay 10 min – hotplate bake: 110°C for 3 min. Leave for 1 hour to rehydrate before exposure.	38 µm thick
	Exposure (EV 420 aligner)	1500 mJ/cm ² in hard contact	
	Development	Puddle develop in AZ 400K at 3:1 (DI: Developer) for 4-6 mins	
Bottom Cu winding Deposition	Automated Cu plating system (Digital Matrix SA/1b)	Rotation/min: 15 rpm, 0.4 A ramp over 3 mins and plated at 0.107 A/hr for 20 µm thickness.	20 µm thick (0.23 µm/min)
AZ9260 removed	Wet bench (Puddle mode)	Resist strip in acetone & Rinse in IPA to clear acetone.	-
AZ9260 metal moulding resist (Via)	Spin coating (DNS /Screen-track)	Apply PR Clariant AZ 9260 -Layer 1 Spin 1000 rpm-30 sec – leave wafer on a flat surface for 10 min - Hotplate bake: 110°C for 100 sec – delay 10 min to rehydrate. Spin layer 2: same spin program as for layer-1, delay 10 min – hotplate bake: 110°C for 3 min. Leave for 1 hour to rehydrate before exposure.	38 µm thick
	Exposure (EV 420 aligner)	1500 mJ/cm ² in hard contact.	
	Development	Puddle develop in AZ 400K at 3:1 (DI: Developer) for 4-6 min.	
Cu Via Deposition	Automated Cu plating system (Digital Matrix SA/1b)	Rotation/min: 15 rpm, 0.4 A ramp over 3 mins and plated at 0.08 A/hr for 15 µm thickness.	15 µm thick (0.23 µm/min)

Cu seed etch	Wet bench (Puddle mode)	Cu seed etch in 200 gm of Ammonium persulphate in 1 L DI water.	0.2 $\mu\text{m}/\text{min}$
Ti seed etch	Wet bench (Puddle mode)	Etching done in BOE solution. Etch time <10 secs.	2 nm /sec
SU-8 (Inter-metal deposition)	Spin coating (DNS /Screen-track)	Apply photoresist NANOTM SU- 8 50 Wait 2 mins; Spin a 2000 rpm for 30 sec, Prebake: ramp up to 65 °C, wait for 10 min, ramp up to 95 °C leave for 30 min, ramp down slowly to room temperature. Allow 1 hour for wafer to rest before exposure.	40 μm (Thickness)
	Exposure (EV 420 aligner)	Exposure dose: 400 mJ/cm ² .	
	Development	Post Exposure Bake: ramp up to 65 °C, wait for 1 min, ramp up to 95 °C, leave for 10 min, ramp down to room temperature, Leave overnight. Development in EC solvent (PGMEA). Dry under compressed N ₂ . Post-bake on a ramped hotplate at 95 °C for 2 min.	
Ti seed deposition	Magnetron sputtering (Hybrid Nordiko advanced energy NDX system)	Ti 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step at 1 kW for 1 min. Deposition at 0.3 kW for 4.5 min.	20 nm thick (44 - 46 Å / min)
Ni₈₁Fe₁₉ seed deposition	Magnetron sputtering (Hybrid Nordiko advanced energy NDX system)	NiFe 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step at 1 kW for 1 min. Deposition at 1 kW for 4 min.	100 nm thick (233-245 Å / min)
Ni₄₅Fe₅₅ deposition	In-house electroplating system	Details given in appendix-B.	3.5 μm (550 Å/min)
SU-8 (Inter-metal deposition)	Spin coating (DNS /Screen-track)	Apply photoresist NANOTM SU- 8 50 Wait 2 mins; Spin a 2000 rpm for 30 sec, Prebake: ramp up to 65 °C, wait for 10 min, ramp up to 95 °C leave for 30 min, ramp down slowly to room temperature.	50 μm (Thickness)

		Allow 1 hour for wafer to rest before exposure.	
	Exposure (EV 420 aligner)	Exposure dose: 400 mJ/cm ² .	
	Development	Post Exposure Bake: ramp up to 65 °C, wait for 1 min, ramp up to 95 °C, leave for 10 min, ramp down to room temperature, Leave overnight. Development in EC solvent (PGMEA). Dry under compressed N ₂ . Post-bake on a ramped hotplate at 95 °C for 2 min.	
Ni₈₁Fe₁₉ etching	Wet bench (Puddle mode)	Details of etchant given in appendix-B.	Lateral etch: 15 µm (max.).
Ti seed deposition	Magnetron sputtering (Hybrid Nordiko advanced energy NDX system)	Ti 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step at 1 kW for 1 min. Deposition at 0.3 kW for 4.5 min.	20 nm thick (44 - 46 Å / min)
Cu seed deposition	Magnetron sputtering (Hybrid Nordiko advanced energy NDX system)	Cu 8-inch target, Ar gas at 0.004 mbar pressure. Initial RF roughening step @ 1 kW for 1 min. Deposition at 1 kW for 3.7 min.	200 nm (444-446 Å/min)
THB-151N metal moulding resist	Spin coating (DNS /Screen-track)	Details of the recipe given in appendix-B.	90 µm thick
	Exposure (Karl Suss MA6 system)	1100 mJ/cm ² in hard contact in 32 mW/cm ²	
	Development	Puddle develop in TMA238WA solution for 9-15 mins.	
Top Cu winding Deposition	Automated Cu plating system (Digital Matrix SA/1b)	Rotation/min: 15 rpm, 0.4 A ramp over 3 mins and plated at 0.107 A/hr for 20 µm thickness.	20-25 µm thick (0.23 µm /min)
Cu seed etch	Wet bench	Cu seed etch in 200 gm of Ammonium persulphate in 1 L DI water.	0.2 µm/min

	(Puddle mode)		
Ti seed etch	Wet bench (Puddle mode)	Etching done in BOE solution. Etch time <10 secs.	2 nm /sec

V. Appendix

a. $Ni_{45}Fe_{55}$ electroplating bath composition

Materials	gms / L	Specifications
$NiCl_2 \cdot 6H_2O$	450	Metal salt of the metal to be deposited for flow of electricity (Sigma Aldrich)
$FeCl_2 \cdot 4H_2O$	26	Metal salt of the metal to be deposited for flow of electricity (Sigma Aldrich)
Boric acid	75	Increases conductivity and act as a buffer to maintain the pH (Sigma Aldrich)
Saccharin	15	Reduces film stress and grain refiner (Sigma Aldrich)
1, 3, 6 - Naphthalene Trisulphonic acid	12	Brightening agent (Sigma Aldrich)
Sulfosalicylic acid	15	Complexing agent to eliminate precipitation (Sigma Aldrich)
Triton X-100	1.5	Smoother and continuous surface morphology (Sigma Aldrich)
NaOH pellets	-	Added periodically to increase the pH to 2.5 (Sigma Aldrich)
Dilute HCl (1:10)	37%	Added periodically reduce the pH to 2.5 (Sigma Aldrich)
Pulse-Reverse-Current waveform	-	Forward current: 550 mA and forward time: 18.4 m-secs
		Off time: 0.5 m-secs
		Reverse Current: 3.85 A and reverse time: 0.6 m-secs
		Off time: 0.5 m-secs
pH and temperature	-	2.5 and room temperature

b. THB-151N Metal Moulding Photoresist Recipe

Thickness: $82.5 \mu m \pm 2.5 \mu m$

Steps	Values
THB 151N Dispensed	The resist covers 50% of the total wafer surface area at room temperature.
Wait time	5 mins on a flat surface

Spin Coating	300 rpm / 25 secs + No Spin / 30 secs + 300 rpm / 10 secs + 650 rpm / 30 secs (main speed)
Wait time	10 mins on a flat surface
1st Soft Bake	Ramp up to 130 °C / 10 mins on standard hot-plate and down to room temperature
Cooling Time	20 mins on flat surface
Exposure Dose (mJ/cm²)	1100 mJ/cm ² (Hard contact and high intensity i-g-h bulb: 32 mW/cm ²)
Waiting Time	30 mins
Development Time	9-15 mins (high process margin)
Thickness Obtained	82.5 µm ± 2.5 µm (flat surface) 90 µm ± 3 µm (patterned surface)

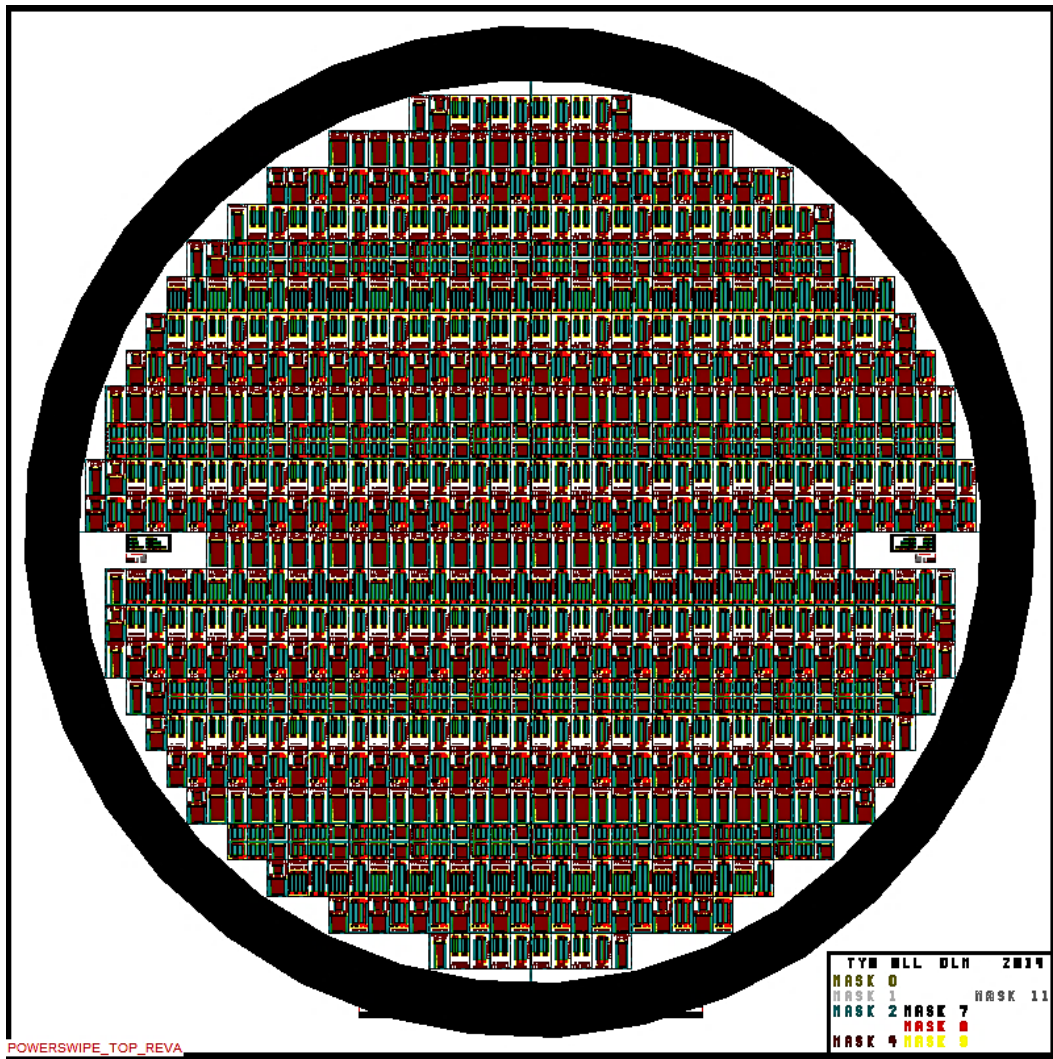
Thickness: 52.5 µm ± 2.5 µm

Steps	Values
THB 151N Dispensed	The resist covers 50% of the total wafer surface area at room temperature.
Wait time	5 mins on a flat surface
Spin Coating	300 rpm / 25 secs + No Spin / 30secs + 300 rpm / 10secs + 1100 rpm / 30secs (main speed)
Wait time	10 mins on a flat surface
1st Soft Bake	Ramp up to 130 °C /5 mins on standard hot-plate and down to room temperature
Cooling Time	20 mins on flat surface
Exposure Dose (mJ/cm²)	700 mJ/cm ²
Waiting Time	20 mins
Development Time	4-6 mins
Thickness Obtained	52.5 µm ± 2.5 µm (flat surface)

Thickness: 32.5 µm ± 2.5 µm

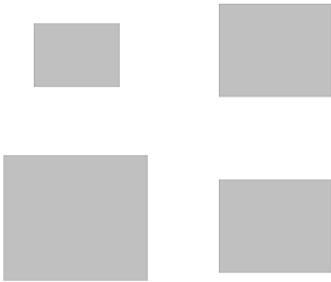
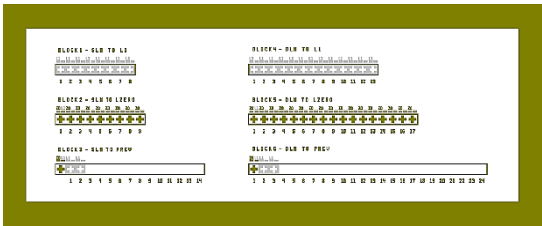
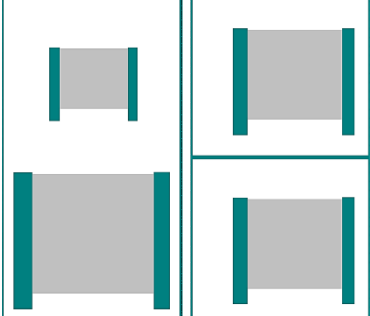
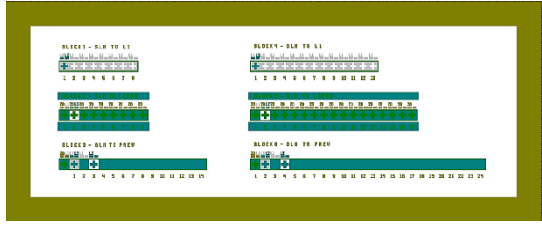
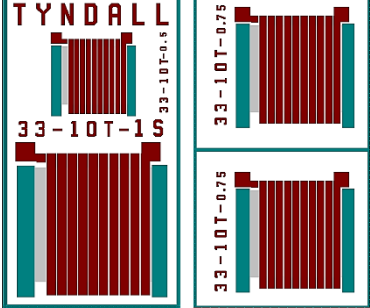
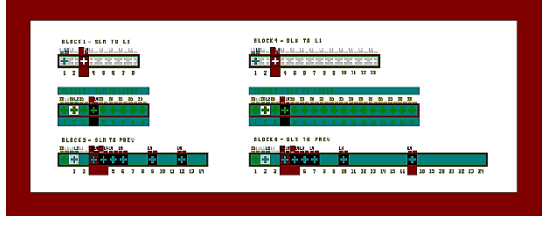
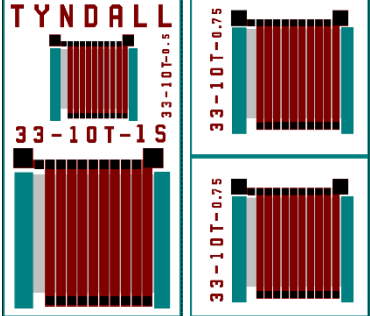
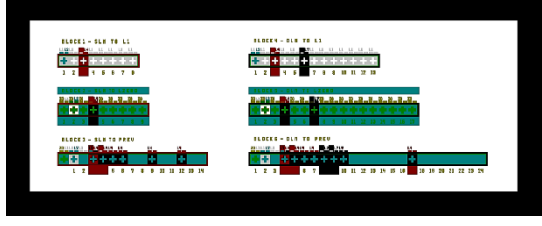
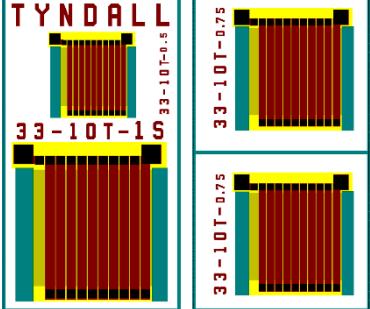
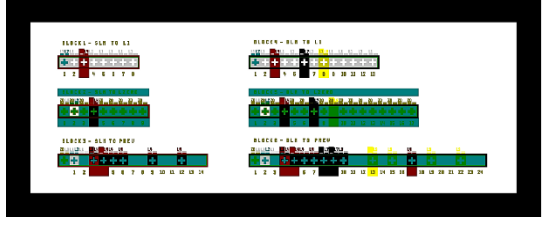
Steps	Values
THB 151N Dispensed	The resist covers 50% of the total wafer surface area at room temperature.
Wait time	5 mins on a flat surface
Spin Coating	300 rpm / 25 secs + No Spin / 30 secs + 300 rpm / 10 secs + 2000 rpm / 30 secs (main speed)
Wait time	10 mins on a flat surface
1st Soft Bake	Ramp up to 120 °C /5 mins on standard hot-plate and down to room temperature
Cooling Time	20 mins on flat surface
Exposure Dose (mJ/cm²)	550 mJ/cm ²
Waiting Time	10 mins
Development Time	5-7 mins
Thickness Obtained	32.5 µm ± 2.5 µm (flat surface)

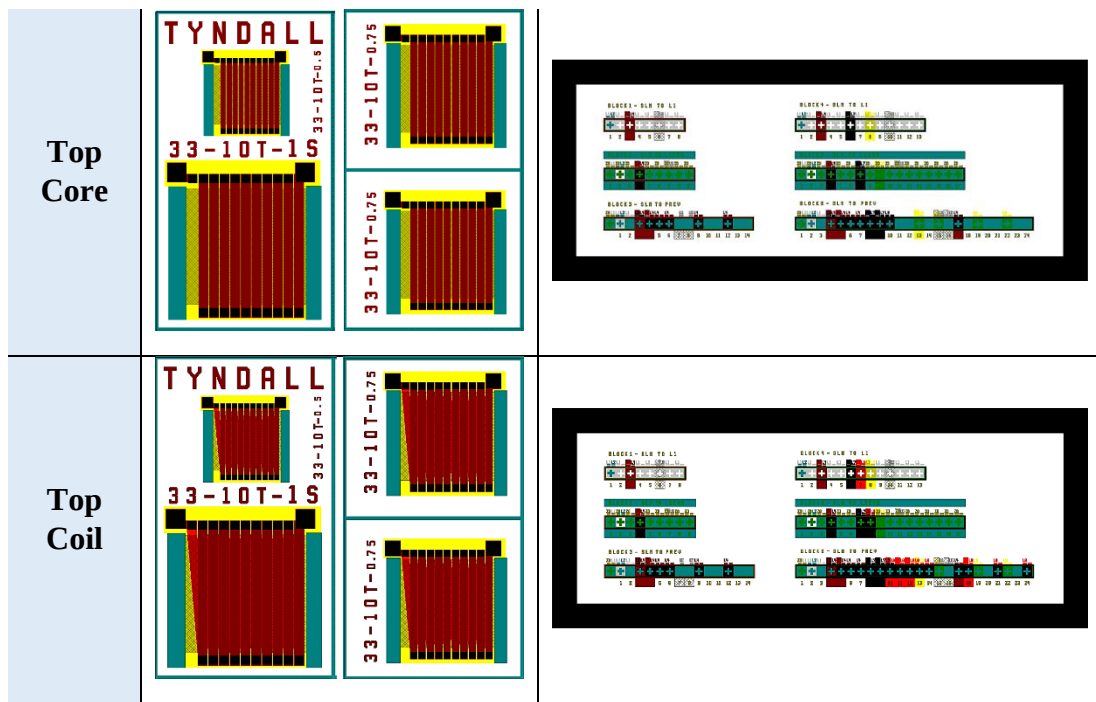
c. Mask Layouts



780 devices in a wafer

Process	Device Layout	Alignment Marks
Zero Level	The diagram shows a 2x2 grid of blocks, each containing an 8x8 grid of cells. The blocks are labeled as follows: BLOCK1 - SLN TO L1: An empty 8x8 grid. BLOCK2 - SLN TO LZERO: An 8x8 grid where the first row is filled with yellow crosses. BLOCK3 - SLN TO PREU: An 8x8 grid where the first row is filled with yellow crosses. BLOCK4 - DLN TO L1: An empty 8x8 grid. Each grid has a header row with numbers 1 through 8, and a footer row with numbers 1 through 8.	

Bottom Core		
BCB (IMD)		
Bottom Coil		
Via		
SU-8		



Bottom Core



BCB (Inter-layer-dielectric)



Bottom coil



Via



SU-8 (Inter-metal-dielectric)



Top Core



Top coil

VI. Appendix

a. Dielectric (SU-8, BCB and Parylene-C) Surface Activation

Process Steps	Standard cleaning: Acetone, IPA and DI
Surface preparation	Oxygen plasma asher: 100 W / 5 mins
Self-assembled monolayer activation	Prepare a 50ml solution with 46.5 ml Ethanol + 2.5 ml DI water.
	Add 1 ml 3-Aminopropyltrimethoxysilane (APTES) to the solution for 2% APTES solution (pH: 5).
	Immerse the samples in the APTES solution for 25 mins.
	Remove excess SAM in ethanol solution for 5 mins in sonicator.
	Bake in oven for 30 mins for 120 °C.
Palladium Catalyzation	Prepare palladium solution: 0.0125 gms PdCl ₂ , 1.5 mls HCl in 2 mls Triton X-100 in 50ml solution.
	Immerse wafer/sample to PdCl ₂ solution for 2 minute at 65°C.

VII. Appendix

a. Closed-core solenoid Mathematica model

(** Input Parameters**)

$U0=4*\pi*10^{-7};$

$Ur=280;$

$Coreresist=45*10^{-8};$

$Curesist=1.74*10^{-8};$

$tc = 25*10^{-6};$

$ti = 15*10^{-6};$

$tt = 50*10^{-6};$

$gap = 20*10^{-6};$

$f = 20*10^{-6};$

$viawidth = Wc;$

$footprint = 0.75*10^{-6};$

$tm = 3.5*10^{-6};$

$Wc = 53*10^{-6};$

(**corelength = $(Nr+1)*Wc+Nr*gap$;**)

$corelength = 860*10^{-6};$

$corewidth = 580*10^{-6};$

$Inductance = Nr^2*U0*Ur*corewidth*tm/corelength/2;$

(** Solve Parameters**)

Do [Nr=n;

(** $Wc=(4\ gap\ Inductance\ Nr+4\ gap\ Inductance\ Nr^2+2\ gap\ Nr^2\ tm\ U0\ Ur+2\ gap\ Nr^3\ tm\ U0\ Ur+2\ Nr^2\ tc\ tm\ U0\ Ur+2\ Nr^3\ tc\ tm\ U0\ Ur-\sqrt{(-4\ gap\ Inductance\ Nr-4\ gap\ Inductance\ Nr^2-2\ gap\ Nr^2\ tm\ U0\ Ur-2\ gap\ Nr^3\ tm\ U0\ Ur-2\ Nr^2\ tc\ tm\ U0\ Ur-2\ Nr^3\ tc\ tm\ U0\ Ur)^2-4\ (-2\ Inductance-4\ Inductance\ Nr-2\ Inductance\ Nr^2)\ (-2\ gap^2\ Inductance\ Nr^2+footprint\ Nr^2\ tm\ U0\ Ur-2\ gap^2\ Nr^3\ tm\ U0\ Ur-2\ gap\ Nr^3\ tc\ tm\ U0\ Ur)})/(2\ (-2\ Inductance-4\ Inductance\ Nr-2\ Inductance\ Nr^2))/N$;**)

(* $corewidth=footprint/(corelength)-2*tc-2*gap$;)*)

```

Rdc=Nr*Curesist*(corelength+2*gap+tc+tm+ti+tt)*2/Wc/tc;
B = (U0*Ur*Nr*500*10-3)/(2*corewidth+2*tt);
(*assuming current=500 mA*)
Inductance=Nr2*U0*Ur*corewidth*tm/corelength/2;
Print ["Nr=",Nr,"   Wc=",Wc,"   Rdc=",Rdc, "   Inductance=",Inductance, "
corelength=", corelength, "   corewidth=", corewidth, "   B=", B],

{n,1,20}]

```

```

Nr = 1   Wc = 53/1000000   Rdc = 0.02207   Inductance = 5.4476*10-10 B = 0.09106
Nr = 2   Wc = 53/1000000   Rdc = 0.04414   Inductance = 2.17907*10-9 B = 0.18212
Nr = 3   Wc = 53/1000000   Rdc = 0.06621   Inductance = 4.9029*10-9 B = 0.27318
Nr = 4   Wc = 53/1000000   Rdc = 0.08829   Inductance = 8.71627*10-9 B = 0.36424
Nr = 5   Wc = 53/1000000   Rdc = 0.11036   Inductance = 1.36192*10-8 B = 0.4553
Nr = 6   Wc = 53/1000000   Rdc = 0.13243   Inductance = 1.96116*10-8 B = 0.54636
Nr = 7   Wc = 53/1000000   Rdc = 0.15451   Inductance = 2.66936*10-8 B = 0.63742
Nr = 8   Wc = 53/1000000   Rdc = 0.17658   Inductance = 3.48651*10-8 B = 0.72848
Nr = 9   Wc = 53/1000000   Rdc = 0.19865   Inductance = 4.41261*10-8 B=0.81954
Nr = 10  Wc = 53/1000000   Rdc = 0.22072   Inductance = 5.44767*10-8 B=0.9106
Nr = 11  Wc = 53/1000000   Rdc = 0.24280   Inductance = 6.59168*10-8 B=1.00166
Nr = 12  Wc = 53/1000000   Rdc = 0.26487   Inductance = 7.84464*10-8 B=1.09272
Nr = 13  Wc = 53/1000000   Rdc = 0.28694   Inductance = 9.20656*10-8 B = 1.18378
Nr = 14  Wc = 53/1000000   Rdc = 0.30902   Inductance = 1.06774*10-7 B = 1.27484
Nr = 15  Wc = 53/1000000   Rdc = 0.33109   Inductance = 1.22573*10-7 B = 1.3659
Nr = 16  Wc = 53/1000000   Rdc = 0.35316   Inductance = 1.39460*10-7 B = 1.45696
Nr = 17  Wc = 53/1000000   Rdc = 0.37523   Inductance = 1.57438*10-7 B = 1.54802
Nr = 18  Wc = 53/1000000   Rdc = 0.39731   Inductance = 1.76504*10-7 B = 1.63908
Nr = 19  Wc = 53/1000000   Rdc = 0.41938   Inductance = 1.96661*10-7 B = 1.73014
Nr = 20  Wc = 53/1000000   Rdc = 0.44145   Inductance = 2.17907*10-7 B = 1.8212

```