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MEMS based Fabrication of High Frequency Integrated Inductors on Ni-Cu-Zn Ferrite Substrates

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Highlights: Material Characterization of Ni-Cu-Zn ferrite substrate and process developed for on-ferrite integrated micro-inductor fabrication.

Abstract: A surface micro-machining process is described to realize planar inductors on ferrite \((\text{Ni}_{0.49}\text{Zn}_{0.33}\text{Cu}_{0.18}\text{Fe}_2\text{O}_4)\) for high frequency applications (< 30 MHz). The highly resistive nature (~ \(10^8 \) Ω-m) of the Ni-Cu-Zn substrate allows direct conductor patterning by electroplating of Cu windings through a photoresist mould on a sputtered seed layer and eliminates the need for a dielectric layer to isolate the windings from the bottom magnetic core. Measured inductances ~ 367 nH (DC resistance ~ 1.16 Ω and Q-value >14 at 30 MHz) and ~ 244 nH (DC resistance ~ 0.86 Ω and Q-Value ~ 18 at 30 MHz) at 1 MHz for elongated racetrack (10.75 nH/mm²) and racetrack inductors (12.5 nH/mm²), respectively show good agreement with simulated finite element method analysis. This device can be integrated with power management ICs PMICs for cost-effective, high performance realization of power-supply in package (PSiP) or on-chip (PSoC). This simple process lays the foundation for fabricating closed core ferrite nano-crystalline core micro-inductors.
1. Introduction

In the last two decades there has been considerable progress integrating soft magnetic materials with complementary metal oxide semiconductor (CMOS) based processes to achieve inductor/transformer solutions for DC-DC converter circuitry [1-3]. An insulating layer is required to isolate the soft magnetic core from the copper windings. This introduces additional stray capacitance which reduces the operation frequency. Moreover, most soft magnetic materials (Co-Ni-Fe alloys) being conductive in nature contribute to core eddy current losses [4]. This limits the thickness of the core material to be deposited as determined by the skin depth for a specific operation frequency. An alternative method to eliminate these inherent limitations would be utilise ferrite core based inductors. Although there has been considerable research on ferrite core inductors and transformers with a packaged ferrite core [5-6] very few reports are available to address fully integrated ferrite core solutions [7-9]. Integrating ferrite materials in a CMOS compatible process remains a significant challenge. Moreover, low saturation flux densities restrict its application to low current ratings.

Ferrites not uniformly magnetized and have small areas with magnetic moments oriented in the same direction called Weiss domains. These are separated from neighbouring domains by Bloch walls. The magnetization of the moments either due to displacement of Bloch walls (Globus-Guyot mechanism [10]) or rotation of magnetic moments (Snoek mechanism [11]) depends on the frequency of operation. The properties of soft ferrites (such as Mn-Zn, Ni-Zn and Ni-Cu-Zn) is determined by the material composition and the sintering process. Figure 1, depicts the inductance density vs. Q-values of integrated ferrite micro-inductors for high frequency applications. It is important to note that, NiZn based are the most widely used ferrites for high initial permeability and functional frequency in > 1 MHz applications. Previous attempts include surface mounting ferrites on Si substrates with Cu windings [12] or wire-bonded windings with ferrite-epoxy glob cores [13] on the IC to realize PSiP. Other approaches include ferrite cores co-packaged with solenoid bonded wires [5]. Although high inductance densities have been achieved using such routes, a completely integrated solution still remains a major challenge for ferrite based micro-inductors. Previously reported integrated micro-inductor have suggested low Q-values (<12 at 80 MHz) and inductance densities (2.8 nH/mm²) [14].
LTCC (low temperature co-fired ceramics) [20-21] ferrites have provided a partial solution to this issue. LTCC processing allows ferrite particles to blend with ceramic ferrites stacked on a desired substrate and fired under high pressure conditions. As a result LTCC ceramic technology can be employed to achieve a high level of integration. However, wafer shaped ceramic ferrites along with surface micro-machining processes would enable CMOS based device fabrication integrated for low power-high current conversion applications. In this work, we provide such a solution with MEMS based process to achieve an integrated micro-inductor fabrication on Ni-Cu-Zn substrates for high frequency power conversion.

2. Experimental Procedure

(a) Material Characterization

In this work, Ni-Cu-Zn based ferrite sintered to form a 10 cm diameter and 1066 µm thick diced substrate (CMD5005 from Ceramic Magnetics, Inc., USA) was chosen [22]. This ferrite material has functional frequencies < 100 MHz with initial permeability < 2000 and resistivity ~ 10^8 Ω-m. Such properties make it ideal for integrated power magnetic component applications (such micro-inductors and micro-transformers). The surface micro-structure was observed in a scanning electron microscope (SEM-Quanta FEG650). From SEM energy dispersive X-ray (EDX) analysis the composition was estimated to be Ni_{0.6}Zn_{0.35}Cu_{0.18}Fe_{2}O_{4}. Figure 2, shows the surface microstructure of closely packed Ni-Cu-Zn ferrite. The surfaces analysis suggests uniformly distributed grains of < 5 µm width.
The crystalline phases were identified by X-ray diffraction (XRD) (Phillips PANalytical X’pert Pro) analysis. Figure 3 shows the XRD analysis of Ni-Cu-Zn ferrite structure. The patterns reveal a cubic spinel Ni-Cu-Zn ferrite (JCPDS NO. 08-0234) phase. This is in accordance with previously reported works on Ni-Cu-Zn ferrites [23-24]. The average crystalline size calculated from $d_{(311)}$ using the Scherrer formula was $\sim 34$ nm. The high level of crystallization as evident from the peak can be attributed to the high temperatures (usually between 950 °C and 1350 °C) required in the preparation of these ferrites [25-26].

The ferrite wafer is subjected to an external magnetic field ($H > 200$ Oe ($\sim 15.9$ KA/m)) at $\sim 10$ Hz at room temperature to ensure that the material is completely saturated. The static B-H characteristic is shown in figure 4. The hysteresis characteristic suggests a coercivity of $\sim 1.95$ Oe ($\sim 155$ A/m) and saturation flux density ($B_{sat}$) $\sim 0.37$ T (also validated from the datasheet). Low $B_{sat}$ restricts ferrite core
inductors to low current applications. It is important to note that ferrite exhibits low core eddy current losses, but also poor saturation flux density by comparison with nano-crystalline materials (Ni, Fe and Co based) which have saturation flux densities $> 1$ T.

Figure 4. Static hysteresis curve of a 1066 µm thick ferrite wafer (full 10 cm diameter NiCuZn wafer in inset).

Figure 5. Permeability response of 50 µm thick Ni-Cu-Zn sample (3.5 x 3.5 mm$^2$) at null field strength.

Figure 5 depicts the initial permeability response to frequency (10 MHz - 9 GHz) of a 50 µm thick and 3.5 x 3.5 mm$^2$ Ni-Cu-Zn sample. It is known that ferrite material with ‘σ’ inner stress have the initial permeability dependencies ($\mu_i$) given by [27]:

\[ \mu_i = \frac{1}{\mu_0} \frac{B}{H} \]

Figure 5. Permeability response of 50 µm thick Ni-Cu-Zn sample (3.5 x 3.5 mm$^2$) at null field strength.
Initial permeability ($\mu_i$) $\propto \frac{M_S^2 G_s}{nK + b\sigma\lambda_s}$ (1)

where, $M_s$ is the saturation magnetization, $G_s$ is the grain size, $K$ is the magneto-crystalline anisotropy constant and $\lambda_s$ is the magnetostriction constant.

Based on equation 1 this suggests that small grain size and low saturation magnetization reduces the initial permeability of the sample. Although initial permeability at 10 kHz from the product datasheet is >2000. The measured initial permeability at 10 MHz of the 50 µm thinned Ni-Cu-Zn sample suggested an initial permeability of ~ 140 is in agreement with the material datasheet. Increasing the ZnO content during the sintering process delivers high initial permeability [28]. As observed from the initial permeability response, unlike nano-crystalline materials (Ni-Co-Fe based alloys) the cut-off frequency of Ni-Cu-Zn far exceeds 200 MHz. Moreover, the ferromagnetic resonant frequency (FMR) peak is > 3 GHz. This is in agreement with previously reported analysis [29].

(b) Fabrication Process

Prior to any processing, the compatibility of the ferrite wafer was established with different wet chemicals to be used in subsequent fabrication steps. Unlike photoresist processes on silicon, ferrite wafers were found to be incompatible with developers containing potassium hydroxide and potassium borates. As a result THB-151N (from JSR Micro) resist and the associated chemicals for processing were selected for the work. The resist developer and removers where found to be compatible with the previously developed wafer based micro-fabrication process-flow. We first rinsed the ferrite wafer in IPA, acetone and DI water followed by nitrogen drying. The wafer was then dehydrate baked on a standard hotplate in a ramp up mode up to 90 ℃ and then maintained for 2 minutes at this temperature. It was followed by 70 nm Ti / 150 nm Cu thin films DC sputtered on the wafer as adhesion and seed layers, respectively (as shown in figure 6 (a)). Thick temporary photoresist THB-151N was spin-coated on a Laurell spinner (Model: WS-400B-6NPP/ LITE-AS) with negative tone acrylic based photoresist THB-151N. The unexposed parts of the wafer were removed with TMA 238WA (a metal ion free developer form JSR Micro) as previously reported [30-31] (figure 6 (b)). A resist thickness of ~ 40 µm was obtained and measured using a Tencor profilometer (P-10).

Figure 7 depicts the microscopic images of the copper conductor winding pattern pads (Figure 7 (a)) and stripes (Figure 7(b)) before resist stripping and copper plating. A dilute sulphuric acid etch was performed to remove the underlying oxide layer on the copper surface. The wafer was electroplated in the defined photoresist pattern in an automated electroplating system (Digital Matrix-SA/1b) at 0.25 A in DC mode to achieve a winding thickness of ~30 µm (figure 6 (d)). The resist was stripped in THB-S17 solution, exposing the underlying Cu seed layer which was removed in an
ammonium-persulphate solution, while the Ti adhesion layer was removed in a brief hydrofluoric acid dip (figure 6 (e)).

Figure 6. Ferrite integrated inductor process flow. (a) Ti/Cu sputtered as seed layer. (b) Moulding resist spin coated, exposed and developed. (c) Copper winding electroplated. (d) Moulding resist stripped and (e) Seed etched.

Figure 7. Winding patterns before seed layer removal. (a) Inductor pads and (b) Winding stripes (70 µm).

This process provides a solution to ferrite integration for high frequency (< 10 MHz) power conversion. The designed device footprint is < 22 mm² for a 5 turn design of elongated racetrack (ERT) (figure 8 (a)) and < 30 mm² for 6 turns of racetrack pattern (RT) (figure 8 (c)). As observed from the figure, the micro-windings are clearly developed and the seed layer fully etched. Considerable resist delamination could be observed on non-planar surfaces and it gets more severe for layouts with smaller patterns. Hence, it is important that a surface is uniform and planar. The cross-section of the integrated inductors depicts the 30 µm thick copper windings on the ferrite substrate. Table–I gives the detailed parameters and specifications of the fabricated micro-inductor on a Ni-Cu-Zn ferrite wafer.
3. Results and Discussion

ANSOFT Maxwell finite element method (FEM) simulations were performed to estimate the inductance and DC resistance of designed inductors with and without ferrite cores. The estimated inductance from elongated racetrack inductors 242 nH inductance (with ~ 0.82 Ω DC resistance) and 6 turn conventional racetrack inductors suggest 370 nH inductance (with ~1.06 Ω DC resistance). Corresponding air-core designs show 202 nH and 308 nH inductances with elongated racetrack and racetrack inductors, respectively. Figure 9 depicts the measured Inductance, Q-value and resistance output of two different planar inductor designs (elongated racetrack and racetrack) on Ni-Cu-Zn wafer measured with an Agilent 4285A precision LCR meter (75 KHz-30 MHz). As shown in figure 9 (a), an initial inductance of ~ 244 nH at 1 MHz can be achieved from the 5 turn elongated inductor with a DC resistance of ~0.87 Ω. While the 6 turn racetrack design has a maximum inductance of ~367 nH with ~1.16 Ω DC resistance (figure 9 (b)). Although the lower permeability of the core material limits the inductance density, it also ensures that the core remains unsaturated. The measured values agree well with the FEM simulated ferrite inductor designs. This increase in inductance (~ 20% from air-core) can be attributed to thicker and low conductive ferrite which allows more flux to be confined in
the core in both devices, and increases inductance density. However, the continued increase in Quality (Q) factor suggests a value beyond 30 MHz for both devices. The inductance decrease at higher frequencies can be attributed to reduction in the Ni-Cu-Zn initial permeability. Inductance densities of 12.24 nH /mm² and 10.67 nH /mm² achieved with the elongated racetrack and racetrack inductors, respectively, are significantly higher (> 6 times) than some of the previously reported integrated ferrite inductors (~ 2 nH/mm²) [18, 20].

![Figure 9. Measured inductance vs. frequency response and Q-value of the fabricated micro-inductors on Ni-Cu-Zn wafer < 30 MHz (a) racetrack and (b) Elongated racetrack inductors.](image)

This process has enabled direct copper deposition on ferrite wafers without the need for an insulating layer. Moreover, this process lays the foundation for fabricating complete closed core inductors with nano-crystalline (Ni-Fe-Co based) magnetic thin film as the top core. This could decrease the process complexity from a conventional 5 mask process on silicon to 3 mask layer steps on ferrite to improve cost and time efficiency. ANSOFT Maxwell FEM simulations suggests ~ 423 nH inductance with 5 turn elongated racetrack inductor and ~554 nH with 6 turn racetrack inductor with nano-crystalline top core (Ni₄₅Fe₅₅; resistivity~ 45 µOhm-cm and initial permeability~ 280), increasing inductance > 80% in both cases. This can be attributed to the closed flux path between the top nano-crystalline core and ferrite substrate. Moreover, such a closed core ferrite-nanocrystalline hybrid inductor would be ideal to maintain stable inductances over a very wide frequency range.

4. Conclusion

A comprehensive MEMS based surface micro-machining process for the fabrication of integrated micro-inductors on ferrite substrates (Ni-Cu-Zn) for < 100 MHz applications has been developed. Compatible wet chemical processes were established for the fabrication of the inductors. The magnetic and structural properties of the ferrite material has been analysed in detail. The ferrite grain size was ~ 34 nm (estimated from XRD analysis). The static BH loop tracer suggested a saturation flux density of 0.37 T. The composition of Ni₀.₄₅Zn₀.₃₅Cu₀.₁₈Fe₂O₄ was derived from EDX analysis. A compatible photoresist (THB-151N) process was developed appropriate to the materials and the
overall fabrication process. Electrical characteristics of the fabricated devices exhibited a linear inductance response < 30 MHz. An initial inductance of ~367 nH and ~244 nH was measured on racetrack and elongated racetrack inductors, respectively. Moreover, the maximum Q-value of ~14 and ~18 were measured at 30 MHz for those designs. We achieved inductance densities of ~12.24 nH/mm² and ~10.67 nH/mm² with racetrack and elongated racetrack devices, respectively. Future work will focus on integrating a top core with nano-crystalline material to realise completely closed core integrated magnetic micro-inductors.

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[22] CMD5005 Datasheet (www.magneticsgroup.com/pdf/CMD5005.pdf)


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