Improved high permeability CoZrTaB laminated thin films with novel CMOS compatible dielectric material

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This paper present an optimized CoZrTaB-based laminated thin films with a novel wet etch-able oxide dielectric material. Wet etching capability was studied on the stack material exhibiting a narrow and clean undercut. Good uniaxial anisotropy with low coercivity was achieved via in-situ magnetic alignment during magnetron sputtering. Permeability of 432 and Q-factor of 23.4 at 100 MHz were observed in high frequency permeameter measurement. Finally thermal annealing was carried out at various temperatures. Uniaxial anisotropy was maintained up to 300 °C, while an enhancement of permeability (by 25%) was observed.

***Index Terms*—CMOS compatible, high permeability, high frequency soft magnetic material, inductor,**

I. Introduction

The on-going trend toward miniaturization of granular power electronic products with ever-increasing performance has stimulated the demand on the development of novel high performance magnetic materials systems compatible with the CMOS microfabrication processes in integrated magnetics technology [1]. Integrated inductors with high permeability and low coercivity magnetic materials will generate a significant enhancement on the inductance density within a small footprint [2]. Eddy current loss in magnetic core become dominant at the higher MHz frequency range. Laminated structures, consisting of multiple thin magnetic layers separated by dielectric and pattering have been shown to successfully improve the high frequency losses or the quality factors (Q-factor). Sputtering deposition has been widely used to deposit magnetic thin films compatible with the CMOS back-end-of-line (BEOL) process [1]. Most commonly used materials are NiFe-based [3] and Cobalt-based [4]-[6] systems with different dielectric materials (aluminum nitride, sputtered oxides etc.).

In this paper, a novel wet etch-able oxide dielectric material CoZrTaB oxide (O-CZTB) was developed. A laminated thin film structure was produced by alternate sputtering of CZTB and OCZTB layers. DC characterization showed good uniaxial anisotropy with low coercivity. Permeability spectrum testing showed a permeability of 432 and a Q-factor of 23.4 at 100MHz. The results of a thermal annealing study are also discussed.

II. Experimental Details

A. Fabrication and Characterization tool

Amorphous $Co_{84}Zr_4Ta_4B_8$ (atomic %) multilayer thin films were deposited by magnetron sputtering (Lesker PVD model CMS-18HV) from a 3-inch single alloy target (99.9% purity). The sputtering chamber was pumped down to a base pressure of 10-7 Torr, and then argon gas was introduced resulting in a sputtering pressure of 5 mTorr to start deposition of the CZTB magnetic films. The deposition of the films was carried out in an applied magnetic field with homogeneous distribution across a Si (100) wafer (p-type, 4 inch), which was created by custom designed permanent magnets fixed to chamber.

A thermal oxide layer SiO_2 of 250 nm thickness was grown on the Silicon wafers as an insulator, then a 20 nm thick adhesion layer of Ti was sputtered before the deposition of the magnetic films. During the sputtering of magnetic layers, a DC power of 500 watts was applied to the CZTB sputter target. On top of each magnetic layer, novel thin oxide dielectric layers (O-CZTB) was produced by the reactive sputtering from the CoZrTaB target and O_2 gas. The deposition process of the dielectric layer was optimized in order to have high resistivity, low stress and good uniformity in film thicknesses (4.5% standard deviation) across the wafer. The developed O-CZTB have good insulation properties with a measured resistivity of ~10^9 μΩ.cm using the standard four-probe technique. Surface roughness was characterized using AFM (Bruker Dimension Icon). The root mean square roughness (Rq) of O-CZTB single layers were measured over a 10 μm × 10 μm scan area, and are shown in Fig. 1. As the thickness increases, Rq also increases but remains at a small value, indicating a smooth surface texture of the O-CZTB material.

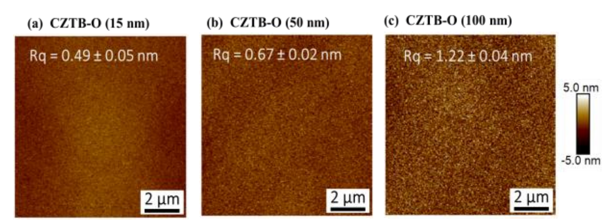

Fig. 1. AFM images of OCZTB single layers with thickness 15nm (a), 50nm (b) and 100nm (c).

Magnetic laminated thin films (1 μm) were developed by alternate layers of CZTB (100 nm) and O-CZTB (15nm). The amorphous structural properties of the films were investigated by X-ray diffraction (XRD, Philips Xpert diffractometer, Cu Kα-1.54 Å) with no crystalline peaks. The soft magnetic properties were investigated using a B-H hysteresis loop tracer (SHB, MESA 200 HF) at room temperature. The high-frequency (3 MHz – 4 GHz) permeability of films was measured using 4 mm × 4 mm samples by employing Ryowa PMM-9G Permeameter.

B. *Wet etching process*

A thick magnetic lamination stack (2 µm) was deposited by alternative layers of CZTB (100 nm) and O-CZTB (15nm), in order to test the wet etching capability. Each CZTB layer is 100 nm while thickness of the O-CZTB dielectric material is 15 nm. A standard photolithography patterning process was applied on the wafer. Then the 4-inch wafer was laser diced into a couple of coupons for wet etching process optimization. A mixture of acid etching agent was developed. Patterning schematic diagram is shown in Fig. 2, with optical top view and SEM cross section images. A clear undercut of ~ 14 µm with good vertical etching sidewall can be observed.

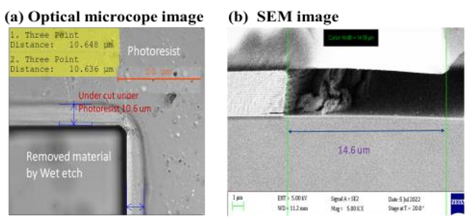

Fig. 2. a) Optical top view of the sample after etching b) SEM image of the cross section of the etched sample.

III. Data and Discussion

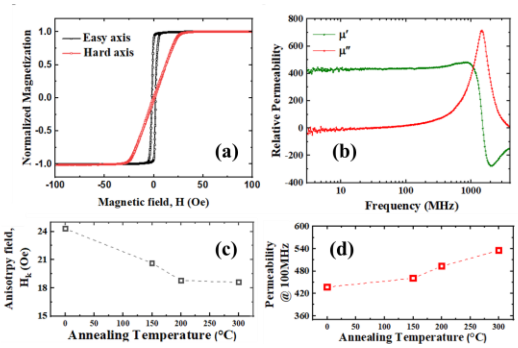

Fig. 3. a) BH loop measurements b) Permeability spectrum from 3MHz to 4GHa, c) anisotropy field H_k and d) permeability (at 100MHz) variation according to simple annealing temperature.

TABLE I

Summary of Sputtered Magnetic Materials Used as Laminated Core

Magnetic Materials	Dielectric	Stack thickness (µm)	µ	Frequency (MHz)
Co-based [5]	Oxide	~ 5	800	
CoZrTa [8]	Oxide	4	800	30
CoZrTa [9]	Al2O3	1.6	600	50-100
CoZrTa [10]	CoO	~ 4	400	100
CoZrTaB *	O-CZTB	1	432	100
CoZrTaB [6]	AlN	4	350	40
CoFeB [11]	SiO2	0.4	700	20
NiFe [3]	SiO2	3.5	600	20

* refer to the data in this work. µ refer to the permeability.

Easy and hard magnetic anisotropy axis hysteresis loops of the CZTB multilayer films were presented in Fig. 3-a. Overlapping behavior of positive and negative external magnetic field sweeps in the hard axis B-H loops were observed (low coercivity of 0.72 Oe), confirming uniaxial magnetic anisotropy were successfully induced. Thus a magnetic anisotropy field (H_k) strength of 24.3 Oe can be abstracted using the Stoner-Wohlfarth model considering a single anisotropy [7]. Good soft magnetic properties can result in coherent magnetic rotation during frequency excitation, and hence is very beneficial in order to have the material working at high frequency with low losses. Frequency dispersion of complex permeability µ(*f*) spectra were shown in Fig. 3-b, with µ' representing the real part while µ" the imaginary part. A permeability of 432 can be observed up to 100 MHz, with a good Q-factor of 24.3. Table 1 shows the comparison summary of sputtered magnetic core in recent years. As-deposited samples were then thermal annealed at temperatures from 150 to 300 °C (Fig. 3-c, d). Uniaxial anisotropy remained up to 300°C. As annealing temperature increased, H_k decreased while permeability increased (up to 25% at 300 °C).

IV. Conclusions

In this work, a new oxide dielectric material (O-CZTB) was developed along with good wet etching capability. CoZrTaB laminated thin films together with O-CZTB material were then sputtered as demonstration. Good uniaxial anisotropy with low coercivity of 0.72 Oe was tested. A permeability of 432 and Q-factor of 24.3 was observed at 100MHz. Finally, simple thermal annealing treatments were done between 150 to 300 °C. Permeability enhancement of 25% was observed after annealing at 300 °C.

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