Magnetic properties of electroplated nano/microgranular NiFe thin films for rf application

Y. Zhuang, M. Vroubel, B. Rejaei, and J. N. Burghartz

Laboratory of High-Frequency Technology and Components, Delft University of Technology, Mekelweg 4, 2600 GA Delft, The Netherlands

K. Attenborough
OnStream Microsystems Technology (MST), Lodewijkstraat 1, Eindhoven, The Netherlands

(Received on 10 November 2004; published online 17 May 2005)

A granular NiFe thin film with large in-plane magnetic anisotropy and high ferromagnetic-resonance frequency developed for radio-frequency integrated circuit (IC) applications is presented. During the deposition, three-dimensional (3D) growth occurs, yielding NiFe grains (φ ~ 1.0 μm). Nanonuclei (φ ~ 30–50 nm) are observed in single NiFe grains by atomic-force microscopy (AFM). The in-plane magnetic anisotropy is estimated to be ~50 mT. The frequency-dependent complex permeability is extracted. By taking the NiFe film as a magnetic core, solenoid-type inductors are fabricated and demonstrated and show a high operating frequency (~5.5 GHz) with a maximum quality factor (~3). © 2005 American Institute of Physics.

EXPERIMENTS

The cores of the solenoidal inductors were NiFe thin films electroplated on 0.1-μm-thick Ti and 0.1-μm-thick Cr seed layers, respectively. The plating was carried out in an external magnetic field (80 mT) with a current density of 4 mA/cm² for 5 min. The resulting thickness and composition were 1.0 μm, Fe-29.1%, Ni-71.9% for Ti seed and 0.5 μm, Fe-16.3%, Ni-83.7% for Cr seed, respectively. During the deposition, three-dimensional (3D) growth occurred when the NiFe film was deposited on Ti seed, yielding the NiFe grains (φ ~ 1.0 μm), while the NiFe film on Cr seed exhibited a smooth surface topography [Figs. 1 (a) and 1(b)]. Nanosized nuclei (30–50 nm) were observed on single NiFe grains by atomic force microscopy (AFM) [Fig. 1 (a-I), (a-II), and (a-III)].

FIG. 1. Micrograph of surface morphology of NiFe/Ti core (a), and NiFe/Cr core (b). Scanning electron microscopy micrographs (a-I) and (a-II) and atomic force microscopy graph (a-III) demonstrated the nodular granular growth. (c) Top view of the four-turn solenoid inductor with line width, line spacing, and core size of 6 μm, 10 μm, and 60×120 μm², respectively.
II, and (a-III)]. Magnetic $M$-$H$ loop measurements were performed on a Princeton AGM2900 test apparatus. Microstrip lines were fabricated on a Si substrate to extract the frequency dependency of the complex permeability. On-chip four-turn solenoidal inductors with NiFe/Ti, NiFe/Cr, and SiO$_2$ dummy cores were fabricated by using a CMOS-compatible process described in Ref. 8. The width and spacing of the lines of solenoid coil were 6 and 10 $\mu$m, respectively, and the core size was $60 \times 120 \mu m^2$ [Fig. 1(c)]. Inductor measurements were carried out on an Agilent network analyzer (HP 8510).

**DISCUSSION**

The granular NiFe/Ti ($200 \times 2000 \mu m^2$) exhibited a much smaller magnetic anisotropy $H_k$ in the plane of the film, than in the direction normal to the film, as shown in Fig. 2(a). The $M$-$H$ loop measurements performed in the film plane at different azimuth angles from 0° to 180° (30° steps) turned out to be identical. This indicates that the in-plane magnetization of the micro/nanosized grains is randomly distributed. In this case, the $M$-$H$ loop represents an average of the magnetization over the assembly of the micro/nanosized grains. From the almost linear relationship between the magnetization ($M$) and the applied magnetic field ($H$) [line AB in the inset of Fig. 2(a)], the anisotropy field $H_k$ was estimated to be $\sim 50$ mT by extrapolation of the line AB. The reasons of the observed large anisotropy field of the granular film are very likely related to the selected seed layer, the initial condition of plating, and the nanosized fine structure in the grains. From the slope of the line AB, a dc permeability $\mu_{dc}$ of about ten was estimated. For comparison, measurements of a uniform NiFe film plated on the Cr seed were also performed [Fig. 2(b)]. Here, well-defined magnetic easy and hard axes were observed with $H_k \sim 5$ mT and $\mu_{dc} \sim 260$.

**FIG. 2.** The $M$-$H$ loop measurements of (a) NiFe/Ti core ($200 \times 2000 \mu m^2$), and (b) NiFe/Cr core ($200 \times 2000 \mu m^2$). A high internal magnetic anisotropy field $H_k$ was obtained from the NiFe/Ti core, which is ten times higher than that of the NiFe/Cr core. Clear magnetic easy and hard axes were observed on the NiFe/Cr core.

The frequency-dependent real ($\mu_{real}$) and imaginary ($\mu_{imag}$) parts of permeability was extracted and shown in Fig. 3. In order to extract the permeability, microstrip structures with 50-$\mu$m-wide and 2200-$\mu$m-long signal line were fabricated. The size of the magnetic core was $200 \times 2000 \mu m^2$. The uniform NiFe/Cr film exhibited a clear FMR around 1–2 GHz manifested by the sharp drop of $\mu_{real}$ and a peak in $\mu_{imag}$. Below the FMR, $\mu_{real}$ was found to be $\sim 260$, which coincides very well with the value obtained from the $M$-$H$ loop measurement. The granular NiFe/Ti film, however, did not show a clear ferromagnetic-resonance peak up to $\sim 8$ GHz. This can be attributed to the random orientation of the magnetization. The FMR frequency is proportional to $H_k$, i.e., the component of $H_k$ perpendicular to the excited ac field. Due to the randomly oriented $H_k$ of $\sim 50$ mT in the granular NiFe/Ti film, the micro/nanograins with a magnetization perpendicular to the excited ac field resonated at high FMR frequencies. The grains, however, resonated at much lower frequency when their magnetization was parallel to the excited ac field. As a result, this lead to an extraordinary broadening of the FMR peak and smeared out the FMR peak. The $\mu_{real}$ and the $\mu_{imag}$ in this case, represent the average permeability of the micro/nanograins resonating at different frequencies. The randomness and the low fill factor of the micro/nanograins ($\sim 30\%$) resulted in a low $\mu_{real}$ (13 at 0.1 GHz and 10 at 1 GHz), which fitted well with the $M$-$H$ loop measurement. In the vicinity of FMR of the uniform NiFe/Cr film (1–3 GHz), the $\mu_{imag}$ of the granular NiFe/Ti film showed a more than ten times lower value than that of the uniform NiFe/Cr film. This is because of the absence of the FMR of the granular NiFe/Ti film, which spreads the losses over the entire frequency range.

Finally, the results obtained for the four-turn solenoidal inductors with the granular NiFe/Ti the uniform NiFe/Cr and SiO$_2$ dummy cores were compared in Fig. 4. The inductor with the granular NiFe/Ti core showed a twofold enhancement of inductance over the reference (SiO$_2$ core) inductor in a broad frequency range (0.3–10 GHz) and
exhibited a maximum quality factor \( Q_{\text{max}} \) of 3 at 5.5 GHz, which was 2.6 times larger than that of the inductor with the uniform NiFe/Cr core. No significant drop of inductance was observed until 10 GHz.

**SUMMARY**

Nano/microgranular NiFe film was deposited by electroplating on a 0.1-μm-thick Ti seed layer. The magnetic anisotropy field was observed to be \( \sim 50 \) mT. On-chip microinductors with the granular cores were built and shown to have higher-quality factors and higher maximum operating frequency, compared to devices built using uniform magnetic cores.


