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

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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 ($\phi \sim 1.0$ μm). Nanonuclei ($\phi \sim 30-50$ nm) are observed in single NiFe grains by atomic-force microscopy (AFM). The in-plane magnetic anisotropy is estimated to be $\sim$50 mT. The frequency-dependent complex permeability is extracted. By taking the NiFe film as a magnetic core, solenoid-type inductors are fabricated and demonstrated and show a high operating frequency ($\sim$5.5 GHz) with a maximum quality factor ($\sim$3). © *2005 American Institute of Physics*. [DOI: 10.1063/1.1857391]

INTRODUCTION

Integrated radio-frequency (rf) passive components are crucial for the development of cost-effective rf/bipolar complementary metal-oxide semiconductor (BiCMOS) and rf/CMOS technologies.[1] Implementation of ferromagnetic (FM) films in a rf integrated circuit (IC) fabrication process will improve the performance of on-chip inductive components on the one hand, and will also allow for integration of other rf/microwave components in Si technology, such as isolators, circulators, nonreciprocal phase shifters and tunable components on the other hand.[2,3] Considerable efforts are underway to develop magnetic materials with high saturation magnetization, large magnetic anisotropy field, and high resistivity, though the improvement is still far from sufficient for device applications.[4–7] The main drawbacks are the low ferromagnetic-resonance (FMR) frequency and the high electric conductivity (σ), which result in low operating frequencies $f(Q_{max})$ (the frequency where the quality factor Q reaches the maximum) and low-quality factors Q of devices.[8–10] Recently, nano/microsize granular FM films have been reported with low σ ($<10^4$ S/m) deposited by sophisticated multiple-target sputtering techniques.[11] In IC processing, however, a more cost-effective deposition method, such as electroplating, is certainly preferable, provided that nano/micropatterning is feasible.

In this paper, we present a low-cost nano/microstructured NiFe film deposited by electroplating on a Ti seed layer. For comparison, a NiFe film was also deposited on a Cr seed layer. The NiFe film on the Ti seed layer exhibited a large magnetic anisotropy field of $\sim$50 mT in the film plane. The complex permeability of the films was extracted using integrated microstrips. Solenoid-type inductors with the nanostructured NiFe/Ti core demonstrated a high operating frequency ($\sim$5.5 GHz) and a quality factor ($\sim$3).

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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/cm^2 for 5 min. The resulting thickness and composition were 1.0 μm, Fe-29.1%, Ni-71.9% on 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 ($\phi \sim 1.0$ 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-

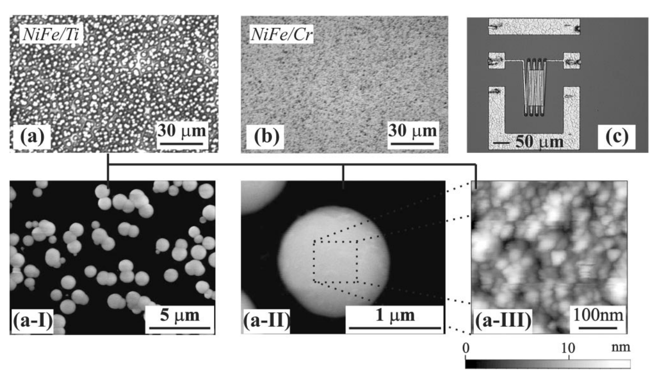

FIG. 1. Micrograph of surface morphology of NiFe/Ti core (a), and NiFe/Cr core (b). Scanning electron microscopy micrographs (a-I) and (a-II) and atomic force microscopy graph (a-III) demonstrated the nodular granular growth. (c) Top view of the four-turn solenoid inductor with line width, line spacing, and core size of 6 μm, 10 μm, and 60×120 μm^2, respectively.

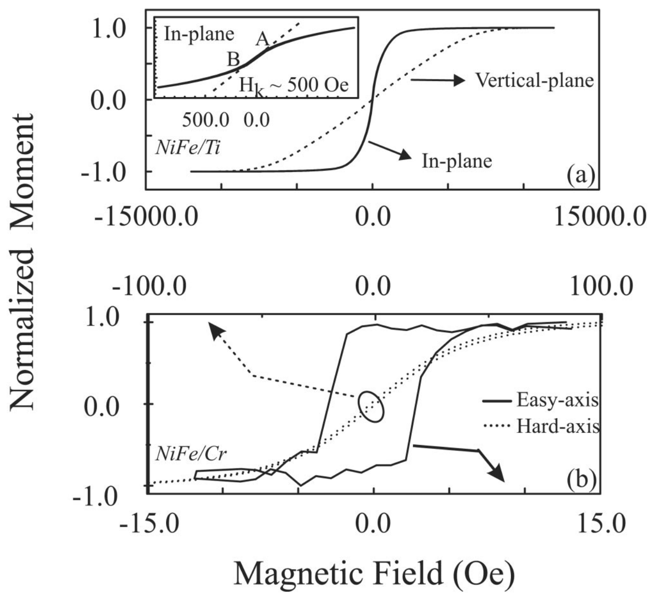

FIG. 2. The *M-H* loop measurements of (a) NiFe/Ti core ($200\times 2000\ \mu m^2$), and (b) NiFe/Cr core ($200\times 2000\ \mu m^2$). A high internal magnetic anisotropy field H_k was obtained from the NiFe/Ti core, which is ~ten times higher than that of the NiFe/Cr core. Clear magnetic easy and hard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

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.[12] 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 μm, 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 ~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 μ_{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~5 mT and μ_{dc}~260.

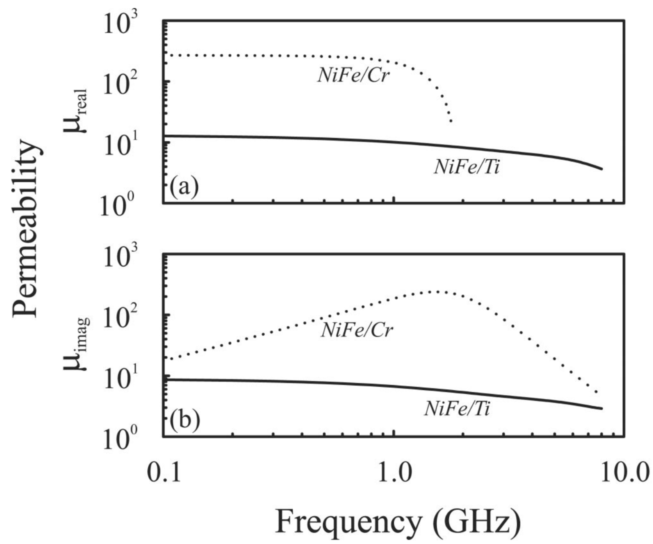

FIG. 3. Extracted complex permeability as a function of frequency (a) real part $-\mu_{real}$, (b) imaginary part $-\mu_{imag}$. The dimensions of the NiFe/Ti and NiFe/Cr cores are $200\times 2000\ \mu m^2$.

The frequency-dependent real (μ_{real}) and imaginary (μ_{imag}) parts of permeability was extracted and shown in Fig. 3.[12] In order to extract the permeability, microstrip structures with 50-μm-wide and 2200-μm-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 μ_{real} and a peak in μ_{imag}. Below the FMR, μ_{real} was found to be ~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 ~8 GHz. This can be attributed to the random orientation of the magnetization.[13] The FMR frequency is proportional to H_k^a, i.e., the component of H_k perpendicular to the excited ac field. Due to the randomly orientated H_k of ~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 μ_{real} and the μ_{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 (~30%) resulted in a low μ_{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 μ_{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 solenoid 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

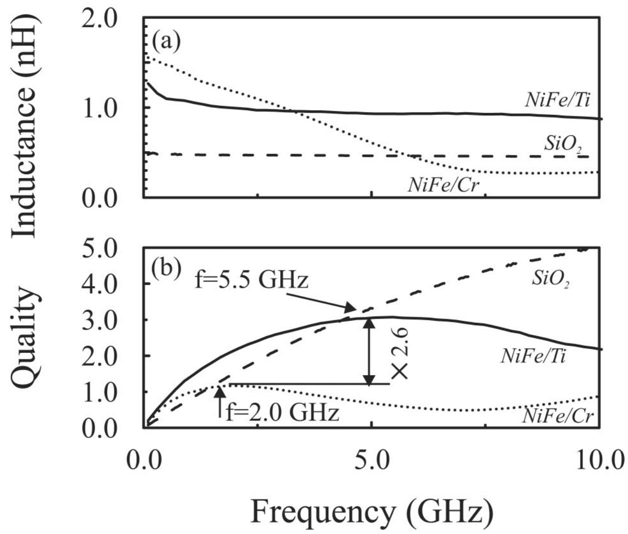

FIG. 4. Comparison of four—turn solenoid inductors with the NiFe/Ti NiFe/Cr and the SiO_2 cores. The inductor with NiFe/Ti core shows a twofold enhancement of inductance over the SiO_2 core inductor, and higher-quality factor than the NiFe/Cr core due to the high FMR and the low eddy current loss.

exhibited a maximum quality factor (Q_{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 ~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.

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