Shape-induced ultrahigh magnetic anisotropy and ferromagnetic resonance frequency of micropatterned thin Permalloy films

Y. Zhuang,[a] M. Vroubel, B. Rejaei, and J. N. Burghartz
High-Frequency Technology and Components, Delft University of Technology, Mekelweg 4, 2600 GA Delft, The Netherlands

K. Attenborough[b]
OnStream MST, Lodewijkstraat 1, 5652 AC Eindhoven, The Netherlands

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Magnetic anisotropy $H_k > 200$ Oe was observed from bar-shaped Permalloy strips. The film was deposited on sputtered Cr seed layer by electroplating under ~800 Oe external magnetic field. Tiny degradation of H_k was observed after 30 min postannealing at 400 °C in the absence of external magnetic field. The Permalloy strip with in-plane aspect ratio of 40:1 showed the ferromagnetic resonance at ~5.3 GHz. The ferromagnetic resonance frequency and magnetic anisotropy decreased to ~1 GHz and ~50 Oe, respectively, as the in-plane aspect ratio reduced from 40:1 to 10:1. In comparison, Permalloy strips plated on combined Ti/TiN seed layers did not show clear anisotropy features. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2162067]

INTRODUCTION

Further development of radio-frequency (rf) bipolar complementary metal-oxide semiconductor (BiCMOS) and CMOS technologies relies on significant performance improvement and size reduction of rf passive components. Integration of ferromagnetic (FM) thin films in integrated circuits (ICs) is one of the most promising technologies to achieve such a goal.[1–3] Despite considerable efforts, so far the low ferromagnetic resonance (FMR) frequency and the high magnetic loss of magnetic materials have limited the operation frequency and quality factor of the devices. The magnetic loss is determined by the imaginary part of the permeability (μ''), which follows $\mu'' \propto f_r^{-4}$ (f_r is the ferromagnetic resonance frequency).[4] Therefore, FM films with high FMR frequency potentially reduce magnetic loss, on the one hand, and lead to higher possible operation frequencies, on the other hand.

Among the developed FM materials so far,[5–7] Permalloy (Py) has attracted much attention for rf IC applications not only for its supersoft magnetic properties, but also for its wide use in magnetic recording industry. However, it is well known that, for rf IC applications, Py suffers from a low magnetic anisotropy field H_k (2–6 Oe),[8–13] and consequently, low FMR frequency (<100 MHz) since $f_r \propto H_k^{1/2}$.[14] More seriously, due to the growth of grains[15] and the induced magnetostriction,[16] the anisotropy field H_k drops significantly at temperatures between 300–400 °C. In today's state-of-the-art standard CMOS technology, there are several processing steps done at 400 °C after deposition of the first aluminum metal layer. This indicates that, for compatible integration, magnetic properties of the films are required to be stable at 400 °C.

In this work, we demonstrated a simple method to obtain an overall magnetic anisotropy of $H_k > 200$ Oe and a FMR frequency ~5.3 GHz from an electroplated micropatterned Py film. The Py film was deposited by electroplating on a Cr seed layer with a thickness of 0.5 μm and structured into bar-shaped strips with various in-plane aspect ratios. Thermal annealing processing was performed at 400 °C in the absence of an external magnetic field to examine the film's thermal stability. Complex permeability at rf was extracted from structured Py films plated on both the Cr and the combined Ti/TiN seed layers for comparison.

EXPERIMENTS

Py films were deposited by electroplating on a sputtered 100-nm-thick Cr layer and a 100-nm-thick Ti layer capped with 10 nm of TiN. After coating and patterning of a 2-μm-thick photoresist layer by lithography, the Py films were plated through the defined window in the photoresist. The bar-shaped Py strips were formed by removing the photoresist and selective etching of the seed layer. The plating was carried out with an external magnetic field (800 Oe) applied along the long side of the bar with a current density of 4 mA/cm^2 for 5 min. The resulting thickness and composition were 0.5 μm, Fe-16.3%, Ni-83.7% for Cr seed and 0.4 μm, Fe-13.6%, Ni-86.4% for Ti/TiN seed, respectively. To extract the rf permeability, microstrip structures were fabricated (the detailed processing was described in Ref. 2). The structure contains a signal line (the top metal) and a ground layer (the bottom metal), both made from aluminum sputtered at 350 °C. SiO_2 layers were deposited at 400 °C as insulation layers between the Py layer and the top and bottom metals. The rf measurements were carried out on an Agilent network analyzer (HP 8510). Magnetic properties of the structured Py films were characterized on a Princeton AGM2900 test apparatus.

[a]FAX: +31 15 262 3271; electronic mail: y.zhuang@dimes.tudelft.nl
[b]Present address: Philips Research Leuven, Kapeldreef 75, B-3001 Leuven, Belgium.

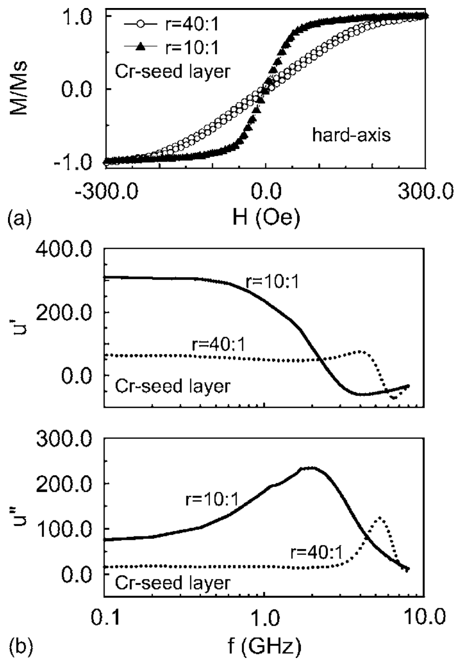

FIG. 1. Normalized magnetic *B-H* loop measurements along the hard axis, i.e., perpendicular to the applied magnetic field during deposition (a), and frequency-dependent real (μ') and imaginary parts (μ'') of the permeability (b) of plated bar-shaped Py strips on Cr seed layer with in-plane aspect ratios of 40:1 and 10:1. The Py strips exhibit ferromagnetic resonance at ~5.3 GHz for the strip with an in-plane aspect ratio of 40:1, and at ~1 GHz for the strip with an aspect ratio of 10:1.

DISCUSSION

Figure 1 compared the magnetic properties of bar-shaped Py strips plated on Cr seed layer with a length (the long side) of 2 mm and in-plane aspect ratios *r* (length/width) of 40:1 and 10:1. The magnetic *B-H* loops [Fig. 1(a)] were recorded along the short side of the strip, i.e., perpendicular to the applied magnetic field during deposition, defined as the magnetization hard axis. The measurements were performed after the completion of device fabrication, i.e., after 400 ° C SiO_2 deposition and 350 °C aluminum deposition. The sample showed ultrahigh magnetic anisotropy $H_k > 200$ Oe for the ratio of 40:1, which was larger than the calculated pure shape-induced anisotropy ~140 Oe based on volume averaging of the demagnetizing field.[17] Magnetic anisotropy $H_k > 50$ Oe was observed for a sample with an aspect ratio of 10:1, in a fairly good agreement with the calculation of ~60 O e. Since the ferromagnetic resonance frequency $f_r \propto H_k^{1/2}$, as a result of the high H_k, the sample with an aspect ratio of 40:1 exhibited resonance at 5.3 GHz. Reducing the aspect ratio to 10:1, the FMR occurred at ~1 GHz [Fig. 1(b)]. Additionally, the higher FMR frequency led to a significant reduction of μ'', consequently lowering the magnetic loss, which is favorable for device applications.

To further examine the thermal stability, postannealing at 400 °C in the absence of a magnetic field was performed, analogous to the standard CMOS processing. Before and after the postannealing, magnetic *B-H* loops were measured along the hard axis [Fig. 2(a)] and easy axis [Fig. 2(b)] for the sample with an aspect ratio of 40:1. A noticeable difference was observed along the hard axis, showing a slight degradation of the H_k. The large shape aspect ratio of the Py bar strip seems to preserve H_k. As a result, a high H_k ~150 Oe was obtained, although both grain growth and the magnetostriction induced by SiO_2 encapsulation may have occurred.[15,18] Since high-temperature processing (400 °C SiO_2 deposition and 350 °C aluminum deposition) and post-annealing were performed in the absence of a magnetic field, the magnetic anisotropy became aligned randomly by the local magnetization, which resulted in a constricted hysteresis loop [Fig. 2(b)].[19] The constriction effect became more pronounced after the postannealing.

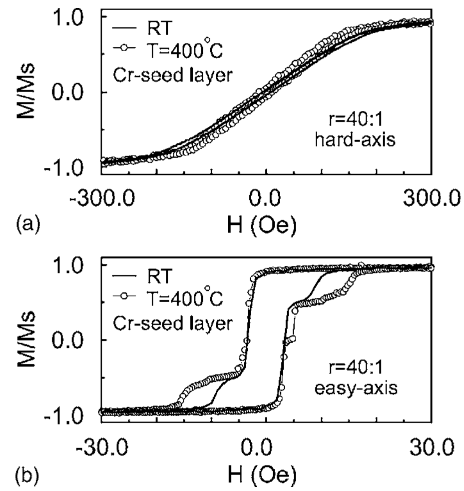

FIG. 2. Comparison of normalized magnetic *B-H* loop measurements before and after 30 min 400 °C annealing along (a) the hard axis and (b) easy axis. The in-plane aspect ratio of the Py strip bar is 40:1.

To exclude shape-induced magnetic anisotropy, a Py strip on a Cr seed layer with an in-plane aspect ratio of 1:1 was fabricated and measured in Fig. 3. In this case, no preferred shape anisotropy was seen along the hard and easy axes. Compared with Figs. 3(a) and 3(b), clear magnetic anisotropy was observed in the range of 10–15 Oe, which is larger than the value reported.[8–13] This might be caused by the SiO_2 encapsulation. Further investigation is in progress. Significant constriction effect was observed after 400 °C

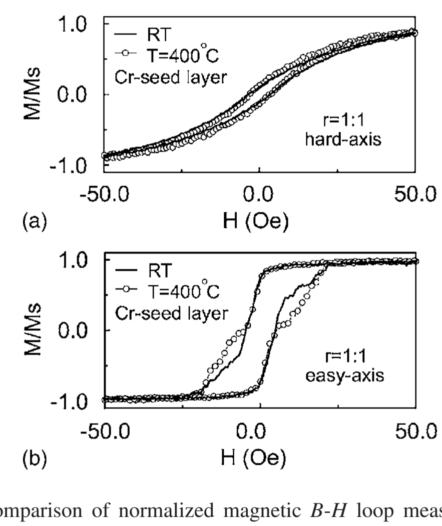

FIG. 3. Comparison of normalized magnetic *B-H* loop measurements (a) perpendicular (the hard axis) and (b) parallel (the easy axis) to the applied external magnetic field during deposition before and after 400 °C annealing for 30 min. The in-plane aspect ratio of the Py strip bar is 1:1.

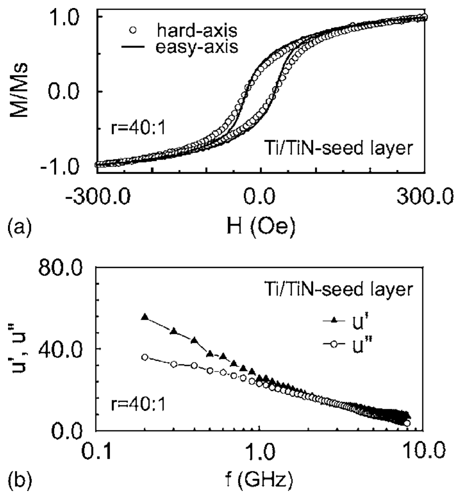

FIG. 4. (a) Normalized magnetic *B*-*H* loop measurements along the hard axis and easy axis. The sample is the plated bar-shaped Py strips on Ti/TiN seed layer with an in-plane aspect ratio of 40:1. (b) Frequency-dependent real (μ') and imaginary parts (μ'') of the permeability.

postannealing [Fig. 3(b)], which was much more pronounced compared with a Py strip with a larger aspect ratio of 40:1 (Fig. 2). The pronounced constriction effect in the low-aspect-ratio sample implies that a large aspect ratio (consequently, large shape anisotropy field) prevents magnetic anisotropy from random alignment by local magnetization.

For comparison, the same deposition method was employed to electroplate Py on a combined Ti/TiN seed layer. The bar-shaped Py strips with an in-plane aspect ratio of 40:1 did not exhibit clear distinguishable easy and hard axes *B*-*H* loops [Fig. 4(a)]. Continuous drop of the real and imaginary parts of permeability as frequency increased was observed in Fig. 4(b). The lack of characteristic easy and hard axes was related to the large grain with a diameter of 200–300 nm observed by scanning electron microscopy and the interdiffusion of Ti atom into the Py film at the interface.

SUMMARY

High magnetic anisotropy $H_k > 200$ Oe with ferromagnetic resonance frequency up to 5.3 GHz was obtained from bar-shaped Permalloy strips with an aspect ratio of 40:1. The magnetic anisotropy strongly depends on the choice of the electroplating seed layer. The large shape anisotropy facilitates the preservation of the high H_k and prevents the constriction effect due to random magnetization during high-temperature processing.

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