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A comparative study of the magnetic properties of thin permalloy films

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Abstract

This work presents comparative results of magnetic measurements (coercive field, saturation magnetization and anisotropy) performed on thin $Ni_{81}Fe_{19}$ and $Ni_{80}Fe_{15}Mo_5$ films (50–600 nm thick) deposited by rf plasma sputtering at various power values (0.55–3.3 W/cm^2), with respect to the deposition parameters and thermal annealing.

Keywords: Thin magnetic films; Film texture; Coercive field; Magnetic anisotropy; Thermal annealing

1. Introduction

The manufacture of high-performance magnetic materials by microelectronic techniques has become a major trend in the research and development of magnetic microsensors and magnetic microactuators. $Ni_{81}Fe_{19}$ and $Ni_{80}Fe_{15}Mo_5$ were deposited by rf sputtering in an Ar plasma at 0.36 Pa (the residual vacuum was 0.5×10^{-4} Pa) with power deposition varying from 0.5 to 3.3 W/cm^2. The Ni–Fe alloy was non-magnetostrictive [1]. Targets were of 16 cm diameter and the anode–cathode distance was 8 cm. The effective composition of the thin films is poorer in Fe (about 2% lower than the targets, measured by EDX analysis). The substrates used were ⟨111⟩, p-type, 50 Ω cm silicon (single-crystal), and the same with thermal oxide (SiO_2), 1 μm thick (amorphous). Measurements performed on different samples with the same deposition parameters, composition and thickness, showed good reproducibility of magnetic properties.

2. Magnetic characterization

Magnetic measurements were performed using an alternating gradient type magnetometer [2] in parallel configuration (field parallel to the film plane) on 3×3 mm^2 samples. The initial magnetization curves and hysteresis loops were recorded.

The hysteresis loops of Ni–Fe–Mo and Ni–Fe films were compared. The saturation magnetization M_s was 0.68 T for Ni–Fe–Mo and 0.87 T for Ni–Fe. Measurements performed on a great number of samples showed that these values were independent of film thickness (for the explored range of 0.05–0.6 μm) and deposition parameters.

Power deposition mainly affects the coercive field H_c of these films (Fig. 1). The samples used were Ni–Fe–Mo and Ni–Fe, with a thickness of about 0.4 μm, deposited on single-crystal substrates. H_c decreases as power deposition increases for both types of sample and is lower (for the same power deposition and thickness) for Ni–Fe–Mo than for Ni–Fe. The decrease of H_c might be due to the higher deposition rate at higher power deposition, resulting in smaller grain sizes [3].

Measurements of the anisotropy field of as-deposited films were always performed along the easy and hard magnetic axis, at ambient temperature; the initial magneti-

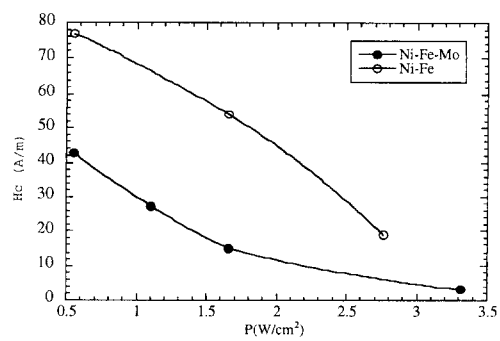

Fig. 1. H_c as a function of power deposition at 0.36 Pa pressure; film thickness 0.4 μm.

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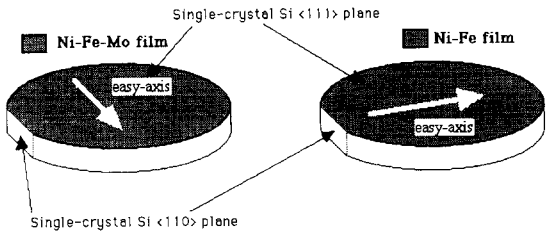

Fig. 2. Relation between the magnetic anisotropy of thin films and single-crystal substrate orientation

zation curves provide the values for the anisotropy field H_k and the anisotropy energy ΔA, defined by:

$$\Delta A = \left(\int_0^{M_s} H\,\mathrm{d}M\right)_{\text{hard axis}} - \left(\int_0^{M_s} H\,\mathrm{d}M\right)_{\text{easy axis}}. \quad (1)$$

As-deposited films present uniaxial magnetic anisotropy in the film plane. For single-crystal substrates, Ni–Fe–Mo films have the easy axis (EA) oriented parallel to the substrate ⟨110⟩ direction; Ni–Fe films have the EA oriented perpendicular to it (Fig. 2). Both materials present a high anisotropy ΔA which decreases when film thickness increases. For amorphous substrates the anisotropy strongly decreases; for example, a Ni–Fe film 0.4 μm thick, 0.5 W/cm^2 power deposition, has a ΔA of 138 J/m^3 when deposited on a single-crystal substrate and of 67 J/m^3 when deposited on an amorphous substrate. This anisotropy can be interpreted as an effect of the surface substrate (steps along the single-crystal substrate) on the film growth.

In order to improve the magnetic anisotropy, thermal annealing was carried out on both materials. The annealing temperatures were 254, 325, 375 and 415°C, in an inert atmosphere (Ar), for 1 h, under an external magnetic field of 288 kA/m applied in the film plane, parallel and perpendicular to the EA. Because of film contamination during annealing, we had to passivate the samples by depositing a thin (0.09 μm) Si_3N_4 film. The samples used were 0.1 μm thick deposited on a single-crystal substrate with 0.55 W/cm^2 power deposition.

The highest annealing temperature was lower than the Curie temperature (T_C) of the Ni–Fe alloy (570°C), but higher than that of the Ni–Fe–Mo alloy (380°C); in fact,

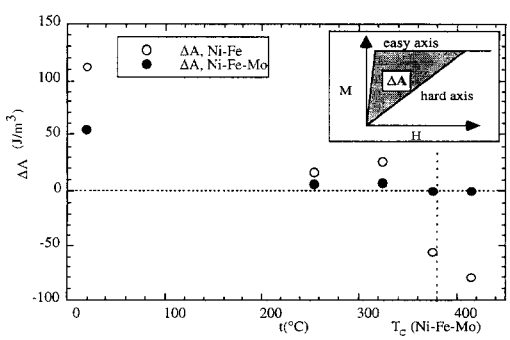

Fig. 3. Comparative evolution of the anisotropy energy as a function of the annealing temperature.

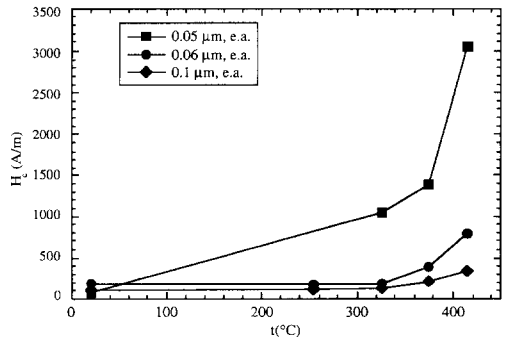

Fig. 4. H_c as a function of the annealing temperature for various thicknesses of Ni–Fe films.

we observed completely different effects for each material (Fig. 3).

In the case of Ni–Fe–Mo, on increasing the annealing temperature, the anisotropy decreases and disappears above 375°C; H_k also decreases, from 180 to 50 A/m. The value of the external annealing field is not high enough to induce an EA for this material (those samples annealed in the field perpendicular to the intrinsic EA do not present any change in direction, i.e. the EA after annealing has the same direction as before). Measurements performed after annealing at 375 and 415°C show the material to be absolutely isotropic; H_c decreases as a function of the annealing temperature up to T_C.

For Ni–Fe, the evolution of ΔA shows a decrease in the anisotropy, followed by a change of its sign, above 325°C; H_k is almost constant for annealed films, and lower than that of as-deposited films. The direction of the EA after annealing is induced by the external field (the EA has the same direction as the annealing external field). H_c slightly increases up to 325°C, and then rapidly increases for higher annealing temperatures (Fig. 4). An interesting effect is the dependence of H_c as a function of film thickness, at the same annealing temperature. Thinner (< 0.1 μm) films show a much stronger dependence of H_c on temperature. We interpret this variation to be an effect of the increase of the grain size during thermal annealing, following a preferential direction (induced by the external annealing field). Preliminary AFM observations showed grain sizes of around 0.04 μm for as-deposited Ni–Fe. In this range, H_c is an increasing function of the grain size [3]. For thinner films (≈ 0.05 μm), the grain growth becomes 2D when the grain size is equal to the film thickness.

3. Conclusion

The coercive field H_c and the saturation magnetization M_s are lower for Ni–Fe–Mo than for Ni–Fe. Both thin film materials show in-plane uniaxial magnetic anisotropy, correlated with the substrate orientation. As-deposited Ni–Fe shows a higher anisotropy than Ni–Fe–Mo; for each material, the anisotropy energy is higher when deposited

on single-crystal substrates. The two materials have completely different behaviour when they are thermally annealed in a magnetic field (H_c and ΔA). Further analysis of film structure is needed for a better understanding of their magnetic properties.

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