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Domain imaging, MOKE and magnetoresistance studies of CoFeB films for MRAM applications

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Abstract

We present a detailed study on domain imaging, Kerr effect magnetometry (MOKE) and magnetoresistance (MR), for a series of 20 nm $Co_{73.8}Fe_{16.2}B_{10}$ thin films, both as-deposited (amorphous) and annealed (crystalline). By considering the two different (orthogonal) in-plane magnetization components, obtained by MOKE measurements, we were able to study the uniaxial anisotropy induced during CoFeB-deposition and to discriminate the magnetization processes under a magnetic field parallel and perpendicular to such axis. MOKE magnetic imaging enabled us to observe the dominant magnetization processes, namely domain wall motion and moment rotation. These processes were correlated with the behavior of the magnetoresistance, which depends both on short-range spin disorder electron scattering and on the angle between the electrical current and the spontaneous magnetization ($\boldsymbol{M}_S$). A simple numerical treatment based on Stoner–Wolfarth model enables us to satisfactorily predict the magnetization behaviour observed in these films. A comparison between the results in $Co_{73.8}Fe_{16.2}B_{10}$ films and the previous ones obtained in annealed $Co_{80}Fe_{20}$ films, show that the introduction of boron in CoFe reduces significantly the coercive and saturation fields along the easy axis (e.g. H_c from $\sim 2\,kA\,m^{-1}$ down to $\sim 0.5\,kA\,m^{-1}$). Also, the magnetization along the hard axis saturates at lower fields. We conclude that amorphous and nanocrystalline CoFeB films show low coercive fields and abrupt switching, as well as absence of short-range spin disorder effects after switching when compared with $Co_{80}Fe_{20}$.

Keywords: Tunnel junction; Magnetic coupling; Domain imaging; Magneto-optical Kerr effect; Anisotropic magnetoresistance; Magnetic reversal processes

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1. Introduction

Tunnel junctions (TJ) consisting of two ferromagnetic (FM) layers separated by an insulator [1] are strong candidates for leading technological applications such as sensor elements in read heads [2] and non-volatile magnetic random-access memories (MRAMs) [3]. The magnetization of one of the FM layers (pinned layer) is fixed by an underlying antiferromagnetic (AFM) layer, whereas the magnetization of the other FM layer (free layer) reverses almost freely when a small magnetic field is applied. Due to spin dependent electron tunneling one can thus have two distinct resistance (R) states, associated with the magnetizations of the pinned and free layers parallel (low R) or antiparallel (high R). To improve device performance, one continuously aims to achieve higher tunnel magnetoresistance (TMR), better thermal stability and low ferromagnetic coupling (H_f) between pinned and free layers. The use of amorphous CoFeB films in the free and pinned layers of optimized tunnel junctions enabled us to obtain a TMR coefficient as high as 70% [4], good transport properties upon annealing up to 673 K [5] and coercive and coupling fields as low as $\sim 160\,Am^{-1}$ [6].

Here we present a study on the magnetoresistance (MR), Kerr Effect vectorial magnetometry and domain imaging of a series of 20 nm $(Co_{73.8}Fe_{16.2})B_{10}$ films, both as-deposited and annealed. A CCD camera with $\sim 10\,\mu m$ resolution enabled direct domain visualization. X-ray diffraction showed that the annealed films were crystalline, with a strong (1 1 0)

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texture, while the as-deposited CoFeB films were amorphous [6].

By considering the two different in-plane magnetization ($\boldsymbol{M}$) components (given by vectorial magneto-optical Kerr effect (MOKE) magnetometry), we study the $\boldsymbol{M}$-processes under longitudinal (easy axis) and transverse (hard axis) fields ($\boldsymbol{H}$). The results are compared with simultaneous MR measurements and magnetic domain visualization. Under transverse fields magnetic rotation processes dominate and lead to good correlation between the behavior of $\boldsymbol{M}$, MR and domain changes under $\boldsymbol{H}$. For longitudinal fields the $\boldsymbol{M}$-processes are mainly due to domain wall displacements (180° magnetization reversals) and no MR dependence is observed in this case, both for the annealed and amorphous CoFeB films. Thus, the uniaxial anisotropy is responsible for the different magnetization reversal processes observed when the $\boldsymbol{H}$ is applied along the easy or hard axes.

2. Experimental details

We studied a series of as-deposited and annealed (10 min at 553 K) $(\mathrm{Co}_{73.8}\mathrm{Fe}_{16.2})\mathrm{B}_{10}$ thin rectangular films (4 mm × 4 mm × 20 nm for the as-deposited sample and 3 mm × 14 mm × 20 nm for the annealed sample) grown on glass substrates by ion-beam deposition [6]. A magnetic field of $240 \times 10^3\ \mathrm{A\,m}^{-1}$ was applied along the longitudinal direction during deposition, inducing an easy axis direction in all the studied films. The magnetic properties were investigated at room temperature by Magneto-Optical Kerr effect (MOKE), domain imaging and MR measurements [7]. MOKE hysteretic cycles were obtained using a vectorial MOKE magnetometry unit simultaneously measuring both in-plane magnetization components, allowing us to obtain the technical magnetization vector $\boldsymbol{M}(\boldsymbol{H})$ in the two common in-plane geometries: the *transverse* geometry, with $\boldsymbol{H}$ in the film plane and perpendicular to the laser-beam incident plane; and the *longitudinal* geometry, in which the in-plane field is parallel to the incident plane. A greyscale CCD camera with ~10 μm of resolution is used to acquire the magnetic domain images. Each image is saved in a bitmap format with 8 bit of information and is then differentiated with respect to the magnetically saturated image to enhance image contrast. In both systems the sample is located in the center of a pair of Helmholtz coils.

The four probe technique was used for the MR measurements, with the electric current along the long axis of our rectangular films and the in-plane applied magnetic field parallel or at right angles to the electrical current. In ferromagnetic 3d-transition metals the electric resistivity depends on the angle θ between the electrical current and the spontaneous magnetization $\boldsymbol{M}_\mathrm{S}$, through the so called anisotropic magnetoresistive effect (Smit mechanism; see [8]):

$$\rho(\boldsymbol{H}) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\theta, \tag{1}$$

where $\rho_\perp(\rho_\parallel)$ is the resistivity when $\boldsymbol{M}$ is saturated perpendicular (parallel) to the electrical current. A magnetoresistive coefficient (at field $\boldsymbol{H}$) is defined as:

$$\frac{\Delta\rho}{\rho} = \frac{\rho(\boldsymbol{H}) - \rho(0)}{\rho(0)}. \tag{2}$$

For a film with $\boldsymbol{M}_\mathrm{S}$ always in plane and starting with a random demagnetized state one has $\rho(0) = \frac{1}{2}\rho_\parallel + \frac{1}{2}\rho_\perp$. If the film has uniaxial anisotropy ($\pm\boldsymbol{M}_\mathrm{S}$ domains) one then simply has $\rho(0) = \rho_\parallel$. The so called anisotropic magnetoresistance ratio (AMR) is given by [8]:

$$\mathrm{AMR} = \frac{\rho_\parallel - \rho_\perp}{\rho(0)}. \tag{3}$$

3. Experimental results

3.1. MOKE magnetometry and imaging

The magnetic loops obtained for the $\mathrm{Co}_{73.8}\mathrm{Fe}_{16.2}\mathrm{B}_{10}$ thin films (as-deposited and annealed) are presented in Fig. 1. The uniaxial anisotropy impressed during film growth is readily apparent, having the easy (hard) axis oriented parallel (perpendicular) to the light scattering plane defined by the incident laser beam and the film normal. The easy direction coincides with the long axis of the rectangular films.

For $\boldsymbol{H}$ parallel to the easy axis we observe, in the as-deposited CoFeB film (Fig. 1a), a rectangular hysteretic cycle with a coercive field $H_\mathrm{c} \simeq 477\ \mathrm{A\,m}^{-1}$, whereas $H_\mathrm{c} \sim 955\ \mathrm{A\,m}^{-1}$ for the annealed film (Fig. 1e) i.e. the amorphous state reduces the coercive field by a factor of ~2. The saturation magnetic field (H_s; taken where irreversibility vanishes and a constant magnetization plateau sets in) is also greatly reduced, from $H_\mathrm{s} \sim 1990\ \mathrm{A\,m}^{-1}$ for the annealed film to $H_\mathrm{s} \sim 1273\ \mathrm{A\,m}^{-1}$ in the amorphous CoFeB film. As expected, a zero transverse magnetization component is measured in both films under a longitudinal magnetic field (Fig. 1b and f).

For $\boldsymbol{H}$ perpendicular to the easy axis, typical quasi-linear transverse-component $M_\mathrm{T}(\boldsymbol{H})$ cycles are observed as displayed in Fig. 1d and h. However, small coercive fields are still observed, of $557\ \mathrm{A\,m}^{-1}$ and $318\ \mathrm{A\,m}^{-1}$ for the as-deposited and annealed films, respectively, leading to very narrow hysteretic cycles; the saturation field is virtually the same in both cases, $H_\mathrm{s} \sim 3980\ \mathrm{A\,m}^{-1}$ (here H_s is taken where the magnetization plateau sets in; for $\boldsymbol{H}$ along the hard direction, this occurs above the irreversibility point). On the other hand, the longitudinal magnetization component in both films (M_L, Fig. 1c and g) exhibits a small field dependence on the approach to saturation, except for the sudden magnetization reversal at $H_\mathrm{c} \sim 1194\ \mathrm{A\,m}^{-1}$ and $2228\ \mathrm{A\,m}^{-1}$, for the as-deposited and annealed CoFeB films respectively. On the other hand, $H_\mathrm{s} \sim 7960\ \mathrm{A\,m}^{-1}$ in both cases.

Comparing these results with those previously obtained in annealed $\mathrm{Co}_{80}\mathrm{Fe}_{20}$ films [7], we notice that the introduc-