Enhancement of uniaxial magnetic anisotropy in Fe thin films grown on GaAs(001) with an MgO underlayer

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The understanding and control of anisotropy in Fe films grown on cubic systems such as GaAs and MgO has been of interest from the point of view of applications in devices. We report magnetic anisotropy studies on Fe/GaAs(001) and Fe/MgO/GaAs(001) prepared by pulsed laser deposition. In Fe/GaAs(001), magneto optical Kerr effect (MOKE) measurements revealed a dominant uniaxial anisotropy for Fe thickness less than 20 monolayers (ML) and this was confirmed by ferromagnetic resonance (FMR) studies. Multiple steps in the hysteresis loops were observed for Fe films of thickness 20 and 25 ML. Whereas, in Fe/MgO/GaAs(001), even at 25 ML of Fe, the uniaxial anisotropy remained dominant. The anisotropy constants obtained from FMR spectra have shown that the relative strength of uniaxial anisotropy is higher as compared to the cubic anisotropy constant in the case of Fe/MgO/GaAs(001). © *2011 American Institute of Physics*. [doi:10.1063/1.3556941]

I. INTRODUCTION

The study of magnetic anisotropy in Fe films deposited on cubic systems such as GaAs(001) substrates is quite intriguing due to the observation of a uniaxial anisotropy, which modifies the fourfold (cubic) anisotropy caused by the crystalline symmetry.[1] A cubic anisotropy with the easy axes of magnetization along the [100] and [010] directions is found in addition to a uniaxial anisotropy with easy direction along [110]. The uniaxial component is reportedly dominant at low Fe thickness, and the relative strength of the cubic anisotropy increases gradually as the thickness increases. It is important that we should be able to control the uniaxial anisotropy because it is helpful for device applications such as magnetic tunnel junctions and spin-torque oscillators.[2]

A possible description of the effective anisotropy constants $K_U^{\rm eff}$ for the uniaxial and $K_1^{\rm eff}$ for cubic anisotropy in thin ferromagnetic films is given[3,4] by

$$K_U^{\rm eff} = K_U^V + \frac{K_U^i}{t_{\rm eff}};\ K_1^{\rm eff} = K_1^V + \frac{K_1^i}{t_{\rm eff}}, \qquad (1)$$

where $t_{\rm eff}$ is the effective thickness of ferromagnetic film, K_U^V and K_1^V represent the volume contribution, K_U^i and K_1^i represent the interface contributions to the effective anisotropies. As reported in some experiments,[3] $K_U^i > K_1^i$. So, when $t_{\rm eff}$ is sufficiently small, $K_U^{\rm eff}$ would dominate over $K_1^{\rm eff}$. In order to induce uniaxial anisotropy, several methodologies are proposed such as oblique incidence molecular beam epitaxy of Fe films on MgO,[5] grazing incidence Ar^+ sputtering,[6] and use of vicinal surfaces. The magnetic anisotropy is also known to depend on the method of deposition used[7] and on the material of capping layers.[8] In our work, we have made a comparison of samples where the Fe films are grown directly on GaAs with the ones where the Fe films have an underlayer of MgO. The contribution of the uniaxial anisotropy to the effective anisotropy in Fe films diminishes for higher Fe thickness. Using MOKE and FMR measurements, we show that the inclusion of a MgO interface extends the contribution of the uniaxial anisotropy to a higher Fe thickness.

II. EXPERIMENTAL DETAILS

Commercially available GaAs(001) wafers were cleaved and cleaned in acetone followed by a rinse in dilute HF for about 1 min just before it was transferred into the load-lock of the pulsed laser deposition system. The deposition system consists of an ultrahigh vacuum chamber (base pressure: $\sim 5 \times 10^{-11}$ Torr) with an 8-target carrousel system for laser ablation. The laser beam, with wavelength of 248 nm, is derived from a Kr-F excimer source. During deposition, the laser pulse energy was about 300 mJ, the pulse rate being 5 Hz. Two sets of samples were prepared. The first set had samples with Fe films of different thicknesses grown on the GaAs substrates and then capped with 10 ML MgO, denoted as 10 ML MgO/n ML Fe/GaAs(001). The second set had Fe films of various thicknesses grown on an underlayer of 15 ML MgO on the GaAs substrates and capped with 10 ML MgO, denoted as 10 ML MgO/n ML Fe/15 ML MgO/GaAs(001). In both the sets, the thickness of the Fe films was varied up to 50 ML.

MOKE measurements were performed ex-situ, in a longitudinal configuration at room temperature (RT). The sample was mounted on a flat face at the end of a cylindrical holder with gradations, whose axis was perpendicular to the magnetic field produced by the pole pieces of an electromagnet. A hall field sensor was used to measure the magnetic field. In order to evaluate the anisotropy constants, FMR was used. FMR measurements were performed at RT using a

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commercial Bruker EMX X-band spectrometer where the dc magnetic field could be varied up to 1.2 T. The frequency of the microwave radiation was 9.4 GHz. A 100-kHz magnetic field modulation of 0.2 mT was used along with a phase sensitive detector in order to obtain a better signal to noise ratio. A goniometer arrangement with a quartz rod, as a sample holder, was used for precise angular variation with respect to the magnetic field. The quartz rod was always perpendicular to the magnetic field. For the in-plane anisotropy constants, the samples were carefully mounted at the bottom of the quartz rod such that the axis of the quartz rod was perpendicular to the plane of the sample.

III. RESULTS AND DISCUSSIONS

Figure 1 shows the plot of remanent MOKE signal versus the in-plane angle at which the magnetic field is applied with respect to the [110] direction of the substrate for 10 ML Fe of both sets of samples. The MOKE curves showed nearly a square shaped single jump hysteresis which became progressively s-shaped as the orientation of the magnetic field approached the hard axis. This indicates that with the 15 ML MgO underlayer, the easy axis of magnetization is in the $[\bar{1}10]$ direction and close to [110] without the underlayer. The anisotropy is predominantly uniaxial. As the thickness of the Fe film is increased, we expect that the effective cubic anisotropy should gain strength over the uniaxial component. In Fig. 2, the MOKE hysteresis loops for the 25 ML Fe films are shown. In Fig. 2(a), we see the presence of multiple jumps in the hysteresis loops for the 25 ML Fe/GaAs(001) sample. In the same set of samples, the data for 20 ML Fe was similar. The occurrence of such multiple steps in hysteresis loops has been reported earlier[9] in the case of Fe films grown on MgO(001) substrates and has been attributed to the nucleation and propagation of 90° domain walls during the magnetization reversal. The occurrence of multiple jumps indicates that the anisotropy is not dominantly uniaxial, though a polar plot of remanent MOKE signal would show two lobes and could mislead us in thinking that the anisotropy is dominantly uniaxial. This indicates that the cubic anisotropy is gaining strength as compared to the uniaxial component. For 25 ML Fe/15 ML MgO/GaAs(001), a single step hysteresis loop is seen in Figs. 2(c) and 2(d). This suggests that the fourfold anisotropy is still much weaker than the uniaxial component.

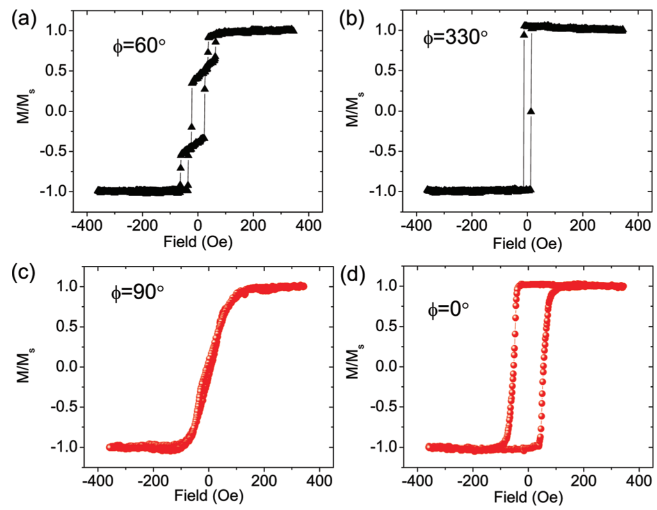

FIG. 2. (Color online) The MOKE hysteresis signals showing: (a) Multiple steps for 10 ML MgO/25 ML Fe/GaAs(001). (b) Hysteresis loop for 10 ML MgO/25 ML Fe/GaAs(001). (c) Hard axis loop for 10 ML MgO/25 ML Fe/15 ML MgO/GaAs(001). (d) Easy axis loop for 10 ML MgO/25 ML Fe/15 ML MgO/GaAs(001). The angles ϕ indicated in (a)–(d) are with respect to [110] of GaAs.

In order to investigate these aspects further, in-plane FMR measurements were done on the samples with 25 ML Fe. Figure 3 shows a plot of the resonant fields obtained from the FMR data at the corresponding in-plane angle of the applied field with respect to the [110] direction of the substrate. A minimum of the resonance field indicates an easy direction of magnetisation.[10] The polar plots reveal that for the Fe, grown directly on GaAs, four lobes are observed. The resonance field is significantly larger close to the 0°, 180° directions (1200 Oe), as compared to the 90°, 270° directions (800 Oe). The angular dependence is very different for 25 ML Fe film with an underlayer of MgO. The plot is almost elliptical, with a maximum along 90°, 270° directions (1050 Oe) and a minimum along 0°, 180° directions (750 Oe). This distinct difference in the polar dependence implies that a cubic anisotropy contribution could be present in the second set though it is much weaker than the uniaxial component with an easy axis in the [110] direction. This

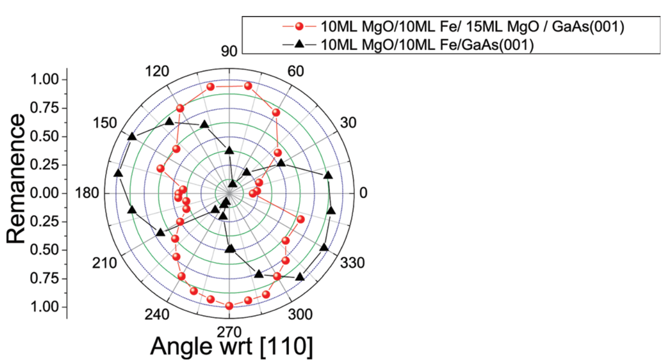

FIG. 1. (Color online) Normalized remanent MOKE curves for 10 ML Fe films.

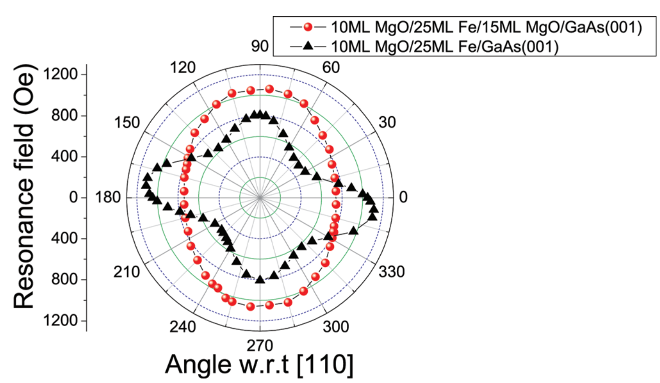

FIG. 3. (Color online) Resonance fields from the FMR spectra for 25 ML Fe films.

observation comes in support of our conclusions deduced from the MOKE curves. This means that the fourfold component of anisotropy increases in strength much faster as we increase the thickness in the case of Fe films grown directly on GaAs(001) than in the case where an underlayer of MgO is present. Also, in Fig. 3, we see that for the case of the Fe films grown directly on GaAs the trough between two adjacent lobes at about 135° is unequal in magnitude with respect to the trough at 45°. This could be because the uniaxial easy axis is at a nonzero angle with respect to [110], while the fourfold easy axes are at ⟨100⟩ orientations. A fit of the resonance field values to the equation

$$\left(\frac{\omega}{\gamma}\right)^2 = \left\{H\cos(\phi-\phi_H)+4\pi M_{eff}+H_{||2}\cos 2\phi+H_c\cos 4\phi\right\} \times \left\{H\cos(\phi-\phi_H)+2H_{||2}\cos 2\phi+4H_c\cos 4\phi\right\}, \quad (2)$$

derived from the Landau Lifshitz equation, is used to extract the anisotropy constants.[8] Here, H is the dc applied magnetic field, ϕ is the angle of the magnetization vector, ϕ_H is the angle of the applied magnetic field with respect to the [110] direction of the substrate, ω is the frequency of the microwaves, and γ is the gyromagnetic ratio. In addition, we have

$$4\pi M_{\rm eff} = 4\pi M_s - \frac{2(K_1+K_{\perp 2})}{M_s}, \quad H_{||2} = \frac{2K_{||2}}{M_s}; \quad H_c = \frac{K_1}{2M_s} \quad (3)$$

where K_1 is the cubic magnetocrystalline anisotropy constant, $K_{||2}$ is the in-plane uniaxial component, $K_{\perp 2}$ is the second order perpendicular anisotropy constant, and M_s is the saturation magnetization. For the 25 ML Fe film, the uniaxial anisotropy values are 4.35×10^4 J/m^3 without MgO underlayer and 12.79×10^4 J/m^3 with the MgO underlayer. In the same films, the cubic anisotropy values are 15.99×10^4 J/m^3 without MgO underlayer and -2.49×10^4 J/m^3 with MgO underlayer. The same analysis for the 50 ML Fe film yielded a uniaxial anisotropy value of 1.37×10^4 J/m^3 and a cubic anisotropy value of 6.76×10^4 J/m^3 with the MgO underlayer. We see that as the thickness increases, the relative strength of cubic anisotropy increases. The bulk value of K_1 for Fe is 5×10^4 J/m^3.

It is to be noted that, as we increase the film thickness, we observe that the orientation of the easy axis of anisotropy changes, similar to some earlier reports.[11,12] As we increase the Fe film thickness to 50 ML, MOKE remanent magnetization curves show a cubic nature. For the case without an MgO underlayer, the four lobes are no longer prominent but appear as a small modulation over the polar plot of remanence. Hence the anisotropy is weak, as shown (triangles) in Fig. 4. But, for the case with the MgO underlayer, the four lobes are still seen properly (circles) in Fig. 4. So, in this case, anisotropy is stronger, though it has a character closer to bulk Fe.

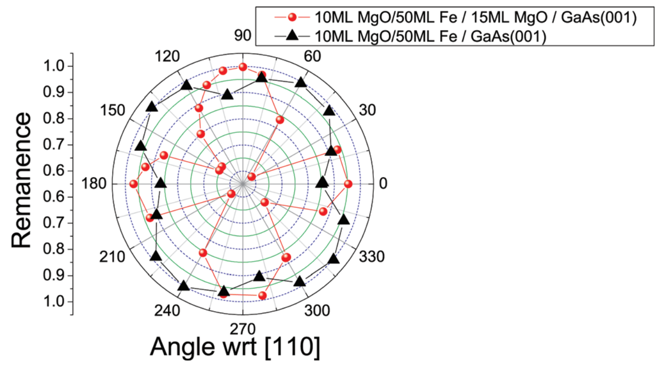

FIG. 4. (Color online) Normalized MOKE remanent magnetization curves for 50 ML Fe films.

From these experiments, it is clear that the Fe/MgO interface determines the kind of anisotropy exhibited by Fe films. Though Fe/MgO(001) films may not show an intrinsic uniaxial magnetic anisotropy, it is reported that interface texture of MgO(001) could cause uniaxial anisotropy.[13] There have been suggestions in the literature that the uniaxial anisotropy could be arising due to stress in the Fe films. But it has not been affirmed. Growth modes may not be important in determining the anisotropy as some researchers have shown that surface reconstructions have no effect on the resulting uniaxial anisotropy.[3,14] We can speculate that spin–orbit interactions coming from the Fe layers near the interfaces or possible electronic decoupling between Fe and GaAs could have important roles to play. Detailed experiments investigating the origin of the anisotropy have to be performed to arrive at a firm conclusion.

IV. CONCLUSION

We have demonstrated that the magnetic anisotropies are different in magnitude and orientation depending on the interfaces. In particular, when Fe films are grown on GaAs(001) with an underlayer of MgO, the magnetic anisotropy remains dominantly uniaxial up to a higher thickness as compared to direct deposition on GaAs. Thus we have demonstrated a method to control the magnetic anisotropy of Fe films to a certain extent by introducing interfacial layers.

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