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Revealing the volume magnetic anisotropy of Fe films epitaxied on GaAs(001) surface

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The in-plane magnetic anisotropy in Fe films grown on GaAs(001) was investigated quantitatively by the magneto-optic Kerr effect with a rotating magnetic field. The clear $1/d_{Fe}$ relation of the uniaxial magnetic anisotropy indicates a surprising volume contribution with easy axis along the GaAs $[1\bar{1}0]$ direction. Such volume anisotropy was found to be sensitive to the growth temperature and also strongly correlate with the interface anisotropy. Our results may introduce a new aspect for further understanding the origin of uniaxial magnetic anisotropy in Fe/GaAs(001) system. © *2011 American Institute of Physics*. [doi:10.1063/1.3572028]

Magnetic anisotropy, originating from spin–orbit coupling, usually respects the lattice symmetry, thus the in-plane uniaxial anisotropy should not exist in (001) Fe film due to its fourfold lattice symmetry. However, Fe film grown on GaAs(001) with a cube-on-cube orientation, exhibits a remarkable and surprising in-plane uniaxial magnetic anisotropy (UMA) with an easy axis (EA) parallel to the GaAs[110] direction.[1] Proper understanding of the origin of this in-plane UMA still remains one of the unanswered questions in modern magnetism, and is also of crucial importance in spintronics, especially for studying the spin injection from a ferromagnetic layer into the semiconductor substrate.[2,3] Phenomenologically, magnetic anisotropy of a thin film usually consists of the volume anisotropy and the interface anisotropy, and separating the volume contribution and the interface contribution may provide a deeper insight into the origin of the UMA in Fe/GaAs(001).[4–9] Most previous studies only focused on the interface contribution and neglected the volume contribution. However, an unusual UMA with EA along the $[1\bar{1}0]$ direction in 13 nm thick Fe film was reported,[9,10] indicating there is another contribution different with the interface anisotropy. Due to the limited positive K_u points,[10] it is not clear whether the volume anisotropy plays a role in this unusual UMA. In this letter, we quantitatively studied the thickness dependent magnetic anisotropy in Au/Fe/GaAs(001) system, and found a significant positive volume contribution of UMA with $[1\bar{1}0]$ EA. Such a volume contribution was found to be very sensitive to the growth temperature. Our results also show a surprising correlation between the volume contribution and the interface contribution of the UMA, indicating the observed volume anisotropy may be due to the Fe/GaAs anisotropic interface.

The surfaces of commercial Si-doped GaAs(001) substrates were cleaned with 1 keV Ar^+ bombardment at room temperature followed by annealing at 600 °C.[11] The reflection high-energy electron diffraction (RHEED) pattern indicates well-ordered and smooth (4×6) GaAs(001) reconstructed surface. Fe films were epitaxied at different temperatures with the growth pressure better than 8×10^{-10} torr. The growth rate was determined by a quartz thickness monitor. The Fe film was grown into a wedge shape (the slope ~10 ML/mm) with a 4 nm Au capping layer.

Magnetic properties of the Fe layers were investigated by *ex situ* longitudinal magneto-optic Kerr effect (MOKE) at room temperature. Taking advantage of the small laser beam size (<0.2 mm), the thickness dependent magnetic properties from one wedge sample can be systematically studied. Figures 1(a)–1(c) show MOKE hysteresis loops with 70 °C growth temperature. A UMA with a [110] EA can be clearly seen for 15 monolayers (MLs) Fe film. The strength of this UMA decreases with the increasing Fe thickness, so the fourfold anisotropy with EA along ⟨100⟩ directions will dominate for thicker films, then both hysteresis loops with the magnetic field $H\|[110]$ and $H\|[1\bar{1}0]$ show hard-axis loops [Fig. 1(b)]. But for 105 ML Fe film, the saturation field Hs along [110] is slightly larger than that along $[1\bar{1}0]$, indicating the lower energy for $M_{Fe}\|[1\bar{1}0]$ than $M_{Fe}\|[110]$.

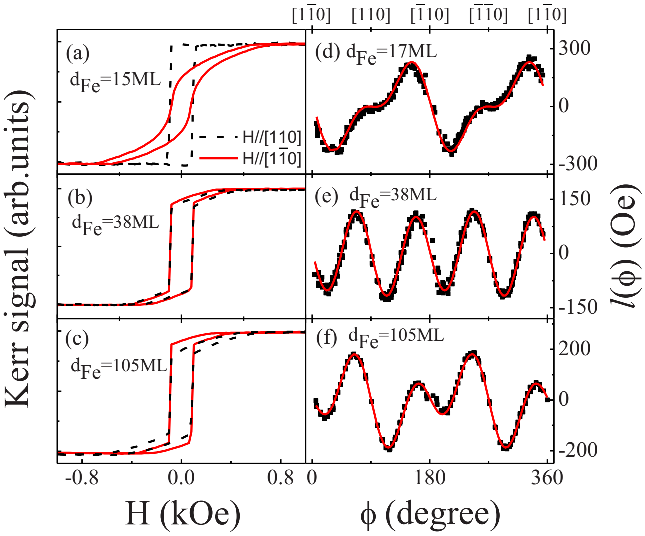

FIG. 1. (Color online) [(a)–(c)] The hysteresis loops with H along [110] (dash lines) and $[1\bar{1}0]$ (solid lines), and [(d)–(f)] the typical $\ell(\phi)$ curves with different Fe thicknesses. The applied field is 1500 Oe. The solid lines in [(d)–(f)] are the fitting curves.

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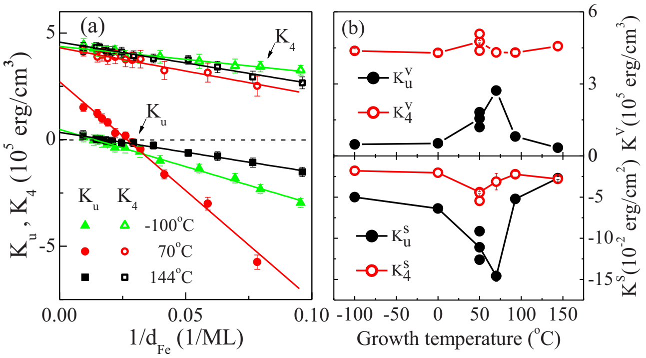

FIG. 2. (Color online) (a) The $1/d_{Fe}$ dependence of K_u (full symbols) and K_4 (open symbols) with different growth temperatures. (b) Dependence on the growth temperature of the fitted values K_u^V, K_4^V, K_u^S, and K_4^S.

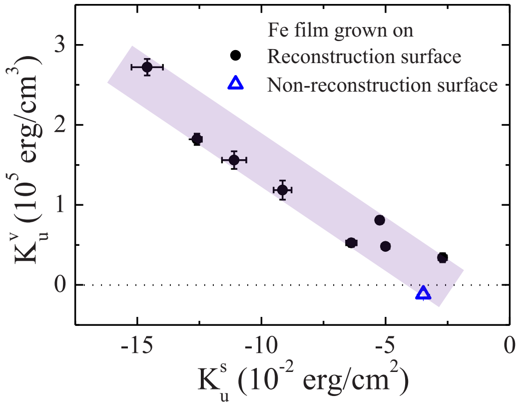

FIG. 3. (Color online) The volume UMA K_u^V as a function of the interface UMA K_u^S. The gray shadow is a guide for eyes.

The MOKE with a rotation-of-field (ROT-MOKE) was applied to quantitatively study the thickness dependent magnetic anisotropy from the wedged sample. The ROT-MOKE method is based on the principle of magnetic torquemetry in thin films.[12] In a sufficiently large magnetic field, the energy density $E(\phi)$ can be written as follows:[13]

$$E(\phi) = -M_s H\cos(\alpha-\phi) + K_u \sin^2\phi + K_4\sin^2(\phi + \pi/4)\cos^2(\phi+\pi/4). \tag{1}$$

Here, M_S is the saturation magnetization, α is the angle between the field and the $[1\bar{1}0]$ direction, ϕ is the angle between the $[1\bar{1}0]$ direction and the magnetization. The EA of the UMA is $[1\bar{1}0]$ for $K_u>0$ and $[110]$ for $K_u<0$, and the EA of the fourfold anisotropy is along the $\langle 100\rangle$ directions for $K_4>0$ and along the $\langle 110\rangle$ directions for $K_4<0$. The equilibrium angle ϕ is obtained by minimizing the free energy with respect to ϕ, and the anisotropy field $\ell(\phi)$ can be expressed as follows:[13]

$$\ell(\phi) = H\sin(\alpha-\phi) = \frac{K_u}{M_s}\sin 2\phi - \frac{K_4}{2M_s}\sin 4\phi. \tag{2}$$

Then K_u and K_4 can be fitted by the experimental $\ell(\phi)$ curve. Typical $\ell(\phi)$ curves are shown in Figs. 1(d)–1(f) with different Fe thicknesses. The $\ell(\phi)$ curves show a twofold symmetry for both 17 ML and 105 ML Fe, and only the fourfold symmetry exists in the $\ell(\phi)$ curve of 38 ML Fe. If taking the bulk value of Fe magnetization $M_S = 1714$ emu/cm^3, the fitted K_u is -3.0×10^5 erg/cm^3 for 17 ML Fe but $+1.5\times 10^5$ erg/cm^3 for 105 ML Fe. Therefore, the sign reversal of K_u clearly indicates the EA switching from $[110]$ to $[1\bar{1}0]$.

In order to examine the volume contribution of the UMA, the magnetic anisotropy has to be carefully studied as a function of Fe thickness, as shown in Fig. 2(a). Here, in order to avoid the possible influence of morphology evolution for thin Fe films,[14] we only present the data from Fe films with $d_{Fe}>10$ ML. For Fe film grown at 70 °C, K_u shows a clear sign reversal from negative to positive while increasing the thickness. If fitted by $K_u = K_u^V + K_u^S/d_{Fe}$, the volume contribution K_u^V of UMA can be obtained as 2.72 $\times 10^5$ erg/cm^3, and the interface contribution K_u^S is -0.146 erg/cm^2, so the sign reversal of UMA at d_{Fe} ~ 40 ML is due to the interplay between the interface UMA with EA$\parallel[110]$ and the volume UMA with EA$\parallel[1\bar{1}0]$. The $1/d_{Fe}$ dependence indicates a constant volume contribution in the Fe film within the studied thickness range.[15]

The UMA in Fe/GaAs(001) depends strongly on the growth temperature. Figure 2(a) also shows the thickness dependent anisotropy for Fe film grown at -100 °C and 144 °C with much weaker uniaxial anisotropies. Figure 2(b) shows the fitted K_u^V and K_u^S as a function of growth temperature. Here it should be noted that the fourfold anisotropy K_4 also has good $1/d_{Fe}$ dependence, i.e., $K_4 = K_4^V + K_4^S/d_{Fe}$. The volume contribution K_4^V and the interface contribution K_4^S have little dependence on growth temperature, and the average values $K_4^V \approx 4.5\times 10^5$ erg/cm^3 and $K_4^S \approx -3.3 \times 10^{-2}$ erg/cm^2 agree fairly well with reported values.[1,4,6,7] Both K_u^V and K_u^S have a strong dependence on the growth temperature, and the significant positive K_u^V only exists for Fe films grown at a temperature around 60 °C, so this K_u^V was rarely detected in previous studies.[4–10] However, recently both Thomas *et al.*[10] and Kardasz *et al.*[9] discovered the positive in-plane UMA in ~ 13 nm thick Fe film, which is consistent with our results. Here, the advantage of the measurement on a wedge sample with a large thickness range of 10–110 ML should be noted, and our measurements can avoid the influence from the possible different growth condition if performing the measurement on different samples with fixed thickness.

In Fig. 2(b), we noticed a correlation between K_u^V and K_u^S, i.e., K_u^V increases with K_u^S, as shown in Fig. 3 which shows a clear linear dependence between K_u^V and K_u^S. No UMA was discovered in Fe/Au(001) system,[16] so the measured interface anisotropy K_u^S should be related to the properties at the Fe/GaAs interface[4] though its precise origin is still missing.[1] The correlation between K_u^V and K_u^S indicates that the volume contribution also has a certain relation with the interface properties in Fe/GaAs(001) system. It is well known that the GaAs(001)-4×6 reconstruction surface contains the ordered atomic stripes,[4,17,18] which can induce a interface lattice shear in Fe film,[8,9,19] resulting in a long range in-plane lattice strain across the Fe film, then such in-plane lattice strain may further induce the in-plane volume UMA. However, the thickness dependent in-plane UMA may be a complex process involving the lattice strain caused by the interface shear and the onset of misfit dislocation.[8,9,19]

The properties of the buried Fe/GaAs interface are usually hard to be detect but may be modified by roughing the GaAs(001) surface before Fe film growth. We purposely re-

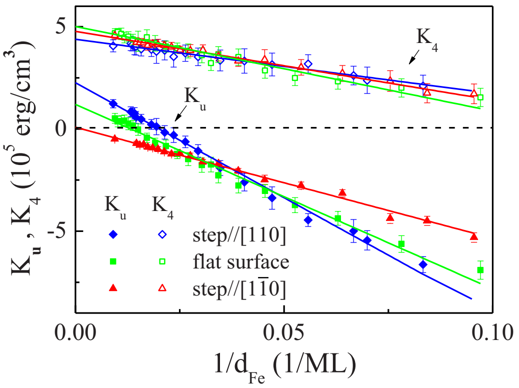

FIG. 4. (Color online) The UMA K_u and the fourfold anisotropy K_4 as a function of $1/d_{Fe}$ for Fe films grown on a flat surface, a [110]-type step surface and a [$1\bar{1}0$]-type step surface.

moved the surface reconstruction by Ar^+ ion sputtering at room temperature, and the RHEED image from this sputtered surface still showed the good diffraction pattern without any reconstruction streaks. The volume UMA of Fe film grown on such non-reconstructed GaAs(001) surface at 50 °C was found to be very weak, as indicated by the triangular spot in Fig. 3. So the results in Fig. 3 strongly indicate the observed volume UMA and interface UMA are induced by the same physical origin.

To further check the effect of the ordered atomic alignment at GaAs(001) surface on magnetic anisotropy, we performed the studies on Fe films grown on GaAs(001) vicinal surfaces. The vicinal surface contains the atomic steps which can induce an in-plane UMA in a FM film grown on top.[20] Two different types of GaAs(001) vicinal surface with 4° miscut with the atomic steps along the [110] direction and the [$1\bar{1}0$] direction were used. Figure 4 shows the thickness dependent K_u and K_4 for Fe films deposited on the stepped and flat GaAs(001) substrates at 50 °C. The good $1/d_{Fe}$ dependencies can be observed for all three samples. The fourfold anisotropies K_4 show very little difference but the UMAs are significantly different from each other. The fitted volume anisotropy K_u^V on the [110]-type step surface is 2.26×10^5 erg/cm^3, but is very close to zero (K_u^V=0.08 $\times 10^5$ erg/cm^3) on the [$1\bar{1}0$]-type step surface. However, K_u^V of Fe film on a flat surface is 1.12×10^5 erg/cm^3. Our results indicate that the atomic steps can induce an additional volume UMA (K_u^V) with the EA perpendicular to the atomic steps. Moreover, the stronger interface anisotropy (K_u^S) was observed on the [110]-type step surface with larger volume UMA, which further proves the correlation between the volume contribution and the interface contribution of the UMA.

In conclusion, through the thickness-dependent measurement of magnetic anisotropy in Au/Fe/GaAs(001) system, we quantitatively separated the volume and interface contributions, and observed a positive volume UMA K_u^V with the EA along the [$1\bar{1}0$] direction. The UMA of Fe films were found to be sensitive to the growth temperature. The correlation between the volume and the interface contribution of the UMA indicates that K_u^V may be attributed to the Fe/GaAs anisotropic interface. Our results may introduce a new aspect for further understanding the origin of UMA in Fe/GaAs(001) system.

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