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Damien Louis, Ia. Lytvynenko, Thomas Hauet, Daniel Lacour, Michel Hehn, Stéphane Andrieu, François Montaigne

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D. Louis[1], Ia. Lytvynenko[2], T. Hauet[1], D. Lacour[1], M. Hehn[1], S. Andrieu[1], and F. Montaigne[1]

[1] Institut Jean Lamour, UMR CNRS 7198, Université de Lorraine, 54506 Vandoeuvre-lès-Nancy, France
[2] Sumy State University, 2, Rymskogo-Korsakova Str., 40007 Sumy, Ukraine

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ABSTRACT

The value and sign of V/Fe interface anisotropy are investigated. Epitaxial V/Fe/V/Au layers with different iron thicknesses were grown on single-crystalline (001) MgO substrate by ultra-high vacuum molecular beam epitaxy. Magnetometry was used to measure magnetizations and out-of-plane anisotropy field. From these values, we quantify the number of dead layers due to V/Fe or Fe/V interfaces, and compare it with the literature. We deduce that dead layers occur mostly at the bottom V/Fe interface. An average value for V/Fe and Fe/V interface anisotropy around 0 ± 0.1 erg/cm^2 (mJ/m^2) was thus deduced.

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1. Introduction

Research on spintronic devices such as magnetic random access memories (MRAM) and magnetic sensors have generated a perpetual need in original magnetic materials. As the thickness of the magnetic thin films (e.g. electrodes for giant or tunnel magnetoresistance multilayer) have shrunk, the influence of interfaces has become crucial. The control of the magnetic configuration using interfacial effect is still heavily studied: e.g. exchange bias with ferromagnetic / anti-ferromagnetic interfaces [1], coercivity control with hard/soft bilayer in recording media [2], multiferroism with ferromagnetic/ferroelectric interface [3], magnetization induction at oxide/oxide interface [4], Dzyaloshinskii–Moriya interaction [5], etc. One of the most studied features is the interface-induced anisotropy that originates from the hybridization between two layers composed of different chemical elements like Co/Pt, Co/Ni, etc. (see Ref. [6] for a review). Recently, we investigated V/Fe/MgO as a model system to characterize electrical control of the magnetic anisotropy by a bias voltage [7,8]. Although the interface magnetization and in-plane bulk anisotropy in [Fe/V] multilayers have been widely studied in the past [9-12], we could not find in the literature a clear thickness dependence allowing to precisely determine the interface anisotropy for V/Fe interface.

In the present report, we show magnetometry data obtained on epitaxial V/Fe (t)/V trilayer grown by ultra-high vaccum molecular beam epitaxy (MBE). Magnetization versus field loops at room temperature are presented both for in-plane and out-of-plane field orientation relative to the V/Fe/V interfaces. The magnetization at saturation and anisotropy field are plotted as a function of the Fe thickness t from which we extract an average value for Fe/V and V/Fe interface anisotropy constant.

2. Experiments

The samples were grown on single-crystalline MgO (100) substrate using MBE with a base-pressure lower than 10^{-10} Torr. The V (20nm) buffer layer was deposited at room temperature and annealed at 600°C. Fe layers of thickness t ranging from 0.7 nm (5 atomic layers) to 5 nm (35 atomic layers) were grown at room temperature, annealed at 350°C and capped with V(5nm)/Au(5nm) with no further annealing).

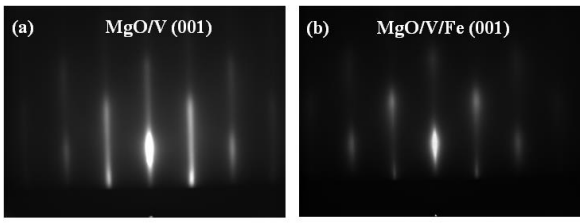

Fig. 1 RHEED patterns along the (001) BCC axis for (a) annealed V(20nm) buffer layers deposited on MgO and (b) MgO/ V/Fe (1nm) along (001) direction.

Fluxes were calibrated by quartz or reflection high energy electron diffraction (RHEED) oscillations in-situ during growth and with ex-situ X-ray small angle reflectivity. The epitaxial relationship,

growth mode, number of deposited MLs, and surface flatness were controlled in situ using RHEED. Fig. 1 shows RHEED pattern for annealed V and Fe layers along the (001) direction and confirms good crystalline quality of the films. Later, magnetization curves were measured using commercial rotating sample vibrating sample magnetometer (VSM) and commercial SQUID-VSM.

3. Results and discussions

Fig. 2(a) shows normalized magnetization versus field loops measured both for in-plane magnetic field and out-of-plane magnetic field for V/Fe(2nm)/V stack. Out-of-plane direction corresponds to a magnetic hard axis direction for the Fe layer. In-plane field measurement with field applied along Fe (100) direction shows square loop with full magnetization at remanence (see zoom in Fig. 2(b)). In Fig.2(c) is plotted the remanent magnetization extracted from hysteresis loops obtained for various in-plane applied field direction. As expected for cubic Fe bulk magnetic anisotropy, four lobes with full remanence are observed and in-between the lobes remanent magnetization is 75% of the saturation magnetization

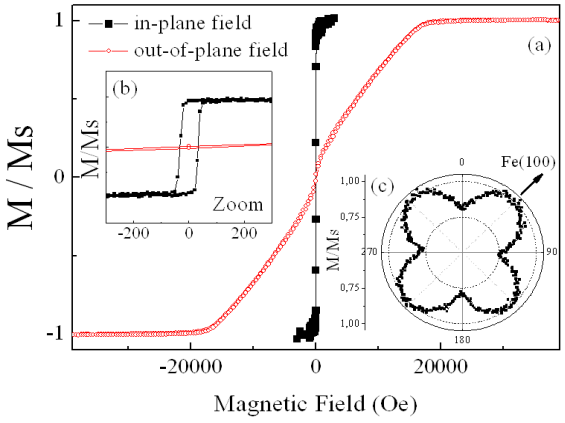

Fig. 2. (a) Normalized magnetization versus field loop for in-plane along (100) Fe direction (black solid squares) and out-of-plane (open red circles) field respectively for a V/Fe (2 nm)/V stack. (b) Zoom of the main figure around zero field show square hysteresis cycle. (c) Normalized remanent magnetization as a function of field angle when applied in film plane demonstrates bulk cubic ansiotropy.

From the magnetization versus field curves, one can extract magnetization at saturation. Here this quantity has been obtained by dividing the measured moment value measured by magnetometry by the nominal Fe volume. In Figure 3, we plot saturation magnetization times thickness (t), i.e. areal magnetic moment, as a function of the deposited Fe thickness (t). The areal magnetic moment vs t should be a straight line passing through 0, with a slope equal to the bulk Fe magnetization (about 1720 emu/cm^3). Although the slope is as expected, the line crosses zero for 0.3 nm. This result is coherent with a reduction of Fe magnetization at the interface with V which is reported in the literature. This has been explained by roughness, charge transfer, intermixing and anti-parallel polarization of the V [9,11,13]. An oxygen contamination of the starting V(001) surface should also contribute to these magnetic dead layers in Fe grown at room temperature [10]. Interestingly, the same deadlayer thickness (t_{dl}) is found in Ref. [7] for a MgO substrate/V/Fe/MgO stack where Fe is grown on V in the very same conditions (same setup). As no reduction of magnetization is observed at Fe/MgO interface when MgO is grown on Fe [14], this suggests that the main loss of magnetization occurs at bottom V/Fe interface. Although vanadium anti-parallel polarization may happen at both interfaces, the main reduction must originate from the oxygen contamination of the V buffer layer (O segregation after the buffer layer annealing [10]), that does not occur for the top (not annealed) V layer.

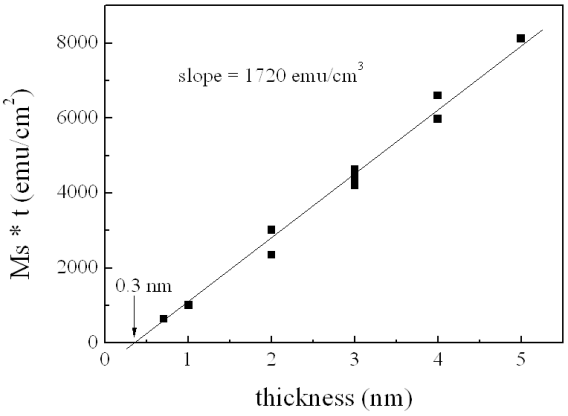

Fig. 3. Areal magnetization versus Fe thickness. The linear fit has positive slope value 1720 emu/cm^3. It crosses zero areal moment for a non-zero-thickness meaning that Fe magnetization is reduced in average over about 2 atomic layers.

In fig. 2, hard axis loop is obtained when the field is applied perpendicularly to the V/Fe interface. It means that the magnetization lies preferentially in the film plane. The same behavior has been observed for all tested samples. Same conclusion is reported in the literature for Fe thickness as thin as three atomic layers [12]. To further investigate the role of Fe/V and Fe/V interface in stabilizing or destabilizing in-plane magnetization, we calculate the effective anisotropy constant from the anisotropy field H_{keff} extracted from the out-of-plane field hard axis loops as K_{keff} = ½ $M_S.H_{keff}$. Various origins of effective anisotropy are usually distinguished as in equation (1), here in CGS and including the deadlayers [6] :

$$K_{eff}.(t_{Fe} - t_{dl}) = (K_V - 2\pi M_S^2).(t_{Fe} - t_{dl}) + Ki \quad (1)$$

K_V is the magnetic volume anisotropy and Ki is the interfaces anisotropy acting in the Fe layer. The $2\pi M_S^2$ term comes from the shape anisotropy for a thin film. The negative sign shows that this anisotropy term tends to align the magnetization in the film plane. The thickness t is the nominal thickness of the film and t_{dl} is the deadlayer thickness equal to 0.3 nm.

To quantify the different terms, we plot in Fig. 4 $K_{eff}.(t_{Fe} - t_{dl})$ as a function of $(t_{Fe} - t_{dl})$. All values $K_{eff}.(t_{Fe} - t_{dl})$ are negative which confirm that the effective anisotropy favors in-plane orientation of magnetization for all Fe thicknesses. A linear evolution is obtained whose slope is also negative. It means that $K_V - 2\pi M_S^2$ term here provides an in-plane anisotropy. If we consider only $-2\pi M_S^2$ term, one finds M_S = 1720 emu/cm^3, in good agreement with value measured extracted from Fig. 3 and with Fe bulk magnetization. It confirms that K_V is small as compared with shape anisotropy [15,16]. Note that the role of strain on K_V term in V/Fe multilayers has been studied in details in Ref. [17]. However, we have shown in a previous study [18] that the critical thickness for plastic relaxation during Fe growth on a V(001) surface containing oxygen at room temperature is lower than 1 monolayer (i.e. lower than 0.14 nm). This means that Fe layer relaxes to its stable bcc structure, leading to small magnetoelastic anisotropy.

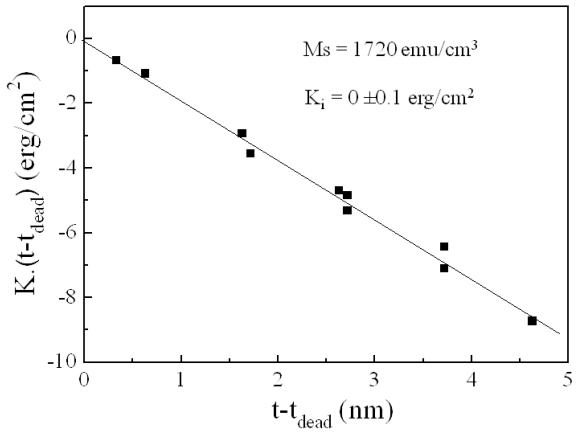

Fig. 4. Effective anisotropy constant Keff times the corrected thickness tFe-tdl as a function of t_{Fe}-t_{dl} at 300K for both V/Fe/V. The line is a fit using Eq. (1) with negative slope corresponding to a magnetization 1720 emu/cm^3 and a value at zero thickness corresponding to a value of Ki = 0± 0.1 erg/cm^2.

The value of anisotropy Ki extracted from the curve Fig. 4 at zero thickness is close to zero. Actually, regarding the accuracy of our measurements and fit, we have to consider an error bar of at most ± 0.1 erg/cm^2. This result is in agreement with Ref. [11] where the anisotropy of the orbital and spin moments is extracted from ferromagnetic resonance and compared with first-principle calculations. The value of Ki originates from the bottom V/Fe interface and from the top Fe/V. Since we know that atomic arrangement at V/Fe and Fe/V are different, we cannot assure that both interface lead to zero but it is most probable.

4. Summary and Conclusions

To fill the lack of information about Fe/V interface anisotropy in the literature, we studied the influence of the Fe thickness on the magnetic properties of single-crystal V/Fe(t)/V trilayer grown on bcc MgO substrate. Magnetometry allows measuring magnetization at saturation and out-of-plane anisotropy field. A total of 0.3 nm deadlayers is found and mainly attributed to the lower V/Fe interface. In plotting the anisotropy constant deduced from the anisotropy field, as a function of thickness, we conclude that the volume anisotropy is dominated by in-plane demagnetization field whereas the interface anisotropy related to Fe/V interface is around zero with accuracy equal to ± 0.1 erg/cm^2.

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