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Exchange bias and asymmetric magnetization reversal in ultrathin Fe films grown on GaAs (001) substrates

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Magnetization measurements on a series of Fe films grown by molecular beam epitaxy on GaAs (001) substrates and capped with a thin Au layer reveal interesting exchange bias (EB) properties at low temperatures. The observed exchange bias decreases rapidly with increasing temperature, and completely disappears above 30 K. While the Fe samples were not grown with an intentionally deposited antiferromagnetic (AFM) layer, X-ray reflectometry, X-ray absorption near-edge spectroscopy carried out near the L-edge of Fe, and comparison with similar Fe/GaAs samples capped with Al, which do not show exchange bias, suggest that the exchange bias in the GaAs/Fe/Au multilayers is caused by an AFM Fe oxide at the Fe/Au interface formed by penetration of oxygen through the Au capping layer. The observed exchange bias is accompanied by a strikingly asymmetric magnetization reversal of the Fe films occurring when the magnetic field is applied at angles away from the easy axis of the film. The observed asymmetry can be interpreted in terms of a competition between cubic, uniaxial, and unidirectional magnetic anisotropy characteristic of the exchange-biased Fe film. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4798515]

I. INTRODUCTION

Magnetic properties such as magnetic anisotropy, magnetic exchange coupling, and exchange bias (EB)1,2 in heterostructures involving ferromagnetic (FM) layers3 have been extensively studied in both all-metallic multilayers (e.g., permalloy/Cu4 and MnF2/Fe5) and in multilayers combining magnetic and non-magnetic semiconductors (e.g., GaMnAs/GaAs6 and GaMnAs/MnO7,8). By comparison, heterostructures involving combinations of a ferromagnetic metal layer and a semiconductor have been explored to a much lesser degree. Such combinations are, however, important because of their potential for electronic applications,9,10 particularly in systems where the ferromagnetic metal layer can be used as a spin injector or a spin filter coupled to a semiconductor device.

An example of such metal/semiconductor hybrid structure is represented by Fe films deposited epitaxially on GaAs. This is a unique materials combination, made possible by the fortuitous lattice match between the (001) faces of the fcc GaAs and of the bcc x-phase Fe, allowing fabrication of thin Fe/semiconductor heterostructures of exceptionally high crystalline quality.11–13 While this hybrid Fe/GaAs system, consisting of a canonical ferromagnet and an important semiconductor, has not been as thoroughly explored as its fully metallic or fully semiconductor counterparts, it has already attracted considerable interest both because of the interesting basic properties of the Fe film created in this way, and because of the potential for spintronic applications of this combined metal/semiconductor system.14,15

In this paper, we will focus on two fundamental properties of the Fe/GaAs(001) structure: the unusual exchange bias which this hybrid system exhibits at low temperatures, and the asymmetric magnetization reversal which accompanies such exchange bias.

II. EXPERIMENTAL DETAILS

A. Sample preparation

The ultrathin Fe films were grown by low-temperature molecular beam epitaxy (LT-MBE) on GaAs (001) substrates. Figure 1 shows schematically the interface of an unreconstructed As-terminated GaAs (001) surface and the first layer of the deposited bcc Fe (001) film, revealing the fortuitous lattice match of the two materials (where the lattice parameter of Fe aFe = 2.866 Å is very close to one-half of aGaAs = 5.653 Å).

Briefly, the sample preparation is carried out as follows. Prior to the Fe growth, the GaAs (001) epi-ready wafers are annealed in the MBE chamber at about 600 °C in As2 flux to remove native oxides. The process is monitored by reflection high energy electron diffraction (RHEED) until a (2 × 4) GaAs surface reconstruction appears. A GaAs buffer layer is then deposited to a thickness of about 100 nm at 600 °C to obtain an atomically flat surface. Subsequently, the wafer is cooled to room temperature (RT) and transferred in ultra-high vacuum to a chamber containing an electron-beam evaporator, which we use to generate the Fe flux. The Fe film is then deposited directly on the As-terminated (001) GaAs surface at room temperature and is capped by a nominal 2 nm Au layers (also grown using the e-beam evaporator) to prevent oxidation after the wafer is removed from the MBE chamber.
A series of five samples was grown in this manner, all with the nominal Fe thicknesses of 4 nm and with Au capping layers of ~2 nm. The structural parameters of the series are shown in Table I. In addition to the above GaAs/Fe/Au structures, several GaAs/Fe/Al structures were also grown under identical conditions, to allow comparison of the effects of Au and Al capping.

B. Superconducting quantum interference device (SQUID) magnetometry

Magnetization measurements of the Fe/GaAs films were carried out using a SQUID. Prior to measurements, the samples were zero-field-cooled (ZFC) to 5 K. The angular and temperature dependences of magnetic hysteresis loops of the films were then measured between 5 K and RT. The magnetic field in these measurements was applied in the plane of the film at different orientations and was swept from 2.0 kOe.

C. X-ray reflectometry and X-ray absorption spectroscopy

X-ray reflectivity measurements were used to characterize the GaAs/Fe/Au films. The experiments were carried out at the Advanced Photon Source of Argonne National Laboratory (Beamline 4-ID-D) using 8 keV monochromatic x-rays (\(\lambda = 1.5519 \text{ Å}\)). The intensity of the specular reflection of the X-ray beam measured as a function of angle showed an oscillatory spectrum due to interference of the reflected x-rays from the interfaces within the structure. From the period of the interference spectrum, we were then able to estimate the thicknesses of the constituent layers using a standard fitting procedure, as described below. Additionally, the amplitude of the oscillations and the overall intensity provided information on the chemical profile and the roughness of the interfaces within the structure. To obtain further information on the chemical composition of the multilayer, we have also performed element-specific X-ray absorption near-edge structure (XANES) measurements at the L_{2,3} edge of Fe. The XANES measurements were carried out in the fluorescent yield (FY) mode at the 4-ID-C beamline of the Advanced Photon Source.

III. RESULTS

Figure 2 shows low-temperature hysteresis loops for a representative Fe film grown on a GaAs (001) substrate and capped by a thin Au layer (sample A in Table I). The sample was zero-field cooled (ZFC) to 5 K, and hysteresis loops were measured with the magnetic field applied along the [110] direction of the Fe film at several temperatures, as shown in the series of panels in Fig. 2. One should note that there is a finite net magnetization in the Fe film even after ZFC due to a weak residual field in the SQUID system (of the order of 2 Oe), causing a net magnetization at the point marked “S”, i.e., at the starting point of the first field sweep. The first (training) sweeps are shown in black in Fig. 2, and all red loops are observed after the first initial saturation. The hysteresis observed at the lower temperatures clearly show that the center of the hysteresis loop is shifted to the right of the zero-field axis, indicating the presence of exchange bias. The position of the center of the loop gives an exchange bias field of about \(H_E = 256 \text{ Oe}\) at 5 K. As the temperature increases from 5 K up to 20 K (Figs. 2(b) to 2(d)), the shift of the hysteresis loops (and thus the exchange bias field) decreases, and at 25 K and above the center of the loop eventually coincides with the zero-field axis. It is interesting that the shape of the hysteresis is slightly asymmetric at temperatures when exchange bias is observed, but becomes quite symmetric at and above 25 K. We will discuss the possible origin of this asymmetry in Sec. IV D.

The observed temperature dependence of the exchange bias field \(H_E\) is shown in Fig. 3. As seen in Fig. 2, we observe a finite net \(H_E\) at a lower temperature than the very pronounced broadening of the hysteresis loop in the GaAs/Fe/Au system. From this, we infer that the Néel temperature of the antiferromagnetic (AFM) layer must be significantly higher than 25 K, but we do not know its exact value. We have tentatively ascribed the observed exchange bias phenomenon to the formation of an as yet unspecified oxide of Fe (quite possibly FeO) at the Fe/Au interface due to penetration of oxygen through the Au capping layer. As a working hypothesis, we will assume that the oxide formed in this

![Graph](image-url)

**FIG. 1.** Atomic arrangement at the GaAs/Fe interface for an As-terminated unreconstructed GaAs (001) face and the epitaxial bcc Fe. The crystallographic orientations are indicated on the left of the figure.
way is FeO, which is antiferromagnetic, with a Néel temperature of 200 K. However, owing to the nature of its formation, it is reasonable to expect that this oxide will vary significantly in both thickness and in composition, and such variations can automatically lead to lowering of the Néel temperature below the above value. Such reduced blocking temperature is not unexpected. As seen in many studies of thin AFM layers antiferromagnets (at thicknesses of a few nm), the blocking temperature can be much less than the nominal or measured Néel temperature.

As noted, the magnetic coercivity $H_C$ is quite high at low temperatures ($H_C = 248$ Oe at 5 K), but also decreases rapidly as the temperature increases above $\sim 30$ K (see Fig. 3). The observed hysteresis loops show a clear training effect at all studied temperatures, as shown in Figs. 2(a) to 2(f), where the first hysteresis cycle is shown in black, and subsequent sweeps are in red. The microscopic origin of this training effect is generally recognized as originating from an initial rearrangement of uncompensated interfacial spins in the antiferromagnetic layer. One should note that all features shown in the sample used for Fig. 2 are also consistently seen in the remaining four samples, with similar values of the exchange shift and coercivity.

The angular dependence of magnetic hysteresis loops of the iron thin film was studied at 5 K by rotating the orientation of the applied magnetic field in the plane of the film from $\varphi_H = 0^\circ$ to $\varphi_H = 90^\circ$, i.e., from $H[110]$ to $H[110]$ (see Fig. 4). Exchange bias with a strikingly asymmetric behavior of the magnetization reversal (i.e., different shape of the magnetization path for the up-sweep and the down-sweep) was clearly observed at all azimuthal angles except at $0^\circ$ and $90^\circ$ in all samples of the series, as shown in the left-hand panels of Fig. 5 for sample C. The experimental sweeps of the hysteresis loops in the left-hand panels of Fig. 5 are recorded after the sample was first taken to saturation, ensuring that the sample is homogeneous and can be regarded as a single domain. The right-hand panels of Fig. 5 show corresponding computer simulations of the hysteresis loops, as will be discussed in Sec. IV C.

Finally, in certain cases, the observed hysteresis showed an interesting double-loop behavior, shown in Fig. 6, which we include for completeness. The origin of this behavior will be discussed in Sec. IV.

IV. DISCUSSION OF RESULTS

The results described above reveal two important magnetic properties of the Fe films grown epitaxially on GaAs (001) substrates and capped by Au: the presence of exchange bias, and a striking asymmetry of hysteresis loops observed in the course of magnetization reversal at field orientations away from high-symmetry axes. We discuss the possible origins of these effects below.

A. Identification of AFM layer in GaAs/Fe/Au structures

The observation of exchange bias in hybrid GaAs/Fe/Au structures illustrated by Fig. 2 implies the existence of an AFM layer at one (or both) interfaces of the ferromagnetic Fe film, which establishes such exchange bias via coupling between the FM Fe layer and the AFM layer. In our case, there are two possibilities of forming such an interfacial
One possibility is the formation of AFM Fe$_2$As at the Fe/GaAs interface,\textsuperscript{19,20} which has been discussed by Lepine\textsuperscript{21} However, since the nominal Néel temperature of Fe$_2$As is 367 K,\textsuperscript{12,22} and cooling down of our specimens starts at room temperature, we exclude this possibility. This conclusion will further be corroborated by experiments on Fe/GaAs samples capped by Al, described below, which do not show exchange bias.

The other possibility is the presence of an AFM Fe oxide that has formed at the Fe/Au interface by penetration of oxygen through the thin Au capping layer on the Fe film. It has been reported in the literature that an Au thickness of 1.4 nm is sufficient to effectively prevent the oxidation of the Fe film.\textsuperscript{23} While our capping layer nominally exceeds that thickness, which could result in exposing regions of the Fe layer to the atmosphere,\textsuperscript{24} Here, there are three possibilities to consider:\textsuperscript{25} the formation of Fe$_2$O$_3$ or FeO, both of which are antiferromagnetic; or of Fe$_3$O$_4$,\textsuperscript{26} which is ferrimagnetic. Since the Néel temperature of Fe$_2$O$_3$ is known to be 950 K,\textsuperscript{27} the Curie temperature of Fe$_3$O$_4$ is 825 K,\textsuperscript{28} and the Néel temperature of FeO\textsuperscript{28,29} is 200 K, we will assume as a working hypothesis that a thin irregular layer of AFM FeO forms at the Fe/Au interface, thus giving rise to the observed exchange bias in the hybrid GaAs/Fe/Au structures.

To establish the structural profile of the samples being investigated, we performed X-ray reflectivity experiments as described in Sec. II C, above. A representative reflectivity spectrum is shown in Fig. 7. The reflectivity spectrum was fitted using Parratt’s recursive formula,\textsuperscript{30,31} by employing the reflectometry analysis program Reflfit from NIST Center for Neutron Research\textsuperscript{32} and tabulated atomic scattering factors. This fit yields information on the thicknesses of the layers that make up the assumed GaAs/Fe$_2$As/Fe/FeO/Au structure, as well as the roughness of interfaces in this multilayer. We find that the best fit can be obtained by assuming a thickness of 3.65 nm for the Fe layer, with thin interfacial layers with densities lower than that of Fe on either side. The measured reflectivity data were modeled by assuming that the layer between GaAs and Fe (the “bottom” layer) is Fe$_2$As, as discussed by Lepine\textsuperscript{et al.}\textsuperscript{21} and that the “top” layer consists of FeO. The best fit, obtained by using the
densities of Fe and of the assumed interfacial Fe$_2$As and FeO layers and by using their thicknesses as fitting parameters, is shown in red in Fig. 7 by the red curve. The thicknesses of the successive layers $d$ obtained from the best fit are as follows: $d_{\text{Fe(2)As}} = 0.73 \pm 0.19$ nm, $d_{\text{Fe}} = 3.65 \pm 0.48$ nm, $d_{\text{FeO}} = 1.4 \pm 0.48$ nm, and $d_{\text{Au}} = 1.72 \pm 0.36$ nm. Note that the roughness of our Au capping layer obtained from fitting the reflectivity data is quite high, consistent with the possibility of forming an oxide at the Fe surface$^{33}$ by oxygen penetration of the Au cap.

Our conclusion regarding the presence of a thin FeO layer at the Fe/Au interface is further confirmed by surface-sensitive, element-specific XANES measurements shown in Fig. 8. Figure 8 shows Fe L$_{2,3}$ XANES spectra recorded for the FY mode at room temperature for two Fe/GaAs samples, one with Au capping (blue; sample A) and the other with Al capping (red). Note that the XANES data for the Au-capped sample show a clear splitting of the near-edge peak at $\sim$707 eV characteristic of the presence of an Fe oxide at the Fe/Au interface,$^{34}$ while the data for the Al-capped specimen are characteristic of bulk Fe,$^{35,36}$ indicating that the Fe surface in this case is not oxidized.

B. Exchange bias and coercive field

There is a well-known feature observed in materials displaying exchange bias: the coercive field is considerably greater than in non-exchange-biased systems, as revealed by the width of the hysteresis loop.$^1$ As an example, this is seen in the width of the hysteresis in Fig. 2. We illustrate this further in Fig. 9, where we compare the hysteresis loops of a GaAs/Fe/Au multilayer, which exhibits exchange bias (taken from Fig. 2) with the hysteresis observed in a GaAs/Fe/Al structure, where the Fe layer is capped by a protective layer of Al, and the exchange bias is not observed. Note that we have also grown the Fe films with thicker (>3 nm) Au cap, which behave similarly with respect to the samples capped with Al, showing no exchange bias.

Figure 9 shows an additional important feature relevant to the present exchange-bias data. Even at temperatures where the exchange bias disappears ($T > 25$ K), the coercive field remains very large compared to that of the GaAs/Fe/Al multilayer. This can be understood as follows. As the temperature increases, the overall range of the antiferromagnetic order in the AFM layer will decrease, and so will the net exchange bias, until it vanishes. Nevertheless, local randomly distributed AFM clusters will remain. These clusters can impede the reversal of magnetization by acting as pinning centers that create a “drag” on the Fe magnetization as the field is reversed, and thus leading to higher coercive fields even after the net exchange-bias shift of the hysteresis loop is no longer present. This effect is expected to be especially pronounced when the AFM layers are ultrathin, i.e., at thicknesses where the blocking temperature begins to show a strong dependence on the thickness of the film.$^{17}$

Figure 9 also has implications that corroborate our conclusion made earlier that the AFM layer responsible for exchange bias in GaAs/Fe/Au structure is formed at the Fe/Au interface. The two multilayers used in Fig. 9, GaAs/Fe/Au and GaAs/Fe/Al, were grown in the same way, the only difference being the capping layer. Thus, the GaAs/Fe interface is the same in both cases. The fact that the GaAs/Fe/Al system does not exhibit exchange bias shows that the AFM layer responsible for this effect must be at the Fe/Au interface of the GaAs/Fe/Au structure, and is most likely caused by the formation of an oxide at the surface of the Fe layer. This is reasonable, since Al cap reacts readily with oxygen
and can thus inhibit its penetration to the Fe layer. Thus, our assumption that the AFM layer is caused by partial oxidation of the Fe layer through the Au cap appears to be most likely.

C. Angular dependence of magnetization reversal

A striking result of this investigation is the pronounced asymmetry in the shape of the hysteresis loops observed when the field \( H \) is applied at different angles \( \Phi_H \), as seen in left panels of Fig. 5 measured on sample C. All five samples in the series of our hybrid GaAs/Fe structures show a similar behavior. Specifically, when the field is applied along the [110] direction (\( \Phi_H = 0^\circ \)), the exchange-biased hysteresis is characterized by abrupt irreversible transitions when the magnetization switches direction, as expected for magnetization reversal with the field \( H \) applied along the easy axis. At \( \Phi_H = 90^\circ \) (hard axis), the magnetization reversal is completely coherent, i.e., reversibly, smoothly following the applied field, as expected for \( H \) applied along the hard axis. However, at intermediate values of \( \Phi_H \), the magnetization reversal shows a distinctly different behavior during its down-sweep and up-sweep: just before the switching field is reached, there is a very narrow field region where the reversal follows a smooth (coherent, i.e., reversible) path in the down-sweep branch (left side) of the hysteresis, and a much wider field range of such coherent field dependence in the up-sweep (right side) branch. This asymmetric angular dependence of magnetization is characteristic of exchange-biased systems and has been reported for a number of structures in the literature.37–40

To gain insight into the asymmetry of the hysteresis in the shown GaAs/Fe/Au system shown in Fig. 5, we carried out computer simulations of the observed angular dependence of the hysteresis loops. The calculations are carried out based on the single-domain Stone-Wohlfarth model of a Fe film41 modified by adding a unidirectional anisotropy term collinear with the uniaxial magnetic anisotropy. The magnetic free energy per unit volume can in this case be expressed as

\[
F = -M_s H \cos(\varphi - \varphi_H) - K_F \cos(\varphi - \xi) - K_u \cos^2(\varphi - \xi) + (1/4)K_1 \sin^2 2\varphi, \tag{1}
\]

where \( M_s \) is the saturation magnetization; \( H \) is the applied field; angles \( \varphi \) and \( \varphi_H \) give the direction of magnetization and the applied field, respectively, as defined in Fig. 4; angle \( \xi \) is the direction of the exchange field \( K_F/M_s \) (in the present situation \( \xi = 180^\circ \)); and the terms \( K_1 \) and \( K_U \) are the cubic and the uniaxial anisotropy parameters for the Fe film. Finally, \( K_F \) is the new unidirectional anisotropy term added to \( F \) to account for exchange bias. Here, one should note that, while the Fe grown on a GaAs[100] substrate is dominated by the uniaxial anisotropy, which establishes the overall easy axis of the system along the [110] axis, the cubic symmetry of Fe introduces cubic easy axes along the in-plane (100) directions, which result in four local minima in the free energy landscape. This in turn results in switching of magnetization between these energy minima as the orientation of the applied field is varied.

In the simulation, we use the following values for the anisotropy terms: \( 2K_1/M_s = 600 \text{ Oe} \) and \( 2K_U/M_s = 1100 \text{ Oe} \), which are determined from fitting the magnetization curve obtained at \( \varphi_H = 90^\circ \). The exchange field \( K_F/M_s = 180 \text{ Oe} \) is estimated from the shift of the hysteresis loop at \( \varphi_H = 0^\circ \) for sample C used for these measurements. Hysteresis loops are then determined numerically via energy minimization of Eq. (1). The fields at which magnetization switches from one local minimum to the adjacent minimum are obtained by comparing the difference between two free energy minima separated by a barrier height, as calculated using the parameters given above. Here, we have assumed that the magnetization switches from one minimum to the adjacent lower minimum at the point when the energy difference between the two minima equals the height of the energy barrier between the two minima. As shown by the right-hand panels of Fig. 5, this simple model satisfactorily reproduces the shapes of the hysteresis loops for the angles \( 0^\circ < \varphi_H < 90^\circ \).

Our simulations thus indicate that the asymmetric hysteresis loops are intrinsic to exchange-biased FeO/FeGaAs structures, as has indeed been observed and simulated in many other FM/AFM systems.37–41 The main characteristics of the asymmetric behavior of magnetization are determined by the competition between the uniaxial anisotropy and the exchange (unidirectional) anisotropy in such systems. It should be noted that the additional presence of cubic anisotropy in our system makes the situation somewhat more complicated—the asymmetry of the hysteresis loops appears in a slightly wider angular region in the simulation (compare, e.g., the observed and simulated curves for \( \varphi_H = 61^\circ \) in Fig. 5). Nevertheless, our simulation clearly shows that the magnetization reversal described by Eq. (1) follows the same mechanism as that observed previously in other exchange biased systems.

The observed asymmetry on the magnetization reversal observed in the GaAs/Fe/Au system can be summarized as follows. Around the uniaxial easy direction (i.e., [110]), the hysteresis loops are found to be irreversible and symmetric (the same “sharpness” of the irreversible transitions in the up-sweep and down-sweep curves, as seen for \( \varphi_H = 0^\circ \) in Fig. 5. However, smoother fully reversible portions of the hysteresis curves appear at angles away from this easy direction, and are seen to grow with increasing \( \varphi_H \), but unequally (i.e., asymmetrically) on the left and on the right sides of the hysteresis. This finally transforms again to a symmetric but now smooth and fully reversible curve as the field orientation approaches the hard axis, \( \varphi_H = 90^\circ \). It is gratifying that all the trends observed experimentally are very closely reproduced in the simulation, providing support to the assumptions made in formulating the free energy picture as given in Eq. (1).

D. Exchange-bias-induced double hysteresis

We finally discuss the exchange-bias-induced double hysteresis effect shown in Fig. 6. As described earlier, the SQUID magnetization data shown in Figs. 2, 5, and 6 were taken in zero-field-cooling (ZFC) mode. While there is a weak remnant field of \( \sim 2 \text{ Oe} \) in the SQUID system, this may not be sufficient to uniformly magnetize the Fe film at room
FIG. 10. Hysteresis loops for sample D (shown in the upper panel of Fig. 6), observed after field cooling in $\pm 2.0$ and $-2.0$ kOe. Field cooling results in disappearance of the double loop seen in Fig. 6.

temperature, as seen in the difference between the training and the post-saturation loops in Fig. 2. Thus, it is also likely that, in some cases upon zero-field cooling, the Fe film consists of a distribution of domains magnetized along the two opposite easy axes directions. This will then result in “seeding” of two populations of opposite AFM domains as the system is cooled below the Néel temperature. As a consequence, after cooling the system will consist of two magnetic sub-systems, with two similar hysteresis loops that are exchange-bias-shifted in two opposite directions, since the oppositely seeded AFM regions will each lead to two opposite exchange bias fields.

This form of double hysteresis is quite common in many exchange-biased systems where fluctuations of the AFM magnetization can occur. From these arguments, it follows that the populations of such oppositely ordered AFM regions in a sample showing such double loops can be determined by the relative amplitudes of the two loops exchange biased in opposite directions that result in the overall shape shown in Fig. 6. It is possible that the slight asymmetry in the hysteresis loops seen in Fig. 2 also arises from a small but finite population of AFM regions that are oppositely exchange-biased.

Since the AFM ordering is nucleated by the initial ordering landscape in the ferromagnetic film, the shape of such multiple loops can, therefore, be controlled by the cooling process. To test this hypothesis, we measured the hysteresis of sample D (corresponding to the upper panel of Fig. 6) after cooling in a 2.0 kOe field. The resulting data are shown in Fig. 10. As expected, the double loop disappears upon field cooling. Furthermore, when the direction of the cooling field is reversed, the sign of the exchange bias is also reversed confirming the picture described above.

V. CONCLUDING REMARKS

Exchange bias of the GaAs/Fe/Au hybrid system was investigated using five specimens. Based on this study, we have arrived at the following conclusions:

1. Exchange bias in this system appears at low temperatures (below about 25 K).
2. The exchange bias field $H_E$ increases as the temperature decreases, and is typically of the order of 100 Oe.
3. Exchange bias is accompanied by a large coercive field $H_C$ of the same order as $H_E$ at 5 K. However, the large value of $H_C$ survives to temperatures considerably above the temperature at which the exchange bias itself disappears (i.e., above the blocking temperature).
4. From the data obtained by XANES and x-ray reflectivity, we ascribe the appearance of exchange bias in GaAs/Fe/Au multilayers to an oxide layer (most likely FeO) that forms as a result of oxygen penetrating the thin Au layer used for capping the system. This is corroborated by the fact that GaAs/Fe/AI multilayers grown under identical conditions as the GaAs/Fe/Au system do not show exchange bias.
5. The asymmetric behavior of the hysteresis loops of the exchange-biased GaAs/Fe/Au system observed at different angles of the in-plane magnetic field can be successfully simulated by using the standard formulation of magnetic free energy, with an added unidirectional exchange-bias energy term, showing that the magnetic properties of the Fe layers are well represented by the Stoner-Wohlfarth model. This result provides a practical basis for further quantitative analysis of this and related Fe/semiconductor hybrid systems.

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