Antiferromagnetic exchange coupling between GaMnAs layers separated by a nonmagnetic GaAs:Be spacer

J. Leiner,1,a) K. Tivakornsasithorn,1 X. Liu,1,b) J. K. Furdyna,1 M. Dobrowolska,1 B. J. Kirby,2 H. Lee,3 T. Yoo,3 and Sanghoon Lee3,c)

1Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA
2Center for Neutron Research, NIST, Gaithersburg, Maryland 20899, USA
3Department of Physics, Korea University, Seoul 136-713, Korea

(Submitted 18 November 2010; received 15 October 2010; accepted 2 November 2010; published online 22 March 2011)

Interlayer exchange coupling (IEC) between two Ga0.95Mn0.05As layers separated by Be-doped GaAs spacers was investigated using magnetometry and neutron scattering measurements, which indicated the presence of robust antiferromagnetic IEC under certain conditions. We argue that the observed behavior arises from a competition between the IEC field and magnetocrystalline anisotropy fields intrinsic to GaMnAs layers. We estimate the magnitude of the IEC field and show how it decays with increasing temperature. © 2011 American Institute of Physics. [doi:10.1063/1.3536669]

I. INTRODUCTION

Ferromagnetic (FM) dilute magnetic semiconductors (DMSs) continue to be of great interest because of their potential for spin-electronic applications.1 Although much progress has been made in understanding DMS materials, particularly in the canonical III-V system Ga0.75Mn0.25As,2 many issues still remain unresolved. One of these is the nature of interlayer exchange coupling (IEC) in GaMnAs-based multilayers. Here it is particularly important to establish under what conditions the IEC between adjacent GaMnAs layers is antiferromagnetic (AF) or FM, since manipulation of such IEC can serve as the basis for a wide range of devices. A study of two GaMnAs layers separated by a nonmagnetic GaAs spacer is particularly useful, since such a trilayer enables one to examine in fine detail the specific properties of GaMnAs that determine IEC.

II. SAMPLE PREPARATION

The GaMnAs/GaAs:Be/GaMnAs trilayer used in this study was grown by molecular beam epitaxy (MBE) on a (100) GaAs substrate at 250 °C, by first growing a Ga0.95Mn0.05As layer to a thickness of 17.2 nm (bottom layer), then a 4.3 nm thick GaAs spacer doped by Be (doping level estimated as 1021 cm−3, based on the temperature of the Be cell), and finally a Ga0.95Mn0.05As layer 8.6 nm thick (top layer). The average hole concentration of the trilayer is 2 × 1020 cm−3. The top GaMnAs layer was made half as thick as the bottom layer so that the contribution of each layer could be identified in magnetometry measurements.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Superconducting quantum interference device (SQUID) measurements were used to measure the temperature dependence of the trilayer magnetization M(T). The sample was oriented so that the measured magnetization and the applied field H was parallel to the cubic easy axis [100] of the GaMnAs layers.3 The sample was either field cooled (FC) in a field of 1.5 mT, or zero field cooled (ZFC), and the magnetization was then measured as the temperature was increased in various applied fields shown in Fig. 1. Figure 1(a) shows a clear trend: The higher the applied field after ZFC, the lower the temperature at which the magnetization undergoes a sharp transition to larger magnitudes. We attribute this transition to...
the top layer of the sample switching from antiparallel to parallel magnetic alignment with respect to the magnetization of the bottom layer. Figure 1(b) shows the complimentary scenario where, after field cooling, there is a transition from parallel to antiparallel alignment. Note that this transition occurs despite the presence of a positive applied field of 0.4 mT, indicating that AF IEC is robust in the range from ~22 to 32 K. If negative fields are applied [also shown in Fig. 1(b)], this range of robust AF IEC is extended to lower temperatures. Negative applied fields eventually cause the magnetization reversal of the bottom layer as well, due to the reduction of coercivity with increasing temperature.

The variation of the IEC field $H_E$ with temperature can be estimated by plotting the parallel/antiparallel transition temperatures vs the applied field $H$. These data, representing the two coercive fields $H_{C1}$ and $H_{C2}$ as a function of temperature, can be fitted using exponential decay functions with the same decay constant. The average of $H_{C1}$ and $H_{C2}$ gives the magnitude of the exchange field $H_E$. This is equivalent to measuring the center of minor hysteresis loops of top layer as a function of temperature. Figure 2 also shows a green point placed at a value of $H_E$ previously estimated from the minor hysteresis loop at 15 K, corroborating the present method of estimating $H_E$.

We now show evidence obtained by polarized neutron reflectometry (PNR) for the picture of IEC presented above. PNR measurements were carried out for this sample with $H$ applied along the [110] GaMnAs direction, and an incident monochromatic neutron beam (neutron wavelength of 0.475 nm) spin-polarized either parallel (spin-up) or antiparallel (spin-down) to the applied field $H$. The spin-up and spin-down nonspin-flip specular reflectivities measured as a function of the scattering wave vector $Q$ provide information on the depth profile of the in-plane magnetization parallel to $H$, which can be model-fitted using exact dynamical calculations to determine the actual magnetizations of the individual GaMnAs layers within the trilayer structure.

![FIG. 2. (Color online) Plot of the temperatures at which the alignment changes from antiparallel to parallel vs applied magnetic field. The ZFC and FC data were each fitted to an exponential decay function with the same decay constant. $H_E$ was determined by taking the average of the two curves, shown as the solid blue line. The gray (green) circle marks the value of $H_E$ previously determined from a direct hysteresis loop measurement.](image1)

After cooling to either 5 or 30 K in zero field, a small field (<1 mT) was applied to ensure polarization of the neutron beam, and PNR spectra were measured to determine the spontaneous (i.e., ZFC) magnetization state of the trilayer. The field was then cycled between ±800 and −800 mT before returning below 1.0 mT for PNR measurements to investigate the robustness of the initial magnetization state. Since the difference between the spin-up and spin-down nonspin-flip reflectivities is small, it is convenient to plot the fitted PNR data in the form of $Q$-dependent spin asymmetry. Panel (a) corresponds to spin-asymmetry after cooling in zero field to 30 K. (b) shows 5 K ZFC data after cycling and returning to 0.65 mT; (c) shows spin-asymmetry obtained in 0.18 mT after cooling in zero field to 30 K, and (d) shows spin asymmetry for the ZFC case obtained at 30 K after cycling and returning to 0.18 mT. The magnetic field was applied along the [110] direction. The solid lines are best fits to the data. The magnetizations corresponding to these best fits are shown in each panel. Dashed lines are fits obtained with the same model, but with the magnetization of the top GaMnAs layer reversed.

![FIG. 3. (Color online) Fitted PNR data of the trilayer sample plotted as $Q$-dependent spin asymmetry. Panel (a) corresponds to spin-asymmetry after cooling in zero field to 5 K, collected in an applied field of 0.65 mT; (b) shows 5 K ZFC data after cycling and returning to 0.65 mT; (c) shows spin-asymmetry obtained in 0.18 mT after cooling in zero field to 30 K; and (d) shows spin asymmetry for the ZFC case obtained at 30 K after cycling and returning to 0.18 mT. The magnetic field was applied along the [110] direction. The solid lines are best fits to the data. The magnetizations corresponding to these best fits are shown in each panel. Dashed lines are fits obtained with the same model, but with the magnetization of the top GaMnAs layer reversed.](image2)
alignment is very robust, with $\beta$ increasing dramatically, indicating parallel magnetization alignment, with $M_{\text{top}} = 16 \text{ kA/m}^{-1}$ and $M_{\text{bot}} = 26 \text{ kA/m}^{-1}$. At 30 K in 0.2 mT immediately after ZFC [Fig. 3(c)], we obtain a low value of $\beta$, corresponding to antiparallel alignment, with $M_{\text{top}} = -10 \text{ kA/m}^{-1}$ and $M_{\text{bot}} = 13 \text{ kA/m}^{-1}$. After field cycling at 30 K [Fig. 3(d)], $\beta$ increases only slightly, but is still below unity, indicating that the antiparallel alignment is very robust, with $M_{\text{top}} = -6 \text{ kA/m}^{-1}$ and $M_{\text{bot}} = 17 \text{ kA/m}^{-1}$. The PNR data thus indicate that the top and bottom layers spontaneously magnetize in the antiparallel (AF) configuration at both 5 and 30 K, thus confirming the presence of AF IEC. However, the cycling process shows the antiparallel state not to be robust at 5 K, presumably due to a strong cubic anisotropy field at this low temperature, which locks the FM alignment after field cycling. However, the AF alignment clearly becomes robust at higher temperatures, as shown by the value of $\beta < 1$ after cycling at 30 K. These results are similar to what has previously been observed for a GaMnAs/GaAs:Be superlattice.\(^8\) For completeness we also used PNR to measure the saturation magnetization of the layers at 810 mT at 30 and 40 K, where the results were $M_{\text{top}} = 12 \text{ kA/m}^{-1}$, $M_{\text{bot}} = 24 \text{ kA/m}^{-1}$, and $M_{\text{top}} = 11 \text{ kA/m}^{-1}$, $M_{\text{bot}} = 20 \text{ kA/m}^{-1}$, respectively, indicating that the Curie temperatures of both bottom and top layer are above 40 K. This conclusion is also supported by the SQUID data shown in Fig. 1(a), which shows that with an applied field of 50 mT, there is no dip in the magnetization curve, indicative of two Curie temperatures.

The magnetometry data, together with the magnetizations of the top and bottom GaMnAs layers measured by PNR, allows us to estimate the free energy in terms of exchange field, and in-plane uniaxial and cubic anisotropy fields ($H_E$, $H_{U}$, and $H_C$). Magnetization vectors can therefore be predicted under the conditions of interest. After ZFC, at low temperatures the magnetizations of the top and bottom layers $M_t$ and $M_b$, are aligned antiparallel, and their free energies are offset due to exchange coupling, as shown in Fig. 4(a). As the temperature increases, both $M_t$ and $M_b$ rotate toward the uniaxial easy axis [90° and 270°, respectively, as shown in Fig. 4(c)]. When $H_U$ of the top layer is around zero, and $H_C$ of the two layers also approaches zero, $M_t$ aligns along 90°, while $M_b$ forms a multidomain state with a total $M_b$ along 270° suggested by the calculation of free energy. This state is the result of the competition between the exchange field and the rotating uniaxial easy axis in the top layer.\(^9,10\) As the temperature keeps increasing, $H_U$ of the top layer changes sign and $H_E$ becomes too small, so the average $M_t$ of top layer turns into zero, as shown in Fig. 4(d) and supported by the SQUID data shown in Fig. 1. If the sample is field cooled, the magnetization vectors align parallel after cooling due to the influence of the field. As the sample is warmed, $M_b$ will remain in its free energy minimum until the decreasing cubic anisotropy field causes that minimum to disappear, at which point $M_t$ will align as shown in Figs. 4(a) and 4(c). These arguments provide a qualitative picture for the origin of the robust AF configuration.

ACKNOWLEDGMENTS

This work was supported by the NSF Grant Nos. DMR06-03752 and DMR10-05851; by a NSF EAPSI Grant No. OISE-0914013; by Mid-career Researcher Program through NRF grant funded by the MEST (No. 2010-0025880) and (No. 2009-0085028).