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Spacer-thickness dependence of interlayer exchange coupling in GaMnAs/InGaAs/GaMnAs trilayers grown on ZnCdSe buffers

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ABSTRACT

Interlayer exchange coupling (IEC) between GaMnAs layers in GaMnAs/InGaAs/GaMnAs tri-layers was studied by magnetization measurements. Minor hysteresis loops are observed to shift in a direction indicating the presence of ferromagnetic (FM) IEC in the structures. The strength of the FM IEC clearly exhibits an exponential decrease with respect to nonmagnetic InGaAs spacer thickness. The fitting of the spacer thickness dependence of the FM IEC to an exponential decay function provides a decay length of 3.3 ± 0.3 nm, which is relatively large compared to metallic multilayers, indicating a long ranged IEC in systems based on GaMnAs.

Interlayer exchange coupling (IEC) between magnetic layers has received a great deal of attention since the discovery of giant magnetoresistance (GMR) in the Fe/Cr/Fe trilayer [1] and Fe/Cr superlattice [2] (SL) structures. Controlling the IEC between ferromagnetic (FM) and antiferromagentic (AFM) coupling is crucial for implementing such effects for practical applications [3,4]. In this context, much theoretical and experimental work has been performed to identify the characteristics of IEC in ferromagnetic multilayer systems [5,6]. The IEC in metallic ferromagnetic multilayers was found to oscillate between FM and AFM IEC as a function of the nonmagnetic spacer thickness due to indirect Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction [5,7]. Compared to research on metallic systems, much less work has been done on FM-semiconductor-based multilayers, even for structures involving the most well-known FM GaMnAs. For example, even though theoretical results indicated the possibility of both FM and AFM IEC between GaMnAs layers in multilayer structures, for a long time only FM IEC was observed in the experiments [8–11]. More recently, AFM IEC has been observed in GaMnAs-based multilayers with p-type-doped non-magnetic spacers [12–14]. However, experimental observation of oscillatory behavior between FM and AFM IEC as a function of nonmagnetic spacer thickness in FM-semiconductor multilayers still remains a challenge [15].

To date the dependence of IEC on the spacer thickness has been carried out on GaMnAs-based systems grown on GaAs substrates [9], in which the magnetization of the GaMnAs layers is in the film plane. Unfortunately, in-plane magnetic anisotropy of a GaMnAs film is very complex, including a mixture of cubic and uniaxial anisotropies [16], which makes understanding of the IEC process difficult. The investigation of this process would be significantly simpler if one could use GaMnAs multilayers with perpendicular magnetic anisotropy, because the analysis of the magnetization reversal is much easier in such systems than for systems with two in-plane magnetic easy axes. Chiba *et al.* has already used a structure with out-of-plane magnetization by growing a GaMnAs/GaAlAs trilayers on an InGaAs buffer layer, which provides tensile strain in the GaMnAs/GaAlAs combination, and results in out-of-plane magnetic easy axes in the GaMnAs layers [17]. That investigation, however, was primarily focused on the dependence of IEC on the effect of the energy barrier between the two GaMnAs layers by varying the Al concentration in the GaAlAs spacer. Some work on spacer-thickness dependence of IEC in multilayers based on FM InMnAs with out-of-plane easy axis has also been reported [18]. However, IEC in GaMnAs-based multilayers with an out-of-plane magnetization has never been systematically investigated by varying the spacer thickness.

In the present study we address this issue by strategically designing a series of GaMnAs trilayer structures. Instead of using InGaAs buffers, we have chosen the ZnCdSe material (which has a larger lattice parameter (a_{ZnCdSe}=5.77 Å) than GaMnAs (a_{GaMnAs}=5.67 Å) as the buffer to introduce the tensile strain. This provides a further advantage for investigating IEC, since the valence band of ZnCdSe (E_g=2.60 eV) is higher than that of GaMnAs (E_g=1.42 eV), so that the p-type carriers remain in the GaMnAs layer.

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Table 1
Spacer thicknesses, Magnetizations, Minor loop shifts, and IEC strengths in GaMnAs/InGaAs/GaMnAs trilayer structures.

Sample	A	B	C	D
InGaAs spacer thickness (nm)	2.8	5.6	14	56
Magnetization (emu/cm^3)	191	205	171	194
Minor loop shift (Oe)	15.0	6.00	1.70	0.40
IEC strength (μJ/m^2)	8.99	3.91	0.93	0.26

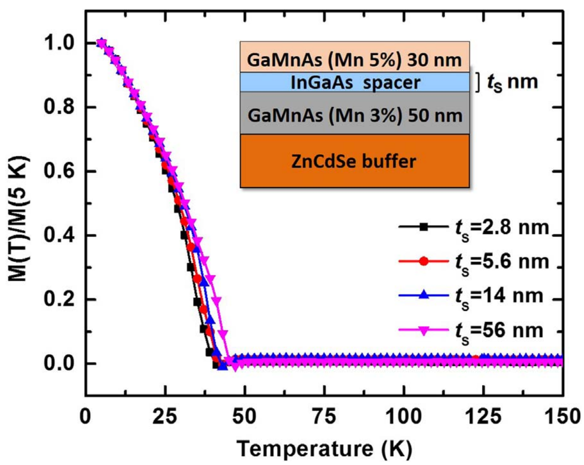

Fig. 1. Temperature dependence of magnetization measured on the four GaMnAs/InGaAs/GaMnAs trilayer structures used in this study. The InGaAs spacer thickness is given as t_s in the figure. The inset shows a schematic diagram of the GaMnAs/InGaAs/GaMnAs trilayer structures grown on a ZnCdSe buffer.

A series of GaMnAs/InGaAs/GaMnAs trilayers were prepared by using low-temperature molecular beam epitaxy on semi-insulating GaAs(001) substrates. Prior to the growth of the trilayer structure, a 2 μm ZnCdSe buffer layer with 27% Cd was grown on the GaAs substrate. The bottom GaMnAs layer with a 3% of Mn concentration was then grown directly on top of the ZnCdSe buffer [19] to a thickness of 50 nm. A InGaAs layer with 30% In was then grown to serve as the nonmagnetic spacer, whose thickness was varied from 2.8 to 56 nm in the sample series (see Table 1). Finally, each GaMnAs/InGaAs/GaMnAs trilayer structure was completed by growing a 30 nm GaMnAs layers with a 5% Mn concentration on top of the InGaAs spacer. The use of InGaAs spacer layer ensures out-of-plane magnetic easy axis in both GaMnAs layers [20]. The structure schematic is shown in the inset of Fig. 1. The InGaAs spacers and the ZnCdSe buffers induce a tensile strain on the top and bottom GaMnAs layers in the trilayer respectively, thus ensuring that the easy magnetization direction in both GaMnAs layers are out-of-plane [17,21–23]. The trilayers were investigated by measuring the magnetization using a superconducting quantum interference device (SQUID) magnetometer. During the measurements the external magnetic field was applied perpendicular to the film plane, and the temperature was varied 5–300 K.

The temperature dependence of magnetization was first measured by a SQUID magnetometer to identify the magnetic properties of GaMnAs layers in the trilayer structures. Fig. 1 shows out-of-plane magnetizations for all samples. The magnetization behaves almost same for all samples used in this study, with a Curie temperature near 40 K. A slight difference in the magnetic property between the samples may be caused by the fluctuation in the growth condition of GaMnAs layer, which is rather sensitive to the flux of sources and growth time of

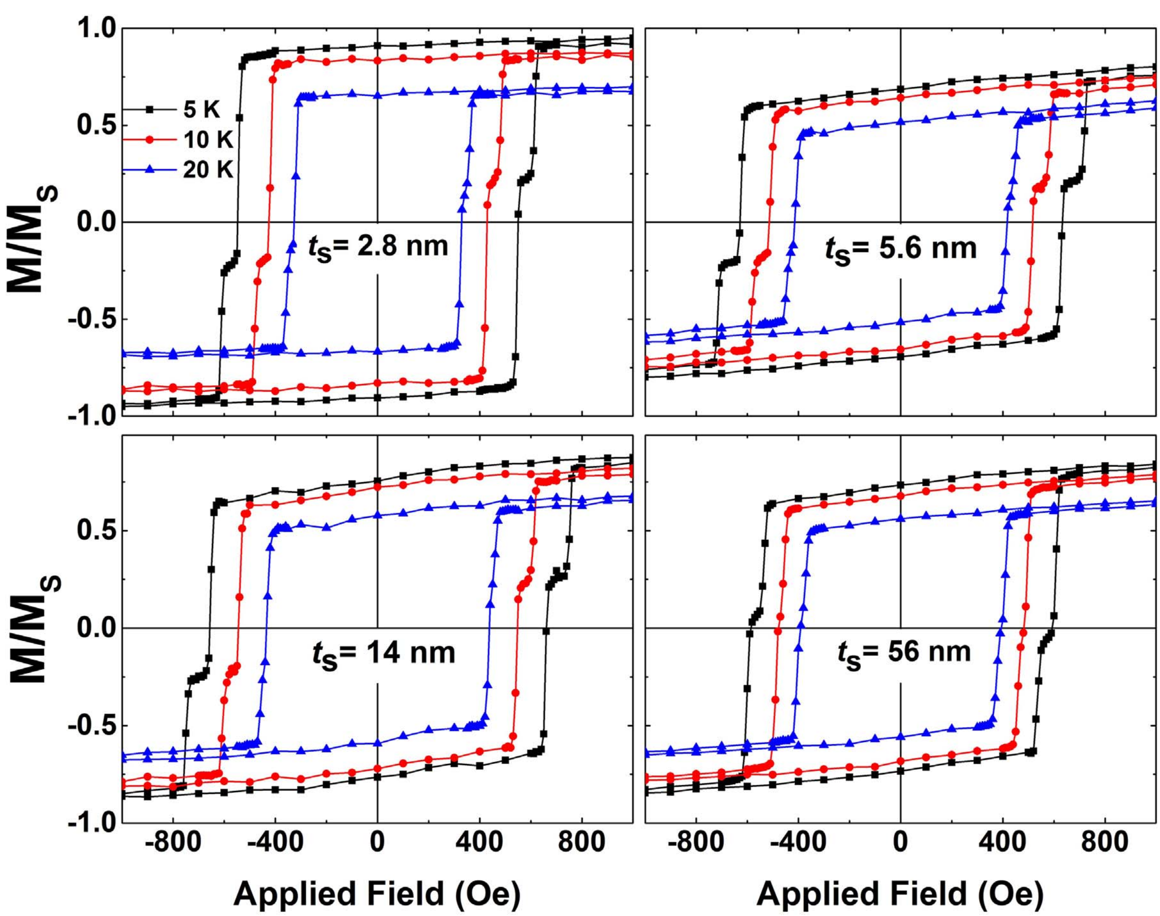

Fig. 2. Hysteresis loops on the four GaMnAs/InGaAs/GaMnAs trilayer structures at 5 K, 10 K, and 20 K. All samples show a well-resolved two step feature in the hysteresis measured at 5 K, indicating successive magnetization reversals of the individual GaMnAs layers in each trilayer.

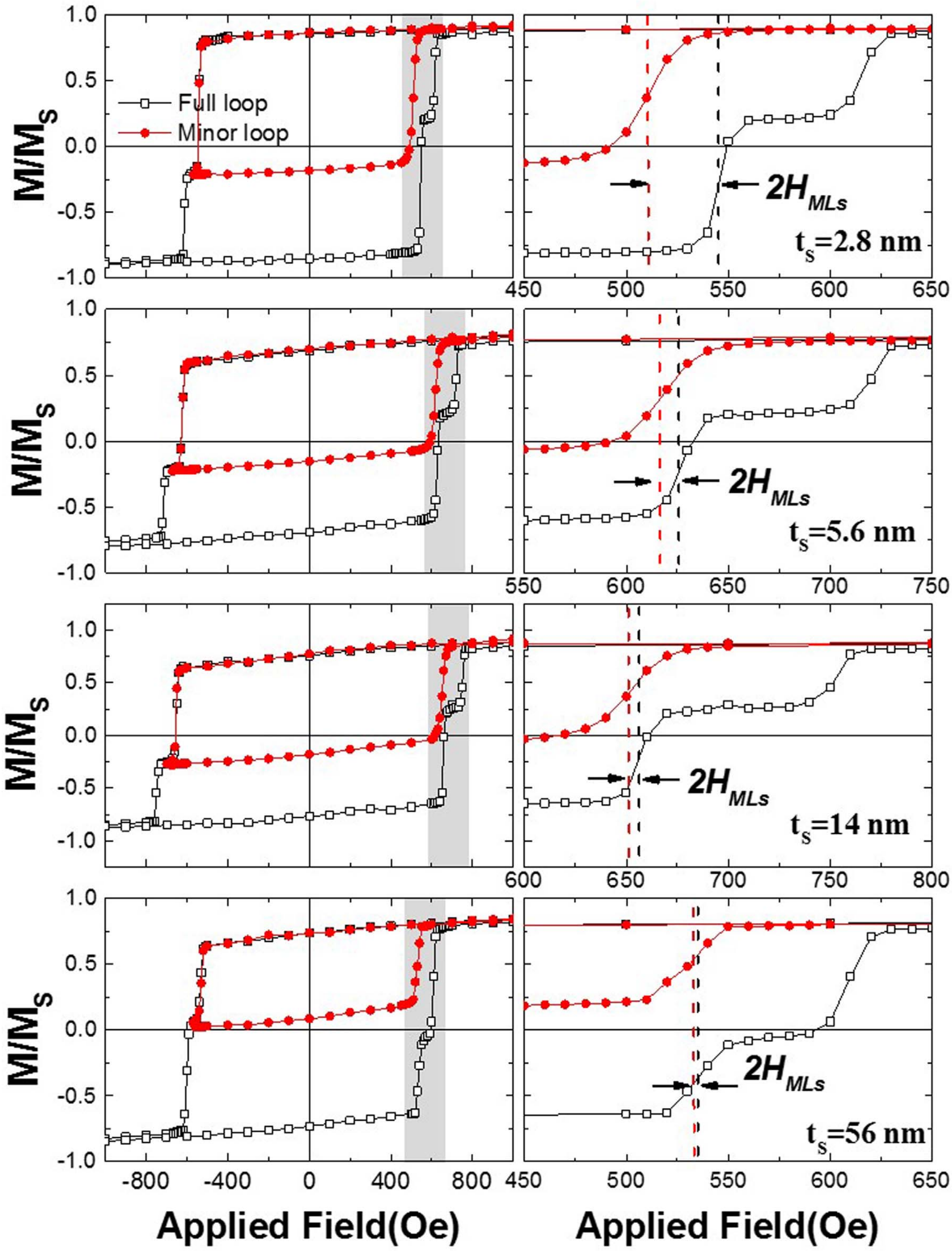

Fig. 3. (Color online) Full and minor hysteresis loops observed during magnetization reversal at 5 K for the four GaMnAs/InGaAs/GaMnAs trilayers. Open squares and solid circles represent full and minor hysteresis loops, respectively. The shaded region in each left-hand panel shows the shift of minor hysteresis loops with respect to the full loop. The shaded regions are shown on magnified scale in the corresponding panels on the right. The shifts of the minor loops are marked with vertical dotted lines in each panel.

structures. However, since our study focused on the interlayer interaction which manifested by the shift of the hysteresis, small fluctuation in the magnetic properties of GaMnAs layers can be tolerated for the comparison of spacer thickness dependence of their IEC.

With this information, we performed magnetization reversal measurements by applying an external magnetic field along the out-of-plane direction. The hysteresis measured at three different temperatures in this configuration is shown in Fig. 2 for each sample. The hysteresis at 5 K shows a clear two-step transition for each sample, indicating that the two GaMnAs layers in each trilayer reverse their magnetization at slightly different fields due to differences in their individual magnetizations. This step, however, disappears at 20 K, the hysteresis becoming a single loop, similar to a hysteresis in single GaMnAs layers, indicating that the coercive fields of the two GaMnAs

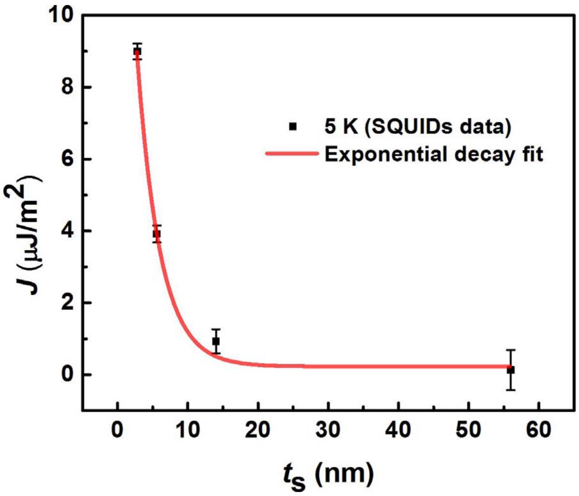

Fig. 4. (Color online) The FM IEC strength obtained from the shifts of minor loops for the four samples with different spacer thicknesses. The red solid line is the best fit to the exponential decay function, $J = J_0 e^{-t_s/t_0}$, as discussed in the text.

layers in a trilayer become nearly identical at 20 K. This behavior with increasing temperature is the same for all four samples, as seen in Fig. 2.

To fully investigate the IEC between pairs of GaMnAs layers, one must be able to monitor the behavior of magnetization reversal separately for the individual GaMnAs layers in each structure. For this purpose we focus on experiments carried out at 5 K, where the magnetization reversal is well resolved for the two GaMnAs layers comprising each sample. To examine the details of IEC, we recorded minor hysteresis loops by sweeping the external field within limited field regions, in which one GaMnAs layer experiences a magnetization reversal, while the magnetization of the partner FM layer remains unaffected. Such minor loops (red solid circles) are plotted together with corresponding full loops (black squares) in the left column of Fig. 3. As seen in the figure, the center of the minor loop shifts to the left with respect to the full loop (i.e., the shift is to the negative field direction). This shift can be seen more clearly in the corresponding right panels, where the field regions marked by shaded rectangles in the left panels are shown on magnified scale.

The shift direction of the minor loops relative to the full loops indicates the presence of a ferromagnetic (FM) IEC between the two GaMnAs layers in each trilayer. The strength J of the FM IEC can be determined from the shift (H_{MLs}) of the minor hysteresis loop from zero-field using the relation $J = M_s H_{\mathrm{MLs}} t_{\mathrm{FM}}$, where M_s is the spontaneous magnetization and t_{FM} is the thickness of the ferromagnetic layer [17,24,25]. The shifts of the minor loop and the estimated strengths of the FM IEC for the four samples used in this study are summarized in Table 1.

Importantly, the strength of the FM IEC observed for the trilayer with a 2.8 nm InGaAs spacer is 8.99 μJ/m^2, *an order of magnitude larger* than the 0.5 μJ/m^2 value observed on a GaMnAs/GaAlAs/GaMnAs trilayer with the same spacer thickness (2.8 nm) grown on an InGaAs buffer [17]. However, the IEC strength of 0.93 μJ/m^2 observed on our sample with a 14 nm spacer is conspicuously *smaller* than the 7.76 μJ/m^2 value observed on an InMnAs/InAs/InMnAs tri-layer with a similar dimension of nonmagnetic spacer thickness (i.e.,15 nm of InAs) reported by Yanagi *et al.* [18] We note here that the InGaAs spacers used in our system form smaller energy barriers between the two magnetic layers than the GaAlAs spacers in Ref [17]., but lager barriers than the InAs spacers in Ref [18].. We suggest that the observed magnitude of the IEC coupling in our system, which lies between the IEC values in the two previously studied systems, reflects a direct dependence of IEC on the magnitude of energy barriers introduced by the spacer layers, thus establishing that the barrier height is an important factor for controlling the IEC in FM semiconductor trilayers.

As one can see from Table 1, the FM IEC strength of the structures decreases monotonically with increasing InGaAs spacer thickness, and eventually approaches zero for the sample with a spacer thickness of 56 nm. Such thickness dependence of the FM IEC can be described by an exponential decay behavior expected from Bruno's model [5], and observed in many metallic ferromagnetic trilayers with insulating and/or semiconducting spacers [26–29]. We find that our IEC results can also be described by an exponential decay function in the form of $J = J_0 e^{-t_s/t_0}$, where J_0 is a measure of the coupling strength at zero spacer limit, t_s is the InGaAs spacer thickness, and t_0 is the decay length of the IEC. Fig. 4 shows the best fitting result for such behavior, obtained with J_0 =21 ± 2 μJ/m^2 and t_0 =3.3 ± 0.3 nm. The value of J_0 from the best fit is now in the same order of magnitude as that obtained from the analysis of InMnAs/InAs/InMnAs trilayers [18].

We note, however, that the decay length of 3.3 nm observed on our FM semiconductor system is relatively large compared to the decay length normally observed in FM metal-based trilayers structures with semiconductor or insulator spacers, in which it ranges from 0.15 to 2.2 nm [26–29]. This decay length is in the similar range as the hole spin coherence length of 1.4 nm expected from theoretical Monte Carlo simulations of IEC in GaMnAs/GaAs/GaMnAs trilayer systems [30]. This indicates that the IEC in GaMnAs-based multilayers is a long-range interaction over the nonmagnetic spacer. Such long-range IEC was also previously reported for GaMnAs-based antiferromagnetically-coupled multilayers, in which the IEC was observed for GaAs spacer thicknesses of up to 7.0 nm [9,10,31]. Our results thus provide experimental evidence for the presence of unexpectedly long-ranged IEC regardless of the type of coupling, either AFM or FM, between GaMnAs layers separated by non-magnetic spacers.

In summary, we have investigated the nonmagnetic spacer thickness dependence of IEC in GaMnAs/InGaAs/GaMnAs trilayers grown on a ZnCdSe buffer. The shifts of minor hysteresis loops show that the IEC between the two GaMnAs layers in such tri-layer structures is ferromagnetic. The magnitude of the IEC in our system is enhanced by using InGaAs spacers, which provide a lower energy barrier between the GaMnAs layers than either GaAs or GaAlAs spacers used in earlier studies. The strength of the observed FM IEC clearly reveals an exponential decay behavior with increasing thickness of the nonmagnetic InGaAs spacers. The decay length of the FM IEC, t_0=3.3 ± 0.3 nm, is in the similar range as the hole spin coherence length obtained from theoretical analysis of the IEC in GaMnAs/GaAs/GaMnAs trilayers [30]. The present result obtained on our FM-coupled systems constitutes complementary evidence to earlier observations on AFM-coupled systems that the IEC in GaMnAs-based multilayers is long-range in character, independent of the type of magnetic inter-layer coupling.

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