Magnetoresistance effect and interlayer coupling of (Ga, Mn)As trilayer structures

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We have investigated the magnetic and magnetotransport properties of (Ga, Mn)As/(Al, Ga)As/(Ga, Mn)As semiconductor-based magnetic trilayer structures. We observe a weak ferromagnetic interlayer coupling between the two ferromagnetic (Ga, Mn)As layers as well as magnetoresistance effects due to spin-dependent scattering and to spin-dependent tunneling. Both the coupling strength and the magnetoresistance ratio decrease with the increase of temperature and/or the increase of Al composition of the nonmagnetic (Al, Ga)As layer.
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Giant magnetoresistance (GMR) effect due to spin-dependent scattering in metallic multilayers,[1] and tunneling magnetoresistance (TMR) effect due to spin-dependent tunneling in ferromagnet/insulator/ferromagnet tunnel junctions[2] are both attracting much attention because of their potential applications in magnetic recording technology and memory devices. Multilayers with semiconducting nonmagnetic layers are expected to have advantages over the all-metal systems owing to the possible control of the carrier concentration by external parameters, such as temperature, illumination, or electric fields. It was discovered that Fe/Si/Fe trilayers with amorphous silicon spacers exhibit antiferromagnetic interlayer exchange coupling between the Fe layers.[3] Magnetoresistance (MR) effect (smaller MR ratio (0.01%–0.5%) than GMR) was observed in Fe/Si multilayers and MnGa/GaAs/MnGa trilayers,[4,5] and heat induced as well as photoinduced modulation of interlayer exchange coupling was reported in Fe/Si multilayers.[6,7] Magnetic multilayers made of epitaxially grown semiconductors alone can be monolithically integrated into semiconductor circuitry and are expected to offer even higher potential. Semiconductor multilayers may also provide a test bench for study of the MR effects and the magnetic coupling because of its simple band structure. The GaAs based ferromagnetic semiconductor, (Ga, Mn)As,[8] can readily be incorporated into GaAs/(Al, Ga)As heterostructures[9] and thus offers an excellent opportunity to study the MR effects and interlayer coupling in semiconductor magnetic multilayer structures. The maximum transition temperature T_c of (Ga, Mn)As is about 110 K (Mn composition $x=0.053$), and T_c can be controlled by x ($T_c \sim 2000x$ K).[10] Our previous magnetotransport study showed ferromagnetic interlayer coupling in (Ga, Mn)As/(Al, Ga)As/(Ga, Mn)As trilayer structures, where the interlayer coupling was obtained from the differences in the magnetization process observed by transport among samples having in-plane easy axis of magnetization.[11] In this letter, we present the observation of spin-dependent scattering and spin-dependent tunneling, in addition to the interlayer coupling, in semiconducting (Ga, Mn)As/(Al, Ga)As/(Ga, Mn)As trilayer structures having the easy axis of magnetization perpendicular to the plane.

We prepared a set of 30 nm $(Ga_{0.95}Mn_{0.05})As$/2.8 nm $(Al_yGa_{1-y})As$/30 nm $(Ga_{0.97}Mn_{0.03})As$ trilayer structures on 50 nm $(Al_{0.30}Ga_{0.70})$ grown by low temperature molecular beam epitaxy (substrate temperature $T_{sub}=250\,°C$) onto 1 μm $(In_{0.15}Ga_{0.85})As$ buffer layer grown at 500 °C on semi-insulating GaAs (100) substrates (shown in the inset of Fig. 1). In order to produce different coercive forces, the Mn composition x of the top and the bottom layers were set to 0.05 and 0.03, respectively. The $(Al_yGa_{1-y})As$ spacer layer acts as a potential barrier in the valence band. Samples with varying Al composition y (0.14, 0.30, 0.42, and 1.00) were prepared in order to change the barrier height ($550y$ meV). A thick lattice-relaxed (In, Ga)As buffer layer was employed to introduce tensile strain in the trilayer structure, which results in a magnetic easy axis perpendicular to the plane.[12] This direction of easy axis allows us to determine the magnetization M of the two ferromagnetic layers by the Hall

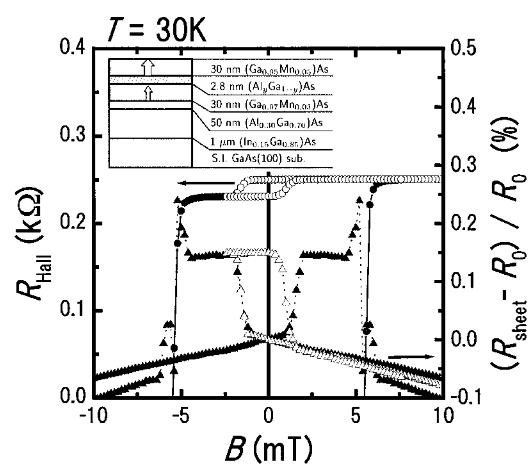

FIG. 1. Magnetotransport properties of $(Ga_{0.95}Mn_{0.05})As/(Al_{0.14}Ga_{0.86})As/(Ga_{0.97}Mn_{0.03})As$ trilayer structure at $T=30$ K. Closed and open symbols show the major and minor loops, respectively. The clear increase of R_{sheet} was observed in the step region of R_{Hall}, where the magnetization of the two (Ga, Mn)As layers are aligned antiparallel. The minor loop of R_{Hall} is skewed by the presence of ferromagnetic coupling between the two (Ga, Mn)As layers. The coupling strength J can be calculated by this shift. The inset shows the sample structure.

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measurements; the Hall resistance R_{Hall} of (Ga, Mn)As is dominated by the anomalous Hall effect which is proportional to the perpendicular component of M. Because of the uniaxial easy axis, the magnetic field B applied perpendicular to the sample plane produces either parallel or antiparallel M of the two (Ga, Mn)As layers having different coercive force. The dc sheet resistance R_{sheet} and R_{Hall} were measured simultaneously by the use of Hall bar geometry (current-in-plane, CIP, configuration) with the distance between the potential probe of 80 μm and the Hall bar width of 60 μm. The local information of M was obtained from R_{Hall}. TMR was also measured by the use of $20\times 20\,\mu\mathrm{m}^2$ device (current-perpendicular-to-plane configuration); after the mesa formation by removal of the unwanted top (Ga, Mn)As layer and the spacer layer by wet etching, one electrode was formed on the top and the other on the bottom (Ga, Mn)As layers, respectively. Direct magnetization measurements were also performed using a superconducting quantum interference device commercial magnetometer using large area samples. In all measurements, B was always applied perpendicular to the sample plane.

Figure 1 shows B dependence of R_{Hall} and $(R_{\mathrm{sheet}}-R_0)/R_0$ of a trilayer structure with $y=0.14$ at temperature $T=30$ K, where R_0 is the sheet resistance at $B=0$ ($R_0=2.576\,\mathrm{k}\Omega$ at 30 K). Here, the raw data was separated into the odd and even functions to obtain R_{Hall} and R_{sheet}, respectively. Results of a minor loop measurement, a hysteresis loop of the (Ga, Mn)As layer with smaller coercive force, are also shown in Fig. 1 by open symbols. The step feature observed in the major loop of R_{Hall} at $B=-2$ mT (a half loop is shown in Fig. 1) reflects the reversal of magnetization of the (Ga, Mn)As layers with $x=0.03$. The clear increase of R_{sheet} observed in the step region of R_{Hall}, where M of the two (Ga, Mn)As layers are aligned antiparallel, indicates the presence of a spin-dependent scattering.[13] Here, a minor loop of R_{sheet} that corresponds to the minor loop of R_{Hall} (and hence M) is also clearly observed, strongly supporting the interpretation that the observed MR effect is due to the spin-dependent scattering. T and y dependence of MR ratio $\Delta R/R_0=(R_{\mathrm{AP}}-R_0)/R_0$, where R_{AP} is the sheet resistance with antiparallel M configuration, are plotted in Figs. 2(a) and 2(b), respectively. Clear MR effect due to the spin-dependent scattering is observed only between 25 and 40 K. This is because the $(\mathrm{Ga}_{0.97}\mathrm{Mn}_{0.03})$As layer undergoes a magnetic phase transition into the paramagnetic phase above 40 K, and the resistance of $(\mathrm{Ga}_{0.97}\mathrm{Mn}_{0.03})$As layer is too high to observe clear MR effect below 25 K; the $(\mathrm{Ga}_{1-x}\mathrm{Mn}_x)$As with low Mn composition x (below about $x=0.03$) is known to be insulating.[10] As shown in Fig. 2, the MR ratio decreases with the increase T and/or y. The T dependence is believed to reflect the dependence of the MR ratio on M and thus on the spin polarization of the holes in the $(\mathrm{Ga}_{0.97}\mathrm{Mn}_{0.03})$As layer, and the y dependence due to the decrease of the number of holes that travel across the (Al, Ga)As layer.

Interlayer coupling is also determined from the minor loop measurements. As can be seen in Fig. 1, the coercive force of minor loop for the sample with $x=0.14$ is skewed. The presence and the direction of the skew indicate the presence of ferromagnetic interlayer coupling between the two

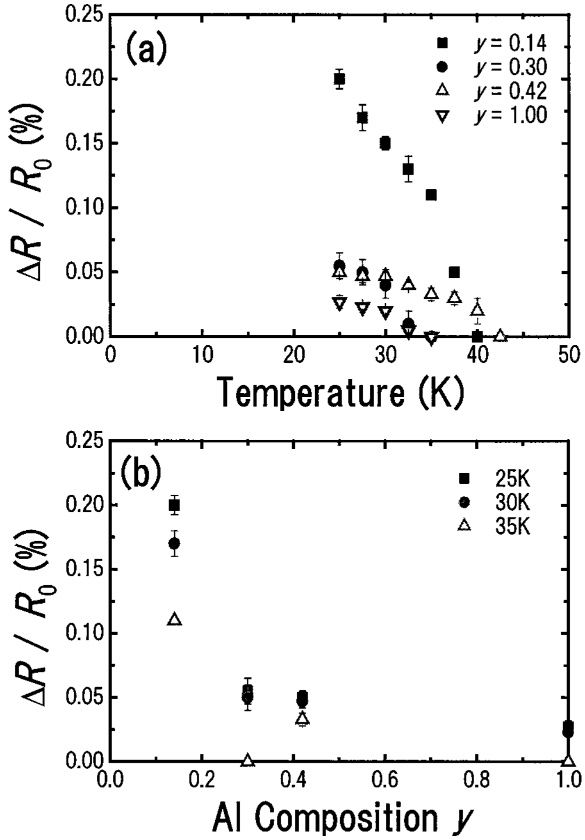

FIG. 2. (a) Temperature and (b) Al composition dependence of MR ratio ($\Delta R/R_0$) in the current-in-plane configuration. MR ratio decreases with the increase of temperature and/or y.

(Ga, Mn)As layers. In order to obtain the degree of the skew at T below 25 K, where the high resistance of the $(\mathrm{Ga}_{0.97}\mathrm{Mn}_{0.03})$As layer makes it difficult to measure the minor loops by transport measurements, the direct magnetization measurements were also performed. The magnetization measurements revealed that the coercive force of $(\mathrm{Ga}_{0.97}\mathrm{Mn}_{0.03})$As layer is larger (smaller) than $(\mathrm{Ga}_{0.95}\mathrm{Mn}_{0.05})$As layer below (above) 15 K. From the magnetic field shift $B_s(T)$ of the minor loop with respect to $B=0$, one can calculate the magnitude of the coupling J by $J=M_s(T)B_s(T)d$, where $M_s(T)$ is the spontaneous magnetization and d the thickness of the magnetic layer. We calculated $M_s(T)$ assuming Mn spin of 5/2 and the Brillouin function behavior and used $d=30$ nm, the thickness of the (Ga, Mn)As layer. The obtained T and y dependence of J are shown in Figs. 3(a) and 3(b). As shown in Fig. 3(a), J becomes smaller with increase of T (reduction of M). The overall trend seen in Fig. 3(b) indicates that J decreases with an increase of y (increase in hole barrier), which suggests that the interlayer coupling is mediated by itinerant and/or tunneling holes. The coupling is always ferromagnetic, although theory predicts antiferromagnetic coupling under certain sets of parameters.[14] The magnitude of J is orders of magnitude smaller than those reported in metallic systems, and about three orders of magnitude smaller than that reported previously in the (Ga, Mn)As based trilayers with an in-plane easy axis.[11] It is not clear at the present stage whether the direction of the easy axis results in this large difference in the coupling strength.

Finally, we show the results of vertical magnetotransport

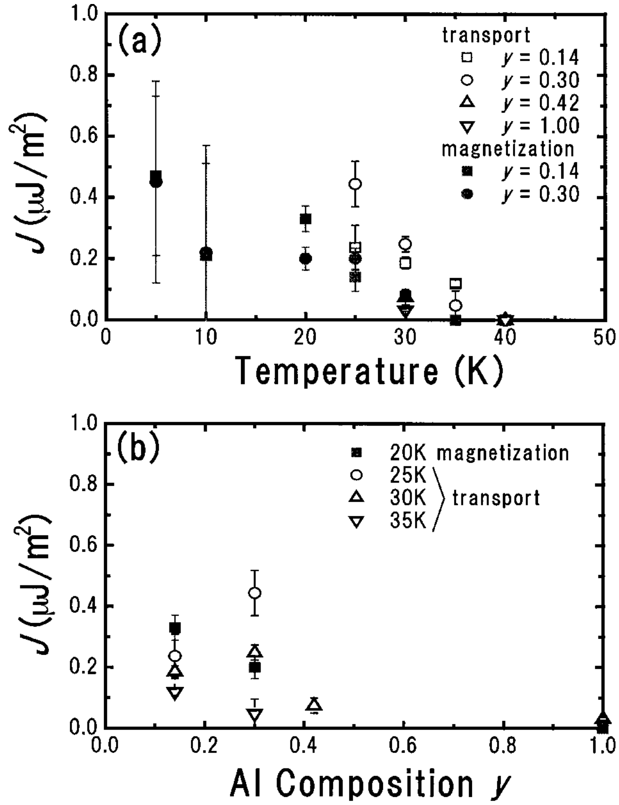

FIG. 3. (a) Temperature and (b) Al composition dependence of the coupling strength J. Closed and open symbols show J from the magnetization measurements and from the transport measurements, respectively.

measurements. Figure 4(a) shows the B dependence of M and (b) the B dependence of MR, both at 20 K, of a trilayer structure with an AlAs barrier layer ($y=1.00$). T dependence of the MR ratio is shown in the inset of Fig. 4. The difference in coercive forces produces the plateau structure observed in Fig. 4(a), where M of the two ferromagnetic layers are antiparallel. The resistance increase is observed between 8 and 16 mT, precisely in the field region of antiparallel configuration of M.[15,16] The MR ratio is about 5.5% at 20 K, more than one order of magnitude larger than those observed in the CIP configuration described above. These two experimental results, together with the fact that the valence band barrier produced by AlAs is very high (550 meV) in this sample so that all the holes must be transported across the AlAs layer by tunneling, indicate that the MR effect observed here is TMR rather than the MR effect due to spin-dependent scattering. The TMR ratio becomes smaller with the increase of temperature due most probably to the decrease of M of (Ga, Mn)As. As in the case of CIP configuration, the sharp TMR feature started to smear out below 20 K, where the coercive field of the $x=0.03$ layer starts to spread out.

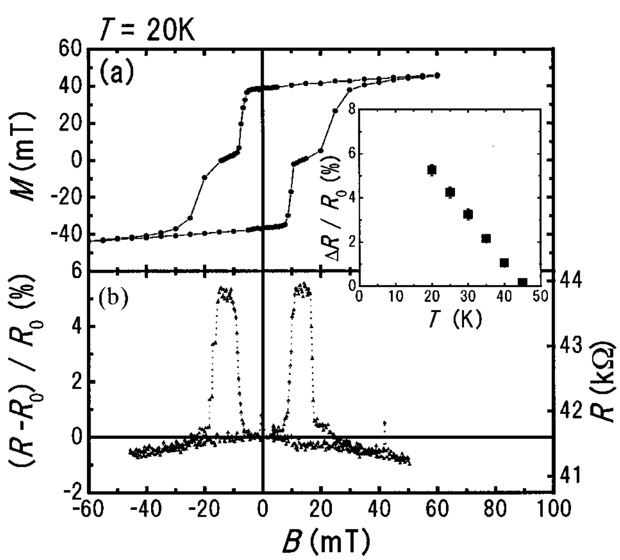

FIG. 4. (a) Magnetization and (b) tunneling magnetoresistance curve of a $(Ga_{0.95}Mn_{0.05})As/AlAs/(Ga_{0.97}Mn_{0.03})As$ tunnel junction at 20 K. Inset shows the temperature dependence of TMR ratio.

In conclusion, we have shown the magnetoresistance effects originating from the spin-dependent scattering and the spin-dependent tunneling, and the magnetic interlayer coupling between the two ferromagnetic layers in the semiconducting (Ga, Mn)As/(Al, Ga)As/(Ga, Mn)As trilayer structures. They decrease with increasing temperature and can be controlled by the Al composition of the intermediary nonmagnetic layer. The present results show the possibility of new semiconductor device with an added functionality of magnetic multilayers. This new possibility is technological important especially in view of the recent prediction of room temperature ferromagnetic semiconductors.[17]

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