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Tunneling magnetoresistance in (Ga,Mn)As/Al–O/CoFeB hybrid structures

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Tunneling magnetoresistance (TMR) in $Ga_{0.92}Mn_{0.08}As/Al-O/Co_{40}Fe_{40}B_{20}$ trilayer hybrid structure as a function of temperature from 10 to 50 K with magnetic field $|H| \leq 2000$ Oe has been studied. TMR ratio of 1.6% at low fields at 10 K was achieved with the applied current of 1 μA. The behavior of junction resistance was well explained by the tunneling resistance across the barrier. Strong bias dependences of magnetoresistance and junction resistance were presented. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3068418]

Efficient electrical injection of spin-polarized electrons is one of the most important technologies for realizing new functional devices based on spins in semiconductors. Transition metal doped III-V compound semiconductor offers an unprecedented opportunity to explore ferromagnetism in semiconductors. Ferromagnetism due to spin-spin interactions is mediated by holes in the valence band and changing the Fermi level using codoping and electric fields or light can directly manipulate the magnetic ordering. A ferromagnetic semiconductor (Ga,Mn)As is one of the promising materials for spin-polarized carrier injector because of its high spin polarization, and Curie temperature T_C as high as 110 K was first reported in 1996 by Ohno.[1] High spin polarization predicted by the band structure calculation[2] with support from experimental results showing high spin polarization[3] of over 85% by Andreev reflection in this kind of materials makes them more attractive for further investigation, especially their potential application in spintronic devices. Tunneling magnetoresistance effect has been observed in (Ga,Mn)As/(Al,Ga)As/(Ga,Mn)As epitaxial multilayers grown by low temperature molecular beam epitaxy (MBE) technique.[4–10]

Recently, demonstration of spin injection from ferromagnetic metal into (Ga,Mn)As through wide band semiconductor tunnel barrier such as ZnSe[11] and AlAs[12] has been successfully obtained due to the high Curie temperature of ferromagnetic metal and especially the lattice match between epitaxially grown films. Pioneering works in spin injection through interband spin-polarized tunneling in $(Ga,Mn)As/n^+$-GaAs Easki tunnel structures[13–15] and diffusive spin injection[16] from (Ga,Mn)As to adjacent GaAs have been demonstrated by Ohno and co-workers. Tunneling anisotropic magnetoresistance[17] (TAMR) and tunnel spectroscopy[18] in the system of Au/Al–O/(Ga,Mn)As were studied, and TAMR arises from spin-orbital coupling. Al–O has been widely adopted in Magnetic Tunnel Junctions (MTJs) as an insulating barrier because of the good wetting property of Al and its feasible oxidation by a plasma oxidation technique.[19] However, knowledge on the hybrid MTJ structure of (Ga,Mn)As consisting of aluminum oxide as a tunneling barrier is still missing. In this work, we report the fabrication of MTJ based on $Ga_{0.92}Mn_{0.08}As/Al-O/Co_{40}Fe_{40}B_{20}$ hybrid structures grown by MBE and magnetron sputtering together. The results of bias and temperature dependences of TMR ratio have been studied systematically.

The hybrid structure was grown on semi-insulating GaAs substrate, consisting of $GaAs(50)/Ga_{0.92}Mn_{0.08}As(400)/GaAs(1)/Al-O(1.2)/Co_{40}Fe_{40}B_{20}(5)/Ir_{22}Mn_{78}(10)/Ru(10)$ (thickness in nanometers). First, 50 nm thick GaAs buffer layer was deposited with substrate temperature $T_S = 560$ °C in a V80MARKI MBE system in order to grow (Ga,Mn)As on the smooth surface. Then 400 nm thick $Ga_{1-x}Mn_xAs$ layer (where $x=0.08$) and 1 nm thick GaAs were grown at $T_S=250$ °C, where 1 nm GaAs is used to prevent Mn diffusion into alumina layer after growth. The growth details could be found elsewhere.[20] After the growth of $Ga_{0.92}Mn_{0.08}As$ film in the MBE chamber, the sample was clearly packed and transferred into the load lock chamber of the sputtering system when the clean surface was confirmed by atomic force microscope. The amorphous alumina oxide layer was formed by plasma oxidation in the sputtering system, followed by the deposition of $Co_{40}Fe_{40}B_{20}/Ir_{22}Mn_{78}/Ru$ metallic multilayers, where Ru acts as capping layer. Junctions with size of 8×16 μm^2 were patterned by conventional UV lithography combined with argon ion milling. A four probe dc transport measurement was performed as a function of temperatures (down to 10 K) and magnetic field (up to 2000 Oe) in a physical properties measurement system by Quantum Design. Here, positive bias (current) refers to current flowing from the bottom electrode to the top electrode.

Figure 1 shows the temperature dependence of the junction resistance and (Ga,Mn)As single layer resistance at zero fields. The right upper inset is the schematic of the junction

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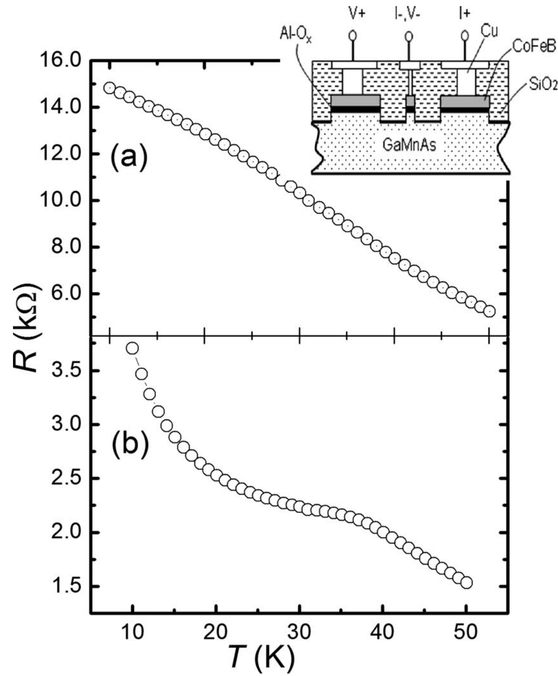

FIG. 1. Temperature dependence of the junction resistance and (Ga,Mn)As single layer resistance in zero field. Inset shows the schematic of the junction pattern and measurement geometry.

pattern and four probe geometry used for this measurement. The top electrode of the junction is directly connected to Cu through a relatively large pad with size of $300\times300\ \mu m^2$. The top and bottom electrodes were isolated by SiO_2. Compared to the junction size of $8\times16\ \mu m^2$, the pad resistance is only 0.1% and is neglected. (Ga,Mn)As single layer resistance was measured by two probe sensing measurement through this pad. The as-grown (Ga,Mn)As is a highly self-compensated ferromagnetic semiconductor which exhibits semiconducting behavior at low temperatures with Curie temperature of 35 K, shown in Fig. 1(b). A hump was observed at 35 K, which has been confirmed by several groups in the range of $x=0.015-0.071$ Mn concentrations.[21] Figure 1(a) shows typical junction resistance as a function of temperature which shows very strong temperature dependence and increases with decreasing temperature.

R-H loops of the typical spin-valve-type junction at $T=10$ K with sensing current of $+1\ \mu A$ are shown in Fig. 2. The free layer (Ga,Mn)As and the reference layer CoFeB are magnetically parallel at the magnetic field $H=-2000$ Oe. As field is swept from -2000 to 2000 Oe, (Ga,Mn)As first switches at around 100 Oe, while the magnetization of the reference layer CoFeB exchange biased by antiferromagnet IrMn sustained, leading to an antiparallel configuration; then CoFeB switches at around 1000 Oe, resulting in a parallel state. The almost zero-hysteretic negative MR behavior in the parallel state (tilted part of *R-H* loop) was similar to our previous report,[22] probably due to the coherent magnetization rotation of both the two magnetic layers toward the applied magnetic field and the suppression of magnetic disorder at the (Ga,Mn)As/Al–O interface as well. In addition, slight asymmetry from current polarity was observed in resistance measurement which can be attributed to the different

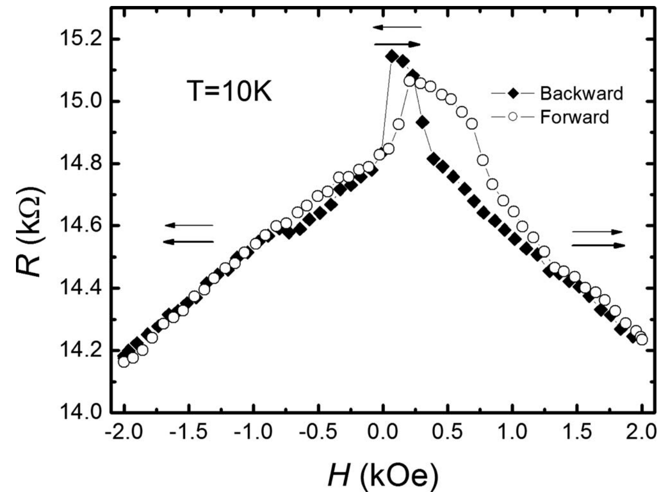

FIG. 2. Typical junction resistance vs magnetic field in the field range of 2000 Oe at 10 K; forward corresponds to sweeping field from negative to positive and backward vice versa.

barrier heights on the two sides of the insulator.

The temperature dependence of the TMR is shown in Fig. 3. Clear resistance change with sensing current of $+1\ \mu A$ associated with magnetization switching of (Ga,Mn)As has been observed. Coercivity (H_c) of (Ga,Mn)As decreases with increasing temperature, where H_c are 30, 20, 10, and 7.5 Oe at 10, 15, 20, and 25 K, respectively. The relatively small H_c is expected for thick (Ga,Mn)As layer[23] where the thickness of the bottom (Ga,Mn)As layer was 400 nm. TMR ratios, 1.6%, 1.4%, 1.2%,and 1.0% at 10, 15, 20, and 25 K, respectively, were obtained which decrease faster with increasing temperature and TMR almost drops to zero as temperature approaches T_C. Bias dependences of junction resistance and TMR ratio are shown in Fig. 4. Junction resistance decreases rapidly with increasing dc bias, showing much stronger bias dependence than that in conventional 3*d* transition metal MTJs, e.g., CoFe/Al–O/CoFe. The strong bias dependence of parallel state resistance at 10 K as shown in Fig. 4(a) in terms of zero bias anomaly is widely believed to be due to the corre-

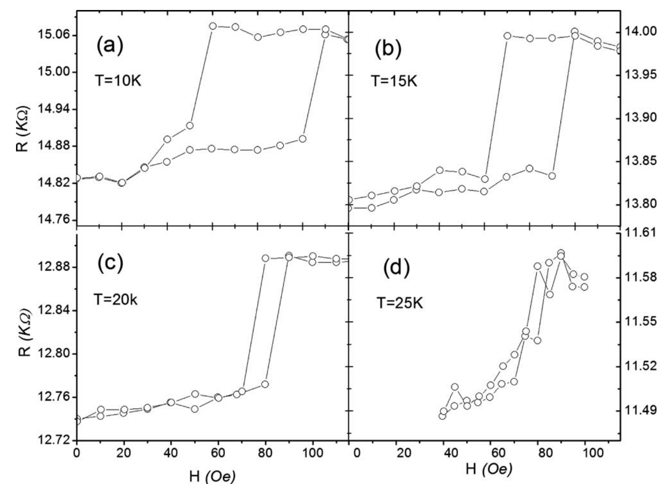

FIG. 3. Minor *R-H* loops in the switching field range of the (Ga,Mn)As layer were measured at $T=10$, 15, 20, and 25 K, respectively.

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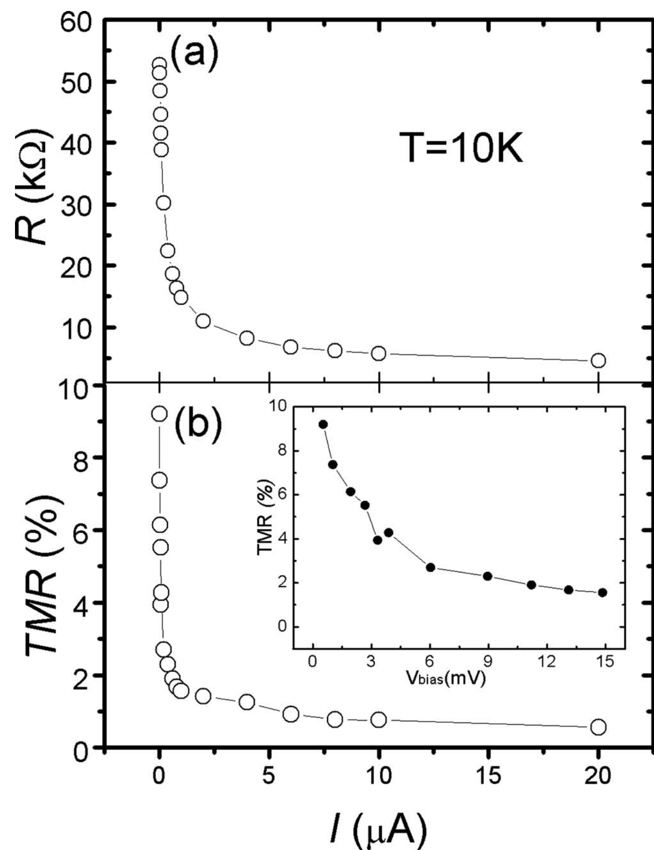

FIG. 4. Junction resistance and TMR ratio vs direct sense current at 10 K. Inset of (b) shows TMR ratio dependence of dc bias.

lation gap in (Ga,Mn)As (Refs. 11 and 18) and very recently systematically studied by Russo *et al.*[23] TMR ratio dependence of direct sensing current is shown in Fig. 4(b); TMR ratio decreases rapidly with increasing sensing current. The inset of Fig. 4(b) shows the dc bias voltage dependence of TMR ratio in the low bias range. V_{half} at which TMR drops to one-half of its maximum is 2.7 mV. This is due to the relatively low Fermi energy of (Ga,Mn)As and large increase in the empty states even with small bias (see Ref. 6). In our case, the Fermi energy of the as-grown semiconducting (Ga,Mn)As is even smaller, and hence an even stronger bias dependence can be expected.

In summary, we have observed TMR in $Ga_{0.92}Mn_{0.08}As/Al-O/Co_{40}Fe_{40}B_{20}$ hybrid structures at low temperatures from 10 to 25 K. Clear switching behavior of *R-H* minor loop in the low field range shows TMR ratio of 1.6% at 10 K. Strong bias dependences of both resistance and TMR ratio were presented, probably due to the correlation gap in (Ga,Mn)As and its low Fermi energy, similar to that observed in (Ga,Mn)As/AlAs/MnAs hybrid structures. V_{half} at which TMR ratio drops to one-half of its maximum is 2.7 mV.

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