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Spin-polarized transport in hybrid $(Zn,Cr)Te/Al_2O_3/Co$ magnetic tunnel junctions

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Tunnel magnetoresistance (TMR) of 21% is observed at low temperature in hybrid magnetic tunnel junctions (MTJs) composed of a magnetic semiconductor (Zn,Cr)Te and Co electrodes separated by an alumina barrier. The TMR is observed up to 250 K, which is a considerable improvement over previous work on MTJs with semiconductor electrodes. The temperature and bias dependence of the TMR are consistent with a transport model involving spin-polarized tunneling and spin-independent hopping through impurity states. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2205177]

The inclusion of the spin degree of freedom of electrons in modern electronics has made a profound impact on both fundamental physics and device applications,[1] leading to an emerging field of "spintronics." One important material system in spintronics is magnetic tunnel junctions (MTJs).[2] The study of MTJs not only enhances our understanding of the nature of spin-polarized tunneling and the electronic structures of ferromagnetic electrodes[2,3] but also enables us to build devices such as magnetic random access memories (MRAMs) and magnetic read heads. Another interesting topic of the spintronics is diluted magnetic semiconductors (DMSs), which provide us the possibility to control the ferromagnetism through electrical[4] or optical[5] means and to inject spin more efficiently into semiconductors.[6] Many experiments have been carried out to study tunnel magnetoresistance (TMR) and spin-polarized transport in MTJs with DMS electrodes. In all semiconductor MTJs, for example, Tanaka and Higo observed up to 75% of TMR at 8 K in $(Ga,Mn)As/AlAs/(Ga,Mn)As$ junctions,[7] Chiba *et al.* reported 290% TMR in a $(Ga,Mn)As/GaAs/(Ga,Mn)As$ junction at 0.39 K,[8] and Mattana *et al.* studied the TMR and Mn diffusion effect in $(Ga,Mn)As/AlAs/(Ga,Mn)As$ junctions.[9] Experiments on the hybrid MTJs consisting of DMS and metal electrodes have also been performed, for example, Chun *et al.* studied $(Ga,Mn)As/AlAs/MnAs$ junctions and observed 30% TMR at 5 K.[10] Saito *et al.* reported TMR of 14.5% in junctions made of $(Ga,Mn)As/AlAs/CrTe$.[11] Very recently, Toyosaki *et al.* studied the TMR and bias dependence in $(Ti,Co)O_2/Al_2O_3/FeCo$ junctions.[12] In most cases TMR only exists at very low temperature and decreases rapidly with temperature.[7–11] This is in part because of the low Curie temperature (T_c) of (Ga,Mn)As. Therefore, it is of great importance to have a DMS spin injector which could work at higher temperature. In addition, most of the above MJTs were fabricated with molecular beam epitaxy (MBE) and it would be advantageous if these types of MTJs can be fabricated with magnetron sputtering systems.

One material system that has potential to address these two issues is (Zn,Cr)Te which has been discovered to be a room temperature DMS. Magnetic circular dichroism (MCD) experiments[13] indicate that magnetism is mediated through an sp-d interaction between Cr dopants and ZnTe host. We have fabricated (Zn,Cr)Te by magnetron sputtering and studied anomalous Hall effect (AHE) in this system.[14] In this letter, we report the fabrication and characterization of hybrid $(Zn,Cr)Te/Al_2O_3/Co$ MTJs. We observed 21% of TMR at 5 K. TMR decreases with increasing temperature, but persists up to 250 K. The temperature dependence of the TMR can be explained by a theoretical model proposed by Shang *et al.*[15] based on two current contributions: one from spin-polarized tunneling and the other due to spin-independent hopping through impurity states.

The MTJs were deposited in a magnetron sputter system with a base pressure of 2×10^{-7} Torr. The structure is $Si/(Zn,Cr)Te(50)/Al(0.75-2.75)$ $+oxidation/Co(15)/Cu(70)$, where the numbers in parentheses are layer thickness in nanometers. The Cr atomic concentration in the (Zn,Cr)Te layer is controlled to be at 20%. The barrier is fabricated by depositing a wedge-shaped Al layer, followed by *in-situ* plasma oxidation at 60 mTorr of oxygen for 120 s. MTJ samples with areas from 0.0078 to 0.125 mm^2 were defined by standard photolithography and ion-beam etching.[3,16] Transport measurements were performed using a four-probe technique. In our case, positive bias refers to current flowing from the top electrode to the bottom electrode.

After plasma oxidation, there are under-, optimal- and overoxidized regions along the Al wedge, similar to our previous studies.[16] Here we focus on the optimally oxidized MTJs that have the maximum TMR value. Figure 1(a) shows the TMR curves at different temperatures for such junctions. The TMR is defined as $(R_{AP}-R_P)/R_P$ where R_{AP} and R_P are the resistance of the junction corresponding to the antiparallel and parallel states of magnetizations in the two electrodes. Comparison with the magnetic hysteresis loop [Fig. 1(b)] indicates that the sharp increase in resistance around 60 Oe is due to the magnetization reversal of the Co layer.

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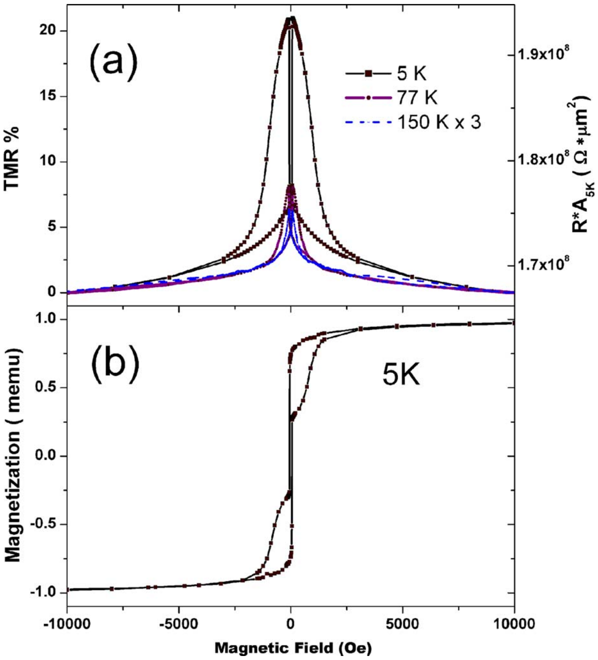

FIG. 1. (Color online) (a) TMR curves for (Zn,Cr)Te/Al_2O_3/Co junctions at different temperatures. The right axis shows the product of junction area and resistance at 5 K. (b) Hysteresis loop for unpatterned samples measured by SQUID at 5 K.

For $H > 60$ Oe, the magnetization in (Zn,Cr)Te layer gradually switches and the resistance starts to decrease and levels off at higher fields. Although the magnitude of the TMR decreases rapidly with temperature, distinct TMR curves are observed at 77 and 150 K, which is a considerable improvement over MTJs based on (Ga,Mn)As.[7–11]

The differential conductance dI/dV, is shown in Fig. 2(a) at a number of temperatures. The zero bias anomaly, referring to the dip in dI/dV curve near zero bias, is observed at 5 K. The zero bias anomaly is generally attributed to the existence of a soft gap at the Fermi energy (E_F) of the electrode formed by the depletion of density of states at E_F due to Coulomb interactions.[17,18] This zero bias anomaly can be correlated to the existence of a soft Coulomb gap at E_F in the (Zn,Cr)Te electrode which leads to $T^{-1/2}$ dependence of logarithmic resistance log R at low temperature, as shown in Fig. 2(b). The bias dependence of TMR is shown in Fig. 2(c). The TMR decreases rapidly with increasing bias, similar to (Ga,Mn)As/AlAs/MnAs (Ref. 10) and (Ga,Mn)As/AlAs/CrTe junctions.[13] Interestingly, we see a very symmetrical TMR about zero bias, despite the huge difference in the two electrodes. This is due to the increasing number of spin-independent hopping channels at higher energy,[19,20] as will be discussed later. The inelastic hopping through localized states will lead to a symmetrical bias dependence.[21] At low temperature we do see the asymmetrical bias dependence of TMR at low bias as shown in the insert of Fig. 2(c). With increasing bias voltage, more and more assisted hopping channels will participate in the conduction process, leading to a much more symmetrical bias dependence of TMR than those observed in MTJs where direct tunneling still dominates at higher bias.[2,16] The $V_{1/2}$, defined as the bias voltage corresponding to the half of the maximum TMR, are −89 and 56 mV under negative and positive biases, respectively. The small $V_{1/2}$ in the (Ga,Mn)As based MTJs is attributed to the small exchange splitting (~100 meV) of (Ga,Mn)As.[10] The small $V_{1/2}$ in both positive and negative biases in our case could be due to the small exchange splitting of (Zn,Cr)Te or due to the hopping through the localized states in the barrier at higher bias, as will be discussed next.

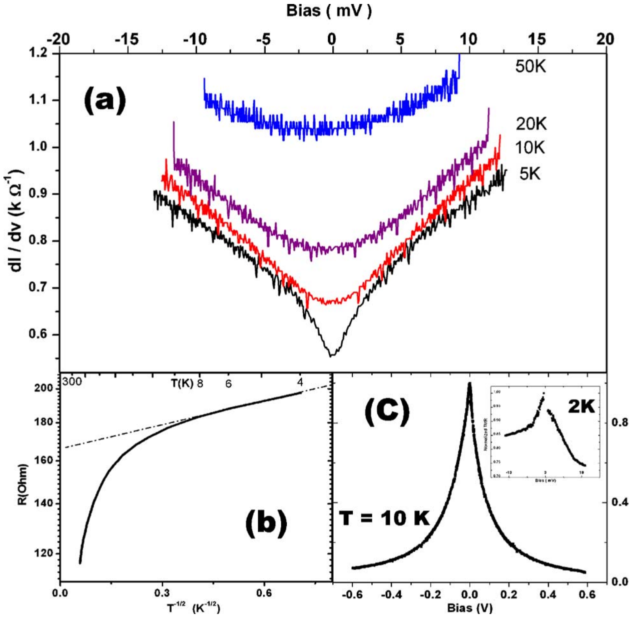

FIG. 2. (Color online) (a) dI/dV curves for (Zn,Cr)Te/Al_2O_3/Co junctions at different temperatures. (b) Resistance in logarithmic scale as a function of $T^{1/2}$ for (Zn,Cr)Te electrode. (c) Bias dependence of TMR at 10 K. Inset shows bias dependence at 2 K.

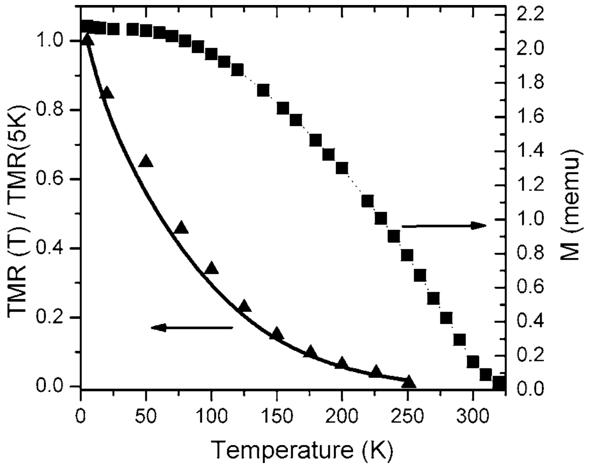

FIG. 3. Temperature dependence of magnetization (squares) for (Zn,Cr)Te single layer film and normalized TMR (triangles) for (Zn,Cr)Te/Al_2O_3/Co junctions. Solid curve is the fit to the mode for the temperature dependence of TMR (see text).

Figure 3 shows the temperature dependence of the TMR and magnetization of (Zn,Cr)Te film. The striking future is that TMR decreases much faster than the magnetization with increasing temperature. Similar behavior was also reported in (Ga,Mn)As based junctions,[9,10] but no definite explanations were given. Here we use the model developed by Shang *et al.*[15] The total conductance of junction can be written as $G(\theta) = G_T(1 + P_1P_2 \cos \theta) + G_{SI}$, where the first term is due to direct tunneling which is spin dependent; the second term, G_{SI}, is due to spin-independent contributions. Then the TMR from Julliere's formula[22] can be written as TMR

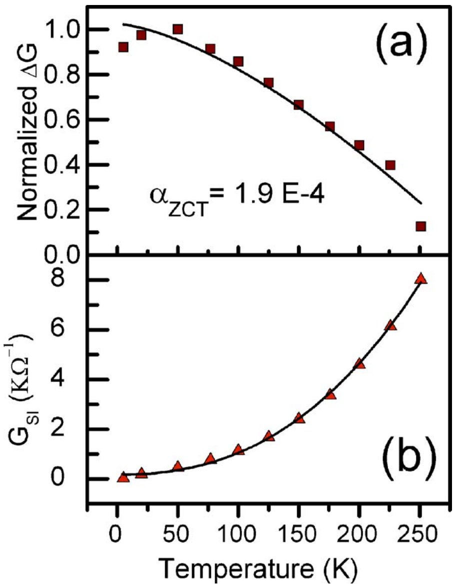

FIG. 4. (a) Temperature dependence of normalized ΔG for $(\mathrm{Zn,Cr})\mathrm{Te}/\mathrm{Al_2O_3}/\mathrm{Co}$ junctions. The solid line is the fitting using $\Delta G = 2G_T P_1 P_2 = 2G_T P_{\mathrm{ZCT}} P_{\mathrm{Co}}\,(1-\alpha_{\mathrm{ZCT}} T^{3/2})(1-\alpha_{\mathrm{Co}} T^{3/2})$. (b) Temperature dependence of the spin-independent part of the conductance with a solid line fitting using $G_{\mathrm{Si}} = \sigma_0 + \sigma_2 T^{1.33} + \sigma_3 T^{2.5}$.

$=(2P_1P_2)/(1-P_1P_2+G_{\mathrm{SI}}/G_T)$. The elastic direct tunneling conductance coefficient G_T only depends weakly on temperature and will be treated as constant.[15] It follows easily that the conductance difference between parallel and antiparallel states, defined as ΔG, satisfies $\Delta G = 2G_T P_1 P_2 = 2G_T P_{\mathrm{ZCT}} P_{\mathrm{Co}} (I-\alpha_{\mathrm{ZCT}} T^{3/2})(I-\alpha_{\mathrm{Co}} T^{3/2})$, where P_{ZCT} and P_{Co} are the zero temperature spin polarization of the (ZnCr)Te and Co electrodes, respectively. The spin polarization is assumed to have the same temperature dependence as surface magnetization, which is described by the spin wave excitation model with $T^{3/2}$ dependence. ΔG can be fitted reasonably well using this equation, as evident in Fig. 4(a). By taking $\alpha_{\mathrm{Co}} = 3\times 10^{-6}\ \mathrm{K}^{-3/2}$,[15] we find $\alpha_{\mathrm{ZCT}} = 1.9 \times 10^{-4}\ \mathrm{K}^{-3/2}$, which is about one order smaller than for (Ga,Mn)As,[7] presumably due to the much higher T_C of (Zn,Cr)Te.[15] Further, we can determine G_{SI} from the total conductance as $G_{\mathrm{SI}} = \langle G\rangle - G_T$, where $\langle G\rangle$ is the average conductance between parallel and antiparallel states. G_T can be estimated from the fitting of ΔG by assuming $P_{\mathrm{ZCT}} P_{\mathrm{Co}}$ to be the experimental value given by Julliere's formula.[22] The temperature dependence of G_{SI} is shown in Fig. 4(b). The value of G_{SI} increases monotonically with temperature. Generally, the conduction due to hopping through localized states in the barrier can be described as $G = \Sigma G_N = \Sigma \sigma_N T^{\gamma(N)}$,[19,20] where G_N stands for the hopping conduction through N localized states in the barrier, and $\gamma(N) = N - [2/(N+1)]$. This type of hopping is associated with the emission (or absorption) of a phonon and so it is strongly temperature dependent. As shown in Fig. 4(b), G_{SI} is well fitted by $\sigma_0 + \sigma_2 T^{1.33} + \sigma_3 T^{2.5}$, which corresponds to the hopping through two and three localized states. The coefficient values are $\sigma_0 = 1.6\times 10^{-4}\ \Omega^{-1}$, $\sigma_2 = 3.7\times 10^{-7}\ \Omega^{-1}\ \mathrm{K}^{-1.33}$, and $\sigma_3 = 7.2 \times 10^{-9}\ \Omega^{-1}\ \mathrm{K}^{-2.5}$, indicating that contribution from a three-step hopping is much larger than two-step hopping. Given G_{SI} and G_T, we are at a good position to investigate the origin of the temperature dependence of TMR. The solid curve in Fig. 3 is the calculated temperature dependence of TMR by this model, which fits the experimental data very well. The rapid increase of spin-independent conductance G_{SI} with temperature due to thermally assisted hopping leads to a rapid decrease in TMR. The fast decrease of TMR with bias could come from the increase of G_{SI} terms, which are activated at higher bias.[19] This may also explain the symmetrical behavior of TMR and small $V_{1/2}$ in the bias dependence. Significant spin-independent hopping through multiple states is likely associated with $\mathrm{Al_2O_3}$ barrier. In our case, barrier height is about 1 eV, much less than typically values of 2.5 eV in MTJs based on metallic electrodes.[3] Other contributions may be from the interface between (Zn,Cr)Te and $\mathrm{Al_2O_3}$ which is not characterized at present. Higher TMR values and better temperature performance are expected through optimization of the interface and barrier quality.

In summary, we have fabricated $(\mathrm{Zn,Cr})\mathrm{Te}/\mathrm{Al_2O_3}/\mathrm{Co}$ junctions and achieved 21% of TMR at 5 K. The TMR persists up to 250 K, which is considerably higher than MTJs having DMS electrodes in previous studies.[7–11] The fast decrease of TMR with increasing temperature is primarily attributed to the rapid increase of the spin-independent conductance with temperature. This could be reduced by improving the interface and barrier quality.

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