Magnetoresistance studies on Co/AlO$_X$/Au and Co/AlO$_X$/Ni/Au tunnel structures

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We report on magnetoresistance (MR) studies on Co/AlO$_X$/Au and Co/AlO$_X$/Ni/Au magnetic tunnel junctions. In spite of the fact that the difference between the two samples is merely a 3 nm thick Ni layer, there is a sharp contrast in MR behavior indicating that the electronic structure at the interface between the ferromagnetic electrodes and the insulating barrier dominates the MR signal. The former sample exhibits a clear tunneling anisotropic MR (TAMR), with the characteristic correlation between resistance and current direction, in contrast to the latter sample which displays a conventional tunneling MR (TMR) dominated by the relative orientation between the magnetization directions of the two electrodes. In addition, the TAMR has a much stronger temperature dependence than the TMR, indicating a much faster drop-off of the tunneling density of states anisotropy than the tunneling electron spin polarization with increasing temperature. Finally, we propose a possible simple way to distinguish TAMR from normal TMR by measuring the resistance of the device at different angles of the external magnetic field. *© 2008 American Institute of Physics*. [DOI: 10.1063/1.3000614]

Magnetic tunnel junctions (MTJs) can exhibit large resistance differences for parallel and antiparallel alignment of the magnetization direction of the two magnetic electrodes, leading to the widespread use in memory and sensor applications.[1] Spin transport in ferromagnet/nonmagnetic/ferromagnet (F/N/F) sandwich structures has been extensively studied both experimentally and theoretically.[2–4] To draw correct conclusions on, e.g., spin injection/detection and spin accumulation in such structures, it must be verified that the observed magnetoresistance (MR) signal originates from spin-polarized electron transport through the nonmagnetic component. Recently, a spin valve-like effect known as TAMR was reported in tunnel structures with only one magnetic electrode.[5–7] These results emphasize the importance of clarifying the origin of tunneling MR (TMR)-like signals in F/N/F experiments. In this work, we present a comparative MR study of Co/AlO$_X$/Au and Co/AlO$_X$/Ni/Au tunnel junctions where very different MR behaviors are observed and interpreted in terms of different physical mechanisms.

The MTJs are fabricated on top of a 300 nm thick SiO$_2$ layer thermally grown on a Si substrate. Figure 1(a) shows a Co/AlO$_X$/Au/AlO$_X$/Co double tunnel junction device with the two ferromagnetic electrodes coupled to the central Au island via AlO$_X$ tunnel barriers. The wirelike Au island measures 150 nm in length, 20 nm in width, and 25 nm in thickness (more details about the fabrication process can be found in Ref. 7). The preparation of corresponding Co/AlO$_X$/Ni/Au tunnel junctions follows a similar procedure except that a thin 3 nm Ni layer was deposited on top of the Au layer. After the fabrication, conductance measurements were carried out at 4.2 K in a liquid helium dewar. Figure 1(b) shows the differential conductance versus gate and drain biases for a typical device at 4.2 K. The periodical dark regions correspond to low differential conductance regimes, indicating that the device behaves as a single electron transistor.[8] Following these measurements, the sample is transferred to a cryostat housing a 6 T superconducting mag-

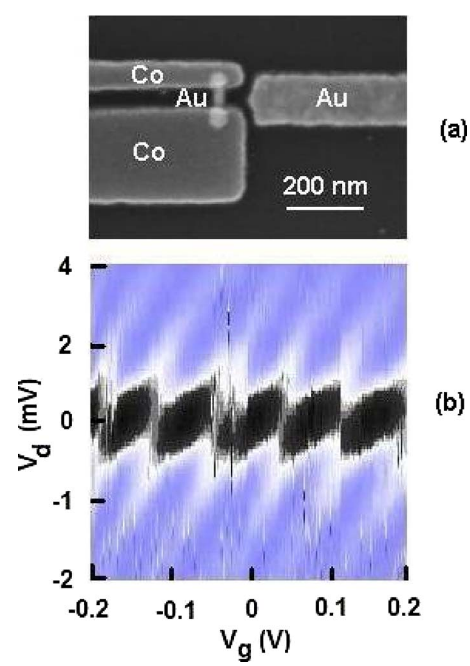

FIG. 1. (Color online) (a) Scanning electron microscopy/ image of the Co/AlO$_X$/Au double tunnel junction. The central Au island has dimensions of 150 nm (length)×20 nm (width)×25 nm (thickness); (b) Color-scaled differential conductance vs gate (V_g) and drain (V_d) bias.

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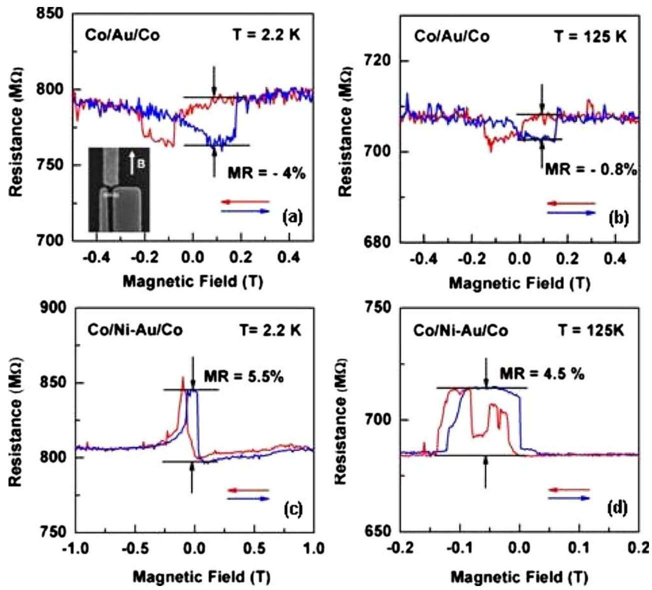

FIG. 2. (Color online) MR for $Co/AlO_X/Au$ double tunnel junctions at (a) 2.2 K and (b) 125 K, respectively, as well as for $Co/AlO_X/Ni/Au$ double tunnel junctions at (c) 2.2 K and (d) 125 K, respectively, with the in-plane field applied parallel to the long (easy) axis of the Co electrode.

net where magnetoresistance measurements are carried out. The magnetic field is in the plane of the device with a tunable orientation with respect to the orientation of the electrodes.

Figures 2(a) and 2(b) show the resistance traces measured on a $Co/AlO_X/Au$ double tunnel junction at 2.2 and 125 K, respectively, for two magnetic field sweep directions, with the in-plane magnetic field applied parallel to the long axis of the Co electrodes. An inverse MR signal with a magnitude of −4% can be clearly resolved at 2.2 K and it decreases dramatically down to −0.8% as the temperature increases to 125 K. In contrast, a very different MR behavior is observed for samples with a 3 nm thick Ni layer deposited on top of the Au layer. Figures 2(c) and 2(d) show the MR for such a $Co/AlO_X/Ni/Au$ double tunnel junction for two sweep directions. For this device, the MR signal is positive and decreases slightly from 5.5% at 2.2 K to 4.5% at 125 K. As we showed in a recent paper, the MR signal observed in Figs. 2(a) and 2(b) is not due to injection and detection of spin-polarized current via the central Au island, but rather to a magnetization-dependent tunneling density of states (DOS) in the Co electrodes induced by spin-orbit (s-o) interaction.[7] The MR signals in Figs. 2(c) and 2(d), however, follow the conventional TMR phenomenology in MTJs[9] and can be ascribed to the tunneling spin polarization of the Co electrode and the Ni layer, modified by the insulating barrier. The results in Figs. 2(a) and 2(c) clearly demonstrate the decisive role of the electronic structure of the interface between the ferromagnetic electrode and the insulating barrier on the spin-dependent tunneling current, in very good agreement with earlier work done by LeClair.[10] Apparently, spin-dependent tunneling between the two magnetic layers becomes the dominant transport mechanism as the interfacial configuration changes from $Co/AlO_X/Au$ to $Co/AlO_X/Ni$, resulting in normal TMR.

The nature of the different physical mechanisms responsible for the MR signals in the two MTJs considered above can be further elucidated by investigating their temperature dependence. As shown in Figs. 2(b) and 2(d), the MR decreases by a factor of 5 as the temperature is increased from 2.2 to 125 K for the $Co/AlO_X/Au$ double junction, whereas for the $Co/AlO_X/Ni/Au$ double junction the MR decreases only slightly. The observed decrease in the TMR with increasing temperature for the $Co/AlO_X/Ni/Au$ junctions is primarily attributed to a decreased spin polarization of the electrodes due to excitation of magnons.[11,12] At present, we do not have a detailed understanding of the strong temperature dependence of the TAMR observed for the $Co/AlO_X/Au$ junctions. The most likely mechanism for the TAMR is that the s-o interaction causes a mixing of $3d$ minority and majority spin states, as well as $4s$ and $3d$ orbitals of the same spin channel, resulting in an anisotropic tunneling DOS at the Fermi level.[13,14] A detailed theoretical analysis would require spin density functional calculations, which is clearly beyond the scope of the present work. Nevertheless, a qualitative understanding of the large difference in temperature dependence between TMR and TAMR can be gained by considering the magnetocrystalline anisotropy. Magnetocrystalline anisotropy is the energy cost to realign the magnetization from one crystallographic direction to another, originates from s-o interaction, which couples the spin to the orbital angular momentum. The s-o interaction lifts the $3d$ band degeneracies near the Fermi level which provides significant contributions to the magnetocrystalline anisotropy energy.[15] Since the origin of both magnetocrystalline anisotropy and TAMR reported in this paper is s-o interaction, we expect qualitatively a similar temperature dependence.

For uniaxial systems, Callen and Callen relate the temperature dependence of the magnetocrystalline anisotropy constant to the temperature dependence of the magnetization with the equation $[K_1(T)/K_1(0)]=[M(T)/M(0)]^3$,[16] with $M(T) \propto T^{-3/2}$ for temperatures lower than the Curie temperature due to excitation of magnons. Since the tunneling spin polarization and magnetization follow the same temperature dependence law,[11,12] the expression above thus indicates a much stronger decrease of any MR signatures originating from s-o interaction (e.g., TAMR) than from tunneling spin polarization (e.g., TMR).

The strong decrease of the TAMR signal with increasing temperature in MTJs with one magnetic electrode is problematic for spintronics applications. Here it would be interesting to explore magnetic electrodes made of materials such as FePt and CoPt in which the strength of the s-o coupling is enhanced due to the presence of the heavy element Pt.[17,18]

We conclude our analysis of the two types of MTJs by considering how the direction of the applied magnetic field affects the MR signal. Figures 3(a) and 3(b) show the MR traces of a single $Co/AlO_X/Au$ tunnel junction while sweeping the magnetic field in two directions, with the field applied parallel and perpendicular to the long axis of the Co electrodes, respectively. The sign of the MR for the former case is negative, while it is positive for the latter one because of the magnetization-dependent tunneling DOS in Co electrodes.[7] In contrast, this anisotropic MR phenomenon is not observed in the $Co/AlO_X/Ni$ tunneling junction, as shown in Figs. 3(c) and 3(d), where both sweep directions display a positive MR. This shows that the local magnetization of Co and Ni electrodes near the tunnel junction are in a noncollinear configuration for both cases at low magnetic field, giving rise to a high resistance state. When the external

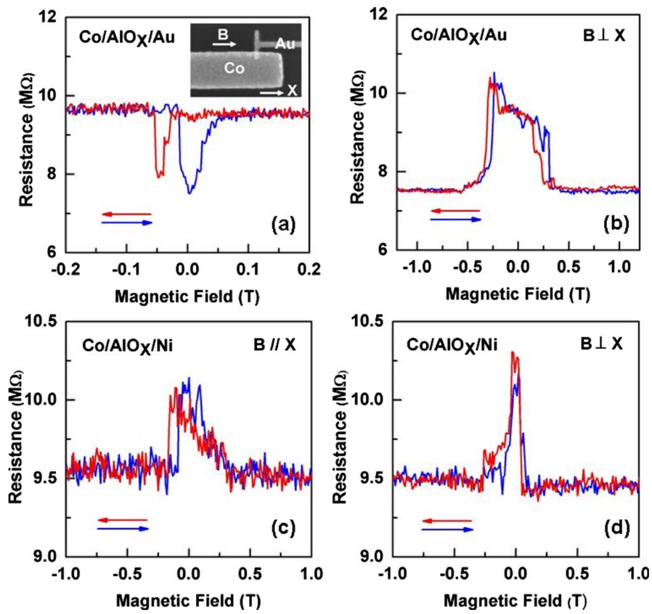

FIG. 3. (Color online) MR for Co/AlO_X/Au double tunnel junctions with (a) in-plane field applied parallel and (b) perpendicular to the long (easy axis) of the Co electrode. (c) and (d) show similar measurements for Co/AlO_X/Ni junctions. $T=4.2$ K in all measurements.

field strength is large, the magnetizations of the Co and Ni electrodes become parallel and aligned with the field resulting in a low resistance state.[19] This set of experiments suggests a simple and feasible way to distinguish between conventional TMR and TAMR. The need of distinguishing between these two effects is especially important in F/N/F nanostructures used for studying spin transport through a central nonmagnetic component. As we have seen here, the existence of a spin valve-like signal does not always result from injection and detection of a spin-polarized current in the magnetic tunneling structure.[20] Therefore, careful reference measurements are necessary to draw correct conclusions.

In summary, we have carried out detailed MR studies on Co/AlO_X/Au and Co/AlO_X/Ni MTJs. We can change the MR behavior of the former structure from TAMR to conventional TMR by inserting a 3 nm thick Ni layer in between the AlO_X and the Au layer, indicating the interface sensitivity of the MR signal. The MR observed in the former structure drops very fast with increasing temperature, in comparison with the moderate decrease of normal TMR for the latter one. We ascribe this behavior to the much faster decrease of the s-o induced tunneling DOS anisotropy with temperature in comparison to the temperature dependence of the tunneling spin polarization of the MTJs. We also demonstrate a straightforward approach to distinguish between TAMR and conventional TMR by measuring the MR for different directions of the magnetic field.

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