Bias voltage and temperature dependence of magnetotunneling effect

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We have studied systematically the magnetotunneling properties of several metallic magnetic-tunnel-junction systems ($Ni_{80}Fe_{20}$–insulator–$Ni_{80}Fe_{20}$, $Ni_{80}Fe_{20}$–I–Co, Co–I–Co, $Ni_{40}Fe_{60}$–I–Co). The room-temperature magnetoresistance MR value at zero-bias ranges between 16% and 27%, depending on the spin polarization of the electrodes. There seems to be a general bias dependence of MR in all of these systems. In particular, it requires a bias in the range of 0.22–0.23 V to suppress the maximum MR value by half. We have also measured the bias dependence of MR as a function of barrier parameters (thickness and oxidation time). At low temperature, a sharp cusplike feature appears near zero bias. In some cases, low-temperature MR values substantially exceed expectations from established spin-polarization.
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Magnetic-tunnel junctions (MTJs) are emerging as a new class of magnetoresistive (MR) devices.[1–7] MTJs have demonstrated a number of technical advantages over the existing giant magnetoresistance (GMR) devices. Metallic GMR structures are inherently highly conductive, so a large current density is required to generate enough voltage signal. For a tunnel junction, however, device resistance can in principle be controlled by barrier parameters.

Magnetic-tunnel junctions have been studied since the 1970s.[1] One of the perplexing properties observed since then is a strong supression of magnetoresistance with bias voltage on a junction.[5,8–10] This bias voltage dependence could convey information about the detailed process of spin-polarized tunneling. In this paper, we present an on-going study of the bias voltage and temperature dependence of MTJs particularly with transition metals and alloys as both electrodes.

The magnetic-tunnel junctions employed in this study are made by magnetron sputtering. The base pressure of the deposition system is lower than 1×10^{-8} Torr. A typical layer sequence is represented in Fig. 1(a). A thin layer of Al was deposited and subsequently plasma oxidized in the chamber to form the tunnel barrier. The nominal thickness of this Al layer is in the range of 5–15 Å. The oxygen pressure during oxidation is 100 mTorr, and oxidation times range from 30 s to 7 mins. A ferromagnet–antiferromagnet–ferromagnet (FM–AFM–FM) sandwich structure is deposited to provide exchange biasing for the bottom electrode. This technique separates the magnetic response of the top electrode from that of the bottom, and enables us to attain saturated antiparallel configurations of the junction. After the deposition, a lithographical patterning procedure was used to fabricate the MTJ devices as small as 1×1 μm.[2] The details of this process have been described elsewhere.[5–7]

The blanket multilayer films are examined by a vibrating-sample magnetometer at room temperature after the deposition. Figure 1(b) shows a typical result. Three distinct hysteresis loops of varying sizes can be clearly seen, corresponding to the three ferromagnetic layers in the FM–AFM–FM sandwich structure of the bottom electrode, and have been shifted due to the exchange biasing effect. The centered hysteresis loop is generated by the top electrode. For more details about the magnetic properties of MTJs, refer to Refs. 5 and 6.

The hysteresis loops of the two electrodes are well reproduced by the tunneling resistance of the junction, as shown in Fig. 2(a). Between the hysteresis loops, the magnetization of the electrodes are antiparallel to each other, and junction resistance is maximized due to the mismatch of spin-polarized bands across the tunnel barrier. At higher field in either direction, the electrodes are aligned to be parallel and junction resistance reduces to a minimum value. This magnetoresistance effect can be understood qualitatively in the framework of the two-current model, first proposed by

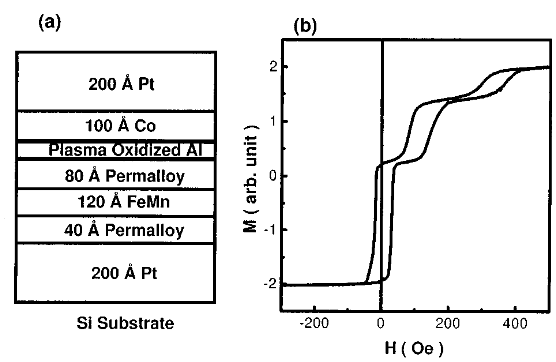

FIG. 1. (a) Layer sequence of a typical MTJ junction with exchange biased bottom electrode, and (b) the magnetization curves of one blanket multilayer film consisting of the MTJ structure. Three distinctive hysteresis loops can be seen corresponding to the three ferromagnetic layers in the film.

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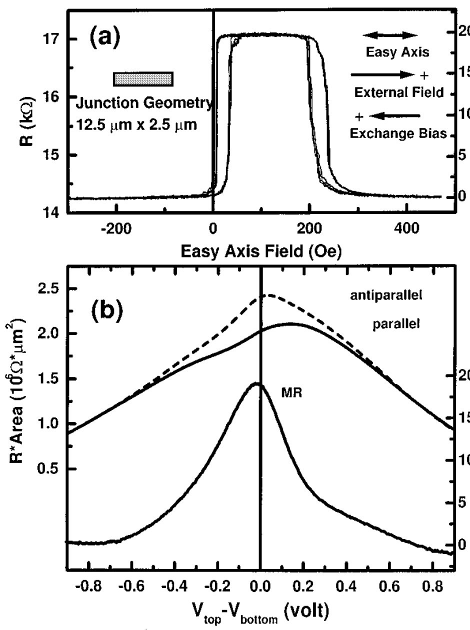

FIG. 2. (a) Resistance vs magnetic-field curves of a typical MTJ device at room temperature; the geometry of the junction as well as the relative orientation of exchange bias, easy axis, and external field are shown in the inset. (b) Differential junction resistance in parallel (solid) and antiparallel (dashed) configurations as a function of dc bias voltage on the junction. (c) Magnetoresistance, calculated using the differential resistance data, as a function of dc bias.

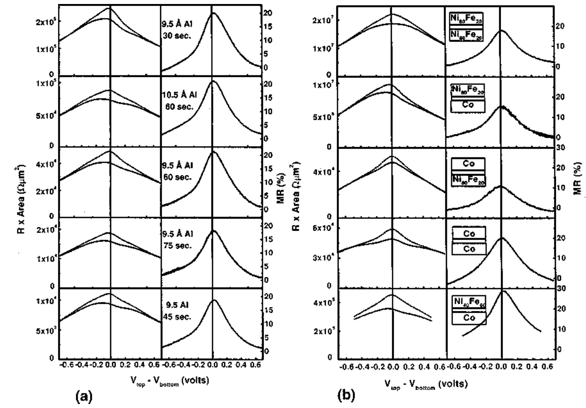

FIG. 3. (a) Bias dependence (room temperature) of junction resistance in both parallel (solid) and antiparallel (dashed) configurations and MR in a series of junctions with a Co base electrode and $Ni_{80}Fe_{20}$ counter electrode, but different barrier fabrication conditions (shown in the insets). (b) Same plots as (a) for a series of junctions with various electrode material combinations (shown in the insets).

Julliere.[1] Assuming the two spin species of electrons tunnel through the barrier independently, the two-current model predicts the magnetoresistance, defined as the difference in resistance divided by the minimum value, as

$$\frac{\Delta R}{R_{\mathrm{P}}}=\frac{R_{\uparrow\downarrow}-R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}=\frac{J_{\mathrm{P}}}{J_{\mathrm{AP}}}-1=\frac{1+P_1P_2}{1-P_1P_2}-1=\frac{2P_1P_2}{1-P_1P_2}, \tag{1}$$

where P_1 and P_2 are the spin-polarization factor of the two electrodes. The spin polarization of a number of materials has been measured in a series of tunneling experiments between ferromagnets and superconductor (FM–I–S) by Meservey and Tedrow.[11] We will later assemble a comparison of our results with these spin-polarization factors.

The simple two-current model does not take into consideration the effects of electron band structure, tunnel barrier transmission, and spin-flipping excitations into consideration, and thus, predicts no bias voltage dependence for the magnetoresistance. Experimenters,[1–4] however, have always observed a substantial decrease in MR with the application of bias. The differential resistance in parallel (solid) and antiparallel (dashed) states as well as the MR of one of our junctions are plotted versus dc bias in Fig. 2(b). The bias dependence of the differential resistance has the general feature of a metal–insulator–metal tunnel junction in that resistance decreases with bias and has a smooth maxima close to zero bias. The detailed shape of the curve shows deviations from simple calculations such as Simmon's formula.

We have measured the bias dependence of *R* and MR in MTJs with various electrode material and barrier parameters. The results are summarized in Figs. 3(a) and 3(b). Figure 3(a) plotted the bias dependence of *R* and MR in a series of junctions all with a Co base electrode and permalloy ($Ni_{80}Fe_{20}$) counter electrode, but differing barrier fabrication conditions. The junction conductance has been normalized by junction area, and thus, provides a measure of the barrier transmission coefficient. The graphs are ordered such that the parameter R^* area (inverse unit-area conductivity) decreases from the top graph. Nominal thicknesses of the Al layer as well as oxidation times are indicated in the insets with each pair of curves. Due to the exponential dependence of tunneling conductance on barrier thickness and height, R^* area of these samples vary by more than a factor of 20 even though the barriers are very similar. It is evident from this set of curves that little if any change in the bias dependence of tunneling resistance and MR is incurred by changing the barrier transmission, within the range of our data.

Figure 3(b) shows the same representative bias dependence for a series of junctions with different electrode material combinations. Although the material combinations are far from complete, the data seem to suggest a correlation between the bias dependence of the junction resistance with the material of the negatively biased electrode. Particularly, when the Co electrode is negatively biased there is a dip in the resistance curve at about 150 mV, and when $Ni_{80}Fe_{20}$ is negatively biased this feature is not present. This observation is consistent with the band-structure effect. Since the tunneling current comes mostly from electrons near the Fermi level of the positive electrode, which are closest in energy to the barrier top, variation in their tunneling probability as a function of bias is a mapping of the negative electrode's density of states above its Fermi level. Differences in the electrode-barrier interface cannot be ruled out as another possible cause of this correlation. The bias dependence of the MR ratio, however, does not vary as much as the resistance itself. Although the maximum MR ratio changes from 12% to 28%, the bias voltage needed to suppress the MR to half of its maximum value within each junction falls within the narrow range of 220–230 mV. We have not identified any correlation between electrode material and variations in the half-

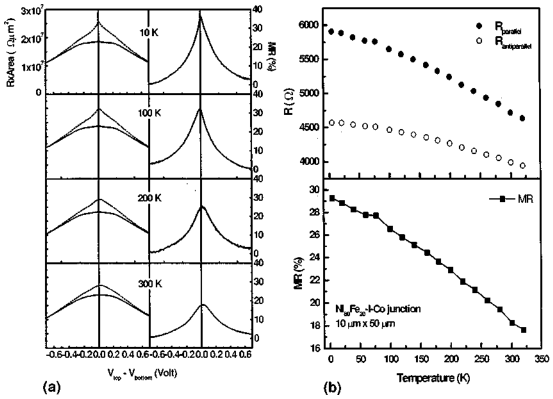

FIG. 4. (a) Bias dependence of R and MR of one MTJ at reduced temperatures. Plots follow the same convention used in Figs. 3(a) and 3(b). (b) Junction resistance and MR plotted as a function of temperature.

maximum bias voltage or the slight asymmetry in the MR curves. This surprisingly ''universal'' behavior is difficult to understand considering the close relationship between the spin polarization of the material and the MR. Since all these measurements are carried out at room temperature, the underlying mechanism should have a correspondingly high-energy scale. This is also indicated by the size of half-maximum bias.

We have also measured the bias dependence of MTJs at reduced temperature. The results are summarized in Fig. 4(a). As the samples are cooled from room temperature, a cusplike peak gradually develops at zero bias. This peak is limited within about $+/-100$ mV, and is much more pronounced in the antiparallel configuration than in parallel case. This zero-bias peak and the difference in peak height for the two magnetic configurations account for most of the increase in both junction resistance and MR at zero bias, which are plotted in the Fig. 4(b). This cusplike peak has been attributed to magnon excitations at the electrode-barrier interface by Zhang *et al.*[12] This theory has predicted some significant characteristics of the zero-bias peak, such as the cusplike shape and the size difference in the two magnetic configurations. We have not been able to distinguish the predicted $T \log T$ functional form of the temperature dependence of the zero-bias resistance from other possibilities. Aside from the zero-bias peak just discussed, the general bias dependence at higher voltage ranges does not change significantly with temperature.

Figure 5 compares our results with those of Meservey and Tedrow. The horizontal position of the points shows the MR values calculated using formula (1). The vertical positions then indicate the highest MR measured in each group of junctions, at room temperature (filled) and liquid-helium temperature (open). The room-temperature MR (black square) is generally 70%–90% of the predicted value, while low-temperature values have less dependence on electrode material and, for low P materials, are much higher than predicted. The reduction of MR at room temperature could come from the smearing of the Fermi surface or from thermally activated conduction that is spin independent. Another

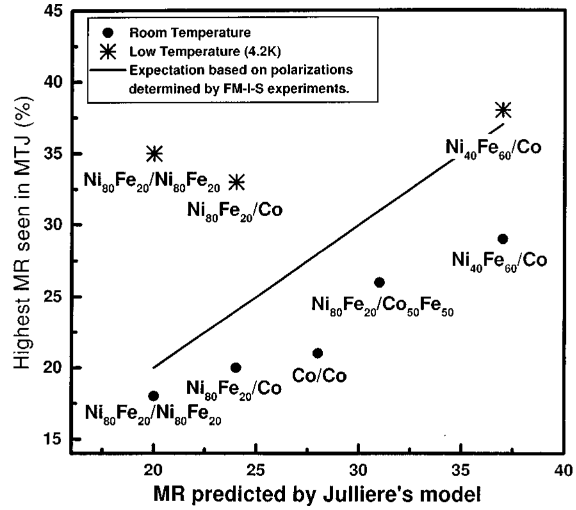

FIG. 5. Maximum MR values measured for MTJs with several electrode material combinations vs predicted values using the two-current model and spin-polarization factors measured in FM–I–S tunneling experiments. Room-temperature data are plotted as filled circles and liquid-helium temperature data as open circles, and solid lines indicate the prediction.

factor to be concerned is the loss of magnetization at elevated temperature, i.e., magnon excitation in the material or at the interface. Although the low-temperature data are not as extensive as those at room temperature, the continuity in temperature dependence and consistency in different junctions clearly precludes defects as the reason for the higher MR observed. Whether this discrepancy is due to some subtle difference between FM–I–S and FM–I–FM tunneling or other spin-dependent effects beyond the two-current model is unknown. It is also possible that the polarization values determined 20 years ago may need to be refined.

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