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Tunnel conductance as a probe of spin polarization decay in Cu dusted Co/Al₂O₃/Co tunnel junctions

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Tunneling magnetoresistance (TMR), dynamic resistance and bias dependence measurements were performed on Co/Al₂O₃/Co magnetic tunnel junctions with a thin Cu layer inserted at either the Co/Al₂O₃ ("bottom") or Al₂O₃/Co ("top") interfaces. Careful comparative analysis allows detailed growth characteristics to be elucidated, as well as providing information on the underlying mechanisms behind spin polarized transport in these structures. Conductance for top dusted junctions is indicative of parallel Co/Al₂O₃/Co and Co/Al₂O₃/Cu junctions, consistent with three-dimensional growth of Co and Cu on Al₂O₃, while conductance for bottom dusted junctions shows novel behavior dissimilar to either type of junction. The bias dependence of the TMR, surprisingly, is unaffected by either type of dusting. © 2000 American Institute of Physics.

The extreme sensitivity of the tunneling conductance (dI/dV) has been used to extensively investigate a diverse array of phenomena such as the superconducting density of states, spin polarization in ferromagnets, and magnon excitations. The recent breakthrough of Moodera et al. in the area of magnetic tunnel junctions (MTJs) has caused a resurgence of interest in the area of tunneling. Of special fundamental and practical interest are questions such as the nature of the bias dependence of the tunneling magnetoresistance (TMR), the role of magnetic excitations, and the effects of added impurities and interlayers. Previously, we have investigated TMR as a function of Cu interlayer ("dusting") layer thickness with Cu inserted at either the Co/Al₂O₃ ("bottom") or Al₂O₃/Co ("top") interfaces. With the aid of in situ growth studies, it was found that Cu on Al₂O₃ (top) grows in a three-dimensional (3D) manner [see inset to Fig. 1(a)], leading to a longer TMR decay length, while Cu on Co grows in a nearly layer-by-layer manner [see inset to Fig. 1(b)], giving an extremely fast decay of the TMR. The apparently long length scales previously observed for interlayers grown on Al₂O₃ were attributed to nonideal surface coverage, resulting in a large fraction of the tunnel conductance originating from Co, rather than the Cu interlayer.

In this letter, we show that the conclusions reached by in situ growth studies, i.e., nonideal surface coverage of Cu interlayers on Al₂O₃, can be drawn from careful analysis of the tunneling dynamic resistance or conductance. Further, we show that additional analysis on junctions with well-grown Cu layers (bottom dusted) provides information beyond that obtained from the TMR decay with Cu thickness, e.g., information on the mechanisms behind spin polarized transport through thin nonmagnetic layers. It is found for well-grown Cu layers that magnetic excitations are strongly affected by the added interfacial layer, while the bias dependence of the TMR is surprisingly unaffected.

Ferromagnetic tunnel junctions were prepared by ultra high vacuum (UHV) direct current (dc)/radio frequency magnetron sputtering, with plasma oxidation of Al used to form the tunnel barriers. The details of this fabrication procedure and in situ growth characterization have been described elsewhere. Junction resistances and dynamic resistances (dV/dI) were measured at 5 K using standard alternating current lock-in techniques at a frequency of 1 kHz, though the results are presented here as dI/dV for convenience. Figure 1(a) shows conductance versus voltage data at 5 K, with nominally parallel magnetizations of the two Co electrodes, for top dusted junctions with 2.8, 4.2, and 7.7 Å Cu, as well as a control junction (no Cu). Note that for all data presented, the bottom electrode is biased positively for V > 0. For all top dusted junctions, the conductance still exhibits the features typical of Co/Al₂O₃/Co control junctions, such as the cusp-like behavior for low bias and the local minima at ±250 mV. Only small changes are observed when adding Cu, notably for positive bias. In contrast, conductance versus voltage data for bottom dusted junctions with 2.5, 3.1, and 4.2 Å Cu, as well as a control junction, are shown in Fig. 1(b). In this case, the cusp-like feature and the local minima at ±250 mV gradually disappear, reaching a more parabolic shape, unlike either Co/Al₂O₃/Co or Co/Al₂O₃/Cu junctions [see Fig. 2(a)]. This simple, qualitative analysis already clearly indicates that for top dusted junctions, Cu interlayers have much less effect than for bottom dusted junctions, suggesting nonideal growth as observed previously.

The cusp-like feature around V = 0, clearly visible for the control junction and top dusted junctions, has been attributed to localized interfacial spin excitations and is observed only for junctions with at least one magnetic electrode, though the effects are strongest when both electrodes were magnetic. Spin wave excitations by hot electrons have been shown to qualitatively and quantitatively reproduce the anomalies near zero bias in these types of junctions. For bottom dusted junctions [Fig. 1(b)], in contrast to top dusted junctions, the addition of ultrathin Cu layers clearly dampens these features. The induced spin polarization of Cu sp-type...
electrons, believed to be responsible for tunneling, is expected to be negligible in this case. Thus, we may attribute this rapid loss of magnon associated features to be indicative of the extreme interface sensitivity of tunneling, apparently sampling only the outermost monolayers of the metal electrodes adjacent to the tunnel barrier, in this case the essentially unpolarized Cu. This picture also qualitatively explains the TMR vs $d_{\text{Cu}}$ data [see Fig. 2(b)], which shows an approximately exponential decrease with a monolayer length scale as a function of Cu thickness.

With the reasonable assumption that the Cu clusters are thicker than 2 ML [see Fig. 1(a)], the conductance for junctions with Cu above may be approximated by Co/Al$_2$O$_3$/Co (Co–Co) and Co/Al$_2$O$_3$/Cu (Co–Cu) junctions in parallel. Figure 2(a) shows the tunnel conductance, averaged over parallel and antiparallel magnetizations, for Co–Co and Co–Cu junctions, and a junction with 2.8 Å Cu above. The conductance for the dusted junction can be duplicated quite well by adding in parallel the Co–Co and Co–Cu conductances, in this case in the proportions 45% Co–Cu and 55% Co–Co. This corresponds to an average Cu island thickness of 6.2 Å (3 ML), consistent with the assumption. Assuming Cu on Al$_2$O$_3$ grows in islands of equal height (viz. 6.2 Å), we may estimate the expected TMR for top dusted junctions by simply adding Co–Co (55%) and Co–Cu (45%) contributions in parallel. For 6.2 Å Cu on Co, the measured normalized TMR is approximately 0.08 [see Fig. 2(b)]. Using contributions of 0.08 for 45% of the surface and 1.0 for the remaining portion, we expect a normalized TMR for island growth of 0.59, in reasonable agreement with the measured value of 0.64 as seen in Fig. 2(b).

All top dusted junctions $d_{\text{Cu}}=1.4$–10.5 Å exhibited features of Co/Al$_2$O$_3$/Co conductance, suggesting that even for quite thick Cu interlayers on Al$_2$O$_3$, a completely closed layer is not yet achieved, consistent with scanning Auger electron spectroscopy (AES) measurements. Scanning AES measurements on Cu layers grown on Al$_2$O$_3$ revealed that even for 30 Å Cu, the underlying Al and O Auger peaks could be observed, while for Cu grown on Co, the underlying Co was unobservable beyond ~15 Å. In this light, the long decay length scale of the TMR for top dusted junctions compared to bottom dusted junctions is easily explained, once again corroborating the original conjecture of 3D growth of Cu on Al$_2$O$_3$.

Given that top and bottom dusted junctions exhibit different TMR decay length scales and conductance–voltage characteristics, it might be expected that the bias dependence of the TMR would also be different. However, this is not the case. Shown in Fig. 3, for a number of top and bottom dusted junctions, is the normalized “dynamic” bias dependence ($\Delta G/G_0$). Here we choose to show the normalized conductance change as a function of bias, rather than the usual resistance ($\Delta R/R_0$) change, due to its greater sensitivity. The conductance change is roughly linear in voltage below $\pm$250 mV, as Zhang et al. predict for localized interfacial spin excitations. For top dusted junctions, we expect that the regions covered with Co will dominate the dynamic bias dependence as they do the TMR decay and conductance. For each type of junction, the essentially non-spin-polarized Cu
introduces no additional magnetic excitations which would give rise to an additional bias dependence. Additional spin-dependent scattering at Co–Cu or Cu–Al₂O₃ interfaces is expected to be unaffected by a dc bias over the junction, and contribute only to an overall decrease in TMR. We further note that while the dynamic bias dependence becomes negative, the true TMR (ΔR/R_p) does not become negative (we measure the slope of the I(V) curve rather than the secant). The negative (ΔG/G_{ap}) reflects the fact that the antiparallel resistance is changing more rapidly with bias than the parallel resistance as the TMR tends to zero, and thus the conductance difference briefly becomes negative before tending to zero.

Thusfar, several theoretical models have been proposed to account for the addition of nonmagnetic interfacial layers in MTJs. To date, none of these models predict the strong, monotonic decrease of TMR with Cu thickness as observed for well-grown bottom doped junctions, and only Zhang and Levy have discussed the effects of added interfacial layers on the tunneling conductance. Theoretical results predict that spin-dependent scattering with coherent transmission should give rise to an oscillating TMR as a function of interlayer thickness, or even an enhancement. However, if the spin dependent scattering significantly alters (i.e., more than a few percent) the spin equilibrium in the interlayer, interface-dominated tunneling may not observe these effects. The influence of altering the Al₂O₃ interface bonding may also play an important role, as it has been shown to even change the sign of the apparent polarization in some cases. Further, if the rate of spin relaxation in the interlayer is large compared to the rate of tunneling, any spin imbalance resulting from spin-dependent scattering may be too quickly destroyed to be observed in the tunnel current. However, lack of coherent electron transmission due to disorder, nonepitaxial electrodes, or diffuse scattering cannot be ruled out as well.

We have performed dynamic resistance and TMR bias dependence studies on Co/Al₂O₃/Co tunnel junctions with a thin Cu layer inserted at either the Co/Al₂O₃ (bottom) or Al₂O₃/Co (top) interfaces. For Cu grown on Al₂O₃, transport measurements indicate 3D growth, in accordance with in situ growth studies, showing the extreme sensitivity and utility of the tunneling conductance to interfacial changes. For well-grown Cu on Co, the conductance data show different behavior from either Co–Co or Co–Cu junctions. Finally, these results help to illuminate topics which require more detailed theoretical treatment.

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15This is not the same as ΔR/R_p for finite bias.