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Bulk-like contribution to tunnel magnetoresistance in magnetic tunnel junctions*

Zhu Tao(朱 涛)[a)b)], Zhan Wen-Shan(詹文山)[a)], Shen Feng(沈 峰)[c)],
Zhang Ze(张 泽)[c)], X. H. Xiang[b)], G. Landry[b)], and John Q. Xiao[b)]

[a)] *State Key Laboratory for Magnetism, Institute of Physics, Chinese Academy of Sciences, Beijing* 100080, *China*
[b)] *Department of Physics and Astronomy, University of Delaware, Newark, Delaware* 19716, *USA*
[c)] *Beijing Laboratory of Electron Microscopy, Institute of Physics, Chinese Academy of Sciences, Beijing* 100080, *China*

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We have demonstrated that the bulk-like contribution to tunnelling magnetoresistance (TMR) exists in the magnetic tunnel junctions, and is determined by the tunnelling characteristic length of the ferromagnetic electrodes. In the experiment, a wedge-shaped CoFe layer is inserted at the interface between the insulating barrier and the reference electrode. It is found that TMR ratio increases from 18% without CoFe layer to a saturation value of 26.5% when the CoFe thickness is about 2.3 nm. The tunnelling characteristic length, l_{tc}, can be obtained to be about 0.8 nm for CoFe materials.

Keywords: tunnelling magnetoresistance, magnetic tunnel junctions
PACC: 7570P, 7570C

1. Introduction

Magnetic tunnel junctions (MTJs) with two ferromagnetic (FM) electrodes separated by an insulating layer exhibit large tunnel magnetoresistance (TMR) at room temperature, making them promising candidates for magnetic random access memory devices, magnetic recording heads, and other magnetic sensors.[1−3] One of the important issues in the spin polarized tunnelling (SPT) phenomena is the characteristic length that determines the electron contribution to TMR. The value of this characteristic length will determine whether the TMR is solely an interfacial effect or bulk contribution. Physically, it seems that the contribution to the tunnel current should be from electrons within this characteristic length which is defined by an exponential probability, as in any conducting process. The interface contribution will dominate only when this length scale is very short (of the order of interlayer distance). Most recently, nonmagnetic insertion layers have served as a useful experimental probe for the investigation of interface properties in MTJ.[4,5] In this paper, we describe the experimental details of magnetic metal insertion in MTJ and demonstrate that the bulk-like contribution can be described by the tunnelling characteristic length (l_{tc}) in MTJ, which has unambiguously determined to be about 0.8 nm for the CoFe electrode.

2. Experiments

The typical MTJ structure, using Py (permalloy = $Ni_{81}Fe_{19}$) as the top and bottom FM electrodes, is Si/Py(20) / Cu(6) / FeMn(12) / Py(8) / Al_2O_3 / Py(13) / Cu(50), denoted by Py/Al_2O_3/Py. The numbers in parentheses are the layer thickness in nanometre unit. The samples were deposited on Si(100) in a magnetron sputtering system. The details can be found elsewhere.[6,7] To investigate the FM electrode thickness dependence of the TMR, the junctions was fabricated by inserting a wedge-shaped CoFe ($Co_{50}Fe_{50}$) layer between the insulating barrier and the reference FM electrode, denoted by Py/CoFe(t)/Al_2O_3/Py. The sample structure is shown in Fig.1. Here we choose inserting the CoFe wedge under the Al_2O_3 barrier, because the metal layers could grow smoothly or in a nearly layer-by-layer manner on the metallic bottom electrode in MTJ to avoid spurious effects due to cluster-like growth at the top Al_2O_3 interface.[5]

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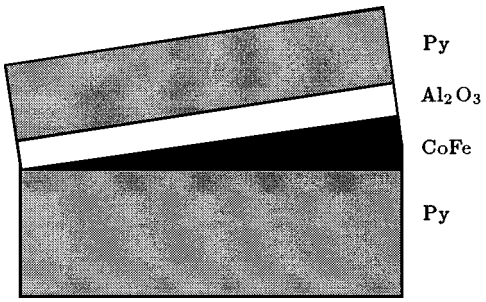


Fig.1. The sample structure for wedge-shaped CoFe layer inserted in the MTJ.

In order to confirm the layer-by-layer growth of bottom electrode in MTJ, high-resolution transmission–electron microcopy (HRTEM) was performed on the sample of Si / Ta(5) / NiFe(5) / FeMn(12) / NiFe(6) / Al_2O_3 / NiFe(6) / Ta(5), using a transmission–electron microcopy of JEM-2010. Figure 2 is the HRTEM cross-sectional image, which shows a direct picture of such different layer growth morphologies in MTJs. In the bottom electrode, the columnar growth of these well-textured layers[8] leads to an average grain size of a few tens of nanometres. In contrast, the top electrode has a much smaller average grain size of about several nanometres with random crystallographic orientations, suggesting a characteristic feature of a near layer-by-layer growth in the bottom electrode and a three-dimensional growth in the top electrode.

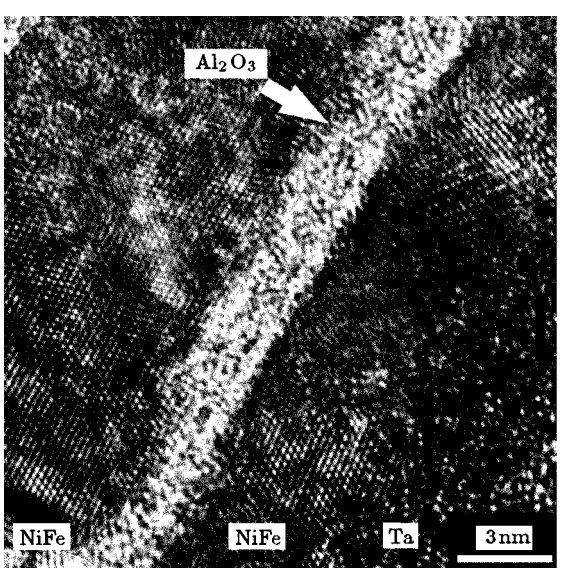


Fig.2. The typical HRTEM cross-section image of the MTJ. The right/left-hand side of the Al_2O_3 barrier corresponds to the top/bottom electrode.

3. Results and discussion

In Fig.3, TMR at room temperature as a function of applied field is shown for junctions with CoFe insertion layers. TMR is expressed using the definition: TMR=$(R_{AP}-R_P)/R_P$, where R_{AP} and R_P represent the junction resistances when the two FM electrodes have their magnetizations antiparallel and parallel, respectively. A clear antiparallel alignment of the FM electrodes is observed, confirmed by vibrating sample magnetometer measurements. Another feature seen from Fig.3 is that the pinning field decreases with the thickness of CoFe insertion layer. This can be explained from the expression of exchange field (H_E) in ferromagnetic-antiferromagnetic (FM/AFM) system,

$$H_E \propto 1/M_{FM}t_{FM}, \tag{1}$$

where M_{FM} and t_{FM} are the magnetization and thickness of the FM layer, respectively, and the $1/t_{FM}$ dependence of H_E has been demonstrated by many experiments.[9] Thus the pinning field decreases with t_{FM} when the thickness of CoFe insertion layer increases.

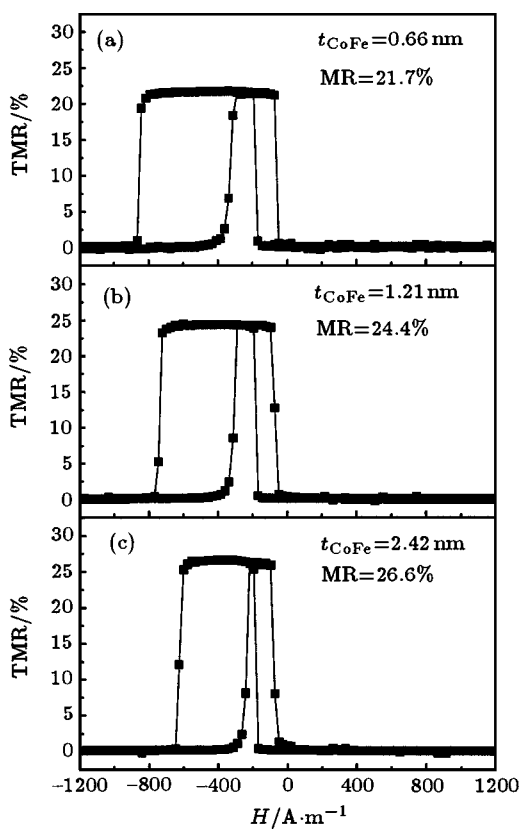


Fig.3. TMR as a function of applied field for Py/CoFe(t)/Al_2O_3/Py with (a) t=0.66 nm, (b) t=1.21 nm, and (c) t=2.42 nm CoFe insertion layers.

Figure 4 shows the CoFe thickness dependence of the TMR in Py/CoFe(t)/Al_2O_3/Py with a wedge-shaped CoFe layer inserted below the 1.26 nm Al layer

with full oxidation of 60 s. It is seen clearly that the TMR increases from 18% to a saturation value of 26.5% when the CoFe thickness is about 2.3 nm (solid circles). The open circles in Fig.4 are the TMR ratios of the MTJ samples without an inserted CoFe layer, for $Py/Al_2O_3/Py$ (made in a single run), measured along the same direction across the wafer as in the former sample, showing a much more uniformity of TMR (with a TMR fluctuation of 2% along the wafer, less than 1% in the centre region).

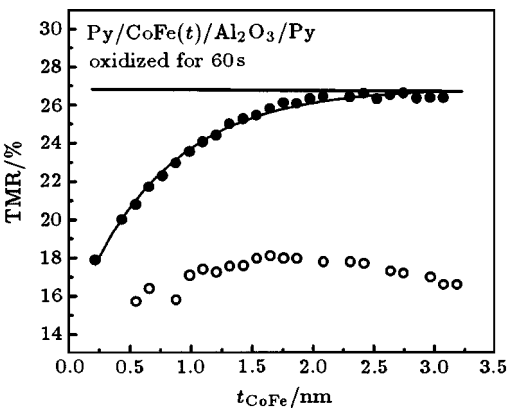


Fig.4. CoFe thickness dependence of the TMR in $Py/CoFe(t)/Al_2O_3/Py$ oxidized for 60 s (solid circles). The open circles are the TMR ratios of the uniform $Py/Al_2O_3/Py$ MTJs measured across the wafer as in the former samples.

The slow saturation of TMR observed can have a number of possible structure-related origins. The granular-like structure at the thin end of CoFe wedge or interdiffusion between CoFe and Py layers may be the obvious possibilities. Hence, the energy-filtered parallel electron energy loss spectroscopy (PEELS) was preformed. The experiments proved that the wedge CoFe grows coherently on top of Py without intermixing within the instrument resolution of 1 nm.[6] Although we cannot completely rule out the small intermixing at the interface resulting from the sputtering process, the intermixing, however, is limited within 1 nm (instrument resolution) and will not alter our conclusions, because the MR still has 15% increase when the CoFe thickness increases from 1 nm to the saturation value (2.3 nm). It is clear that TMR has a significant bulk-like contribution, i.e. the total contribution comes from deeper monolayers.

According to the Jullière model,[10] TMR is proportional to the spin polarization of FM electrodes. If we assumed that CoFe and NiFe have the same tunnelling characteristic length, the effective spin polarization P_1 of bottom $CoFe(t)/Py$ (Py is thick enough) composite FM film can be written as[6]

$$P_1(t) = P_{\mathrm{CoFe}}[1 - \exp(-t/l_{\mathrm{tc}})] + P_{\mathrm{Py}}\exp(-t/l_{\mathrm{tc}}), \quad (2)$$

where P_{CoFe} and P_{Py} represent the spin polarization of CoFe and Py, respectively. By combining Eq.(2) with the Jullière model, $\mathrm{TMR}=2P_1P_2/(1 - P_1P_2)$, where P_1 and P_2 are the spin polarization of the bottom and top FM electrodes, respectively, we fitted the TMR of $Py/CoFe(t)/Al_2O_3/Py$ and then obtained $l_{\mathrm{tc}} \approx 0.8$ nm for CoFe. The fitted results are shown in Fig.5, in which the TMR contributions from the CoFe and Py are also presented. It is striking to see that the first two monolayers contribute about 40% of the total TMR, and 60% contribution is from the third to 10th layers.

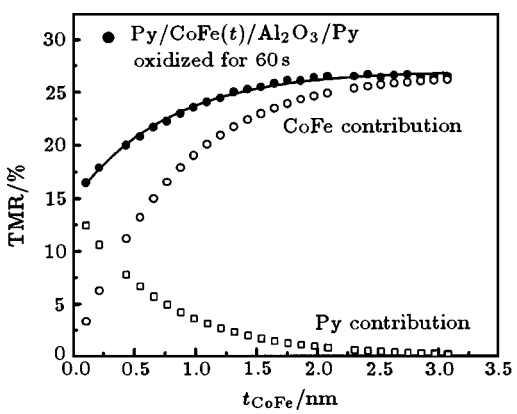


Fig.5. The calculated contribution of TMR value from each constituent, CoFe (open circles) and Py (open squares), of the bottom FM electrode in $Py/CoFe(t)/Al_2O_3/Py$ oxidized for 60 s.

It should also be stressed that the current experiment is different from those with FM electrodes of varying thickness.[4,11] In those experiments, one often encounters the fine size effects, such as low magnetization and Curie temperature often seen in ultrathin FM layer. In our experiment, the thick Py reference electrode beneath the thin CoFe electrode ensures the bulk-like properties in CoFe layer. The small difference in polarization between Py and CoFe layers[12] permits us to study the bulk-like contribution from the CoFe electrode. From this experiment, we can obtain $l_{\mathrm{tc}} \approx 0.8$ nm for CoFe. At the first glance, it seems that our results are contradictory to other results emphasizing the interfacial contribution. We merely argue that whether the bulk or interface contribution dominates the transport depends on the value of l_{tc}. For the interface contribution to TMR to dominate, materials should have a very short l_{tc}, which is greatly influenced by boundary effects.

In the case of normal metal tunnelling, the tunnelling current is related to the bulk spectral function and the effective range of the many-body-interactions are typically of the Fermi wavelength by calculating these spectral functions using the WKB approximation.[13] However, in the case that the electrodes are superconducting metals, this spectral function is the superconducting coherent length, which is very long. Furthermore, there is also a crucial difference between the tunnelling effect of the normal metal and the magnetic metal, the spectral functions in SPT have to take into account the conservation of the spin and transverse momentum and energy within a bias voltage. Hence, in CoFe-based MTJs, the bulk-like contribution to TMR comes from total 10 monolayers, indicating that the spin-dependent tunnelling samples the density of states within several wavelengths.

4. Conclusion

We have demonstrated that the bulk-like contribution to TMR exists in the magnetic tunnelling process, which is determined by the tunnelling characteristic length of the FM electrodes. For interfacial contribution to dominate, the electrode should have a very short l_{tc} of an atomic scale. In CoFe-based MTJs, there is a significant bulk-like contribution from deeper monolayers with $l_{\mathrm{tc}} \approx 0.8$ nm.

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