Exchange splitting and bias-dependent transport in EuO tunnel barriers

M. Müller[1,2], G.-X-Miao[2], J. S. Moodera[2]

[1] IFF-9: Electronic Properties
[2] Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge MA, USA

We study characteristic features of spin filter tunneling in EuO-based magnetic tunnel barriers. Transport measurements show a unique voltage dependence, which give direct evidence for a spin filtering effect without relying on the use of external magnetic fields for spin detection. The variation of the effective tunnel barrier height systematically correlates with the spontaneous magnetization of EuO and allows the evaluation of spin filter efficiency of magnetic tunnel barriers by fully electrical means.

Realizing highly spin-dependent electron transport is an important challenge in spintronics, either for obtaining large magnetoresistive effects or for establishing spin injection into semiconductors. Magnetic tunnel junctions (MTJs) are main building blocks of spintronic devices and their figure of merit, i.e. the tunnel magnetoresistance (TMR) ratio, has steadily increased over the last two decades. An emerging route to realize spin-polarized tunneling is using a magnetic tunnel barrier as the spin-selective element. This approach does not require FM electrodes as the source of spin-polarized carriers, but takes advantage of the spin-dependent tunnel probabilities in a magnetic tunnel barrier: In contrast to its nonmagnetic counterpart, *two* spin-split barrier heights ($\Phi_\uparrow$, $\Phi_\downarrow$) are in effect and a highly spin-polarized tunnel current is created due to the exponential dependence of the tunneling probabilities on barrier heights.

Spin filter (SF) tunneling has been observed up to now only in few materials, such as selected Europium chalcogenides, spinel ferrites and perovskites [2, 3]. The effectiveness of spin filtering is intimately connected with the magnetic ordering of the magnetic insulator, in particular with the magnitude of exchange splitting E_{xc} of the conduction band. We studied electronic transport and its dependence on magnetic ordering in Europiumoxide (EuO) spin filter tunnel barriers, with EuO being a prototype Heisenberg ferromagnet with a bulk Curie temperature T_C of 69 K and a bandgap of 1.12 eV, with an exchange splitting of the conduction band of up to 0.6 eV below T_C [4].

Current-voltage $(I\text{-}V)$ characteristics across EuO spin filter tunnel barriers typically reveal a highly nonlinear shape, which is indicative of tunnel transport. Basically, two different tunneling mechanisms must be expected in a magnetic tunnel barrier at different bias voltages, i.e. direct tunneling (DT) and Fowler-Nordheim (FN) tunneling. DT occurs when the applied bias voltage is less than the average barrier height, whereas FN tunneling is observed if the bias voltage exceeds it. Due to the reduced effective barrier width, the probability for FN tunneling is much larger compared to that of DT.

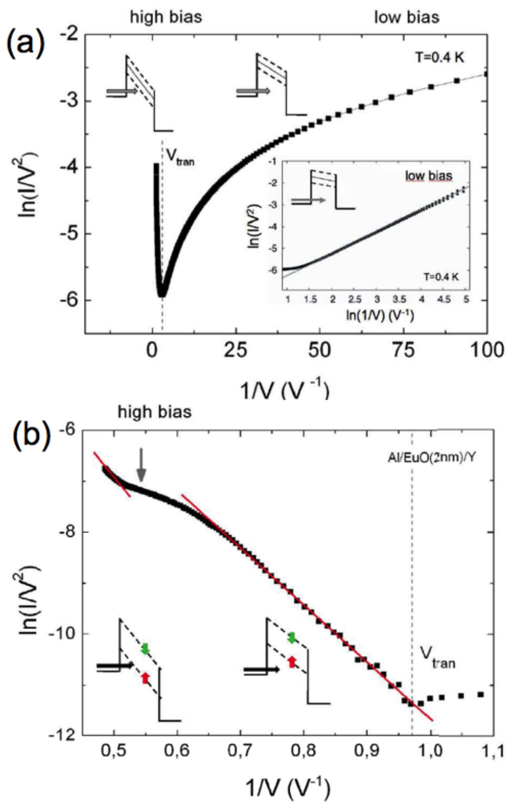

FIG. 1: (a) $\ln(I/V^2)$-$1/V$ plot of an Al/EuO(4 nm)/Y junction at T=0.4 K. The dotted line denotes the transition voltage at which the transport mechanism changes from DT to FN tunneling. (b) $\ln(I/V^2)$-$1/V$ plot for the high bias region of an Al/EuO(2 nm)/Y junction. Two onsets of linear decaying slopes are observable, separated by a crossover region.

Within a two-current model and applying the WKB approximation, we show in Ref. [1] that both tunnel transport mechanisms can be directly compared by rearranging $I\text{-}V$ curves in terms of the variables $\ln(I/V^2)$ and $1/V$. We derived, that in the high bias voltage regime a plot of $\ln(I/V^2)$ versus $1/V$ will yield a linear curve, the slope of which depends on the barrier height. In the low bias regime, however, a plot of $\ln(I/V^2)$ against $1/V$ will exhibit a logarithmic growth, which describes transport in terms of direct tunneling. Using those criteria, one can distinguish different tunneling mechanisms.

In Fig. 1(a), the tunneling characteristics across a 4 nm thick EuO tunnel barrier at 0.4 K is shown at positive bias. Two distinct voltage regimes are evident from this plot: At low bias, the curve follows a logarithmic growth, with transport being interpreted as direct tunneling. The dotted line denotes the transition voltage V_{tran}, above which a linear behavior appears. In this high bias region, transport is carried by FN tunneling. Fig. 1(b) shows the high bias transport region for a 2 nm thick EuO barrier on a larger scale, with *two* linear decaying slopes joined by a crossover region. This particular shape is attributed to the spin-selective onsets of FN tunneling. Raising the bias above V_{tran} for the lower barrier height ($V \geq \Phi_\uparrow$) leads to a sharp increase of tunnel current ($\Phi_\uparrow \leq V < \Phi_\downarrow$). If the bias exceeds the upper conduction band $\Phi_\downarrow$, FN tunneling for the second spin type sets in and leads to a further significant increase of the tunnel current. The data thus provides direct evidence for spin filtering, as it clearly visualizes the stepwise onset of two FN tunneling regimes.

In general, our findings show that the tunneling spin polarization resulting from the specific transport mechanism in magnetic tunnel barriers is highly bias voltage-dependent. In particular, the highest spin polarization is to be expected for bias voltages, for which FN tunneling is active for one spin type only, whereas transport for the second spin type is by direct tunneling. Moreover, it becomes clear that by choosing the appropriate bias voltage, the spin polarization P provided by spin filter tunneling in principle can be tuned to any value between $0 \leq P \leq 100\%$.

In order to quantify the exchange splitting E_{xc} of EuO spin filter tunnel barriers, a systematic study of the temperature-dependent I-V behavior was performed. In Fig. 2(a), we compile the I-V characteristics of an Al/EuO(4 nm)/Y system over a wide temperature range. The current increases rapidly with bias voltage, and we note a pronounced shift of the I-$V(T)$ curves towards higher bias voltages with increasing temperature. Above 80 K, the temperature-dependent voltage shift disappears. We conclude, that the temperature-dependent shift of the I-V curves is mainly due to a change in barrier height, $\Delta\Phi(T) = \Phi_0 - \Phi_{\uparrow(\downarrow)}(T)$, brought about by the spontaneous conduction band splitting in EuO for $T < T_C$. Within the Weiss molecular field model, the exchange splitting E_{xc} may be approximated as $E_{xc}(T) \propto J_{df} S\sigma(T)$, where J_{df} is the d-f exchange constant, $S = 7/2$ is the spin quantum number of an Eu^{2+} ion and $\sigma(T)$ the reduced magnetization $M(T)/M(T = 0)$ of EuO. Hence, the change of the effective barrier height $\Delta\Phi(T)$ corresponds to half of the exchange splitting as $\Delta\Phi(T) = 1/2\, E_{xc}(T)$. We determined the relative change of the EuO barrier height with the

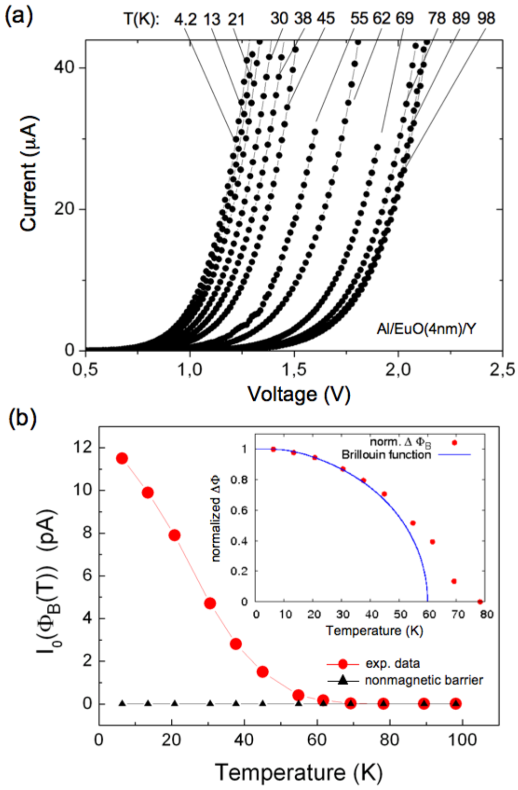

FIG. 2: (a) I-$V(T)$ plot of an Al/EuO(4 nm)/Y spin filter tunnel junction at positive bias. (b) Saturation current $I_0(\Phi_{\uparrow(\downarrow)}(T))$ as a function of T, shown together with the result for a nonmagnetic barrier. The inset shows the normalized change in effective barrier height $\Delta\Phi(T)$ fitted to a Brillouin function with $S = 7/2$.

result shown in the inset of Fig. 2(b). By fitting $\Delta\Phi(T)$ to a Brillouin function ($S = 7/2$), the correlation between the spontaneous magnetization originating from the Eu^{2+} magnetic moment and the lowering in barrier height is visualized. An exchange splitting of $E_{xc} = (0.49 \pm 0.04)$ eV was deduced and the resulting SF efficiency was determined as $P \approx 80\%$.

In summary, we were able to assign characteristic transport mechanisms in Eu-based spin filter tunnel barriers, revealing direct evidence for spin filtering without relying on external magnetic fields for spin detection. Moreover, we determined the exchange splitting E_{xc} by fully electrical means. The deduced spin filter efficiency implies that electron transport through EuO barriers is highly spin selective and thus of great interest for the use as spin polarizers or -detectors in spintronic devices.

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