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Comparision of Magnetocurrent and Transfer Ratio in Magnetic Tunnel Transistors with Spin-Valve Bases Containing Cu and Au Spacer Layers

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Comparison of magnetocurrent and transfer ratio in magnetic tunnel transistors with spin-valve bases containing Cu and Au spacer layers

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Abstract

The magnetocurrent of magnetic tunnel transistors with spin-valve base structures is found to be nearly insensitive to whether the spacer layer material in the spin valve is Cu or Au. By contrast the in-plane magnetoresistance of the same spin valves differs by almost a factor of two. Furthermore, the transfer ratio of the transistor structure is an order of magnitude lower for Au compared to Cu spacer layers. We attribute these different behaviors to the significant role of spin-dependent interface scattering for electrons near the Fermi energy but to much weaker such scattering for hot electrons in the energy range considered (~1-2eV).

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The properties of magnetoelectronic devices such as spin valves and magnetic tunnel junctions (MTJ) are extremely sensitive to the structure and electronic properties of the interfaces within the thin film multilayered structures. For example, spin-dependent electron transmission and reflection at the ferromagnetic (FM)/non-magnetic interfaces of a spin valve drastically influences its magnetoresistance (MR)[1,2]. Similarly, the tunneling MR of an MTJ depends critically on the structure and composition of the interfaces between the FM electrodes and the tunnel barrier[3]. A particularly interesting device is the magnetic tunnel transistor (MTT)[4,5], for which the magnetic field sensitivity can be up to two orders of magnitude larger than that of a spin valve or MTJ. In one configuration of the MTT electrons are injected from a non-magnetic metal emitter across a tunnel barrier into a spin-valve base (see Fig. 1(a)). Some of these electrons traverse the spin-valve sandwich and are subsequently collected in a semiconductor substrate. Due to strong spin filtering in the FM base layers, the collector current depends critically on the orientation of the magnetic moments within the spin-valve. The relative change in the collector current of the MTT, the magnetocurrent (MC), can be compared with the MR of a spin valve or MTJ. The interface between the metal base and the semiconductor substrate as well as the interfaces between the FM and non-magnetic layers within the spin-valve sandwich are critical for the operation of the MTT device. In this letter we directly compare magneto-transport measurements on MTTs with in-plane MR measurements on the spin-valve base structure within the same MTT structure. These measurements reveal that interface scattering strongly influences both the collector current of an MTT and the MR of its spin-valve base.

The MTTs were deposited by magnetron sputtering on GaAs(001) substrates at room temperature. A first metal shadow mask was used to form a rectangularly shaped spin-valve base layer comprised of a 50 Å $Co_{70}Fe_{30}$/40 Å Cu or Au/50 Å $Ni_{81}Fe_{19}$ sandwich. This metal base, 1 x 8 mm^2 in size, was used to measure the in-plane MR of the spin-valve sandwich. A thin Al film (18 Å thick) was deposited on top of the spin-valve base, which was subsequently plasma oxidized to form an Al_2O_3 tunnel barrier. A second shadow mask was used to define a ~200 Å thick Al_2O_3 isolation layer, which insulates the emitter from the base and the GaAs(001) collector. Finally, the emitter (Cu or Au) was deposited through a third metal shadow mask. The transport measurements on the MTTs and the in-plane MR measurements on the spin-valve sandwiches were made using a four-point geometry at 77 K (see Fig. 1(b) and (c)). The collector current of the MTT was measured through a separate metal contact on the GaAs(001) substrate.

Figure 2 shows the magnetic field dependence of the collector current for MTTs with Cu and Au spacer layers, respectively, in the spin-valve base. Giant collector current changes are obtained when the relative orientation of the base magnetic moments of the MTT are varied in a small external field. The collector current is largest when the base magnetic moments are aligned parallel to the magnetic field. When the magnetic field is reversed, the magnetic moment of the NiFe layer switches at about 20 Oe, whereas the orientation of the CoFe moment remains unaltered up to ~120 Oe and 50 Oe for spin valves with a Cu and Au spacer layer, respectively. The switch from parallel to anti-parallel alignment of the base magnetic moments produces a giant MC of more than 1200% at an emitter/base bias voltage of 1.6 V. The MC of an MTT is therefore much larger than the MR of a spin valve or MTJ. Interestingly, the MC values are almost the same for spin-valve base structures with Cu and Au spacer layers.

Another important property of the MTT device is the transfer ratio. The transfer ratio is defined as the ratio of the collector current (I_C) to the tunnel current (I_E). For parallel (P) and anti-parallel (AP) alignment of the base magnetic moments this ratio can be written as:

$$\left(I_C / I_E\right)_{P(AP)} = e^{-t_{NiFe}/\lambda_{NiFe}^{\uparrow(\downarrow)}} T_{NiFe/S}^{\uparrow(\downarrow)} e^{-t_S/\lambda_S} T_{S/CoFe}^{\uparrow} e^{-t_{CoFe}/\lambda_{CoFe}^{\uparrow}} T_{CoFe/GaAs}^{\uparrow} + e^{-t_{NiFe}/\lambda_{NiFe}^{\downarrow(\uparrow)}} T_{NiFe/S}^{\downarrow(\uparrow)} e^{-t_S/\lambda_S} T_{S/CoFe}^{\downarrow} e^{-t_{CoFe}/\lambda_{CoFe}^{\downarrow}} T_{CoFe/GaAs}^{\downarrow},$$

where ↑ and ↓ refer to majority and minority electrons, S is the spacer material, λ is the hot electron attenuation length, t is the layer thickness, and T is the interface transmission coefficient. Fig. 3(a) compares the transfer ratio of otherwise similar MTTs with Cu and Au spacer layers. Contrary to the MC, the transfer ratio depends strongly on the spacer layer material of the spin-valve base. The transfer ratio is about 10 times smaller for Au than for Cu for both parallel and anti-parallel alignment of the base magnetic moments. Since previous measurements of hot electron attenuation lengths in Cu and Au show them both to be much larger than the spacer layer thicknesses in our MTTs[6], the large difference in transfer ratio can be attributed to hot electron scattering at the spacer layer interfaces. The increase of the transfer ratio with increasing emitter/base bias over several orders of magnitude is qualitatively the same for both spacer layer materials. This is mainly due to a rapid increase of the number of conduction band states in the GaAs collector, i.e., an increase of $T_{CoFe/GaAs}$[5,7].

The extent of interface scattering can be extracted by comparing the transfer ratio of MTTs with base layers formed from either a spin-valve or a single FM layer, each with the same total FM layer thickness. As shown in Fig. 3(b), the transfer ratio of an MTT with a 50 Å CoFe/40 Å Cu/50 Å CoFe spin valve is the same as that of an MTT with a single 100 Å thick CoFe base layer at small emitter/base bias. This not only confirms that $\lambda_{\mathrm{Cu}} >> 40$ Å at $V_{EB} = 1$ V, but also shows that the amount of hot electron scattering at the CoFe/Cu interfaces is negligibly small, i.e., the interface transmission coefficient $T_{\mathrm{Cu/CoFe}} \approx 1$. The small difference in MTT transfer ratio between the spin-valve and single layer bases at elevated emitter/base bias may be explained by a reduction of λ_{Cu} with electron energy due to enhanced electron-electron interactions[8]. Similarly, as evidenced by transport data on MTTs with NiFe/Cu/NiFe and NiFe bases (square symbols in Fig. 3(b)), the transmission coefficient of the NiFe/Cu interfaces is also close to 1. By contrast, the hot electron transmission at the interfaces with Au spacer layers is much less efficient. From the measurements of Fig. 3(a) and Fig. 3(b) it follows that $T_{NiFe/Au}T_{Au/CoFe} \approx 0.1$ over the entire energy range. The large difference in transfer ratio between CoFe and NiFe base layers is due to strong hot electron scattering at the NiFe/GaAs interface, i.e., $T_{NiFe/GaAs} << T_{CoFe/GaAs}$.

For the MTT device it is reasonable to assume that most of the hot electrons traverse the spin-valve base in high velocity *s-p* states. For majority electrons this seems reasonable since the majority *d*-band is completely filled. On the other hand, the minority *d* band in CoFe and NiFe crosses the Fermi level, but band structure calculations indicate that the upper edge of this band is located in the lower part of the energy range in which we conducted the MTT transport measurements[9]. The structure of the *s-p* band is similar for both spin states and the hot electrons in this band can be treated as free electrons. In the free electron approximation, the interface transmission coefficients are calculated by projecting free-electron Fermi surfaces onto the interface Brillouin zone. Electrons with parallel wave vector less than the Fermi wave vectors of the materials on either side of the interface are readily transmitted. Thus, since hot electron transport is largely perpendicular to the spin-valve layers in an MTT, transmission coefficients would be expected to be large for both majority and minority electrons, and irrespective of whether the spacer layer material is Cu or Au. The similar MC values that are obtained for spin-valve bases with either Cu or Au spacer layers is consistent with this simple picture: hot electron scattering at the spacer interfaces does not depend on the spin state of the electrons and consequently the MC is solely the result of spin filtering in the CoFe and NiFe layers. It does not, however, explain the difference in transfer ratio for MTTs with Cu and Au spacer layer. We attribute this difference to strong spin-independent scattering of hot electrons at the NiFe/Au and Au/CoFe interfaces, which might originate from defects associated with the much larger lattice mismatch for Au as compared to Cu.

Figure 4 shows in-plane MR measurements on spin-valve sandwiches with Cu and Au spacer layers. The in-plane MR effect is two times larger for Cu than for Au. The significantly larger MR effect in spin valves with a Cu spacer layer is in agreement with the superior MR values that have been found in Co/Cu multilayers[10]. To account for the similar MC of an MTT for Cu and Au spacer layers, yet very different in-plane MR values of the corresponding spin-valve bases, note that the transport of electrons takes place at the Fermi energy in the MR measurements. At this energy, the majority and minority states have a strikingly different character for both the CoFe and NiFe layers. Majority electrons are still largely transported in high velocity *s-p* bands, whereas minority electrons have mainly *d* character. This difference results in strong band structure effects and spin-dependent interface transmission and reflection coefficients[2]. The band structure differences between Cu and Au, in combination with the larger number of defects at the interfaces of the Au spacer layer, lead to the significant difference in the in-plane MR values.

In summary, we have identified the importance of interface scattering in MTTs and spin valves. The MC of an MTT, which originates from hot electron transport perpendicular to a spin-valve base structure, is similar for Cu and Au spacer layers. In this device most of the electrons traverse the spin-valve base in the high velocity *s-p* bands, which leads to a negligible spin-dependence of the spacer layer interface transmission coefficient. The spacer material, and in particular the number of defects at its interface, only influences the transfer ratio of the MTT device. The transfer ratio is found to be about 10 times larger for Cu than for Au. Contrary to this, the in-plane MR of the same spin-valve sandwich strongly depends on the spacer material. This dependence is mainly due to the different character of the majority and minority states at the Fermi level, leading to spin-dependent interface transmission coefficients.

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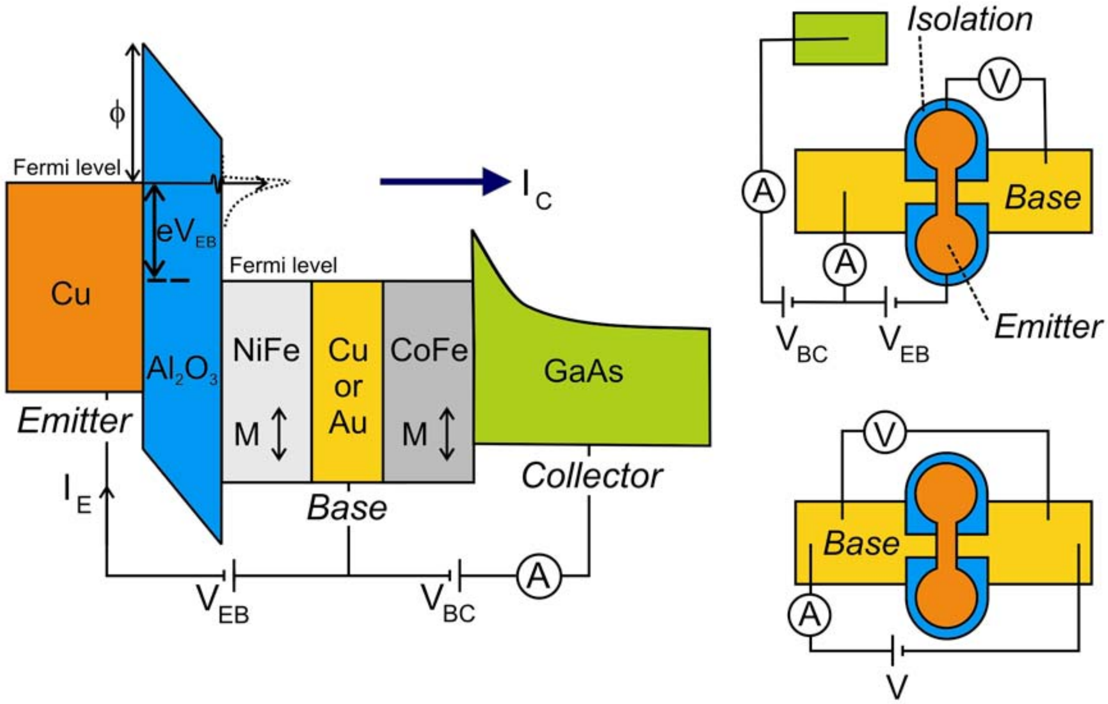

Fig. 1. (a) Schematic energy diagram of the MTT device showing a Cu emitter separated from the spin-valve base layer by an Al2O3 tunneling barrier. The spin valve is comprised of ferromagnetic CoFe and NiFe layers separated by Au or Cu spacer layers. The energy of the injected hot electrons is varied by varying the emitter-base bias voltage. The Schottky barrier formed at the interface between the spin-valve base layer and the GaAs collector is slightly reverse biased in these experiments. (b) Experimental setup for the MTT measurements and (c) the in-plane MR measurements of the spin-valve base.

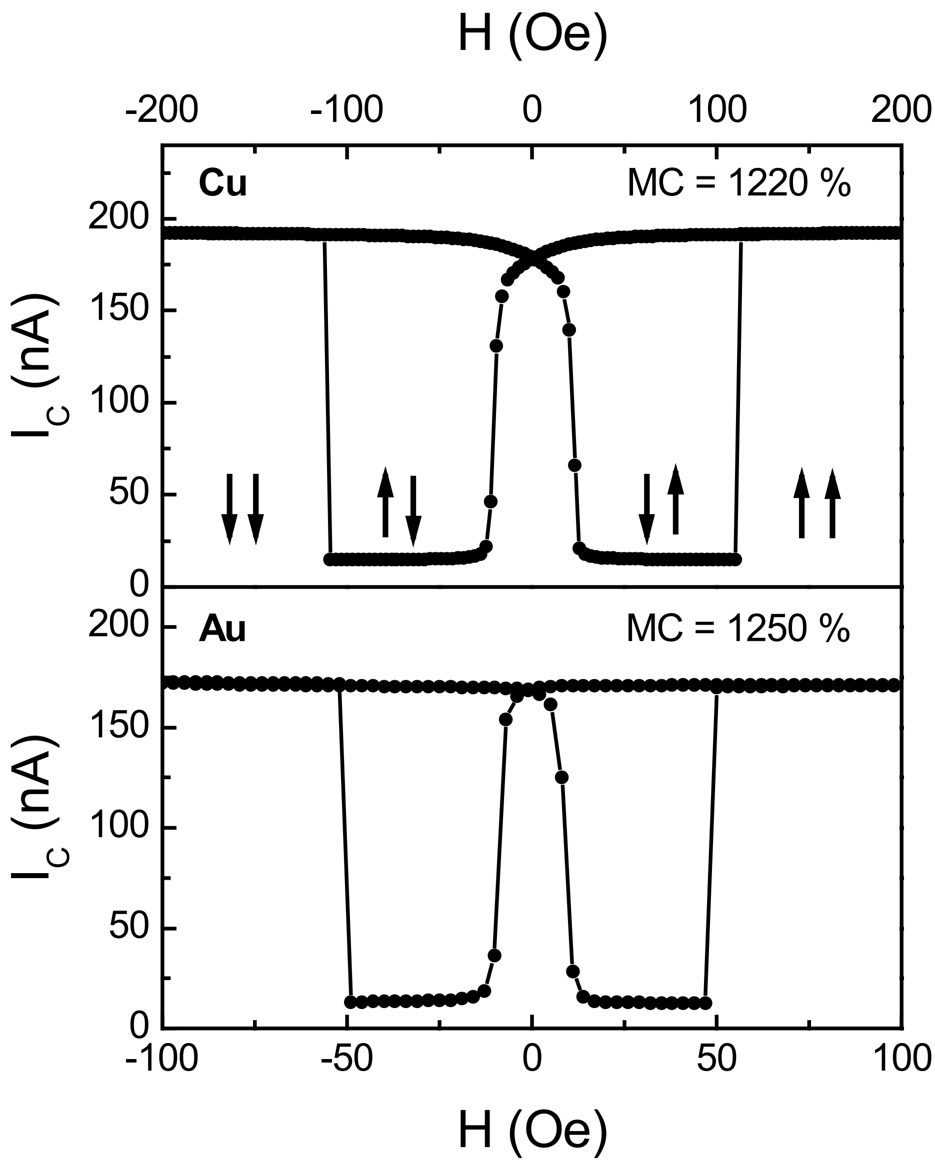

Fig. 2. Magnetic field dependence of the collector current at V_{EB} = 1.6 V for an MTT with a 50 Å CoFe/40 Å Cu/50 Å NiFe (upper panel) and a 50 Å CoFe/40 Å Au/50 Å NiFe (lower panel) spin-valve base. A giant MC of more than 1200% is measured for both MTTs.

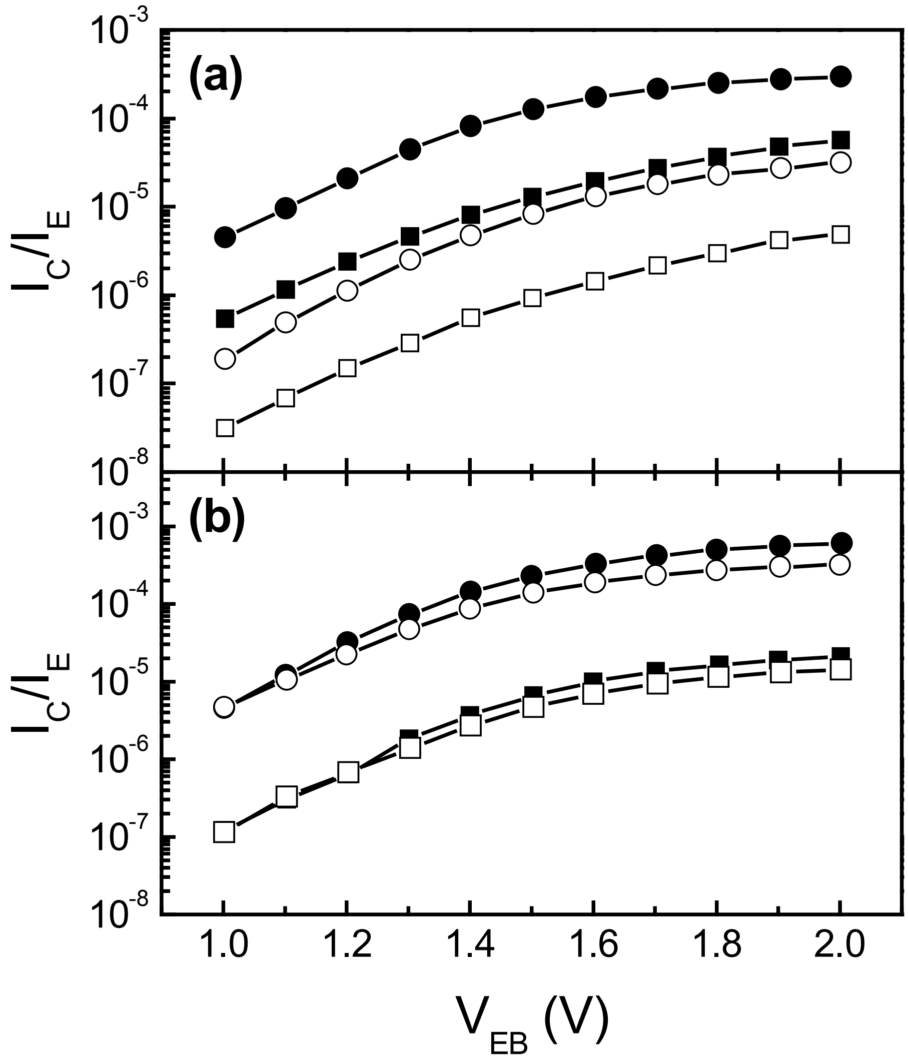

Fig. 3. (a) Emitter/base bias dependence of the transfer ratio for an MTT with a 50 Å CoFe/40 Å Cu/50 Å NiFe (circles) and 50 Å CoFe/40 Å Au/50 Å NiFe (squares) spin-valve base for parallel (solid symbols) and anti-parallel (open symbols) alignment of the base magnetic moments. (b) Comparison of the transfer ratio for a spin-valve and a single layer base with the same total FM layer thickness. The circles represent data for CoFe bases: 50 Å CoFe/40 Å Cu/50 Å CoFe (open circles) and 100 Å CoFe (solid circles). The squares represent data for NiFe bases: 50 Å NiFe/40 Å Cu/40 Å NiFe (open circles) and 100 Å NiFe (solid circles).

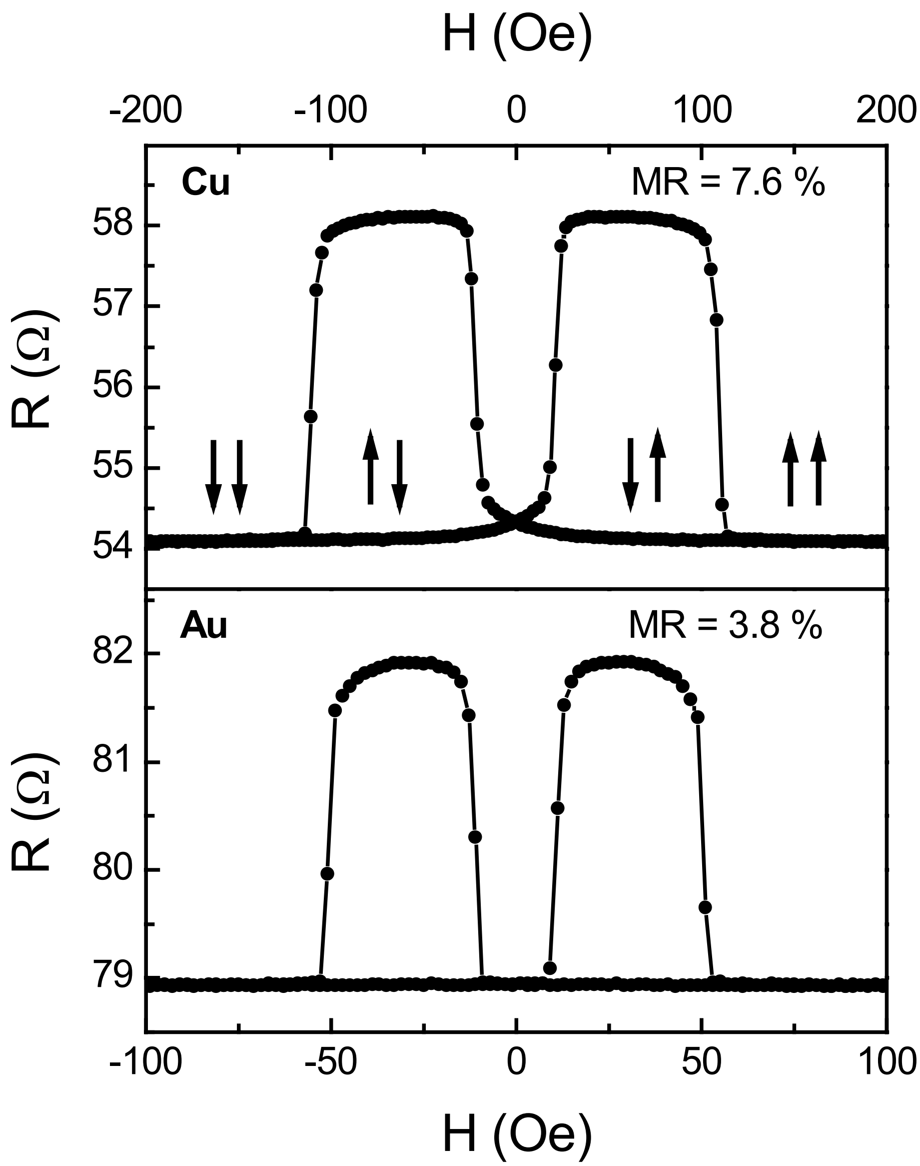

Fig. 4. In-plane MR measurements on a 50 Å CoFe/40 Å Cu/50 Å NiFe (upper panel) and a 50 Å CoFe/40 Å Au/50 Å NiFe (lower panel) spin-valve structure. The MR is significantly larger for the spin-valve with a Cu spacer layer.