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Spin-valve effect in soft ferromagnetic sandwiches

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We demonstrate in a variety of systems that the in-plane resistivity of sandwiches of *soft* ferromagnetic layers separated by nonmagnetic metallic layers depends on the relative angle between their magnetizations. We observe this phenomenon, which we term the spin-valve effect, in sandwiches where we are able to control the relative angle between the magnetizations of two ferromagnetic layers either by constraining one layer through exchange anisotropy or by fabricating layers with different coercivities. In the first case, for example Si/50 Å Ta/60 Å NiFe/25 Å Cu/40 Å NiFe/50 Å FeMn/50 Å Ta we have seen relative changes in resistance of more than 4% at room temperature in a range of in-plane field of 0 to 15 Oe. In a system where the layers have different coercivities, Si/8 × (30 Å Fe/60 Å Ag/30 Å Co/60 Å Ag), we observed a relative change of 1.6% at room temperature for fields between 0 and 50 Oe. Since the ferromagnetic layers are essentially decoupled and have high squareness, one can rule out any mechanism requiring scattering by domain walls. The usual anisotropic magnetoresistance in these structures is much smaller than the spin-valve effect. In contrast to noble metals, when using Ta, Al, Cr or Pd spacers of similar thickness (20 to 150 Å) between layers of permalloy, only the anisotropic magnetoresistance is observed. We believe the spin-valve effect to be related to spin-dependent scattering at the interface and within the ferromagnetic layers, in balance with spin-dependent relaxation within the layers. We also report the observation of a weak exchange-like coupling between the ferromagnetic layers.

The magnetotransport properties of thin films and multilayers have attracted considerable attention in the past three years, particularly following the discovery of giant magnetoresistive (MR) effects in Fe/Cr multilayers [1, 2]. However the studies in this area have focused on systems exhibiting a strong antiferromagnetic coupling, such as in $(\mathrm{Fe/Cr})_n$ [1-6] or $(\mathrm{Co/Ru})_n$ [3], where measurement of resistivity for parallel and antiparallel alignment is straightforward. In this paper, we describe new results observed in sandwiches consisting of two ferromagnetic layers separated by a metallic nonmagnetic interlayer, which do not possess a strong exchange-like coupling through the intermediate interlayer. In the present structures antiparallel alignment between the magnetizations of the ferromagnetic layers does not rise naturally from the existence of antiferromagnetic coupling. Consequently, to be able to vary the angle between the two magnetizations, we either constrain the magnetization of one layer by exchange anisotropy while that of the other layer is free (e.g., $\mathrm{Ni_{81}Fe_{19}/Fe_{50}Mn_{50}}$ with NiFe), or we use two ferromagnets with different coercivities (Fe with Co or Fe deposited in 50 Oe with Fe deposited in 400 Oe, or NiFe with $\mathrm{Ni_{80}Co_{20}}$). Typically, fields between 0 and 50 Oe are sufficient to change the relative orientation of the magnetizations of the two layers from parallel to antiparallel alignment. We show that associated with the change in relative orientation there can be very large changes in resistivity when the interlayer is an ultrathin layer of noble metal (Cu, Ag, Au). We term this the spin-valve effect.

The samples were prepared on Si substrates at ambient temperature, in a computer-controlled dc magnetron sputtering system with a base pressure of 10^{-7} Torr. An argon plasma was used with deposition rates ranging from 0.5 to 2 Å/s.

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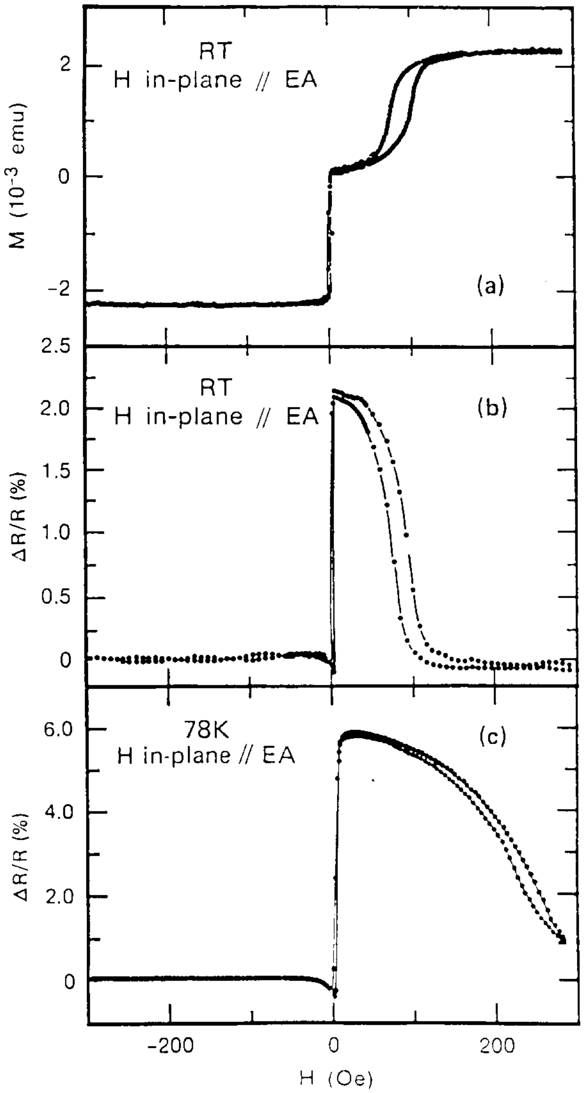

Fig. 1. Hysteresis loop at room temperature (a); magnetoresistance at room temperature (b) and at 78 K (c) for a sample with structure Si/150 Å NiFe/26 Å Cu/150 Å NiFe/100 Å FeMn/20 Å Ag. The field is applied along the easy axis, antiparallel to the exchange field created by FeMn.

Resistance was measured using standard four-point geometries with the net current flowing in the plane of the structure.

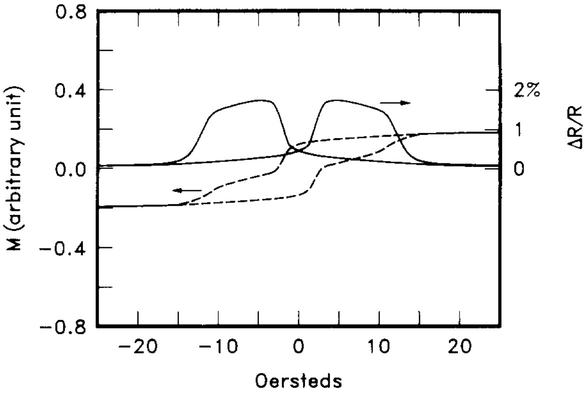

Fig. 2. Hysteresis loop and magnetoresistance at room temperature of a sample with structure Si/100 Å Ta/40 Å NiFe/60 Å Cu/40 Å NiCo/50 Å Ta.

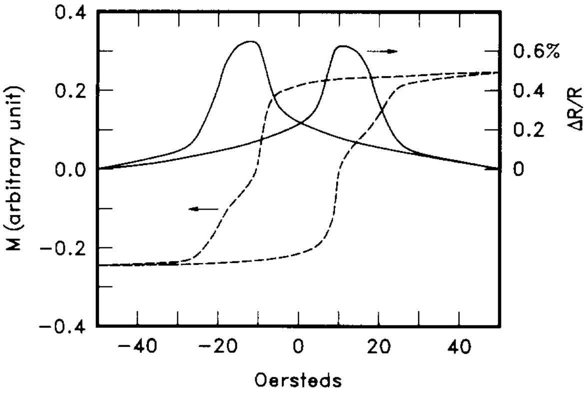

Fig. 3. Hysteresis loop and magnetoresistance at room temperature of a sample with structure Si/30 Å Fe/62 Å Ag/30 Å Co/62 Å Ag.

Fig. 1a and b shows the magnetization curve and the change of resistance relative to parallel alignment, measured at room temperature (RT) for a sample with the following structure: Si/150 Å NiFe/26 Å Cu/150 Å NiFe/100 Å FeMn/20 Å Ag. The reversals of the magnetizations of the two Permalloy layers occur successively near 2 and 90 Oe. Between these values a sharp rise in resistance is observed. At RT this change is 2% while at 78 K it is 6%, see fig. 1c. A 4.1% change in resistance at RT for field swept from 0 to 15 Oe was obtained for Si/50 Å Ta/60 Å NiFe/25 Å Cu/40 Å NiFe/50 Å FeMn/50 Å Cu.

We have also observed the spin-valve effect in samples consisting of ferromagnetic layers with different coercivities. Figs. 2 and 3, respectively, show the magnetization curves and resistivity variations for samples with structures: Si/100 Å Ta/40 Å NiFe/60 Å Cu/40 Å NiCo/50 Å Ta and

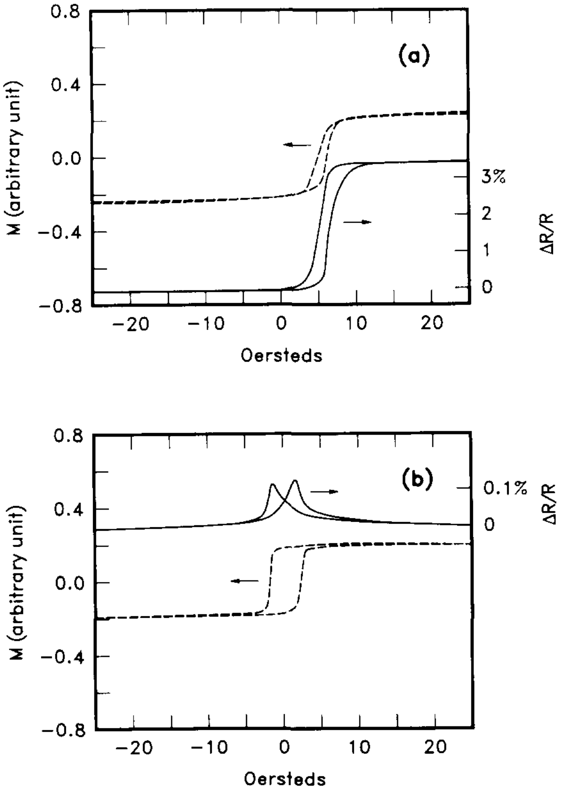

Fig. 4. Hysteresis loops and magnetoresistance curves of two samples with structures: Si/50 Å Ta/66 Å NiFe/25 Å X/44 Å NiFe/50 Å FeMn/50 Å Ta with (a) X = Cu and (b) X = Ta.

Si/30 Å Fe/62 Å Ag/30 Å Co/62 Å Ag. In the first structure NiFe has a lower coercivity than NiCo, while in the second Fe has a lower coercivity than Co. In both cases, an increase in resistance is observed when the magnetizations of the two ferromagnetic layers are antiparallel. Similar results, but requiring much higher fields applied perpendicular to the film plane, were reported recently for Co/Au/Co sandwiches [7].

Fig. 4 shows the magnetoresistance and magnetization curves of samples which differ only in the nonmagnetic interlayer used. The structures are Si/50 Å Ta/66 Å NiFe/25 Å X/44 Å NiFe/50 Å FeMn/50 Å Ta, with X = Cu or Ta. In both cases the exchange anisotropy field produced by FeMn shifts the hysteresis loop of the constrained layer to around 150 Oe so that in the range of field −25 to +25 Oe only the reversal of the bottom Permalloy layer is observed. We draw attention to two important points: 1) for the structure with Cu interlayer the antiparallel alignment of the magnetizations leads to a large increase in resistance (3.5% at room temperature) while for Ta no change is observed except for two small peaks which we ascribe to the usual anisotropic magnetoresistance of Permalloy; 2) for the sample with Cu interlayer the hysteresis loop of the bottom permalloy layer is shifted by 5.7 Oe from the origin while no shift is seen for the sample with Ta. This indicates that a ferromagnetic coupling exists in the former case but not in the latter. This difference could be attributed to some microstructural difference in the NiFe layers grown on the different interlayers which may have induced different magnetostatic coupling. However, we have observed this phenomenon systematically: each time the spin-valve effect was seen (with Cu, Ag, Au, Pt), a shift also occurred. In contrast, for Ta, Al and Cr layers of similar thicknesses, which did not produce a measurable spin-valve effect, no shift was observed. The exact meaning of this correspondence is not clear at the moment. Nevertheless it suggests that both the magnetoresistance and the interlayer coupling depend on a continuous exchange of polarized electrons between the ferromagnetic layers.

We believe that the mechanism of magnetoresistance in the spin-valve effect is closely related to the giant MR effect previously observed in coupled systems such as Fe/Cr or Co/Ru multilayers. For these strongly coupled systems a two-current model with interfacial spin-dependent impurity scattering has been developed by several authors [2, 4–6]. However, the results shown here lead us to emphasize the role of bulk versus interfacial scattering. In $Ni_{81}Fe_{19}$, it is known [9] that the scattering of spin down electrons on Fe impurities in the host of Ni has a much higher cross-section than the scattering of spin up electrons ($\alpha = \rho\downarrow/\rho\uparrow = 20$). As a result, in the sandwich structure, when the magnetizations of the two layers are parallel the current is mostly carried by the up electrons which have long mean free path everywhere in the structure. This short circuit by the up electrons leads to the state of low resistance. On the contrary, for antiparallel alignment of the magnetizations, both species of electrons are strongly scattered in the bulk of either one or the other ferromagnetic layer. The resistance is then increased compared to the previous case. In addition to this basic mechanism for the magnetoresistance which has been first described for Fe/Cr multilayers with the assumption of interfacial spin-dependent scattering, we propose another mechanism: due to the strong spin-dependent scattering of conduction electrons in $Ni_{81}Fe_{19}$, mostly electrons of the majority band tend to escape from each ferromagnetic layer. This generates a flow of emitted electrons with a net polarization determined by the orientation of the magnetization of the source layer. In the systems using Permalloy, the flow of emitted electrons seems to be very well transmitted through noble metals (especially Cu) from one ferromagnetic layer to the other. On the contrary, the present results show that for Al, Ta, Cr and Pd the flow is either suppressed or electrons are depolarized or both. For noble metal interlayers, by symmetry, each ferromagnetic layer receives a flow of polarized electrons coming from the adjacent ferromagnetic layer with a polarization determined by the direction of the magnetization of the source layer. Consequently, for parallel alignment a dynamic balance is trivially maintained between incoming and outgoing electrons. In contrast, for antiparallel alignment and nonzero net current, an increasing imbalance would develop between incoming and outgoing flows of opposite polarization, were it not for an additional spin-flip mechanism within each ferromagnetic layer [8].

In summary, we have fabricated sandwich structures consisting of two ferromagnetic layers separated by a conducting nonmagnetic interlayer. We are able to change the magnetizations of the two layers from parallel to antiparallel alignment and observe a change in resistivity; we term this the spin-valve effect. The effect is present when Cu, Ag, Au and Pt are used as interlayers, but is not observed for Al, Ta, Cr or Pd interlayers. We have pointed out that for nonzero current an additional spin-flip mechanism is required to maintain spin balance between incoming and outgoing electrons within each ferromagnetic layer. This mechanism together with bulk spin-dependent scattering are at the origin of the increase of resistance for antiparallel alignment.

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References

[1] G. Binasch, P. Grünberg, F. Saurenbach and W. Zinn, Phys. Rev. B 39 (1989) 4828.

[2] M. N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich and J. Chazelas, Phys. Rev. Lett. 61 (1988) 2472. A. Barthelemy, A. Fert, M.N. Baibich, S. Hadjoudj, F. Petroff, P. Etienne, R. Cabanel, S. Lequien, F. Nguyen Van Dau and G. Creuzet, MMM Conf., paper HO-1, Boston (1989).

[3] S.S.P. Parkin, N. More and K.P. Roche, Phys. Rev. Lett. 64 (1990) 2304.

[4] R.E. Camley and J. Barnas, Phys. Rev. Lett. 63 (1989) 664.

[5] P.M. Levy, K. Ounadjela, C. B. Sommers, A. Fert and S. Zhang, MMM Conf., paper HA-02, Boston (1989).

[6] B.A. Gurney, D.R. Wilhoit, V.S. Speriosu and I.L. Sanders, IEEE Trans. on Magn. MAG-26 (1990) in press.

[7] C. Dupas, P. Beauvillain, C. Chappert, J.P. Renard, F. Triqui, P. Veillet, E. Velu and D. Renard, MMM Conf., paper FP-23, Boston, (1989).

[8] B. Dieny, V. S. Speriosu, S.S.P. Parkin, B.A. Gurney, D.R. Wilhoit and D. Mauri, Phys. Rev. B (to be published).

[9] O. Jaoul, I.A. Campbell and A. Fert, J. Magn. Magn. Mat. 5 (1977) 23.