Inverse magnetoresistance in the simple spin-valve system $Fe_{1-x}V_x/Au/Co$

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(Received 2 December 1994)

Magnetoresistance (MR) measurements have been performed on Fe/Au/Co and $Fe_{1-x}V_x/Au/Co$ trilayers with perpendicular orientation of the magnetization of the thin ferromagnetic layers. While the MR is larger for an antiparallel arrangement of the magnetizations than for a parallel one in Fe/Au/Co (the usual spin-valve-type MR), an inverse spin-valve effect is observed in $Fe_{1-x}V_x/Au/Co$. This inverse MR is attributed to an increase of the density of states at the Fermi level for majority-spin electrons when Fe is alloyed with V.

Giant magnetoresistance (GMR) (Refs. 1–3) has been widely studied in a large number of magnetic multilayers. It is now well established that GRM is due to spin-dependent scattering of the conduction electrons in the bulk or at the interface of the ferromagnetic (F) layers.[4,5] More precisely, the scattering probability D for a conduction electron crossing a ferromagnetic layer depends on its spin orientation with respect to that of the majority band so that $D\uparrow \neq D\downarrow$, where $D\uparrow$ ($D\downarrow$) refers to electrons with spin parallel (antiparallel) to majority-spin band. The spin asymmetry of scattering is usually defined by $\alpha = D\downarrow/D\uparrow$.[6]

In a sandwich system with ferromagnetic layers F_1 and F_2, the magnetoresistance ratio $\Delta R/R$ is given in first approximation by

$$\Delta R/R = (R_{AP} - R_P)/R_P \propto (D_1\downarrow - D_1\uparrow)(D_2\downarrow - D_2\uparrow) , \tag{1}$$

where R_{AP} and R_P are the resistances of an antiparallel and parallel arrangement of the magnetization directions of F_1 and F_2, respectively. For equivalent ferromagnetic layers, the resistance is larger for an antiparallel arrangement than for a parallel one ($\Delta R/R > 0$), which is the normal GMR, independently of whether $\alpha > 1$ or $\alpha < 1$. On the other hand, if F_1 and F_2 are different such that $\alpha_1 > 1$ ($D_1\downarrow > D_1\uparrow$) and $\alpha_2 < 1$ ($D_2\downarrow < D_2\uparrow$), one would expect an *inverse* GMR ($\Delta R/R < 0$).

This simple basic idea has been checked by George *et al.*[7] on a Cu-based multilayer in with F_1 is a Fe film and F_2 a 4-Å-thick Cr film intercalated between two thicker Fe films. This structure exhibits the expected inverse MR at low field but also a normal MR, i.e, $dR/dH < 0$ at high field. This relatively complex behavior attributed to the misalignment of the magnetizations of the two Fe layers separated by Cr in F_2 "makes the inverse MR effect less clear than might have been expected."[7]

In order to provide an unambiguous check of the above picture, we have considered the $Co/Au/Fe_{(1-x)}V_x$ system. This system was chosen for the following reasons. The scattering rate $D\uparrow$ is expected to be proportional to the density of states at the Fermi energy $n\uparrow(E_F)$ [likewise $D\downarrow \propto n\downarrow(E_F)$]. For Co, which is a strong ferromagnet, one has $n\uparrow(E_F) < n\downarrow(E_F)$, i.e., $\alpha(\text{Co}) > 1$. On the other hand, due to its bcc structure, Fe exhibits a pronounced valley in the density of states with $n\uparrow(E_F) > n\downarrow(E_F)$ because the Fermi level lies in the bottom of this valley for the minority spins. The position of the Fermi level for the majority spins, near the upper edge of the $3d$ band, is, however, such that the spin asymmetry is rather weak, as seen in Fig. 1. The asymmetry can be considerably enhanced by alloying the Fe with a $3d$ metal of lower valence such as V, as sketched in Fig. 1. Fe and V form solid solutions with a bcc structure over the whole concentration range $0 < x < 1$.[8] The $Fe_{(1-x)}V_x$ alloy is ferromagnetic up to $x = 50\%$ (Ref. 9) and follows nicely a rigid band behavior, as can be seen from the Slater-Pauling curve.[10] The latter means that upon alloying with V, the majority-spin $3d$ band moves

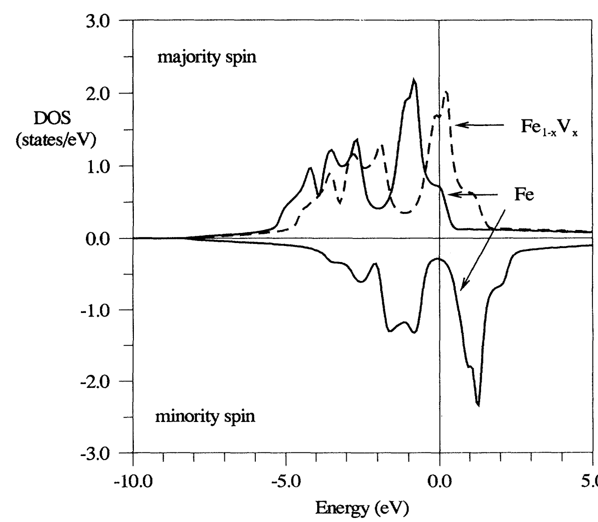

FIG. 1. Density of states of Fe (solid line). Upper panel, majority spin; lower panel, minority spin. The zero of energy is taken at the Fermi level. Broken line: sketch of the majority spin density of states for a $Fe_{(1-x)}V_x$ alloy, with $x \approx 30\%$.

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towards higher energy whereas the minority-spin 3*d* band remains essentially unchanged, as sketched in Fig. 1. The maximum asymmetry, and hence maximum inverse MR, is expected for a valence reduction of about one electron, i.e., for a V concentration around 30 at. %.

To perform comparative MR studies, three different samples, Au(5)/Fe(0.5)/Au(*t*)/Co(0.6)/Au(28), Au(5)/$Fe_{0.82}V_{0.18}$(0.8)/Au(t)/Co(0.6)/Au(28), and Au(6)/$Fe_{0.7}V_{0.3(t)}$/Au(2.35)/Co(0.6)/Au(28), in which the layer thicknesses are given in nm, have been prepared by evaporation in ultrahigh vacuum on glass substrates. The Au interlayer of the first two samples and the FeV layer in the third one have a stepped wedge shape with ten different thicknesses, *t*, ranging from 2 to 11 atomic monolayers (AL). All samples were grown on an atomically flat Au(111) buffer layer. Detailed studies of the growth and crystalline structure of similar samples have been published elsewhere.[11,12] The FeV alloy was prepared by evaporating simultaneously Fe from an alumina crucible and V using an electron gun. Precise determination of the alloy concentration was obtained by measuring separately the Fe and V deposition rates with a quartz microbalance, immediately before and after deposition of the alloy layer. Both measurements gave the same value to within a few percent, which gives confidence that the alloy concentration is constant within the layer. For the present experiments, a crucial point is that both ferromagnetic layers have their easy magnetization axis perpendicular to the film plane. In addition, the coercive field of the Co layer, H_1, is much larger than the coercive field of the Fe or FeV layer, H_2, and thus a perfect antiparallel alignment of the magnetization directions of the two F films can be achieved over a wide field range, $H_1 > H > H_2$. Moreover, this allows an easy determination of the interlayer coupling from the shift of the minor hysteresis loop as previously reported.[13]

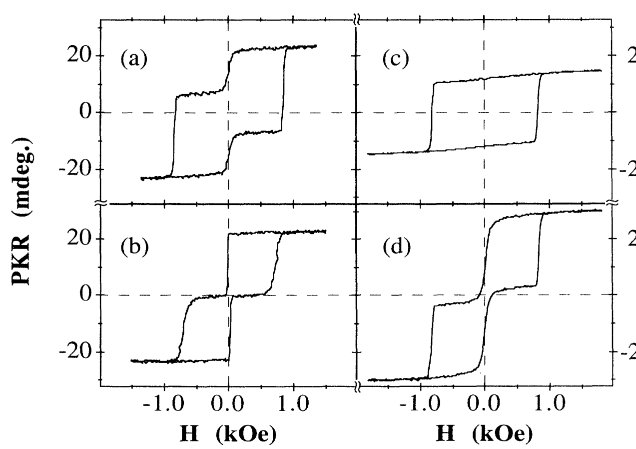

FIG. 2. Hysteresis loops of Fe/Au/Co and $Fe_{1-x}V_x$/Au/Co trilayers measured at room temperature by polar Kerr rotation on films with an Au interlayer thickness $t = 2.35$ nm (10 AL) and Co thickness $t = 0.6$ nm (3 AL). (a) Fe(0.5 nm); (b) $Fe_{0.82}V_{0.18}$(0.8 nm); (c) $Fe_{0.7}V_{0.3}$(0.8 nm); (d) $Fe_{0.7}V_{0.3}$(2 nm). The higher coercive field is the one of the Co layer. Notice the squareness of the FeV layer magnetization in (b) and (d). In (c), the FeV layer is still paramagnetic ($T_c < 300$ K).

Hysteresis curves for Fe/Au/Co, $Fe_{0.82}V_{0.18}$/Au/Co, and $Fe_{0.7}V_{0.3}$/Au/Co trilayers with an Au interlayer thickness of 10 AL, measured by polar Kerr rotation at room temperature, are shown in Fig. 2. One may notice the rather rectangular shape of the magnetization curve of the FeV layer, Figs. 2(b) and 2(d), compared to that of the pure Fe layer, Fig. 2(a). The FeV layer in Fig. 2(c) is paramagnetic at 300 K. Clearly, alloying Fe with V leads to a considerable increase in the crossover thickness t^* at which the easy axis changes it orientation from perpendicular to parallel to the film plane. For Fe(110) sandwiched by Au(111), $t^* \approx 3$ AL at low temperature[14] while $t^* \approx 6$ AL for $Fe_{0.82}V_{0.18}$ and $t^* > 11$ AL for $Fe_{0.7}V_{0.3}$.[15] The MR curves of the same trilayers under perpendicular magnetic field are shown in Fig. 3. The MR curves have the plateau shape usual for two F films with rectangular magnetization loops and different coercivities.[16,17] While the GMR of Fe/Au/Co, Fig. 3(a), is normal (i.e., the largest resistance corresponds to the antiparallel arrangement of the magnetization directions), the GMR of $Fe_{1-x}V_x$/Au/Co is inverse, Figs. 3(b), 3(c), and 3(d). This effect cannot be an anisotropic magnetoresistance effect since the magnetization of the F layers remain perpendicular to the film plane, only the mutual direction of the magnetizations changes. This is the ideal situation for isolating the spin-value effect. Although very clear, the observed inverse GMR is small. At low temperature, in similar Au/M/Au/Co/Au structures, the maximum value of the GMR, $\Delta R/R$, is about 8% for M=Co, 3% for M=Fe, -0.2% for $M = Fe_{0.82}V_{0.18}$, and -0.7% for $Fe_{0.7}V_{0.3}$. One may point out that the strong reduction of GMR from Co to Fe reflects a decrease in $(D\downarrow - D\uparrow)$ that we attribute crudely to the fact that $n\uparrow(E_F)$ and $n\downarrow(E_F)$ become closer together. Such a MR reduction has also been observed from Co/Cu to Fe/Cu multilayers.[18] In $Fe_{1-x}V_x$, $(D\downarrow - D\uparrow)$ becomes negative and its magnitude increases with the vanadium concentration x.

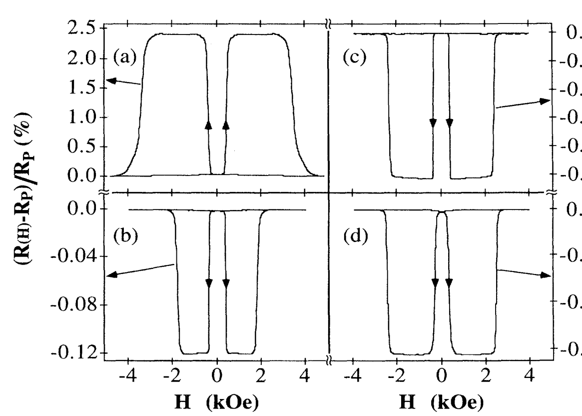

FIG. 3. Magnetoresistance curves of Fe/Au/Co and $Fe_{1-x}V_x$/Au/Co trilayers with $t_{Au} = 10$ AL and $t_{Co} = 3$ AL measured at $T = 60$ K. (a) Fe(0.5 nm); (b) $Fe_{0.82}V_{0.18}$)(0.8 nm); (c) $Fe_{0.7}V_{0.3}$(0.8 nm); (d) $Fe_{0.7}V_{0.3}$(2 nm).

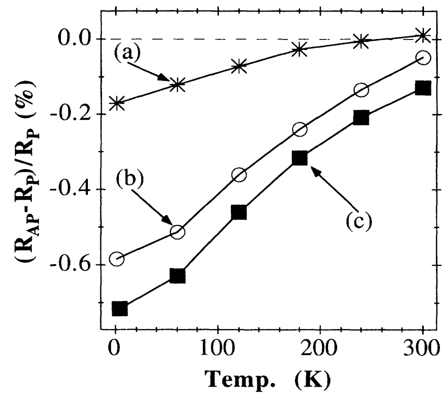

FIG. 4. Magnetoresistance of $Fe_{1-x}V_x$/Au/Co trilayers with $t_{Au}=10$ AL and $t_{Co}=3$ AL versus temperature. (a) $Fe_{0.82}V_{0.18}$(0.8 nm); (b) $Fe_{0.7}V_{0.3}$(0.8 nm); (c) $Fe_{0.7}V_{0.3}$(2 nm).

In order to confirm that the inverse MR is due to a difference in sign of ($D\downarrow$-$D\uparrow$) for FeV with respect to Co, we have prepared a sample with two identical F layers, Au(5)/$Fe_{0.82}V_{0.18}$(0.8)/Au(t)/$Fe_{0.82}V_{0.18}$(0.8)/Au(25). Its MR is barely measurable, except for Au thicknesses corresponding to the first peak, $t=5$ AL, and to the second peak, $t=10$ and 11 AL, of AF coupling.[19] A normal (i.e., always positive) MR is observed in agreement with Eq. (1), $\Delta R/R=+0.024$ and $+0.016\%$ for $t=5$ and 10 AL, respectively, at 1.4 K.

The temperature dependence of the inverse GMR for a few samples is shown in Fig. 4. $\Delta R/R$ decreases in magnitude as the temperature increases, but remains negative up to room temperature in the films with $x=30\%$. In the films with $x=18\%$, $\Delta R/R$ goes through zero near 240 K, and takes negligibly small positive values at room temperature. This high-temperature sensitivity is certainly due to the fact that ($D\downarrow$-$D\uparrow$) is very close to zero and thus sensitive to minor changes in the Fermi level position. Furthermore, spin-flip scattering processes are probably non-negligible at room temperature. The very small MR values measured in the films with two identical $Fe_{0.82}V_{0.18}$ layers, about 0.02% at low T, confirms the very small value of ($D\downarrow$-$D\uparrow$) for these layers. The small magnitude of ($D\downarrow$-$D\uparrow$) and the fact that it is positive for a pure Fe layer are not expected from Fig. 1. We attribute this to the fact that the density of states of ultrathin films of Fe on Au or Ag is different from the bulk one. In particular, the majority-spin band is much narrowed and thus nearly full, hence $n\uparrow(E_F)$ is much smaller than its bulk value.[20] Even for thicker layers, the same band narrowing effect would happen at the interfaces and would strongly affect the MR if the MR is mainly due to interfacial scattering. MR experiments on similar FeV/Au/Co films with different V concentrations and thicknesses are in progress to determine more precisely the importance of interfacial and bulk scatterings.

In summary, we have presented a simple idea based on the tailoring of the density of states to achieve inverse magnetoresistance in multilayers involving homogeneous ferromagnetic layers. The validity of this idea has been demonstrated in a simple sandwich film consisting of two ferromagnetic layers, Co and FeV alloy embedded in Au(111). Such experiments are of large current interest for understanding the microscopic origin of GMR and testing the existing theories.[21,22]

The authors wish to thank N. Bardou and A. Bounouh for their help in magneto-optical experiments. One of us (M. M.) is funded by a European Community HCM program in the frame of the network "EuroGMR." Institut d'Electronique Fondamentale is Unité de Recherche Associée au Centre National de la Recherche Scientifique (URA 22).

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