Towards a Unified Picture of Spin Dependent Transport in and Perpendicular Giant Magnetoresistance and Bulk Alloys

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From data on $(\mathrm{Fe}_{1-x}\mathrm{V}_x/\mathrm{Cu}/\mathrm{Co}/\mathrm{Cu})_N$ multilayers, we show that Fe doped with V gains a negative spin asymmetry for bulk scattering ($\beta < 0$), which, combined with the positive asymmetry of Co, accounts for the inverse current perpendicular to the plane (CPP) giant magnetoresistance (GMR) we observe. More precisely, the competition between positive and negative asymmetries for interface and bulk scatterings in FeV leads to inverse (normal) GMR for layers thicker (thinner) than a compensation thickness. The negative β of FeV is consistent with theoretical predictions and bulk alloy data. The current in the plane (CIP) GMR is not reversed, which illustrates the role of channeling in CIP. [S0031-9007(97)02803-2]

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The giant magnetoresistance (GMR) of magnetic multilayer—a drop of resistance when a magnetic field aligns the magnetizations of consecutive layers [1,2]—is attributed to spin dependent scattering but several questions are still subject to debate: (a) What are the respective contributions from scattering at the interface and within the layers (bulk scattering)? (b) Can the spin asymmetry be tailored by doping the magnetic layers or by other means, and can spin asymmetries of opposite sign be obtained? (c) What is the relation between measurements in CIP (current in the plane) and CPP (current perpendicular to the plane) geometries?

It is already known that CPP-GMR measurements can give *quantitative* answers to (a) [3,4]. Armed with this technique, we show *quantitatively* that there is an affirmative answer to (b) in this work by doping the magnetic layers. Finally, for point (c), we show the comparatively weak influence of bulk scattering in CIP, likely due to channeling effects related to the existence of quantum well states.

In this work, we measure both CIP and CPP-GMR of $(\mathrm{Fe}_{1-x}\mathrm{V}_x\ t_{\mathrm{FeV}}/\mathrm{Cu}\ 2.3\ \mathrm{nm}/\mathrm{Co}\ 0.4\ \mathrm{nm}/\mathrm{Cu}\ 2.3\ \mathrm{nm})_{20}$ multilayers sputtered on Si(100) substrates. The FeV films were made by cosputtering Fe and V from a Fe target in which V disks were embedded. The concentration of V was verified by x-ray fluorescence measurements. The magnetic field was parallel to the layers and the samples were measured at 4.2 K with the usual method of Nb contacts for CPP measurements [4].

In magnetic multilayers containing only one type of ferromagnetic metal, the resistance is higher in the antiparallel state and we refer to the GMR as normal. In multilayers of the type $(A/\mathrm{Cu}/\mathrm{B}/\mathrm{Cu})_N$, an inverse GMR, with resistance higher in the parallel state, is expected in samples with alternating ferromagnetic layers of two different materials which have opposite spin asymmetries. Inverse CIP-GMR has already been observed in Fe/Cu multilayers in which ultrathin Cr layers have been inserted in the center of every second Fe layer to reverse its spin asymmetry [5], and also in FeV/Au/Co multilayers [6]. In this Letter, we present examples of inverse CPP-GMR. We recall the notation of CPP-GMR [7]. The resistivities of the magnetic layers for the majority and minority spin electrons are written as

$$\rho_{\uparrow(\downarrow)} = 2\rho_{\mathrm{F}}^{*}(1 \mp \beta)\,. \tag{1}$$

Similarly, the interface resistances for unit area are written as

$$r_{\uparrow(\downarrow)} = 2r_{b}^{*}(1 \mp \gamma)\,, \tag{2}$$

where β and γ are the spin asymmetry coefficients of bulk and interface scatterings, respectively.

As it appears below, the inverse CPP-GMR of our (FeV/Cu/Co/Cu) multilayers is associated with the contrast between the positive value of β and γ in the Co layers [8] and the negative value of β in the FeV layers. We will see that an inverse CPP-GMR is observed when, above a critical thickness of FeV, the contribution from bulk scattering in FeV (with $\beta < 0$) exceeds the contribution from scattering at the FeV/Cu interfaces (with $\gamma > 0$).

In Fig. 1, we show an example of inverse GMR [Fig. 1(a)] and the corresponding magnetization curve [Fig. 1(b)]. The magnetization of the FeV layers is reversed and saturated in a field of about 200 Oe, while a much stronger field around 2000 Oe is necessary to progressively align the ultrathin Co layers, as already reported [9]. This gives rise to a field range with antiparallel alignment of the magnetization in consecutive magnetic layers. When the arrangement of the magnetizations of the two layers goes from parallel to antiparallel the resistivity drops [Fig. 1(a)], which is the expected inverse GMR effect. The MR is not large, and, unlike in other systems with larger MR ratios, the background MR associated with the Nb contacts is not negligible. For R_P, the resistance of the parallel state, we take the values indicated in Fig. 1(a), which corresponds with the termination of hysteresis and the final saturation of the Co layers.

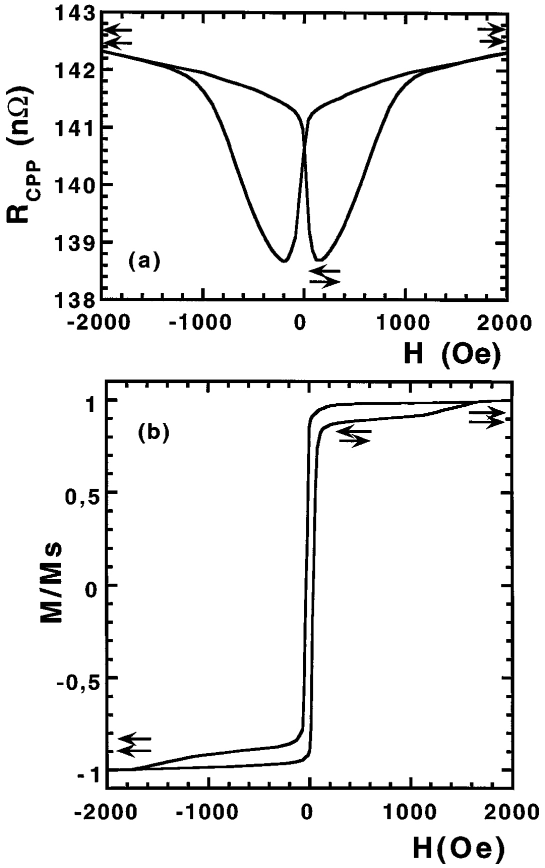

FIG. 1. Magnetoresistance (a) and magnetization (SQUID) (b) curves at 4.2 K for a ($Fe_{72}V_{28}$ 6 nm/Cu 2.3 nm/Co 0.4 nm/Cu 2.3 nm$)_{20}$ multilayer.

In Fig. 2, we plot the saturation MR of samples with $Fe_{72}V_{28}$ layers as a function of the thickness of FeV, t_{FeV}. This demonstrates that the GMR can be tuned from normal [inset (a)] to inverse [inset (b)] by increasing t_{FeV}. The thickness t^*_{FeV} of the crossover from normal to inverse is between 2 and 3 nm. This unambiguously confirms the role of bulk scattering in FeV, and the competition between the contributions of the scattering at the FeV/Cu interface with γ positive, and of bulk scattering inside the FeV layers with β negative. At small thicknesses of FeV, the interface scattering wins, the global asymmetry of the FeV layers is positive, like that of the Co layers [8], and the GMR effect is normal. At larger thickness of FeV, the bulk scattering predominates, so that the global asymmetry of FeV/Cu is now negative, giving rise to alternating asymmetries in the FeV and Co layers and therefore to inverse GMR. The crossover thickness t^*_{FeV} is the thickness for which the bulk and interface contributions to the spin asymmetry of the FeV layers balance each other.

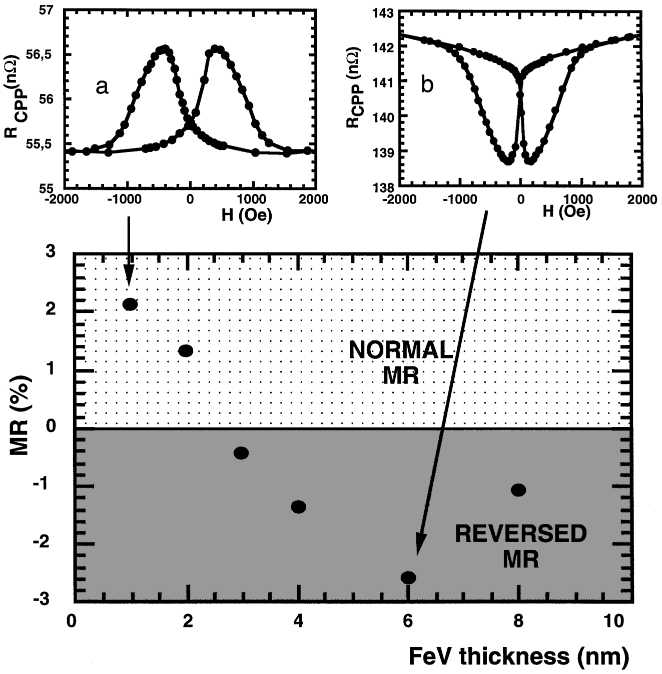

FIG. 2. Variation of the MR ratio at saturation with the thickness of FeV in ($Fe_{72}V_{68}$/Cu 2.3 nm/Co 0.4 nm/Cut_{FeV} 2.3 nm$)_{20}$ samples. We have adopted the positive (negative) sign for normal (inverse) GMR. Inset (a): Normal magnetoresistance curve for 1 nm thick FeV layers. Inset (b): Inverse GMR for 6 nm thick FeV layers.

In the long spin diffusion length limit [7,10,11], the interface resistances, $r^*_{\mathrm{FeV/Cu}}(1 \mp \gamma_{\mathrm{FeV/Cu}})$, and the "bulk resistances," $\rho^*_{\mathrm{FeV}}(1 \mp \beta_{\mathrm{FeV}})t^*_{\mathrm{FeV}}$, are simply additive in the majority and minority spin channels (self-averaging property) and the compensation thickness t^*_{FeV} is given by the balance equation

$$2r^*_{\mathrm{FeV/Cu}}\gamma_{\mathrm{FeV/Cu}} + \rho^*_{\mathrm{FeV}}\beta_{\mathrm{FeV}}t^*_{\mathrm{FeV}} = 0\,. \tag{3}$$

In Fig. 3, we show the variation of the resistance for unit area in the parallel state, AR^P (A is the sample area), and the resistance variation, $A\Delta R = A(R^{\mathrm{AP}} - R^P)$, as a function of the thickness of FeV, for several concentrations of V. As the concentration of V decreases from 28 to 10.3 at. %, the compensation thickness t^*_{FeV} increases from around 2 to around 8 nm; that is, as the concentration decreases, the bulk contribution balances the interface contribution less rapidly.

We have tried to account for all the experimental results gathered in Fig. 3 with the classical expressions of the long spin diffusion length limit [7,10,11]. In the antiparallel (AP) and parallel (P) configurations, the resistances of the spin ↑ and spin ↓ channels $R\uparrow$ and $R\downarrow$ are written

$$\begin{aligned} AR^{\mathrm{AP}}_{\uparrow(\downarrow)} = {} & 4r^*_{\mathrm{Nb/FeV}} + 40[\rho^*_{\mathrm{FeV}}t_{\mathrm{FeV}}(1 \pm \beta_{\mathrm{FeV}}) + 2^*_{\mathrm{FeV/Cu}}(1 \pm \gamma_{\mathrm{FeV/Cu}}) \\ & + 2\rho^*_{\mathrm{Cu}}t_{\mathrm{Cu}} + \rho^*_{\mathrm{Co}}t_{\mathrm{Co}}(1 \mp \beta_{\mathrm{Co}}) + 2r^*_{\mathrm{Co/Cu}}(1 \mp \gamma_{\mathrm{Co/Cu}})]\,, \end{aligned} \tag{4}$$

$$AR^{\mathrm{P}}_{\uparrow(\downarrow)} = 4r^*_{\mathrm{Nb/FeV}} + 40[\rho^*_{\mathrm{FeV}} t_{\mathrm{FeV}}(1 \mp \beta_{\mathrm{FeV}}) + 2r^*_{\mathrm{Fev/Cu}}(1 \mp \gamma_{\mathrm{FeV/Cu}}) + 2\rho^*_{\mathrm{Cu}} t_{\mathrm{Cu}} + \rho^*_{\mathrm{Co}} t_{\mathrm{Co}}(1 \mp \beta_{\mathrm{Co}}) + 2r^*_{\mathrm{Co/Cu}}(1 \mp \gamma_{\mathrm{Co/Cu}})]. \quad (5)$$

The final resistance is

$$AR^{\mathrm{P(AP)}} = \frac{AR_{\uparrow}^{\mathrm{P(AP)}} AR_{\downarrow}^{\mathrm{P(AP)}}}{AR_{\uparrow}^{\mathrm{P(AP)}} + AR_{\downarrow}^{\mathrm{P(AP)}}}. \quad (6)$$

For Co/Cu, we have used the parameters deduced from previous experiments on Co/Cu multilayers [12]: $2r^*_{\mathrm{Co/Cu}} = 1.05\ f\Omega\ \mathrm{m}^2$, $\rho^*_{\mathrm{Co}} = 76\ \mathrm{n}\Omega\ \mathrm{m}$, $\gamma_{\mathrm{Co/Cu}} = 0.75$, $\beta_{\mathrm{Co}} = 0.46$, $\beta_{\mathrm{Cu}} = 1$, and $\rho^*_{\mathrm{Cu}} = 4.5\ \mathrm{n}\Omega\ \mathrm{m}$. For each concentration, we have determined the values of $r^*_{\mathrm{FeV/Cu}}$, ρ^*_{FeV}, $\gamma_{\mathrm{FeV/Cu}}$, and β_{FeV} giving the best fit with our results for both $AR^p$and $A\Delta R$. We present these values in Table I.

As expected, the inverse GMR is due to a negative value of β_{FeV} (bulk scattering spin asymmetry in FeV). We learn that β_{FeV} is practically independent of the concentration of V between 15 and 28 at. % at least. The scattering spin asymmetry at the FeV/Cu interface is also affected by alloying with V: $\gamma_{\mathrm{FeV/Cu}}$ remains positive but decreases as the concentration of V increases. The concentration dependence of the compensation thickness $t^*_{\mathrm{FeV}} = 2r^*_{\mathrm{FeV/Cu}}\gamma_{\mathrm{FeV/Cu}}/\rho^*_{\mathrm{FeV}}|\beta_{\mathrm{FeV}}|$ from Eq. (1) is due to both some increase of $\rho^*_{\mathrm{FeV}}|\beta_{\mathrm{FeV}}|$ and some decrease of $r^*_{\mathrm{FeV/Cu}}\gamma_{\mathrm{FeV/Cu}}$ at increasing concentration of V.

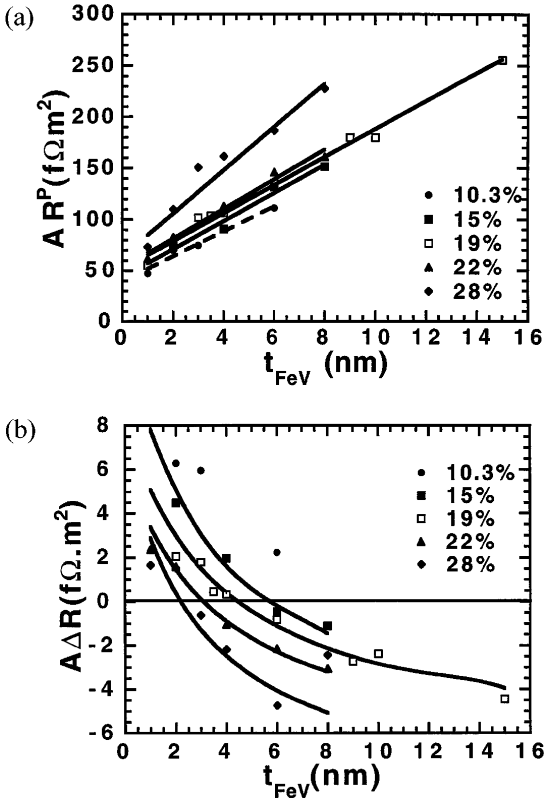

FIG. 3. (a) The area times the resistance in the parallel state AR^p and (b) the resistance variation $A\Delta R$ as a function of the thickness of the $\mathrm{Fe}_{1-x}\mathrm{V}_x$ layers for different concentrations of V. The solid lines are fits obtained with Eqs. (4)–(6).

The multilayers we have studied represent a spectacular example of system with competing asymmetries, negative for bulk scattering in FeV, positive for the FeV/Cu interfaces and the Co layers. The opposite sign of bulk and interface asymmetries in the FeV layers gives rise to a compensation thickness; the opposite sign of the spin asymmetries of the Co layers and the "thick" FeV layers gives rise to inverse GMR. The negative sign we find for FeV is in agreement with that found for the scattering by V impurities in Fe [13]. Our absolute value of β_{FeV}, $0.11 \leq |\beta_{\mathrm{FeV}}| \leq 0.15$, is smaller than that found for V impurities, $|\beta| \sim 0.7$, which could be due to the existence of additional scattering by atomic disorder in the multilayers and, perhaps, to some intrinsic decrease of $|\beta|$ with the concentration. Whereas a positive asymmetry due to a higher density of states at the Fermi level for the minority spin direction is expected for Ni, Co, Fe, and most of their alloys, the negative asymmetry of the scattering of V impurities in Fe has been related to the existence of a resonant scattering on the V sites for the majority spin direction at the Fermi level [13], in agreement with recent *ab initio* calculations by Mertig *et al.* [14]. A negative asymmetry is also expected for alloys of Ni with V and Cr, Co with Cr and Mn, Fe with Cr [13,14].

We have also performed current in plane measurements on our samples. *Surprisingly the CIP-GMR is not inverted.* This casts an interesting light on the difference between CPP and CIP, as recently emphasized by calculations of Zahn *et al.* [15]. In the CPP geometry, the current is carried by "delocalized" electrons, that is, electrons that are not confined or partly confined in one type of layer and propagate throughout the whole structure. These electrons encounter both bulk and interface scattering centers. In addition, at least in the self-averaging long spin diffusion length limit [7], all the scattering processes (bulk and interface) are simply additive. The CIP-GMR is less sensitive to bulk scattering for two reasons.

First, the characteristic *scaling length of the CIP geometry* is the mean free path (MFP) and bulk scattering in only a thickness of the order of the MFP in the magnetic layers along the interfaces contributes to the GMR.

The second reason is more fundamental and related to the existence of quantum well states (QWS) [16]. QWS electrons, partly confined in the nonmagnetic layers, contribute significantly to the conduction in the CIP but not in the CPP geometry [15]. As these electrons are not affected (or weakly affected) by bulk scattering in the magnetic layers, this also reduces the

TABLE I. Experimental compensation thickness t^*_{FeV}, and best fit parameters for $r^*_{\mathrm{FeV/Cu}}$, ρ^*_{FeV}, β_{FeV}, and $\gamma_{\mathrm{FeV/Cu}}$ for several concentrations of V in Fe.

x (at. %)	t^*_{FeV} (nm)	$r^*_{\mathrm{FeV/Cu}}$ ($\mathrm{f\Omega\,m^2}$)	$\gamma_{\mathrm{FeV/Cu}}$	ρ^*_{FeV} ($\mathrm{n\Omega\,m}$)	β_{FeV}
10.3	Not known	0.26	Not determined	558	Not determined
15	5.7	0.36	0.58	638	−0.11
19	4.45	0.56	0.30	644	−0.11
22	3.1	0.61	0.22	672	−0.12
28	2.2	0.84	0.21	997	−0.15

weight of the bulk scattering in the CIP geometry. It thus turns out that spin dependent bulk scattering is more influential in CPP, and this is well illustrated by our observation of inverse CPP-GMR and normal CIP-GMR in the same samples. This explains some different conclusions on the importance of bulk scattering derived from CIP and CPP experiments.

In conclusion, our results of inverse CPP-GMR offer several insights into the mechanism of GMR.

(1) The spin asymmetry coefficient β, positive in most systems, can be reversed by doping Fe layers with V, in agreement with previous measurement performed on dilute alloys [13] and theoretical calculations in the dilute limit [14]. A negative β has also been recently observed by doping Fe and Ni layers with Cr [17].

(2) The system we have studied is a spectacular example in which bulk and interface scatterings unambiguously compete and pull in opposite ways ($\beta < 0$ and $\gamma > 0$); the interface wins at small thickness, bulk scattering prevails at larger thicknesses, and there is a compensation thickness where the GMR passes through zero.

(3) The GMR is reversed in the CPP geometry but not in the CIP one, which shows the weaker influence of spin dependent bulk scattering in the CIP geometry. This results from the short scaling length of the CIP conduction (the mean free path) and the influence of channeling effects (quantum well states).

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