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Unified picture of spin-dependent transport in GMR multilayered structures and bulk ferromagnetic alloys

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Abstract

We have observed a *positive* (inverse) CPP-MR in magnetic multilayers of the forms: (a) $(XY/Cu/Co/Cu)_n$ with XY being the alloys \overline{FeCr} , \overline{FeV} , \overline{NiCr} , \overline{CoCr} , and (b) $(Z/Cr/NiFe/Cr)_n$ with $Z = Fe$ and Co . For (a) the inverted results arise primarily from spin-dependent scattering in the *bulk* of the alloy, and are linked consistently to: (1) their magnetization; (2) band-structure calculations and (3) resistivity of bulk alloys. For (b) samples, the inverse MRs arise primarily from the scattering at the Fe/Cr and Co/Cr *interfaces*. Inverse MR for X/Y interfaces and XY alloys (eg. $\overline{Fe/Cr}$ and \overline{FeCr}) arises from the similarity of the matching problem of X and Y d levels at interfaces and in alloys. For all XY the CIP-MR was *negative*, confirming that CIP-MR is strongly influenced by channeling effect and current inhomogeneities. © 1998 Elsevier Science B.V. All rights reserved.

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Magnetoresistance measurements with the measuring current perpendicular to the plane of the multilayers (CPP-MR) on $(F/N)_n$ multilayers (F = ferromagnetic metal, N = non-magnetic) can quantitatively determine the relative amounts of spin-dependent scattering occurring in the bulk F metal and at the F/N interface [1]. If ρ_{\downarrow} (ρ_{\uparrow}) is the resistivity of the spin-down (up) electrons, the relative parameters are α_b , α_1 , β , and γ where $\alpha_b = \rho_{\downarrow}/\rho_{\uparrow} = (1 + \beta)/(1 - \beta)$ refers to bulk scattering and $\alpha_1 = (1 + \gamma)/(1 - \gamma)$ refers to scattering at the F/N interface. Here we investigate under what circumstances α_b is $>$ or $<$ 1, i.e. β is $+$ or $-$, and similar circumstances for α_1 and γ .

For $(F/N)_n$ multilayers the MR is always negative (normal). But for $(F_1/N/F_2/N)_n$ multilayers, the MR may be positive (inverse), if α_{b1} (α_{11}) is $>$ 1 and α_{b2} (α_{12}) is $<$ 1. Renard et al. [2] observed an inverse CIP-MR for $\overline{FeV/Au/Co}$ trilayers. We have seen an inverse CPP-MR for $(\overline{FeV/Cu/Co/Cu})_n$ multilayers [3]. From the CPP-

MR data, β and γ can be estimated. For \overline{FeV} , the result is that β is negative and γ for the $\overline{FeV/Cu}$ interface is positive. By analogy with the results of spin-dependent transport in bulk alloys, we have assumed that the Slater-Pauling curve which gives the magnetic moment/atom versus the number of d-electrons per atom, should indicate which alloys we may expect to have a negative β . In that curve, there is a very clear delineation between those alloys which give a positive slope and those with negative slopes. With this in mind we have measured the CPP-MR of the \overline{FeCr} , \overline{CoCr} , \overline{NiCr} and \overline{FeV} alloys (all with positive slopes on the Slater-Pauling curve) and \overline{NiCu} and \overline{FeCu} with negative slopes.

For the first four alloys, and for moderate alloy thicknesses, the CPP-MR was inverted with $\beta <$ 1 and $\gamma >$ 1. This results in a competition between bulk and interface scattering to determine whether the MR will be normal or inverse. For very thin alloy samples the bulk scattering is small and the interface scattering wins, giving a normal CPP-MR. For samples with thicker alloy layers the bulk scattering wins and the CPP-MR is inverted. At a specific thickness the two effects balance giving zero CPP-MR.

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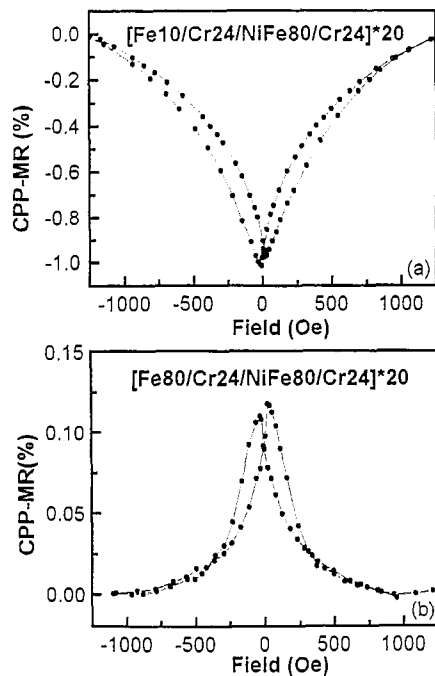


Fig. 1. (a) The positive CPP-MR in $(\text{Fe}/\text{Cr}/\text{NiFe}/\text{Cr})_n$ multilayers for thin (1 nm) Fe layers. (b) The negative MR for thick (8 nm) Fe layers.

For the NiCu and FeCu samples the CPP-MR is normal so that these six systems correlate well with the Slater–Pauling slopes. For a more complete analysis one must calculate the residual resistivity of the alloys taking the band structure into account. Calculations of ρ_{\uparrow} and ρ_{\downarrow} by Mertig et al. [4] yield values of α_b which are entirely consistent with our results.

Surprisingly, the CIP-MR (measuring current in plane-MR) is negative for all the samples. We ascribe this to: (1) the existence of channeling effects in CIP measurements (like those involved in the formation of quantum-well states). Calculations show that for Co/Cu [5] a significant part of the current in the CIP geometry is carried by quantum-well-state electrons that are confined in the Cu and do not undergo bulk scattering in the Co. (2) the different scaling lengths associated with CIP and CPP measurements. For CPP measurements the characteristic length is the spin-diffusion length which is probably > 10 nm, whereas that for the CIP measure-

ment is the electron mean free path, which for the alloys used is ≈ 1 nm. Consequently, for CIP-MR, effective bulk scattering of electrons occurs only in a small depth of the bulk layer.

These experiments show most clearly the significant difference between CIP and CPP measurements, and help resolve the question of the relative importance of bulk and interface scattering. A comparison between multilayers with Cu and Au spacer layers should be interesting, since the results of Renard et al. [2] suggest closer interface and bulk contributions to the CIP-MR of Au multilayers.

Next question: Is it possible to produce a negative γ ? We reason that the problems of the matching of the d levels at an interface between transition metals A and B, and for an impurity B in A are somewhat similar. If B in A produces a negative β , will the A/B interface have a negative γ ? To test this we have measured the CPP-MR of $(\text{X}/\text{Cr}/\text{Py}/\text{Cr})_n$ multilayers with $\text{X} = \text{Fe}$ and Co . In both cases, the MR was inverse for thin X layers, and normal for thicker layers (Fig. 1). This is the behaviour one would expect for negative γ for the X/Cr interfaces and positive parameters elsewhere. This agrees with the results of George et al. [6], who produced an inverse CPP-MR by introducing Fe/Cr interfaces into basically Fe layers.

We conclude that there are consistent links between the magnetic and resistive properties of the alloys of the ferromagnetic metals with their neighbours. The MR can be semi-quantitatively described by transport theory which takes the band structure into account.

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