Current perpendicular to plane Giant Magnetoresistance (GMR) in laminated nanostructures

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Abstract

We theoretically studied spin dependent electron transport perpendicular-to-plain (CPP) in magnetic laminated multilayered structures by using Kubo formalism. We took into account not only bulk scattering, but the interface resistance due to both specular and diffuse reflection and also spin conserving and spin-flip processes. It was shown that spin-flip scattering at interfaces substantially reduces the value of GMR. This can explain the experimental observations that the CPP GMR ratio for laminated structures only slightly increases as compared to non-laminated ones despite lamination induces a significant increase in CPP resistance.

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We considered the spin dependent electron transport perpendicular-to-plain (CPP) in magnetic multilayered structures of the type $(N/F)_n(N^{\text{spacer}})(F/N)_m$, where F is ferromagnetic, N is nonmagnetic metal, $n$ and $m$ denote the number of bilayer repeats. The thickness of N layers in the $(N/F)_n$ is small enough ($\sim 5\text{Å}$) so that the adjacent F layers are coupled ferromagnetically and the thickness of $(N^{\text{spacer}})$ layer is larger ($\sim 20\text{Å}$) so that the total magnetization of $(N/F)_n$ and $(F/N)_m$ can be switched from parallel to antiparallel orientation by an external magnetic field.

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We took into account that Fermi momentum of the majority spin subband in Co practically coincides with Fermi momentum of Cu, and for minority spin subband these momenta are quite different. So for parallel orientation of the magnetizations in all layers the majority spin channel has very low resistance, in contrast minority spin electrons undergo fort reflection at Co/Cu interfaces so that this channel has a low conductivity. For the antiparallel orientation of magnetizations of (N/F)$_n$ and (N/F)$_m$ stacks, both spin channels exhibit low conductivity. The change of overall conductivity between parallel and antiparallel magnetic configurations determines the CPP-GMR amplitude. In contrast to the present study, we emphasis that in Valet and Fert theory of CPP-GMR [1], the difference of Fermi momentum for different metals and different spin subbands was not taken into account.

The spin-dependent current through the system has been calculated in Kubo formalism using the same approach as in Ref. [2]. We calculated the Green function $G_\kappa(z, z')$ for the considered multilayer. It is the solution of the following equation [3]:

$$\left[\frac{\hbar^2}{2m} \left( \frac{\partial^2}{\partial z^2} - \kappa^2 \right) + E_f - \Sigma(z) \right] G_\kappa(z, z') = \delta(z - z'),$$

where $m$ is the effective electron mass, $\hbar \kappa$ is the electron momentum in $XY$-plane of the film, and $z$ is the direction perpendicular to the film plane, $\Sigma$ is the coherent potential (CP). We include in the definition of the coherent potential not only the usual contributions of the spin-dependent electron scattering in the bulk of every layer (which influences the imaginary part of the CP), but we also take into account the difference in the positions of the bottoms of the spin subbands in Cu and Co, which enters in the real part of the CP. As a result $\Sigma(z)$ is step function of coordinate and depends on electron spin and relative orientation of magnetizations in the two magnetic laminated layers.

Besides specular reflection at interfaces, electron may undergo diffuse scattering due to interfacial roughness. So we add to the bulk CP interfacial contribution in the form $\Sigma^{in}(z_i) = V_i \delta(z - z_i)$, where $z_i$ is the position of interface $i$. $\Sigma^{in}(z_i)$ is calculated from CPA equation. In calculation of the $\Sigma^{in}(z_i)$ we take into account spin conserving and spin flip interfacial scattering. For that the CP the vertex corrections were calculated within the same approximations. The bulk vertex correction are taken into account by introducing an effective electric field which has been calculated by solving the equation of nondivergency of the current as in [4]:

$$j^\uparrow(z) = \int \sigma^\uparrow(z, z') E^\uparrow(z')dz' = \text{const}$$

$$j^\downarrow(z) = \int \sigma^\downarrow(z, z') E^\downarrow(z')dz' = \text{const}$$
Fig. 1 shows the dependence of the GMR of the structure $(\text{Cu}(5\,\text{Å})\text{Co}(b))_3 \text{Cu}(30\,\text{Å})(\text{Co}(b)\text{Cu}(5\,\text{Å}))_3$ on the thickness $b$ of the Co layer. The parameters are given in the caption of fig. 1. These correspond to a case where the spin-conserving interfacial scattering gives substantial contribution to the total resistance of the system. The curve exhibits an oscillatory behavior with relatively high values at resonances, when approximately the condition $k_f b = 2\pi n$ is fulfilled. In the considered case of large diffuse scattering, the influence of spin flip processes is relatively weak. In fig. 2 a similar dependence is shown in a case of relatively weak diffuse scattering at interfaces. The value of GMR increases in comparison to the former case, if there no spin-flip scattering.

In experiment [5] for the laminated structure $\text{Py}(60\,\text{Å})/\text{Cu}(40\,\text{Å}) [\text{Co}(10\,\text{Å})/\text{Cu}(5\,\text{Å})]_3 \text{Cu}(35\,\text{Å})$ the reported value of the GMR is 40%, meanwhile for the non-laminated one the GMR value is 25%. These values are close to the results of our calculations. We came to the conclusion that lamination may really enhance the GMR value due to the additional spin dependent reflection at Cu/Co interfaces. However, the strong diffuse interfacial scattering, especially the spin flip one diminishes this effect. In conclusion, lamination of the CoCuCo structure does not increase the GMR value due to the interplay of specular reflection and diffuse scattering on interfaces.

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References

[1] T. Valet and A. Fert Phys. Rev. B 48 (1993) 7099
[2] C. L. Kane, R. A. Serota, P. A. Lee P. Phys. Rev. B 37 (1988) 6701
[3] A. Vedyaev, N. Ryzhanova, B. Dieny, P. Dauguet, P. Gandit and J. Chaussy Phys. Rev. B 55 (1997) 3728
[4] H. E. Camblong, P. M. Levy and S. Zhang Phys. Rev. B 51 (1995) 16052
[5] K. Eid, W. P. Pratt, Jr., and J. Bass J. Appl. Phys. 93 (2003) 3445
Fig. 1. The GMR dependence on Co thickness $b$ for the structure $(Cu(5\text{Å})Co(b))_3Cu(30)(Co(b)Cu(5\text{Å}))_3$ in the strong interface scattering. Where $k^\uparrow_{fCo} = 1\text{Å}^{-1}$, $k^\downarrow_{fCo} = 0.6\text{Å}^{-1}$, $k^\uparrow_{fCu} = k^\downarrow_{fCu} = 1\text{Å}^{-1}$; $l^\uparrow_{Co} = 100\text{Å}$, $l^\downarrow_{Co} = 100\text{Å}$, $l^\uparrow_{Cu} = l^\downarrow_{Cu} = 200\text{Å}$, $k_{fi}$ are the corresponding Fermi momentum, $l_i$ are the corresponding mean free paths. $V^\uparrow_{Co/Cu} = 1.1\text{ eV}$, $V^\downarrow_{Co/Cu} = 1.7\text{ eV}$ are the scattering potentials on the Co/Cu interfaces, $x=0.5$ is impurities concentration. For the initial system Co(30Å)/Cu(30Å)/Co(30Å) the GMR value is 0.51 for the same parameters.

Fig. 2. Same dependence of GMR in the case of weak interfacial scattering. $\text{Im} V^\uparrow_{Co/Cu} = 0.1\text{ eV}$. $V^\uparrow_{Co/Cu} = 0.1\text{ eV}$, $V^\downarrow_{Co/Cu} = 0.3\text{ eV}$ are the scattering potentials on the Co/Cu interfaces, $x=0.5$ is impurities concentration. For the initial system Co(30Å)/Cu(30Å)/Co(30Å) the GMR value is 0.54 for the same parameters.