Spin-diffusion effect in the ferromagnet–metal bilayer

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Abstract

Spin accumulation in a ferromagnet–metal bilayer is investigated by means of the Boltzmann transport equation. We consider the spin-dependent diffusive scatterings from different mean free paths between the ferromagnet and the metal, and find that the resultant spin-diffusion length depends both on the interfacial properties and on the mean free paths, and that it usually is less than the metal mean free path.

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Spin accumulation occurs when a current flows across the interfaces of magnetic multilayers [1–3]. P.C. van Son et al. used a phenomenological diffusion equation [1], derived by Valet and Fert from the Boltzmann transport equation [2], to specify the variation of the chemical potential with the so-called spin-diffusion length on the scale of a few micrometers [1–3]. However, the experimentally observed spin-diffusion length seems to be only a few nanometers, and the tunneling magnetoresistance ratio of the ferromagnet–metal–insulator–ferromagnet junction decays thus rapidly with increasing metal thickness [4–7]. In this paper, we consider the spin-dependent diffusive scatterings from different mean free paths in a ferromagnet–metal bilayer, and find the resultant spin-diffusion length to be well below the metal mean free path. Moreover, it can be even zero in particular cases.

The spin-dependent electron distribution with boundary effects and in the presence of a uniform electric field $\mathbf{E}$ is given by the formula

$$f_{\mathbf{k}}^{\sigma}(\varepsilon, \mathbf{r}) = \frac{1}{\exp[\beta(\varepsilon - \mu_{\mathbf{k}}^{\sigma}(\mathbf{r}))] + 1}, \quad (1)$$

where ε is the electron energy, and $\mathbf{k}$ is its wave vector at the position $\mathbf{r}$. The spin-dependent chemical

potential is

$$\mu_{\mathbf{k}}^{\sigma}(\mathbf{r}) = \mu^0 + \sigma h - \lambda^{\sigma} \mathbf{e}_{\mathbf{k}} \cdot e\mathbf{E} + \Delta\mu_{\mathbf{k}}^{\sigma}(\mathbf{r}), \quad (2)$$

where μ^0 is the spin-independent chemical potential, the spinor σ is $+1$ ($-1, 0$) for the spin-up (spin-down, spin-independent) state, h is the molecular field of the ferromagnet, σh is its internal exchange energy, λ^{σ} is the electron mean free path, $-e$ is the electron charge, and $\mathbf{e}_{\mathbf{k}}$ is a unit vector in the transport direction. In Eq. (2) the anisotropic chemical potential change $-\lambda^{\sigma} \mathbf{e}_{\mathbf{k}} \cdot e\mathbf{E}$ is due to the applied electric field $\mathbf{E}$, and the boundary chemical potential change $\Delta\mu_{\mathbf{k}}^{\sigma}(\mathbf{r})$ encompasses all possible induced boundary effects. The electron distribution $f_{\mathbf{k}}^{\sigma}(\varepsilon, \mathbf{r})$ is required to satisfy the Boltzmann transport equation in the relaxation time approximation,

$$\frac{df_{\mathbf{k}}^{\sigma}(\varepsilon, \mathbf{r})}{dt} = -\frac{f_{\mathbf{k}}^{\sigma}(\varepsilon, \mathbf{r}) - f_{\mathbf{k}}^{\sigma,0}(\varepsilon)}{\tau^{\sigma}}, \quad (3a)$$

where $f_{\mathbf{k}}^{\sigma,0}(\varepsilon)$ is the Fermi–Dirac equilibrium distribution and τ^{σ} is the relaxation time. The boundary chemical potential change $\Delta\mu_{\mathbf{k}}^{\sigma}(\mathbf{r})$ therefore is valid under

$$\mathbf{e}_{\mathbf{k}} \cdot \nabla_{\mathbf{r}}[\Delta\mu_{\mathbf{k}}^{\sigma}(\mathbf{r})] = -\frac{\Delta\mu_{\mathbf{k}}^{\sigma}(\mathbf{r})}{\lambda^{\sigma}}, \quad (3b)$$

where the mean free path is $\lambda^{\sigma} = v_{\mathbf{F}}^{\sigma} \tau^{\sigma}$ and the Fermi velocity is $v_{\mathbf{F}}^{\sigma}$. In the ferromagnet–metal bilayer, the

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electric field $\mathbf{E}$ is applied parallel to the z -axis, which is perpendicular to the ferromagnet–metal interface. The film thickness of the left ferromagnet and of the right metal are designated as a and b , respectively. Accordingly, the electron distribution $f_{\mathbf{k}}^{\sigma}(\varepsilon, \mathbf{r})$ and the boundary chemical potential change $\Delta\mu_{\mathbf{k}}^{\sigma}(\mathbf{r})$ follow from Eqs. (1)–(3):

$$f_{\mathbf{k}}^{\sigma}(\varepsilon, \mathbf{r}) = f_{\mathbf{k}}^{\sigma,0}(\varepsilon) + \frac{\partial f_{\mathbf{k}}^{\sigma,0}(\varepsilon)}{\partial \varepsilon} \times \left[e\lambda^{\sigma} E \cos \theta - G_{\mathbf{k}}^{\sigma} \exp \left[\frac{-z}{\lambda^{\sigma} \cos \theta} \right] \right], \quad (4a)$$

$$\Delta\mu_{\mathbf{k}}^{\sigma}(\mathbf{r}) = G_{\mathbf{k}}^{\sigma} \exp \left[\frac{-z}{\lambda^{\sigma} \cos \theta} \right], \quad (4b)$$

where $\cos \theta = \mathbf{e}_{\mathbf{k}} \cdot \mathbf{e}_z$. The undetermined coefficient $G_{\mathbf{k}}^{\sigma}$ depends on the boundary conditions, including the diffusion parameter D , the non-diffusive transmission parameter T , and the non-diffusive reflection parameter R . In the following, we denote all physical variables by the subscripts F, M, and F–M in order to indicate the related outer surfaces and the interface of the ferromagnet–metal bilayer.

To study the spin accumulation within the metal, which results from the injected spin-dependent electrons of the ferromagnet, we assume the boundary conditions as follows; $D_F = 0$, $T_F = 0$, and $R_F = 1$ for the source at $z = -a$, $D_M = 0$, $T_M = 1$, and $R_M = 0$ for the drain at $z = b$, and $D_{F-M} = D$, $T_{F-M} = 1 - D$, and $R_{F-M} = 0$ for the ferromagnet–metal interface at $z = 0$. As the ferromagnet is a good spin-polarized source for the metal drain, it is reasonable to approximate $2a \gg \lambda_F^+$, $2a \gg \lambda_F^-$, and $a > b$. After some algebra, the difference ratio between the spin-dependent chemical potentials within the metal can be derived as

$$\frac{\mu_{\mathbf{k},M}^+(z) - \mu_{\mathbf{k},M}^-(z)}{\mu_M^0} = \frac{(eE\lambda_M \cos \theta)}{\mu_M^0} (D_{F-M}^+ - D_{F-M}^-) \times \exp \left[\frac{-z}{\lambda_M \cos \theta} \right], \quad (5a)$$

where $\lambda_M^+ = \lambda_M^- = \lambda_M$ and the spin-dependent diffusive scattering at the ferromagnet–metal interface is given by [8]

$$D_{F-M}^{\sigma} = \left[1 - \frac{\lambda_F^{\sigma}}{\lambda_M^{\sigma}} (1 - D) \right]. \quad (5b)$$

Eqs. (5a) and (5b) show that the asymmetry of the different spin-dependent mean free paths between the ferromagnet and the metal, $\lambda_F^+/\lambda_M^+ \neq \lambda_F^-/\lambda_M^-$, causes the asymmetry of the different spin-dependent diffusive scatterings, $D_{F-M}^+ \neq D_{F-M}^-$. This is one reason for the spin accumulation with $\mu_{\mathbf{k},M}^+(z) \neq \mu_{\mathbf{k},M}^-(z)$ in the ferro-

magnet–metal bilayer. It is clear from Eqs. (5a) and (5b) that the interfacial diffusive scattering, i.e., D , and the incident angle θ strongly effect the spin accumulation injected from the ferromagnet into the metal. Moreover, a larger spin accumulation occurs at higher values of the ratio $(\lambda_F^+ - \lambda_F^-)/\lambda_M$. The metal spin-diffusion length A is defined to specify the existence of the spin accumulation, which is assumed as a distance from the ferromagnet–metal interface with $\mu_M^0 \exp[-1]$. In a good case, with $(eE\lambda_M)/\mu_M^0 = 1$, $(\lambda_F^+ - \lambda_F^-)/\lambda_M = 1$, $\theta = 0$, and $D = 0$, the spin-diffusion length A is the mean free path λ_M . In contrast, no spin accumulation occurs for either $D = 1$ or $\theta = \pi/2$, where $A = 0$.

In summary, the spin-diffusion length within the metal part of the ferromagnet–metal bilayer is due to the fact that the spin-dependent electrons injected from the ferromagnet undergo different spin-dependent diffusive scatterings, i.e., D_{F-M}^+ and D_{F-M}^- , near the ferromagnet–metal interface. The spin-diffusion length is comparable to the mean free path in metal only under good conditions. If the interfacial diffusive scatterings or the smaller asymmetry of the spin-dependent diffusive scatterings take place, the spin-diffusion length becomes much less than the mean free path in metal, and can even down to zero in particular cases. This is a possible reason for the reported experimental small spin-diffusion length [4–7].

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