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Letter to the Editor

# Calculations of hot electron magnetotransport in a spin-valve transistor at finite temperatures

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**Abstract**

Hot electron magnetotransport in a spin-valve transistor has been theoretically explored at finite temperatures. We have calculated the parallel and anti-parallel collector current by changing the relative spin orientation of the ferromagnetic layers at finite temperatures. In this model, hot electron energy redistribution due to spatial inhomogeneity of Schottky barrier heights and hot electron spin polarization in the ferromagnetic layer at finite temperatures have been considered. The results of these model calculations agree with experimental data in a semi-quantitative manner. We therefore suggest that both these effects should be taken into account when one explores the hot electron magnetotransport in a spin-valve transistor at finite temperatures.


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## 1. Introduction

Since the discovery of giant magneto resistance (GMR) [1] in magnetic multilayer structures, spin dependent transport has been extensively studied because of its fundamental interest as well as practical applications. For instance, magnetic tunneling junctions (MTJ) [2] have been explored very actively for device applications. Monsma et al. presented a spin-valve transistor [3] as a new type of magnetoelectronic device. One major difference between the MTJ and spin-valve transistor is the transport behaviour of the electrons due to the different structure of SVT from the MTJ [4]. One needs to explore the *hot* electron transport in the spin-valve transistor, while the electrons near the Fermi level mostly contribute to the current in the MTJ. Hot electron transport properties are related to the unoccupied density of states above the Fermi level and have an exponential dependence on the inelastic mean free path [5]. Very recently, Jansen et al. [6] reported the temperature dependence of the collector current changing the relative spin orientation in the ferromagnetic layers as well as the magnetocurrent. According to their observations, when the magnetic moments are parallel, the collector current (parallel collector current) increases up to 200 K and decreases above that, meanwhile the anti-parallel collector current

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increases up to room temperature. In addition, a huge magnetocurrent is also observed (roughly 350% at room temperature). A spin mixing mechanism due to thermal spin waves and energy redistribution due to spatial inhomogeneity of the Schottky barrier heights at finite temperatures are suggested to account for the experimental data by the authors of Ref. [6].

On the theory side, the effect of hot electron spin polarization has been suggested [7]. Interestingly, it has been obtained that the hot electron spin polarization has a substantial contribution to the hot electron magnetotransport, and this suggestion is supported by the magnetocurrent at finite temperatures [8]. However, the theoretical calculations cannot account for the parallel and antiparallel collector current at finite temperatures because only the relative importance of hot electron spin polarization and spin mixing due to thermal spin waves has been explored. In these calculations, we shall study the hot electron magnetotransport taking into account the spatial inhomogeneity of Schottky barrier height distribution and the spin dependent self-energy effect in the ferromagnetic layers.

## 2. Model

The typical structure of a spin-valve transistor is Si/N/F/N/F/N/Si [4] where N and F stand for the normal and ferromagnetic metal layer, respectively. The electrons injected across the Schottky barrier at the emitter side penetrate the spin-valve base and the energy of injected hot electrons is influenced by the distribution of Schottky barrier heights [9]. Once the electrons start to penetrate the spin-valve base we need to explore the Green's function $G_\sigma(\vec{k}, E)$, which describes the propagation of the electrons of spin $\sigma$ in each layer. We can write this as

$$G_\sigma(\vec{k}, E) = \frac{1}{E - \varepsilon_\sigma(\vec{k}) - \Sigma_\sigma(\vec{k}, E)}. \tag{1}$$

In the normal metal layer the Green's function has no spin dependence, thus the hot electrons are not spin polarized until they reach the first ferromagnetic layer. However, in the ferromagnetic material the hot electron has strong spin dependent self-energy [11]. Therefore, the inelastic mean free path of the hot electron is spin dependent, which results in the spin-dependent attenuation in the ferromagnet. Then, by virtue of the fact that the self-energy has spin dependence, the hot electrons will be spin polarized after penetrating the ferromagnetic layer. Of course, the hot electrons will be attenuated in the normal metal layers as well. Since the hot electron transport has an exponential dependence on the inelastic mean free path [5], and the attenuation in the normal metal layer has no influence on the spin dependent hot electron magnetotransport, we are able to focus our interest on the hot electron transport in the ferromagnetic layers.

In this model it is assumed that we have the same type of normal metal layers with the same thickness in the spin-valve base. We then define $\Gamma_\mathrm{N} = \exp(-w_\mathrm{N}/l_\mathrm{N})$ to account for the attenuation in the normal metal layer where $w_\mathrm{N}$ is its thickness, and $l_\mathrm{N}$ is the inelastic mean free path in the normal metal layer. As remarked above, the hot electron has a strong spin dependent inelastic mean free path in the ferromagnets; we therefore define $\gamma_{\mathrm{M(m)}_i} = \exp(-w_i/l_{\mathrm{M(m)}_i})$ to describe the attenuation in the ferromagnetic layer $F_i$ of majority (minority) spin electrons, respectively. Here, $w_i$ is the thickness of the ferromagnetic layer, and the $l_{\mathrm{M(m)}_i}$ stands for the inelastic mean free path of majority (minority) spin electron. Generally speaking, the hot electron inelastic mean free path depends on the energy and temperature, hence we need to take into account these dependencies for quantitative analysis of the hot electron magnetotransport.

Taking into account the distribution of Schottky barrier heights and spin dependent self-energy effect, we can write the parallel collector current as

$$\begin{aligned}\tilde{I}^\mathrm{P}(T) = {} & \int_{\varepsilon_\mathrm{l}}^{\varepsilon_\mathrm{u}} \mathrm{d}\varepsilon \int_0^T \mathrm{d}T' D(\tilde{\varepsilon}(T'))\Gamma_\mathrm{N}^3(\tilde{\varepsilon}(T')) \\ & \times \gamma_{\mathrm{M}_1}(\tilde{\varepsilon}(T'))\gamma_{\mathrm{M}_2}(\tilde{\varepsilon}(T')) \\ & \times \left[1 + \frac{\gamma_{\mathrm{m}_1}(\varepsilon(\tilde{T}'))}{\gamma_{\mathrm{M}_1}(\varepsilon(\tilde{T}'))}\frac{\gamma_{\mathrm{m}_2}(\varepsilon(\tilde{T}'))}{\gamma_{\mathrm{M}_2}(\varepsilon(\tilde{T}'))}\right] \\ & \times \Theta(\tilde{\varepsilon}(T') - V_\mathrm{b})\end{aligned} \tag{2}$$

and the anti-parallel collector current as

$$\tilde{I}^{\mathrm{AP}}(T) = \int_{\varepsilon_l}^{\varepsilon_u} \mathrm{d}\varepsilon \int_0^T \mathrm{d}T' D(\tilde{\varepsilon}(T'))\Gamma_{\mathrm{N}}^3(\tilde{\varepsilon}(T')) \times \gamma_{\mathrm{M}_1}(\tilde{\varepsilon}(T'))\gamma_{\mathrm{M}_2}(\tilde{\varepsilon}(T')) \times \left[\frac{\gamma_{\mathrm{m}_1}(\varepsilon(\tilde{T}'))}{\gamma_{\mathrm{M}_1}(\varepsilon(\tilde{T}'))} + \frac{\gamma_{\mathrm{m}_2}(\varepsilon(\tilde{T}'))}{\gamma_{\mathrm{M}_2}(\varepsilon(\tilde{T}'))}\right] \times \Theta(\tilde{\varepsilon}(T') - V_{\mathrm{b}}), \tag{3}$$

where $\Theta$ is a step function. $V_{\mathrm{b}}$ is the Schottky barrier height at the collector side, and $\tilde{\varepsilon}(T')$ is the energy of hot electron. In what follows, the energy is measured from the Fermi level of the metallic base. As mentioned above the Schottky barrier heights are not constant, but have spatial distribution [9], and this affects the energy distribution of injected hot electrons. We then denote the $\varepsilon_u$ and $\varepsilon_l$ as the upper and lower bound of the hot electron energy at zero temperature. At finite temperature $T$ this electron gains a fraction of energy due to thermal effect with width $4k_{\mathrm{B}}T$ [6,10], then the energy of the electron at finite temperatures can be written as

$$\tilde{\varepsilon}(T') = \varepsilon + 4k_{\mathrm{B}}T', \tag{4}$$

where $\varepsilon$ is the energy at zero temperature. The function $D$ describes the energy distribution at finite temperatures. Based on the Schottky barrier heights [9], in these calculations we assume that the energy of hot electrons has a Gaussian distribution at zero temperature. At finite temperatures, the energy of hot electrons will be redistributed due to thermal energy. We thus model the energy distribution of the hot electrons at finite temperatures as

$$D(\tilde{\varepsilon}(T')) = \frac{N_0}{2} c_1 \exp[-\alpha_1(\varepsilon - \varepsilon_{\mathrm{m}})^2] \times c_2 \exp[-\alpha_2(4k_{\mathrm{B}}T'/4k_{\mathrm{B}}T)], \tag{5}$$

where $c_1$ and $c_2$ are the normalization constants, $\varepsilon_{\mathrm{m}}$ is the energy of the maximum distribution at zero temperature, $\alpha_1$ and $\alpha_2$ describe the widths of the distribution, and $N_0$ is the total number of injected electron (spin up and spin down) across the Schottky barrier per unit time per unit area. One should note that the distribution function $D$ describes the distribution of hot electron energy with respect to the Fermi level of the spin-valve base. In Eqs. (2) and (3), we can replace the ratio of the spin dependent attenuation in the ferromagnetic layer by hot electron spin polarization $p_{\mathrm{H}_i}(\tilde{\varepsilon}(T'))$ using the relation

$$\frac{\gamma_{\mathrm{m}_i}(\tilde{\varepsilon}(T'))}{\gamma_{\mathrm{M}_i}(\tilde{\varepsilon}(T'))} = \frac{1 - P_{\mathrm{H}_i}(\tilde{\varepsilon}(T'))}{1 + P_{\mathrm{H}_i}(\tilde{\varepsilon}(T'))}. \tag{6}$$

We thus obtain the expression for the parallel and anti-parallel collector current as

$$\tilde{I}^{\mathrm{P}}(T) = \int_{\varepsilon_l}^{\varepsilon_u} \mathrm{d}\varepsilon \int_0^T \mathrm{d}T' D(\tilde{\varepsilon}(T'))\Gamma_{\mathrm{N}}^3(\tilde{\varepsilon}(T')) \times g_1(\tilde{\varepsilon}(T'))g_2(\tilde{\varepsilon}(T'))\Theta(\tilde{\varepsilon}(T') - V_{\mathrm{b}}) \times (1 + P_{\mathrm{H}_1}(\tilde{\varepsilon}(T')))(1 + P_{\mathrm{H}_2}(\tilde{\varepsilon}(T'))) \times \left[1 + \frac{1 + P_{\mathrm{H}_1}(\tilde{\varepsilon}(T'))}{1 - P_{\mathrm{H}_1}(\tilde{\varepsilon}(T'))}\frac{1 - P_{\mathrm{H}_2}(\tilde{\varepsilon}(T'))}{1 + P_{\mathrm{H}_2}(\tilde{\varepsilon}(T'))}\right], \tag{7}$$

$$\tilde{I}^{\mathrm{AP}}(T) = \int_{\varepsilon_l}^{\varepsilon_u} \mathrm{d}\varepsilon \int_0^T \mathrm{d}T' D(\tilde{\varepsilon}(T'))\Gamma_{\mathrm{N}}^3(\tilde{\varepsilon}(T')) \times g_1(\tilde{\varepsilon}(T'))g_2(\tilde{\varepsilon}(T'))\Theta(\tilde{\varepsilon}(T') - V_{\mathrm{b}}) \times (1 + P_{\mathrm{H}_1}(\tilde{\varepsilon}(T')))(1 + P_{\mathrm{H}_2}(\tilde{\varepsilon}(T'))) \times \left[\frac{1 - P_{\mathrm{H}_1}(\tilde{\varepsilon}(T'))}{1 + P_{\mathrm{H}_1}(\tilde{\varepsilon}(T'))} + \frac{1 - P_{\mathrm{H}_2}(\tilde{\varepsilon}(T'))}{1 + P_{\mathrm{H}_2}(\tilde{\varepsilon}(T'))}\right], \tag{8}$$

where $g_i(\tilde{\varepsilon}(T'))$ is a spin averaged attenuation in the ferromagnetic layer. As one can understand from Eq. (6), the function $g_i(\tilde{\varepsilon}(T'))$ has no spin dependence. To analyze the hot electron magnetotransport, it is necessary to know the temperature and energy dependence of the hot electron spin polarization and inelastic mean free path. In the discussion of these issues, the hot electron inelastic mean free path varying the spin and energy in the ferromagnets [11] has been presented at zero temperature. In this theoretical calculation, various spin dependent inelastic scattering processes such as spin wave excitations, Stoner excitations, and spin non-flip scattering have been included. However, the temperature dependence of the hot electron inelastic mean free path and spin polarization at low energy have not been explored extensively either experimentally or theoretically to the author's knowledge so far. There is an example of a lifetime measurement for Co [12], but the experimental data do not contain the information of the temperature dependence. We will therefore take advantage of zero temperature calculations [11] and model the hot electron spin polarization at finite temperatures. For the $\Gamma_N \times (\tilde{\varepsilon}(T'))$, it is of importance to note that the attenuation of low energy electrons in the normal metal is around 100 Å [13]. This is several times greater than that calculated in the ferromagnets [11]. This may imply that the inelastic scattering in the ferromagnetic layers is important in the hot electron magnetotransport. Hence, we assume that the inelastic mean free path in a normal metal layer is constant within the temperature and energy ranges of our interest. We also replace the $\tilde{g}_i(\varepsilon(T'))$ by $\tilde{g}_i(\varepsilon(0))$. One can note that these two terms $\Gamma_N(\tilde{\varepsilon}(T'))$ and $\tilde{g}_i(\varepsilon(T'))$ enter into the parallel and anti-parallel collector simultaneously. Therefore, they have no influence on the spin dependent magnetotransport, save for the magnitude of the collector current. This property enables us to explore the parallel and anti-parallel collector current expressed below since our interests are the spin dependent magnetotransport and magnetocurrent at finite temperatures. Thus, we will explore the collector current which will be the maximum in magnitude of the collector current in the spin-valve transistor:

$$I^{P}(T) = \int_{\varepsilon_l}^{\varepsilon_u} d\varepsilon \int_0^T dT' D(\tilde{\varepsilon}(T'))\Gamma_N^3(\tilde{\varepsilon}(0)) \times g_1(\tilde{\varepsilon}(0))g_2(\tilde{\varepsilon}(0))\Theta(\tilde{\varepsilon}(T') - V_b) \times (1 + P_{H_1}(\tilde{\varepsilon}(T')))(1 + P_{H_2}(\tilde{\varepsilon}(T'))) \times \left[1 + \frac{1 - P_{H_1}(\tilde{\varepsilon}(T'))}{1 + P_{H_1}(\tilde{\varepsilon}(T'))}\frac{1 - P_{H_2}(\tilde{\varepsilon}(T'))}{1 + P_{H_2}(\tilde{\varepsilon}(T'))}\right] \quad (9)$$

and

$$I^{AP}(T) = \int_{\varepsilon_l}^{\varepsilon_u} d\varepsilon \int_0^T dT' D(\tilde{\varepsilon}(T'))\Gamma_N^3(\tilde{\varepsilon}(0)) \times g_1(\tilde{\varepsilon}(0))g_2(\tilde{\varepsilon}(0))\Theta(\tilde{\varepsilon}(T') - V_b) \times (1 + P_{H_1}(\tilde{\varepsilon}(T')))(1 + P_{H_2}(\tilde{\varepsilon}(T'))) \times \left[\frac{1 - P_{H_1}(\tilde{\varepsilon}(T'))}{1 + P_{H_1}(\tilde{\varepsilon}(T'))} + \frac{1 - P_{H_2}(\tilde{\varepsilon}(T'))}{1 + P_{H_2}(\tilde{\varepsilon}(T'))}\right]. \quad (10)$$

One can also easily obtain the magnetocurrent by the definition

$$\mathrm{MC}(T) = \frac{I^{P}(T) - I^{AP}(T)}{I^{AP}(T)}. \quad (11)$$

In this model we take the inelastic mean free path in the normal metal as 90 Å, and for the functions $g_i$ and $P_H$ in Eqs. (9) and (10) we will adopt the results presented in Ref. [11]. To mimic the structure reported in Ref. [6], the thickness of a normal metal layer has been taken as 35 Å. We assume that the first ferromagnetic layer is Ni with thickness 60 Å and Fe the second ferromagnetic layer with thickness 30 Å. Since the Schottky barrier heights have roughly 0.2 eV distribution [9], we take 0.8, 0.9, 1 eV for $\varepsilon_l$, $\varepsilon_m$, $\varepsilon_u$ in Eqs. (5), (9) and (10), respectively, and the Schottky barrier height at the collector is assumed to be 0.9 eV.

## 3. Results and discussions

We now discuss the results of model calculations. Fig. 1(A) presents the energy distribution of the hot electrons at zero temperature, and Fig. 1(B) displays the variation of the number of hot electrons which can contribute to the collector current due to the finite temperature effect. At zero temperature, only half of the injected electrons have higher energies than the collector barrier height, and can contribute to the collector current. With increasing temperature $T$ the number of hot electrons having higher energies than the barrier height increases as one can see from Fig. 1(B), therefore the collector current will also increase. For instance if there is no event to suppress the current due to, for instance, angle dependence at the interface [14] and various scattering processes in any layer, then the current will be increased by approximately 50% at room temperature compared with that of zero temperature case.

Fig. 2 presents the parallel and anti-parallel collector current as expressed in Eqs. (9) and (10) at finite temperatures. One can clearly see that the parallel and anti-parallel collector current behave differently at finite temperatures. The parallel collector current shows a different trend near 200 K, meanwhile the anti-parallel current increases up to room temperature. One should note the role of the hot electron spin polarization and the energy distribution of injected electrons at finite temperatures. As we can see from Fig. 1, the number of hot electrons which can contribute to

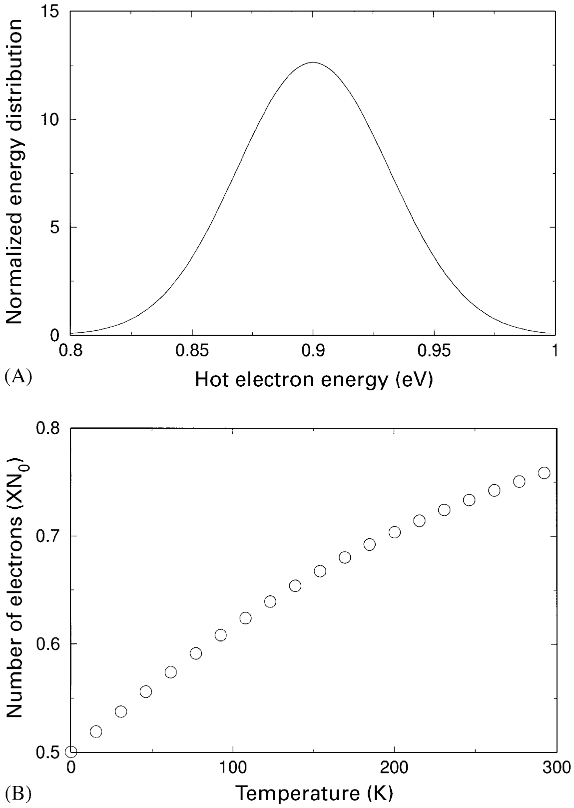


Fig. 1. (A) The normalized energy distribution of hot electrons at zero temperature. (B) The number of electrons which can contribute to the collector current due to finite temperature effect.

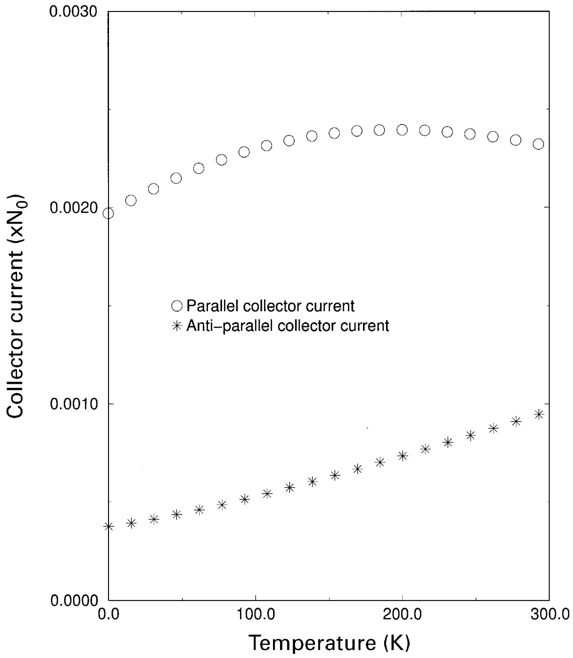


Fig. 2. The parallel and anti-parallel collector current with the hot electron spin polarization $P_{\mathrm{H}_i}(\tilde{\varepsilon}(T')) = P_{\mathrm{H}_i}(\tilde{\varepsilon}(0))(1-[T/T_c]^{3/2})$. The critical temperature has been taken as 1200 K for Fe and 630 K for Ni.

the collector current increases with temperature $T$, thus we can understand the increase of both the parallel and anti-parallel collector current. However, beyond 200 K the parallel and anti-parallel collector currents behave differently. We interpret this in terms of hot electron spin polarization. $1 - P_{\mathrm{H}_i}(\tilde{\varepsilon}(T'))$ and $1 + P_{\mathrm{H}_i}(\tilde{\varepsilon}(T'))$ in Eqs. (9) and (10) contribute to the collector current in the opposite way. $1 - P_{\mathrm{H}_i}(\tilde{\varepsilon}(T'))$ increases with temperature $T$ while $1 + P_{\mathrm{H}_i}(\tilde{\varepsilon}(T'))$ decreases with $T$, therefore they are competing each other and contribute differently to the collector current. As a result, the hot electron spin polarization tends to suppress the parallel collector current and enhance the anti-parallel collector current. Finally, the competition between the hot electron spin polarization and the redistribution of hot electron energy due to the finite temperature effect controls the collector current at finite temperatures. For the parallel collector current we note that the hot electron spin polarization has substantial influence on the collector current above 200 K since the collector current is expected to be approximately 50% higher than at room temperature from Fig. 1. Similarly, one can expect the same behaviour for the anti-parallel collector current. However, the anti-parallel collector current is increased more than would be expected from the results of Fig. 1. The overall behaviour of the parallel and anti-parallel collector current show the same trend as in Fig. 2 of Ref. [6]. Note from Fig. 2 that the output collector current is roughly $10^{-3}$ times smaller than the input current. Since the experimental data show [6] that the output collector current is approximately reduced by $10^{-6}$ times, these calculations suggest that the collector current will be reduced by three orders of magnitude in the non-magnetic part of the spin-valve. Interestingly,

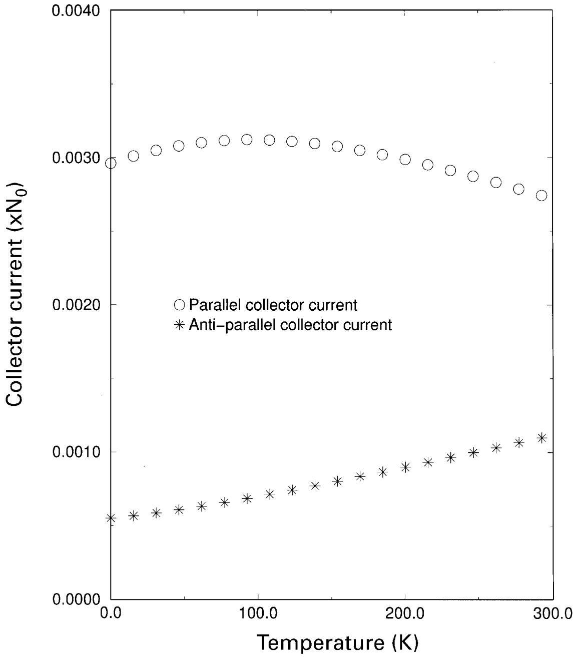


Fig. 3. The parallel and anti-parallel collector current with 0.1 eV width and 0.92 eV peak in emitter Schottky barrier.

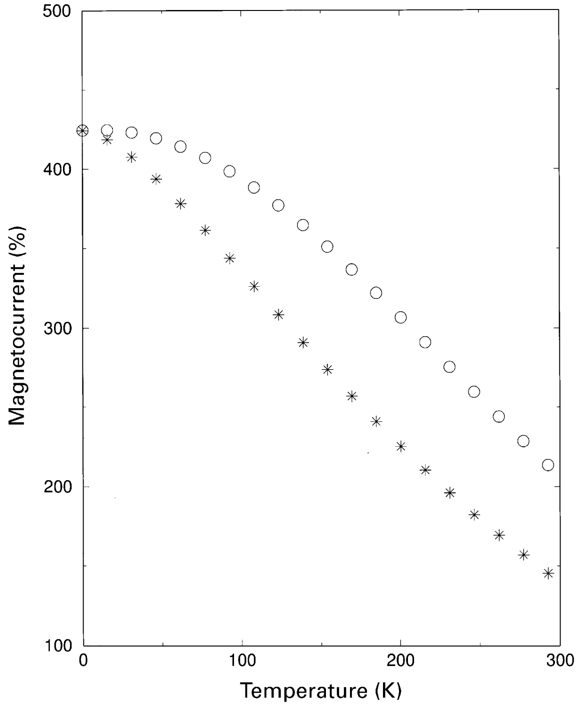


Fig. 4. The magnetocurrent at finite temperatures. The asterisk displays the case with $P_{H_i}(\tilde{\varepsilon}(T')) = P_{H_i}(\tilde{\varepsilon}(0))(1 - [T/T_c]^{3/2})$, and the circle is for $P_{H_i}(\tilde{\varepsilon}(T')) = P_{H_i}(\tilde{\varepsilon}(0))(1 - [T/T_c]^2)$.

the transfer ratio measurement of the non-magnetic transistor [10] shows approximately $10^{-3}$ reduction in the output collector current.

It is also of interest to explore the effect of spatial variation of Schottky barrier heights. We thus vary the width of Schottky barrier at the emitter and the most probable barrier height. Here, we take 0.92 eV for the peak of the barrier height and 0.1 eV for its width. Fig. 3 displays the spin dependent collector current with those parameters. If one compares this with Fig. 2, one can note that qualitative behaviour of the spin dependent hot electron magnetotransport has been changed. For instance, the parallel collector current starts to decrease near the temperature $T = 100\,\mathrm{K}$ and the anti-parallel collector current increases rather slowly compared to Fig. 2. We can understand this from the spatial distribution of the barrier heights. Since the large portion of the energy distribution of the injected hot electrons is already out of the collector barrier height, thus we have rather weak temperature dependence in the number of hot electrons whose energy is higher than the collector Schottky barrier height.

We now discuss the magnetocurrent. It is of interest to explore the hot electron spin polarization dependence of magnetocurrent. Hence, we display the magnetocurrent for two different cases in Fig. 4. Here, we take the same Schottky barrier parameter as in Fig. 2. The asterisk represents the magnetocurrent with $P_{H_i}(\tilde{\varepsilon}(T')) = P_{H_i}(\tilde{\varepsilon}(0))(1 - [T/T_c]^{3/2})$, and the circle is the case for $P_{H_i}(\tilde{\varepsilon}(T')) = P_{H_i}(\tilde{\varepsilon}(0))(1 - [T/T_c]^2)$. It should be pointed out that the magnitude of the magnetocurrent is affected even by a temperature independent factor if it has spin dependence, thus we need to look at the normalized magnetocurrent. Keeping this in mind, one can note that the magnetocurrent decreases with temperature $T$ monotonically, and agrees with the experimental data of Ref. [6] in the semi-quantitative manner if one normalizes the magnetocurrent at zero temperature. One can also see that the magnetocurrent is very sensitive to the temperature dependence of hot electron spin polarization.

In conclusion, the hot electron magnetotransport property has been studied theoretically including the influence of the hot electron spin polarization resulting from spin dependent self-energy in the ferromagnets and the energy redistribution of hot electrons due to spatial inhomogeneity of Schottky barrier heights at finite temperatures. We obtain that the parallel, antiparallel collector current, and magnetocurrent agree with experimental data semiquantitatively. In addition, we have presented that the qualitative behavior of the hot electron magnetotransport also depends on the spatial inhomogeneity of Schottky barrier heights. Hence, this implies that it is essential to explore the temperature and energy dependence of the inelastic scattering processes in the ferromagnetic layer as well as in the normal metal layer including the Schottky barrier effect for quantitative understanding.

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