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The contribution of hot-electron spin polarization to the spin-dependent magnetotransport in a spin-valve transistor at finite temperatures

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Abstract
The effect of spin mixing due to thermal spin waves and the temperature dependence of the hot-electron spin polarization to the collector current in a spin-valve transistor (SVT) has been theoretically explored. We calculate the spin dependence of the collector current as well as the temperature dependence of the magnetocurrent at finite temperatures to investigate the relative importance of the spin mixing and the hot-electron spin polarization. In this study the inelastic scattering events in ferromagnetic layers have been taken into account to explore our interests. The theoretical calculations suggest that the temperature dependence of the hot-electron spin polarization makes a substantial contribution to the spin-dependent magnetotransport at finite temperatures in the SVT.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Ultrathin magnetic multilayers exhibit unique properties not found in bulk materials. For example, the magnetic tunnelling junction (MTJ) [1] displays conductance strongly dependent on the relative orientation of the magnetization of the two ferromagnetic materials. Recently, the spin-valve transistor (SVT) [2] has been suggested as a new magnetoelectronic device, since a huge magnetic response for a very small applied field has been realized. This SVT has a very different structure [3] and transport property compared with the conventional MTJ. In a SVT, electrons injected into the metallic base across a Schottky barrier (emitter side) penetrate the spin-valve base and reach the opposite side (collector side) of the transistor. When these injected electrons traverse the spin valve, they are above the Fermi level of the metallic base. Therefore, *hot*-electron magnetotransport should be taken into account when one explores the collector current in a SVT.

When one discusses the transport of hot electrons in materials, one should note that the transport properties of hot electrons are different from those of Fermi electrons. For instance, in a MTJ, the spin polarization of the Fermi electrons substantially depends on the density of states at the Fermi level. In contrast, the *hot*-electron transport properties are related to the density of unoccupied states above the Fermi level, and this has an exponential dependence on the inelastic mean free path [4]. Indeed, this electron inelastic mean free path plays a very important role when one explores transport properties of hot electrons. For example, Pappas *et al* [5] measured a substantial spin asymmetry in the electron transmission through an ultrathin film of Fe deposited on Cu(100). This experiment implies that an understanding of the spin dependence of the inelastic mean free path is essential to the interpretation of the information obtained from spin-polarized probes. In view of this, theoretical calculations of the spin-dependent inelastic electron mean free path [6,7] have been presented. In these theoretical calculations, a substantial spin-dependent scattering rate was obtained. Along with this, the spin dependence of the scattering rate on varying the energy of the probe beam electrons was also explored. Generally, experimental data from spin-polarized electron spectroscopies have been interpreted in terms of Stoner excitations, where one discusses the spin-dependent electron inelastic mean free path. Interestingly, the importance of spin-wave excitations [8] in ferromagnetic Fe has been demonstrated experimentally, and theoretical calculations [7] also show that the spin-wave excitations contribute significantly to the inelastic mean free path at low energies (roughly up to 1 eV above the Fermi level). This experimental and theoretical evidence suggests that the properties of spin-wave excitations at low energy should be investigated in more detail in relation to the SVT, as the electron energy in a SVT is roughly 1 eV above the Fermi level.

For the SVT structure, Jansen *et al* [9] reported very interesting behaviours of the spin-dependent collector current at finite temperatures. The measured collector current across the spin valve shows unusual features depending on the relative orientation of the magnetic moment in the ferromagnetic layers at finite temperatures. When the magnetic moments are parallel in each layer, the collector current (parallel collector current) is increasing up to 200 K and decreasing beyond that temperature, while the anti-parallel collector current is increasing up to room temperature. Generally speaking, the scattering strength increases with temperature T in ordinary metals. This implies that any thermally induced scattering process enhances the total scattering. One then expects the observed collector current to be decreasing with increasing temperature T in any spin configuration of the SVT. Hence, the temperature dependence of the measured collector current may not be related to the ordinary scattering events in the metallic base. Two different processes are suggested to explain this observation for the SVT. One is the spatial distribution of the Schottky barrier. With increasing temperature T, electrons have more chance to overcome the Schottky barrier on the collector side because of the shift of the injected electron energy due to the thermal energy. This mechanism, however, cannot account for the temperature dependence of the collector current beyond 200 K. Besides, the Schottky barrier distribution does not have any spin dependence, and cannot affect the magnitudes of the parallel and anti-parallel collector currents differently. Thus, authors of [9] attribute the measured temperature dependence of the collector current to the spin-mixing effect due to thermal spin waves.

Along with this spin-mixing mechanism, we believe that *hot*-electron spin polarization may also have an influence on the spin dependence of the collector current [10] at finite temperatures. As shown in the [7], the inelastic scattering strength of hot electrons shows strong spin asymmetry at zero temperature in a ferromagnet. Now, if the temperature increases, then the spin asymmetry of the inelastic scattering strength will be reduced, since the magnetic moment will be decreasing. Thus, we believe that the spin asymmetry will be zero above a critical temperature. As a result, the spin-dependent hot-electron inelastic scattering strength will be temperature dependent and this temperature dependence may affect the hot-electron magnetotransport even in the absence of the spin-mixing effect. Thus, it will be of interest to estimate the relative importance of the spin mixing due to thermal spin waves and the hot-electron spin polarization to the spin dependence of the collector current at finite temperatures. Unfortunately, the hot-electron spin polarization at low energy (roughly speaking 1 eV above the Fermi level) has not been extensively explored. Although there is an example of lifetime measurement for Co [11] in the energy regime relevant to the SVT, it does not contain any data on the temperature dependence. In this calculation we therefore model the hot-electron spin polarization. This will be discussed below. Now, our main interest is in understanding what gives the substantial contribution to the behaviours of the parallel and anti-parallel collector currents at finite temperatures. Magnetocurrent may not be a useful quantity for our purposes, because magnetocurrent depends on the difference of the parallel and anti-parallel collector currents. In addition, it is also influenced by the magnitude of the anti-parallel collector current by the very definition of magnetocurrent [9]. Therefore, even a small change in parallel and anti-parallel collector currents may dramatically affect the magnetocurrent. We thus have to calculate both the parallel and the anti-parallel collector current to explore the issue raised in [9].

If one is interested in the absolute magnitude of the collector current, one obviously needs to take into account many spin-independent scattering events as well as spin-dependent scattering processes. Along with this, one may also consider angle dependence [12] even if electrons have enough energy to overcome the Schottky barrier on the collector side. In addition, the Schottky barrier height distribution [3] can also affect the magnitude of the collector current. Our interest, once again, is in understanding the effect of the spin mixing and the hot-electron spin polarization on the parallel and anti-parallel collector currents at finite temperatures. In view of this, we do not include the inelastic scattering effect in normal metal layers. An exponential dependence on the inelastic mean free path of the (both parallel and anti-parallel) collector currents [4] enables us to consider just the events in ferromagnetic layers when we focus on the issue raised in [9].

2. Model

A SVT has typically Si/N/F/N/F/N/Si structure [3] where N denotes normal metal, and F represents ferromagnetic metal, and we apply a bias voltage between the semiconductor and the normal metal. Thus, electrons are injected across the Schottky barrier into the spin-valve base. We now suppose that N_0 spin-up and spin-down electrons pass across the Schottky barrier per unit time per unit area. Since the Schottky barrier exists at the interface of normal metal and semiconductor, we do not expect any spin dependence when the hot electrons are injected into the normal metal on the emitter side. In addition, the hot electrons may not undergo any spin-dependent scattering in the normal metal. Therefore, the hot electrons are not spin polarized until they reach the first ferromagnetic layer in the spin-valve base. Since there is no spin dependence in the normal metal, we suppose that no hot electrons are lost during the propagation in the normal metal, as remarked earlier. Now, our interest is the hot-electron transport in the ferromagnets. Thus, we should explore the Green function, which describes the propagation of a hot electron with spin σ:

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

As we remarked earlier, the imaginary part of the proper self-energy $\Sigma_\sigma(\vec{k}, E)$, which is related to the inelastic mean free path, has substantial spin asymmetry in ferromagnets [6, 7]. Therefore, the hot electrons will be spin polarized after they penetrate the first ferromagnetic layer because the inelastic mean free path depends on the spin state. We now define $\gamma_{M\,(m)}(T)$ to take into account spin-dependent inelastic scattering in the ferromagnets at temperature T. This term describes attenuation of the current of hot electrons of spin up or spin down in the ferromagnet due to inelastic scattering. We can relate $\gamma_{M\,(m)}(T)$ to the inelastic mean free path by means of an expression such as $\gamma_{M\,(m)}(T) = \exp[-w/l_{M\,(m)}(T)]$ where $l_{M\,(m)}(T)$ is the inelastic mean free path of a majority- (minority-) spin electron in ferromagnetic material at temperature T, and w is the thickness of that material. For example, with initially N_0 injected electrons, $N_0\gamma_{M\,(m)}(T)$ electrons will pass the ferromagnetic layer if they are majority- (minority-) spin electrons. This $\gamma_{M\,(m)}(T)$ is related to the spin polarization of hot electrons. One should note that spin polarization of hot electrons enters into the spin-valve system, not that of Fermi electrons. Of course, we will have a self-energy contribution due to the elastic scattering process; however, as one can see from the experimental data [9], the output current has been suppressed roughly by six orders of magnitude; we thus only take into account the spin-dependent inelastic effect in this model calculation. One may need to consider the elastic scattering events as well if one wants to explore the hot-electron magnetotransport fully quantitatively.

The hot-electron spin polarization $P_{\rm H}(T)$ and spin-flip probability $P(T)$ are essential quantities for exploring our main topic. This spin-flip probability due to thermal spin-wave emission or absorption gives a spin-mixing effect. It has been shown in [6] that the scattering rates of both majority- and minority-spin electrons resulting from thermal spin-wave emission (for minority-spin electrons) and absorption (for majority-spin electrons) are virtually the same at low temperatures; thus the probabilities of spin flips caused by thermal spin-wave emission and absorption will have the same temperature dependence. If a spin-flip process is operating, the parallel collector current from spin-up source electrons can be calculated in the following way. $N_0\gamma_M(T)$ electrons penetrate the first ferromagnetic metal layer. Among these electrons, $N_0\gamma_M(T)(1 - P(T))$ electrons retain their spin-up state, and $N_0\gamma_M(T)(1 - P(T))\gamma_M(T)$ electrons will be collected in the spin-up state. Along with this, $N_0\gamma_M(T)P(T)$ electrons are created having the opposite spin state, resulting from the spin-flip process as well, and $N_0\gamma_M(T)P(T)\gamma_m$ electrons are collected in the spin-down state. Finally, the total number of collected electrons that are spin-up electrons becomes $N_0\{\gamma_M^2(T)(1 - P(T)) + \gamma_M(T)\gamma_m(T)P(T)\}$. One can follow the same scheme to calculate the contribution to the current from spin-down source electrons, and also readily obtain the expression for the anti-parallel collector current. We thus write the parallel collector current as

$$\tilde{I}_{\rm c}^{\rm P}(T, P(T)) = N_0\gamma_M^2(T)\left[\left\{1 + \left(\frac{\gamma_m(T)}{\gamma_M(T)}\right)^2\right\}(1 - P(T)) + 2\left(\frac{\gamma_m(T)}{\gamma_M(T)}\right)P(T)\right]. \quad (2)$$

Similarly, the anti-parallel collector current becomes

$$\tilde{I}_{\rm c}^{\rm AP}(T, P(T)) = N_0\gamma_M^2(T)\left[\left\{1 + \left(\frac{\gamma_m(T)}{\gamma_M(T)}\right)^2\right\}P(T) + 2\left(\frac{\gamma_m(T)}{\gamma_M(T)}\right)(1 - P(T))\right]. \quad (3)$$

As remarked earlier, we can relate $\gamma_M(T)$ and $\gamma_m(T)$ to the hot-electron spin polarization $P_{\rm H}(T)$ at finite temperatures. We write this as

$$\frac{\gamma_m(T)}{\gamma_M(T)} = \frac{1 - P_{\rm H}(T)}{1 + P_{\rm H}(T)}. \quad (4)$$

From this expression, most generally we express $\gamma_M(T)$ and $\gamma_m(T)$ as

$$\gamma_M(T) = g(T)(1 + P_{\rm H}(T)) \quad (5)$$

and

$$\gamma_m(T) = g(T)(1 - P_{\rm H}(T)) \quad (6)$$

where $g(T)$ is a function of temperature T. This function $g(T)$ enters into $\gamma_M(T)$ and $\gamma_m(T)$ simultaneously, so the detailed form of $g(T)$ does not have an impact on our work, except that of affecting the magnitudes of the parallel and anti-parallel collector currents expressed in equations (2) and (3). Therefore, when one explores the effect of the spin mixing and the temperature dependence of the hot-electron spin polarization on the collector current, depending on the relative spin orientation of the ferromagnetic layers, one can treat the function $g(T)$ simply as a prefactor. This enables us to explore the collector current, expressed below, in order to study the object of our interest in this work. By substitution equations (5) and (6) into (2) and (3), we obtain

$$I_{\mathrm{c}}^{\mathrm{P}}(T, P(T)) = N_0(1 + P_{\mathrm{H}}(T))^2\left[\left\{1 + \left(\frac{1 - P_{\mathrm{H}}(T)}{1 + P_{\mathrm{H}}(T)}\right)^2\right\}(1 - P(T)) + 2\frac{1 - P_{\mathrm{H}}(T)}{1 + P_{\mathrm{H}}(T)}P(T)\right] \tag{7}$$

and

$$I_{\mathrm{c}}^{\mathrm{AP}}(T, P(T)) = N_0(1 + P_{\mathrm{H}}(T))^2\left[\left\{1 + \left(\frac{1 - P_{\mathrm{H}}(T)}{1 + P_{\mathrm{H}}(T)}\right)^2\right\}P(T) + 2\frac{1 - P_{\mathrm{H}}(T)}{1 + P_{\mathrm{H}}(T)}(1 - P(T))\right]. \tag{8}$$

In these equations, we do not take into account the effect of $g(T)$ as explained above. One can also see that magnetocurrent satisfies the following property from the definition of magnetocurrent:

$$\mathrm{MC}(T, P(T)) \equiv \frac{I_{\mathrm{c}}^{\mathrm{P}}(T, P(T)) - I_{\mathrm{c}}^{\mathrm{AP}}(T, P(T))}{I_{\mathrm{c}}^{\mathrm{AP}}(T, P(T))} = \frac{\tilde{I}_{\mathrm{c}}^{\mathrm{P}}(T, P(T)) - \tilde{I}_{\mathrm{c}}^{\mathrm{AP}}(T, P(T))}{\tilde{I}_{\mathrm{c}}^{\mathrm{AP}}(T, P(T))}. \tag{9}$$

As we mentioned, the temperature dependence of the hot-electron spin polarization in the low-energy regime (roughly speaking, 1 eV above the Fermi level) has not been investigated actively. In our calculations, we examine two test cases:

$$P_{\mathrm{H}}(T) = P_0\left(1 - \left[\frac{T}{T_{\mathrm{c}}}\right]^{3/2}\right) \tag{10}$$

and

$$P_{\mathrm{H}}(T) = P_0\left(1 - \left[\frac{T}{T_{\mathrm{c}}}\right]\right) \tag{11}$$

where P_0 is the hot-electron spin polarization at zero temperature, and T_{c} is the critical temperature of the ferromagnetic metal of interest. In our calculations we take $T_{\mathrm{c}} = 650$ K to simulate pseudo-permalloy. We also assume that the spin-mixing probability $P(T)$ has a $T^{3/2}$-dependence on temperature T by virtue of the fact that number of thermal spin waves [6] is proportional to $T^{3/2}$. We then write this as $P(T) = cT^{3/2}$ where c is a parameter. In these calculations we limit the temperature ranges to from zero to room temperature ($T = 300$ K) as reported on in the experiment in [9]. If we define P_{r} as a spin-flip probability at room temperature (300 K), the parameter c in $P(T)$ can be written as $c = P_{\mathrm{r}}[1/300\ \mathrm{K}]^{3/2}$. One then can express $P(T)$ as $P(T) = P_{\mathrm{r}}[T/300\ \mathrm{K}]^{3/2}$. We take the maximum spin-flip probability to be at 300 K in our numerical calculations, to further our interests. (The maximum spin-flip probability is 0.5, and one can understand this from equations (2) and (3).)

3. Results and discussion

Now, we discuss the results of our model calculations. Figures 1(a) and (b) display the parallel and anti-parallel collector currents expressed by equations (7) and (8) without the

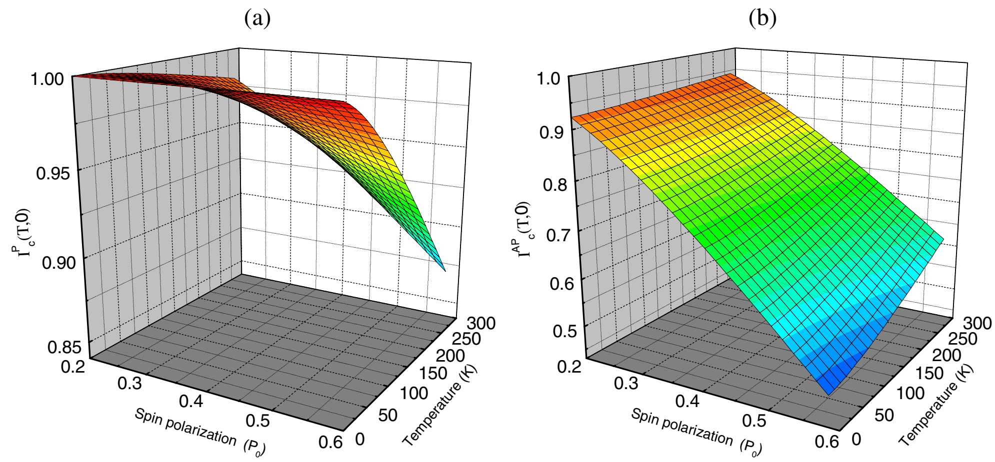

Figure 1. (a) The parallel collector current $I_c^P(T, 0)$ expressed by equation (6) with normalization at $T = 0$. Here, we take $P_H(T)$ as $P_H(T) = P_0(1 - [T/T_c]^{3/2})$. (b) The anti-parallel collector current $I_c^{AP}(T, 0)$ expressed in equation (7). This is the relative magnitude with respect to the parallel collector current. The same hot-electron spin polarization is taken into account.

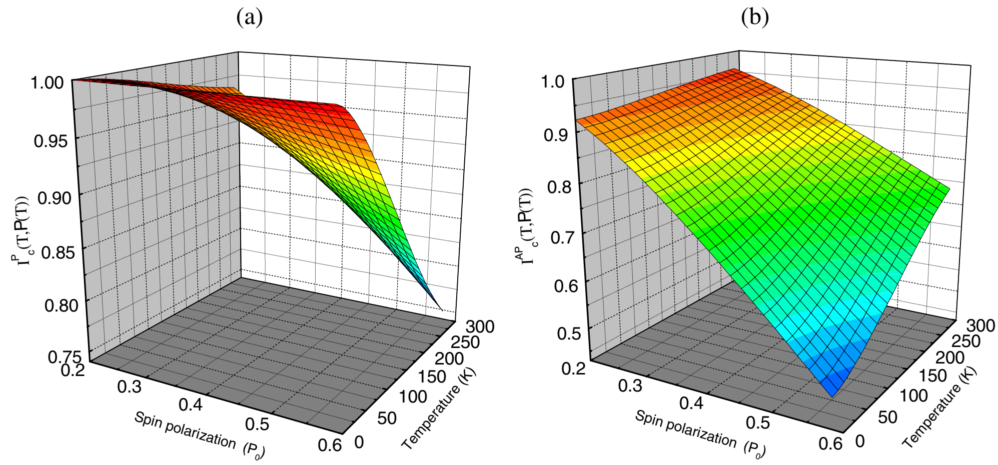

Figure 2. (a) The parallel collector current $I_c^P(T, P(T))$ expressed by equation (6) with normalization at $T = 0$ including the spin-mixing effect. $P_H(T) = P_0(1 - [T/T_c]^{3/2})$ is used in this calculation. (b) The anti-parallel collector current $I_c^{AP}(T, P(T))$ expressed by equation (7). This is the relative magnitude with respect to the parallel collector current. The same hot-electron spin polarization is used.

spin-mixing effect (here, $P(T) = 0$ and $P_H(T) = P_0(1 - [T/T_c]^{3/2})$. The parallel collector current is normalized at $T = 0$, and the anti-parallel collector current is the relative magnitude with respect to the parallel collector current. One can clearly see that the parallel collector current is decreasing, and the anti-parallel collector current is increasing with temperature T. $1 + P_H(T)$ and $1 - P_H(T)$ behave in opposite ways with temperature T. Thus, these two terms are competing with each other and contributing differently to the parallel and anti-parallel collector currents. Figures 2(a) and (b) represent the spin-dependent collector current including the spin-mixing effect with the same $P_H(T)$ as in figure 1. One can see that the parallel and anti-parallel collectors are changed upon including spin mixing.

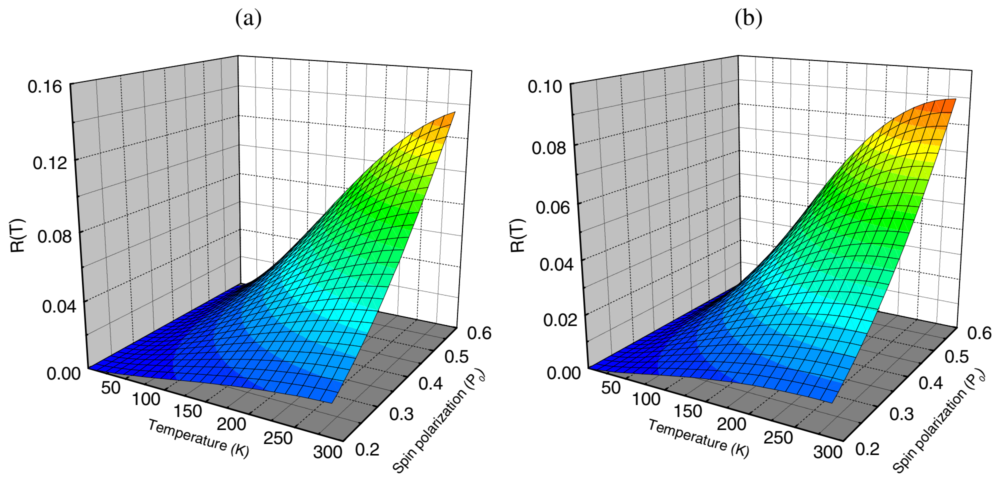

Figure 3. (a) The ratio $[I_c^P(T,0) - I_c^P(T,P(T))]/I_c^P(T,0)$ with $P_H(T) = P_0(1 - [T/T_c]^{3/2})$. (b) The same quantity as in (a), but with $P_H(T) = P_0(1 - [T/T_c])$.

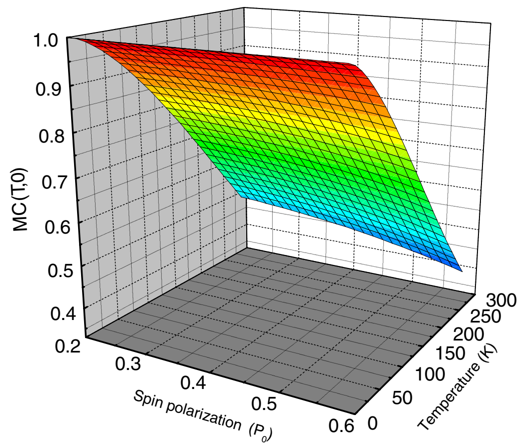

Figure 4. The magnetocurrent at finite temperatures without spin mixing. Here, we take $P_H(T) = P_0(1 - [T/T_c]^{3/2})$.

However, the deviation from the results in figure 1 is not substantial. To evaluate how much the collector current is influenced by introducing the spin-mixing effect, we calculate the quantity $R(T) = [I_c^P(T,0) - I_c^P(T,P(T))]/I_c^P(T,0)$. Figure 3(a) presents $R(T)$ with $P_H(T) = P_0(1 - [T/T_c]^{3/2})$, and figure 3(b) shows the case with $P_H(T) = P_0(1 - [T/T_c])$. From figures 3(a) and (b), we find that the parallel collector current has been changed by roughly 10% when $P_0 = 0.6$. For the anti-parallel collector, we obtain almost the same result. This implies that the substantial temperature dependence of the collector current depending on the relative spin orientation in the ferromagnetic layers can be explained by taking into account the hot-electron spin polarization, without introducing a spin-mixing mechanism. We interpret our results as follows. We estimate the wavevector of thermally excited spin waves by setting DQ_T^2 equal to $k_B T$; thus at room temperature $Q_T \approx 0.3$ Å^{-1} if we take $D \approx 400$ meV Å^2. This is a small fraction of the distance to the zone boundary. Therefore, only a few per cent of the Brillouin zone contains thermally excited spin waves. One should note that a $T^{3/2}$-dependence of the thermal spin waves is obtained if we integrate over the whole Brillouin zone. However, only a small volume of the Brillouin zone contributes to the thermal spin waves at room temperature; we therefore have an even weaker temperature dependence of thermal spin waves than the one that we have modelled in our work. As a result, the spin-mixing mechanism marginally contributes to both the parallel and the anti-parallel collector currents at finite temperatures. In figure 4, we present the magnetocurrent without the spin-mixing effect. Here, it should be pointed out that the magnitude of the MC itself even depends on temperature-independent quantities if they have spin dependence. Therefore we need to explore the normalized MC for our purposes in this work. We thus present the normalized MC at $T = 0$. One can see that the magnetocurrent also accords with the experimental data of [9] semi-quantitatively.

In conclusion, we have explored the collector current in a SVT at finite temperatures in order to gain an understanding of the influence of spin mixing due to the thermal spin waves and the temperature dependence of the hot-electron spin polarization on the collector current. We obtain that the hot-electron spin polarization contributes substantially to the spin dependence of the collector current at finite temperatures, unlike the effect of the spin mixing. Here, we do not claim that there is no spin-mixing mechanism due to thermal spin waves. Once again, when we discuss the relative importance of the spin mixing and the hot-electron spin-polarization effect on the collector current at finite temperatures, we suggest that majority of the temperature dependence of the collector current stems from the temperature dependence of the hot-electron spin polarization even if we have a spin-mixing process. Since the inelastic scattering strength of the hot electrons depends on the ferromagnetic material, as shown in [7], we expect the hot-electron spin polarization to be different for each ferromagnet. Therefore, we believe that experimentally one could test our results by measuring the temperature dependence of the MC while varying the type of ferromagnets in the spin-valve base. We hope that this work will stimulate further related studies on areas such as hot-electron spin polarization at finite temperatures and the temperature dependence of the electron inelastic mean free path at low energy.

References

[1] Moodera J S, Kinder L R, Wong T M and Meservey R 1995 *Phys. Rev. Lett.* **74** 3273

[2] Monsma D J, Lodder J C, Popma J A Th and Dieny B 1995 *Phys. Rev. Lett.* **74** 5260

[3] Anil Kumar P S, Jansen R, van't Erve O M J, Vlutters R, de Haan P and Lodder J C 2000 *J. Magn. Magn. Mater.* **214** L1

[4] Sze S M 1969 *Physics of Semiconductor Devices* (New York: Wiley)

[5] Pappas D P, Kämper K P, Miller B P, Hopster H, Fowler D E, Brundle C R, Luntz A C and Shen Z X 1991 *Phys. Rev. Lett.* **66** 504

[6] Hong Jisang and Mills D L 1999 *Phys. Rev.* B **59** 13 840

[7] Hong Jisang and Mills D L 2000 *Phys. Rev.* B **62** 5589

[8] Plihal M, Mills D L and Kirschner J 1999 *Phys. Rev. Lett.* **82** 2579

[9] Jansen R, Anil Kumar P S, van't Erve O M J, Vlutters R, de Haan P and Lodder J C 2000 *Phys. Rev. Lett.* **85** 3277

[10] Hong Jisang and Anil Kumar P S 2001 *J. Magn. Magn. Mater.* **234** 274

[11] Aeschlimann M, Bauer M, Pawlik S, Weber W, Burgermeister R, Oberli D and Siegmann H C 1997 *Phys. Rev. Lett.* **79** 5158

[12] Mizushima K, Kinno T, Tanaka K and Yamauchi T 1998 *Phys. Rev.* B **58** 4660