Modelling of magnetotransport of hot electrons in a spin-valve transistor

Jisang Hong[a)]
Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany

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This article explores the magnitude of spin dependent collector current in a spin-valve transistor varying the combination of ferromagnetic layers at finite temperatures. In these calculations, the spatial inhomogeneity of the Schottky barrier at the emitter side and spin dependent self-energy effect in ferromagnets have been taken into account. In addition, the magnetocurrent has been presented as well. It has been ascertained that the magnitude of spin dependent collector current strongly depends on the type of spin-valve base since the inelastic scattering strength is different in each material. These calculations may help find the best structural combination of ferromagnetic layers in the spin-valve base. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1461061]

I. INTRODUCTION

Magnetic multilayer structures provide many interesting phenomena. For instance, the magnetic tunneling junction (MTJ)[1] is being widely explored for the purpose of magnetoelectronic device. However, one difficulty for real device application in a MTJ is that the magnetoresistance decreases rapidly with applied bias voltage.[2] Interestingly, a new type of promising magnetoelectronic device, the so-called spin-valve transistor (SVT),[3] has been suggested by Monsma *et al.* as well. Unlike the conventional MTJ, one encounters different structure[4] and properties in this SVT. For instance, a SVT typically has a $Si/N_1/F_1/N_2/F_2/N_3/Si$ structure where $N_i(i=1...3)$ represents normal metal, and $F_i(i=1,2)$ stands for ferromagnetic layer. In this structure, electrons crossing the Schottky barrier (emitter side) penetrate the spin-valve base, and the energy of hot electrons is above the Fermi level of metallic base. Thus, *hot* electron magnetotransport should be taken into account when one explores the SVT.

In the magnetic tunneling junction, electrons near the Fermi level mostly contribute to the tunneling current, and spin polarization of these Fermi electrons strongly depends on the density of states near the Fermi level. In contrast, the *hot* electron transport is related to the density of unoccupied states above the Fermi level, and it has an exponential dependence on electron inelastic mean free path.[5] The exponential dependence on the inelastic mean free path results in many interesting features in a hot electron device such as the SVT (incorporated with magnetism). For instance, a collector current has strong sensitivity to the relative spin orientation in the ferromagnetic layers because of its exponential dependence on the inelastic mean free path, and magnetocurrent does not depend on any spin independent attenuation. These properties indicate that the SVT can be a very favorable candidate for a magnetoelectronic device. Very recently, Jansen *et al.*[6] reported the temperature dependence of collector current and magnetocurrent as a function of the relative spin orientation in the ferromagnetic layers. They obtained huge magnetocurrent even at room temperature and unusual temperature dependence of collector current. On the theory side, the role of hot electron spin polarization at a finite temperature has been explored to understand the spin dependence of hot electron magnetotransport.[7,8] According to these theoretical results, the spin dependent hot electron magnetotransport is substantially influenced by the hot electron spin polarization at finite temperatures.

As remarked earlier, the SVT has been suggested as another type of magnetoelectronic device for real applications. A major advantage of this structure is in the sensitivity of collector current to the relative spin orientation of the ferromagnetic layers because of an exponential dependence of the collector current on the inelastic mean free path. On the other hand, it has a serious difficulty for practical purposes since the output collector current is small. According to the measurement,[6] when the relative spin orientation of the ferromagnetic layers is parallel, the collector current (parallel collector current) is roughly 8–10 nA, and the antiparallel collector current is around 2–3 nA with 2 mA input current. Thus, a major effort in this area is to find the best structure for large output collector current. Bearing this in mind, we shall study the spin dependent collector current varying the combination of the ferromagnetic layers in the spin-valve base, and explore how the magnitude of current and Monte Carlo (MC) depend on the combination at finite temperatures.

II. MODEL

In these model calculations, the normal metal layers are considered to be the same material, hence, the focus of interest is on the magnetotransport in the ferromagnetic layers. As experimentally presented, the Schottky barrier has a spatial distribution,[9] thus one should take into account the effect of the Schottky barrier distribution phenomenologically. Here, one should note that the Schottky barrier exists at the interface of normal metal and semiconductor without any spin dependence, so that the spatial inhomogeneity of the Schottky barrier only effects the magnitude of the collector current with the same weight for a parallel and antiparallel

[a)]Electronic mail: hongj@uci.edu

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configuration. In addition, it does not change the MC. Now, the central issue of this work is to analyze the magnitude of the collector current and the magnetocurrent at finite temperatures changing the ferromagnetic layer combination. For the sake of argument, the SVT structure is denoted as F_1/F_2 because normal metal layers are not changed at all in the calculations of this model. The Fe/Fe, Ni/Fe, and Ni/Ni structures will be explored in this work because Fe has the largest magnetic moment, and Ni has the smallest one in $3d$ ferromagnetic transition metals.

Once the hot electrons start to penetrate the spin-valve base, one then needs to explore the Green's function $G_\sigma(\mathbf{k},E)$, which describes the propagation of the electron (spin up and spin down) in each material. One can write this as

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

Theoretical calculations of spin dependent self-energy[10] including the effect of spin wave excitations, Stoner excitations, and various spin–nonflip processes in ferromagnets, have been presented. The theoretical calculations show that the self-energy $\Sigma_\sigma(\mathbf{k},E)$ has a strong spin dependence in ferromagnets, so that the inelastic mean free path is spin dependent in the ferromagnetic materials. This author defines $\gamma_{M_i}(E,T)$ to describe the spin dependent inelastic scattering effect of majority spin electrons in ferromagnetic material F_i at finite temperatures and $\gamma_{m_i}(E,T)$ for minority spin electrons. One can write this as $\gamma_{M_i(m_i)}(E,T)=\exp[-w_i/l_{M_i(m_i)}(E,T)]$, where $l_{M_i(m_i)}(E,T)$ is the inelastic mean free path of majority (minority) spin electron in ferromagnetic layer F_i at temperature T, and w_i is the thickness of that material. One can also relate these $\gamma_{M_i}(E,T)$ and $\gamma_{m_i}(E,T)$ to the hot electron spin polarization. Definitely, there will be an attenuation when the hot electrons are passing through the normal metal layer N as well as ferromagnetic layer F_i. The author denotes the attenuation in the normal metal layer N as $\Gamma_N(E,T)$. As remarked herein, the current has an exponential dependence on the electron inelastic mean free path, therefore, the inelastic scattering effect in a normal metal layer has the same influence on any combination of ferromagnetic layers giving exactly the same contribution to the parallel and antiparallel collector current. This exponential dependence of the collector current on the inelastic mean free path enables us to focus only on the ferromagnetic layers. As remarked in the beginning, the issue of this work is the ferromagnetic layer dependence of hot electron magnetotransport at finite temperatures, thus interface scattering due to band mismatch[11] has not been considered in these calculations assuming weak temperature dependence.

Since the hot electrons are not spin polarized until they reach the first ferromagnetic layer, we therefore can say that $N_0/2$ spin up and spin down electrons are injected into the spin-valve base per unit time per unit area, respectively. Here, N_0 is the total number of injected hot electrons across the Schottky barrier including spin up and spin down. After they enter the ferromagnetic layer, the hot electrons will suffer from strong spin dependent inelastic scatterings. Since the inelastic scattering scattering rate depends on energy, one needs to know the energy distribution of the injected hot electrons at finite temperatures. Based on the Schottky barrier heights measurement,[9] in these calculations, one can 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 effects. From the experimental measurement of the Schottky barrier distribution[9] and according to Jansen *et al.*,[6] it is supposed that the hot electron has a $4k_BT$ distribution at temperature T, and one can write

$$\tilde{\epsilon}(T')=\epsilon+4k_BT', \tag{2}$$

where ϵ is the energy at zero temperature. Now, the energy distribution of injected hot electrons at finite temperature T is modeled as

$$D[\tilde{\epsilon}(T')]=\frac{N_0}{2}c_1\exp[-\alpha_1(\epsilon-\epsilon_m)^2]\times c_2\exp[-\alpha_2(4k_BT'/4k_BT)], \tag{3}$$

where the c_1 and c_2 are the normalization constants, ϵ_m is the energy of the maximum distribution at zero temperature, and α_1 and α_2 describe the width of the distribution.

Taking into account the inelastic scattering in the spin-valve base, one obtains the spin dependent parallel collector current

$$I^P(T)=\int_{\epsilon_l}^{\epsilon_\mu}d\epsilon\int_0^T dT'D[\tilde{\epsilon}(T')]\Gamma_N^3[\tilde{\epsilon}(T')]\gamma_{M_1}[\tilde{\epsilon}(T')]\times\gamma_{M_2}[\tilde{\epsilon}(T')]\times\left[1+\frac{\gamma_{m_1}[\epsilon(\tilde{T}')]}{\gamma_{M_1}[\epsilon(\tilde{T}')]}\frac{\gamma_{m_2}[\epsilon(\tilde{T}')]}{\gamma_{M_2}[\epsilon(\tilde{T}')]}\right]\times t[\tilde{\epsilon}(T'),V_b]\Theta[\tilde{\epsilon}(T')-V_b], \tag{4}$$

and the antiparallel collector current is

$$I^{AP}(T)=\int_{\epsilon_l}^{\epsilon_\mu}d\epsilon\int_0^T dT'D[\tilde{\epsilon}(T')]\Gamma_N^3[\tilde{\epsilon}(T')]\gamma_{M_1}[\tilde{\epsilon}(T')]\times\gamma_{M_2}[\tilde{\epsilon}(T')]\times\left[\frac{\gamma_{m_1}[\epsilon(\tilde{T}')]}{\gamma_{M_1}[\epsilon(\tilde{T}')]}+\frac{\gamma_{m_2}[\epsilon(\tilde{T}')]}{\gamma_{M_2}[\epsilon(\tilde{T}')]}\right]\times t[\tilde{\epsilon}(T'),V_b]\Theta[\tilde{\epsilon}(T')-V_b], \tag{5}$$

where $t[\tilde{\epsilon}(T'),V_b]$ describe the quantum mechanical transmission probability in the presence of a potential barrier V_b. One can rewrite the aforementioned expressions in terms of hot electron spin polarization[7]

$$I^P(T)=\int_{\epsilon_l}^{\epsilon_\mu}d\epsilon\int_0^T dT'D[\tilde{\epsilon}(T')]\Gamma_N^3[\tilde{\epsilon}(T')]g_1[\tilde{\epsilon}(T')]\times g_2[\tilde{\epsilon}(T')]\Theta[\tilde{\epsilon}(T')-V_b]\times\{1+P_{H_1}[\tilde{\epsilon}(T')]\}\times\{1+P_{H_2}[\tilde{\epsilon}(T')]\underline{\ast} t[\tilde{\epsilon}(T'),V_b]\}\times\times\left[1+\frac{1-P_{H_1}[\tilde{\epsilon}(T')]}{1+P_{H_1}[\tilde{\epsilon}(T')]}\frac{1-P_{H_2}[\tilde{\epsilon}(T')]}{1+P_{H_2}[\tilde{\epsilon}(T')]},\right. \tag{6}$$

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$$I^{AP}(T)=\int_{\epsilon_l}^{\epsilon_\mu}d\epsilon\int_0^T dT' D[\tilde{\epsilon}(T')]\Gamma_N^3[\tilde{\epsilon}(T')]g_1[\tilde{\epsilon}(T')]$$
$$\times g_2[\tilde{\epsilon}(T')]\Theta[\tilde{\epsilon}(T')-V_b]$$
$$\times\{1+P_{H_1}[\tilde{\epsilon}(T')]\}1+P_{H_2}[\tilde{\epsilon}(T')]\}t[\tilde{\epsilon}(T'),V_b]$$
$$\times\left[\frac{1-P_{H_1}[\tilde{\epsilon}(T')]}{1+P_{H_1}[\tilde{\epsilon}(T')]}+\frac{1-P_{H_2}[\tilde{\epsilon}(T')]}{1+P_{H_2}[\tilde{\epsilon}(T')]}\right], \quad (7)$$

where $g_i[\tilde{\epsilon}(T')]$ is a spin averaged attenuation in the ferromagnetic layer, and $P_{H_2}[\tilde{\epsilon}(T')]$ is the hot electron spin polarization. Then, one can easily obtain the MC by the definition

$$MC(T)=\frac{I^P(T)-I^{AP}(T)}{I^{AP}(T)}. \quad (8)$$

For a quantitative analysis of the hot electron magnetotransport, it is necessary to know the temperature dependence of the inelastic mean free path in the ferromagnetic layers as well as in the normal metals. Unfortunately, no adequate reliable data is available. Here, it is of importance to note that the attenuation of low energy electron in the normal metal is around 100 Å.[12] It is several times greater than that in the ferromagnets.[10] This implies that the inelastic scattering in the ferromagnetic layers enters importantly into the magnetotransport. Hence, in these model calculations, it is assumed that the attenuation in the normal metal is constant within the energy and temperature of interest. This author also takes the spin averaged quantity $g_i(E,T)$ at $T=0$.

III. RESULTS AND DISCUSSION

From the experimental measurement of the Schottky barrier height, the author chose 0.2 eV width in the energy distribution at zero temperature taking 0.9 eV as an energy of maximum distribution, and the collector Schottky barrier height is assumed to be 0.87 eV. 90 Å was taken for inelastic mean free path in the normal metal layer with thickness 35 Å. The thickness of the first and second ferromagnetic layers is 60 Å and 30 Å, respectively. We take advantage of the theoretical results in Ref. 10 for the spin averaged attenuation in the ferromagnetic layers. Since the temperature and energy dependence of hot electron spin polarization is not clearly understood neither theoretically nor experimentally so far, we model the hot electron spin polarization. Since the number of thermal spin waves is proportional to $T^{3/2}$, $P_H(E,T)=P_0(E)(1-[T/T_C]^{2/3})$ was taken, where $P_0(E)$ is the hot electron spin polarization at zero temperature, and T_C is the critical temperature of ferromagnetic material. The T_C for Ni and Fe has been taken as 630 K and 1200 K, respectively.

The results of the model calculations are now discussed. Presented is the spin dependent collector current for various combinations of the ferromagnetic layer in the spin-valve base from Figs. 1–3. One can see that the parallel and antiparallel collector current behave differently with temperature T in any combination. Since the experimental measurement[6] has been made with $Ni_{80}Fe_{20}$/Co spin-valve base, the theoretical calculations with Ni/Fe base in Fig. 2 may be the most relevant structure to the experimental reality, if one wants to compare the results with the experimental data. For instance,

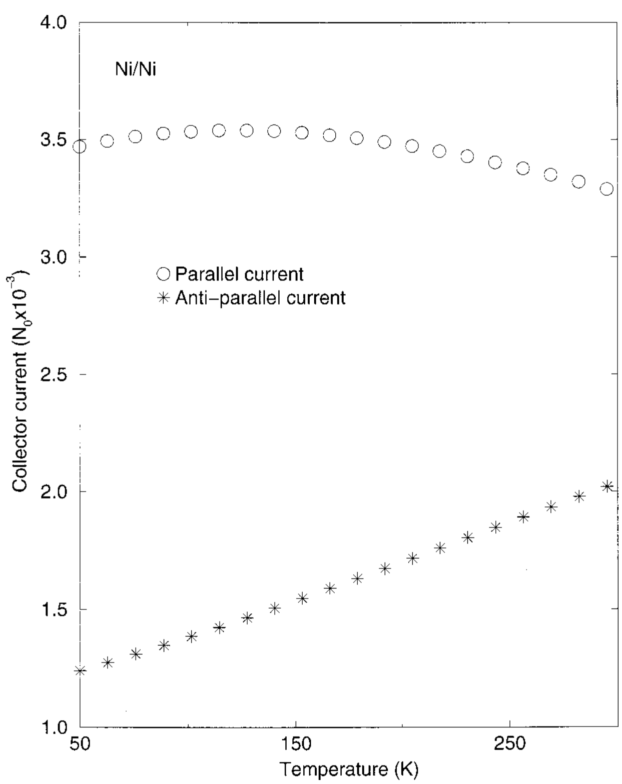

FIG. 1. Temperature dependence of parallel and antiparallel collector current with Ni/Ni base.

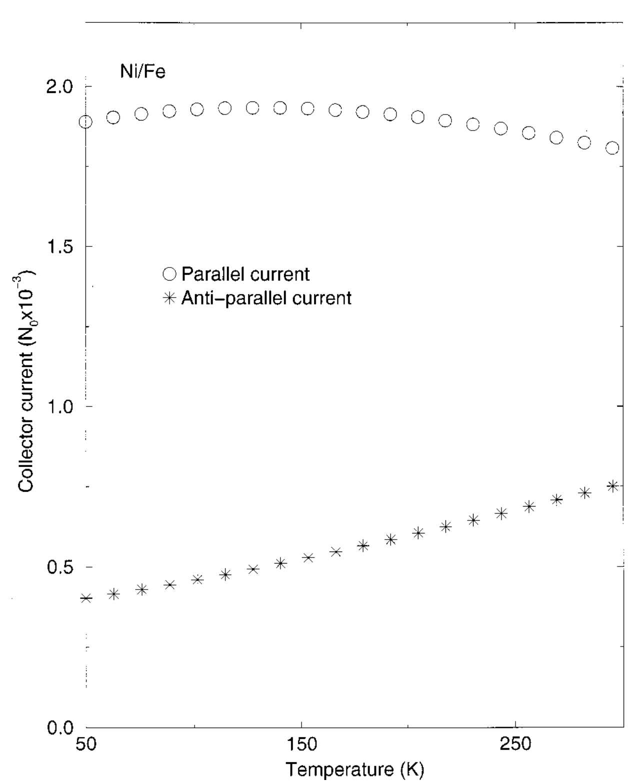

FIG. 2. Temperature dependence of parallel and antiparallel collector current with Ni/Fe base.

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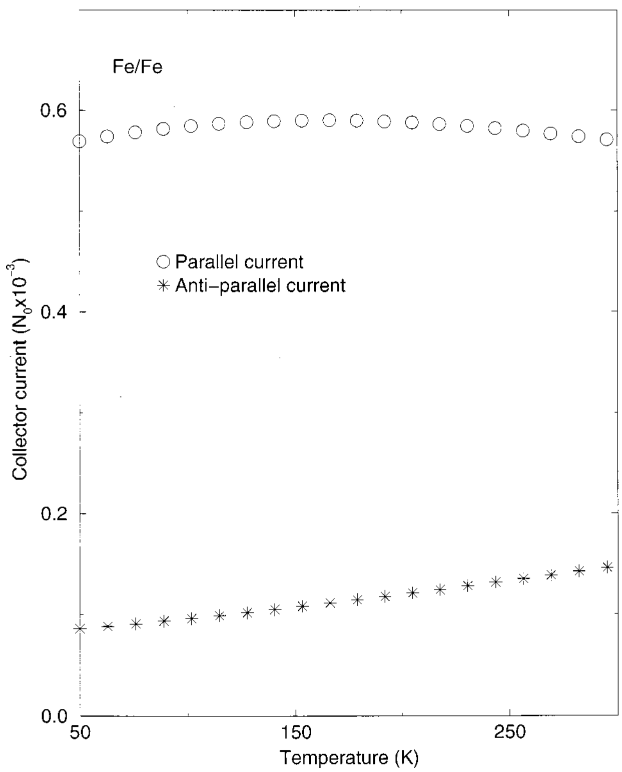

FIG. 3. Temperature dependence of parallel and antiparallel collector current with Fe/Fe base.

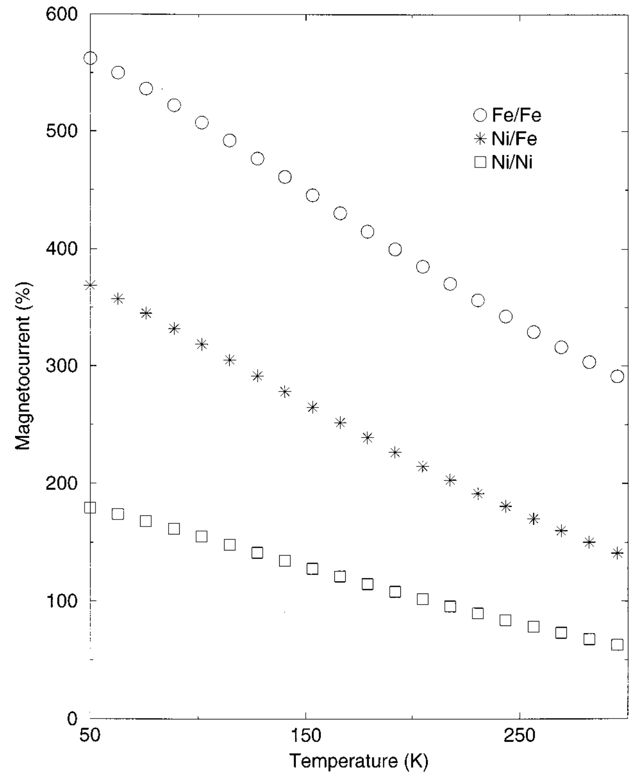

FIG. 4. Temperature dependence of magnetocurrent with various combination of ferromagnetic layers in the base.

parallel collector current increases up to around 150 K and starts to decrease beyond it while the antiparallel collector current increases up to room temperature. With different ferromagnetic layers in the base, one also obtains almost the same temperature dependence. This feature is attributed to the effect of hot electron spin polarization. The role of hot electron spin polarization has been well explained in Refs. 7 and 8. Now, the interest of this author is in the the magnitude of the collector current for different combinations since for application purposes the magnitude of collector current has been one of the main issues in the SVT. One can clearly see that the largest collector current can be obtained from Ni/Ni as shown in the Fig. 1, while the Fe/Fe structure in Fig. 3 produces the smallest collector current. For example, the antiparallel collector current of Ni/Ni base is greater by almost one order of magnitude compared with that of the Fe/Fe base. For parallel current, the author also obtained a similar trend. This was interpreted in terms of spin dependent inelastic mean free path in the ferromagnetic materials. As presented in Ref. 10, the hot electron has a very stronger inelastic scattering strength in Fe than in Ni. Thus, the inelastic mean free path in Fe is shorter than in Ni, therefore the Ni/Ni combination produces the largest collector current. Figure 4 represents the magnetocurrent at finite temperatures. The Ni/Ni combination displays the smallest magnetocurrent and the most rapid temperature variation while we obtain the largest output collector current. In contrast, the Fe/Fe has the opposite property. This temperature dependence of magnetocurrent can be understood in terms of hot electron spin polarization at finite temperatures. Since the critical temperature of Fe is roughly twice that of Ni, the hot electron spin polarization varies rapidly in Ni compared to Fe.

In conclusion, the spin dependent collector current and magnetocurrent as a function of the ferromagnetic layer combination have been explored. It was ascertained that the Ni/Ni combination produces the largest output collector current. The magnetocurrent shows the most rapid temperature variation with the smallest magnitude. The Fe/Fe structure has the opposite property. Since the magnitude of the collector current has been one of the issues in the SVT for practical applications, it is intended that this work will stimulate experimental investigation.

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