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Temperature dependence of magnetocurrent in spin-valve transistor: a phenomenological study

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Abstract

The temperature dependence of magnetocurrent in the spin-valve transistor has been theoretically explored based on phenomenological model. We find that temperature dependence of the collector current strongly depends on the relative orientation of magnetic moment of ferromagnetic metals due to spin mixing effect. For example, the parallel collector current is decreasing with increasing temperatures, while the anti-parallel collector current is increasing. We then obtain decreasing magnetocurrent with increasing temperatures. The result accords with the experimental data in qualitative manner. Along with this, we find that temperature dependence of hot electron spin polarization can also contribute to the magnetocurrent at finite temperatures. This phenomenological model calculations suggest that it is essential to understand the relative importance of spin mixing effect and hot electron spin polarization in the spin-valve transistor at finite temperatures. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

After its discovery of giant magneto resistance (GMR) [1] in magnetic multilayer structure, it has been extensively studied in relation to the magnetic tunneling junction (MTJ). Very recently, a new type of potential magneto electronic device, the so called spin-valve transistor, is suggested [2] as well. In the conventional ferromagnetic tunneling junction structure, spin dependent transport property of electron near the Fermi level has been explored. Unlike the magnetic tunneling junction, the spin-valve transistor (SVT) has different structure [3]. In a SVT, electrons injected into the metallic base across a Schottky barrier (emitter side) pass through the spin-valve and reach the opposite side (collector side) of transistor. When these injected electrons traverse the metallic base electrons are above the Fermi level. Hence, hot electron magnetotransport should be considered in the spin-valve transistor.

The transport property of hot electrons may be different from that of Fermi electrons. For instance, spin polarization of Fermi electrons mainly depends on the density of states at the Fermi level, while the spin polarization of *hot*

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electron is related to the density of unoccupied states above the Fermi level. One can probably interpret the spin polarization of hot electrons in terms of inelastic mean free path. In ferromagnetic materials, clearly inelastic mean free path of probe beam electron is spin dependent. For example, Pappas et al. [4] measured substantial spin asymmetry in the electron transmission through ultrathin film of Fe deposited on Cu (1 0 0). This implies that understanding of spin dependence of the inelastic mean free path is essential to the interpretation of the information obtained from spin polarized probe. Most of cases, energy of probing beam electron, roughly speaking, ranges from several eV above the Fermi level, and experimental data are interpreted in terms of Stoner excitations. Interestingly, in relation to the hot electron transport property, substantial scattering contribution from spin wave excitations at low energy in ferromagnetic Fe [5] was reported experimentally, and also theoretical calculations [6,7] showed the same result. Based on these works, we believe that spin polarization of hot electron at low energy is strongly influenced by spin wave excitations. Nevertheless, transport property of hot electron is not fully understood at very low energy regime at finite temperatures. It is necessary to probe the temperature dependence of the hot electron transport property in relation to the spin-valve transistor (for example, within 1 eV range from the Fermi level).

Jansen et al. reported very interesting experimental measurement at finite temperatures [8] in the spin-valve transistor. They measured collector current across the spin-valve changing the relative orientation of magnetic moment at finite temperatures. Surprisingly, they found out that the collector current showed very different behaviors at finite temperatures strongly depending on the relative spin orientation in ferromagnetic layers. The parallel collector current is increasing up to 200 K and decreasing after that, while the anti-parallel collector current is increasing up to room temperature. We believe that scattering strength increases with temperature T in ordinary metals. This implies that any thermally induced scattering process enhances the total scattering. One then expects that measured current will be decreasing with increasing temperature T in any configuration. As the authors of Ref. [8] commented, the increase of collector current with temperature T may not be related to the ordinary scattering events in the metallic base. Two different mechanisms are suggested by the authors of Ref. [8]. One is the spatial distribution of Schottky barrier height. Authors of Ref. [8] claim that this may explain the behaviors of both parallel and anti-parallel collector current up to 200 K because thermal energy contributes to overcome the Schottky barrier height at collector side with increasing temperature T. However, beyond that temperature regime the parallel collector current is decreasing, in the mean time the anti-parallel collector current is still increasing. Furthermore, this mechanism is not related to any spin dependent property, but only for the absolute magnitude of both parallel and anti-parallel collector current. Therefore, authors of Ref. [8] attribute the measured temperature dependence of magnetocurrent to the spin mixing effect. Basically spin mixing is spin-flip process by thermal spin wave emission or absorption at finite temperatures [8]. For example, majority (minority) electron can flip its spin by absorbing (emitting) thermal spin wave, and then it goes into spin down (up) channel. In this paper we will focus our efforts on the temperature dependence of magnetocurrent at finite temperatures due to thermal spin wave emission and absorption to investigate the issue raised in Ref. [8]. Along with that, the effect of hot electron spin polarization at finite temperatures will be also discussed.

2. Phenomenological model

Spin-valve transistor has typically Si/N/F/N/F/N/Si structure [3] where N denotes normal metal, and F represents ferromagnetic metal assuming the same ferromagnetic materials. Since the injected electrons across the Schottky barrier at the emitter side are not spin polarized before they penetrate the first ferromagnetic layer the number of spin up and spin down electrons will be the same. Then, we can say that N_0 spin up and spin down electrons are prepared, respectively. When these electrons penetrate magnetic layer some of injected source electrons will be lost due to inelastic scattering effect in spin-valve base. We introduce $\gamma_{\mathrm{M(m)}}(T)$ to describe the inelastic scattering effect in ferromagnetic layer for majority (minority) spin electrons. The $\gamma_{\mathrm{M(m)}}(T)$ can be expressed as $\gamma_{\mathrm{M(m)}}(T) = \exp[-w/l_{\mathrm{M(m)}}(T)]$ where $l_{\mathrm{M(m)}}(T)$ is an inelastic mean free path of majority (minority) spin electron in ferromagnetic material at temperature T, and w is the width of that material. With initial N_0 source electrons $N_0\gamma_{\mathrm{M(m)}}(T)$ electrons will penetrate the ferromagnetic layer if they are majority (minority) spin electrons. This $\gamma_{\mathrm{M(m)}}(T)$ is related to the spin polarization of hot electrons. One should note that spin polarization of hot electrons enters in the spin-valve system, not that of Fermi electrons. There is an example for hot electron lifetime of Co [9] at very low energy (roughly speaking, 1 eV above the Fermi level). Temperature dependence of hot electron spin polarization, however, is not clearly understood either in theoretically or experimentally at low energies. The central issue of this paper is in understanding the temperature dependence of magnetocurrent by thermal spin wave emission or absorption along with the effect of hot electron spin polarization. If one is interested in the absolute magnitude of the collector current one obviously needs to take into account many spin dependent scattering events as well as spin independent scattering processes. In addition, one also has to consider angle dependence [10] even if electrons have enough energy to overcome the Schottky barrier at the collector side. When we explore temperature dependence of magnetocurrent we do not include any spin and temperature independent processes because all these factors are not relevant to the temperature dependence of magnetocurrent.

We remark again that the issue here is the temperature dependence of magnetocurrent due to spin mixing effect and hot electron spin polarization at finite temperatures. In that spirit we suppose that spin-flip probability, expressed as $P(T)$, by thermal spin wave emission or absorption at finite temperatures is proportional to $T^{3/2}$ by virtue of fact that the number of spin waves at finite temperature are proportional to $T^{3/2}$. It is shown in Ref. [6] that scattering rate of both majority and minority spin electron resulting from thermal spin wave emission and absorption is virtually the same at low temperatures. In our calculations we accept the results of Ref. [6], then one can understand that the spin-flip probability from thermal spin wave emission and absorption will have the same form. Without spin-flip process, the parallel collector current from spin-up electrons is $N_0\gamma_{\mathrm{M}}^2(T)$, and the current from spin-down electrons is $N_0\gamma_{\mathrm{m}}^2(T)$. In the anti-parallel case, the current from spin-up and spin-down electrons becomes $N_0\gamma_{\mathrm{M}}(T)\gamma_{\mathrm{m}}(T)$, respectively. In the above, it is assumed that there is no attenuation in normal metal layers so that no electron is lost within those layers. By the virtue of the fact that collector current has an exponential dependence on the electron inelastic mean free path due to the hot electron transport property [11], any spin independent attenuation length does not contribute to temperature dependence of magnetocurrent (MC) even if the attenuation length has temperature dependence. From this property of hot electron, we can assume that there is no attenuation in normal metal layer when we explore temperature dependence of magnetocurrent. If spin-flip process is operating by thermal spin wave emission or absorption at finite temperatures, the parallel collector current from spin-up source electrons can be calculated in the following way. $N_0\gamma_{\mathrm{M}}(T)$ electrons penetrate the first ferromagnetic metal layer. Among these electrons, $N_0\gamma_{\mathrm{M}}(T)(1-P(T))$ electrons keep their spin-up state, and $N_0\gamma_{\mathrm{M}}(T)(1-P(T))\gamma_{\mathrm{M}}$ electrons will be collected with spin-up state. In the mean time $N_0\gamma_{\mathrm{M}}(T)P(T)$ electrons are created having the opposite spin state resulting from spin-flip process, and $N_0\gamma_{\mathrm{M}}(T)P(T)\gamma_{\mathrm{m}}(T)$ electrons are collected with the spin-down. Finally, the total number of collected electrons from the initial N_0 spin-up source electrons become $N_0\{\gamma_{\mathrm{M}}^2(T)(1-P\times(T))+\gamma_{\mathrm{M}}(T)\gamma_{\mathrm{m}}(T)P(T)\}$. One can follow the the same scheme to calculate the contribution to the current from spin-down source electrons. $N_0\gamma_{\mathrm{m}}(T)$ electrons penetrate the first layer, then $N_0\gamma_{\mathrm{m}}(T)(1-P(T))\gamma_{\mathrm{m}}(T)$ electrons are collected with spin-down. Meanwhile, $N_0\gamma_{\mathrm{m}}(T)P(T)$ electrons have opposite spin state (spin-up state). These now become the majority spin electrons to the second layer, and $N_0\gamma_m(T)(1-P(T))\gamma_M(T)$ electrons are collected. Then, the contribution to the current from spin-down source electrons become $N_0\{\gamma_m^2(T)(1-P(T))+\gamma_M(T)\gamma_m(T)P(T)\}$. Following the similar way, one can obtain the expression for anti-parallel collector current. The anti-parallel collector current then becomes $N_0\{\gamma_M(T)\gamma_m(T)\ (1-P(T))+\gamma_M(T)\gamma_M(T)P(T)\}$, and $N_0\{\gamma_M(T)\gamma_m(T)(1-P(T))+\gamma_m(T)\gamma_m(T)P(T)\}$ from spin-up and spin-down source electrons, respectively. As mentioned above, $P(T)$ describes spin-flip probability by thermal spin wave emission or absorption at finite temperatures, which is assumed to be $P(T)=cT^{3/2}$. Here c is a parameter, and $P(T)\leqslant 1$ should be satisfied for any temperature T. In our calculations we limit the temperature ranges from zero to room temperature ($T=300\,\mathrm{K}$). With this limitation we write the spin flip probability $P(T)$ in another way. If we assume finite spin flip probability at room temperature ($T=300\,\mathrm{K}$), expressing P_r, the parameter c in $P(T)$ can be written as $c=P_\mathrm{r}\times[1/300\,\mathrm{K}]^{3/2}$. We then write the $P(T)$ as $P(T)=P_\mathrm{r}\times[T/300\,\mathrm{K}]^{3/2}$. Now, the total collector current in parallel case influenced by spin-flip process due to thermal spin wave emission and absorption becomes

$$I_c^\mathrm{P}(T)=N_0\gamma_\mathrm{M}^2(T)\left[\left\{1+\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)^2\right\}(1-P(T))+2\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)P(T)\right]. \quad (1)$$

Similarly, the anti-parallel collector current is

$$I_c^\mathrm{AP}(T)=N_0\gamma_\mathrm{M}^2(T)\left[\left\{1+\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)^2\right\}P(T)+2\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)(1-P(T))\right]. \quad (2)$$

With the expression of collector current, one can readily obtain the magnetocurrent (MC) defined [8] as

$$\mathrm{MC}(T)=\frac{I_c^\mathrm{P}(T)-I_c^\mathrm{AP}(T)}{I_c^\mathrm{AP}(T)}. \quad (3)$$

As mentioned earlier, one can easily relate phenomenological parameter $\gamma_{\mathrm{M(m)}}(T)$ to hot electron spin polarization $P_\mathrm{H}(T)$ in such a way

$$\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}=\frac{1-P_\mathrm{H}(T)}{1+P_\mathrm{H}(T)}. \quad (4)$$

Generally speaking, hot electron spin polarization will be temperature dependent. This implies that $\gamma_{\mathrm{M(m)}}(T)$ is also temperature dependent. It will be also of interest to explore the magnetocurrent at finite temperatures due to temperature dependence of hot electron spin polarization. Relating with this issue, as remarked earlier, we do not have enough information of hot electron spin polarization at finite temperatures. Therefore, We only test very simple case such as $P_\mathrm{H}(T)=P_0\ (1-(T/T_\mathrm{c})^{3/2})$. Here, P_0 is spin polarization of hot electron at $T=0$, and T_c is critical temperature of ferromagnetic metal. If one supposes that hot electron spin polarization is temperature independent one can obtain scaled collector current which is divided by $N_0\gamma_\mathrm{M}^2(T)$ even without knowing that prefactor. We express the scaled collector current as

$$\tilde{I}_c^\mathrm{P}(T)=\left[\left\{1+\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)^2\right\}(1-P(T))+2\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)P(T)\right]. \quad (5)$$

$$\tilde{I}_c^\mathrm{AP}(T)=\left[\left\{1+\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)^2\right\}P(T)+2\left(\frac{\gamma_\mathrm{m}(T)}{\gamma_\mathrm{M}(T)}\right)(1-P(T))\right]. \quad (6)$$

One also easily obtain MC. If we include temperature dependence of hot electron spin polarization, then we are not able to calculate collector currents I_c^P and I_C^AP separately because we have unknown prefactor γ_M in Eqs. (1) and (2). Fortunately, even in this case we can still calculate temperature dependence of MC because of the cancellation of unknown prefactor γ_M.

3. Results and discussion

We now discuss the results of our model calculations. First, we explore the case when the hot electron spin polarization is temperature

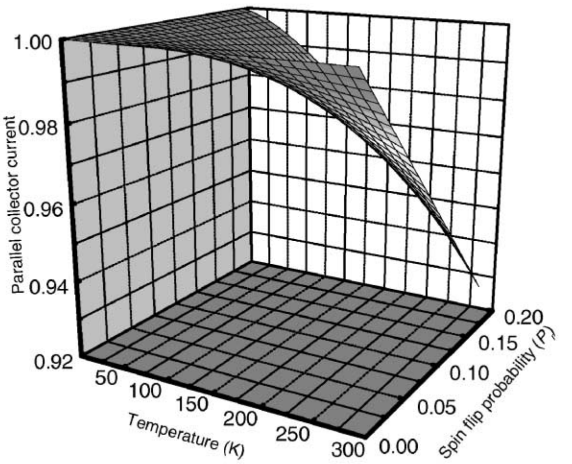

Fig. 1. The parallel collector current expressed in Eq. (5) with normalization at $T = 0$. Hot electron spin polarization P_0 at $T = 0$ is taken as 0.5, and P_r represents the spin flip probability at room temperature ($T = 300\,K$).

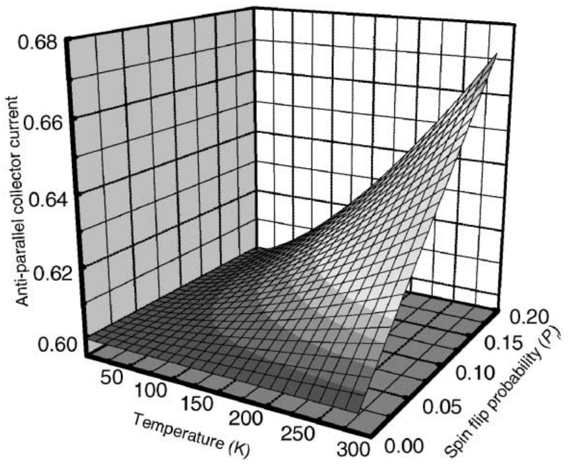

Fig. 2. The anti-parallel collector current in anti-parallel case expressed in Eq. (6). This is the relative magnitude with respect to the parallel current which is normalized at $T = 0$.

independent. In this case $\gamma_{M(m)}$ is temperature independent. Fig. 1 displays the parallel collector current expressed in Eq. (5) with normalization at $T = 0$. Please note that here we are considering the effect of only spin dependent scattering. If there is no spin mixing effect, there is no temperature dependence as it is expected. Now, when the spin mixing process is operating one can clearly see that the collector current is decreasing with increasing temperature T. Fig. 2 shows the anti-parallel collector current expressed in Eq. (6). This is the relative magnitude with respect to the parallel collector current. In this case, there is no temperature dependence at zero spin flip probability like parallel case. However, when the spin-flip probability is increasing the collector current is also increasing with temperature T. From these results, we find that spin mixing effect due to thermal spin wave at finite temperature contributes to the collector current quite differently depending on the relative orientation of magnetic moment in ferromagnetic metals. Fig. 3 represents the temperature dependence of magnetocurrent. As one can expect from the Figs. 1 and 2, we obtain that the magnetocurrent at finite temperatures accords with the experimental data in qualitative manner.

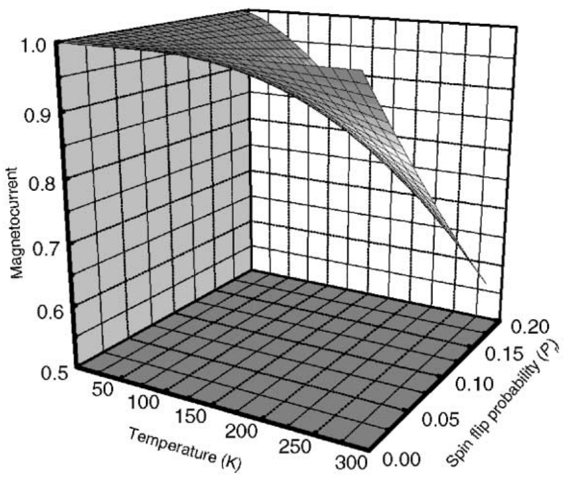

Fig. 3. Magneto current at finite temperature with temperature independent hot electron spin polarization.

We now explore the effect of temperature dependence of hot electron spin polarization to the magnetocurrent. Fig. 4 displays the magnetocurrent when we include the temperature dependence of hot electron spin polarization with Eqs. (3)–(6). One can clearly see that magnetocurrent is decreasing even at zero spin-flip probability with increasing temperature T. This raises an interesting question. Authors of Ref. [8] suggest the spin mixing effect as an origin of measured

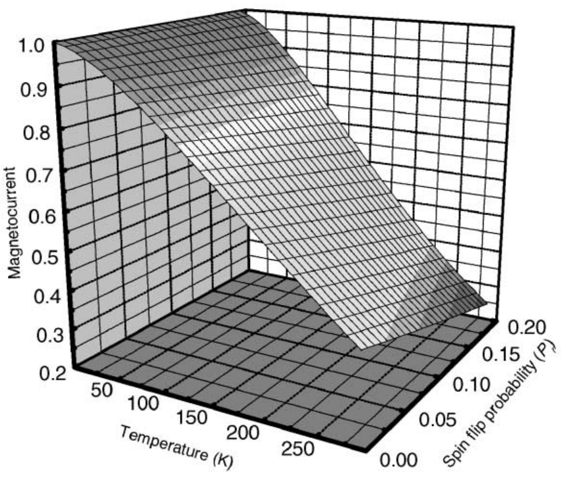

Fig. 4. Magneto current at finite temperature with temperature dependent hot electron spin polarization. The form of temperature dependence is described in the text. Here, we take the critical temperature $T_c = 650\,\mathrm{K}$ simulating pseudo permalloy.

temperature dependence of magnetocurrent. We also obtain qualitatively similar results when we consider the contribution to magnetocurrent from thermal spin wave emission and absorption at finite temperature without including temperature dependence of hot electron spin polarization. In addition, as one can see from Fig. 4 temperature dependence of hot electron spin polarization can also contribute to the magnetocurrent at finite temperatures. This fact implies that it is essential to probe relative importance of spin-mixing effect and temperature dependence of hot electron spin polarization for clear understanding the magnetocurrent at finite temperatures in spin valve transistor.

In conclusion, we have explored the magnetocurrent due to the spin mixing effect from thermal spin wave emission and absorption at finite temperatures. We obtain that spin mixing effect contributes to the collector current differently depending on the relative orientation of magnetic moment of ferromagnetic materials. Our calculations accord with the experimental data qualitatively. Along with that, we also find that temperature dependence of hot electron spin polarization also contributes to magnetocurrent at finite temperatures.

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