Temperature Dependence of Magneto Current in Spin Valve Transistor: A phenomenological Study

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Abstract

The temperature dependence of magneto current in the spin valve transistor system is theoretically explored based on phenomenological model. We find that the collector current strongly depends on the relative orientation of magnetic moment of ferromagnetic metals due to spin mixing effect. For example, the collector current is decreasing in the parallel case with increasing temperature, and it is increasing in anti-parallel configuration. We then obtain decreasing magneto current with increasing temperature. The result accords with the experimental data in qualitative manner. This phenomenological model calculations suggest that spin mixing effect may play an important role in the spin valve transistor system at finite temperature.
I. INTRODUCTION

After discovery of giant magneto resistance (GMR) \([1]\) in magnetic multilayer structure, it has been extensively studied in relation to the ferromagnetic tunneling junction. In addition to the traditional ferromagnetic junction structure, a new type of potential magneto electronic device, so called spin valve transistor, is suggested \([2]\). In the conventional ferromagnetic tunneling junction structure, spin dependent transport property of electron near the Fermi level has been explored. But, spin valve transistor (SVT) has different structure \([3]\) compared to the conventional ferromagnetic tunneling junction system. In a SVT structure, electrons injected into the metallic base from one side of transistor (emitter side) pass through the spin valve and reach opposite side (collector side) of transistor. While these injected electrons are passing across the metallic base they are above the Fermi level. These become hot electrons in spin valve transistor.

The transport property of hot electron may be different from that of Fermi electron. For instance, spin polarization of Fermi electron mainly depends on the density of states at Fermi level. However, the spin polarization of hot electron is related to the density of unoccupied states above the Fermi level. One can possibly interpret the spin polarization of hot electron in terms of inelastic mean free path. In ferromagnetic materials, clearly 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(100). 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 was reported in ferromagnetic Fe \([5]\) experimentally, and also theoretical calculations \([6,7]\) present the same results. Based on these results, 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 temperature. So, it is necessary to probe the temperature dependence of the hot electron transport property more explicitly at low energy (for example, within 1 eV range from the Fermi level) in relation to the spin valve transistor.

In spin valve transistor structure, Jansen et al reported very interesting experimental measurement at finite temperature \([8]\). They measured collector current across the spin valve changing the relative orientation of magnetic moment at finite temperature. Surprisingly, they obtain that the collector current has very different feature at finite temperature strongly depending on the relative orientation of magnetic moment. The collector current in parallel case is increasing up to 200 K and decreasing beyond that temperature regime. On the other hand in anti-parallel case, the current is increasing up to room temperature. We believe that scattering strength increases with temperature \(T\) in ordinary metal. 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 increase of collector current in both configurations up to 200 K because more electrons can overcome the Schottky barrier height at collector side with increasing temperature T. However, beyond that temperature regime collector current in parallel case is decreasing while collector current in anti-parallel case is still increasing. Furthermore, this mechanism is not related to any spin dependent property, except for the absolute magnitude of collector current. Therefore, authors of Ref. 8 attribute measured temperature dependence of magneto current to the spin-mixing effect. Basically spin mixing is spin-flip process by thermal spin wave emission or absorption at finite temperature \[1\]. For example, minority electron can flip its spin by emitting thermal spin wave, and then it goes into spin up channel. In this paper we mainly explore the temperature dependence of magneto current due to thermal spin wave emission and absorption.

II. PHENOMENOLOGICAL MODEL

For the sake of argument, we assume that spin valve has \(N/F/N/F/N\) structure where \(N\) denotes normal metal, and \(F\) represents ferromagnetic metal assuming the same material. Suppose that the same number of spin up and spin down electrons with the number \(N_0\) are prepared, respectively. In SVT structure, the energy of injected electron on the top of Schottky barrier at emitter side is around 0.9 eV relative to the Fermi level of metallic base. Here, we assume that all source electrons have the same energy. When these electrons penetrate magnetic layer certain fractions of source electrons will be lost by attenuation factors. We introduce phenomenological parameter \(\gamma_{M(m)}\) to describe that for majority (minority) spin electrons. With initial \(N_0\) source electrons it is assumed that \(N_0\gamma_{M(m)}\) electrons pass the ferromagnetic layer if they are majority (minority) spin electrons. This phenomenological parameter \(\gamma_{M(m)}\) 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 spin polarization of Co \[10\] at very low energy (roughly speaking, 1 eV above the Fermi level). However, spin polarization of hot electrons, especially for low energy regime, is not clearly understood either in theoretically or experimentally at finite temperature. The central issue of this paper is in understanding of temperature dependence of magneto current by thermal spin wave emission or absorption. 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 \[11\] even if electrons have enough energy to overcome the collector barrier. When we explore temperature dependence of magneto current we do not include any spin and temperature independent process even if it has spin dependent property because all these factors are not relevant to the temperature dependence of magneto current.

One should note that the issue here is the temperature dependence of magneto current by spin mixing effect at finite temperature. In that spirit we suppose that spin-flip probability, expressed as \(P(T)\), by thermal spin wave emission or absorption at finite temperature is proportional to \(T^{3/2}\) by virtue of fact that the number of spin waves at finite temperature are proportional to \(T^{3/2}\). Without spin flip process, assuming parallel configuration, the
current from spin-up electrons (source electrons with number \(N_0\)) is \(N_0\gamma_M^2\), and the current from spin-down electrons is \(N_0\gamma_m^2\). In the anti-parallel case, the current from spin-up and spin-down electrons becomes \(N_0\gamma_M\gamma_m\), respectively. In the above, it is assumed that there is no attenuation in normal metal layer so that no electron is lost within that layer. Since any spin independent attenuation length does not contribute to temperature dependence of magneto current (MC) even if the attenuation length has temperature dependence. By the virtue of the fact that collector current has an exponential dependence on the electron mean free path due to the nature of hot electron transport property [12], our assumption is acceptable when we even explore temperature dependence of magneto current. If spin-flip process is operating by thermal spin wave emission or absorption at finite temperature, the current, in parallel case, from spin-up source electrons can be calculated in the following way. \(N_0\gamma_M\) electrons penetrate the first ferromagnetic metal layer. Among these electrons, \(N_0\gamma_M(1 - P(T))\) electrons keep their spin-up state, and \(N_0\gamma_M(1 - P(T))\gamma_M\) electrons will be collected with spin-up state. However, \(N_0\gamma_M P(T)\) electrons are created with opposite spin resulting from spin-flip process, and \(N_0\gamma_M P(T)\gamma_m\) electrons are collected with the spin-down. Finally, the total number of collected electrons from spin-up source electrons with electron number \(N_0\) become \(N_0\{\gamma_M^2(1 - P(T)) + \gamma_M\gamma_m P(T)\}\). One can follow the same scheme to calculate the contribution to the current from spin-down source electrons. \(N_0\gamma_m\) electrons penetrate the first layer, then \(N_0\gamma_m(1 - P(T))\gamma_m\) electrons are collected with spin-down. Meanwhile, \(N_0\gamma_m P(T)\) electrons have opposite spin state (spin-up state). These now become the majority spin electrons to the second layer, and \(N_0\gamma_m(1 - P(T))\gamma_M\) electrons are collected. Then, the contribution to the current from spin-down source electrons become \(N_0\{\gamma_m^2(1 - P(T)) + \gamma_m\gamma_m P(T)\}\). Similarly, the current in the anti-parallel case becomes \(N_0\{\gamma_M\gamma_m(1 - P(T)) + \gamma_M\gamma_M P(T)\}\), and \(N_0\{\gamma_M\gamma_m(1 - P(T)) + \gamma_m\gamma_m P(T)\}\) 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 temperature, which is assumed to be \(P(T) = cT^{3/2}\). Here \(c\) is a parameter, and \(P(T) \leq 1\) should be satisfied for any temperature \(T\). In our calculations we limit the temperature ranges from zero to room temperature (300 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 (300 K), expressing \(P_r\), the parameter \(c\) in \(P(T)\) can be written as \(c = P_r \times [\frac{T}{300K}]^{3/2}\). We then write the \(P(T)\) as \(P(T) = P_r \times [\frac{T}{300K}]^{3/2}\)

Now, the total collector current in parallel case influenced by spin-flip process due to thermal spin wave emission and absorption becomes

\[
I_c^P = N_0\gamma_M^2\{1 + (\frac{\gamma_m}{\gamma_M})^2\}(1 - P(T)) + 2(\frac{\gamma_m}{\gamma_M})P(T)\].
\[
\tag{1}
\]

Similarly, in the case of anti-parallel

\[
I_c^{AP} = N_0\gamma_M^2\{1 + (\frac{\gamma_m}{\gamma_M})^2\}P(T) + 2(\frac{\gamma_m}{\gamma_M})(1 - P(T))\].
\[
\tag{2}
\]

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

\[
MC = \frac{I_c^P - I_c^{AP}}{I_c^{AP}}
\]
\[
\tag{3}
\]
As mentioned earlier, one can easily relate phenomenological parameter $\gamma_{M(m)}$ to hot electron spin polarization $P_H(T)$ in such a way

$$\frac{\gamma_m}{\gamma_M} = \frac{1 - P_H(T)}{1 + P_H(T)}$$

Generally speaking, hot electron spin polarization will be temperature dependent. This implies that $\gamma_{M(m)}$ is also temperature dependent. It also will be very interesting to explore the magneto current at finite temperature 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 temperature. Therefore, We only test very simple case such as $P_H(T) = P_0(1 - (T/T_c)^{3/2})$. 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 $N_0\gamma_M^2$, even without knowing that prefactor. We express the scaled collector current as

$$\tilde{I}_c^P = \left[1 + \left(\frac{\gamma_m}{\gamma_M}\right)^2\right](1 - P(T)) + 2\left(\frac{\gamma_m}{\gamma_M}\right)P(T)$$

$$\tilde{I}_c^{AP} = \left[1 + \left(\frac{\gamma_m}{\gamma_M}\right)^2\right]P(T) + 2\left(\frac{\gamma_m}{\gamma_M}\right)(1 - P(T))$$

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 $\gamma_M$ in Eq. (1) and Eq. (2). Fortunately, even in this case we can still calculate temperature dependence of MC because of cancellation of unknown prefactor $\gamma_M$.

### III. 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 independent. In this case we assume $\gamma_{M(m)}$ is temperature independent. Fig. 1 displays the collector current expressed in Eq. (5) with normalization at T=0. 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 collector current expressed in Eq. (6). This is 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 magneto current. As one can expect from the Fig. 1 and 2, we obtain that the magneto current at finite temperature accords with the experimental data in qualitative manner.
Fig. 4 displays the magneto current when we include temperature dependence of hot electron spin polarization. One can clearly see that magneto current is decreasing even at zero spin flip probability with increasing temperature T. This raises an interesting question. Authors of Ref. 8 suggests the spin-mixing effect as an origin of measured temperature dependence of magneto current. We also obtain qualitatively similar results when we consider the contribution to magneto current from thermal spin wave emission and absorption at finite temperature without including temperature dependence of hot electron spin polarization. But, as one can see from Fig. 4 temperature dependence of hot electron spin polarization can also contribute to the behavior of magneto current at finite temperature. This fact implies that it is essential to probe relative importance of spin-mixing effect and temperature dependence of hot electron spin polarization for understanding the magneto current at finite temperature in spin valve transistor.

In conclusion, we explore the magneto current due to spin mixing effect from thermal spin wave emission and absorption at finite temperature. 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 accords with experimental data qualitatively. In addition, we find that temperature dependence of hot electron spin polarization also contributes to magneto current at finite temperature. For clear understanding of relative importance from thermal spin wave effect and temperature dependence of hot electron spin polarization, we believe that one needs to study this from the microscopic theory.
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FIGURES

FIG. 1. The 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 $P$ represents the spin flip probability at room temperature ($T = 300 \text{ K}$).

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

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

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 $T_c = 650K$ simulating pseudo permalloy.