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Bias voltage and temperature dependence of hot electron magnetotransport

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We present a qualitative model study of energy and temperature dependence of hot electron magnetotransport. In this model calculation, the strong spin dependent inelastic scattering strength of hot electrons and spin mixing due to thermal spin waves have been taken into account. In addition, spatial inhomogeneity of Schottky barrier height has been considered. This calculations display that the magnetocurrent accords with the recent experimental data qualitatively at room temperature if we include the spin mixing effect with hot electron spin polarization although the experimental observation is not easy to interpret. Thus, if one measures the temperature dependence of magnetocurrent, then the mechanism suggested here will be tested whether it is acceptable.

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I. INTRODUCTION

An introduction of a *hot* electron magnetoelectronic device by Monsma *et al.*[1] has brought great interest in the hot electron magnetotransport. Very recently, another interesting observation has been reported by Jansen *et al.*[2] at finite temperatures in the hot electron device. They obtained unusual behaviors of the collector current with temperature T depending on the relative spin orientation of the ferromagnetic layers and huge magnetocurrent even at room temperature. One should take into account transport of *hot* electron in the discussions of such interesting phenomena. Although the hot electron magnetotransport has not been extensively explored unlike the transport of Fermi electrons, there are examples of theoretical study of hot electron magnetotransport in a spin-valve transistor.[3,4] In that study, a temperature dependence of hot electron magnetotransport has been explored, and the importance of hot electron spin polarization has been suggested in a spin-valve transistor.

There have been great amount of studies in the applied bias voltage dependence of magnetoresistance in a magnetic tunneling junction (MTJ). For instance, Moodera *et al.*[5] measured bias and temperature dependence of junction magnetoresistance (JMR) in the MTJ. They obtained rapid decreasing JMR with applied bias voltage, which is very intrinsic property of ferromagnetic junctions and explained in terms of the temperature dependence of surface magnetization. Unlike large volume of data in the MTJ, only few data are available in the hot electron magnetotransport study. In the issue of bias voltage dependence of hot electron magnetotransport (not the temperature dependence), it has been presented experimentally by Mizushima *et al.*[6] Theoretical studies to account for the experimental observation have been also presented by the authors of the Refs. 6–9. They claim that the inelastic scattering contributes to reduce the magnetoresistance above 1.5 eV, and the elastic scattering at the interface of base and collector (forward focusing effect) enhances the magnetoresistance around 1 eV. However, it is not quite clear how the forward focusing effect increases the magnetocurrent since it happens at the interface of normal metal and semiconductor (we do not expect strong spin dependence). In addition, in their discussion one should note the experimental data presented in the Ref. 6. Figure 5 in Ref. 6 shows the hysteresis curve of the sample. One can easily understand that the switching of the ferromagnetic layers is not well defined. If the switching is well defined it should occur within very narrow ranges of applied magnetic field. However, the hysteresis curve of Fig. 5 in Ref. 6 shows very broad features. There may be several factors contributing to broaden the hysteresis curve. For instance, the thickness of ferromagnetic layer is too thin, so that the sample may have locally different coercivity field (the thickness of Fe layers was 10 and 15 Å in the spin-valve base of Ref. 6). Therefore, it may be very difficult to extract essential physics when one explores the hot electron magnetotransport based on the data of Ref. 6.

Hence, in this work we shall explore the hot electron magnetotransport varying the bias voltage and temperature assuming very well defined switching of spin-valve base. Since the total thickness of spin-valve base is more than 100 Å and the hot electron very strong inelastic scattering strength even at low energy in ferromagnet,[10] we believe that the inelastic scattering process may be essential to understand the hot electron transport in this type of structure. Therefore, our interest is in the hot electron magnetotransport influenced by the spin dependent inelastic scattering in ferromagnets resulting in hot electron spin polarization and spin mixing[2] due to thermal spin waves. We also take into account the spatial inhomogeneity of Schottky barrier effect.[11] Then, the theory suggested in this work will be tested if one measures the temperature dependence of hot electron magnetocurrent varying the bias voltage.

II. MODEL STUDY

We consider the system described in Fig. 1 to explore the issue of this work. The normal injection to the barrier surface is assumed in this model calculations and we also suppose that the normal metal layers are the same material with the same thickness. It is well known that we can write the hot electron tunneling current through the insulating barrier[12] as

$$I_t(eV)=\int_{-\infty}^{\infty} dE f_e(E-eV)[1-f_b(E)]D_e(E)P_t(E), \qquad (1)$$

where $f_e(E)$ and $f_b(E)$ are the Fermi-Dirac distribution functions in the emitter and base, respectively, $D_e(E)$ is the density of the states in the emitter, and $P_t(E)$ is the transmission probability through the barrier. It is necessary to

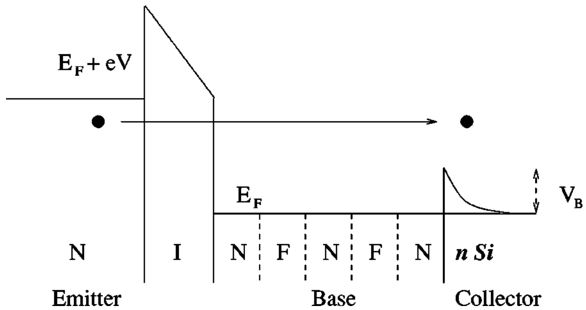

FIG. 1. A schmetic display of model explored in this work. The bias voltage is applied between the emitter and base. The hot electrons are injected into the metallic base, and collected across the Schottky barrier.

know the exact shape of potential barrier for quantitative analysis of the tunneling current. Very recently, a ballistic electron microscopy study of aluminum barrier[13] for magnetic tunneling junction has been presented. It shows that the barrier height is very sensitive to the thickness of the insulating barrier. Since we have no reliable experimental data about bias and temperature dependence of hot electron magnetotransport we shall study the hot electron magnetotransport qualitative manner assuming sharp junction barrier. The energy of tunneled electrons are above the Fermi level of the spin-valve base, then the hot electron transport should be taken into account. The injected hot electrons will suffer from various elastic and inelastic scattering events in the first normal metal layer, however, the hot electrons are not spin polarized until they reach the first ferromagnetic layer. In the ferromagnetic layer, the hot electrons have strong spin dependent self-energy,[10] so that the inelastic mean free path is spin dependent. Therefore, the hot electrons will be spin polarized after passing the first ferromagnetic layer. One should note that the influence of the band mismatch at the interface of ferromagnet and normal metal on the current has been discussed by Rippard *et al.*,[14] and we will have the same band mismatch in our system. However, we will consider very ideal case in this work without any band mismatch.

The issue now is the hot electron magnetotransport in the spin-valve base. Due to strong spin dependent inelastic scattering strength,[10] the hot electrons will have spin dependent attenuation in ferromagnet and by the virtue of the fact that the hot electron transport has an exponential dependence on the inelastic mean free path[15] we are able to focus on the process in the ferromagnets when we explore spin dependent transport of hot electrons. To take into account the spin dependent attenuation in the ferromagnetic layer, we define $\gamma_M(E,T)$ and $\gamma_m(E,T)$ which can be written as $\gamma_M(E,T) = \exp[-w/l_M(E,T)]$ and $\gamma_m(E,T)=\exp[-w/l_m(E,T)]$, where w is the thickness of the ferromagnetic layer and $l_{M(m)}(E,T)$ is the inelastic mean free path of majority (minority) spin electron in the ferromagnetic layer at the energy E and temperature T. One should note that there is a Schottky barrier at the collector side, thus the energy of hot electrons should be larger than the Schottky barrier height to contribute to the collector current. As shown in the experimental measurement,[11] the Schottky barrier has spatial distribution. In this model calculations, we assume the distribution of Schottky barrier

$$h^c(\Phi_c,\Phi_c^0)=\frac{1}{\sqrt{2\pi W_c^2}}\exp(-[\Phi_c-\Phi_c^0]^2/2W_c^2), \tag{2}$$

where W_c is the width of the collector barrier height, and Φ_c^0 is the most probable height of the collector Schottky barrier. The role of hot electron spin polarization has been explained in Refs. 3,4 to account for the temperature dependence of hot electron magnetotransport. In addition, we also include the spin mixing effect due to thermal spin waves. For instance, majority spin hot electron flips its spin by absorption of thermal spin waves or minority spin hot electron flips the spin state by emission of spin wave. If we include the inelastic scatterings in ferromagnets, normal metal layers, spin mixing effect and spatial distribution of the Schottky barrier heights, we can write the spin dependent collector current

$$\begin{aligned}
\tilde{I}^P&(eV,T,\Phi_c^0)\\
&=\int_{-\infty}^{\infty}dE\int_0^{\infty}d\Phi_c f_e(E-eV)[1-f_b(E)]D_e(E)P_t(E)\\
&\times\Gamma_N^3(E,T)\gamma_{M_1}(E,T)\gamma_{M_2}(E,T)h^c(\Phi_c,\Phi_c^0)\\
&\times\left[\left\{1+\frac{\gamma_{m_1}(E,T)}{\gamma_{M_1}(E,T)}\frac{\gamma_{m_2}(E,T)}{\gamma_{M_2}(E,T)}\right\}[1-P_{SW}(E,T)]\right.\\
&\left.+\left\{\frac{\gamma_{m_1}(E,T)}{\gamma_{M_1}(E,T)}+\frac{\gamma_{m_2}(E,T)}{\gamma_{M_2}(E,T)}\right\}P_{SW}(E,T)\right]\\
&\times\Theta(E-\Phi_c)t(E,\Phi_c),
\end{aligned} \tag{3}$$

and in the antiparallel case

$$\begin{aligned}
\tilde{I}^{AP}&(eV,T,\Phi_c^0)\\
&=\int_{-\infty}^{\infty}dE\int_0^{\infty}d\Phi_c f_e(E-eV)[1-f_b(E)]D_e(E)P_t(E)\\
&\times\Gamma_N^3(E,T)\gamma_{M_1}(E,T)\gamma_{M_2}(E,T)h^c(\Phi_c,\Phi_c^0)\\
&\times\left[\left\{1+\frac{\gamma_{m_1}(E,T)}{\gamma_{M_1}(E,T)}\frac{\gamma_{m_2}(E,T)}{\gamma_{M_2}(E,T)}\right\}P_{SW}(E,T)\right.\\
&\left.+\left\{\frac{\gamma_{m_1}(E,T)}{\gamma_{M_1}(E,T)}+\frac{\gamma_{m_2}(E,T)}{\gamma_{M_2}(E,T)}\right\}[1-P_{SW}(E,T)]\right]\\
&\times\Theta(E-\Phi_c)t(E,\Phi_c),
\end{aligned} \tag{4}$$

where $\Gamma_N(E,T)$ accounts for the hot electron attenuation in the normal metal layer, Θ is a step function, $t(E,\Phi_c)$ represents the quantum mechanical transmission probability in the presence of Schottky barrier, and $P_{SW}(E,T)$ displays the spin flip probability due to thermal spin waves. It is useful to rewrite the above expressions in terms of hot electron spin polarization. With the relation

$$\frac{\gamma_m(E,T)}{\gamma_M(E,T)}=\frac{1-P_H(E,T)}{1+P_H(E,T)}, \tag{5}$$

we obtain

$$\tilde{I}^{P}(eV,T,\Phi_c^0) = \int_{-\infty}^{\infty} dE \int_0^{\infty} d\Phi_c f_e(E-eV)[1-f_b(E)]D_e(E)P_t(E) \times \Gamma_N^3(E,T) g_1(E,T) g_2(E,T) \times \Theta(E-\Phi_c) t(E,\Phi_c) h^c(\Phi_c,\Phi_c^0) \times \left[\left\{ 1 + \frac{1-P_{H_1}(E,T)}{1+P_{H_1}(E,T)} \frac{1-P_{H_2}(E,T)}{1+P_{H_2}(E,T)} \right\} \times [1-P_{SW}(E,T)] + \left\{ \frac{1-P_{H_1}(E,T)}{1+P_{H_1}(E,T)} + \frac{1-P_{H_2}(E,T)}{1+P_{H_2}(E,T)} \right\} P_{SW}(E,T) \right] \tag{6}$$

and

$$\tilde{I}^{AP}(eV,T,\Phi_c^0) = \int_{-\infty}^{\infty} dE \int_0^{\infty} d\Phi_c f_e(E-eV)[1-f_b(E)]D_e(E)P_t(E) \times \Gamma_N^3(E,T) g_1(E,T) g_2(E,T) \Theta(E-\Phi_c) t(E,\Phi_c) \times h^c(\Phi_c,\Phi_c^0) \left[\left\{ 1 + \frac{1-P_{H_1}(E,T)}{1+P_{H_1}(E,T)} \frac{1-P_{H_2}(E,T)}{1+P_{H_2}(E,T)} \right\} \times P_{SW}(E,T) + \left\{ \frac{1-P_{H_1}(E,T)}{1+P_{H_1}(E,T)} + \frac{1-P_{H_2}(E,T)}{1+P_{H_2}(E,T)} \right\} \times [1-P_{SW}(E,T)] \right], \tag{7}$$

where $P_{H_i}(E,T)$ is the hot electron spin polarization in each ferromagnet and $g_i(E,T)$ is the spin averaged attenuation in ferromagnet. We take $P_H(E,T) = P_0(E)(1-[T/T_c]^{3/2})$ by the virtue of the fact that the number of thermal spin waves are proportional to $T^{3/2}$. Here, $P_0(E)$ is the hot electron spin polarization at zero temperature. which will be extracted from the theoretical calculations[10] and T_c is the critical temperature of the ferromagnet. Although the spin averaged attenuation $g(E,T)$ in the ferromagnet has no spin dependence save for affecting the magnitude of the collector current, it has been supposed that $g(E,T) = g(E)\exp(-T/T_c)$. Once we obtain the spin dependence collector current, then magnetocurrent (MC) can be calculated by the definition

$$MC(eV,T,\Phi_c^0) = \frac{I^p(eV,T,\Phi_c^0) - I^{AP}(eV,T,\Phi_c^0)}{I^{AP}(eV,T,\Phi_c^0)}. \tag{8}$$

Since the hot electron magnetotransport is not understood even qualitative manner so far, we will focus on qualitative understanding, not quantitative study. In the issue of spin mixing, if the energy of injected hot electron is very close to the Schottky barrier height, then the spin mixing effect may not play an important role to the collector current since the energy loss tends to suppress the collector current because a Schottky barrier exists at the collector side. Thus, in this model calculations we assume that the spin mixing effect is operating when the energy of hot electron is greater than the Schottky barrier height even after losing the largest spin wave energy. For instance, if we simply relate $E_{SW} = D_{SW} Q_{\max}^2$ where D_{SW} is the spin stiffness constant and $Q_{\max}$ is the maximum wave vector (possibly near the Brillouin zone boundary) of spin wave, we then take $E_{SW} \approx 0.4$ eV.

III. RESULTS AND DISCUSSIONS

We assume that both the ferromagnetic layers in spin-valve base schematically represented in Fig. 1 are Fe, and take 45 and 20 Å for the thickness of first and second ferromagnetic layer, respectively. 20 Å is used for the thickness of the insulating barrier, 30 Å for normal metal layer, and 2.5 eV is assumed for the barrier height relative to the Fermi level of emitter material. We choose the $\Phi_0^c = 0.9$ eV and $W_c = 0.1$ eV. Here, it is of importance to note that the attenuation of low energy electron in the normal metal is around 100 Å.[16] It is several times greater than that calculated in the ferromagnets.[10] We therefore believe that the attenuation in ferromagnet has a substantial role in the hot electron transport. As a result, the inelastic mean free path in normal metal layer is taken as 90 Å for the energy and temperature ranges of our interest. For the spin flip probability, we suppose that a hot electron has 30% of spin flip probability due to thermal spin wave at 300 K if it is operating. Since our purpose is to understand the bias dependence qualitatively after including the spin mixing effect, therefore the assumption stated above may contain the essential physics to explore the main issue of this work even if it does not reflect exact temperature and energy dependence.

Figure 2 displays the spin dependent collector current at zero and 300 K with increasing bias voltage. As one can see, the current is very small if the bias voltage is less than Φ_0^c while it is increasing rapidly beyond it. It is also interesting to compare both zero and room temperature cases. The parallel collector current is drastically decreased compared with that of zero temperature while the anti-parallel collector current is decreasing rather smoothly. One should note that the role of hot electron spin polarization as explained in the Refs. 3,4. For instance, the hot electron spin polarization tends to suppress the parallel collector current while it contributes to enhance the antiparallel current. Thus, we believe that the hot electron spin polarization causes the different behavior with temperature. Now, we display the main results of this calculation in Fig. 3. The circle shows the MC at zero temperature. The MC increases with bias voltage as one can see. At zero temperature, we have only spin dependence from hot electron spin polarization, and the spin asymmetry of hot electron inelastic scattering strength tends to increase up to around 2 eV according to the theoretical calculations.[10] Now, it is of interest to consider the MC at 300 K. In this case, both the hot electron spin polarization and spin mixing due to thermal spin wave have been taken into account. One can clearly note that the MC increases up to around 1.3 eV and starts to decrease above it. This qualitative behavior accords with the experimental data energy. It should be pointed that the measured MC is around 250% and the theoretical calculation shows approximately 120%. One can understand

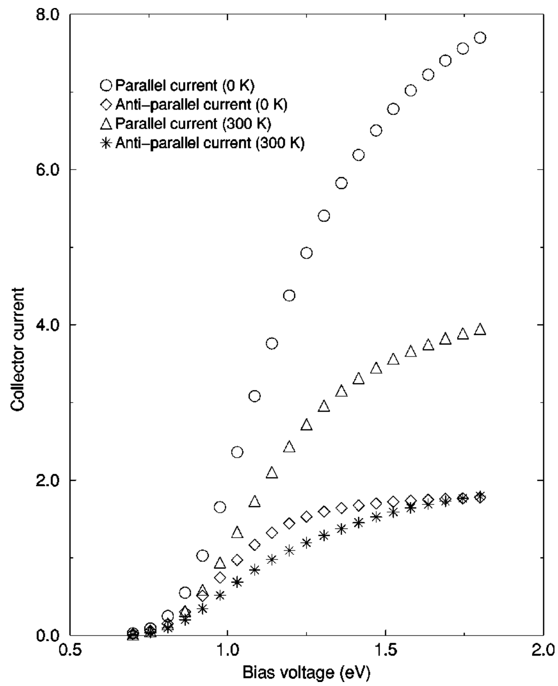

FIG. 2. The parallel and antiparallel collector current at zero and 300 K. Here, T_c is taken as 1200 K.

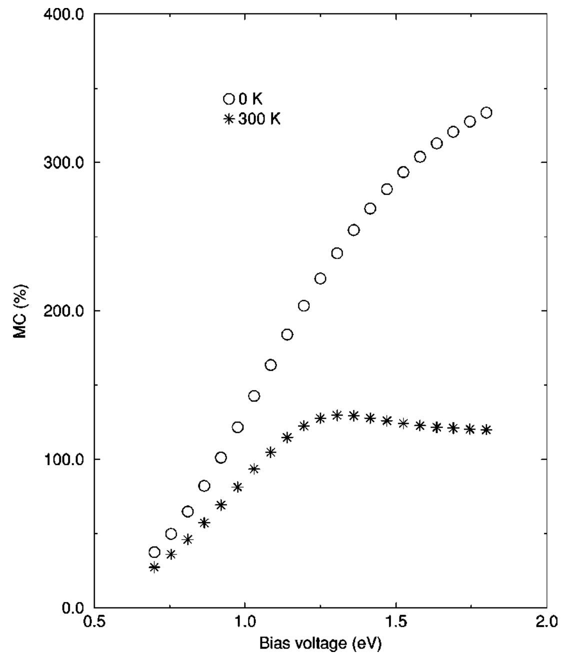

FIG. 3. The bias voltage dependence of magnetocurrent at zero and 300 K with different hot electron spin polarizatoin. The asterisk displays the MC at 300 K and the circle is the one at zero temperature.

that the MC is sensitive to the magnitude of the spin dependent collector current itself, then the MC can be enhanced by spin dependent scattering process even if it has no temperature dependence. In this calculation, we have not considered such process since our interest is to explore the temperature and bias dependence of hot electron magnetotransport qualitatively. However, we obtain that the calculated MC at room temperature shows similar trend in a qualitative manner. Thus, this model calculation indicates that the spin dependence of hot electron transport is obscured by the spin mixing and this effect plays an important role in the structure discussed in this work if the bias voltage is sufficiently larger than the Schottky barrier height.

In conclusion, we have explored the applied bias voltage and temperature dependence of hot electron magnetotransport assuming well defined switching of spin-valve base. In this model calculations we have taken into account the spin dependent inelastic scattering effect and spin mixing due to thermal spin waves. We have also considered the spatial inhomogeneity of Schottky barrier effect. The MC increases up to near 1.3 eV and we believe that this comes from the hot electron spin polarization. At room temperature, the MC shows substantially different feature from the zero temperature due to spin mixing effect and the result agrees with the experimental data qualitative manner although the experimental measurement is not clear to interpret since the switching is not well defined. Thus, if one measures the MC varying the bias voltage and temperature, then the mechanism due to hot electron spin polarization and spin mixing as described above will be tested.

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