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Temperature dependence of magnetocurrent in a magnetic tunnel transistor

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The temperature dependence of magnetocurrent (MC) and transfer ratio has been investigated in a magnetic tunnel transistor (MTT) with a ferromagnetic (FM) emitter of Co or Ni₈₀Fe₂₀. MTT devices of sizes ranging from 10 to 100 μm in diameter were fabricated using a standard photolithography process and predefined Si substrates. This reduces the edge leakage current across the collector Schottky diode and enables room-temperature operation. For the MTT with both Co and Ni₈₀Fe₂₀ emitter, we obtain a MC of about 80% at room temperature. This corresponds to a tunnel spin polarization of the FM emitter/Al₂O₃ interface of 29% at 1 V, demonstrating that the tunnel current is still spin-polarized at a high bias voltage. © 2005 American Institute of Physics. [DOI: 10.1063/1.2125120]

I. INTRODUCTION

Since the discovery of the giant magnetoresistance (GMR) effect, spin-dependent transport in magnetic multilayers and tunnel junctions has been extensively studied because of its potential for application in magnetic memories, read heads, and field sensors.^{1–3} By combining these magnetoresistive elements with semiconductors, the spin-valve transistor (SVT) has been developed as another type of spintronic device.⁴ The SVT is a three-terminal device that consists of a metallic spin-valve base sandwiched between two semiconductors that act as emitter and collector, respectively. It has been reported that the SVT shows huge relative magnetic response, called magnetocurrent (MC), of more than 300% at room temperature. The SVT is based on the spin-dependent transport of nonequilibrium, so-called hot electrons, rather than Fermi electrons. The hot-electron energy in the SVT is determined by the Schottky barrier height of the metal/semiconductor combination of the emitter. By replacing the Schottky barrier emitter by a tunnel barrier, another type of hot-electron transistor, the magnetic tunnel transistor (MTT), has been derived.^{5,6} Unlike the SVT, the hot-electron energy can be tuned by varying the bias voltage across the tunnel barrier. An increase of the output current and transfer ratio can be expected by the increase in the hot-electron energy.

There are two different MTT designs. The first one has a nonmagnetic metal emitter electrode and a spin-valve base.⁷ The second design consists of a ferromagnetic emitter and a base with a single ferromagnetic layer. In this work, we focus on the MTT of the second design (Fig. 1). In this structure, spin-polarized hot electrons are injected into the base by tunneling. After spin-dependent transmission through the ferromagnetic base, they are collected in the conduction band of the semiconductor provided they have the right energy and momentum to overcome the Schottky barrier. Two factors determine the spin sensitivity of the device: (i) spin-

dependent tunneling from the emitter and (ii) spin-dependent scattering of the hot electrons in the base.⁸ Since the MTT operates with typical emitter bias of the order of 1 V and the magnetocurrent depends on the tunneling spin polarization, the MTT can be used to study the spin polarization of ferromagnetic/insulator interfaces at high bias voltage.

So far, the MTT has been studied mostly at the low temperature of 77 K because the rather large MTTs fabricated with shadow masks have a significant leakage current across the collector Schottky diode at room temperature.^{5–7} In this study, we have introduced predefined Si substrates and a photolithography process so as to be able to study the temperature dependence of the MC and the transfer ratio up to room temperature. This allows us to probe the tunnel

FIG. 1. (a) Schematic energy diagram of a MTT with a ferromagnetic (FM) emitter and a base with a single ferromagnetic layer. (b) The layer structure of a lithographically defined MTT.

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FIG. 2. Magnetocurrent (MC) (a) and TMR (b) vs magnetic field for a MTT with Si/Au(7 nm)/Co(8 nm)/Al₂O₃(2.4 nm)/Ni₈₀Fe₂₀(10 nm)/Au(10 nm) at the emitter bias of 1 V and room temperature.

spin polarization up to room temperature, removing a limitation of the standard technique of tunneling into a superconductor.⁹

II. EXPERIMENTS

Samples were deposited by thermal evaporation in a molecular-beam epitaxy system at a base pressure of 10^{-10} mbar. The structure of the MTT was *n*-type Si / Au(7 nm) / Co(8 nm) / Al₂O₃(2.4 nm)/FM(10 nm)/Au(10 nm), where FM is Ni₈₀Fe₂₀ or Co(1 nm)/Ni₈₀Fe₂₀(9 nm). The films were grown on a lithographically defined area of a Si wafer, surrounded by a thick SiO₂ to reduce device size and eliminate edge leakage currents across the collector diode (see Fig. 1). The leakage current across the Schottky barrier in the patterned MTT is less than 0.1 nA at room temperature. The Al₂O₃ barriers were formed by plasma oxidation of a thin Al layer. MTT devices were fabricated using standard photolithography, ion-beam etching, and lift-off techniques. The diameter of the active area of the devices varied from 10 to 100 μ m and that of the base-collector diode from 20 to 130 μ m. Transport measurements were conducted using a four-point geometry for the emitter-to-base tunnel junction and a separate Ohmic contact to the back of the Si collector. The temperature dependence of the magnetocurrent was investigated between 100 K and room temperature.

III. RESULTS AND DISCUSSIONS

Figure 2(a) shows the collector current at room temperature as a function of magnetic field for a MTT with a Ni₈₀Fe₂₀ emitter. The emitter bias voltage is 1 V. The largest collector current of 6.63 nA is obtained when both ferromagnetic layers are aligned parallel to each other. In the antiparallel state the collector current reduces to 3.7 nA, resulting in a MC of 79% at room temperature. The leakage current of

less than 0.1 nA across the collector Schottky barrier is negligible compared to the output collector current.

From the measured MC value, the tunnel spin polarization can be extracted as follows. The MC of a MTT with a ferromagnetic emitter is determined by spin-dependent tunneling from the emitter and spin-dependent transport of hot electrons in the base. The MC can be expressed as:⁸

$$MC = \frac{2P_{t,E}P_B^*}{1 - P_{t,E}P_B^*}, \quad (1)$$

where $P_{t,E}$ is the tunnel spin polarization from the emitter and P_B^* is the transmission polarization of the base, defined as

$$P_B^* = \frac{\delta_M^M \exp(-t/\lambda_M) - \delta_m^m \exp(-t/\lambda_m)}{\delta_M^M \exp(-t/\lambda_M) + \delta_m^m \exp(-t/\lambda_m)}. \quad (2)$$

Here, δ_M and δ_m are the fraction of majority and minority electrons, t is the FM base layer thickness, and λ_M and λ_m are the hot-electron attenuation lengths for the majority and minority spins.

The tunnel spin polarization $P_{t,E}$ is determined by the choice of emitter material and insulator. However, the transmission polarization of the base is dependent on the base layer thickness. Since the attenuation length of the majority-spin electrons is considerably larger than that of minority spins,^{10–12} at a large base thickness only majority spins can be transmitted ($P_B^* \sim 1$), and the MC is saturated at a value of $2P_{t,E}/(1 - P_{t,E})$ and is dependent only on the tunnel spin polarization. This allows the MTT to be used to probe the tunnel spin polarization of ferromagnetic/insulator interfaces at a high bias.

A MC of 79% corresponds to a tunnel spin polarization of the Ni₈₀Fe₂₀/Al₂O₃ emitter interface of 29%, demonstrating that the tunnel current is still highly spin-polarized at a high bias voltage of 1 V. However, the tunnel magnetoresistance (TMR) at 1 V for the same junction is only 3.2% [Fig. 2(b)], while the TMR is about 22% at a bias of 20 mV (not shown). This proves that the disappearance of TMR at high bias does not necessarily imply that the tunnel current is no longer spin-polarized. Tunneling electrons originate mainly from states near the Fermi energy of the emitter at all bias voltages even though the electron energy distribution becomes broader with increasing bias voltage. However, the empty states of the base into which electrons can tunnel depend on the bias voltage. These states are near the Fermi energy at low bias where the maximum TMR ratio is obtained and well above the Fermi energy at large bias voltage where the TMR ratio drops drastically. Thus, the low spin polarization of the states well above the Fermi energy is responsible for the drop of the TMR at high bias, although other effects such as a change in the barrier shape, spin-wave scattering, and phonon scattering should also be taken into account.

Figure 3(a) shows the temperature dependence of the MC for MTTs with Co (open squares) and Ni₈₀Fe₂₀ (solid circles) emitters. The MC at 100 K is around 94% for both emitter materials. As the temperature is increased to room temperature, the MC gradually decreases to 82% for a MTT

FIG. 3. Temperature dependence of the MC (a) and tunnel polarization (b) for MTTs with a Co (open squares) and a $\text{Ni}_{80}\text{Fe}_{20}$ (solid circles) emitter. The line represents the fits to $P = P_0(1 - \alpha T^{3/2})$. The emitter bias voltage is 1 V.

with a Co emitter and 79% for that with a $\text{Ni}_{80}\text{Fe}_{20}$ emitter. The MTT with the Co emitter shows slightly weaker temperature dependence than that with the $\text{Ni}_{80}\text{Fe}_{20}$ emitter. It has been reported that the MC of the spin-valve transistor decreases with increasing temperature due to thermal spin-wave scattering in the FM layer.¹³ The thermal spin-wave scattering can also affect the temperature dependence of the MC in the MTT. However, the thermal spin-wave attenuation length for Co is quite long compared to that for $\text{Ni}_{80}\text{Fe}_{20}$ (Ref. 11) and its effect on the transmission polarization P_B^* of the base is a few percent, which is too weak to explain the drop of the MC with temperature. This implies that the temperature dependence of the MC is mainly due to that of the tunnel spin polarization. Figure 3(b) shows the temperature dependence of the tunnel spin polarization extracted from the MC value in Fig. 3(a). The tunnel polarization decreases from 32% to 29% as the temperature is increased from 100 K to room temperature. The solid line in Fig. 3(b) represents the fit obtained by using $P = P_0(1 - \alpha T^{3/2})$, where P_0 is the spin polarization at 0 K and α is a material-dependent constant. This equation was previously used to describe the variation of TMR with temperature.¹⁴ The fitting gives a P_0 of 33% and α of $3 \times 10^{-5} \text{ K}^{-3/2}$. These values agree well with the data in Ref. 14.

Figure 4 shows the temperature dependence of the MC and the transfer ratio ($I_{\text{collector}}/I_{\text{emitter}}$) at different emitter bias voltages. The emitter bias voltage is 0.9 V (squares), 1 V (circles), and 1.3 V (triangles). The MC of a MTT decreases with temperature for all bias voltages. The temperature dependence of the MC does not change much with emitter bias voltage. On the other hand, the temperature dependence of the transfer ratio is strongly affected by bias voltage. The transfer ratio increases with increasing temperature for a bias of 0.9 V, while it decreases with temperature for 1.3 V. The attenuation length of hot electrons is shortened with increasing temperature because of the temperature-dependent scat-

FIG. 4. Temperature dependence of the MC (a) and the transfer ratio (b) for a MTT with $\text{Si}/\text{Au}(7 \text{ nm})/\text{Co}(8 \text{ nm})/\text{Al}_2\text{O}_3(2.4 \text{ nm})/\text{Ni}_{80}\text{Fe}_{20}(10 \text{ nm})/\text{Au}(10 \text{ nm})$ at different emitter bias voltages. The emitter bias voltage is 0.9 V (squares), 1 V (circles), and 1.3 V (triangles).

tering by phonons and spin waves.¹¹ Thus, a lower transfer ratio can be expected at a high temperature. It is in agreement with the results for a bias voltage of 1.3 V. However, the transfer ratio at a bias of 0.9 V rather increases with temperature. The increase of the transfer ratio can be explained by the increase of the hot-electron energy with temperature. At high temperatures the thermal energy is added to the hot-electron energy given by the emitter bias voltage. This slight change in hot-electron energy gives rise to the increase of the transfer ratio at a bias voltage of 0.9 V that is just above the Schottky barrier height of 0.8 eV of the collector. For a bias voltage of 1 V, this effect compensates the reduction in the transfer ratio due to scattering, resulting in temperature-independent transfer ratio. At a larger bias, the slight thermal change in hot-electron energy has little influence on the transmission since the hot-electron energy is much higher than the Schottky barrier height where the transfer ratio (I_C/I_E) does not depend much on hot-electron energy.¹⁵

IV. CONCLUSIONS

The temperature dependence of the MC and the transfer ratio for a MTT with a ferromagnetic emitter and a single ferromagnetic base has been investigated between 100 K and room temperature. As the temperature is increased, the MC decreases slightly from 94% at 100 K to 80% at room temperature, which corresponds to a tunnel spin polarization of 32% and 29% at 1 V, respectively. This demonstrates that the tunnel current is still spin-polarized at a high bias voltage. The transfer ratio increases with increasing temperature for a bias just above the collector Schottky barrier height, while it decreases with temperature for a larger bias.

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