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Bias voltage dependence of magnetocurrent in magnetic tunnel transistors

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The magnetocurrent of magnetic tunnel transistors is measured as a function of emitter/base bias voltage. A nonmonotonic bias dependence is found for magnetic tunnel transistors with a GaAs collector, whereas a monotonic decrease of the magnetocurrent with bias voltage is observed for transistors with a Si collector. A model including spin-dependent inelastic electron scattering in the ferromagnetic base layer and strong electron scattering at the base/collector interface can well account for the experimental results. The different bias dependences of magnetic tunnel transistors with GaAs and Si collectors is attributed to the different conduction band structures of these semiconductor collectors.

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INTRODUCTION

Spin-dependent hot electron transport in ferromagnetic materials has been extensively studied particularly as it may be important for the functionality of various magnetoelectronic devices.[1–14] One intriguing device utilizing spin-dependent hot electron transport is the spin-valve transistor (SVT).[13,14] In the SVT, a ferromagnetic (FM) spin-valve base structure is sandwiched between two metal/semiconductor Schottky barriers, which serve as the emitter and the collector, respectively. The collector current (I_C) depends critically on the alignment of magnetic moments within the spin-valve base. A relative change in the collector current, or so-called magnetocurrent (MC), of more than 300% has been reported at room temperature.[15] The energy of the hot electrons in the SVT is determined by the Schottky barrier height (Φ_S) of the emitter. Because it is very difficult to vary Φ_S over a wide energy range, the hot electron energy is limited to ~0.9 eV. An alternative to the SVT is the magnetic tunnel transistor (MTT), in which a tunnel barrier is used to create a hot electron current.[16,17] The hot electron energy in this device can be tuned by varying the bias voltage across the tunnel barrier. The MTT is therefore a powerful tool to study hot electron transport over a wide energy range. There are two basic MTT designs. The first one consists of a FM emitter and a single FM base layer. Large collector current outputs (up to ~1.6 μA), in combination with moderate MC (64%) at room temperature, have been reported for such an MTT recently.[18] The second design has a FM spin-valve base instead of a single FM layer base. A giant MC exceeding 3400% has been observed in MTTs with such a design.[19]

In this paper we concentrate on MTTs with a single FM base layer. In these MTTs a spin-polarized hot electron current is injected from the FM emitter into the FM base. As these electrons traverse the base layer, they lose energy and/or change momentum due to scattering. Only those electrons that maintain enough energy to overcome the Schottky barrier at the base/collector interface and that are transmitted into one of the available conduction band states of the semiconductor collector contribute to the collector current. Because the scattering rate in the FM base is spin dependent,[1–9,13,14,20–22] the collector current is very sensitive to the relative alignment of the emitter and base magnetic moments. The MC, defined as $\mathrm{MC}=(I_{C,P}-I_{C,AP})/I_{C,AP}$, exceeds 100% at 77 K where $I_{C,P}$ and $I_{C,AP}$ are the collector current for parallel and anti-parallel alignment, respectively. In this paper, we report on the variation of the MC as a function of the emitter/base bias voltage (V_{EB}), i.e., the hot electron energy, in MTTs with GaAs(001), GaAs(111), and Si(001) collectors. For MTTs with a GaAs collector, a pronounced nonmonotonic bias dependence of the MC is observed,[23] whereas for MTTs with a Si collector the MC decreases monotonically with the bias voltage. A model based on spin-dependent inelastic electron scattering in the base layer and strong electron scattering at the base/collector interface is proposed to explain the experimental results. The different bias dependences for MTTs with GaAs and Si collectors is explained by taking into account the different conduction band structures of these semiconductors.

EXPERIMENT

The MTTs were fabricated by dc magnetron sputtering at room temperature. Three shadow masks were used to form the emitter, the isolation pads which electrically insulate the emitter from the base and the collector, and the base layer, respectively. The active area of the device was $\sim 150 \times 100\ \mu\mathrm{m}^2$ and the base area was $\sim 1\times 8\ \mathrm{mm}^2$. The structures of the MTTs were semiconductor/t FM/23-Å $\mathrm{Al_2O_3}$/50-Å $\mathrm{Co_{84}Fe_{16}}$ ($\mathrm{Co_{70}Fe_{30}}$ for sample 6 in Table I)/300-Å $\mathrm{Ir_{22}Mn_{78}}$/50-Å Ta, where t is the thickness of the base layer, the FM is $\mathrm{Co_{84}Fe_{16}}$, $\mathrm{Co_{70}Fe_{30}}$ or $\mathrm{Ni_{81}Fe_{19}}$, and the semiconductor is n-type GaAs(001) $[\sim(0.7\text{–}3.6)\times 10^{17}\ \mathrm{cm^{-3}}]$, GaAs(111) $[\sim(3\text{–}5.4)\times 10^{16}\ \mathrm{cm^{-3}}]$ or Si(001) $[\sim(0.5\text{–}2)\times 10^{15}\ \mathrm{cm^{-3}}]$. An overview of several different structures that have been studied is given in Table I. The GaAs substrates were annealed at 520 °C in the vacuum deposition chamber prior to film growth to remove a thin surface oxide layer. The Si substrates were cleaned in an iso-propanol alcohol degreasing bath and dried in warm nitrogen. Then the surface oxide was removed in a 6% HF acid solution followed by a short distilled water rinse before loading into the deposition chamber.

The large base area of the MTTs fabricated with shadow masks gives rise to a significant leakage current across the

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TABLE I. The base, collector structure, and TMR of some typical MTT samples.

Sample number	Base	Collector	TMR (%)
1	30-Å $Co_{84}Fe_{16}$	GaAs (001)	46.4
2	45-Å $Co_{84}Fe_{16}$	GaAs (001)	40.7
3	100-Å $Co_{84}Fe_{16}$	GaAs (001)	31.7
4	74-Å $Ni_{81}Fe_{19}$	GaAs (001)	14.7
5	30-Å $Co_{84}Fe_{16}$	GaAs (111)	29.0
6	3-Å Fe| 50-Å $Co_{70}Fe_{30}$	Si (001)	33.8

Schottky barrier at room temperature. To reduce this leakage current, the transport measurements were conducted at 77 K. The bias voltage dependence of the MC is summarized in Fig. 1. MTTs with a GaAs collector (samples 1–5) had different base layer materials, and were grown on top of substrates with two different crystalline orientations. However, they all show a pronounced nonmonotonic bias voltage dependence of the MC [Fig. 1(a)]. When the bias voltage V_{EB} exceeds the Schottky barrier height ($\sim$0.78 V), a large MC is observed. The MC decreases with V_{EB} up to about 1.1 V, then increases slightly and finally decreases gradually. The quantitative difference between these samples is most likely due to a difference in film growth and/or tunnel barrier formation. For example, the growth of magnetic tunnel junctions depends critically on the materials used and the growth of the base layers can be quite different on GaAs(001) and GaAs(111) substrates. This likely accounts for variations in the tunneling magnetoresistance (TMR) values measured on samples 1–5 (Table I).

Note that the MC of a single base layer MTT depends on both the spin filtering in the base layer and the polarization of the electrons injected from the emitter into the base (i.e., the emitter spin polarization). When the CoFe base layer is much thicker than the minority spin electron attenuation length the MC is limited by the emitter polarization.[24] The emitter polarization is very sensitive to the interface between the FM metals and the tunnel barrier. The smaller MC of samples 2 and 3 compared to that of sample 1 can therefore be explained by the variation of the emitter polarization due to different FM metal/tunnel barrier interface formations. Another important consideration is that spin filtering will eventually be limited by spin-flip scattering mechanisms in the base layer which will give a lower limit to the minority electron current. This will also limit the maximum possible MC value.[19] If we ignore spin-flip scattering for MTTs with thick enough base layers the bias dependence of the MC should become weak. We do not observe this which suggests that the spin-mixing effect should be taken into account for thick base layers. This effect is not included in our model and is beyond the scope of this paper.

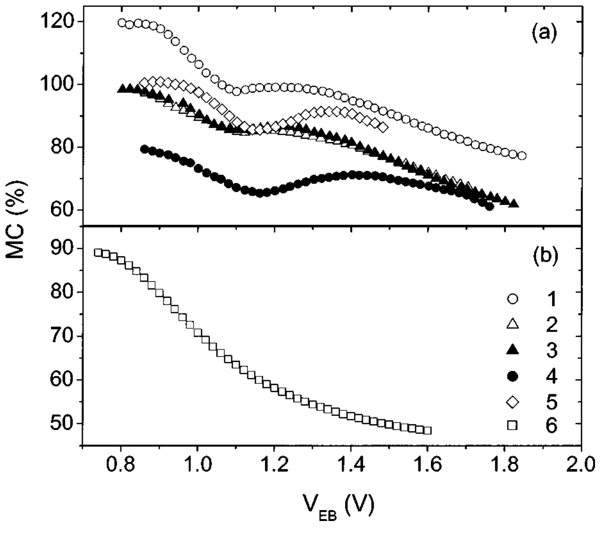

FIG. 1. The bias voltage dependence of the MC for the MTTs listed in Table I with (a) GaAs and (b) Si collectors, respectively.

For the Si sample (sample 6), a thin Fe layer is inserted at the base/collector interface to reduce silicide formation between the Si substrate and the $Co_{70}Fe_{30}$ base layer. Note that, in this case, contrary to the MTTs with a GaAs collector, the MC decreases monotonically as a function of bias voltage [Fig. 1(b)].

MODEL

Hot electron transport across metal/semiconductor Schottky barriers has been studied by ballistic electron emission microscopy (BEEM).[25–27] The model presented here is similar to the BEEM model, but is extended to include spin-dependent electron scattering in the base layer. In this model, the collector current is calculated by the following equation:

$$\begin{aligned} I_{C,P(AP)}(V_{\mathrm{EB}}) &= I_E(0.5+0.5P_E)\exp(-t/\lambda_{\uparrow(\downarrow)})\cdot\int_{\phi_S}^{eV_{\mathrm{EB}}} f_{\uparrow(\downarrow)}(E) \\ &\quad\times\int D_{\uparrow(\downarrow)}(E,k_\parallel)T(E,k_\parallel)dk_\parallel dE \\ &\quad+I_E(0.5-0.5P_E)\exp(-t/\lambda_{\downarrow(\uparrow)})\cdot\int_{\phi_S}^{eV_{\mathrm{EB}}} f_{\downarrow(\uparrow)}(E) \\ &\quad\times\int D_{\downarrow(\uparrow)}(E,k_\parallel)T(E,k_\parallel)dk_\parallel dE, \end{aligned} \tag{1}$$

where I_E is the tunneling current injected from the emitter into the base, P_E is the emitter spin polarization, t is the base layer thickness, $\lambda_{\uparrow(\downarrow)}$ is the spin-dependent attenuation length for majority (minority) electrons, E is the hot electron energy, $f_{\uparrow(\downarrow)}$ is the energy distribution function of the hot electrons at the base/collector interface, $D_{\uparrow(\downarrow)}$ is the angular distribution function of the hot electrons at the base/collector interface, T is the electron transmission coefficient across the Schottky barrier, and $k_\parallel$ is the component of the electron wave vector parallel to the layers. The angular distribution $D_{\uparrow(\downarrow)}$ is assumed to be a two-dimensional Gaussian distribution centered at $k_\parallel=0$ with a width of $\sigma_{\uparrow(\downarrow)}$, where σ is a fraction of k_B, the maximum hot electron wave vector in the base layer [$k_B=\sqrt{2m_0(eV_{\mathrm{EB}}+E_F)/\hbar^2}$, where m_0 is the free electron mass, and E_F is the Fermi energy]. The energy distribution $f_{\uparrow(\downarrow)}$ is assumed to be a half-Gaussian centered at eV_{EB} with a width of $\varepsilon_{\uparrow(\downarrow)}$. The transmission coefficient T is calculated using Eqs. (5) and (6) of Ref. 26.

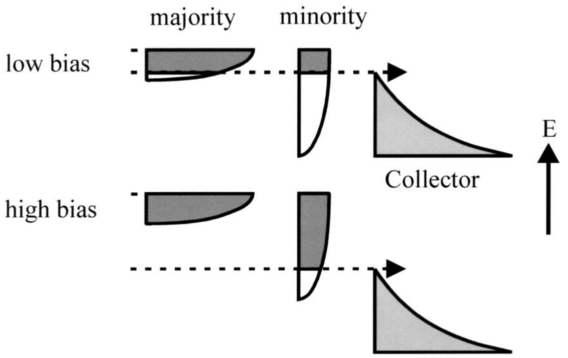

FIG. 2. Schematic illustration of the energy distribution for the majority and minority electrons at the base/collector interface. The shaded areas indicate electrons that have enough energy to surmount the Schottky barrier. At a low bias voltage (upper half), most of the majority electrons but only a small fraction of the minority electrons have enough energy to surmount the Schottky barrier. At a high bias voltage (lower half), this asymmetry is reduced.

In the MTT, spin-polarized hot electrons are injected from the emitter into the base. The injected electrons initially have very narrow angular and energy distributions because the tunneling process is highly sensitive to the tunnel barrier height and thickness. As these hot electrons traverse the base layer, they experience spin-dependent inelastic scattering and lose energy. Since the scattering rate is typically lower for majority electrons than for minority electrons, the minority electrons lose more energy and consequently end up with a broader energy distribution. Additional electron scattering occurs at the base/collector interface after which part of the electrons are collected into the semiconductor substrate. This interface scattering broadens the hot electron angular distribution.

The GaAs conduction band has lowest energy at the center of the Brillouin zone (Γ valley). At an energy of ~0.29 eV above the top of the Schottky barrier, there are eight local minima along the $\langle 111 \rangle$ axes (L valleys). At an even higher energy, ~0.48 eV above the Schottky barrier height, there are six local minima along the $\langle 001 \rangle$ axes (X valleys).[28] When the bias voltage exceeds the Schottky barrier height by a small margin, a hot electron current is collected through the central Γ valley. Because of their narrow energy distribution, a relatively large portion of the majority electrons is able to surmount the Schottky barrier and contribute to the collector current. On the other hand, only a small portion of the minority electrons has enough energy to be collected. This is schematically illustrated in Fig. 2. The large spin asymmetry results in a large MC. At elevated emitter/base bias voltage, increasingly more of the scattered minority electrons are able to surmount the Schottky barrier. The increase of the minority electron current gives rise to a smaller MC. If all the conduction bands open up at the same energy level, a monotonic decrease of the MC with the bias voltage is expected, as observed in MTTs with a Si collector. However, for GaAs, the L valleys and the X valleys open up at higher energies than the Γ valley. When these valleys become available for hot electron injection, they favor the collection of majority electrons and thus tend to increase the MC. This leads to the observed nonmonotonic bias voltage dependence of the MC for MTTs with GaAs collectors.

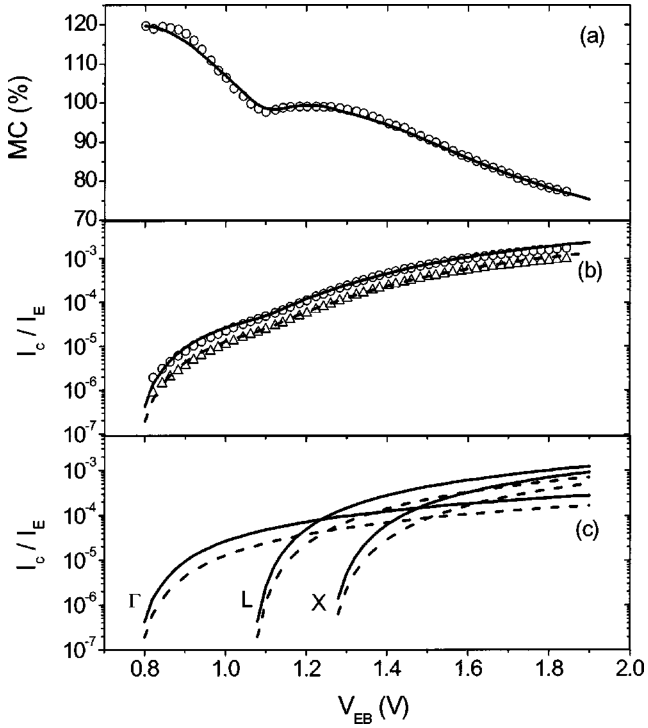

FIG. 3. The measured (symbols) and calculated (lines) bias voltage dependence of (a) the MC and (b) and (c) the transfer ratio for both parallel (circles/solid lines) and antiparallel (triangles/dashed lines) alignment of the emitter and base magnetic moments in MTTs from sample 1. (c) displays the calculated transfer ratio for the Γ, L, and X conduction band valleys separately. The angular distribution is assumed to be broad and identical for majority and minority electrons.

DISCUSSION

We focus our discussion on samples 1 and 6. The main conclusions are applicable to all the samples, although the fitting parameters may vary from sample to sample.

The measured MC (open circles) and the calculated MC (solid line) are plotted in Fig. 3(a) for sample 1. The fitting parameters used in the calculation are $\Phi_S = 0.78$ V, $P_E = 0.5$, $E_F = 8.9$ eV, $\lambda_\uparrow = 50$ Å, $\lambda_\downarrow = 20$ Å, $\varepsilon_\uparrow = 0.1$ eV, $\varepsilon_\downarrow = 0.3$ eV, and $\sigma_\uparrow = \sigma_\downarrow = 0.5$. An energy dependent electron effective mass is assumed: $m^* = m^*(0)(1 + \alpha E)$, where $m^*(0)$ is the electron effective mass at the conduction band minima, α is the nonparabolicity parameter of the conduction band, and E is the electron energy with respect to the bottom of the conduction band. For the Γ valley we used $m^*_\Gamma(0) = 0.067 m_0$, $\alpha_\Gamma = 0.69\ \mathrm{eV}^{-1}$; for the L valleys, $m^*_{L,l}(0) = 1.9 m_0$, $m^*_{L,t}(0) = 0.075 m_0$, $\alpha_L = 0.65\ \mathrm{eV}^{-1}$; and for the X valleys, $m^*_{X,l}(0) = 1.3 m_0$, $m^*_{X,t}(0) = 0.23 m_0$, $\alpha_X = 0.5\ \mathrm{eV}^{-1}$.[26] Here m_0 is the free electron mass. The subscripts l and t refer to longitudinal and

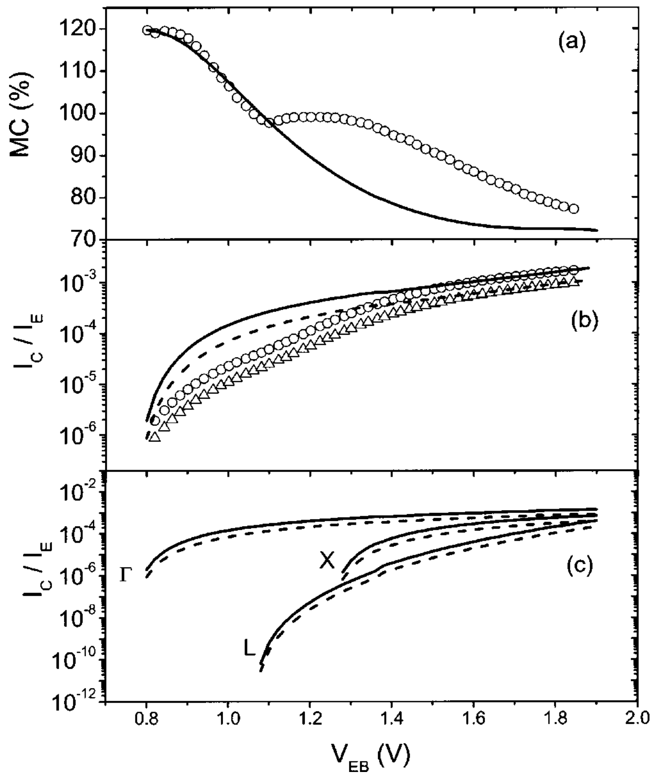

FIG. 4. Similar to Fig. 3. The angular distribution is assumed to be narrow and identical for the majority and minority electrons.

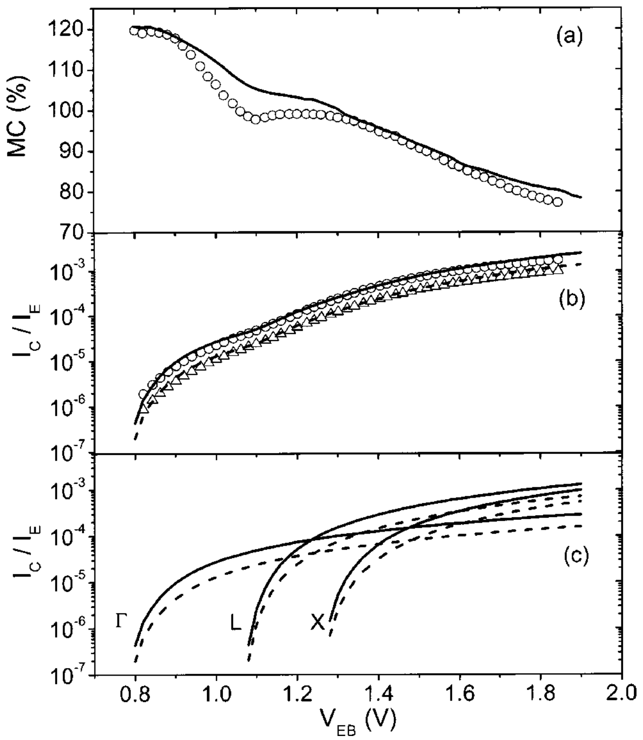

FIG. 5. Similar to Fig. 3. The angular distribution is assumed to be broad but not identical for the majority and minority electrons, with the minority electrons having a broader distribution.

transverse electron effective mass, respectively. In Fig. 3(b), the measured transfer ratio I_C/I_E for parallel (open circles) and antiparallel (open triangles) alignment of the base and the emitter magnetic moments are plotted together with the results from the calculations (solid line for parallel alignment and dashed line for antiparallel alignment). The calculated results agree very well with the experimental results. In Fig. 3(c), the contributions to the collector current from the different conduction band valleys are calculated separately. At a low bias voltage, all the electrons are injected into the Γ valley. At $V_{EB} \approx 1.1$ V, the L valleys become available for electron collection. Initially, more majority electrons are collected than minority electrons, and an increase of the MC is observed. The electron effective mass of the L valleys is much larger than that of the Γ valleys. Consequently, the number of available energy states in the L valleys increases very rapidly with the bias voltage. The contribution to the collector current from the L valleys is therefore significant, as reflected by a small kink in the transfer ratio at $V_{EB} \approx 1.1$ V [Fig. 3(b)]. As the bias voltage increases further, more minority electrons are injected into the L valleys and the MC starts to decrease again. The energy states in the X valleys become available for electron injection at $V_{EB} \approx 1.3$ V. However, the current collected through the Γ and L valleys is already very large and hence no significant change in the MC or the transfer ratio is caused by the small additional current collected through the X valleys.

For the calculation shown in Fig. 3, a broad angular distribution is assumed for both majority and minority electrons. This assumption is essential to reproduce the non-monotonic bias voltage dependence of the MC. Since the L valleys are located far from the center of the Brillouin zone, a large parallel wave vector is required to access the conduction band states in these valleys. If the angular distribution is narrow, only a few electrons have large parallel wave vectors and electron collection through the L valleys hardly contributes to the total collector current. This would result in a monotonic decrease of the MC with the emitter/base bias voltage, as clearly illustrated in Fig. 4(a). In this calculation we assumed the same fitting parameters as those used in Fig. 3, except for the much narrower angular distribution: $\sigma_\uparrow = \sigma_\downarrow = 0.1$. As discussed above, the narrow angular distribution results in a small contribution of the L valleys to the collector current [see Fig. 4(c)]. Although the opening of the L valleys still tends to increase the MC, the collector current is dominated by electron collection through the central Γ valley and therefore the MC varies monotonically with the bias voltage.

In the previous calculations, we assumed that the minority electrons have a broader energy distribution than the majority electrons due to their higher scattering probability in the base layer. Yet we assumed that the majority and the minority electrons have the same angular distribution. It may appear natural to assume that the angular distribution is also broader for the minority electrons than for the majority electrons. However, the measured non-monotonic bias dependence cannot be reproduced with this assumption, as illustrated by Fig. 5(a). In this calculation the fitting parameters are the same as those used in Fig. 3 except that $P_E = 0.46$, $\sigma_\uparrow = 0.5$, and $\sigma_\downarrow = 0.7$. The broader angular distribution makes it easier for the minority electrons to access the L valleys than for the majority electrons. This partly compensates for the lower collection efficiency

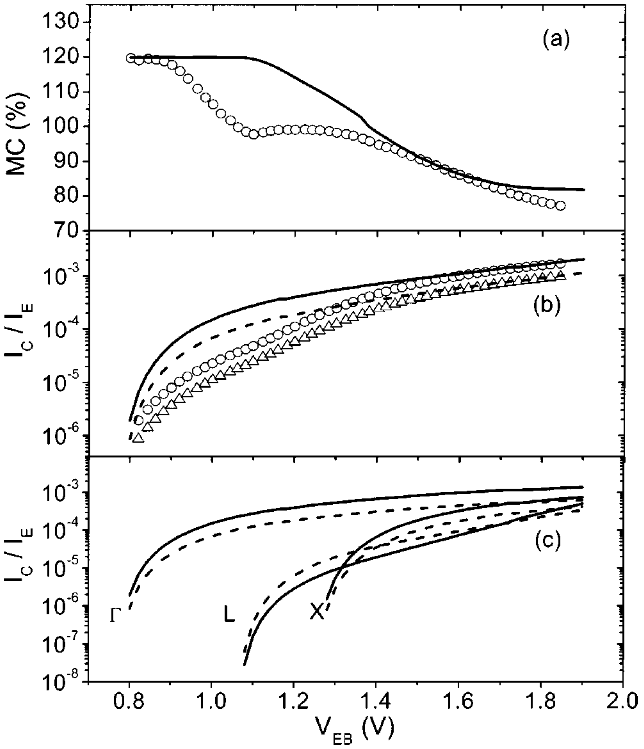

FIG. 6. Similar to Fig. 3. In this calculation, the energy distribution is assumed to be narrow and identical for the majority and minority electrons. The angular distribution is assumed to be narrow for the majority electrons and broad for the minority electrons.

of the minority electrons due to their broader energy distribution. As a consequence, when the *L* valleys open up, the ratio of the number of collected majority electrons and minority electrons is reduced and the MC decreases monotonically with the bias voltage. A similar angular distribution of the majority and minority electrons, which is necessary to explain the experimental results, suggests efficient spin-independent electron scattering at the metal/semiconductor interface. This interface scattering may be due to metal/semiconductor alloying, residual oxide on the GaAs surface and/or interfacial defects. Elastic scattering at nonepitaxial metal/semiconductor interfaces has been used to explain similar BEEM currents for the Au/Si(001) and Au/Si(111) systems.[27] In a previous study, we also observed strong scattering at the base/collector interface.[24]

If we assume that the majority and minority electrons have a similar energy distribution but a different angular distribution, the experimental results cannot be explained either. Figure 6 shows the calculation results assuming a narrow angular distribution for the majority electrons and a broad angular distribution for the minority electrons. The fitting parameters in Fig. 6 are the same as those in Fig. 3, except that $P_E=0.39$, $\varepsilon_\uparrow=\varepsilon_\downarrow=0.1$ eV, $\sigma_\uparrow=0.1$, and $\sigma_\downarrow=0.5$. At a low bias, the MC stays approximately constant since the same energy distribution is assumed for both the majority and minority electrons. When the *L* valleys open up, more minority electrons are collected than majority electrons because they have larger parallel wave vectors and therefore can access the *L* bands more easily. As a result, the MC decreases. On the other hand, if we assume a broad angular distribution for the majority electrons and a narrow angular distribution for the minority electrons, the MC will become negative (not shown), which is opposite to what we observed in our experiments. Note that a very similar bias voltage dependence of the MC is measured for both the GaAs(001) and GaAs(111) substrates, although the projection of conduction bands onto the interface plane is very different for the two substrate orientations. This is a strong indication that the measured bias voltage dependence of the MC cannot be explained by different angular distributions for the majority and minority electrons.

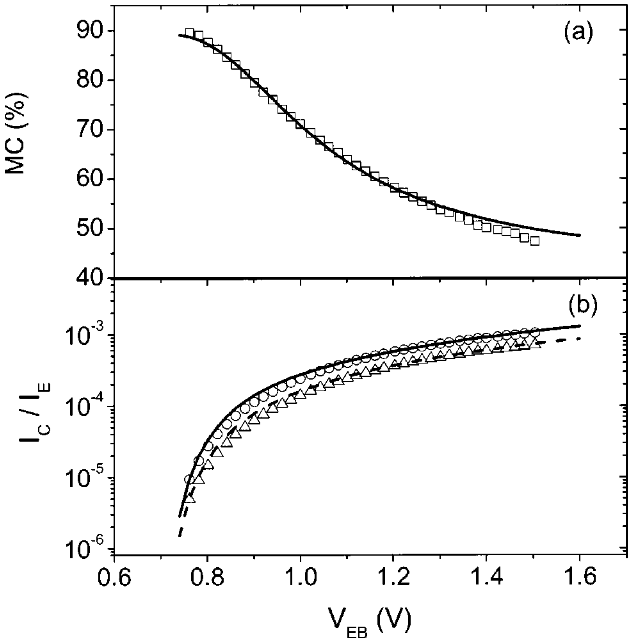

FIG. 7. The measured (symbols) and calculated (lines) bias voltage dependence of (a) the MC and (b) the transfer ratio for both parallel (circles/solid line) and antiparallel (triangles/dashed line) alignment of the emitter and base magnetic moments in the MTT of sample 6. The angular distribution is assumed to be broad and identical for majority and minority electrons.

The Si conduction band has six valleys located along the ⟨001⟩ axes and they have the same energy minimum. Hence, a monotonic decrease of the MC with the emitter/base bias voltage is expected according to our model. The experimental results are consistent with this prediction, as shown in Fig. 7. Here we assumed the following fitting parameters: $\Phi_S=0.72$ V, $P_E=0.417$, $E_F=8.9$ eV, $\lambda_\uparrow=50$ Å, $\lambda_\downarrow=28$ Å, $\varepsilon_\uparrow=0.08$ eV, $\varepsilon_\downarrow=0.26$ eV, and $\sigma_\uparrow=\sigma_\downarrow=0.5$. The energy-dependent electron effective masses used in the calculation were $m_l^*(0)=0.98m_0$, $m_t^*(0)=0.19m_0$, and $\alpha_\Gamma=0.5\ \mathrm{eV}^{-1}$.[25,29]

SUMMARY

The MTT is a powerful tool to probe spin-dependent hot electron transport in metals, semiconductors and across their interfaces. A nonmonotonic bias voltage dependence of the MC is observed in MTTs with a GaAs collector, whereas a monotonic decrease of the MC with the bias voltage is observed in MTTs with a Si collector. A model is presented to explain the dependence of the MC on the bias voltage and the semiconductor electronic structures. In this model, different energy distributions are assumed for the majority and minority electrons, which is a direct result of spin-dependent inelastic scattering probabilities in the FM base layer. In addition, an identically broad angular distribution is assumed for both the majority and minority electrons, which is justified by efficient electron scattering at the metal/semiconductor interface. The calculations based on this model agree very well with the experimental results. The nonmonotonic bias behavior of the MC found for MTTs with a GaAs collector is due to the three energy minima in the GaAs conduction band. When the second energy minima (the L points) become available for hot electron collection, the increase of the majority electron current is relatively larger than the increase of the minority electron current, giving rise to an increase of the MC. Such an effect is absent for MTTs with a Si collector. For MTTs with Si collectors the MC decreases monotonically with the emitter/base bias voltage due to a reduction of the spin asymmetry in the electron collection efficiency at elevated electron energies.

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