Nonmonotonic Bias Voltage Dependence of the Magnetocurrent in GaAs-Based Magnetic Tunnel Transistors

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Magnetic tunnel transistors are used to study spin-dependent hot electron transport in thin CoFe films and across CoFe/GaAs interfaces. The magnetocurrent observed when the orientation of a CoFe base layer moment is reversed relative to that of a CoFe emitter, is found to exhibit a pronounced nonmonotonic variation with electron energy. A model based on spin-dependent inelastic scattering in the CoFe base layer and strong electron scattering at the CoFe/GaAs interface, resulting in a broad electron angular distribution, can well account for the variation of the magnetocurrent in magnetic tunnel transistors with GaAs(001) and GaAs(111) collectors.

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Spin-dependent hot electron transport in ferromagnetic (FM) thin films and electron transmission at metal/semiconductor interfaces are key ingredients to the operation of many magnetoelectronic devices. Various experimental techniques have been used to study spin-dependent hot electron scattering in FM 3*d* transition metal films [1–6]. Electron transmission at metal/semiconductor interfaces has been extensively studied using ballistic electron emission microscopy (BEEM) [7–14]. The magnetic tunnel transistor (MTT), which combines a magnetic tunnel junction with a semiconductor collector, is a magnetoelectronic device based on spin-dependent hot electron transport across a FM metal film and subsequent collection of electrons in a semiconductor substrate [15–17]. The collector current of the MTT exhibits a giant magnetic field response. In this Letter we show that the magnetocurrent (MC) of MTTs with GaAs(001) and GaAs(111) collectors varies nonmonotonically with increasing electron energy and we introduce a model that accounts well for this dependence. The influence of spin-dependent hot electron scattering in the FM film, hot electron scattering at the metal/semiconductor interface, and the semiconductor conduction band structure are discussed in detail.

In one form of the MTT spin-polarized electrons are injected from a FM emitter across a tunnel barrier into a FM base layer (see Fig. 1). By changing the bias voltage across the tunnel barrier (V_{EB}) the energy of the injected electrons can be varied. When the electron energy exceeds the Schottky barrier height (ϕ_S) at the metal/semiconductor interface, a collector current I_C is measured. I_C represents electrons that are transported across the base layer and the base/collector interface. The injected spin-polarized electron current is further spin filtered by spin-dependent scattering in the FM base. Thus I_C depends critically on the relative orientation of the base and emitter magnetic moments, as described by $\mathrm{MC} = (I_{C,P} - I_{C,AP})/I_{C,AP}$, where $I_{C,P}$ and $I_{C,AP}$ are the collector current for parallel (P) and antiparallel (AP) alignment of these moments. I_C also depends on the conduction band structure of the semiconductor substrate. We consider here (001) and (111) oriented GaAs collectors. GaAs has a direct conduction band minimum at the Brillouin zone center (Γ point) and higher energy indirect minima at the L and X points of the Brillouin zone. The separation between the Γ and the L and X points is 0.29 and 0.48 eV, respectively [18].

The structure of the MTTs, formed by magnetron sputtering through a sequence of shadow masks, is GaAs/30 Å CoFe/25 Å Al_2O_3/50 Å CoFe/300 Å $Ir_{22}Mn_{78}$/50 Å Ta, where CoFe = $Co_{84}Fe_{16}$. The Al_2O_3 barrier is formed by plasma oxidizing an 18 Å thick Al layer. The pinning of the CoFe emitter by the antiferromagnetic IrMn layer enables independent switching of the CoFe base layer in small magnetic fields. Current-voltage measurements at room temperature reveal $\phi_S \sim 0.78$ and ~ 0.84 eV at the CoFe/GaAs(100) and CoFe/GaAs(111) interfaces, respectively.

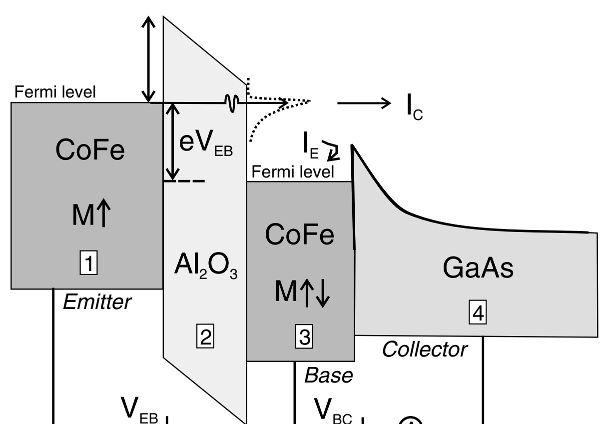

FIG. 1. Schematic energy diagram of an MTT. Region 1 is the emitter, region 2 is the Al_2O_3 tunnel barrier, and region 3 is the base. The collector is GaAs (region 4).

Figure 2 shows typical data of MC as a function of emitter/base bias V_{EB} for MTTs with GaAs(001) and GaAs(111) collectors at 77 K (open circles). The experimental results for the two different substrate orientations are qualitatively the same [19]. The MC is largest at small bias ($V_{EB} \approx \phi_S/e$), decreases with bias up to $V_{EB} \approx \phi_S/e + 0.3$ V, after which it increases slightly and then decreases monotonically. Interestingly, the minimum of MC occurs at an electron energy that coincides with the onset of hot electron transmission into the GaAs L conduction band valleys. This suggests that the nonmonotonic variation of MC depends not only on spin-dependent hot electron scattering in the FM base but also on the detailed electronic structure of the GaAs collector. In the following, model calculations will be used to explain the similar bias dependence of MC in MTTs with GaAs(001) and GaAs(111) collectors.

The model presented here is based on those often used in BEEM studies [12–14]. In this model the collector current is given by

$$I_{C,P(AP)}(V_{EB}) = I_E(0.5 + 0.5P_E)\exp(-t/\lambda_{\uparrow(\downarrow)}) \cdot \int_{\phi_S}^{eV_{EB}} f_{\uparrow(\downarrow)}(E) \int D(E, k_{\|})T(E, k_{\|})dk_{\|}dE$$
$$+ I_E(0.5 - 0.5P_E)\exp(-t/\lambda_{\downarrow(\uparrow)}) \cdot \int_{\phi_S}^{eV_{EB}} f_{\downarrow(\uparrow)}(E) \int D(E, k_{\|})T(E, k_{\|})dk_{\|}dE,$$

where I_E is the tunnel 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 attenuation length for majority (minority) electrons within the FM base, $f_{\uparrow(\downarrow)}$ is the corresponding spin-dependent energy distribution function near the CoFe/GaAs interface, D is the angular distribution of the electrons after scattering in the base, and T is the transmission coefficient at the CoFe/GaAs interface. $f(E)$ is assumed to be a half Gaussian of width ε, centered at eV_{EB} (see inset of Fig. 2). $D(E, k_{\|})$ is modeled as a two-dimensional Gaussian distribution of width σ, where σ is a proportion of the maximum electron wave vector k_B in the base ($k_B = \sqrt{k_{B\perp}^2 + k_{B\|}^2} = \sqrt{2m_0(E_F + eV_{EB})/\hbar^2}$, where $\perp$ and $\|$ indicate perpendicular and parallel to the interfaces, m_0 is the free electron mass, and E_F is the Fermi energy of the CoFe base layer). Equations (5) and (6) from Ref. [14] are used to calculate the transmission coefficient at the CoFe/GaAs interface. We note that the electron attenuation lengths used in this calculation have a slightly different definition from those extracted from base layer thickness dependent measurements of the collector current [20,21]. In an MTT transport measurement, the strict separation between λ and $f(E)$ is not possible.

The solid lines in Fig. 2 represent fits to the experimental data for the GaAs(001) and GaAs(111) substrates. The nonmonotonic variation of MC with V_{EB} is reproduced for both substrate orientations when the electron angular distribution is assumed to be broad *and* the energy distribution of minority electrons is taken to be broader than that of majority electrons. The small quantitative difference between experiment and calculation for GaAs(111)-based MTTs at elevated bias is explained by the choice of the model parameters. The calculations assume the same values for λ, $f(E)$, $D(E, k_{\|})$, and $T(E, k_{\|})$ for both substrate orientations, whereas these parameters might differ due to structural differences for MTTs grown on different GaAs facets. The initial decrease of MC is a direct result of the spin asymmetry in the electron energy distribution. This asymmetry is largest at energies close to eV_{EB} (see inset of Fig. 2). Hence, a maximum MC is measured when collection of hot electrons through the Γ valley is possible for electrons with small energy loss only, i.e., when $eV_{EB} \approx \phi_S$.

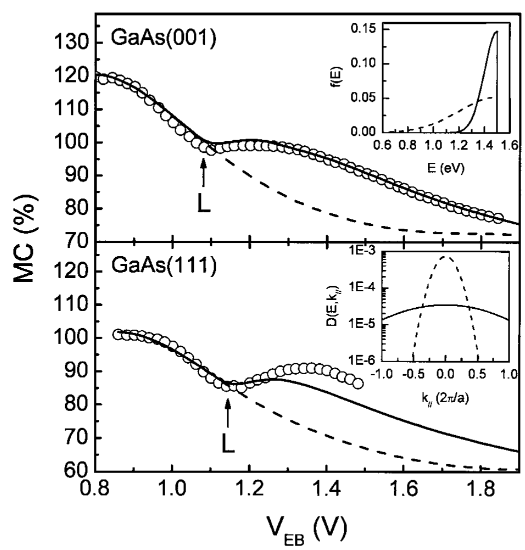

FIG. 2. Bias dependence of MC for MTTs with GaAs(001) and GaAs(111) collectors. The solid line in the upper panel represents a model calculation for GaAs(001) with $\lambda_\uparrow = 50$ Å, $\lambda_\downarrow = 20$ Å, $\varepsilon_\uparrow = 0.1$ eV, $\varepsilon_\downarrow = 0.3$ eV, $\sigma = 0.5$, $P_E = 50\%$, $E_F = 8.9$ eV, $t = 30$ Å, and $\phi_S = 0.78$ eV. The dashed line represents a calculation with the same parameters, except for a smaller angular distribution function: $\sigma = 0.1$. The two fits to the GaAs(111) data are calculated with the same parameters, except that $P_E = 45\%$ and $\phi_S = 0.84$ eV. The arrow indicates the onset of electron transmission into the GaAs L conduction band valleys. The first inset shows the electron energy distribution function for $\varepsilon = 0.1$ eV (solid line) and $\varepsilon = 0.3$ eV (dashed line) at $V_{EB} = 1.5$ V. The second inset shows the electron angular distribution function for $\sigma = 0.1$ (dashed line) and $\sigma = 0.5$ (solid line) at $V_{EB} = 1.5$ V.

With increasing V_{EB}, electrons with larger energy loss are able to surmount the Schottky barrier as well. This decreases the ratio of majority to minority hot electrons near the CoFe/GaAs interface and thus MC. The same holds for hot electron collection through the L valleys. The increase of MC at the onset of hot electron transport into the L valleys can therefore only be explained if the contribution of the L valleys to the total collector current is comparatively large. For GaAs, the Γ valley is centered at zero parallel wave vector, whereas either all or six out of eight L valleys are centered at large parallel wave vectors for GaAs(001) and GaAs(111), respectively. Hence, only if the electrons have a broad angular distribution will there be a significant contribution of the L valleys to the total collector current for either substrate orientation. Indeed, for a narrow angular distribution a monotonic decrease of MC with V_{EB} is calculated (dashed lines in Fig. 2).

Figure 3 shows the measured and calculated transfer ratio (I_C/I_E) for parallel and antiparallel alignment of the emitter and base magnetic moments. Again, the measurements for both GaAs(001) and GaAs(111) can be modeled only by assuming broad electron angular distributions. For narrow $D(E, k_{\|})$ the contribution of the Γ valley to the collector current is much too large to account for that observed. The striking similarity between the transfer ratios for both substrate orientations is similar to that found in, for example, BEEM experiments on Au/Si [8,10,12] and Pd/Si [9]. These BEEM results have been explained by hot electron scattering in the metal film [8], multiple passages of electrons through the metal in combination with diffuse scattering at the boundaries [10], focusing of electrons along specific directions [11], and strong hot electron scattering at the metal/semiconductor interface [9,13]. Since the attenuation lengths in CoFe are small compared to those in noble metals, multiple passages of hot electrons through the base can be ignored in MTTs with a CoFe base. Furthermore, a focusing effect would result in strikingly different angular distributions for (001) and (111) substrates, which does not agree with our experiments. The question as to whether bulk or interface scattering is predominantly responsible for the broad electron angular distribution has been addressed by base layer thickness dependent measurements of the transfer ratio in GaAs(001)-based MTTs. These measurements reveal that hot electron scattering at the CoFe/GaAs(001) interface is about 50 times larger than in the bulk of a 30 Å CoFe film at large V_{EB} [21]. Thus we conclude that strong scattering at the CoFe/GaAs interface redistributes the incoming electron flux, i.e., the parallel momentum of hot electrons is not conserved during transmission. This leads to a large contribution of the L valleys to the total collector current, which, in combination with a spin-dependent electron energy distribution, accounts for the nonmonotonic bias dependence of MC. Strong electron scattering at the FM metal/semiconductor interface may result in considerable spin mixing and hence to a possible reduction of the collector current polarization. This might account for the low spin-injection efficiencies observed in FM metal/semiconductor systems [22,23].

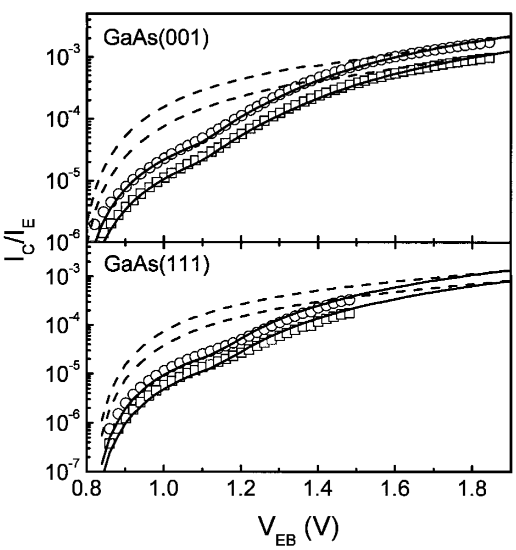

FIG. 3. Transfer ratio I_C/I_E for parallel (circles) and antiparallel (squares) orientation of the emitter and base magnetic moments. The lines represent fits to the experimental data for broad ($\sigma = 0.5$, solid lines) and narrow ($\sigma = 0.1$, dashed lines) electron angular distributions. The parameters in the calculation are the same as those used to calculate the bias dependence of MC (Fig. 2).

Figure 4 illustrates how the spin asymmetry in the electron energy distribution influences the bias dependence of MC. Qualitative agreement between experiment and calculation is obtained only if the energy distribution of minority electrons is assumed to be broader than that of majority electrons. The spin-dependent broadening of the electron energy distribution can be rationalized by spin-dependent electron-electron interactions. For CoFe the majority d band is fully occupied, whereas a portion of the minority d band is unoccupied [24]. Scattering of minority electrons into empty d states above the Fermi level is efficient and is often held responsible for the difference between the majority and minority attenuation lengths in FM $3d$ transition metals [1–5]. Minority electrons that are scattered into empty d states excite electrons with either spin from occupied states below the Fermi level. For CoFe the number of excited minority electrons will be significantly larger than the number of excited majority electrons due to the absence of a majority d band just below the Fermi level. This scattering process plus others [25] thus contribute to a spin-dependent electron energy distribution.

Another spin-dependent process is spin wave scattering [6,26–28] which results in small energy losses and large spin asymmetry. The conservation of angular momentum limits the emission of spontaneous spin waves to minority electrons turning them into majority electrons [29]. This

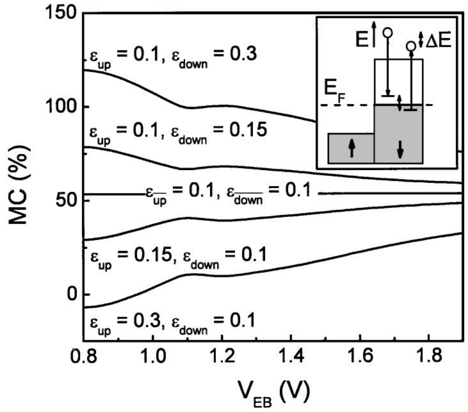

FIG. 4. Influence of the electron energy distribution on the dependence of MC on V_{EB} [calculated for GaAs(001)]. Except for $\varepsilon\uparrow$ and $\varepsilon\downarrow$, the parameters are the same as those used to calculate the solid lines in Figs. 2 and 3. The inset illustrates an electron-electron scattering event that produces a spin asymmetry in the electron energy distribution: scattering of a minority electron into an empty d state results most probably in the excitation of another minority electron from below the Fermi level.

process broadens the energy distribution of majority electrons, whereas it eliminates minority electrons from the collector current. Spontaneous spin wave emission might therefore contribute to the small minority electron attenuation lengths in FM metals [6], but it cannot account for the bias dependence of MC.

Finally, we note that it has been proposed that the observed monotonic dependence of MC on V_{EB} in Si-biased MTTs (for biases up to 1.5 V) can be explained by spin-dependent elastic scattering [30]. If we include only such scattering in our model then we would also find a *monotonic* decrease of MC for both GaAs(001) and GaAs(111). Our inelastic scattering model, on the other hand, explains the *nonmonotonic* variations of MC in GaAs-based MTTs, as well as the monotonic decrease of MC observed in Si-based MTTs (Si has a single conduction band minimum) [15,31].

In summary, we have shown that MTTs prepared using GaAs(001) and GaAs(111) collectors display large magnetocurrents which vary nonmonotonically with increasing hot electron energy. The energy dependence of MC is explained by a combination of spin-dependent broadening of the electron energy distribution in the FM base layer, as a result of electron-electron interactions, and strong hot electron scattering at the metal/semiconductor interface, which leads to a significant transport of hot electrons into GaAs conduction band valleys with large parallel wave vector. The strong diffuse scattering at the FM metal/semiconductor interface may have implications for the injection of significantly spin-polarized electron current into semiconductors.

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