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Ferroelectric Switch for Spin Injection

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Ferroelectric switch for spin injection

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A method for the switching of the spin polarization of the electric current injected into a semiconductor is proposed, based on injecting spins from a diluted magnetic semiconductor through a ferroelectric tunnel barrier. We show that the reversal of the electric polarization of the ferroelectric results in a sizable change in the spin polarization of the injected current, thereby providing a two-state electrical control of this spintronic device. We also predict a possibility of switching of tunneling magnetoresistance in magnetic tunnel junctions with a ferroelectric barrier and coexistence of tunneling magnetoresistance and giant electroresistance effects in these multiferroic tunnel junctions. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2138365]

Spin injection into semiconductors has recently aroused significant interest due to potential applications in spin electronics, promising to incorporate spin degrees of freedom into existing semiconductor technologies (for a recent review, see Ref. 1). The feasibility of using semiconductors is supported by their capability to carry highly spin-polarized currents over long distances,[2] by ferromagnetic ordering of $3d$ transition metal dopants in diluted semiconductors,[3] and by the successful demonstration of electrical spin injection at room temperature.[4–6] The major thrust of the most investigations is to achieve the highest-possible spin polarization of the injected current.[7,8] Meanwhile the possibility to switch the spin polarization between two values might be an important issue for the future spintronic devices.

In this letter we propose a method for the switching of the spin polarization of the injected current. This method is based on injecting spins from a diluted magnetic semiconductor through a ferroelectric thin film which serves as a tunneling barrier for injected carriers. We show that the reversal of the electric polarization of the ferroelectric film leads to a sizable change in the spin polarization of the tunneling current. This provides a two-state electrical control of the spin polarization, including the possibility of switching from zero to nonzero or from negative to positive spin polarization and vice versa.

The proposed method is based on using a *ferroelectric tunnel junction* that represents a ferroelectric barrier separating two electrodes.[9] The possibility of using ferroelectrics as tunnel barriers is supported by recent experimental[10,11] and theoretical[12] findings, suggesting that ferroelectricity persists down to a nanometer scale. Recent experiments indicate that the electrical resistance in metal/ferroelectric/metal junctions with ultrathin barriers depends on the orientation of the electric polarization which can be switched by an applied electric field.[13] Based on these results, in our previous work we have predicted the existence of a *giant electroresistance* (GER) effect in ferroelectric tunnel junctions.[9] The GER originates from the change in the potential profile induced by the polarization reversal in the ferroelectric barrier due to the different screening lengths in the electrodes with unequal charge densities.

In this letter we investigate how the change in the potential profile caused by the switching of the electric polarization affects the conductance of the minority- and majority-spin carriers injected from a diluted magnetic semiconductor (DMS) through a ferroelectric (FE) barrier to a nonmagnetic (normal) semiconductor (NS). We consider a semi-infinite DMS electrode placed in the half-space $z<0$ (layer 1), a FE barrier of thickness d (layer b), and a NS electrode placed in the half-space $z>d$ (layer 2). We use a free-electron model within an effective mass approximation to describe the electronic structure of the system. The exchange splitting of the free-electron bands in the DMS is introduced via exchange splitting parameter Δ_{ex} such that the spin-dependent potential in the DMS layer is given by $V_1^\sigma = V_1 \pm 1/2\Delta_{ex}$, where σ is the spin index ($\sigma = \downarrow, \uparrow$). Since the Fermi energy, E_F, is constant throughout the structure, the electronic potential in the NS electrode, V_2, with respect to V_1 is controlled by the carrier concentrations in the DMS and NS electrodes. The barrier is represented by a rectangular potential of height U with respect to E_F, which implies that the work functions of the two electrodes are assumed to be the same.

In order to take into account the depolarizing field in the ferroelectric layer and the screening fields in the electrodes and to get the potential profile across the system we follow the procedure of Ref. 9. The electric polarization $\mathbf{P}$ of the ferroelectric creates surface charge densities, $\pm\sigma_P = \pm|\mathbf{P}|$, on the two surfaces of the ferroelectric film. These polarization charges, $\pm\sigma_P$, are screened by the screening charge per unit area $\mp\sigma_S$, which is induced in the two electrodes. Assuming that the ferroelectric is perfectly insulating and imposing the short-circuit condition, we obtain the screening potential in the Thomas-Fermi approximation,

$$\varphi(z) = \begin{cases} \dfrac{\sigma_S \delta_1 e^{-|z|/\delta_1}}{\varepsilon_1}, & z \leqslant 0 \\ \dfrac{\sigma_S \delta_2 e^{-|z|/\delta_2}}{\varepsilon_2}, & z \geqslant d. \end{cases} \tag{1}$$

Here ε_1 and ε_2 are the dielectric permittivities of the DMS and NS electrodes, δ_1 and δ_2 are the Thomas-Fermi screen-

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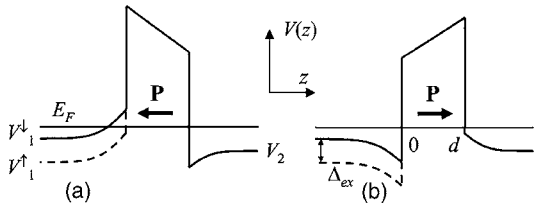

FIG. 1. Schematic representation of the potential profile, $V(z)$, in a DMS/FE/NS tunnel junction for the electric polarization pointing to the left (a) and to the right (b). The dashed and solid lines show the potential seen by the majority- and minority-spin carriers respectively. The horizontal solid line denotes the Fermi energy, E_F.

ing lengths in the two electrodes, and σ_S is the magnitude of the screening charge per unit area. The latter is to be the same in the two electrodes due to the charge conservation condition. The screening charge σ_S can be found from the continuity of the electrostatic potential, resulting in

$$\sigma_S = \frac{dP/\varepsilon_b}{\delta_1/\varepsilon_1 + \delta_2/\varepsilon_2 + d/\varepsilon_b}, \tag{2}$$

where ε_b is the dielectric permittivity of the ferroelectric barrier. The screening length in the electrodes can be obtained using the standard approach,[14] which leads to the following equations for the DMS and NS electrodes:

$$\delta_{1,2}^{-2} = \frac{e^2}{4\pi^2\varepsilon_{1,2}}\left(\frac{2m_{1,2}}{\hbar^2}\right)^{3/2}\{\sqrt{E_F - V_{1,2}^{\uparrow}} + \sqrt{E_F - V_{1,2}^{\downarrow}}\}, \tag{3}$$

where m_1 and m_2 are effective masses of the DMS and NS electrodes, respectively, and $V_2^{\uparrow}=V_2^{\downarrow}=V_2$.[15]

Figure 1 shows the overall potential profile, $V(z)$, which is the sum of the electrostatic potential, $\varphi(z)$, the electronic potential in the electrodes, which controls the position of the bottom of the bands, and the rectangular potential profile discussed above for the FTJ. An important observation which follows from Fig. 1 is that, for the electric polarization of the FE barrier pointing to the left (i.e., towards the DMS electrode), majority-spin carriers experience an additional barrier compared to minority-spin carriers [compare the solid and dashed lines in Fig. 1(a)]. This occurs if the magnitude of the electrostatic potential at the DMS/FE interface, $\varphi_1 \equiv |\varphi(0)|$, is larger than the Fermi energy with respect to the bottom of the minority-spin band, i.e., $E_F - V_1^{\downarrow} - \varphi_1 < 0$. If this condition is met, the spin polarization of the tunneling current is positive and weakly dependent on the potential barrier height. On the other hand, for the electric polarization pointing to the right [Fig. 1(b)], i.e., towards the NS electrode, the tunneling barrier is the same for majority and minority spins [compare the solid and dashed lines in Fig. 1(b)]. In this case, the magnitude of the spin polarization of the tunneling current is largely controlled by the exchange splitting of the bands and the potential profile across the structure. When $E_F - V_1^{\downarrow} - \varphi_1 > 0$, the asymmetry between Π_R and Π_L is due to the different barrier transparencies as a result of the different band structures of the two electrodes. Thus, by reversing the electric polarization of the FE barrier it is possible to switch the spin polarization of the injected carriers between two different values, thereby providing a two-state spin-polarization control of the device.

In order to make these arguments quantitative, we calculate the conductance of the DMS/FE/NS junction using the Landauer formula,

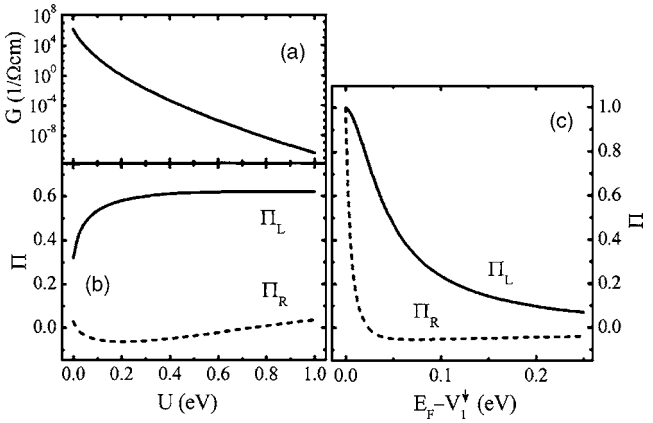

FIG. 2. Total conductance, $G=G^{\uparrow}+G^{\downarrow}$, (a) and spin polarization (b,c) of injected current in a DMS/FE/NS tunnel junction as a function of potential barrier height (a,b) and the Fermi energy (c) for the polarization of the ferroelectric barrier pointing to the left (solid lines) and pointing to the right (dashed lines) for $d=3$ nm. In (a) and (b) $E_F - V_1^{\uparrow}=0.06$ eV and $V_1=V_2$; in (c) $U=0.5$ eV and $V_2 - V_1^{\uparrow}=0.025$ eV.

$$G_\sigma = \frac{e^2}{h}\int \frac{d\mathbf{k}_\parallel}{(2\pi)^2} T_\sigma(E_F, \mathbf{k}_\parallel). \tag{4}$$

Here G_σ is the conductance per spin per unit area, $T(E_F, \mathbf{k}_\parallel)$ is the transmission coefficient in the spin channel σ evaluated at the Fermi energy E_F for a given value of the transverse wave vector $\mathbf{k}_\parallel$. The transmission coefficient is obtained by solving numerically the Schrödinger equation for an electron moving in the potential $V(z)$ by imposing a boundary condition of the incoming plane wave normalized to unit flux density and by calculating the amplitude of the transmitted plane wave. In the calculations we assume the exchange splitting in the DMS electrode $\Delta_{ex}=0.05$ eV.[3] The effective masses of carriers in the electrodes are set to be $m_1=m_2=0.2m$ (m is a free electron mass), and the dielectric permittivities are $\varepsilon_1=\varepsilon_2=10\varepsilon_0$ (ε_0 is the permittivity of vacuum). The polarization and the dielectric constant of the ferroelectric are assumed to be $P=40\ \mu\mathrm{C/cm}^2$ and $\varepsilon_b/\varepsilon_0=2000$ which are representative values for perovskite ferroelectrics.[16] The effective mass in perovskite ferroelectrics is relatively high, so we assume that $m_b=2m$. The spin polarization of the conductance is defined by $\Pi=G^{\uparrow}-G^{\downarrow}/G^{\uparrow}+G^{\downarrow}$.

Figures 2(a) and 2(b) show the calculated conductance and spin polarization of the conductance as a function of the potential barrier height, U, in the ferroelectric barrier. Here we assume that $E_F - V_1^{\uparrow}=0.06$ eV and $V_1=V_2$, resulting in carrier concentrations $n_1=3.6\cdot10^{19}\ \mathrm{cm}^{-3}$, $n_2=3\cdot10^{19}\ \mathrm{cm}^{-3}$ and screening lengths $\delta_1=0.64$ nm, $\delta_2=0.66$ nm. It is seen that, for **P** pointing towards the DMS electrode, the spin polarization, Π_L, is positive and is weakly dependent on U, reflecting an additional tunneling barrier for minority spins [Fig. 1(a)]. On the other hand, for the **P** pointing towards the NS electrode, the spin polarization, Π_R, is slightly negative at not too large values of U and becomes positive at $U>0.75$ eV. The latter result can be understood in terms of spin-dependent tunneling across a rectangular barrier.[17] Thus, using an appropriate FE barrier, it is possible to change the spin polarization of injected carriers from positive to negative and vice versa by reversing the electric polarization of the FE barrier.

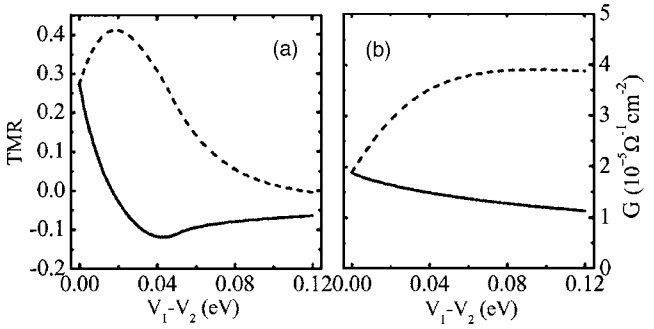

FIG. 3. Tunneling magnetoresistance (a) and conductance, G, for parallel magnetization of the electrodes (b) in a DMS/FE/DMS tunnel junction versus potential difference in the two magnetic semiconductors for the electric polarization of the ferroelectric barrier pointing to the left (solid lines) and pointing to the right (dashed lines) for $d=3$ nm and $U=0.5$ eV.

The degree of the spin polarization change in response to the electric polarization reversal depends on the carrier density in the semiconductors. This is illustrated in Fig. 2(c), which shows the dependence of the Π_L and Π_R on the Fermi energy with respect to the bottom of the minority-spin band in the DMS. When $E_F \leqslant V_1^{\downarrow}$ the DMS is fully spin polarized and hence $\Pi_L=\Pi_R=1$. With increasing the carrier concentration and hence E_F, the spin polarization drops down much faster for the **P** pointing to the right than for the **P** pointing to the left, resulting in a sizable difference in the spin polarizations Π_R and Π_L. Therefore, by changing the density of carriers in the semiconductors it is possible to tune values of the spin polarization for a two-state control of the electronic device.

Finally, we discuss the effect of the electrical polarization reversal on tunneling magnetoresistance (TMR) in magnetic tunnel junctions with a FE tunnel barrier (for a recent review on TMR, see Ref. 18). These multiferroic tunnel junctions (MFTJ) have not yet been realized experimentally but might be promising in providing an additional degree of freedom in controlling TMR. Figure 3(a) shows the calculated TMR in a tunnel junction with two DMS electrodes separated by a FE barrier. The TMR ratio was defined by

$$\mathrm{TMR} = \frac{G_P - G_{\mathrm{AP}}}{G_{\mathrm{AP}}},$$

where G_P and G_{AP} are the conductances for the parallel and antiparallel magnetization, respectively. In the calculation we assumed the same exchange splitting in the two DMS, $\Delta_{\mathrm{ex}}=0.05$ eV, and varied rigidly the potential V_2 with respect to V_1 which can experimentally be achieved by doping. As is seen from Fig. 3(a), for $V_1=V_2$ the TMR is about 30% and is independent of the orientation of **P**. The increasing potential difference in the two DMS results in the enhancement of TMR for the **P** pointing to the right, whereas for the **P** pointing to the left the TMR drops down and becomes negative. At these conditions the MFTJ works as a device which allows switching the TMR between positive and negative values. As follows from Fig. 3(b), there is a sizable difference in the overall conductance of the junction for the two orientations of polarization. This is the consequence of the GER effect predicted in our previous work.[9] Therefore, there is a coexistence of TMR and GER effects in the multiferroic tunnel junctions.

In conclusion, we have proposed a new device which permits switching the spin polarization of the current injected from a diluted magnetic semiconductor through a ferroelectric barrier into a normal semiconductor by reversing the electric polarization of the ferroelectric. We predicted the possibility of switching of TMR in multiferroic tunnel junctions (MFTJs) in which magnetic electrodes are separated by a ferroelectric barrier and demonstrated the coexistence of TMR and GER effects in these junctions. We hope that our results will stimulate experimental studies of the ferroelectric and multiferroic tunnel junctions for application in spintronics.

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