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 experimental10,11 and theoretical12 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.12 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 $\Delta_{\text{ex}}$ such that the spin-dependent potential in the DMS layer is given by $V_{\text{ex}} = V_1 \pm 1/2 \Delta_{\text{ex}}$, where $\sigma$ is the spin index ($\sigma = \uparrow, \downarrow$). 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 $P$ of the ferroelectric creates surface charge densities, $\pm \sigma_p = \pm |P|$, on the two surfaces of the ferroelectric film. These polarization charges, $\pm \sigma_p$, are screened by the screening charge per unit area $1/\varepsilon_s$, 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,

$$\varphi(z) = \begin{cases} \sigma_0 \delta_1 e^{-z/\delta_1} / \varepsilon_1, & z \leq 0 \\ \sigma_0 \delta_2 e^{-z/\delta_2} / \varepsilon_2, & z \geq d. \end{cases}$$

Here $\varepsilon_1$ and $\varepsilon_2$ are the dielectric permittivities of the DMS and NS electrodes, $\delta_1$ and $\delta_2$ are the Thomas-Fermi screened
In order to make these arguments quantitative, we calculate the conductance of the DMS/FE/NS junction using the Landauer formula,

$$G = \frac{e^2}{h} \int \frac{dk}{(2\pi)^2} T_{ab}(E_F, k_b).$$

Here $G$ is the conductance per spin per unit area, $T(E_F, k_b)$ is the transmission coefficient in the spin channel $\alpha$ evaluated at the Fermi energy $E_F$ for a given value of the transverse wave vector $k_b$. 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 $\Delta_{ex}=0.05\,\text{eV}$. The effective masses of carriers in the electrodes are set to be $m_1=2m_2$, $m_2=0.2m$ ($m$ is a free electron mass), and the dielectric permittivities are $\varepsilon_1=\varepsilon_2=10\varepsilon_0$ ($\varepsilon_0$ is the permittivity of vacuum). The polarization and the dielectric constant of the ferroelectric are assumed to be $P=40\,\mu\text{C/cm}^2$ and $\varepsilon_1/\varepsilon_0=2000$ which are representative values for perovskite ferroelectrics. The effective mass in perovskite ferroelectrics is relatively high, so we assume that $m_3=2m$. The spin polarization of the conductance is defined by $\Pi = G^\uparrow - G^\downarrow + G^\downarrow$. 

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 $E_F-V_{1^\downarrow}=0.06\,\text{eV}$ and $V_{1^\uparrow}=V_{2^\uparrow,\downarrow}$, resulting in carrier concentrations $n_1 = 3.6\times10^{19}\,\text{cm}^{-3}$, $n_2 = 3\times10^{19}\,\text{cm}^{-3}$ and screening lengths $\delta_1=0.64\,\text{nm}$, $\delta_2=0.66\,\text{nm}$. It is seen that, for $P$ pointing towards the DMS electrode, the spin polarization, $\Pi_L$, 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, $\Pi_R$, is slightly negative at not too large values of $U$ and becomes positive at $U>0.75\,\text{eV}$. The latter result can be understood in terms of spin-dependent tunneling across a rectangular barrier. 

$$\text{FIG. 1. Schematic representation of the potential profile, } V(z), \text{ in a DMS/FE/NS tunnel junction for the electric polarization pointing to the left (a) and to the right (b). The dashed and solid lines show the potential seen by the majority- and minority-spin carriers respectively. The horizontal solid line denotes the Fermi energy, } E_F.$$
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 $TMR = \frac{G_\parallel - G_\perp}{G_\parallel}$ on the Fermi energy with respect to the bottom of the minority-spin band in the DMS. When $E_F \leq |V_1|$ 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 $\Pi_R$ and $\Pi_L$. 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

$$TMR = \frac{G_p - G_{AP}}{G_p},$$

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, $\Delta \approx 0.05$ 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. 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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15We note that in semiconductors the screening length depends on temperature due to the temperature dependence of the carrier concentration. The carrier concentrations in the electrodes determine the Fermi energy with respect to the bottom of the bands making temperature indirectly included in the theory.