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# Spin-filtering junctions with double ferroelectric barriers*

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An FS/FE/NS/FE/FS double tunnel junction is suggested to have the ability to inject, modulate and detect the spin-polarized current electrically in a single device, where FS is the ferromagnetic semiconductor electrode, NS is the nonmagnetic semiconductor, and FE the ferroelectric barrier. The spin polarization of the current injected into the NS region can be switched between a highly spin-polarized state and a spin unpolarized state. The high spin polarization may be detected by measuring the tunneling magnetoresistance ratio of the double tunnel junction.

**Keywords:** ferroelectric barrier, tunnel junction, spin detection
**PACC:** 0560, 7225, 7340T

## 1. Introduction

Incorporating spins into existing charge-based semiconductor technology can add substantially more capability and performance to electronic products.[1] Three essential elements of a semiconductor spin transport device are as follows: (i) a mechanism for electrically injecting spin-polarized current, (ii) a practical means for spin manipulation and transport, and (iii) an electronic scheme for detecting the resulting spin polarization.[2] So far, the spin injection and manipulation elements have been a field of bursting interest. Many endeavors have been made, such as the famous Datta–Das spin field-effect transistor,[3] magnetic p–n junction,[4] and spin-filtering junctions with ferromagnetic,[5−7] ferroelectric,[8] or multiferroic,[9−12] insulator barriers.

Tunnel barriers are of great importance to spin-filtering junctions. In ferromagnetic barrier junctions, the exchange splitting of the barrier band can lead to spin-dependent barrier heights so as to benefit a high spin polarization. In ferroelectric (FE) barrier junctions, when the ferromagnetic semiconductor (FS) is selected as the spin injector electrode, the reverse of the electric polarization in FE barrier can produce spin-dependent changes in the electrostatic potential profile across the junction, thereby resulting in a sizable change in spin polarization of the injected current and providing two-state electrical control.[8] In a multiferroic barrier junction, both ferromagnetism and ferroelectricity of the barrier can cause a four-level spin polarization modulation of the injected current,[9] Most reported spin-filtering junctions, including the multiferroic barrier junction, focused on modulating current among states with different spin polarization values. In reality, it is also interesting to switch the spin polarization of currents between a highly spin polarized state and a spin unpolarized state, which may be very useful in spintronics applications.

As to the spin detection element, spin-polarized currents flow with net magnetization[10] and therefore can be sensed by conventional Kerr[2] or Faraday rotation,[12] in which an extra linearly polarized probe laser or circularly polarized light pulses are needed. Another popular method is to use a spin light-emitting diode configuration[13] to produce a circularly polarized light. This method indicates exactly the spin polarization of electron density in the NS region rather than the spin polarization of injected current. If the injected current is small or the electron density in the NS is high, however, the measured spin polarization may be very low, even though the injected current is highly polarized.[14] The other method is to measure the electric current of a ferromagnetic metal/NS single junction. This is based on the theory that the Rashba spin-orbit interaction may induce an asymmetry for

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electrons with different spins traveling along a particular direction. To date, the theoretical prediction and experimental observation[15] have been an issue.[16,17] In this work, we propose a spin-filtering tunnel junction with an FS/FE/NS/FE/FS structure, which can demonstrate a fully electrical scheme for achieving spin injection, modulation and detection in a single device. The injected current can not only be multiple-modulated with different spin polarizations, but also be switched between a highly spin polarized state and a spin unpolarized state. The high spin polarization can also be determined by measuring the tunneling magnetoresistance (TMR) of the double tunnel junction.

## 2. Formalism

As illustrated in figure 1(a), we first consider the left single barrier junction with an FS electrode for $x < 0$, an NS electrode for $x > d$, and an FE barrier of thickness $d$ inbetween. $\Delta_{\rm FS}$ is the spin splitting parameter of the FS electrode, and $\Delta_{\rm NS} = 0$. $\mu_{\rm FS}$ ($\mu_{\rm NS}$) is the Fermi energy with respect to the band bottom for the FS (NS) electrode. The special potential profile that distinguishes our model from the conventional one is the band bending $\varphi_{\rm FS}(x)$ and $\varphi_{\rm NS}(x)$ near two interfaces. They are related to electric polarization $\boldsymbol{p}$ in the ferroelectric[8] by

$$\varphi_i^{\mp}(x) = \frac{e\sigma_s\delta_i \mathrm{e}^{-|x|/\delta_i}}{\varepsilon_i} \pm \Delta_i \quad (i = \mathrm{FS},\ x \le 0), \tag{1}$$

$$\varphi_i(x) = -\frac{e\sigma_s\delta_i \mathrm{e}^{-|x-d|/\delta_i}}{\varepsilon_i} \quad (i = \mathrm{NS},\ x \ge d), \tag{2}$$

and very important in the following discussion. Here superscript $-(+)$ denotes the minority (majority) subband,

$$\delta_i^{-2} = \frac{e^2}{4\pi^2\varepsilon_i}\left(\frac{2m_i}{\hbar^2}\right)^{3/2}(\sqrt{\mu_i + \Delta_i} + \sqrt{\mu_i - \Delta_i})$$

is the Thomas–Fermi screening length, and

$$\sigma_s = \frac{-d\lambda|\boldsymbol{p}|/\varepsilon_{\rm FE}}{\delta_{\rm FS}/\varepsilon_{\rm FS} + \delta_{\rm NS}/\varepsilon_{\rm NS} + d/\varepsilon_{\rm FE}}$$

is the screening charge per unit area, with $\varepsilon_i$ the dielectric permittivity, and $\lambda = +1$ $(-1)$ for $\boldsymbol{p}$ orienting toward the NS (FS) region. From the potential profile, the transmission probability of the single junction $T_\sigma^L$ for $\sigma = \uparrow$ (spin up) or $\downarrow$ (spin down) channel can be numerically calculated by a transfer matrix method.[18]

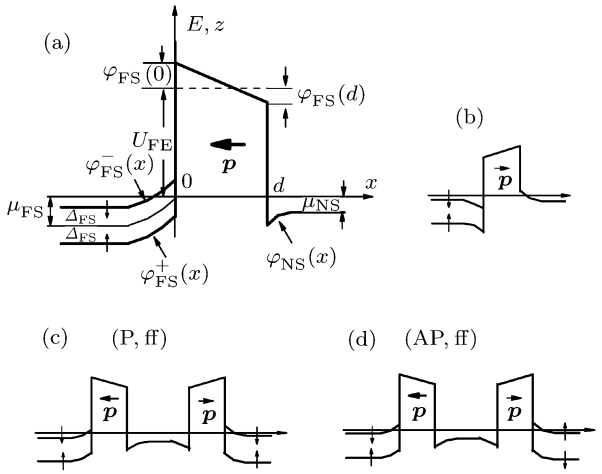



**Fig.1.** Schematic potential profiles of an FS/FE/NS single tunnel junction (a, b) and an FS/FE/NS/FE/FS tunnel junction (c, d). Here P (AP) stands for the parallel (antiparallel) magnetization configuration, and ff denotes that $\boldsymbol{p}$ in the left (right) FE barrier points to the left (right) FS electrode.

Then, another same single junction is introduced to form the FS/FE/NS/FE/FS double barriers junction. The sequential tunneling occurs if the thickness $d$ of the middle NS layer is smaller than the spin diffusion length $\lambda_{sp}$ but larger than the coherence length $\lambda_\phi$ of electronic wave functions. For electrons sequentially tunneling[19] through the two FE barriers, the total transmission probability for each spin channel is given by[20]

$$T_\sigma = \frac{T_\sigma^L T_\sigma^R}{(T_\sigma^L + T_\sigma^R - T_\sigma^L T_\sigma^L)}. \tag{3}$$

Here, $T_\sigma^L$ ($T_\sigma^R$) is the transmission probability of the left (right) single junction. The conductance of the spin-up (down) channel is obtained by the Landauer formula

$$G_\sigma = \frac{e^2}{\hbar} T_\sigma(E_F, k_\parallel = 0) \tag{4}$$

with the consideration that only the conduction electrons at the Fermi level with wave vector normal to the barrier make main contributions to conductance at zero bias voltage.[21] The total conductance of the junction is $G = G_\uparrow + G_\downarrow$ and the spin polarization of the current is defined as $\alpha = (G_\uparrow - G_\downarrow)/G$ for a small bias voltage. For $\alpha = \pm 1$, the injected current is fully polarized. For $\alpha = 0$, the injected current is unpolarized. There are eight junction states in the present junction. The magnetization in the left FS electrode is fixed to the $+z$ direction. The magnetization in the

right FS electrode can be parallel (P) or antiparallel (AP) to the former one by changing the orientation of the magnetic field. The electric polarizations $\boldsymbol{p}$ in two FE barriers may point to the FS electrode (f) or point to the NS region (n) by applying electric pulses, forming four types of states: (ff), (nn), (fn), and (nf).

## 3. Calculation and discussion

In the following calculations, parameters are taken according to references [8] and [22] as $m_{\rm FS} = m_{\rm NS} = 0.2m_e$ and $m_{\rm FE} = 2m_e$ with $m_e$ the free electron mass, $\varepsilon_{\rm FS} = \varepsilon_{\rm NS} = 10\varepsilon_0$ and $\varepsilon_{\rm FE} = 2000\varepsilon_0$ with $\varepsilon_0$ the permittivity of the vacuum, the barrier height is taken as $U_{\rm FE} = 0.5$ eV and the barrier width as $d = 3$ nm. The other parameters are $\mu_{\rm FS} = 0.1$ eV, $\mu_{\rm NS} = 0.02$ eV, and $\Delta_{\rm FS} = 0.09$ eV. Figure 2 shows the spin polarization of the injected current as a function of the magnitude of $\boldsymbol{p}$ for different combinations of the magnetization alignment in two FS electrodes and orientations of $\boldsymbol{p}$ in two FE barriers. First, for the two electric polarizations $\boldsymbol{p}$ both orient toward the FS electrodes (ff state), the spin polarization of the injected current can be switched from a highly spin-polarized state to a vanishingly spin-polarized state by changing the magnetization configuration from P to AP, and *vice versa*. Second, for the P magnetization configuration, different electric polarizations in two FE barriers result in different $\alpha$, the largest in the ff state and the smallest in the nn state. Such a spin polarization of currents is mainly determined by two factors: the spin polarization of the FS electrode and the spin-dependent tunneling barrier, the latter arising from the band-bending effect. If $\boldsymbol{p} = 0$, there is no band bending, $\varphi_{\rm FS}(x) = 0$ and $\varphi_{\rm NS}(x) = 0$, and the barrier is spin-independent. In this case, the current is only affected by the polarization of FS electrode. Therefore, $\alpha$ tends to the polarization of FS electrode for the P alignment and is vanishing for the AP alignment. If nonzero $\boldsymbol{p}$ points to the FS electrode, the band bending only adds an additional barrier for the spin-up channel, as shown in figure 1(a), so that the spin-dependent barrier benefits a high spin polarization. If $\boldsymbol{p}$ points to the NS region, electrons in both spin channels see a same additional barrier, as shown in figure 1(b). The barrier is spin-independent, but the decreased spin polarization of FS electrode causes a low spin polarization of current. It is the reason why $\alpha$ increases with $|\boldsymbol{p}|$ in the (P, ff) state, but decreases in the (P, nn) state. On the other hand, the barrier for the spin-up channel is equal to that for the spin-down channel under (AP, ff) or (AP, nn) state,[23] so that the current is always spin unpolarized.

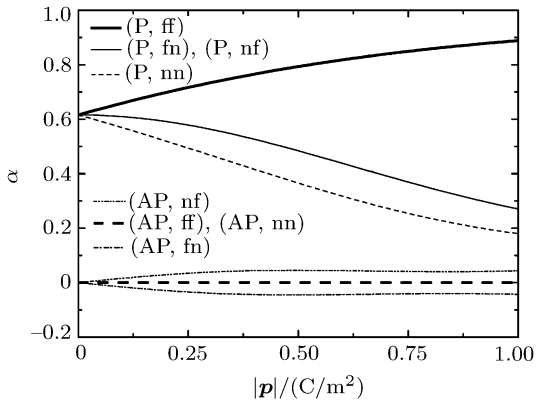



**Fig.2.** Spin polarization $\alpha$ of current as a function of the magnitude of $\boldsymbol{p}$.

Figure 3 gives the numerically calculated result of TMR/$\alpha^2$ as a function of $|\boldsymbol{p}|$, where $\alpha$ is obtained in the P magnetization alignment. If the two FE barriers are completely symmetric in either (ff) or (nn) configuration, i.e., $\boldsymbol{p}$ in either barrier orients towards the FS electrode (or the NS region), TMR/$\alpha^2 = 1$ is always satisfied, indicating that the spin polarization of current can be determined experimentally by measuring the TMR ratio. If the two FE barriers are asymmetric, such as in either (fn) or (nf) configuration, TMR/$\alpha^2 = 1$ no longer holds. Actually, the relation of TMR $= \alpha^2$ can be deduced exactly. A small bias voltage $V/2$ and $-V/2$ are applied to the

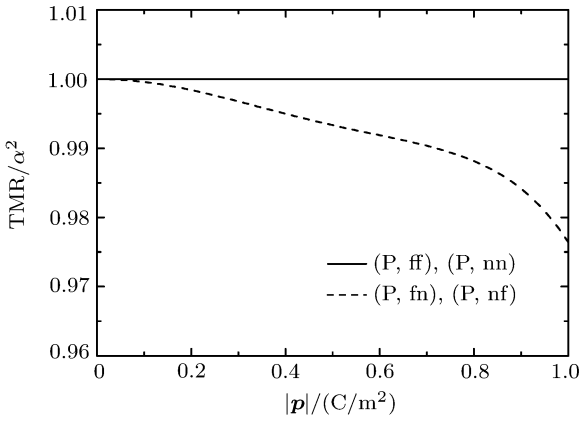



**Fig.3.** TMR/$\alpha^2$ as a function of the magnitude of $\boldsymbol{p}$. The solid line is obtained with $\boldsymbol{p}$ in either (ff) or (nn) configuration, and the dashed line with $\boldsymbol{p}$ in either (fn) or (nf) configuration.

left and the right FS electrodes, respectively. For the (P, ff) state, the number of the spin-up (spin-down)

electrons tunneling into NS region through the left FE barrier is equal to that of spin-up (spin-down) electrons tunneling out the NS region through the right FE barrier. Hence the tunneling conductance of single junction $G_\sigma^L = G_\sigma^R$, and the total current density is

$$J_{\rm P} = \frac{V}{2}(G_\uparrow^L + G_\downarrow^L). \tag{5}$$

For the (AP, ff) state, the situation is quite different. The difference between the number of spin-up and spin-down electrons tunneling into and out of the NS region should induce an accumulation of electrons with one spin and a deficiency of electrons with the other spin,[19,24] As a result, the chemical potentials of the two spin channels in the NS region are shifted by $\pm\delta\mu$, respectively. $\delta\mu$ can be determined by the spin-current continuity conditions, i.e.,

$$(V/2 - \delta\mu)G_\uparrow^L = (V/2 + \delta\mu)G_\uparrow^R$$

for the spin-up channel, and

$$(V/2 + \delta\mu)G_\downarrow^L = (V/2 - \delta\mu)G_\downarrow^R$$

for the spin-down channel. Owing to the symmetry, we have relation $G_\uparrow^L = G_\downarrow^R$ and $G_\downarrow^L = G_\uparrow^R$, so that $\delta\mu = \alpha V/2$. The total current density is then given by

$$J_{\rm AP} = \frac{V}{2}[G_\uparrow^L(1-\alpha) + G_\downarrow^L(1+\alpha)]. \tag{6}$$

From TMR $= (J_{\rm P} - J_{\rm AP})/J_{\rm P}$, it then follows

$$\text{TMR} = \alpha^2. \tag{7}$$

# 4. Summary

In conclusion, the spin-filtering junction with two FE tunneling barriers is suggested to multiple modulate the spin polarization of the current injected into the NS region. Such a spin-filtering junction can switch the current between a highly spin-polarized state and a spin unpolarized state, and the highest spin polarization can be detected by measuring the TMR ratio of the double tunnel junction. Though the present model is simple and cannot describe real system quantitatively because it does not take into account realistic band structure of materials and atomic modifications at the interfaces due to electric polarization reversal,[25] the consideration of these complicated factors will not change the qualitative results obtained here.

# References


[1] Zutic I, Fabian J and Sarma S D 2004 *Rev. Mod. Phys.* **76** 323

[2] Crooker S A, Furis M, Lou X, Adelmann C, Smith D L, Palmstrom C J and Crowell P A 2005 *Science* **309** 2191

[3] Datta S and Das B 1990 *Appl. Phys. Lett.* **56** 665

[4] Chen P Y, Deng N, Dong H, Ren M and Zhang L 2007 *Chin. Phys.* **16** 1440

[5] Li M K, Kim N M, Lee S J, Jeon H C and Kang T W 2006 *Appl. Phys. Lett.* **88** 162102

[6] Gajek M, Bibes M, Barthelemy A, Bouzehouane K, Fusil S, Varela M, Fontcuberta J and Fert A 2005 *Phys. Rev.* B **72** 020406(R)

[7] Gajek M, Bibes M, Varela M, Fontcuberta J, Herranz G, Fusil S, Bouzehouane K, Barthelemy A and Fert A 2006 *J. Appl. Phys.* **99** 08E504

[8] Zhuravlev M Y, Jaswal S S and Tsymbal E Y 2005 *Appl. Phys. Lett.* **87** 222114

[9] Wang J and Li Z Y 2008 *J. Appl. Phys.* **104** 033908

[10] Gajek M, Bibes M, Fusil S, Bouzehouane K, Fontcuberta J, Barthelemy A and Fert A 2007 *Nature Materials* **6** 296

[11] Wang J, Zhu B F and Liu R B 2008 *Phys. Rev. Lett.* **100** 086603

[12] Kikkawa J M and Awschalom D D 1999 *Nature* (London) **397** 139

[13] Ohno Y, Young D K, Beschoten B, Matsukura F, Ohno H and Awschalom D D 1999 *Nature* (London) **402** 790

[14] Albrecht J D and Smith D L 2002 *Phy. Rev.* B **66** 113303

[15] Hammar P R, Bennett B R, Yang M J and Johnson M 1999 *Phys. Rev. Lett.* **83** 203

[16] Monzon F G, Tang H X and Roukes M L 2000 *Phys. Rev. Lett.* **84** 5023

[17] Molenkamp L W, Schmidt G and Bauer G E W 2001 *Phys. Rev.* B **64** 121202

[18] Ando Y and Itoh T 1987 *J. Appl. Phys.* **61** 1497

[19] Mattana R, George J M, Jaffres H, Nguyen Van Dau F, Fert A, Lepine B, Guivarch A and Jezequel G 2003 *Phys. Rev. Lett.* **90** 166601. In this paper, electrons were confirmed to sequentially tunnel through the fractioned double tunnel junction GaMnAs/AlAs/GaAs/AlAs/GaMnAs, which is a stucture similar to our model.

[20] Datta S 1995 *Electronic Transport in Mesoscopic Systems* (Cambridge: Cambridge University Press) Chaps. 3 and 6

[21] Duke C B 1969 *Tunneling in Solids* (New York: Academic)

[22] Ju S, Tian C Y, Guo G Y and Li Z Y 2007 *Phys. Rev.* B **75** 064419

[23] The schematic potential profile of the (P,ff) state is given in Fig.1(d) as an example.

[24] Ma J, Sun J and Wang J 2004 *Mod. Phys. Lett.* B **18** 411

[25] Velev J P, Duan C G, Belashchenko K D, Jaswal S S and Tsymbal E Y 2007 *Phys. Rev. Lett.* **98** 137201