Anisotropy of spin-dependant electron transport in nonmagnetic resonant tunneling structures

J. Radovanović*, G. Isić*, and V. Milanović*

Faculty of Electrical Engineering, University of Belgrade, Serbia

Center for Solid State Physics and New Materials, Institute of Physics, Belgrade, Serbia

Abstract — **The spin-orbit coupling in noncentrosymmetrical semiconductor nanostructures gives rise to Rashba and Dresselhaus effects through which electron momentum and spin are coupled. Following some recent theoretical studies indicating that in resonant tunneling structures where one of the effects is dominant a significant level of spin polarization might be obtained, we extend the previous model to account for both effects and investigate how can they be used to overcome some spin-filtering limitations occuring when there is only one spin-dependent mechanism present. The dependence of transmission probabilities on lateral momentum direction (i. e. anisotropy) is recovered in the proposed model, thus offering means to improve the design of existing nonmagnetic spin filters.**

Introduction

The nonvanishing spin-dependent terms in the Hamiltonian describing a semiconductor heterostructure appear whenever there is no inversion symmetry. The effects of inversion asymmetry (IA) in heterostructures are conveniently divided into ones arising from the IA of the semiconductor material itself - bulk inversion asymmetry (BIA), and to those which arise from the IA of the structure - structure inversion asymmetry (SIA), which may be induced either by growing an asymmetric structure or by the use of external electric field.

The present-day interest in these effects is refueled by the nascent field of spintronics [1] the essential prerequisite for which is to have a device capable of producing spin-polarized current. The spin-injection into semiconductors from ferromagnetic materials [2], [3] and magnetic semiconductors [4], [5] has already been demonstrated experimentally and investigated theoretically [6]-[8]. However, there seem to be many links missing when transferring from a conceptual solution to real devices [9], [10]. A principal benefit of all-semiconductor spin-filters is that they are expected to be easily incorporated into the existing semiconductor technology.

During the past couple of years, there has been a number of papers [11]-[16] relevant to our work. Here we consider the one-sided collector case applied to a InAs-GaAs-AlAs system where the advantage of carefully tailored anisotropy is clearly visible.

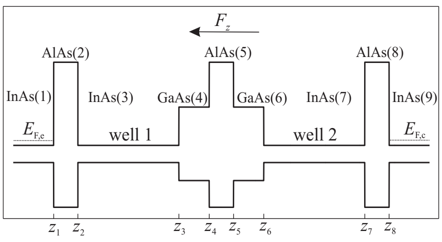

Figure 1. The conduction and valence band edge profile of TB-RTD based on InAs-AlAs-InAs-GaAs-AlAs-GaAs-InAs-AlAs-InAs. In calculations $E_{F,e}$=0.1eV (N_D~10^{18}cm-3) and T≈0K was used. Layers are assumed to be grown along z||[001] with z_1=0, z_2=24Å, z_3=124Å, z_4=154Å, z_5=178Å, z_6=218Å, z_7=318Å, z_8=332Å. The structural parameters obtained from [13] read: E_c(InAs)=0, E_c(AlAs)=1.724eV, E_c(GaAs)=0.792eV, m(InAs)=0.02m_0, m(AlAs)=0.15m_0, m(GaAs)=0.63m_0, γ(InAs)=130eVÅ^3, γ(AlAs)=3.6eVÅ^3, γ(GaAs)=24eVÅ^3, E_g(InAs)=0.356eV, E_g(AlAs)=3eV, E_g(GaAs)=1.52eV, Δ(InAs)=0.41eV, Δ(AlAs)=0.279eV, Δ(GaAs)=0.341eV.

Brief outline

The main features of spin dependent transport in resonant tunneling structures are examined for the case of a triple-barrier resonant tunneling diode (TB-RTD) shown in Fig. 1.

We consider conduction-band electrons described by the two-component envelope function

$$\psi(z) = \eta_+(z)\chi_+ + \eta_-(z)\chi_- \qquad (1)$$

where χ_+ and χ_- are two orthogonal spinors and $\eta_+(z)$ and $\eta_-(z)$ are complex valued functions describing the spatial distribution of probability amplitudes along z||[001]. The envelope functions $\psi(z)$ are obtained by solving the anvelope function equation

$$H\psi(z) = E\psi(z) \qquad (2)$$

for the spin-dependent effective Hamiltonian H which includes the Rashba contribution due to SIA, described by H_R, [17]-[21], and Dresselhaus contribution due to BIA, described by H_D, [11], [22]. Let $\mathbf{k}_{\|}$ be the in-plane wave vector, $k_x=k_{\|}\cos\varphi$ its component along [100] and $k_y=k_{\|}\sin\varphi$ the component along [010] direction. We assume that electrons in regions 1 and 9 (the emitter and collector), respectively, see Fig. 1, are in thermodynamical equilibrium with Fermi levels $E_{F,e}=E_{F,c}$, as long as the applied voltage V_{CE} is zero, and that with $V_{CE}>0$ the equilibrium is approximately retained but with $E_{F,e}-E_{F,c}=V_{CE}$, leading to a net current density J. Far from the junction, the electrons spin is coupled only with the crystal field of the bulk material, i. e. only the BIA term exists. Thus, the spin states are described by the spinors

$$\chi_\sigma(\varphi) = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -\sigma\exp(-i\varphi) \end{bmatrix}, \quad \sigma = \pm \qquad (3)$$

The electrons with $\chi_\sigma(\varphi)$ are said to form the "σ" spin-subband of the given region (1 or 9). Since H_R and H_D do not commute, the spin of an electron incident to the junction from either side is going to be changed in the process of tunneling, so if the electron approaches the junction from e. g. the emitter's "σ" spin-subband, it will have associated both the probability of tunneling into the collector's "+" and "-" spin-subband, $T_{\sigma+}$ and $T_{\sigma-}$, respectively.

Dividing up the overall current density J to contributions from electrons with a given φ and spin-state "σ" in the collector region, $j_\sigma(\varphi)$, we may write the expression for the average spin polarization of J along the spin-analyzing axis described by the spin operator $\sigma_\omega=\sigma_x\cos\omega+\sigma_y\sin\omega$ as

$$P(\omega) = -\frac{1}{J}\int_{\varphi_c-\Delta\varphi/2}^{\varphi_c+\Delta\varphi/2}\left[j_+(\varphi) - j_-(\varphi)\right]\cos(\omega+\varphi)\,d\varphi \qquad (4)$$

Simple symmetry considerations reveal that $P(\omega)$=0 if $\Delta\varphi$ (the collector opening angle) appearing in (4) is 2π. Therefore, in order to obtain nonzero $P(\omega)$ it is necessary to have $\Delta\varphi$<2π.

In this work, we discuss how different quantities appearing in (4) influence the magnitude of $P(\omega)$ and, particularly, how the presence of both H_R and H_D affects the dependence of transmission probability resonances on φ. A numerical simulation is carried out to demonstrate the salient features of the structure from Fig. 1.

Numerical results

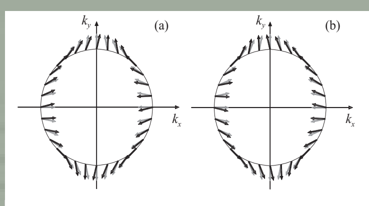

Figure 2. Black arrows: spin directions of the upper quasibound states (a) in well 1 and (b) in well 2 for $k_{\|}$=0.009Å^{-1} and F_z=0, estimated by averaging the H_R and H_D operators. Gray arrows: spin directions of the upper spin-subband in emitter and collector (these are 'exact').

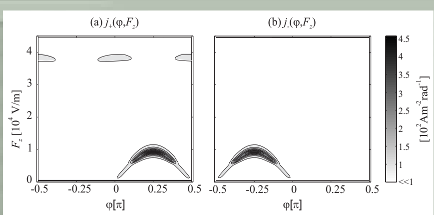

Figure 3. The dependance of (a) $j_+(\varphi)$ and (b) $j_-(\varphi)$ on the external electric field F_z for the TB-RTD described in Fig. 1, drawn, for reasons of clarity, over the range [-π/2, π/2] instead of the minimal [-π/4, π/4] range. The white area ('<<1') represents the regions where the current densities $j_+(\varphi)$ and $j_-(\varphi)$ are below 0.5 units, yet for the most of it $j_+(\varphi)$ and $j_-(\varphi)$ have values several orders of magnitude below 1 unit which is why we use '<<1' instead of '0.5'.

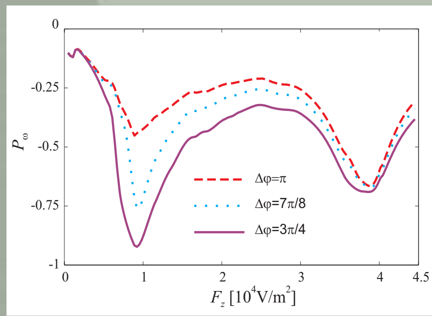

Figure 4. The polarization $P_\omega(F_z)$ for the TB-RTD with parameters given in Fig. 1, calculated for ω=-π/4, φ_c=π/4, for three values of Δφ: (a) dashed line, Δφ=π, (b) dotted line, Δφ=7π/8 and (c) solid line, Δφ=3π/4. The two cases, (b) and (c), with the reduced collector opening angle, have a higher peak of polarization than the theoretical maximum of 2/π [23] for isotropic structures.

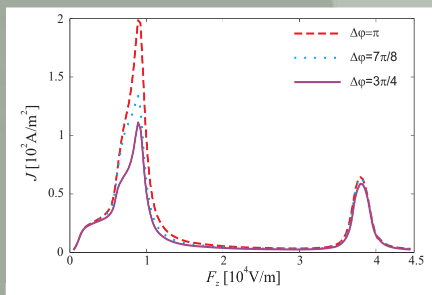

Figure 5. The total current density $J(F_z)$ for the TB-RTD with parameters given in Fig. 1, calculated for ω=-π/4, φ_c=π/4, for three values of Δφ: (a) dashed line, Δφ=π, (b) dotted line, Δφ=7π/8 and (c) solid line, Δφ=3π/4.

References

[1] I. Žutić, J. Fabian, and S. Das Sarma, *Rev. Mod. Phys.*,vol. 76, pp. 323-410, April 2004.
[2] C. -M. Hu, J. Nitta, A. Jensen, J. B. Hansen, and H. Takayanagi, *Phys. Rev.* B, vol. 63, p. 125333, March 2001.
[3] M. Ramsteiner, *J. Supercond.*, vol. 16, pp. 661-669, Aug. 2003.
[4] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, and L. W. Molenkamp, *Nature*, vol. 402, pp. 787-790, Dec. 1999.
[5] B. T. Jonker, Y. D. Park, B. R. Bennett, H. D. Cheong, G. Kioseoglou, and A. Petrou, *Phys. Rev.* B, vol. 62, pp. 8180-8183, Sep. 2000.
[6] Y. Guo, J. -Q. Lu, B. -L. Gu, and Y. Kawazoe, *Phys. Rev.* B, vol. 64, p. 155312, Sep. 2001.
[7] J. C. Egues, C. Gould, G. Richter, and L. W. Molenkamp, *Phys. Rev.* B, 64, p. 195319, Oct. 2001.
[8] J. Radovanović, V. Milanović, Z. Ikonić, and D. Indjin, *J. Appl. Phys.*, vol. 99, p. 073905, April 2006.
[9] G. Schmidt, *J. Phys.* D, vol. 38, pp. 107-122, March 2005.
[10] I. Žutić, *J. Supercond.*, vol. 15, pp. 5-12, Feb. 2002.
[11] V. I. Perel', S. A. Tarasenko, and I. N. Yassievich, *Preprint* cond-mat/0301098, Jan. 2003.
[12] A. Voskoboynikov, S. S. Liu, and C. P. Lee, *Phys. Rev.* B, vol. 59, pp. 12514-12520, May 1999.
[13] A. Voskoboynikov, S. S. Lin, C. P. Lee, and O. Tretyak, *J. Appl. Phys.*, vol. 87, pp. 387-391, Jan. 2000.
[14] T. Koga, J. Nitta, H. Takayanagi, and S. Datta, *Phys. Rev. Lett.*, vol. 88, p. 126601, March 2002.
[15] K. Gnanasekar, and K. Navaneethakrishnan, *Phys. Lett.* A, vol. 341, pp. 495-503, March 2005.
[16] L. Yu, H. C. Huang, and O. Voskoboynikov, *Superlattices Microstruct.*, vol. 34, pp. 547-552, May 2004.
[17] Y. A. Bychkov, and E. I. Rashba, *J. Phys.* C, vol. 17, pp. 6039-6045, Nov. 1984.
[18] E. A. de A. e Silva, *Phys. Rev.* B, vol. 46, pp. 1921-1924, July 1992.
[19] E. A. de A. e Silva, G. C. La Rocca, and F. Bassani, *Phys. Rev.* B, vol. 50, pp. 8523-8535, Sep. 1994.
[20] E. A. de A. e Silva, G. C. La Rocca, and F. Bassani, *Phys. Rev.* B, vol. 55, pp. 16293-16299, June 1997.
[21] E. A. de A. e Silva, and G. C. La Rocca, *Phys. Rev.* B, vol. 59, pp. 15583-15585, June 1999.
[22] G. Dresselhaus, *Phys. Rev.*, vol. 100, pp. 580-586, Oct. 1955.
[23] D. Z. -Y. Ting, X. Cartoixa, *Phys. Rev.* B, vol. 68, 235320, December 2003.