AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **98**, 023716 (2005); doi: 10.1063/1.1994945
View online: http://dx.doi.org/10.1063/1.1994945
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/98/2?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **98**, 023716 (2005)

Time-resolved spin filtering in semiconductor symmetric resonant barrier structures

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(Received 16 July 2004; accepted 14 June 2005; published online 29 July 2005)

Spin-dependent tunneling in semiconductor symmetric double barrier structures is studied theoretically. Our calculation is based on the effective one-band Hamiltonian and Dresselhaus spin-orbit coupling. We demonstrate that the ratio of the tunneling times of electrons with opposite spin orientations can vary over a few orders in magnitude. The large and tunable ratio of the tunneling times can serve as the basis in the development of all-semiconductor dynamic spin filters. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1994945]

I. INTRODUCTION

Since the spin-dependent electronic device was proposed by Datta and Das,[1] the utilization of the spin-orbit coupling has been one of the key topics of semiconductor spintronics. However, a most elementary issue, an efficient means to obtain spin-polarized currents in semiconductor structures, has not been resolved yet. The conductivity mismatch between metals and semiconductors impedes the electron transport and makes the injection of spin-polarized electronic currents from strongly magnetized metals inefficient, as Schmidt *et al.*[2] pointed out. The reported experimental results on the polarization efficiency in metal-semiconductor junctions are less than 1%.[3] On the other hand, the spin-orbit interaction in semiconductors lifts the spin degeneracy of electrons' energy and results in spin-dependent transport through semiconductor junctions.

The spin-orbit interaction of electrons in III-V semiconductor materials is usually described by two contributions to the effective one-band spin-dependent Hamiltonian. One, often referred to as the Rashba term, is induced by the inversion asymmetry of the macroscopic potential,[4] which can be controlled by external electric-field or material growth techniques. The other, referred to as the Dresselhaus term,[5] is due to the inversion asymmetry of the zinc-blende lattice. The interplay between these two terms has been studied by de Andrada e Silva,[6] showing that for narrow-gap semiconductors, the contribution from the Rashba term to the spin-orbit interaction dominates over that from the Dresselhaus term. Hence the Dresselhaus term is often neglected. Calculations based on the Rashba spin-orbit interaction in III-V semiconductor heterostructures have been performed,[7–12] showing the all-semiconductor tunneling structures can be a feasible means to obtain electronic spin-polarized currents. However, it was suggested recently[11,13,14] that even through a single symmetric barrier, where the contribution from the Rashba term cancels out due to macroscopic symmetry,[7] electrons can tunnel highly spin-polarized because of the Dresselhaus term.

In this paper we elaborate on this idea and evaluate the spin-dependent tunneling (delay) time in a symmetric resonant tunneling structure. The tunneling time is an important quantity in a tunneling process that determines the dynamic working range of tunneling devices. In this work we take the "stationary phase approach" to define the tunneling time, as taken by Bohm[15] and Voskoboynikov *et al.*[16] Our following discussion will reveal that when the spin-orbit interaction effect comes into play, the ratio of the tunneling time between differently spin-polarized electrons can gain a few orders of magnitude. This provides the theoretical basis for time-resolved spin filtering. We also suggest that one can manipulate the tunneling time to a great variety by changing the barrier width. The relation between the delay time and the width is simple and can be used as a rule to select working frequencies.

This paper is organized as follows. In Sec. II we detail our calculation of the electron spin-dependent transmission amplitude, of polarization efficiency, and of tunneling time. In Sec. III, the results of calculations for InGaAs/InAlAs/InGaAs double barrier tunnel structure are presented. In Sec. IV we summarize the results.

II. POLARIZATION EFFICIENCY AND TUNNELING TIME

We consider the spin-dependent tunneling process through a symmetric double barrier structure grown along the $z\|[001]$ direction, as shown in Fig. 1(a). Taking the stationary phase approach the tunneling time is described to be the phase delay time, which is the energy derivative of the phase Θ of the transmission amplitude[16]

$$\tau_\sigma = \hbar \frac{\partial \Theta_\sigma}{\partial E_z}, \qquad (1)$$

where $\Theta_\pm = \arg|t_\pm|$, E_z denotes the longitudinal component of the electron's energy (corresponding to a motion parallel to the heterostructure growth direction), and $\sigma = \pm 1$ refers to the spin polarization.

Our calculation is performed on the basis of the effective electronic one-band Hamiltonian, energy- and position-dependent electron effective mass approximation, and the Ben Daniel–Duke boundary conditions.[17] The layers of the structure are perpendicular to the z axis and the in-plane

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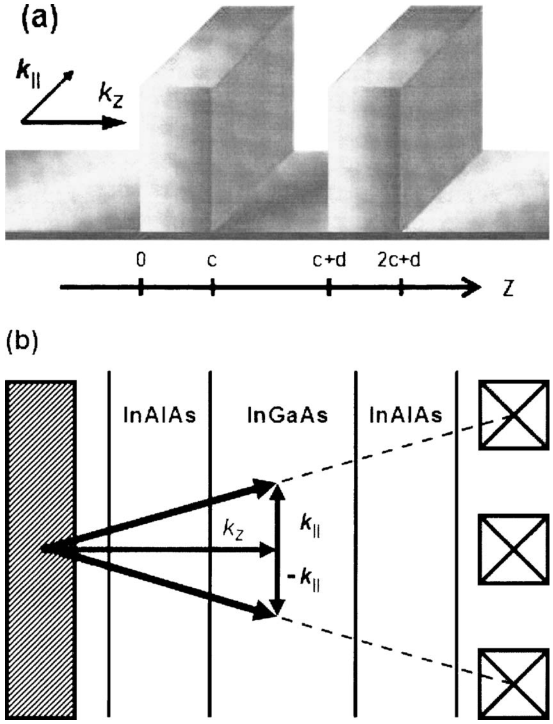

FIG. 1. (a) Sketch of electron tunneling with the wave vector $(\mathbf{k},k_z)$, where $\mathbf{k}$ is the in-plane wave vector and $z\|[001]$ the direction of the structure growth. The variation of the band parameters forms a symmetric double barrier tunneling heterostructure. (b) A schematic illustration of a possible spin-filter implementation.

electron's wave vector is $\mathbf{k}$. With the above assumptions the electronic wave function in the jth region can be presented as

$$\Phi_{\sigma}(x,y,z)=\psi_{j\sigma}(z)\exp[i(k_x x+k_y y)], \tag{2}$$

where $k=\sqrt{k_x^2+k_y^2}$ and $\Psi_{j\sigma}(z)$ satisfies the z component of the Schrödinger equation

$$\hat{H}_{j\sigma}\psi_{j\sigma}(z)=E\Psi_{j\sigma}(z), \tag{3}$$

with the spin-dependent Hamiltonian in each region,[13]

$$\hat{H}_{j\sigma}=\hat{H}_{j0}+\hat{H}_{j\mathrm{SO}}. \tag{4}$$

In Eq. (4) H_{j0} is the Hamiltonian of the system without spin-orbit interaction,

$$\hat{H}_{j0}=-\frac{\hbar^2}{2m_j(E)}\left(\frac{d^2}{dz^2}-k^2\right)+E_{jc},$$

and

$$\frac{1}{m_j(E)}=\frac{2P^2}{3\hbar^2}\left[\frac{2}{E-E_{jc}+E_{jg}}+\frac{1}{E-E_{jc}+E_{jg}+\Delta_j}\right] \tag{5}$$

presents the energy- and position-dependent reciprocal effective mass. E_{jc}, E_{jg}, and Δ_j stand for the position-dependent conduction-band edge, band gap, and the spin-orbit splitting in the valence band. P is the momentum matrix element.[17] In Eq. (4) $\hat{H}_{j\mathrm{SO}}$ is the spin-dependent part of the Hamiltonian which originates from the Dresselhaus term (in the symmetrical structure the Rashba spin-orbit coupling vanishes[7]). When the kinetic energy of electrons is substantially smaller than the barrier's height we can present this term as the following:[13]

$$\hat{H}_{j\mathrm{SO}}=\gamma_j(\hat{\sigma}_x k_x-\hat{\sigma}_y k_y)\frac{d^2}{dz^2}, \tag{6}$$

where $\hat{\sigma}_x$ and $\hat{\sigma}_y$ are the corresponding x and y components of the vector of the Pauli matrices $\hat{\sigma}=\{\hat{\sigma}_x,\hat{\sigma}_y,\hat{\sigma}_z\}$ and γ_j is a material constant of the jth region.

The boundary conditions for the solution $\Psi_{j\sigma}(z)$ at the interface between the j and $j+1$ regions have been introduced in Ref. 17,

$$\frac{1}{m_j(E)}\left[\frac{d}{dz}\Psi_{j\sigma}(z)\right]_{z=z_j}=\frac{1}{m_{j+1}(E)}\left[\frac{d}{dz}\Psi_{j+1\sigma}(z)\right]_{z=z_j},$$

$$\Psi_{j\sigma}(z_j)=\Psi_{j+1\sigma}(z_j). \tag{7}$$

To diagonalize the Hamiltonian one can put the in-plane wave vector $\mathbf{k}$ along the x direction $(k_y=0)$ and take the electronic wave functions to be

$$\Psi_{j\pm}(z)=\psi_{j\pm}(z)\begin{pmatrix}1\\ \mp 1\end{pmatrix},$$

which are eigenfunctions of $\hat{\sigma}_x$.

The general solution of Eq. (3) in a given jth region has the form

$$\psi_{j\sigma}(z)=a_{j\sigma}\phi_{j\sigma}^{+}(z)+b_{j\sigma}\phi_{j\sigma}^{-}(z),$$

where $\phi_{j\sigma}^{\pm}(z)$ is a pair of linearly independent solutions of Eq. (3) within that region. In the regions $j=1,3,5$ the solutions are the following plane wave sets:

$$\phi_{j\sigma}^{\pm}(z)=\exp(\pm ik_j z),$$

where

$$k_j(E_z,k)=\frac{\Sigma_{j\sigma}}{\hbar}\sqrt{2m_j(E_z,k)(E_z+E_{1c}-E_{jc})-\hbar^2\left[1-\frac{m_j(E_z,k)}{m_1(E_z,k)}\right]k^2},$$

$$\Sigma_{j\sigma}=\sqrt{1+\sigma\frac{2\gamma_j m_j(E_z,k)}{\hbar^2}k},$$

and E_z is the longitudinal component of the total energy in the first region,

$$E=E_{1c}+E_z+\frac{\hbar^2k^2}{2m_1(E_z,k)}.$$

We use this expression, along with Eq. (5), to find the dependence of $m_j(E_z,k)$ on $E(E_z,k)(j=1-5)$. In the regions $j=2,4$ the solutions are chosen to be

$$\phi_{j\sigma}^{\pm}(z)=\exp(\pm q_j z),$$

where

$$q_j(E_z,k) = \frac{\Sigma_{j\sigma}}{\hbar}\sqrt{2m_j(E_z,k)(E_{jc}-E_{1c}-E_z)+\hbar^2\left[1-\frac{m_2(E_z,k)}{m_1(E_z,k)}\right]k^2}.$$

The coefficients $\{a_{j\sigma},b_{j\sigma}\}$ are to be determined from the boundary conditions in Eq. (7). The sets of coefficients in neighboring regions are related by the transfer matrix M:[18]

$$\begin{pmatrix} a_{j\sigma} \\ b_{j\sigma} \end{pmatrix} = M_{\sigma}^{j}\begin{pmatrix} a_{j+1\sigma} \\ b_{j+1\sigma} \end{pmatrix}.$$

According to the boundary conditions in Eq. (7) the matrix M_{σ}^{j} is written as[7]

$$M_{\sigma}^{j} = \frac{1}{\Delta_j}\begin{pmatrix} \Lambda_{j+}^{-} & \Lambda_{j+}^{+} \\ -\Lambda_{j-}^{-} & -\Lambda_{j-}^{-} \end{pmatrix},$$

with

$$\Delta_j = \Delta_j^{+}-\Delta_j^{-}, \quad \Delta_j^{\pm} = \left\{\frac{d}{dz}\ln[\psi_{j\sigma}^{\pm}(z)]\right\}_{z=z_j}$$

$$\Lambda_{j+}^{\pm} = \left(\frac{m_j}{m_{j+1}}\Delta_j^{\pm}-\Delta_j^{+}\right)\frac{\psi_{j+1\sigma}^{\mp}(z_j)}{\psi_{j\sigma}^{+}(z_j)},$$

$$\Lambda_{j-}^{\pm} = \left(\frac{m_j}{m_{j+1}}\Delta_j^{\pm}-\Delta_j^{-}\right)\frac{\psi_{j+1\sigma}^{\mp}(z_j)}{\psi_{j\sigma}^{+}(z_j)}.$$

The double barrier tunneling structure consists of four interfaces, so the total transfer matrix is written as

$$M_{\sigma} = \Pi_{j=1}^{4}M_{\sigma}^{j}.$$

Electrons are injected from the region of $j=1$. The transmitted waves will appear in the region of $j=5$. With this assumption the transmission amplitude is given by

$$t_{\sigma} = \frac{1}{(M_{\sigma})_{11}},$$

and the spin-dependent delay time is written as

$$\tau_{\sigma}(E_z,k) = -\hbar\frac{\partial \arg[(M_{\sigma})_{11}]}{\partial E_z}.$$

The polarization efficiency of the structure was defined in Ref. 7 to be

$$P = \frac{|t_+|^2-|t_-|^2}{|t_+|^2+|t_-|^2}.$$

III. CALCULATION RESULTS

In Fig. 2 we demonstrate the numerical results of the polarization efficiency P of an electron's tunneling through a resonant symmetric structure made of $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}/\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As}$ heterojunctions. All calculations are performed within a region on the (E_z,k) plane where the total energy of electrons is substantially smaller than the barrier's height [see Eq. (6)]. The numerical values of γ in different materials are obtained for InAs and GaAs from Ref. 13, for AlAs from Ref. 21, and for alloys with the Vegard's superposition law in Ref. 22. One can see that the polarization efficiency shows typical resonant behaviors as a function of the longitudinal energy and in-plane wave number. The peaks correspond to the spin-split lowest resonant levels on the (E_z,k) plane. The splitting of the resonant levels results in an abrupt change of the sign of the polarization efficiency.

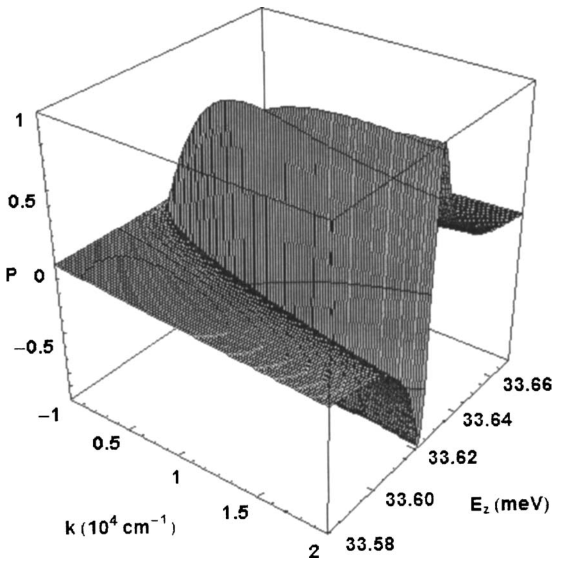

FIG. 2. Polarization efficiency P calculated for an $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}/\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As}/\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ DBT structure (see Fig. 1). The structure parameters are obtained in Ref. 20: $E_{1g}=0.418$ eV, $E_{2g}=1.52$ eV, $\Delta_1=0.38$ eV, $\Delta_2=0.341$ eV, $m_1(0)=0.044m_0$, $m_2(0)=0.084m_0$ (m_0 is the free-electron mass), $\gamma_1=0.0769$ eV nm^3 (Ref. 13), $\gamma_2=0.0734$ eV nm^3 (Ref. 21), $c=6$ nm, and $d=12$ nm.

The delay time of tunneling electrons with two opposite spin polarizations is presented in Fig. 3. The position of the peak corresponds to the resonant tunneling level, at which the tunneling electron is "trapped" in the quasibound states of the well. Although the positions of the peak for the two opposite spin polarizations do not seem to have the same functional dependence on (E_z,k), the distance between them in E_z is proportional to k, in accordance to the linear dependence on k of the Dresselhaus spin spliting of the levels in the well.

Since the positions of the peaks depend sharply on E_z and k, we present in a logarithmic scale the ratio of the delay time between oppositely spin-polarized electrons (see Fig. 4). This ratio increases with the length of k and can gain a few orders in magnitude.

The ratio of the delay times can be tuned by means of structural design. For this reason we present in Fig. 5 the dependence of the maximal delay time on the barrier thickness c and the well width d. The delay time increases with increasing c and d, but has different functional dependencies on each of them. From the calculation results presented in Fig. 5 for τ_+, one can approximate the dependencies as the following formula:

$$\tau_+ \propto d^2\exp(\alpha c),$$

where α is a constant; for τ_- of the same structure, one can recalculate it from the logarithmic ratio. For our symmetric InGaAs/InAlAs/InGaAs double barrier structure $\alpha \approx 0.074$ when $d=18$ nm. Applying this formula one can determine

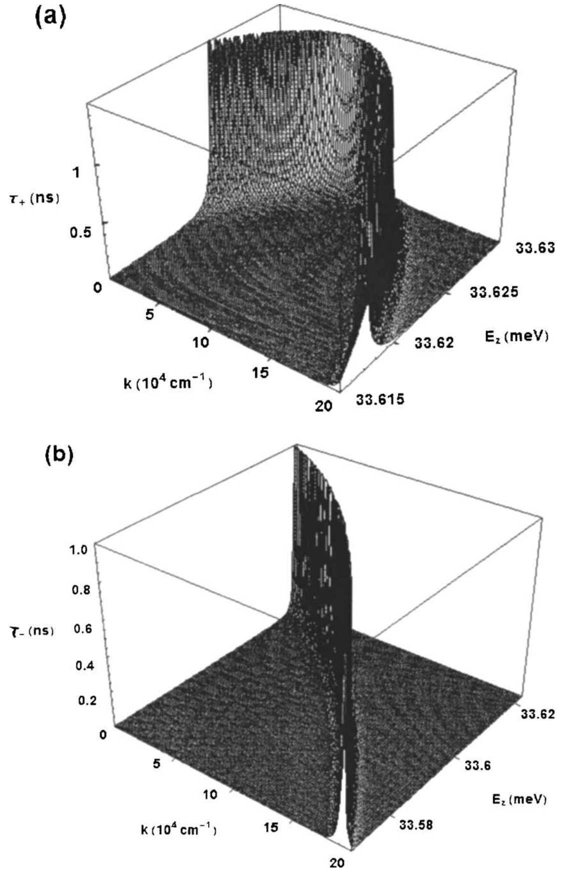

FIG. 3. The delay time for the structure in Fig. 2. (a) Delay time for electrons with spin "up." (b) Delay time for electrons with spin "down."

the actual region of frequencies where the structure is applicable to spin-dependent electronic devices.

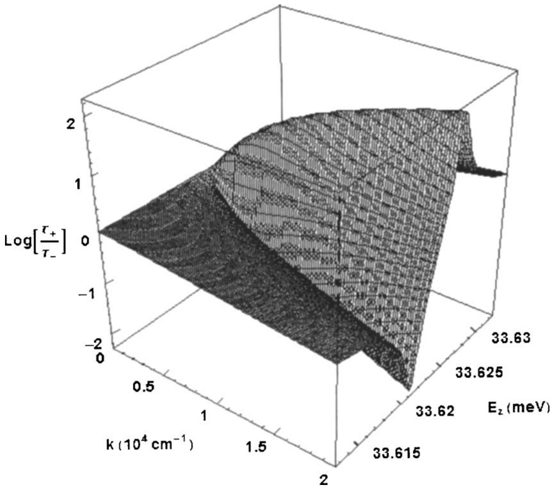

FIG. 4. Ratio between the delay time for different polarizations of the electron spin. The structure is the same as in Fig. 2.

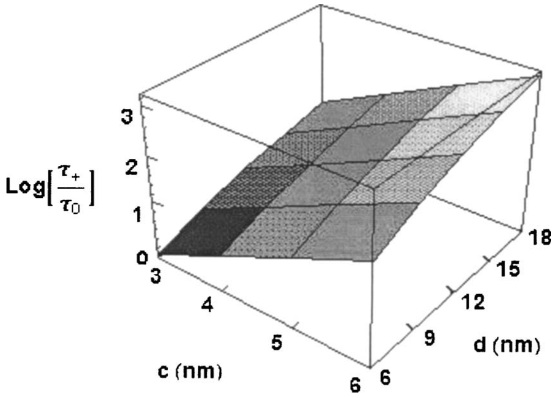

FIG. 5. The variation of the maximum delay time with respect to (a) the barrier thickness and (b) the well width. The constant $\tau_0=10^{-12}$ s is defined for normalization. The structure is the same as in Fig. 2.

The large and tunable ratio of spin-dependent delay times in symmetric structures provides a new method to perform spin filtering. Once we have clear spin-distinguishable times of the tunneling processes, the cutoff frequencies of electrons differently spin polarized will also split. By selecting an appropriate region of frequency, the current contribution from electrons with a lower cutoff frequency can be greatly suppressed. In this sense we achieved time-resolved spin filtering. This dynamic regime is more efficient than the conventional static regime. Indeed, in the static regime the means to spin filtering is a large spin splitting of resonant levels in the well,[9] which requires a large transversal dc bias (or built-in electric field). In symmetrical structures instead one can perform the dynamic spin filtering even when only a weak time-dependent signal is applied. We mention by pass that the spin-relaxation processes can also be suppressed by the same means.

An important point that tends to be missed is the fact that the spin filtering based on the spin-orbit coupling requires a control of the electrons' in-plane momentum.[9,11,12] Figure 1(b) illustrates schematically the basic concept of a dynamic spin filter fabricated in a split multicollector configuration. The in-plane momentum control of electrons and the dynamic spin filtering are achieved by sending a series of high-frequency voltage pulses to different leads of the multicollector. Another method to control the electrons' in-plane momentum was demonstrated recently with side-gated resonant devices in a dc regime.[12]

IV. CONCLUSIONS

Based on the stationary phase concept and the effective one-band Hamiltonian with the Dresselhaus spin-orbit coupling, we present the numerical results of the tunneling time through a realistic InGaAs/InAlAs/InGaAs resonant symmetric structure. It is shown that the polarization efficiency of the structure has a well-defined resonance behavior, which leads to a considerable spin polarization of electrons tunneling through. In the lower-energy region, the ratio between the tunneling times of electrons with opposite spin orientations can vary over a few orders in magnitude. The results indicate that the Dresselhaus spin-orbit coupling separates the time-dependent response of differently spin-polarized tunneling electrons. Furthermore, the large and tunable ratio of the tunneling times provides a possible way to construct a dynamic spin filter. The characteristic time of such devices also has been estimated and presented, showing simple functional dependencies on the barrier thickness and the well width. The dependencies can be exploited to design spintronic devices working in the desired frequencies.

This work was supported by the National Science Council of R.O.C. under Contract No. NSC 93-2112-M-009-008.

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