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Electron-spin polarization by resonant tunneling

Erasmo A. de Andrada e Silva
Instituto Nacional de Pesquisas Espaciais, CP515, 12201 São José dos Campos, São Paulo, Brazil

Giuseppe C. La Rocca
Dipartimento di Fisica, Università di Salerno, 84081 Baronissi (Sa), Italy
and INFM, Scuola Normale Superiore, 56126 Pisa, Italy

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The spin-dependent electron resonant tunneling through nonmagnetic III–V semiconductor asymmetric double barriers is studied theoretically within the envelope function approximation and the Kane model for the bulk. It is shown, in particular, that an unpolarized beam of conducting electrons can be strongly polarized, at zero magnetic field, by a spin-dependent resonant tunneling, due to the Rashba mesoscopic spin-orbit interaction. The electron transmission probability is calculated as a function of the electron's energy and angle of incidence. Specific results for tunneling across lattice matched politype $Ga_{0.47}In_{0.53}As/InP/Ga_{0.47}In_{0.53}As/GaAs_{0.5}Sb_{0.5}/Ga_{0.47}In_{0.53}As$ double barrier nanostructures show, for instance, sharp spin-split resonances, corresponding to resonant tunneling through spin-orbit split quasibound ground and excited electron states (quasisubbands). The calculated polarization of the transmitted beam in resonance with the second quasisubband shows that polarization bigger than 50% can be achieved with this effect. [S0163-1829(99)50724-8]

Besides its electric charge the electron carries also its intrinsic angular momentum. The spin dependence of the electronic properties of artificial nanostructures is one of today's leading problems in the physics of electronic devices. The interest lays both on the improvement of actual devices, like the GaAs polarized electron source (GaAs-PES),[1] and on the search for new devices.[2] The effects of the spin degree of freedom on the electron quantum confinement in III–V semiconductor nanostructures have been considered experimentally[3] as well as theoretically,[4–7] and the relevant physics have been reasonably well clarified. On the other hand, while, for example, a better understanding of the spin-dependent electron transmission through ferromagnetic metal thin layers[8] and tunnel junctions[9] has been recently obtained, very little has been done to elucidate the microscopic mechanisms of electron spin-polarized transport across nonmagnetic semiconductor heterostructures.[10]

The spin dependence of the electronic properties of such structures at zero applied magnetic field originate from the spin-orbit interaction. The lifting of the spin degeneracy in the conducting subbands when the system lacks inversion symmetry is of particular interest to both electron optical and transport properties.[3,4,6,7] Such symmetry in common GaAs heterostructures is, in general, broken by both microscopic and mesoscopic contributions to the electron potential. They are due to the polarity of the bond and to the asymmetries in the band-gap engineering, respectively, and produce different wave vector or **k** dependence of the energy splitting between states with opposite spins. This in turn leads to spin-dependent electron transport effects of a somewhat different character.

Here, we present the results of our investigations on the effects of the specular asymmetry along the growth direction on the spin-dependent electron quantum (coherent and vertical) transport in III–V asymmetric nanostructures. Such effects come from the so-called Rashba spin-orbit term (linear in k), which besides being adjustable according to the asymmetry fabricated, has been shown to be, in general, the strongest one in the case of structures with narrow gap materials.[4,6,7] As the main result, we obtain a new spin-dependent resonant tunneling effect, that can, in principle, be used for the polarization of electron beams. The effects of the microscopic k^3 term are going to be treated elsewhere.

The Rashba spin-orbit term, which can be derived from general symmetry arguments,[11] does not depend on the structure's orientation with respect to the crystal axis; it depends only on the angle θ between the growth direction ($\hat{z}$) and the electron's wave-vector **k**. It can be written as

$$H_{so}=\frac{d}{dz}\beta(z,E)|\mathbf{k}|\sin\theta=\frac{d}{dz}\beta(z,E)k_{\parallel}. \tag{1}$$

The coupling parameter β as given by the eight-band Kane model reads[7]

$$\beta(z,E)=\frac{P^2}{2}\left(\frac{1}{E-U(z)-E_v(z)}-\frac{1}{E-U(z)-E_v(z)+\Delta(z)}\right), \tag{2}$$

where $U(x)$ is the electrostatic potential from the depletion layer or applied external field, E_v is the edge of the valence band, Δ is the spin-orbit splitting in the maximum of the valence band, and P is the interband momentum matrix element. Simple spin-dependent boundary conditions for the envelope functions can be derived in the presence of this term[7] and the problem of the spin-dependent quantum transport can be studied within the standard envelope function approach.

Let us then consider the problem of an electron scattered by an ideal asymmetric double barrier potential with perfect translation symmetry along the plane of the interfaces, as

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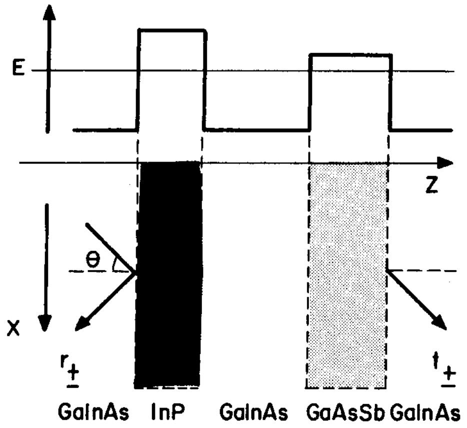

FIG. 1. Illustration of the spin-dependent scattering of conducting electrons by an asymmetric double barrier III–V semiconductor nanostructure. The conduction-band-edge profile has been drawn in the upper part and a view of the xz plane (a look from the top) in the lower, showing the angle of incidence θ.

illustrated in Fig. 1. In the case of normal incidence ($\theta=0$) the electron wave vector has no component parallel to the interfaces ($k_\parallel=0$), there is no spin-orbit interaction and one has the spin independent resonant tunneling (across asymmetric double barrier) problem.[12] If instead the crossing is oblique ($\theta\neq 0$), the nonzero electron's $k_\parallel$ is conserved and the result for the transmission probability will depend on the orientation of the electron's spin. We here obtain such transmission probability from the solution of the stationary problem $H_\pm F_\pm = EF_\pm$, for each spin orientation along the direction $\hat{y}$ perpendicular to both $\mathbf{k}_\parallel$ and $\hat{z}$. In the flat-band and zero-bias conditions $[U(z)=0]$, the envelope function in the layer material j is of the form $F_\pm = e^{ik_\parallel x}(A^j_\pm e^{ik_j z} + B^j_\pm e^{-ik_j z})$, and the effective Hamiltonian is given by

$$H_\pm(E) = -\frac{\hbar^2}{2}\frac{d}{dz}\frac{1}{m(E,z)}\frac{d}{dz} + E_c(z) \pm H_{so}(E), \tag{3}$$

where $E_c(z)$ gives the conduction-band-edge profile and

$$\frac{1}{m(E,z)} = \frac{P^2}{\hbar^2}\left(\frac{2}{E-E_v(z)} + \frac{1}{E-E_v(z)-\Delta(z)}\right) \tag{4}$$

is the inverse of the energy-dependent effective mass as given by the same Kane model for the bulk.

Now we can consider an incoming electron with definite energy E and spin + or − (up or down with respect to $\hat{y}$), and solve for the spin-dependent transmission coefficient $t_\pm$. Using standard transfer-matrix method the solution is straightforward:

$$\begin{pmatrix} t_\pm \\ 0 \end{pmatrix} = M_\pm^{(2)} \begin{pmatrix} e^{ik_zL} & 0 \\ 0 & e^{-ik_zL} \end{pmatrix} M_\pm^{(1)} \begin{pmatrix} 1 \\ r_\pm \end{pmatrix}, \tag{5}$$

where the $M_\pm^{(j)}$, $j=1,2$ are the spin-dependent transfer matrices corresponding to the two different barriers, L is the well width and $k_z = \sqrt{[2m_0(E)/\hbar]E}\cos(\theta)$ is the electron's wave vector along the growth direction. The transfer matrix is obtained directly from the spin-dependent boundary conditions[7] and can be written as

$$M_\pm^{(j)} = \frac{m_0 m_j}{2k_z\rho_j}\sinh(\rho_j d_j)\begin{pmatrix} e^{-ik_zd_j} & 0 \\ 0 & e^{ik_zd_j} \end{pmatrix}\begin{pmatrix} P & Q_\pm \\ Q_\pm^* & P^* \end{pmatrix}, \tag{6}$$

with

$$P = \frac{2k_z\rho_j}{m_0 m_j}\frac{1}{\tanh(\rho_j d_j)} + i\left[\left(\frac{2k_\parallel}{\hbar}\right)^2(\beta_0-\beta_j)^2 + \left(\frac{k_z^2}{m_0^2} - \frac{\rho_j^2}{m_j^2}\right)\right] \tag{7}$$

and

$$Q_\pm = \frac{4k_zk_\parallel}{\hbar^2 m_0}(\beta_0-\beta_j) + i\left[\left(\frac{2k_\parallel}{\hbar}\right)^2(\beta_0-\beta_j)^2 - \left(\frac{k_z^2}{m_0^2} + \frac{\rho_j^2}{m_j^2}\right)\right], \tag{8}$$

where d_j is the barrier j width, $\hbar k_\parallel = \sqrt{2m_0E}\sin\theta$ is the conserved momentum parallel to the interfaces, and $\rho_j = \sqrt{(2m_j/\hbar^2)(E_c^j - E) + k_\parallel}$ is the decay coefficient of the evanescent wave inside the barrier j. We remember that $\{m_0,\beta_0\}$ and $\{m_j,\beta_j\}$, the well and barrier material parameters, respectively, are energy dependent in accord to the expressions (4) and (2) above. In the limit of $\beta_0=\beta_j=0$ (or $\Delta_0=\Delta_j=0$), i.e., no spin-orbit interaction, the above transfer matrix reduces to the usual spin-independent expression.[13]

Finally, if one now considers an unpolarized beam of incoming conducting electrons, it is possible to calculate the polarization of the transmitted beam defined by

$$P(E,\theta) = \frac{T_+(E,\theta) - T_-(E,\theta)}{T_+(E,\theta) + T_-(E,\theta)}, \tag{9}$$

where $T_\pm = t_\pm t_\pm^*$ is the spin-dependent transmission probability. We should mention that the above obtained transfer matrix can be used to calculate the spin-dependent tunneling across single asymmetric barriers; however, the polarization of the transmitted beam in this case is quite small.[10] As shown here, a much larger polarization can be obtained with asymmetric double barriers due to the spin-dependent electron resonant tunneling effect.

As a practical and realistic example we have calculated the transmission probability and the polarization of the transmitted beam for the case of a lattice matched politype $Ga_{0.47}In_{0.53}As/InP/Ga_{0.47}In_{0.53}As/GaAs_{0.5}Sb_{0.5}/Ga_{0.47}In_{0.53}As$ double barrier nanostructure, with typical parameters (see figure caption). The results, shown in Fig. 2, present sizable spin splittings in the sharp tunneling resonances. A splitting of ~3 meV between the spin opposite transmission peaks is obtained in the case of resonant tunneling through the second quasi-sub-band. The effect is smaller in the case of tunneling through the ground quasisubband, due to a smaller Rashba spin-orbit effect in the lower lying levels of these flat band asymmetric structures in accord to a smaller importance of the spin-dependent boundary conditions as discussed in Ref. 7. Note also that the results have been shown here as a function of electron's energy

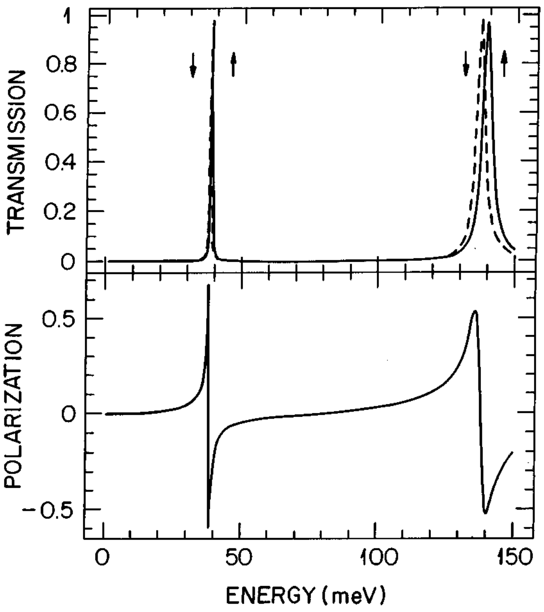

FIG. 2. Obtained spin-dependent electron transmission probability for crossing an asymmetric double barrier $Ga_{0.47}In_{0.53}As/InP/Ga_{0.47}In_{0.53}As/GaAs_{0.5}Sb_{0.5}/Ga_{0.47}In_{0.53}As$ polytype lattice matched nanostructure, illustrated in Fig. 1. The two doublets correspond to transmission through the ground and first excited spin-slit quasisubbands, respectively. In the lower panel is plotted the polarization of the transmitted beam. The bulk parameters used are the low-temperature values reported in the Landolt-Börnstein tables and we have used $L = 150$ Å, $\theta = \pi/4$, and for the InP and $GaAs_{0.5}Sb_{0.5}$ barriers $d_1 = 40$ Å, $V_1 = 0.4$ eV and $d_2 = 60$ Å, $V_2 = 0.15$ eV, respectively.

for a fixed θ, but it is clear that similar results are obtained as a function of θ for a fixed energy.

The polarization of the transmitted beam plotted in the lower part of Fig. 2 presents simple polarized electron scattering oscillations.[14] The obtained polarization in the case of resonance with the second quasisubband is seen to be over 50%. Even larger polarizations (and splittings) can be obtained not only with the use of different and new material combinations, but also with a careful optimization of the structure's parameters d_1, d_2, and L. The above results for this polytype double barrier structure demonstrate the main features of the spin-dependent electron resonant tunneling effect, both qualitatively and quantitatively. Results for other asymmetric heterostructures can be easily obtained with the use of the transfer matrix in Eq. (6), however corrections due to the k^3 term may be of importance for a more quantitative prediction, particularly in the case of large gap compounds.

Summarizing, we have presented the electron-spin-polarization effect due to the Rashba spin-orbit term in the resonant tunneling through asymmetric double barrier III–V semiconductor nanostructures. Specific calculations have been performed for the spin-dependent electron transmission probability across polytype double barrier structures, that show spin-split resonances able to polarize the transmitted beam up to over 50%. The fabrication of samples in which electrons are injected in and collected from double barrier semiconductor structures with a given angle with respect to the growth direction would permit a direct observation of the predicted effects. In view of the continuous improvement in the nanolithography technology, the specific example considered above leads us to believe that in the near future it will be possible to test and hopefully apply the present theory of the spin-dependent electron resonant tunneling in the development of new electron-polarized devices.

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