Spin polarization in non-magnetic nanostructures

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Abstract. Quantum transport that takes into account spin polarization has a high potential for research on optimal heterostructures for fabrication of nano-spintronic devices and quantum computing. This work theoretically analyzes different materials on the basis of type-II strained heterostructures like InAs/GaSb, InSb/GaSb, InSb/GaAs, and GaSb/GaAs by means of the spin polarization that considers the interacting spin coupling type: k²-Dresselhaus and Rashba in the electric barriers and the influence of in-plane magnetic field on spin polarization. The results obtained for the polarization of spin are in function of the energy applied to the electron, well width, height of barrier, and magnetic field intensity. This suggests that these features could be engineered in the fabricating of tunable spin-dependent electronic devices, such as spin switches based on double-barrier non-magnetic semiconductors.

1. Introduction
Spin-dependent electron transport in low-dimensional mesoscopic systems has recently drawn much attention due to its potential for future electronic device applications in the field of spintronics [1-3]. This new emerging field deals with the active manipulation of the electron’s spin (and not only its charge), adding a spin degree of freedom to the conventional charge-based technology, which has the potential advantages of multifunctionality: longer decoherence times and lengths, increased data processing speed, decreased electric power consumption, and increased integration densities compared with conventional semiconductor devices [1]. In addition to improving contemporary technology, spintronics may also contribute to the field of quantum computation and quantum information in which the quantum information may be contained in the spin, transmitted when the spin is polarized [4].

In the field of spintronics, one of the most important requirements is the completion of spin injection. Hence, some studies have focused on this topic [5-8], particularly, in ferromagnetic (FM) metals in semiconductor heterostructures, but the efficiency of spin injection is disappointingly small due to the conductivity mismatch between the FM metal and the semiconductor. Therefore, an alternative approach is based on the combination of an electric barrier (EB) and a magnetic barrier (MB) in a two-dimensional electron gas system (2DEG) proposed by Papp and Peeters [9,10]. The effects caused by the MB system are very different from the well-known potential barrier because the electron tunneling becomes a two-dimensional (2D) problem. Transmission depends not only on the energy of the impeding electrons, but also on the direction of their velocity toward the barrier. When it takes into account electron charge and spin, electronic transport can become spin polarized. Accordingly, in this work we only considered heterostructures based on double-barrier non-
magnetic semiconductors in the presence of EB, as proposed by JD Lu et al. [11] and magnetic field in the plane of the barrier, also of the interacting spin coupling type: \(k^3\)-Dresselhaus and Rashba in the barriers that according to Glazov et al. [12], who investigated the effect of spin-dependent resonant tunneling through the symmetric double barrier in the presence of the Dresselhaus spin-orbit (DSO) term and found that the transmission coefficient was strongly dependent on the spin orientations and on the wave vector of the electrons. Also, it has been found that the Rashba spin-orbit interaction (RSO) plays a more important role than the DSO term in the large spin polarization at zero magnetic field [11]. Therefore, it is expected that said behaviors are similar when spin-dependent tunneling is analyzed through the double-barrier heterostructure with the influence of in-plane magnetic field and the effects of Dresselhaus and Rashba spin-orbit coupling.

2. Model and theoretical calculation

Analysis of electron tunneling initially considered a wave vector \(\vec{k} = (k_{||}, k_z)\) through a double-barrier symmetrical potential height \(V_0\) of type zinc-blende based on double-barrier non-magnetic semiconductors grown along the [001] plane (Figure 1). The components wave vector \(\vec{k}\), characterized in that, the first is in the plane of the barrier and the following is a normal component to the direction of tunneling. Indeed, \(\vec{k} = (k_{\mathrm{Cos}}, k_{\mathrm{Sin}}, k_z)\), where \(\varphi\) is the polar angle of the wave vector \(\vec{k}\) in-plane [100] and [010].

![Figure 1. This figure shows the spin transmission through of axis z [001] in a model of symmetrical electric barrier-double, under the influence of in-plane magnetic field \(B\) on spin polarization. \(a_{l,r}\) are the barrier width and \(a_w\) is the well width.](image)

By calculating spin polarization and the probability of tunneling for up and down spin under the RSO and DSO, considering influence of in-plane magnetic field \(B\) on spin polarization, we can build the Hamiltonian:

\[
\hat{H}_j = -\frac{\hbar^2}{2m_j^*}(k_{\mathrm{Cos}}^2 + k_z^2) + V_0 + \hat{H}_D + \hat{H}_R + \hat{H}_Z
\]

where \(m_j^*\) the effective mass, with \(j = w, b\) (well and barrier), \(V_0\) is the potential of EB, \(\hat{H}_D\) is the spin-dependent \(k^3\)-Dresselhaus term is simplified [14] to \(\hat{H}_D = \beta_D (\hat{\sigma}_x k_z - \hat{\sigma}_z k_x)\), \(\hat{H}_R\) is in-plane Rashba term due to heteropotential asymmetry \(\hat{H}_R = \alpha_R (\hat{\sigma}_y k_y - \hat{\sigma}_z k_x)\), where \(\beta_D\) and \(\alpha_R\) are constants characteristic of the material and \(\hat{H}_Z\) Zeeman spin splitting is related to in-plane magnetic
field, given by the expression \(\hat{H}_k = \frac{1}{2} g^i_\mu^i \hat{\sigma} \cdot \vec{B}\). Where \(\hat{\sigma} = (\sigma_x, \sigma_y, \sigma_z)\) and each \(\hat{\sigma}_i\) as Pauli matrices, \(k_i\) the components of the electron wave vector, \(g^i_\mu^i \) corresponds to effective Landé factor, \(\mu_\mu^i = e\hbar /2m^i_\mu^i\) is the Bohr magneton and \(\vec{B} = (BCos\theta, BSin\theta, 0)\) magnetic field orientation.

Solving the Schrödinger-Pauli equation, \(\hat{H}_k \psi\), generated by the expression (1) requires that the wave function, \(\psi\), is disengaged for the spin and magnetic field, considers the spinors that diagonalize the terms: Dresselhaus \(\hat{\chi}_D^\pm(\varphi) = \frac{1}{\sqrt{2}}(1, \mp e^{-i\varphi})^T\), and Zeeman \(\hat{\chi}_Z^\pm(\theta) = \frac{1}{\sqrt{2}}(1, \pm e^{-i\theta})^T\), and a function \(u = u_\sigma(z)\) that describes the behavior of the electron in the tunneling direction and a plane wave and parallel to the plane of the EB \(\exp(i\vec{k} \cdot \vec{\rho})\) in which \(\vec{\rho}\) is a vector in the plane of the barrier given by \(\vec{\rho} = (x, y)\), consequently,

\[
\psi = \hat{\chi}^\sigma \ u_\sigma(z) \exp(i\vec{k} \cdot \vec{\rho})
\]

Under the considerations of the wave function, \(\psi\), the symbol \(\sigma = \pm\) refers to the states of spin up \(\uparrow\) and spin down \(\downarrow\). Accordingly, the function \(u_\sigma\) is defined in the regions 1, 2, 3, 4, and 5 as:

\[
u_\sigma(z) = \begin{cases} 
A_1 e^{i\rho_1(z-z_0)} + B_1 e^{-i\rho_1(z-z_0)} & \text{if } z < z_0 \\
A_2 e^{i\rho_2(z-z_2)} + B_2 e^{-i\rho_2(z-z_2)} & \text{if } z_0 < z < z_1 \\
A_3 e^{i\rho_3(z-z_3)} + B_3 e^{-i\rho_3(z-z_3)} & \text{if } z_1 < z < z_2 \\
A_4 e^{i\rho_4(z-z_3)} + B_4 e^{-i\rho_4(z-z_3)} & \text{if } z_2 < z < z_3 \\
A_5 e^{i\rho_5(z-z_3)} & \text{if } z > z_3
\end{cases}
\]

where \(\rho_\sigma\) denotes the wave vectors through the barriers including Dresselhaus, Rashba, and Zeeman terms are given by:

\[
\rho^2_\sigma = \left(\frac{2m^i_\mu^i V - E}{\hbar^2} + \frac{2\alpha_m m^i_\mu^i}{\hbar^2} k_{||} + \frac{m^i_\mu^i g^i_\mu^i \mu_\mu^i}{\hbar^2} B + k_{\perp}^2 \right) \left(1 \pm \frac{2\beta_d m^i_\mu^i}{\hbar^2} k_{||} \right)^{-1}
\]

and \(k_{\sigma}\) is the reciprocal length of decay of the wave function in the wells:

\[
k_{\sigma}^2 = \frac{2m^i_\mu^i E}{\hbar^2} \pm \frac{m^i_\mu^i g^i_\mu^i \mu_\mu^i}{\hbar^2} B - k_{||}^2
\]

Taking into account the boundary conditions, the transmission coefficient, \(T_\sigma\), can be calculated by a transfer-matrix method [15] and the spin polarization, \(P\), that determines the difference of transparency for the spin states \(\uparrow\) and \(\downarrow\) through the EB is:

\[
P = \frac{T_+ - T_-}{T_+ + T_-}
\]

3. Results and discussions

In our numerical calculations we always chose \(k_{||} = 2 \times 10^8 \text{ m}^{-1}\) and system electric barrier-double \(a_x = a_y = 5\text{ nm}\) and \(a_w = 5\text{ nm}\). The relevant parameters for non-magnetic semiconductors InAs, InSb, GaSb, and GaAs are references [11] and [16-19].
Figure 2. Symmetric double-barrier structure in the presence of the DSO and RSO for non-magnetic semiconductors: InAs/GaSb, InSb/GaSb, InSb/GaAs, and GaSb/GaAs $a_z = a_y = a_w = 5\,\text{nm}$ at fixed $k_e = 2 \times 10^6\,\text{m}^{-1}$. (a) Spin polarization as a function electron energy, the EB height $V_0 = 320\,\text{meV}$. For the following plots, the energy applied electron according to each heterostructure is $E^{(1)} = 200\,\text{meV}, E^{(2)} = 240\,\text{meV}, E^{(3)} = 220\,\text{meV}$, and $E^{(4)} = 140\,\text{meV}$. (b) Spin polarization as a function of well width. (c) Spin polarization as a function of EB height. (d) Spin polarization as a function of magnetic field with EB height $V_0 = 320\,\text{meV}$. Initial state spin with polar angle of $\varphi = \frac{\pi}{4}$.

In Figure 2, the study is carried out at a zero magnetic field. When observing Figure 2 (a) it has the spin polarization as a function of the energy applied to the electron in heterostructures with best polarization percentages: InAs/GaSb and GaSb/GaAs with approximately 83%, but the latter with a faster relaxation spin due to the amplitude between the peaks, while the InSb/GaSb heterostructure has a lower polarization percentage, from about 67% but with a wider range of peaks generating a slower spin relaxation – ideal for manufacturing nano-devices. The figure 2 (b) shows the spin polarization as a function of width of well. We obtain resonant peaks in a width of 5 nm between
for InAs/GaSb, and similar behaviors around of this value for different nanostructures. In addition, the periodicity is not seen as reported by JD Lu et al. [13], because in our work we report the results in the conduction band, unlike JD Lu et al. In Figure 2 (c) we worked spin polarization depending on the height of the EB where only one peak of about 320 meV occurs because the energy of the electrons in each non-magnetic semiconductors corresponds to resonant energy given in Figure 2 (a), without generating new periodicity.

The studying the influence of in-plane magnetic field to the non-magnetic semiconductors are shown in Figure 2 (d) two cases are presented: the first for a direction of the magnetic field \( \theta = -\frac{1}{4} \pi \), that is observed on the scale of 0 to 1 T. The spin down decreases as the field is increased. Therefore the increases up spin, and the second for a direction of the magnetic field \( \theta = \frac{1}{4} \pi \), that is observed on the scale of -1 to 0 T, where the phenomenon is totally opposite to the first case. Generating a spin switch of which could be developed in the process of building engineering spintronic devices.

In the analysis of spin polarization in terms of the energy applied from the electron to the InAs/GaSb and InSb/GaAs heterostructures different intensities of magnetic field \( (B = 0, 0.1, 1 \text{T}) \) were used. Figure 3 (a) shows a resonant peak in \( E = 66 \text{meV} \) and \( B = 0.1 \text{T} \), where polarization is 100%, but with a deficiency in width between the very small corresponding to spin up and spin down peaks compared to those obtained at an energy of \( E = 200 \text{meV} \). Here, it is also observed that for more intense magnetic fields in the order of \( B = 1 \text{T} \) saturation occurs, but spin relaxation spin increases in these resonant states because the transmission coefficients \( T^+ \) and \( T^- \) are separated, as shown in Figure 4 (a).

![Figure 3](image_url)

**Figure 3.** Symmetric double-barrier structure \( a_L = a_R = a_w = 5 \text{nm} \) at fixed \( k_z = 2 \times 10^8 \text{m}^{-1} \), and EB height \( V_0 = 320 \text{meV} \). Spin polarization in the presence of the Dresselhaus and Rashba spin-orbit coupling as a function of electron energy to different magnetic field for the heterostructure: InAs/GaSb and InSb/GaAs. Energy applied electron is \( E = 200 \text{meV} \) for (a) and \( E = 220 \text{meV} \) for (b). Initial state spin of \( \varphi = \frac{1}{4} \pi \).
Figure 4. Symmetric double-barrier structure $a_L = a_R = a_w = 5\text{nm}$ at fixed $k_0 = 2 \times 10^8 \text{ m}^{-1}$, and EB height $V_0 = 320\text{meV}$. Spin polarization and transmission coefficient in the presence of the Dresselhaus and Rashba spin-orbit coupling as a function of magnetic field for the heterostructure InAs/GaSb and InSb/GaAs. Energy applied electron is $E = 200\text{meV}$ for (a) and $E = 220\text{meV}$ for (b). Initial state spin with polar angle of $\varphi = \frac{\pi}{4}$. In heterostructures shown in Figures 3 and 4 (b) a high sensitivity to the effects of low magnetic field is observed, reaching 100% polarization. With a spin relaxation (change of spin down to up) favorable since the separation between the peaks is not abrupt; suggesting future studies of spintronics in asymmetric double barrier heterostructures of InAs/GaSb/InAs/GaAs/InAs types.

4. Conclusions
We have theoretically investigated electron transport through spin-dependent non-magnetic semiconductors with DSO and RSO. When the heterostructure does not include magnetic field, it only has the spin-orbit coupling; we predict that spin-polarization spontaneously emerges in this heterostructure due to the combination of the coherence interaction effect of the DSO and RSO. But if InAs / GaSb and InSb / GaAs heterostructures are influenced by the magnetic field due efficiency of spin polarization and the probability transmission obtained in this work; that is very important for purposes of application, since the energy scales applied to electron and magnetic field is experimentally controllable, as the field direction. Therefore, spin relaxation can be thought out that depends strongly on this compensation DSO and RSO coupling [20], which can be used in fabrication of spin dependent optoelectronic devices.

By studying the influence of in-plane magnetic field in the $\theta = -\frac{1}{4} \pi$ direction, which decreases the spin down to measure magnetic field increases, therefore, generating spin up increases, totally opposite case when the magnetic field is oriented to $\theta = \frac{\pi}{4}$. generating a spin switch that could be developed during the process of engineering building spintronic devices.

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