SPIN POLARIZATION RESONANT TUNNELING WITH DRESSELHAUS AND RASHBA SPIN-ORBIT COUPLING IN THE PRESENCE OF HYDROSTATIC PRESSURE AND THE MAGNETIC FIELD

TUNELAMIENTO RESONANTE ESPIN-POLARIZADO CON ACOPLAMIENTO ESPÍN-ÓRBITA DE DRESSELHAUS Y RASHBA EN PRESENCIA DE PRESIÓN HIDROSTÁTICA Y CAMPO MAGNÉTICO

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ABSTRACT

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Whereas electron transport through spin polarization has a high potential for applications of electronic devices, making relevant the study of the physical effects inherent to the spin; are shown with this work theoretical results which allow investigations done about possible optimal heterostructures for spin filter manufacturing. The spin polarization is analyzed using the resonant tunneling on a double potential barrier considering the semiconductor heterostructure of $GaAs/Ga_{1-x}Al_xAs/GaAs$. The physical-mathematical model presented includes the interaction of coupling of the spin type: k^3-Dresselhaus and Rashba in the barriers, Rashba before and after them and Dresselhaus in the well. In addition all the heterostructure is subjected to a constant magnetic field and hydrostatic pressure (PH); because of these additional effects, the model also considers the g factor of Landé as function of the PH. The estimates obtained for the spin polarization is in function of the energy applied to the electron, the magnetic field and fixed PH.

Key words: Spin polarization, Dresselhaus and Rashba Spin-orbit coupling, Spin filters.

RESUMEN

Considerando que el transporte electrónico mediante la polarización de espín tiene un alto potencial en aplicaciones de dispositivos electrónicos, haciendo relevante el estudio de los efectos físicos inherentes al espín;

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se muestran con este trabajo resultados teóricos que permiten realizar investigaciones sobre posibles heteroestructuras óptimas para la fabricación de filtros de espín. La polarización de espín se analiza mediante el tunelamiento resonante en una doble barrera de potencial considerando la heteroestructura semiconductora de GaAs/Ga$_{1-x}$Al$_x$As/GaAs. El modelo físico-matemático que se presenta incluye la interacción de acoplamiento de espín tipo: k^3-Dresselhaus y Rashba en las barreras, Rashba antes y después de ellas y Dresselhaus en el pozo. Además toda la heteroestructura es sometida a campo magnético constante y a presión hidrostática (PH); debido a estos efectos adicionales, el modelo también considera el factor g de Landé como función de la PH. Los cálculos obtenidos para la polarización de espín está en función de la energía aplicada al electrón, el campo magnético y PH fijas.

Palabras clave: Polarización de espín, Acoplamiento espín orbita Dresselhaus y Rashba, Filtros de espín.

1. Introduction

Most of proposals for the spintronic devices are sometimes spin polarized transport through interfaces in various hybrid structures. Structures of double resonant barrier are not only rich in physics but also useful for various device fabrications. To determine the viability of the devices in mention is essential to answer questions of how to transport and detect spin polarized and how keeping its spin polarization over a relatively long time. Schmidt et al. proposed that the conductivity mismatch of metal and semiconductor structure causes a fundamental obstacle for electrical injection in ferromagnetic semiconductor [1]. As a result, Rashba uses tunneling contact at the interface of semiconductor and metal [2]. Sun et al. Polarized spin current generated in the semiconductor by the effect Rashba coupling [3,4].

On this work is presented a theoretical study to analyze the efficiency of polarization in any heterostructure type of double-barrier through spin orbit coupling k^3-Dresselhaus (DSOC) given on the crystalline structure zinc-blende type, which generates a breaking of reversal symmetry (BIA) [5], present in the barriers and well that are generated by the heterostructure as GaAs/Ga$_{1-x}$Al$_x$As/GaAs and coupling in the plane Rashba (RSOC) that is generated by the rupture of structural inversion symmetry (SIA) [6] in the barriers [7] before and after them.

2. Method

For the analysis of the electron tunneling, initially is considered a wave vector $k=\left(k_{\parallel},k_z\right)$ through a system of dual potential barrier of symmetrical of height $V_{0,P}$ generated by a heterostructure type GaAs/Ga$_{1-x}$Al$_x$As/GaAs which grows along z on the direction $[001]$; the components $k_{\parallel}$ and k_z are also wave vectors, the first in the plane of the barrier and the following is a component normal to the direction of tunneling. In fact, $k=\left(k_{\parallel}Cos\varphi, k_{\parallel}Sen\varphi, k_z\right)$ where φ is the polar angle of the wave vector k in plane xy. The calculation of the spin polarization and the probability of tunneling for the spin up and down under the DSOC and RSOC, considering effects of magnetic field and hydrostatic pressure, is based the Hamiltonian:

$$\hat{H}=-\frac{\hbar^2}{2m_P^*}\left(k_z^2+k_{\parallel}^2\right)+V_P\left(z,x\right)+\hat{H}_{SO} \qquad (1)$$

Where m_P^* is the effective mass in function of the PH, $V_P\left(z,x\right)$ is the potential of the heterostructure that dependent on concentration of Al and of the PH by ref. [8,9], and $\hat{H}_{SO}$ is the Hamiltonian effective dependant of the spin, which is the addition of the spin orbit interaction k^3-Dresselhaus $\hat{H}_D=\beta_D\left(\hat{\sigma}_x k_x-\hat{\sigma}_y k_y\right)k_z^2$, the term in the plane Rashba $\hat{H}_R=\alpha_R\left(\hat{\sigma}_x k_y-\hat{\sigma}_y k_x\right)$ and the contribution of the magnetic field given by Zeeman $\hat{H}_z=\frac{1}{2}g_P^*\mu_B\left(\hat{\sigma}\cdot\vec{B}\right)$ [5,6,7,10]. Where β_D y α_R are constants characteristic of each material, $\hat{\sigma}=\left(\hat{\sigma}_x,\hat{\sigma}_y,\hat{\sigma}_z\right)$, with $\hat{\sigma}_i$ as the matrices of Pauli, k_i the components of the electron wave vector, g_P^* corresponds to factor of Landé effective in function of the PH, μ_B is the magneton of Borh and $\vec{B}=\left(BCos\theta,BSen\theta,0\right)$ magnetic field orientation.

To solve the equation of Schrödinger-Pauli $\hat{\mathrm{H}}_{b,w}\hat{\psi}=\mathrm{E}\hat{\psi}$ generated by the expression (1) requires that the wave function $\hat{\psi}$, and disengaged for the effects of spin and magnetic field, for this considered the spinors of Dresselhaus $\hat{\chi}_{\pm}^{D}$ and the Zeeman $\hat{\chi}_{\pm}^{B}$, which are supplementary [10,11] and allow diagonalize the Hamiltonians that relate, a function $u=u\left(z\right)$ which describes the behavior of the electron on the tunneling direction and a plane wave parallel to the plane of the barrier $exp[i\vec{k}_{\parallel}\cdot\vec{\rho}]$ where $\vec{\rho}$ is a vector in the plane of the barrier given by $\vec{\rho}=\left(x,y\right)$, accordingly must be $\hat{\psi}=\hat{\chi}_{\pm}^{D}u_{\pm}\left(z\right)exp[i\vec{k}_{\parallel}\cdot\vec{\rho}]$.

Under the considerations of the wave function $\hat{\psi}$, the function u_{σ}, where $\sigma=\pm$ makes reference to the spin states up "+" and spin down"−", is defined by the expression:

$$\begin{cases} A_{\sigma}^{L} exp\left[i\kappa_{\sigma,1}z\right]+B_{\sigma}^{L} exp\left[-i\kappa_{\sigma,1}z\right] & si \quad -a_{L}<z \\ C_{\sigma}^{L} exp\left[\rho_{\sigma}z\right]+D_{\sigma}^{L} exp\left[-\rho_{\sigma}z\right] & si \quad -a_{L}<z<0 \\ E_{\sigma} exp\left[i\kappa_{\sigma,2}z\right]+F_{\sigma} exp\left[-i\kappa_{\sigma,2}z\right] & si \quad 0<z<a_{w} \\ C_{\sigma}^{R} exp\left[\rho_{\sigma}z\right]+D_{\sigma}^{R} exp\left[-\rho_{\sigma}z\right] & si \quad a_{w}<z<a_{w}+a_{R} \\ A_{\sigma}^{R} exp\left[i\kappa_{\sigma,1}z\right]+B_{\sigma}^{R} exp\left[-i\kappa_{\sigma,1}z\right] & si \quad z>a_{w}+a_{R} \end{cases} \qquad (2)$$

The wave vectors $\kappa_{\sigma,1}^{2}$, $\kappa_{\sigma,2}^{2}$ and ρ_{σ}^{2} are functions in terms of the electron energy applied to the hydrostatic pressure and the magnetic field. Determine:

Where a_L and a_R represents the width of the left and right barriers respectively, a_w the width of the well. The wave vectors $\kappa_{\sigma,1}^{2}$, $\kappa_{\sigma,2}^{2}$ and ρ_{σ}^{2} are functions in terms of the electron energy applied to the hydrostatic pressure and the magnetic field. Determine:

$$k_{P,R,j}=\alpha_{R}\frac{2m_{P,j}^{*}}{\hbar^{2}}k_{\parallel}, \qquad (3)$$

$$k_{P,D,j}=1\pm\beta_{D}\frac{2m_{P,j}^{*}}{\hbar^{2}}k_{\parallel}, \qquad (4)$$

$$k_{P,B,j}=\frac{m_{P,j}^{*}g_{P,j}^{*}\mu_{B}^{j}}{\hbar^{2}}B. \qquad (5)$$

For $j=w,b$, which w is associated with the results given by the well and b and the barrier, is obtained:

Table 1. Wave vectors along the direction of magnetic field application.

$\theta=-\frac{\pi}{4}$	$\kappa_{\sigma,1}^{2}=\rho_{P,w}^{2}\pm k_{P,R,w}\pm k_{P,B,w}$	$\kappa_{\sigma,2}^{2}=\frac{\rho_{P,w}^{2}\pm k_{P,B,w}}{k_{P,D,w}}$	$\rho_{\sigma}^{2}=\frac{\rho_{P,b}^{2}\mp k_{P,R,b}\mp k_{P,B,b}}{k_{P,D,b}}$
$\theta=\frac{3\pi}{4}$	$\kappa_{\sigma,1}^{2}=\rho_{P,w}^{2}\pm k_{P,R,w}\mp k_{P,B,w}$	$\kappa_{\sigma,2}^{2}=\frac{\rho_{P,w}^{2}\mp k_{P,B,w}}{k_{P,D,w}}$	$\rho_{\sigma}^{2}=\frac{\rho_{P,b}^{2}\mp k_{P,R,b}\pm k_{P,B,b}}{k_{P,D,b}}$

Considering to $\rho_{P,w}^{2}$ and $\rho_{P,b}^{2}$ analogous to those defined in ref. [7, 10, 11]

For calculating the coefficients of transmission, T_{σ}, through the heterostructure GaAs/Ga$_{1-x}$Al$_x$As/GaAs was used the standard conditions of border of Ben Daniel-Duke for the barriers of the left and right and the method of the transfer matrix for the whole system, thus obtaining an expression involving the spin up and the spin down, with the various variables specified in this work. The efficiency of spin polarization is determined by

$$P=\frac{T_{+}-T_{-}}{T_{+}+T_{-}} \qquad (6)$$

3. Results and discussion

For the analysis of the theoretical results was considered the semiconductors of GaAlAs, Ga$_{0.70}$Al$_{0.30}$As y GaAs, since they are crystal structure with constant of similar network. On consequence the relevant parameters needed for simulations involving the above materials are shown in Table 2 below.

Table 2. Parameters for the semiconductors.

	GaAlAs	**Ga$_{0.70}$Al$_{0.30}$As**	**GaAs**
β_D, eV A^3	19.7 [12]	18 [14]	24 [14]
α_R, eV A	0.0047 [13]	0.025 [13]	0.0873 [7]
g_P^{*}/g_0	−0.43 [15]	0.4 [15]	−0.44 [15]

Values are given at atmospheric pressure.

The wave vector in the plane of the barrier is fixed for all simulations $k_{\parallel}=2\times10^{8}\,m^{-1}$ according ref. [6,7,10,11]. The thickness of the barriers are worked as $a_L=a_R=3nm$ and width of well as $a_w=8nm$, to $T=80K$.

In Fig. 1.a) is observed that polarization given by all the conditions that this paper suggests (1) reaches 2% favoring spin down, while if only considers in the barriers the effects DSOC y RSOC (2) the polarization rises to 6% but favoring the spin up. For Fig. 1.b) Is observed greater symmetry in polarization, appearing equally in the spin inversion, of up to (2) to down in (1). This same phenomenon occurs again to only consider the effect DSOC in the well.

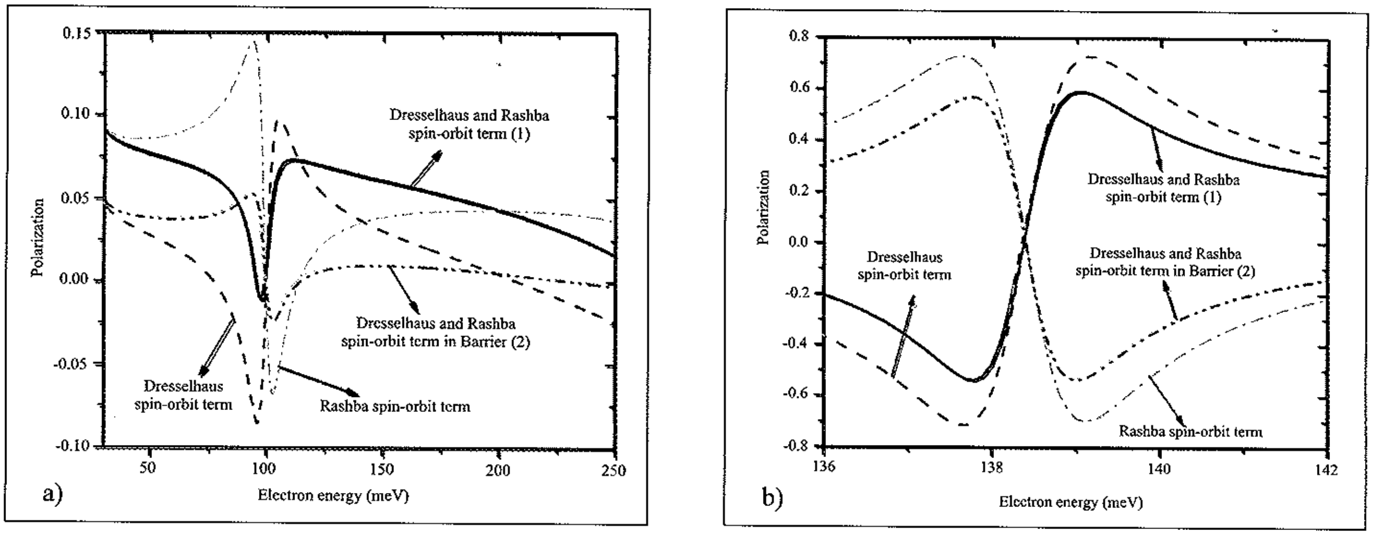

Figure 1. Spin polarization for the system double barrier of potential corresponds to the heterostructures of a) GaAs/GaAlAs/GaAs, b) GaAs/ $Ga_{0.70}$ $Al_{0.30}$As /GaAs, depending on the energy applied, at atmospheric pressure without the presence of magnetic field.

The presence of magnetic field favors appreciably the spin up polarization in the heterostructures (2), approximately a 90% to $B = 4T$, but as HP increases spin polarization decreases helping the spin down from 10% to about 35%, as shown in Fig. 2.a), this effect can be counteracted by changing the direction of application of the field favoring the spin up from 35% to 42%. In an analogous manner behaves the heterostructure (1), but with lower efficiency.

In Fig. 2.b) is observed a balance point in a range between 7.5 to 8 Kbar approximately, where the spin polarization is invariant, which indicates that the terms involving the magnetic field in table 1 are made zero, implies in turn that the factor of Landé must be zero to GaAs and GaAlAs since this factor increases as the PH increases according to the ref. [15], likewise shows that the spin up polarization rate decreases to the balance point and then it slowly increases after him, as the magnetic field increases to the heterostructure (1), till $B = 0.5T$.

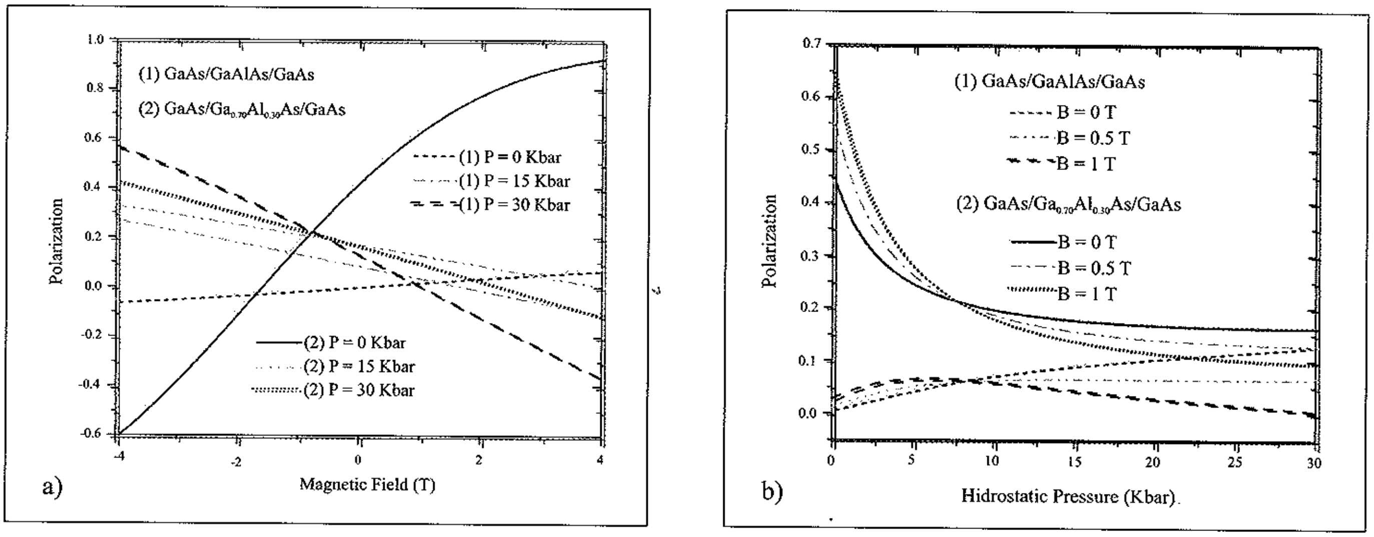

Figure 2. Spin polarization under all conditions proposed for this work. With a energy applied to the electron of $E_{(1)} = 100\,\mathrm{meV}$ and $E_{(2)} = 140\,\mathrm{meV}$. Is considered an initial state for the spin of $\varphi = \frac{\pi}{4}$.

4. Conclusions

The effect of moderate pressures to which they are exposed electronic devices in their construction process generated significant changes in the conduction bands in the materials that make up; situation that is reflected in the loss of spin polarization for the heterostructures in study; fact that can be largely reduced by reversing the direction of the magnetic field to consider.

For heterostructures analyzed by taking into account the effect DSOC and RSOC in the barriers prevails the spin up, but when added DSOC in the well and RSOC before and after of the barriers inversion occurs in the spin. Therefore these interactions continue encouraging the manufacturing engineering for the spin valves, based on double barriers given by non-magnetic semiconductors.

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References

G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, B. J. Van Wees, "Fundamental obstacle for electrical spin injection from a ferromagnetic metal into a diffusive semiconductor", Phys. Rev. B, vol. **62**, pp. R4790-R4793, 2000.

E.I. Rashba, "Theory of electrical spin injection: Tunnel contacts as a solution of the conductivity mismatch problem", Phys.Rev. B, vol. **62**, pp. R16267-R16270, 2000.

Q. Sun, J. Wang, H. Guo, "Quantum transport theory for nanostructures with Rashba spin-orbital interaction", Phys.Rev. B, vol. **71**, pp. 165310: 1-11, 2005.

Q. Sun, X. C. Xie, "Spontaneous spin-polarized current in a nonuniform Rashba interaction system", Phys.Rev. B, vol. **71**, pp. 155321: 1-6, 2005.

V. I. Perel, S. A. Tarasenko, and I. N. Yassievich, "Spin-dependent tunneling through a symmetric barrier", Phys. Rev. B., vol. **67**, pp. 201304:1-3, 2003.

K. Gnanasekar, K. Navaneethakrishnan, "Spin-polarized resonant tunneling in double-barrier structure" Phys. E., vol. **28**, pp. 328-335, 2005.

A. John Peter, "Electron-spin polarization in a non-magnetic heterosturcture", Phys. Let. A., vol. **372**, pp. 5239-5242, 2008.

A. M. Elabsy, "Effect of the $\Gamma - X$ crossover on the binding energies of confined donors in single GaAs/$Al_xGa_{1-x}As$ quantum-well microstructures" J. Phys. Condens. Matter., vol. **6**, pp. 10025-10030, 1994.

J. A. Zuñiga, S. T. Perez-Merchancano, L.E. Bolivar Marinez, "Tunelamiento en una doble barrera de potencial tipo Pöschl-Teller afectada por presión hidrostática", RCF., vol. **43**, pp. 812-817, 2011.

Mohammad Reza Khayatzadeh Mahani, "Influence of in-plane magnetic on spin polarization in the presence of the oft-neglected k^3-Dresselhaus spin-orbit coupling", Phys. Let. A., vol. **372**, pp. 6022-6025, 2008.

Jian-Dou Lu and Jian-Wen Li, "The effects of Dresselhaus and rashba spin-orbit intereactions on the electron tunneling in a non-magnetic heterostructure", Applied Surface Science, vol. **256**, pp. 4027-4030, 2010.

M. A. Toloza Sandoval, A. Ferreira da Silva, E. A. de Andrada e Silva, G. C, La Rocca, "Rashba and Dresselhaus spin-orbit interaction strength in GaAs/GaAlAs heterojunctions", Phys. Procedia, vol. **28**, pp.95-98, 2012.

Robert H Silsbee, "Spin–orbit induced coupling of charge current and spin polarization", J. Phys.: Condens. Matter, vol. **16**, pp. R179-R207, 2004.

Hu Li-Yun, Zhou Bin, "Spin-dependent Breit-Wigner and Fano resonances in photon-assisted electron transport through a semiconductor heterostructure", Chin. Phys. B., vol. **20**, pp. 067201:1-8, 2011.

J.R. Mejia-Salazar, "Hydrostatic pressure and coupling-barrier effects on the cyclotron effective mass and Landé g factor in GaAs-$Ga_{1-x}Al_xAs$ doublé coupled quantum wells", Phys. E., vol. **44**, pp. 1196-1201, 2012.