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Transport spin dependent in nanostructures: Current and geometry effect of quantum dots in presence of spin-orbit interaction

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Abstract. In this work, we study the quantum electron transport through a Quantum Dots Structure (QDs), with different geometries, embedded in a Quantum Well (QW). The behaviour of the current through the nanostructure (dot and well) is studied considering the orbital spin coupling of the electrons and the Rashba effect, by means of the second quantization theory and the standard model of Green's functions. Our results show the behaviour of the current in the quantum system as a function of the electric field, presenting resonant states for specific values of both the external field and the spin polarization. Similarly, the behaviour of the current on the nanostructure changes when the geometry of the QD and the size of the same are modified as a function of the polarization of the electron spin and the potential of quantum confinement.

1. Introduction

In semiconductor nanostructures, spin-orbit coupling produces a splitting of electron states. Here, the spin of the electron generally shows an asymmetric inversion in these structures due to the presence of magnetic fields in the system which are applied in the direction of growth of the quantum mechanism, generating a Zeeman effect that significantly affects the behaviour of the electrons. In this context, the investigation of quantum transport influenced by time independent potentials is of great importance in the study of semiconductor nanostructures, since it is feasible to control the dynamics of electrons using polarization voltages that can lead to practical applications. Experimentally [1-3], different authors have shown how some properties of nanostructures and in particular, the current are dependent on the spin of the carriers: this led to the quantum transport of semiconductor nanostructures information to be controlled by manipulation of the spin using for this purpose, an applied voltage between the contact points of the structure [3]. At present, the study of the effects of particle spin is very important due to the control effects that can be induced in the quantum mechanics, because they produce changes in the coupling of the system and in the structure of the bands of the mechanism. Proof of this are the Rashba and Dresselhaus effects, which simply modify the quantum information in the system [4-10]. Thus, the study of the carriers in QDs with different shape and size embedded in a QW [11-19] have shown the appearance of new effects in the behaviour of the tunnelling current and spin information processes. In these structures, the spin states can be manipulated in a coherent sense. The above contributes to the research in spintronic based on the sensitive manipulation of spin and current of nanostructures and encodes various applications of quantum nanodevices, such as double barrier heterostructure (DBH) and similar [16].

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In this paper, we study quantum transport through semiconductor nanostructures involving QDs of different size and embedded geometries that act as a bridge for the information from one contact to another in our quantum mechanism. Here we work with the general quantum theory of quantum transport using the tight binding model and Keldysh's second quantization theory nonequilibrium in Green's formalism of functions to describe the resonant states in the system taking into account the Rashba interaction having a relevant effect on the current intensity [11-19]. We also conduct an exhaustive discussion of physical ideas in which we underlie the concepts that we used, as well as detailed interpretation of our results. We complement our numerical results with analytical models that show the physical importance of our model of semiconductor nanostructure, in which we have embedded different QDs.

2. Model and theoretical calculation

In this work, we study the electron resonant tunnelling through a QD of (InGa)As of different geometries (lens, ring and pyramid) embedded in a DBH of GaAS-(Ga,Al)As, that was grown in the z-direction and is connected to two semiconductor leads, as shown in Figure 1. Our quantum system is subjected to an external electric field applied in the z direction and to an asymmetric confinement potential, facilitating the analysis of the interaction orbital of spin Rashba.

\[ \hat{H}_{SO}(r) = \hat{p}^2/2m_e + V(r) + H_{SO}(r). \]  

Figure 1. This picture shown the effective potential grown in the z-direction of our DBH system with different QDs embedded: (a) QDs in lens shape of radius \( R=50 \text{Å} \) (b) ring shape of internal radius \( R_{\text{int}}=30 \text{Å} \) and external radius \( R_{\text{ext}}=50 \text{Å} \) and (c) pyramid shape, whose base is an equilateral triangle of side \( L=100 \text{Å} \). The barrier width is 80Å, the barrier height \( \Delta E = 300 \text{meV} \), the QW width is 100 Å and the band offset between the BDH and the QD is \( \Delta E_{\text{i}} = 262 \text{meV} \).

The Hamiltonian \( H(r) \) associated to the electron transport through a quantum mechanical system is QD-DBH given by:

where the first term is the kinetic energy, second term is the potential energy and the third term is the Rashba spin orbit (SO) interaction. The \( H_{SO}(r) \) term reduces to the form

\[ \hat{H}_{SO} = \hat{\sigma}/2h [\sigma(\hat{p} \times \hat{\sigma}) + (\hat{p} \times \sigma)\hat{\sigma}]. \]

The vector \( \sigma = [\sigma_x, \sigma_y, \sigma_z] \) represents the Pauli matrices, the vector \( \hat{p} \) of the momentum operator and \( \alpha \) Rashba SO interaction strength [4]. The expression \( H_{SO} \) can be split in two terms, \( H_{R1} \) and \( H_{R2} [4] \). Thus, \( H_{SO} = H_{R1} - H_{R2} \), where \( H_{R1} = 1/(2h)[\alpha \sigma_x p_y + \sigma_y p_\alpha] \) and \( H_{R2} = 1/(2h)[\alpha \sigma_y p_x + \sigma_x p_\alpha] \).
. $H_{R2}$ makes a spin precession and the $H_{R2}$ term can cause spin flips between different energy levels. $H_{R2} = (1/h)\alpha x \sigma_y$.

The Hamiltonian in equation (1) of the DBH device connected to two leads ($\beta = L,R$), and considering the Rashba SO interaction ($H_{SO}$ with $\alpha \neq 0$) can be written in the standard Anderson model:

$$H = H_{QD-DBH} + \sum_{\beta=L,R} H_\beta + H_T,$$

where $H_{QD-BDH} = \sum_{n,s} \varepsilon_n d_n^{\dagger} d_n + \sum_{n,m,s} \left[ t_{so}^{\beta} d_n^{\dagger} d_m^s + H.c \right]$ is the Hamiltonian from the QD-DBH device, $H_\beta = \sum_{k,s} \varepsilon_{k,s} a_{k,s}^{\dagger} a_{k,s}$, for the leads and $H_T = \sum_{k,s} \left[ t_{LDBH} a_{1k,s}^{\dagger} d_s + t_{RDBH} e^{-iK_s L} d_{Rs}^{\dagger} a_{k,s} + H.c \right]$, is the coupling between the leads and QD-DBH device.

The amount $\hat{n}_{ns} = d_{ns}^{\dagger} d_{ns}$ is the number operator, $s = \uparrow, \downarrow$ is the spin index, in which it describes the spin state with spin-up or spin down, respectively. $n$ is quantum number for the eigenstates of the single-particle Hamiltonian (1), at the isolated QD region with eigenenergy $\varepsilon_n = \langle n \mid H \mid n \rangle$. The second term in the last expression $H_{QD-BDH}$ is the Rashba $H_{R2}$ interaction in the second quantization with $t_{so} = 0.3meV$ intensity [4] are the elements for the non-diagonal matrix that takes into account the transition process among levels when $(n_\uparrow) \rightarrow (m_\downarrow)$ for $n \neq m$. $k\beta$ is the quantum index for $\beta$ lead with eigenenergy $\varepsilon_{k\beta} = \langle k\beta \mid H \mid k\beta \rangle$. $H_T$ is the Rashba interaction in the second quantization that gives place to a spin dependent phase factor $-iK_s L$ with $(K_s = \alpha m^* \hbar^2)$ where $m^*$ the effective mass and L is the dimension of our double-barrier system in the z-direction.

The quantum transport in the DBH device can be solved using the standard Green functions method proposed by Keldysh [15] and the electron current equation with spin up or spin down in our quantum device, which involves two contacts in the semiconductor nanostructure, quantum dots embedded of different geometries and external electric field, can take the form of:

$$I = \frac{2e}{h} \int \frac{d\omega}{2\pi} \text{Re} [t_{LDBH} G_{DBH}^\omega(\omega) + t_{RDBH} G_{DBH}^\omega(\omega)]$$

(2)

where the Green function $G^{\omega}(\omega)$ is the transform Fourier of $G(t)$ that allows to perform the calculations of our quantum model considering the frequency spectrum or the quantized energies of the system.

3. Results and discussions

For our DBH of GaAs-(Ga,Al)As we consider the effective electronic mass for the GaAs of $m^* = 0.067 m_0$, $m_0$ is the free electron mass, the Fermi level $E_F = 100meV$, the barrier height $\Delta E = 300meV$, the band offset between the BDH and the QD is $\Delta E_1 = 262meV$, the width of the barrier (B) and the well (W) of 80Å and 100Å, $\alpha = 3 \times 10^{-11} eV m$ Rashba SO interaction strength, $t_{so} = 0.3meV$, and $t_{LDBH} = t_{RDBH} = 1$, respectively.

Figure 2(a) shows current vs. voltage for a Rashba effect value of $\kappa_s L = \pi / 4$, without QD and with S$'$ and S$''$. We can observe that the current increases in function of the applied voltage in the DBH device presenting certain current peaks voltage values. This happens when an electron in the sea of Fermi in the emitter enters in resonance with a bounded level in the QW. Also, as the applied voltage continues increasing, the electron is no longer in resonance with the bounded level in the QW generating a negative differential current, if the applied voltage continues increasing, this current will continue growing in the system, showing the resonance behaviour for higher voltage values. In addition, we also
can observe in Figure 2(a) that the peaks with $S^-$ go first into resonance with a greater intensity compared to the peaks with $S^+$ and without Rashba effect, showing fundamentally that with this type of polarity (spin down) improves the electronic transportation in the system.

![Graphs showing current vs. voltage for different QD shapes and spin states.](image)

**Figure 2.** This figure exhibit current as a function of the applied voltage for our DBH model: (a) without QD and three different spin values, (b) lens, (c) ring and (d) pyramid, for two different Rashba effect values $K_R L = \pi/4$ and $K_R L = 3\pi/4$ and with spin up ($S^+$) and spin down ($S^-$).

Figure 2(b) shows the current vs. voltage for a QD in lens shape of a 50Å radius embedded in a DBH, with $S^+$, $S^-$ and with two Rashba interaction values $K_R L = \pi/4$ and $K_R L = 3\pi/4$. We are shown that the current in function of the applied voltage changes significantly when it is compared to the results obtained in Figure 2(a). Likewise, is shown that due to the QD presence in lens shape, there is a higher concentration of resonant states for some voltage values. And, in the case for the spin down, it shows that behaviour the current intensity is lower in the DBH in the phase $K_R L = \pi/4$ than in $K_R L = 3\pi/4$. For example, for voltage values close to 0.4V, in the same way, when we analyse the spin up case for the two phases quoted above, it is observed that the current intensity values decrease when the system has embedded lens in the confinement well as expected in the DBH in the presence of QDs. In this context, a higher number of peaks in certain voltage values are also determined, which implies a greater tunnelling of carriers when comparing Figures 2(a) and 2(b).
In Figure 2(b), we observe that the current has a greater intensity for electrons with $S^\uparrow$ compared to those of $S^\downarrow$, presenting a shift of the peaks with $S^\uparrow$ to lower voltage values. This is because the 2D gas electrons first tunnel into the emitter of the device, when they are in resonance with the states bounded in the QD and then are in resonance with the bounded states in the QW. In the 0.1 - 0.3V voltage range, these tunnelling peaks are associated to the QD linked levels, and between 0.3-0.5V these tunnelling peaks are associated with the confined levels in the QW. In addition, it is observed that the Rashba effect has a significant influence on the tunnelling current, presenting a higher peak for the interaction $K_{\theta}L = 3\pi/4$ than for interaction $K_{\theta}L = \pi/4 \mod \pi$ when the electrons have $S^\uparrow$; and for electrons with $S^\downarrow$ the current intensity behaviour is inverted, being the greater peak with interaction $K_{\theta}L = \pi/4 \mod \pi$ compared to the curve with interaction $K_{\theta}L = 3\pi/4 \mod \pi$.

Figure 2(c) shows the current characteristic curve vs voltage for a QD in the shape of a ring with internal radius $R_{\text{int}}=30\, \text{Å}$, and external radius $R_{\text{ext}}=50\, \text{Å}$ embedded in a DBH, with spin up and spin down and with two values of Rashba interaction $K_{\theta}L = \pi/4$ and $K_{\theta}L = 3\pi/4 \mod \pi$. In this figure, a higher number of peaks are observed than in previous results for similar voltage values, indicating a higher concentration of resonant states favouring quantum electron tunnelling. This is due to the change of geometry in the QD in the DBH, which indicates that our system is sensitive to the geometric change of dots. It is observed that the current changes its behaviour when the $S^\uparrow$ and $S^\downarrow$ cases with phases $K_{\theta}L = \pi/4 \mod \pi$ and $K_{\theta}L = 3\pi/4 \mod \pi$ are studied. This behaviour is similar to the one observed in Figure 2(b) only that due to the morphology of the QD, the current behaviour shows higher values for spin down with a phase $K_{\theta}L = 3\pi/4 \mod \pi$ than for a phase $K_{\theta}L = \pi/4 \mod \pi$ showing again an improvement of tunnelling when the system is polarized with spin down.

Figure 2(d) shows similar behaviours of the current intensity in function of voltage as in Figure 2(b) and (c), but they show a greater system efficiency when the QD geometry is changed, allowing to conclude in these cases, that the concentration of these resonant peaks is higher when the confinement increases and the QDs morphology changes.

4. Conclusions
In this work, we have studied the behaviour of current as a function of voltage for a double potential barrier system (DBH) that has QDs of different geometry. The study of current intensity was done using a Hamiltonian from the system in the formalism of the second quantization, where we included among others, the spin-orbit coupling. Here was highlighted that the interacting spin orbits Rashba type, is dominant throughout the DBH generating two main effects: it gives rise to an extra spin-dependent phase factor and spin-flip between levels allowing a change in the current intensity behaviour when spin-up or down states are taken into account, indicating that the spin polarization changes. Likewise, we observe that the current intensity in our DBH is susceptible to the presence of QDs and that this is significantly modified when the morphology of the QDs changes.

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References
[1] D Z Y Ting and X Cartoixà 2004 InAs/GaSb/AlSb Resonant Tunneling Spin Device Concepts Physica E 20 350
[2] Thomas Schäpers 2016 Semiconductor spintronics (Boston: Walter Gruyter Gmbh)
[3] Peter Michler 2017 Quantum dots for quantum information technologies (Switzerland: Springer Nature)
[4] Qin Feng Sun, Jian Wang and Hong Guo 2005 Quantum transport theory for nanostructures with Rashba spin-orbital interaction Phys. Rev. B 71 165310

5
[5] T Noda, N Koguchi 2006 Current voltage characteristics in double-barrier resonant tunneling diodes with embedded GaAs quantum rings *Physica E* **32** 550

[6] K Gnanasekar, K Navaneethakrishnan 2006 Effects of Rashba spin–orbit interaction on spin-dependent resonant tunneling in ZnSe/Zn$_{1-x}$Mn$_x$Se multilayer heterostructures *Physica E* **35** 103

[7] Ernie Pan, Yu Zou, Peter W Chung and Yan Zhang 2009 Interlayer correlation of embedded quantum-dot arrays through their surface strain energy distributions *Phys. Rev. B* **80** 073302

[8] C M Ryu and S Y Cho 1998 Phase evolution of the transmission coefficient in an Aharonov-Bohm ring with Fano resonance *Phys. Rev. B* **58** 3572

[9] S Murakami, N Nagaosa and S C Zhang 2003 Dissipationless quantum spin current at room temperature *Science* **05**(301) 1348

[10] J Sinova, D Culcer, Q Niu, N A Sinitsyn, T Jungwirth and A H MacDonald 2004 Universal intrinsic spin hall effect *Phys. Rev. Lett.* **92** 126603

[11] B K Nikolic, L P Zarbo, and S Souma 2010 *The Oxford Handbook on Nanoscience and Technology: Frontiers and Advances* vol 1, ed A V Narlikar and Y Y Fu (New York: Oxford University Press) chapter 24 pp 814–866

[12] D J Paul 2010 *The Oxford Handbook on Nanoscience and Technology: Frontiers and Advances* vol 3, ed A V Narlikar and Y Y Fu (New York: Oxford University Press) chapter 5 pp 181-204 Dimitry D Vvedensky 2010 *The Oxford Handbook of Nanoscience and Technology: Frontiers and Advances* vol 3, ed. A V Narlikar and Y Y Fu (New York: Oxford University Press) chapter 6 pp 205-243

[13] S M Mirzanian and A A Shokri 2013 Angular dependence of shot noise in the presence of Rashba spin–orbit coupling in semiconductor spintronics junctions *Physica E* **54** 59

[14] N Niketić Vitomir Milanović and Jelena Radovanović 2014 Properties of the resonant tunneling diode in external magnetic field with inclusion of the Rashba effect *Solid State Communications* **189** 52

[15] L V Keldysh 1965 Diagram Technique for Nonequilibrium Processes *Sov. Phys. JETP* **20** 1018

[16] J H Marin, I D Mikhailov and L F García 2007 Charge distribution in quantum dot with trapped exciton *Physica B* **398** 135

[17] D S Smirnov, M M Glazov, E L Ivchenko and I Lanco 2015 Theory of optical spin control in quantum dot microcavities *Phys. Rev. B* **92** 115305

[18] Leonor Chico, A Latge and Luis Brey 2015 Symmetries of quantum transport with Rashba spin–orbit: graphene spintronics *Phys. Chem. Chem* **17** 16469

[19] Ichiro Tanaka, Y Tada, S Nakatani, K Uono, I Kamiya and H Sakaki 2010 Resonant tunneling of electrons through single self-assembled InAs quantum dot studied by conductive atomic force microscopy *Physica E* **42** 2606