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Tunable strength saddle-point contacts impact on quantum rings transmission

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ABSTRACT

A particular subject of investigation is the role of several sadle-point contact (QPC) parameters on the scattering properties of an Aharonov–Bohm–Aharonov–Casher quantum ring (QR) under Rashba-type spin orbit interaction. We discuss the interplay of the conductance with the confinement strengths and height of the QPC, which yields new and tunable harmonic and non-harmonics patterns, while one manipulates these constriction parameters. This phenomenology may be of utility to implement a novel way to modulate spin interference effects in semiconducting QRs, providing an appealing test-platform for spintronics applications.

1. Introduction

Spintronics [1] has been addressed as a viable future for the electronic industry. As we approach the limits in the compaction to efficiency rate of electronic devices, the investigations on this field become more necessary and relevant. The Rashba spin orbit interaction (SOI-R) [2] has been appointed as a successful mechanism towards manipulating the electronic spin. Based on this effect a field effect transistor was theoretically designed [3].

Quantum rings (QRs) has became an appealing playground for electrons quantum interference effects such as the Aharonov–Bohm (AB) [4] and the Aharonov–Casher (AC) [5] effect, both considered as Berry-like events [6]. The oscillations in the total conductance due to this phenomena have been widely discussed in earlier works [7–10] for QRs and other topologies [11]. Appropriately using these effects the outgoing current of the QR can be tuned attending the spin polarization and then could be used for applications, at least at a theoretical level. They constitute the cornerstone of larger systems, such as QRs chains [12] and lattices [13].

A recent theoretical approach to QRs [14], departs from previous models [7,8,12], due a unique treatment of the QR inlet/outlet, that connects it to the source/drain of electrons, respectively. The constrictions were taken as two-dimensional potential barriers, in the form of a saddle-point quantum point contact (QPC) and besides, allocated in the QR periphery (see Fig. 1), thus conforming a truly different lead-to-ring interface junctions. This modelling solves several issues related to how the lead-to-ring coupling was described, eliminating – as a bonus – the free parameter ε accounting for the system transparency, which was responsible for none-physical sense numerical disadvantages [15,16]. Multiple degrees of freedom to handle up the QR phenomenology were introduced within this model, making it interesting towards possible spintronics real-word applications.

In this paper we discuss some features of the spin-resolved conductance G_σ for a given system under tunable strength saddle-point contacts. Within the transfer matrix formalism, G_σ contains the full information of the scattering process of the system under study, *i.e.* a QR with three QPCs. The expected AB and AC conductance oscillations arise as the external magnetic flux and the SOI-R strength constants vary. We focus our attention to the conductance dependence on the electrons reservoir energy and several QPCs parameters, such as the QPC strength $\hbar\omega_{x,y}$ and the saddle-point height V_o. A remarkable difference with previous model [14,15,16] is the fact that the saddle-point height is taken to be non-zero and represents a new parameter focusing on controlling the electron conductance. We find substantial variations for G_σ as the external magnetic field increases, apart from the AB oscillations.

The influences of the QPCs lead to an additional conductance harmonics, that appear when the transmission coefficients in the QPCs grow. This has been reported previously [8] but we find differences regarding the period of this harmonics, and the fact that this period can be manipulated.

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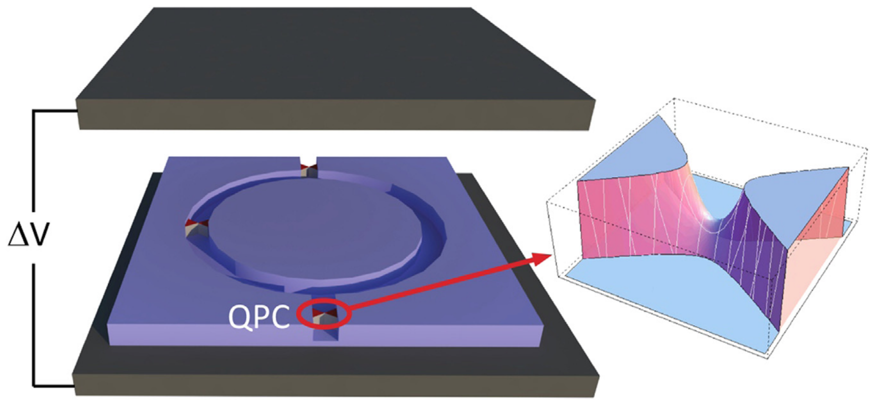

Fig. 1. Physical system, quantum ring with three quantum saddle-point contacts with SOI-R in an external magnetic field.

2. Theoretical model

An schematic representation of our setup is shown in Fig. 1. The inlet/outlet QPCs are placed just outside the entrance/exit of the QR (see Fig. 1), thereby they are not taken into account as part of it, but as part of its connection to the two-dimensional electron gas (2DEG), populating the source/drain electrodes. This is what we name here as the *lead-to-ring junction*. We shall refer hereafter to the scatterers on the lead-to-ring junctions as QPC1 (at the inlet, labelled as QPC in Fig. 1) and QPC2 (at the outlet), while the one in the QR upper arm, is represented as QPC3.

By an external gate voltage (V_g) applied on top of the QR in the z direction on a semiconductor interface, the SOI-R is created. The external magnetic field B is also directed along the z-axis of the interface. Considering a $2D$ potential barrier (see inset of Fig. 1), the saddle-point (SP) QPCs influence is accounted by

$$V_{\rm SP} = -\frac{1}{2}m\omega_x^2x^2 + \frac{1}{2}m\omega_y^2y^2 + V_o, \tag{1}$$

where $\hbar\omega_j = \mp\frac{1}{2}m\omega_j^2j^2$, with $j = x, y$, are the confinement energies in the x and y directions and V_o is the SP energy. The total Hamiltonian of the QPCs takes into account $V_{\rm SP}$ plus the effects of B. Electronic transport properties through a barrier of this kind has been previously studied [17] and

$$t_{\rm SP}(\epsilon) = \frac{1}{4}\left[\frac{\Gamma\left(\frac{1}{4}-\frac{1}{4}i\epsilon\right)}{\Gamma\left(\frac{1}{4}+\frac{1}{4}i\epsilon\right)}e^{i\pi/4} + \frac{\Gamma\left(\frac{3}{4}-\frac{1}{4}i\epsilon\right)}{\Gamma\left(\frac{3}{4}+\frac{1}{4}i\epsilon\right)}e^{-i\pi/4}\right], \tag{2}$$

was obtained for the transmission amplitude, where Γ is the gamma function. This yields for the QPC transmission coefficient $T_{\rm SP} = |t_{\rm SP}|^2$, a simplified expression

$$T_{\rm SP}(\epsilon) = \frac{1}{1+e^{-\pi\epsilon}}, \tag{3}$$

being, $\epsilon = (E_g - V_o)/E_1$, and the *guiding center* energy $E_g = E - E_2(n_L + \frac{1}{2})$. The flux conservation imposes over (3) the statistic rule $T_{\rm SP} + R_{\rm SP} = 1$. Here E_ν (with $\nu = 1, 2$) takes the form

$$E_\nu = \frac{\nu\hbar}{2\sqrt{2}}\sqrt{\sqrt{\Omega^4 + 4\omega_x^2\omega_y^2} + (-1)^\nu\Omega^2}\quad , \tag{4}$$

with $\Omega^2 = \omega_c^2 + \omega_y^2 - \omega_x^2$; $\omega_{x,y}$ the frequencies related to the confinement energies $\hbar\omega_{x,y}$; while ω_c and n_L stand for the cyclotron frequency and for the Landau-level index, respectively, both associated to the electron movement in B.

The motion in this kind of potential was decomposed in two terms, one responsible for the magnetic effects and the other one for the quantum transport through the barriers. Directly related to these terms we find n_L and E_g. From general grounds, the analysis of the scattering coefficients is quoted within two regimes of interest: (i) $E_g > V_o$, for the transmitted electrons and (ii) $E_g < V_o$ for the tunneling electrons. A further analysis of expression (3) demonstrates that the transmission coefficient in the tunneling case decreases extremely fast in terms of ϵ since the exponential term $e^{-\pi\epsilon}$ takes positive definite values and thereby T drops drastically. In the limit case when $E_g = V_o$, *i.e.* the SP energy matches that of the guiding center, $\epsilon = 0$ and $T_{\rm QPC} = 1/2$ are obtained. Due to non-novel enough phenomenology arises when changing from the transmitting to the tunneling regime, we consider the transmission case solely.

2.1. 1D-QR Model

We take the single-electron Hamiltonian in the presence of an external magnetic field and SOI-R [9]

$$\hat{H}_{\rm QR} = \frac{1}{2\,m}\left(\vec{p} - \frac{e}{c}\vec{A}\right)^2 + \alpha\left[\sigma\times\left(\vec{p} - \frac{e}{c}\vec{A}\right)\right], \tag{5}$$

where $\vec{A}$ stands for the vector potential and α represents the SOI-R strength. The second term in (5) is accounted for the SOI-R. We have neglected the Zeeman term associated with B in the QR [14]. Transferring (5) into polar cylindrical coordinates (r, φ) it reads, $H(r, \varphi) = H_o(r) + H'(r, \varphi)$. Within the strong radial confinement limit (narrow QR), the energy along radial direction becomes significant larger than that for SOI-R and for electrons winding the QR [14,18], thereof a perturbative treatment holds. By setting the radial variable to a fixed value $r=a$ (being a the QR radius) and then neglecting its derivatives, a pure azimuthal-angular effective one-dimensional (1D) Hamiltonian $H_{1D}(\varphi) = \langle R_o(a)|H'(a, \varphi)|R_o(a)\rangle$ had been deduced [9]

$$\hat{H}_{1D}(\varphi) = \frac{\hbar}{2}\left[\omega_o\left(-i\frac{\partial}{\partial\varphi} + \frac{\Phi}{\Phi_o}\right)^2 + \omega_R\left(\cos\varphi\sigma_x + \sin\varphi\sigma_y\right)\right.$$
$$\left.\times\left(-i\frac{\partial}{\partial\varphi} + \frac{\Phi}{\Phi_o}\right) - \frac{i\omega_R}{2}\left(\cos\varphi\sigma_y - \sin\varphi\sigma_x\right)\right], \tag{6}$$

being $|R_o(a)\rangle$ the eigenfunctions of the purely radial term $H_o(a)$ in the lowest radial mode; Φ the magnetic field flux; Φ_o the flux quanta e/hc and σ_i the corresponding Pauli matrixes, taking $i = x, y$. The stationary Pauli equation shall describe the electron spin dynamic in the closed QR, since (6) is a time independent Hamiltonian. The solutions can be cast as plane waves multiplied by the corresponding spinors in the form [9,14]