Physica E 73 (2015) 135–140

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Spin polarization of the asymmetric quantum point contact and conductance anomalies in the case of resonances

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HIGHLIGHTS

- Resonances substantially affect the spin polarization of the current.
- Localized spin–orbit interaction and resonances generate 0.5 conductance plateau.
- Significant spin polarization arises even in the one-electron approach.
- In the presence of resonances, the polarization increases due to the side voltage.
- We explain why 0.5 plateau appears only in the limited range of side gate values.

ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form
27 May 2015
Accepted 28 May 2015
Available online 1 June 2015

Keywords:
Quantum point contact
Conductance
Spin polarization
Rashba interaction
Lateral spin orbit coupling
Resonances

ABSTRACT

We study spin polarization and conductance of the asymmetric quantum point contact. We consider both Rashba coupling and lateral spin–orbit interaction induced by laterally asymmetric confinement potential. We show that in longitudinally symmetric quantum point contact, the spin polarization is not accompanied by the appearance of the conductance plateau at $0.5G_0$ ($G_0 = 2e^2/h$). In longitudinally asymmetric quantum point contact the above plateau arises due to the presence of resonant states within the using one-electron approximation. An explanation of the experimental fact that the plateau exists only for a limited range of variation of the gate voltage is given.

1. Introduction

Spintronics, in which widely used both charge and spin of electrons, is the subject of great interest in the last one or two decades. The use of the spin degrees of freedom opens up the possibility of creating of very small and extremely fast devices with low power consumption. The main goal of spintronics is to create efficient spin valve devices controlling electric and spin currents. Ferromagnetic materials embedded in the device structure are usually used as a source of polarized electrons and for detecting the spin polarization. The control of the spin polarization can be used both external and internal effective magnetic fields due to the spin–orbit interaction (SOI) of electrons. Because of the high miniaturization of modern electronic devices, the use of ferromagnetic contacts and external magnetic fields has many undesirable side effects. Considerable efforts have been made in the last decade to find ways to create and control a spin-polarized current by purely electrical methods, mainly by the SOI [1–4]. Symmetry features are very important for the SOI [5]. In particular, in the case of asymmetric confinement of a two-dimensional electron gas in the perpendicular direction, this contribution is known as the Rashba interaction [6–9]. In a laterally asymmetric quantum point contact (LAQPC), an additional contribution to the SOI arises due to the lateral spin–orbit coupling (LSOC). In quasi-one-dimensional quantum wires this contribution was considered [10–12] in the study of the separation of electrons with different spins along the edges of the channel. Recently, in experimental studies of conductance of the LAQPC in the absence of an external magnetic field, the conductance plateau at $G \approx 0.5G_0$ ($G_0 = 2e^2/h$) was found [13–17]. It is considered that the 0.5-structure is a testament to the high spin polarization of the current in the LAQPC [13,18,19]. However, we show [20] that this anomaly of the

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http://dx.doi.org/10.1016/j.physe.2015.05.032
1386-9477/

conductance may be due to multichannel interference even without taking into account the SOI. Note that the one-electron calculation of the spin polarization current considering the LSOC due to the asymmetry of the transverse confinement potential does not reproduce the 0.5-conductance plateau [21]. The conductance modeling within the nonequilibrium Green's function formalism in the case of the LAQPC showed [22,23] that almost complete spin polarization is achieved when the following conditions hold: (a) the presence of an asymmetry transverse confinement, (b) the existence of the LSOC, and (c) the presence of the strong electron–electron interaction [13,23,24]. The condition (c) seems to be insufficiently substantiated because the authors obtained the 0.5 plateau of the conductance curve by the adjustment of the electron–electron interaction strength [23,25].

In this paper, we once again consider the spin polarization taking into account the Rashba interaction and a LSOC which are localized in a LAQPC region. We show that the presence of resonance electronic states associated with the longitudinal asymmetry of a QPC allows us to obtain a high degree of spin polarization and also the 0.5 conductance plateau. We obtained a nonmonotonic dependence of the maximum spin polarization on the potential difference between the side gates. This explains the experimentally observed [14–16,24] disappearance of the 0.5 structure with increasing of the asymmetry of the lateral confinement.

The paper is organized as follows. In Section 2 the model and the calculation method of the spin-dependent conductance are described. Spin polarization and conductance of the longitudinally symmetric contact are discussed in Section 3. The effect of the violation of the longitudinal symmetry on spin polarization and conductance is investigated in Section 4. The obtained results are summarized in Section 5.

2. Model and calculation method

We consider an infinite along the x-axis quasi-one-dimensional quantum wire in the plane xy, with a LAQPC which is localized at $|x|\leq an_v$ where a is the lattice constant of the square lattice. Suppose that the Rashba interaction and LSOC are generated by perpendicular (along the z-axis) and lateral (along the y-axis), respectively, external gate voltage, and are localized in the LAQPC region. In the tight-binding approach, the Hamiltonian of the system reads

$$\hat{H} = \hat{H}_0 + \hat{H}_R + \hat{H}_{so} + \hat{W} \tag{1}$$

where

$$\hat{H}_0 = \epsilon \sum_{\sigma=1}^{2} \sum_{n=-\infty}^{+\infty} \sum_{m=1}^{M} \hat{C}^{\dagger}_{n,m,\sigma} \hat{C}_{n,m,\sigma} - t \sum_{\sigma=1}^{2} \sum_{n=-\infty}^{+\infty} \left[\sum_{m=1}^{M} (\hat{C}^{\dagger}_{n+1,m,\sigma} \hat{C}_{n,m,\sigma} + \text{H. c. }) + \sum_{m=1}^{M-1} (\hat{C}^{\dagger}_{n,m+1,\sigma} \hat{C}_{n,m,\sigma} + \text{H. c. }) \right]. \tag{2}$$

Here $\hat{C}^{\dagger}_{n,m,\sigma}$ and $\hat{C}_{n,m,\sigma}$ are creation and annihilation operators of an electron at the site (n,m) with spin σ ($\sigma=1$ and $\sigma=2$ corresponds to $(1, 0)^T$ and $(0, 1)^T$, respectively), and M is the number of atomic layers along the axis y. We assume that the energy ϵ at the site and the hopping integral $t > 0$ do not depend on the site number. Further, ϵ is taken as the energy origin.

The Hermitian Rashba term [20] has the form

$$\hat{H}_R = \sum_{\sigma,\sigma'} \sum_{n,m} \left[\frac{t_{so}(n+1) + t_{so}(n)}{2} (\hat{C}^{\dagger}_{n+1,m,\sigma} (i\sigma_y)_{\sigma',\sigma} \hat{C}_{n,m,\sigma'} + \text{H. c. }) + t_{so}(n) (\hat{C}^{\dagger}_{n,m+1,\sigma} (i\sigma_x)_{\sigma',\sigma} \hat{C}_{n,m,\sigma'} + \text{H. c. }) \right] \tag{3}$$

where $t_{so} = \hbar\alpha/2a$ for $|n| \leq n_v - 1$ and $t_{so} = 0$ otherwise, α is the Rashba parameter, and $\hat{\boldsymbol{\sigma}} = (\hat{\sigma}_x, \hat{\sigma}_y, \hat{\sigma}_z)$ are Pauli matrices.

In the tight-binding approach, the contribution to the Hamiltonian corresponding to LSOC reads [20]

$$\hat{H}_{so} = -\frac{\tau_{so}}{2} \left\{ \sum_{\sigma,\sigma'} \sum_{n,m} [V'_y(n+1, m)(i\sigma_z)_{\sigma',\sigma} \hat{C}^{\dagger}_{n+1,m,\sigma} \hat{C}_{n,m,\sigma'} + V'_y(n, m)(i\sigma_z)^*_{\sigma',\sigma} \hat{C}^{\dagger}_{n,m,\sigma'} \hat{C}_{n+1,m,\sigma} - V'_x(n, m+1)(i\sigma_z)_{\sigma',\sigma} \hat{C}^{\dagger}_{n,m+1,\sigma} \hat{C}_{n,m,\sigma'} - V'_x(n, m)(i\sigma_z)^*_{\sigma',\sigma} \hat{C}^{\dagger}_{n,m,\sigma'} \hat{C}_{n,m+1,\sigma}] + \text{H. c.} \right\} \tag{4}$$

where $\tau_{so} = \hbar\beta/2a$ (β is a LSOC parameter depending on contact material). The term corresponding to the side gates potential has the form

$$\hat{W} = \sum_{\sigma} \sum_{n,m} V(n, m) \hat{C}^{\dagger}_{n,m,\sigma} \hat{C}_{n,m,\sigma'}. \tag{5}$$

Values of the potential $V(n, m)$ and its partial derivatives $V'_x(n, m)$ and $V'_y(n, m)$ at the site (n,m) in our model are determined by the expression [20]

$$V(x, y;\, V_g, \Delta V) = V^{(s)}(x, y;\, V_g) + V^{(a)}(x, y;\, \Delta V) \tag{6}$$

where V_g is the potential in the QPC and ΔV corresponds to the side gate. The potential $V^{(s)}(x, y;\, V_g)$ is even in y, it is different from zero only in the region $|x| \leq an_v$, and it is defined by a function of the saddle type [26,27,20]. We distinguish, as in [27], three regions in the LAQPC with the help of parameters X_p and L_p ($p = 1, 2, 3$); the region number is $N(x) = p$ if $|x - X_p| \leq L_p/2$. According to [27] we put

$$V^{(s)}(x, y;\, V_g) = \delta_{N(x),2} \eta V_g [1 + \cos(2\pi(x - X_N)/L_N)] + d_N [U^{(+)}(x, y) + U^{(-)}(x, y)] \tag{7}$$

where

$$U^{(\pm)}(x, y) = \frac{1}{a^2}(y - Y_{\pm}(x))^2 \Theta[\pm(y - Y_{\pm}(x))], \quad Y_{\pm}(x)) = y_0 \pm \frac{L_y}{4}[1 - \cos(2\pi(x - X_N)/L_N)]. \tag{8}$$

Here $\Theta(y)$ is the Heaviside function ($\Theta(y) = 1$ for $y > 0$ and $\Theta(y) = 0$ otherwise) and $y_0 = a(M+1)/2$ is the coordinate of the middle layer. Parameters L_N, X_N, d_N and η are the same as in [20,27].

Asymmetric with respect to y contribution ΔV by analogy with the condenser field is modeled by the expression [20]

$$V^{(a)}(x, y;\, \Delta V) = \gamma\left(\frac{x}{a}\right) \frac{y - y_0}{a} \Delta V \tag{9}$$

where $\gamma(n) = \gamma_0$ for $|x| \leq an_v$ and $\gamma(n) = 0$ otherwise. The quantity γ_0 depends on the materials of the device and geometry of the electrodes.

Denote by $t^{\sigma\sigma'}_{l,l'}$ the amplitudes of an electron scattering from the