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Spin polarization and conductance of the laterally asymmetric quantum point contact

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ABSTRACT

We calculate conductance and polarization for the laterally asymmetric quantum point contact. We consider both Rashba coupling and spin–orbit interaction induced by asymmetric lateral confinement, without external magnetic field. We show that a conductance plateau may appear at $0.5G_0$ ($G_0 = 2e^2/h$), without Rashba coupling and lateral spin–orbit interaction. For a spin-polarized injected current, the lateral spin–orbit interaction gives additional control of the conductance by varying the side gates potential. For unpolarized electrons, the spin polarization arises along all coordinate axes. There is a possibility of switching of spin polarization by the gates potential.

1. Introduction

A characteristic feature of the ballistic electron transport in quasi-one-dimensional structures is the appearance of a plateau at $G = nG_0$, $n = 1, 2, \ldots$ where $G_0 = 2e^2/h$, e is the electron charge, and h is the Planck constant. This well-known phenomenon is explained in the one-electron Landauer–Büttiker approach [1]. However, there is a structure of the conductance arising in a number of experiments which has no commonly accepted explanation. This applies both to the 0.7-structure that arises when the conductance of the symmetric channel is measured (see, for example, [2] and also [3] and other articles in this thematic journal issue), and to the characteristics of the conductance of the laterally asymmetric quantum point contact (LA QPC) [4–9]. Despite the lack of consensus on the mechanism of 0.7-anomaly, it is generally accepted that many-electron effects are at the basis of this phenomenon. Nevertheless, as shown in [10], in experiments where due to technological or other reasons the longitudinal symmetry of the nanocontact is broken, a conductance plateau of the one-electron nature may arise in the region that is characteristic for a true 0.7-structure.

To explain the conductance anomalies in the LA QPC, the spin polarization of tunneling electrons is often used now. This is largely due to the finding of the mentioned features at $G \approx 0.5G_0$ and such localization of the conductance plateau was recognized as the experimental evidence for the existence of the spin polarization of the current in the QPC generated by the lateral spin–orbit coupling (LSOC) due to the lateral asymmetry of the confinement potential [6,9,13]. Despite the great attractiveness of the idea of creating a spin-polarized current by methods of nonmagnetic spintronics [14], it should be noted that the experimental manifestation of the 0.5-structure is not direct evidence of the existence of spin polarization. The available theoretical studies on this topic are scarce and they often contain hypothetical statements (a very strong electron–electron interaction in [14]) or an incorrect approach (a non-Hermitian Rashba operator in [15]).

The use of the spin polarization model meets with some difficulties in explaining the experimental results, such as the features of the conductance differing from the 0.5 one, the disappearance of the effect with the increase of the potential asymmetry, and the resonance shape of the observed features [4–6].

The objective of this paper is to study in detail the influence of the asymmetric lateral confinement potential of the QPC with associated spin–orbit interaction and Rashba interaction on both the conductance and spin polarization in the QPC. The results were obtained within the Landauer–Büttiker approach by solving numerically the Lippmann–Schwinger equation. The paper is organized as follows. In Section 2 we present the model and the calculation method of the spin-dependent conductance. In Section 3 we consider the conductance in the absence of spin–orbit interactions. The influence of spin–orbit interactions on the electron transport is investigated in Section 4. Section 5 contains a study of the spin polarization of the initially unpolarized electron current which induced by the LSOC and Rashba effect. In contrast to [16], we consider both magnetic and non-magnetic contacts. In conclusion, we briefly discuss the results and their possible application.

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2. Model and calculating method

We consider a quasi-one-dimensional electron system with a local Rashba interaction in the region $|x| \le an_v$ where a is the lattice constant, and the additional LSOC induced by the lateral asymmetry of the confinement side gates potential. We assume that our system is infinite in the x direction and is described by the tight-binding Hamiltonian

$$\widehat{H} = \widehat{H}_0 + \widehat{H}_R + \widehat{H}_{so} + \widehat{V} \tag{1}$$

where

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

Here $\widehat{C}^{\dagger}_{n,m,\sigma}$ ($\widehat{C}_{n,m,\sigma}$) are the creation (annihilation) operators at the site (n,m) with the spin state σ ($\sigma = 1$ corresponds to $(1,0)^T$ and $\sigma = 2$ corresponds to $(0,1)^T$), and M is the number of transverse atomic layers of the system along y. Energy ϵ is on-site energy and $t > 0$ is hopping integral between the nearest neighbors. The correct Hermitian form of the Rashba term in the continuous case is [17–19]

$$\widehat{H}_R = \alpha(x)(\widehat{\sigma}_x \widehat{p}_y - \widehat{\sigma}_y \widehat{p}_x) + \frac{\hbar}{2}(i\widehat{\sigma}_y)\alpha'(x) \tag{3}$$

where $\widehat{\mathbf{p}} = (\widehat{p}_x, \widehat{p}_y, 0)$ is the electron momentum, $\widehat{\sigma} = (\widehat{\sigma}_x, \widehat{\sigma}_y, \widehat{\sigma}_z)$ are the Pauli matrices and $\alpha(x)$ is a Rashba parameter. However, in the tight-binding approximation for the local Rashba interaction, similar to the spatially homogeneous case, the expression $\widehat{H}_R = \alpha(x)(\widehat{\sigma}_x \widehat{p}_y - \widehat{\sigma}_y \widehat{p}_x)$ where $\alpha(x)$ is not equal to zero only in the region of spin–orbit interaction, is often used [15,16,22,23]. This operator is not Hermitian. We use in (1) the symmetrized Hermitian expression of the form

$$\widehat{H}_R = \sum_{\sigma,\sigma'} \sum_{n,m} \left[\frac{t_{so}(n+1) + t_{so}(n)}{2} \left(\widehat{C}^{\dagger}_{n+1,m,\sigma} (i\sigma_y)_{\sigma',\sigma} \widehat{C}_{n,m,\sigma'} + \text{H.c.} \right) + t_{so}(n) \left(\widehat{C}^{\dagger}_{n,m+1,\sigma} (i\sigma_x)_{\sigma',\sigma} \widehat{C}_{n,m,\sigma'}, + \text{H.c.} \right) \right] \tag{4}$$

where

$$t_{so}(n) = \begin{cases} \hbar\alpha/2a, & |n| \leqslant n_v - 1, \\ 0, & \text{elsewhere.} \end{cases} \tag{5}$$

Formula (4) comprises additional components, as compared with the expression obtained from the spatially uniform Rashba operator by replacing α with $\alpha(n)$. The inclusion of these terms is important to take into account the conservation of charge in the region $|x| \leqslant an_v$, especially in the case where the spin–orbit interaction affects a small number of lattice sites, or in studies of resonant states having, as known, small imaginary parts. The operator corresponding to the gates potential has the form

$$\widehat{V} = \sum_{\sigma} \sum_{n,m} V(n,m) \widehat{C}^{\dagger}_{n,m,\sigma} \widehat{C}_{n,m,\sigma} \tag{6}$$

where

$$V(x,y) = V^{(s)}(x,y;V_g) + V^{(a)}(x,y;\Delta V), \tag{7}$$

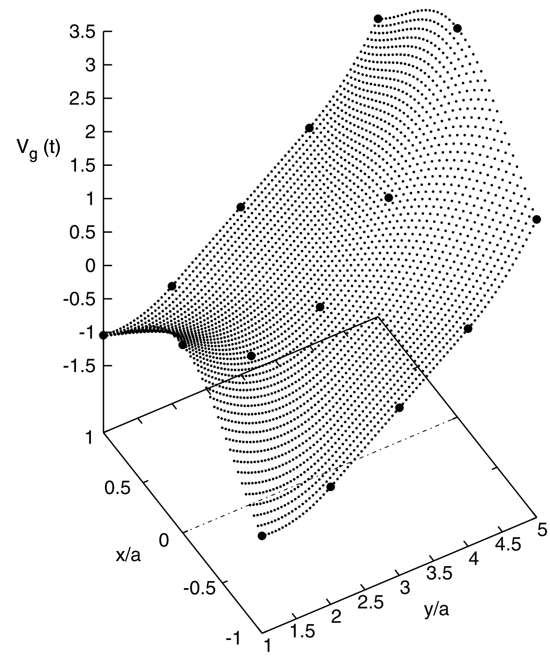

Fig. 1. The potential of the LA QPC ($\Delta V = 0.75t/\gamma_0$).

V_g specifies the magnitude of the contact barrier, and ΔV describes the potential difference of the side gates. The function $V^{(s)}(x,y;V_g)$ is even in y; it coincides with the potential for the longitudinally symmetric case [10] having the form

$$V^{(s)}(x,y;V_g) = cV_g\left[1 + \cos(2\pi x/L_x)\right] + d\left[U^{(+)}(x,y) + U^{(-)}(x,y)\right] \tag{8}$$

where

$$U^{(\pm)}(x,y) = \frac{1}{a^2}\left(y - Y_\pm(x)\right)^2 \Theta\left[\pm\left(y - Y_\pm(x)\right)\right],$$
$$Y_\pm(x) = y_0 \pm \frac{L_y}{4}\left[1 - \cos(2\pi x/L_x)\right]. \tag{9}$$

Here $\Theta(y) = 1$ for $y > 0$ and $\Theta(y) = 0$ otherwise, $y_0 = a(M+1)/2$ is the coordinate of the middle layer, and the parameters $L_x = 4a$ and $L_y = (M-1)a$ define the region where the potential does not vanish: $|x| \leqslant L_x/2$, $|y - y_0| \leqslant L_y/2$. As in [10], we put $c = 4.165$ and $d = 0.45t$. The asymmetric in y contribution to the gates potential, by analogy with the field of the capacitor, is modeled by

$$V^{(a)}(x,y;\Delta V) = \gamma\left(\frac{x}{a}\right)\frac{y - y_0}{a}\Delta V, \tag{10}$$

where

$$\gamma(n) = \begin{cases} \gamma_0, & |n| \leqslant n_v, \\ 0, & \text{elsewhere.} \end{cases} \tag{11}$$

The quantity γ_0 depends on the contact material and the geometry of the electrodes. In contrast to the potential used in [15], we obtain the symmetric case passing to the limit as $\Delta V \to 0$. The plot of the potential (7) for $\Delta V = 0.75t/\gamma_0$ is displayed in Fig. 1.

The lateral spin–orbit interaction is given by the Hermitian operator [20,21]

$$\widehat{H}_{so} = \beta\widehat{\sigma}_z\left(V'_x(x,y)\widehat{p}_y - V'_y(x,y)\widehat{p}_x\right) \tag{12}$$

where β is the intrinsic LSOC parameter. Within the difference approximation, the Hermitian operator corresponding to (12) has the form