J Supercond Nov Magn (2013) 26:2209–2212
DOI 10.1007/s10948-012-1430-7

ORIGINAL PAPER

Conductance and Thermopower of a Quantum Dot with Fano–Rashba Effect

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Received: 15 November 2011 / Accepted: 10 January 2012 / Published online: 29 January 2012

Abstract We investigate the conductance and thermopower of a Rashba quantum dot coupled to ferromagnetic leads. We show that the interference of localized electron states with resonant electron states leads to the appearance of the Fano–Rashba effect. This effect occurs due to the interference of bound levels of spin-polarized electrons with the continuum of electronic states with an opposite spin polarization. We obtain an important enhancement of the thermopower due to the Fano–Rashba effect.

Keywords Quantum dot · Conductance · Thermopower

1 Introduction

Recently, there has been much interest in understanding the manner in which the unique properties of nanostructures may be exploited in spintronic devices, which utilize the spin degree of freedom of the electron as the basis of their operation [1–4]. The main challenge in the field of spintronics is to achieve the injection, modulation, and detection of electron spin in nanometer scale structures. In 1990, Datta and Das [1] proposed a spin transistor, based on the electron spin precession controlled by an external electric field via spin–orbit coupling. In this proposal, ferromagnetic contacts were used as spin-polarized source and detector. A natural feature of these devices is the direct connection between their conductance and their quantum-mechanical transmission properties, which may allow their use as an all-electrical means for generating and detecting spin polarized distributions of carriers.

Quantum dots (QDs) are very promising nanostructures due to their physical properties and applications as electronic devices. These nanostructures are small semiconductor or metal structures in which electrons are confined in all three dimensions [5]. They are characterized by the discreteness of energy and charge, and for this reason also QDs are often called as “artificial atoms.” Enforcing this analogy, Fano [6] and Dicke effects [7] were also found to be present in QD configurations. On the other hand, Song et al. [2] described how a spin filter may be achieved in open QD systems by exploiting Fano resonances that occur in their transmission characteristic. In a QD in which the spin degeneracy of carrier is lifted, they showed that the Fano effect may be used as an effective means to generate spin polarization of transmitted carriers and that electrical detection of the resulting polarization should be possible.

The Rashba spin–orbit interaction arises from a structure inversion asymmetry resulting from the asymmetry of the in-plane confining potential in semiconductor heterostructures [8]. On the other hand, the Fano effect arises from the interference between a localized state and the continuum. In general, the condition for the Fano effect is the presence of two scattering channels at least: the discrete level and continuum band. The Fano effect in electronic transport through a single-electron transistor allows to alter the interference between the two paths by changing the voltages on various gates. Kobayashi et al. [6] reported the first tunable Fano ex-

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periment in which a well-defined Fano system is realized in an Aharonov–Bohm ring with a QD embedded in one of its arms. Recently, Fano-type resonances due to the interaction of electron states with opposite spin orientation have been studied [9–11].

The thermoelectric properties of material is a relevant issue in condensed matter physics. Usually they are studied in open system when the steady-state current vanishes. A relevant quantity to study is the thermoelectric power or thermopower that it is given by the ratio between the voltage induced when a difference of temperature is applied between two contacts ($S=-\Delta V/\Delta T$).

Here, we investigate the conductance and thermopower of a Rashba quantum dot coupled to ferromagnetic leads. The aim of our study is to probe the role of Fano–Rashba effect in thermoelectric effects of the quantum dot device. We show that the interference of localized electron states with resonant electron states leads to the appearance of the Fano–Rashba effect. This effect occurs due to the interference of bound levels of spin-polarized electrons with the continuum of electronic states with an opposite spin polarization. We obtain an important enhancement of the thermopower due to the Fano–Rashba effect.

2 Model

The system under consideration is formed by one QD connected to two ferromagnetic leads, as shown schematically in Fig. 1. The full system is modeled by the noninteracting Anderson Hamiltonian, namely $H=H_L+H_D+H_I$ with

$$H_L=\sum_{i,\sigma=\uparrow\downarrow}\varepsilon_\sigma c_{i\sigma}^\dagger c_{i\sigma}-v\sum_{\langle i\neq j\rangle,\sigma=\uparrow\downarrow}\left(c_{i\sigma}^\dagger c_{j\sigma}+c_{j\sigma}^\dagger c_{i\sigma}\right),$$

$$H_D=\sum_{\sigma=\uparrow\downarrow}\varepsilon_{0\sigma}d_\sigma^\dagger d_\sigma,$$

$$H_I=-V_0\sum_{\sigma=\uparrow\downarrow}\left(d_\sigma^\dagger c_{1\sigma}+c_{1\sigma}^\dagger d_\sigma+d_\sigma^\dagger c_{-1\sigma}+c_{-1\sigma}^\dagger d_\sigma\right) \quad (1)$$
$$-\sum_{\sigma,\sigma'=\uparrow\downarrow}t_{so}[\sigma_x]_{\sigma\sigma'}\left(d_\sigma^\dagger c_{1\sigma'}+c_{1\sigma}^\dagger d_{\sigma'}\right)$$
$$-\sum_{\sigma,\sigma'=\uparrow\downarrow}t_{so}[\sigma_x]_{\sigma\sigma'}\left(d_\sigma^\dagger c_{-1\sigma'}+c_{-1\sigma}^\dagger d_{\sigma'}\right),$$

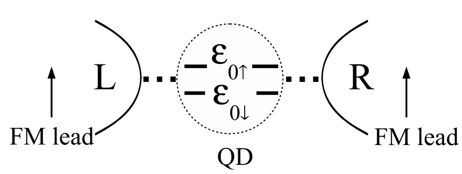

Fig. 1 Schematic view of a QD connected to two ferromagnetic leads

where $c_{i\sigma}^\dagger$ is the creation operator of an electron at site i of the leads in the σ spin state ($\sigma=\uparrow,\downarrow$), and $d_\sigma^\dagger$ is the corresponding operator of an electron with spin σ of the QD. Moreover, $n_{d\sigma}=d_\sigma^\dagger d_\sigma$. Here, ε_0 is the energy level of the QD and V_0 is the coupling between the QD and the leads. The hopping in the wire is $-v$ and the potential in the ferromagnetic leads to be set as $\varepsilon_\sigma=\Delta[\sigma_z]_{\sigma\sigma}$, where $\vec{\sigma}=(\sigma_x,\sigma_y,\sigma_z)$ is the Pauli matrix vector.

The stationary states of the Hamiltonian H can be written as

$$|\psi_\sigma\rangle=\sum_{j=-\infty,\,j\neq 0}^{\infty}a_{j\sigma}|j\rangle+b_\sigma|0\rangle, \quad (2)$$

where $a_{j\sigma}$ and b_σ are the probabilities amplitudes to find the electron at the site j or at the QD, respectively, with energy at infinite $\omega=\varepsilon_\uparrow-2v\cos k$ or $\omega=\varepsilon_\downarrow-2v\cosh\kappa$. These amplitudes obey the following linear difference equations:

$$(\omega-\varepsilon_\sigma)a_{j\sigma}=-v(a_{j+1,\sigma}+a_{j-1,\sigma}),\quad j\neq -1,0,1, \quad (3a)$$

$$(\omega-\varepsilon_\sigma)a_{-1\sigma}=-va_{-2\sigma}-V_0b_\sigma-t_{so}[\sigma_x]_{\sigma\overline{\sigma}}b_{\overline{\sigma}}, \quad (3b)$$

$$(\omega-\varepsilon_\sigma)a_{1\sigma}=-va_{2\sigma}-V_0b_\sigma-t_{so}[\sigma_x]_{\sigma\overline{\sigma}}b_{\overline{\sigma}}, \quad (3c)$$

$$(\omega-\widetilde{\varepsilon}_{0\sigma})b_\sigma=-V_0(a_{1,\sigma}+a_{-1,\sigma})$$
$$-t_{so}[\sigma_x]_{\sigma\overline{\sigma}}(a_{1,\overline{\sigma}}+a_{-1,\overline{\sigma}}), \quad (3d)$$

where $\widetilde{\varepsilon}_{0\sigma}$ is the renormalized energy level of the QD with spin σ, $\widetilde{\varepsilon}_{0\uparrow}=\varepsilon_0+\mu B$ and $\widetilde{\varepsilon}_{0\downarrow}=\varepsilon_0-\mu B$. In order to study the solutions of the above equations, we assume that the electrons are described by a plane wave with unitary incident amplitude, r and t being the reflection and transmission amplitudes. Thus, we get

$$a_{j\uparrow}=e^{ikj}+re^{-ikj},\quad j<0, \quad (4a)$$

$$a_{j\uparrow}=te^{ikj},\quad j>0, \quad (4b)$$

$$a_{j\downarrow}=Ce^{\kappa j},\quad j<0, \quad (4c)$$

$$a_{j\downarrow}=De^{-\kappa j},\quad j>0. \quad (4d)$$

Inserting this solution in the equation of motion, we get a inhomogeneous system of linear equations for t, r, C, D, and a_j, leading to the following expression for the transmission amplitude t. From the transmission amplitude, we obtain the transmission probability as $T_e(\omega)=|t|^2$.

The electronic conductance and thermopower can be obtained from the integral ($\mathcal{I}_n$):

$$G(\mu,T)=\frac{e^2}{h}\mathcal{I}_0(\mu,T), \quad (5)$$

$$S(\mu,T)=\frac{1}{qT}\frac{\mathcal{I}_1(\mu,T)}{\mathcal{I}_0(\mu,T)}, \quad (6)$$

where f is the Fermi–Dirac distribution, h is the Planck constant and $T_e(\omega)$ is the transmission probability, given by [11],

$$T_e(\omega) = \frac{1}{1 + \left[\cot k(\omega) + \frac{N(\omega)}{4D(\omega)\sin k(\omega)}\right]^2}, \tag{7}$$

here

$$N(\omega) = t_{so}^2 \omega_\downarrow + V_0^2 \omega_\uparrow + \frac{e^\kappa}{4} \omega_\downarrow \omega_\uparrow, \tag{8}$$

$$D(\omega) = \frac{e^\kappa}{4}\left[t_{so}^2 \omega_\uparrow + V_0^2 \omega_\downarrow\right] + \left(t_{so}^2 - V_0^2\right)^2 \tag{9}$$

with $\omega_\uparrow = \omega - \varepsilon_{0\uparrow}$ and $\omega_\downarrow = \omega - \varepsilon_{0\downarrow}$.

3 Result

Figure 2 displays the spin-dependent linear conductance versus the gate voltage ε_0 for different values of the spin-orbit coupling at fixed magnetic field. As expected, the linear conductance shows two Fano resonances and a Fano antiresonance as a function of the Fermi energy. The antiresonance in the conductance occurs at $\varepsilon_0 = \xi_- + \mu B \alpha_+/\alpha_-$. For small values of magnetic field ($\mu B/v \ll 1$), the conductance of the system can be written approximately as a convolution of a Fano line shape and a Breit–Wigner line shape. This is

$$G_\uparrow \approx \frac{e^2}{h}\left[\frac{(\varepsilon_- + q)^2}{\varepsilon_-^2 + 1} \cdot \frac{1}{\varepsilon_+^2 + 1}\right], \tag{10}$$

where q is the Fano parameter characterizing line shape asymmetry ($q = \alpha_+/\alpha_-$) and $\varepsilon_\pm$ are the detuning parameters measuring the energy ε_0 from the resonance centers and normalized by the resonance half-width $\varepsilon_- = (\varepsilon_0 - \xi_-)/\mu B$, $\varepsilon_+ = (\varepsilon_0 - \xi_+)/(2\alpha_- \sin k_F)$.

Figure 3 displays the spin-dependent thermopower as a function of the gate voltage ε_0 for the same parameters of Fig. 2. We note that large values of thermopower is obtained in the Fano-line-shape regime, and very small value of it is obtained in the BreitWigner-shape regime. These results are similar to the thermopower obtained by Liu and Yang [12] in a double quantum-dot molecular junction. The common element in both cases is the Fano effect that produces antiresonances in the transmission probability. In our work, the Rashba spin–orbit coupling opens a new channel to the conduction that interferes with the direct channel, the key ingredient to produce the destructive interference of the Fano effect. The electron with spin up can tunnel directly through the level $\widetilde{\varepsilon}_{0\uparrow}$ without spin-flip processes or also can tunnel indirectly through the level $\widetilde{\varepsilon}_{0\uparrow}$ with two spin-flip processes. The interference between the two tunneling paths gives rise the Fano–Rashba effect.

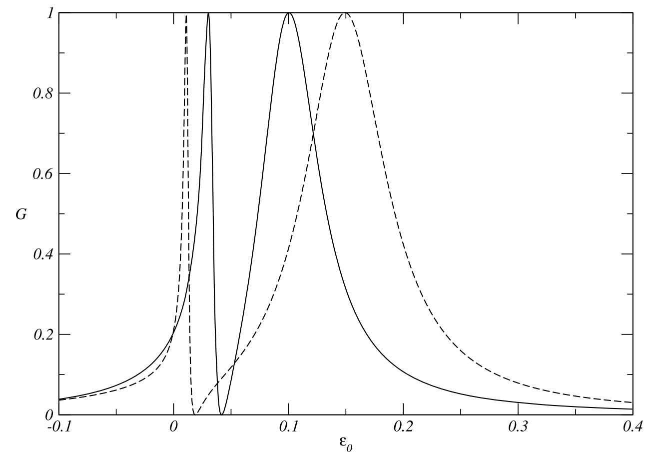

Fig. 2 Spin-dependent conductance as a function of the gate voltage ε_0 for different values of the spin–orbit coupling, $t_{so} = 0.04$ (*solid line*) and $t_{so} = 0.08$ (*dashed line*) when $\mu B/2v = 0.003$ and $T = 1.0$ mK

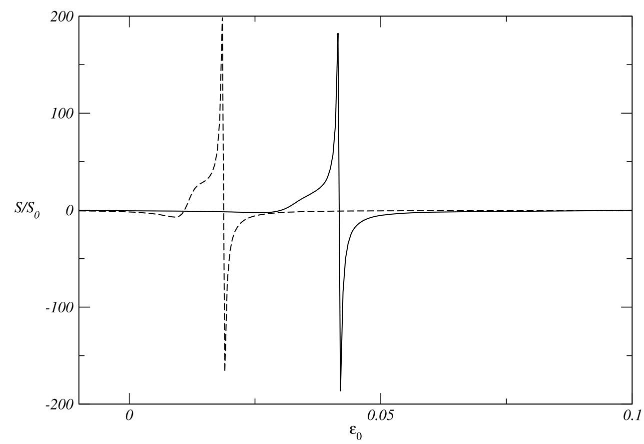

Fig. 3 Spin-dependent thermopower as a function of the gate voltage ε_0 for different values of the spin–orbit coupling, $t_{so} = 0.04$ (*solid line*) and $t_{so} = 0.08$ (*dashed line*) when $\mu B/2v = 0.003$ and $T = 1.0$ mK

4 Summary

In this work, we investigate the conductance and thermopower of a Rashba quantum dot coupled to ferromagnetic leads. We show that the interference of localized electron states with resonant electron states leads to the appearance of the Fano–Rashba effect. This effect occurs due to the interference of bound levels of spin-polarized electrons with the continuum of electronic states with an opposite spin polarization. We obtain an important enhancement of the thermopower due to the Fano–Rashba effect.

Acknowledgements P.A.O. acknowledge to FONDECYT grant number 1100560. R.P.A.L. acknowledge financial support by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and PRONEX/FAPEAL.

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