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Spin-flip effects on Andreev reflection process

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Abstract

We investigate the nonequilibrium transport properties of a quantum dot in the normal-metal and superconductor hybrid system, where the Andreev reflection plays the important role. The electron spin-flip effect in quantum dot is explicitly taken into account. By using the nonequilibrium Green's function (NEGF) approach, we first give a general current formula which is valid for any bias and temperature, then we discuss the linear conductance in terms of the local density of states. The various resonant peaks appear for the different spin-flip strengths in quantum dot. Finally, we numerically calculate the current-bias characteristic when the bias is smaller than the superconductor gap.

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Keywords: Andreev reflection; Spin-flip; Quantum dot

In the last decade, the quantum transport properties of mesoscopic hybrid normal metal (N)–superconductor (S) systems have been widely studied [1–4] theoretically. The key physics is so-called Andreev reflection (AR) [1] due to the appearance of a new energy scale—superconductor energy gap Δ. The Andreev reflection means an incoming electron from normal side is reflected as a hole at the N/S interface, thereby transferring a Cooper pair into the superconducting condensate. Many works have been done on the subject that the electron resonant tunneling through a quantum dot (QD), either superconducting QD (SQD) or normal QD (NQD), connected to two electrodes, including a variety of hybrid structures such as S–SQD–S, N–SQD–N, S–NQD–S, N–NQD–S, etc. As for the N–NQD–S structures (simply by N–QD–S hereafter), Beenakker [1] presented a general multichannel S-matrix description and predicted the resonant Andreev tunneling for a single-level QD in the zero-bias limit. Later, Claughton et al. generalized Beenakker's theory to the finite bias case and found that the differential con-

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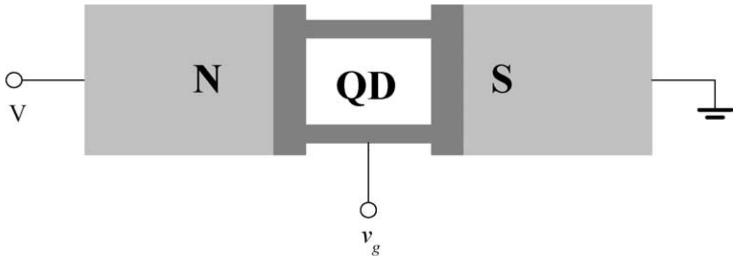

Fig. 1. Schematic plot of the system considered in this work.

ductance resonances are strongly suppressed in the weak-coupling limit [2]. Sun et al. investigated the electron tunneling through a multiple-level QD N–QD–S structure [5], the different kinds of resonant behaviors in the current versus the gate voltage were found. Fazio et al. investigated the resonant Andreev tunneling through a strong interacting QD in a N–QD–S structure, discussed how the Kondo effect can influence the two-particle tunneling, and obtained an enhancement of the Kondo anomaly in the I–V curves due to the presence of a superconducting electrode [6].

Very recently, the spin-dependent transport phenomena have attracted much attention and formed a new research field-spintronics. This is because spin-based electronic devices have many advantages including the longer coherent lifetime for the spin of electron, faster data proceeding speed, and less electric power consumption [7]. A number of spin-related phenomena in quantum dots, including spin degeneracy, exchange interaction, spin blockade, and Kondo effect, have been observed [8–13]. Since a quantum dot is inevitably affected by its environments, the presence of hyperfine interaction, spin-orbital interaction and magnetic impurities may cause to the spin-flip [14] of electrons in quantum dot. In particular, as pointed by Loss [15], the hyperfine interaction becomes more important in the materials such as GaAs, (Ga, Al)As and InAs. In this Letter, we will address the nonequilibrium Andreev transport properties of a QD in hybrid NS systems. Especially, the spin-flip interaction in QD is taken into account. This system is shown schematically in Fig. 1. The chemical potential of S is set to zero. QD is designed to provide a link between N and S, so that the AR can take place through discrete energy states of QD.

The Hamiltonian of the N–QD–S system is given by:

$$H = H_N + H_S + H_D + H_T, \tag{1}$$

where

$$H_N = \sum_{k,\sigma} \epsilon_k C^+_{k\sigma} C_{k\sigma}, \tag{2}$$

$$H_S = \sum_{q,\sigma} \epsilon_q C^+_{q\sigma} C_{q\sigma} + \sum_q \left(\Delta C^+_{q\uparrow} C^+_{-q\downarrow} + \Delta C_{-q\downarrow} C_{q\uparrow}\right), \tag{3}$$

$$H_D = \sum_\sigma \epsilon_0 d^+_\sigma d_\sigma + r\left(d^+_\uparrow d_\downarrow + d^+_\downarrow d_\uparrow\right), \tag{4}$$

$$H_T = \sum_{k,\sigma} \left[t_N C^+_{k\sigma} d_\sigma + t^*_N d^+_\sigma C_{k\sigma}\right] + \sum_{q,\sigma} \left[t_S C^+_{q\sigma} d_\sigma + t^*_S d^+_\sigma C_{q\sigma}\right]. \tag{5}$$

Here, H_N describes the noninteracting electrons in the left normal-metal lead, $C^+_{k\sigma}$ ($C_{k\sigma}$) are the creation (annihilation) operators of the electron in the left lead, $\epsilon_k = \epsilon^0_k + qV$, and V is the voltage of the left lead. H_S is the Hamiltonian of the right superconducting lead with the chemical potential fixed to zero as the ground, while Δ the pair potential (sometimes called the gap function). H_D describes the quantum dot, here we have applied a gate voltage which controls the energy level of the dot so that $\epsilon_0 = \epsilon^{(0)}_0 + qv_g$. Without loss of generality, we set $\epsilon^{(0)}_0 = 0$. The second term in H_D is used to describe the spin-flip effect [16–18] in the quantum dot, which may