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Anti-bias voltage electron-Kondo transport in a quantum dot device driven by a graphene sheet

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ABSTRACT

We theoretically investigate the manipulation of electron-Kondo transport through a single-quantum dot (QD) two-electrode device by introducing a side-coupled graphene sheet. It is shown that with increase of coupling strength between the QD and the zero-potential graphene sheet, the anti-bias voltage capability of the QD–electrode Kondo resonance is improved obviously. This causes a high-conductance QD–electrode channel to be opened up for electron transport within a wide bias voltage range. Moreover, the conductance/current of the Kondo channel can be accurately controlled by adjusting the potential of the graphene sheet. These results may be useful for the observation of nonequilibrium Kondo effect and the design of high-conductance control device.

1. Introduction

Very recently, quantum dot (QD)–graphene composites have been successfully fabricated [1–4]. Graphene [5,6], a single-layer two-dimensional material, has high electron conductivity and mobility, which are very useful properties in nanotechnology. However, the fact of zero-bandgap limits its applications in nanoelectronics because a finite bandgap is an essential expectation for the "on/off" operations in the electron devices. In contrast, semiconducting QD has extensive applications [7–10] based on its special quantum size effects and discrete energy spectrums. Naturally, the QD–graphene composite is a good candidate since it combines the advantages of two materials. Therefore, it is necessary to known precisely the QD–graphene interplay influence on electron transport behaviors in various QD–graphene composite systems.

In some typical QD–electrode devices [11–15], The Kondo resonance provides an excellent channel to electron transport through the QD from the external electrodes in the low temperature. Conductance of the Kondo channel can reach a unitary limit, i.e., $G = 2e^2/h$. However, this Kondo channel is sensitive exceedingly to the bias voltage V across the QD. For a small bias voltage, its conductance falls off with V^2 because the bias voltage opens up a phase space for non-Kondo transitions, which leads to a powerful suppression of the Kondo resonance [16,17]. Therefore, the improvement of anti-bias voltage capability of the Kondo resonance should be an important and interesting topic in nanoelectronics since it affects the conductivity of the QD devices. However, to our knowledge, less attention has been paid to it till now. Based on the successful fabrication of the QD–graphene composites, we propose a scheme to improve this capability here, and accordingly to enhance the conductivity of the QD devices.

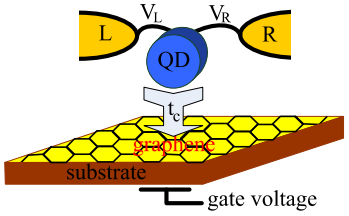

Fig. 1. (Color online.) Scheme of the model system: A quantum dot is sandwiched in the source (L) and drain (R) electrodes and side-coupled to the graphene sheet with the coupling strength t_c. The potential of the graphene can be adjusted by the gate voltage applied to its substrate.

In this letter, using the slave boson (SB) mean field approximation (MFA) and the Green's function technology, by introducing a side-coupled graphene sheet, we theoretically investigate the manipulation of electron-Kondo transport through a strongly correlated QD from two metal electrodes as shown in Fig. 1. The central part of this system is a QD device which consists of a QD and two

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metal electrodes. The side-coupled graphene sheet is introduced as an external accessory to manipulate electron transport through the QD device. According to the Tersoff–Hamann approach [18,19], the QD–graphene coupling strength is accurately adjustable by varying their distance. We show that when the potential of the graphene sheet is fixed at the Fermi energy of two metal electrodes, with increase of the QD–graphene coupling strength, the Kondo resonance level in the QD device is greatly broadened. This behavior improves the anti-bias voltage capability of the QD–electrode Kondo resonance, and opens up a high conducting channel for electron transport through the QD device under a rather larger bias voltage applied to two metal electrodes. The differential conductance possesses a high ridge, closing to $2e^2/h$, within a rather wider range of bias voltage. This is an interesting property because it allows us to observe experimentally the nonequilibrium Kondo effect [16,17] at a rather large bias voltage. Moreover, the conductance/current in the QD device can be accurately controlled by adjusting the gate voltage applied to the graphene sheet. Our results may be useful for the design of high-conductance control device [20–23].

2. Hamiltonian and method

In our considered composite system, the Hamiltonian for the QD device is described by a two-fold ($N = 2$) degenerated one-impurity Anderson Hamiltonian. In limit of the intra-dot Coulomb repulsion $U \to \infty$, it can be read as

$$H_1 = \sum_{k\alpha,\sigma} \epsilon_{k\alpha,\sigma} c^\dagger_{k\alpha,\sigma} c_{k\alpha,\sigma} + \sum_\sigma \epsilon_0 f^\dagger_\sigma f_\sigma + \frac{1}{\sqrt{N}} \sum_{k\alpha,\sigma} \left(V_{k\alpha} c^\dagger_{k\alpha,\sigma} b^\dagger f_\sigma + \text{H.c.} \right) + \lambda \left(b^\dagger b + \sum_\sigma f^\dagger_\sigma f_\sigma - 1 \right), \tag{1}$$

where the first term describes two metal electrodes in which $c^\dagger_{k\alpha,\sigma}(c_{k\alpha,\sigma})$ is electron creation (annihilation) operator with wave vector k and spin $\sigma = \pm 1$ in the left ($\alpha = L$) or right ($\alpha = R$) side and $\epsilon_{k\alpha\sigma}$ is the corresponding single-electron energy. The second term stands for the Hamiltonian of the QD with energy ϵ_0 in the SB representation [24,25], in which electron creation (annihilation) operator is expressed by $f^\dagger_\sigma b(b^\dagger f_\sigma)$, where $b(f^\dagger_\sigma)$ is the auxiliary boson (pseudo-fermion) operator for the empty (singly occupied) state of the QD. The third term is electron tunneling from the electrodes to the QD with relevant matrix element $V_{k\alpha}$. The last term with a Lagrange multiplier λ represents a constraint of $\Sigma_\sigma f^\dagger_\sigma f_\sigma + b^\dagger b = 1$ for the QD to forbid electronic double occupancy under the limitation $U \to \infty$.

The Hamiltonian for the QD–graphene coupling part (including the graphene sheet) can be written as

$$H_2 = \sum_{k_x,k_y,\sigma} (u + \varepsilon_{k_x k_y}) d^\dagger_{k_x,k_y,\sigma} d_{k_x,k_y,\sigma} + \frac{1}{\sqrt{N}} \sum_{k_x,k_y,\sigma} t_c \left(f^\dagger_\sigma b d_{k_x,k_y,\sigma} + \text{H.c.} \right) \tag{2}$$

with the low-energy spectrum of the graphene sheet

$$\varepsilon_{k_x k_y} = \pm t \sqrt{1 - 4\cos(\sqrt{3}k_y/2)\cos(3k_x/2) + 4\cos^2(\sqrt{3}k_y/2)}, \tag{3}$$

in which $d^\dagger_{k_x,k_y,\sigma}(d_{k_x,k_y,\sigma})$ is π-electron creation (annihilation) operator of graphene sheet and the potential u of the sheet can be varied by adjusting the gate voltage applied to its substrate [see Fig. 1]. t is the nearest-neighbor π-electron hopping integral and t_c is the QD–graphene coupling strength. Therefore, the total Hamiltonian of our model system is $H = H_1 + H_2$.

We solve the total Hamiltonian H by employing MFA, in which SB operator $b(t)$ is replaced by its expectation value $\tilde{b} = \langle b(t) \rangle / \sqrt{N}$, i.e., neglecting the fluctuation around the average $\langle b(t) \rangle / \sqrt{N}$. The MFA is exact for describing the spin fluctuation (Kondo regime) at low temperatures. Employing the similar technology as that used in Refs. [26,27], the unknown parameters $\tilde{b}$ and λ can be obtained by resolving a set of equations under the conditions of minimal energy $\partial \langle H(\lambda, \tilde{b}) \rangle / \partial \lambda = 0$ and $\partial \langle H(\lambda, \tilde{b}) \rangle / \partial \tilde{b} = 0$. Employing the equation of motion approach of the Green's function, one can also obtain the full retarded Green's function of the QD

$$G^r_{ff,\sigma}(\omega) = \left[\omega - \epsilon_{QD} - \tilde{b}^2 t_c^2 \Re \left[g^r_{G,\sigma}(\omega) \right] + i \left(\Gamma^\sigma_L + \Gamma^\sigma_R + \Gamma^\sigma_G \right) \right]^{-1} \tag{4}$$

and its density of states (DOS) $\rho_{QD}(\omega) = -2\tilde{b}^2 \Im[G^r_{ff,\sigma}(\omega)]/\pi$. Here, $\epsilon_{QD} = \epsilon_0 + \lambda$ is the Kondo resonance level in the QD and $\Gamma^\sigma_{L(R)} = \tilde{b}^2 \Gamma^\sigma_{0,L(R)}$ is the width of QD–electrode Kondo resonance level [25], where $\Gamma^\sigma_{0,\alpha} = \pi \Sigma_{k\sigma} V_{k\alpha} V^*_{k\alpha} \delta(\omega - \epsilon_{k\alpha,\sigma})$ is the QD–electrode correlated function, containing all interference paths of the metal $L(R)$-electrode. In the wide band limitation with the energy interval of $-D < \omega < D$, the total correlated function $\Gamma^\sigma_0 = \Gamma^\sigma_{0L} + \Gamma^\sigma_{0R}$ is taken as a constant. The width of QD–graphene Kondo resonance level is taken as $\Gamma^\sigma_G = \tilde{b}^2 \Gamma^{0,\sigma}_G$, where $\Gamma^{0,\sigma}_G = -t_c^2 \Im[g^r_{G,\sigma}(\omega)]$ is the QD–graphene correlated function with the retarded Green's function of the isolated graphene sheet $g^r_{G,\sigma}$. It is worth noting that $\Gamma^{0,\sigma}_G$ is the function of graphene-potential u, which can be adjusted by a gate voltage applied to it [see Fig. 1]. For preciseness and simplicity, we adopt Peres et al.'s method [28,29] to express the retarded Green's function $g^r_{G,\sigma}$, which allows us to take into account the nonlinear bands of the graphene and not only its linear ones around the Dirac point (potential u) in our calculation. Its imaginary part reads

$$\Im \left[g^r_{G,\sigma}(\omega) \right] \cong -\left[\frac{\omega - u}{\sqrt{3}t^2} + \frac{(\omega - u)^3}{3\sqrt{3}t^4} + \frac{5(\omega - u)^5}{27\sqrt{3}t^5} \right], \tag{5}$$

and real part is taken as

$$\Re \left[g^r_{G,\sigma}(\omega) \right] = P_1(\omega, u) + P_2(\omega, u) \ln \frac{(\omega - u)^2}{D_c^2 - (\omega - u)^2} \tag{6}$$

with the polynomial functions

$$P_1(\omega, u) = -\frac{\omega - u}{3t^2} - \frac{5}{27t^4} \left[\frac{(\omega - u)}{2} D_c^2 + (\omega - u)^3 \right],$$
$$P_2(\omega, u) = \frac{\omega - u}{D_c^2} + \frac{(\omega - u)^3}{3t^2 D_c^2} + \frac{5}{27 D_c^2 t^4} (\omega - u)^5. \tag{7}$$

Here, the cut-off energy is chosen as $D_c^2 = \sqrt{3}\pi t^2$.

In this work, our topic is to investigate the manipulation of the election-Kondo transport through the QD device by applying a side-coupled graphene sheet, which can be verified by a low-temperature current from L-electrode to R-electrode via the QD [30]

$$I_{LR} = \frac{e}{h} \sum_\sigma \int_{-eV_{LR}/2}^{eV_{LR}/2} d\omega T^\sigma_{LR}(\omega) \tag{8}$$

and its linear conductance