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Photon-assisted electronic structure and transport for a quantum dot*

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This paper investigates theoretically the electronic structure and transport of a two-level quantum dot irradiated under a strong laser field at low temperatures. Using the method of Keldysh equation of motion for nonequilibrium Green functions, it examines the time-averaged density of states and conductance for the system with photon polarization parallel with and perpendicular to the tunnelling current direction respectively. It is demonstrated that, by analysing some numerical examples, more photon sidebands resonance states and multi- and single-photon transitions are found when diagonal matrix elements dominate the interaction, while the electronic transitions due to multiphoton absorption are more or less suppressed when off-diagonal interaction dominates.

Keywords: quantum dot, laser field, density of states, nonequilibrium Green functions
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The time-dependent quantum transport through mesoscopic systems has attracted much attentions in recent years (see, e.g., a review article[1] and references therein). However, a driven two-level system, such as two-level quantum dot (QD) or wire, is physically important since it has been proven to be very useful in describing many aspects of interaction between light and quantum-confined electrons, and in applications of solid-state electronic devices.[2]

A number of new features as well as unexpected phenomena have been revealed both experimentally[3,4] and theoretically[5−15] in this area. The photon sidebands of ground states[3] and the Coulomb blockade additional peaks[4] have been observed in a GaAs/AlGaAs heterostructure QD under a high microwave irradiation. The resonant tunnelling in a parabolic quantum well (QW) structure under a uniform transverse magnetic field,[5] including the Terahertz-field-induced modulation of intersubband absorptions and in-plane spin-polarized transport in QWs[6] has been investigated. The electron transport for a two-level quantum wire irradiated under a time-varying field has been analysed respectively by means of the nonequilibrium Green function (NGF)[7] and the scattering matrix approach.[8] The same system but with Gaussian-type scatters has been investigated[9] by means of T-matrix Lippmann–Schwinger approach. The electron tunnelling through an ultrasmall QD[10] and the two coupled QDs[11] in the presence of a time-dependent microwave field have been studied by the NGF. Using the similar approach, Yang and Li[12] have investigated the conductance of a QD suffering an AC anti-symmetry gate voltage in the rotating-wave approximation (RWA), the interesting Fano resonance and a peak splitting of conductance have been predicted. Almost all of the studies mentioned above have used the limitation of weak photon intensity. However, the improvements in laser technology allow experimenters to produce very strong laser pulse which can result in some interesting nonlinear effects in its interaction with quantum-confined electrons, such as absolute negative conductance. Absolute negative conductance, resulting from the field-induced phase difference of current and voltage, is an interesting phenomenon in electron transport physics. This phenomenon has been studied for a double barrier structure[13] and superlattices.[14] By means of NGF, Niu and Lin[15] have investigated the electronic structure (usually referred to the electron density of states (DOS)) and current–voltage characteristics for a two-level quantum wire irradiated under a strong laser field, and the absolute negative resistance states

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have been expected.[15] However, they have not considered the important cases of a laser field resonant with quasiparticle transition and the dependence of conductance on the incident laser frequency. To the best of our acknowledge, few works have considered the DOS[7,15] and the dependence of conductance on the external field frequency for a driven QD system.[16]

In order to investigate the electronic structure of a two-level QD under a resonant laser field irradiation and the dependence of conductance on the incident laser frequency, in this paper, we present a theoretical investigation of the electron DOS and conductance for the system with dominating diagonal and off-diagonal electron–photon interaction respectively. Using the nonequilibrium Keldysh formulism, we show some different transport characteristics for the similar physical system in comparison with the previous works.[6−8,11,12,14,15,17]

The NGF approach has been employed in last decades to study a variety of problems beyond the linear response regime.[18] This method does not involve RWA which is available[12] when the field intensity and the electron–photon interaction are sufficiently weak. Meir and Wingreen[19] have derived a formula for the current through a region of interacting electrons using the nonequilibrium Keldysh formulism. Under the widely adopted adiabatic approximation,[7,8,10,15,17] we assume that the external laser field only causes a rigid shift in the single-electron energy spectrum. Therefore, the Hamiltonian for an irradiated two-level QD connected to two electrode leads is[7,15]

$$\begin{aligned} H = & \sum_{k,\alpha\in \mathrm{L/R}} \varepsilon_{k,\alpha} a^+_{k,\alpha} a_{k,\alpha} + \sum_{i=1,2} \varepsilon_i c^+_i c_i \\ & + \sum_{k,\alpha\in \mathrm{L/R},i} (T_{k,\alpha;i} a^+_{k,\alpha} c_i + \mathrm{H.c.}) \\ & + \sum_{i,j=1,2} V_{ij} \cos(\Omega t) c^+_i c_j, \end{aligned} \tag{1}$$

where the operator $a^+_{k,\alpha}(a_{k,\alpha})$ creates (annihilates) an electron with momentum k in mode α in either the left (L) or the right (R) lead, and $c^+_i(c_i)$ creates (annihilates) an electron at level ε_i in the QD. The coupling between the electrode leads and the dot with strength $T_{k,\alpha;i}$ is represented by the third term, and the last term describes the electron–photon interaction in the dot, where V_{ij} is the dipole interaction matrix element (ME) and Ω is the incident laser frequency. Furthermore, in the above Hamiltonian we have neglected the spin and electron–electron interactions for simplicity although much attentions have been paid to the manipulation of the electron spin degree of freedom for applications in spintronics.[17,20]

If we use the usually defined Green Function (GF)[7,12,15,17,19]

$$G^{r/a}_{ij}(t_2,t_1) = \mp \mathrm{i}\theta(\pm t_2 \mp t_1)\langle\{c_i(t_2), c^+_j(t_1)\}\rangle, \tag{2}$$

then the corresponding Keldysh equation of motion (EOM) of retarded GF is

$$\begin{aligned} & \mathrm{i}\frac{\partial}{\partial t_2} \ll c_i(t_2), c^+_j(t_1) \gg^r \\ = & \ \delta(t_2-t_1)\langle\{c_i(t_2), c^+_j(t_1)\}\rangle \\ & + \ll [c_i(t_2), H], c^+_j(t_1) \gg^r . \end{aligned} \tag{3}$$

Substituting Hamiltonian (1) into Eq.(3) and transforming the variables to $t_2 - t_1$ and t_1, and then performing the Fourier transformation to change the variable $t_2 - t_1$ into ω, we finally obtain the retarded GF, i.e.

$$\begin{aligned} & (\omega - \varepsilon_i) \ll c_i, c^+_j(t_1) \gg^r_\omega \\ = & \ \delta_{ij} + \frac{1}{2}\sum_{k=1,2} [V_{ik}\mathrm{e}^{\mathrm{i}\Omega t_1} \ll c_k, c^+_j(t_1) \gg^r_{\omega+\Omega} \\ & + V^*_{ik}\mathrm{e}^{-\mathrm{i}\Omega t_1} \ll c_k, c^+_j(t_1) \gg^r_{\omega-\Omega}] \\ & + \Sigma_{ij}\sum_{k=1,2}(1-\delta_{ik}) \ll c_k, c^+_i(t_1) \gg^r_\omega, \end{aligned} \tag{4}$$

where

$$\begin{aligned} \Sigma_{ij} = & \ \Sigma^{\mathrm{L/R}}_{ij}(\omega) \\ = & \ 2\pi\sum_k T^*_{k,\mathrm{L/R};i} T_{k,\mathrm{L/R};j} \delta(\omega - \varepsilon_{k,\mathrm{L/R}}), \end{aligned} \tag{5}$$

is the self-energy describing the influence of the leads. It is seen from Eq.(4) that the NGF is coupled by the dot-lead coupling, and each Fourier component with frequency ω is coupled to the components with frequencies $\omega + \Omega$ and $\omega - \Omega$. We calculate the time-averaged NGF up to the second order as usual,[21] then the time-averaged DOS and conductance at low temperatures are respectively[7,15,17]

$$\mathrm{DOS} = -\frac{1}{\pi}\mathrm{Im}[G^r(\omega,\omega)], \tag{6}$$

and[12,17,19]

$$G = \frac{2e^2}{h}\mathrm{Tr}[\Sigma^{\mathrm{L}}(\omega)G^a(\omega,\omega)\Sigma^{\mathrm{R}}(\omega)G^r(\omega,\omega)], \tag{7}$$

where the $G^{r/a}(\omega,\omega)$ is the time-averaged retarded/advanced GF.

In the following, we present some numerical examples of the calculated time-averaged DOS and conductance for the system. The energy spacing $\Delta\varepsilon$ between the two levels which are assumed relatively

to be at -0.5 and $+0.5$ in the QD is taken to be the energy unit. The Fermi level in the leads without bias voltage is set to be zero. In the wide-band approximation the real part of the self-energy is negligible,[7,10,12,15,17] and we simply assume that $\Sigma_{11} = \Sigma_{22} = 0.1$, $\Sigma_{12} = \Sigma_{21} = 0.05$. The choice of these typical parameters is based on the following consideration. Usually the strength of electron–photon interaction depends on the photon intensity, polarization and the size of the QD. Under the irradiation of a strong laser[7,15,17] with an electric field of order 10^5–10^6 V/m, the electron–photon interaction MEs are comparable to or several times larger than the level spacing in the QD with the width of order 10–100 nm. Anyway, lasers with this intensity have been employed in experiments.[22]

As the problem depends strongly upon the geometry of the incident laser, we consider the time-averaged DOS when the polarization of the incident laser is parallel with and perpendicular to the QD in the dipole approximation respectively. Since the main physics may appear at the vicinity of the resonance frequency, we only give the result of resonance case $\Omega = 1.0$. The calculated time-averaged DOS as a function of energy ($\sim \omega$, in arbitrary units) is illustrated in Fig.1 for two different strengths of diagonal and off-diagonal MEs. Firstly, we assume that the diagonal MEs are 2.0 and 1.0, namely, twice or equal to the level spacing in the dot while the off-diagonal MEs are simply zero since their influences are negligible[15,17] in this case. As shown by the solid line in Fig.1(a), it is interesting to note that the DOS takes on series of peaks with dip structures at sidebands $\varepsilon_1 \pm \Omega$ and $\varepsilon_2 \pm \Omega$. Physically, this phenomenon can be understood as follows. When an isolated QD is subjected to the external laser field, interference effects between the widened sidebands (due to the coupling between electrode leads and the QD) are observed as resonance peaks and dip structures. The resonance peaks near the two original levels are smaller than others, this is due to the strong interaction MEs we have chosen. When the diagonal MEs decrease to 1.0, as shown by the dashed line in Fig.1(a), there are four sharp resonance peaks at $\varepsilon_1 \pm \Omega$ and $\varepsilon_2 \pm \Omega$ except for the two additional resonance peaks at $\omega \sim -\Omega$ and Ω. We may owe this qualitative difference in the DOS between these two cases to the intensity of electron–photon interaction. Since we have considered the resonance case for the system, the above results are quantitatively different from those in Ref.[15] (see, e.g., Fig.2 in Ref.[15]) where a series of symmetrically distributed resonance peaks have been shown for the nonresonance case.

Secondly, Fig.1(b) depicts the transverse polarization case with the assumption that the off-diagonal MEs are 1.0 and 0.5, i.e., equal to or half of the level spacing in the dot while the diagonal ones are simply zero in the dipole approximation. One can note that the four major resonance peaks within the range of $|\omega| < 1.5$ appear symmetrically about zero, and the peaks near the two original levels are suppressed due to the resonance absorption or emission. These results are quantitatively different from those in Ref.[15] (see, e.g., Fig.3(b) in Ref.[15]) and Ref.[12], especially in the stronger electron–photon interaction case (see the solid line in Fig.1(b)) since the RWA is invalid when electron–photon interaction is comparable with the level spacing in the dot. Since the variation of the dot-lead coupling strength only changes the width of the resonance peaks but not their positions, the features in the present case may be attributed to the electron–photon interaction.

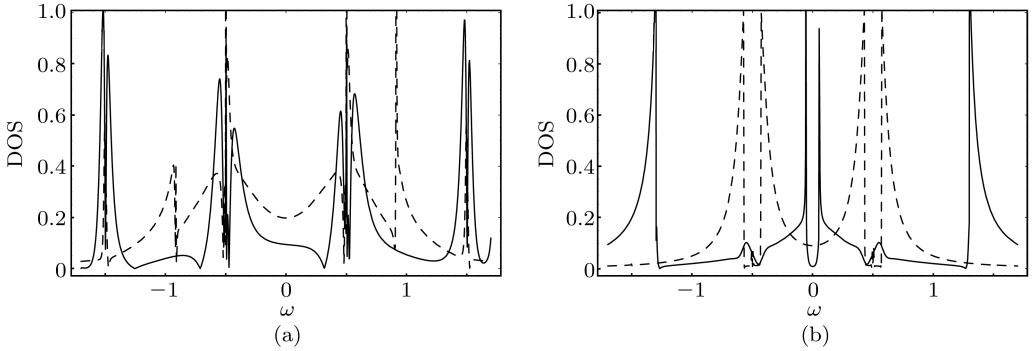


Fig.1. The time-averaged DOS as a function of energy ($\sim \omega$, in arbitrary units) for different diagonal and off-diagonal MEs. The incident laser frequency is $\Omega = 1.0$, (a) the diagonal MEs are $V_{11} = V_{22} = 2.0$ for solid line and $V_{11} = V_{22} = 1.0$ for dashed line, and (b) the off-diagonal MEs are $V_{12} = V_{21} = 1.0$ for solid line and $V_{12} = V_{21} = 0.5$ for dashed line, respectively.

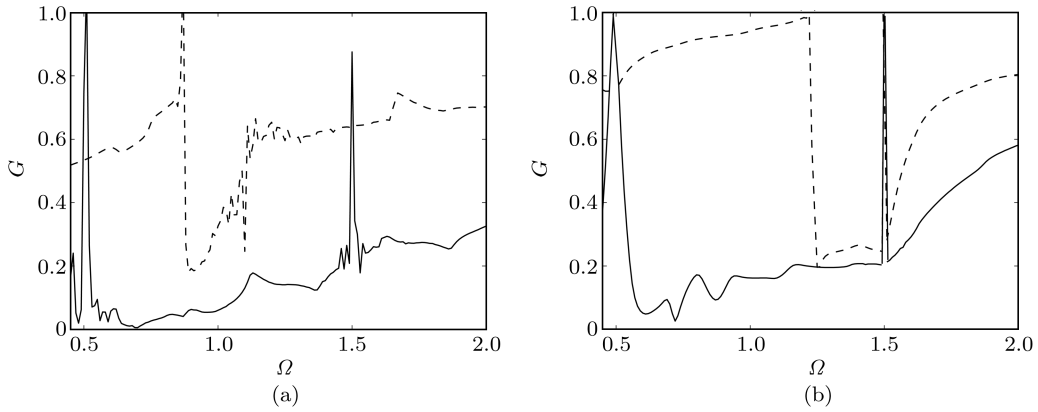


Fig.2. The time-averaged conductance G (in units of $2e^2/h$) as a function of the incident laser frequency Ω (in arbitrary units). The incident electron energy $\omega = -1.0$, and all the other parameters are the same as those in Fig.1.

Finally, Fig.2 displays the time-averaged conductance G (in units of $2e^2/h$) for a fixed incident electron energy ($\omega = -1.0$) as a function of the incident laser frequency Ω, while all the other parameters are the same as those in Fig.1. In the stronger diagonal MEs case, as shown by the solid line in Fig.2(a), there is a conductance peak at $\Omega = 0.5$ and 1.5 respectively since the electron can transmit to the two main resonance levels through photon absorption $\omega + \Omega = \pm 0.5$. When the diagonal MEs decrease to half of the original values (see the dashed line in Fig.2(a)), the two major resonance peaks are shifted to 0.8 and 1.7 respectively and there is a series of resonance peaks in the range of $0.8 < \Omega < 1.25$. It should be pointed out that there are more resonance peaks within the lower frequency range due to the attendance of multi- and single-photon processes.[15] It implies that too high frequency of the external field is unfavorable to the quantum transitions under the selected system of parameters. Furthermore, the intersubband transition case is shown in Fig.2(b). As expected there is a resonance conductance peak at $\Omega = 0.5$ and 1.5 respectively for the stronger off-diagonal MEs (see the solid line in Fig.2(b)), wherever, as the dashed line shown in Fig.2(b), a resonance step-like structure is formed near 1.2 except for a peak at 1.5 for the weaker off-diagonal MEs case. One can note that the conductance structure with off-diagonal MEs domination is not so rich as that for diagonal ones due to the suppression of the multiphoton absorption.[15] Anyway, both the electron DOS and transport properties of QD systems are sensitive to the strength of electron–photon interaction (and hence the external field intensity) and the frequency of the external field, which may be applied to the detection of the external field.

In summary, using the method of Keldysh EOM for NGF, we have theoretically investigated the electronic structure of a two-level QD under irradiation of a strong laser field resonant with the quasiparticle transition and the dependence of conductance on the incident laser frequency. Some numerical examples of the time-averaged resonance DOS and conductance for the two cases of diagonal and off-diagonal electron–photon interaction dominating the processes are demonstrated respectively. We have found that the DOS with diagonal interaction shows more resonance states and that with off-diagonal interaction displays a symmetrically distributed structure. Furthermore, attributing to the attendance of multi- and single-photon processes, we find more resonance peaks with diagonal MEs domination for a fixed incident electron energy. In all cases the electron DOS and conductance are sensitive to the intensity and frequency of the external field, which may be utilized to detect the related parameters of the external field. However, the experimental observation for these effects and further theoretical investigations on the system with impurity, spin or electron–electron interactions would be worth carrying out.

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