

Quantum mechanical approach for photon-associated electron tunneling through a quantum dot

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Photon-associated electron tunneling (PAT) in a quantum dot is studied by a fully quantum-mechanical approach. An experiment to determine the electron-photon coupling coefficient g and the photon number of the system is proposed to distinguish whether the system is in the quantum situation or the semiclassical situation. It is also found that the PAT current is assisted or suppressed depending on the shift of the environment photon-intensity-dependent photon sidebands.

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I. INTRODUCTION

Photon-associated electron tunneling (PAT), and related applications such as electron pumping¹ and single-photon emission,² attracted theoretical and experimental researchers in the past few years.³⁻⁷ Most theoretical investigations used the semiclassical model to describe a photon field which has been treated as a time dependent ac field $eV \cos \omega t$ (Refs. 4 and 8) (where ω is the frequency of the semiclassical photon field). The semiclassical approach is able to predict the “sideband” phenomenon which is due to the influence of an electromagnetic field, and opens tunneling channels by exchanging an energy of $n\hbar\omega$ ($n = \pm 1, \pm 2, \pm 3 \dots$) with a resonant system.^{4,7,9} However, phenomena of the fully quantum-mechanical nature,^{8,9} of the photon field, such as photon emission in the dark and the creation of a corresponding sideband that assists the electronic tunneling current,⁹ cannot be obtained by semiclassical models.

Recently, a quantum electrodynamic description of photon-assisted tunneling through a single-electron resonant level system was reported by Foden and Whittaker,⁹ using a canonical transformation to describe the quantum PAT process. They only considered nontransition processes (i.e., the processes $|a, n\rangle \rightarrow |a, n\rangle$ and $|b, n\rangle \rightarrow |b, n\rangle$), but did not include transition processes (i.e., the processes $|a, n\rangle \rightarrow |b, n+1\rangle$ and $|b, n\rangle \rightarrow |a, n-1\rangle$) and photon sidebands created at $\epsilon_0 + n\hbar\omega - \Delta$. The photon sidebands depend on the n photons interacting with the electron, but are independent of the field intensity of the environment. Foden and Whittaker also pointed out that the classical field approximation is a valid one for the present experiments, not because the field intensities are high but because the coupling between the electrons and the field is weak.

An environmental-field-strength-dependent photon sideband was reported by Brune *et al.*⁵ They employed a semiclassical approach, and considered an inner transition (i.e., the transition process mentioned above). They performed a time-dependent unitary transformation to remove the time dependence of the dot Hamiltonian, and obtained photon sidebands located at $\epsilon = (\epsilon_a + \epsilon_b \pm \hbar\omega \pm \Omega)/2$, where $\Omega = \sqrt{(\epsilon_a - \epsilon_b - \hbar\omega)^2 + |\Delta_f|^2}$ is the Rabi frequency and Δ_f is the coupling strength of the field.

In this paper we derive a relation between the coupling strength and the number of photons of the field Δ_f . The relation between the sideband shift, which depends on the

electron-photon coupling and the photon number, is also obtained. We propose to measure the photon sideband shift to distinguish whether the electron-photon interacting system is in the semiclassical situation or the quantum situation.

II. MODEL AND FORMULA

In this work, we consider a system which contains a two-level quantum dot (represented by a for the higher level and b for the lower level) treated as the electron-photon interacting region, and two leads (represented by R and L) coupled to the dot. The total Hamiltonian for the described system can be expressed as

$$H_{tot} = H_{int} + H_c + H_T, \quad (1)$$

where $H_c = \sum_{\alpha \in R, L} \epsilon_{\alpha} c_{\alpha}^{\dagger} c_{\alpha}$ is the Hamiltonian for the electron in the lead, $H_T = \sum_{\alpha \in R, L; i \in a, b} V(t)_{\alpha \alpha, i} d_i^{\dagger} c_{\alpha} + \text{H.c.}$ is the tunneling Hamiltonian, and H_{int} is the Hamiltonian for the interacting region (central region):

$$H_{int} = H_e + H_{ph} + H_{e-ph} = \sum_{i=a, b} \epsilon_i d_i^{\dagger} d_i + \sum_k \hbar \omega_k b_k^{\dagger} b_k + \hbar \sum_k g_k (d_a^{\dagger} d_b b_k + d_b^{\dagger} d_a b_k^{\dagger}). \quad (2)$$

In the above expression, $d_i^{\dagger}(d_i)$, $c_{\alpha}^{\dagger}(c_{\alpha})$, and $b_k^{\dagger}(b_k)$, are creation (annihilation) operators for the electron in interacting region, the electron in the lead, and the photon. The subscripts i, α , and k indicate the electron states in the interacting region ($i \in a, b$; a indicates the higher level, and b indicates the lower level), the electronic wave vectors in the lead, and the photonic wave vector. In our model, the Hamiltonian of the photon part is summed independently over all possible wave vectors, hence each can be treated individually. For simplicity, we will treat a single-mode photon in this work, and the subscript k will be ignored in later description. The rotating-wave approximation⁸ is considered in the electron-photon interacting Hamiltonian H_{e-ph} .

The electron-photon coupling coefficient $g_k = \vec{P} \cdot \vec{E}_k / \hbar$ is an important quantity in this work, where $\vec{P} = e \langle i | \vec{r} | j \rangle$ is the electric dipole transition matrix element. $\vec{E}_k = (\hbar \omega_k / 2 \epsilon_0 V)^{1/2} \hat{\epsilon}_k$, where k is the wave vector of the photon field and $V = LA$ (L is the length of the cavity and A is

the transverse area of the optical resonator).⁸ It can be recognized that the electron-photon coupling coefficient is one of the properties of the system, and cannot be modified by modulating the photon intensity. Hence the strength of the electron-photon coupling is independent of the photon intensity.

In this paper, we treat the electron-photon interacting system as a quasiparticle, and employ a transport formula for interacting resonant tunneling which is evolved from the Keldysh nonequilibrium Green-function technique^{3,10} developed by Wingreen *et al.*¹¹ to calculate the photon-associated tunneling dc current. The transport (current) formulas are

$$J = \sum_{\alpha \in R, L} J_{\alpha}^{in} + J_{\alpha}^{out}, \quad (3)$$

$$J_{\alpha}^{in} = -\frac{e}{\hbar} T_{\alpha} u_{\alpha}(t) \int \frac{d\epsilon}{\pi} f_L(\epsilon) \text{Im}\{A_{\alpha}(\epsilon, t)\}, \quad (4)$$

$$J_{\alpha}^{out} = -\frac{e}{\hbar} T_{\alpha} \sum_{\alpha \in L, R} T_{\alpha} \int \frac{d\epsilon}{2\pi} f_L(\epsilon) |A_{\alpha}(\epsilon, t)|^2 = -\frac{e}{\hbar} T_{\alpha} N(t), \quad (5)$$

$$A_{\alpha}(\epsilon, t) = \int d\tau_1 u_{\alpha}(\tau_1) G^r(t, \tau_1) \times \exp\left[i\epsilon(t - \tau_1) - i \int_t^{\tau_1} d\tau_2 \Delta_{\alpha}\right], \quad (6)$$

where $G^r(t, \tau_1)$ is the retarded Green function for the interacting quasiparticle in the interacting region (including the tunneling effect). All information about the transport and the interacting region can be obtained from the retarded Green function.

According to Ref. 11, it is obvious that in the time independent case $A_{i,\alpha}(\epsilon)$ is just the Fourier transform of the retarded Green function $G^r(\epsilon)$. In many-particle theory, the spectral function of the described system is $a(\epsilon) = -2 \text{Im} G$,¹⁴ which is the probability to obtain a particle with energy ϵ . Hence the input current formula [Eq. (4)] describes the electron in the left lead [described by $f_L(\epsilon)$, the occupation of the electron in the left lead] entering the central region (the interacting region) when the central region provides the probability of the electron in the lead being occupied. Equation (5) shows that the output current is proportional to the occupation in the central region $N(t)$. Interpretations of the current formula can also be seen obtained in Refs. 11 and 12. Information about the transport and the interacting region can be obtained from the retarded Green function corresponding to the quasiparticle in the central region.

In order to employ the conductance formulas, we first have to obtain the retarded Green functions corresponding to the interacting quasiparticle in the interacting region. There are four possible interacting processes $|b, n\rangle \rightarrow |b, n\rangle$, $|a, n\rangle \rightarrow |a, n\rangle$, $|b, n+1\rangle \rightarrow |a, n\rangle$, and $|a, n-1\rangle \rightarrow |b, n\rangle$; two of them are nontransition processes (diagonal terms) and the other two are transition processes (off-diagonal terms). a is

the higher level electronic state, b is the lower level state, and n is the photon number of environment.

The contour-ordered Green function describing the transition processes, for example, $|b, n+1\rangle \rightarrow |a, n\rangle$, is constructed as a base on the unperturbed transition quasiparticle Green function which is defined as $g_{an, bn+1}^0(t, t') \equiv -i_n \langle T_C d_a(t) d_b^+(t') [b^+(t')/\sqrt{n+1}] \rangle_n$. The S matrix which describes the electron-photon interaction is

$$S_{e-ph} \equiv T_C \left\{ \exp \left[-i \int d\tau_1 H_{e-ph}(\tau_1) \right] \right\}. \quad (7)$$

We insert the S matrix into the unperturbed transition quasiparticle Green function, and employ Dyson's expansion to expand the S matrix and the Wick's theorem to rearrange the operators; the perturbed transition Green function is then obtained as

$$G_{an, bn+1}(t, t') \equiv i \frac{g}{\sqrt{n+1}} \int d\tau g_{an, an}^0(t, \tau) g_{bn, bn}^0(\tau, t') D_n(\tau, t') + i g^2 \int \int d\tau_1 d\tau_2 g_{an, an}^0(t, \tau_1) g_{bn, bn}^0(\tau_1, \tau_2) D_n(\tau_1, \tau_2) G_{an, bn+1}(\tau_2, t'), \quad (8)$$

where $D_n(\tau_1, \tau_2) \equiv -i_n \langle T_C b(\tau_1) b^+(\tau_2) \rangle_n$ and $g_{bn, bn}^0(\tau_1, \tau_2) \equiv -i_n \langle T_C d_b(\tau_1) d_b^+(\tau_2) \rangle_n$. Using the Langreth theorem^{11,13} and taking a Fourier transformation, the retarded Green function corresponding to Eq. (8), with energy ϵ , is obtained as

$$G_{an, bn+1}^r(\epsilon) = \frac{g\sqrt{n+1}}{\left(\epsilon - \epsilon_a + \frac{\Delta}{2} - \frac{\Omega_{R, n+1}}{2}\right) \left(\epsilon - \epsilon_a + \frac{\Delta}{2} + \frac{\Omega_{R, n+1}}{2}\right) + i\delta}, \quad (9)$$

where $\Omega_n \equiv \sqrt{\Delta^2 + 4g^2 n}$ is the Rabi frequency and $\Delta \equiv \epsilon_a - \epsilon_b - \hbar\omega$. The retarded Green function for the process $|a, n-1\rangle \rightarrow |b, n\rangle$ can be found by the same way as $|b, n+1\rangle \rightarrow |a, n\rangle$:

$$G_{bn, an-1}^r(\epsilon) = \frac{g\sqrt{n}}{\left(\epsilon - \epsilon_b - \frac{\Delta}{2} - \frac{\Omega_{R, n}}{2}\right) \left(\epsilon - \epsilon_b - \frac{\Delta}{2} + \frac{\Omega_{R, n}}{2}\right) + i\delta}. \quad (10)$$

The contour Green function corresponding to the nontransition process $|b, n\rangle \rightarrow |b, n\rangle$ is

$$G_{bn, bn}(t, t') = -i \theta(t - t')_n \langle T_C S_{e-ph} d_b(t) d_b^+(t') \rangle_n. \quad (11)$$

Using the same method in the treatment of the transition process, the retarded Green function with energy ϵ is given by

$$G_{bn,bn}^r(\epsilon) = \frac{\epsilon - \epsilon_b - \Delta}{\left(\epsilon - \epsilon_b - \frac{\Delta}{2} - \frac{\Omega_{R,n}}{2}\right)\left(\epsilon - \epsilon_b - \frac{\Delta}{2} + \frac{\Omega_{R,n}}{2}\right) + i\delta}. \quad (12)$$

Similarly, the retarded Green function for the process $|a,n\rangle \rightarrow |a,n\rangle$ can be expressed as

$$G_{an,an}^r(\epsilon) = \frac{\epsilon - \epsilon_a - \Delta}{\left(\epsilon - \epsilon_a + \frac{\Delta}{2} - \frac{\Omega_{R,n+1}}{2}\right)\left(\epsilon - \epsilon_a + \frac{\Delta}{2} + \frac{\Omega_{R,n+1}}{2}\right) + i\delta}. \quad (13)$$

The time-dependent form of the Green functions can be obtained by taking the Fourier transform of the Green functions of energy, i.e., Eqs. (9), (10), (12), and (13). The forms of the time representation Green functions are similar to the result obtained by the well-known Jaynes-Cummings model⁸ which was successful in describing an atom interacting with the quantum photon field in the subject of “cavity QED.”⁸ This similarity is reasonable, since the quantum dot can be considered as an artificial atom.

Under a consideration of the tunneling effect, the self-energy contains an electron-photon interacting term and also includes the tunneling effect,¹¹ that is,

$$\Sigma_{tot}^r = \Sigma_{e-ph}^r + \Sigma_L^{T,r} + \Sigma_{iR}^{T,r} = \Sigma_{i,e-ph}^r - i \frac{\Gamma_L + \Gamma_R}{2},$$

and the retarded Green function including the tunneling effect can be obtained by replacing $i\delta$ by

$$i \left(\frac{\Gamma_{i,\kappa L} + \Gamma_{i,\kappa R}}{2} + \delta \right) \sim i \frac{\Gamma_{i,\kappa L} + \Gamma_{i,\kappa R}}{2}.$$

It is convenient to obtain the physical meaning of this argument in the time domain. If a quasiparticle retarded Green function that does not include the tunneling effect is given by $G_0^r(t-t')$, then the quasiparticle retarded Green function including the tunneling effect can be expressed by $G_0^r(t-t')e^{-\Gamma(t-t')}$, which contains the decay rate Γ of the quasiparticle due to the perturbation of tunneling Hamiltonian. (For our system, $\Gamma = -2 \text{Im} \Sigma_{tot}^r = \Gamma_L + \Gamma_R$). From Eqs. (9) and (10), which correspond to the transition process, it must be noted that the transition processes always exit when a PAT occurs, except that the electron-photon coupling coefficient g is small enough to be ignored.

III. DISCUSSION AND RESULT

The peak positions of spectral functions $a(\epsilon) = -2 \text{Im} G^r(\epsilon)$,¹⁴ i.e., photon sidebands corresponding to the described photon-associated tunneling system in this work, are shown in Fig. 1. The peak positions of the photon sidebands appear at $\epsilon_{b,n}^{\uparrow,\downarrow} = \epsilon_b + (\Delta/2) \pm (\Omega_{R,n+1}/2)$ and $\epsilon_{a,n}^{\uparrow,\downarrow} = \epsilon_a - (\Delta/2) \pm (\Omega_{R,n+1}/2)$. The energy shifts of the photon sidebands splitting from higher resonant level are $\Delta_{b,n}^{\uparrow,\downarrow} = |(\Delta/2)$

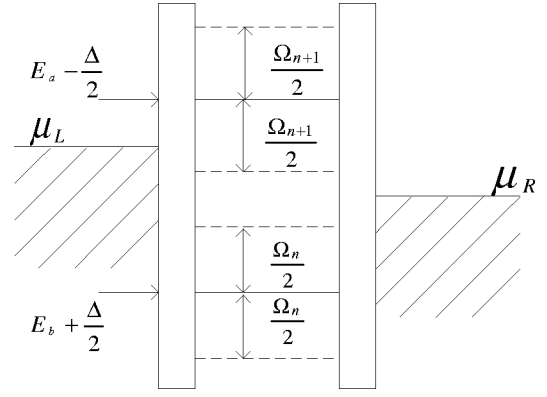


FIG. 1. Energy landscape of a two-level quantum dot; the higher level is E_a and the lower level is E_b . The photon sidebands (dash line) are created at $E_b + (\Delta/2) \pm (\Omega_{R,n}/2)$ due to the processes $|b,n\rangle \rightarrow |b,n\rangle$ and $|a,n-1\rangle \rightarrow |b,n\rangle$. The photon sidebands are created at $E_a - (\Delta/2) \pm (\Omega_{R,n}/2)$ due to the processes $|a,n\rangle \rightarrow |a,n\rangle$ and $|b,n+1\rangle \rightarrow |a,n\rangle$. The electron will transport into dot when the chemical potential $\mu_{L/R}$ matches the photon sidebands (dashed line).

$\pm (\Omega_{R,n}/2)|$ and the energy shifts of the photon sidebands splitting from the lower resonant level are $\Delta_{a,n}^{\uparrow,\downarrow} = |-(\Delta/2) \pm (\Omega_{R,n+1}/2)|$, where $\Omega_{R,n} = \sqrt{\Delta^2 + 4g^2n}$. Hence $\sqrt{(\Delta_{a,n}^{\uparrow,\downarrow})^2 - (\Delta_{b,n}^{\uparrow,\downarrow})^2} = g$, when $\Delta \ll \Omega_{R,n}$. Contrasting this with the result obtained by the semiclassical approach shown in Ref. 5, the energy shifts of the photon sidebands are the same, i.e., $\Delta_b^{\uparrow,\downarrow} = \Delta_a^{\uparrow,\downarrow} = |(\pm(\Delta/2) \pm (\Omega_{R,n}/2)|$ and $\Delta_a^{\uparrow,\downarrow} - \Delta_b^{\uparrow,\downarrow} = 0$. Hence the quantum situation, which must be described by the quantum approach, and the semiclassical region, which can be explained well by the semiclassical approach, can be distinguished clearly from each other by measuring the photon sideband energy shift. If the quantity $\sqrt{(\Delta_{a,n}^{\uparrow,\downarrow})^2 - (\Delta_{b,n}^{\uparrow,\downarrow})^2} = g$ is significant when comparing it to the energy scale of the system energy, then the photon-associated electron tunneling system is in the quantum situation. The physical meaning of this result can be understood to mean that the weak photon intensity will cause a large shift of the photon sideband due to the large electron-photon coupling coefficient g when the PAT system is in a quantum situation. Conversely, the system is in a semiclassical situation when g is small or n is very large, so that $\sqrt{(\Delta_{a,n}^{\uparrow,\downarrow})^2 - (\Delta_{b,n}^{\uparrow,\downarrow})^2} = g \sim 0$. In order to compare this effect, Figs. 2(a)–2(c) show the current peaks with fixed value $\Delta_{b,n}^{\uparrow,\downarrow} = 1.0, 0.5$ [the insets Figs. 2(a) and 2(b)] and various photon numbers; hence g corresponding to $\Delta_{b,n}^{\uparrow,\downarrow} = 1.0$ is larger than g corresponding to $\Delta_{b,n}^{\uparrow,\downarrow} = 0.5$ for the same photon number. When the photon number is large, the system is in a semiclassical situation and $(\Delta_{a,n}^{\uparrow,\downarrow})^2 \approx (\Delta_{b,n}^{\uparrow,\downarrow})^2$ (i.e., the system is in a semiclassical situation); hence we can set $\Delta_{a,64}^{\uparrow,\downarrow} \approx \Delta_{b,64}^{\uparrow,\downarrow}$ (i.e., in the case of Figs. 2(a)–2(c) the system can be treated as a semiclassical system when $n=64$, in which $g=0.016$ is very small compared to the energy scale of system), and obtain the quantity $(\Delta_{a,n}^{\uparrow,\downarrow})^2 - (\Delta_{b,n}^{\uparrow,\downarrow})^2$ by the quality $(\Delta_{a,n}^{\uparrow,\downarrow})^2 - (\Delta_{a,64}^{\uparrow,\downarrow})^2$. This shows that the quantum situation is more prominent [i.e., the quantity $(\Delta_{a,n}^{\uparrow,\downarrow})^2 - (\Delta_{a,64}^{\uparrow,\downarrow})^2$ is

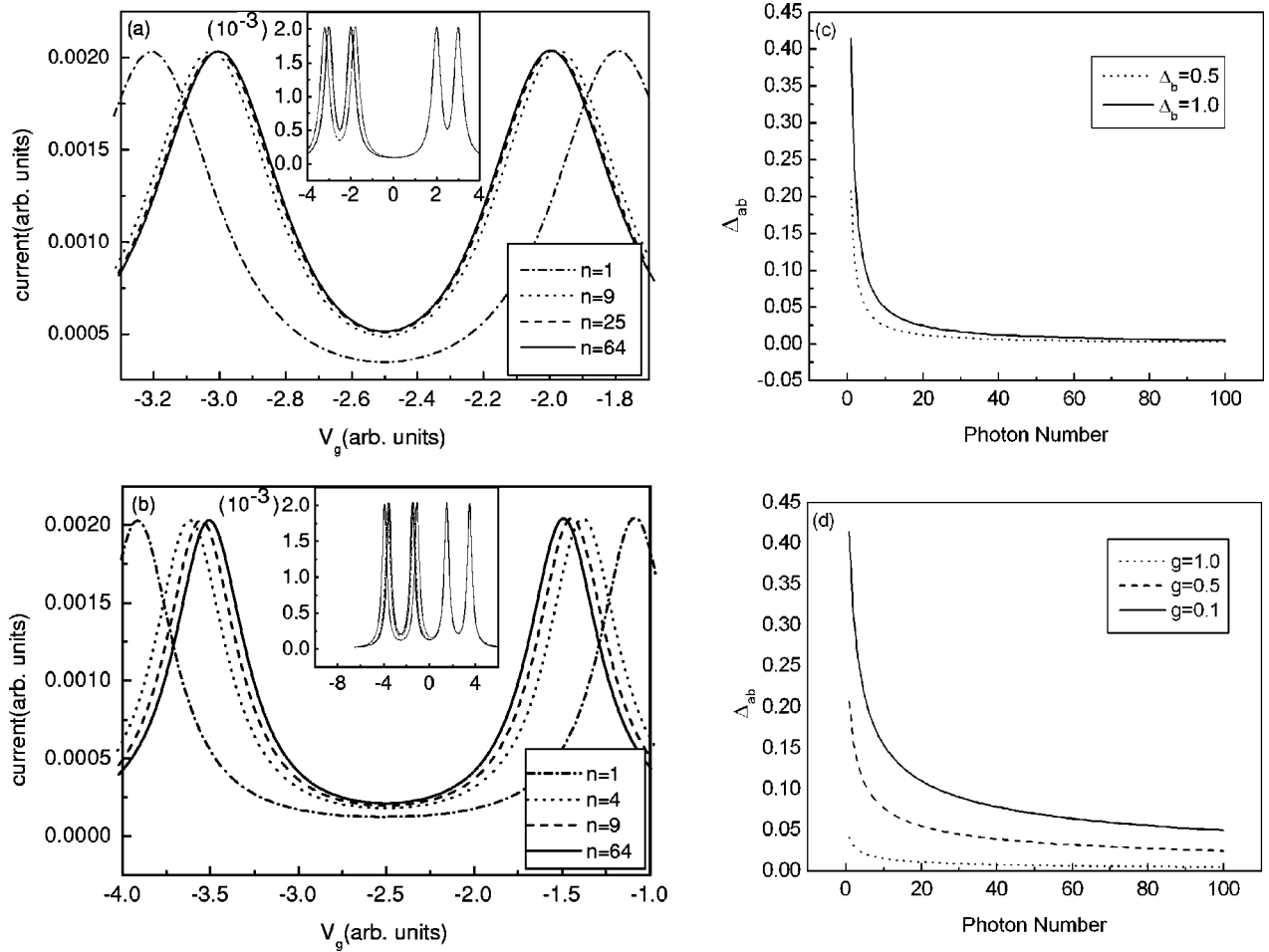


FIG. 2. I_{dc} - V_g curve of PAT in a dot system in which $E_a = 2.5$, $E_b = -2.5$, $\Gamma_L = \Gamma_R = \Gamma/2 = 0.5$, $\Delta = 0.5$, and $T = 10^{-3}$. (a) and (b) show the current peaks corresponding to a photon sideband splitting from a higher level E_a , for $|\Delta_b^{\uparrow\downarrow}| = 0.5$ and $|\Delta_b^{\uparrow\downarrow}| = 1.0$, respectively. The insets (a) and (b) are the I_{dc} - V_g curves corresponding to the sideband splitting from E_a and E_b , respectively. (c) shows $\Delta_{ab}(n) = \Delta_a^{\uparrow\downarrow}(n) - \Delta_b^{\uparrow\downarrow}(n)$, with $\Delta_b^{\uparrow\downarrow} = 0.5$ and $\Delta_b^{\uparrow\downarrow} = 1.0$. (d) shows $\Delta_{ab}(n)$ with $g = 1, 0.5$, and 0.1 .

larger] for a larger electron-photon coupling coefficient [Fig. 2(b)] or a lesser photon number [Figs. 2(a)–2(c)]. In Fig. 2(d), we show that $\Delta_{ab,n} \equiv \Delta_a^{\uparrow\downarrow} - \Delta_b^{\uparrow\downarrow}$ is more significant (quantum situation) when the electron-photon coupling coefficient is larger and the photon number is much lower, and vice versa. Another quantum phenomenon is the process $|an\rangle \rightarrow |an\rangle$ under a dark environment, i.e., $n = 0$; the corresponding sidebands appear at $\epsilon_a - (\Delta/2) \pm (\Omega_{R,1}/2)$ and have a nonzero amplitude which increases as g is increased. This result is due to the virtual photon emission and absorption processes, and can be ignored as g is close to zero which is in the semiclassical situation.

The PAT current can be estimated by the current formulas [Eqs. (3)–(6)] developed by Wingreen *et al.* The PAT currents are shown in Fig. 3, in which the right lead energy and gate voltage are set to zero and $\epsilon_a = 2.5$ and $\epsilon_b = -2.5$. The current will be assisted or suppressed by a photon field due to the shift of the photon sideband under electron-photon interaction. While the photon sideband $\epsilon_{a,n}^{\downarrow}$ or $\epsilon_{b,n}^{\uparrow}$ does not surpass the right lead energy, the corresponding current of each sideband is assisted—for instance, the currents corresponding to sidebands $\epsilon_{a,n}^{\downarrow}$ and $\epsilon_{b,n}^{\uparrow}$ for $n = 1$ and 9 are assisted (i.e., the current is assisted as the photon number is

increased). While the photon sideband $\epsilon_{a,n}^{\downarrow}$ or $\epsilon_{b,n}^{\uparrow}$ exceeds the right lead energy, the corresponding current of each sideband is suppressed—for instance, the currents corresponding to sidebands $\epsilon_{a,n}^{\downarrow}$ and $\epsilon_{b,n}^{\uparrow}$ for $n = 25$ and 64 are suppressed (i.e., the current is suppressed as the photon number is in-

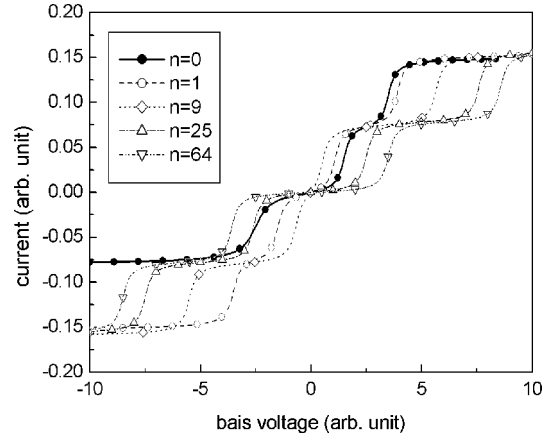


FIG. 3. I_{dc} - V_g curve of PAT under various photon field intensities in which $E_a = 2.5$, $E_b = -2.5$, $\Gamma_L = \Gamma_R = \Gamma/2 = 0.5$, $g = 1.0$, and $T = 10^{-3}$.

creased). But the currents corresponding to $\epsilon_{a,n}^\uparrow$ and $\epsilon_{b,n}^\downarrow$ are always suppressed. These phenomena are caused by the photon-field-strength-dependent photon sideband positions, i.e., the splitting of the photon sideband is increased due to the increase of the Rabi frequency $\Omega_n \equiv \sqrt{\Delta^2 + 4g^2n}$ as the photon number n is made larger. One can note that as the left lead voltage is less than the right lead voltage, the current direction is from the right lead to the left lead, i.e., the current is reversed (i.e., negative).

In many quantum optic experiments, there are some techniques to count the photon number. According to the above discussion, we propose a feasible experiment to determine the electron-photon coefficient g and the photon number n , and thus are able to distinguish whether the system is in a quantum situation or not. One can input a photon field with a frequency equal to the energy spacing between the ground state and the first excited state of a quantum dot into the PAT system, and modulate the gate voltage to decide the peak positions $\epsilon_{a,n}^{\uparrow,\downarrow}$ and $\epsilon_{b,n}^{\uparrow,\downarrow}$. Afterwards, one can obtain the photon sideband peak shifts $\Delta_{a,n}^\uparrow = \Delta_{a,n}^\downarrow = (\epsilon_{a,n}^\uparrow - \epsilon_{a,n}^\downarrow)/2$ and $\Delta_{b,n}^\uparrow = \Delta_{b,n}^\downarrow = (\epsilon_{b,n}^\uparrow - \epsilon_{b,n}^\downarrow)/2$. Hence the electron-photon coupling g can be determined by the relation $g = \sqrt{(\Delta_{a,n}^\uparrow)^2 - (\Delta_{b,n}^\uparrow)^2}$, and the photon number is obtained by $n = (\Delta_{b,n}^\uparrow/g)^2$. Note that the normal electric detectors (excluding the counting photon number experiment) do not detect the absolute photon intensity (photon number) but only the relative photon intensity. Using the method proposed above, one can obtain the g factor and the absolute photon intensity (photon number) of the PAT system.

Many reports convening on the ‘‘cavity QED’’ studied an atom interacting with a quantum photon field in a superconductor cavity.^{8,15} Since the properties of a quantum dot are well known to be similar to those of an atom, it may be

possible to implement some experiments which study the interaction between an electron in a quantum dot and a quantum photon field by means of enclosing the quantum dot in a superconductor cavity. Some experiments related to the cavity QED, such as the microscopic maser,¹⁵ may also be implemented by the apparatus suggested above.

In summary, the sidebands caused by a single photon emission are $\epsilon_{a,n}^{\uparrow,\downarrow} = \epsilon_a - (\Delta/2) \pm (\Omega_{R,n+1}/2)$, and the sidebands created due to a single-photon absorption are $\epsilon_{b,n}^{\uparrow,\downarrow} = \epsilon_b + (\Delta/2) \pm (\Omega_{R,n}/2)$. The sidebands depend on the Rabi frequency $\Omega_{R,n}$, which relates to the photon number (the intensity) of the environment and causes the PAT current to be assisted or suppressed for some appropriate contact energies. The energy level splitting due to two levels interacting with a photon can be also found in Ref. 5 by the semiclassical approach. However, in the present paper, we take one step ahead to explain the difference between quantum and semiclassical situations. We also point out that one can distinguish whether the system is in a quantum situation or not by certain specially arranged experiments. For the properties of the quantum situation of PAT (the large g or small photon number situation), we suggest a possible way to determine the electron-photon coupling g and the photon number of the system. We also point out that the PAT current is not always assisted due to the electron-photon interaction, but may also be suppressed. The assistance or suppression of the PAT current depends on the shift of the environmental-photon-intensity-dependent photon sideband.

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