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Delocalization of electrons by cavity photons in transport through a quantum dot molecule

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ABSTRACT

We present results on cavity-photon-assisted electron transport through two lateral quantum dots embedded in a finite quantum wire. The double quantum dot system is weakly connected to two leads and strongly coupled to a single quantized photon cavity mode with initially two linearly polarized photons in the cavity. Including the full electron–photon interaction, the transient current controlled by a plunger-gate in the central system is studied by using quantum master equation. Without a photon cavity, two resonant current peaks are observed in the range selected for the plunger gate voltage: The ground state peak, and the peak corresponding to the first-excited state. The current in the ground state is higher than in the first-excited state due to their different symmetry. In a photon cavity with the photon field polarized along or perpendicular to the transport direction, two extra side peaks are found, namely, photon-replica of the ground state and photon-replica of the first-excited state. The side-peaks are caused by photon-assisted electron transport, with multiphoton absorption processes for up to three photons during an electron tunneling process. The inter-dot tunneling in the ground state can be controlled by the photon cavity in the case of the photon field polarized along the transport direction. The electron charge is delocalized from the dots by the photon cavity. Furthermore, the current in the photon-induced side-peaks can be strongly enhanced by increasing the electron–photon coupling strength for the case of photons polarized along the transport direction.

An opto-electronic device provides a different platform of electron transport, namely photon-assisted transport (PAT) [1]. In the PAT, the energy levels of an electronic system have to match to photon frequency of a radiation source to control the electron motion. Therefore, the photon emission and the photon absorption processes play an essential role to enhance electron transport [2]. For that purpose, an electrostatic potential produced by a plunger-gate is applied to the electronic system to shift its energy levels in and out of resonance. The plunger-gate is widely used to control charge current [3], thermal current [4], photo-current [5] and spin-dependent current [6] for various quantized systems coupled to photon radiation.

The PAT controlled by plunger-gate has been investigated to study electrical [7] and optical [8,9] properties of a double-quantum dot (DQD) system , in which the PAT can be used as a spectroscopic tool in two different regimes defined by a zero [10], and non-zero [11] bias voltage. At zero-bias voltage, the DQD works as a proper electron pumping device in which the photon absorption process leads to electron tunneling producing a dc current. In the non-zero bias voltage, both the photon absorption and the photon emission processes generate a dc current. Recently, both regimes have been realized experimentally in a DQD system at low temperature [12,13].

The most important application of a DQD system in the quantum regime is intended for information storage in a quantum state [14], quantum-bits for quantum computing [15,16], and quantum information processing in two-state system [17]. Recent experimental work has focused on using the two lowest energy states contributing to tunneling processes in a DQD working as a two state system: The ground state resonance, and a photon-induced excited state resonance. They observed multiphoton absorption processes up to the four-order contributing to the electron transport [13].

Based on the above-mentioned considerations, we analyze PAT in serial double quantum dots embedded in a quantum wire. The DQD system is connected to two leads and coupled to a photon cavity with linearly polarized photons in the x- and y-directions, where the transport along the quantum wire is in the x-direction. As will be seen in our results the essential difference from the

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more traditional modeling of photo assisted transport is the presence of a photon cavity with few photons and the fact that we will monitor the resonant transport in the transient regime approaching a steady state regime for single-electron tunneling processes.

A quantum master equation (QME) formalism is utilized to investigate transient transport of electrons controlled by the plunger-gate in the system without and with a single-photon mode [3]. Generally, there are two types of QME when characterized according to memory effects, energy-dependent coupling, and the system-leads coupling strength: The Markovian and the non-Markovian QME. In the case of the Markovian approximation, the system-leads coupling is assumed weak and independent of energy, memory effect are ignored and most commonly a steady state is sought [18–21]. In the non-Markovian approach, the system is energetically coupled to the leads including memory effect in the system [22–24]. Since we are interested in studying transient transport of electrons in a regime with possible resonances, the non-Markovian model is used in our system [25].

In addition, we assume the DQD system to be connected to the leads through a non-zero or small bias window, where the two lowest energy states of the QDQ system can be isolated in the bias window: The ground state and the first-excited state. Our model of the DQD system can be seen as a qubit. In which the states $|0\rangle$ and $|1\rangle$ can be represented in terms of the ground state and the first-excited state. We will show how the single-photon mode affects the electron transport through both states when located in the bias window and demonstrate the role of photon activated states in the transient current. The double serial quantum dot is essential here: The two lowest single-electron states of the dot molecule have very different symmetry. The ground state has a symmetric wavefunction, but the excited state has an antisymmetric one. The conduction through the ground state is thus higher than through the excited one. The "inter-dot tunneling" can be influenced by a photon mode polarized in the transport direction, thus strongly modifying the conduction through the photon replicas of the states in a photon cavity. The nontrivial details of this picture will be analyzed in this paper reminding us that the effects rely on the geometry of the system and states beyond the ground state and the first excited one.

The rest of the paper is organized as follows. In Section 1 we introduce the model to describe the electron transport through a DQD embedded in a quantum wire connected to two leads and a photon cavity. Section 2 contains two subsections, the system without and with the photon cavity. In the absence of the photon cavity, the transient current through the system controlled by the plunger-gate is demonstrated in the presence of the electron–electron interactions in the DQD system. In the photon cavity, the photon-assisted electron transport in the system is presented for a system initially with no electron, but with two linearly polarized photons in the single-photon mode. Finally, conclusions are provided in Section 3.

1. Model and computational methods

The aim of this study is to model a photon-assisted electron transport in a DQD system connected to two identical electron reservoirs (lead) and coupled to a single photon mode in a cavity. Our first step is to look at the central system, in which electrons are confined in two dimensions. We assume a finite quantum wire with hard-wall ends at $x=\pm L_x/2$ with length $L_x=165$ nm. It is parabolically confined in the y-direction (perpendicular to the transport direction) with transverse confinement energy $\hbar\Omega_0=2.0$ meV. The embedded quantum dots are modeled by two identical Gaussian potentials in the quantum wire defined as

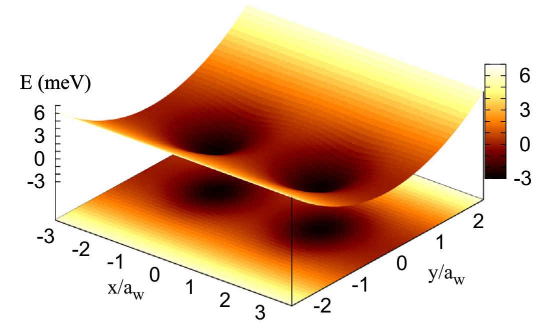

Fig. 1. Schematic diagram depicts the potential representing the DQD embedded in a quantum wire with parameters $B=0.1$ T, $a_w=23.8$ nm, and $\hbar\Omega_0=2.0$ meV.

$$V_{\rm DQD}(x,y)=\sum_{i=1}^{2}V_i\exp[-\beta_i^2((x-x_i)^2+y^2)], \tag{1}$$

with quantum-dot strength $V_{1,2}=-2.8$ meV, $x_1=35$ nm, $x_2=-35$ nm, and $\beta_{1,2}=5.0\times10^{-2}$ nm^{-1} such that the radius of each quantum-dot is $R_{\rm QD}\approx 20$ nm. A sketch of the DQD system under investigation is shown in Fig. 1. We should mention that the distance between the dots is $L_{\rm DQD}=35$ nm $\simeq 1.47a_w$, and each dot is 25 nm $=1.05a_w$ away from the nearest lead, where a_w is the effective magnetic length.

The DQD system is in a rectangular photon cavity with a single photon mode. The photons in the single photon mode are linearly polarized in the x- or y-directions, meaning that the photon polarization in the cavity is assumed to be parallel or perpendicular to the transport direction with respect to the electric field

$$\mathbf{A}_{\rm ph}=A_{\rm ph}(a+a^{\dagger})\hat{\mathbf{e}}, \tag{2}$$

where $A_{\rm ph}$ is the amplitude of the photon vector potential, $a^{\dagger}(a)$ are the creation (annihilation) operators for a photon, respectively, and $\hat{\mathbf{e}}$ determines the polarization with

$$\hat{\mathbf{e}}=\begin{cases}(e_x,0), & {\rm TE}_{011}\\ (0,e_y), & {\rm TE}_{101},\end{cases}$$

where ${\rm TE}_{011}$ (${\rm TE}_{101}$) indicates the parallel (perpendicular) polarized photon in the transport direction, respectively.

In the following sections, we shall couple the DQD system to both the photon cavity and the leads.

1.1. DQD system coupled to cavity

We consider the closed DQD system to be strongly coupled to a photon cavity. The many-body (MB) Hamiltonian

$$H_S=H_{\rm DQD}+H_{\rm Cavity}+H_{\rm Int} \tag{3}$$

consists of the Hamiltonian for the closed DQD system with the electron–electron interaction $H_{\rm DQD}$, the free photon cavity Hamiltonian $H_{\rm Cavity}$, and the Hamiltonian for the electron–photon interaction $H_{\rm Int}$.

The DQD system (and the external leads) is placed in an external uniform perpendicular magnetic field $B\hat{z}$ in the z-direction defining an effective lateral confinement length $a_w=(\hbar/m^*\sqrt{(\omega_c^2+\Omega_0^2)})^{1/2}$, where the effective electron mass is $m^*=0.067m_e$ for GaAs material and $\omega_c=eB/m^*c$ is the cyclotron frequency. The Hamiltonian for the DQD system in a magnetic field including the electron–electron interaction can be written as

$$H_{\rm DQD}=\sum_{i,j}\langle\psi_i|\left\{\frac{\boldsymbol{\pi}_e^2}{2m^*}+V_{\rm DQD}+eV_{\rm pg}\right\}|\psi_j\rangle\delta_{i,j}d_i^{\dagger}d_j$$
$$+H_{\rm Coul}+H_Z, \tag{4}$$