Electron transport through a quantum dot assisted by cavity photons

Nzar Rauf Abdullah¹, Chi-Shung Tang², Andrei Manolescu³ and Vidar Gudmundsson¹

¹ Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland
² Department of Mechanical Engineering, National United University, 1, Lienda, Miaoli 36003, Taiwan
³ School of Science and Engineering, Reykjavik University, Menntavegur 1, IS-101 Reykjavik, Iceland

E-mail: cstang@nuu.edu.tw and vidar@raunvis.hi.is

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Abstract
We investigate transient transport of electrons through a single quantum dot controlled by a plunger gate. The dot is embedded in a finite wire with length $L_x$ assumed to lie along the $x$-direction with a parabolic confinement in the $y$-direction. The quantum wire, originally with hard-wall confinement at its ends, $±L_x/2$, is weakly coupled at $t = 0$ to left and right leads acting as external electron reservoirs. The central system, the dot and the finite wire, is strongly coupled to a single cavity photon mode. A non-Markovian density-matrix formalism is employed to take into account the full electron–photon interaction in the transient regime. In the absence of a photon cavity, a resonant current peak can be found by tuning the plunger-gate voltage to lift a many-body state of the system into the source–drain bias window. In the presence of an $x$-polarized photon field, additional side peaks can be found due to photon-assisted transport. By appropriately tuning the plunger-gate voltage, the electrons in the left lead are allowed to undergo coherent inelastic scattering to a two-photon state above the bias window if initially one photon was present in the cavity. However, this photon-assisted feature is suppressed in the case of a $y$-polarized photon field due to the anisotropy of our system caused by its geometry.

(Some figures may appear in colour only in the online journal)

1. Introduction

Electronic transport through quantum dot (QD) related systems has received tremendous attention in recent years due to its potential application in various fields, such as the implementation of quantum computing [1], nanoelectromechanical systems [2], photodetectors [3], and biological sensors [4]. The QD-embedded structure can be fabricated in a two-dimensional electron gas, controlled by a plunger-gate voltage, and connected to the leads by applying an external source–drain bias voltage.

Electronic transport under the influence of time-varying external fields is one of the interesting areas. Transport phenomena in the presence of photons have been intensively studied in many mesoscopic systems [5–14]. Among the various quantum confined geometries to characterize the photon-assisted features are, for example, a quantum ring with an embedded dot for exploring mono-parametric quantum charge pumping [7], a single QD for investigating single-electron (SE) tunneling [8], a quantum wire for studying electron population inversion [9], and a quantum point contact involving photon-induced intersubband transitions [10, 11]. Recently, the electrical properties of double QD systems influenced by electromagnetic irradiation have been studied [12, 13], indicating a spin-filtering effect [12], and two types of photon-assisted tunneling related to the ground state and excited state resonances [13]. The classical and quantum response was investigated experimentally in terms of the sharpness of the transition rate, which depends on the thermal broadening of the Fermi level in the electrodes and the broadening of the confined levels [14].

In the above-mentioned examples the photon-assisted transport was induced by a classical electromagnetic field. It is also interesting to investigate electronic transport through...
a QD system influenced by a quantized photon field. A single-photon source is an essential building block for the manipulation of the quantum information coded by a quantum state [15]. This issue has been considered by calculating the resonant current carried by negatively charged excitons through a double QD system confined in a cavity [16], where resonant tunneling between two QDs is assisted by a single photon. Recently several experimental groups have successfully coupled a single quantum dot with one cavity mode [17–20]. However, modeling of transient electronic transport through a QD in a photon cavity is still in its infancy.

To study time-dependent transport phenomena in mesoscopic systems, a number of approaches have been employed. In closed systems, the Jarzynski equation was derived by defining the free-energy difference of the system between the initial and final equilibrium state in terms of a stochastic Liouville equation [21] or microscopic reversibility [22]. In open quantum systems where the system is connected to electron reservoirs, the Jarzynski equation can be derived using a master equation approach to investigate fluctuation theorems [23] and dissipative quantum dynamics [24]. In order to investigate interaction effects on the transport behavior, several approaches have been proposed based on the quantum master equation (QME) applied to a quantum measurement of a two-state system [25], calculation of current noise spectrum [26], and the counting statistics of electron transfers through a double QD [27].

The QME describes the evolution of the reduced density (RD) operator caused by the Hamiltonian of the closed system in the presence of electron or photon reservoirs. Thus, the QME usually consists of two parts: one describing the unitary evolution of the closed system and the other being a dissipative part describing the influence of the reservoirs [28].

In an open current-carrying system weakly coupled to leads, master equations within the Markovian and wide-band approximations have been commonly derived and used [29–31]. The coupling to electron or photon reservoirs can be considered to be Markovian and the rotating wave approximation is often used for the electron–photon coupling [29]. The QME may reduce to a ‘birth and death master equation’ for populations [30], or modified rate equations [31]. The energy dependence of the electron tunneling rate or the memory effect in the system are usually neglected.

The non-Markovian density-matrix formalism with energy-dependent coupling elements should be considered to study the full counting statistics for electronic transport through interacting electron systems [32–34]. It was noticed that the Markovian limit neglects coherent oscillations in the transient regime, and the rate at which the steady state is reached does not agree with the non-Markovian model [35]. The Markov approximation shows significantly longer times to reach a steady state when the tunneling anisotropy is high, thus confirming its applicability only in the long-time limit. To investigate the transient transport, a non-Markovian density-matrix formalism involving energy-dependent coupling elements should be explicitly considered [36].

The aim of this work is to investigate how the \( x \)- and \( y \)-polarized single-photon modes influence the ballistic transient electronic transport through a QD embedded in a finite quantum wire in a uniform perpendicular magnetic field based on the non-Markovian dynamics. We explicitly build a transfer Hamiltonian that describes the contact between the central quantum system and semi-infinite leads with a switching-on coupling in a certain energy range. By controlling the plunger gate, we shall demonstrate robust photon-assisted electronic transport features when the physical parameters of the single-photon mode are appropriately tuned to cooperate with the electron–photon coupling and the energy levels of the Coulomb interacting electron system.

The paper is organized as follows. In section 2, we model a QD with interacting electrons embedded in a quantum wire coupled to a single-photon mode in a uniform magnetic field, in which the full electron–photon coupling is considered. The transient dynamics is calculated using a generalized QME based on a non-Markovian formalism. Section 3 demonstrates the numerical results and transient transport properties of the plunger-gate controlled electron system coupled to the single-photon mode with either \( x \)- or \( y \)-polarization. Concluding remarks will be presented in section 4.

2. Model and theory

In this section, we describe how the embedded QD, realized in a two-dimensional electron gas in gallium arsenide (GaAs), can be described by the potential \( V_{QD} \) in a finite quantum wire and its connection to the leads in a uniform perpendicular magnetic field. The plunger-gate controlled central electronic system is strongly coupled to a single-photon mode that can be described by a many-body (MB) system Hamiltonian \( H_S \), in which the electron–electron interaction and the electron–photon coupling to the \( x \)- and \( y \)-polarized photon fields are explicitly taken into account, as depicted in figure 1(a). A generalized QME is numerically solved to investigate the dynamical transient transport of electrons through the single QD system.

2.1. QD-embedded wire in magnetic field

The electron system under investigation is a two-dimensional finite quantum wire that is hard-wall confined at \( x = \pm L_w/2 \) in the \( x \)-direction, and parabolically confined in the \( y \)-direction. The system is exposed to an external perpendicular magnetic field \( \mathbf{B} = B_z \hat{z} \), defining a magnetic length \( l = (\hbar/eB)^{1/2} = 25.67B(T)\ h^{1/2} \text{ nm} \), and the effective confinement frequency \( \Omega_0^2 = \omega_c^2 + \Omega_0^2 \), being expressed in the cyclotron frequency \( \omega_c = eB/m^*c \) as well as in the bare confinement energy \( \hbar \Omega_0 \) characterizing the transverse electron confinement. The system is scaled by the effective magnetic length \( a_w = (\hbar/m^*\Omega_0)^{1/2} \). Figure 1(b) shows the embedded QD subsystem scaled by \( a_w \), where the QD potential is considered of a symmetric Gaussian shape

\[
V_{QD}(x, y) = V_0 \exp[-\beta_0(x^2 + y^2)]
\]

with strength \( V_0 = -3.3 \text{ meV} \) and \( \beta_0 = 3.0 \times 10^{-2} \text{ nm}^{-1} \) such that the radius of the QD is \( R_{QD} \approx 33.3 \text{ nm} \).
2.2. Many-body model

In this section, we describe how to build up the time-dependent Hamiltonian $H(t)$ of an open system that couples the QD-embedded MB system to the leads. The Coulomb and photon interacting electrons of the QD system are described by a MB system Hamiltonian $H_S$. In the closed electron–photon interacting system, the MB-space $|\tilde{\nu}\rangle$ is constructed from the tensor product of the electron–electron (state basis $|\nu\rangle$) and the eigenstates $|N\rangle$ of the photon number operator $a_d^\dagger a_d$, namely $|\tilde{\nu}\rangle = |\nu\rangle \otimes |N\rangle$ [37]. The Coulomb interacting ME states of the isolated system are constructed from the SE states [38].

The time-dependent Hamiltonian describing the MB system coupled to the leads

$$H(t) = H_s + \sum_{l=L,R} [H_l + H_{T_l}(t)]$$

consists of a disconnected MB system Hamiltonian $H_s$, and the ME Hamiltonian of the leads $H_l$ where the electron–electron interaction is neglected. In addition, $L$ and $R$ refer to the left and the right lead, respectively. Moreover, $H_{T_l}(t)$ is a time-dependent transfer Hamiltonian that describes the coupling between the QD system and the leads.

The isolated QD system including the electron–electron and the photon–electron interactions is governed by the MB system Hamiltonian

$$H_s = \sum_{ij} \langle \psi_i | \left[ \frac{\pi^2}{2m^*} + V_{QD} + eV_{pg} \right] | \psi_j \rangle d_i^\dagger d_j + H_{e-e} + H_{ph} + H_Z$$

where $|\psi_i\rangle$ is a SE state, $d_i^\dagger$ ($d_i$) are the electron creation (annihilation) operators in the central system, and $H_{ph} = \hbar \omega_{ph} a_d^\dagger a_d$ is the photon Hamiltonian. In addition, $\pi = \pi_e + \frac{e}{\hbar} A_{ph}$, where $\pi_e = p + \frac{e}{\hbar} A_{electron}$ is composed of the momentum operator $p$ of the electronic system and the vector potential $A_{electron} = (0, -By, 0)$ represented in the Landau gauge. $H_Z$ is the Zeeman energy $\pm g^* \mu_B B$, where $\mu_B$ is the Bohr magneton and $g^*$ the effective Lande $g$-factor for the material.

In the Coulomb gauge, the photon vector potential can be represented as

$$A_{ph} = A_{ph}(a + a^\dagger) \hat{e},$$

if the wavelength of the cavity mode is much larger than the size of the central system. Herein, $A_{ph}$ is the amplitude of the photon field. The electron–photon coupling strength is thus defined by $g_{ph} = eA_{ph} \Omega_{ph}/c$. In addition, $\hat{e} = (e_x, 0)$ indicates the electric field is polarized parallel to the transport direction in a TE01 mode, and $\hat{e} = (0, e_y)$ denotes the electric field is polarized perpendicular to the transport direction in a TE101 mode. Moreover, we introduce the plunger-gate voltage $V_{pg}$ to control the alignment of quantized energy levels in the QD system relative to the electrochemical potentials in the leads. In the second term of equation (3), $\hbar \omega_{ph}$ is the quantized photon energy, and $a_d^\dagger (a_d)$ are the operators of photon creation (annihilation), respectively. The last term $H_{e-e}$ describes the electron–electron interaction.

In a second quantized form, the isolated MB system Hamiltonian $H_s$ can be separated as

$$H_s = H_e + H_{ph} + H_{e-ph} + H_Z$$

where $H_{e-ph}$ is the Coulomb interacting electron Hamiltonian

$$H_e = \sum_i \left( E_i + eV_{pg} \right) d_i^\dagger d_i + \frac{1}{2} \sum_{ijrs} (V_{Coal}) d_i^\dagger d_j^\dagger d_s d_r,$$

where $E_i$ is the energy of a SE state, $V_{pg}$ is the electrostatic potential of the plunger gate, and

$$\langle V_{Coal} \rangle = \langle ij | V_{Coal} | rs \rangle = \int d\mathbf{r} dr' \psi_i^S(\mathbf{r})^* \psi_r^S(\mathbf{r}')^*$$

$$\times V(\mathbf{r} - \mathbf{r}') \psi_r^S(\mathbf{r}') \psi_i^S(\mathbf{r})$$

are the Coulomb matrix elements in the SE state basis, with $\psi_i^S(\mathbf{r})$ being the SE state wavefunctions and $V(\mathbf{r} - \mathbf{r}')$ the Coulomb interaction potential [38]. The second part in equation (5) is the photon Hamiltonian $H_{ph} = \hbar \omega_{ph} \hat{N}_{ph}$, with $\hat{N}_{ph} = a_d^\dagger a_d$ being the photon number operator. The third part
in equation (5) is the electron–photon coupling Hamiltonian
\[ H_{e-ph} = g_{ph} \sum_{ij} \hat{d}_i \hat{d}_j (a + a^\dagger) \]
\[ + \frac{\mu^2}{\hbar^2 \omega^2} \sum_{ij} \hat{d}_i \hat{d}_j \left[ \hat{N}_{ph} + \frac{1}{2} (a^\dagger a^\dagger + aa + 1) \right] \] (8)
with the dimensionless electron–photon coupling factor \( g_{ph} \) [39]. An exact diagonalization method is used to solve the Coulomb interacting ME Hamiltonian for the central system [40]. In order to couple the central system to the leads connecting to the left (right) reservoir with chemical potential \( \mu_L (\mu_R) \), it is important to consider all MB states in the system and SE states in the leads within an extended energy interval \( [\mu_R - \Delta_R, \mu_L + \Delta_L] \) in order to include all the relevant MB states involved in the dynamic transient transport.

The second term in equation (2) is the noninteracting ME Hamiltonian in the lead \( l \) given by
\[ H_l = \int dq \left[ e \langle \psi_l(q) c_l^\dagger c_l q \rangle \right] \] (9)
where we combine the momentum of a state \( q \) and its subband index \( n_l \) in lead \( l \) into a single dummy index \( q = (n_l, q) \); we thus use \( \int dq = \sum_{n_l} \int dq \) to symbolically express the summation and integration for simplicity. In addition, \( c_l^\dagger \) and \( c_l \) are, respectively, the electron creation and annihilation operators of the electron in the lead \( l \).

The system–lead coupling Hamiltonian is expressed as
\[ H_{TL}(t) = \chi_l(t) \sum_i \int dq \left[ c_{il}^\dagger T_{qil} d_i + d_i^\dagger (T_{qil})^* c_{il} q \right] \] (10)
where \( \chi_l(t) = 1 - 2 \exp[\alpha_l(t - t_0)] + 1 \) is a time-dependent switching function with a switching parameter \( \alpha_l \), and
\[ T_{qil} = \int dr dr' \psi_{qil}(r', r) g_{qil}(r, r') \] (11)
indicates the state-dependent coupling coefficients describing the electron transfer between a SE state \( | \tilde{\psi} \rangle \) in the central system and the extended state \( | q \rangle \) in the leads, where \( \psi_{qil}(r) \) is the SE wavefunction in the lead \( l \) and \( g_{qil}(r, r') \) denotes the coupling function [36].

2.3. General formalism of the master equation

The time evolution of electrons in the QD-leads system satisfies the Liouville–von Neumann (LvN) equation [41, 42]
\[ i\hbar \dot{W}(t) = [H(t), W(t)] \] (12)
in the MB-space, where the density operator of the total system is \( W(t) \), with the initial condition \( W(t < t_0) = \rho_{0L} \rho_{RS} \). Electrons in the lead \( l \) in steady state before coupling to the central QD system are described by the grand canonical density operator [43]
\[ \rho_l = \frac{e^{-\beta (\hat{H} - \mu_l N_l)}}{Tr[e^{-\beta (\hat{H} - \mu_l N_l)}]} \] (13)
where \( \mu_l \) denotes the chemical potential of lead \( l \), \( \beta = 1/k_B T_l \) is the inverse thermal energy, and \( N_l \) indicates the total number of electrons in lead \( l \). The LvN (equation (12)) can be projected on the central system by taking the trace over the Hilbert space of the leads to obtain the RD operator \( \rho(t) = Tr_L Tr_R W(t) \), where \( \rho(t_0) = \rho_S [44, 45] \). We diagonalize the electron–photon coupled MB system Hamiltonian \( H_S \) within a truncated Fock space built from 22 SE states \( \{| \mu \rangle \} [39, 46] \), then the system is connected to the leads at time \( t = t_0 \) thus containing a variable number of electrons. We include all sectors of the MB Fock space, where the ME states with zero to four electrons are dynamically coupled to the photon cavity with zero to 16 photons. The diagonalization gives us a new interacting MB state basis \( | \tilde{\nu} \rangle \), in which \( | \tilde{\nu} \rangle = \sum \nu \tilde{W}_{\nu} | \tilde{\nu} \rangle \), with \( \tilde{W}_{\nu} \) being a unitary transformation matrix with size \( N_{MB} \times N_{MB} \). SE states are labeled with Latin indices and many-particle states have a Greek index. The spin information is implicit in the index. The spin degree of freedom is essential to describe correctly the structure of the few-body Fermi system. This allows us to obtain the RD operator in the interacting MB state basis \( \tilde{\rho}(t) = W^\dagger \rho(t) W \).

Using the notation
\[ \Omega_{qil}(t) = U^\dagger_S(0) \int_{t_0}^t ds \chi_l(s) \Pi_{qil}(s) \]
\[ \times \exp \left[ -i \hbar (t - s) \epsilon_l(q) \right] U_S(t), \] (14)
where
\[ \Pi_{qil}(s) = U_S(s) (\tilde{T}_l^\dagger \tilde{\rho}(s) [1 - f_l(\epsilon_l(q))] \]
\[ - \tilde{\rho}(s) (\tilde{T}_l^\dagger f_l(\epsilon_l(q)) U^\dagger_S(s), \] with \( U_S(t) = \exp[iH_S(t - t_0)/\hbar] \) being the time evolution operator of the closed central system and \( f_l(\epsilon_l(q)) = [\exp(\epsilon_l(q) - \mu_l) + 1]^{-1} \) being the Fermi function in lead \( l \) at \( t = t_0 \), the time evolution of the RD operator can then be expressed as
\[ \frac{d\tilde{\rho}(t)}{dt} = -\frac{i}{\hbar} [H_S, \tilde{\rho}(t)] - \frac{1}{\hbar^2} \sum_{l=L,R} \chi_l(t) \]
\[ \times \int dq \left[ | \tilde{T}_l(q) \rangle, \Omega_{qil}(t) \right] + h.c. \] (15)
The first term governs the time evolution of the disconnected central interacting MB system. The second term describes the energy dissipation of interacting electrons through charging and discharging effects in the central system by the leads. In the second term, \( \tilde{T}_l(q) \) is the interacting MB coupling matrix
\[ \tilde{T}_l(q) = \sum_{\mu,\nu} T_{\mu\nu l}(q) | \tilde{\nu} \rangle (\tilde{\nu}), \] (16)
in which both the Coulomb interaction and the electron–photon coupling have been included. Here \( T_{\mu\nu l}(q) = \sum_{\tilde{\nu}} T_{qil}(\tilde{\nu} | \tilde{\nu} \rangle (\tilde{\nu}) \) indicates the coupling of MB states \( | \tilde{\nu} \rangle \) in the central system caused by the coupling to the SE states in the leads described by the coupling matrix \( T_{qil} \).
2.4. Charge and current

We now focus on the physical observables that we calculate for the QD system. The mean photon number in each MB state \(|\tilde{\nu}\rangle\) can be written as

\[
N_{\text{ph}} = \langle \tilde{\nu} | \hat{N}_{\text{ph}} | \tilde{\nu} \rangle, \tag{17}
\]

where \(\hat{N}_{\text{ph}}\) is the photon number operator. The average of the electron number operator can be found by taking the trace of the MB states \(|\tilde{\nu}\rangle\) in the Fock space, namely \(\langle \hat{N}_\nu (t) \rangle = \text{Tr}[W(t)\hat{N}_\nu]\).

The mean value of the interacting ME charge distribution in the QD system is thus defined by

\[
Q(r, t) = e \sum_{i,j} \psi^*_i(r) \psi_j(r) \sum_{\mu, \nu} (\hat{\mu} | d_{j}^{\dagger} | \tilde{\nu} \rangle \langle \tilde{\nu} | \hat{\mu}^{\dagger} \rangle_{\nu} (t) \tag{18}
\]

where \(e > 0\) stands for the magnitude of the electron charge, and \(\hat{\mu} (t) = (\tilde{\nu} | \hat{\mu} (t) | \tilde{\nu} \rangle\) is the time-dependent RD matrix in the MB-space.

In order to analyze the transient transport dynamics, we define the net charging current

\[
I_Q(t) = I_L(t) + I_R(t) \tag{19}
\]

where \(I_L(t)\) indicates the partial charging current from the left lead into the system, and \(I_R(t)\) represents the partial charging current from the right lead into the system. Here, the left and right partial currents \(I(t)\) can be explicitly expressed in the following form

\[
I_L(t) = -\frac{e}{\hbar} \chi_L(t) \times \sum_{\mu} \int dq \langle \tilde{\nu} | \hat{\chi}_L (q) | \Omega_{\nu} (t) \rangle + \text{h.c.} | \tilde{\nu} \rangle. \tag{20}
\]

3. Results and discussion

In this section, we consider a QD embedded in a finite quantum wire system, made of a high-mobility GaAs/AlGaAs heterostructure with an electron effective mass \(m^* = 0.067m_e\) and relative dielectric constant \(\varepsilon_r = 12.4\), with length \(L_x = 300\) nm and bare transverse electron confinement energy \(h\Omega_{0} = 2.0\) meV. A uniform perpendicular magnetic field \(B = 0.1\) T is applied and, hence, the effective magnetic length is \(a_w = 23.8\) nm and the characteristic Coulomb energy is \(E_C = e^2/(2\varepsilon_r a_w) \approx 2.44\) meV. The effective Lande \(g\)-factor \(g^* = 0.44\).

We select \(\beta_0 = 3.0 \times 10^{-2}\) nm\(^{-1}\) such that the radius of the embedded QD is \(R_{\text{QD}} = 1.4a_w\). The QD system is transiently coupled to the leads in the \(x\)-direction that is described by the switching parameter \(a^2 = 0.3\) ps\(^{-1}\) and the nonlocal system–lead coupling strength \(\Gamma_L = 1.58\) meV nm\(^{-2}\) [38]. A source–drain bias \(V_{\text{bias}}\) is applied, giving rise to the chemical potential difference \(\Delta \mu = eV_{\text{bias}} = 0.1\) meV.

To take into account all the relevant MB states, an energy window \(\Delta_E = 5.5\) meV is considered to include all active states in the central system contributing to the transport. The temperature of the system is assumed to be \(T = 0.01\) K, such that the typical MB energy level spacing is greater than the thermal energy, namely \(\Delta E_{\text{MB}} \gg k_B T\). The thermal smearing effect is thus sufficiently suppressed. In the following, we shall select the energy \(\hbar\omega_{\text{ph}}\) of the photon mode to be smaller than the characteristic Coulomb energy, namely \(E_C > \hbar\omega_{\text{ph}}\). In the following, we shall demonstrate the plunger-gate controlled transient transport properties both in the case without a photon cavity and in the case including a photon cavity with either an \(x\)– or \(y\)-polarized photon field.

The energy of the photons, \(\hbar\omega_{\text{ph}}\), will in both polarization cases be held at 0.3 meV. For the length of the central system, \(L_y = 300\) nm, the photon energy will be comparable to the spacing of energy levels connected to motion of the electrons in the \(x\)-direction. We can thus expect the \(x\)-polarized photons to be able to promote resonances with translation in the \(x\)-direction—the transport direction. The confinement energy in the \(y\)-direction, \(\hbar\Omega_{0} = 2.0\) meV, on the other hand, is large enough to ensure almost all photon-induced motion in the \(y\)-direction to be out-of-resonance phenomena. This simple picture is slightly modified by the embedded quantum dot. The anisotropy of the central system can be expected to show up in the photon-activated processes investigated, due to the interplay of the photon energy and the characteristic energy scales for \(x\)- and \(y\)-motion.

3.1. Without a photon cavity

First, we consider the QD embedded in a quantum wire without a photon cavity in a uniform magnetic field \(B = 0.1\) T that is coupled to the leads acting as SE reservoirs controlled by a source–drain bias. In figure 2(a), we show the SE energy spectrum in the leads (red) as a function of wavenumber \(q\) where the chemical potentials are \(\mu_L = 1.2\) meV and \(\mu_R = 1.1\) meV (green). (b) The ME energy spectrum in the central system as a function of plunger-gate voltage \(V_{\text{pg}}\) including SE states (1ES, red dots) and two-electron states (2ES, blue dots). The SE state in the bias window is almost doubly degenerate due to the small Zeeman energy.
modes, while higher subbands contribute to the evanescent modes. In addition, the chemical potential (green) is \( \mu_L = 1.2 \) meV in the left lead and \( \mu_R = 1.1 \) meV in the right lead, implying the chemical potential difference \( \Delta \mu = 0.1 \) meV. Figure 2(b) shows the ME energy spectrum of the QD system, in which the electron–electron interaction is included while no electron–photon coupling has been introduced. Both the energies of SE states \( N_e = 1 \) (1ES, red dots) and two-electron states \( N_e = 2 \) (2ES, blue dots) vary linearly proportional to the applied plunger-gate voltage \( V_{pg} \), but with different slopes. The two-electron states are located at relatively higher energies due to the Coulomb repulsion effect in the QD-embedded system.

The SE state energy is tunable as a function of plunger-gate voltage \( V_{pg} \) following \( E_{SE}(V_{pg}) = E_{SE}(0) + eV_{pg} \). We rank the SE and ME states by energy. In the absence of a plunger-gate voltage, the lowest active SE states in the central system are \( \{4\} \) and \( \{5\} \), with energies \( E_4(0) = 0.741 \) meV and \( E_5(0) = 0.744 \) meV, respectively. These two SE states may enter the chemical potential window \( [\mu_L, \mu_R] = [1.1, 1.2] \) meV by tuning the plunger-gate voltage to be \( V_{pg} \approx [0.35, 0.45] \) mV. Consequently, the SE states occupying the first subband in the left lead are allowed to tunnel into the central ME system, resonantly tunneling from the left to the right lead, manifesting a main-peak feature in charging current \( I_Q = 0.112 \) nA at \( V_{pg} = 0.4 \) mV, as shown in figure 3.

In the following sections, we shall place the QD system in a photon cavity with a single-photon mode. We shall analyze the transient transport properties for the cases with linear polarizations in either the \( x- \) or \( y- \)direction.

3.2. \textit{x}-polarized photon mode

Here, we demonstrate how the QD embedded in a quantum wire can be controlled by the plunger gate and how it is influenced by the photon field, where the electric field of the \( \text{TE}_{011} \) mode is polarized in the \( x- \)direction. The initial condition of the system under investigation is an empty central system (no electron) that is coupled to a single-photon mode with one photon present, connected to the leads with a source–drain bias. The MB energy spectrum of the electron–photon interacting MB system is illustrated in figure 4. As shown in the previous section, active states enter the bias window around \( V_{pg} = 0.4 \) mV in the case with no photon cavity. It is interesting to note that additional active states can be included around \( eV_{pg} = eV_{pg}^0 \pm \hbar\omega_{ph} \), as is clearly seen in figure 4, implying that the \( x- \)polarized photon field induced active propagating states can be found around \( V_{pg} = 0.1 \) and 0.7 mV when the photon energy is \( \hbar\omega_{ph} = 0.3 \) meV. The additional photon-induced propagating states play an important role in enhancing the electron tunneling from the leads to the QD system.

Figure 5 shows the net charging current \( I_Q \) as a function of the plunger-gate voltage \( V_{pg} \) in the presence of the photon cavity. The net charging current \( I_Q \) is plotted as a function of plunger-gate voltage \( V_{pg} \) at time \( t = 220 \) ps in the case of no photon cavity. Other parameters are \( B = 0.1 \) T and \( \Delta \mu = 0.1 \) meV.

Figure 3. The net charging current \( I_Q \) is plotted as a function of plunger-gate voltage \( V_{pg} \) at time \( t = 220 \) ps in the case of no photon cavity. Other parameters are \( B = 0.1 \) T and \( \Delta \mu = 0.1 \) meV.

Figure 4. MB energy spectrum versus the plunger-gate voltage \( V_{pg} \) in the case of an \( x- \)polarized photon field, where zero-electron states \( (N_e = 0, \text{ green dots}) \), single-electron states \( (N_e = 1, \text{ red dots}) \), and two-electron states \( (N_e = 2, \text{ blue dots}) \) are included. Other parameters are \( B = 0.1 \) T, \( \Delta \mu = 0.1 \) meV, and \( \hbar\omega_{ph} = 0.3 \) meV.

Figure 5. The net charging current \( I_Q \) versus the plunger-gate voltage \( V_{pg} \) in the case of an \( x- \)polarized photon field at time \( t = 220 \) ps with different electron–photon coupling strengths: \( g_{ph} = 0.1 \) meV (blue solid), \( g_{ph} = 0.2 \) meV (green dashed), and \( g_{ph} = 0.3 \) meV (red dotted). Other parameters are \( \hbar\omega_{ph} = 0.3 \) meV, \( \Delta \mu = 0.1 \) meV, and \( B = 0.1 \) T.
of the $x$-polarized photon field at time $t = 220$ ps. We fix the photon energy at $\hbar \omega_{ph} = 0.3$ meV and change the electron–photon coupling strength $g_{ph}$. A main peak around $V_{pg} = 0.4$ meV is found, a robust left side peak around $eV_{pg} = eV_{pg}^0 - \hbar \omega_{ph}$ is clearly shown, and a right side peak around $eV_{pg} = eV_{pg}^0 + \hbar \omega_{ph}$ can be barely recognized. The left side peak exhibits photon-assisted transport feature from the SE MB states $|\tilde{2}\rangle$ and $|\tilde{2}\rangle$ in the bias window by absorbing a photon energy $\omega_{ph}$ to the SE MB states $|\tilde{2}\rangle$ and $|\tilde{2}\rangle$ above the bias window. However, the opposite photon-assisted transport feature caused by a photon emission (the right side peak) is significantly suppressed.

The main charge current peaks for $V_{pg} = 0.4$ meV are $I_Q = 0.120, 0.173$, and 0.270 nA corresponding to $g_{ph} = 0.1$ meV (blue solid), $g_{ph} = 0.2$ meV (green dashed), and $g_{ph} = 0.3$ meV (red dotted), as shown in figure 5. Our results demonstrate that the current carried by the electrons with energy within the bias window can be strongly enhanced by increasing the electron–photon coupling strength. At $V_{pg} = 0.1$ meV, the left side peaks in the charging current are $I_Q = 0.017, 0.072$, and 0.103 nA, corresponding to $g_{ph} = 0.1, 0.2$, and 0.3 meV. This implies that the electrons may absorb the energy of a single photon and, hence, the charging current manifests photon-assisted transport.

To identify the active MB states contributing to the transient transport, we show the characteristics of the MB states at $V_{pg} = 0.4$ and 0.1 meV in figures 6(a) and (b), respectively. The main peak and the right side peak in $I_Q$ shown in figure 5. More precisely, there are five MB states contributing to the main peak in $I_Q$ at $V_{pg} = 0.4$ meV. The five active MB states are: $|\tilde{1}\rangle$, $|\tilde{1}\rangle$, and $|\tilde{1}\rangle$ with energies $E_{17} = 1.143$ meV and $E_{18} = 1.145$ meV in the bias window ($N_c = 1, N_{ph} = 0.04$), $|\tilde{2}\rangle$, and $|\tilde{2}\rangle$, with energies $E_{21} = 1.439$ meV and $E_{23} = 1.441$ meV above the bias window ($N_c = 1, N_{ph} = 0.96$) shown in figure 6(a), and [53] with energy 2.488 meV (not shown). It is interesting to notice that $E_{17} + \hbar \omega_{ph} \cong E_{21}$ and $E_{18} + \hbar \omega_{ph} \cong E_{23}$, implying a photon-assisted transport through the higher MB states.

When an electron enters the QD system it interacts with the photon in the cavity. Its energy is thus not in resonance with the electron states in the bias window, but with the electron states, photon replicas, which are with a photon energy $\hbar \omega_{ph}$ above the states in the bias window. The photon-activated states above the bias window contain approximately one more photon than the states in the bias window and, hence, the main peak in $I_Q$ is mainly due to a single-photon absorption mechanism. In addition to the main-peak feature at the plunger-gate voltage $V_{pg}$, two side peaks can be recognized at $eV_{pg}^S = eV_{pg}^M \pm \hbar \omega_{ph}$ induced by photon-assisted transport, where the system satisfies $e\Delta V_{MS} = e(V_{pg}^M - V_{pg}^S) \equiv \hbar \omega_{ph}$. It has been pointed out that this plunger-gate controlled photon-assisted transport is repeatable with a period related to the Coulomb charging energy [47].

Figure 6(b) shows how the left side peak in the net charging current $I_Q$ shown previously in figure 5 is contributed by the MB states. First, the left current $I_L = 0.001$ nA and the right current $I_R = -0.001$ nA contributed by the $|\tilde{2}\rangle$ and $|\tilde{2}\rangle$ MB states (green squared dot) containing $N_c = 1$ and $N_{ph} = 0.96$ within the bias window are almost negligible, implying the left side peak in $I_Q$ is not induced by the resonant tunneling effect. Second, the $|\tilde{2}\rangle$ and $|\tilde{2}\rangle$ MB states (pink squared dot) contain $N_c = 1$ and $N_{ph} = 0.04$, with energies $E_{24} = 1.376$ meV and $E_{25} = 1.379$ meV above the bias window. These two states contribute, respectively, to the charging current $I_{24} = 0.0$ nA ($I_{L,24} = 0.003$ nA, $I_{R,24} = -0.003$ nA) and $I_{25} = 0.001$ nA ($I_{L,25} = 0.007$ nA, $I_{R,25} = -0.006$ nA) and, hence, generate a charging current $I_Q = 0.001$ nA. Third, the $|\tilde{2}\rangle$ and $|\tilde{2}\rangle$ MB states (orange squared dot) contain $N_c = 1$ and $N_{ph} = 1.96$, with energies $E_{26} = 1.435$ meV and $E_{28} = 1.438$ meV above the bias window. These two states contribute, respectively, to the charging current $I_{26} = 0.01$ nA ($I_{L,26} = 0.010$ nA, $I_{R,26} = 0.0$ nA) and $I_{28} = 0.004$ nA ($I_{L,28} = 0.005$ nA, $I_{R,28} = -0.001$ nA) and, hence, generate a photon-assisted tunneling current $I_{Q}^{ph} = 0.014$ nA. The main contribution of the left side peak in the charging current is then $I_Q \approx I_Q^{ph} + I_{Q}^{ph} = 0.015$ nA, which coincides with the result shown in figure 5.

The schematic diagram in figure 7 is shown to illustrate the dynamical photon-assisted transport processes involved in

![Figure 6](image-url)
the formation of the main peak and the left side peak in the net charging current $I_Q$ shown in figure 5. It is illustrated in figure 7(a) that the transport mechanism forming the main peak in $I_Q$ is mainly due to the photon-assisted tunneling to the MB states above the bias window containing approximately a single photon. Figure 7(b) represents the two main transport mechanisms forming the left side peak in $I_Q$. The electrons in the left lead may absorb two photons to the MB states containing approximately two photons above the bias window. After that, the electrons may either perform resonant tunneling to the right lead (red solid arrow) or undergo multiple inelastic scattering by absorbing and emitting a photon energy $\hbar \omega_{ph}$ in the QD system (blue dashed arrow). This is the key result of this paper.

To get better insight into the dynamical electronic transport, the spatial distribution of the ME charge at $t = 220$ ps is shown in figure 8. Similar to the QD system in the absence of the photon cavity, the ME charge distribution at the main peak in $I_Q$ forms resonant peaks at the edges of the QD, as shown figure 8(a), that are related to an antisymmetric state in the QD. The partial occupation contributed by the photon-activated resonant MB states $|\phi_2\rangle$ and $|\phi_3\rangle$ are 0.432e and 0.454e, respectively. Comparing to the case with no photon cavity, the slight enhancement in the ME charge indicates that the tunneling of electrons into the QD system becomes faster in the presence of the photon cavity and, hence, the charging current is enhanced. It is shown in figure 8(b) that the ME charge in the case of the side peak in $I_Q$ manifests an extended SE state, which is formed outside the QD. The partial occupations contributed by the photon-activated resonant MB states $|\phi_4\rangle$ and $|\phi_5\rangle$ are 0.018e and 0.025e, respectively. By increasing the photon energy $\hbar \omega_{ph}$, the left side peak in $I_Q$ can be enhanced and is shifted to lower energy (not shown). The slight asymmetry seen in the charge distribution in figure 8(b) is caused by the $x$-polarized electric field of the photons.

3.3. $y$-polarized photon mode

We consider here the TE_{101} y-polarized photon mode, where the electric field of the photons is perpendicular to the transport direction through the QD system. The QD system is assumed initially to contain no electron $N_e = 0$, but one photon in the cavity $N_{ph} = 1$. Since our system is considered to be anisotropic, elongated in the $x$-direction, we shall demonstrate that the photon-assisted transport effect is much weaker in the case of a y-polarized photon mode in comparison with that of x-polarization discussed in section 3.2.

In figure 9, we present the MB energy spectrum as a function of plunger-gate voltage $V_{pg}$ for a QD system influenced by a y-polarized field with photon energy $\hbar \omega_{ph} = 0.3$ meV. Besides the propagating state at $V_{pg} = 0.4$ meV within the bias window (green lines), there are two additional electronic propagating states appearing at $V_{pg} = 0.1$ and 0.7 meV, caused by the presence of the photon field, as marked by the square dots shown in the figure.

Figure 10 shows the net charging current in the case of a y-polarized photon field, in which there is initially one photon $N_{ph} = 1$ with energy $\hbar \omega_{ph} = 0.3$ meV fixed while the electron–photon coupling strength is changed. It is seen that the main-peak currents at $V_{pg} = 0.4$ mV are:

Figure 7. Schematic representation of photon-activated resonance energy levels and electron transition by changing the plunger-gate voltage $V_{pg}$ at the main peak (a) and the left side peak (b) in figure 5. The QD system is embedded in a photocavity with a photon energy $\hbar \omega_{ph}$ and photon content $N_{ph}$ in each many-body state. The chemical potential difference is $\Delta \mu = \mu_L - \mu_R$, and $\Gamma_{LR}$ is the coupling strength between the QD system and the leads.

Figure 8. The spatial distribution of the many-electron charge density of the QD system with an x-polarized photon field at time 220 ps corresponding to the main peak (a) and the left side peak (b) for the case of $\hbar \omega_{ph} = 0.1$ meV shown in figure 5 (blue solid line). Other parameters are $\hbar \omega_{ph} = 0.3$ meV, $B = 0.1$ T, $a_w = 23.8$ nm, $L_e = 300$ nm, and $\hbar \omega_0 = 2.0$ meV.
Figure 9. MB energy spectrum versus the plunger-gate voltage $V_{pg}$ in the case of a $y$-polarized photon field: zero-electron states $N_e = 0$ (green dots), single-electron states $N_e = 1$ (red dots), and two-electron states $N_e = 2$ (blue dots). Other parameters are $B = 0.1 \, T$, $\Delta \mu = 0.1 \, meV$, $\hbar \omega_0 = 2.0 \, meV$, $\hbar \omega_{ph} = 0.3 \, meV$, and $g_{ph} = 0.1$.

$\bar{I}^M_Q = 0.115 \, nA$ for $g_{ph} = 0.1 \, meV$ (blue solid), $\bar{I}^M_Q = 0.127 \, nA$ for $g_{ph} = 0.2 \, meV$ (green dashed), and $\bar{I}^M_Q = 0.159 \, nA$ for $g_{ph} = 0.3 \, meV$ (red dotted). Moreover, a weak left side-peak current at $V_{pg} = 0.1 \, meV$ can be recognized: $\bar{I}^S_Q = 1.0 \, pA$ for $g_{ph} = 0.1 \, meV$, $\bar{I}^S_Q = 1.7 \, pA$ for $g_{ph} = 0.2 \, meV$, and $\bar{I}^S_Q = 3.2 \, pA$ for $g_{ph} = 0.3 \, meV$. We notice that both the side- and main-peak currents are enhanced when the electron–photon coupling strength is increased. In order to get a better understanding of the current enhancement, we repeat the analysis of the photon-activated MB energy states contributing to the electronic transport.

In figure 11(a), we show the MB states at $V_{pg} = 0.4 \, meV$ and $g_{ph} = 0.1$. The active MB states are $|\bar{2}\rangle$ and $|\bar{3}\rangle$, with energies 1.141 and 1.144 meV in the bias window ($N_{ph} = 0$), $|2\rangle$ and $|3\rangle$, with energies 1.441 and 1.444 meV above the bias window ($N_{ph} = 1$), and $|53\rangle$ with energy 2.483 meV ($N_{ph} = 1$). It should be noticed that $E_{16} + \hbar \omega_{ph} \equiv E_{21}$ and $E_{18} + \hbar \omega_{ph} \equiv E_{23}$, indicating that these two MB states above the bias window are photon-activated states. Furthermore, the higher active MB state with energy approximately the same as the characteristic Coulomb energy, that is $E_{53} \approx E_C$, indicates a correlation induced active two-electron state.

The net charging current at $V_{pg} = 0.4 \, meV$ exhibiting the main current peak in figure 10 at $t = 220 \, ps$ is mainly contributed by the MB states $|21\rangle$ ($I_{L,21} = 0.127 \, nA$, $I_{R,21} = 0.125 \, nA$) and $|23\rangle$ ($I_{L,23} = -0.032 \, nA$, $I_{R,23} = -0.018 \, nA$). This indicates that the electrons in the left lead can absorb one photon to the state $|21\rangle$, then emit one photon, performing resonant tunneling to the right lead and contributing to the charging current $I_{21} = 0.252 \, nA$. Moreover, an opposite transport mechanism can occur for the electrons in the right lead through the state $|23\rangle$, thus contributing to the charging current $I_{23} = -0.05 \, nA$. The scattering processes through these two states result in a photon-assisted tunneling current $\bar{I}^S_Q = 0.202 \, nA$. A small current through $|53\rangle$ is found due to the charging effect, namely $I_L = 0.002 \, nA$ and $I_R = -0.087 \, nA$, hence contributing to the charging current $\bar{I}^S_Q = -0.085 \, nA$ due to the charging effect. The contribution to the main peak in the charging current is therefore $\bar{I}^S_Q \approx \bar{I}^S_{ph} + \bar{I}^S_Q = 0.117 \, nA$. This analysis is consistent with the result shown in figure 10.

In figure 11(b), we show the MB states at $V_{pg} = 0.1 \, meV$ and $g_{ph} = 0.1$. The active MB states are: $|20\rangle$ and $|22\rangle$, with energies $E_{20} = 1.141 \, meV$ and $E_{22} = 1.144 \, meV$ in the bias window ($N_{ph} = 0$); $|24\rangle$ and $|25\rangle$, with energies 1.368 and 1.371 meV above the bias window ($N_{ph} = 0$); and $|27\rangle$ and $|29\rangle$, with energies $E_{27} = 1.441 \, meV$ and $E_{29} = 1.444 \, meV$ ($N_{ph} = 2$). We notice that $E_{20} + \hbar \omega_{ph} \equiv E_{27}$ and $E_{22} + \hbar \omega_{ph} \equiv E_{29}$. This implies that the two MB states $|27\rangle$ and $|29\rangle$ above the bias window are photon-activated states.

In figure 10, the net charging current at $V_{pg} = 0.1 \, meV$ manifests a small side-peak current $\bar{I}^S_Q = 1.0 \, pA$ at $t = 220 \, ps$. This left side-peak structure in $I_Q$ is mainly contributed by the MB states $|20\rangle$ ($I_L = 1.1 \, pA$, $I_R = -0.9 \, pA$) and $|22\rangle$ ($I_L = 1.2 \, pA$, $I_R = -0.9 \, pA$) in the bias window. These two states contribute to the resonant tunneling current, $\bar{I}^L_Q = 0.5 \, pA$, which is related to the charge accumulation effect. In addition, the states $|27\rangle$ ($E_{27} = 4 \times 10^{-3} \, pA$) and $|29\rangle$ ($E_{29} = 2 \times 10^{-3} \, pA$) contribute to a very weak charging current $\bar{I}^S_Q = 6 \times 10^{-3} \, pA$ due to photon-assisted tunneling. The contribution to the side-peak current is therefore $\bar{I}^S_Q \approx \bar{I}^S_{ph} + \bar{I}^S_Q = 0.51 \, pA$. The suppression of the side-peak current in the case of $y$-polarization is due to the anisotropy of our system. The dipole momentum in the $y$-direction is much smaller than in the $x$-direction, and so is the electron–photon interaction strength.
and the left side peak in figure 10 (blue line, the mean electron number in the many-body state $|\tilde{n}\rangle$ (blue dashed line), the mean photon number $N_{\tilde{p}}$ (red line) of the main peak $V_{pg} = 0.4$ mV (a), and the left side peak $V_{pg} = 0.1$ mV (b). The magnetic field is $B = 0.1$ T, $\Delta \mu = 0.1$ meV, $g_{ph} = 0.1$ meV, $\hbar \omega_{ph} = 0.3$ meV. In the case of a $y$-polarized photon field.

Figure 11. The many-body energy spectrum $E_{\mu}$ (dotted green), the mean electron number in the many-body state $|\tilde{n}\rangle$ (blue dashed line), the mean photon number $N_{\tilde{p}}$ (red line) of the main peak $V_{pg} = 0.4$ mV (a), and the left side peak $V_{pg} = 0.1$ mV (b). The magnetic field is $B = 0.1$ T, $\Delta \mu = 0.1$ meV, $g_{ph} = 0.1$ meV, $\hbar \omega_{ph} = 0.3$ meV. In the case of a $y$-polarized photon field.

Figure 12. The spatial distribution of the ME charge density in the case of a $y$-polarized photon field at time 220 ps: (a) $V_{pg} = 0.4$ mV and (b) $V_{pg} = 0.1$ mV corresponding, respectively, to the main peak and the left side peak in figure 10 (blue line, $g_{ph} = 0.1$ meV). Other parameters are $\hbar \omega_{ph} = 0.3$ meV, $B = 0.1$ T, $a_w = 23.8$ nm, $L_a = 300$ nm, and $\hbar \omega_0 = 2.0$ meV.

The ME charge distribution in the presence of the $y$-polarized photon mode is shown in figure 12. It is seen that the main-peak current in figure 10 forms an elongated broad bound state in the central system due to the electron–photon interaction, as shown in figure 12(a). Moreover, the side-peak current in figure 10 forms a photon-assisted resonant state at the edges of the QD embedded in the quantum wire, as is shown in figure 12(b). We notice that the charge distribution maxima around $x \approx \pm a_w$ of the main peak in IQ at $V_{pg} = 0.4$ mV with $g_{ph} = 0.1$ meV are almost the same in the cases without and with the photon mode. As a consequence, the main-peak current $I_{Q}^{M} \approx 0.1$ nA for these cases. Furthermore, the charging current maxima are located around $x \approx \pm 3a_w$ in the case of $x$-polarization and around $x \approx \pm 2a_w$ in the case of $y$-polarization. The charge distribution maxima in the case of $x$-polarization are closer to the edges of the central system, implying a higher left side-peak current at $V_{pg} = 0.1$ mV.

4. Concluding remarks

We have performed numerical calculations to investigate the transient current and charge distribution of electrons through a QD embedded in a finite wire coupled to a single-photon mode with $x$- or $y$-polarization. A non-Markovian theory is utilized, where we solve a generalized QME that includes the electron–electron Coulomb interaction and electron–photon coupling. Initially, we examined the case without a photon cavity. In the short-time regime, the charging current exhibits a significant charge accumulation effect. In the long-time regime, the charging current is suppressed due to the Coulomb blocking effect. Furthermore, we have analyzed the photon-assisted current and the characteristics of photon-activated MB states with various parameters coupled to a single-photon mode in the photon cavity. The photon-assisted current peaks are enhanced by increased electron–photon coupling strength.

In the case of a QD system coupled to an $x$-polarized photon mode, the main current peak is enhanced by the electron–photon coupling. The electrons may absorb a single photon, manifesting a photon-assisted secondary peak which also incorporates correlation effects. In the case of a QD coupled to a $y$-polarized photon mode, the main current peak is enhanced by the electron–photon coupling. The photons may absorb a single photon, manifesting a photon-assisted secondary peak which also incorporates correlation effects. The secondary peak current in the case of $y$-polarization is suppressed due to the anisotropy of our system.

The cavity photon assisted or enhanced transport here was attainable by selecting a narrow bias window in order to facilitate the resonant placement and isolation of a spin-pair of states with a single-electron component by the plunger gate in the bias window. The bias window was kept in the lowest part of the MB energy spectrum and the low photon energy guarantees in most cases that only states close to this very discrete part of the spectrum are relevant to the transport. This is in contrast to our experience with a large bias window, where the coupling to the cavity photons most often reduces the charging of the central system [39, 46, 48].

Our proposed plunger-gate controlled transient current in a single-photon mode influenced QD system should be observable due to recent rapid progress of measurement technology [49]. The realization of a single-photon influenced QD device and the generation of plunger-gate controlled transient transport may be useful in quantum computation applications.

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