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Exciton complexes assisted transition channels in the optically excited single-electron tunneling units

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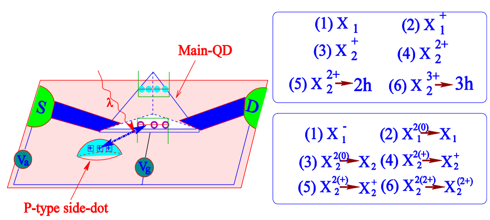
HIGHLIGHTS

- The emission in the optically excited single-electron tunneling devices is studied.
- The exciton complexes channels are classified into electron-like and hole-like ones.
- The weight functions associated with the channels can be tuned by gate/bias voltages.
- There exist competition mechanisms leading to blueshift or redshift of the emission.

GRAPHICAL ABSTRACT

The spontaneous emission processes in the optically excited single-electron tunneling units are dominated by the 12 exciton complexes channels, where $X_i^{n\pm}$ and $X_i^{2(n+)}$ represent charged excitons and biexcitons, respectively.



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ABSTRACT

The emission spectrum from the optically excited single electron tunneling devices, electrostatically coupled to a p-type side quantum dot, has been investigated. The 12 exciton-complexes transition processes have been found and can be classified into six electron-like and six hole-like transition processes. The self-consistent numerical analysis shows that the gate and bias voltages can be tuned to change the weight functions associated with the particular exciton-complexes transition processes, thereby influencing the intensity and frequency-dependence of the spontaneous emission signals. The energy discrepancies up to the quadratic terms with respect to bias voltages are taken into account to interpret different degrees of the Stark shifts experienced by the electron and the hole. There exist several competition mechanisms, where the increase of the gate voltage can neutralize the shift to lower-energy transition channels produced by the increase of the hole occupancy in the side dot, and the interdot repulsive and attractive Coulombic blockades compete with each other to determine the superiority or inferiority of the different resonance channels. The electron-like resonance channels can be switched to the hole-like ones or vice versa in the optical spectra by tuning the gate voltages.

1. Introduction

Single-electron tunneling (SET) devices, consisting of quantum dots (QDs) with source and drain electron reservoirs, have become an indispensable component of nanoelectronics [1–10]. The artificial tailoring of the energy levels [11–21] and the externally controllable gate and bias voltages have made the SET play versatile roles in transport and optical processes [2,3,22–29] in nanostructures. Besides these, the fine energy structures induced by the many-body electron–electron, electron–hole, and hole–hole interactions [2,3,7,8,22,23,25,27–31] in the SET have provided a possible platform for quantum information processing [31,32,37]. Thus, studying the optical processes is an effective way of illuminating the resonance channels generated by the exciton complexes in the optically excited SET.

Recently, Royo et al. [18] numerically studied two laterally coupled quantum dots confined in different parabolic potentials. In the framework of the dipole approximation, the contributions of the neutral exciton and negatively/positively trions to the emission

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spectra have been located and analyzed under different circumstances in the framework of the Fermi golden rule. Later, they performed the photoluminescence spectroscopy experiment on the coupled quantum dot systems, where the traces of exciton and charged exciton (exciton X, positively/negatively charged trions $X^{+/-}$, and double-charged exciton X^{2-}) had been captured in the photoluminescence lineshape [16].

Kleemans et al. [8] investigated photoluminescence spectra of a semiconductor quantum dot interacting with a degenerate electron gas experimentally, where the many-body excitons, such as the neutral and multiply charged excitons, were found to play an important role in the optical processes. The Coulomb interactions among the holes and the electrons in both the QD and the continuum electron gas lead to the different formation mechanisms of the exciton complexes: Mahan exciton and hybrid exciton.

The spontaneous emission spectra (SES) in the optically excited single-QD with source and drain were studied by Kuo and Chang with the help of Keldysh correlation Green's functions [2], where the exciton, biexciton, positively and negatively trions had been found. In our work, besides the first optically excited QD, the second externally controlled p-type QD has been introduced as an impurity dot, where the two QDs couple together via the Coulomb interactions [22,29]. The analytical expression for the SES has been obtained, and the 12 mechanisms from the exciton complexes induced by many-body Coulombic interactions in the intradot and interdot have been revealed. The tuning effects of the bias and gate voltages on the optical spectra have been analyzed with the detailed numerical analysis. The work is organized as follows: Section Section 2 gives the model with physical settings, where the Hamiltonian governing the optical processes has been given. Section 2.3 gives the analytical and numerical analysis on the SES, and the concluding remarks are presented in Section 3.

2. The spontaneous emission from the optically excited SET

2.1. The model and the physical backgrounds

The single-electron tunneling device consists of n-type source–drain junctions, the intrinsic QD and the second p-type side-dot. The pumping laser light excites the carriers in the wetting layer, and these optically generated carriers undergo relaxation processes, such as electron–phonon and impurity scattering processes into the intrinsic quantum dot (see Fig. 1). The phonon-bottleneck effect in the low temperature has been adopted [33]. The pumping-induced electron occupation number can be safely neglected due to the fact that the tunneling rate $\Gamma_e(\equiv \Gamma_L+\Gamma_R)$ ($\Gamma_{L(R)}$ is the tunneling rate between the intrinsic dot and the left (right) lead) is usually much larger than both the electron capture rate from the wetting layer to the intrinsic dot $\gamma_{e,c}$

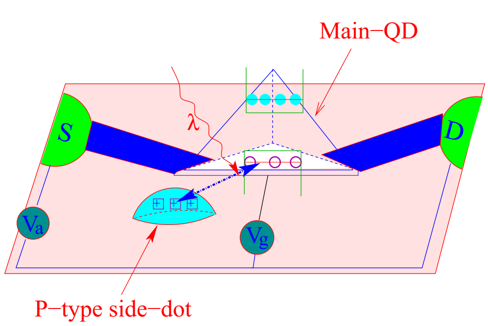

Fig. 1. The schematic diagram of the optically excited single-electron tunneling devices, electrostatically connected to a p-type side-dot, where S and D are the source and the drain, respectively, the filled cyan circles and unfilled purple circles represent the optically excited electrons and holes, respectively, while ⊞ represents the hole in the p-type side-dot.

and the electron–hole recombination rate R_{eh} in the intrinsic dot within the time scale of interest. On the contrary, the holes persistently present in the process of the electron tunneling, whose occupation number in the intrinsic dot can be estimated as follows [2]: $n_{h,\sigma}=\gamma_{h,c}N_{h,\mathbf{k}}/(\gamma_{h,c}N_{h,-\mathbf{k}}+R_{eh}N_{e\sigma}+\Gamma_{h,s})$, where $N_{e(h),\mathbf{k}}\equiv\langle b^{\dagger}_{e(h),\mathbf{k}}b_{e(h),\ \mathbf{k}}\rangle$ represents the electron (hole) number in the wetting layer generated by the light excitation: $\mathcal{H}_{opex}=\sum_{k\sigma l}(\lambda_0 e^{i\omega_0 t}b_{e,k,\sigma}b_{h,k,-\sigma}+\ h.c.)$. $N_{h,\mathbf{k}}$ can be described semiclassically as $N_{h,\mathbf{k}}\approx\mathcal{I}\cdot\Gamma_{h,s}/\gamma_{h,c}$ by introducing the following parameters: the dimensionless light excitation power $\mathcal{I}$; the hole capture rate from the wetting layer to the intrinsic dot $\gamma_{h,c}$; and the phenomenological hole-impurity scattering rate $\Gamma_{h,s}$. The electron occupation number in the intrinsic dot $N_{e,\sigma}$ need to be determined self-consistently instead. The Hamiltonian describing the above processes can be written as follows:

$$
\begin{aligned}
\mathcal{H}_0 = & \sum_{i=(e,h,s),\sigma} E_i d^{\dagger}_{i,\sigma}d_{i,\sigma}+\sum_{k,\sigma,\ell=L,R}\epsilon_k c^{\dagger}_{k,\sigma,\ell}c_{k,\sigma,\ell} \\
& +\sum_{k\sigma\ell}(V_{k,\sigma,\ell}c^{\dagger}_{k,\sigma,\ell}d_{e,\sigma}+V^{\dagger}_{k,\sigma,\ell}d^{\dagger}_{e,\sigma}c_{k,\sigma,\ell}) \\
& +\sum_{i,\sigma}^{(e,s,h)} U_{i,i}d^{\dagger}_{i,\sigma}d_{i,\sigma}d^{\dagger}_{i,-\sigma}d_{i,-\sigma}+\sum_{i\neq j,\sigma,\sigma'}^{(e,h)} U_{i,j}d^{\dagger}_{i,\sigma}d_{i,\sigma}d^{\dagger}_{j,\sigma'}d_{j,\sigma'} \\
& +\sum_{i,\sigma,\sigma'}^{(e,h)} U_{i,s}d^{\dagger}_{i,\sigma}d_{i,\sigma}d^{\dagger}_{s,\sigma'}d_{s,\sigma'} \\
& +(\lambda e^{i\omega t}a^{\dagger}d_{e,\sigma}d_{h,-\sigma}+\lambda^{*}e^{-i\omega t}ad^{\dagger}_{h,-\sigma}d^{\dagger}_{e,\sigma})+\mathcal{H}_{opex}+\mathcal{H}_{e-p}, \qquad (1)
\end{aligned}
$$

where $d_{i,\sigma}$ ($d^{\dagger}_{i,\sigma}$) represents the annihilation (creation) electron/hole operator with spin σ in the intrinsic dot; $d_{s,\sigma}$ ($d^{\dagger}_{s,\sigma}$) represents annihilation (creation) hole operator with spin σ in the p-type second side-dot; $c_{k,\sigma,\ell}$ ($c^{\dagger}_{k,\sigma,\ell}$) represents the annihilation (creation) electron operator in source and drain. The first two terms on the right hand side of the above equation describe the electrons, holes in the two dots and electron reservoirs in the left and right leads, respectively. The third term describes the hopping among the source, the drain and the intrinsic dot. The intra-dot Coulomb interactions in both the intrinsic and side dots are described in the fourth to sixth terms, where the fourth term describes the electron–electron and hole–hole interactions in the two dots, the fifth term describes the electron–hole interactions in the intrinsic dot, and the sixth term describes the electron–hole and hole–hole interactions between the intrinsic and side dots. For the sake of clarity, we represent the electron–electron, electron–hole and hole–hole interaction strengths in the intrinsic dot with the symbols U_e, U_{eh}, and U_h, respectively. while U_{es} and U_{hs} are used to describe the interaction strengths between the holes in the side dot and the electrons and holes in the intrinsic dot, respectively. The optical generation and recombination of the electron–hole in the intrinsic dot are described in the seventh term, where $a^{\dagger}(a)$ is the creation (annihilation) operator for the photon, and λ is the coupling strength between the photon and the carriers in the intrinsic dot. The last two terms describe the optical excitation (pumping) of electrons and holes and electron–phonon relaxation processes in the wetting layer, which are used to estimate the holes' occupation number in the intrinsic dot through relaxation processes.

The spontaneous emission spectrum (SES) involves in the optical process of the single-photon emitting by the recombination of the electron in the conduction band and the heavy hole in the valence band. It provides one of the important ways in probing the fine structures of the resonance mechanisms in the semiconductor nanostructures [2,8,16–18,24,27,30,37].

2.2. The analytical results

The SES can be obtained by introducing the equal-time 'lesser' (correlation) Green's function $G^{<}_{eh,\sigma}(t)$, which is defined as $G^{<}_{eh,\sigma}(t)=-i\langle a^{\dagger}(t)d_{h,-\sigma}(t)d_{e,\sigma}(t)\rangle$. The equation of motion for the