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Emission spectra from Coulomb-coupled quantum dot in the n–n junction

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ABSTRACT

The exact expression for the spontaneous emission spectra from the Coulomb-coupled quantum dots embedded in n–n junction quantum dot has been obtained. All resonance mechanisms involving in the system have been classified into two classes, intra-resonance and inter-resonance mechanisms. It is found that the resonance mechanisms dominating the emission spectra experiences transitions from intra-resonance, coexistence of the inter- and intra-resonance, to inter-resonance with the increasing of the electron occupation number in the second quantum dot.

1. Introduction

Quantum dots (QD) can function as a microelectronic unit such as a transistor, forming the basis of nanoelectronics [1]. The fine energy structures of the resonant/bound state, such as exciton, charged exciton (trion), or even biexciton structure due to electron–hole correlations [3,4,6–8,5,9,10] have provided ways of controlling the electron and hole dynamics through using the optical light, paving road for the solid state realization of the quantum communication and quantum computing [2,5,10,9,11–15]. Exploration of all these phenomena and applications in semiconductor QD necessitates the studies on the resonant energy structures in the transport and optical properties of the single-electron transistor, which consists of the three-terminal device, with source, gate and drain, for example, the self-assembled direct-gap InAs/GaAs QD buried into the source and drain [1].

Ediger and coauthors studied the photoluminescence of the close-symmetric InAs/GaAs and InGaAs/GaAs coupled QDs, where the fine structures of the exciton complexes, singly-charged, the trion, doubly-charged and neutral exciton underlines the peaks of the spectra [7]. The role of the resonance mechanisms generated by the electron–hole correlation on the electronic and optical properties of the QDs has been emphasized.

In the framework of the Keldysh non-equilibrium Green's function, Kuo and Chang gave an analysis on the emission spectra, tunneling current and differential conductance in different configurations of the single-electron transistor, where a single QD is embedded into p–n, and n–n junctions [3]. It is found that the sharp peaks both in tunneling current and emission spectra, reveal the exciton, charged exciton, and even biexciton mechanisms, coexisting in the complicated optical and transport processes. Inspired by their work, we introduce the second quantum dot into the system. The second QD can be considered as an impurity dot or deliberately manufactured using Stranski–Krastanow method. The two quantum dots are coupled together through the Coulomb interactions [6,7]. Using the Keldysh formalism, we obtain a closed set of equations, through which the effect of the Coulomb interactions on the spontaneous emission spectra can be disclosed. All the resonance mechanisms involved in spontaneous emission spectra due to the electrons and holes correlations have been identified and analyzed through the analytical and numerical methods. The influence of the electron occupation number in the second QD on the modification of the optical processes has been given in details, all the neutral and charged electron and hole complexes have been associated with the resonance mechanisms in the optical processes.

The Letter is organized as follows: Section 2 gives the background, where the model Hamiltonian governing the spontaneous emission process has been given. The analytical and numerical analysis on the spontaneous emission spectra are given in Section 3, and Section 4 concludes our work.

2. The model and formalism

The single-electron tunneling device considered here consists of n-type source–drain junctions, the main intrinsic quantum dot and the n-type second side-dot, whose Hamiltonian can be separated into two parts, $\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{coul}$. $\mathcal{H}_0$ describes the free electrons

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and holes part together with the hopping between the main QD and source–drain junctions, and can be written as follows:

$$\mathcal{H}_0 = \sum_{i=(e,h),\sigma} E_i d^\dagger_{i,\sigma} d_{i,\sigma} + \sum_{\sigma} E_{2e} d^\dagger_{2e,\sigma} d_{2e,\sigma} + \sum_{k,\sigma,l=L,R} \epsilon_k c^\dagger_{k,\sigma,l} c_{k,\sigma,l} + \sum_{k\sigma l}\big(V_{k,\sigma,l} c^\dagger_{k,\sigma,l} d_{e,\sigma} + V^\dagger_{k,\sigma,l} d^\dagger_{e,\sigma} c_{k,\sigma,l}\big) \quad (1)$$

where $d_{i,\sigma}$ ($d^\dagger_{i,\sigma}$) represents the annihilation (creation) electron/hole operators with spin σ in the intrinsic main QD; d_{2e} ($d^\dagger_{2e}$) is annihilation (creation) electron operator with spin σ in the n-type second side-QD; $c_{k,\sigma,l}$ ($c^\dagger_{k,\sigma,l}$) represents the annihilation (creation) electrons operators in source and drain, and the last term describes the hopping between the source, drain and main intrinsic QD, the absence of the hopping between the main QD and the second QD has been assumed [6].

The laser light excites the carriers in the wetting layer, and this pumping process is described in a semi-classical way as, $\mathcal{H}_{opex} = \sum_{k\sigma l}(\lambda_0 e^{i\omega_0 t} b_{e,k,\sigma} b_{h,k,-\sigma} + \lambda_0^\dagger e^{-i\omega_0 t} b^\dagger_{h,k,-\sigma} b^\dagger_{e,k,\sigma})$, where $b_{e,k,\sigma}$ and $b_{h,k,-\sigma}$ are the paired electron–hole annihilation operators in the wetting layer. The optically-generated carriers in the wetting layer undergoes relaxation processes, such as electron–phonon and impurity scattering processes into the main quantum dots. The phonon absorption is neglected here due to the phonon–bottleneck effect in the low temperature situation [3,16].

Since the tunneling rate Γ_e ($\equiv \Gamma_L + \Gamma_R$) ($\Gamma_{L(R)}$ is the tunneling rate between the main QD and the left (right) lead) is much larger than the electron–hole recombination rate R_{eh} [3], during the time scale of the interest, the holes persistently present in the process of the electron tunneling. The electrons and holes Coulomb interactions part $\mathcal{H}_{coul}$ can be written as,

$$H_{coul} = \sum_{i,\sigma}^{(e,2e,h)} U_{i,i} d^\dagger_{i,\sigma} d_{i,\sigma} d^\dagger_{i,-\sigma} d_{i,-\sigma} + \sum_{i\neq j,\sigma,\sigma'}^{(e,h)} U_{i,j} d^\dagger_{i,\sigma} d_{i,\sigma} d^\dagger_{j,\sigma'} d_{j,\sigma'} + \sum_{i,\sigma,\sigma'}^{(e,h)} U_{i,2e} d^\dagger_{i,\sigma} d_{i,\sigma} d^\dagger_{2e,\sigma'} d_{2e,\sigma'}, \quad (2)$$

where the first term describes the electron–electron and hole–hole interactions in the two QDs, the second term describes the electron–hole interactions in the main QD, the last term describes the electron–electron/hole interactions between the side QD and main QD. U_e, U_{eh}, U_h are the electron–electron,electron–hole and hole–hole intra-interaction strengths in the main QD respectively, while U_{2e} is the electron–electron interaction strengths in the second QD, U_{ey} and U_{hy} are the interaction strengths between the electrons in the second QD and electrons and holes in the main QD respectively.

3. Spontaneous emission spectra

The spontaneous emission signal provides an alternative way of probing the fine structures of the resonance mechanisms in the nanostructures [19,17,3,18]. In order to calculate the spontaneous emission spectra, we should include the physical processes involving in the single-photon emission processes induced by the quantum transition between the electron in the conduction band and the heavy hole in the valence band of the semiconductor QD. Besides the Hamiltonian $\mathcal{H}$ defined previously, the additional optical process term describing the generation and recombination of the electron–hole in the main QD should be included, $\mathcal{H}_{op} = \sum_Q (\lambda e^{i\omega t} a^\dagger d_{e,\sigma} d_{h,-\sigma} + \lambda^* e^{-i\omega t} a d^\dagger_{h,-\sigma} d^\dagger_{e,\sigma})$, where $a^\dagger(a)$ is the creation (annihilation) operator for the photon, and λ is the coupling strength between the photon and carriers in the main QD. The single-photon emission spectrum can be obtained by introducing the equal-time 'lesser' (correlation) Green's function $G^<_{eh}(t,t)$, which is defined in the following form:

$$G^<_{eh}(t,t) = -i\big\langle a^\dagger(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (3)$$

where the physical significance of creating the single-photon by the recombination of the electron and hole is clearly seen. The lesser Keldysh Green's function $G^<_{eh}(t,t)$ (polarization) can be obtained as follows in the Fourier-transformed space:

$$\omega G^<_{eh}(\omega) = \left(E_e + E_h - U_{eh} + i\frac{\Gamma}{2}\right) G^<_{eh}(\omega) + \lambda^* \mathcal{F} + (U_e - U_{eh}) G^<_{eeh}(\omega) + (U_h - U_{eh}) G^<_{ehh}(\omega) + (U_{ey} - U_{hy})\big(G^<_{ehy}(\omega) + G^<_{ehy'}(\omega)\big), \quad (4)$$

where $\mathcal{F}$ is the generalized phase-space filling, defined as $\mathcal{F} \equiv \langle a^\dagger a\rangle(1 - N_{e,\sigma} - n_{h,-\sigma}) - n_{h,-\sigma} N_{e,\sigma}$. In order to determine the final expression for lesser Green's function $G^<_{eh}$, the electron-screened and hole-screened [20,21] photon-generated transition lesser Green's function should be introduced, which are defined as follows:

$$G^<_{eeh}(t,t) = -i\big\langle a^\dagger(t) \hat{N}_{e,-\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (5a)$$

$$G^<_{ehh}(t,t) = -i\big\langle a^\dagger(t) \hat{n}_{h,\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (5b)$$

$$G^<_{ehy}(t,t) = -i\big\langle a^\dagger(t) \hat{n}_{2e,\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (5c)$$

$$G^<_{ehy'}(t,t) = -i\big\langle a^\dagger(t) \hat{n}_{2e,-\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle. \quad (5d)$$

Further calculation shows that these electron (hole)-screened correlation functions depend on the double-electron-screened and exciton-screened photon-generated electron–hole transition correlation functions,

$$G^<_{eehy}(t,t) = -i\big\langle a^\dagger(t) \hat{N}_{e,-\sigma}(t) \hat{n}_{2e,\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (6a)$$

$$G^<_{eehy'}(t,t) = i\big\langle a^\dagger(t) \hat{N}_{e,-\sigma}(t) \hat{n}_{2e,-\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (6b)$$

$$G^<_{ehyy'}(t,t) = -i\big\langle a^\dagger(t) \hat{n}_{2e,\sigma}(t) \hat{n}_{2e,-\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (6c)$$

$$G^<_{eehh}(t,t) = -i\big\langle a^\dagger(t) \hat{N}_{e,-\sigma}(t) \hat{n}_{h,\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (6d)$$

$$G^<_{ehhy}(t,t) = i\big\langle a^\dagger(t) \hat{n}_{h,\sigma}(t) \hat{n}_{2e,\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (6e)$$

$$G^<_{ehhy'}(t,t) = i\big\langle a^\dagger(t) \hat{n}_{h,\sigma}(t) \hat{n}_{2e,-\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (6f)$$

where the first two correlation Green's functions describe the inter double-electron-screened electron–hole recombination mechanism in the main QDs, while the third one involves the double-electron screening from the second QD. The last three correlation functions account for the intra and inter exciton-screened electron–hole recombination mechanisms. These correlation functions with quadruple-subscript will be determined through the recruiting the photon-generated negatively-charged trion-screened [20–22] and triple-electron-screened electron–hole recombination correlation functions,

$$G^<_{eehhy}(t,t) = -i\big\langle a^\dagger(t) \hat{N}_{e,-\sigma}(t) \hat{n}_{h,\sigma}(t) \hat{n}_{2e,\sigma}(t) d_{h,-\sigma}(t) d_{e,\sigma}(t)\big\rangle, \quad (7a)$$