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EXCITON ENERGY OF THE InAs/GaAs SELF-ASSEMBLED QUANTUM DOT IN A SEMICONDUCTOR MICROCAVITY *

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We report on the theoretical study of the interaction of the quantum dot (QD) exciton with the photon waveguide models in a semiconductor microcavity. The InAs/GaAs self-assembled QD exciton energies are calculated in a microcavity. The calculated results reveal that the electromagnetic field reduces the exciton energies in a semiconductor microcavity. The effect of the electromagnetic field decreases as the radius of the QD increases. Our calculated results are useful for designing and fabricating photoelectron devices.

Keywords: quantum dot, microcavity
PACC: 7135, 7320

I. INTRODUCTION

The exciton–photon coupled system in a semiconductor quantum microcavity (QMC) structure has attracted much attention in both fundamental and applied research.[1−8] Until now, most of the theoretical and experimental studies have been focused on the interaction systems of the quantum well (QW) exciton with the photon waveguide models in QMC. The QMC structures investigated in most detail consisted of a times $\lambda/2$ GaAs cavity sandwiched between two distributed Bragg reflector (DBR) mirrors which consist of many periods of $\lambda/4$ AlAs and $Al_xGa_{1-x}As$ layers. One or three QWs were placed at the antinodes of the QMC.

In the resonance regime between the exciton and photon, the two modes couple together to form cavity polaritons.[2] The splitting between the coupled mode features on resonance is known as the vacuum Rabi splitting. In bulk semiconductor materials, the Rabi splitting is only about several μeV. In the system of the QW in the QMC, the QW and the microcavity provide separate control of the exciton and photons, and the Rabi splitting can reach about 1meV. If we imbed the quantum dot (QD) in the QMC, the exciton states will be affected more strongly by the photon waveguide models.

The QD imbedded in the QMC can be used to fabricate semiconductor laser or infrared detectors. The absorption in the QD is quite different from that of the QW.[9] In the QW, the absorption does not exist when the electric vector of light is parallel to the QW plane (perpendicularly incident), which introduces some difficulties in fabricating the infrared detector. In the QD, the absorption exists when light is incident along any direction, which is beneficial to fabricating the infrared detector.

In the framework of effective mass envelope function theory, we have studied the exciton states of the InAs/GaAs self-assembled QD.[10] In this paper, we will study the interaction of the QD exciton (QDE) with the photon waveguide models in QMC.

II. THEORETICAL MODEL

Our calculating model is composed of one layer of InAs/GaAs QD imbedded at the centre (antinodes) of a QMC. The QD layer is perpendicular to the growth direction, i.e. the axial of the QMC. We choose the growth direction as the Z direction of our coordinate system, and assume the InAs self-assembled QD to be a cylinder. In the Z direction, the width of the QD is L. In the parallel direction, the radius of the QD is R. By invoking periodic boundary conditions[11] and expanding the electron and hole wavefunctions in terms of normalized plane-wave states, we can calculate the electron and hole states.

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In the QD, the exciton Hamiltonian in second quantization form can be written as

$$H_{\rm ex} = \hbar\omega_{\rm ex} A^{2\dagger} A^2, \tag{1}$$

where $\hbar\omega_{\rm ex}$ is the exciton energy, $A^{2\dagger}$ and A^2 are the exciton creation and annihilation operators, respectively. In contrast of the case of the QW, the excitons have no dispersion in the plane due to the breaking of the translation symmetry along the parallel directions.

We assume the length of the microcavity to be L'. The vector potential of the electromagnetic field is expanded as[12]

$$\begin{aligned}\boldsymbol{A}(x) =& \sum_{\vec{q},q_z} \sqrt{\frac{2\pi\hbar v}{SL'(q^2+q_z^2)^{1/2}}} \\ &\cdot \left[A^1_{\vec{q},q_z} {\rm e}^{{\rm i}\vec{q}\cdot\rho} + A^{1\dagger}_{\vec{q},q_z} {\rm e}^{-{\rm i}\vec{q}\cdot\rho}\right] \cos(q_z z)\epsilon_{\vec{q},q_z}, \end{aligned}\tag{2}$$

where $\vec{q}$ is the photon wave vector in the plane, $q_z = 2n\pi/L'$, $v = c/\sqrt{\epsilon_0}$, ϵ_0 is the dielectric constant. n takes any integer value in the range $(-\infty, +\infty)$.

The electromagnetic field Hamiltonian in the second quantization form is

$$H_{\rm el} = \sum_{\vec{q},q_z} \hbar v|\vec{q}+\vec{q}_z| A^{1\dagger}_{\vec{q},q_z} A^1_{\vec{q},q_z}, \tag{3}$$

where $A^{1\dagger}_{\vec{q},q_z z}$ and $A^1_{\vec{q},q_z}$ are the photon creation and annihilation operators, respectively.

The interaction Hamiltonian between the exciton and photon is composed of two terms,[12]

$$H_I = H_I^{(1)} + H_I^{(2)}, \tag{4}$$

with

$$H_I^{(1)} = \sum_{\vec{q},q_z} {\rm i} C_{\vec{q},q_z} (A^2 - A^{2\dagger})(A^1_{\vec{q},q_z} + A^{1\dagger}_{-\vec{q},-q_z}), \tag{5}$$

and

$$\begin{aligned} H_I^{(2)} =& \sum_{\vec{q}} \sum_{q_z,q_z'} D_{\vec{q},q_z,q_z'} (A^1_{\vec{q},q_z} + A^{1\dagger}_{-\vec{q},-q_z z}) \\ &\cdot (A^1_{-\vec{q},-q_z'} + A^{1\dagger}_{\vec{q},q_z' z}). \end{aligned}\tag{6}$$

In the above equations,

$$C_{\vec{q},q_z} = \omega_{\rm ex}\sqrt{\frac{2\pi\hbar v}{L'}} \frac{1}{(q^2+q_z^2)^{\frac{1}{4}}} \mu_{\rm cv}(\vec{q},q_z) I(\vec{q},q_z), \tag{7}$$

$$D_{\vec{q},q_z,q_z'} = \frac{C_{\vec{q},q_z} C^*_{\vec{q},q_z'}}{\hbar\omega_{\rm ex}}, \tag{8}$$

and

$$I(\vec{q},q_z) = \int {\rm d}r_\parallel \int_{-\frac{L'}{2}}^{\frac{L'}{2}} {\rm d}z f(r) {\rm e}^{{\rm i}(r_\parallel\cdot\boldsymbol{\rho} + q_z z)}, \tag{9}$$

where $\mu_{\rm cv}(\vec{q},q_z) = e\langle v \mid \epsilon_{\vec{q},q_z}\cdot x \mid c\rangle$ is the dipole matrix element between the valence and conduction bands, and $f(r) = f_v^*(r) f_c(r)$ is the envelope function at the Γ point in the Brillouin zone.

The whole Hamiltonian reads

$$H = H_{\rm ex} + H_{\rm el} + H_I^{(1)} + H_I^{(2)}. \tag{10}$$

We define a polariton operator,

$$\begin{aligned} B =& \sum_{\vec{q},q_z} \left[W(\vec{q},q_z) A^1_{\vec{q},q_z} + X(\vec{q}) A^2_{\vec{q}} \right. \\ &\left. + Y(\vec{q},q_z) A^{1\dagger}_{-\vec{q},-q_z} + Z(\vec{q}) A^{2\dagger}_{-\vec{q}}\right]. \end{aligned}\tag{11}$$

The coefficients of the above operators can be determined by the following equation,

$$[B, H] = EB. \tag{12}$$

From this equation, we can acquire the exciton energy E in the QMC. This can be calculated by

$$(\hbar\omega_{\rm ex})^2 - E^2 = \frac{4E^2}{\hbar\omega_{\rm ex}} \sum_{\vec{q},q_z} \frac{\hbar v\sqrt{q^2+q_z^2}|C_{\vec{q},q_z}|^2}{\hbar^2 v^2 (q^2+q_z^2)^2 - E^2}. \tag{13}$$

$I(\vec{q},Q_z)$ can be simplified if we choose the confinement function $f(r)$ to be a step function with values $1/\pi R^2 L$ inside the QD and zero outside. From Eq.(9), we obtain

$$\begin{aligned} I(\vec{q},Q_z) =& \frac{1}{\pi R^2 L} \int_0^R \rho{\rm d}\rho \int_0^{2\pi} {\rm d}\theta \\ &\cdot \int_{-L/2}^{L/2} {\rm d}z {\rm e}^{{\rm i}q\rho\cos\theta} \cos(q_z z) \\ =& \frac{4}{qRq_z L} \sin\left(q_z \frac{L}{2}\right) J_1(qR), \end{aligned}\tag{14}$$

where J_1 is the first-order Bessel function. Only one QD is considered in our theoretical model, while the experimental microcavity samples can contain more than one layer QDs and there are many QDs in every layer for strengthening the exciton–photon interactions. Therefore, the dipole matrix element obtained for fitting the experimental results is actually effective, and equals the real dipole matrix element multiplied by a factor larger than one.

Ⅲ. RESULTS AND DISCUSSION

In the following calculation, we choose the same material parameters as Ref.[10] and the dipole matrix element $\mu = 3.2\times10^{-25}$cm·C. When L=3nm, we have L'=300nm.

We have calculated the energies of heavy-hole excitons as a function of the QD radius R. The results

are shown in Fig.1. The dotted line denotes the results in which the effects of the electromagnetic field are excluded. From Fig.1, we can find that the exciton energies are lower than those excluding the effects of the electromagnetic field, and these decrease as R increases.

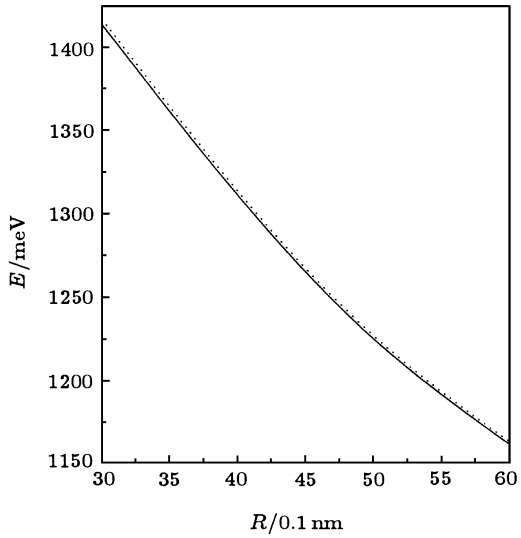


Fig.1. The energies of heavy-hole excitons as a function of the QD radius. The solid and dotted lines are the results of including and excluding, respectively, the effects of the electromagnetic field.

Figure 2 gives the energy difference ΔE of heavy-hole excitons as a function of the QD radius R. When R is very large, the QD becomes a QW. The interaction energy is only about $1 \sim 2$meV, which is close to the interaction energy between the QW and the QMC.[6] As R decreases, the confinement effect of the QD is enhanced and the interaction energy can reach about 4 meV, which is twice the interaction energy between the QW and the QMC.

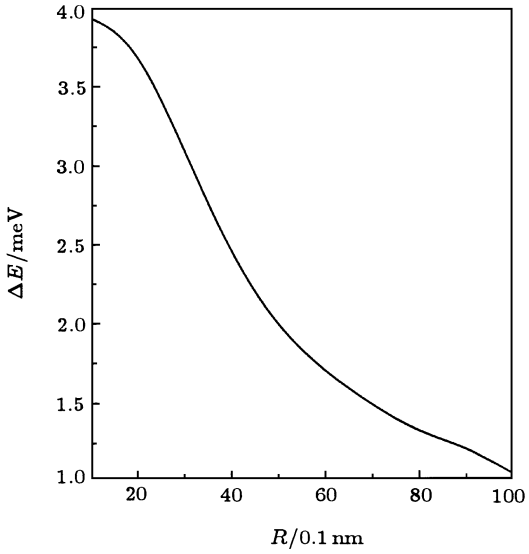


Fig.2. The energy differences of heavy-hole excitons as a function of the QD radius.

The effects of the QD shape and the dielectric constant on excitonic states have been calculated in Refs.[13] and [14], in which the results showed that the effects of the QD shape and the dielectric constant on excitonic states are not negligible. Considering the effects of the QD shape and dielectric constant, the interaction between excitons and photons in a QMC is worth studying in future work.

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