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Hybrid Exciton-Polaritons in a Bad Microcavity Containing the Organic and Inorganic Quantum Wells

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Abstract *We study the hybrid exciton-polaritons in a bad microcavity containing the organic and inorganic quantum wells. The corresponding polariton states are given. The analytical solution and numerical result of the stationary spectrum for the cavity field are finished.*

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1 Introduction

Quantum wells (QWs) embedded in semiconductor microcavity structures have been the subject of extensive theoretical and experimental investigations. We know that the excitons play a fundamental role in the optical properties of the QWs. The photodevices of excitons may have small size, low power dissipation, rapidness and high efficiency. All of these properties are required to the integrated photoelectric circuits.

The excitons are classified as Wannier excitons (they have large radius and weak oscillator strength) and Frenkel excitons (they have small radius and strong oscillator strength) by the size of the exciton model radius.

Recently, a new excitonic state — hybrid exciton state in the composite organic and inorganic semiconductor heterostructures has been described by pioneering works.[1−7] Since then from quantum well (QW) to quantum dot, the hybrid exciton states due to resonant mixing of Frenkel and Wannier–Mott excitons have been demonstrated. Reference [1] shows that the hybrid excitons possess a strong oscillator strength and a small saturation density (or large radius). Reference [3] proposes to couple Frenkel excitons and Wannier–Mott excitons through an ideal microcavity.

There are two different coupling regimes into which the interaction between the cavity field and optical transition of the excitons can be classified. One is the weak coupling regime where the exciton-photon coupling is very small and can be treated as a perturbation to the eigenstates of the uncoupled exciton-photon system. Another is the strong coupling regime where the exciton-photon coupling is so strong that it is no longer treated as perturbation. In the strong coupling regime, the QW excitons emit photons into the cavity. The photons are bounced back by the mirror and reabsorbed by the QWs to create excitons again. So the Rabi oscillations are formed. The exciton-polariton mode splitting in a semiconductor microcavity is also observed by many experimental groups, such as in Refs [8] and [9].

In this paper, we will deal with the hybrid exciton-polariton states for the organic and inorganic QWs in a bad cavity. In Sec. 2, we use the motion equations included damping effect to give the mixed hybrid-exciton and cavity field modes, that is, hybrid exciton-polariton. In Sec. 3, we will give the emission spectrum of the system in the case of the stationary state and the corresponding numerical results are also given. In Sec. 4, a simple conclusion is given.

2 Model and Exciton-Polariton States

We begin with the Hamiltonian of the organic and inorganic quantum wells in an ideal microcavity[3]

$$H = \sum_k [\hbar\omega_W A_k^\dagger A_k + \hbar\omega_F B_k^\dagger B_k + \hbar\Omega a_k^\dagger a_k] + \sum_k [\hbar\Gamma_{13}(A_k^\dagger a_k + A_k a_k^\dagger) + \hbar\Gamma_{23}(B_k^\dagger a_k + B_k a_k^\dagger)]\,, \quad (1)$$

where A_k ($A_k^\dagger$), B_k ($B_k^\dagger$) and a_k ($a_k^\dagger$) are usual boson operators for Wannier excitons, Frenkel excitons and cavity fields. $\Gamma_{13} = (1/\hbar)P_W^{01}E_0$ and $\Gamma_{23} = (1/\hbar)P_F^{01}E_0$, $P_{W,F}^{01}$ are the moment matrix elements for Wannier and Frenkel excitons from the ground state to the first excited state. E_0 is the amplitude of the vacuum electric field at the center of cavity. This Hamiltonian is linear. For a bad microcavity, we could solve it by the motion equation included the damping coefficient and obtain any mixed solutions of the hybrid exciton and cavity field.

But here, we only deal with the case of a single mode cavity field. That is, the above equation is simplified into

$$H = \hbar\omega_W A^\dagger A + \hbar\omega_F B^\dagger B + \hbar\Omega a^\dagger a + \hbar\Gamma_{13}(A^\dagger a + Aa^\dagger) + \hbar\Gamma_{23}(B^\dagger a + Ba^\dagger)\,. \quad (2)$$

So we have the motion equation

$$\frac{\partial a}{\partial t} = -\mathrm{i}\Omega a - \mathrm{i}\Gamma_{13}A - \mathrm{i}\Gamma_{23}B - \gamma_1 a\,, \quad (3a)$$

$$\frac{\partial A}{\partial t} = -\mathrm{i}\omega_W A - \mathrm{i}\Gamma_{13} a - \gamma_2 A\,, \tag{3b}$$

$$\frac{\partial B}{\partial t} = -\mathrm{i}\omega_F B - \mathrm{i}\Gamma_{23} a - \gamma_3 B\,. \tag{3c}$$

In order to describe the properties of the bad cavity, the damping coefficients, γ_i are added phenomenologically to Eqs (3). In fact, when we write out the interaction between the system and reservoir, we could give a motion equation which includes the fluctuation terms and dissipative terms by the Markov approximation. However, because we want to discuss the exciton-polaritons in the strong coupling regime, we are not interested in the noise properties of the system. So the fluctuation terms may be neglected.

By making use of the Fourier transformation, we have

$$(\mathrm{i}\gamma_1 + \omega - \Omega)a(\omega) = \mathrm{i}a(0) + \Gamma_{13}A(\omega) + \Gamma_{23}B(\omega)\,, \tag{4a}$$

$$(\mathrm{i}\gamma_2 + \omega - \omega_W)A(\omega) = \mathrm{i}A(0) + \Gamma_{13}a(\omega)\,, \tag{4b}$$

$$(\mathrm{i}\gamma_3 + \omega - \omega_F)B(\omega) = \mathrm{i}B(0) + \Gamma_{23}a(\omega)\,, \tag{4c}$$

where $a(0)$, $A(0)$ and $B(0)$ are initial operators for the cavity field, Wannier excitons and Frenkel excitons respectively. In order to obtain $a(t)$, we need solve the pole equation

$$(\mathrm{i}\gamma_1 + \omega - \Omega)(\mathrm{i}\gamma_2 + \omega - \omega_W)(\mathrm{i}\gamma_3 + \omega - \omega_F) - (\mathrm{i}\gamma_2 + \omega - \omega_W)\Gamma_{23}^2 - (\mathrm{i}\gamma_3 + \omega - \omega_F)\Gamma_{13}^2 = 0\,. \tag{5}$$

The solutions of this cubic equation could be obtained analytically by using any mathematics handbook, such as Ref. [10]. But usually, a cubic equation can be solved more quickly with numerical methods than with analytical procedures. So, we set the forms of the analytical solutions of Eq. (5) as $\omega_1 = \omega_1' - \mathrm{i}\Gamma_1$, $\omega_2 = \omega_2' - \mathrm{i}\Gamma_2$ and $\omega_3 = \omega_3' - \mathrm{i}\Gamma_3$ respectively. If we make

$$\begin{aligned} F(\omega) = {} & \mathrm{i}(\mathrm{i}\gamma_2 + \omega - \omega_W)(\mathrm{i}\gamma_3 + \omega - \omega_F)a(0) \\ & + \mathrm{i}\Gamma_{23}(\mathrm{i}\gamma_2 + \omega - \omega_W)B(0) \\ & + \mathrm{i}\Gamma_{13}(\mathrm{i}\gamma_3 + \omega - \omega_F)A(0)\,, \end{aligned} \tag{6}$$

we have $a(t)$ as

$$a(t) = \frac{F(\omega_1)}{\Delta_1\Delta_2}\,\mathrm{e}^{-\mathrm{i}\omega_1 t} - \frac{F(\omega_2)}{\Delta_2\Delta_3}\,\mathrm{e}^{-\mathrm{i}\omega_2 t} + \frac{F(\omega_3)}{\Delta_1\Delta_3}\,\mathrm{e}^{-\mathrm{i}\omega_3 t} \tag{7}$$

with $\Delta_1 = \omega_1 - \omega_2$, $\Delta_2 = \omega_1 - \omega_3$ and $\Delta_3 = \omega_2 - \omega_3$. ω_i are determined by the pole equation. This equation indicates that the strong coupling of the two kinds of QW exciton states and cavity field results in three new eigenstates. Their eigenvalues are ω_1, ω_2 and ω_3 respectively. These states are just hybrid exciton-polariton states. Their energy splittings are Δ_1, Δ_2 and Δ_3 respectively.

3 Stationary Spectrum

For the case of the ergodic and stationary process, the emission spectrum of the system is defined as[11]

$$S(\omega) = \int_0^\infty \mathrm{e}^{-\mathrm{i}\omega t}\langle a^\dagger(t)a(0)\rangle\,\mathrm{d}t + \mathrm{c.c}\,. \tag{8}$$

If the cavity field, Wannier exciton and Frenkel exciton are initially in the number states $|n_c\rangle$, $|n_W\rangle$ and $|n_F\rangle$ respectively, then

$$\langle a^\dagger(t)a(0)\rangle = \bar{n}_c\Big[-\mathrm{i}\frac{E(\omega_1)}{\Delta_1^*\Delta_2^*}\,\mathrm{e}^{\mathrm{i}\omega_1 t} + \mathrm{i}\frac{E(\omega_2)}{\Delta_2^*\Delta_3^*}\,\mathrm{e}^{\mathrm{i}\omega_2 t} - \mathrm{i}\frac{E(\omega_3)}{\Delta_1^*\Delta_3^*}\,\mathrm{e}^{\mathrm{i}\omega_3 t}\Big], \tag{9}$$

where $\bar{n}_c$ is mean photon number of the cavity field and

$$E(\omega) = (\mathrm{i}\gamma_2 + \omega - \omega_W)(\mathrm{i}\gamma_3 + \omega - \omega_F)\,. \tag{10}$$

As the general exciton-polaritons,[12] if we assume that the damping is moderate, the process is almost ergodic and stationary. It is deserved to point out that all of the parameters excepting for ω are fixed by the properties of the organic and inorganic QWs as well as microcavity material. We may always choose some moderate parameters so that the stationary condition could be satisfied. So the spectrum of the system is

$$S(\omega) = \frac{A}{(\omega - \omega_1')^2 + \Gamma_1^2} + \frac{B}{(\omega - \omega_2')^2 + \Gamma_2^2} + \frac{C}{(\omega - \omega_3')^2 + \Gamma_2^3} \tag{11}$$

with

$$A(\omega) = 2\bar{n}_c\frac{\mathrm{Re}\,[E(\omega_1)\Delta_1\Delta_2(\omega - \omega_1)]}{|\Delta_1|^2|\Delta_2|^2}\,, \tag{12a}$$

$$B(\omega) = 2\bar{n}_c\frac{\mathrm{Re}\,[E(\omega_2)\Delta_3\Delta_2(\omega - \omega_2)]}{|\Delta_3|^2|\Delta_2|^2}\,, \tag{12b}$$

$$C(\omega) = 2\bar{n}_c\frac{\mathrm{Re}\,[E(\omega_3)\Delta_3\Delta_1(\omega - \omega_3)]}{|\Delta_3|^2|\Delta_1|^2}\,. \tag{12c}$$

We find that when the system reaches stability, the hybrid exciton-polariton spectrum is superposition of three Lorentzian lines which are expected. The exciton-polariton splitting may be measured at the peak points of the emission spectrum which are determined by the condition $\mathrm{d}S(\omega)/\mathrm{d}\omega = 0$.

We apply the general Eq. (11) to give a numerical sketch map. We firstly adopt the assumption of Ref. [3], namely $\omega_F = \Omega$, $\omega_W = \omega_F(1 + \delta)$, $\delta = 10^{-2}$.

Now we give a set of possible values for the above parameters. $\bar{n}_c$ only determines the amplitude of the spectrum, so we set $\bar{n}_c = 1$. We assume that $\omega_F = \Omega = 1562$ meV, $\Gamma_{23}^2 = 16$ meV, $\Gamma_{13}^2 = 8$ meV, $\gamma_1 = 0.1$ meV, $\gamma_2 = 0.18$ meV and $\gamma_3 = 0.12$ meV. We give the sketch map of the spectrum for the system in Fig. 1.

This sketch map shows there are sudden changes near the three peaks. If we choose moderate parameters $A(\omega)$, $B(\omega)$ and $C(\omega)$ as slow varying functions of ω near the peaks and consider them as constant, the sudden varying points will disappear, the precise stationary spectrum is given.

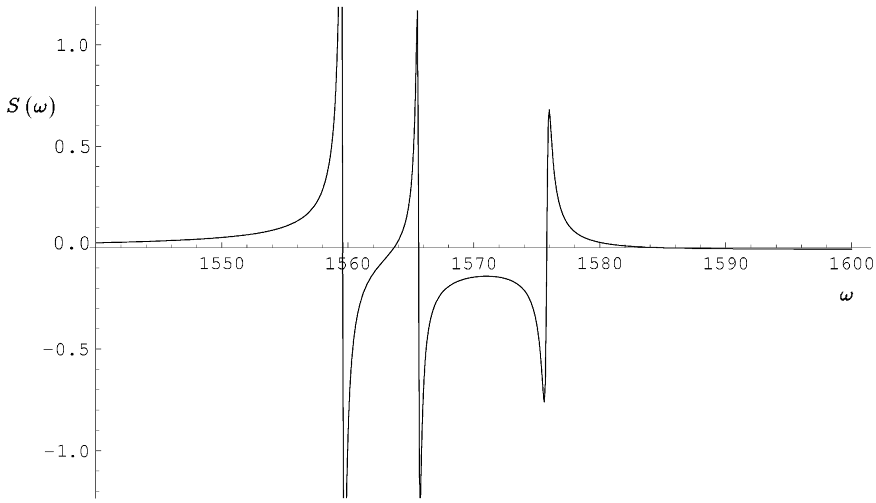

Fig. 1 Schematic drawing for the emission spectrum.

4 Conclusion

In conclusion, the hybrid exciton-polariton states in a bad microcavity containing the organic and inorganic quantum wells are given. Although we only discuss a single-mode model, this approach could also be applied to general case. This paper shows that the hybrid exciton-polaritons decay at three different rates. The analytical and numerical results of the emission spectrum for the exciton-polaritons are also given.

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