CHIN.PHYS.LETT. Vol. 19, No. 6 (2002) 843

In-Plane Propagation of Cavity Polaritons in a Quantum Semiconductor Microcavity *

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(Received 7 March 2002)

Considering that the coupling among the heavy-hole exciton, light-hole exciton and the cavity photon can form bipolaritons in a quantum semiconductor microcavity, we calculate the group velocities of the cavity polaritons at different incident angles using the coupling model of three harmonic oscillators. The result indicates that the group velocities of the low and middle branches of the cavity polaritons have extrema, but the group velocities of the high branch increase with the increasing incident angle.

PACS: 71. 36. +c, 78. 66. − w, 42. 50. − p, 71. 35. − y

Since the study of strong coupling between the exciton and photon in quantum microcavity (QMC) structures originated from the pioneering work of Weisbuch *et al.*[1] in 1992, who demonstrated the occurrence of strong exciton–photon coupling in reflectivity spectra from GaAs–GaAlAs-based QMCs, the recent development of the structures has resulted in a major boost to both the experimental and theoretical investigations of exciton–polariton in semiconductors.[2,3] The strong coupling between excitons and photons results in the Rabi oscillations between the new eigenstates of the system (called the cavity polariton).[4]

The main difference between strong coupling atoms and excitons in semiconductors is the delocalized nature of the eigenstates, which have in-plane dispersion curves due to the two-dimensional translational invariance in layers.[5] The symmetry of the interaction system leads to a one-to-one correspondence between a polariton wave vector in the cavity and the direction of the emitted photon. This allows us to observe the polariton dispersion curve using angle-resolved photoluminescence and reflectivity experiments.[6,7]

A new manifestation of the in-plane dispersion, namely, the propagation of polaritons in the plane of a microcavity has been given by Freixanet *et al.*.[8] In their experiment, they only measured the group velocities of the lower branch polariton formed by coupling between the cavity mode and the heavy hole as a function of the in-plane wave vector k_{p} (or the incident angle).

Up to now most experiments about QMCs have been carried out by using $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ quantum wells.[1,6,9] Because of the strain in the $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ quantum wells, the light-hole features can be neglected,[10] whereas in GaAs quantum wells the light-hole features cannot be neglected.[11]

In this Letter, we make use of the three-harmonic-oscillator coupling model[12] to calculate the group velocities of the cavity polaritons formed by the coupling among the heavy-hole exciton (HHE), light-hole exciton (LHE) and the photon at different incident angles.

The bipolariton quasimodes diagonalize the Hamiltonian expressed in the basis of the three uncoupled modes (HHE, LHE and cavity mode) by the matrix

$$\begin{bmatrix} E_c-\gamma_c & g_{ch} & g_{cl} \\ g_{ch} & E_{hh}-\gamma_{hh} & 0 \\ g_{cl} & 0 & E_{lh}-\gamma_{lh} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} = E \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix}, \tag{1}$$

where

$$g_{ch} = \hbar \left(\frac{e^2 f_{hh} N}{2 n_c^2 \varepsilon_0 m_0 L_{\mathrm{eff}}} \right)^{1/2},$$

$$g_{cl} = \hbar \left(\frac{e^2 f_{lh} N}{2 n_c^2 \varepsilon_0 m_0 L_{\mathrm{eff}}} \right)^{1/2}$$

are the coupling strengths between the cavity mode and the HHE or LHE,[13] respectively. n_c, L_{eff} and N denote the index of the cavity, the effective cavity length that takes into account the penetration of the cavity mode inside the Bragg mirrors, and the effective quantum well number respectively; e and ε_0 are the charge of an electron and the permittivity in vacuum, respectively; $\hbar$ is the Planck constant; E_{hh}, E_{lh} and E_c denote the HHE, LHE and cavity mode energies, respectively; m_0 is the electron mass; f_{hh} and f_{lh} are the oscillator strength of the transition per unit area of HHE and LHE, respectively; and γ_{hh}, γ_{lh}

*Supported by the National Natural Science Foundation of China under Grant Nos 69896260 and 69937010.
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and γ_c are the linewidths of the HHE, LHE and cavity mode, respectively. $E_c(k_p) = \left(E_0 + \hbar^2 k_p^2 c^2 / n_c^2\right)^{1/2}$ is the cavity mode energy and $E_0 = hc/n_c L_c$ is the photon energy for $k_p = 0$ with $k_p = E(k)\sin\theta/\hbar c$ being the projection of incident light on the quantum well plane, where θ is the incident angle. The exciton energy dispersion is parabolic, i.e.

$$E_x(k_p) = E_{x0} + \hbar^2 k_p^2 / 2M_x \quad x = \text{HHE or LHE}, \quad (2)$$

where M_x is the HHE (LHE) effective mass. Though photons are not massive particles, the cavity energy dispersion can be approximated, for $k_p \ll 2\pi/L_c$, by

$$E_c(k_p) = E_{c0} + \frac{\hbar^2 k_p^2}{2M_c}, \quad (3)$$

where $M_c = n_c^2 E_{c0}/c^2$ is a kind of effective mass of the cavity photon[10] and is about $10^{-5}\, m_0$.

The real part of the eigenvalues of Eq. (1) provides the energies of the bipolariton mode. These eigenmodes are a linear superposition of the cavity mode, HHE and LHE with the corresponding weights $|\alpha_1|^2$, $|\alpha_2|^2$ and $|\alpha_3|^2$.

The group velocities of the cavity mode, HHE and LHE can be expressed as[14]

$$v_{gx}(k_p) = \frac{1}{\hbar}\frac{\partial E(k_p)}{\partial k_p} \quad x = \text{cavity mode, HHE, or LHE}. \quad (4)$$

From the energy dispersions of exciton and cavity (Eqs. (3) and (4)) one can see that among the uncoupled cavity mode, HHE and LHE, the cavity mode has the highest group velocity and the LHE takes the higher one.

The group velocity of the cavity polariton can be written as

$$v_g(k_p) = |\alpha_1|^2 v_{\text{gcavity}}(k_p) + |\alpha_2|^2 v_{gHH}(k_p) + |\alpha_3|^2 v_{gLH}(k_p). \quad (5)$$

We assume that the structure is a $\lambda/2\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ microcavity embedded between 20 pairs $\lambda/4$ GaAs/AlAs Bragg layers on the top (air side) and 25 pairs on the bottom (substrate side), where the substrate consists of GaAs. Three 10 nm GaAs–$\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ quantum wells are located in the middle of the cavity with the resonant energy of 1.542 eV. The transition energies of HHE and LHE are 1.550 and 1.562 eV, respectively. According to Ref. [13], the effective quantum well number is about 1.5 in such a microcavity. The oscillator strengths of HHE and LHE are assumed to be $f_{hh} = 5.4 \times 10^{16}\mathrm{m}^{-2}$ and $f_{lh} = 2.2 \times 10^{16}\mathrm{m}^{-2}$ for a 10 nm GaAs quantum well.[15]

The group velocities of the three-branch cavity polaritons are plotted in Figs. 1(a)–1(c). From Fig. 1(a) we can see that at small angles the group velocities of the low energy branch increase since the low branch demonstrates mainly the cavity-mode-like feature because of the larger weight occupied by the cavity mode. While at larger angles, the energy of the cavity mode is higher than that of the HHE, and the HHE occupies larger weight, the low branch demonstrates mainly the feature of HHE. Accordingly, the group velocities increase at first and then decrease with the increasing angle.

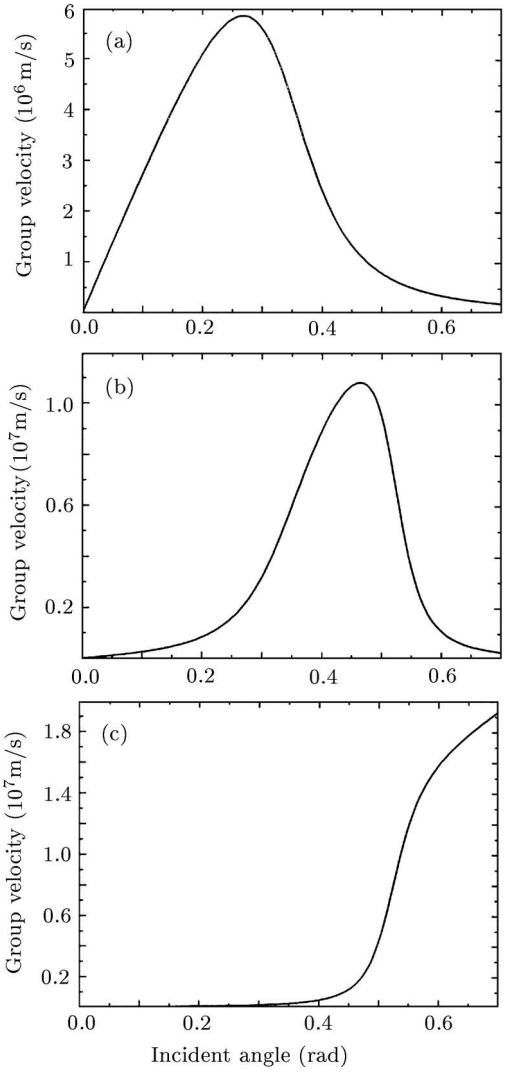

Fig. 1. Cavity polariton group velocities of the low (a), middle (b) and high (c) energy branches versus the incident angle.

For the middle energy branch (Fig. 1(b)), because the energy of the cavity mode exceeds that of the HHE and then that of the LHE with the increasing angle, it exhibits successively HHE-like, cavity-mode-like and LHE-like natures. The HHE has the largest weight at first and then decreases with the increasing angle. Meanwhile the weight of the cavity mode first increases and reaches an extremum and then decreases, but the weight occupied by the LHE always increases with the increasing angle and finally has the largest

weight. Thus the group velocities increase and reach an extremum, and then decrease with the increasing angle.

For the high energy branch (Fig. 1(c)), because the weight occupied by the cavity mode increases[16] with the increasing angle and the weight occupied by the HHE and LHE decreases with the angle, the group velocities increase with the increasing angle.

In conclusion, we have made use of the three-harmonic-oscillator coupling model to calculate the group velocities of three branch cavity polaritons resulted from the coupling among the cavity mode, HHE and LHE. Because of the different weights occupied by the cavity mode, HHE and LHE in the three-branch cavity polaritons, the group velocities of the low and middle energy branches first increase with the increasing angle, then decrease with the further increase of the angle, whereas the group velocities of the high energy branch increase with the angle.

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