Dynamics of Cavity Polaritons in a GaAs Quantum-well Semiconductor Microcavity

Liu Wenkai[1], An Yanwei[1], Lin Shiming[2], ZHang Cunshan[3], Zhang Changnian[1]
1 *College of Information, North China University of Technology, Beijing* 100041
2 *State Key Laboratory on Integrated Optoelectronics, Institute of semiconductor, Chinese Academy of Science, Beijing* 100083
3 *College of Information, Hebei University of Technology, Tianjin* 300130

Abstract To provide the dynamics of cavity polariton in semiconductor microcavity containing GaAs quantum-well, the dispersions of the three cavity polaritons have been given by the model of three coupled oscillators, meanwhile the linewidths, group velocities and the mass of the three cavity polaritons have been demonstrated. The results indicated that because of the weight occupied by the photon, heavy hole exciton and light hole extiton in the three cavity ploariton the cavity polaritons exhibited different dynamic behaviors.

Keywords Photons; Excitons; Cavity polaritons; Quantum well; Semiconductor microcavity
CLCN TN248.4 **Document data** A

0 Intuoduction

Since the study of strong coupling phenomena between the exciton and photon, which results in the formation of cavity polaritons (CPs)[1], in quantum microcavities (QMCs) in 1992[2], the recent development of QMCs has resulted in a major boost to the experimental and theoretical investigations of CPs phenomena in semiconductors[3~8].

As a mixture of the exciton and cavity photon, the CPs exhibit the properties of the exciton and photon. At different detuning (the energy difference between the cavity photon and exciton without coupling) which can be made by changing the length of cavity or incident angle[7,9] the CPs may demonstrate mainly the features of the exciton or cavity photon. So some attributes of CPs such as linewith, mass and group velocities may vary with the detuning.

Up to now most experiments about QMCs are used InxGa$_{1-x}$ As quantum wells[2,5~10]. Because of the strain in In$_x$Ga$_{1-x}$As quantum wells the features of the light-hole exciton can be neglected. However in a GaAs quantum well the features of the light-hole exciton can't be overlooked[11]. In this paper, by making use of the model of three coupled oscillators the linewiths, mass and group velocities of the CPs formed by the coupling between the cavity photon and heavy-hole exciton (HHE) or light-hole exciton (LHE) have been given.

1 Theoretical model

In the model of three coupled oscillators the eigenequation of the interaction system can be written as follows[16]

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

Where

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

Eq. (2) are the coupling strength between the cavity photon and HHE or LHE respectively[12]. 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 photon inside the Bragg mirrors and quantum well number. e and ε_0 are the charge of an electron and the permittivity of vacuum, $\hbar$ is the Planck constant. E_{hh}, E_{lh} and E_c denote the energies of HHE, LHE and the cavity photon. m_0 is the electron mass, f_{hh}, f_{lh} are the oscillator strength of the transition per unit area of HHE and LHE. γ_{hh}, γ_{lh}, and γ_c are the linewidths of HHE , LHE and the cavity photon . And $|\alpha_i|^2$ represents the weight of cavity photon, HHE and LHE in corresponding CPs.

The real parts of the eigenvalues of Eq. (1) provide the energies of the CPs, and the imaginary components of the eigenvalues give the linewindths of corresponding CPs.

1.1 Group velocity

The energy of a uncoupled photon with quantized wavevector $k_c = 2\pi/L_c$, and in-plane wavevector k_p in the medium, is given by[11]

$$E_c(k_p) = (E_0 + \hbar^2 k_p^2 c^2 / n_c^2)^{1/2} \quad (3)$$

Where $E_0 = hc/n_c L_c$ is the energy of the photon for $k_p = 0$, $k_p = E(k) \sin\theta / \hbar c$[8] is the projection of incident light on the quantum well plane, and θ is incident angle. The dispersion of a "bare" exciton is[4]

$$E_x(k_p) = E_{x_0} + \hbar^2 k_p^2 / 2M_x \ (x = \mathrm{HH}, \mathrm{LH}) \quad (4)$$

Where M_x is the HHE (LHE) effective mass, and E_{x_0}

Tel: 010-88802837 Email: liuwk_ncut@tom.com
Received date: 2004-06-14

is the energy of exciton at $k_p = 0$. Though the photon is not massive particles, the dispersion of the cavity photon can be approximated, for $k_p \ll 2\pi/L_c$, by

$$E_c(k_p) = E_0 + \hbar^2 k_p^2/2M_c \tag{5}$$

Where $M_c = n_c^2 E_0/c^2$ is a kind of effective mass of the cavity photon[11] and about $10^{-5}m_0$.

The group velocity of the cavity photon, HHE and LHE can be expressed as[13]

$$v_{gx}(k_p) = \frac{1}{\hbar}\frac{\partial E(k_p)}{\partial k_p} \quad (x = c, \mathrm{HH}, \mathrm{LH}) \tag{6}$$

From the dispersions of the exciton and photon (Eq. 4 and Eq. 5), it can be seen that among the uncoupled the cavity photon, HHE and LHE, the cavity photon has the fastest group velocity and LHE takes the second place.

The group velocity of the cavity polariton can be written as

$$v_g(k_p) = |\alpha_1|^2 v_{gc}(k_p) + |\alpha_2|^2 v_{g\mathrm{HH}}(k_p) + |\alpha_3|^2 v_{g\mathrm{LH}}(k_p) \tag{7}$$

1.2 Mass of CPs

In semiconductor the kinetic energy of the CP can be written as[17]

$$\frac{\hbar k_p^2}{2M_p} = |\alpha_1|^2\left(\frac{\hbar k_p^2}{2m_c}\right) + |\alpha_2|^2\left(\frac{\hbar k_p^2}{2m_{hh}}\right) + |\alpha_3|^2\left(\frac{\hbar k_p^2}{2m_{lh}}\right) \tag{8}$$

From the above equation, the mass of CP can be derived

$$M_p = \frac{1}{\dfrac{|\alpha_1|^2}{m_c} + \dfrac{|\alpha_2|^2}{m_{hh}} + \dfrac{|\alpha_3|^2}{m_{lh}}} \tag{9}$$

2 Results and Discussion

We assume the structure is a $\lambda/2$ $Al_{0.3}Ga_{0.7}As$ microcavity embedded between 20 pairs $\lambda/4$ GaAs/AlAs Bragg layers on the top (air side) and 25 pairs on the bottom (substrate side). The substrate is GaAs. Three 10 nm GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells are located in the middle of the cavity. Following the standard envelop - function model E_{hh0} and E_{lh0} are about 1.550 eV and 1.562 eV respectively. The oscillator strength of HHE and LHE exciton assume to be $f_{hh} = 5.4 \times 10^{16}\,m_{-2}$ and $f_{lh} = 2.2 \times 10^{16}\,m^{-2}$ for a 10nm GaAs quantum well[14]. The linewidths of HHE and LHE, which include inhomogeneous broadening, are 3 meV and 2 meV, which are reasonable according to reference[15]. The linewidth of the uncoupled cavity photon can written as[11]

$$\gamma_c = c(1 - R)/n_c L_{eff} \tag{10}$$

Where c is the speed of light in vacuum, R is the reflectivity of mirror at resonance.

From Eq. (1), (4), (5) one can gain the dispersion of the high energy cavity polariton (HP), medium energy cavity polariton (MP) and low energy cavity polariton (LP), which can be gained, which are plotted in Fig. 1(a). And Fig. 1(b) shows the linewidths of the three CPs. Clear anticrossing behaviour is observed among the CPs.

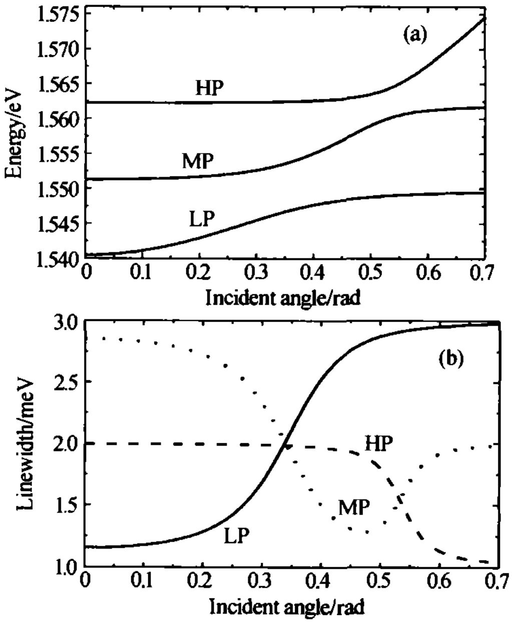

Fig. 1 (a) Energy of the three CPs, (b) Linewidths of the LP, MP, HP

Meanwhile the weights of the cavity photon (LHE and HHE) in the three CPs can be calculated from Eq. (1), (4) and (5) which are shown in Fig. 2(a) ~ (c).

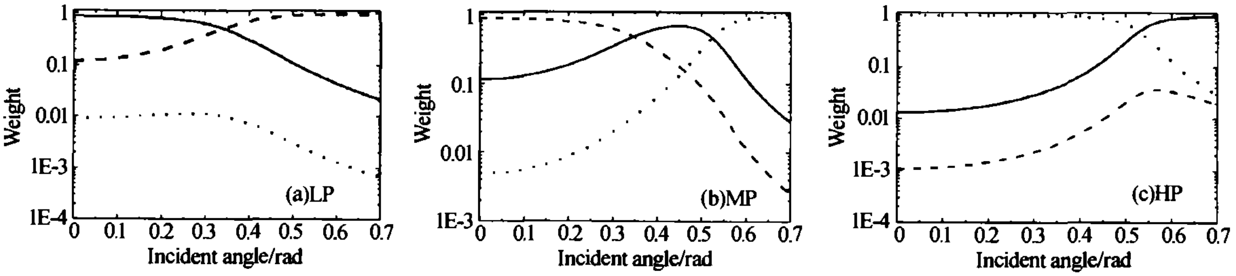

Fig. 2 Weight of the cavity photon (solid line), HHE (dashed line) and LHE (dotted line)

The group velocities of the three CPs calculated according to Eq. (7) are displayed in the Fig. 3. The solid, dashed and dotted line represent the group velocity of the LP, MP and HP respectively. Since at small in-plane wavevector (or incident angle) the cavity photon holds larger weight in LP (see Fig. 2

(a), solid line), while at larger in-plane wavevector HHE occupies larger weight (Fig. 2 (a), dashed line), the group velocity of the LP increases firstly and then decreases. Two reasons answer for the group velocity of the MP's (dashed line in Fig. 3) increasing to maximum then decreasing with the increase of in-plane wavevector, the one is the weight of the cavity photon in MP (see Fig. 2(b), solid line) increases to maximum firstly and then decreases; the other is the weight of LHE in MP (see Fig. 2(b), dotted line) always increases with in-plane wavevector until up to the largest weight. Since the weight of the cavity photon in HP (Fig. 2(c) solid line) increases with in-plane wavevector, and the weight occupied by HHE and LHE decreases (see Fig. 2(c) dashed and dotted line), the group velocity of the HP increases with in-plane wavevector.

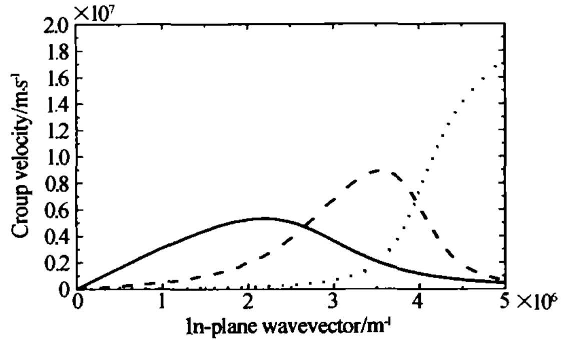

Fig. 3 Group velocities of LP (solid line), MP (dashed line) and HP (dotted line) as a function of in-plane wavevector

From Eq. (9) one can get the mass of the three CPs vs. incident angle which is illustrated in Fig. 4. As a mixture of the cavity photon whose effective mass is about $10^{-5}m_0$, HHE and LHE, the mass of CPs is much lower than that of HHE or LHE. As the weight of HHE in LP (see Fig. 2(a), dashed line) increases with incident angle, the mass of the LP (Fig. 4 solid line) increases. The increased weight of the cavity photon in HP (see Fig. 2(c), solid line) is responsible for the decreased mass of the HP (dashed line in Fig. 4). The fluctuated mass of the MP (dotted line Fig. 4) is resulted from two reasons. The one is the varied weight of the cavity photon in MP (see Fig. 2(b) solid line); the other is from the increased weight of LHE in MP (see Fig. 2(b) dotted line).

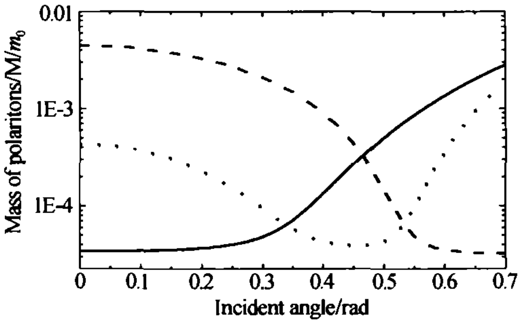

Fig. 4 Mass of LP (solid line), Mp (dotted line) and HP (dashed line)

3 Conclusion

In a GaAs quantum-wells semiconductor microcavity the interaction between the cavity photon and HHE or LHE leads to the formation of the three CPs. By the model of three coupled oscillators the dispersions and the linewidths of the three CPs (LP, MP and HP) have been calculated. There is clear anticrossing behaviour among the three CPs. Since the weight of the cavity photon, HHE and LHE in the three CPs is different, the group velocities and mass of the three CPs vary with in-plane wavevector (or incident angle). The group velocities of the LP and MP increase to an extremum and then decrease, but the group velocity of the HP increases with the increase of in-plane wavevector all the time. For the same reason the mass of the three CPs changes with incident angle. Because of the inverse relation between the mass of the CPs and those of the uncoupled particles, the mass of the LP increases with angle, the mass of the MP increases firstly and then decreases with angle, and the mass of the HP decreases with angle.

References

1 Norris T, Rhee J K, Sung CY, *et al.* Time-resolved vacuum Rabi oscillations in a semiconductor quantum microcavity. *Phys Rev B*, 1994, **50**(7): 14663 ~ 14667

2 Weisbuch C, Nishioka M, Ishikawa A, *et al.* Observati- on of the coupled exciton-photon mode splitting in a semiconductor quantum microcavity. *Phys Rev Lett*, 1992, **69**(3): 3314 ~ 3317

3 Alexey V K. Motional narrowing of inhomogene- ously broadened excitons in a semiconductor microcavity: Semiclassical treatment. *Phys Rev B*, 1998, **57**(2): 3757 ~ 3761

4 Freixanet T, Sermage B, Tiberj A, *et al.* In-plane propagation of excitonic cavity polaritons. *Phys Rev B*, 2000, **61**(5): 7233 ~ 7236

5 Messin G, Karr J Ph, Baas A, *et al.* Parametric polari- on amplification in semiconductor microcavities. *Phys Rev Lett*, 2001, **87**(10): 127403-1 ~ 4

6 Sandip G, Thomas J C, Stephanie B. Photoreflectance line shape symmetry and quantum-well ground-state exciton energy in vertical-cavity surface-emitting laser structures. *Appl Phys Lett*, 2001, **78**(3): 3250 ~ 3252

7 Whittaker D M, Kinsler P, Fisher T A, *et al.* Motional narrowing in semiconductor microcavities. *Phys Rev Lett*, 1996, **77**(3): 4792 ~ 4795

8 Houdre R, Weisbuch C, Stanley R P, *et al.* Measurement of cavity-polariton dispersion curve from angle resolved photoluminesc -ence experiments. *Phys Rev Lett*, 1994, **73**(2): 2043 ~ 2046

9 Karaiskaj D, Maxisch T, Ellmers C, *et al.* Linewidths in a semiconductor microcavity with variable strength of normal-mode coupling. *Phys Rev B*,1999,**59**(10):13525 ~ 13530

10 Berger J D, Lyngnes O, Gibbs H M, *et al.* Magnetic field enhancement of the exciton- polariton splitting in a semiconductor quantum-well microcavity: The strong coupling threshold. *Phys Rev B*, 1996,**54**(1): 1975 ~ 1979

11 Skolnick M S, Fisher T A, Whittaker D M. Strong coupling phenomena in quantum microcavity structures Semicond. *Sci Technol*, 1997,**13**(2):645 ~ 657

12 Savona V, Andreani L C, Schwendimann P, *et al.* Quantum well excitons in semiconductor microcavities: Unified treatment of weak and strong coupling regimes. *Solid State Commun*, 1995,**93**(3): 733 ~ 737

13 Madelung O. Introduction to Solid-State Theory, Berlin, Springer, 1996. 357 ~ 370

14 Gil B, Andreani L C, Pasquarello A, *et al.* Line-shape analysis of the reflectivity spectra of GaAs/(Ga, Al) As single quantum wells grown on (001)- and (311)-oriented substrates. *Phys Rev B*, 1990,**41**(2):2885 ~ 2890

15 Xia J B, Zhu B F. Semiconductor Superlattice Physics, Shanghan, Science and Technology Press, 1995. 83 ~ 90

16 Panzarini G, Andreani L C, Armitage A, *et al.* Exciton-light coupling in single and coupled semiconductor microcavities polariton disper -sion and polarization splitting. *Phys Rev B*, 1999,**59**(15): 5082 ~ 5089

17 Zheng Houzhi. Semiconductor Micrcavity: Physics and Its Applications. *Chin J Semicond*, 1997,**18**(7): 481 ~ 491

18 Duan Xiaofeng, Niu Yanxiong, Zhang Chu, *et al.* Light propagation characteristics of 1-D photonic crystal. *Acta Photonica Sinica*, 2003,**32**(9): 1086 ~ 1089

GaAs量子阱半导体微腔中腔极化激元的动态行为

刘文楷[1] 安艳伟[1] 林世鸣[2] 张存善[3] 张常年[1]
(1 北方工业大学信息学院 北京 100041)
(2 中国科学院半导体研究所集成光电子国家重点实验室,北京 100083)
(3 河北工业大学信息学院,天津 300130)

收稿日期:2004-06-14

摘 要 GaAs量子阱半导体微腔中,光子同时与重空穴激子、轻空穴激子耦合形成腔极化激元.本文采用三谐振子耦合模型,计算了腔极化激元的三支的色散关系、线宽、有效质量及其群速度;结果表明,由于腔极化激元的三支中光子、重空穴激子、轻空穴激子所占的权重随着平面波矢(或入射角度)变化,腔极化激元三支的线宽、有效质量及其群速度呈现出不同的动态行为.

关键词 光子;激子;腔极化激元;量子阱;半导体微腔

Liu Wenkai received the M. S. degree in physics from Hebei University of Technology, China, in 1999. And in 2002 he received the Ph. D. degree in microelectronics from Institute of Semiconductor, CAS. Now he is working at North China University of Technology. His interesting research is on excitons and polaritons in semiconductor nanostructures and optoelecronic devices.