Polaritons in semiconductor microcavities: effect of Bragg confinement

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Abstract: We propose a semiconductor microcavity structure in which the cavity layer is entirely both optically and electronically active. Optical spectra at normal incidence are studied theoretically, showing the drastic effects of the cavity polariton mode splitting and of the Bragg mirror confinement.

1. Introduction

The semiconductor microcavity has proven to be very useful for studying the interaction of light with confined excitons. Recently Weisbuch *et al* have observed a coupled exciton-photon mode splitting in an AlGaAs microcavity with GaAs quantum wells [1]. Many efforts have been devoted to the study of controlled spontaneous emission in semiconductor microcavities [2,3], to the fabrication of vertical cavity surface-emitting lasers [4] and of the so-called thresholdless lasers [3].

So far most of the cavity systems studied were built with optical resonant media in which excitons are sharply localized in quasi two dimensional (2D) quantum wells. More generally, the cavity layer itself can be both optically and electronically active. Inside such a cavity photons and excitons interact and travel back and forward, resulting in coupled modes and polariton interferences. Not only the coupled exciton-photon mode splitting, but also the fine structure of the polaritons can be expected because of the spatial dispersion of the excitons. In this work we study the cavity polariton and show how the polariton and the Bragg mirror confinement modify the cavity spectrum. Numerical results at normal incidence will be discussed for demonstration of the controlled photon-exciton interaction in λ - and $\lambda/2$ -cavity of GaAs.

2. Theory

In a perfect bulk crystal polaritons are stationary states. Each polariton propagates independently with well defined energy and wave vector because of the conservation of the crystal momentum. In a thin layer the crystal translational invariance breaks down and the polariton interference occurs [5].

If the thin layer is a Fabry-Pérot (FP) cavity enclosed by two Bragg mirrors such that the FP resonance frequency and the center frequency of the Bragg mirror stop band are adjusted to the exciton energy, a strong exciton-photon coupling regime can be achieved and the polariton properties drastically altered. Let us consider a cavity schematically shown in figure 1. For the sake of simplicity we will limit ourselves to the case of normal incidence and assume a one level parabolic exciton band. We need to calculate the transfer matrix of all stack layers.

When the layer is resonant, which is the case of the cavity, the transfer matrix is given by [5]:

$$m_j = \left[\begin{pmatrix} \lambda_1^* & \lambda_1 \\ n_{11}\lambda_1^* & -n_{11}\lambda_1 \end{pmatrix} + \begin{pmatrix} \lambda_2^* & \lambda_2 \\ n_{12}\lambda_2^* & -n_{12}\lambda_2 \end{pmatrix} Q_r \right] \left[\begin{pmatrix} \lambda_1 & \lambda_1^* \\ n_{11}\lambda_1 & -n_{11}\lambda_1^* \end{pmatrix} + \begin{pmatrix} \lambda_2 & \lambda_2^* \\ n_{12}\lambda_2 & -n_{12}\lambda_2^* \end{pmatrix} Q_r \right]^{-1}, \quad (1)$$

With Pekar's additional boundary condition(ABC),
i.e, $\sum_i P_i|_{\text{surface}} = 0$, for example,

$$Q_\tau = -\frac{\varepsilon_{\lambda 1}}{\varepsilon_{\lambda 2}} \begin{pmatrix} \lambda_2^* & \lambda_2 \\ \lambda_2 & \lambda_2^* \end{pmatrix}^{-1} \begin{pmatrix} \lambda_1^* & \lambda_1 \\ \lambda_1 & \lambda_1^* \end{pmatrix}, \quad (2)$$

where $\lambda_i = \exp(jk_{\lambda i}l_i/2)$, $\varepsilon_{\lambda i} = n_{\lambda i}^2 = c^2k_i^2/\omega^2 - \varepsilon_\infty$.
 l_λ is the cavity length, and $k_i(i = 1, 2)$ the wave
vectors given by the polariton eigenvalue equation:

$$\frac{k^2c^2}{\omega^2} = \varepsilon_\infty + \frac{4\pi\beta\omega_0^2}{\omega_0^2 + \hbar k^2/M_{ex}^* - \omega^2 - i\Gamma\omega}, \quad (3)$$

where M_{ex}^* is the heavy-hole exciton effective mass,
 ω_0 is the zero momentum exciton energy, $4\pi\beta$ is the
exciton oscillator strength, and Γ the exciton broad-
ening parameter.

When the layer is off-resonance, which is the
case of the $\lambda/4$ layer of the Bragg mirrors, the
transfer matrix is given by classic optics [6],

$$m_j = \begin{bmatrix} \cos(\frac{\omega}{c}n_jl_j) & -i\frac{1}{n_j}\sin(\frac{\omega}{c}n_jl_j) \\ -in_j\sin(\frac{\omega}{c}n_jl_j) & \cos(\frac{\omega}{c}n_jl_j) \end{bmatrix}, \quad (4)$$

where l_j and n_j denote the thickness and the refrac-
tion index of the j th layer ($n_jl_j = \pi c/2\omega_0$).

Then the reflection and the transmission coeffi-
cient of a N layer stack can be expressed as

$$r = \frac{M_{21} + n_{sub}M_{22} - M_{11} - n_{sub}M_{12}}{M_{21} + n_{sub}M_{22} + M_{11} + n_{sub}M_{12}}, \quad (5)$$

$$t = \frac{2}{M_{11} + n_{sub}M_{12} + M_{21} + n_{sub}M_{22}}, \quad (6)$$

where n_{sub} is the refraction index of the substrate,
and M_{ij} the matrix elements of $M =$
 $m_1 \dots m_j \dots m_N$.

3. Results and discussion

We have computed reflectance and transmission
spectra of different cavity configurations using
GaAs parameters ($\hbar\omega_0=1515\text{meV}$, $\Gamma = 0.1\text{meV}$,
 $M_{ex}^* = 0.49m_0$, $4\pi\beta=1.325 \times 10^{-3}$, $\varepsilon_\infty=12.53$)
and $n_j^2 = 9.8$ (11.7) and $l_j = 65.3\text{nm}$ (59.8nm) for
AlAs (AlGaAs) $\lambda/4$ layers of the Bragg mirrors.

In figure 2 we show the reflectance (a), transmis-
sion (b), and absorption (c) spectra calculated with
a λ -cavity confined by two Bragg reflectors of 20
(AlAs, AlGaAs) pairs. The solid and the dashed
lines represent respectively the results obtained
with finite and infinite mass excitons.

Clearly the coupled exciton-photon mode split-
ting appears with both cavity excitons and the fine

Figure 1. Schematic representation of a semiconductor microcavity with Bragg mirror confinements.

Figure 2. Calculated reflectance (a), transmission (b) and absorption (c) spectra of a GaAs λ -cavity confined by two Bragg reflectors with 20 AlAs/AlGaAs pairs. Solid and dashed lines show respectively the results obtained using finite and infinite mass excitons.

structures in the solid lines are due to the spatial dispersion of the excitons because of the interference with the additional wave [5]. The coupled mode splitting is equivalent to the vacuum-field Rabi splitting in atomic physics and quantum electronics [1], which is proportional to the square root of the oscillator strength. This has been proven, in agreement with both linear dispersion analysis and quantum theory (it is worth noting that the splitting at the cross point of a bulk polariton is also proportional to the square root of the oscillator strength, i.e. $2\omega_c = \sqrt{4\pi\beta/\epsilon_\infty} \omega_0$).

Now we examine in more details the effect of the Bragg mirror confinement by considering a bare cavity grown on a *single* Bragg reflector (such an asymmetric microcavity can also be obtained by etching the left Bragg reflector of the structure shown in figure 1). We show in figure 3 the spectra calculated with four stack arrangements. Several points can be addressed: (i) no cavity mode does appear so that no coupled mode splitting occurs. This is because of the poor reflection at one of the cavity surfaces; (ii) the appearance of the polariton peaks drastically depends on the sequence of the Bragg pair: they are enhanced (a,c) or inhibited (b,d) only depending on whether in the supporting Bragg mirror $n_1 < n_2$ or $n_1 > n_2$; (iii) in the case of polariton enhancement ($n_1 < n_2$) the well defined structures can be interpreted in terms of the exciton center-of-mass (CM) quantization [5]. In fact, the cavity polariton reflectance minima are very close to the exciton CM quantization energies given by $E_n = \hbar\omega_0 + n^2\hbar^2\pi^2/(2M_{ex}^*\lambda^2)$.

Figure 3. Calculated reflectance spectra of λ - (a,b) and $\lambda/2$ -cavities (c,d) of GaAs grown on a *single* Bragg reflector of 20 (AlAs,AlGaAs) pairs ($n_{sub} = \sqrt{12.53}$). Solid and dashed lines show respectively the results obtained using finite and infinite mass excitons. (a) and (c) are obtained with the Bragg layer sequence $n_1 < n_2$; (b) and (d) are obtained with the sequence $n_1 > n_2$.

It should be remarked that in the present case the polariton peak amplitudes are not simply related to the exciton oscillator strength. We have to consider a photon-exciton interaction starting from the Fermi's Golden Rule and taking into account the density of states of both photons and excitons. Here we discuss a simple explanation based on a cavity mode exciton-photon interaction. Inside the cavity the spatial variation of the photon states ($\phi_\lambda(z)$) is of the same order of that of the exciton CM motion ($\psi_{ex}(z)$). Since both $\phi_\lambda(z)$ and $\psi_{ex}(z)$ are slowly varying in comparison with the crystal Bloch function, a separation of the atomic scale

dipole-field matrix element is allowed and, therefore, the transition probability is proportional to the square of the overlap,

$$P_{\psi_0 \rightarrow \psi_{ex}} \propto \left| \int \phi_\lambda(z) \psi_{ex}(z) dz \right|^2 \quad (7)$$

Hence the selection rule of the cavity polariton is determined by the parity of $\phi_\lambda(z)$ and $\psi_{ex}(z)$. We assume that the exciton CM envelope function, $\psi_{ex}(z) = \sqrt{2/l_\lambda} [\cos(n\pi z/l_\lambda), \sin(n\pi z/l_\lambda)]$, where $n = [\text{even}, \text{odd}]$ integers. We also recall that at the center of the stop band of a Bragg mirror, the reflection coefficient is given by $r|_{\omega_0} = [1 - n_{sub}(n_1/n_2)^{2N}] / [1 + n_{sub}(n_1/n_2)^{2N}]$, where N is the total number of $\lambda/4$ Bragg layers. For large N , $r = 1$ if $n_1 < n_2$ and $r = -1$ if $n_1 > n_2$. So the optical waves in the cavity in front of the Bragg mirror also have the spatial variation close to *cosine* ($r = 1$) or *sine* ($r = -1$) forms. Clearly with these simple trigonal functions the overlap of eq. (7) gives a detailed account on the cavity polariton amplitudes and explains the structure enhancement or inhibition in the calculated spectra in figure 3.

We would like to mention that the calculation presented in this work is a simple version which can be improved by including more material and physical characteristics. To compare the calculated quantized energy levels with experimental data, for instance, the exciton confinement thickness should be smaller than the cavity length because of the exciton dead layers near the cavity surfaces. Typically the dead layer thickness is of the order of the exciton Bohr radius [5].

4. conclusion

In conclusion, optical spectra of excitons confined in GaAs cavities have been studied theoretically. It has been shown that inside the cavity the interaction of light with the excitons can be modulated by growing the cavity with suitable Bragg reflectors. Thus, the coupled photon-exciton mode splitting can be observed and the fine polaritonic structures enhanced or inhibited. We hope that the proposed cavity system, which is both optically and electronically resonant, can also be useful to study other interesting phenomena.

The authors would like to thank Drs. J.Massies, C. Deparis and G.Neu for their excellent collaborations. One of us, Y.C. is grateful to the Scuola Normale Superiore of Pisa for hospitality and to Drs. C.L.Andreani, B.Gil, and D.S. Citrin for useful discussions.

5. References

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