

## Exciton-photon coupling in photonic wires

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Cavity-polariton mode dispersion and exciton-photon coupling effects have been investigated by angle-resolved photoluminescence in a two dimensionally confined semiconductor Bragg microcavity (photonic wires) with a quantum well (QW) inserted in the cavity layer. The lateral photon confinement results in the appearance of additional photonic modes. The strong exciton-photon coupling leads to the formation of cavity polaritons with energy-wave vector dispersion corresponding to the photonic wires with ideal QW's (the coupling only between the photon and exciton modes with the same lateral symmetry). The small influence of QW potential fluctuations disturbing exciton lateral symmetry undoubtedly shows that the polaritons form via coherent collective exciton states. [S0163-1829(98)52512-X]

Recently, planar semiconductor microcavities (MC) with distributed Bragg reflectors have been extensively investigated due to remarkable possibilities for controlling the exciton properties via the coupling with the cavity resonance photon mode. In particular, the polaritonlike coupling between the exciton and the resonator photon mode results in Rabi splitting and modification both of exciton and cavity photon mode dispersion.<sup>1-5</sup> Experimental reports mostly concern the system consisting of one or more quantum wells (QW) embedded in a  $\lambda$  or  $3/2\lambda$  active layer cavity between two stacks of Bragg mirrors.<sup>6-8</sup> This geometry may be regarded as two-dimensional (2D) both for carriers in the well and light in the Fabry-Perot resonator. Properties of MC's have been investigated in the regimes of the weak and strong exciton-photon coupling. In the first case a modification of the radiative emission rate and pattern is observed, whereas in the latter case the exciton-photon coupling appears, which could be observed even at room temperature.<sup>6</sup> Cavity-polariton dispersion has been measured from angle-resolved photoluminescence (PL) experiments under low excitation levels.<sup>7,8</sup> The situation changes qualitatively at high excitation levels creating concentrations of free carriers which cause the bleaching of cavity polaritons and leads to transition to the weak coupling regime.<sup>8</sup>

Very recently, studies of semiconductor MC's with 3D optical confinement have been reported.<sup>9,10</sup> In these structures, referred to as photonic dots, optical vertical confinement by the epitaxially grown high-quality Bragg mirrors is combined with lateral confinement due to large refractive index discontinuity at the etched sidewalls. This results in a discrete, dispersionless structure of optical eigenmodes.

In the present paper we investigate the cavity-polariton dispersion and exciton-photon coupling in semiconductor MC's with 2D optical confinement, or in photonic wires. The lateral light confinement leads to additional photonlike modes. However, in contrast to the case of 3D confinement dots, all the photon modes have the energy-wave vector ( $E - k$ ) dispersion along the wire axis. The peculiarities of this

dispersion under conditions of exciton-photon coupling are the main purpose of our paper.

In photonic wires with an ideal QW, the exciton-photon coupling should result in coupling only between the states of the same lateral symmetry.<sup>11</sup> This means that the photonic-like modes with energy  $E_m(k=0)$  smaller than exciton energy  $E_X(k=0)$  anticross corresponding exciton mode  $E_{X,m}$ . Note, however, that the QW potential fluctuations localize the excitons at the lengths much smaller ( $< 100$  nm) than the photonic wire width (a few microns) and disturb the lateral symmetry of the exciton states. As a result, each photonic mode interacts with all the localized exciton states rather than with the only exciton mode of the same symmetry. Thus one can expect that the QW disorder can produce relevant changes in the cavity-polariton dispersion in the photonic wires.

On the other hand, recent studies of planar MC's have not revealed any drastic influence of QW disorder on planar cavity polariton. In particular, Houdre *et al.*<sup>12</sup> and Savonna and Weisbuch<sup>13</sup> have shown that when neglecting  $k$  scattering, even large inhomogeneous exciton energy broadening weakly influences cavity-polariton states. Lifting the in-plane momentum conservation in the planar MC's does not lead to any drastic changes either.<sup>14,15</sup> The Rabi splitting still exists for sizable values of disorder parameter, indicating that the  $k$  conserving exciton-photon interaction prevails over the  $k$ -nonconserving exciton-disorder interaction. Moreover, in agreement with experiment<sup>14</sup> the polariton inhomogeneous broadening is smaller than what is expected from the  $k$ -conserving models<sup>12,13</sup> due to "motional narrowing" of polariton modes.<sup>14,15</sup> Therefore, one can expect that the QW disorder will produce, as well, rather weak changes in the cavity-polariton dispersion in the photonic wires.

In the present paper we have studied the cavity-polariton dispersion in the photonic wires. The strong exciton-photon coupling has been found to lead to the formation of cavity polaritons with dispersion corresponding to the photonic wires with ideal QW's. That is consistent with recent studies

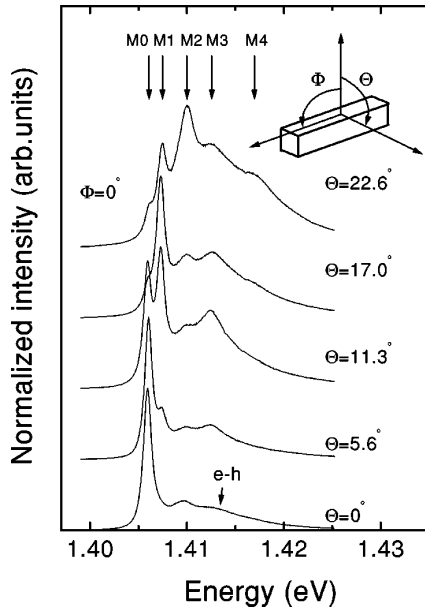


FIG. 1. PL spectra for 4  $\mu\text{m}$  wires recorded at high excitation power for different angles  $\Theta$ . Vertical arrows indicate the energies of the photonic modes. Plasma recombination peak is labelled  $e-h$ . The inset shows the directions for the angles  $\Phi$  and  $\Theta$ .

of cavity polaritons in planar MC's. The reasons for the small effect of QW disorder on photonic wires are discussed.

The sample in use is originally a planar molecular beam epitaxially (MBE) grown MC. It consists of 21 and 19 AlAs/GaAs mirror pairs below and above the active layer, respectively, constituting highly reflective distributed Bragg reflectors (DBR). The cavity layer consists of  $\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$  70  $\text{\AA}$  wide QW placed at the center of a GaAs  $\lambda$  cavity, i.e., at the antinode position of the electric field. The Fabry-Perot mode in the structure is located slightly below the exciton peak. Arrays of photonic wires with lateral sizes between 6 and 2  $\mu\text{m}$  and lengths of about 200  $\mu\text{m}$  were fabricated by electron beam lithography and dry etching through the top mirror stack only.

The dispersion of cavity polaritons has been investigated by angle-resolved PL. The sample was placed into the optical cryostat with the temperature  $T=5$  K. PL was excited with the use of a HeNe laser, dispersed by a 0.5 m monochromator and detected by a liquid nitrogen cooled CCD camera.

As was mentioned above, lateral confinement of the photon modes in 1D MC's leads to the additional quantization of photon states and leaves dispersion of the modes only along the wire axis ( $Ox$ ). The energies of the photonic modes  $M_m$  can be described as<sup>9</sup>

$$E_m(k_x) = \sqrt{E_{\text{DBR}}^2 + \frac{\hbar^2 c^2}{\epsilon_{\text{eff}}} \left[ k_x^2 + \frac{(m+1)^2 \pi^2}{L_y^2} \right]}. \quad (1)$$

Here  $E_{\text{DBR}}$  is the energy of the vertical cavity mode,  $m=0, 1, \dots, L_y$  is the lateral width of the photonic wire and  $\epsilon_{\text{eff}}$  is the effective dielectric constant.<sup>9</sup>

The lateral photon mode quantization is clearly observed in angle-resolved PL spectra of highly ( $P=1600$  W/cm<sup>2</sup>) excited photonic 4  $\mu\text{m}$  width wires shown in Fig. 1. Figure 1 shows that the lowest photonic mode M0 dominates in the

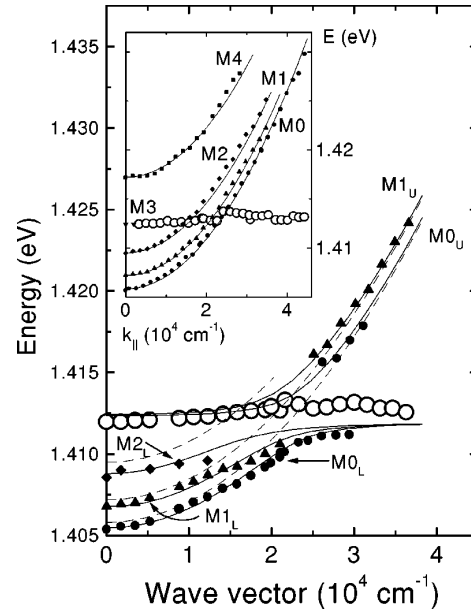


FIG. 2. Energy dispersion (dark symbols) of polariton modes for 4  $\mu\text{m}$  width wires recorded at low excitation power. Indexes  $L$  and  $U$  denote lower and upper polariton branches. Big open circles show the energy of the exciton peak which corresponds mostly to the recombination of the excitons from the regions between the photonic wires. The dispersion of the photonlike modes at high excitation power is shown by dotted lines. Solid lines are the fit made with the use of Eq. (2) (see text). The inset shows the dispersion of the photonic modes (dark symbols) and the positions of the plasma recombination peak (big open circles) at the high excitation power. Solid lines are obtained with the use of Eq. (1).

spectrum recorded at the normal direction ( $\Theta = \Phi = 0^\circ$ ). With increasing  $\Theta$  the intensity of the M0 mode reduces, whereas the higher modes appear and then become subsequently dominating in the PL spectrum. Such a behavior of the photonlike mode intensities is due to the different far field emission patterns. In general, the symmetry consideration predicts that only the odd modes (M1, M3, ...) are strictly forbidden at  $\Theta = 0^\circ$ . This is in agreement with experiment. Figure 1 shows that the mode M1 is absent in the  $\Theta = 0$  spectrum whereas there is observed a weak narrow line corresponding to the mode M2. In addition, the spectra display a broad weak line  $eh$  at 1.413 eV. This line corresponds to the emission of a highly excited excitonic system in the QW and comes mainly from the QW regions free from DBR.

Figure 1 shows that up to 5 photonic modes are observed in the range of  $\Theta < 23^\circ$  and that their energies do not depend on  $\Theta$ . Using Eq. (1) we have found that  $E_m$  are well fitted with  $L_y = 5$   $\mu\text{m}$ , which exceeds slightly the DBR width  $L = 4$   $\mu\text{m}$ . The discrepancy is not surprising because the cavity layer is not etched between the wires. Therefore the light electric field spreads partly into the regions uncovered by DBR which increases the effective photonic wire width.<sup>16</sup>

The dispersion of photonic modes can be extracted from measurements of the photonic mode energies in the PL spectra recorded at different  $\Phi$ .<sup>7</sup> The inset in Fig. 2 displays the  $k_x$  dispersion for several photonlike modes. The dependences were extracted from sets of spectra recorded at  $P = 1600$  W/cm<sup>2</sup> for  $\Theta = 0^\circ$  and  $18^\circ$ . The large open circles

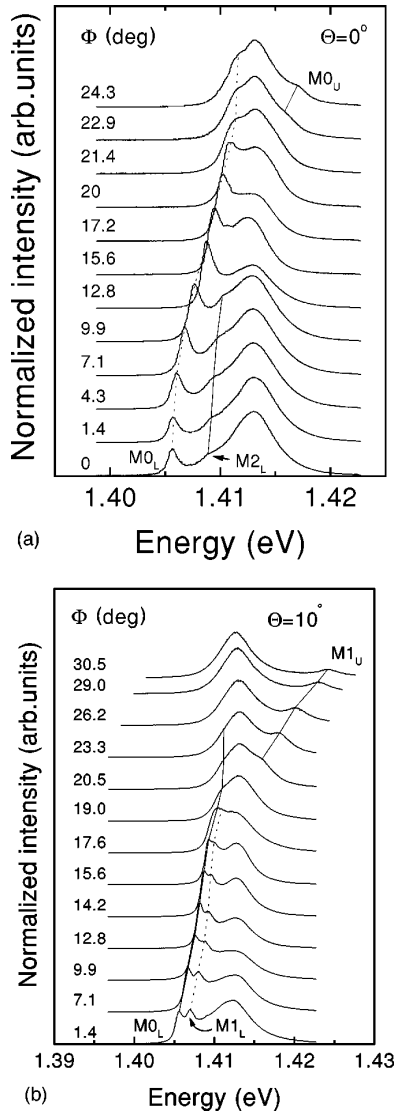


FIG. 3. PL spectra of the photonic wires taken at  $\Theta = 0$  (a) and  $\Theta = 10$  (b) for various values of  $\Phi$  at low excitation power. Dotted lines are guides for the eye. Indexes  $L$  and  $U$  denote lower and upper polariton branches.

indicate the energy of the  $eh$  peak while small symbols show the M0 to M5 photonic mode energies. The energy of the mode M3 is shown only at  $k_x < 10^3 \text{ cm}^{-1}$  because at high  $\Phi$  this line is not resolved at used  $\Theta = 0^\circ$  and  $18^\circ$ . Experimental dependences in Fig. 2 are well described by expression (1) with  $\varepsilon_{\text{eff}} = 10.9 \pm 0.1$ . As expected this value is close to the average value of  $\varepsilon$  for AlAs (8.8) and GaAs (12.5). This is illustrated in the inset in Fig. 2 by solid lines.

The inset in Fig. 2 shows that the cavity modes cross the exciton mode without any peculiarities in their dispersion. This means that the exciton-photon interaction is weak. That is not surprising because the spectra were recorded at high excitation power which provides exciton density exceeding  $10^9 \text{ cm}^{-2}$  so that the exciton screening effects suppress the exciton-photon coupling.<sup>8</sup> To observe the coupling we have decreased  $P$  down to  $300 \text{ W/cm}^2$  in order to generate exciton density well below the exciton-plasma transition.

Figures 3(a) and 3(b) display the sets of spectra recorded at  $\Theta = 0^\circ$  and  $10^\circ$  for various angles  $\Phi$ . These sets have been

used to determine the  $\Phi$  dependence of the modes M0, M1, and M2. It is seen that similar to the case of high excitation density the line M0 has the same spectral position at  $\Theta = 0^\circ$  and  $10^\circ$  in the whole range of  $\Phi \leq 20^\circ$  and the lines M0–M2 shift to the higher energies with increasing  $\Phi$ . However, the energies of all photonic modes differ from their values at high excitation power and in addition, the lines M0–M2 demonstrate a well-pronounced anticrossing with an exciton peak. The lower branches of M0, M1, and M2 tend to the exciton energy whereas two new lines appear above the exciton line at large  $\Phi$  which could be assigned to the upper branches of the modes M1 and M0. The exciton peak at 1.413 eV does not disappear from the spectrum at any  $\Phi$  because of the large contribution made by excitons from the space regions between the DBR strips.

The polariton modes dispersion extracted from sets of spectra plotted in Fig. 3 is displayed in Fig. 2. Dashed lines show the energies of these modes for high excitation density when the coupling of exciton and cavity modes is highly suppressed. The comparison of the mode energies at low and high excitation levels shows that the exciton-photon coupling results in the shift of cavity modes with  $E < E_X$  to the low energy side and of those with  $E > E_X$  to the higher energies. Such a behavior is possible only if each photonic wire mode couples strongly to the only exciton mode with the similar lateral symmetry. Taking into account this experimental result we can use a simple equation for two anticrossing levels in order to describe the cavity-polariton mode dispersion:<sup>17</sup>

$$E_{mU,L}^2(k_x) = \frac{\Sigma^2 \pm \sqrt{\Sigma^4 - 4E_{X,m}^2(k_x)E_m^2(k_x)}}{2}. \quad (2)$$

Here  $E_{mU,L}(k_x)$  is the energy of the upper (lower) branch,  $E_m(k_x)$  and  $E_{X,m}(k_x)$  are the energies of the photonic mode and excitons of the same symmetry in the absence of exciton-photon coupling,  $\Sigma^2 = E_{X,m}^2(k_x) + E_m^2(k_x) + \Omega_m^2$ , where  $\Omega_m$  is the splitting between the upper and lower modes at the resonance.

To fit the experimental dependences we have extracted  $E_m(k_x)$  from the high excitation spectra when the exciton-photon coupling is suppressed. Furthermore, we have used the exciton energy  $E_X = 1.413 \text{ eV}$  as  $E_{X,m}$  both for  $m = 0, 1,$  and  $2$  because the confinement for exciton energy in the wires with  $L > 1 \mu\text{m}$  is negligible. In addition, for small  $m = 0-2$  the splitting  $\Omega_m$  in the wide photonic wires should be nearly independent of  $m$ . Thus we have in Eq. (2) only one parameter  $\Omega$  which is used as an adjustable parameter. We have found that the best fit takes place with  $\Omega = 3 \text{ meV}$ .<sup>18</sup> The corresponding fit curves are shown in Fig. 2 by solid lines. They are in good agreement with the experimental curves.

Thus we have shown that the cavity-polariton dispersion is described in the framework of the model suggesting the coupling only between the photon and exciton modes with the same lateral symmetry. Such a behavior is expected in the case of the “ideal” QW structure. However, Fig. 3 shows that the exciton emission line halfwidth in our QW exceeds  $1 \text{ meV}$  and hence the exciton localization length is much smaller than  $L_y = 5 \mu\text{m}$ . The localization should result in the broken symmetry of the low energy excitonic states in the wire and could lead to qualitative changes in the cavity-

polariton dispersion. However, the experiment shows that the polariton dispersion is similar to that predicted for an "ideal" structure. To explain this behavior one should assume that the photon mode induces in the photonic wire some coherent collective exciton state of the same symmetry. It is obvious that such a state completed from many individual localized and extended excitonic states is possible because the photon wavelength is much larger than the exciton radius. The coupling of an induced coherent exciton state with a photon state of the same symmetry will be similar to that in the wire with ideal QW under the condition that its scattering time into some localized exciton state exceeds the Rabi oscillations period. This means that no qualitative changes in the photonic wire polariton dispersion are expected till the exciton dephasing time compares with the Rabi frequency.

In conclusion, the cavity-polariton mode dispersion and the exciton-photon coupling effects have been investigated in semiconductor MC with photon confinement in two dimensions. The lateral confinement has been shown to result in

additional photonic modes which emit light at nonzero angles  $\Theta$ . The strong exciton-photon coupling at low exciton density leads to the formation of cavity polaritons. The experimental polariton dispersion curves are in good agreement with those calculated in the framework of the model, suggesting coupling only between the photon and exciton modes with the same lateral symmetry. QW potential fluctuations disturbing the QW exciton symmetry have small influence on the polariton dispersion, which indicates the importance of coherent collective exciton states in the polariton formation. With increasing density the exciton screening destroys the strong coupling regime and the photonic modes display the quadratic dispersion law.

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<sup>11</sup>Actually, the boundary conditions are slightly different for excitons and photons which leads to the multiple-mode interaction regime even for a disorder-free QW. However, it is clear that  $m$ - $m$  interactions should be highly dominating.  
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<sup>15</sup>V. Savona *et al.*, *Phys. Rev. Lett.* **78**, 4470 (1997).  
<sup>16</sup>In our recent measurements on the photonic wires fabricated by deep etching through all the Bragg mirror layers we have obtained a very good agreement between the DBR width and the fitted value of  $L_y$ .  
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<sup>18</sup>We have determined as well the magnitude of the exciton-photon splitting in the initial planar MC from similar angle-resolved measurements just before the wire fabrication, and found it to be equal to 4 meV. This value is larger than in the wires which seems to originate from the reduced finesse of the patterned structure.