Far-field emission pattern and photonic band structure in one-dimensional photonic crystals made from semiconductor microcavities

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One-dimensional (1D) photonic crystals have been investigated by angle-resolved photoluminescence measurements. The crystals have been fabricated out of a semiconductor microcavity by lateral etching of photonic wires with a 1D lattice of small holes in the top mirror stack along the wire axis. The photonic band structure of such photonic crystals has been shown to demonstrate very small photonic gaps and can be regarded as a set of modes with the dispersion curves being replicas of the photonic wire modes periodically shifted with an integer number of the Brillouin zone periods. The replicas are well observed only for the even photonic wire modes which have the antinodes at the hole locations. The far-field emission pattern of the replicas demonstrates a much wider angle distribution than that of the main modes having the energy minima at $k=0$. [S0163-1829(99)02915-X]

At present, the study of photonic crystals is a subject of active research.[1–4] In these systems the periodicity in distribution of materials with different refractive indexes leads to the formation of photonic band structure. The refractive index modulation can provide photonic band gaps in analogy with electronic band-gaps in semiconductors. The fact that photons with the energy in this gap are forbidden to propagate through the structure can open the possibilities to use the photonic band gap materials for device applications, e.g., to realize lasers with zero threshold current[2] or to fabricate semiconductor waveguides with ultrasmall space requirement realized on linear defects in crystal lattice.[1,3]

Very recently, investigations of a photonic band-gap system based on coupled semiconductor microcavities with three-dimensional (3D) optical confinement (photonic dots) were reported.[4] The refractive index modulation in these structures was tailored by the variation of the length or the width of semiconductor channels between the dots. The transformation from atomlike discrete photon eigenvalues to the crystal-like photonic band structure was observed when about 10 ''atoms'' (dots) were connected in the chain.

In the present paper we study photonic wires with a set of etched holes situated at the center of the wire forming a 1D hole lattice. The 2D optical confinement in the wires provides quantized photon modes of different field distribution symmetry with the dispersion only along the wire axis O_x. The hole induced periodic modulation of the refractive index along O_x leads to the formation of photonic band structure. Here we are interested in the effects appearing at the small modulation of the refractive index. Therefore we use the structures with holes of small lateral size and with depth smaller than the thickness of the top mirror stack. Such a hole lattice has been found, on one hand, to result in a relatively small energy gap, which allows us to describe the photonic band structure in the weak link approximation, but, on the other hand, to lead to a drastic change in the far-field emission patterns.

The sample used for investigations was originally a planar molecular-beam-epitaxy-grown microcavity (MC). It consisted of 21 and 19 AlAs/GaAs mirror pairs below and above the active layer, respectively, constituting highly reflective distributed Bragg reflectors. The cavity layer consisted of an $In_{0.14}Ga_{0.86}As$ 70-Å-wide quantum well placed at the center of a GaAs λ cavity, i.e., at the antinode position of the electromagnetic field. The Fabry-Pérot mode in the structure is located at about 1.38 eV, which is approximately 30 meV below the exciton peak. Thus the exciton-photon coupling for the lowest modes is negligible. The arrays of wires with a length of 150 μm and a width L_y from 5 to 8 μm have been fabricated on the basis of a planar MC by dry-etching of the top mirror stack. For different arrays the period a between 2 μm square holes varies from 5 to 9 μm. The holes had a pyramidal shape with a depth of up to 15 AlAs/GaAs mirror pairs. The micrograph of the structures is shown in Fig. 1.

Angle-resolved photoluminescence (PL) measurements were performed in an optical He cryostat at a bath temperature of 7 K. The angles of PL registration were measured from the sample normal (O_z) in the plane of the wire axis xz (angle Φ) and in the perpendicular plane yz (angle Θ). A HeNe laser was used for excitation and a double 1 m monochromator and a nitrogen cooled CCD camera were used for the registration of the PL signal.

The lateral photon quantization in wires leaves the mode dispersion only along the wire axis O_x.[5] It can be determined from the angle-resolved PL measurements when the angle Θ is kept constant and Φ is changed since momentum k_x is connected with the photon wave vector in vacuum by the relation $k_x = q\cos\Theta\sin\Phi$. The dispersion can be described by the following equation:[5]

$$E_m(k_x) = \sqrt{E_{\rm vc}^2 + \frac{\hbar^2 c^2}{\varepsilon_{\rm eff}}\left[k_x^2 + \frac{(m+1)^2\pi^2}{L_y^2}\right]}. \qquad (1)$$

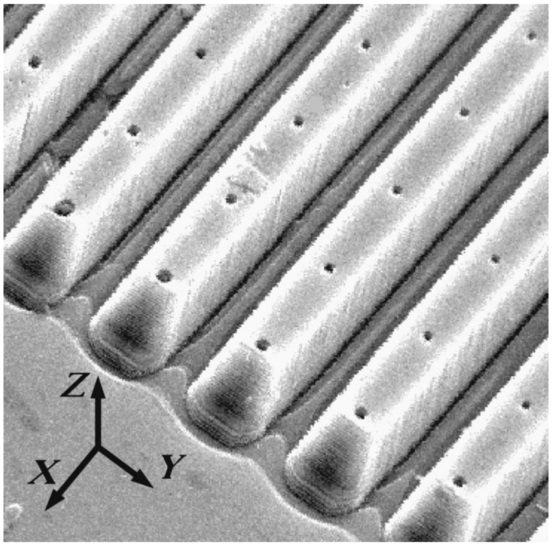

FIG. 1. Micrograph of the photonic wires with the hole lattice.

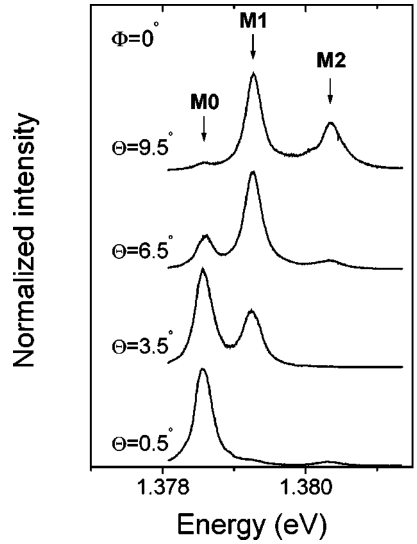

FIG. 2. PL spectra for the wires of 8 μm width and 7 μm hole lattice period recorded at $\Phi = 0°$ for various Θ.

Here $E_{\rm vc}$ is the energy of the vertical cavity mode and $\varepsilon_{\rm eff}$ is the effective dielectric constant. The mode number $m = 0,1 \ldots$ corresponds to the number of mode nodes.

The hole lattice period a corresponds to the period $k_{x0} = 2\pi/a$ in reciprocal space. The lattice constants of our structures varying from 5 to 9 μm correspond to k_{x0} in the range of $(0.7-1.3)\times 10^4$ cm^{-1}. Photons with such values of k_{x0} and the energy $E \sim 1.38$ eV propagate in the directions with $\Phi \approx 5.7°-10.5°$. Thus the range of Φ from 0° to 35° which we use for PL angle dependence measurements corresponds to a k_x range covering several Brillouin zones. In our structures with a weak periodic modulation of refractive index along the wire axis, the photon band gaps induced by a hole lattice are relatively narrow. Therefore the photon band structure can be treated in the zero approximation of the weak link limit. In this approximation the $E-k_x$ dispersion over several Brillouin zones except a small range near the Brillouin zone boundaries can be considered as a set of replicas of the wire dispersion shifted along k_x by an integer number of the reciprocal space periods. In other words, the replicas are described by Eq. (1), where k_x is replaced by

$$k_x' = k_x - (n-1)2\pi/a, \tag{2}$$

where $n = 1,2 \ldots$.

Figure 2 displays typical angle-resolved spectra for the 8 μm width wires with a 7 μm hole lattice period (referred to as 8/7 μm below) recorded at $\Phi = 0°$ and various Θ. The signal is polarized normal to the wire axis. The strongest line at $\Theta \approx 0°$ corresponds to the mode $M0$ as was expected from the consideration of the mode field distribution symmetry. At $\Theta \approx 0°$ the mode $M1$ is almost absent and $M2$ is seen as a weak line. When increasing Θ the energies of the modes remain constant (due to confinement in the O_y direction) while their intensities change: the mode $M0$ gradually disappears from the spectra while the $M1$ emission peak arises and becomes dominating at $\Theta = 6.5°$. The mode $M2$ vanishes at $\Theta = 3.5°$ and appears again at larger Θ displaying the main intensity maximum at $\Theta = 12°$. The oscillating behavior of the intensity of this mode is related to the nodal properties of the mode $M2$ field distribution across the wire.

Figure 3(a) displays PL spectra for the wires 8/7 μm at $\Theta = 5°$ and various values of angle Φ. At this Θ the lines $M0$ and $M1$ dominate in the PL spectra. At $\Phi < 3.8°$ they shift with increasing angle to higher energies. At $\Phi = 3.8°$ the mode $M0$ is split into a poorly resolved doublet. At this Φ the light wave number k_x is equal to π/a (where $a = 7$ μm), i.e., it corresponds to the first Brillouin zone boundary. Hence, the observed $M0$ splitting at $\Phi = 3.8°$ is connected with the formation of the photonic band gap. The gap magnitude is very small, of order of the linewidth, due to the weak modulation of the refractive index. At higher Φ the upper component of the doublet follows the dispersion law of the ground mode for wires without a hole lattice, whereas the lower component labeled as A decreases in energy. The energy of the line A reaches its minimum at $\Phi = 7.6°$ ($k_x = 2\pi/a$), where it coincides with that of the mode $M0$ at $\Phi = 0°$. Thus, the line A should be attributed to the replica of the mode $M0$ in the second Brillouin zone.

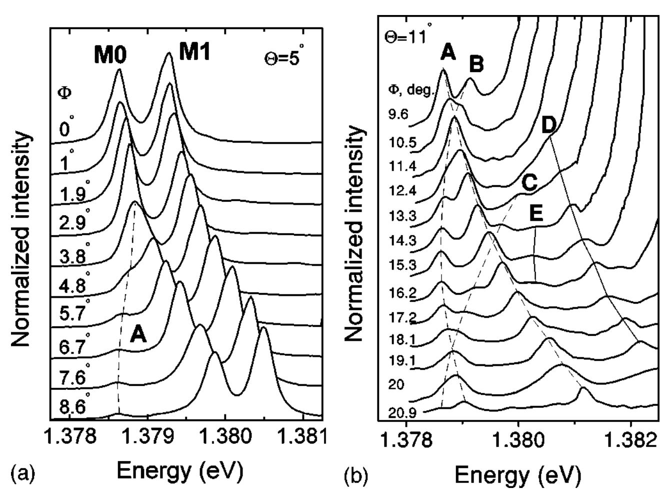

FIG. 3. PL spectra for the wires of 8 μm width and 7 μm hole lattice period taken at $\Theta = 5°$ (a) and $\Theta = 11°$ (b) for different values of Φ. The dashed lines trace the positions of the mode $M0$ replicas A, B, and C and thin solid lines show the energies of the mode $M2$ replicas D and E.

Figure 3(b) shows a set of spectra of the wires 8/7 μm for $\Theta = 11°$ and various Φ between 9.6° and 20°. The mode $M0$ is very weak and not seen. In contrast, the line A is well resolved and observed in the spectra. At $\Phi = 9.6°$ it is located at 1.3787 eV. As expected from Eqs. (1) and (2) for the range of $k_x > 2\pi/a$ the energy of mode A increases with Φ. In addition to the line A, one more line B is well resolved in the spectra. Its energy is 1.3791 eV at $\Phi = 9.6°$. With an increase of Φ the line B shifts to lower energy. At $\Phi = 11.4°$ the line B crosses the line A. This value of Φ corresponds to the lower boundary of the third Brillouin zone $k_x = 3\pi/a$. The energy of the line B has a minimum at $\Phi = 15.3°$ ($k_x = 4\pi/a$) and further increases with Φ. Another line, C, appears in the spectrum at $\Phi = 13.3°$ at an energy slightly higher than the line A. In the whole range of angles from $\Phi = 13.3°$ to 20.9° the energy of this peak decreases. At $\Phi = 19.1°$ ($k_x = 5\pi/a$) the modes B and C cross each other at $E = 1.3787$ eV, which is equal to the mode A energy at $\Phi = 11.4°$ ($k_x = 3\pi/a$) and the mode $M0$ energy at $\Phi = 3.6°$ ($k_x = \pi/a$). Thus the modes B and C can be considered as replicas of the mode $M0$ in the third and the fourth Brillouin zones, respectively.

In addition to the mode $M0$ replicas, two more features denoted as D and E are also seen in the spectra of Fig. 3(b). The line D appears in the $\Phi = 12.4°$ spectrum at energy 1.3805 eV and shifts to higher energy with increasing Φ. In contrast, the mode E after it is resolved at $\Phi = 14.3°$ moves to lower energy with angle. The positions of these peaks are traced by thin lines in Fig. 3(b). The modes are shifted by 0.6 meV to higher energies as compared to the lines A and B. This shift coincides with the energy gap between $M0$ and $M2$ and, hence, the lines D and E should be ascribed to the mode $M2$ replicas.

Figure 4 displays the dispersion of modes extracted from angle-resolved PL. The solid symbols show the dispersion of the main modes $M0-M2$ with a minimum at $k_x = 0$. These modes have a quasiquadratic monotonous $E(k_x)$ dependence. It is clearly seen that the dispersion of the modes A, B, and C repeats excellently the mode $M0$ dispersion with the shift along the k_x axis of $2\pi/a$, $4\pi/a$, and $6\pi/a$, respectively. Similar replicas are observed for the mode $M2$. In Fig. 4 the energy of these modes is shown by open symbols. Thus, Eqs. (1) and (2) can be used to describe the mode dispersion. The fit curves are displayed by solid lines. They confirm that the experimental points shown as open circles and diamonds correspond to the replicas of even $M0$ and $M2$ modes, respectively. No lines which could be ascribed to replicas of the odd $M1$ mode are observed in the PL spectra in Figs. 2 and 3, which indicates that the used hole lattice does not influence the far field emission pattern of this mode in the photonic wire.

The very different hole lattice influence on even ($M0$,$M2$) and odd ($M1$) modes is well expected. The even modes have the antinodes of their field distributions at the center of the wire where the holes are located. Therefore their wave functions are transformed strongly by the holes. On the contrary, the odd mode $M1$ has a node at the center of the wire and the hole lattice causes a small change in its field distribution. Hence, in the far-field emission pattern the replicas of this mode are much weaker than those of $M0$ and $M2$.

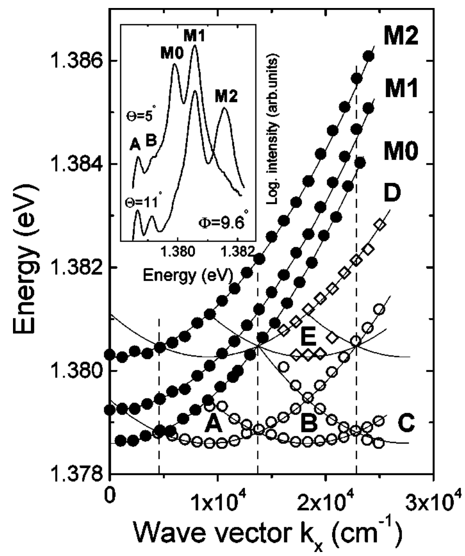

FIG. 4. Energy dispersion of photon modes in photonic wires with the hole lattice. Dark symbols show the dispersion of the main photonic modes. Open circles and diamonds are the mode $M0$ and $M2$ replicas, respectively. Solid lines represent the fit obtained with Eqs. (1) and (2). The vertical dashed lines show the Brillouin zone boundaries. The inset displays the PL spectra for the wires of 8 μm width and 7 μm hole lattice period recorded at $\Phi = 9.6°$ for $\Theta = 5°$ and 11°.

The observed picture of photon states in the structure can be treated in terms of ''folded'' modes similarly to the description of the acoustical phonon modes in semiconductor superlattices.[6] The dispersion relation for the phonon modes is obtained by folding the bulk dispersion curve in reciprocal space into the first Brillouin zone. In our case the ''folded'' modes emission lines have relatively low intensities at small k_x and are not observed in the first Brillouin zone where they overlap with the much stronger lines $M0-M2$. However, the photon mode ''folding'' is well resolved in the Brillouin zones with larger numbers where the modes $M0-M2$ have rather high energy.

Let us now consider the angle dependence of the intensity of the modes $M0$,$M2$ and their replicas in detail. The maximum intensity of the mode $M0$ is at $\Theta = 0°$. With increasing Θ the intensity of $M0$ monotonously decreases to zero. The range of angles in which $M0$ is observed depends on the wire width: the smaller the width, the wider the angle range.[7] The inset of Fig. 4 shows that in the structure with $L_y = 8$ μm $M0$ is still very strong at $\Theta = 5°$ while it almost vanishes at $\Theta = 11°$. At the same time the $M0$ replicas A and B display no noticeable change in their intensity in this range of Θ. In a similar way, the mode $M2$ is observed at the narrower angle range than its replicas. Thus the far-field emission patterns for the main modes and their replicas are quite different. We have compared the angle dependence of the PL intensity of the main modes $M0-M4$ in wires having a lattice of holes with the calculated ones for the 8 μm wire without the hole lattice and have found them to be very similar. This means that the PL signal of the modes $M0-M4$ comes mainly from the regions of the wires between the holes where an electromagnetic field of the modes spreads through the whole wire width. The PL of the replicas has a much wider angle range of observation, which indicates that their emission comes mainly from regions with smaller wire width, i.e., from regions adjacent to the holes.

In conclusion, a 1D photonic crystal was fabricated on the basis of a semiconductor MC by etching of photonic wires with a hole lattice along the wire axis. The weak periodic modulation of the media refractive index in the top mirror stack along the wire axis leads to the formation of the photonic band structure. It has been shown that to get a dramatic impact on the far-field emission pattern of even photonic wire modes is possible with a relatively weak periodic modulation of the media refractive index by etching shallow holes in the top mirror stack. Such a hole lattice along the wire axis does not influence the dispersion and far-field emission pattern of the odd wire modes having the nodes at hole locations. It produces as well only negligible photonic gaps for the even modes with antinodes at the wire center but results in the appearance of well pronounced even mode replicas shifted in k_x with an integer number of the Brillouin zone periods. The replicas have a wider angle Θ range of observation than the main photonic wire modes. The 1D photon crystal $E-k$ dispersion is well described in a weak link approximation and can be treated in terms of ''folding'' $E-k_x$ dispersion of the wire into the reduced Brillouin zone. To realize the photonic band structure with well pronounced photonic gaps, the deep etched holes shall be used.[8]

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