Nearly in-plane photoluminescence studies in asymmetric semiconductor microcavities

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Abstract

The photoluminescence from asymmetric microcavities consisting of AlAs/GaAs Bragg mirror and InGaAs/InGaAsP quantum-well cavity layer was studied in different geometry. The cavity mode in the nearly in-plane photoluminescence is explained by the constructive interference for light leaving the sample near the angle of total reflection. The vacuum Rabi-splitting, the intensity enhancement of the cavity mode and the motional narrowing are demonstrated in the temperature-dependent photoluminescence, hence obtaining initial evidences of strong coupling between the exciton and the cavity mode in the nearly in-plane direction. Our studies also suggest that the linear dispersion model provides a better description of the exciton–photon interaction of microcavities in the in-plane direction. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Semiconductor quantum wells embedded in a microcavity have attracted great interest since the first observation of normal-mode coupling by Weisbuch et al. [1]. In semiconductor microcavities, confinement of photons around the quantum well is achieved with distributed Bragg reflectors (DBRs), the emission from the electronic states is thus strongly modified and a new photon–matter state occurs. In general, the photon–matter interaction gives rise to two regimes, i.e. the weak and strong coupling regimes, depending on the relative strength of the coupling and damping mechanism. In the weak coupling regime, the coupling between the photons and crystal excitation is considered as a perturbation for the electronic system and no splitting is formed at resonance. The electron–hole spontaneous emission is modified by the confined photons and leads to the enhancement of intensity and the alternation of emission

rate. On the other hand, the system in the strong coupling regime can be described as a framework of a doublet of cavity polaritons. The cavity polaritons provide a wealth of interesting phenomena in semiconductor physics, for example, the vacuum Rabi-splitting [1–4], the Rabi oscillation in time domain [5], and the motional narrowing effect [6–7]. Most of the studies in strong coupling investigate the microcavity effects in the surface-normal direction. It is known that studying the photon–matter interaction in the in-plane direction has some special benefits in characterizing the layered structures. For example, the in-plane photoluminescence has been used to determine the quantum-well luminescence without the influence of the upper mirror in vertical cavity surface-emitting lasers (VCSELs) [8]. The layer thickness in the Bragg mirror can also be obtained without destruction of the layer structure [8]. In addition, the in-plane photoluminescence technique has been applied also to study the defect-driven interdiffusion in VCSELs [9]. In microcavity structures, one interesting question for fundamental physics is whether the normal-mode coupling occurs in the direction parallel to the epitaxial layer [10]. According to the linear dispersion theory, the cavity

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resonance can be split because of the effect of linear absorption and dispersion [11] and the normal-mode splitting will disappear in the in-plane direction of the epitaxial layer. On the contrary, the excitonic quantum model predicts a change in energy levels and a mode splitting can be observed in all directions [10]. To verify the theoretical predictions regarding the in-plane normal-mode splitting in microcavities, the in-plane photoluminescence becomes an important tool. Recently, Schaafsma et al. observed a mode splitting in side emission from a VCSEL and supported the excitonic quantum model; however, according to their paper, the question is still open [10]. Here, we study the photoluminescence on asymmetric microcavities in different detecting directions. In the exact in-plane direction the photoluminescence exhibits a pure quantum-well emission and no mode splitting is observed. In the *nearly* in-plane direction (the detecting angle is off a small angle to the in-plane direction) the photoluminescence shows a quantum-well exciton and two additional cavity modes. The splitting between the quantum-well exciton and the cavity mode is found to reveal the strong coupling with increasing temperature. Based on our studies, we confirm the prediction of the linear dispersion model regarding the light–matter interaction in the in-plane direction.

2. Experiment

The asymmetric microcavity studied in this work consists of a GaAs/AlAs Bragg mirror and a cavity layer (no top mirror). The Bragg mirror employed 27 pairs of GaAs/AlAs quarter-wave stacks to increase the reflectivity and bandwidth of the reflector. The constituent layers were designed to produce a high-reflectance band centered at a wavelength of 1550 nm. The cavity layer consisted of two sets of 15 InGaAs/InGaAsP strain-compensated multiple quantum wells separated by 80 nm of lattice matched InGaAsP spacer and grown on an InP substrate. The compressive strain wells and tensile strained barriers lead to a strain-compensated quantum well, which has been demonstrated to have a low effective loss because the critical thickness constraint is lifted [12]. Since the GaAs/AlAs Bragg mirror is grown on a GaAs substrate, a novel wafer-bonding technique is used to integrate the InP-based quantum well (cavity layer) with the GaAs-based Bragg mirror [13]. The photoluminescence was measured using an Ar ion laser as the excitation source. The laser beam was focused on to the surface of the sample near the cleaved edge. In the surface-normal photoluminescence, the sample was illuminated perpendicular to the surface and the reflected emission was focused on to the slit of a monochromator through a beam-splitter. A germanium detector was used to read the photoluminescence signal. In the in-plane photoluminescence, the emission is detected for collecting the light which leaves the sample surface near the angle of total internal reflection.

Fig. 1. The photoluminescence spectrum of the asymmetric microcavity at normal detection at 11 K.

3. Results and discussion

Before studying the in-plane photoluminescence, we measured our sample in the surface-normal direction. Fig. 1 shows the photoluminescence spectrum of the sample performed at normal incidence at 11 K. A main peak positioned at 1548 nm is seen in the spectrum. To find out the origin of the peak we performed the temperature-dependent studies (not shown). As the temperature increased, the peak shifted toward the longer wavelength at a rate of $0.78 \text{ \AA/}^\circ\text{C}$. Based on the finding, the main peak is attributed to the luminescence due to the Fabry-Perot resonance from the air/cavity-layer interface and the Bragg mirror. For the in-plane photoluminescence, the incident light illuminates in the usual way perpendicular to the sample surface but now it is detected parallel to the sample surface. The inset of Fig. 2 shows the geometry of the in-plane photoluminescence. The in-plane photoluminescence of the sample at 11 K is shown in Fig. 2. A broad peak positioned at 1485 nm is seen in Fig. 2. Under this configuration, the luminescence is unaffected by the cavity interfaces and Bragg mirror, hence we can extract the signal from the quantum well in the cavity layer. The broad exciton linewidth at 1485 nm is

Fig. 2. The in-plane photoluminescence spectrum of the asymmetric microcavity at 11 K. The inset shows the in-plane photoluminescence configuration.

due to the inhomogeneous broadening, which may arise from the interface roughness and indium alloy fluctuations. Similar broad features have been found in the in-plane photoluminescence measurements [8,14]. Thus, with different geometry, the photoluminescence coming from the cavity effect or the quantum-well emission can be obtained separately.

As the detecting direction is rotated by a small angle to the in-plane direction, the *nearly* in-plane photoluminescence is realized. The inset of Fig. 3 shows the schematic geometry of the nearly in-plane photoluminescence. Fig. 3 shows the photoluminescence spectrum measured from an angle of 4° to the in-plane direction. In addition to the quantum-well transition (Fig. 2), two sharp peaks are shown in Fig. 3. Two possible mechanisms could be considered to explain the appearance of the two additional peaks. One is the leaky mode of the DBRs. Leaky modes are electromagnetic modes stemming from the peculiar structure of the DBRs, which introduce additional resonance at finite angles. However, the linewidth of the leaky modes should be broader than that of the cavity modes at normal incidence, owing to the low reflectivity of the DBRs at large angles [15]. In our measurements, the linewidth of the additional peaks in Fig. 3 is much smaller than that of the cavity mode in Fig. 1. Consequently, we rule out the possibility for assigning the additional peaks as the leaky modes of the DBRs. Another possible mechanism of the sharp peaks is the cavity modes arising from the constructive interference created by the interaction of the radiation leaving the sample surface near the angle of total internal reflection. We call them the in-plane cavity modes since the cavity modes are measured in the in-plane direction of the sample surface. Fig. 4 shows the schematic diagram of the in-plane cavity mode resulting from the constructive interference. The interference can be created at any two interfaces in the layered structures. However, owing to the emission mechanism of the photoluminescence, the peaks coming from the in-plane cavity modes can only appear within the spectral region where the photoluminescence extends. Using a formula similar to Ref. [8], the in-plane cavity modes can

Fig. 3. The nearly in-plane photoluminescence spectrum of the asymmetric microcavity at 11 K.

Fig. 4. The schematic diagram of the constructive interference from the light leaving the sample surface near the angle of total internal reflection.

be expressed as:

$$m\lambda = \sum_i 2n_i d_i / \cos \alpha_i - 2d_i \tan \alpha_i, \quad (m = 1, 2, \dots)$$

where n_i , d_i , and α_i are refractive index, thickness, and angle of total reflection of an individual layer i , respectively. If we take $d_1 = 222.5$ nm (15 quantum wells plus the 80-nm InGaAsP spacer), $n = 3.55$ (obtained from the angle-dependent measurements of Fabry-Perot resonance) and $\alpha = 16.36^\circ$, the calculated constructive wavelength is 1515 nm, which is consistent with the wavelength of one sharp peak in Fig. 3 (1518 nm). In addition, if we take $d_2 = 213$ nm (14 quantum wells plus the 80-nm InGaAsP spacer), the calculated wavelength 1450 nm is close to the wavelength of another sharp peak (1447 nm). Thus, the sharp peaks in nearly in-plane photoluminescence can be analyzed by the in-plane cavity mode, arising from the light leaving the sample surface near the angle of total reflection.

To verify whether the in-plane cavity mode could interact with the quantum-well exciton, the temperature-dependent measurements are performed. The interaction of the quantum-well exciton and the in-plane cavity mode is achieved by varying the temperature since the exciton decreases rapidly with increasing temperature, while the cavity mode decreases slowly. Fig. 5 shows the nearly in-plane photoluminescence spectra of the sample as a function of temperature. Basically, the spectrum in Fig. 5 can be resolved by the combination of three Gaussian profiles.

Fig. 5. The nearly in-plane photoluminescence spectra of the asymmetric microcavity as a function of temperature.

An example (nearly in-plane photoluminescence at 100 K) for using a Gaussian profile to analyze the signal is shown in the inset of Fig. 5. In Fig. 5 the quantum-well exciton shifts monotonously toward the longer wavelength as the temperature is increased. However, the behavior of the in-plane cavity mode is different. It shifts toward the shorter wavelength from 11 to 100 K but back to the longer wavelength beyond 100 K. Anti-crossing behavior is clearly seen in Fig. 6, where the observed peak positions in Fig. 5 are plotted as a function of temperature. To our knowledge, this is the first demonstration of anti-crossing behavior in the in-plane configuration in microcavity structures. We attribute the anti-crossing feature to the mixed exciton–photon states or the cavity polaritons. The minimum energy separation between the quantum-well exciton and the in-plane cavity mode is 11 meV occurring at a temperature of 100 K. The separation between the two polaritons on resonance is known as the vacuum Rabi-splitting, which is a character of strong coupling effect between the excitons and photons. It should be noted that the cavity polaritons are not easily observed in an asymmetric microcavity. For a microcavity structure, the formation of cavity polaritons depends on the coupling of the excitons and the cavity mode and the broadening mechanism. The asymmetric microcavities normally have weak coupling owing to the low reflectivity of the cavity/air interface. However, in the in-plane direction the reflectivity of the cavity/air interfaces is high because of the total internal reflection. Hence, the increase of the reflectivity leads to an enhancement of the strength and a reduction of the broadening on the cavity mode. The coupling of the excitons and cavity mode can thus be more pronounced and cavity polaritons are easier to form.

The temperature variation of the peak intensities of the in-plane cavity mode and the quantum-well exciton extracted from Fig. 5 are plotted in Fig. 7. We observe an enhanced emission from the in-plane cavity mode for temperatures up to 100 K, then the emission decreases for higher temperature. The intensity enhancement of the in-plane cavity mode

Fig. 6. Peak wavelength of nearly in-plane photoluminescence are plotted as a function of temperature. The vacuum Rabi-splitting at resonance is marked.

Fig. 7. The peak intensities of the cavity mode and the quantum-well exciton extracted from Fig. 5 are plotted as a function of temperature.

at the resonant wavelength is due to the increased coupling between the photons and excitons. The temperature of the maximum intensity of the in-plane cavity mode in Fig. 7 corresponds to that of the minimum energy position of the in-plane cavity mode in Fig. 6. Hence, the phenomenon of intensity enhancement is in good accordance with the anti-crossing effect. The linewidth (full width at half maximum, FWHM) of the in-plane cavity mode and the quantum-well exciton from Fig. 5 are plotted as a function of temperature in Fig. 8. The linewidth of the cavity mode increases monotonously with the increasing temperature; however, the linewidth of the quantum-well exciton decreases from 80 nm at 11 K to 40 nm at 100 K and increases for higher temperature. In microcavities, the decrease in linewidth at resonance is called motional narrowing and was observed in many reports [6,7,16]. The motional narrowing originates from the quantum nature of the propagation of the exciton center-of-mass along the quantum-well plane (disordered potential) [16]. The linewidths of polaritons are broadened, both homogeneously owing to the finite lifetime of the cavity photon, and inhomogeneously owing to the interaction with disorder in quantum wells. The on-resonance

Fig. 8. The linewidths (full width at half maximum, FWHM) of the cavity mode and quantum-well exciton from Fig. 5 are plotted as a function of temperature.

polaritons, being part photon, have very long wavelengths compared with those typical for excitons. The inhomogeneous broadening is, therefore, reduced by averaging over a large area of disorder potential [6].

According to the linear dispersion model, the vacuum Rabi-splitting is based on the classical multibeam interference applied to a cavity where the medium has frequency-dependent dispersion in absorption and the refractive index. The splitting will change with different emission angle and should disappear in the side of the cavity (in-plane direction). On the other hand, the exciton quantum model predicts that the spectrum of a cavity may change in all directions. The center wavelength of the spectrum in the in-plane direction would be closer to the modified peak and the vacuum Rabi-splitting could exist [10]. Recently, Schaafsma et al. observed a mode splitting in side emission from VCSELs [10]. They verified that the mode splitting in their experiment is the vacuum Rabi-splitting and their result is consistent with the excitonic quantum model. However, their conclusion is not very definite according to their report. In our studies, there is no splitting in the exact in-plane photoluminescence as shown in Fig. 2. This result has also been found in Ref. [14] in the edge-emitted photoluminescence. As the detecting direction is tuned by a small angle ($\sim 4^\circ$) to the exact in-plane direction, the in-plane cavity mode and the quantum-well exciton interact with each other, forming the cavity polaritons and revealing the strong coupling effect. It should be noted that the nearly in-plane photoluminescence is very sensitive to the detecting direction. A small change in detecting angle may lead to the disappearance of the in-plane cavity mode. Based on the above studies, we suggest that there is no normal-mode splitting in the exact in-plane direction in microcavities and the interpretation from the linear dispersion model is more convincing.

4. Conclusions

In conclusion, photoluminescence studies of asymmetric microcavity structures have been performed in the surface-normal, in-plane, and nearly in-plane directions. The in-plane cavity mode in the nearly in-plane photoluminescence is interpreted by the constructive interference created by the interaction of the light leaving the sample surface near the angle of total internal reflection. Temperature-dependent photoluminescence was also studied in the nearly in-plane direction. The effects of the vacuum Rabi-splitting, the

intensity enhancement, and the motional narrowing were observed in the temperature-dependent photoluminescence. We consequently demonstrate that the cavity polaritons are formed in the nearly in-plane direction for the first time. In addition, by using a different detecting configuration, we suggest that the linear dispersion model is more convincing to elucidate the light–matter interaction of microcavities in the in-plane direction.

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