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Tuning of exciton–photon coupling in a planar semiconductor microcavity by applying hydrostatic pressure

Jidong Zhang, Hao Zhang, Jinghao Chen, Yuanming Deng, Chengyong Hu, Long An, Fuhua Yang, Guo-Hua Li and Houzhi Zheng

National Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, PO Box 912, Beijing 100083, People's Republic of China

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Abstract

By means of hydrostatic pressure tuning, we have observed the strong-coupling exciton–polariton mode in a planar microcavity with an InGaAs/GaAs quantum well embedded in it, over a pressure range from 0.37 to 0.41 GPa. The experimental data can be fitted very well to a corresponding theoretical formula with a unique value of the vacuum Rabi splitting equal to 6.0 meV. A comparison between pressure tuning and other tuning methods is made as regards to what extent the intrinsic features of the exciton and cavity will be influenced during the tuning procedure.

Since the first report on Rabi splitting in a planar Fabry–Perot cavity, composed of AlAs/$Al_{0.4}Ga_{0.6}As$ distributed Bragg reflectors (DBRs) of thickness $\lambda/4$ [1], there has been great interest in studying modes with such strong exciton–photon coupling in various semiconductor microcavities (SMCs)—much like the situation for the early study of atoms in a microcavity [2]. The important features have been examined by measuring cavity–polariton dispersion curves in angle-resolved photoluminescence (PL) spectra (Houdré *et al* [3]), by applying electric fields and magnetic fields, as well as by changing the temperature (by Fisher *et al* [4,6], Tigon *et al* [5] and Armitage *et al* [7]). Their excellent work reveals much important essential physics. In all of these experiments one has to have an appropriate means to tune the frequencies of the exciton mode and cavity mode in order to bring them into resonance. Obviously, it is desirable for the intrinsic features of both the exciton (e.g. oscillator strength) and the microcavity (e.g. Q-factor) to remain unchanged as much as possible throughout the tuning procedure. Tuning by scanning a light spot across a SMC wafer which is of a different cavity length has the problem that the entities detected at different steps of the tuning procedure are not the same. Because of the existence of inhomogeneity in the plane of the quantum wells (QWs), there may be some fluctuation in the behaviours of the exciton–polariton among different spots. In view of this, the samples used should be of high quality as regards

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uniformity. As it is tuned by changing the detection angle, the Q-factor of the cavity will deteriorate, as verified by a calculation based on an optical transfer matrix method, when the exciton–polariton resonance appears at large values of the parallel wavevector. For tuning by an electric field, the problem arises from the applied field reducing the exciton oscillator strength, and changing the features of the exciton–polariton substantially. On the other hand, tuning by varying temperature involves some other complexities that make comparison with the related theoretical model difficult.

The purpose of the present work is to probe the exciton–photon coupling mode by applying hydrostatic pressure, which has not yet been employed in investigating SMCs. It is well known that the energy of an exciton in an InGaAs QW shifts higher relatively quickly under hydrostatic pressure, due to the deformation in the crystal lattice; however, under the same conditions, the variation of the cavity mode energy must be very small, because the refractive index of the cavity material hardly shows any significant change [8]. If the exciton energy is lower than that of the cavity mode under atmosphere pressure, it is possible to tune the energies of the exciton and photon into resonance. This kind of tuning method is good in that, since GaAs and $In_{0.13}Ga_{0.87}As$ have pressure coefficients that are nearly the same, the band offset in the conduction band of GaAs/$In_{0.13}Ga_{0.87}As$ heterostructures remains almost unchanged with varying hydrostatic pressure. On the other hand, the variation of the Q-factor of the cavity under the pressure used in the experiment is also very small [9]. Accordingly, tuning by hydrostatic pressure may plausibly be considered a feasible way to look at the true behaviour of the exciton–polariton in the SMC. We have used the pressure-tuning method, and observed the typical behaviour of the exciton–polariton appearing in a pressure range from 0.37 to 0.41 GPa, which can be fitted very well to the theoretical formula with a unique value of the vacuum Rabi splitting that is equal to 6.0 meV.

The planar microcavity sample with InGaAs QWs as the active medium was grown on a (100)-oriented, undoped GaAs substrate by molecular beam epitaxy (MBE). A nominally $(3\lambda/2)$-thick cavity spacer layer (GaAs) was sandwiched between the bottom and top $\lambda/4$ GaAs/AlAs DBR mirrors, which consist of 19 and 15 pairs of GaAs/AlAs layers respectively. Two groups of three stacked layers of InGaAs QWs were embedded at two antinodes of the planar cavity. A wedge-shaped cavity—as is desirable in experiments to aid the tuning—was achieved by stopping the substrate rotation during the MBE growth of the space layer, while two DBR mirrors were grown during the rotation.

The sample, of size $100 \times 100\ \mu m^2$, was mounted in a diamond anvil cell (DAC) together with a small piece of ruby. The latter was used to monitor the applied pressure. A 4:1 methanol–ethanol mixture was used as the pressure-transmitting medium. (The nonhydrostatic component in the cell is negligible within the pressure range used, which is estimated from the relative shift of the R_1 and R_2 lines of ruby.) The photoreflection (PR) spectra were measured with a halogen lamp used as the white light source, and PL spectra were excited by the 5145 Å line of an Ar^+-ion laser. Both PR and PL signals were collected by a JY-HRD2 monochromator and detected by a photomultiplier. In order to make sure that the measurements are all made at the same position on the sample, the measuring spot was carefully checked to be unshifted by a microscope each time the hydrostatic pressure was adjusted. All measurements are made at 77 K.

Figure 1 shows the PR and PL spectra under different pressures. At $p = 0$ GPa, the deep peak in the reflection spectrum is assigned to the cavity mode, and the peak in the PL spectrum is attributed to exciton luminescence. Presumably, due to the quality of the QW, the PL peak of the light holes is not observed. As seen, there is no coupling between the exciton and the cavity mode at $p = 0$ GPa. With increasing pressure, the exciton peak shifts much faster to the high-energy side than does the cavity mode. Although the linewidth of the heavy-hole

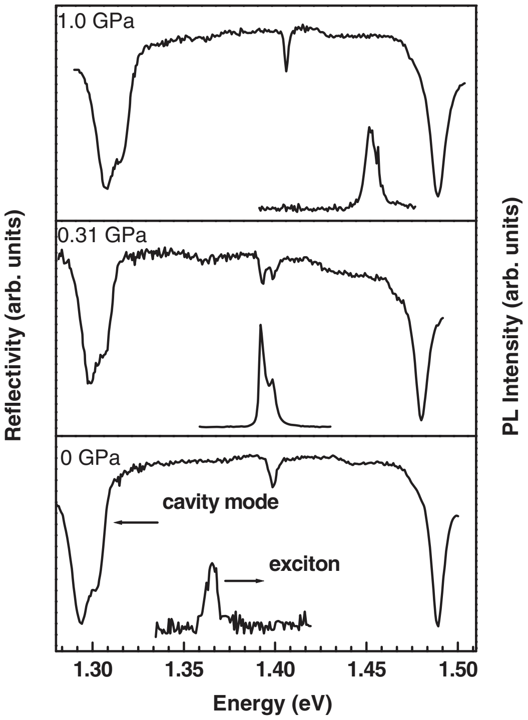

Figure 1. PR and PL spectra at 77 K under different hydrostatic pressures.

spectrum is not very narrow, a clear splitting can be found in our experimental result. One still observes the Rabi splitting, showing up in both the PR and PL spectra, as the exciton mode comes close in energy to the cavity mode (when the pressure is between 0.37 and 0.41 GPa). The detailed evolution of the exciton–polariton in the PR spectra is shown in figure 2, where the PR spectra were measured under different hydrostatic pressures. The measured dependences of the energies of the exciton and cavity modes on pressure are presented in figure 3. The energies of the exciton and photon exhibit linear behaviour with increasing pressure, which can be fitted by the following linear equations:

$$E_c = 1.40\text{ eV} + 0.014\text{ eV GPa}^{-1} \times p;$$
$$E_x = 1.36\text{ eV} + 0.101\text{ eV GPa}^{-1} \times p.$$

Here E_c is the energy of the cavity mode and E_x is the energy of the exciton mode. From the above equations, one knows that the pressure coefficient of the exciton mode is seven times larger than that of the cavity mode. This is expected from their respective physical mechanisms. The variation of the exciton energy is due to the shift of the Γ valley for both GaAs and InGaAs brought about by applied hydrostatic pressure. The pressure coefficient that we measured matches very well with the reported data for InGaAs QWs [8]. The shift of cavity mode energy is very small, since it is caused by the variation of the refractive index and cavity length under hydrostatic pressure.

We fit the data by treating the cavity and exciton modes as coupled oscillators [3], and describing the situation by a 2 × 2 matrix Hamiltonian:

$$H = \begin{bmatrix} \varepsilon_e(p) & \hbar\Omega_i/2 \\ \hbar\Omega_i/2 & \varepsilon_c(p) \end{bmatrix}. \tag{1}$$

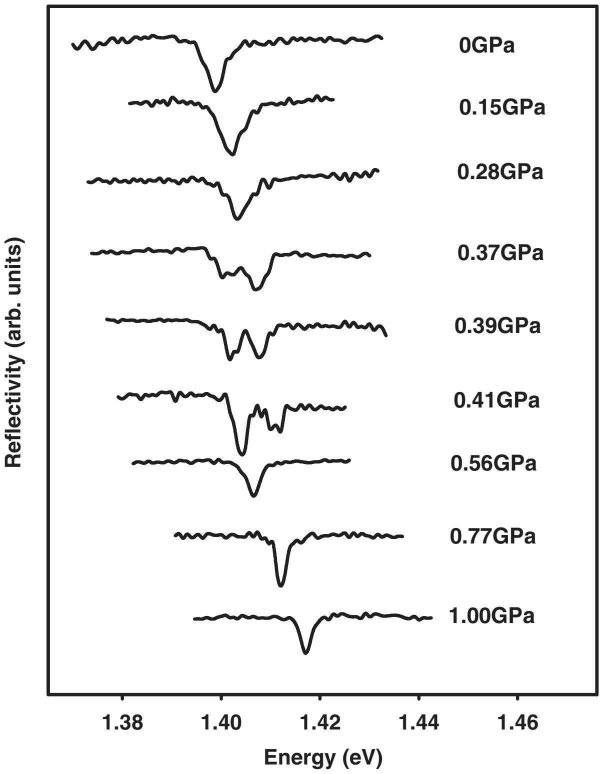

Figure 2. PR spectra measured at different hydrostatic pressures.

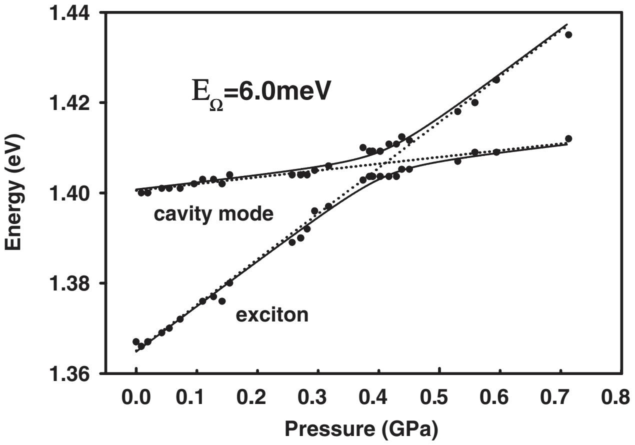

Figure 3. Dispersion of exciton and cavity mode energies with applied pressure. The full curves are theoretical fits to equation (2).

Here $\varepsilon_e(p)$ and $\varepsilon_c(p)$ are the energies for the exciton and cavity mode under a particular pressure, respectively. Ω_i is the vacuum Rabi splitting. Diagonalizing this Hamiltonian, one gets the eigenvalues as given by

$$\varepsilon_{\pm} = \frac{\varepsilon_e + \varepsilon_c}{2} \pm [(\hbar\Omega)^2 + (\varepsilon_e - \varepsilon_c)^2]^{1/2}. \tag{2}$$

As demonstrated in figure 3, the fitting to the experimental data is very good, with a unique value of 6.0 meV for the vacuum Rabi splitting Ω_i.

The theoretical expression for the Rabi frequency is

$$\Omega \propto \left[\frac{2e^2}{n_c \varepsilon_0 m_e}\left(\frac{N_{QW}}{L_{eff}}\right) f_{ex}\right]^{1/2}, \tag{3}$$

where N_{QW} is the number of QWs in the cavity; L_{eff} is the effective cavity length; n_c is the refractive index of the cavity materials; e, ε_0 and m_e have their common meanings; and f_{ex} is the exciton oscillator strength per unit area. The latter can eventually be determined from

$$f_{ex} = \frac{2}{m_e E_g} |P_{cv}|^2 \left| \int \mathrm{d}z\, \chi_c(z) \chi_v(z) \right|^2 |\phi(0)|^2. \tag{4}$$

Here, $\chi_{c,v}(z)$ are the axial envelope functions for electrons and holes; $\phi(0)$ is the in-plane excitonic function $\phi(r_e - r_h)$ at $r_e - r_h = 0$; P_{cv} is the interband momentum matrix element. As the pressure is increased from 0 to 1.0 GPa, E_g changes by no more than 5%, and so does the effective mass m_e. Obviously, the last two terms, $|\int \mathrm{d}z\, \chi_c(z)\chi_v(z)|^2$ and $|\phi(0)|^2$, dominate the possible variation of f_{ex} under pressure, since the band offset and the shape of GaAs/$\mathrm{In}_{0.13}\mathrm{Ga}_{0.87}$AS QWs remain almost unchanged on applying pressure due to their nearly zero pressure coefficients. As a result, the envelope wavefunctions, $\chi_c(z)$, $\chi_v(z)$ and $\phi(0)$ can hardly show any significant change. The fact that a unique value of $\Omega = 6.0$ meV was used in our fitting procedure is in accordance with the above theoretical analysis. In this respect, compared with the other tuning methods, tuning by varying hydrostatic pressure does have the advantage that it keeps the possible changes in the intrinsic features of both exciton and cavity modes to a minimum.

In summary, we have, for the first time, studied the behaviour of exciton–polaritons in a planar SMC by means of a pressure-tuning method. The exciton–polariton appears in the anticrossing region from 0.37 to 0.41 GPa, and can be fitted very well by the theoretical formula with a unique value of the vacuum Rabi splitting that is equal to 6.0 meV. It is also elucidated that tuning by pressure in studying the exciton–cavity coupling mode in a SMC can keep the intrinsic features of both exciton and cavity modes almost unaffected.

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