Temperature dependence of the cavity-polariton mode splitting in a semiconductor microcavity

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Photoluminescence has been used to study microcavity polaritons in the strong-coupling regime. Temperature-dependent measurements show that the cavity-polariton splitting depends strongly on the sample temperature via the homogeneous exciton broadening. The measured cavity-polariton splittings are well described by a semiclassical theory in terms of the linewidth of the bare exciton and empty cavity mode. Consequently, from the temperature dependence of the cavity-polariton splitting, the homogeneous exciton broadening has been directly extracted from the bare exciton linewidth. [S0163-1829(98)07539-0]

Quantum wells (QW's) embedded in semiconductor microcavity structures have been the subject of extensive theoretical and experimental investigation.[1–4] By effectively reducing the number of available photon modes it is possible to modify and tailor the emission properties of optoelectronic devices with respect to spontaneous emission control and linewidth enhancement. In particular, when the exciton is strongly coupled to the cavity-photon mode, the exciton transition energy is altered and a normal mode energy splitting between the two resulting polariton modes is observed. Since microcavity polaritons scatter essentially via exciton events, the magnitude of the cavity-polariton splitting will vary with temperature in a manner that depends on the role of the inhomogeneous and homogeneous exciton broadening. This topic has been addressed theoretically by several authors,[5–8] and clearly there is a need to make a detailed investigation of the effects of the exciton broadening on the luminescent properties of semiconductor microcavities.

In this paper we report a systematic investigation of the emission properties of a semiconductor microcavity in the strong coupling regime by nonresonant photoluminescence (PL) experiments between 15 K and room temperature. By increasing the sample temperature we effectively tune the exciton linewidth via the homogeneous exciton broadening, and measure the temperature dependence of the cavity-polariton splitting. Comparison with a semiclassical theory[9] suggests that for the sample studied in this work the inhomogeneous exciton broadening has no effect on the magnitude of the cavity-polariton splitting, and the experimental results are well described in terms of the temperature dependence of the homogeneous exciton linewidth.

The microcavity structure we will discuss was grown by molecular-beam epitaxy in a Varian GEN II modular system on an undoped GaAs substrate. The layer sequence is shown schematically in Fig. 1. Two GaAs/AlAs distributed Bragg reflector (DBR) mirrors, consisting of 18.5/15 pairs for the bottom and top mirrors, respectively, were used to form a nominally λ-sized microcavity with three 7 nm $In_{0.14}Ga_{0.86}As$ QW's grown at the central antinode position. In the design of the structure, the large variation in the temperature dependence of the bare exciton energy (~0.25 nm/K) and the empty cavity mode (~0.03 nm/K) was considered with respect to the useful temperature range over which the cavity mode and exciton emission energy coincide. During growth of both the top and bottom GaAs cavity spacer layers the wafer rotation was stopped, and the substrate orientation aligned identically with the Ga source cell. This maximizes the cavity wedge shown schematically in Fig. 1, and enables the energy of the cavity mode to be varied across the sample due to a variation in the cavity spacer thickness. The DBR mirrors and three QW's were all grown with wafer rotation. In maximizing the structure with respect to the maximum usable temperature range, the cavity mode was designed to be ~20 nm below the QW emission energy at room temperature. The PL emission of the microcavity were then investigated between 15 K and room temperature while still satisfying the resonance condition.

Following growth, the sample was mounted on the cold finger of a closed-cycle helium cryostat and characterized by PL. An argon-ion laser was used to excite the sample and the collected luminescence was detected using a liquid-nitrogen-cooled photomultiplier tube. PL spectra were recorded as a function of the excitation position across the sample for a series of different sample temperatures using an excitation density of ~2 W/cm^2, in the low-excitation regime.

Figure 2 shows the variation of the 15-K PL peak positions as a function of distance across the sample. Scanning across the sample the cavitylike peak moves towards the excitonlike peak due to the variation in the cavity spacer thickness. Simultaneously, the intensity of the predominantly excitonlike feature increases due to increased coupling to the cavity mode. As the energy of the empty cavity mode is scanned across the resonant position, an anticrossing of the two modes with a splitting of 5 meV characterizing the strong-coupling regime is observed.

In determining the role of the exciton broadening in the strong-coupling regime, we have investigated the cavity-polariton mode splitting as a function of increasing sample temperature. The results are shown in Fig. 3. As the temperature is varied, the sample position is continually adjusted to minimize the PL peak separation and thus to determine the resonant excitation position. A distinct trend is evident from Fig. 3; namely, that the PL splitting reaches a maximum value at 90 K and is much reduced for higher temperatures. Qualitatively the same type of behavior has been reported theoretically for a homogeneously[9] and an inhomo-

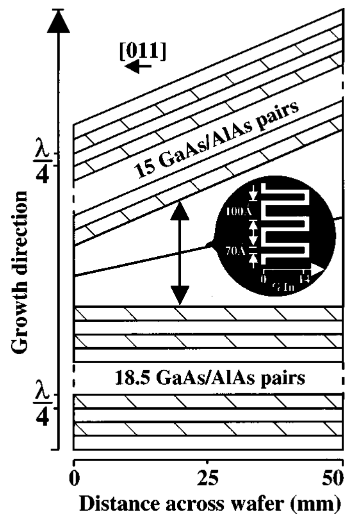

FIG. 1. Schematic diagram of the semiconductor microcavity investigated in this work.

geneously[5] broadened exciton system, and the magnitude of the cavity polariton splitting can be described by a relationship of the form[9]

$$\Omega = 2\sqrt{|V|^2 - (\gamma_c - \gamma_{ex})^2/4}, \qquad (1)$$

where V is the exciton-photon coupling constant, γ_c represents the half linewidth of the empty cavity mode, and λ_{ex} is the half linewidth of the bare exciton and accounts for all the exciton broadening.[10] Clearly, from Eq. (1), the cavity-polariton splitting reaches a maximum value when $\gamma_c = \gamma_{ex}$, and the overlap between the exciton and cavity mode is a maximum. Since the exciton linewidth broadens with increasing sample temperature due to exciton-phonon interactions, a maximum is observed in the cavity-polariton splitting at a temperature when the half linewidth of the bare exciton and empty cavity are approximately equal.

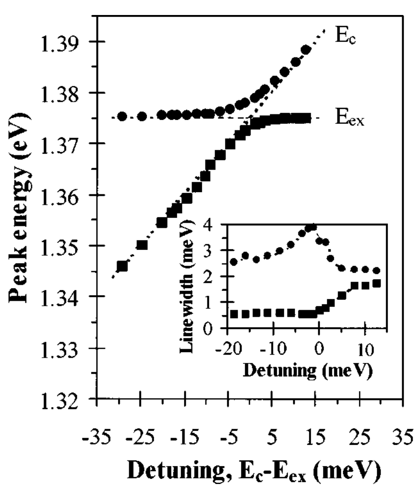

FIG. 2. 15-K peak PL energies plotted as a function of the exciton-cavity detuning. The dashed lines show the position of the bare exciton (E_{ex}) and the empty cavity mode (E_c). The inset shows the linewidth of the upper (circles) and lower (squares) polariton states.

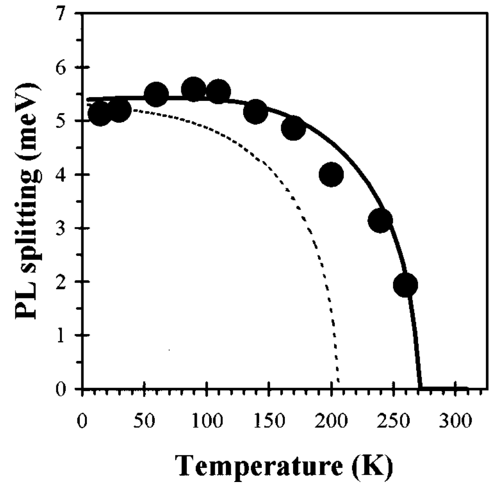

FIG. 3. Variation of the cavity-polariton splitting measured by PL as a function of the sample temperature. The circles represent the experimental data, while the solid and dotted lines represent fits to the data using Eq. (2), with an inhomogeneous exciton half linewidth γ_{inh} equal to 0 and 1.25 meV, respectively.

The experimental data, shown as the solid circles in Fig. 3, have been modeled using the semiclassical model described above, where the cavity-polariton splitting measured in PL, $\Omega_{PL}(T)$, is given by[9]

$$\Omega_{PL}(T) = \left\{ 2\Omega\left[\Omega^2 + 4\left(\frac{\gamma_c+\gamma_{ex}}{2}\right)^2\right]^{1/2} - \Omega^2 - 4\left(\frac{\gamma_c+\gamma_{ex}}{2}\right)^2 \right\}^{1/2} \qquad (2)$$

where Ω is the cavity-polariton splitting given in Eq. (1). The exciton-photon coupling constant V can be extracted in terms of the QW and microcavity parameters as given in Ref. 9. The oscillator strength for a 70-Å $In_{0.14}Ga_{0.86}As/GaAs$ QW was taken to be 5×10^{12} cm^{-2},[3,11] and the mirror reflectivity was calculated using a standard matrix method. When fitting the data we have assumed the reflectivity of the top and bottom mirrors to be symmetric. The mirror penetration depth was calculated to be ~0.41 μm corresponding to a value of $V=1.59$ meV at room temperature. We have also taken into account the effective number of quantum wells and the refractive index variation with wavelength.

The bare exciton and empty cavity linewidths were estimated from the 15-K PL spectra, collected within an angular spread of less than $\Delta\theta<2°$ with respect to normal incidence, at high exciton-cavity detuning. In addition to the anticrossing of the polariton energies shown in Fig. 2, the inset shows the polariton broadening as a function of the detuning. For large exciton-cavity detuning, the linewidth of the predominantly exciton and cavitylike peaks are 2.5 and 0.6 meV, respectively. At 15 K the exciton linewidth is predominantly inhomogeneous in nature due to an uncertainty in the well width and alloy composition of the QW's. The narrow QW linewidth measured at high exciton-cavity detuning indicates the extremely high quality of the crystal growth. In the low-temperature regime, $T<100$ K, the homogeneous exciton linewidth should depend linearly on temperature due to acoustic-phonon scattering. For higher temperatures opticalphonon broadening is expected to become dominant. The solid line shown in Fig. 3 is a fit to the data using an expression for the exciton broadening $\gamma_{ex}(T)$ of the form[12]

$$\gamma_{ex}(T)=\gamma_{inh}+\gamma_{hom}=\gamma_{inh}+\gamma_A T+\frac{\gamma_{LO}}{\exp\left(\frac{E_{LO}}{kT}\right)-1}, \quad (3)$$

where γ_{inh} is a constant inhomogeneous term and γ_{hom} represents the homogeneous exciton broadening. The second term on the right-hand side of Eq. (3) accounts for the broadening due to acoustic phonons and the third term represents the homogeneous broadening due to scattering by LO phonons. For a LO phonon energy of $E_{LO}=35$ meV, the best fit produces a linear scattering coefficient $\gamma_A=5.5$ μeV/K, $\gamma_{LO}=7.0$ meV, and $\gamma_{inh}=0$. The fitted values for γ_A and γ_{LO} are consistent with low-temperature luminescence measurements in the GaAs/$Al_xGa_{1-x}As$ QW system,[13,14] but the value for the inhomogeneous exciton component is not in good agreement with the value obtained from the 15-K PL spectra measured at high-exciton cavity detuning. One possible explanation for this disagreement is that the cavity-polariton splitting is independent of the inhomogeneous exciton linewidth. Previous works[5,6] have reported a similar tendency in the case of an inhomogeneously broadened system. In particular, when the inhomogeneous broadening is small compared to the cavity-polariton splitting ($\gamma_{inh}=1.25$ meV$\ll\Omega_{PL}=5$ meV), the inhomogeneous exciton broadening is not expected to influence the magnitude of the cavity-polariton splitting.[5] The effect of adding the small inhomogeneous component ($\gamma_{inh}=1.25$ meV) to the exciton linewidth is shown by the dotted line in Fig. 3, keeping all other parameters constant. Clearly, when the inhomogeneous broadening is included, the theory does not reproduce the maximum in the PL splitting. This can be explained by considering the nature of the cavity and exciton broadening, which should be the same when the cavity-polariton splitting is a maximum.[5] For the sample studied here, this corresponds to a temperature when the homogeneous linewidths of the bare exciton and empty cavity mode are approximately equal.

In summary, we have systematically examined the temperature dependence of the cavity-polariton mode splitting in PL for a semiconductor microcavity in the strong-coupling regime. By the careful design of a wedged-shaped cavity structure, a study of the cavity-polariton states between 15 K and room temperature is possible. We have shown that the magnitude of the PL splitting is well described by a semiclassical polariton model by considering the appropriate exciton scattering mechanisms. For the high-quality microcavity sample studied in this work, we have shown that the inhomogeneous exciton broadening does not contribute to the PL peak splitting, which is determined by the homogeneous linewidth of the bare exciton and empty cavity mode. A maximum in the PL splitting is observed when the homogeneous exciton linewidth and empty cavity linewidth are approximately equal, which occurs at a temperature of $\sim$90 K. From the analysis of the temperature dependence of the cavity-polariton splitting we were thus able to directly extract the homogeneous component of the exciton broadening. These results are expected to be important for optimizing microcavity structures with respect to room-temperature device performance.

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