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Linewidths in a semiconductor microcavity with variable strength of normal-mode coupling

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The variation of the normal-mode coupling in a semiconductor microcavity is demonstrated by reducing the cavity quality through stepwise removing top mirror pairs. The dependence of the measured normal-mode coupling linewidths on the cavity quality is well reproduced by calculations on the basis of a linear dispersion theory with broadened excitons in a microcavity. [S0163-1829(99)08421-0]

Semiconductor microcavities are presently a field of great interest both due to their applications for vertical-cavity surface emitting lasers[1] and due to their potential for fundamental studies on light-matter coupling.[2] The strong interaction of quantum-well excitons and photons in a microcavity leads to coupled modes when exciton and cavity resonances aproach each other. In analogy to the vacuum Rabi-splitting of atoms in a cavity, normal-mode coupling of excitons[3,4] results in two separate peaks in reflectivity spectra of semiconductor microcavities.[2] The energy positions of the two peaks exhibit a polariton-like anticrossing behavior as the energetic position of either the exciton resonance or the cavity resonance is varied. Tuning of the cavity resonance can be achieved for example by spatial variation of the cavity thickness[5] and the exciton resonance can be shifted by variation of temperature.[6] In the narrow-linewidth limit, the splitting Ω between the two peaks is a measure of the strength of the exciton-photon interaction and depends on the number of quantum wells N in the cavity and the effective cavity thickness according to $\Omega \propto \sqrt{N/L_{\mathrm{eff}}}$.[7]

In the past, the linewidths of the normal modes and particularly the influence of disorder on the linewidths have attracted a lot of attention.[6,8–10] There has been a controversy on whether disorder influences excitons in the strong-coupling regime in a different way than excitons in the weak-coupling regime. Whittaker and co-workers[6] measured the normal-mode linewidths as a function of detuning between exciton and cavity energy and found that the linewidths around resonance were smaller than intuitively expected. They explained this observation in terms of a cavity-polariton picture. Excitons and photons in a microcavity form new quasiparticles, the cavity polaritons. From the dispersion relation of these polaritons effective masses have been deduced which are much smaller than those of excitons. Their conclusion was that cavity polaritons would be much less influenced by disorder than excitons without a microcavity since the zero-point motion of a lighter particle averages over a larger disordered region thereby reducing the broadening due to disorder. The cavity-polariton linewidths would then be smaller than one would expect from a simple combination of the exciton and cavity-mode linewidths.[6,8] The effect was called ''motional narrowing.''

Recently, Ell and co-workers[9] claimed that these effects are not required for the description of normal-mode linewidths in present experiments. They obtained very good agreement of experimental results on different samples with a linear dispersion theory. The principle of this theoretical approach is that the susceptibility of the quantum well excitons without cavity is determined independently. On the basis of this susceptibility the light-propagation through the microcavity with the quantum wells is calculated, e.g., with the tranfer-matrix technique. Hence the backaction of the cavity on the exciton linewidth itself is neglected whereas the light-matter coupling between the exciton and the cavity, that leads to normal-mode coupling, is included. The results of these calculations agree very well with linewidth measurements on samples of different qualities where the exciton broadening is either larger or smaller than the width of the cavity mode or comparable to it.[9] However, ''motional narrowing'' was still very recently claimed to play ''an essential role in explaining the reduced linewidths close to resonance.''[10]

In this contribution, we give further evidence for the fact that polaritonic effects are not required to explain the normal mode linewidths even close to resonance. We study the normal-mode linewidth at and around the resonance regime on one sample with variable normal mode coupling. The damping of the cavity mode and thus the sample quality is changed by selective removal of a consecutive number of top-mirror pairs on the same sample. The variation of the damping of the cavity mode changes the photon lifetime in the cavity from values much longer that the exciton homogeneous lifetime down to values shorter than the exciton lifetime. The removal of top-mirror pairs also reduces the effective cavity length and thus the normal mode coupling on the same sample in contrast to the approach of Ell and coworkers where different samples were used.[9] The experimental results are compared with calculations from a linear dispersion theory in order to clarify further the role of disorder on the normal-mode linewidths at resonance.

Our structure is a 2λ sin-type cavity with 4×3 strain-compensated (GaIn)As/Ga(PAs) quantum wells placed in the antinodes of the electric field in the cavity. The bottom Bragg mirror consists of 15 and the top mirror consists of 12.5 pairs of AlAs/GaAs $\lambda/4$ layers.[11] Using selective etching, we can remove a variable number of top-mirror pairs (TMPs) at different sample positions in order to reduce the cavity quality. For the experiment, a staircase-like structure

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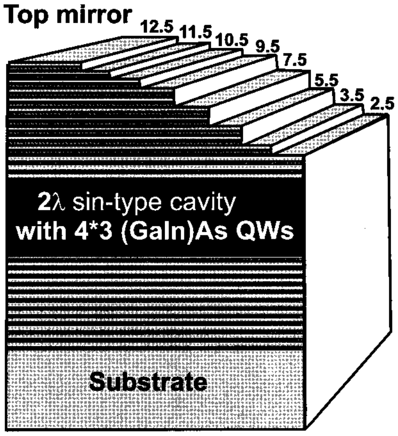

FIG. 1. Scheme of the sample structure.

is used which is shown schematically in Fig. 1. The calculated top-mirror reflectivity changes from 98.98% for 12.5 TMPs to 66.69% for 2.5 TMPs.

We measure reflectivity spectra of our sample at different positions and determine the energetic positions of the two normal modes as a function of temperature. The homogeneity of our sample is so good that we cannot tune exciton and cavity mode into resonance by a variation of the position on the sample parallel to the stairs. Therefore we tune through the dispersion of the modes across the resonance by variation of temperature.

The temperature dependence of the energy positions of the normal modes is shown in Fig. 2 for 11.5 and 2.5 TMPs. In both cases, an anticrossing behavior is observed with a minimum distance of the two branches at 75 K, where exciton and cavity mode are in resonance. As a result of the large number of quantum wells in our sample, a large normal-mode splitting of 10.42 meV is obtained for 11.5 TMPs. The splitting is reduced to 6.71 meV for 2.5 TMPs. The variation of the splitting with the number of TMPs demonstrates that the partial removal of the top mirror not only varies the damping of the photon mode (cavity-mode linewidth) but also changes the exciton-photon interaction considerably.

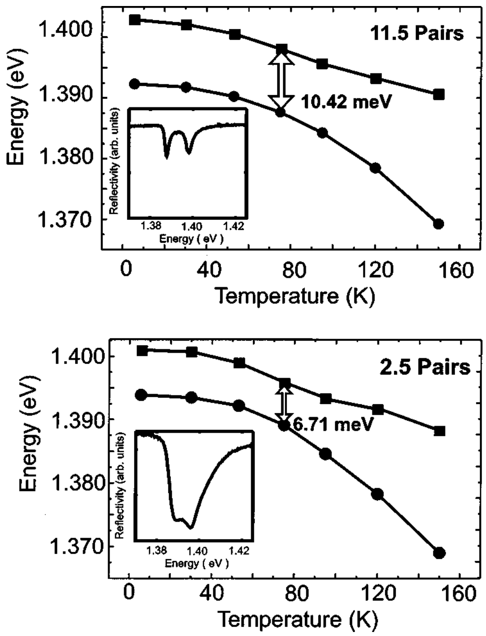

FIG. 2. Energy positions of the two normal modes as a function of sample temperature for 2.5 top-mirror pairs (top) and for 11.5 top-mirror pairs (bottom). The insets show the corresponding reflectivity spectra at $T=75$ K (resonance).

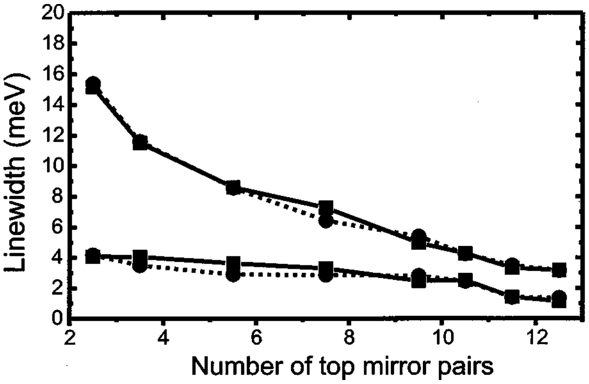

FIG. 3. Experimental and theoretical normal-mode linewidths at resonance as a function of the number of TMPs. The squares depict the experimental data; the circles show the theoretical data. The solid and the dotted lines are guides to the eye for the experimental and for the theoretical data, respectively.

We measure the normal-mode linewidths close to resonance for different numbers of TMPs, i.e., for various cavity qualities. The measured reflectivity spectra at resonance (75 K) are shown for 11.5 TMPs and 2.5 TMPs as insets in Fig. 2. The temperature-dependent contribution to the strongly inhomogeneously broadened exciton linewidth (6 meV) is negligible up to 150 K so that the tuning into resonance by increasing the temperature up to 75 K has no influence on

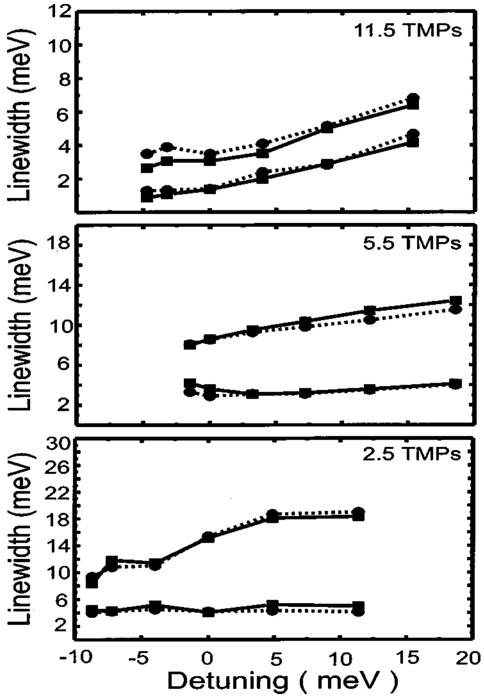

FIG. 4. Experimental and theoretical normal-mode linewidths as a function of detuning between exciton and cavity resonance for 11.5 TMPs (top), 5.5 TMPs (middle), and 2.5 TMPs (bottom).

our results. Two peaks are resolved at resonance for all numbers of TMPs, even for 2.5 TMPs normal-mode coupling is clearly visible. The linewidth of the high energy (upper) branch increases monotoneously from 3 meV for 12.5 TMPs to 15 meV for 2.5 TMPs while the linewidth of the lower branch increases from 1 meV for 12.5 TMPs to 4 meV for 2.5 TMPs. Numerical values for the linewidths are obtained by a double Lorentzian fit to the measured reflectivity spectra. These values are depicted as a function of the number of TMPs and in the resonance regime in Fig. 3.

To further analyze the experimental results and to determine the validity of the linear dispersion theory, we reconstruct the quantum-well susceptibility. The top and bottom mirrors of the microcavity sample are removed completely by etching and the absorption spectrum of the remaining quantum wells is measured at different temperatures. The absorption spectra correspond very well to those of a reference sample grown under the same conditions but without Bragg mirrors. The refractive index spectra and the optical susceptibility are obtained with a Kramers-Kronig transformation. The susceptibility is used for a calculation of the microcavity reflectivity using the transfer-matrix technique.

The theoretical results obtained from linear dispersion theory are also plotted in Fig. 3 showing that the experimental results are very well reproduced. Hence, it is sufficient to use the effective susceptibility that implicitly includes the disorder effects. It should be pointed out that in contrast to previous experiments we vary the strength of the normal mode coupling on the same sample by almost a factor of 2. Nevertheless, we still do not find features which cannot be described by the linear dispersion theory. To further confirm this result, we study the linewidths as a function of detuning between exciton and cavity for different numbers of TMPs. The corresponding experimental and theoretical data are compared in Fig. 4 for 11.5 TMPs, 5.5 TMPs, and 2.5 TMPs, respectively. The experimental values for the detuning are obtained from a fit to the dependence of exciton energy on temperature. Again, the experimental observations are well reproduced by the linear dispersion theory.

In conclusion, we have studied the normal-mode linewidths on a sample with variable cavity quality and normal mode coupling. Quantitative agreement is found between measurements and calculations on the basis of a linear dispersion theory. Our results confirm that ‘‘motional narrowing’’ effects[6,8,10] do not play an important role in the normal-mode linewidth even at and around resonance and thus further confirm the results of Ell and co-workers.[9]

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