Actively Tuned and Spatially Trapped Polaritons

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Abstract. We report active tuning of the polariton resonance of quantum well excitons in a semiconductor microcavity using applied stress. Starting with the quantum well exciton energy higher than the cavity photon mode, we use stress to reduce the exciton energy and bring it into resonance with the photon mode. At the point of zero detuning, line narrowing and strong increase of the photoluminescence are seen. By the same means, we create an in-plane harmonic potential for the polaritons, which allows trapping, potentially making Bose-Einstein condensation of polaritons analogous to trapped atoms possible. We demonstrate drift of the polaritons into this trap.

Microcavity polaritons have in the past decade been the object of great interest for many scientists [1, 2, 3, 4, 5, 6, 7, 8, 9] interested in the study of Bose-Einstein condensation (BEC). These particles, which are mixed states of photons and excitons, have a very light mass, which in principle allows them to condense at critical temperatures near room temperature. For two-dimensional bosonic systems to truly condense at finite temperatures, the application of potential traps or confinement in a region of finite size is essential. [10] Here we present a method to actively couple the exciton mode to the cavity mode at fixed $k_{||} = 0$ and at the same time create an in-plane spatial trap for both the lower and upper polaritons. The polariton photoluminescence (PL) jumps up dramatically at resonance, and both the PL and the reflectivity show line narrowing as the system approaches resonance.

The sample studied consists of three sets of four GaAs/AlAs quantum wells embedded in a GaAs/AlGaAs microcavity, with each set of quantum wells at an antinode of the confined mode, similar to the structure used in previous work.[1] The cavity is designed in such a way that it is initially negatively detuned, with $\delta \approx -20 \text{ meV}$ ($\delta = E_{\text{cav}} - E_{\text{ex}}$). A force is applied on back side of the 150 μ m thick substrate with a rounded-tip pin, with approximately 50 μ m tip radius, as shown in Figure 1. This pushes the exciton energy down toward the cavity mode, at the same time creating a harmonic potential, following the method published previously[11, 12] for excitons. The harmonic potential is centered in the plane of at the point of pin-sample contact.

Figure 2 shows the reflectivity spectrum as a function of position on the sample, showing the anticrossing of the upper and lower polariton branches as the cavity length is varied, due to the thinning of the layer thickness by about 10% toward the edge of the wafer, which is part of the growth process. The pin stress point is chosen several millimeters to

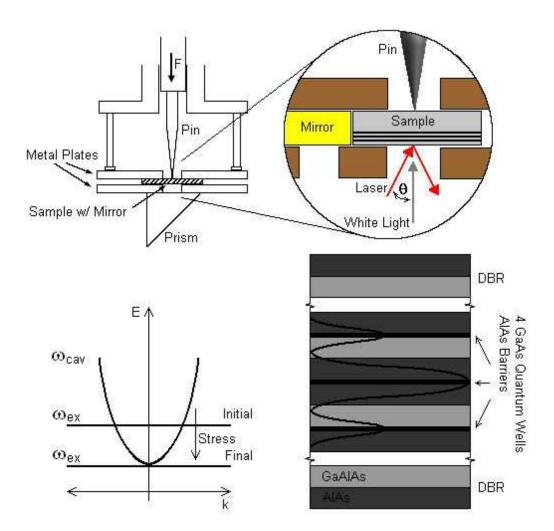


FIG. 1: Upper diagram: geometry of the experiment. Lower right: structure of the microcavity. Lower left: effect of stress tuning.

the right of the crossover point, the point of strongest coupling. Figures 3 and 4 show photoluminescence and reflectivity data for a sequence of increasing stresses applied to this sample. For the photoluminescence, a helium-neon laser source (633 nm) is used to excite the sample off-resonantly, well above the band gap, at $\theta = 12^{\circ}$ incidence, and defocused to a spot size of several millimeters to cover the entire region of observation. Photoluminescence emission collected normal to the sample is directed to a spectrometer and captured with a Photometrics back-illuminated CCD camera. For the sample reflectivity, a collimated

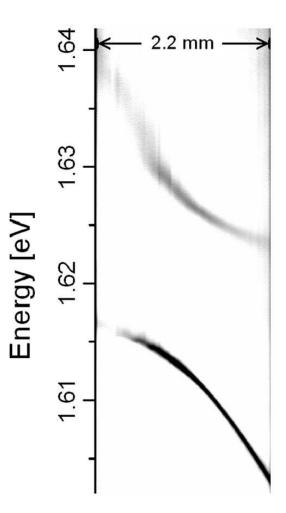


FIG. 2: Reflectivity spectrum as a function of position on the sample, for zero stress. The polariton energy shifts as the cavity length shifts, due to the thinning of the layers away from the center of the wafer.

light beam (750 nm-1000 nm) is directed normal to the sample. The reflected light is also collected normal to the sample. The mirror placed in the same plane as the sample is used to normalize the sample reflectance. For all the experiments, the sample was maintained at the temperature of 4.2 K. At this low temperature, no luminescence is seen from the upper polariton. Upper polariton emission for this sample starts to appear at about 40 K.

As seen in these figures, a harmonic potential for both the upper and lower polaritons is

created. The polaritons are clearly in the strong coupling regime, since if they were not, only the exciton states would respond to stress; the stress has negligible effect on the dielectric constants of the materials and therefore negligible effect on the cavity mode in the weak coupling limit. The energy gap between the upper and lower polariton branches decreases, while the overall energy shifts lower due to the band gap reduction.

In addition to the energy shift of the bands, a striking increase of the photoluminescence occurs, as seen in Figure 4. This is similar to the increase of photoluminescence at resonance seen by tuning of the resonance using a wedge of varying cavity thickness,[13] but the increase in the present case is dramatic, a factor of about 100. The increase of the total photoluminescence emitted from the front surface is consistent with an increase of the coupling constant at resonance. Consistent with the strong coupling, one can see in Figure 4 the narrowing of the reflectivity spectra as the bare excitons and bare photon modes approach resonance [15] during stress tuning.

Since there is an energy gradient for the polaritons, one expects that they will undergo drift. Figure 5 shows spatially resolved photoluminescence when the laser is tightly focused and moved to one side of the potential minimum in the lower polariton branch. Drift is clearly observed over a distance of more than 100 μ m, similar to the drift seen earlier[14] for polaritons in an energy gradient created by a wedge of the cavity thickness. The increase of the PL intensity seen in Figure 4 may be partly related to this effect, since polaritons will concentrate at the bottom of the well instead of diffusing away from the excitation spot.

This method of trapping opens a wide variety of possibilities and promise in the area of microcavity research and BEC of polaritons. Typically, only a tiny region of a wafer is in the strong coupling regime, due to the wedge of the layer thicknesses in standard growth

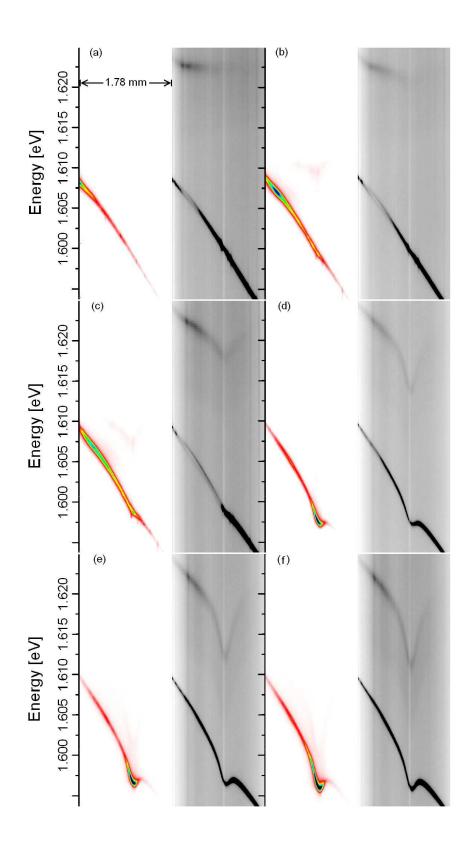


FIG. 3: Left: Luminescence spectrum as a function of position on the sample, for various levels of force on the pin stressor, (a) unstressed, (b) 0.75 N, (c) 1.50 N, (d) 2.25 N, (e) 2.63 N, (f) 2.85 N (white: minimum; black: maximum intensity). These images were created by illuminating the entire observed region (2.2 mm diameter) with a 5 mW HeNe laser. Right: The corresponding reflectivity (black: 0.0; white: 1.0). A harmonic potential is clearly seen in both upper and lower

processes. By using stress, one is no longer limited to this small region; the method allows the freedom to use nearly any part of the wafer and tune the bands to the region of strong coupling. Using electric field to tune the resonance[16] has the drawback that the oscillator strength of the exciton changes strongly with electric field. Also, as discussed above, a harmonic potential minimum is essential for Bose-Einstein condensation of polaritons or any other particles in two dimensions. The point of high stress becomes a confining point for carriers, which can be used in a polariton laser. In previous experiments,[1] the carriers were in free expansion with diffusion, with energy shifts which depended on the local density.[7] The present experiments allow theory to treat a quasiequilibrium gas with a known confining potential.

Acknowledgements. We wish to thank V. Hartwell, Z. Vörös, and A. Heberle for the invaluable comments and discussions, and H. Deng, G. Weihs, and Y. Yamamoto for contributions to the design of this sample. This material has been supported by the National Science Foundation under Grant No. 0404912 and by DARPA under Army Research Office Contract No. W911NF-04-1-0075.

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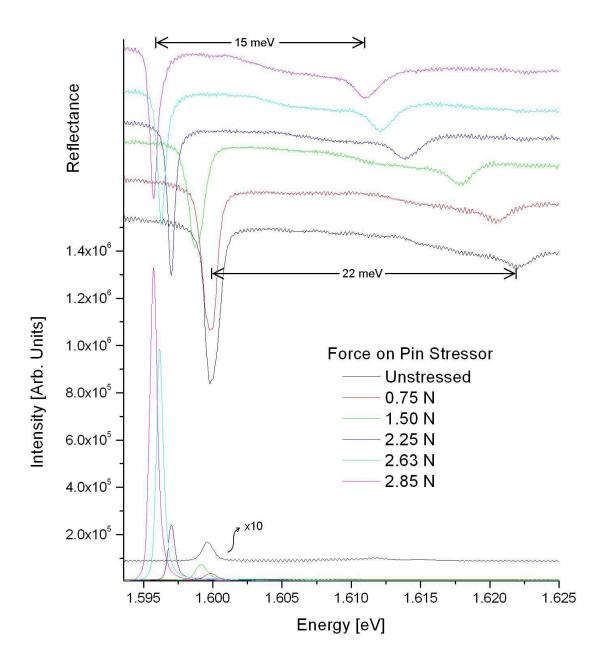


FIG. 4: Top: Reflectivity at the bottom of the stress well, for a series of applied forces. Bottom: Photoluminescence emission of the lower polariton, taken with the HeNe excitation source (900 μ W) focused (75 μ m) at the bottom of the stress well.

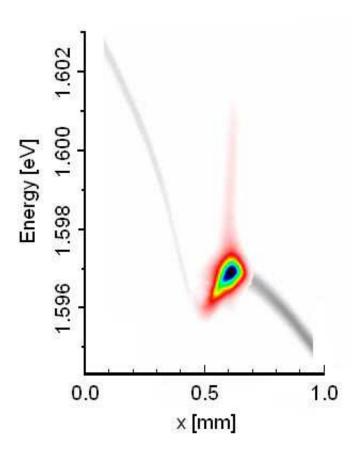


FIG. 5: Spatially resolved photoluminescence for 2.85 N applied force (white: minimum, black: maximum intensity) with the laser focused (75 μ m) and shifted away from the bottom of the stress well. The photoluminescence is superposed on the reflectivity spectrum (gray) for the same conditions, to show the location of the well.