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Lasing and polariton condensation: Two distinct transitions in GaAs microcavities with stress traps

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We have used stress to create a harmonic potential for polaritons in GaAs microcavities and have previously reported that the polaritons undergo spontaneous coherence in the trap. In this paper we present results for both trapped conditions and resonant, nontrapped conditions in the same sample. We find that the results are qualitatively different with two distinct types of transitions. At low density in the trap, the polaritons remain in the strong coupling regime while going through the threshold for onset of coherence; at higher density, there is a different threshold behavior, which occurs with weak coupling and can be identified with lasing; this transition occurs both with and without a trap. The transition at lower density can therefore be identified as a type of nonequilibrium Bose–Einstein condensation. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3140822]

Several recent papers[1–7] have shown dramatic effects of spontaneous coherence of polaritons in microcavities. These quasiparticles, well described elsewhere,[8] have the property of being a weakly interacting, two-dimensional boson gas with extremely light mass ($\sim 10^{-4} m_0$, where m_0 is the vacuum electron mass.)

Two goals in these experiments have essentially a philosophical motivation. One is to show that the coherence is truly spontaneous and not just mapping of the coherence of the pump laser to the coherence of the light emission from the microcavity states. Although it has recently been argued[9] that even when a coherent pump laser directly couples to the polariton states, the coherence of the polariton population still reflects spontaneous symmetry breaking and is not directly coupled to the coherence of the laser; others[10] have argued that the case of direct coupling of the laser to the polariton states can be treated entirely as a classical nonlinear process. One way to avoid any question of inherited coherence is generate the polaritons through an inherently incoherent process, e.g., one that involves phonon emission.

A second goal is to show that the coherence truly involves the electronic states so that we can term this type of transition "coherent matter," similar to a superconductor. This goal means that the system should remain in the "strong coupling" regime, that is, that the eigenstates of the system are equal mixtures of photon and exciton (electron-hole pair). If the system is not in strong coupling, it is essentially the same as a standard laser.

To accomplish the first goal, two methods of pumping can be used. One is to use a laser resonant in energy with the polariton states but with very steep angle of incidence.[3] Since the in-plane momentum $k_\parallel$ must be conserved in both the absorption and emission process when carriers in the 2D plane couple to external photons, the high angle of incidence creates excitons with large in-plane $k_\parallel$. It is then assumed that the excitons must emit many phonons before scattering down into low-$k_\parallel$ states and converting into polaritons near $k_\parallel = 0$ and the interaction with the phonons destroys all the original coherence from the laser. One drawback of this method is that the absorption near resonance in the microcavity is poor, and therefore very intense laser pulses must be used to produce enough polaritons to see coherence effects. A second method is to tune the pump laser to the first absorption maximum above the stop band of the cavity.[1,2] In this case the carriers must emit many phonons to fall down into the polariton states, and therefore, just as in the high-incidence angle method, the emission of the phonons destroys the original coherence. The strong absorption allows the use of much less intense continuous wave (cw) laser pumping.

The main method of demonstrating the second goal, showing that the system is in the strong coupling regime during the onset of coherence, is to monitor the shifts in the upper and lower polariton spectral lines. In the case of weak coupling, the splitting between the upper and lower polaritons at resonance will vanish, and the photon emission will occur at the energy of the cavity mode. Thus one expects that if the coherent photon emission occurs with photon energy near to the lower polariton energy and well below the bare cavity photon mode and the upper polariton energy is relatively unshifted, then the system is still in the strong coupling regime. As reported earlier,[2] in our experiments using stress to produce an in-plane harmonic potential for the polaritons and incoherent cw pumping above the stop band as in the second method described above, we have observed a transition above a critical pump intensity, which is indicated by spectral narrowing, first-order coherence, onset of linear polarization, and nonlinear gain of the output light. The upper and lower polariton states shifted less than 0.5 meV during this transition, compared to a Rabi splitting of 15 meV, consistent with strong coupling.

Experiments with similar pumping conditions in nearly identical structures, without stress trapping,[11] raise important

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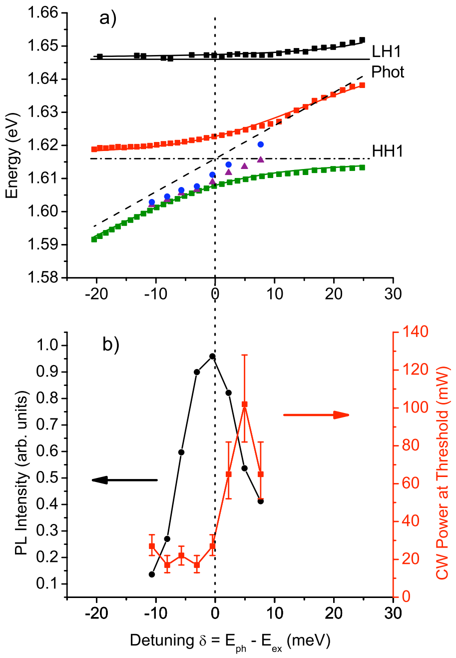

FIG. 1. (Color online) (a) Squares: energy of the reflection maxima in the cavity as a function of detuning when no stress is applied, with the sample in helium vapor at $T=4$ K. The data are fit to a simple model of coupled states using the exciton energies ($HH1$, $LH1$) and cavity photon energy (Phot) shown on the plot. Triangles: the photon emission energy as a function of detuning when a laser excites the sample with power at the threshold for coherent effects defined as the point of maximum line width before spectral narrowing occurs. Circles: the photon emission energy when the laser exciton power is increased by a factor of 1.6 beyond the threshold power. (b) Photoluminescence intensity of the lower polariton line as a function of detuning for laser excitation density well below threshold (1.8 mW, with spot size 35 μm). The intensity is maximum at resonance, $\delta=0$. (c) The laser power needed to reach the threshold for coherent behavior [corresponding to the power used for the triangles in (a)]. Laser spot size was 25 μm; laser photon energy was 714 nm at the absorption band at the top edge of the microcavity stop band.

questions, however. One issue is that a cavity system may be in the weak coupling limit even if the shift in the lower polariton line is not all the way to the bare cavity photon energy. The data in Ref. 11, which we have reproduced (as shown in Fig. 1) for our samples with nearly identical design, clearly show that at high pump intensity, the system can be pushed into weak coupling, even though the shift in the emitted photon energy was about half of the Rabi energy Ω_R, i.e., only about halfway to the bare cavity photon energy. The reason is presumably that the cavity photon energy is renormalized by the strong pumping, giving it a redshift. This implies that a system can be in weak coupling even if the energy of the emission is well below the bare cavity mode.

Another issue is that the total carrier density in the case of the trapped polaritons in our experiments is not so much different from the total carrier density in the case of weak coupling. Figure 2 shows the gain curves in a GaAs microcavity for four different conditions. The blue line with inverted triangles shows the gain curve in the case when stress is applied to create a spatial trap for the polaritons. The cav-

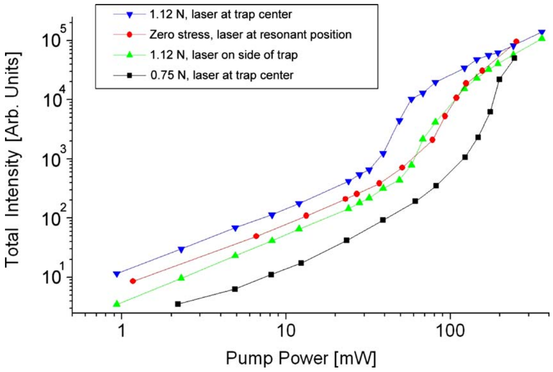

FIG. 2. (Color online) Peak photoluminescence intensity at $k_{\parallel}=0$ vs cw pump power for different amounts of force on the pin stressors and at different positions of the sample. The pump laser wavelength in each case was tuned to the first absorption maximum above the stop band to give maximum absorption. Laser focus spot size for the stressed cases was 47 μm; for the unstressed case, 24 μm.

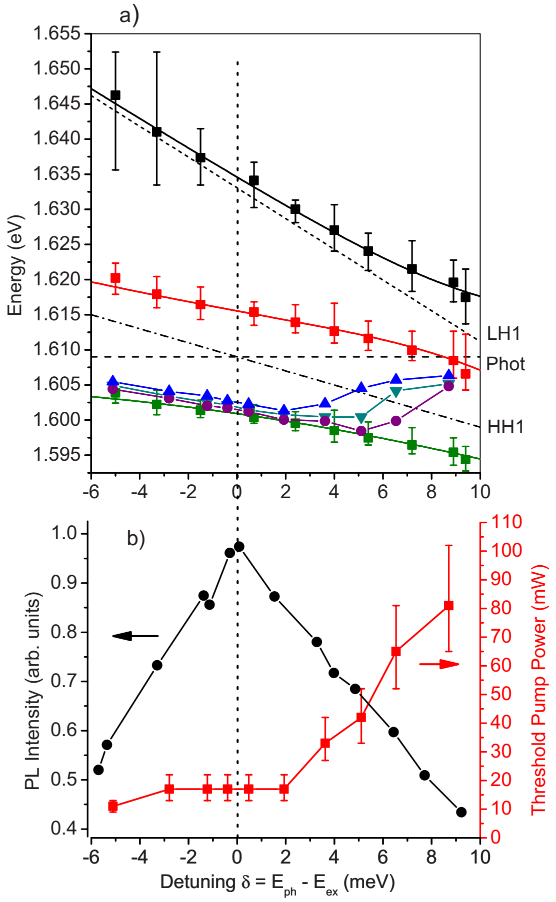

FIG. 3. (Color online) (a) Squares: energy of the reflection maxima of the cavity as a function of detuning when stress is applied to vary the exciton energy while leaving the cavity photon energy unchanged. The data are fit to a simple model of coupled states using the exciton energies ($HH1$, $LH1$) and cavity photon energy (Phot) shown. Circles: the peak photon emission energy as a function of detuning when a laser excites the sample with power at the threshold for spectral narrowing. Inverted triangles: the photon emission energy when the laser excitation power is increased by a factor of 1.7 beyond the threshold. Upright triangles: the photon emission energy when the laser excitation power is increased by a factor of 2.5 beyond the threshold. (b) Circles, left axis: photoluminescence intensity of the lower polariton line as a function of detuning for laser excitation density well below threshold (9 mW, with spot size 85 μm). Squares, right axis: the laser power needed to reach the threshold for coherent behavior [corresponding to the power used for the circles in (a)]. Laser spot size was 30 μm; laser photon energy was 716 nm at the absorption maximum at the top edge of the microcavity stop band.

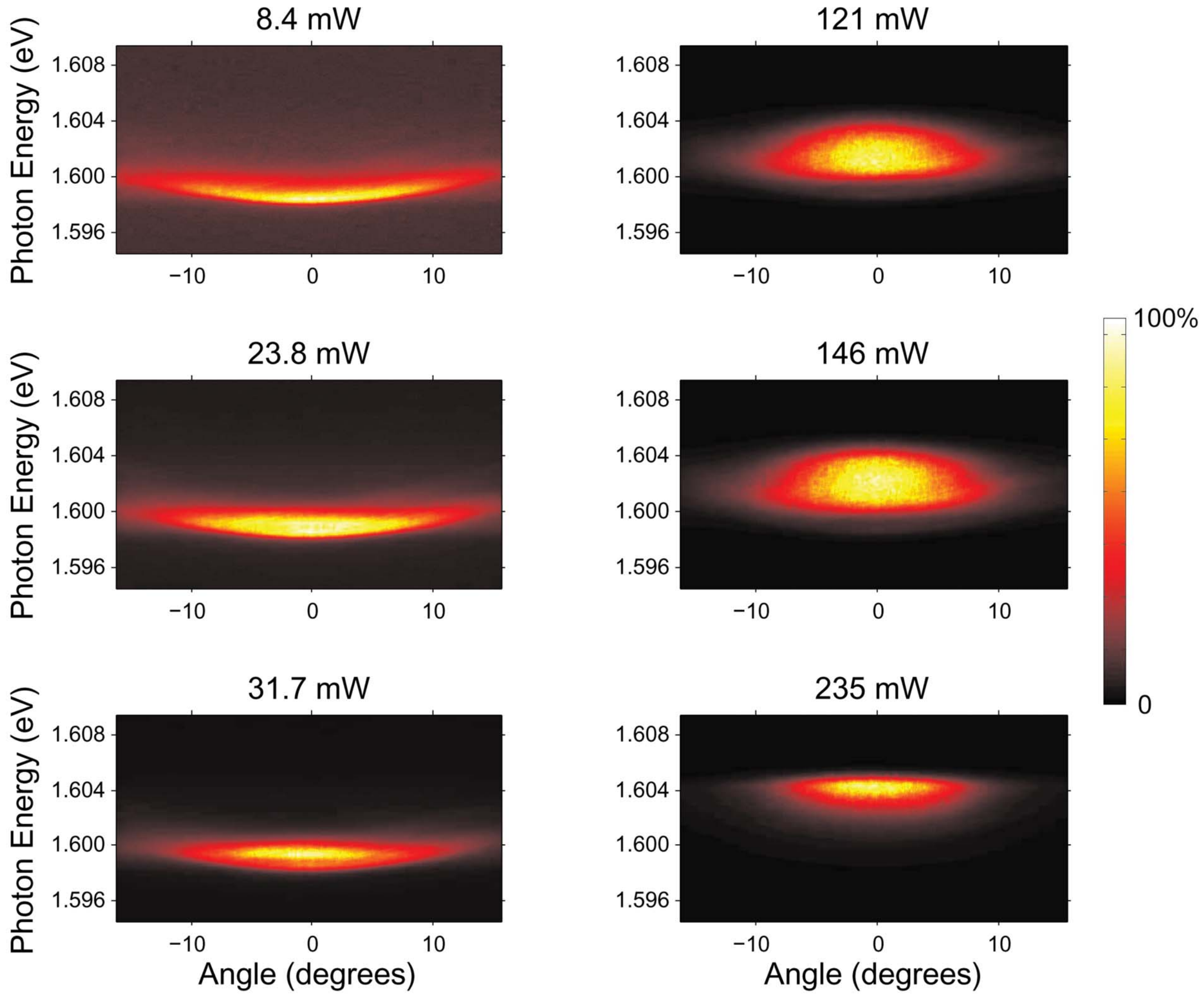

FIG. 4. (Color online) Angle-resolved and spectrally resolved emission from center of the stress trap in the microcavity structure for several different cw pump powers. The sample was in helium gas at 4 K; laser focus spot size was 25 μm.

ity is near resonance, slightly negatively detuned by a few meV, that is, the polariton states are on the photonlike side of the resonance. When the stress is released (black line with squares) the threshold for the nonlinear gain increases. There are two reasons for this. One is the decreased trapping as the stress decreases, and the second is the fact that releasing the stress takes the system out of resonance, making the lower state much more photonlike. To distinguish between the effect of the trap and the effect of moving away from resonance, one can move the excitation spot to a region on the sample where the exciton and photon states are already in resonance without need for stress tuning. This case is shown as the red circles in Fig. 2. This case is similar to the case of excitation when the cavity is near resonance, as in the case of the blue curve with triangles, but far from the center of a stress trap. This case is shown as the green triangles in Fig. 2.

Clearly, the trap is playing a role since the threshold intensity for nonlinear gain with trapping is less than for the case of resonance and no trapping (and the threshold with trapping decreases even further with increasing stress). However, the difference in the pump intensity at the threshold between the trapped and untrapped resonant cases is not more than a factor of four or so.

The argument can be made that if the carrier densities are comparable, the physics cannot be much different. On first principles, of course, this need not be true. Many phase transitions occur, which have sensitive dependence on the total particle density. A Mott transition[12] from a system with mostly excitons to one dominated by free-carrier plasma has been shown can occur with a very sharply defined density.[13] Nevertheless, we would like to directly test whether the behavior of the coherent emission is different in the two cases. To do this we can look at the behavior of the system as the detuning is varied, not by varying the cavity length, as in Fig. 1, but by varying the exciton energy by changing the stress.

Figure 3(a) shows the energy of the states as the stress is increased to change the detuning. The microcavity in this case is the same structure as used in Ref. 2 but with a much thicker substrate, which gives a much shallower trapping potential, i.e., lower spring constant for the effective harmonic potential felt by the polaritons. The point of resonance, i.e., the point of crossing of the bare cavity mode and the exciton mode, can be identified in two ways. First, we fit the shifts in the lines with stress to a simple model of coupled states, which will be presented elsewhere.[14] The result is shown as the solid lines in Fig. 3(a). Second, we monitor the total photoluminescence intensity at very low pump intensity, as shown in Fig. 3(b). As in Fig. 1(b), the photoluminescence has a maximum at the point of resonance (though it has been shown that there is a fine structure very near to the resonance point.[15]) The full width at half maximum of the photoluminescence intensity resonance around $\delta=0$ is about 10 meV in both cases of Figs. 1(b) and 3(b).

As seen in Fig. 3(a), when the pump power is increased to the threshold for coherent effects, the energy of the emission shifts upward slightly, around 0.5 meV, but follows the lower polariton energy as it shifts lower with increasing stress until the detuning is around 4 meV. This clearly shows that the emission is still in the strong coupling regime since it follows the exciton shift with stress. For detuning greater than 4 meV, the energy of the emission shifts up to near the bare cavity photon energy [indicated by the dashed line in Fig. 3(a)]. At this point it is reasonable to assume that the system is no longer in strong coupling and the transition is a standard lasing transition, redshifted relative to the bare cavity mode, as in Fig. 1(a) and in Ref. 11. As shown in Fig. 3(b), to reach the standard lasing transition when the system is strongly detuned, higher pump power, about a factor of two, must be used.

This indicates that two different transitions, polariton lasing (nonequilibrium polariton Bose-Einstein condensation) and standard lasing, are occurring in the same sample. We therefore look to see *both* of these transitions occurring at the *same* point in the microcavity sample by changing the pump intensity. Figure 4 shows that this indeed is the case. Figure 4(a) shows the emission at very low pump power. The spectral width is narrow, consistent with the low density and temperature of the polaritons. When the density is increased, the spectral width first broadens [Fig. 4(b)], as expected for collision broadening when the polaritons are at high enough density for substantial polariton-polariton scattering. At the critical threshold for coherence, the spectrum narrows [Fig. 4(c)]. All of the spectral widths in these measurements are broader than the intrinsic line width for at least two reasons. One is that the multimode pump laser has fluctuations in power, which lead to shifts in the density-dependent blueshift of the line in time-averaged experiments. In the experiments of Love *et al.*,[5] when an intensity-stabilized laser is used, very narrow line widths (~0.05 meV) and long coherence times (~150 ps) are recorded for this type of polaritonic transition. Another reason for the spectral broadening is spatial integration over the entire trapped region in these angle-resolved experiments, including contributions from polaritons over a range of densities.

When the pump power is increased even further [Figs. 4(d) and 4(e)], the emission broadens strongly and shifts strongly upward. This is consistent with high-density effects such as phase-space filling and strong polariton-polariton interaction leading to breakdown of the pure polariton picture and onset of weak coupling. Finally, as shown in Fig. 4(f), a *second* line narrowing is seen at the same spot in the sample. This corresponds to standard lasing.

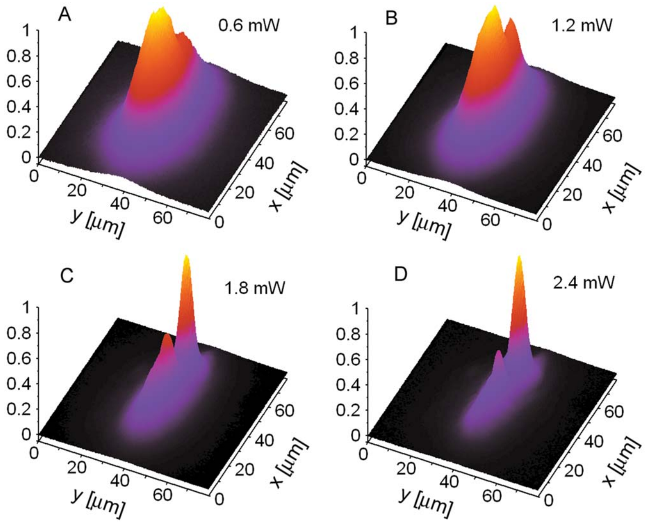

FIG. 5. (Color online) Two-dimensional spatial profile of the emission at $k_{\|}=0\pm5.2°$ for the average laser excitation powers given for quasi-cw excitation with 2.4% duty cycle at 1 kHz. The images were obtained by using a lens system to project the light from the sample plane onto a CCD camera.

There are therefore two distinct transitions. The lower-power threshold can be identified with Bose condensation of polaritons in the strong coupling limit, which occurs only when the trap exists, while the higher threshold can be identified with standard lasing in the weak coupling regime and occurs in the unstressed sample as well as in the stressed sample when it is detuned away from resonance. The trap plays an essential role in making the polariton condensate transition possible. If there is no trap, only the lasing transition can be seen in these samples. If there is a trap, both transitions can occur.

Figure 5 shows the spatially resolved light emission from the stress trap in the case when the pump laser is aimed not at the center but to the side of the trap. A low duty cycle of the pump laser is used to avoid lattice heating, giving the polaritons long drift distance in the trap. At low power [Fig. 5(a)], the polaritons reach a nearly equilibrium distribution cloud centered on the middle of the trap. As the pump laser power is increased [Figs. 5(b)–5(d)], two things happen. A very narrow peak appears at the center of the trap, while a large emission gain also occurs at the point of the laser pump. The former can be identified with polariton condensation in the center of the trap,[16] while the latter is essentially a lasing transition, which occurs at high density at the spot of maximum pumping. In steady state, some fraction of the carriers escapes from this region to fall down into the center of the trap and move into cold polariton states. We therefore see that the two transitions occur at separate spatial positions as well as at two distinct emission energies and densities.

As discussed above, the interest in the polariton condensate is partly philosophical in the desire to show spontaneous coherence of matter in the strongly coupled regime. This work also shows a way to reduce the threshold for coherent light emission. Work in microcavities with very high-quality reflection has also given indications of two distinct thresholds.[17] In that case, the condensation is aided by longer lifetime of the polaritons, while in our case, the condensation is aided by the trapping.

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