Transition from a microcavity exciton polariton to a photon laser

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(Received 6 February 1997)

In a previous paper [Phys. Rev. A **54**, R1789 (1996)], we reported the observation of a laserlike transition in a single GaAs quantum well microcavity and gave the interpretation as spontaneous buildup of coherent exciton-polariton population via stimulated polariton-phonon emission. In this Brief Report, we present new experimental data and correct our previous interpretation for the microcavity polariton system at high density. We observe a continuous transition from a microcavity polariton emission to a bare photon laser. This conclusion is based on the measurements of the angular resolved photoluminescence, linewidth, and intensity of the lasing line as well as the reflection spectrum under cw pumping. [S1050-2947(97)07606-3]

PACS number(s): 42.55.−f, 71.35.−y, 71.36.+c

Two well-known phenomena arising from Bose statistics are (1) Bose-Einstein condensation (BEC) of massive bosonic particles (such as rubidium and sodium atoms), and (2) stimulated emission of massless photons from incoherent nonequilibrium (inverted) reservoirs, i.e., lasers. There are proposals for the intermediate concept such as atom lasers [2] and exciton lasers [3], i.e., stimulated emission of massive bosonic particles from nonequilibrium reservoirs (matter-wave ''lasers'').

When quantum well excitons strongly couple with an electromagnetic field in a microcavity, the coupled exciton-photon system forms new dressed states called the microcavity exciton-polaritons. Due to their light mass compared with bare exciton mass, microcavity exciton polaritons have a large de Broglie wavelength ($\lambda_B = 7\ \mu$m) at 4 K. This can be compared with that of bare excitons ($\lambda_B = 0.07\ \mu$m) at 4 K and the exciton Bohr radius ($a_B \sim 0.02\ \mu$m). At density where the center-of-mass wave function of the individual quasiparticle have appreciable overlap, it is expected that quantum statistical effects, such as stimulated emission in an exciton-polariton laser, would play an important role. Thus, for the microcavity polariton, these effects emerge with much smaller densities than a bare exciton. In a previous paper [1], we reported a laserlike transition in a GaAs single quantum well (SQW) microcavity and gave an interpretation based on the exciton-polariton laser. In this Brief Report, we take back our previous interpretation by presenting additional experimental studies. The GaAs SQW microcavity system makes a transition from the exciton polaritons in a strong-coupling regime to a bare photon in a weak-coupling regime before the laserlike transition occurs. That is, the final-state stimulation of exciton polaritons loses the competition against the exciton bleaching. We will describe below the details of our experimental evidences for the conclusion.

Our sample, grown by molecular beam epitaxy, consists of a single 20 nm GaAs quantum well (QW) in a half-wavelength distributed Bragg reflector (DBR) cavity. The cavity buffer layer is tapered along one direction so that the cavity resonant frequency varies with sample position. The sample was cooled down to 4.2 K in a liquid helium cryostat. To avoid time-dependent effects, a cw Ti:sapphire laser, operating at 767 nm, was used as the pump. It was focused to a 30 μm spot on the sample. The cavity emission into the normal direction was measured by a spectrometer. A weak probe beam from a mode-locked Ti:sapphire laser, operating at 810 nm, was incident onto the central part of the pump spot on the sample. The reflected probe beam was guided to a spectrometer.

We measured the cavity emission and the probe reflection as we increased the pump power. The sample position was chosen where the cavity photon energy is close to the QW heavy-hole (HH) exciton energy. Figure 1(a) shows the reflection spectra of the probe at different pump power. The QW exciton density corresponding to 1 mW pump power is about 2×10^{9} cm^{-2}. At low pump power, the strong coupling of both QW HH exciton and LH exciton to the cavity photon state results in three exciton-polariton states, corresponding to the three dips in the reflection spectrum. As the pump power increases, the exciton-polariton peaks get broadened, and the normal mode splitting also reduces slightly. Eventually at high enough power, the system makes a continuous transition to the weak-coupling regime, and the reflection spectrum has only one dip which corresponds to the bare cavity photon mode. Figure 1(b) shows the emission spectra taken simultaneously at the corresponding pump powers. At low pump power, the emission spectrum features two HH exciton-polariton peaks. The slight blue shift of the exciton-polariton frequency in the reflection spectrum as compared with the emission spectrum is due to the 5° incident angle of the probe beam. As the pump power increases,

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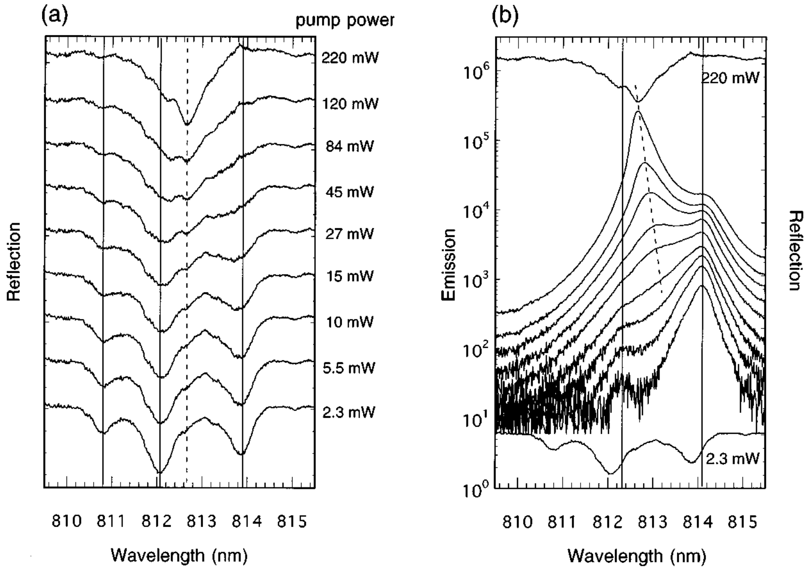

FIG. 1. (a) The reflection spectra of the probe at different incident pump powers. (b) The cavity emission spectra at the pump powers corresponding to (a). Two reflection spectra at low and high pump power also shown for comparison.

a third peak emerges in between the two exciton-polariton peaks, and its intensity grows nonlinearly. By comparing with the reflection spectrum, the third emission peak appears at the wavelength which approaches to the cavity photon mode. Therefore, it indicates that the system starts lasing at the cavity photon mode. Due to the nonuniform spatial distribution of the light intensity over the pump spot, the probe reflection spectrum changes from a single cavity photon mode to three exciton-polariton modes as we move the probe spot from the pump spot center to its edge. This indicates the excitons are saturated in the central part of the pump spot, but not in the edge. In the emission spectrum, the lasing line is from the center of the pump spot, and lower HH exciton polariton peak is from the edge of the pump spot. This was confirmed by the fact that the lower HH exciton polariton emission intensity was suppressed significantly when we measured the emission only from the central part of the pump spot [4].

We also measured the cavity emission spectra at different directions and pump powers. Figure 2(a) shows the energies of the two HH exciton-polaritons as a function of $k_\parallel$ at low pump power. From the second derivative of their angle dispersion curves at $k_\parallel=0$, we deduced the effective mass of the HH exciton polaritons are $1.7m_{ph}$ and $3.0m_{ph}$, respectively, where m_{ph} is the cavity bare photon mass. Note that the exciton polaritons at an exact anticrossing point should have the effective mass of $2m_{ph}$. This indicates that the cavity photon energy is slightly blue shifted with respect to the HH exciton energy. Figure 2(b) shows the angle dispersion curves of the lasing line and the lower HH exciton polariton at high pump power. The effective mass of the lasing line is very close to the bare cavity photon mass, which confirms the bare photon nature of the lasing line. The slight decrease in the lower polariton effective mass may be due to the blue shift of the HH exciton energy.

Figure 3(a) shows the linewidth of the lasing line and the lower HH exciton-polariton peak as a function of emission angle at high pump power. The linewidth of the lower HH exciton-polariton peak increases as $k_\parallel$ increases, because excitons with larger $k_\parallel$ not only radiatively decay but also relax down to the smaller $k_\parallel$ states by acoustic phonon emission.

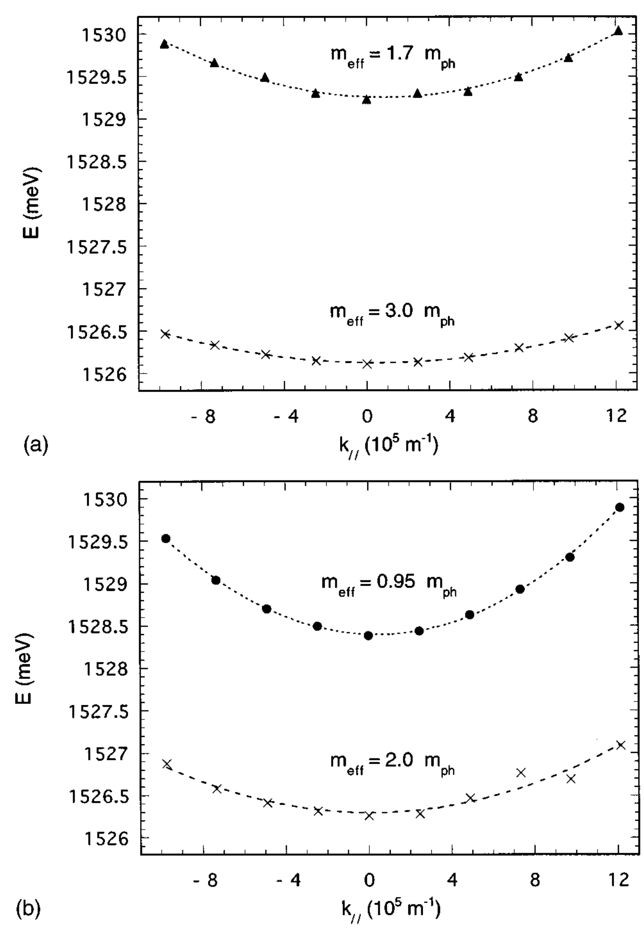

FIG. 2. (a) The energies of the two HH exciton polaritons as a function of $k_\parallel$ at an incident pump power of 2.3 mW. (b) The energies of the lasing line (closed circle) and the lower HH exciton polariton (cross) as a function of $k_\parallel$ at an incident pump power of 120 mW.

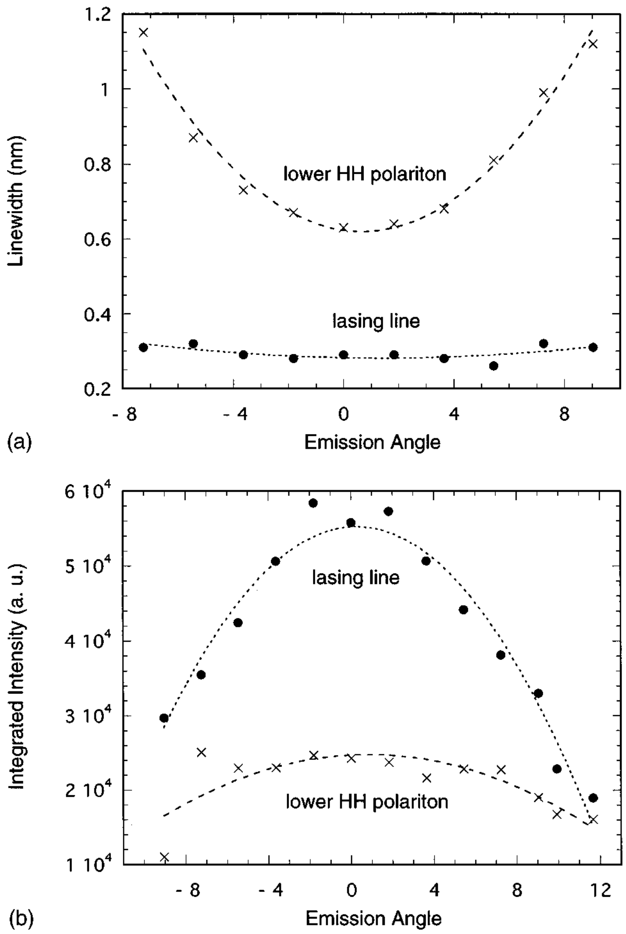

FIG. 3. (a) The linewidth of the lasing line (closed circle) and the lower HH exciton-polariton peak (cross) as a function of the emission angle (in the air) at an incident pump power of 120 mW. (b) The integrated intensity of the lasing line (closed circle) and the lower HH exciton-polariton peak (cross) as a function of the emission angle (in the air) at an incident pump power of 120 mW.

However, the linewidth of the lasing line is almost independent of the emission angle, which is a characteristic of a photon laser. The intensity of the lasing line drops rapidly as the emission angle increases, as shown in Fig. 3(b). The half angle of the emission lobe is about 8° in the air, which is close to the divergence angle of the cavity bare photon mode as determined by the cavity Q value [5]. Therefore, the microcavity system indeed behaves like a photon laser at high pump power.

We have repeated our experiment at other sample positions and observed similar lasing phenomena. Although at different sample positions the cavity-exciton detuning is different, and, hence, the effective mass of the exciton polaritons varies a lot, the lasing line features a universal effective mass, which is the bare cavity photon mass. As an example, Fig. 4 shows the data taken at another sample position. From the evolution of the cavity emission spectra as a function of the pump power, it seems that no additional emission peak emerges, and the intensity of the middle exciton polariton grows nonlinearly. This looks like a spontaneous buildup of the polariton population, which might be originated from the stimulated generation of coherent exciton polaritons through phonon scattering process [1]. However, the simultaneous measurement of the reflection spectra shows that, as the pump power increases, the QW excitons become saturated and the exciton polaritons eventually disappear. At high pump power, the reflection spectrum shows only the bare cavity photon mode, which is very close to the wavelength of the middle exciton polariton.

In conclusion, we observe a continuous transition directly from the exciton-polariton emission to the bare photon laser without going through the intermediate phase of the exciton-polariton laser [3]. This suggests that in our sample the size of the polariton center of mass wave function is much

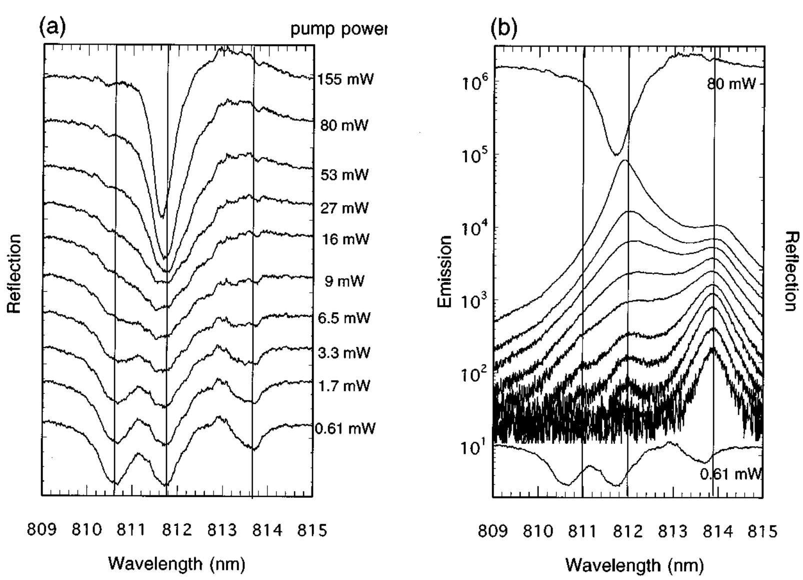

FIG. 4. At a different sample position, (a) the reflection spectra of the probe at different incident pump powers. (b) The cavity emission spectra at the pump powers corresponding to (a). Two reflection spectra at low and high pump power also shown for comparison.

smaller than the polariton thermal de Broglie wavelength (calculated using the measured quasiparticle mass) due to the exciton localization caused by the QW interface roughness and impurities. The reduction of the actual size of the polariton wave function along the QW plane increases the exciton- polariton laser threshold density to above the exciton saturation density.

We would like to acknowledge Professor H. Wang, Dr. P. B. Littlewood, Dr. P. M. Platzman, Professor H. Gibbs, and Professor G. Khitrova for stimulating discussions.

[1] S. Pau, H. Cao, J. Jacobson, G. Björk, Y. Yamamoto, and A. Imamoğlu, Phys. Rev. A **54**, R1789 (1996).

[2] H. M. Wiseman and M. J. Collett, Phys. Lett. A **202**, 246 (1995); M. Holland, K. Burnett, C. Gardiner, J. I. Cirac, and P. Zoller, Phys. Rev. A **54**, R1757 (1996).

[3] A. Imamoğlu and R. J. Ram, Phys. Lett. A **214**, 193 (1996); A. Imamoğlu, R. J. Ram, S. Pau, and Y. Yamamoto, Phys. Rev. A **53**, 4250 (1996).

[4] H. Wang (private communication).

[5] Y. Yamamoto, S. Machida, K. Igeta, and G. Björk, in *Coherence, Amplification, and Quantum Effects in Semiconductor Lasers*, edited by Y. Yamamoto (Wiley, New York, 1991).