Bipolariton laser emission from a GaAs microcavity

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Biexciton emission properties were studied in a single GaAs quantum well semiconductor planar microcavity by photoluminescence measurements at low temperatures. At high pump intensity a bipolariton emission appears close to the lower polariton mode. This new mode appears when we detune the cavity resonance out of the lower polariton branch, showing a laser like behavior. Very small line widths were measured, lying below 110 µeV and 150 µeV for polariton and bipolariton emission respectively. The input/output power (I/O) measurements show that the bipolariton emission has a weaker coupling efficiency compared to previous results for polariton emission. Simultaneous photoluminescence and near field measurements show that the polariton and bipolariton emission are spectrally and spatially separated.

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I. INTRODUCTION

In recent years the possibility to realize low-dimensional heterostructures such as quantum wells (QW) enhanced the Coulomb interactions between electrons and holes in these structures. The interaction of excitons with photons is also increased with the spatial confinement in low-dimensional systems. Recent development of microcavity structures enhanced the interaction of photons and excitons producing exciton-polariton quasi-particles (polariton). The interaction between single excitons is also possible, creating biexcitons or excitonic molecules and therefore, the bipolaron particle in a microcavity.

The semiconductor planar microcavity (SMC) is a Fabry-Perot cavity formed by two distributed Bragg reflectors (DBR) separated by a multiple integer of λ/2 distance. Quantum wells are located at the anti nodes position of the cavity electromagnetic field. The photons are confined inside the cavity in the grown direction, modifying the energy dispersion relationship to a parabolic form. Tuning the photon energy inside the cavity is possible to resonantly excite QW excitons and create polaritons states distributed in the upper and lower polariton branches (UP and LP). In a high Q microcavity, the coupling between cavity photons and excitons leads to a strong coupling regime in the SMC identified by the Rabi splitting with frequency Ω. One of the most intriguing characteristics is the polaritons integer spin, obeying Bose-Einstein statistic, consequently the polaritons could condensate to a final state. An other interesting effect in a SMC, polaritons created at high pump intensity with a parallel wave vector (k∥), such that the LP population per mode reaches one, can be scattered elastically into two polaritons, one in the bottom of the LP branch (signal) and the other one to a higher energy side (idler). This mechanism preserves phase coherence and a high intensity emission signal for the two correlated beams, besides a laser like source light.

Neukirch et al. addressed one of the first experimental evidence of biexcitons in a SMC. By using a II-VI SMC, they could distinguish between bipolaritons and polaritons resonance in pump-probe experiments. Several other groups followed studying the properties of bipolaritons in SMC using mainly pump-probe and four-wave mixing experiments. Baars et al. mapped the energy dispersion relationship for the bipolariton and compared it with calculations described by 4x4 matrix Hamiltonian for a coupled four-level model. The correct description of the biexcitons formation in the SMC comes with the bipolariton formalism that leads to similar polariton dispersion curves, showing an lower and upper bipolariton branch (LB and UB) associated with a splitting frequency.

In this paper we report optical characteristics of a bipolariton emission in a GaAs QW SMC. Our results show laser like linewidth narrowing in the bipolariton emissions, and also a emission intensity relation with excitation power (I/O data). The bipolariton emission was observed to be blue or red shifted from the LP depending of the detuning (Δ = E_{c} - E_{x}, where E_{c} is the cavity resonance energy and E_{x} the exciton energy). The emission far field image shows two emissions pattern, spatially and spectrally separated.

II. EXPERIMENTAL DETAILS

The SMC used in this experiment was grown by molecular beam epitaxy (MBE) and consists of a single 100 GaAs QW in the middle of a λ/n (where n stands for the refractive index of the layer) cavity of Al_{0.3}Ga_{0.7}As, sandwiched between 24 (top) and 29.5 (bottom) pairs of distributed Brag reflectors Al_{0.2}Ga_{0.8}As/AlAs. The microcavity was designed to operate at λ = 800 nm which
matches the QW emission when cooled to 7 K. The cavity length varies across the sample position, which allows positive and negative detuning with respect to the match between the cavity resonance and the exciton emission. More details on the sample can be found in Ref. [12].

The experiment was performed using a liquid helium cold finger cryostat held at a temperature of 7 K. A continuous wave (CW) Ti:Sapphire tunable laser with an variable angle of incidence with respect to the cavity normal direction was used to excite the sample. The emission was collected from the sample in a backscattered geometry and dispersed by the 1800 gr/mm grating spectrometer and detected by a charge couple device (CCD) camera. For the near field images, we used a second camera in front of the emission that could be easily removed for the spectra measurements.

III. RESULTS AND DISCUSSION

The LP emission was observed pumping the SMC at \( k_\parallel = 7.7 \times 10^3 \text{ cm}^{-1} \) with an energy \( \Omega = 3.2 \text{ meV} \) above the lower polariton branch. Out of this optimum condition, by detuning the cavity resonance (\( \Delta > 0 \)), strong LB emission was induced close to the LP peak with 400 mW pump power, as illustrated in Fig. 1. We could see one asymmetry in the polariton laser spectrum for small blue shift \( \Delta \), which evolved to two separate line emission (0.25 meV) as \( \Delta \) increases. The figure shows a series of photoluminescence spectrum normalized with respect to the backscattered laser intensity for a fixed 400 mW pump power. The total \( \Delta \) shift corresponds to a range of 1.9 meV or a 1.4 mm shift in cavity position. The LB mode has a higher energy in relation to LP emission and the energy difference between them increases while \( \Delta \) is shifted for higher energies. Fig. 1(b) shows the full width at half maximum (FWHM) of the photoluminescence (Fig. 1(a)) as a function of the detuning. This linewidth behavior shows the LB formation process (decreasing) while the LP FWHM increases indicate the LP laser efficiency loss due to the higher.

In Fig. 2 we observe the LB behavior by lowering the pump power for a fixed detuning. The LB mode appears in this measurement 0.27 meV red shifted from the LP mode (Fig. 2(a)), contrary to the observed shift in the previous experiment (Fig. 1). The integrated intensity relation I/O shows a transition from spontaneous LB emission to a laser like behavior around 400 mW pump power threshold (Pth). This transition is also observed in Fig. 2(c) for the FWHM of both emissions as function of the pump power. At 400 mW the LB FWHM decreases rapidly and become stationary at 500 mW with a value of 130 \( \mu \text{eV} \). The usual kink in the linewidth and the I/O curve at Pth is not clear enough here because the LB mode is too close the LP mode and we could not separate both spectra clearly for lower excitation pump power.

The LP emission that was always above the threshold has a value of 100 \( \mu \text{eV} \) FWHM whose behavior have been described by Cotta et al. [12]. The interesting point here is that the bipolariton linewidth narrowing never reach the polariton linewidth, even in the previous measurement, where the polariton laser emission goes down for larger detuning.

The population inversion is a well known behavior in usual lasers. One way to characterize it is to observe the kink from spontaneous to laser emission in a logxlog input/output power measurement data. The coupling efficiency \( \beta \) is related with this kink and quantifies the efficiency of the laser. In SMC the polariton laser can operate with almost no population inversion [12], and can reach high values as shown by Yamamoto et al. [14]. Our results for the LB emission showed a larger kink in the I/O data curve and also in the linewidth data, compared to our previous behavior observed for the polariton laser [12]. These observations show qualitatively one inversion population behavior for this bipolariton laser. In the I/O curve should be possible to quantify \( \beta \) by the inverse amplitude of the kink, however our data intensity resolution were limited by the spectrum resolution (Fig. 1(a)) and it is possible only to preview one \( \beta \) in the order of previous results for microcavity laser [12].

The effect of creating the bipolariton emission at high pump powers is directly associated to the condition of the formation of biexcitons. This particle is created when
FIG. 2: (a) LP and LB PL spectra as a function of pump power. (b) The FWHM behavior for the two emission peaks. (c) Integrated power relation.

there is a high density of excitons in the QW, them by Coulomb interaction they interact with each other producing excitonic molecules. We interpreted our results as the following: at high pump power and resonance condition, the LP scattering is effective, but when the cavity is detuned, the LP scattering channel decreases the efficiency, increasing the biexciton population in the QW inducing thus the bipolariton emission.

We observed in our cavity that the LB emission was blue shifted at in the PL spectra in Fig. 11 while it was red shifted in Fig. 4. This could be explained examining the energy dispersion relation both for polariton and bipolariton in microcavities. The first one has been extensively studied in the past few years but in the case of bipolaritons much work has to be done to fully understand their energy dispersion relation. In a quantum mechanical approach the energy dispersion relation is calculated for polaritons in microcavities, where the exciton energy can be simplified as a constant in range of small wave vectors (our $k_{\parallel}$ vector is still a good approximation). The exciton photon coupling obeying a parabolic energy dispersion form, leads to the formation of the LP and UP branches. Changing the cavity detuning, the form of energy dispersion relation of the LP and UP can be slightly modified, so depending on the $\Delta$ shift we are able to change the energy of the transition of the LP and UP to the valence band, and the resonance condition. In a simplified model, the bipolariton energy dispersion form is quite similar to the polariton one. Considering that the biexciton energy is $E_{xx}(k) = 2E_x(k) - E_b^{xx}$, where $E_x(k)$ is the exciton and $E_b^{xx}$ is the biexciton binding energy. In this equation the biexciton energy is almost twice the exciton energy, but in fact the recombination process and photon frequency emitted ($\nu_{xx}$) of the biexciton can be understand as follows:

$$(\text{biexciton}) \rightarrow (\text{exciton}) + \nu_{xx}$$

(1)

By energy conservation law, we have:

$$\nu_{xx} = E_x(k) - E_b^{xx}$$

(2)

The equations above shows that transition energy of the biexciton is in fact lower than the exciton recombination energy. For simplification $E_x(k)$ is also constant in the range of small wave vectors, then it can couple with two cavity photons and form the bipolariton upper and lower branches. Also these branches depends on $D$, thinking in the UP, LP, UB and LB all together as a function of the $\Delta$. Now, to interpret our experimental results for the LB behavior, what would happen is that for some detunings the photon emitted by the LB can have higher or lower energy with respect to the LP emission, because the two quasi-particles have different effective mass, than the form of the energy dispersion relation will change differently. In Ref. 4 a calculation of the energy dispersion for polariton and bipolariton as a function of the detuning shows that the LP and LB energy can reach the same values. But this calculation was restricted to some detunings detuning values and did not show crossing effect on the energy dispersion relation. Further calculation is calculations are necessary to stand this interpretation, but it is beyond the present scope of this paper.

Finally we measured the near field image with the respective spectra at 400 mW pump power for the LP only (Fig. 11a) and for both LP and LB (Fig. 11b) emission by placing a second camera in front of the collimated beam before the spectrometer. The inserted picture in Fig. 11 (b) shows a second pattern for the bipolariton emission and bellow it the intensity profile of the image showing clearly that there are two separated beams. Also, both profiles (LP and LB) are well fitted with a gaussian curve. This measurement confirms the distinct operation mechanism for the polariton and the bipolariton laser in the microcavity.
**IV. CONCLUSION**

In conclusion, by detuning the cavity position of the sample for a fixed energy and high pump power, i.e. detuning the cavity energy in relation to the exciton, we observed bipolariton emission in a GaAs planar microcavity. The emission power (I/O) data relation and the linewidth behavior show one usual laser behavior with population inversion in the bipolariton emission. The observed bipolariton emission was red or blue shifted relative to the polariton emission, depending on the cavity detuning. This switching effect is still a matter of study to understand the bipolariton scattering process in a microcavity. The near field images shows that the both emissions can be not just spectrally separated, but spatially separated as well.

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