Exciton Polariton Emission from a Resonantly Excited GaAs Microcavity

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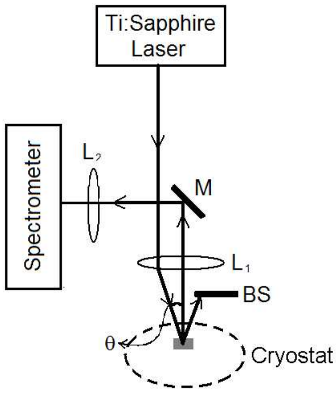
Coherent emission efficiency in a 100Å GaAs SQW microcavity was enhanced one order when pumped resonantly at 10 K, compared to the off-resonant excitation. The usual kink observed in the exciton emission linewidth as well as in the emission intensity in relation to the pump power, changes smoothly instead of the usual abrupt kink observed in the off-resonant microcavity laser. In addition, polarization measurements show a correlation relationship between the pump light polarization and the cavity emission polarization.

Cavity quantum electrodynamics effects (CQED) in a semiconductor microcavities with a volume of $\sim \lambda^3$ have been studied intensively in the last decade by many groups [1-5]. In contrast to the usual laser, which displays a well defined kink in the input-output (I/O) power curve, there is a dramatic change for this behavior in a cavity with high Q factor, i.e. high mode coupling efficiency (β). This β factor has been enhanced from 1%[1, 2] in a Fabry Perot microcavity laser to 5% in a hemispherical cavity[3], and even more in a whispering gallery mode cavity[4]. In addition, Rabi splitting effects were observed in the cavity reflectance spectrum, characterizing a weak coupling regime in a planar microcavity[5]. All these effects were observed by off-resonant excitation techniques. On the other hand, changing to resonant excitation process, exciton-polariton (e-p) emission was observed for special pump beam incidence angle[6, 7, 8]. The emission nature of the e-p has been intensively discussed in the literature due to the possibility of generation of exciton condensed states [9-12], and also to explore the coherence property in a mesoscopic system[13].

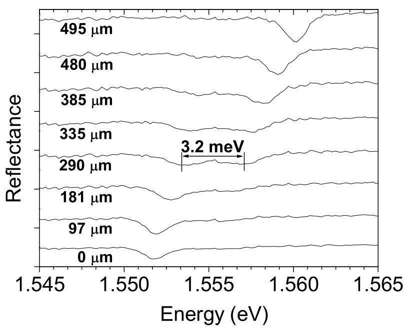
We have studied experimentally a single quantum well (SQW) GaAs microcavity laser by off and resonant excitation techniques. The white light reflectance, photoluminescence and polarization characteristics of the cavity emission was measured at 10 K. A Rabi Splitting of the cavity mode was observed in the low intensity white light reflectance, and such coupling regime was studied for higher pump intensity, and for different wave vector excitations. The optical properties of the resonantly excited cavity show a non linear laser regime, showing us differences in relation to the off-resonant laser. These results are discussed in terms of the exciton polariton emission compared to a bare exciton laser, which depends on the excitation condition angle close or far from the "magic" incidence angle [10, 11] of the pump light.

The GaAs planar microcavity structure was grown by molecular beam epitaxy (MBE). The cavity is formed by a 100Å GaAs SQW between two spacer layers of $Al_xGa_{1-x}As$ (x = 0.3) with a thickness of λ/n. The cavity layers are sandwiched between two distributed Bragg reflector (DBR) mirrors formed by 29.5 (below) and 24 (upper) pairs of $Al_xGa_{1-x}As$ (x = 0.2)/AlAs layers with thickness of λ/(4n) (n stands the respective refraction index of each layer). The cavity was designed in order to get the resonance window around 800nm, which matches the 100Å GaAs SQW photoluminescence peak when cooled to 10 K. Thus, by growing half of the cavity without rotation in the MBE machine, we could find easily one position around the wafer, that matches the SQW emission peak with the cavity resonance.

We used a CW Ti:Sapphire tunable laser to pump either off-resonant and resonantly. The sample was cooled down to 10 K in a cold finger cryostat. The pump laser has a incidence angle θ, and the direct reflection of the pump was cut-off by a beam stopper (Fig. 1a). The normal mode emission was collected and collimated by the same lens used to focalize the pump laser. The emission light was dispersed by a 1800 grooves per millimeter grating in a Jobin Yvon (T64000) spectrometer, and detected by a charge coupled device (CCD) camera. To reduce sample heating, we used a chopper on the path of the excitation laser beam. The focalization lens has a 7.5 cm focal length, providing a spot diameter of ϕ ~20 μm. The cavity structure characterization was done with a white light reflectance spectrum at 10 K, which gave us a cavity window full width half maximum of FWHM = 2.4 Å around λ_r = 7985 Å. This value results in a cavity Q factor of 3300, i.e. the vacuum field in this microcavity should be enhanced by a factor of 2(1+R)/(1-R) = 2102. This high Q and the λ cavity volume enabled us to observe a Rabi splitting of 3.2 meV, as shown in the white light reflectance spectrum measured as a function of the cavity position (Fig. 1b).



(a)



(b)

Figure 1. (a) Experimental setup for resonant excitation and normal mode emission measurement. (b) Rabi splitting observed in the reflectance spectrum of the white light as a function of the position (0 to 495μm) in the microcavity.

The experimental results for the off-resonant excitation at 740 nm, i.e. the I/O pumping power relation, is shown in Fig. 2. The inverse relation of the kink's amplitude in this I/O data curve (solid square symbols) gives us a β estimation of $\sim$1% in good agreement with the theoretical limit for a planar DBR microcavity structure[14]. We attribute this higher performance to a confinement of the exciton dipole oscillator in the plane of the 100 Å SQW, which enhances the gain in the planar cavity mode. High performances of the β factor in a planar Fabry Perot cavity have been observed already by Yokoyama in a dye microcavity laser[15]. The kink on the I/O pump power data curve indicates a threshold pump of 140 mW. If we consider the beam loss by reflections and considering an absorption coefficient of $\approx 10^4$ cm^{-1}[16], a recombination time of 0.2 ns for the 100 Å SQW [17], the estimated intensity pump threshold is P$_{th}$ ≈ 105 W/cm^2 or one exciton density of $\simeq 8.4 \times 10^{17}$ cm^{-3}. This high β value with the corresponding P$_{th}$ $'$s density, and the previous normal mode splitting of 3.2 meV, certify us the high quality of our microcavity sample.

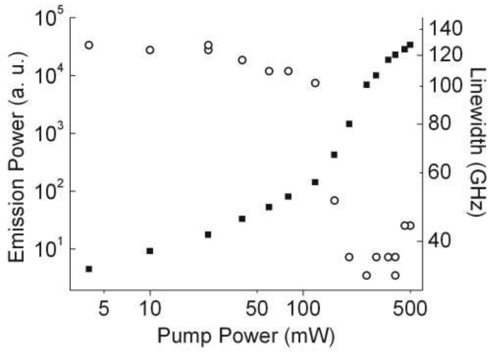
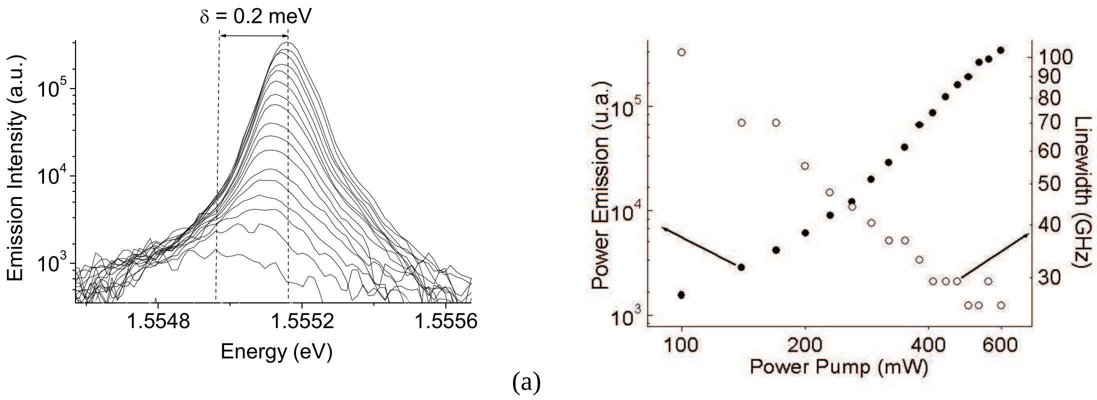


Figure 2. I/O power measurement for a off-resonant excitation (closed circles), and linewidth(open blocks) & pump power.

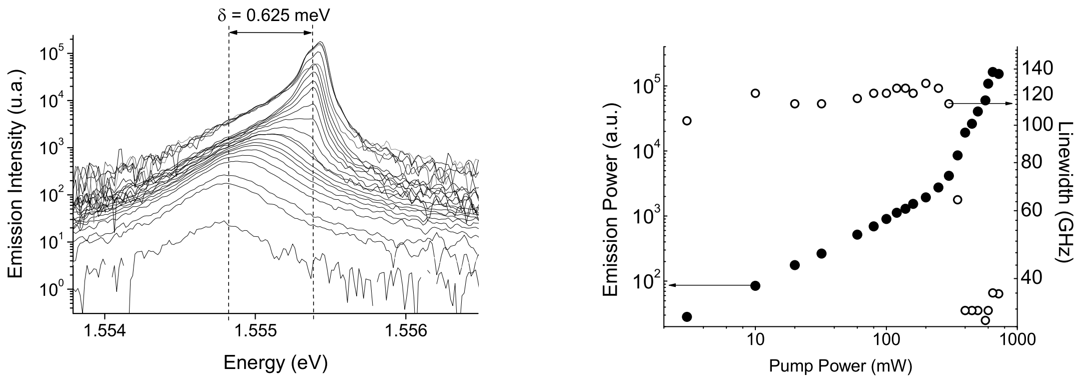
The resonant pumping excitation with the incidence angle $\theta = 6.8°$ (in plane wave vector $k_{\|} = 9162$ cm^{-1}), was measured by tuning the pump energy higher (Δ = 1.6 meV) than the cavity emission. The value of Δ was fixed by observing the maximum efficiency of the cavity emission intensity as a function of the pump wavelength. These results are shown in Fig. 3a by the PL spectra sequence as a function of the pump power. In these curves, there is a small blue shift of the emission peak ($\delta \leq 0.2$ meV) as we increased the pump power. In the I/O data (peak intensity of the photoluminescence spectra) for this resonant excitation (Fig. 3b), we did not observe a clear kink in the curve around the P$_{th}$ (300 mW), but instead a smooth transition indicating a higher value for the β value ($\sim$17 %). In agreement with the I/O data, the emission linewidth as a function of pumping power also does not present a kink, it just decreases continuously in a sharp contrast with the off-resonant excitation behavior of the planar microcavity laser[18].

An analogous measurement was performed for a smaller θ of 3.4° (k$_{\|}$ = 5206 cm^{-1}). We found the optimum pump energy Δ = 5.5 meV higher than the cavity resonance λ_r. In Fig. 4a we show the PL spectra sequence as a function of pump power, where we can observe a relatively larger blueshift of δ = 0.62 meV of the peak energy for this case. The I/O data for this measurement (Fig. 4b) shows again a clear kink in the curve around P$_{th}$, which is observed also in the corresponding linewidth curve (Fig.4-c). This kink provide a $\beta \sim$ 1% for this resonantly excited cavity with k$_{\|}$ = 5206 cm^{-1}. We can still see a nonlinear behavior in the I/O data above P$_{th}$, which should come from the higher transversal mode order in the high pump regime. This effect is confirmed by the increase of the linewidth observed for higher pumping rates (Fig. 4b).



(a) (b)

Figure 3. (a) photoluminescence spectra as a function of pump power (the used power intensity sequence is the same illustrated in part b)) for resonant excitation at $k_{\|}$ = 9162 cm^{-1}, (b) I/O of the peak power obtained from the photoluminescence s spectra (closed circles) and the Linewidth (open circles) versus pump power.



(a) (b)

Figure 4. (a) photoluminescence spectra sequence as a function of pump power(the power intensity sequence is illustrated in part b) for resonant excitation at $k_{\|}$ = 5206 cm^{-1}, (b) photoluminescence intensity peak power (closed circles) obtained from the photoluminescence spectra and the linewidth (open circles) as a function of pump power.

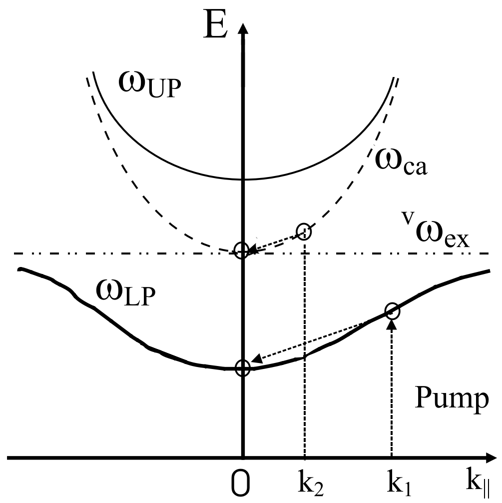


Figure 5. Energy flow paths for generation of the e-p and the exciton with k_1 wave vectors through lower (ω_{LP}) polariton branch, and the ω_{ca} (cavity photon energy) dispersion of the wave vector k_2 before emission.

When we excited with a smaller wave vector ($k_{\|}$ = 5206 cm^{-1}), we observed that the "kink" at P_{th} reappeared, i.e. the coupling efficiency of the emission decreased, showing us different scattering process in these two wave vector pumping experiments. For smaller wave vector, we believe the exciton polariton emission is quenched due to the bottle neck effect for wave vector smaller than the magic angle[17]. The behavior of the measured photoluminescence spectra (fig.3,4), and the relation between δ for these two experiments,i.e. a larger blue shift in the small wave vector, leads us to conclude one e-p lower branch emission for $k_{\|}$ = 9162 cm^{-1} and an exciton emission for excitation at the wave vector $k_{\|}$ = 5206 cm^{-1}as illustrated in Fig. 5.

In these resonant pumping experiments, the reflected pump light was cut-off by a beam stopper, but a small intensity of the scattered pump light could still be detected with the cavity emission. This experimental configuration permitted us to measure the polarization relationship between excitation and emission beams. One polarizer was fixed in front of the spectrometer and a tunable λ/2 plate was positioned in the pump beam$'$s path, in order to analyze the emission by rotating the pump polarization. In Fig. 6 we have the polarization intensity$'$s relation measurement for the resonantly excited cavity emission (right axis) compared with the pump polarization (left axis) at 440 mW. As we can observe, the exciton emission polarization orientation clearly follows the pump polarization orientation besides its lower polarization visibility. This behavior is not observed in the polarization dependence of the exciton emission in the off-resonantly excited microcavity laser, as well as in the resonantly excited cavity with smaller wave vector, as shown in Fig. 7. Some previous works claim that the polarization effects in a microcavity are due to the strain effect in the SQW[20] or are due to the bi-refringence effect[21]. In this experiment, however, the e-p polarization effect is a singular behavior of the scattering process coherence and not by structural characteristics of the microcavity. The polarization dependence observed in this work shows directly the maintenance of the polarization during the e-p scattering process when generated from the lower e-p branch, which is not observed when we excite with smaller wave vector. This result corroborates with the coherence between the input laser and the output beam from the e-p scattering observed in the parametric amplification of the light by e-p microcavity [22].

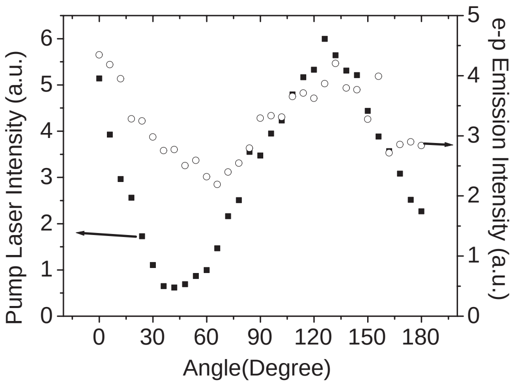


Figure 6. e-p emission polarization relationship for resonant excitation at $k_{\|}$ = 9162 cm^{-1} (right axis, open circles) and 440 mW, compared to the pump polarization light(left axis, closed circles).

The I/O curve, as well as the transition in the linewidth around the P_{th}, show us an improvement of more than an order of magnitude in the β value (1% up to $\sim$ 17%) when an e-p was generated by exciting the lower branch. It decreased back to around 1% when we excited in the lower wave vector case. This lower β value is clearly observed also in the measured emission linewidth as a function of the pump power (Fig. 4b). Also, the blue shift in the exciton emission peak was much larger (0.62 meV) in the smaller wave vector excitation case, whose process is quite similar to the usual off-resonant exciton laser process. The observed blue shift ($\leq$ 0.2 meV) in the lower branch dispersion (Fig. 3) indicate no transition from the e-p emission to exciton emission when we increased the pump power. Those results comes close to the behavior observed by Stevenson [10]. This comparison lead us to conclude an exciton polariton emission process in our sample beyond the P_{th} intensity.

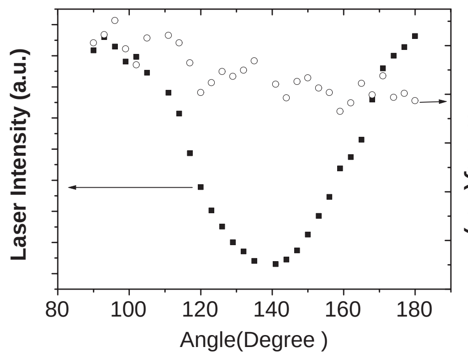


Figure 7. Pump (left axis, closed blocks) and cavity emission (right axis, open circles) intensity relationship as a function of the polarization angle for resonant excitation of the cavity at $k_{\|} = 5206$ cm^{-1} and 440 mW.

The P_{th} observed in the resonantly excited e-p (lower branch) laser emission was around 300 mW, with a measured 63% reflection loss in the pump beam. Considering the absorption coefficient of the pump light (α) one order of magnitude smaller in this resonant case[23], we estimate a density of n $\simeq 10^{16}$ cm^{-3} for the generated e-p at the P_{th} excitation level. This value is much smaller than the previous off-resonant density at the respective P_{th}, which was estimated to be of the order of 8.4×10^{17} cm^{-3}. This smaller density enables us to estimate an e-p pair approximation length of d ~ 100 nm. These values lead us to a picture of an e-p condensation into a final state in this resonantly excited lower branch e-p emission. The evaluated value for the e-p approximation $d \simeq$ 100 nm indicates a much higher efficiency for the e-p emission process compared to the usual off-resonant P_{th} carrier density in the microcavity.

The mode coupling efficiency (β) analysis, the blue shift (δ) and the polarization's correlation demonstrate that the coupling regime is strengthened when we excite the lower e-p branch, when compared to the usual off-resonant and or small wave vector excitation process. We measured a strong coupling regime only for low excitation regime with the white light reflectance spectrum (Fig. 1b), and we do not know how far this strong regime remain when we increase the excitation power, but these results assure us one non linear regime for this exciton polariton emission from this SQW GaAs microcavity. Particularly, the small blue shift may be a sign for the state condensation of the exciton polariton, which comes in a good approach for our previous P_{th} density estimation.

In summary, a planar λ GaAs SQW microcavity resonantly excited with a wave vector $k_{\|}$ = 9162 cm^{-1} at the lower polariton branch, presented a e-p emission beyond the P_{th}, i.e. a strong coupling regime far above the low pump regime observed in the Rabi Splitting measurement. A clear polarization correlation between the excitation laser and the e-p emission was observed when we excited the lower e-p branch, confirming us the coherence nature of the emitted light. The thermal scattering process in the smaller wave vector excitation case leads the emission process to a bare exciton laser, as usually observed in the off-resonant microcavity lasers. Finally, our results indicate that our microcavity sample presents a non linear laser emission characteristics, which show us a powerful system to study coherent scattering process of the exciton polariton.

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