

Spatial distribution of strong and weak coupled exciton–polaritons in semiconductor microcavities

Dario Ballarini*, Alberto Amo, Daniele Sanvitto, Luis Viña, Maurice Skolnick, John Roberts

Física de Materiales, Universidad Autónoma de Madrid, C/Francisco Tomás y Valiente, Madrid 28049, Spain

Available online 9 October 2007

Abstract

The coexistence of polaritons in different coupling regimes inside the same excited area is experimentally studied in InGaAs semiconductor microcavities by means of spatially and time-resolved photoluminescence. Different positions inside the spot are selected with a resolution of 10 μm in order to analyze the spatial distribution of polaritons, which present different emission energies. Islands with a high density of polaritons are present at every scanned position and their spatial distribution follows the Gaussian profile of the excitation intensity.

© 2007 Elsevier B.V. All rights reserved.

PACS: 78.47.+p; 78.55.Cr; 71.36+c

Keywords: Microcavities; Polaritons; Ultrafast spectroscopy; Strong coupling

1. Introduction

Semiconductor microcavities exhibit unique characteristics in solid-state physics due to the mixed nature of their eigenstates. Indeed, if the coupling interaction between the cavity mode (CM) and the quantum-well (QW) exciton is stronger than the exciton broadening (strong coupling regime), the real eigenstates of the system, called polaritons, are linear combinations of photons and excitons. The dispersion relations of the upper polariton branch (UPB) and the lower polariton branch (LPB) are very different with respect to those of the bare modes. The bosonic nature of polaritons allows them to create a Bose–Einstein condensate [1] at the bottom of the LPB, if the polariton occupation factor is bigger than one at $K_{\parallel} = 0$ (K_{\parallel} is the momentum in the QW plane).

At resonance and $K_{\parallel} = 0$, the LPB is separated from the bare CM by an energy $\Omega/2$, where Ω is the Rabi splitting. Ω is a measure of the strength of the coupling between the exciton and the photon and is directly proportional to the exciton oscillator strength f_{ex} . When the carrier density

increases, f_{ex} is screened by the presence of others electron–hole pairs.

In a microcavity, increasing the polariton density, the coupling is reduced due to a screening of the Coulomb interaction between the fermions (electrons and holes) that compose the excitons and consequently the LPB energy shifts towards the CM: the strong coupling is lost and polaritons get converted in the bare exciton and photon modes (weak-coupling regime); eventually, for very high powers, the excitons also ionize and a plasma of oppositely charged particles in the presence of the electromagnetic radiation in the cavity is obtained. Only if a sufficiently high density of polaritons, without losing the strong coupling regime, is achieved (occupation factors larger than 1), a polariton condensate can be created. Otherwise, with the increase of the excitation intensity the system undergoes a transition from the strong- to the weak-coupling regime. In Ref. [2], it has been demonstrated that for spin-polarized polaritons this transition is determined by the density of polaritons with a given spin orientation. The strength of the coupling was determined from the LPB emission energies for the two-spin population as a function of the excitation power.

In this work, we perform a confocal scanning of the LPB emission across the laser-excited area with a

*Corresponding author. Tel.: +34 91 497 4771; fax: +34 91 497 8579.
E-mail address: dario.ballarini@uam.es (D. Ballarini).

resolution of $10\ \mu\text{m}$ to study the spatial distribution of this transition.

2. Experimental set-up and sample

The sample is a $3/2\lambda$ microcavity of GaAs with dielectric Bragg mirror of $\text{Al}_{0.1}\text{Ga}_{0.9}\text{As}/\text{AlAs}$ and two stack of three $\text{In}_{0.06}\text{Ga}_{0.94}\text{As}$ QWs ($100\ \text{\AA}$) embedded at the anti-node positions of the electric field in the cavity. The experiments are performed at the temperature of $5\ \text{K}$. Optical excitation is provided by 2-ps-long pulses of a $\text{Ti}:\text{Al}_2\text{O}_3$ laser tuned at the energy of $1.63\ \text{eV}$, almost $180\ \text{meV}$ higher than the considered exciton resonance. Photoluminescence (PL) from the $K_{\parallel}\sim 0$ polariton states is selected by a pin hole and dispersed by a spectrograph that is coupled with a streak camera to allow a spectral- and temporal-analysis of the emission. Polarization optic is used to excite with

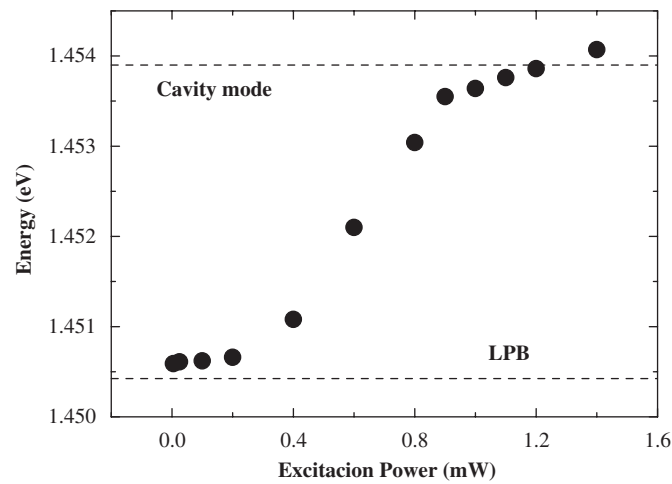


Fig. 1. Emission energy of the LPB at resonance and $K_{\parallel} = 0$ as a function of the excitation power for a $3/2\lambda$ microcavity of GaAs with $\text{In}_{0.06}\text{Ga}_{0.94}\text{As}$ quantum wells.

circularly polarized light (σ^+) and detect the co-polarized emission (σ^+). The image of the sample is magnified $2.5\times$ and a pin-hole with a diameter of $25\ \mu\text{m}$ is used in the plane of the image to select only a small part of the excited area. In this way, we can compare PL coming from different point of the excited spot with a final resolution of $10\ \mu\text{m}$.

3. Results and conclusions

The transition from the strong- to the weak-coupling regime has been studied [2] measuring the energy of the LPB at $K_{\parallel} = 0$ as a function of the excitation power P . At low P , the system is in the strong coupling regime and the LPB emits at $1.4505\ \text{eV}$; with increasing P , the LPB emission blue shifts as depicted in Fig. 1. At $P > 1\ \text{mW}$, the system is in the weak-coupling regime and the PL is due to bare cavity photons. The PL intensity increases linearly with the excitation power for $P < 0.6\ \text{mW}$ and superlinearly at higher P , due to the increasing importance of the stimulated polariton–polariton scattering [3], until a saturation is obtained in the weak-coupling regime.

Let us analyze now in detail a streak-camera image of the PL emission as, for example, the one shown in Fig. 2 for $P = 0.8\ \text{mW}$. The LPB is shifted towards the CM at short time, when the high density of carriers reduces the strong coupling and the PL intensity is superlinear with P . At longer times, when the polariton density becomes smaller, the LPB emits at $1.4505\ \text{eV}$ and recovers its linear emission regime. The inset in Fig. 2 shows the energy spectrum of the PL at short time (70 ps): the blue-shifted LPB emission (S) coexists at short time with a non-shifted LPB emission (L) peaked at $1.4505\ \text{eV}$. The S peak is due to PL coming from a region with a high density of polaritons (the emission energy corresponds to a renormalized Ω and the PL intensity is superlinear with P) while the L peak is due to a region with a low density of polaritons in the

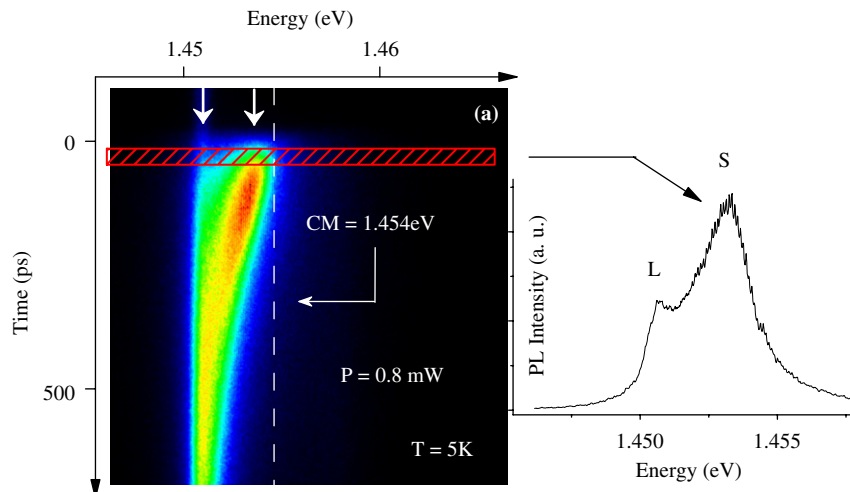


Fig. 2. Streak camera image of PL emission with $P = 0.8\ \text{mW}$. The cavity mode (CM) is indicated by the dashed line; the white arrows indicate the two coexisting emissions S and L. The inset depicts the energy spectrum at 70 ps.

linear emission regime. These regions are coexisting in the excited spot.

The coexistence of linear- and non-linear-regime emissions has been attributed in the literature to different intensities in the excitation as a consequence of the Gaussian profile of the laser spot [4]. According to this explanation, the S-emission would originate at the center of the spot, where a high density of polaritons is present, and the L-emission at the border of the spot.

To check whether the coexistence of the linear- and non-linear-regime emissions at short times is due to the Gaussian profile of the laser beam (diameter = 200 μm), we have scanned the emission spot with a resolution of 10 μm to discriminate the PL coming from different positions of the excited area.

Fig. 3 shows the spectra obtained with the pin-hole placed at the center, 50 and 100 μm apart from the center of the laser spot, respectively.

If the coexistence were originated from a high polariton density at the center and a lower density at the border of the spot, it would be expected an S-emission from the center and an L-emission from the border, where the intensity does not reach the non-linear threshold. However, we detect both components all over the excitation spot with

a resolution of 10 μm . Moreover, the separation in energy between the peaks remains constant over the whole emission area, ruling out the spatial variation of intensity of the excitation spot as the origin of the coexistence of the S- and the L-emission, which should yield a decreasing splitting moving from the center towards the edges of the spot. It means that islands with different polariton densities are located all over the excitation area. Point defects in the cavity can produce a spatially non-uniform potential, allowing polaritons to populate preferentially some positions inside the excited area [5–7]. Similar regions have been identified as polariton condensates in recent experiments [1].

Fig. 3e shows the intensities of the S- and L-emissions as a function of the position inside the spot. The ratio between the S- and L-peak intensities is well described by a Gaussian centered at the middle of the excitation spot, as exposed in Fig. 3f. It has to be noted that if the S-emission were originated at the center and L-emission at the borders of the spot, one should expect that the ratio would be superlinear on the excitation intensity, due to stimulated scattering process occurring where a large excitation is present, and therefore not yielding a Gaussian profile. Actually, S-signals originate from separate islands smaller

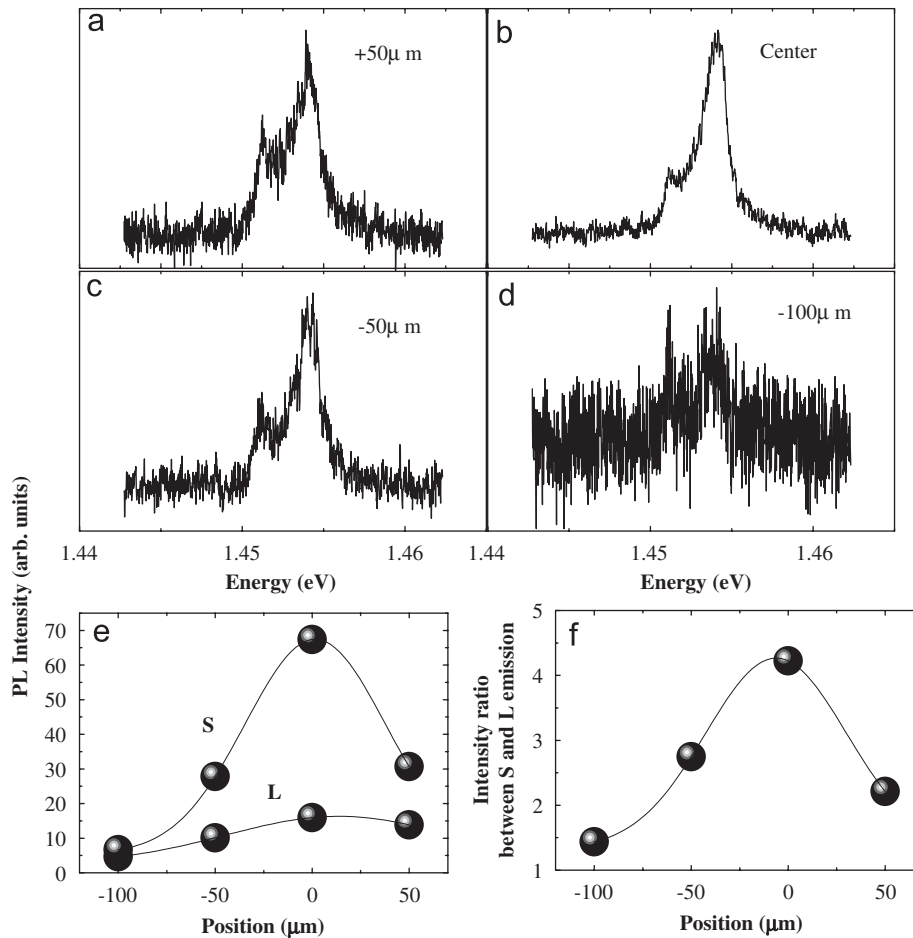


Fig. 3. PL spectra after 70 ps observed with the pin-hole placed at the center (b), 50 μm (a, c) and 100 μm (d) apart from the center. (e) PL intensity of the S- and L-emission versus the position. (f) Intensity ratio between S- and L-peak versus the position, fitted by a Gaussian centered at the middle of the spot.

than our spatial resolution, coexisting with low-density regions in the linear emission regime, and the number of islands giving rise to the S-emission follows a Gaussian distribution along the spot.

In conclusion, S-emission, corresponding to high densities of polaritons, originates in islands non-uniformly distributed all over the sample, and the Gaussian profile of the laser beam only determines the probability to reach the critical density of polaritons in such islands. This can be explained considering fluctuations in the photonic potential in the cavity. Minima in the fluctuations lead polaritons to preferentially occupy potential wells of $\sim 5\text{--}10\ \mu\text{m}$ size, where non-linear process is stimulated [5,6].

Acknowledgments

This work was partially supported by the Spanish MEC (MAT2005-01388, NAN2004-09109-C04-04, and QOITCSD2006-00019), the CAM (S-0505/ESP-0200),

and the “Marie-Curie” MRTN-CT-2003-503677. Two of the authors (D.B. and A.A.) acknowledge a scholarship of the FPU program of the Spanish MEC.

References

- [1] J. Kasprzak, M. Richard, S. Kundermann, et al., *Nature* 443 (2006) 409.
- [2] D. Ballarini, A. Amo, L. Vina, et al., *Appl. Phys. Lett.* 90 (2007) 201905.
- [3] L. Klotowski, A. Amo, M.D. Martin, et al., *Phys. Status Solidi (a)* 202 (2005) 357.
- [4] H. Deng, W. Weihs, D. Snoke, et al., *Proc. Natl. Acad. Sci. USA* 100 (2003) 15318.
- [5] D. Sanvitto, D.N. Krizhanovskii, D.M. Whittaker, et al., *Phys. Rev. B: Condens. Matter Mater. Phys.* 73 (2006) 241308.
- [6] M. Richard, J. Kasprzak, R. Andre, et al., *Phys. Rev. B: Condens. Matter Mater. Phys.* 72 (2005) 201301.
- [7] W. Langbein, in: *Private Communication and Proceedings of 10th International Conference on Optics of Excitons in Confined Systems*, Messina, Italy, 2007.