Sección Especial en Óptica Cuántica / Special Section on Quantum Optics

Quantum and non-linear optics with semiconductor nanostructures

Óptica cuántica y no-lineal con nanoestructuras de semiconductores

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ABSTRACT:

After working for many years on spectroscopy of semiconductor nanostructures our group has recently evolved to study photon-photon correlation in emission from quantum dots and polariton condensation in two-dimensional microcavities.

Keywords: Quantum Dots, Quantum Wells, Microcavities, Polariton Condensation, Photon-Photon Correlations.

RESUMEN:

Tras trabajar durante muchos años en espectroscopia de nanoestructuras de semiconductores, nuestro grupo ha evolucionado recientemente al estudio de correlaciones fotón-fotón en la emisión de luz por puntos cuánticos y en la condensación de polaritones en microcavidades bidimensionales.

Palabras clave: Puntos Cuánticos, Pozos Cuánticos, Microcavidades, Condensación de Polaritones, Correlaciones Fotón-Fotón.

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1. Introduction

Quantum information is a very interesting new field of research. From the scientific point of view it implies a deep study of very basic and conceptual aspects of quantum mechanics while from the point of view of applications it is expected to have a strong social and economical impact. Systems made of atoms, ions or nuclei are, conceptually, good candidates for quantum information processing but they present technological difficulties. Condensed matter systems are becoming a better alternative. Their main problem is the noise and decoherence produced by the enormous number of degrees of freedom. The best way of confronting these problems is to work with coherent states in nanostructures. The candidates for such quantum mechanically robust nanostructures are: superconductors, magnetic and semiconductor materials. Semiconductors present the advantage of allowing the simultaneous use of transport and photonics. Storage and manipulation of quantum information can be efficiently made in the charge and spin degrees of freedom while the essential question of quantum information transmission is better solved by means of quantum optics techniques. The specific interests and advantages with respect to other alternatives for implementing quantum optical information by means of semiconductor nanostructures are: i) Electrical injection which allows interconnection with transport based devices, ii) Scalability (large number of components) with currently available technologies, and iii) Sub-nanosecond time scale allowing ultra-fast repetition. These are the reasons why we have developed a line of experimental and theoretical research in quantum optical information processing with semiconductor nanostructures.

Our group is formed by one theoretical and two experimental groups. One of experimental laboratories is devoted to continuous wave and photon correlation spectroscopy of quantum dots (QD) and zero-dimensional cavities while the other works on the time-resolved spectroscopy of polariton condensates in two-dimensional wells and cavities. Fabrication of semiconductor nanostructures is an essential area which requires a financial support beyond our capabilities. Therefore, we get samples from groups in other institutions. Although almost all of them are international, special mention must be done to our collaboration with two groups of growers in Madrid: the ISOM institute at the UPM and the IMM institute at the CSIC.

2. Our lines of research (Experiment and theory)

2.a. Quantum dots and cavities

Quantum dots and cavities (nanopillars or photonic crystals), in particular: i) single photon emission and detection, ii) entangled photon pairs for quantum repeaters and teleportation, and iii) cavity-mediated inter QD coupling [1-9]. Micro-photoluminescence and photon correlation measurements allow detecting single photon emission from single quantum dots and cavity-mediated inter-dot coupling. Two InAs QD in a GaAs matrix are located near a H1 photonic crystal microcavity (PCM) as shown in Fig. 1, in the weak coupling regime. The sample has been fabricated at the Instituto de Microelectrónica de Madrid. Both QD show single photon emission (SPE) as shown by a clear antibunching dip in the second order correlation function $g^{(2)}(\tau)$, measured in a Hanbury-Brown and Twiss interferometer. The SPE is maintained for different values of the energy detuning Δ between the QD photons and the cavity mode (Fig. 2), which correspond to different linear polarization angles. The QD polarization angle rotates as Δ is varied as a result of the hybridization of the QD and the cavity levels. This result is an important step towards the realization of SPE with continuous control of the polarization angle.

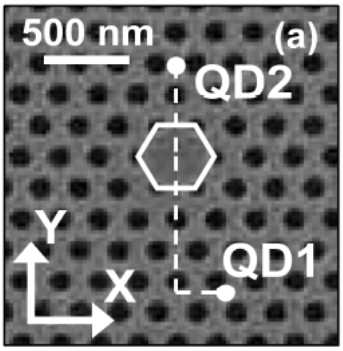

Fig. 1: Scanning electron microscope image of the sample showing the photonic crystal cavity (hexagon) and the approximate location of the QDs.

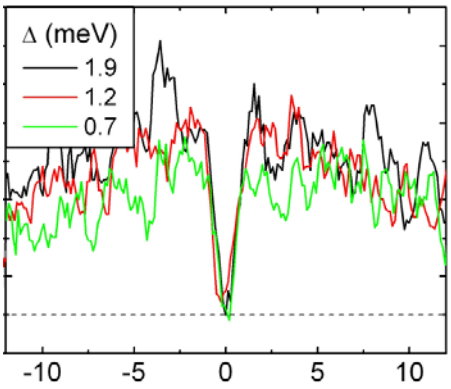

Fig.2. Measured second order photon correlation function for different QD-cavity energy detunings. The central anti-bunching dip is the fingerprint of single photon emission.

The emission of polarization-entangled photon pairs from the biexciton-exciton recombination cascade in selected QDs is an on-going task based on the measurement of the optical matrix density by quantum tomography.

Besides SPE, we have investigated the effective coupling of the QDs shown in Fig.1 by the electromagnetic field of the cavity modes. To this end, the photoluminescence excitation spectra of both QDs have been recorded as a function of the excitation energy (Fig. 3). Besides the expected increase in the emission intensity observed in both QD upon resonant excitation at their own excited states (p-states $P_{1,2}$), shown by the solid Gaussian fits, a strong emission is observed also for excitation at the p-states of the other one (dashed lines), i.e. each QD becomes brighter upon resonant excitation at the p-state of the other one. Considering the distance between the dots (1.4 μm) their mutual coupling cannot happen by direct dipole interaction, but

through their simultaneous coupling to the cavity. This simultaneous coupling has been demonstrated by the Purcell effect observed in time-resolved measurements. These results represent an experimental step toward the realization of quantum logic operations using distant solid-state qubits.

The theoretical analysis all these properties, requires the knowledge of first (spectrum) and second ($g^{(2)}$) correlation functions. This is obtained from the quantum regression theorem and the dynamics of the density matrix as computed from a master equation with rotating-wave and Born-Markov approximations [1-6].

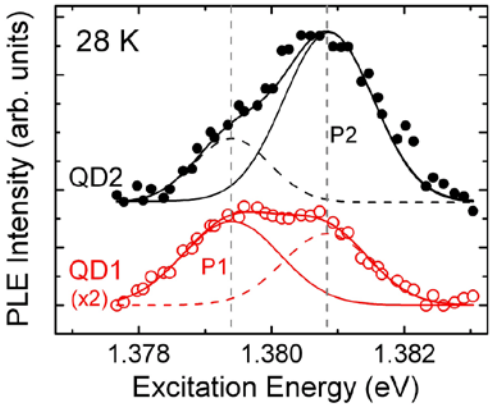

Fig. 3. Photoluminescence excitation spectra of the two QDs showing the standard peaks for intra-QD excitation (solid fit Gaussians) and the inter-QD excitation peaks (dashed lines) due to the effective, cavity-mediated, inter QD coupling.

2.b. Polariton condensates and superfluids (Quantum wells in microcavities)

Semiconductor microcavities are one of the most suitable structures to study light-matter interaction. In the strong coupling regime excitons and photons form mixed states, named cavity polaritons. Our activities on polariton dynamics and its spin properties started more than then 10 years ago with the discovery of a strong influence of exciton-cavity detuning on the spin relaxation of polaritons, [10] and the demonstration of the feasibility to control the polarization of the non-linear, stimulated emission [11] (with samples from E. Mendez at Stony Brook and R. André at Université Joseph Fourier, respectively). Figure 4 shows the polarization-resolved time evolution of the emission from the cavity-like polariton states in a CdTe microcavity in the stimulated emission. For positive detuning, the emission intensity of the σ^+ component of the photoluminescence (solid circles) is much bigger than that of the σ^--polarized one (open circles). This intensity difference gives rise to a non-vanishing polarization of the emission, whose time evolution is depicted in Figs. 2(c&d). The behaviour is quite different for negative detuning, leading to very high negative values of the polarization at very short times after the pulsed excitation. This reversal is related with the sign of a splitting between the energies of the σ^+- and σ^--polarized components of the luminescence.

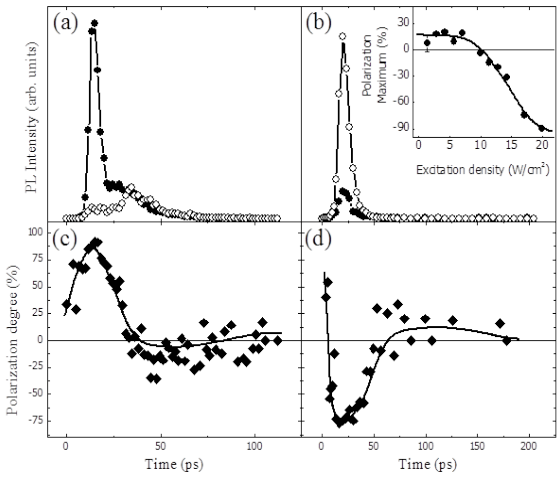

Fig. 4. Polarization-resolved emission (a&b) and degree of circular polarization (c&d) in a CdTe microcavity.

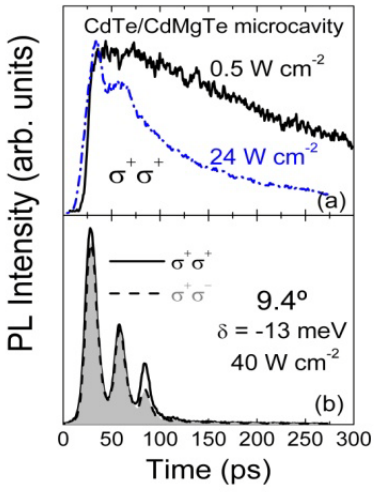

Fig. 5. Polarization-resolved emission in a CdTe microcavity at 9.4° and different power densities.

Microcavities also allow for the discovery of a new mechanism of non-linear coupling of optically active and dark crystal states. Figure 5 presents the measured temporal dependence of the photoluminescence intensity from a bottleneck region of a CdTe-based microcavity under non-resonant pumping. Different panels refer to different excitation intensities. The pumping light is always σ^+-polarized. Pronounced beats of the intensity of photoluminescence from the bottleneck region of the exciton-polariton band are observed in the strong coupling regime and at strong pumping. These beats are extremely sensitive to the pumping intensity and vanish for weak pumping. We have shown theoretically that coherent polariton–polariton scattering which leads to the mixing between bright and dark exciton states can be responsible for this effect. [12]

One of the signatures of condensation of polaritons is the build-up of linear polarization ($\wp_\ell$) in its emission. We have recently demonstrated that the dynamics of the condensate formation and its coherence is not determined only by the occupation of the ground state and also shown the profound relationship among the number of particles, the emission linewidth, and $\wp_\ell$, which serves as the order parameter, bringing new insights into the determining factors for out-of-equilibrium Bose-Einstein condensation. [13] However, it is important to note that the direction of $\wp_\ell$ is pinned to a crystallographic axis. Figures 6(a), (b) display the time evolution of the two linearly polarized components of the PL of a CdTe-based microcavity after horizontally polarized excitation for low excitation densities (spontaneous regime) and high excitation (stimulated regime). The intensity of the vertically polarized emission (dashed line) is larger than that of the horizontally polarized one (solid line). This becomes more evident in the time evolution of the $\wp_\ell$, Figs. 6(c&d). The enhancement of $\wp_\ell$ in the stimulated regime is due to the bosonic stimulation effect. In both regimes, the decay time of $\wp_\ell$ is of the order of 1 ns, i.e. much longer than the intensity decay time. The inset shows the time evolution of the circular polarization: it shows a fast decay on a timescale of 40 ps. Thus the linear polarization decay time is much longer than all the other characteristic times of the system. The fact that PL is negative implies a 90º rotation of the polarization plane of the emission with respect to that of the excitation. When the polarization of the excitation is rotated by 90º still the vertically polarized component is the strongest. These results show that the polarization of the emission is pinned to one of the crystallographic axes of the structure. The pinning originates from a splitting of the polariton doublet at k=0, due to optical birefringence in the mirrors and/or the cavity. [14].

We have also shown that condensation of polaritons can spontaneously take place in the quantized levels of native traps (defects) present in the cavities. [15]. Using a coherent excitation triggered by a short optical pulse, in a triggered optical oscillator (TOPO) configuration, we have created and set in motion a macroscopically degenerate state of polaritons that can be made to collide with these defects. [16] These experiments were performed with samples from M. Skolnick at Sheffield University and J. Bloch at LPN-CNRS in Paris. Our results demonstrate that

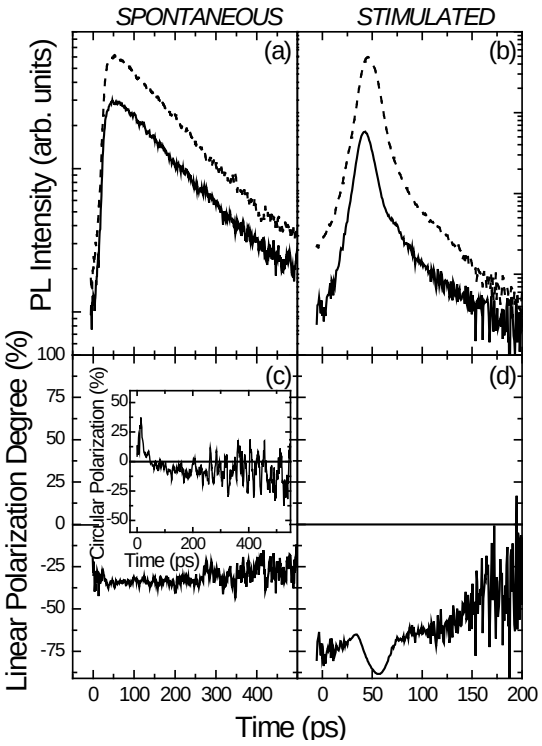

Fig. 6. Polarization-resolved emission (a&b) and degree of linear polarization (c&d) in a CdTe microcavity.

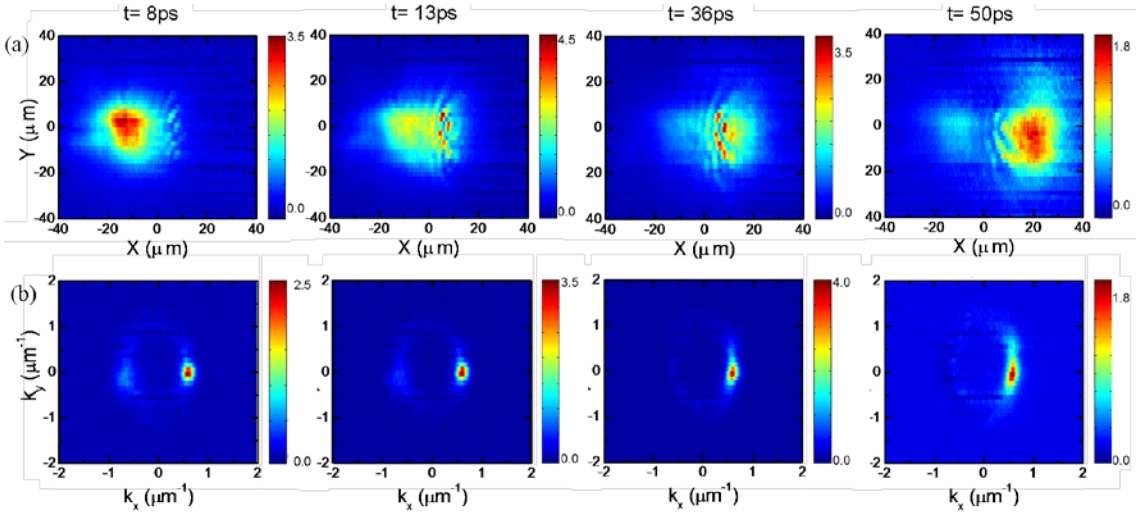

Fig. 7. Polariton droplet colliding with an obstacle (a) and corresponding images in reciprocal space for a GaAs microcavity.

a coherent light–matter packet displays collective dynamics consistent with superfluidity, although one of a highly unusual character as it involves an out-of-equilibrium dissipative system. Figure 7 depicts images of a polariton droplet, in a GaAs-based microcavity, colliding against one of these native defects. a) The moving polariton condensate encounters an obstacle in real space, which is revealed, in real space, by Čerenkov waves caused by pump polaritons travelling at a supersonic speed. However, the signal polaritons pass through the defect in a superfluid fashion without changing direction or scattering against the obstacle. This fact is confirmed by the images taken at the same times in momentum space (b). It is clear that the momentum vector does not change significantly when the condensate crosses the obstacle. The observation of this phenomenon is possible due to a critical slowing down of the elementary excitation dynamics as the threshold for OPO is approached. [17].

The intrinsic non-equilibrium nature of polariton condensates poses fundamental questions about the robustness of the coherence phenomena to dissipation and non-equilibrium. The understanding of superfluid properties of nonequilibrium condensates in a dissipative environment is a fundamental challenge. The hallmark of superfluidity, namely: formation of vortices and metastable persistent flows has been very recently demonstrated in our group. [18] The experimental dynamics of a single vortex, in the same sample shown in Fig.7, is shown in Fig. 8. Panels e–h show the time evolution of the polariton signal after a weak pulsed probe with a vortex of m=1 has been excited. The interference images (a–d) are obtained by overlapping the vortex with a small expanded region of the same image far from the vortex core, where the phase is constant. To better reveal the effect of the imprinting of the vortex into the condensate steady state of the signal, the contribution of the unperturbed polariton signal (in the absence of the probe pulse) is subtracted from all data. In these images, we can observe two effects: immediately after the arrival of the probe, a vortex is generated in the TOPO polaritons and its vorticity is maintained although the population decays in a few tens of picoseconds. After the extra polaritons have disappeared, the vortex remains imprinted into the steady population of the condensate. Although the polariton vorticity is always present and enduring in the TOPO polaritons, only under very high pump power and at specific points in the sample is the vorticity also passed to the steady state of the OPO signal. This not only demonstrates that polariton condensates show unperturbed rotation, but also that a vortex is another stable solution of the final steady state. This is a clear demonstration of superfluid behavior in the non-equilibrium polariton OPO system. All these experimental facts have been theoretically analyzed in terms of a Gross-Pitaevskii equation [18,19].

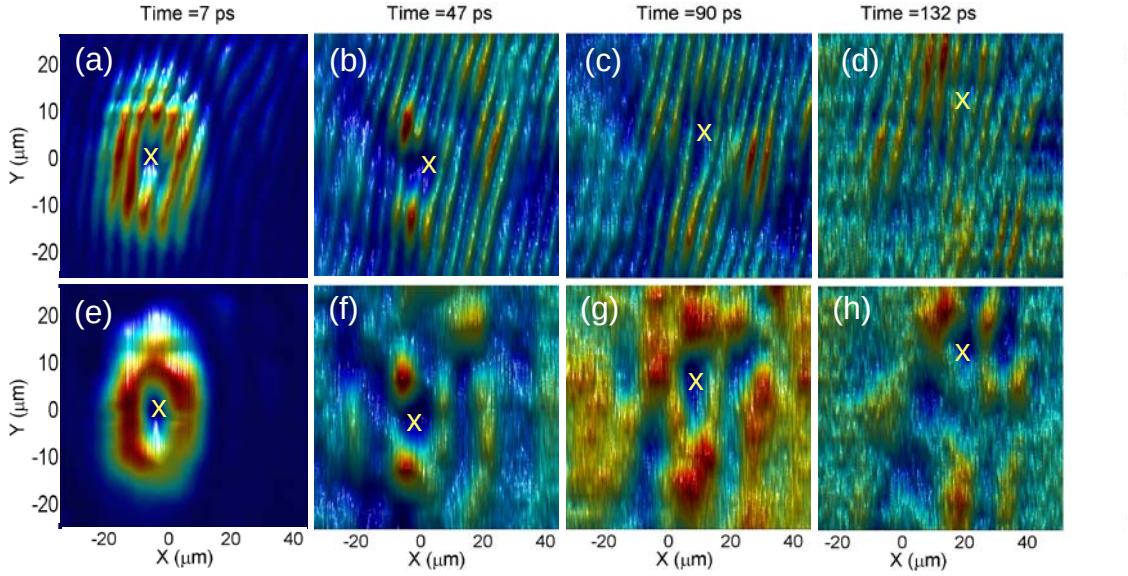

Fig. 8. Interference images (a-d) corresponding to the evolution of vortex with m=1(e-h) created in a GaAs microcavity.

2.c. Quantum plasmonics (Theory)

Preparation of electronic states of quantum dots coupled to plasmonic waveguides. Instead of working with optical modes of microcavities, we have proposed the use plasmon-polariton excitations of metallic nanostructures as the intermediary between the different QD's. The main advantage of these excitations is the tunability of the coherent and disssipative parts of the effective interactions. Figure 9 shows the entanglement between two QD's mediated by the plasmon-polaritons of a plasmonic waveguide when the electronic states are prepared by external lasers. These results have been obtained by means of a master equation in which coupling and decays are computed from classical electrodynamics [20,21].

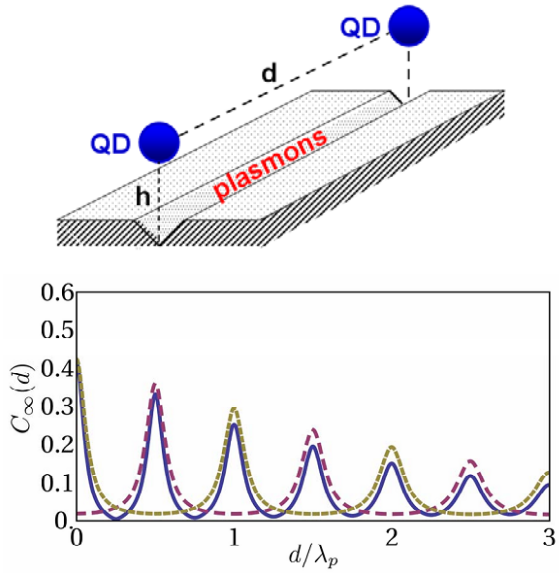

Fig. 9. (a) Two QD's in a plasmonic waveguide. (b) Concurrence of the electronic states of two QD's as a function of the separation between the two QD's for different choices of a continuous laser excitation [21].

3. Conclusions

In the last few years, we have been working in the field of semiconductor nanostructures as components for quantum optics. Many of our results in these low-dimensional (0-D, 1-D and 2-D) systems have received an important attention from the research community and they are mainly contained in the bibliography of this paper.

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