consorzio nazionale interuniversitario per le scienze fisiche della materia

CALL: INNESCO 2007

FIRST YEAR REPORT

TITLE

Photonic Crystal Polaritons for Entangled Photon Generation

PRINCIPAL INVESTIGATOR

Name: Daniele Bajoni
Affiliation: CNISM UdR Pavia and Dipartimento di Elettronica, Università di Pavia
Address: via Ferrata 1
Email:daniele.bajoni@unipv.it
Phone: 00390382985811
Fax: 00390382422583

TOPIC AREAS

1) Optics and Photonics (70%)
3) Solids and Artificially Structured Materials (30%)

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Section 1 Introduction

(Maximum length for the whole of Section 2: three pages)

1.1 Summary of the project objectives

For the first year of the project we proposed the realization of the strong coupling regime between quantum well excitons and the photonic mode of a photonic crystal slab. The aim was to achieve the ability to engineer the dispersion of polariton branches using the unique dispersion properties of photonic crystals. The main risk associated with the task consisted in the unsolved issue of nonradiative recombination of excitons, which occurs when patterning a quantum well and has the potential to hinder strong coupling between excitons and photonic modes.

Once the existence of exciton polaritons in photonic crystals is proved at the end of the first year, photonic structures will be designed to obtain phase matching for polariton scattering in such a way that signal and idler polaritonic states should have comparable photonic character. The occurrence of parametric fluorescence and parametric oscillations will then be experimentally investigated, and second order interference experiments will be set-up to prove the entangled nature of the emitted beams.

1.2 Obtained resources and their allocation

Equipment

Supplier	Bought material	Cost	Description
JOBIN YVON	Holographic grating	2.160,00	Dispersive grating necessary for a spectrophotometer already present at the laboratory
CRISEL INSTRUMENTS	Multichannel coincidence counter	34.003,20	Multichannel Picosecond Event Timer, allows to count and record coincidences among multiple detectors and to resolve tiem dyminamics with 4 ps resolution. It will be of fundamental importance for the prosecution of the present project.
ID QUANTIQUE	Single photon counting module	3647,91	Ultrafast (30 ps) silicon based photodetector, single photon sensitivity
UPS	TVA and duty fees	728,77	
Total		**40.539,88**	

Consumables

Supplier	Bought material	Cost	Description
OPTOPRIM SRL	Laboratory materials	3.739,33	Optical material necessary for experiments
THORLABS	Laboratory materials	159,64	Optical material necessary for experiments
CRISEL	Transport fee	300,00	
PICCOLE SPESE	Laboratory material	36,25	Laboratory material necessary for sample cleaning
ESSEDI SHOP	Computer materials	314,80	
Total		**4550,02**	

Missions

Name	Place	Description	Cost
DANIELE BAJONI	KLINK	Participation to the NOEKS9 Conference	619,79
DANIELE BAJONI	PARIGI	Two weeks stay at LPN laboratory for sample preparation	1.284,02
Total			**1903,81**

Section 2 Scientific Report

(Maximum length for the whole of Section 2: three pages)

2.1 Situation at the start of the project

The development of sources of non-classical states of light, and in particular entangled photon pairs, is of fundamental importance for quantum information processing using protocols including quantum cryptography [1, 2], teleportation [3, 4] or storage of information [5]. An ideal source should be semiconductor-based, monolithically integrable and micrometric in size [6]. Several approaches have been explored to generate entangled photon pairs, including photonic crystal fibers [7], the radiative cascade of a single quantum dot [8] or semiconductor waveguides [9].

An intense research effort has been dedicated to study parametric oscillations of microcavity polaritons. Polaritons are well known to provide very large resonant third order nonlinearities due to strong Coulomb interaction [10]. Thanks to the peculiar dispersion achieved in the exciton-photon strong coupling regime [11,12], phase-matching conditions can be fulfilled in a single planar cavity and efficient parametric oscillation has been obtained [13–15]. However in these experiments, the idler beam intensity was several orders of magnitude weaker than that of the signal, making the evidence of quantum correlations very difficult [16]: classical correlations were demonstrated in a two pump excitation scheme [16], and squeezing has been evidenced in a fully degenerate configuration [17]. Possible solutions have been sought by modifying the microcavity geometry using triple cavities [18] or micropillars [19].

An efficient solution seemed to be the use photonic crystals instead of microcavities to obtain strong coupling with quantum well excitons: in fact, photonic crystals allow to engineer the dispersion of photonic modes by tuning external parameters, like the lattice constant. This would allow to change the phase matching conditions for polariton parametric scattering, so that signal and idler beams of identical intensity could be obtained. However, strong exciton-photon coupling in semiconductor photonic crystals has never been reported for III-V quantum wells. The reason lies in the severe reduction of the exciton lifetime due to nonlinear recombination of excitons at the interfaces with air, which form when patterning a quantum well [20].

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2.2 Situation at the end of the project

The first part of the work has been devoted to the design and the realization of GaAs-based waveguide structures with both quantum wells and photonic crystals to demonstrate the existence of polaritons in such structures. Strong coupling manifests itself as an anticrossing of polariton mode dispersion where the uncoupled exciton and photon modes would cross: the experimental observation of such anticrossing is a proof that the system is in the strong coupling regime. The first structures we have grown consisted in photonic crystal membranes, i.e. self-sustained planar waveguides with a GaAs core (containing 3 InGaAs quantum wells) and air claddings, patterned with a periodic lattice of air holes. The design was performed by a guided-mode expansion approach. All the investigated samples were grown by molecular beam epitaxy and patterned by inductively coupled plasma at the Laboratoire de Photonique et de Nanostructures. Several types of two-dimensional lattices were designed and experimentally realized, but in all cases the exciton line was broadened by nonradiative decay of excitons and the all the realized structures were in weak coupling (see section “open problems” below). Henceforth, we decided to adopt an original design, outlined in Fig. 1a, in which the photonic crystal is separated from the waveguide core by the upper cladding. The periodic modulation of the refractive index is felt by the guided modes through their evanescent tail which overlaps with the patterned region. In this design we exploit the hybrid nature of polaritons: as the quantum wells remain unpatterned, the polariton's excitonic part remains long lived while their dispersion is modulated by the interaction of their photonic part with the photonic crystal.

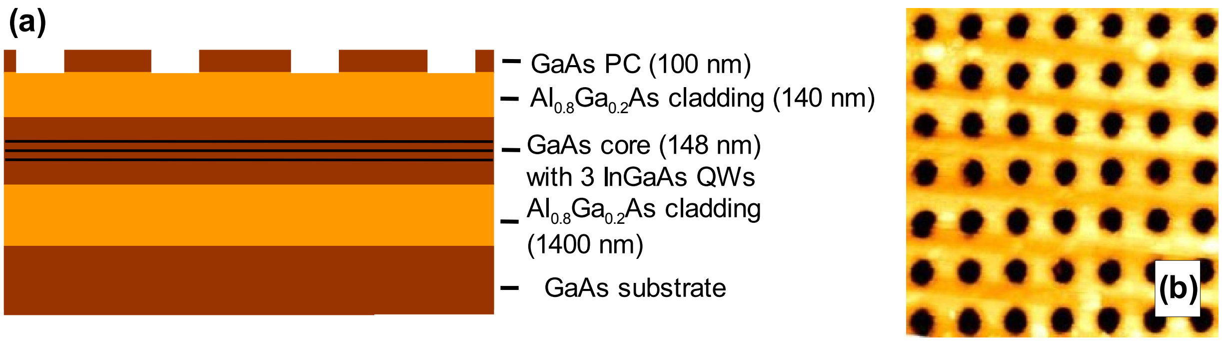

Fig1: (a) scheme of the sample structure. (b)Atomic Force Microscope of the sample's surface

Several samples were realized, all with a square lattice of air holes (see atomic force microscope image in Fig. 1b) and with lattice constant a varying from 245 nm to 260 nm, which were designed in order to obtain a folded photonic mode reaching the exciton energy at 0°, so to obtain strong coupling at normal incidence. To experimentally assess the dispersion of the fundamental modes we have implemented nonstandard spectroscopic techniques. Imaging the photoluminescence (PL) of the structures in the Fourier plane of the focusing objective allowed to directly image the reciprocal plane of the sample (ω versus k). The second technique is resonant scattering (RS) of white light, which consists in measuring reflected light while the sample is placed between cross polarizers, and gives a direct insight of the photonic modes of the samples. Photoluminescence probes the system when it is incoherently populated while resonant scattering is a coherent measurement of the unpopulated system; all measures were carried out at low temperatures (10 K) and a set-up involving direct imaging of reciprocal space was expressly built. In both RS and PL spectra the modes show a clear anticrossing when approching the exciton resonance, which is a

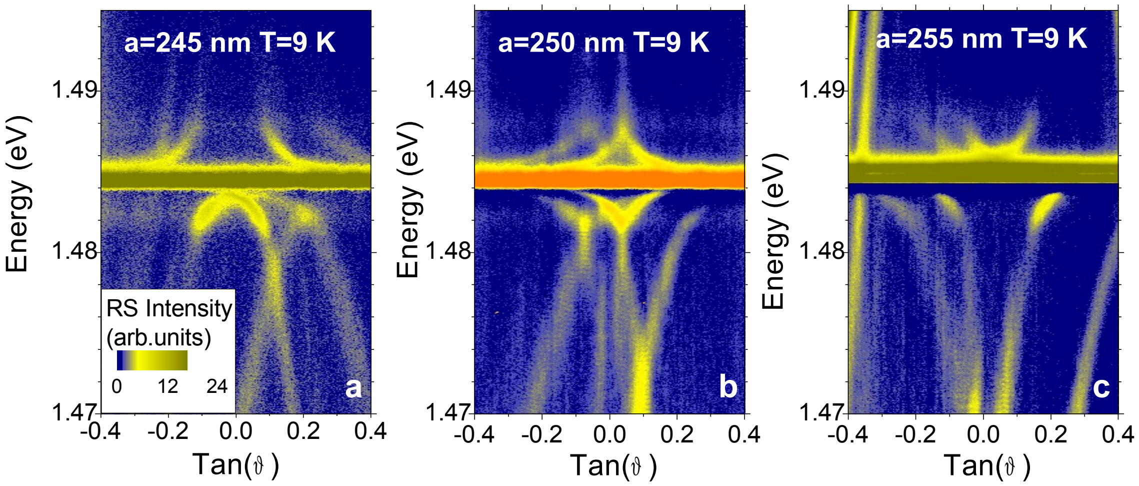

Fig2: Resonant scattering measurements of samples with increasing lattice constant a

direct evidence of the occurrence of the strong coupling regime. Examples of RS spectra as a function of the incidence angle are shown in Fig. 2 for three values of the lattice constant *a*. The polariton dispersion is strongly dependent on *a*: changing *a* by only 2% (5 nm) dramatically transforms the shape of the branches. This result opens the way toward the unique possibility of engineering the polariton dispersion by varying the sample design. Notice the diamond-like shape of the modes in Fig. 2B, completely different to observations for microcavity polaritons, and that the dispersion measured for a=255 nm, with a minimum of the upper branch at ϑ =0, is reversed for a=245 nm which has a maximum for the lower branch at ϑ =0.

These experimental findings have been successfully interpreted in terms of a full quantum theoretical formulation of radiation-matter interaction in such heterostructures. The approach relies on calculating the photonic modes first by a guided-mode expansion method, and then developing a second-quantized formulation of radiation-matter coupling. The calculates mode dispersion for the coupled exciton-photon system resulted in a very close agreement with the experimental data reported in Fig. 2, without any adjustable parameter (see D. Gerace and L.C. Andreani Phys. Rev. B 75, 235325 (2007) for details).

2.3 Details on main results

2.3.1 Result A - Strong coupling in two-dimensional photonic crystals.

photonic crystals were realized on GaAs-waveguides containing quantum wells using an original design which leaves the quantum wells intact. The samples were investigated using resonant scattering and photoluminescence which show clear anticrossing of the modes in reciprocal space, proving the strong coupling regime

2.3.2 Result B: Engeneerable polariton dispersion.

The measured shape of the polariton branches is strongly dependent on the lattice constant of the photonic crystals: a change of few percent in the lattice constant completely changes the dispersion. It is therefore possible to engineer polariton dispersion, the shape and curvature of the polariton branches by carefully choosing the shape of the two dimensional photonic lattice.

2.3.3 Result C: Sample design and quantum theoretical formulation

Samples were successfully designed by using a guided mode expansion method, in which the photonic mode dispersion is tailored for the given structure in order to have exciton-photon resonance in various regions of the dispersion diagram. The exciton-photon coupled system is modelled by a full quantum formulation, and the polariton dispersion and splitting are correctly predicted without adjustable parameters.

<u>Section 3</u> **Open problems**

<u>(Maximum length for the whole of Section 3: one page)</u>

The results described in the previous section demonstrate the occurrence of strong coupling between the modes of a photonic crystal and excitons confined in quantum wells; these results have been obtained with the adoption of a new design which leaves the quantum wells unpatterned as detailed above. This design will be then employed to meet the goals for the successive two years of the project, including the demonstration of entangled photon emission from polaritons in photonic crystals.

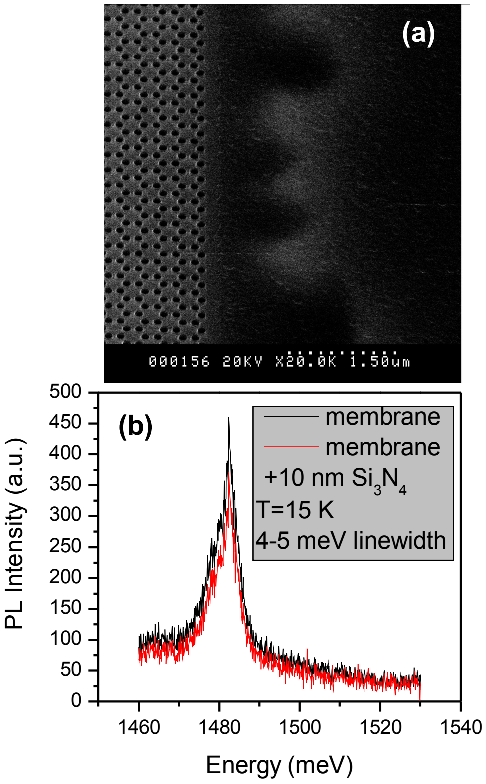

Fig3: a) Scanning electron microscope imageof a photonic crystal membrane with exagonal lattice. Notice the underetching on the left side of the Patterned zone. b) Photoluminescence spectra of the exciton line of the sample of (a) before (black line), and after (red line) passivation with Si3N4

As mentioned in section 2.2, photonic crystal membranes have been realized at the beginning of the project (a scanning electron photograph image is shown in Fig. 3a), but the observation of strong coupling in photonic crystal membranes has been prevented by nonlinear recombination of excitons at the interfaces. In practice, strong coupling is a periodic exchange of energy between excitons and photon modes (Rabi oscillations); the drilling of the quantum wells introduces an air interface where excitons can recombine nonradiatively and the effect is that the exciton lifetime becomes so short that energy is lost before the first oscillation can be completed. The spectral signature of nonradiative recombination is the large exciton linewidth which is found in the patterned samples (4-5 mev, with respect to 0.7 meV in the unpatterned samples). Post-etching passivation techniques have been tried, in particular deposition of a thin layer of Si_3N_4, but the exciton linewidth remained unchanged, as it can be seen in Fig 3b.

The observation of strong coupling in membranes is however important and is nowadays matter of interest for several research groups in polariton physics. Inserting defects in photonic crystal membranes has been in fact demonstrated as an efficient way to obtain ultra-high finesse cavities and efficient monodimensional waveguides, which could be used respectively to confine polariton condensates [21] or guide polariton superfluids [22]. Nonradiative recombination of excitons is a problem that plague GaAs-based systems [20] but is almost absent in InP-based systems [23]. In the second part of the project we propose to investigate the possibility of achieving strong coupling between quantum well excitons and InP photonic crystal membranes, to prove the realization of photonic crystal nanocavities and waveguides in polariton devices.

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Section 4 Summary

4.1 Publications, invited talks, and other performance indicator

4.1.1 Publication list:

Bajoni, D. Gerace, M. Galli, J. Bloch, R. Braive, I. Sagnes, A. Miard, A. Lemaître, M. Patrini, L.C. Andreani "EXCITON POLARITONS IN TWO-DIMENSIONAL PHOTONIC CRYSTALS": the paper has passed the presubmission inquiry to Nature Photonics, and submission will follow shortly. The paper has been published on the preprint repository arXiv, paper number...

4.1.2 Invited talks: none

4.1.3 Oral presentations: Oral presentation at the "9th International Conference on Physics of Light-Matter Coupling in Nanostructures", to be held in Lecce, Italy, 16-20 April 2009.

4.1.4 Poster presentations: none

4.1.5 Performance indicators

(On the basis of the above lists and of the results described in section 2, list the performance indicators given at project submission that have been satisfied)

Indicator A: *Milestone for the first year was the observation of the strong coupling regime in a photonic crystal waveguide.* Strong coupling has been achieved and the possibility to engineer the dispersion of the polariton branches has been experimentally demonstrated, as detailed in section 2.

Indicator B: *Relevance and innovation level of research proposal for basic physics and for devices.* Research on the physics of excitons polaritons is an increasingly expanding field. Results reported during the last year include the control of strong coupling at room temperature in GaN and electrical injection of polaritons in GaAs microcavities, both pointing to the application of polariton properties in actual devices. The present results push further the ability of controlling polariton physics and will be of interest for many researchers working in the field.

Indicator C: *Complementarity and cooperation of the partner units with insertion of a new research line in an already well-established laboratory.* The samples have been realized in the framework of a collaboration between the optical spectroscopy laboratory of the University of Pavia and the Laoratoire de Photonique et de Nanostructures in Marcoussis, France. Experimental research on the physics of exciton polaritons has been successfully started at the University of Pavia, as demonstrated by the results shown in section 2. Such experimental activity benefited from the well established background of the group in optical spectroscopy of photonic crystals.

Indicator D: *Adequacy of available technologies and methods to the objectives.* Experimental set-ups have been realized using partly available materials and facilities. Two nonstandard spectroscopic techniques, resonant scattering and direct imaging of Fourier space, have been successfully applied and have permitted to evidence strong coupling in our samples. Theoretical tools have been developed which yield a satisfactory interpretation of the experimental results, and will be applied for sample design in the following years of the project.

Indicator E: *Publications and conference presentations arising from the project.* The activities of the first year of the research are the subject of a submitted article and an oral presentation in an international conference.

4.2 Personnel Training

A student of the Master degree in Optoelectronic Engineering at the University of Pavia is actually performing experiments in the framework of the research detailed above as a final thesis for the master. The work consists in an experimental thorough mapping, using resonant scattering and Fourier imaging photoluminescence, of the structure of the polariton branches in the samples, with the goal of finding triplets of states suitable to observe parametric fluorescence. This activity constitute the first step for the achievement of emission of entangled photon pairs in this sample, which is proposed as final goal of the project. The work will possibly contunue in a PhD degree for the same student.