Exciton polaritons in two-dimensional photonic crystals

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Experimental evidence of strong coupling between excitons confined in a quantum well and the photonic modes of a two-dimensional dielectric lattice is reported. Both resonant scattering and photoluminescence spectra at low temperature show the anticrossing of the polariton branches, fingerprint of strong coupling regime. The experiments are successfully interpreted in terms of a quantum theory of exciton-photon coupling in the investigated structure. These results show that the polariton dispersion can be tailored by properly varying the photonic crystal lattice parameter, which opens the possibility to obtain the generation of entangled photon pairs through polariton stimulated scattering.

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The strong coupling regime between light and matter is characterized by a reversible and coherent exchange of energy between a single material oscillator and a single mode of the electromagnetic field. A particular case is when excitons confined in a semiconductor Quantum Well (QW) are spectrally and spatially resonant with the mode of a vertical semiconductor microcavity, e.g. in structures similar to the Vertical Cavity Surface Emitting Laser [1]. If the coherent light-matter coupling overcomes excitonic and photonic dissipation rates, the strong coupling regime can be achieved in these structures [2, 3]. As a result, exciton-photon hybrid quasiparticles named microcavity polaritons are formed.

Microcavity polaritons have bosonic statistics, fast interaction with the electromagnetic field, and strong optical nonlinearities related to their excitonic parts. These properties have been exploited to obtain a wealth of nonclassical phenomena in the solid state: coherent and macroscopically occupied matter-wave states [4, 5], optical spin Hall effect [6], and superfluidity [7] among others. Their strong optical nonlinearities have been used to demonstrate low-power parametric oscillations of matter-waves [8, 9, 10, 11], considerable interest has been devoted to polariton parametric scattering with the goal of realizing a semiconductor-based, monolithic and micron-sized source of entangled photon pairs. However, quantum correlation experiments are usually hindered by the great intensity difference between signal and idler beams, which is intrinsic to the dispersion of polariton branches in planar microcavities [12]: possible solutions have been sought by modifying the microcavity geometry [10, 13].

Photonic crystals can be used to tune the photonic mode dispersion by suitably modifying the sample design [13]. Photonic crystals in the strong coupling regime give the unique possibility to engineer the dispersion of polariton branches. New ways to achieve phase matching for parametric scattering, e.g. to obtain signal and idler beams of comparable intensity, can thus be envisioned, opening the possibility of measuring quantum correlations between signal and idler polaritons. Early experimental evidence of polaritons in photonic crystals has been reported by using polymers sputtered on gratings [16, 17]. Polymers undergoing strong coupling have very strong oscillator strengths but do not show optical nonlinearities. Although theoretically proposed [18], polaritons in photonic crystals have never been reported in semiconductors, where nonlinearities are very high [11]. The main problem is that, in many semiconductor systems, and in particular in GaAs-based samples, patterning the QW results in a severe reduction of the exciton lifetime by nonradiative recombination at hole sidewalls [19], and consequently in the loss of strong coupling [20].

Here we report the first experimental evidence of strong coupling between excitons confined in a semiconductor QW and the photonic modes of a two-dimensional photonic crystal. To avoid issues related to nonradiative recombination, we adopt an original design: the photonic lattice is spatially separated from the QWs so that polaritons only experience the periodic potential through their photonic part, while leaving the QW intact.

The sample, schematically shown in Fig. 1, was grown by molecular beam epitaxy on a GaAs substrate. A 140 nm thick Al0.8Ga0.2As cladding was first deposited, followed by a 148 nm thick GaAs core with three 8 nm thick In0.05Ga0.95As QWs at its center, a second 140 nm thick Al0.8Ga0.2As cladding and finally a 100 nm GaAs top layer. The top layer was patterned by inductively coupled plasma etching [21] with a square lattice of circular air holes (see Fig. 1): areas with different lattice parameters a=245, 250, 255, and 260 nm were defined. The nominal etch depth is 120 nm. The periodic corrugation yields a dispersion-folding on the guided modes of the slab waveguide within the first Brillouin zone (Fig. 1, upper panel), making them radiative around normal in-
dielectric constants planar GaAs waveguide with between AlGaAs claddings, with dimensional units. The modes are calculated for a symmetric plane of incidence, notice that the energy scale is in adi- Brillouin zone and guided mode dispersion in the experimen- 2

The sample was kept at low temperature in a He-cooled cold finger cryostat. The experimental set-up is out- discussed in the following, and it is shown in the calculated mode dispersion in Fig. 1b.

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low 1 meV in all spectra; the measured Rabi splitting is ≃ 7 meV, comparable to what has been reported for planar microcavities. Notice that, without coupling with the exciton, the modal dispersion would be linear, as discussed below. Figure 2 highlights that the original shape of polariton dispersions in such photonic crystals is for instance the diamond-like shape of the modes in Fig. 2b is completely different from the S-shaped dispersion of microcavity polaritons. Moreover the polariton dispersion dramatically depends on the lattice constant: changing a by only 2% (5 nm) substantially reshapes the branches.

We model the system under investigation by calculating the photonic modes for the planar waveguide in the two-dimensional lattice as in Fig. 1d. The coupling is described by a full quantum formulation, as detailed in Ref. [18]: the Rabi splitting in the polariton mode dispersion depends on the overlap between the guided modes of the slab waveguide and the QW exciton envelope function, as well as on the oscillator strength per unit area [24]. The resulting polariton dispersions are reported in Figs. 2d,e,f, for the same lattice parameters as in Figs. 2a,b,c. Overall, the details of the polariton modes are complicated by the tilted plane of incidence (30°) with respect to the ΓX direction, which removes photonic mode degeneracies. Two photonic branches for each parity can be distinguished at the Γ-point (ϑ = 0°), but only even modes strongly couple to the excitons. There is a good agreement between theory and experiment: the calculated Rabi splitting for these structures is ℏΩR ≃ 7.1 meV and compares very well with the experimentally determined value of ∼ 7 meV, as it can be easily seen by directly comparing Figs. 2b and e. Notice the presence of additional polariton branches in the measurements, which are not reproduced by the theory (an instance is highlighted by a white arrow in Fig. 2b). These additional modes appear only when the plane of incidence does not correspond to a high symmetry direction of the lattice (ΓM or ΓX) and may be related to...
To evidence the difference between strong and weak coupling in our samples, PL measurements with increasing temperature \((T)\) are plotted in Figs. 4a, b, c for a sample with \(a=260\) nm. At \(T=70\) K the sample is still in strong coupling, and shows the same anticrossing as at \(T=8\) K (Figs. 4a, b). Above \(80\) K the Rabi splitting is progressively reduced and at \(T=250\) K (Fig. 4c) strong coupling is lost and the photonic modes cross the exciton resonance. As an illustration, fig. 4d shows the energy variation with temperature of the exciton and of three modes chosen around the exciton at \(\theta = 10^\circ\) (modes 1 and 2, see black circles in Figs. 4a, b) and at low energy at \(\theta = 0^\circ\) (mode 3 see black circle in Fig. 4c) extracted from the spectra. Since the exciton redshift is stronger than that of the photonic modes, increasing temperature changes the detuning between exciton and modes. The exciton and mode 3 cross above \(200\) K, which evidences they are in weak coupling. On the other hand, modes 1 and 2 anticross at \(45\) K, and are thus in strong coupling. Their energies can be fitted by using Eq. 1, in which the uncoupled photonic mode, \(E_{Ph}\), is assumed to have the same dependence on the temperature as mode 3. This loss of strong coupling at high temperature can be understood considering the exciton dephasing rate \(\gamma_X\) in Eq. 1: increasing temperature means increasing \(\gamma_X\) until the term under square root becomes negative, i.e. excitons dephase in a time \(1/\gamma_X\) before a single Rabi oscillation can be completed.

In conclusion, we have shown the strong coupling regime of quantum-well excitons in two-dimensional photonic crystals through both resonant scattering and photoluminescence experiments at low temperature. The present results will open new directions for polariton research: the possibility of engineering phase matching is a considerable step towards achieving a compact and integrable solid-state source of entangled photon pairs. Further applications can be envisioned for polaritons in large band gap materials. Although the strong coupling regime has been already reported at room temperature in GaN \([25, 26]\), ZnO \([27]\) and CuCl \([28]\), fabrication of high quality microcavities for these materials is often impractical due to the large number of required layers. Using planar photonic crystals, and in particular the present design that leaves the active region intact, will turn to be effective for obtaining strong coupling with high quality optical modes at room temperature.

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