Elliptically polarized exciton-polariton condensate in a semiconductor microcavity with a chiral photonic crystal slab

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Abstract. We demonstrate a method for controlling polarization of exciton-polariton condensate emission in a planar semiconductor microcavity based on modification of the electromagnetic mode structure in the microcavity. The modification is realized by fabrication of a chiral photonic crystal slab with partial etching of the upper Bragg mirror lowering the microcavity symmetry to C4. A degree of circular polarization as high as 70% has been demonstrated experimentally in the structure with optimized parameters without the use of a static magnetic field or birefringent wave plates.

1. Introduction

Exciton polaritons in semiconductor microcavities (MCs) are half-light-half-matter boson quasiparticles forming due to coupling of the optical and matter modes in the strong light-matter coupling regime [1]. Just like exciton and light, they are boson particles with an integer spin. Exciton-polariton systems have attracted broad interest during the last decade. Their properties are reliably controlled and probed by optical means as polaritons tunneling through Bragg mirrors turn into photons with the same statistics and vice versa. Owing to the small effective mass, about $10^{-8}$ times smaller than the atom mass, polaritons exhibit quantum coherent properties at relatively low densities of $10^{10}-10^{11}$ cm$^{-2}$ at surprisingly high temperatures [2]. The condensation of polaritons at the low polariton (LP) band bottom in GaAs- and CdTe-based planar MCs is observed up to several tens of Kelvin [3-5] and up to room temperatures in GaN and ZnO-based MCs [6,7].

The total angular momentum $J$ of a heavy-hole exciton-polariton in a quantum-well MC can have two possible projections on the growth axis of the structure, $J_z = +1$ (spin up) or $J_z = -1$ (spin down), corresponding to right and left circularly polarized emitted light, respectively. These states are degenerate due to high MC symmetry. The spontaneous symmetry breaking of the condensate manifests itself in spontaneous buildup of linear polarization of the emitted light [8]. In the absence of pinning, such polarization is randomly chosen by the system and changes stochastically from one

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experiment to another [9]. Reduction of MC symmetry caused by magnetic field (lateral strain) results in splitting of the LP level into two sublevels with orthogonal circular (linear) polarizations.

In the present paper we investigate the possibility of controlling polarization of LP condensate emission in an unstrained planar semiconductor MC using modification of the MC electromagnetic mode structure by fabrication of a chiral photonic crystal slab at a zero magnetic field and show that the degree of circular polarization of LP condensate emission can be controlled by a very thin half-wave plate with a thickness of the order of the emitted light wavelength.

2. Experimental details.

AlAs/AlGaAs/GaAs high Q-factor MC was grown by molecular beam epitaxy on a (001)-oriented GaAs. It consists of a lower and an upper Bragg reflectors with 27 and 23 pairs of AlAs/Al_{0.2}Ga_{0.8}As layers, respectively, and an active layer with three groups of four 13 nm GaAs quantum wells (QWs) separated by 4 nmAlAs barriers. A chiral layer is fabricated by electron-beam nanolithography and dry etching through top N_{etch}= 4.75 Bragg pairs of the upper mirror.

The schematics of the CPC are depicted in Fig. 1. It consists of a square lattice of rectangular pillars that have a broken in-plane mirror symmetry but possess a fourfold rotational axis and provides strong optical activity[10]. The vertical walls of nanopillars are normal to the [110] crystallographic directions. This structure has C4 point symmetry, and it is three-dimensionally chiral, because it does not have planes of mirror symmetry, including the horizontal one.

![Figure 1](image)

The sample is held at temperature T = 10 K in the cryostat. The excitation is carried out with a Ti-sapphire laser in the spectral range of the first reflection minimum of the MC. The laser spot has a diameter of about 10 μm. The emission is collected in an angle range of ±15°. It is dispersed by a monochromator and detected by a Si CCD camera. The polarization of the luminescence is analysed by a quarter wave retarder and linear polarizers feature.

3. Experimental results and discussion.

In [11], taking into account the reciprocity principle and the symmetry of the structure, we showed that a CPC slab with C4 symmetry can work as a waveplate due to Fabry-Perot interference between the vertically propagating modes in the slab and, for some optimal parameters, it can transmit light with one circular polarization and suppress almost entirely light with opposite polarization. No linear
polarization is observed, because the oscillating dipoles are assumed to be randomly linearly polarized in the \( xy \) plane. To obtain a high degree of circular polarization of LP emission, the chiral structure was optimized on the basis of calculations of the frequency dependences of LP emission in the right- and left-circular polarizations using an optical scattering matrix and the modal Fourier method [11, 12].

Basing on the calculations, two periodic structures have been fabricated for experimental studies. They are shown schematically in Figs. 1(a) and 1(b). Sample A has period \( p=1060 \) nm and pillar feature size \( L=544 \) nm, and Sample B has \( p=1200 \) nm and \( L=960 \) nm. The height of the chiral layer is equal to 4.75 Bragg pairs. The horizontal size of chiral structure in each sample is \( 50 \times 50 \) \( \mu \)m\(^2\).

Calculated degrees of circular polarization, \( \rho_c \), of LP emission depend on the angle from the normal to the MC plane. The expected values of \( \rho_c \) are of \(~0.75\) and \(~0.6\) for emission along the normal to the MC plane in the samples A and B, respectively.

In general, the used approximation is not completely valid for describing the condensate emission: the emission is calculated for oscillating point dipoles in the QW plane driven by external excitation, so that the intensities rather than the electromagnetic fields are summed up at the receiver. This approximation should work well below the threshold of LP condensation and is expected to be a reasonable starting point for optimization of the structures.

Figure 2(b) shows circularly polarized emission spectra of LPs from a MC with a CPC at excitation density \( P \) slightly below and above the threshold of LP condensation for Sample A. The detuning of the photon and exciton modes is about -6 meV. Figure 2(b) shows that with a 40% increase in \( P \) the LP emission intensity increases several-fold and the emission spectrum shows a threshold-like transition from a broad to narrow line with full width at half maximum (FWHM) of 0.35 meV. Comparison of the \( \sigma^+ \) and \( \sigma^- \) polarized spectra reveals that the transition is also attended with a large increase in the degree of circular polarization \( \rho_c=(I^- - I^+)/I^+ + I^- \) where \( I^+ \) and \( I^- \) are the emission intensities in the right (\( \sigma^+ \)) and left (\( \sigma^- \)) polarizations, respectively. The spectral dependences of \( \rho_c \) at \( P \) below and above \( P_{th} \) are shown in Fig. 2a. It is seen that \( \rho_c \) increases from \(~0.2\) at \( P=0.7P_{th} \) to \(~0.65\) at \( P=1.05P_{th} \).

The change in the LP emission spectra with increasing pump density is shown in Fig. 3b. It is seen that with increasing pump density (i) the emission intensity increases superlinearly (ii) the emission line being shifted towards higher energies and slightly broadened. Underline that the blue shift of the emission line proves its polariton nature. Indeed, the shift indicates the growth of the repulsive
interaction in the system under study, which is characteristic of LP systems and absent in light ones. Figure 3b shows that the degree of circular polarization changes relatively weakly with $P$, the maximum value of $\rho_c \approx 0.7$ is observed at $P = 1.4 P_{\text{thr}}$ and decreases somewhat with a further increase in $P$ to $\rho_c \approx 0.55$ at $P = 1.7 P_{\text{thr}}$.

Finally, linear polarization along the (110) crystallographic direction of the AlGaAs and GaAs layers, $\rho_{\text{lin}} \approx 0.38$. As a result the total degree of LP emission light polarization $\rho_\Sigma = (\rho_c^2 + \rho_{\text{lin}}^2)^{1/2}$ reaches 0.75. Note that the linear polarization is unexpected for the emission from structures with C4 symmetry. This can be related to possible (i) fabrication-induced deformation of the CPC structures, which could lead to a reduced structural symmetry or (ii) preferential linear polarization of the condensate state.

4. Conclusion.

We have demonstrated that fabrication of a thin, of the order of $\lambda$, CPC slab at the MC top can be used for controlling the degree of circular polarization of LP condensate emission without the use of a static magnetic field or birefringent wave plates. The magnitude of $\rho_c$ in the fabricated structure with optimized parameters depends weakly on the condensate density and reaches 0.65-0.7 at $P = 1.05 - 1.5 P_{\text{thr}}$. In addition, it was found that the condensate emission also exhibits a partial linear polarization. The reason for the presence of linear polarization with the symmetry of the C4 structure is not yet clear and requires further research.

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