Polariton Bose condensation in microcavity in high magnetic fields

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Abstract. The dependences of the exciton-polariton photoluminescence spectra on the intensity of optical excitation and external magnetic fields are investigated in cylindrical mesas based on high-quality microcavities. It was found that with an increase of the intensity of optical excitation above a certain threshold or with an increase of magnetic fields at constant optical excitation, the distribution of exciton-polaritons over Zeeman sublevels becomes substantially non-Boltzmannian.

1. Introduction
The phenomenon of Bose-Einstein condensation is one of the most interesting subjects in the modern fundamental physics. Bose condensate has a number of unusual and unique properties, such as macroscopic coherence, superfluidity, vortex formation, and others. In fact, this is a completely new state of matter. Until now, only one kind of the Bose condensate systems is studied in detail, it is superfluid helium. More recently, other examples of such systems have been discovered. Two of them are excitons and exciton-polaritons [1, 2]. Having a much smaller mass than atoms, the excitons and exciton polaritons in principle can form a Bose condensate, even at room temperature [3].

The most promising is the study of the properties of Bose condensate of exciton polaritons in microcavities. Due to the strong exciton-photon coupling, the mass of exciton polaritons in microcavities is several orders of magnitude smaller than the mass of excitons. This greatly facilitates the conditions for Bose condensation of exciton polaritons. It can be expected that the magnetic field stabilizes this condensed state and thereby contributes to the condensation.

In this paper, we investigated the circular polarization of exciton-polariton photoluminescence (PL) induced by magnetic field in cylindrical mesas etched from high-quality microcavities. In such structures, in addition to the axial quantization of exciton-polaritons, there is also a lateral quantization in the plane of the structure. Since polariton energy spectrum becomes purely discrete with the lateral quantization, this greatly facilitates the analysis of polariton energy distribution. As a result, analysing the dependence of the degree of circular polarization induced by magnetic fields, we can find the distribution of polaritons over energy levels, and thus confirm the condensation of polaritons in microcavities.
In contrast to the results of the paper [4] but in agreement with [5] we did not observe any Zeeman splitting of the exciton-polariton lateral quantization lines in small magnetic fields less than 2T.

2. Experiment and Results

We investigated the spectra of circularly polarized PL in external magnetic fields up to 11 T. The samples under investigation were GaAs-based microcavities. The microcavity is a $5\lambda/2$ thick Al$_{0.2}$Ga$_{0.8}$As cavity surrounded by Bragg mirrors. The top/bottom mirror consists of 32/35 periods of Al$_{0.15}$Ga$_{0.85}$As and AlAs layers with a thickness of $\lambda/4$ each. Inside the microcavity, four sets of three 10 nm quantum wells were placed in the antinodes of the cavity electromagnetic field. The scheme of the structure is presented in figure 1. The quality factor of such structure is determined by the “leakage” of radiation from the microcavity and is about 20000. A set of cylindrical mesas with diameters from 1 to 40 microns was fabricated from this structure.

The PL was excited by a Ti:Sa laser with pulse duration of 2 ps and a repetition rate of 76 MHz. The energy of the exciting quantum of 1.62 eV was chosen in such a way that both the Bragg mirrors and the AlGaAs barriers were transparent for the radiation, which ensured the effective creation of excitons in quantum wells. A micro photoluminescence setup with an excitation spot diameter of 1.5 μm was used to record the PL spectra. It was equipped with microscope objective, a 1-meter double spectrometer and CCD detector.

![Figure 1](image1.png)

**Figure 1.** Energy scheme of the studied structure. The cavity is sandwiched between two Bragg mirrors. Inside the cavity there are four sets of three 10 nm quantum wells located in the maxima of the quantized electromagnetic field (red line).

![Figure 2](image2.png)

**Figure 2.** The PL spectra taken from the 5 μm diameter mesa in magnetic field of 11 T at 5 K and weak optical excitation below a threshold. Black and red curves show the right and left circularly polarized PL components.

In the PL spectra of all mesas, a set of narrow lines with half-width at half maximum less than 0.5 meV was observed, associated with lateral quantization of exciton polaritons in the mesa plane.

The number of the lines and the energy distance between them depend on the mesa diameter. So, more than 10 lines were observed in the mesa with a diameter of 14 μm and only 5 lines in the mesa with a diameter of 5 μm. PL spectrum of a mesa with a diameter of 5 μm at relatively weak level of optical excitation, below a certain threshold value, in a magnetic field of 11 T is shown in figure 2. This figure clearly shows the Zeeman splitting of the lateral quantization levels of exciton polaritons.

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In the magnetic field of 11 T the splitting is 0.35 meV. It can be seen from this figure that, as can be expected, the PL intensity of the lower Zeeman sublevel in the right circular polarization is higher than the intensity of the upper sublevel in the left circular polarization.

The value of the Zeeman splitting in magnetic fields larger than 3 T depends linearly on the magnetic field and does not depend on excitation intensity. In small magnetic fields less than 2 T we could not measure the value of the Zeeman splitting with enough accuracy. Figure 3 shows the dependence of the Zeeman splitting on magnetic fields (asterisks), fitted by a linear function constructed using the least squares method. The effective exciton-polariton g-factor obtained from this fit is $g = 0.7$.

This dependence does not approach the zero value at zero magnetic field. It is possible that in small fields less than 2 T, the Zeeman splitting is small or zero and does not depend on the magnetic field, as it was predicted in [6] and observed in [5].

At a relatively weak level of optical excitation the ratio of PL intensities of the Zeeman components was well described by the Boltzmann distributions of exciton-polaritons over the Zeeman sublevels at the temperature of the experiment (5 K). For example, in the field of 11 T, the Zeeman splitting is 0.35 meV, which gives the ratio of populations of the upper and lower Zeeman components 1:2.

The population of the Zeeman sublevels of exciton polaritons in magnetic fields can be characterized by the PL circular polarization degree $P_{cir} = \frac{I^{-} - I^{+}}{I^{-} + I^{+}}$, where $I^{+}$ and $I^{-}$ are PL intensities in the right and left circular polarizations. Then the ratio of populations 1:2 corresponds to $P_{cir}$ of about 30%.
The increase of optical excitation above a certain threshold at a sufficiently large (> 6T) magnetic field leads to a sharp redistribution of the PL intensities of the ground Zeeman components in favor of the lowest one. As a result, the ratio of the intensities of the components turned out to be essentially not Boltzmannian. The PL circular polarization degree under these conditions was close to 100% (figure 4).

Similarly, non-Boltzmannian distribution was observed at a fixed optical excitation above the threshold, depending on magnetic field. At a certain threshold value of the magnetic field, there was also a sharp redistribution of the intensities of the Zeeman components in favor of the lowest energy component with a degree of circular polarization of ~ 100%.

It can be seen in figure 4 that at relatively weak optical excitation of 0.3 and 0.45 mW, but above the threshold, the magnetic field dependence of PL circular polarization abruptly approaches 100%. This occurs in the field of the order of 6 T. At a relatively strong excitation (1.6 mW), the magnetic field threshold decreases to 4 T. In this case there is no polarization in small magnetic fields in agreement with [5].

3. Conclusion
Thus, with an increase of the exciton-polariton concentration at a fixed magnetic field or with an increase of the magnetic field at a fixed concentration of exciton-polaritons, all polaritons collected on the lowest energy level, that is, the Bose-Einstein condensation of exciton-polaritons takes place. At the same time the exciton polariton distribution over the higher quantization energy levels obeys the Boltzmann statistic.

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