Magnetic-field interaction of spatially confined quantum-well exciton-polaritons

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Abstract. We report on pronounced magneto-optical effects of trapped polariton modes in a single InGaAs quantum well microresonator with a lithographically defined modulation of the cavity length. In our optical polariton traps with diameters ranging from 1 to 10 µm, a confinement potential of 7.5 meV is achieved. In magnetic-field dependent experiments, a diamagnetic shift and a Zeeman splitting of the trap-modes are observed which confirms that the polaritonic nature of the quantized emission modes are preserved even for traps as small as 1 µm. Furthermore, focusing on theoretical estimates using a simple model, we have identified a clear correlation between the polaritons' magnetic response and their excitonic fraction, corresponding to the Hopfield coefficients of the composite particles.

1. Introduction

Exciton-polaritons are the result of strong light–matter coupling in quantum-well (QW) microcavities [1]. These bosonic quasiparticles which combine properties of photons and excitons in a linear superposition have proven to be a model system for the demonstration of dynamical Bose-Einstein condensation (BEC) in semiconductors [2-5]. Since the realization of BEC is not possible in a homogeneous and infinite two-dimensional (2D) system [6], experimentally the condensation of polaritons in a planar system relies on local potential variations. This explains the strong interest in a lateral trapping of the exciton-polaritons.

Various technological approaches have been pursued to structurally tailor the confinement of polaritons [4,7-10]. The low polariton effective mass hereby enables the observation of three-dimensional (3D) quantization effects already for trap diameters on the order of a few microns. With lateral confinement of polaritons, new opportunities for the realization of future quantum light emitters arise that have confined polaritons as the source of indistinguishable single photons and can be utilized for quantum information processing [11]. According to theoretical considerations on the single-polariton level, a photonic dot with high confinement potential for polaritons can act as a single-photon source on the basis of polariton quantum blockade [12].

Our magneto-optical studies of discrete optical modes originating from spatially trapped, zero-dimensional (0D) polaritons, presented in this work, reveal a diamagnetic shift and a Zeeman splitting for magnetic fields up to 5 T. These effects were observed in *k*-space resolved measurements for different trap diameters, ranging from 1 to 10 µm, confirming that the polaritonic properties of the emission modes are preserved for various trap sizes, even for the smallest traps studied. By the use of an external magnetic field, we probe light–matter coupling in our systems via direct manipulation of the excitonic component of the formed quasiparticles, with both the spectral shift and the splitting being attributed to the excitonic fraction of the trapped composite particles [13,10]. We present good agreement between experiment and theory using a simple Hopfield coefficient model to describe both effects. Our results hereby indicate that magneto-optical studies present a reliable tool to identify strong coupling for various exciton-polariton systems.

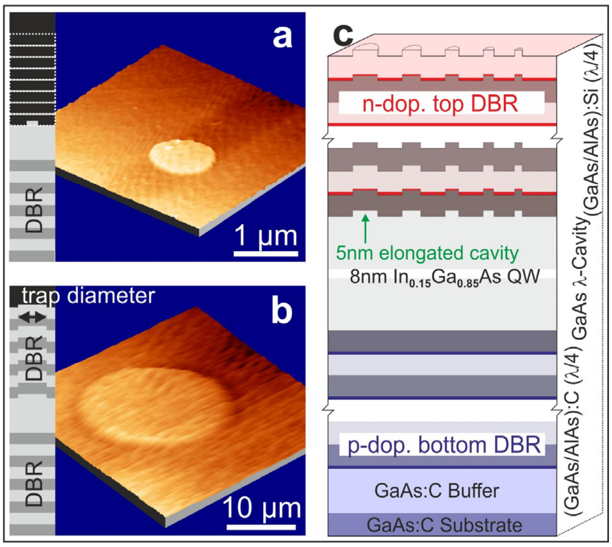

Figure 1: Atomic force microscope image of an etched cavity spacer with (a) a 1-µm diameter before and (b) a 10-µm diameter after top DBR overgrowth. Inset: Schematic layout of the structure. (c) Schematic drawing of a planar microcavity design with a single $In_{0.15}Ga_{0.85}As$ QW [10].

Trapping of polaritons is achieved by a gentle modulation of the optical confinement in a one-λ thick GaAs cavity spacer which is sandwiched between AlAs/GaAs distributed Bragg reflectors (DBRs) with 23/27 top/bottom mirror pairs in our microcavity system [10]. Circular trap diameters d were systematically varied from 0.5 to 10 µm. The active layer of our high-quality planar microresonator, grown by molecular beam epitaxy, consists of a single $In_{0.15}Ga_{0.85}As$ QW. The traps were defined by electron-beam lithography and the structure was patterned by etching the cavity spacer before overgrowth [cf. figures 1a and 1b]. The pattern is preserved during overgrowth. In our system, the unetched area introduces a trap potential V of about −7.5 meV for the locally 5-nm-thicker cavity layer. In such a structure, the unmodified QW provides free 2D excitons, which then couple strongly to 3D localized photon modes and result in 0D polaritonic traps [7,14]. A schematic drawing of our microcavity system is shown in figure 1c.

2. Theoretical Background

The strong coupling of cavity photons and QW excitons in our structure results in the lower and upper polariton energy-momentum dispersion branch (LP/UP), the two eigenstates of the coupled system [1]. In general, the photonic ($|C|^2$) and excitonic ($|X|^2$) contents — referred to as Hopfield coefficients [15] — of the composite particle sum up to unity for each branch at given in-plane wavevector $k_{||}$. For a polariton system at a given detuning $\Delta(k_{||}) = E_C(k_{||}) - E_X(k_{||})$ between the bare exciton and the cavity modes one can calculate both coefficients, $|C(k_{||})|^2$ and $|X(k_{||})|^2$, at corresponding $k_{||}$ [16]. Strong coupling manifests itself by the anticrossing behavior and the characteristic Rabi splitting of $E_{\text{Rabi}} = 2\hbar\Omega_{\text{Rabi}}$ of the polaritonic modes, with the Rabi frequency Ω_{Rabi}. In polaritonic systems, mode tuning can typically be achieved for instance by changing the temperature, and by other means such as an external magnetic field, exploiting the diamagnetic shift as a tuning mechanism.

Magneto-optical effects in polaritonic systems were particularly studied with respect to an increase in the oscillator strength and Rabi splitting with increasing magnetic field [17-21] and to the Zeeman splitting of the exciton-polariton system [13,20]. Furthermore, magneto-optical studies have been recently extended to exciton-polariton condensates [22,23] and quantum-dot polaritonic systems for which a decrease of the oscillator strength has been observed [24,25]. In the presented work, we utilized magneto-optical effects to identify polariton emission from traps.

While the uncoupled photon mode of the QW cavity system does not interact with an external magnetic field, the unperturbed exciton of a QW shifts in energy due to a diamagnetic response

$$\delta E_{\text{dia},X} = \kappa_X B^2 \tag{1}$$

according to Refs. 26 and 27, where κ_X denotes the effective diamagnetic factor of the QW exciton. At the same time, the magnetic field couples to the total angular momentum of the excitonic spin states which causes Zeeman splitting proportional to the field density, given by [28]

$$\Delta E_{ZS,X} = g_X \mu_B B \tag{2}$$

where g_X denotes the effective excitonic g-factor and μ_B the Bohr magneton. By the circular polarization of the emitted light, the two Zeeman-split exciton states can be analyzed and distinguished [13,20]. The diamagnetic shift of a polaritonic system depends on the detuning situation and can be estimated by the associated exciton fraction in terms of the magnetic field–dependent Hopfield coefficient $|X|^2(B)$, i.e. by weighting Eqs. (1) and (2) with $|X|^2(B)$, respectively. The effective mode detuning at present field determines $|X|^2(B)$, taking into account the diamagnetic shift of the QW exciton mode $E_X(B)$ and an increase of $E_{\text{Rabi}}(B)$. In fact, if calculating the system's energy eigenstates [16] with both magnetic-field dependent parameters $E_X(B)$ and $E_{\text{Rabi}}(B)$, the polaritons' diamagnetic shift, which is particularly the result of a detuning change with increasing B, can be well estimated for given B. Taking into account spin-split $E_X(B)$, the same can be done for the Zeeman splitting.

3. Experiment

Utilizing angular resolution of emission in Fourier-space (FF: far-field) spectroscopy (cf. Ref. 5), trap polaritons were investigated for an accessible range of k-vectors and angular mode numbers in micro-photoluminescence (μPL) under high-above-band continuous wave excitation by a diode laser with a 4 μm wide pump spot.

The emission pattern of discrete trap modes reflects the planar energy-momentum dispersion when trap diameters are on the length scale of the particle's wavefunction, which is on the order of a few µm for cavity polaritons [10]. Representative energy-momentum dispersions from polariton modes are shown in figure 2 in false-color intensity profiles collected from a 10-, 2-, and 1-μm trap at 10 K [figures 2a–2c, respectively]. Discrete trap modes are indicated by colored boxes or dotted lines in the graphs. Additionally, background emission from the planar unpatterned system of the surrounding area is observed with the LP and UP dispersion (labeled 'Planar LP/UP'). While a polaritonic-like dispersion is formed by a number of discrete modes which appear for traps with a diameter of 10 μm [figure 2a], the 2- and 1-μm trap signal consist of few discrete modes with respective confinement blue shift in the spectral domain and delocalized features in k-space [figures 2b and 2c], representing the transition from shallow (10 μm) to strong (1 μm) confinement.

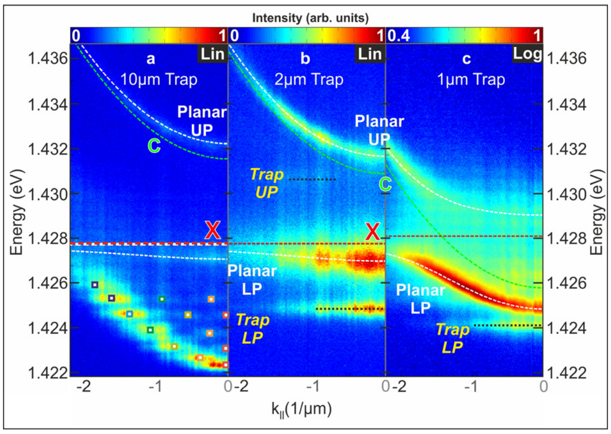

Figure 2: k-space resolved µPL from a (a) 10-μm, (b) 2-μm, and (c) 1-μm polariton trap [10]. Trap modes show quantization effects and are marked by (a) colored boxes and (b) and (c) dotted lines, while both planar polariton branches are detected as background emission. Calculated planar mode dispersions are plotted for the polariton branches (LP/UP, white), as well as for the uncoupled planar photon (C, green) and QW exciton (X, red) mode in dashed lines. The PL intensity in (c) is displayed in logarithmic scale for clarity.

The spectra in figures 2a and 2b were acquired for the same planar detuning $\Delta_{\text{planar}}(k_{||} = 0) = \Delta_{\text{planar}} = 3.7$ meV and are displayed in linear scale, while in figure 2c the detuning is $\Delta_{\text{planar}} = -2.5$ meV and the intensity is plotted with a logarithmic scale for clarity. In our system, the presented trap modes were brought close to resonance with the exciton mode at 1.4277 eV and the effective trap-mode detunings amounting to about −5 to 0 meV (10 μm) and about −2.5 meV (2 and 1 μm). More details about photoluminescence features of the sample can be found in Ref. 10.

4. Results and Discussion

The Zeeman splitting of polaritons has previously been studied in QW microcavities and its dependence on the cavity-exciton detuning identified [13,20]. It was demonstrated that Zeeman-split polaritons result from the independent coupling of left or right circular polarized photon modes with the spin-resolved exciton. Moreover, the magnitude of the splitting corresponded well to the excitonic amplitude of the polariton mode. By means of polarization optics (quarter wavelength plate and linear polarizer), the two polarization components of the Zeeman-split polaritons can be spectrally resolved.

We now examine the behavior of trapped polaritons in external magnetic fields of up to 5 T, which were applied to the sample in a superconducting magneto-cryostat in Faraday configuration, and analyze the magnetic response with respect to the excitonic amplitudes to prove a polaritonic nature of the trap emission [10]. For our QW microcavity system, we derive an exciton Zeeman splitting of ≈0.5 meV at 5 T from the experimental value of the planar LP Zeeman splitting of 0.35 meV for $|X|^2(5\text{ T}) \approx$ 70%. This is in strong agreement with an effective exciton splitting of 0.5 meV that was obtained from dispersion fits to $\sigma^{\pm}$ planar modes at given field and compares well with literature values for QWs with similar material composition and thickness [20,28].

Polaritons confined in 2-μm traps show a well-separated and discrete mode pattern due to a stronger confinement than for 10-μm traps [cf. figure 2 and Ref. 10], on the order of a few meV. In magnetic fields of up to 5 T, we observed both Zeeman splitting and a diamagnetic shift for these modes. We extracted line spectra from FF resolved spectra representing ground-state emission and assigned two observed modes in this spectral range to trap LP and planar LP, respectively, with the planar mode emitting at higher energy. Figure 3a shows $\sigma^{\pm}$ polarized spectra (solid/dashed) in a

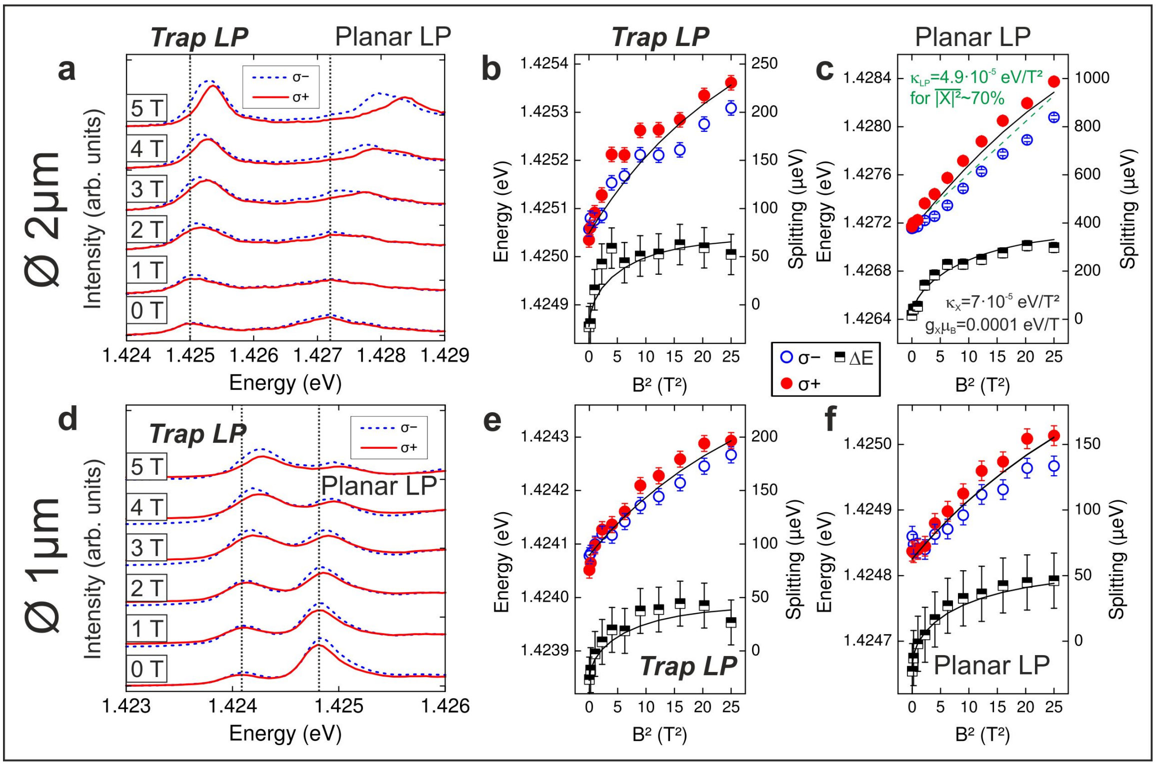

Figure 3: (a) Waterfall presentation of k=0 line spectra for a 2-μm trap mode. $\sigma^{\pm}$ polarized spectra of a magnetic field series are displayed from 0 to 5 T, while dotted vertical lines indicate mode energies at 0 T for guidance. $\sigma^{\pm}$ trap-mode and planar LP energies are plotted vs B^2 (left scale) in (b) and (c), respectively, with the experimental splittings of the modes (squares) shown in the same graphs (right scale) [10]. (d)–(f) represent the same information as in (a)–(c), respectively, for 1-μm trap µPL. Here, solid-line curves represent theoretical estimates, which match well with the experiment, taking into account the Hopfield coefficients at given B.

waterfall diagram for a magnetic field variation from 0 and 5 T, indicating a pronounced energy shift of 0.3/1.0 meV (trap/planar mode) with respect to the 0-T signal. Moreover, a Zeeman splitting of ~0.06/0.35 meV (trap/planar mode) at 5 T can be resolved.

Respective $\sigma^{\pm}$-mode energies are summarized in figures 3b and 3c. In these graphs, mode energies of the trap/planar signal are plotted vs B^2 to reveal the behavior of the shift in comparison to the expectations according to Eq. (1) weighted by corresponding $|X|^2(B)$. In figure 3c, the spectral shift of the planar LP with high excitonic content ($|X|^2(B) \approx 70\%$) shows the expected dependence as a function of the magnetic field. A green dashed line represents a mode shift according to Eq. (1) with diamagnetic coefficient of $\kappa_{LP} = 4.9 \times 10^{-5}$ eV/T^2. However, strong deviations from this characteristic are observed for the trapped LP in figure 3b. This feature can be attributed to a change of the cavity-exciton detuning as a function of the magnetic field, if assuming a linear shift of the QW exciton vs B^2. For LPs with $\Delta \geq 0$ meV, this effect is negligible, but becomes more significant for the LP at the system's transition from resonance ($\Delta \approx 0$ meV) to red detuning ($\Delta < -\hbar\Omega$) [10]. In between, the mixed state of photon and exciton asymptotically approaches the uncoupled photon energy which results in a change of the slope regarding the energy shift.

At 0 T, the detuning of the trap polariton amounts to −1.5meV, for which $|X|^2 \approx 30\%$, while at 5 T, the uncoupled exciton is blue shifted by ≈ 1.7−1.8 meV (with $\kappa_X \approx 7 \times 10^{-5}$ eV/T^2), resulting in a reduction of the excitonic fraction $|X|^2(5\ \mathrm{T}) \approx 19\%$. For theoretical estimations, a magnetic-field induced increase of the Rabi-splitting ($E_{\mathrm{Rabi}}(0\ \mathrm{T}) = 3.5$ meV) of ≈ 0.5−0.6 meV is also taken into account. Theoretical shifts and splittings for the 2-μm trap polariton of 0.30 and 0.08 meV, respectively, strongly agree with experimental data. Figure 3b displays the splitting $\Delta E_{\mathrm{ZS}} = E_{\sigma+} - E_{\sigma-}$ of the polarized modes in the same plot with reference to the right vertical scale. Here, we obtained an initial value of −0.02 meV (at 0 T^2), since the photonic character of the trapped polariton mode adds a polarization imposed splitting (here with negative sign) [10]. An applied magnetic field of ≈1 T compensated this feature by the Zeeman splitting. The expected splitting value at 5 T is thus in strong agreement, if taking this into account, with a thereby determined effective splitting of 0.08 meV.

Due to a detuning change, discussed above for the diamagnetic shift, the Zeeman splitting deviates from the expected linear dependence on the magnetic field with saturation at large fields, while the highly excitonic emission from the planar LP features a linear increase of the splitting according to Eq. (2). Our experimental results indicate that estimates for the diamagnetic shift and Zeeman splitting values need to be determined with respect to the effective Hopfield coefficients corresponding to the respective field B. Taking $|X|^2(B)$ into account, we achieved good congruence of our data with expected values (solid lines) for both energy shift and splitting, as shown in figures 3b and 3c.

In analogy to the 2-μm trap, we present a diamagnetic shift and Zeeman splitting for our 1-μm trap luminescence in figures 3d−3f, providing evidence of 0D polaritons. Energies of the polarized modes presented in figure 3e clearly reveal a diamagnetic shift and Zeeman splitting for the trapped LP with $|X|^2 \approx 15\%/11\%$ (0 T/5 T). Moreover, a good matching of model values with experimental data is again achieved in this study, when considering $|X|^2(B)$. Thus, the experiment proves that strong confinement of ~7.5 meV in polariton traps is feasible by gentle modulation of the cavity height in a planar Fabry-Pérot cavity system, without changing the basic features of exciton-polaritons.

5. Conclusions

In conclusion, we have probed exciton-polariton emission from photonic quantum boxes in a planar, single InGaAs QW microcavity for diameters of 1–10 µm with a strong confinement on the scale of a few meV. Moreover, we have investigated the emission properties of the system subject to an external magnetic field. A dependency of the trap-polaritons' diamagnetic shift and Zeeman splitting on their magnetic-field dependent excitonic fraction has clearly been observed in a magnetic field of up to 5 T, while a simple Hopfield coefficient model has allowed for good theoretical estimates for both Zeeman splitting and diamagnetic shift. Thereby, we have shown that the interaction of polaritons with an external magnetic field serves as a reliable tool to verify the polaritonic character of emission modes under strong confinement.

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