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Exciton-polariton laser diodes

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ABSTRACT

Despite their name polariton lasers do not rely on stimulated emission of cavity photons. The less stringent threshold conditions are the cause that bosonic polariton lasers can outperform standard lasers in terms of their threshold currents. The part-light and part-matter quasiparticles called polaritons, can undergo a condensation process into a common energy state. The radiated light from such a system shares many similarities with the light emitted from a conventional photon laser, even though the decay of the polaritons out of the finite lifetime cavity is a spontaneous process. We discuss properties of polariton condensates in GaAs based microcavities. The system's response to an external magnetic field is used as a reliable tool to distinguish between polariton laser and conventional photon laser. In particular, we will discuss the realization of an electrically pumped polariton laser, which manifests a major step towards the exploitation of polaritonic devices in the real world.

Keywords: Exciton-polaritons, Bose-Einstein condensate, microcavity, semiconductor laser

1. INTRODUCTION

Quantum well (QW) microcavity exciton-polaritons are quasiparticles in the strong light matter coupling regime inside a microcavity [1,2]. They are composite bosons, consisting of part-light and part-matter, combining properties

of both. Being bosonic quasiparticles, they can undergo a dynamical condensation above a critical particle density [3–5]. Condensation in a solid state environment is an interesting topic on its own sake, and a long sought after goal for decades in the solid state community. Compared to other candidates for condensation like ultra-cold atoms and uncoupled excitons, polaritons bear one major advantage: Due to the photonic part of the polaritons, their effective mass can be several orders of magnitude smaller than the electron mass [2], which relieves the requirements on sample temperature. Indeed, condensation of exciton-polaritons in microcavities has been observed up to the room temperature in appropriate material systems, such as high-bandgap semiconductors (GaN, ZnO) [6,7] or organic compounds [8]. Strong interactions of their excitonic parts lead to ground-state condensation via stimulated scattering. The condensate of polaritons is characterized by an off diagonal long range order (spatial coherence), it exhibits properties strongly related to superfluidity (frictionless flow) and the formation of vortices, vortex-pairs and solitons [9-10]. An additional degree of freedom is added to the system due to the exciton's spin. In particular, the exciton spin components can be Zeeman-split in the presence of a magnetic field, which again results in a strong modification of the light polarization emitted from the condensate. The full paramagnetic screening of this Zeeman-splitting (the so-called "spin-Meissner effect") has been predicted in 2006 [11], however its fully consistent and conclusive experimental evidence is still missing. This is most likely a result of the requirement for thermal equilibrium, which can hardly be satisfied in the polariton system as a result of the short lifetime. Nevertheless, several groups have reported strong non-linear effects in magneto-optical spectra of exciton-polaritons. Although full quenching of the Zeeman-splitting has been reported by Larionov et al. [12] and Walker et al. [13] the effect was accompanied by anomalies in the polarization of the polariton condensate, requiring an alternative interpretation of the observed behavior. As we will show in this article, we have carried out magneto-optical experiments on a microcavity sample in the presence of an external magnetic field under electrical pumping. We study the Zeeman-splitting, circular polarization degree and diamagnetic shift of the cavity polariton mode in the low excitation regime, polariton lasing regime and photon lasing regime above the Mott density.

The monochromatic and coherent light emitted from a polariton condensate by the leakage of photons from the cavity makes electrical injection an interesting asset. In contrast to stimulated emission in a weak coupling microcavity, fulfillment of the Bernard-Duraffourg condition (related to gain overtaking the absorption in semiconductor systems in a far out of equilibrium regime requiring the splitting of the quasi-Fermi levels in a diode) are relaxed in the polariton system, which directly points out the possibility to build a coherent light emitting device with a very low threshold [14].

Indeed, the basic capability of a polariton laser operating in the *strong coupling regime* to outperform a photon laser operating in the weak coupling regime has been indicated multiple times in optically pumped systems at cryogenic temperatures, including planar GaAs based microcavity samples [15,16] micropillar cavities [17], and photonic crystal polariton lasers [18]. To date, many milestone experiments towards the realization of functional electrically driven polariton devices were realized, including GaAs-based polariton light emitting diodes operating up to room temperature [19]. In this work, we extend these important accomplishments into the regime of polariton lasing. We can clearly discriminate our prototype device from a conventional VCSEL laser by studying its response to an applied magnetic field, yielding unambiguous evidence of the persistence of the strong coupling regime across the laser threshold.

This paper is organized as follows: Section 2 gives a description of the device fabrication technology and characterization procedure for electrically injected polariton devices. Section 3 focuses on the investigation of electrically generated polariton condensates in the presence of an external magnetic field. Conclusions are given in section 4.

2. DEVICE DESIGN AND CHARACTERIZATION

In this manuscript we present the results of studying condensation under electrical pumping of polaritons. All experiments were carried out in a Fourier-space micro-photoluminescence setup, similar to the one used by Lai et al. [20]. This allows us to directly extract the energy over k -dispersion of the polaritons. We use a $\lambda/4$ plate and a linear polarizer to select either the σ^+ - or σ^- polarized component of the emission.

Figure 1. a) Schematic cross section of a polariton diode. The distributed Bragg reflector (DBR) segments are doped by Si (n-type, bottom DBR) and C (p-type, upper DBR). Delta doped layers are added to improve the electrical properties. **b)** Schematic drawing of the polariton laser device designed for electrical pumping. The device is patterned into 20 μm diameter circles to avoid current spreading.

The sample for electrical injection of exciton-polaritons comprises a four-fold stack of 8 nm thick $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ QWs, separated by 6 nm thick GaAs barriers. The QWs are integrated into an undoped one λ -thick (281 nm) GaAs cavity layer. The cavity is centered between 23 and 27 GaAs (64 nm) / AlAs (71 nm) mirror pairs in the top and bottom DBR layers, respectively. The doping in the mirrors was symmetrically tapered from 1×10^{18} to $3 \times 10^{18} \text{ cm}^{-3}$ in both the n-type and p-type doped sections, as schematically indicated by the grey scale variation in Fig. 1b). In the topmost two p-type mirror pairs, the doping concentration was ramped up to a value of $2 \times 10^{19} \text{ cm}^{-3}$. Delta doped layers (sheet density: 10^{12} cm^{-2}) were included at every second interface in both the top and the bottom DBR section to improve the electrical properties of the devices. The epitaxial wafer was patterned into circular pillar structures with a diameter of 20 μm by reactive ion etching. After sample planarization by benzocyclobutene, ring-shaped p-contacts (Ti-Au) were evaporated at the upper facet of the pillars. The close stack of four InGaAs QWs guarantees a homogeneous vertical carrier injection into each QW. The n-contact on the backside of the wafer consists of a AuGe-Ni-Au alloy (200 nm/70nm/500nm).

The Q-factor of the devices was experimentally determined via optical spectroscopy to be 6300. This does not reach the empty cavity limit, which can have values in excess of 10000 also for doped structures with an equivalent amount of Bragg mirrors [21], but is, most likely, limited by the weak absorption tail of the QWs in the cavity.

3 ELECTRICALLY PUMPED POLARITON LASER

We will first discuss current dependent emission characteristics from the electrically driven device. Carriers are injected into the intrinsic cavity in the direct current (DC) mode, while the sample is held at a temperature of around 8K. In order to stabilize the excitons in the InGaAs QWs, we apply an external magnetic field of 5T.

Figure 2. a) Energy-momentum dispersion characteristics of a polariton laser diode driven under CW conditions at an applied magnetic field of 5T, in the linear regime. b) and c) the polariton laser regime and d) the weak coupling photon laser regime.

The detuning of the selected device amounts to $\Delta = \sim -6.4 \text{ meV}$, which is slightly larger than the Rabi-splitting of 6 meV. A quite negative detuning is chosen as the polariton laser threshold is reduced at negative detunings due to the accelerated dynamics of polariton scattering into the ground state. The corresponding energy-momentum dispersions are shown in Fig. 2a) for the linear regime with an applied current density of $j=31 \text{ A/cm}^2$, 2b) $j=60 \text{ A/cm}^2$ and c) $j=142 \text{ A/cm}^2$ for the polariton lasing regime and 2d) for the regime which we relate to weak coupling lasing with $j=260 \text{ A/cm}^2$. In the linear regime, the emission is dominated by a strong luminescence from finite k -values, the so called bottleneck. However, the shape of the dispersion changes dramatically once the first threshold is overcome: In Fig. 5b, most emission is recorded from the blue shifted energy ground-state, which indicates the onset of stimulated scattering in our device. The emission energy monotonously blueshifts (Fig 5c)) which is caused by exciton-exciton-interactions until a second transition is crossed when it reaches the energy of the uncoupled photon (Fig 5d)). In this regime, the emission is dominated by resolution limited narrow resonances of high brightness, as expected for a conventional microcavity laser diode.

The input-output characteristic of the device is shown in Fig. 3a). The intensity was extracted by integrating over a momentum range of $k = 0 \pm 0.1 \mu\text{m}^{-1}$. It features two pronounced non-linearities, corresponding to the qualitative transitions shown in the dispersions in Fig. 2. The first threshold corresponds with a current density of $j_{\text{th1}} = 58 \text{ A/cm}^2$, while the second transition sets in at $j_{\text{th2}} = 155 \text{ A/cm}^2$. When we trace the energy of the ground-state as a function of the excitation current (Fig. 3b), we observe a blueshift of the polariton resonance until the second threshold is reached. These features are all consistent with our assumption that the strong coupling regime is preserved across the first non-linearity of the input-output characteristic. In order to unambiguously prove this assumption, we perform polarization resolved investigations at various excitation powers. Just as quantum well excitons, microcavity polaritons can experience a Zeeman splitting when being subject to an external magnetic field. This characteristic Zeeman splitting is strongly sensitive to the excitonic fraction $|X|^2$ of the polaritons and persists in the polariton laser regime above a critical magnetic field B_{cr} [11, 12]:

$$\Delta E_{LP}(B, |X|^2) = E_{\sigma+} - E_{\sigma-} = |X|^2 g_x \mu_B (B - B_{\text{cr}})$$

Here, $g_x \mu_B$ is the product of the excitonic g -factor and the Bohr magneton. The polariton density dependence of the critical magnetic field results in a pump-power dependency of the Zeeman splitting, until a complete quenching should occur in the weak coupling regime where no excitonic component remains.

Figure 3. a) Input-output characteristics of the electrically pumped polariton diode, featuring two pronounced thresholds (recorded at 5T). b) Corresponding ground-state energy versus pump-current. The ground-state emission monotonously blueshifts until it pins to the bare cavity mode above the second threshold.

The waterfall diagram in Fig. 4a) shows polarization resolved spectra (σ_+ and σ_-) for varying excitation powers (all recorded at 5T). For the sake of visibility, each spectrum was normalized. The spectra which correspond to the two identified thresholds are indicated in the graph. In fact we reveal a persistence of the Zeeman-splitting of the emission feature across the first threshold, until the second threshold is crossed. The extracted values of the Zeeman-splitting as a function of the excitation power are plotted in Fig. 4b). Once the first threshold is crossed, the extracted values of the Zeeman splitting continuously decrease, which is most likely caused by an interplay of two effects: First, due to the continuous increase of B_{cr} with the density of polaritons, a reduction of the Zeeman splitting detected at the fixed magnetic field of 5T is expected (if the effective g-factor remains unaffected by the excitation power). Second, the transition into the weak coupling regime is continuous, and accompanied by a successive bleaching of excitons. This would, again, result in the decrease of Zeeman splitting due to the increasingly photonic nature of the mode which emits light.

Figure 4. a) Polarization resolved spectra at various injection currents. The continuous blueshift up to the second threshold, the linewidth narrowing above the first threshold and the persisting Zeeman-splitting beyond the first threshold is clearly seen in the data. b) Zeeman splitting dependence on the pump current density is an unambiguous prove of the polariton's hybrid nature.

4. CONCLUSION

We have demonstrated a first prototype of an electrically driven exciton-polariton laser [22]. In congruence with a report in [23] it features a characteristic double threshold, an emission blueshift beyond the first threshold followed by a stable emission energy beyond the second threshold. Most importantly, we could directly monitor the persistence of the strong coupling regime through the first threshold via the characteristic Zeeman-splitting of the ground-state emission. The characteristic behavior of the Zeeman splitting in a polariton laser is a smoking gun experiment for this lasing mode allowing to distinguish it from a standard vertical cavity emitting laser.

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