Polariton Laser Diodes

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Abstract: Exciton-polariton lasers are operated in the strong light matter coupling regime. They promise low threshold operation since population inversion is not inherently necessary. Hence they are of great interest for next generation coherent light sources.
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1. Introduction

Semiconductor diode lasers play a major role in everyday life in our information society. Coherent light is generated by stimulated emission in these structures, which relies on population inversion conditions far off thermal equilibrium. However, stimulated scattering of bosonic quasi particles formed from excitons and photons in a quantum well microcavity has been shown to lead to a macroscopic occupation of an energy ground-state close to thermal equilibrium in strongly coupled quantum well microcavities. This condensation phenomena is known as polariton lasing and it has been demonstrated up to room temperature in wide bandgap semiconductors and organic structures [1,2]. As the process of polariton lasing does not rely on strong out of equilibrium conditions, it can, in principle, occur at much lower powers compared to a conventional diode laser in the weak coupling regime, which explains the practical interest in polariton lasers [3].

We discuss ongoing efforts towards the realization of electrically pumped exciton-polariton lasers. In particular, we describe in detail the response of a polariton laser to an applied magnetic field, which we identify as a reliable tool to distinguish a polariton laser from a standard vertical cavity surface emitting laser (VCSEL).

2. Device Fabrication

The sample for electrical injection of exciton-polaritons was grown by molecular beam epitaxy on n-doped GaAs substrate and comprises a four-fold stack of 8 nm thick $In_{0.15}Ga0_{.85}As$ 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 $1x10^{18}$ to $3x10^{18}$ cm^{-3} in both the n-type and p-type doped sections, as schematically indicated by the grey scale variation in Fig. 1. In the topmost two p-type mirror pairs, the doping concentration was ramped up to a value of $2x10^{19}$ 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, and amounts up to 6300. This does not represent the empty cavity limit, which can have values in excess of 10000 also for doped structures with an equivalent amount of Bragg mirrors [4], but is, most likely, limited by the weak absorption tail of the QWs in the cavity.

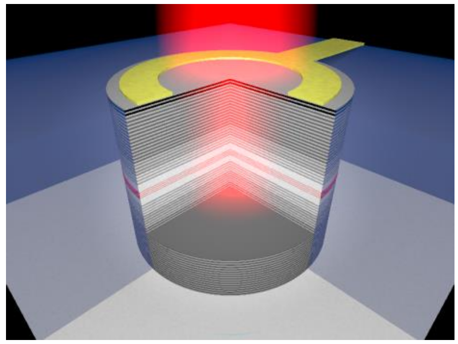

Fig 1. Sketch of the laser diode device. Highly doped regions correspond to darker gray shades.

3. Device characterization

We probe our microcavity polariton diode in the presence of a magnetic field (5T) at a cryogenic temperatures (10K), in order to suppress thermal ionization of excitons in the InGaAs QWs. The magnetic field further stabilizes the excitons and enhances their oscillator strength, leading to an increase of the Rabi-splitting in our device from 5.5 meV to 6.2 meV.

Fig. 2a) shows the recorded energy-momentum dispersion relation from the device below any nonlinearity. The emission follows the parabolic dispersion of the lower polariton branch and shows pronounced features at in plane momentums of 1.5 – 2 1/µm. This so called bottleneck is a result of a reduced relaxation dynamic via phonons and insufficient thermalization of the polaritons. Once a first threshold is crossed, the bottleneck disappears and the significant part of the emission comes out of the lowest energy state, which is slightly blueshifted as a consequence of the renormalization of the chemical potential as well as phase space filling effects. For larger injection currents, a second threshold can be crossed and the device enters the weak coupling regime, corresponding with the exciton Mott density in our device

In order to directly monitor the polaritonic origin of the microcavity emission between the two thresholds, we perform polarization resolved spectroscopy. We focus on left and right circularly polarized light emitted from the diode. As opposed to a standard VCSEL laser, the polariton diode is expected to show a pronounced response to the applied magnetic field resulting from the matter contribution.

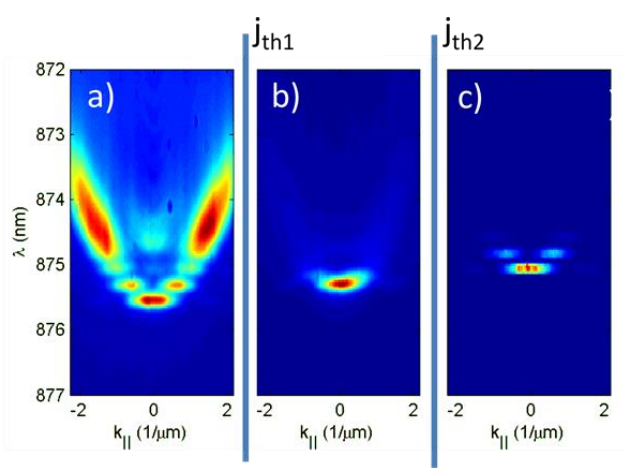

Fig. 2: Momentum resolved electroluminescence spectra of the micorcavity polariton light emitting diode. For low injection currents, the spectrum is features bright signals at finite in plane k-values, which disappear above a threshold (b). After a second transition (c) the emission stems from the uncoupled cavity mode, indicating the breakdown of strong coupling and the operation as a standard VCSEL

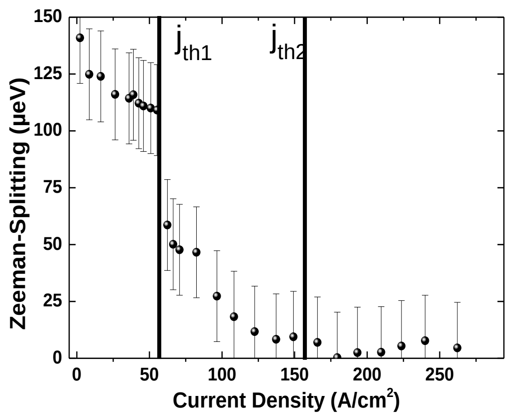

Fig. 3: Zeeman-Splitting as a function of the injected current density. The splitting persists between the two non-linearities, and directly reflects the polaritonic character of the emission.

In particular, polaritons originating from excitons, show a Zeeman-Splitting as both exciton spin components couple to the light field. The Zeeman-splitting of our device recorded at 5T is plotted as a function of the injection current in Fig. 3. We note a first reduction of the splitting above the first threshold, which we attribute spinor interactions in the diode. For increasing currents, the splitting persists until the second threshold and the transition to the weak coupling regime is crossed [5].

4. Acknowledgements

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5. Conclusion

We demonstrate that polartion lasing and condensation can be achieved under electrical current injection into a high Q GaAs based microcavity LED. The polariton laser is characterized by two distinct transitions or non-linearities, and features a strong response to applied magnetic fields.

6. References

[1] S. Christopoulos et al. "Room-temperature polariton lasing in semiconductor microcavities." Phys. Rev. Lett. 98, 126405. (2007).

[2] S. Kéna-Cohen, and S. R. Forrest. "Room-temperature polariton lasing in an organic single-crystal microcavity." Nature Photonics 4, pp. 371- 375 (2010).

[3] A. Imamoglu et al. “Nonequilibrium condensates and lasers without inversion: Exciton-polariton lasers”, Phys. Rev. A 33, pp. 4250- 4253 (1996).

[4] C. Kistner et al. "Demonstration of strong coupling via electro-optical tuning in high-quality systems." Optics Express 16, pp. 15006-15012 (2008).

[5] C. Schneider et al. "An electrically pumped polariton laser." Nature 497, pp. 348-352 (2013).