Universität Bremen

Prof. Dr. rer. nat. habil.
Frank Jahnke

Institute for Theoretical Physics

University of Bremen

P.O. Box 330 440
28334 Bremen, Germany

phone: +49 421-218 62050
fax: +49 421-218 98 62050

jahnke@itp.uni-bremen.de
www.itp.uni-bremen.de

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Universität Bremen, Fachbereich 01, Postfach 330 440, 28334 Bremen

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Dean of the Faculty of Physics,
University of Warsaw

Review of the Ph.D. thesis submitted by Tomasz Jakubczyk

"Effects of photonic confinement on the emission from CdTe quantum dots"

The thesis of Tomasz Jakubczyk addresses experimental investigations of CdTe quantum dots in optical microcavities. The confinement of carrier in all spatial directions by means of self-organized semiconductor quantum dots has received a lot of attention during the past decade. It leads to the realization of so-called artificial atoms with tailored emission properties, which are promising candidates as novel active material for various applications in optoelectronics. A combination of this carrier confinement with the three-dimensional confinement of the optical field in micro- and nano-resonators is of particularly strong interest in fundamental research, allowing for quantum optical effects in semiconductors, as well as for novel applications. In the center of these investigations is the effect that the photon confinement allows to change the spontaneous emission properties of the active material. With single quantum dots in microresonators, efficient nonclassical light sources can be realized. Other applications involve nanolasers with strongly reduced laser threshold or all-optical components for quantum information technologies. The research of Tomasz Jakubczyk is at the heart of these exciting developments. In the past, the majority of investigations have been concentrated on the well-developed GaAs material system, mostly due to high material quality and the availability of the corresponding technology. On the other hand, the GaAs material system is limited to the red and near infrared spectral range and many quantum-dot applications such as single-photon sources or storage and manipulation of quantum states require cryogenic temperatures. This has triggered a revival of the II-VI material system, which is known for its wide band gap covering emission in the green to orange spectral region. Furthermore, high material quality can be combined with large exciton binding energies. This promises many applications like single-photon emission up to room temperature. The prerequisites for these developments are the focus of the present thesis. The combination of CdTe/ZnTe quantum dots with photonic structures based on planar VCSELs has been used to fabricate micropillar resonators. The emission properties of these structures are characterized using an ensemble of quantum dots.

Subsequently single quantum-dot emission in combination with the three-dimensional photonic confinement has been investigated. The work is in the foremost front of investigations in this material system and meets very high standards.

The thesis is well organized and starts with a general introduction to cavity quantum electrodynamics as well as semiconductor nanostructures. All important physical concepts and the theoretical background are very well explained. The subsequent chapter reviews the material growth process and the used experimental methods, the growth of quantum dots, structural analysis techniques, as well as the fabrication of micropillars. With this chapter, Tomasz Jakubczyk demonstrates a profound knowledge in material science and its application to semiconductor nanostructures.

The first set of results in the present thesis involves spectroscopic investigations of the photonic structures. Photoluminescence and reflectivity measurements are used to characterize planar VCSEL structures and to determine cavity-quality Q-factors. Temperature tuning was used to differentiate QD emission lines and optical modes. Subsequently, micropillar resonators fabricated out of the planar structures are studied. Through a direct comparison with theoretical results for the solution of Maxwell's equations for the photonic structures with three-dimensional mode confinement it became possible to unambiguously identify the efficient photonic confinement in the fabricated samples. As a function of the pillar diameter, the shift of the fundamental mode, its Q-factor and the spacing of higher modes have been analyzed. Further evidence for the efficient three-dimensional mode-confinement is obtained from spatially resolved mode profiles, which are again identified in direct comparison with theoretical results.

A second set of investigations involves the demonstration of the Purcell effect in these samples, which requires time-resolved measurements of the photoluminescence decay. The lifetime shortening for quantum dots in resonance with the optical mode is unambiguously demonstrated and impressive values for the Purcell factor are obtained, which underline the high quality of the investigated samples and the carefully applied experimental characterization. The results include an interesting reduction of the photoluminescence intensity directly at resonance condition overlaying the general emission enhancement, as discussed in Section 5.4.2.

As a third topic, the thesis contains results on micropillars with additional radial distributed Bragg reflectors, which leads to inhibition of spontaneous emission due to radial modes. Inhibition factors of three are clearly identified as a proof of principle for this technologically challenging fabrication procedure. The results further underscore the potential inherent in this material system and the used fabrication and processing technology. The thesis concludes with interesting results on the growth of distributed Bragg reflectors on GaSb substrates, which includes HRXRD and optical characterization.

In summary, the work of Tomasz Jakubczyk in this thesis represents important progress in the fabrication and characterization of photonic structures with quantum-dots as active material on the basis of the CdTe/ZnTe material system. State-of-the-art results are obtained with time and frequency-resolved micro-photoluminescence experiments and its in-depth analysis. The thesis is largely based on the very successful collaboration of Tomasz Jakubczyk with the research teams in Warsaw and Bremen. He also collaborated efficiently with the University of

Leipzig and with the theorists in Bremen. The publication of parts of this work in international journals with high impact factor underscores the exceptional quality of this work. The thesis is very well formulated and fulfills all requirements for a dissertation. I strongly recommend the thesis to be admitted to a public defense.

Jahnke

(Prof. Dr. Frank Jahnke)