Preface

Worldwide, many researchers are fascinated from the rich physics of semiconductor quantum dots (QDs) and their high potential for applications in photonics and quantum information technology. QDs are nanometer-sized three-dimensional structures which confine electrons and holes in dimensions of their corresponding De Broglie wavelength. As a result, the energy levels are quantized and for that reason they are also often referred as artificial atoms. Epitaxially grown QDs which are the subject of this book are embedded in a solid state semiconductor matrix and their size, shape, composition, and location can be tailored to a large extent by modern growth techniques. In QDs, excitations can involve more than a single carrier and interaction among the carriers modify or even dominate the emission properties. Therefore, a simple two-level description is only appropriate under certain well defined experimental conditions. Tremendous progress has been obtained in understanding their electronic, optical and spin properties mainly by performing single dot spectroscopy and using appropriate theoretical models.

Spectacular achievements within the last years include the generation of triggered polarization-entangled photon pairs, reaching the strong-coupling regime of interaction between a single quantum dot and a photonic cavity, controlling cavity reflectivity with a single quantum dot, coherent optical manipulation of single electron spins in quantum dots, and controlling the quantum coupling in quantum dot molecules. The progress has been tightly linked to the improvements in growth and nanoprocessing which has allowed the fabrication of micro and nanocavities with high quality factors and ultra-low mode volumes, and to produce quantum dots with radiative efficiencies close to unity. The full advantage of their superior properties can be utilized in the future if a scalable deterministic technology for the spatial and spectral matching of the quantum dot with respect to the device structure can be realized. This includes, e.g., the positioning of the QD with respect to a cavity structure and a macroscopic periphery. This task is still a challenge although recent progress has been made on growing quantum dots on predefined positions or by forming cavities around selected quantum dots.

Exciting applications are compact and robust single and entangled photon sources with ultra-high repetition rates, quantum storage devices, and basic building blocks for, e.g., spin-based quantum information implementations. In addition, high density quantum dot systems are appealing for classical optoelectronic applications such as low-threshold lasers, ultra-fast amplifiers and modulators, and sensitive detectors.

The book is organized as follows: Readers will find an introduction into a microscopic theory to describe luminescence and lasing from semiconductor quantum dots in the contribution from *Christopher Gies, Jan Wiersig, and Frank Jahnke* (Chap. 1). Especially, the first- and second-order correlation functions to characterize the coherence properties and the photon statistics in microcavity lasers with high spontaneous emission coupling into the laser mode are discussed in detail. Special emphasis is placed on the differences between quantum dots and atoms.

Armando Rastelli, Suwit Kiravittaya, and Oliver Schmidt give an overview on the different methods to fabricate optically active quantum dots (Chap. 2). Bottom-up methods based on self-assembled growth, top-down lithographic techniques, and a combination of them are discussed in detail in their contribution. They show a promising route to fabricate QDs with well defined spatial and spectral properties required for scalable devices.

The fascinating optical, electronic, and magnetic properties of wide bandgap semiconductor single quantum dots based on II–VI and group III-nitrides are presented by *Gerd Bacher and Tilmar Kümmell*. Coherent state control, stimulated biexciton emission in individual quantum dots, and room temperature electroluminescence is achieved and superradiance in quantum dot ensembles is also discussed. They further show that a single spin state of an individual magnetic atom in a solid state matrix can be addressed.

Chapters 4 and 5 deal with electron and nuclear spin effects in quantum dots. *Manfred Bayer, Alex Greilich, and Dmitri R. Yakovlev* discuss the coherent spin dynamics of electrons confined in semiconductor quantum dots. To study their spin dynamic circular polarized laser excitation is used to orient the spins and their subsequent coherent precession about an external magnetic field is detected by a Faraday rotation technique. They demonstrate that a spin ensemble can be synchronized by and with a periodic train of laser pulses. In this way a locking of several electron spin precession modes is achieved. *Patrick Maletinsky and Atac Imamoglu* review optical investigations of nuclear spin effects in individual, self-assembled QDs. The coupled electron–nuclear spin system is studied by optically induced dynamical nuclear spin polarization (DNSP) in detail. Especially, time-resolved measurements of DNSP, both in low and in high external magnetic fields are presented and the dominant nuclear spin relaxation mechanisms are identified.

The topic of Chaps. 6 and 7 is on nonclassical light generation. The contribution on quantum dot single-photon sources is written by *myself* where I briefly recall basic concepts of the quantum optical properties of QDs and review the recent progress in this rapidly evolving and fascinating field. New generations of electrically driven single-photon LEDs, new developments on coherent state preparation and single-photon emission in the strong coupling regime are reviewed. The remaining challenges for practical single-photon sources are also discussed. *Andrew Shields, R. Mark Stevenson, and Robert J. Young* describe recent progress in generating pairs of polarization-entangled photons from the biexciton–exciton cascade in single QDs. The biexciton emission is analyzed in the general case of finite fine-structure splitting in the intermediate exciton state of the cascade. A model to describe the factors limiting the fidelity is presented.

Cavity electrodynamics experiments with single dots in high quality micropillar cavities and photonic crystal cavities are discussed in Chaps. 8 and 9. Important aspects in the growth and patterning of quantum dot–micropillar cavities are addressed by *Stefan Reitzenstein and Alfred Forchel*. Especially, the demonstration of the quantum nature in a strongly coupled quantum dot–micropillar system as well as coherent photonic coupling of QDs mediated by the strong light field in high quality micropillar cavities are presented. *Dirk Englund, Andrei Faraon, Ilya Fushman, Bryan Ellis, and Jelena Vučković* discuss quantum dot-embedded photonic crystal devices for classical and quantum information processing. This includes high-speed, low-power lasing dynamics and carrier-induced switching in photonic crystals for classical applications. For quantum information applications, weak and strong coupling regimes are demonstrated and a newly developed technique for coherent dipole access in cavity (CODAC) is introduced.

Chapter 10 is dealing with the physics of coupled quantum dot structures. *Matthew F. Doty, Michael Scheibner, Allan S. Bracker, and Daniel Gammmon* review experimentally measured spectra of coupled quantum dots and explain the interactions that give rise to the spin fine structure. They discuss the formation of molecular states through tunnel coupling of electron and holes and explain resonant changes in the single-spin g factor for holes in the molecular states of coupled quantum dots.

The last chapter of this book reports on applications of single photon sources based on semiconductor QDs to quantum information processing. *Matthias Scholz, Thomas Aichele, and Oliver Benson* give a brief review of the quantum optical properties of quantum dots and introduce free space and fiber-based quantum cryptography experiments. In addition, a first demonstration along linear optics quantum computation is given in their contribution.

Finally, I would like to thank all my colleagues for writing the various chapters and for spending much of their free time for our common book. Very special thanks to my family for their unconditional support and the appreciation for my absence during numerous weekends.

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