HL 70: Quantum Dots and Wires: Theory

Time: Thursday 10:15–13:45 Location: POT 151

HL 70.1 Thu 10:15 POT 151

Lasing and transport properties in a coupled dot-resonator system — •Peiqing Jin, Michael Marthaler, Jared Cole, and Gerd Schön — Institut für Theoretische Festkörperphysik, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany

The study of the interaction between light and matter at the quantum level is of great interest for quantum information. We investigate a system consisting of double quantum dots coupled to an electrical resonator. A pumping scheme induced by the incoherent tunneling between electrodes and dots is considered. For small tunneling rates, the system reaches the non-classical regime where the radiation field exhibits sub-Poissonian statistics. In this regime, the peak of the current through the double dots, which appears at resonance, is almost the same at charge resonance.

The spin degree of freedom is involved when an external magnetic field is present. The difference between the effective magnetic fields provided by nuclear spins in each dot leads to an asymmetry between the two spin channels. Different behavior of the radiation field at the resonance of each spin channel is discussed.

HL 70.2 Thu 10:30 POT 151

Electronic properties of (111)-grown InGaAs/GaAs quantum dots — •Oliver Marquardt and Eoin O'Reilly — Tyndall National Institute, Lee Maltings, Cork, Ireland

InGaAs-QDs grown along the (111)-axis in GaAs exhibit electronic properties that are excellently suited to the generation of single and entangled photons, as required for quantum cryptography or quantum computing purposes.

We employ an eight-band $\mathbf{k}\cdot\mathbf{p}$ model to provide a theoretical study of these nanostructures. Strain and polarisation potentials that modify the bulk electronic properties of the system are calculated using second-order continuum elasticity theory. Moreover, we have taken second-order piezoelectric contributions into account in our calculations of the polarisation potential.

Our studies reveal that, for the case of (111)-grown zincblende InGaAs/GaAs quantum dots, second-order piezoelectric contributions have a significant influence on electron and hole eigenenergies and charge densities. In particular, such second-order contributions are found to significantly reduce the resulting polarisation potentials in comparison to potentials obtained from using only the first-oder piezoelectric constants. This reduction of the piezoelectric potential allows for better electron-hole overlap and thus higher recombination rates and is in much better agreement with recent experimental observations than calculations employing first-order piezoelectric constants only.

HL 70.3 Thu 10:45 POT 151

Spin blockade in the optical response of a charged quantum dot — •Eleftheria Kavousanaki and Guido Burkard — Department of Physics, University of Konstanz, Germany

We theoretically model the population dynamics in a semiconductor quantum dot charged with a single electron in an optical pump-probe setup when the two lowest quantum dot levels are photoexcited. We calculate the differential transmission spectrum as a function of the time delay between the two circularly polarized optical pulses by using a density matrix formalism and treating intraband relaxation with the Lindblad equation. Taking into account both spin conserving and spin-flip relaxation processes we investigate the possibility for spin-dependent blocking of intraband relaxation due to the presence of the ground state electron for zero and finite magnetic fields. We show that the differential transmission spectrum is initially dominated by the fast spin-conserving mechanism before the slower spin-flip processes start to contribute at longer time scales. As a consequence of spin conservation for short time scales, we find a spin blockade effect in the optical recombination process.

HL 70.4 Thu 11:00 POT 151

Monitoring the switching of a Mn spin in a quantum dot by optical signals — •Doris E. Reiter[1], Vollrath Martin Axt[2], and Tilmann Kuhn[1] — [1]Institut für Festkörpertheorie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster — [2]Theoretische Physik III, Universität Bayreuth, 95440 Bayreuth

When a single Mn atom is embedded in a single quantum dot, in the photoluminescence spectrum the exciton line splits into a set of six lines even at zero magnetic field due to the strong exchange interaction between exciton and Mn spin. Each line corresponds to one of the six Mn spin states, such that if the Mn spin is in an eigenstate only a single line with a given spectral position appears. Recently we proposed a protocol to optically switch the Mn spin from a given initial state into all other states using a sequence of laser pulses [PRL **102**, 177403 (2009)]. To monitor the dynamics of the Mn spin state we here propose a pump-probe set-up, for which we calculate the optical signals. For the switching steps during the protocol different signatures in the spectrum appear and most remarkably the spectral position of the line in the probe spectrum shifts according to the Mn spin state. With a modified switching protocol superpositions of different Mn spin states can be generated. In the probe spectrum now instead of a single line two lines at the spectral position of the involved Mn spin states show up, while the line strengths correspond to the weights of the superposition. In this contribution we show how the Mn spin dynamics can be deduced from the optical signals.

HL 70.5 Thu 11:15 POT 151

Theory of exciton fine structure in cubic semiconductor quantum dots — •Erik Welander and Guido Burkard — Department of Physics, University of Konstanz, Konstanz, Germany

We theoretically investigate the radiative recombination of biexcitons in semiconductor quantum dots. The biexciton recombines via one out of two possible intermediate exciton states, causing two linearly photons to be emitted, $|X\rangle|Y\rangle$ or $|Y\rangle|X\rangle$. The order in which the photons are emitted depends on which exciton, $|X\rangle$ or $|Y\rangle$, mediates the recombination (which-way). If the intermediate state is energetically degenerate, a coherent superposition of the two double-photon states is possible, $(|X\rangle|Y\rangle+|Y\rangle|X\rangle)/\sqrt{2}$. This allows the biexciton cascade recombination to produce entangled photon pairs. The geometry dependent electron-hole exchange interaction is known to remove the degeneracy of the intermediate exciton states. Since the polarization of the light then would be entangled with the photon energy, the which-path information would be available via frequency measurements and thus the creation of polarization entangled photons would no longer be possible. We develop a model for the quantum dot exciton fine-structure and its dependence on geometry. The emerging photon states are studied and explicit results are presented for a spatially asymmetric, harmonically confined GaAs quantum dot surrounded by AlAs. Moreover, we examine the possibility of restoring the degeneracy by applying external electric and/or magnetic fields.

HL 70.6 Thu 11:30 POT 151

Interrelation of Biexciton Binding Energies and Structural Properties of GaN/AlN Quantum Dots — •Gerald Hönig, Christian Kindel, Momme Winkelnkemper, Andrei Schliwa, Sven Rodt, Irina Ostapenko, Axel Hoffmann, and Dieter Bimberg — Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany

Nitride-based quantum dots (QDs) are very promising candidates for high-temperature stable, entangled photon pair emitters. Tuning the biexciton energy (E^{xx}) by varying structural parameters [1] is of largest importance for QDs in microcavities, where the emission has to match the cavity-mode. The experimental observation of a sign change of the biexciton binding energy ($E^{bind} := 2E^{x} - E^{xx}$, with E^{x} := exciton energy) in GaN/AlN QDs [2], is theoretically not understood so far. We are able to investigate this feature by using a configuration interaction scheme (CI) based on self-consistent 8-band-$k\cdot p$ Hartree-Fock (HF) states. The self-consistency is crucial since built-in piezo- and pyroelectric fields (on the order of MV/cm) cause a spatial separation between electrons and holes within nitride-based QDs, making a CI basis of renormalised HF states superior to single particle wave functions. We take a close look on different structural parameters influencing E^{xx} as well as the quantity of correlation effects in GaN/AlN QDs. Both, positive and negative biexciton binding energies are possible for respective QD structures. Funded by SFB 787.

[1] A. Schliwa, et al., Phys. Rev. B 79, 075443 (2009)
[2] D. Simeonov, et al., Phys. Rev. B 77, 075306 (2008)

HL 70.7 Thu 11:45 POT 151

Carrier multiplication in quantum dots: Quantum optical emission dynamics — •Franz Schulze, Sandra Cecilia Kuhn, Andreas Knorr, and Carsten Weber — Institut f. Theoretische Physik, Technische Universität Berlin, Germany

Measurements of carrier multiplication in quantum dots based on excitonic and multiexcitonic decay dynamics [1] show potential for its utilization in photovoltaic conversion, but also contradicting results. Theoretical treatments of the process are typically based on stationary methods or simple Bloch equation approaches [2]. As a more fundamental approach to an unambiguous signal of carrier multiplication, we present a microscopically derived dynamical model of carrier multiplication in a single quantum dot. Within this model a time resolved quantum optical emission spectrum is investigated, which shows a behaviour characteristic of the carrier multiplication dynamics observed in the purely electronic system. Different paths in the electronic system leading from an initial optical excitation to the creation of multiple carriers are discussed.

[1] R. D. Schaller and V. I. Klimov, Phys. Rev. Lett. **92**, 186601 (2004)
[2] A. Shabaev, A. L. Efros, and A. J. Nozik, Nano Lett. **6**, 2856 (2006)

15 min. break

HL 70.8 Thu 12:15 POT 151

Reduction of the modulation bandwidth for high carrier scattering in semiconductor QD based laser devices — •Michael Lorke, Torben R. Nielsen, and Jesper Mørk — DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

Semiconductor lasers are central components of current optical technologies such as optical data storage and optical communications. To meet the continuously increasing need for progressively higher data transmission rates, a high modulation bandwidth of the underlying semiconductor device is required. The combination of quantum dots (QDs) with high-quality cavities, e.g. realized by photonic crystals, opens a multitude of possibilities for guiding and modifying the emission properties of QD-based devices via the Purcell effect.

We apply a microscopic theory to study dynamical properties of QD based nanocavity devices. Application relevant quantities such the modulation bandwidth as well as fundamental properties such as the laser linewidth and switch-on behavior are determined consistently from a microscopic semiconductor approach. Our theory predicts a reduction of the modulation bandwidth at high scattering rate allowing for optimization of QD based nanocavity devices. This behavior arises from a delicate balancing of the emission time and the photon lifetime in the cavity, as both the relaxation oscillation frequency and the damping of the relaxation oscillations grow with faster scattering.

HL 70.9 Thu 12:30 POT 151

Exciton fine structure splitting in self-assembled semiconductor QDs: Intrinsic and extrinsic effects — •Ranber Singh and Gabriel Bester — Max-Planck-Institut f\"{u}r Festk\"{o}rperforschung, Heisenbergstrasse 1, 70569 Stuttgart, Germany

There are ongoing efforts to understand excitonic fine structure splitting (FSS) in self-assembled strained (InGaAs/GaAs) and unstrained (GaAs/AlGaAs) quantum dots (QDs). We investigate the excitonic FSS in InGaAs/GaAs and GaAs/AlGaAs QDs of different shapes and sizes using the atomistic pseudopotential approach. We consider the effects of the growth direction, alloy ordering, charged point defects and uniaxial strain. We find that the growth direction, alloy ordering and uniaxial strain affect the FSS quite significantly. However, charged point defects have a rather small effect on the FSS. We obtain a large FSS in small QDs, when the single particle wavefunctions of electrons and/or holes spread into the interface regions between the QD and the barrier. In such a case a small elongation along [110] or [1$\bar{1}$0] in the circular QD base increases the FSS quite significantly. However, if the QD is large enough (which represents the "conventional" case) so that S single particle wavefunctions of electrons and holes are well confined in the center region of the QD, the elongation of the QD has a marginal effect on the FSS.

HL 70.10 Thu 12:45 POT 151

Semiconductor theory for single quantum dot emitters — •Matthias Florian[1], Paul Gartner[1,2], Christopher Gies[1], and Frank Jahnke[1] — [1]Institute for Theoretical Physics, University of Bremen, Germany — [2]National Institute of Materials Physics, Bucharest-Magurele, Romania

The controlled interaction of a single quantum-dot (QD) emitter with a single mode of the confined electromagnetic field is one of the recent remarkable achievements in cavity quantum-electrodynamics. The discrete level structure of QDs and the similarity to atomic systems has been widely used by invoking atomic models to describe QD-systems. But QDs are significantly different due to multiple carriers in the system and a reduced configuration interaction strength. This leads to several configurations, which are energetically close by and involved in the same interaction process. Moreover, typical excitation of carriers in the continuum states of the wetting layer or barrier material can introduce excitation-induced screening and dephasing. To analyze the quantum-mechanical interaction processes, we propose a microscopic theory based on a direct numerical solution of the von-Neumann equation for the coupled carrier-photon system. The Coulomb interaction as well as carrier scattering and dephasing processes are included and their influence on the statistical properties of the emitted photons like coherence, antibunching, and quenching are discussed.

HL 70.11 Thu 13:00 POT 151

Nonclassical light and stimulated emission in the strong coupling regime for single-quantum dot lasers — •Christopher Gies, Kolja Schuh, Matthias Florian, and Frank Jahnke — Institute for Theoretical Physics, University of Bremen, Germany

With a single quantum dot (QD) emitter in a high-quality cavity, the ultimate limit of miniaturization for a semiconductor laser has been reached and new physical effects emerge. Recent experiments on single-QD lasers exhibit an s-shaped input/output curve known from ensemble-based lasers. Also surprising is the transition from photon antibunching to bunching in the laser threshold region before coherent emission is reached. We present a microscopic theory and explain both effects in terms of competing contributions from multi-exciton states that start to contribute at elevated pumping conditions. Excitation-induced dephasing and screening facilitate the off-resonant coupling of multi-exciton transitions. Furthermore, we study stimulated emission in the presence of strong coupling. With increasing pump we can identify signatures of higher rungs of the Jaynes-Cummings ladder in the emission spectrum before excitation-induced dephasing carries the system into the weak coupling regime.

HL 70.12 Thu 13:15 POT 151

Microscopic description of the dynamics of luminescence and dephasing of semiconductor quantum dots — •Heinrich A.M. Leymann[1], Matthias Florian[2], Jan Wiersig[1], and Frank Jahnke[2] — [1]Institut für Theoretische Physik, Universität Magdeburg, 39016 Magdeburg — [2]Institut für Theoretische Physik, Universität Bremen, 28334 Bremen

Semiconductor quantum dots (QDs) are of considerable interest due to their potential for device applications such as lasers and non-classical light sources, as well as fundamental studies.

We present a microscopic theory for the photoluminescence of QDs based on an equation of motion technique. The influence of Coulomb- and carrier-photon interaction will be discussed in terms of correlation functions. A consistent treatment of pumping, scattering and dephasing will be presented that extends the cluster-expansion technique used in [1].

Furthermore results for a single QD emitter coupled to a single cavity mode will be discussed and compared to direct solutions of the von-Neumann equation of the statistical operator, showing excellent agreement.

[1] N. Baer et al., Eur. Phys. J. B 50 411 (2006).

HL 70.13 Thu 13:30 POT 151

Influence of LO-phonon collisions on robust adiabatic passage in semiconductor quantum dots — •Kolja Schuh[1], Michael Lorke[2], and Frank Jahnke[1] — [1]Institute for Theoretical Physics, University of Bremen, Germany — [2]DTU Fotonik, Department of Photonics Enginering, Technical University of Denmark

While Rabi-oscillations can be used to invert a system with a resonant optical pulse, the inversion is very sensitive to pulse parameters like frequency and pulse area. An inversion can also be achieved via an adiabatic passage using a chirped optical pulse. In contrast to a resonant pulse, this inversion is robust over a large parameter scale.

The influence of LO-phonon collisions on robust adiabatic passage in self-assembled semiconductor quantum-dot (QD) systems is analyzed within a quantum-kinetic many-body theory including non-Markovian effects and quasi-particle properties [1]. For QD states the effective LO-phonon coupling is enhanced leading to pronounced dephasing as well as fast carrier scattering processes even in low polar semiconductors.

Numerical results are presented for different InGaAs QD systems including wetting layer contributions. While inversion can be achieved in QD systems with slow dephasing by a pulse length of several ps, this is not possible for systems with fast dephasing and scattering. Achieving inversion in such dots requires a tradeoff between keeping the adiabatic regime and minimizing dephasing and carrier scattering by short and strongly chirped pulses.

[1] K. Schuh et al., APL 94, 201108 (2009).