Quantum Light Emission From Cavity Enhanced LEDs

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I. INTRODUCTION

A particularly promising approach to realize optoelectronic devices based on semiconductor nanostructures are quantum dots coupled to an optical microcavity. Those quantum dot based light emitters are ideal sources for deterministic quantum light emission with tunable photon statistics [2], [3]. In this contribution, we focus on the theory of InAs/GaAs quantum dots (QDs) embedded in a two dimensional wetting layer (WL), cf. Fig.1 [4], [5]. To simulate realistic operating points for devices, the interactions between electrons and holes confined in the QDs and the wetting layer must be taken into account. Therefore, we include Coulomb interaction in the emission process as well as electron-phonon coupling, considering multi-phonon processes based on an effective multiphonon Hamilton operator to calculate the quantum light emission on a microscopical level [6]. Here, we focus on the dynamics at low carrier densities, e. g. single photon emitter limit.

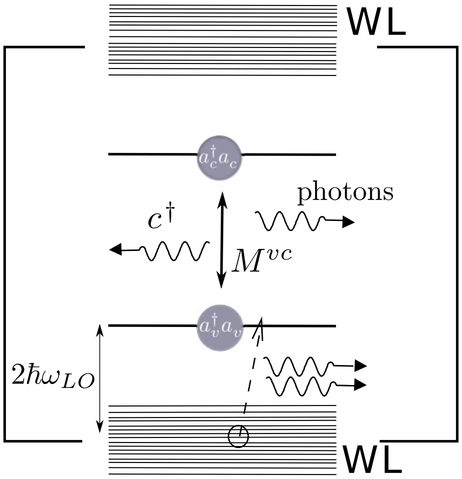

Fig. 1. (a): Full semiconductor QD cavity-QED. Carriers scatter from the WL state into the QD state via multiphonon processes.

II. MULTI-PHONON RELAXATION TIMES

Via electrical injection, carriers populate the bulk and WL material and fill the QDs via multi-phonon processes, cf. Fig. 1(a). In GaAs, the energy gap between wetting layer hole and quantum dot hole states can typically be bridged via the emission of two LO-phonons. In Fig. 2 (a) and (b), relaxation times from the WL into the QD state for different carrier densities in the WL and temperatures of the LO-phonon bath are depicted: (a) from 0 K to 200 K and (b) from 200 K to 600 K. The temperature dependence corresponds to the temperature dependence of the square of the Bose-Einstein-distribution function. The relaxation times are calculated within a higher order Markovian approximation, assuming the whole process is energy conserving [6]. The intermediate processes can violate the energy conservation but are more probable as they approach energy conservation.

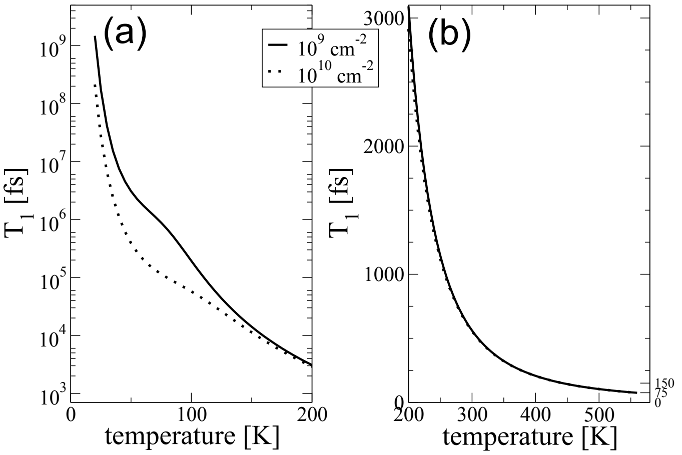

Fig. 2. (a) and (b): relaxation times from the WL into the QD state for different carrier densities in the WL and temperatures of the LO-phonon bath.

III. CARRIER HEATING IN THE WETTING LAYER

Due to the interplay of permanent current injection into the structure and the spontaneous emission removing carriers, the WL carrier distribution is not in equilibrium. A quasi-temperature can be defined, since the real distribution deviates only slightly from the Fermi-Dirac distribution, cf. Fig 2 (a). Investigating this carrier quasi-temperature, we predict a substantial carrier heating in semiconductor based LEDs at low electrical pump currents, cf. Fig. 2(b): The QDs act as a sink for cold carriers, around the Γ-point of the bandstructure [7]. The heating is a result from a decreased number of cold carriers in the WL. Cold carriers scatter fastly into the QD states and the effective temperature rises. On the other hand, increasing current leads to an accumulation of cold carriers

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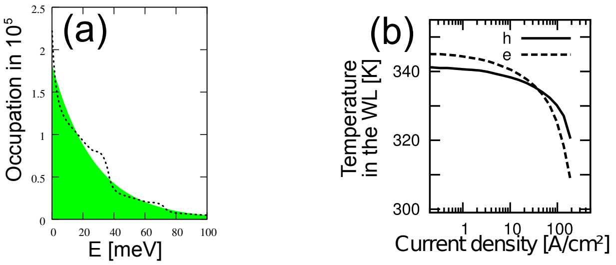

Fig. 3. Carrier dynamics within the WL. (a): a quasi-temperature (dashed) is approximated via a Fermi-Dirac distribtion (shaded). (b) the quasi-temperatures drops for increasing current density.

within the WL and the quasi-temperatures drops, as long as the scattering rate from the WL states into the QD is constant.

IV. QUANTUM LIGHT EMISSION

In the QD, electrons and holes recombine and photons are emitted. If a single-photon emitter is realized [2], [3], the electron and photon dynamics are strongly correlated. Perturbational approaches, such as cluster expansion [8], break down. These systems become accessible within the photon-probability-cluster-expansion [9]: a reliable approach for few photon dynamics in many body electron systems. Observables of interest are expanded in terms of the photon probability to reduce the calculation complexity and to resolve dynamically, how the photon-statistics of the quantum light emission is formed in the emission process.

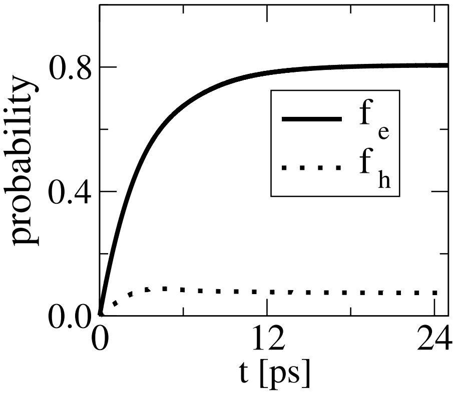

Fig. 4. A single photon emitter is pumped via in- and outscattering of WL carriers assisted by multiphonon processes. Losses and pump mechanism balance out and a steady state condition results: the electron and hole density.

The intensity-intensity correlation function $g^{(2)}$ depends on the electron $f_e(t)$ and hole $f_h(t)$ dynamics inside the QD. Via electronic pump mechanism, it is possible to steer the photon-statistics of the output field, or via LO-phonon scattering, dominant in the low-density limit. In Fig. 4 and 5, the pumping mechanism is included via the multiphonon scattering rates. They strongly depend on the temperature of the LO-phonon bath and the carrier density in the WL. In Fig. 4, the dynamics of the electron and hole densities are plotted. Initially, the QD is unpopulated and the inscattering dominates. Valence und conduction bands are populated, until electron and hole recombine. At the same time, after 8 ps, a photon density is built up and a stationary state is reached, since dephasing and pump mechanisms balance out. An intensity-intensity correlation occurs and the intensity-correlation function $g^{(2)}$ indicates the photon-statistics of the quantum light emission, cf. Fig. 5. Here, with given GaAs-parameter and in dependence on the temperature and the WL carrier-density, a single-photon emitting device is realized, operating in a steady state condition.

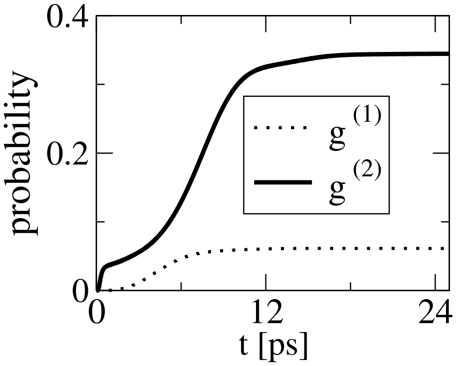

Fig. 5. Photon density and the intensity-intensity correlation function indicating antibunching.

V. CONCLUSION

We propose further experimental and theoretical investigations of optical devices in the single-photon limit and present a theoretical framework to study parameter dependent quantum light emission in semiconductor environments.

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