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Summary

Cavity quantum electrodynamics with quantum dots in microcavities

Paths towards the implementation of quantum computing are currently being explored using a variety of physical systems. In this thesis I report on my study of a viable route towards this goal utilizing quantum dots embedded in optical microcavities. A quantum dot is a semiconductor based system which, when realized in the center of an optical microcavity, can be used to exploit the quantum nature of matter-light interaction to manipulate and readout a single qubit in the form of a confined electron spin. This thesis can be read as a complete story, starting with an introduction of the theoretical prerequisites followed by an overview of the experimental apparatus. The remaining six chapters describe the research undertaken that demonstrates that this is a viable path to follow.

Chapter one introduces the big picture and long-term visionary goal that this thesis is part of. It is followed by a brief introduction to the general concepts fundamental to this field of research. These are quantum dots and microcavities, forming the physical system explored, and cavity quantum electrodynamics, the theoretical language used to describe their interaction. The main focus of the theoretical description is the treatment of the strong and weak coupling regimes that are both addressed experimentally in this thesis. The weak coupling regime is of particular relevance for my experiments.

In chapter two we present the experimental apparatus that has been developed to carry out the experiments. First, we outline the general scheme of the standard setup which includes the optical elements and the cryostat. Modifications and extended configurations for specific experiments are presented in each chapter. As we used a variety of laser sources and detectors, a summary is provided. A substantial amount of work has been spent on the customization and optimization of the cryostat. This has been accounted for by providing additional technical information in appendix A.

A detailed understanding of the physical structure and the optical mode composition in oxide-apertured micropillar cavities is presented in chapter three. A propagation model is developed to explain the frequencies of the transverse modes. The validity of the model as a first approximation is confirmed by experimental measurements. For this purpose we introduce a technique that allows us to record mode profiles with high spatial resolution, an important tool for subsequent experiments. The experimental characterization of the optical modes provides insight into the refractive index distribution of the central cavity region. We find a super-linear distribution of the confined modes that is caused by the shape and properties of the oxide-aperture. The relation between spectral mode splitting and the Purcell factor is discussed.

For a successful implementation of quantum information processing with quantum dots in micropillar cavities the cavity has to be polarization degenerate, and the emission of the QD transition frequency has to match the cavity resonance. Chapter four presents tuning mechanisms that have been developed in order to meet those two requirements. Both tuning methods are based on inducing surface defects that locally alter the strain of the sample. This permanent tailoring method is presented in two parts. First, tuning of the cavity birefringence is explained with the aim of achieving polarization degeneracy. Secondly, the QD transition is tuned to resonate with the transition of a degenerate microcavity.

Chapter five features the importance of working with a single quantum dot in a cavity. A technique that allows active positioning of single quantum dots during the fabrication process is presented. This method provides an efficient and accurate pathway to prepare samples that are suitable to measure the interaction between a quantum dot and a cavity in the strong coupling limit. For measurements in the weak coupling regime, a lower positioning accuracy is sufficient, and a technique is discussed that aims to actively position quantum dots in planar cavities. Finally, we present measurements that highlight the importance of experimenting with single quantum dots. The chapter describes the possibility to waveguide-couple photonic crystal cavities on the same sample.

A theoretical description of the quantum-dot confined electron dynamics is presented in chapter six. Before explaining the four-level system used to model the population and coherence dynamics of a singly charged quantum dot, some important mathematical concepts common to atomic systems are reviewed. Calculated quantum-jump rates between electronic states as a function of the optical intensity of the probing light, and special aspects such as the quantum Zeno effect are discussed. The chapter concludes with an outlook on further extensions for an enhanced model.

This thesis focuses on the exploitation of operation in the weak coupling regime. In chapter seven we provide ideas how a hybrid quantum system could serve for implementation of a controlled NOT gate, and therewith be the building block for a quantum computer. A Bell-state analyzer is the second scheme that is discussed. A discussion of the feasibility of an experimental implementation is provided.

The final chapter shows results from reflection spectroscopy measurements on single quantum dots in a micropillar cavity. From an experimental point of view, it is the most complex part of this thesis. We show how well we can couple a single quantum dot transition to a cavity resonance. We discuss that the coupling efficiency depends on the spatial position of the quantum dot with respect to the center of the cavity. Furthermore, we investigate the dependence of the resonant reflection on the pump power.