Cavity quantum electrodynamics with quantum dots in microcavities

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Summary

In this thesis I have investigated ‘quantum dots’ (QDs) in optical microcavities. In this summary it will be explained how QDs and optical microcavities work, and what in summary the results are that were obtained during my promotion and that are presented in this thesis.

QDs are very small 3D structures consisting of a semiconductor material, Indium Arsenide (InAs), that is surrounded by another semiconductor material, Gallium Arsenide (GaAs). Figure 9.4 (a) shows an electron microscope image of the cross-section of a QD. QDs are spontaneously formed by first depositing InAs on a GaAs substrate, which causes small ‘droplets’ to be formed. Next, these InAs droplets are covered with GaAs. QDs consist of only $10.000 - 100.000$ In and As atoms, and have a pancake-like shape with a diameter of ~ 40 nm (a nm is equal to 10^{-9} meter) and a height of $1 - 2$ nm. InAs has the property that charges in this material have a lower energy than charges in the surrounding GaAs, and charges are therefore confined inside the QD. Furthermore, QDs are optically active, which means that they can absorb a light particle, which is called a photon, and subsequently emit it again. This process is schematically shown in Fig. 9.4 (b). The optical transitions are spectrally narrow, which means that only photons with a certain wavelength (or color) interact; QDs are therefore also called artificial atoms.

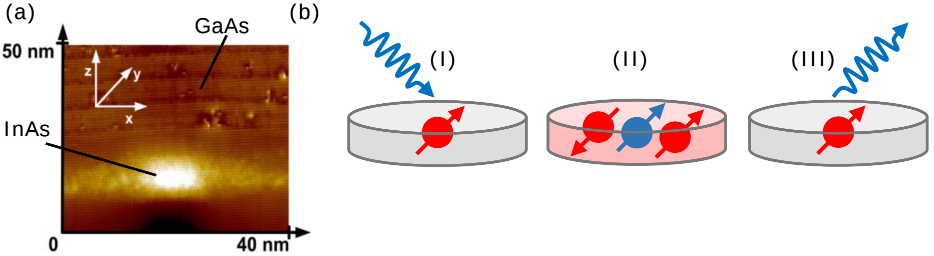

Figure 9.4: (a) Electron microscope image of an InAs quantum dot (QD) embedded inside a GaAs crystal. (b) Schematic representation of the absorption and emission of a photon by a QD charged with a single electron (red ball). (I) A photon is incident on the QD, (II) an electron and hole (blue ball) pair is created, and (III) a photon is emitted.

QDs are grown by our research group in such a structure, that the total charge in the QD can be controlled, such that only a single electron can be put inside it. A confined electron behaves according to the laws of quantum mechanics and is of interest because it can serve as a building block of a new type of ‘quantum’ computer. This computer would make use of the special properties of quantum mechanics and can therefore perform certain calculations much faster than a 'classical' computer. Furthermore, research on QDs is driven by curiosity; as QDs behave according to the laws of quantum mechanics, it is an exciting challenge to see to what extent predictions from these laws can be measured in a laboratory.

Studying, reading-out, and interconnecting QDs can be done using single photons. However, the interaction probability between light and a QD is very small (typically only a couple of percent), as is the same for the chance to collect an emitted photon. This makes experiments challenging, but is also a severe limitation for applications. The solution is to use very small optical microcavities, where 'micro' refers to the μm scale dimensions of the cavities (one μm is equal to 10^{-6} meter). Light that enters a cavity and has the right wavelength that 'fits' inside, bounces on average about 2000 times back-and-forth, before it escapes. We then talk about resonant light that resonates in the cavity.

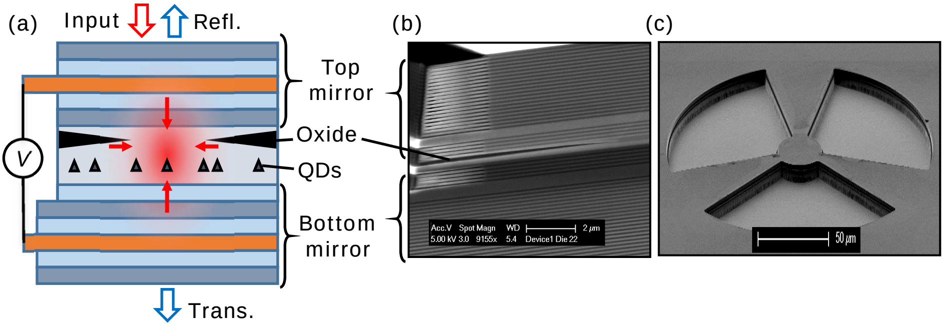

Figure 9.5: The microcavity. (a) Schematic image. Incident light (Input) is confined between the top and bottom mirrors and in the transverse direction by the oxide layer, before it is reflected or transmitted. Electrical contacts are used to apply a voltage V that controls the charge in the QDs. Electron microscope images of (b) a cross-section and (c) a top view of a micropillar (with a diameter of 30 μm).

Figure 9.5 (a) shows a schematic of a microcavity and Figure 9.5 (b,c) display cross-section and top view electron microscope images. Such a microcavity consists of two mirrors that confine the light in the out-of-plane direction. These mirrors are composed of many reflecting layers (composed of GaAs and Al(Aluminium)GaAs) which together act as an extremely good mirror, with a typical reflectivity $> 99.95\%$. To confine light also in the in-plane direction, first a small pillar is etched and, next, one of the layers in the center of the pillar is oxidized. Because the oxide has a lower refractive index than the unoxidized material, and light prefers high refractive index material, this way light is confined by the mirrors and the oxide layer into a small 'box'. The length of the oxide layer is essential; if the oxide layer has not penetrated far enough to the center of the pillar than the cavity is too large and the coupling between QDs and light is not strong enough. However, if the oxide has penetrated too far, the electrical contacts no longer function and neither do the QDs in that case.

The special property of a QD in a cavity is that a single QD, which absorbs in free space only a tiny fraction of the incident light, can now cause a photon, that would otherwise be transmitted by the cavity, to be (nearly) completely reflected. To explain the working mechanism of this process, we start with the interactions that can in general take place between light and matter. In Figure 9.6 (a) three processes are shown: (I) an incident photon does not interact, (II) a photon is absorbed, the QD is excited, and a photon is after some time spontaneously emitted, and (III) the photon is delayed by the QD and experiences a phase change, without being absorbed. This last process can be compared with light that transverses glass: the light is not absorbed, but does 'feel' the glass (SiO_2) molecules which causes it be slowed down, a process that is also described using a refractive index.

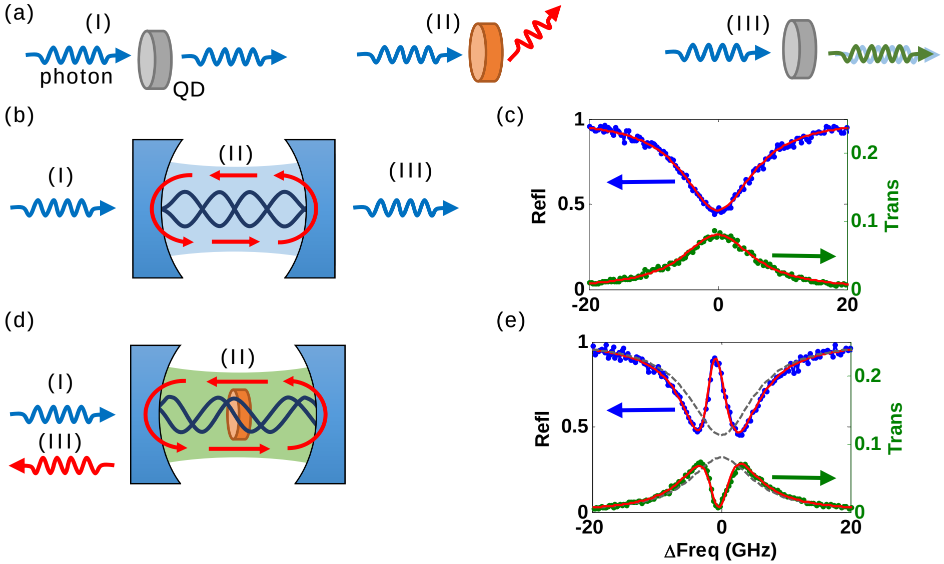

Figure 9.6: A QD in a microcavity. (a) An incident photon and a QD show three kinds of interactions: (I) no interaction, (II) absorption followed by emission, and (III) a phase change, or retardation, of the photon. (b) In an empty cavity, resonant light fits for an integer number of half wavelengths and is transmitted. (c) This results in a dip in the reflection spectrum and a peak in the transmission spectrum of the cavity. (d) In a cavity with a coupled QD a phase change is induced and the ($\Delta f = 0$ GHz) light is no longer resonant causing it to now be reflected. (e) In measurements a peak in the reflection dip and a dip in the transmission peak are now visible.

Figure 9.6 (b) shows schematically the case where light enters an empty cavity. Resonant light fits an integer number of half wavelengths in the cavity and, due to constructive interference, it is transmitted. Figure 9.6 (c) shows the corresponding measurements: along the horizontal axis the frequency of the incident light is scanned, and along the vertical axis we see that the reflectivity has a minimum and the transmittivity has a maximum at the cavity resonance ($\Delta f = 0$ GHz). Figure 9.6 (d) shows what happens when a single QD is coupled to the cavity. A small portion of the light is now absorbed, but most of the light undergoes a delay and phase change that now prevents it from still 'fitting' inside the cavity. This causes the light to be no longer transmitted through the cavity, but instead to be reflected. Measurements in Fig. 9.6 (e) show this effect and are one of the highlights of the work that is presented in this thesis.

This thesis consists of 9 Chapters with roughly the following content:

Chapter 1 is a general introduction to the research field. A general motivation is presented and the most important theoretical concepts are explained. Also, a comparison is made between several experimental systems that have been realized to study (artificial) atoms coupled to photons in cavities, including our own system.

Chapter 2 is a more technical introduction. Details are displayed of the new cryostat that was developed during my dissertation, the optical measurement techniques, the design and fabrication of the samples, and characterization measurements on single QDs.

Chapter 3, 4 and 5 elaborate on the optimization of the oxide layer, which is critical for the proper functioning of the microcavities. In Chapter 3 a technique is presented that enables the real time monitoring of the oxidation process. In Chapter 4 it is demonstrated that the oxidation can also be well controlled in small steps. For these experiments we designed and constructed in Leiden a new oxidation furnace in collaboration with the Fine Mechanical Department. In Chapter 5 it is shown how the shape of the oxide layer can be controlled, and that the optical properties of the microcavities are closely related. This made it possible for us to realize microcavities that are polarization degenerate, which means that every incident polarization is preserved in the cavity. This property is essential for experiments presented in Chapter 6, 7 and 8.

In Chapter 6 charge neutral and singly charged QDs in microcavities are investigated. The optical transitions have different polarization properties that we can now, using the microcavities, clearly observe. Also, these studies enable us to study the coherent and incoherent dynamics of the QDs.

In Chapter 7 a memory effect is described in our system. Light that is coupled into the cavity also induces the excitation of other charges outside of the QDs, which are then trapped by the oxide layer. These trapped charges influence the energy of the QD transition and give rise to hysteresis and other effects. This behavior is explained using simulations and time-resolved measurements.

In Chapter 8 a novel technique is demonstrated to study the coherence and phase of light that is transmitted through the QD-cavity system. If light is scattered by a QD, the coherence of this light contains information on this interaction. We hope to use this information to further improve the properties of the QDs in the future. Also, the cavity and the QD induce a phase shift of the transmitted light, which we can observe with our technique.

Chapter 9 contains an outlook for further experiments and sample improvements, based on the understanding obtained in this thesis. For future research, especially the coherent properties of charged QDs need to be improved, which is possible using the new characterization techniques that have been developed.