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Acousto-Mechanical Tuning of Photonic Crystal Nanocavity Modes

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Abstract—**Surface Acoustic Waves (SAW) are employed to deliberately modify the resonator properties of a high Q photonic crystal membrane (PCM) on a semiconductor nano structure. The SAW periodically deforms the PCM, giving rise to a periodically modulated resonance position of the photonic crystal. While achieving resonance shifts exceeding $\Delta\lambda = 2$ nm, the quality factor of the PCM resonance remains basically unchanged. Combination of the acousto-photonic resonance modulation with single photon generation of acoustically charged quantum dots and quantum posts are discussed in the context of single photon generation of non-classical light.**

Keywords- ***Surface Acoustic Waves, photonic crystal, quantum dots,quantum posts, non-classical light***

I. Introduction

Surface acoustic waves have been proven to be a versatile tool to manipulate charge and spin excitations in low-dimensional semiconductor systems. In particular, in piezoelectric materials such as III-V compound semiconductors the mechanical deformation induced by the SAW is accompanied by larger lateral and vertical electric fields having the same spatio-temporal periodicity. These electric fields strongly interact with mobile charges in the semiconductor whereas the mechanical fields either directly couple to mechanical degrees of freedom or indirectly interact via deformation potential effects.

Since the early 1980, surface acoustic waves have been employed to probe fundamental physical effects in low-dimensional semiconductor structures such as the quantum Hall effects [1] or to transport individual charges and spins [2]. In optically active structures the acoustoelectric fields induced in piezoelectric semiconductors lead to a dissociation and spatial separation of electron-hole pairs (excitons) in a quantum well (QW). This gives rise to a charge conveyance effect [3] which can be further employed to realize, e.g., an acoustically triggered single photon source [4].

In our experiments, the SAW electric fields laterally modulate the confinement potential of a Quantum Well (QW) and spatially separate electrons and holes along the SAW propagation. This is then used to sequentially inject the two carrier species into the confined states of so-called Quantum Dots (QDs) and Quantum Posts (QPs) [5]. We show that this acoustic control of the carrier capture provides a novel tuning mechanism for the charge state of QDs and QPs. Moreover, the SAW conveys photogenerated carriers along its propagation direction over macroscopic distances. We employ this charge conveyance effect to inject electrons and holes into individual QDs and QPs remotely located from the excitation laser spot position, a step towards an acoustically triggered single photon source.

The mechanical deformation induced by a SAW can be further employed to deform and break the periodicity in two-dimensional photonic crystal membranes (PCMs). Using finite-difference time-domain (FDTD) simulations we model our experimental SAW-controlled spectral response of the optical mode of a high-Q nanocavity defined in a PCM. For realistic SAW amplitudes we find a pronounced spectral shift exceeding $\Delta\lambda$=2nm accompanied by only a weak 0.5 times degradation of the Q-factor. In time-integrated experiments, we observe an apparent spectral broadening of the cavity emission consistent with our simulations. In time resolved experiments on such PCMs, however, we in fact observe a mechanically induced periodic modulation of the cavity emission which together with the above mentioned efforts towards a single photon source and employing the Purcell effect will have a large impact on the generation of non-classical light.

II. Experimental Details

A. Samples

For the acoustic charge transport and selective loading of the quantum recombination centers, quantum dots (QDs) and quantum posts (QPs), we employ sophisticated semiconductor layered structures that had been grown by molecular epitaxy (MBE) and contain a single layer of either self-assembled QDs or QPs. The two types of nanostructures studied differ inherently in their morphology and their adjacent two-dimensional QWs as described I detail in [5]. Conventional QDs are flat, 3-5 nm high, In-rich islands with a diameter in the range of 20 nm which nucleate on a thin d≈1 nm InGaAs wetting layer (WL) resembling a narrow QW with a larger effective band gap than the QDs. Self-assembled QPs on the other hand are columnar structures with similar diameters as the QDs but with a different height that can be adjusted with nanometer precision. The QPs are embedded laterally in a thin InGaAs Matrix-QW with a reduced 10% Indium content, too. This ensures full, quasi-zero-dimensional carrier confinement.

To study the interaction of theses quantum systems with SAW, we use interdigital transducers (IDTs) with wave-lengths of λ_{QD}=11.6 µm and λ_{QP}=15 µm for the QD and QP sample, respectively. This correspond to SAW frequencies of f_{QD}= 251.5 MHz and f_{QP}=193 MHz at T=4 K.

The µ-PL (micro photoluminescence) experiments were performed at low temperatures (T=4K) with the sample mounted on the cold finger of an optical He flow-cryostat. Carriers were photogenerated using an externally triggered diode laser providing <100 ps pulses at λ=661 nm, focused to a 2 µm diameter spot using a 50x microscope objective. Weak optical excitation (<100 nW) was employed in order to excite only single s-shell excitons and avoid multi exciton generation. The emission from the sample was collected by the same objective lense, dispersed by a 0.5 m grating monochromator and detected by a liquid N2 cooled Si-CCD detector with an overall resolution <150 µeV.

B. *Photonic crystal membranes*

Photonic crystal membranes (PCM) are meanwhile well established as a versatile planar platform for on-chip implementations of photonic quantum circuits [6]. An important quantum element is a coupled system consisting of such a nanocavity and a single quantum dot, representing a fundamental building block for quantum information networks.

In our experiments, the PCMs were fabricated from a semiconductor heterostructure grown by molecular beam epitaxy. This heterostructure consisted of a 134 nm thick GaAs layer with self-assembled InAs quantum dots in its centre, on top of a 920 nm-thick $Al_{0.7}Ga_{0.3}As$ sacrificial layer. The photonic crystal structure was defined by electron-beam lithography and transferred into the heterostructure by dry chemical ion etching (ICP-RIE). The sacrificial layer was then removed in a subsequent wet-chemical etching step using hydrofluoric acid to release the fully suspended membrane. Titanium/aluminium IDTs with design frequencies of f_{SAW} = 414 MHz, 850 MHz and 1.7 GHz were defined by e-beam lithography, then finalized using a conventional lift-off process at a distance of 1mm from the PCM. The corresponding SAW wavelengths are λ_{SAW} = 28a, 14a and 7a, with a = 0.26 µm being the photonic crystal lattice constant.

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III. Experimental Results

A. *Acoustic charging and manipulation of quantum systems*

First, we want to demonstrate that SAW can be effectively used to trap photo generated charge carriers in the dynamic piezoelectric potentials of the SAW and subsequently conveye them along the quantum wells towards our quantum structures (QDs and QPs) where they are radiatively recombining. The beauty of such acoustically driven charging of quantum systems is that: First, the charges are recombining a a very well defined time and at a very well defined frequency, given by the temporal periodicity of the SAW. Moreover, the charge state of the quantum structures can be extremely well adjusted by both the pumping laser and the SAW intensity.

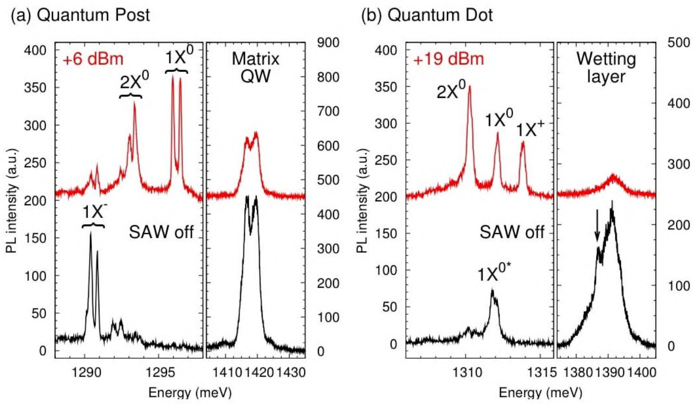

Figure 1. Emission spectra of a single QP and Matrix-QW (a) and a single QD and wetting layer WL (b) without and under the influence of a SAW. With the SAW applied, a clear switching of emission lines attributed to different occupancy states and an overall increase of intensity is observed [5].

In Fig. 1, we depict a typical example of such SAW driven charge conveyence and selective recombination. IN (a), we show the results for Quantum Post QP sample, in (b), the same experiment is depicted for QDs. Both cases for SAW on and SAW off are shown. Most noticeable is the fact that the SAW obviously completely changes the nature of the recombination. A SAW present on the sample typically creates a much richer spectrum with not only a single excitonic line, but also different charge states can be prepared and detected in the emission spectra. Experiments like this for varying SAW amplitudes and optical pumping powers are described in detail in [5], where also a SAW triggered very distinct switching behavior between different charge states is described in detail. Also, we have shown before that single ind individual quantum structures can be adressed this way. For the sake of this communication, we wish to point out the extremely sharp and narrow recombination peaks, being typical for single QPs and QDs in combination with a well defined possible tuning of the charge state of said quantum emitters by employing acoustic pumping.

B. *Acoustically tunable Photonic Crystal Membranes*

As pointed out in the introduction, single quantum emitters are very attractive in the sense that they only contain a small number of elementary charges and – due to the very high sensitivity of the electronic environment to the presence of only a few charges – different charged states such as neutral or (multiply) charged excitons - considerably differ in their recombination energies. These facts make them very promising candidates for future quantum communication. We have shown that SAW in combination with single QDs and QPs can be used to represent such tuneable quantum systems in the last paragraph.

We now turn to the description of Photonic Crystal Membranes PCM that are used in combination with the above quantum emitters to also manipulate the probability for spontaneous emission in such hybrids [7]. A Photonic Crystal together with a crystal defect is usually referred to as an micro resonator for optical frequencies. While the periodicity of the refractive index modulation in such structures defines a photonic bandstructure with photonic bandgaps, the introduction of a crystal defect creates (as usual in plane wave mechanics) allowed states within said bandgap. In semiconductor physics, for example, such defects relate to donor-, acceptor or deep mid gap levels. In PCMs, however, the introduction of crstay defects leads to a pronounced localization of the photon field within a tiny little volume, defined by the size and symmetry of the crystal defect.

It turns out and is a well known effect in the field of photonics that the probability for spontaneus emission of a quantum emitter, in other words the radiative decay rate strongly depends on the so-called Purcell factor F_P [8], basically indicating the spatial overlap of the mode volumes of the resonator V and the emitter modes.

$$F_P = \frac{3}{4\pi^2}\frac{Q}{V}\left(\frac{\lambda}{n}\right)^3 \tag{1}$$

Here, Q represents the quality factor of the resonator, λ the wavelength of the resonating light, and n the refractive index of the resonator material. As can be seen from this simple formula, we can expect an increased recombination rate for high Q, small V resonators with a strong overlap between the mode volume of the emitter and the resonator. The 'problem', however in such man-made and engineered hybrid quantum resonator systems is that both the resonator line width as well as the linewidth of the emitters are extremely narrow and usually do not overlap after the growth of the emitter and processing od the PCM.

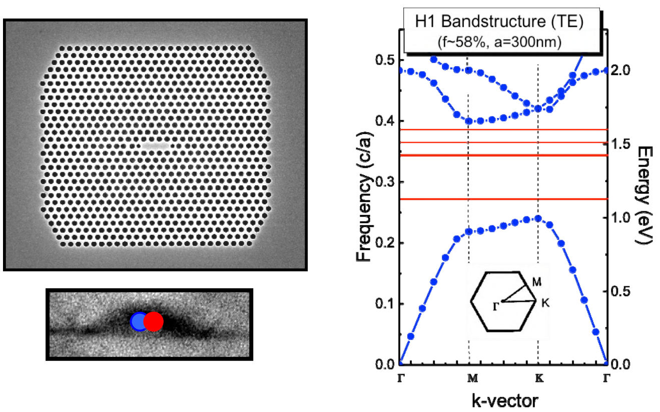

Figure 2. Photonic crystal resonator with defect in the center, giving rise to a photonic band structure (right). A QD is located in the defect area.

The PCM is located between the IDT to excite and launch a SAW which penetrates the PCM and periodically streces and compresses the reonator. This in turn gives rise to a periodic shifting of the resonance frequency or wavelength, eventually 'crossing' the emission frequency and wavelength of the QD emitter.

In Fig. 3 (left), we show the effect of the SAW on the emission spectrum as obtained experimentally in a time averaged experiment. Here, the influence of the SAW on the emission spectrum seems to result in an apparent broadening of the line with two distinct maxima ate either side. This picture, however, changes in time resolved experiments, where SAW and excitation laser are being phase locked with a variable phase shift ΔΦ. Here, as showwn in Fig. 3 (right), we are able to resolve that this apparent broadening in fact results from a periodic shift of the narrow resonance between the two limiting cases being indicated by the maxima in Fig. 3 (left).

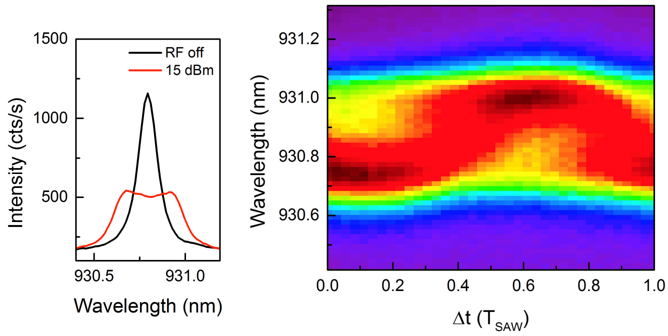

Figure 3. Emission spectrum of the Photonic Crystal membrane with quantum emitter as described in the text. Left: Spectrum without (black) and with SAW (red). The SAW seems to actually broaden the spectral line and resulting in two distinct maxima at either side of the line. Ricght: Time resolved and phyase locked spectrum of the same system. By shifting the phase difference between exciting laser and SAW, we are able to recover the shift of the spectral line, nicely following the SAW frequency.

A more detailled investigation [7] reveals that the SAW in fact does shift the resonance postion, whereas the quality factor (as indicated by the linewidth) is only very weakly affected by the SAW, at least at moderate rf powers, before significant heating sets in. This power dependence of the resonance position shift is shown in Fig. 4, where we plot the shift Δλ as a function of the square root of the applied rf power:

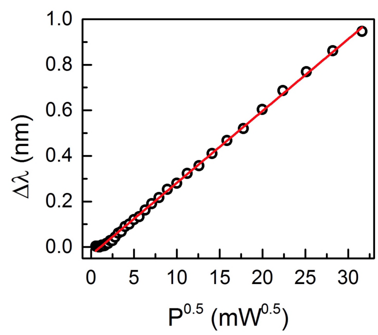

Figure 4. Power dependence of the SAW induced shift of the resonance frequency of our PCM / QD hybrid nanosystem. For relatively moderate powers, Δλ linearly follows the amplitude of the mechanical amplitude of the membrane deformation, caused by the SAW.

IV. Summary

In summary, we have shown that the dynamic fields of a SAW, both the piezoelectric fields as well as the mechanical strain and stress fields can be extremely versatile tools for the deliberate, fast manipulation of semiconductor quantum systems. We could show that quantum emitters like quantum dots or quantum posts can be acoustically 'loaded' with optically generated electron hole pairs, eventually forming excitonic excitations within the dots and posts. Not only is the SAW used to charge these quantum emitters, it is also possible to determine their charge state. These two facts make SAW in combination with QDs and QPs in semiconductor layered systems a very promising tool for quantum communication / quantum optics application and the generation of well defined states of non-classical light.

In combination with a planar micro resonator, a Photonic Crystal membrane, we have been able to show that the mechanical strain and stress fields of a SAW are extremely powerful tools for the fast (> 1 GHz) and controllable tuning of such resonators. We could further show that acoustically triggered and controlled resonator line shifts in excess of 20 line widths are achievable whereas the quality factor of the resonances is only marginally affected.

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