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C. Bödefeld, Achim Wixforth, J. Toivonen, M. Sopanen, H. Lipsanen

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Pumping of Quantum Dots with Surface Acoustic Waves

C. BÖDEFELD¹) (a), A. WIXFORTH (a), J. TOIVONEN (b), M. SOPANEN (b),
and H. LIPSANEN (b)

(a) *Sektion Physik der Ludwig-Maximilians-Universität, Geschwister-Scholl Platz 1,
D-80539 München, Germany*

(b) *Optoelectronics Laboratory, Helsinki University of Technology, Otakaari 7A,
FIN-02150 Espoo, Finland*

Surface acoustic waves on a semiconductor quantum well structure are accompanied by strong lateral piezo-electric fields. Those fields can ionize photo-generated excitons and trap the fragments, electron-hole pairs, in the moving lateral potential wells to the wave. We show that self-assembled quantum dots present in the structure can act as very efficient recombination centers and demonstrate the concept of a periodically pumped quantum dot.

Apart from their importance as active media in novel semiconductor laser structures, the discrete level spectrum of a quantum dot (QD) allows in many aspects a direct comparison to atom. Many of the quantum-optical approaches in atomic physics have yet to be explored for QDs. Periodically pumped QDs offer especially fascinating new possibilities for quantum-optical applications. Several groups are working in the field of single photon emission [1, 2], based on well controlled photon generation. Coulomb blockade and Rabi oscillations are used to get anti-bunching and sub-Poissonian statistics for photons. Here, we would like to present our initial results towards the realization of a single photon emitting light source, based on periodically pumped semiconductor QDs employing surface acoustic waves (SAWs).

It has been shown before that ambipolar transport of electrons and holes in the dynamic lateral potential landscape of SAWs in a semiconductor quantum well (QW) structure is possible [3]. Photo-generated charge carriers can be trapped in the moving lateral potential wells accompanying a SAW, and then be recombined at a remote location on the sample. If the optical properties of this emission site are tailored in a specific manner, the delayed luminescence light can be altered in terms of energy as compared to that of the generation site. Recently, we have shown that SAW driven transport of photo-generated charges into a quantum dot, acting as a quasi zero-dimensional recombination center, could in principle exhibit single photon emission [4].

The excitons are generated in a surface quantum well structure by local illumination of the sample. These excitons are ionized by the strong lateral electric fields of a surface acoustic wave. The ionized carriers are trapped in the local minima of the band gap modulation. Hence, their recombination is strongly suppressed and the carriers are swept along with the wave. If the wave passes a quantum dot with a confining potential that is stronger than the potential of the SAW, the carriers are released from the wave and captured by the dot potential. As electrons and holes arrive behind each other,

¹) e-mail: christoph.boedefeld@physik.uni-muenchen.de

recombination will take place in a periodic manner, given by the SAW frequency. In the limit of a single QD, one would have a periodically pumped single photon light source where the period is induced by the periodicity of the SAW.

Here, we want to show first results on the pumping of an ensemble of QDs using SAW. We use self-organized stress-induced quantum dots grown by metal organic vapor-phase epitaxy [5]. A 6.5 nm thick $\text{In}_{0.1}\text{Ga}_{0.9}\text{As}$ QW on GaAs is overgrown with a 20 nm GaAs cap followed by about three monolayers of InP. Because of the lattice mismatch, the InP grows in the Stranski-Krastanov growth mode forming self-organized islands. They are about 30–35 nm thick and have a lateral dimension of about 65 nm. The density is about $1 \times 10^9 \text{ cm}^{-2}$. Due to the strain of the InP, a QD is induced in the QW underneath each island.

To excite and detect the SAW two interdigital transducers (IDTs) with a center frequency of $f_{\text{SAW}} = 520 \text{ MHz}$ are deposited on the sample employing e-beam lithography. The frequency is determined by the relationship $\lambda_{\text{SAW}} = v_{\text{SAW}}/f_{\text{SAW}}$ where λ_{SAW} – the wavelength of the SAW – is given by the geometry of the IDT. For the given sample cut and orientation the SAW velocity is $v_{\text{SAW}} = 2865 \text{ ms}^{-1}$. Close to one of the IDTs (which we denote as the SAW emitter) the InP islands are completely removed from the surface, using a wet etching process. This provides a plain QW structure without any QDs on about half the sample area (cf. Fig. 1).

The sample is mounted in an optical cryostat and cooled down to the minimum temperature of $T = 3.8 \text{ K}$. A pulsed 780 nm laser diode is used for optical interband excitation above band gap. The photoluminescence (PL) of the sample is analyzed using a triple grating spectrometer with either a cooled CCD or a gated photomultiplier as detector. Variable slits can be inserted in the focal plane of the spectrometer to obtain spatial resolution. By applying a short rf pulse with the frequency f_{SAW} to IDT1 a SAW is launched, propagating from the etched side of the sample to the side where the QDs are present. The second IDT is used to monitor the attenuation and the time delay of the SAW.

To characterize the sample (see Fig. 1) the PL emitted from the excitation area was recorded while the sample was moved in steps of $50 \mu\text{m}$ along the direction of the SAW using a motor stage. One can clearly see the position of the IDTs and the etched region: PL is almost completely suppressed at the IDTs, because of the thickness of the metal structures. In the etched part of the sample, where the InP islands are removed, the QW luminescence is enhanced, because no QDs are present.

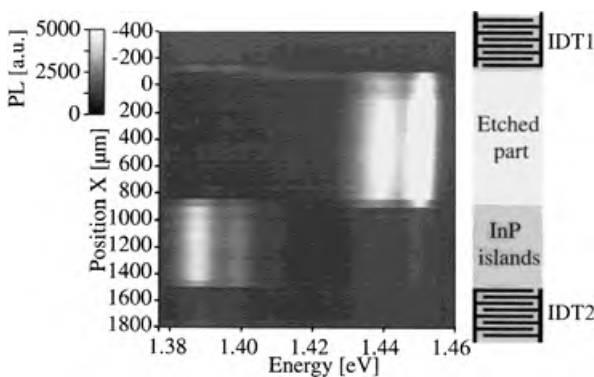


Fig. 1. Spatially resolved, direct photoluminescence of the sample measured along the path of the SAW. The sketch shows the position of the emitting and the receiving transducer. In the etched region ($X = 0 \mu\text{m}$ to $X = 900 \mu\text{m}$) no quantum dots are present, so that a bright quantum well luminescence is observed. At the position of the interdigital transducers (IDT1 and IDT2) the photoluminescence is suppressed because of the metal structures

For the transport experiment, the excitation position was set to $X = 0 \mu\text{m}$. The laser repetition rate was $f = 100 \text{ kHz}$. The laser pulse was 200 ns long, whereas the SAW pulse was 400 ns long. The delay between both pulses was adjusted for a maximum overlap of the SAW and the illuminated area of the sample. A movable slit in an intermediate image plane was used to gain spatially resolved spectra in the direction of the SAW. Two PL images were taken with the CCD: one with the SAW turned on and a reference image without SAW. The ratio of the spectra is plotted in Fig. 2, where one can see that in the excitation region the changes due to the influence of the SAW are vanishingly small. In addition the graph clearly shows a PL signal coming from the QDs located in the region close to the etch border ($X = 900 \mu\text{m}$), which decreases in intensity while moving further ‘downstream’ along the SAW propagation path. No change in the QW luminescence is observed.

We interpret our experimental findings as follows: Optically generated excitons in the QW are dissociated by the strong electric fields accompanying the SAW. The QW structure prevents leaking of the trapped charge along the growth direction of the sample. Therefore they are transported towards the region containing quantum dots. Within the wave, the trapped holes and electrons are separated by about a half wavelength of the SAW [3]. When the wave reaches the area of the sample where the QDs have not been removed, a QD may pluck a carrier while the wave passes by – provided that the QD potential is deep enough. While the SAW moves on the trapped charge carrier – say an electron – stays in the QD, ‘waiting’ for a hole to follow and recombine.

This absorption process reduces, on the other hand, the number of carriers remaining in the SAW. Therefore the PL decreases along the SAW path in the QD region (cf. Fig. 2) due to two mechanisms: The overall number of transported carriers decreases, leading to a reduction of the capture rate. Also, the confinement in the SAW potential is increased as the screening is reduced due to less charge.

In the inset of Fig. 3, the spectrum of the transported PL taken at $X = 900 \mu\text{m}$ is compared to the spectrum of the direct PL (no SAW present) of the same part of the sample. We observe a slight blue shift of about 1 meV , which cannot be explained at the moment.

Time-resolved measurements of the PL have also been performed. A typical trace is shown in Fig. 3. A photomultiplier with a time window of 50 ns was used for this

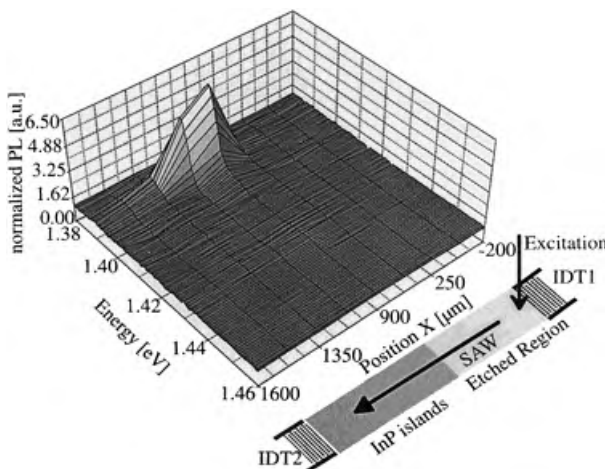


Fig. 2. Spatially resolved measurement of the change in PL intensity caused by a SAW. A slit aperture in an intermediate image plane was used to obtain the spatial information. Just beyond the etch border ($X = 900 \mu\text{m}$), a strong quantum dot luminescence ($E = 1.39 \text{ eV}$) is seen. At the excitation point $X = 0 \mu\text{m}$ no influence of the SAW can be resolved

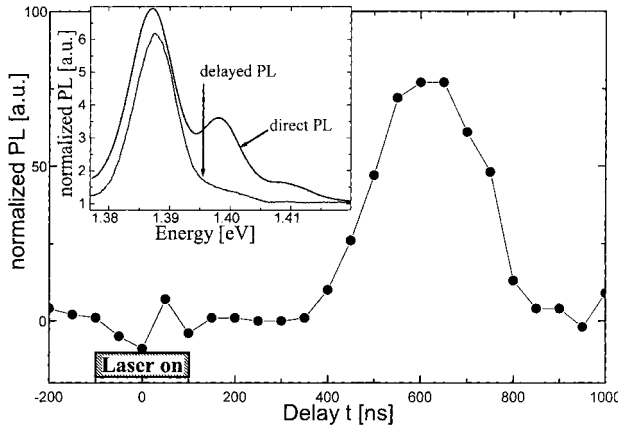


Fig. 3. Time resolved measurement of the change of the QD PL caused by the SAW. At $t = 400$ ns one observes a steep rise of the signal for about 400 ns. The inset shows a comparison of the QD PL taken from $X = 900 \mu\text{m}$ with no SAW applied and the spectrum of the transported light extracted from Fig. 2 at the same position (scaled for clarity)

experiment. The slit position was set to $X = 900 \mu\text{m}$, so that only light coming from the etch boundary was recorded. This reduces stray light from the excitation area. Moreover, the spectral range was set to 1.376–1.42 eV, so that any QW PL was completely blocked. Again, two spectra were recorded, with and without a SAW. The difference between these spectra is plotted against the delay of the detector window with respect to the laser. After $t = 400$ ns a steep rise in the QD PL signal is seen at a position which is about $900 \mu\text{m}$ away from the illuminated area. The luminescence lasts for about 400 ns. This fits well to the length of the SAW pulse.

In summary, we have shown that the optical emission of QDs can be acoustically pumped using SAW. The strictly periodic nature of this pumping mechanism is conceptually different from other schemes reported so far [1, 2]. It is believed that the well defined periodicity of the SAW can in future be used to produce a well defined photon train. However, further experimental work has to be done to directly prove the emission of single photons from the periodically pumped quantum dots. Time resolved experiments in combination with a higher spatial resolution are presently in preparation.

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