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Surface acoustic wave hybrid devices:

High sensitivity conductivity probes and low-jitter single photon sources

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Abstract

We employ surface acoustic waves to probe and manipulate optically active nanosystems. We demonstrate that the attenuation of a SAW provides a high sensitivity probe of the electrical conductivity by measuring the persistent photoconductivity in a multi quantum well structure. Moreover we apply SAW to dissociate photogenerated electron-hole pairs and by acoustic transport convey these at the speed of sound over macroscopic distances to a remote quantum emitter. After inherently sequential injection of electrons and holes, excitons are formed in these artificial atoms which recombine and emit single photons. Our SAW-based approach provides a low-jitter acoustically pumped single photon source with programmable exciton configuration.

Key words: Surface acoustic waves, semiconductor heterostructures, hybrid devices, conductivity probe, single photon source

Introduction

Over the past 20 years surface acoustic waves (SAWs) have been applied to probe and manipulate charge, spin and optical excitations in semiconductor heterostructures [1-4] and nanosystems and optical micro- and nanoresonators [5,6]. In this field of fundamental research these "nanoquakes on a chip" provide a particularly useful and versatile tool for massively parallel addressing a broad variety of nanosystems at radio frequencies via acousto-mechanical and acousto-electric couplings. These allowed for deep insight into the underlying fundamental physical processes [1,2] but also provide routes to novel spintronic [4] and optoelectronic device appications [3,5,6].

In this contribution we highlight our recent advances in the control of electrically and optically active nanosystems employing hybrid SAW devices. We report as first example recent experiments in which we employ SAWs to probe the persistent photoconductivity in II-VI compound semiconductor heterostructures. In the second part of the article we demonstrate the successful realization of an acoustically pumped single photon source based on a quantum post nanoemitter. Such sources of non-classical light are key devices for future quantum cryptography devices.

Probing persistent photoconductivity (PPC) in fused chip hybrid $LiNbO_3$-(ZnCdSe/ZnSe) Multi-Quantum Well devices

Free carriers dynamically screen the electric potential induced by a SAW in a piezoelectric substrate. Thus, the attenuation of a SAW peculiarly depends on the density of mobile charge carriers in the material and provides a direct measure of its conductivity [1]. This scheme has been successfully applied to probe other fundamental physical effects such as the Quantum Hall Effect [1] and can be readily applied to other types of novel materials such as graphene. The absorption coefficient Γ is given by

$$\Gamma = \frac{K_{eff}^2 \cdot k}{2} \cdot \frac{\sigma/\sigma_m}{1+\left(\sigma/\sigma_m\right)^2} \quad (1).$$

In this equation K_{eff} denotes the piezomechanical coupling coefficient of the substrate, k the SAW wavevector and σ_m the charactersitic conductivity given by

$$\sigma_m = \varepsilon_0 (1+\varepsilon_{hyb}) \cdot v_{SAW} \quad (2).$$

This characteristic conductivity depends on the SAW velocity and the relative dielectric constant of the hybrid, determined by the layer sequence of the sample.

Our sample consists of a ZnCdSe/ZnSe heterostructure grown by molecular beam epitaxy (MBE). Five optically active, 4 nm wide $Zn_{0.9}Cd_{0.1}Se$ quantum wells, separated by 8 nm ZnSe barriers are embedded between two 63 nm ZnSe cladding layers. This II–VI multi quantum well (MQW) structure was removed from the substrate and transferred onto the strongly piezoelectric $LiNbO_3$ chip using an etablished epitaxial lift-off technique. A 5.4 mm long delay line of two interdigital transducers (IDTs) was fabricated in a lift-off process. These IDTs allowed for the excitation and/or detection of SAW at f_0 = 115 MHz and f =3f_0. At these frequencies the corresponding values for and σ_m are

$$\sigma_m(f_0) \approx 1.04 \cdot 10^{-6} \Omega^{-1}, \quad \sigma_m(3f_0) \approx 8.75 \cdot 10^{-7} \Omega^{-1}. \quad (3)$$

These small values ensure maximum sensitivity at lowest conductivity levels. The size of the transferred semiconductor film defined the total interaction length between the SAW and the carrier system to s = 2.6 mm.

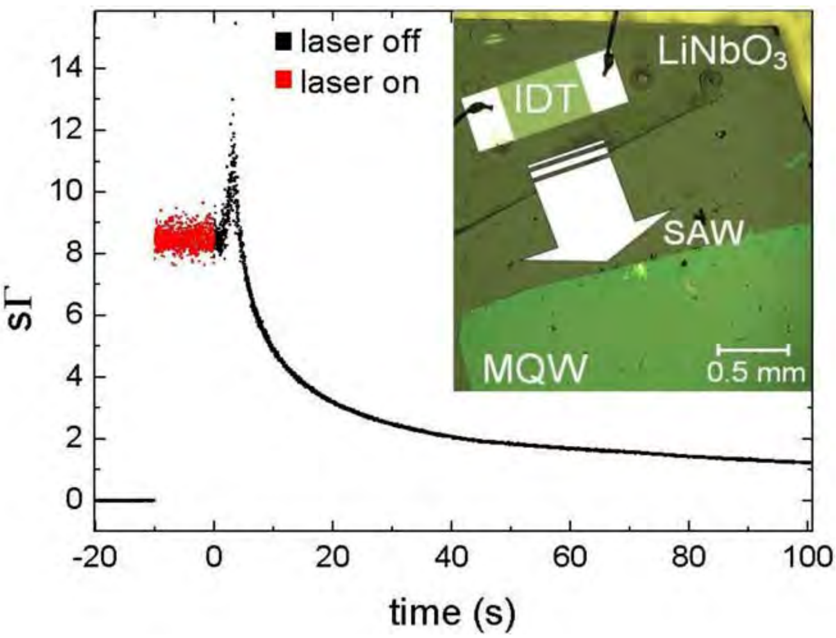

Fig 1: SAW attenuation of for $3f_0$ = 345 MHz *at a low temperatures (T = 35 K), before, during, and after optical excitation. Inset: ZnCdSe/ZnSe MQW heterostructure on a* $LiNbO_3$ *substrate with one wire-bonded IDT. Reprinted with permission from [7]. Copyright 2010, American Institute of Physics.*

In Figure 1 we show a typical measurement of attenuation at the frequency 345 MHz at low temperatures (*T* = 35 K) as a function of time. At the onset of the laser illumination at t = -10 s the attenuation instantly rises. Due to the creation of free charge carriers, the conductivity in the MQW structure rises and the transmission of the SAW is attenuated by approximately 35 dB. At t = 0 s the laser is turned off, after which the attenuation rises to a maximum, before it very slowly decays on a seconds timescale. This maximum is expected from equation (1) when the film conductivity equals the characteristic conductivity, i.e. $\sigma/\sigma_m = 1$.

The data in Figure 1 shows that the SAW propagation is considerably affected during and long after illumination by the laser. This is a rather striking discovery, because in an ideal, clean system with electrons and holes generated in euqal numbers, the dominant loss mechanism would be radiative recombination. However, such processes occur on much faster nanosecond timescales. Therefore, our observation of such a persistent photoconductivity (PPC) points towards a different mechanism being the origin of the observed behavior. In a detailed study for which we employed our SWA-based conductivity probe we were able to identify shallow electronic traps as the dominant contribution to this phenomenon. In addition, this non-invasive technqiue allows for the assessment of the electronic and optical quality of modulated semiconductor heterostructures [7].

Acoustic pumping of single semiconductor quantum emitters for precisely triggered single photon emission

At sufficiently high SAW amplitudes the induced piezoelectric potentials give rise to the dissociation of photogenerated electron-hole pairs, so-called excitons. After dissociation these charges are stored in the acoustically induced potential and conveyed at the speed of sound by the propagating SAW [3]. We employ this mechanism to transport photogenerated electrons and holes from the point of generation to a remotely positioned quantum light emitter to realize an acoustically pumped single photon source [8]. For this unique device the acoustically transported electrons and holes are injected inherently sequential and precisely timed by the SAW [9-11] into the quantum light emitter, which recombine after each acoustic cycle and emit a single photon. As the quantum light emitter we chose a novel type of nanostructure, a so-called quantum post (QP) [12] for which single photon emission has been successfully demonstrated [13]. Since these QPs are embedded in a wide lateral quantum well, acoustic charge transport is highly efficient which allows for superior device performance when compared to conventional quantum dot structures [8]. To demonstrate the operation of such a SAW-driven single photon source, we monolithically integrated IDTs on a weakly piezoactive GaAs-based chip containing a single layer of MBE-grown InGaAs QPs. Two typical images filtering out only the spectral lines of the QP are shown in the left and right panel of Figure 2 for the case without and with a SAW (propagating downwards from left to right), respectively. Since the pump laser at x=y=0 is spatially separated from the QP at x = 30µm and y =0, no electrons and holes are injected into the QP when no SAW is excited by the IDT ("SAW off"). With the SAW present ("SAW on"), electrons and holes are transported from the pump laser's position to that of the QP where one photon is generated per acoustic cycle. In the corresponding emission image in Figure 2, the characteristic Airy-pattern of a single nanoemitter is detected at precisely the position of the QP.

These findings demonstrate that our acoustic technique gives rise to a high-fidelity, dynamic preparation of the emitter's charge and exciton state compared to direct optical pumping without a SAW [8,9]. A combination of this scheme and high quality optical photonic crystal nanocavities – which can be also modulated by a SAW at radio frequencies [6] – promises a new class of hybrid quantum-nano-optomechanical devices for future applications in quantum information processing.

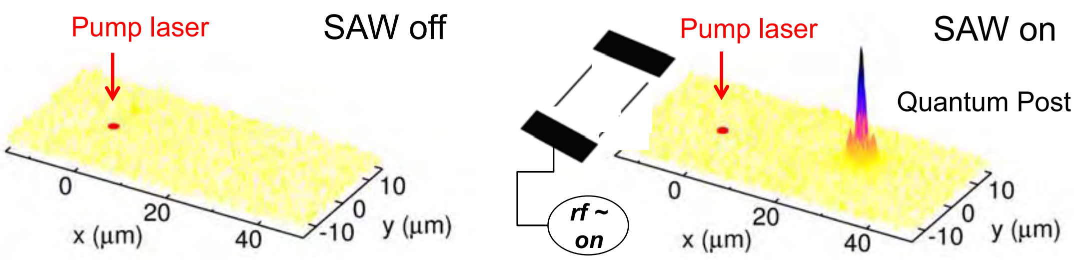

Fig. 2: Near infrared emission image without a SAW (left) and with a SAW applied (right). Photogenerated carriers are transported from the pump laser position to a single quantum post. In this scheme the artificial atom emits a train single photons precisely triggered at the SAW period.

Summary

In summary, we presented two selected recent examples demonstrating that SAWs provide a versatile dynamic tool to probe and manipulate semiconductor nanostructures. We showed that the attenuation of a SAW is a highly sensitive acoustic probe for ultra-low conductivity levels in semiconductor thin films. Finally, we realized an acoustically driven single photon source for future quantum cryptography applications.

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