NANO-QUAKES ON A CHIP: SURFACE ACOUSTIC WAVES IN SEMICONDUCTOR PHYSICS

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The interaction of surface acoustic waves with free carriers in semiconductor nanostructures has turned out to yield a powerful tool not only for the investigation of the dynamic conductivity of such quantum systems. The latter has been shown in the study of the dynamics of the quantum Hall effect.[1] However - to make practical use of this strong interaction, the electromechanical coupling coefficients of state-of-the-art semiconductor layered systems are too small. A hybrid technique, merging the strong piezoelectricity of $LiNbO_3$ or similar substrates with the excellent electronic properties of band gap engineered semiconductor quantum wells tackles this problem. Based on this new hybridization technique, several acoustoelectric high frequency devices have been realized. But also optically generated free electrons and holes in a semiconductor efficiently interact with the piezoelectric fields and potentials accompanying the surface wave. Those are able to field-ionize optically generated excitons leading to an acoustically induced quenching of the photoluminescence of a semiconductor quantum well, and to a system in which photonic signals can be efficiently converted into spatially separated electrons and holes which then can be transported over macroscopic distances along the quantum well. Finally - at a predetermined time and location on the sample – they can be re-assembled into photonic signals. This can also take place in self-assembled quantum dots (QD), if the confining potential of the dots is stronger than the potential of the wave. In the limit of one QD one would have a periodically pumped light source.

Theoretical introduction

The effect of a thin, massless metallization at the surface of a piezoelectric substrate, on which a surface acoustic wave (SAW) is propagating has been discussed in great detail by several authors before,[1,2,3,4] so we can restrict ourselves here to just give the result. It turns out that this leads to a conductivity dependent attenuation Γ and a shift of the SAW velocity $\Delta v/v_0$ given by eq. (1), where $k=2\pi/\lambda$ denotes the wave vector of the SAW, σ the sheet conductivity of the metallic layer, and $\sigma_m=v_0\varepsilon_0(1+\varepsilon_s)$ the 'natural' conductivity of the problem. In Fig. 1, we plot the result for the attenuation Γ and the renormalization of the sound velocity $\Delta v/v_0$ as a function of the sheet conductivity σ. We see that for $\sigma=\sigma_m$ maximum attenuation occurs, whereas $\Delta v/v_0$ exhibits a sharp step like increase around this value.

Hybrid Systems

As discussed before, the interaction between a SAW and the electron system in a semiconductor heterostructure is governed by the size of the electromechanical coupling coefficient K_{eff}^2. For a given material, crystal cut, and type of the surface wave, this material constant is fixed and cannot be altered externally. Following an old idea,[6] we developed a technique, where the coupling coefficient can be enhanced by nearly two orders of magnitude as compared to the monolithic case. The idea is simple: We excite the SAW on the strong piezoelectric (large K_{eff}^2) and then bring the electron system into close vicinity to the surface. The evanescent fields of the SAW then couple into the semiconductor layer and mediate the interaction between the SAW and the electron system. This is achieved by employing a technique introduced by Yablonovitch,[5] the so-called epitaxial lift-off (ELO). Here, below the active layers of the heterojunction a sacrificial layer is grown, which can be selectively etched away, hence leaving the substrate and the thin active layers separated.

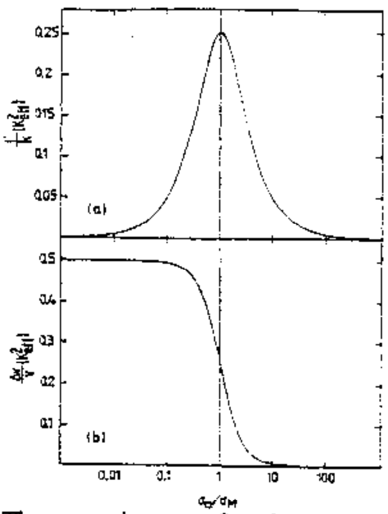

Fig. 1. Conductivity dependent attenuation (a) and relative change of sound velocity (b) for a SAW on a piezoelectric substrate, on which a thin conductive layer is deposited. Maximum attenuation occurs at $\sigma=\sigma_m$, where the impedance matching condition is met.[1]

$$\Gamma = \frac{K_{eff}^2}{2} k \frac{\sigma/\sigma_m}{1+(\sigma/\sigma_m)^2} \quad \text{and} \quad \frac{\Delta v}{v_0} = \frac{K_{eff}^2}{2} \frac{1}{1+(\sigma/\sigma_m)^2} \qquad (1)$$

Those are then transferred on the piezoelectric SAW delay line. The between 100 and 500 nm thin film needs not to be glued or pressed to the substrate surface as van der Waals forces strongly attach it to the SAW delay line. In Fig. 2, we depict a sketch of such a hybrid sample. The semiconductor layers in this example form a voltage tuneable field effect transistor to allow for a defined variation of the carrier density in the heterojunction.[7]

In Fig. 3, we depict a measurement of the SAW transmission parameters of such a device.[8] The sample layout is given in the inset. Here, we have deposited a semiconductor QW sample on a $LiNbO_3$ SAW delay line with split-four IDTs,[9] allowing for the generation of four different frequencies between 100 and 700 MHz. The semiconductor layer is equipped with a gate electrode and an Ohmic contact to apply a bias voltage between the gate and the electron system in the well. The sample is optimized to operate at room temperature. As the gate bias is swept between V_G=0V and some negative bias, the electron channel becomes gradually depleted, leading to a decreasing sheet conductivity. As expected from eq. (1) and Fig. 1, we observe a strong increase of attenuation around V_G=-6 V, indicating that the conductivity approaches the critical conductivity σ_m. At the same time, the sound velocity exhibits its typical step like change around this gate bias or equivalently sheet conductivity. The dashed lines in the figure represent again the result of our simple model calculation. This time, however, eq. (1) had to be modified to account for the effective coupling constant and the effective critical conductivity in the hybrid structure. This modification, based on a perturbative ansatz, is described in detail elsewhere.[10,11] The most striking observation is the fact that the effective coupling in this artificial hybrid system is enhanced by nearly two orders of magnitude as compared to the monolithic case.

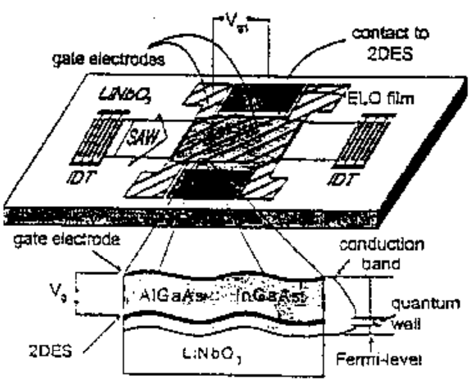

Fig. 2: Sketch of a hybrid system consisting of a strongly piezoelectric substrate and a high mobility semiconductor heterojunction. The active semiconductor layers have been selectively removed from their natural substrate. The epitaxial lift-off (ELO) technique was used for this purpose.[3]

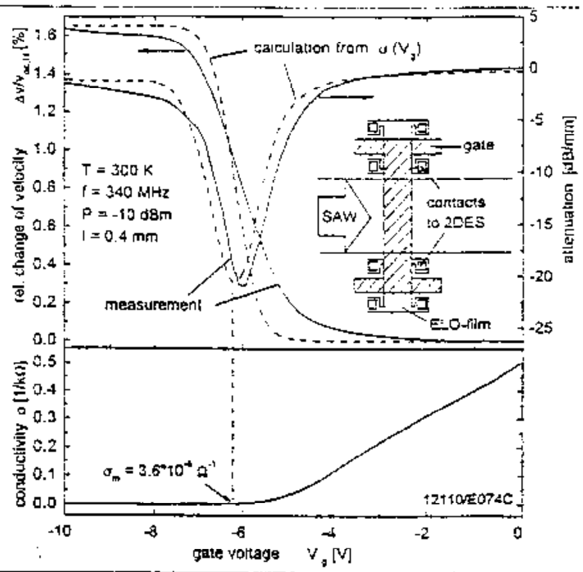

Fig. 3. SAW transmission and velocity change for a semiconductor / piezoelectric hybrid structure as depicted in the inset. Using a gate electrode, the carrier density in the quantum well can be tuned, leading to a tuneable conductivity in the electron channel, as shown in the lower panel. Using this conductivity, we can calculate the expected SAW transmission parameters as shown as dashed lines in the upper panel. The agreement with the experimentally obtained data (full lines) is quite perfect, given the fact that no fitting parameter is used. Note the very large absorption and change of sound velocity in exceed of 1%. Compared to the monolithic case, nearly two orders of magnitude in the strength of interaction are gained.[8]

Interaction of SAW and light

So far, we have discussed doped semiconductor QWs and heterojunctions, in which free carriers were present all the time. Here, we would like to discuss undoped quantum wells (QW), where electrons and holes are generated by illumination of the sample. In our sample, a thin InGaAs - layer is sandwiched between two GaAs barriers, forming a one-dimensional potential well along the growth direction. Once this QW is illuminated with light of sufficiently high energy, but not high enough to also create electron-hole pairs in the barrier material, photo generated charges are only present in the well. These bipolar charges, electrons in the conduction band states and holes in the valence band states may now interact with a SAW propagating across the structure.

In Fig. 4, we depict the measurement of the photoluminescence (PL) of such a QW where a SAW is propagating through the optically excited area of the sample. The sample exhibits a strong and narrow PL line at low temperatures (T=4.2 K) and with no SAW present. The energetic position, the intensity and the width of this line tells us that it is of excitonic origin, as expected for these experimental conditions. The effect of a SAW traversing the illuminated region on the sample from where the PL light originates is clearly seen from the figure: With increasing SAW power, the intensity of the PL strongly decreases, whereas the width and also the energetic position of the line remains nearly unaffected. Eventually, at the highest SAW power shown in the figure, the PL becomes completely quenched.

We explain this effect in terms of the strong in-plane electric fields of the SAW, which field ionize the excitons.[12] A simple estimate of the necessary electric field for ionization of an exciton in a semiconductor quantum well yields $E \sim 10^4$ V/cm.[13] As one can also easily show, such in-plane electric fields are achievable with a SAW of moderate power even on weakly piezoelectric GaAs substrates. Ionization, however, means that the electron and the hole are spatially separated by an electric field. This spatial separation in turn very strongly reduces the wave function overlap between the electron and the hole, and hence the probability for radiative recombination. In turn, this results in a strongly suppressed PL intensity. This is exactly what we observe in our sample.

As the potential modulation of the QW band structure is periodical in space and time, we also expect the electron and hole density distribution to be modulated. In other words, after ionization, the electrons will drift to a local potential minimum in the periodically modulated conduction band states, whereas the holes will drift to a local potential minimum in the respective valence band state. Like in a charge conveyor belt we may expect to now have spatially separated strips of charges in the moving potential wells of the SAW. In contrast to the experiment shown in

Fig. 3, however, we now have bipolar charges, stripes of electrons and holes, that are spatially separated by approximately one-half acoustic wavelength.
The lateral potential modulation moves together with the SAW at the speed of sound, hence we are able to also transport the trapped charge over macroscopic distances across our sample. If we are able to intentionally lift this lateral potential modulation of the SAW or to place a stronger

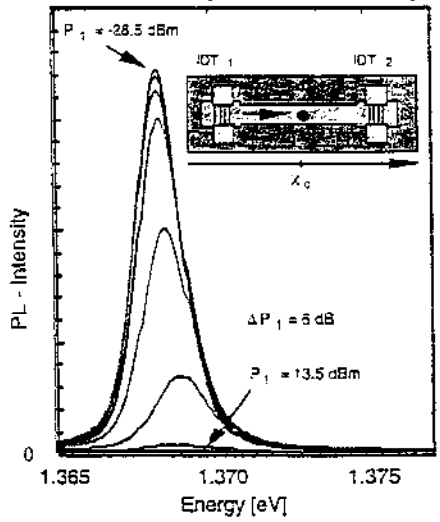

Fig. 4. Photoluminescence of a semiconductor quantum well under the influence of a surface acoustic wave. With increasing SAW power, the intensity of the PL strongly decreases, whereas its energetic position and line width remain nearly unchanged.[14]

confining potential at some location on the sample, being remote from the location of optical generation of the electrons and holes, we should be able to re-convert the trapped bipolar charges into light. Self assembled, strain induced quantum dots grown by metal organic vapor-phase epitaxy[15] are perfectly suitable for this experiment: Their confining potential reaches up to 100 meV for electrons and 50 meV for holes, by simultaneously providing very homogeneous size distribution. The density is about $1*10^9$ cm^2. Furthermore they can be selectively etched away making the definition of the active area very simple: Two IDTs with a center frequency of f_{SAW}=520 MHz are deposited along the [110] direction on the sample to excite and detect the SAW. Close to one of the IDTs (which we denote as the SAW emitter) the InP islands are completely

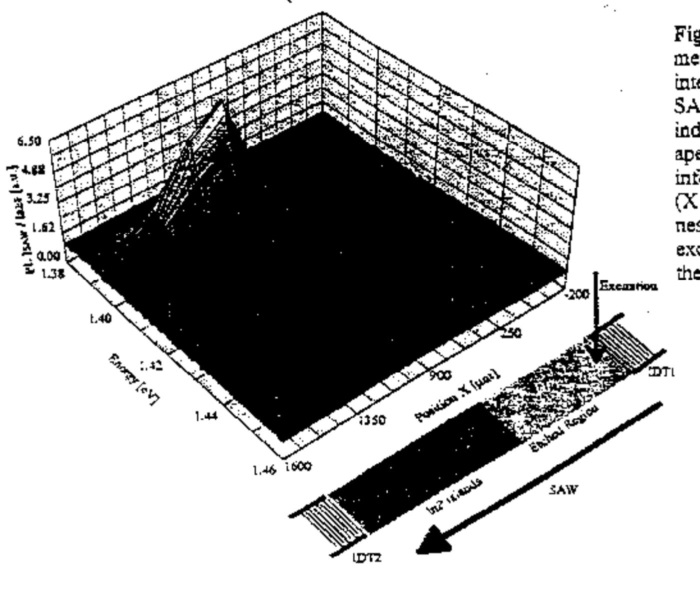

Fig 5. Spatially and spectral resolved measurement of the photoluminescence intensity induced by carriers transported by SAW into a region of self-assembled strain-induced quantum dots (X > 900 μm). A slit aperture was used to obtain the spatial information. Just beyond the etch border (X = 900 μm), strong quantum dot luminescence (E = 1.39 eV) can be seen. At the excitation point (X = 0 μm) no influence of the SAW can be resolved.[16]

removed from the surface. This provides a plain QW structure without any QDs on about half the sample area. By applying a short RF pulse at the frequency f_{SAW} to the IDT 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.

When the wave reaches the area on the sample where QDs are present, a QD may pluck a carrier while the wave passes by. The trapped charge carrier - say an electron - stays in the QD, while the SAW moves on. When additionally a hole is captured by the QD, an exciton is formed and PL can be emitted. As electrons and holes arrive behind each other, 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 periodicity is induced by the periodicity of the SAW.[17]

As one can see the PL decreases along the SAW path in the QD region: The absorption process of the dots reduces the number of carriers remaining caught in the SAW. One can think of two possible effects now: The overall number of transported carriers declines, which leads to a reduction of the capturing rate. Also the confinement in the SAW potential is increased as the screening is reduced due to less charge.

Conclusions

The hybridization of a piezoelectric substrate and a semiconductor thin film device has also led to a new class of devices. Here, especially the strongly enhanced coupling coefficient opened the door to very interesting applications. On the other hand we have shown that ambipolar charges can be not only transported with SAW and recombined at a remote location on the sample. They can also be used to pump QDs, leading to novel concepts of single photon light sources. The strictly periodic nature of this pumping mechanism is conceptually different from other schemes reported so far.[18,19] Here, time resolved experiments in combination with a higher spatial resolution are presently in preparation.

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References:

1. A. Wixforth, M. Wassermeier, J. Scriba, J.P. Kotthaus, G. Weimann, and W. Schlapp, Phys. Rev. B40, 7874 (1989)
2. A.R. Hutson, and D. L. White, J. Appl. Phys. 33, 40 (1962);K.A. Ingebrigsten, J. Appl. Phys. 41, 454 (1970); R. Adler, IEEE Trans. on Son. and Ultrasonics **SU-18**, 115 (1971)
3. A. Wixforth, J. P. Kotthaus, and G. Weimann, Phys. Rev. Lett. 56, 2104(1986)
4. S.H. Simon, Phys. Rev. B 54, 13878 (1996)
5. E. Yablonovitch, T. Gmitter, J. P. Harbison, and R. Bhat, Appl. Phys. Lett. 51, 2222 (1987)
6. A. Wixforth, J. Scriba, M. Wassermeier, and J.P. Kotthaus, J. Appl. Phys. 64, 2213 (1988)
7. C. Rocke, S. Manus, A. Wixforth, H. Nickel, W. Schlapp, and G. Weimann, Appl. Phys. Lett. 65, 2422 (1994)
8. M. Rotter *et al.*, IEEE Ultrasonics Symposium 1997, Toronto, Canada
9. H. Engan, IEEE Trans. Son. Ultrason., SU-22, 395 (1975)
10. B.A. Auld, "Acoustic Fields and Waves in Solids", II, John Wiley&Sons, New York (1973)
11. M. Rotter, Ph. D. Thesis, University of Munich, 1998
12. D.A.B. Miller *et al.*, Phys. Rev. B32, 1043 (1985)
13. C. Rocke, A.O. Govorov, A. Wixforth, G. Böhm, and G. Weimann Phys. Rev. **B57**, R6850 (1998)
14. C. Rocke, S. Zimmermann. A. Wixforth, and J.P. Kotthaus, Phys. Rev. Lett. 78, 4099 (1997)
15. H. Lipsanen, M. Sopanen and J. Ahopelto, Phys. Rev. B 51, 13868 (1995)
16. C. Bödefeld, A. Wixforth. J. Toivonen, M. Sopanen, H. Lipsanen, Phys. stat. sol., in print
17. C. Wiele, F. Haake, C. Rocke, and A. Wixforth, Phys. Rev. A 58, R2680 (1998)
18. J. Kim, O. Benson, H. Kann, and Y. Yamamoto, Nature 397, 500 (1999)
19. J.M. Gérard, B. Sermage, B. Gayral, B. Legrand, E. Costard, and V. Thierry-Mieg, Phys. Rev. Lett. 81, 1110(1998)