THE ROLE OF NONLINEAR ACOUSTOELECTRIC AND ACOUSTOOPTIC INTERACTION IN SEMICONDUCTOR HETEROSTRUCTURE SAW DEVICES

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Abstract — We study the nonlinear aspects of the interaction between charge carriers in a semiconductor quantum well and a surface acoustic wave (SAW). We demonstrate that for large SAW amplitudes the SAW transmission through an electron plasma or an optically generated electron-hole plasma exhibits strong nonlinear aspects, being completely different from each other. First experimental results together with a theoretical model for the nonlinear interaction between SAW and charge carriers in the semiconductor quantum film will be presented. Furthermore, we show that the interaction between quasi one-dimensional electron systems and dynamically created quantum dots on the one side and SAW on the other side leads to novel acoustoelectric effects that can be understood in terms of a quantum theory.

Keywords — SAW, semiconductor heterostructures, hybrid structure, nonlinear interaction, quantum effects

1. INTRODUCTION

In the past, most studies concerning the interaction between charge carriers in a two dimensional (2D) semiconductor quantum system and a SAW on a piezoelectric substrate have been performed with monolithic semiconductor SAW devices. Since the coupling coefficient for such devices is very small (e.g. $K^2_{eff,\mathrm{GaAs}} = 0,064\,\%$), only the linear regime of interaction was accessible. To achieve a SAW induced potential amplitude Φ_{SAW} comparable to the band-gap of a semiconductor and hence access experimentally the strongly nonlinear interaction regime, we use so-called semiconductor piezoelectric hybrid structures. A hybrid structure consists of a submicron thin semiconductor film tightly bonded on top of a strong piezoelectric host crystal, like e.g. $LiNbO_3$. We realize such devices with the epitaxial lift-off technique [1]. The coupling coefficient K^2_{eff} in such structures can be two orders of magnitude larger than in conventional GaAs systems.

The nonlinear interaction is not only of academic interest. One can exploit the nonlinear interaction to realize novel devices like e.g. a non-reciprocal SAW delay line [2], a SAW camera to detect photogenerated charge carrier distributions [3], or an optical delay line based on the storage of optically generated electron-hole pairs in the traveling lateral potential well of a SAW [4].

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Here, we study both experimentally and theoretically the interaction of intense surface acoustic waves with an electron and an electron-hole plasma of a quantum well. The experiments performed on hybrid semiconductor piezoelectric structures exhibit strong nonlinear acoustoelectric and acoustooptic effects due to the formation of moving electron and electron-hole wires, respectively. We show theoretically that the nonlinear interaction of a SAW with a photogenerated electron-hole plasma qualitatively differs from the case of an unipolar electron system. For low temperatures, we consider the regime when the intense SAW forms moving quantum wires. It turns out that the quantum nonlinear interaction qualitatively differs from the classical one.

To model the nonlinear regime theoretically and describe our experimental results, we develop a coupled amplitude theory based on hydrodynamic equations, assuming $K^2_{eff} \ll 1$. The sound absorption coefficient Γ due to the 2D charge carrier plasma is determined by the expression [5]:

$$\Gamma = \frac{\langle jE_{\mathrm{SAW}}\rangle}{I_{\mathrm{SAW}}}, \qquad (1)$$

where $\langle ...\rangle$ denotes spatial averaging, I_{SAW} is the SAW intensity, E_{SAW} is the electric field induced by the SAW in the plane of the 2D plasma, and j is the current of the charge carriers.

2. ELECTRON-HOLE PLASMA AND SAW

In semiconductor heterostructures it is possible to selectively generate an electron-hole plasma in the plane of the quantum well by illuminating the sample with laser light of a specific energy. These photogenerated charge carriers usually decay after some lifetime while re-emitting a secondary photon of characteristic energy. This process is called photoluminescence (PL). The PL can be strongly suppressed under the influence of strong SAW fields. With increasing SAW intensity the homogenously distributed electron hole plasma turns into spatially separated, moving electron and hole wires. The spatial separation in turn very strongly reduces the wave function overlap between the electrons and the holes, and therefore the probability for radiative recombination. Recently we have been able to experimentally observe the quenching of the PL at room temperature for a semiconductor piezoelectric hybrid structure, consisting of a 260 nm thick AlGaAs/GaAs multi quantum well film on top of a $LiNbO_3$ SAW delay line (Fig. 1 (b)). The SAW intensity at which the PL is completely switched off ($I_{\rm SAW} = 21.5\,$dBm), corresponds in our sample to a piezoelectric potential amplitude of the SAW $\Phi_{\rm SAW} = 5\,$V.

The interaction between the charge carriers and the SAW not only strongly modifies the optical properties of the semiconductor film, but also the propagation of the SAW. To model the acoustooptic effect in the presence of permanent homogeneous laser illumination, we include generation and nonlinear recombination terms of the optically generated charges into the 2D hydrodynamic equations. Details of the theory and the simulations can be found in the paper by Kalameitsev et al. [6].

The inset of Fig. 1 (a) illustrates the separation of the initially homogeneous plasma into stripes of electrons and holes. We plot the 2D electron density $n(x')$ and the 2D hole density $p(x')$ as a function of the moving coordinate $x' = x - v_s t$, where v_s is the sound velocity, for two different SAW potential amplitudes. Once the moving potential of the SAW $\Phi_{\rm SAW}$ is increased beyond a threshold value, not only a separation into stripes, but also an accumulation of the charge carriers can be observed. One also recognizes that the functions $n(x')$ and $p(x')$ slightly overlap. This is a necessary condition to achieve a steady state solution with a strong recombination nonlinearity. A noticeable gap between the stripes would lead to a nonstationary accumulation of carriers.

Fig. 1 (a) shows the results for the the absorption coefficient Γ as a function of the lateral SAW potential $\Phi_{\rm SAW}$. The nonmonotonic behavior for $\Phi_{\rm SAW} < 2\,$V correlates with the onset of noticeable separation of the plasma into stripes and with an increase in the mean density N_0 of electrons and holes. For larger $\Phi_{\rm SAW}$ the absorption coefficient decreases and for $\Phi_{\rm SAW} \to \infty$, we find the following asymptotic behavior $\Gamma \propto 1/\Phi_{\rm SAW}$. As a direct consequence one finds that the absorbed energy Q in the presence of permanent homogeneous laser illumination increases as $Q = I\Gamma \propto \Phi_{\rm SAW} \propto \sqrt{I_{\rm SAW}}$. In the next section we will see that this behavior fundamentally differs from the interaction with a unipolar plasma, where no generation or recombination mechanism exists.

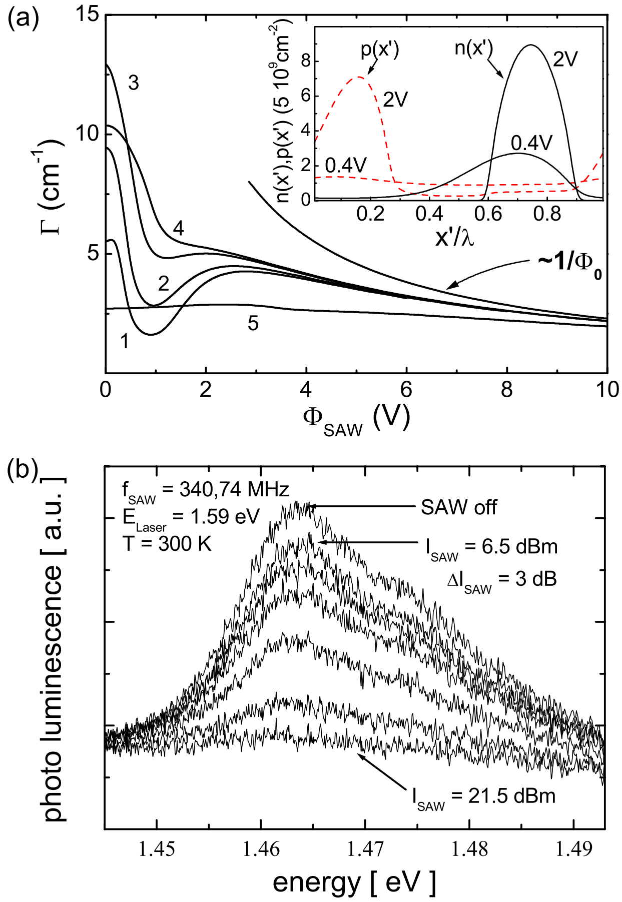

Fig. 1. (a) illustrates the calculated absorption coefficient due to an electron-hole plasma as a function of the SAW potential amplitude $\Phi_{\rm SAW}$ for various optical excitation powers. The numbers 1-5 correspond to the photogenerated 2D carrier densities $n_{s0} = 10^9$, $2\cdot 10^9$, $5\cdot 10^9$, 10^{10}, and $5\cdot 10^{10}$ cm^{-2}, respectively, in the absence of a SAW. The inset in (a) illustrates the separation of electron and holes into stripes with increasing SAW potential. (b) shows experimental results of the photoluminescence spectra of a AlGaAs/GaAs multi quantum well hybrid structure under the influence of a SAW for different acoustic intensities $I_{\rm SAW}$.

3. ELECTRON PLASMA AND SAW

Room-temperature experiments were again performed on hybrid semiconductor $LiNbO_3$ structures. These structures have an additional metallic gate on top of the semiconductor heterostructure [7] to tune the Fermi level and therefore the electron density N_s of the 2-dimensional electron gas. Due to the strong piezoelectricity of the host substrate the SAW can break up a formerly 2D electron plasma into moving wires. This effect was clearly observed in charge transport experiments [7]. For the simulations the following parameters are used: The electron mobility at room temperature is $5000\,{\rm cm^2/Vs}$. The SAW wave length $\lambda = 33\,\mu$m and $v_s = 3.8\cdot 10^5\,$cm/s. Using our theoretical results we can explain the experimental observations (inset of Fig. 2)

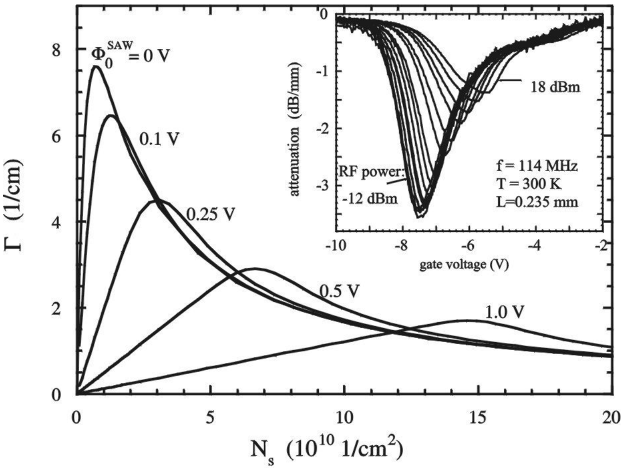

Fig. 2. The calculated absorption coefficient as a function of the carrier density N_s for various potential amplitudes. For high acoustic powers the attenuation is strongly reduced and shifted to higher densities. The experimental results shown in the inset are in good qualitative agreement. Here the density of the electron plasma is tuned by the gate voltage.

Here, too, the nonlinear acoustoelectric interaction results in a strong modification of the SAW attenuation. We see in Fig. 2 that with increasing $\Phi_{\rm SAW}$ the absorption coefficient in general decreases and its maximum is shifted to the higher values of N_s. Further calculations not presented in Fig. 2 show that at low electron densities the SAW absorption coefficient decreases monotonously with increasing sound intensity, whereas at high electron density the absorption coefficient is a non-monotonous function of the sound intensity [5]. This behavior is explained in terms of nonlinear dynamic screening in combination with sound induced formation of moving wires. In the limit $I_{\rm SAW} \to \infty$ one finds $\Gamma_1 \propto 1/I_{\rm SAW}$[5, 8]. In contrast to the electron hole plasma the absorbed energy Q saturates at a constant level.

4. MOVING QUANTUM WIRES

The nonlinear behavior changes dramatically for low temperatures and a sufficiently high intensity of the surface acoustic wave. Under realistic conditions we achieve a piezoelectric potential $\Phi_{\rm SAW}$ of around 1-2 V corresponding to a quantization energy of 1 meV in the moving electron wires. It turns out that for thermal energies smaller than 1 meV, i.e. for temperatures smaller than 10 K, quantum effects will play a major role [9, 10, 11].

The interaction between a SAW and a 2D electron system is characterized by the SAW energy absorbed in an electron system per unit time and area

$$Q = < \mathbf{j}_s(\mathbf{r},t)\mathbf{E}_{\rm SAW}(x,t) >_{\mathbf{r}}, \qquad (2)$$

where $< ... >_{\mathbf{r}}$ means averaging over the surface area of a macroscopic sample, $\mathbf{j}_s$ is the dissipative 2D electron current in the plane of the quantum well induced by the piezoelectric fields of the SAW $\mathbf{E}_{\rm SAW}$, $\mathbf{r} = (x,y)$ is the in-plane coordinate, and t is the time. Here, the Rayleigh SAW propagates in the x-direction. The dissipative current $\mathbf{j}_s$ occur, since the electrons scatter by crystal defects, i.e. by impurities, and in this way heat the crystal. In our model the impurities are assumed to be randomly distributed Coulomb scatteres with homogeneous density. The dissipative current $\mathbf{j}_s$ implies electron transitions in the continuum of states near the Fermi surface. This is because the energy transfer of such transitions is small, as the velocity of sound v_s is typically much less than the electron Fermi velocity v_F. Using this argument, we can conclude that in 2D and 3D systems the sound dissipation is quite effective, because of the strong electronic scattering in the continuum of states near the Fermi level.

The situation changes, if an intense SAW propagating along a 2D system of mobile electrons dynamically creates moving quantum wires. An initially homogeneous density of states of a 2D quantum well turns into a 1D density of states of quantum wires, being strongly peaked at the quantization energies [12].

Fig. 3 shows the SAW absorption as a function of the potential amplitude $\Phi_{\rm SAW}$ for various temperatures. The function $Q(\Phi_{\rm SAW})$ reflects the density of states in a wire. For relatively small SAW potentials the electrons occupy a few 1D subbands and the main contribution to Q comes from inter-subband transitions induced by impurities. The contribution of inter-subband transitions is responsible for the absorption in the quasi-classical and classical regimes. At $\Phi_{\rm SAW} = 0.2$ V the Fermi level coincides with the bottom of the first excited subband which leads to a maximum in the absorption Q. For smaller $\Phi_{\rm SAW}$, the features related to higher subbands are not seen because of the finite temperature. For higher SAW potential amplitudes the electrons only occupy the ground subband and the SAW absorption strongly decreases with increasing SAW potential amplitude $\Phi_{\rm SAW}$ and finally becomes saturated at a constant level. The residual absorption at $\Phi_{\rm SAW} \to \infty$ originates from scattering within the the ground subband and depends on the quality of a quantum well and the electron density.

The inset of Fig. 3 illustrates the difference between the quantum picture of the acoustoelectric interaction and the classical one. At room temperature, the absorption is an increasing function of $\Phi_{\rm SAW}$ and becomes saturated for high sound intensities in the regime when the SAW totally traps all electrons into wires [5]. For the typical room temperature parameters $\mu_{2D} = 5000\,{\rm cm}^2/{\rm Vs}$ and $N_s =$

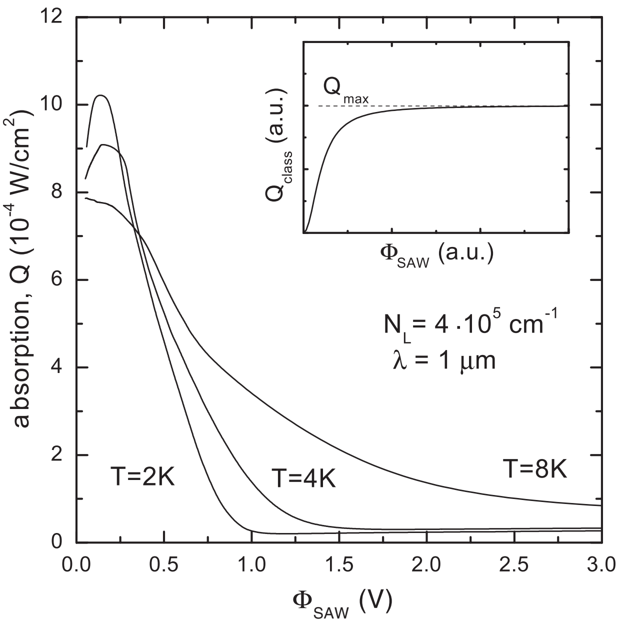

Fig. 3. The calculated absorption as a function of the SAW potential amplitude for dynamically defined quantum wires for various temperatures. The insert shows the Φ_{SAW}-dependency of the classical SAW absorption Q_{class} for the case of an electron system in a quantum well at room temperature.

$4 \cdot 10^9\,\mathrm{cm}^{-2}$ [7], we obtain $Q_{max} \simeq 2 \cdot 10^{-2}\,\mathrm{W/cm}^2$ which is a few orders of magnitude larger than the calculated quantum-limit absorption.

It is also possible to dynamically create quantum dots with two sound waves propagating perpendicular to each other. In such a system the effect of the quantization is expected to be even stronger as the density of states vanishes near the Fermi level and any quasi-elastic transitions become impossible at sufficiently high sound intensities [11].

5. CONCLUSION

We investigated the nonlinear interaction of a SAW with three different charge carrier systems: the photogenerated electron hole plasma, the gate induced classical unipolar electron plasma and the unipolar electron plasma in the quantum limit. In all three systems the homogeneous charge carrier distribution separates into moving charge carrier wires under the influence of high SAW potential amplitudes. However, the asymptotic behavior of the absorbed energy is fundamentally different in the three cases. For the electron hole plasma we find that Q monotonously increases with increasing SAW intensity, while for the classical unipolar electron plasma the absorbed energy increases but saturates at a constant level. For the moving quantum wires the absorbed energy Q decreases and saturates at a constant level that is a few orders of magnitude smaller than for the classical absorption.

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References

[1] E. Yablonovitch, D.M. Hwang, T.J. Gmitter, L.T. Florez, and J.P. Harbison, Appl. Phys. Lett. **56**, 2419 (1990); M. Rotter, C. Rocke, S. Böhm, A. Lorke, A. Wixforth, W. Ruile, and L. Korte, Appl. Phys. Lett. **70**, 2097 (1997).

[2] M. Rotter, W. Ruile, G. Scholl, and A. Wixforth, IEEE Trans. UFFC **47**, 242-248 (2000).

[3] M. Streibl, A. Wixforth, J.P. Kotthaus, A.O. Govorov, C. Kadow, A.C. Gossard, Appl. Phys. Lett. **75**, 4139 (1999).

[4] C. Rocke, S. Zimmermann, A. Wixforth, J.P. Kotthaus, G. Böhm, G. Weimann, Phys. Rev. Lett. **78**, 4099 (1997).

[5] A.O. Govorov, A.V. Kalameitsev, M. Rotter, A. Wixforth, J.P. Kotthaus, K.-H. Hoffmann, N. Botkin, Phys. Rev. B **62**, 2659 (2000).

[6] A.V. Kalameitsev, A.O. Govorov, H.-J. Kutschera, A. Wixforth, JETP Letter **72**, 190 (2000).

[7] M. Rotter, A.V. Kalameitsev, A.O. Govorov, W.A. Ruile, A. Wixforth, Phs. Rev. Lett. **82**, 2171 (1999); M. Rotter, A. Wixforth, A.O. Govorov, W. Ruile, D. Bernklau, and H. Riechert, Appl. Phys. Lett. **75**, 965 (1999).

[8] V.L. Gurevich and B.D. Laikhtman, Sov. Phys. JETP **19**, 407 (1964); Yu.V. Gulyaev, Sov. Phys. - Solid State, **12**, 328 (1970).

[9] L.V. Keldysh, Fiz. Tverd. Tela **4**, 1015 (1962) [Sov. Phys. - Solid State]; V.V. Popov and A.V. Chaplik, Zh. Eksp. Teor. Fiz. **73**, 1009 (1977) [Sov. Phys. JETP].

[10] B.D. Laikhtman and Yu.V. Pogorel'skii, Zh. Eksp. Teor. Fiz. **75**, 1892 (1978) [Sov. Phys. JETP, **8**, 953 (1978)].

[11] A.O. Govorov, A.V. Kalamitsev, V.M. Kovalev, H.-J. Kutschera, A. Wixforth, Phys. Rev. Lett. **87**, 226803 (2001).

[12] J.H. Davies, *The Physics of Low-Dimensional Semiconductors* (Cambridge, University-Press, UK, 1998).