Nonlinear acoustoelectric and acoustooptic effects in semiconductor layered systems

H.-J. Kutschera[1], A. Wixforth[1], A.V. Kalameitsev[2], and A.O. Govorov[2,3]

[1] Sektion Physik der Ludwig Maximilians Universität and CeNS, Geschwister-Scholl-Platz 1, 80539 München, Germany

[2]Institute of Semiconductor Physics, RAS, Siberian Branch, Lavrent'eva Av. 13, 630090 Novosibirsk, Russia

[3] presently at Department of Physics and Astronomy, and CMSS Program, Ohio University, Athens, OH 45701, USA

Abstract— We study both theoretically and experimentally 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-piezocrystal 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 and quantum dots and predict a novel quantum acoustic phenomenon, self-induced acoustic transparency.

I. Introduction

The nonlinear interaction between charge carriers in a two dimensional (2D) semiconductor quantum system and surface acoustic waves (SAW) on a piezoelectric substrate has recently attracted considerable interest from a technological point of view. This interaction can be exploited to realize, e.g. novel sensor devices [1, 2] or optical delay lines [3].

In the past the SAW interaction was already applied in 2D semiconductor heterostructures to study e.g. the quantum Hall effect, electron transport through a quantum-point contact, and commensurability effects [4]. Because of the small electromechanical coupling constant K_{eff}^2 of the used semiconductor substrates, all those experiments have been done in the regime of linear interaction. With the epitaxial lift-off technique one can realize modern semiconductor-piezocrystal hybrid structures [5]. They consist of a submicron thin semiconductor film (AlGaAs) and a substrate made of a strong piezoelectric crystal ($LiNbO_3$). In these structures K_{eff}^2 can be two orders of magnitude greater than in conventional semiconductor systems. Therefore the SAW induced potential amplitude Φ_{SAW} can become comparable to the band-gap of the semiconductor and hence strongly nonlinear acoustoelectric and acoustooptic interaction is accessible to the experiment.

E-mail: hans-joerg.kutschera@physik.uni-muenchen.de

In this paper, we study the transition from the linear to the limit of strongly nonlinear regime in the interaction between SAWs and an electron plasma or a system with photogenerated carriers. First, we demonstrate that for large SAW amplitudes the transmission of the sound wave through an optically generated electron-hole plasma exhibits strong nonlinear aspects. In comparison, the interaction between electrons in doped semiconductor heterostructures and SAW also exhibits nonlinearities at large amplitudes, but turns out to be fundamentally different. Moreover, the interaction between SAWs and quasi one-dimensional electron systems or dynamically created quantum dots at low temperatures leads to novel acoustoelectric quantum effects. It turns out that the quantum nonlinear interaction qualitatively differs from the classical one.

To model the nonlinear regime and describe our experimental results, we develop a coupled amplitude theory based on hydrodynamic equations, assuming $K_{eff}^2 \ll 1$. The sound absorption coefficient Γ and the SAW velocity shift δv_s due to the 2D charge carrier plasma are determined by the expressions [8]:

$$\frac{\delta v_s}{v_s^0} = \frac{\langle j\Phi_{SAW}\rangle}{2I_{SAW}}, \qquad \Gamma = \frac{\langle jE_{SAW}\rangle}{I_{SAW}},$$

where $\langle ... \rangle$ denotes spatial averaging, v_s^0 is the sound velocity in the absence of the plasma, I_{SAW} is the SAW intensity, Φ_{SAW} is the piezoelectric potential of the SAW, 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.

II. Electron-hole plasma and SAWs

To start with, we discuss our theoretical results of the nonlinear acoustoelectric interaction in a hybrid structure in the presence of permanent homogeneous laser illumination. At room temperature an electron-hole plasma is generated in the semiconductor quantum well on top of the piezoelectric host substrate. To model the acoustooptic effect, 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]. Here, we just want to discuss the numeric solutions.

The inset of Fig.1 (a) illustrates the separation of electrons $n(x' = x - v_s t)$ and holes $p(x')$ into stripes once the moving potential Φ_{SAW} of the SAW is increased beyond a threshold value. This is accompanied by an accumulation of the charge carriers. One also recognizes that the functions $n(x')$ and $p(x')$ may slightly overlap. This overlap is necessary to achieve a steady state solution with a strong recombination nonlinearity, because the appearance of a noticeable gap between the stripes would lead to a nonstationary accumulation of carriers.

With increasing lateral SAW potential Φ_{SAW} the absorption coefficient Γ exhibits a general decrease (Fig.1 (a)). The nonmonotonic behavior for $\Phi_{SAW} < 2\,V$ 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 (inset of Fig. 1 (b)). For $\Phi_{SAW} \to \infty$, the sound absorption coefficient decreases as $\Gamma \propto 1/\Phi_{SAW}$. The absorbed energy Q is proportional to $Q = I\Gamma \propto \Phi_{SAW} \propto \sqrt{I_{SAW}}$.

The SAW velocity shows a similar behavior. Up to $2\,V$ the solution is also nonmonotonic for the same reason. With increasing SAW-intensity, the SAW-velocity decreases (Fig.1 (b)), because the plasma becomes more and more dense and strongly screens the field of the SAW. In the limit $I_{SAW} \to \infty$, the SAW velocity shift converges as $\delta v_s \to -K^2_{eff}/2$.

First experiments were performed on InGaAs quantum wells for the case of a spatially inhomogeneous plasma generated by a laser beam [1], so far. The dynamics of electron-hole pairs was also studied by Alsina et al. using spatially-resolved photoluminescence [7].

III. Interaction with an electron system

The dependencies of the interaction between SAW and a electron hole plasma are related to a strong recombination nonlinearity of the photoexcited charge carriers. In a unipolar plasma, however, no recombination mechanism exists and the total number of charge remains constant. Therefore, the behavior of a unipolar plasma in an intense acoustic wave is fundamentally different [8].

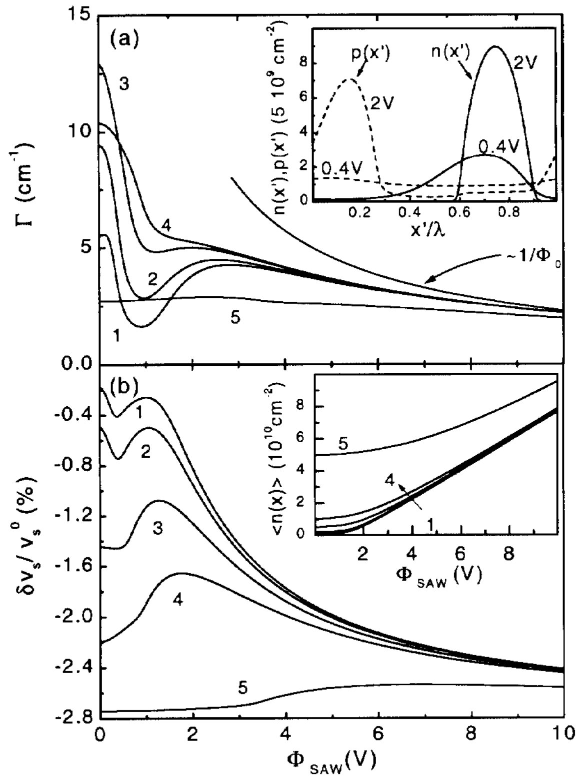

Fig. 1. The calculated absorption coefficient (a) and shift of the SAW-velocity (b) due to an electron-hole plasma as a function of the SAW potential amplitude Φ_{SAW} for various optical excitation powers. The numbers 1-5 correspond to the photogenerated 2D carrier densities in the absence of a SAW $n_{s0} = 10^9$, $2 * 10^9$, $5 * 10^9$, 10^{10}, and $5 * 10^{10}$ cm^{-2}, respectively. $\lambda = 60$ μm; the electron mobility $\mu_e = 2000$ cm^2/Vs and the hole mobility $\mu_h = \mu_e/6$. The inset in (a) illustrates the separation of electron and holes into stripes with increasing SAW potential. The inset of (b) shows the average density $N_e(\Phi_{SAW})$ for various n_{s0}. $K^2_{eff} = 0.056$.

A. Electrons in semiconductor heterostructures

Here, too, the nonlinear acoustoelectric interaction results in an increase of the SAW velocity v_s and a strong modification of the SAW attenuation. At low electron densities the SAW absorption coefficient decreases with increasing sound intensity, whereas at high electron density the absorption coefficient is nonmonotonous function of the sound intensity (Fig. 2). This behavior is explained in terms of nonlinear dy-

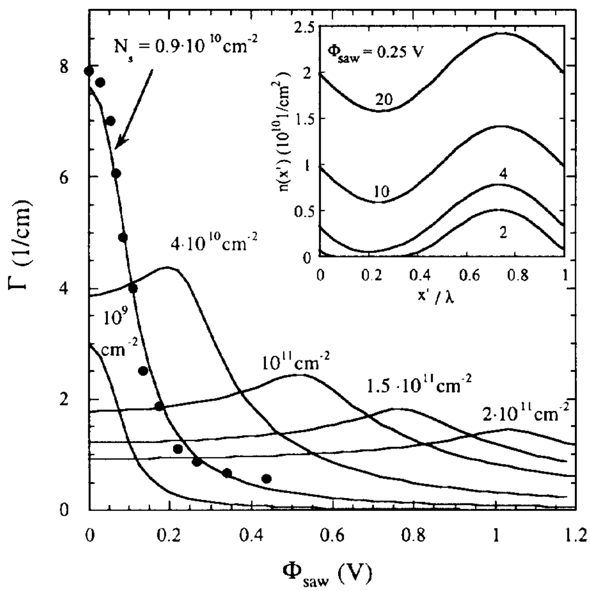

Fig. 2. The calculated absorption coefficient Γ as a function of the SAW piezopotential amplitude Φ^{saw} for various electron densities N_s. The dots show the experimentally measured absorption coefficient at the top gate voltage $-7.5\ V$. In the inset we plot the calculated local carrier density n as a function of the in-plane coordinate x' for different N_s. The numbers attached to the plots correspond to N_s in units of $10^{10}\ cm^{-2}$.

namic screening and the sound induced formation of moving wires. In the limit $I_{SAW} \to \infty$, $\Gamma_1 \propto 1/I_{SAW}$ and $\delta v_s \propto 1/\sqrt{I_{SAW}}$ [8, 9]. In contrast to the electron hole plasma, however, the absorbed energy Q saturates at a constant level.

Room-temperature experiments were performed on the already mentioned hybrid semiconductor-$LiNbO_3$ structures. These structures contain a semiconductor quantum well tightly bound to the $LiNbO_3$ host crystal and a top metallic gate [10] to vary the Fermi level in the electron system. Due to the strong piezoelectricity of the host substrate an effective coupling constant as high as $K^2_{eff} = 0.056$ can be achieved. The SAW then can break up the formerly 2D electron plasma into moving wires. This effect was clearly observed in charge transport experiments [10]. For the simulations the following parameters are used: The electron mobility at room temperature is $5000\ cm^2/Vs$. The SAW wave length $\lambda = 33\ \mu m$ and $v_s = 3.8 * 10^5\ cm/s$. Using our theoretical results we can explain the experimental observations. For the case of the nonlinear SAW absorption coefficient we find a very good quantitative agreement between theory and experiment (dots in Fig. 2).

B. Dynamically created quantum wires and dots at low temperatures

The nonlinear phenomena observed in Ref. [10] at room temperature are well understood. However, for low temperatures and a sufficiently high intensity of the acoustic wave, the classical description can not longer hold because of the quantization of the electronic energy spectrum induced by a SAW [11, 12]. In this section, we show how dramatically the SAW transmission changes when the sound wave creates dynamically-defined 1D and 0D electron states from a formerly homogeneous 2D quantum film.

A simple picture of the acoustoelectric effects is as follows: The effective 'friction' force for a sound wave originates from the dissipative electric current $\mathbf{j}_s$ in the plane of a quantum well induced by the piezoelectric field of a SAW. The electrons scatter by crystal defects, i.e. by impurities, and hence heat the crystal lattice. The sound energy dissipation per unit time and area is then given by

$$Q = < \mathbf{j}_s(\mathbf{r}, t) \mathbf{E}_{SAW}(x, t) >_{\mathbf{r}}, \qquad (1)$$

where $< ... >_{\mathbf{r}}$ means averaging over surface area of a macroscopic sample and $\mathbf{E}_{SAW}$ is the piezoelectric field induced by a SAW. $\mathbf{r} = (x, y)$ is the in-plane coordinate and t is the time. In our model, the Rayleigh SAW propagates in the x-direction. 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 [13]. Further transformation into a quasi zero-dimensional (0D) system is possible involving two SAWs [3] with perpendicular momenta. Here, the electron motion is confined within both in-plane directions and moving quantum dots with a fully quantized spectrum are dynamically created. In this case, the density of states is a set of delta functions. Since in the regime of intense SAW the dissipation basically reflects the density of states, it exhibits quantum oscillations with increas-

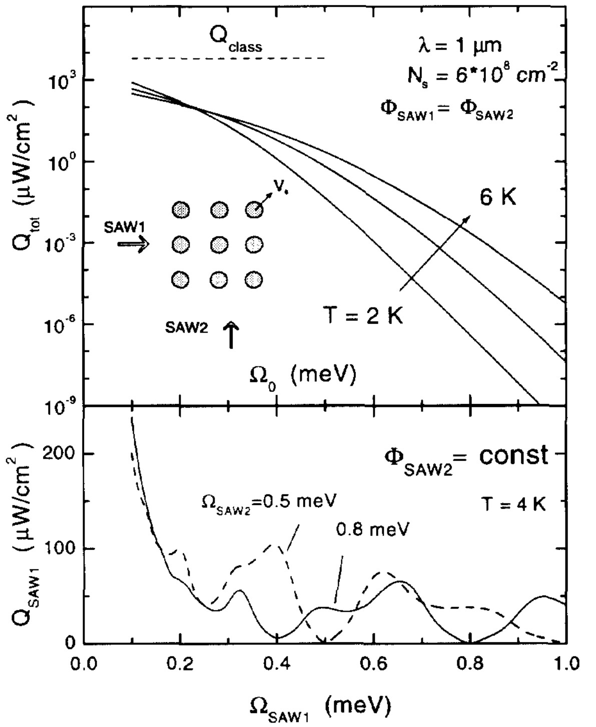

Fig. 3. Calculated absorption of both SAWs Q_{tot} for dynamically defined quantum dots as a function of the sound-induced lateral quantization Ω_0 for the equal intensities of SAWs. The lower part shows the absorption of the SAW1 for fixed intensity of the SAW2.

ing Φ_{SAW}. The sound attenuation is then dramatically be suppressed when the density of states near the Fermi level becomes small (1D) or even vanishes (0D) and electrons near the Fermi level can not scatter anymore.

Fig. 3 depicts the case of dynamically created quantum dots. Here, the effect of the quantization is expected to be very strong as the density of states vanishes near the Fermi level and any quasi-elastic transitions become impossible at sufficiently high sound intensities. To dynamically create moving quantum dots, we consider two perpendicular sound waves, SAW1 and SAW2, producing piezoelectric potentials $\Phi_{SAW1(2)}$ (see inset of Fig. 3). A quantum dot created by the SAWs can be regarded as a 2D anisotropic harmonic oscillator with two frequencies: $\Omega_{SAW1(2)} \propto \sqrt{\Phi_{SAW1(2)}}$. For the symmetric case $\Phi_{SAW1} = \Phi_{SAW2} = \Phi_{SAW}$, the asymptotic behavior for the absorption of both SAWs is

$$Q_{tot} \propto \exp -\frac{\hbar\Omega_0}{2m^* v_s^2} = \exp -\sqrt{\frac{\Phi_{SAW}}{\Phi_s}}, \qquad (2)$$

where $\Omega_0 = \Omega_{SAW1(2)}$, $\Phi_s = 4(m^* v_s^2)^2 m^*/[e\hbar^2 k^2]$, and $\Phi_{SAW} \to \infty$. In the limit of large SAW intensities, quasi-elastic transitions induced by the impurity potential become strongly suppressed and the absorption decreases exponentially, because of the fully quantized spectrum. The effect of quantization on the SAW absorption is really dramatic (Fig. 3). The maximal piezoelectric potentials achieved for hybrid and GaAs structures are about $1-2\ V$ corresponding to $\hbar\Omega_0 \sim 1\ meV$ [3, 10]. The calculated absorption for $\hbar\Omega_0 \sim 1\ meV$ for a temperature $T = 2\ K$ turns out to be 12 orders of magnitude smaller than the one at room temperature! For the asymmetric case $\Phi^0_{SAW1} \neq \Phi^0_{SAW2}$, we find the regime of the quantum interaction between SAWs resulting in giant quantum oscillations (Fig. 3). We note that the method of two SAWs was recently exploited to study the strongly nonlinear acoustoelectric interaction for the system with photogenerated carriers [3].

Acknowledgment

The authors gratefully acknowledge fruitful discussions with J. P. Kotthaus and A. V. Chaplik, and financial support by the Deutsche Forschungsgemeinschaft (DFG), the Volkswagen Stiftung, and the Russian Foundation for Basic Research.

References

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

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

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

[4] A. Wixforth et al., Phys. Rev. B **40**, (1989) 7874; R. L. Willett et al., Phys. Rev. Lett. **71**, (1993) 3846; V. I. Talyanskii et al., Phys. Rev. B **56**, (1997) 15180; J. M. Shilton et al., Phys. Rev. B **51**, (1995) 14770.

[5] E. Yablonovich et al., Appl. Phys. Lett. **56**, (1990) 2419; M. Rotter et al., *ibid* **70**, (1997) 2097.

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

[7] F. Alsina, P. V. Santos, R. Hey, A. García-Cristóbal, and A. Cantarero, Phys. Rev. B **64**, 041304(R) (2001).

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

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

[10] M. Rotter, A.V. Kalameitsev, A.O. Govorov-AO, W.A. Ruile, A. Wixforth, Phs. Rev. Lett. **82**, 2171 (1999), M. Rotter et al., Appl. Phys. Lett. **75**, (1999) 965.

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

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

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