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# Acousto-electric transport through a two-dimensional system in the nonlinear regime

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**Abstract.** Surface acoustic waves strongly interact with a two-dimensional electron plasma in hybrid semiconductor-piezoelectric structures. At high intensities of a surface acoustic wave, nonlinear effects play the main role: the plasma turns into moving electron stripes, the acousto-electric current reaches its maximum, and the absorption of the sound wave is strongly suppressed. The interaction between the surface acoustic wave and the photo-generated carriers results in ionization and drag of excitons. The electron-hole pairs are effectively trapped in the moving potential of the sound wave and then re-assembled into photonic signals. The photoluminescence intensity in the presence of a sound wave strongly depends on the excitation because of screening. Together with experimental data, we present a theoretical description of nonlinear phenomena using hydrodynamic approach.

## Introduction

The interaction between surface acoustic waves (SAWs) and mobile carriers in quantum wells is an important method to study dynamic properties of two-dimensional (2D) systems. The SAW can trap carriers and induce acoustic charge transport (ACT) investigated in a number of systems in a view of possible device applications [1]. Also, the SAW-method was applied to study the quantum Hall effects [2, 3], electron transport through a quantum-point contact [4], lateral nanostructures [5], and commensurability effects in a 2D system [6]. However, all those experiments have been done in the regime of small signals and linear interaction.

Here we study the transition from the linear regime of acousto-electric interaction to the limit of strongly non-linear effects in a 2D electron plasma and in a system with photo-generated carriers [7–9].

## 1 Acousto-electric phenomena in semiconductor-piezoelectric structures

In usual GaAs-based microstructures it is very difficult to realize SAWs with high-amplitude potentials because electro-mechanical coupling in GaAs is relatively weak. The strong piezoelectric interaction is achieved in hybrid structures [7, 8] (Fig. 1), where the SAW-induced potential amplitude can be comparable with the band-gap of a semiconductor. The hybrid structure is fabricated by the epitaxial lift-off (ELO) technique [10] and includes a semiconductor layer tightly bound to a piezoelectric host crystal ($LiNbO_3$) by the van der Waals forces. The semiconductor layer contains a InGaAs-AlGaAs quantum well (QW) with a high-quality 2D electron gas (2DEG), to which Ohmic contacts are formed. The distance between the QW and the piezocrystal is just 32 nm, whereas the distance between

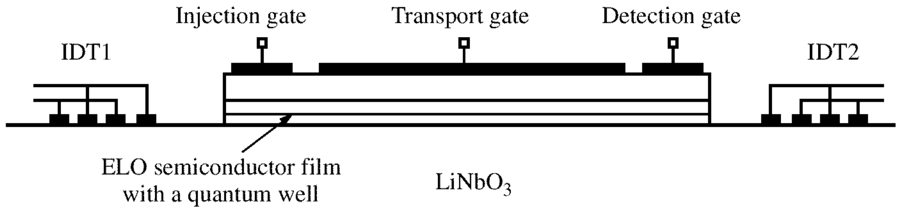


**Fig. 1.** The cross section of a hybrid semiconductor-piezoelectric structure.

the QW and the top transport gate is $d = 450$ nm. By changing the transport-gate voltage $V_t$ we can tune the electron density in a QW. In this structure, travelling SAWs can induce very strong piezoelectric fields in the semiconductor layer due to the strong piezoelectricity of the host $LiNbO_3$-crystal. The SAW is induced and detected by the metal interdigital transducers, IDT1 and IDT2, respectively, at room temperatures [8].

*1.1 Acoustic charge transport*

Transport properties of a 2DEG in the presence of a SAW can be examined by the injection and detection top gates (Fig. 1). The transport gate is kept at a negative voltage, $V_t = -8$ V, so that the QW is depleted. The negative bias at the injection gate is removed for a short moment (0.3 $\mu$s) and electrons are injected into the QW. The SAW flushes a certain amount of injected electrons. These electrons are trapped in the moving potential of the SAW and transported through the sample to the detection gate. The detection gate acts as a Schottky diode charge detector and the electron signal is read out by an oscilloscope. The signal on the detection gate as a function of the time has a form of a peak with a maximum at $t = t_m$. The detection time $t_m$ strongly depends on the SAW intensity, indicating a nonlinear interaction. In Fig. 2 we show the dependence of the ACT-signal velocity, $v = L/t_m$, from the SAW-intensity [8]. Here $L$ is the spacing between the injection and transport gates. The amplitude of the SAW potential $\Phi_0$ is calculated from the SAW intensity $I_{saw}$. With increasing potential $\Phi_0$ the signal velocity first increases and finally saturates at the sound velocity $v_s$. This indicates that the intense SAW completely traps injected electrons into piezopotential minimums.

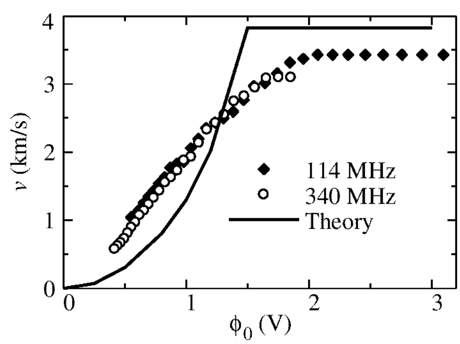


**Fig. 2.** The measured velocity of acoustic charge transport as a function of the SAW-potential amplitude for two SAW frequencies [8]. Theoretical data are also shown.

*1.2 SAW absorption*

The SAW can be strong enough to break up an initially homogenous 2D plasma into moving stripes. Here we study the transmission of a SAW through a 2DEG. The density of a 2DEG

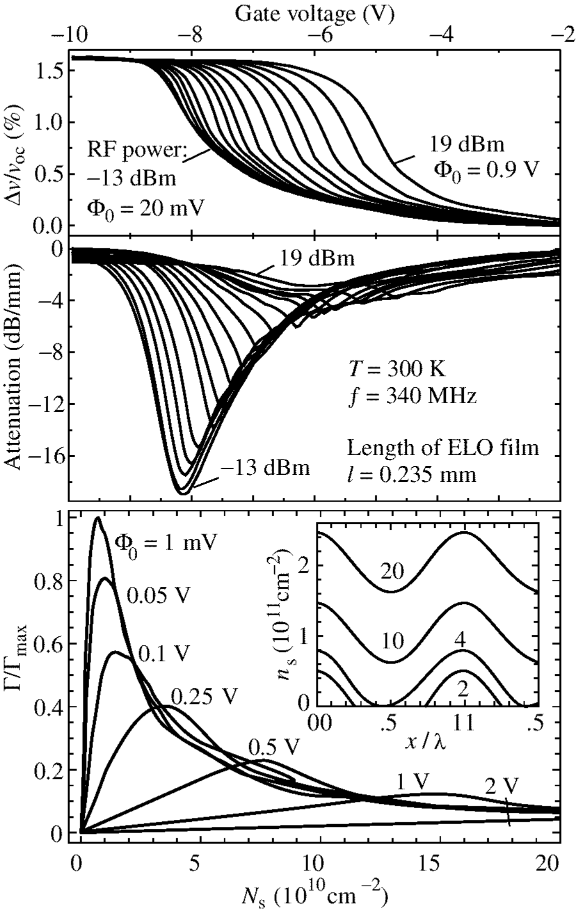


**Fig. 3.** The measured attenuation and the velocity change of a SAW, $\Delta v$, as a function of the gate voltage for different SAW-intensities. The lower part shows the calculated attenuation as a function of the electron density. In the insert we plot the function $n_s(x)$. The numbers attached to the plots correspond to $N_s$ in units of $10^{10}$ cm$^{-2}$ [8].

$N_s$ is varied by the transport-gate voltage. It is known that, at small SAW-intensities, the sound attenuation by electrons $\Gamma$ as a function of the conductivity $\sigma$ exhibits a maximum at $\sigma = \sigma_m$ [11], where $\sigma_m = \epsilon_{\text{eff}} v_s/(2\pi)$ and $\epsilon_{\text{eff}}$ is the effective dielectric constant. At high SAW amplitudes the attenuation is strongly modified: $\Gamma$ is suppressed and its maximum is shifted to higher conductivity. The attenuation for different SAW-intensities is plotted in Fig. 3 as a function of the transport-gate voltage, which determines the conductivity and the electron density in a 2DEG [8].

In order to understand these phenomena we develop a nonlinear theory for acousto-electric effects in 2D [12]. Most of previous theoretical studies on SAW interactions in a 2D plasma [11] relate to the linear regime of interaction, when the equilibrium 2D density $N_s$ is much larger than the perturbation $\delta n_s(x, t)$ caused by a SAW. Here $x$ and $t$ are the in-plane coordinate and the time, respectively. However, in our system, the SAW-potential amplitude is so large that $N_s \sim \delta n_s$. The electron dynamics in our system is described by non-linear hydrodynamic equations. In the long wave-length limit, $kd \ll 1$, the electron-density distribution can be found from the equation [8]

$$en_s(x_1)\mu \left[ \frac{4\pi ed}{\epsilon_s} \frac{dn_s(x_1)}{dx_1} + E_0 \sin(kx_1) \right] + ev_s n_s(x_1) = A_0, \tag{1}$$

where $A_0$ is a constant. Here $k$ is the wave vector of a SAW, $x_1 = x - v_s t$, $E_0$ is the amplitude of a SAW electric field, and $\mu$ and $\epsilon_s$ are the electron mobility and the semiconductor dielectric constant, respectively. The solution of Eq. (1) should be periodic. Numerical solutions for various average 2D densities $N_s \langle n_e(x_1) \rangle$ are shown in the inset of Fig. 3. Here the brackets $\langle \ldots \rangle$ denote the average over the wave length. It can be seen that the electron system forms separated stripes for small values of $N_s$. $\Phi_0 = E_0/k$ is the amplitude of the SAW potential. It follows from Eq. (1) that in the regime of separated strips the average local velocity of the electron plasma, $v = \langle v_e(x_1) \rangle$, is at its maximum and equal to the sound velocity $v_s$. Similar behavior was described in Ref. [13] for 3D.

In Fig. 2, we also plot the calculated average velocity $v$ as a function of the potential $\Phi_0$ using the parameters $N_s = 2.5 \times 10^{10}$ cm$^{-2}$ and $\mu = 5000$ cm$^2$/Vs. Our relatively simple model reproduces the experimental behavior well. The saturation of $v$ reflects the formation of electron stripes.

The absorption of a SAW by electrons is given by the equation $Q = \langle jE_{saw} \rangle$, where $j$ is the electron current and $E_{saw}$ is the SAW electric field. The non-linear absorption coefficient, $\Gamma = Q/I_{saw}$, as a function of $N_s$ was calculated using the solutions of Eq. (1) (Fig. 3). In the limit of high $\Phi_0$ the absorption coefficient is given by $\Gamma = Q_{max}/I_{saw} \propto 1/I_{saw}$ and decreases with increasing SAW-intensity $I_{saw}$ [8, 13]. Theory and experiment are in good agreement: in intense SAWs the calculated absorption coefficient is strongly suppressed and the maximum of $\Gamma(N_s)$ is shifted to higher $N_s$. In the limit of large $N_s$, an asymptotic solution of Eq. (1) was given in Ref. [14] without noting the condition $\sigma_m \ll \sigma$. Also, the Weinreich relation [15] can be very useful to describe the non-linear regime [13, 16].

The shift of the SAW-velocity due to the electron plasma is shown in the upper part of Fig. 3. With increasing $I_{saw}$ the curves are shifted towards larger conductivity $\sigma$ (Fig. 3) which can be understood in terms of screening effects.

## 2 Interaction of acoustic waves with photo-generated carriers

In recent experiments on semiconductor QWs Rocke and co-authors [9] have demonstrated that a photonic signal can be transformed into electron-hole pairs, transported over a macroscopic distance across a sample, and then re-assembled again into light. A strong potential superlattice induced by a SAW spatially separates electrons and holes and thus the life-time is increased by a few orders of magnitude. In contrast to ACT of unipolar charges [1], in this case, the SAW transports two types of carriers, electrons and holes. This experiment develops the principles for realization of photonic memory devices and delay lines.

Another type of experiments deals with the SAW absorption and the phase shift due to the interaction with photo-generated carriers in semiconductor QWs [17, 18]. In the pump-probe experiments [17], a first intense SAW ionizes photo-generated excitons and a second low-intensity SAW is absorbed by electron-hole pairs. Thus, the ionization process due to the piezoelectric fields can be directly observed. At low temperatures in relatively wide QWs, the SAW can induce exciton localization and drag due to the quantum confined Stark effect [18, 20].

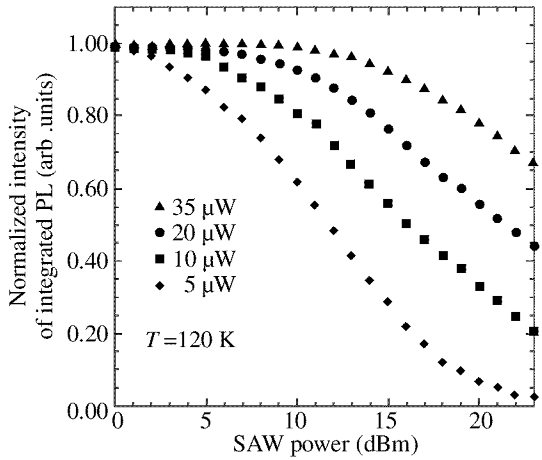


**Fig. 4.** The photoluminescence intensity of a GaAs-based QW as a function of the SAW power for different laser intensities [19].

At high temperatures the SAW interacts mostly with free electrons and holes. The amplitude of the SAW-potential in the presence of photo-generated carriers in the linear regime is given by $\Phi = \Phi_0/|1 + i\sigma/\sigma_m|$, where $\sigma$ is the conductivity of an electron-hole plasma. $\sigma_m$ is relatively low and corresponds to the densities $10^9-10^{10}$ cm$^{-2}$. In optical experiments, the photo-generated electron density can be larger than the above numbers and thus the plasma can effectively screen the SAW potential. The importance of the screening effects in the photoluminescence (PL) spectra of QWs is seen from the experimental data shown in Fig. 4. Here we see that the PL intensity strongly decreases with increasing SAW power due to spatial separation of electrons and holes. At high laser intensities suppression of the PL due to the SAW is not so effective: the PL intensity starts to decrease at higher $I_{saw}$. Thus, at high laser intensities, the photo-generated plasma can effectively screen the SAW potential and prevent suppression of the PL. These preliminary data on acousto-optical interactions show that the screening effect in the presence of a SAW can be utilized to realize optical nonlinearity.

*Acknowledgements*

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## References

[1] M. J. Hoskins, H. Morko and B. J. Hunsinger, *Appl. Phys. Lett.* **41**, 332 (1982); W. J. Tanski, S. W. Merritt, R. N. Sacks, D. E. Cullen, E. J. Branciforte, R. D. Caroll and T. C. Eschrich, *Appl. Phys. Lett.* **52**, 18 (1988).

[2] A. Wixforth, J. P. Kotthaus and G. Weimann, *Phys. Rev.* **B40**, 7874 (1989).

[3] R. L. Willett, R. R. Ruel, K. W. West and L. N. Pfeiffer, *Phys. Rev. Lett.* **71**, 3846 (1993).

[4] V. I. Talyanskii, J. M. Shilton, M. Pepper, C. G. Smith, C. J. B. Ford, E. H. Linfield, D. A. Richie and G. A. C. Jones, *Phys. Rev.* **B56**, 15180 (1997).

[5] G. R. Nash, S. J. Bending, Y. Kershaw, K. Eberl, P. Grambow, and K. von Klitzing, *Surf. Sci.* **361/362**, 668 (1996).

[6] J. M. Shilton, D. R. Mace, V. I. Talyanskii, M. Pepper, M. Y. Simmons, A. C. Churchill and D. A. Ritchie, *Phys. Rev.* **B51**, 14770 (1995).

[7] M. Rotter, C. Rocke, S. Böhm, A. Lorke, A. Wixforth, W. Ruile and L. Korte, *Appl. Phys. Lett.* **70**, 2097 (1997).
[8] M. Rotter, A. V. Kalameitsev, A. O. Govorov, W. Ruile and A. Wixforth, *Phys. Rev. Lett.* **82**, 2171 (1999).
[9] C. Rocke, S. Zimmermann, A. Wixforth and J. P. Kotthaus, *Phys. Rev. Lett.* **78**, 4099 (1997).
[10] E. Yablonovich, D. M. Hwang, T. J. Gmitter, L. T. Florez and J. P. Harbison, *Appl. Phys. Lett.* **56**, 2419 (1990).
[11] K. A. Ingebrigtsen, *J. Appl. Phys.* **41**, 454 (1970); A. V. Chaplik, *Sov. Tech. Phys. Lett.* **10**, 584 (1984).
[12] In 3D systems a nonlinear theory of acousto-electric interactions was developed in a number of papers, see e.g. V. L. Gurevich and B. D. Laikhtman, *Sov. Phys. JETP* **19**, 407 (1964); J. R. A. Beale, *Phys. Rev.* **135**, 1761 (1964); P. N. Butcher and N. R. Ogg, *Brit. J. Appl. Phys.* (*J. Phys. D*), Ser. 2, Vol. 1, 1271 (1968); P. K. Tien, *Phys. Rev.* **171**, 970 (1968).
[13] Yu. V. Gulyaev, *Fiz. Tekhn. Poluprovod.* **12**, 415 (1970) [*Sov. Phys. Semicond.*].
[14] V. A. Vyun, Proceed. of *IEEE Ultrasonic Symposium* (France, 1994), p. 441.
[15] G. Weinreich, *Phys. Rev.* **107**, 317 (1957).
[16] M. Rotter et al., will be submitted to *Appl. Phys. Lett.*
[17] C. Rocke, A. O. Govorov, A. Wixforth, G. Böhm and G. Weimann, *Phys. Rev.* **B57**, R6850 (1998).
[18] M. Streibl et al., in preparation.
[19] M. Streibl, C. Rocke, A. O. Govorov and A. Wixforth, Proceed. of *IEEE Ultrasonic Symposium* (Japan, 1998), in press.
[20] S. Zimmermann, A. O. Govorov, W. Hansen, J. P. Kotthaus, M. Bichler and W. Wegscheider, *Phys. Rev.* **B56**, 13414 (1997).