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Electron Wires Driven by a Surface Acoustic Wave and Nonlinear Acoustoelectric Interactions in Quantum Wells

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Abstract We study both theoretically and experimentally the nonlinear interaction of intense surface acoustic waves (SAW's) with electron and electron-hole plasmas in quantum wells. The experiments performed on hybrid semiconductor-piezoelectric structures exhibit strongly nonlinear acousto-electric effects due to the formation of moving electron wires. To describe the nonlinear phenomena, we develop a coupled-amplitude method for a two-dimensional system in the strongly nonlinear regime of interaction. Theory and experiment are found to be in a good agreement. Also, we show theoretically that the nonlinear interaction of a SAW with a photo-generated electron-hole plasma qualitatively differs from the acousto-electric interaction in the case of an unipolar electron system. For low temperatures, we consider the regime when the intense SAW forms moving quantum wires and develop a theory of the quantum SAW attenuation.

1 Introduction

The interaction between SAW's and mobile carriers in quantum wells is a powerful method to study dynamic properties of two-dimensional (2D) systems. The SAW can trap carriers and induce acoustic charge transport (ACT) [1]. Also, the SAW-method was applied to study the quantum Hall effects, electron transport through a quantum-point contact, and commensurability effects in a 2D system [2]. However, most of those experiments have been done in the regime of small signals and linear interaction. The linear interaction in 2D systems and in nanostructures was theoretically studied in a number of papers [3,4]. Here we study the transition from the linear regime of acousto-electric interaction to the limit of strongly nonlinear effects in a 2D electron plasma and in a system with photogenerated carriers [5–8].

2 Nonlinear acousto-electric interaction in an electron system

The room-temperature experiments with SAW's were performed on the hybrid semiconductor-$LiNbO_3$ structures fabricated by the epitaxial lift-off technique [9]. These structures contain a semiconductor quantum well tightly bonded to the $LiNbO_3$ host crystal and a top metallic gate [5]. Due to the strong piezoelectricity of a hybrid structure a SAW can break up a formerly 2D electron plasma into moving wires. The effect of the wire formation was clearly seen in the ACT experiments from the saturation of the transport velocity [5]. Also, the nonlinear acousto-electric interaction results in an increase of the SAW velocity c_s and in a strong modification of the SAW attenuation. To describe the experimental results we develop a coupled-amplitude theory assuming $K^2_{eff} \ll 1$, where K^2_{eff} is the effective electromechanical coupling coefficient of the hybrid structure. In a short sample, for the SAW-velocity shift δc_s and the absorption coefficient Γ_1 we obtain [6]

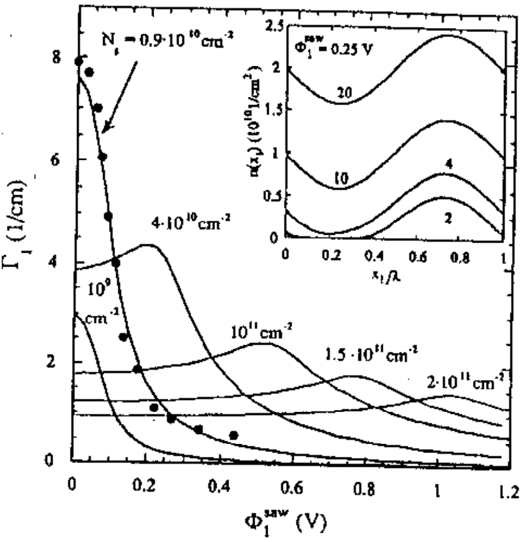

Fig. 1 The calculated absorption coefficient Γ_1 as a function of the SAW piezopotential amplitude Φ_1^{saw} for various electron densities N_s. The dots show the experimentally measured absorption coefficient at the top gate voltage -7.5 V. In the inset we plot the calculated local carrier density n as a function of the in-plane coordinate x_1 for different N_s. The numbers attached to the plots correspond to N_s in units of 10^{10} cm^{-2}.

$$\frac{\delta c_s}{c_s} = \frac{< j_e \Phi_{SAW} >}{2 I_{SAW}}, \quad \Gamma_1 = \frac{< j_e E_{SAW} >}{I_{SAW}}. \qquad (1)$$

where $< ... >$ means averaging, j_e is the 2D current induced by the SAW, and E_{SAW} and Φ_{SAW} are the electric field and the potential induced by the SAW, respectively. I_{SAW} is the SAW intensity.

The electron current was numerically calculated from the nonlinear hydrodynamic equations. We use the following parameters. The electron mobility at room temperature is 5000 cm^2/Vs. The SAW wave length $\lambda = 33\ \mu m$ and $c_s = 3.8 * 10^5\ cm/s$. Using our theoretical results we can explain experimental observations. For the case of the nonlinear SAW absorption coefficient we find a good quantitative agreement between theory and experiment (Fig. 1). At low electron densities the SAW absorption coefficient decreases with increasing sound intensity, whereas at high electron density the absorption coefficient is not a monotonous function of the sound intensity (Fig. 1). This behavior is explained in terms of the nonlinear dynamic screening and the formation of wires. In the limit $I_{SAW} \to \infty$, $\Gamma_1 \propto 1/I_{SAW}$ and $\delta c_s \propto 1/\sqrt{I_{SAW}}$ [6.10].

3 Photogenerated electron-hole plasma

To model the acousto-electric effects in an electron-hole plasma of a quantum well we include into the 2D hydrodynamic equations the generation and nonlinear recombination terms. We see from our results that with increasing SAW intensity the plasma turns into electron and hole wires and the average carrier density N_e increases due to the spatial separation of electrons and holes. In this regime the sound dissipation increases with increasing the SAW-intensity [8]. At the same time, the SAW-velocity decreases [8] (Fig. 2). In the limit $I_{SAW} \to \infty$, the SAW dissipation $Q \propto \sqrt{I_{SAW}}$ and $\delta c_s \to -K^2_{eff}/2$. This is in contrast to the case of an electron plasma, where the sound dissipation saturates and c_s increases at high SAW-intensity [6,10]. Experiments were performed on InGaAs quantum wells for the case of a spatially-inhomogeneous plasma generated by a laser beam [7], so far.

4 Driven quantum wires

At a high SAW intensity electrons in the moving wires can be quantized at low temperature [11]. Our estimations show that the quantization energy under the realistic conditions can be about 2 meV. Using the motion equation for the electron density matrix we calculate the impurity-assisted SAW absorption in the regime of moving quantum wires. A quantum mechanism of the nonlinear acousto-electric interaction arises from the formation of 1D subbands. The SAW absorption is an oscillating function of the acoustic intensity due to the density of states in wires. Furthermore, we find that the SAW absorption does not vanish even in the strictly 1D limit. This is due to electron scattering by impurities in the direction perpendicular to the sound wave vector.

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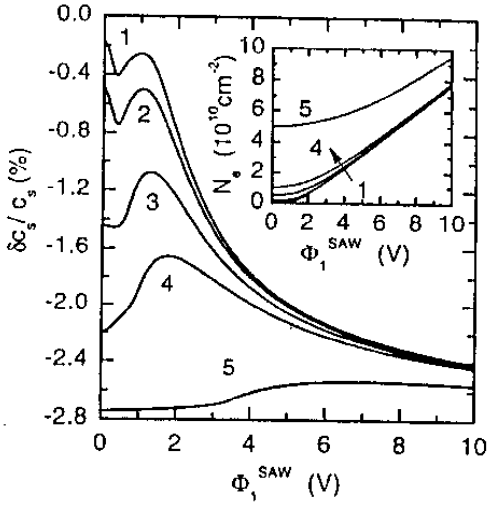

Fig. 2 The calculated shift of the SAW-velocity due to an electron-hole plasma as a function of the SAW potential amplitude Φ_1^{saw} for various optical excitation powers. The numbers 1-5 correspond to the photogenerated 2D carrier densities in the absence of a SAW $n_{s0} = 10^9$, $2 * 10^9$, $5 * 10^9$, 10^{10}, and $5 * 10^{10}\ cm^{-2}$, respectively. $\lambda = 60\ \mu m$; the electron mobility $\mu_e = 2000\ cm^2/Vs$ and the hole mobility $\mu_h = \mu_e/6$. The insert shows the average density $N_e(\Phi_1^{SAW})$ for various n_{s0}. $K^2_{eff} = 0.056$.

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