# Frequency- and spin-dependent absorption of surface-acoustic-waves by a 2D electron gas in the quantum Hall regime

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## Abstract

The dynamic conductivity of a quasi-two-dimensional electron system with a large spin splitting in high magnetic fields is probed via the acousto–electric interaction with a surface acoustic wave. We compare this interaction for the case of non-spin polarized even and spin polarized odd Landau niveaus of the electron system in the integer quantum Hall regime and find a clear violation of a simple relaxation model that describes other features of the interaction properly. We propose differences in the electrical screening in the quasi-two-dimensional electron system in the case of spin polarized and non-spin polarized Landau levels to explain our experimental findings.

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The interaction between the piezoelectric fields of a surface acoustic wave (SAW) and high-mobility quasi-two-dimensional electron systems (2DES) as realized in GaAs/Al$_x$Ga$_{1-x}$As heterostructures was frequently used over the past few years to study the dynamic magnetoconductivity $\sigma(\omega,k,B)$ of the 2DES especially in the integer and in the fractional quantum Hall regime [1–4]. This interaction leads to a conductivity-dependent attenuation and change in velocity of the SAW especially when $\sigma(\omega,k)$ is low as is the case for a 2DES in high magnetic fields. Also acousto–electric effects [5] being related to a phonon drag in SAW experiments were recently used to study the properties of quantum point contacts [6] and single-electron transport driven by SAW. The strong lateral electric fields connected with a SAW on a piezoelectric substrate offer also the possibility of new types of optical experiments, where the electrons and holes building up photon-generated excitons can be separated and transported over large distances [7].

First investigations of the integer quantum Hall effect led to a description of the relaxation-type interaction between the SAW and the 2DES, where the

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piezoelectric fields accompanying the SAW are screened by the 2D-electrons with a time constant ${}_{\mathrm{r}} = (\varepsilon_0 + \varepsilon_{\mathrm{s}})/(\sigma(\omega,k)k)$ [8]. $k = (2\pi/\lambda)$ is the wave vector of the SAW and $\varepsilon_{\mathrm{s}}$ and $\varepsilon_0$ are the dielectric permittivities of the substrate and the free space, respectively. The SAW attenuation and the renormalization of the sound velocity caused by the interaction can therefore be described by [1]

$$\Gamma = \frac{K_{\mathrm{eff}}^2}{2} \cdot k \cdot \frac{(\omega,k)/\sigma_m}{1 + (\sigma(\omega,k)/\sigma_{\mathrm{m}})^2}, \qquad (1)$$

$$v/v_0 = \frac{K_{\mathrm{eff}}^2}{2} \cdot \frac{1}{1 + (\sigma(\omega,k)/\sigma_{\mathrm{m}})^2}, \qquad (2)$$

where $\sigma_{\mathrm{m}} = v_0(\varepsilon_0 + \varepsilon_{\mathrm{s}})$ denotes a critical conductivity where maximum attenuation

$$\Gamma_{\max} = k\frac{K_{\mathrm{eff}}^2}{4} \qquad (3)$$

occurs. The maximum change in the sound velocity can be derived to

$$v_{\max} = \frac{K_{\mathrm{eff}}^2}{2} v_0, \qquad (4)$$

where $v_0$ is the sound velocity for a free surface. Combining Eqs. (1)–(4) leads to an expression marking a semicircle for the phase plot of the SAW attenuation versus velocity change [9]

$$\frac{v}{v_{\max}} - \frac{1}{2}\Big)^2 + \left(\frac{\Gamma}{2\Gamma_{\max}}\right)^2 = \left(\frac{1}{2}\right)^2. \qquad (5)$$

Nevertheless, Eqs. (1), (2) and (5) are valid only if one assumes a negligible imaginary part of the conductivity $\sigma(\omega,k)$ [2]. The presence of an imaginary conductivity in the 2DES would especially lead to a deviation from the semicircle form for the phase plot in Eq. (5).

Although many efforts were made to investigate $(\omega,k)$ in high-mobility 2DES especially in the fractional quantum Hall effect [2,4] and finally led to the discovery of the so-called composite fermions forming in that regime, the influence of disorder and spin polarization of the Landau levels in the integer quantum Hall regime was not yet analyzed.

Here, we would like to present our investigations on the absorption of surface acoustic waves by a disordered 2DES as realized in a low-mobility AlSb/InAs/AlSb quantum well. In InAs, the small effective mass $m_\Gamma^* = 0.023m_{\mathrm{e}}$, corresponding to large Landau level splittings, leads to giant quantum oscillations in the propagation parameters of the SAW in spite of the relative high disorder in the 2DES.

Additionally, the large effective $g$-factor ($g^* = -15$) of InAs offers the possibility to resolve the spin polarized odd Landau levels easily even at relatively high temperatures. Our AlSb/InAs/AlSb type II heterostructures principally consist of a 15 nm InAs quantum well with an electron mobility $\mu = 180\,000\ \mathrm{cm^2/Vs}$. Typical carrier densities range between $N_{\mathrm{S}} = 8 \times 10^{11}$ and $3 \times 10^{12}\ \mathrm{cm^{-2}}$. To achieve information about the frequency- and wave vector-dependence of the absorption of the SAW, we either used state-of-the-art single- and multi-frequency SAW delay lines ($f = 0.2$–$2.5$ GHz) prepared directly onto the heterostructure by electron beam lithography or a multi-frequency SAW delay line on a (YZ-cut) $\mathrm{LiNbO_3}$ substrate. Here, a pair of split-4 interdigital transducers [10] provides a whole set of 12 operating frequencies between $f = 100$ MHz and $f = 2.35$ GHz. A proximity coupling technique where the AlSb/InAs/AlSb heterostructure is pressed face down on the SAW-delay line is then used to couple the SAW to the 2DES [11]. Both types of measurements were carried out by propagating SAW pulses of typically 1 μs duration and analyzing both the amplitude and the phase of the transmitted SAW simultaneously by use of homodyne detection and standard boxcar integration techniques [1]. The SAW delay lines were located in the center of a superconducting solenoid providing magnetic fields up to $B = 15$ T at a temperature of about $T = 2$ K.

In Fig. 1 we depict the experimentally obtained change of the sound velocity in the wave-length regime between $\lambda \approx 15\ \mu\mathrm{m}$ and $\lambda < 1\ \mu\mathrm{m}$ for the monolithic delay lines on the heterostructures. The lower four frequencies were measured on a single sample using a pair of split-4 interdigital transducers [10]. The three higher frequencies were investigated by using single-mode interdigital transducers on three different samples cut from the same wafer as the first one. The curves clearly reflect the Shubnikov–de Haas oscillations of the magnetoconductivity $\sigma_{xx}(B)$. As a first result, a decrease in the velocity shift at odd Landau levels with increasing frequency is observed, that cannot be explained by use of Eqs. (1)–(4). Not shown here is the simultaneously measured attenu-

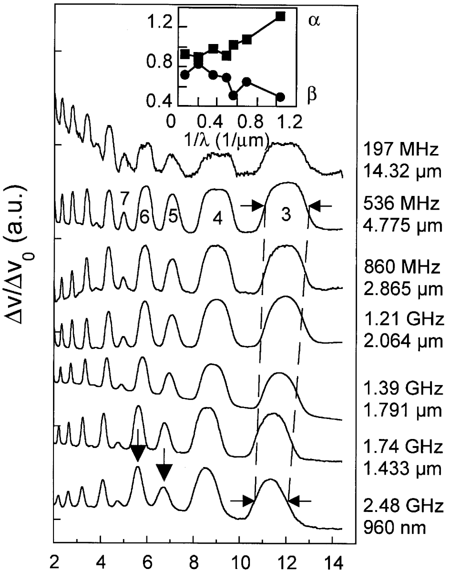

Fig. 1. Normalized shift of the SAW velocity. The traces are shifted for clarity. An obvious decrease of the peaks at the odd filling factors 7, 5 and 3 is visible. Additionally, a narrowing of all peaks with increasing frequency is observed. The inset shows the wave-length dependence of the ratios of the attenuation at filling factors 5 and 6 ($\alpha = \Gamma_5/\Gamma_6$) and the velocity change at the same filling factors ($\beta = (\Delta v/v_0)_5/(\Delta v/v_0)_6$), respectively.

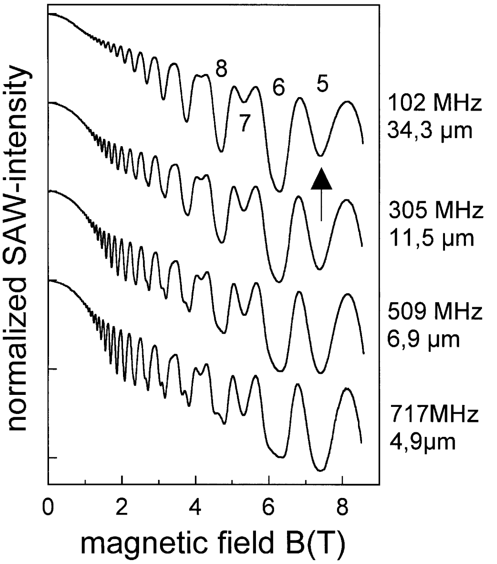

Fig. 2. Normalized SAW attenuation obtained by a proximity coupling hybrid technique. The traces are shifted for clarity. The increase of the absorption peaks for the odd filling factors 7 and 5 is striking.

ation spectrum, where an increase in attenuation at odd Landau levels is observed, in clear contradiction to Fig. 1. In order to compare this behaviour at odd to that observed at even Landau levels, we plot in the inset the ratio of the sound attenuation $\alpha = \Gamma_5/\Gamma_6$ and the change of sound velocity $\beta = (\Delta v/v_0)_5/(\Delta v/v_0)_6$ for filling factors 5 and 6, respectively. The trace for the ratio of the SAW-absorption shows a clear increase with increasing SAW-frequency, whereas the curve for the velocity change decreases. Regarding Eqs. (1)–(4) this ratio should be independent of the SAW-frequency. Therefore, the simultaneous increase of attenuation and decrease of the velocity shift with increasing frequency at odd filling factors, that is not observed for even Landau levels, crucially violates Eqs. (1)–(4) of the simple relaxation model.

The second observation is a narrowing of the observed peaks in $\Delta v/v_0$ at integer filling factors with increasing frequency as is qualitatively predicted by Aleiner et al. [12], for the case that the wavelength of the SAW becomes comparable to the localization length $\xi$ in the disordered 2DES.

As an alternative experiment, in Fig. 2 we present the SAW attenuation measured employing the above-mentioned hybrid system. This plot shows a qualitatively equivalent result to the attenuation data obtained in the measurement above, but this time an even stronger increase of the attenuation at the odd filling factors 7 and 5 with increasing frequency is visible.

The phase plot in Fig. 3 of the attenuation versus the velocity change according to Eq. (5) at an arbitrary frequency $f = 1.7$ GHz demonstrates once more the failure of the relaxation model in describing the measured data correctly. Although the theory fits the curves properly at the even filling factors 4 and 6, this is not the case for the odd filling factors 5 and 3. On the other hand, the semicircle shape of the curves rules out an imaginary contribution to $\sigma(\omega, k)$ which would be an explanation for the violation of the relaxation model.

One possible explanation for this behaviour is a different maximum attenuation $\Gamma_{\max}$ and a different maximum velocity shift $\Delta v_{\max}$ for even and odd

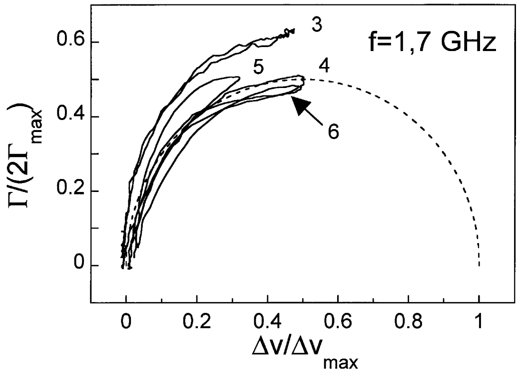

Fig. 3. Phase plot of the normalized SAW attenuation versus velocity change. The theoretical curve fits to the curves obtained at the even but not to the ones at the odd filling factors. However, all curves lie on the semicircles so that no indication for an imaginary part of the conductivity is found.

Landau levels. For the linear theory as represented by Eqs. (3) and (4), this can be ruled out, since no difference is made for odd and even filling factors. Another reason for our observation could be a difference in $\sigma_m$ for spin polarized and non-polarized Landau levels. This effect could in principle be caused by a different frequency-dependent screening mechanism for both cases. Also a frequency-dependent contribution to the SAW-absorption that is not included in the relaxation model could be responsible for this effect. To our knowledge, however, there is no satisfying theoretical description available up to now that could explain our observation. Further experimental and theoretical work is needed to elucidate the role of spin polarization for the acoustoelectric effects that we observe.

In summary, we have investigated the interaction between a surface acoustic wave and a disordered quasi-two-dimensional electron system in an AlSb/InAs/AlSb semiconductor heterostructure as a function of the SAW frequency in the integer quantum Hall effect regime. We find a clear violation of a simple relaxation model for this interaction in the case of spin polarized odd Landau levels and therefore propose different mechanisms for the electronic screening of the electron system when the Fermi energy is located either in spin polarized or non-spin polarized Landau levels.

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