Ultrasonic approach to the integer and fractional quantum Hall effect

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Abstract

The integer and fractional quantum Hall effect is investigated using the acoustoelectric effect in a high mobility two-dimensional electron system. This effect is a result of the interaction of the coherent field of an ultrasonic surface acoustic wave and the completely quantized electron system in strong magnetic fields. The mutual interaction leads to both energy and momentum transfer of the wave to the electrons and is reflected in giant quantum oscillations in the sound-induced currents and voltages in the two-dimensional system. Unlike standard magnetotransport experiments the acoustoelectric effect probes the states of the bulk of the electron system rather than those of the edges and thus is suited to gain insight into the quantum Hall effect from a different point of view.

In piezoelectric semiconductors, the coherent phonon field of a surface acoustic wave (SAW) can couple to mobile carriers via the piezoelectric polarizability of the host material. For the case of a two-dimensional electron system (2DES) like in a GaAs/AlGaAs heterostructure, this interaction is strongest for a small diagonal conductivity $\sigma_{xx} = \sigma_m \approx 3 \times 10^{-7}\ \Omega_{sq}^{-1}$ as present under the conditions of the quantum Hall effect or at very low carrier density [1,2] and leads to giant quantum oscillations of, e.g., the attenuation of the SAW. As reported earlier [3] also large SAW-induced acoustoelectric currents and voltages are observed under these conditions. A most remarkable effect in the regime of both the integer and the fractional quantum Hall effect is the occurrence of a bipolar transverse acoustoelectric field E_y around integer and fractional Landau level filling factors. Such oscillations are observed in the so-called "open geometry" where no macroscopic currents in the sample are permitted. Here, we concentrate on the quantitative explanation of the observed acoustoelectric voltages. Initial results on the acoustoelectric current as observed in "shorted" configuration are discussed in Refs. [3,4].

The SAW is excited by means of interdigital transducers [1,2] at a center frequency of 144 MHz. Typically, 100 μW of RF power is fed into one of the transducers resulting in an acoustic power density of about 1 mW/m. The 2DES is defined into a Hall bar geometry with ohmic contacts serving as voltage probes. Source and

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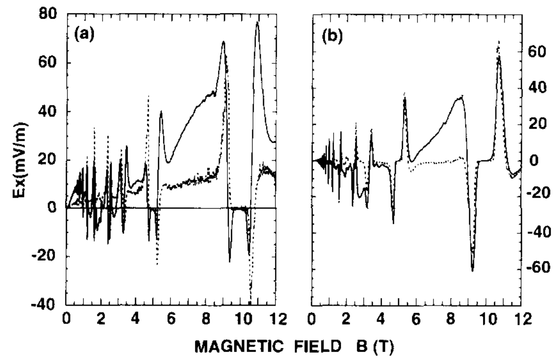

Fig. 1. Experimental results for the acoustoelectric fields E_x (a) and E_y (b) in open geometry as a function of the magnetic field B. The longitudinal field E_x exhibits a characteristic double-peak structure around integer filling factors, whereas the transverse field E_y changes sign around those magnetic field values. The dashed lines are the results of a calculation employing the model as described in the text.

drain contacts of 20 μm width are provided at both ends of the 2DES. The experiments reported here are performed on two different samples: S1 (carrier density $N_S = 2.4 \times 10^{15}\ m^{-2}$; mobility $\mu = 150\ T^{-1}$) and S2 ($N_S = 0.72 \times 10^{15}\ m^{-2}$; $\mu = 150\ T^{-1}$) in open geometry. Both the sound-induced longitudinal field E_x and the transverse field E_y are monitored at the voltage probes using standard lock-in techniques [3,4].

Typical experimental results for sample S1 are shown in Fig. 1 as solid lines. In Fig. 1a the longitudinal field E_x and in Fig. 1b the transverse field E_y are depicted as a function of the magnetic field B. E_x exhibits a double peak structure around integer filling factors ν similar to those observed in SAW transmission measurements [1,2]. In contrast, the transverse field E_y displays bipolar double peaks around integer fillings. Similar results are also obtained in the regime of the fractional quantum Hall effect. This is demonstrated for the low density sample S2 at $T = 0.5$ K and for filling factor $\nu = 1/3$, as shown in Fig. 2a.

Existing theories [5] failed to explain some of our observations quantitatively. For example, the non-zero off-diagonal acoustoelectric voltage E_y in the open geometry is not at all accounted for in Ref. [5]. Also the results as obtained in "shorted geometry" [3,4] are partially in contradiction with this model. More recently, however, a different model of the acoustoelectric interaction has been formulated by Fal'ko and Iordanskii [6] and by Winkler et al. [7]. We here restrict ourselves to a sketch of the basic ideas of this model and refer

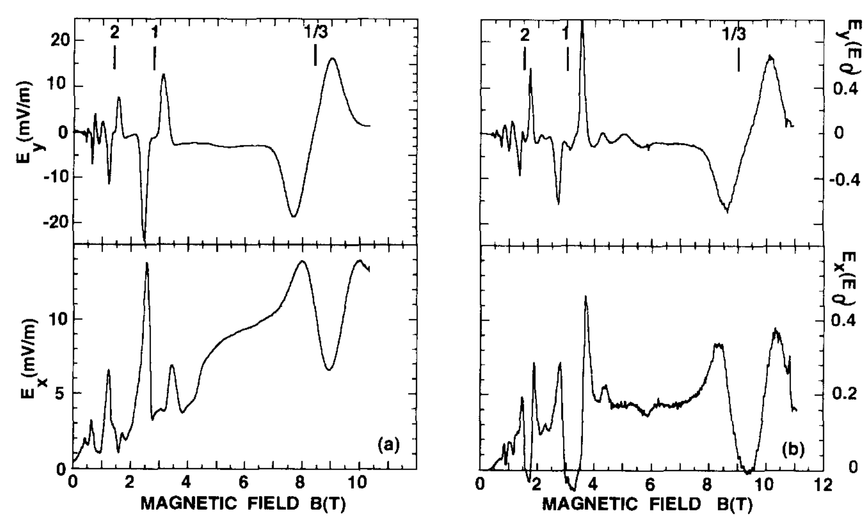

Fig. 2. (a) Experimentally obtained acoustoelectric fields E_x and E_y in open geometry for the low-density sample S2. Also for the fractional filling factor $\nu = 1/3$, the characteristic signature of the acoustoelectric effect is observed. (b) Calculated acoustoelectric fields using measured magnetotransport tensor components.

the reader to a more detailed description in the original references.

On piezoelectric materials a SAW leads to a piezoelectric field propagating with the speed of sound:

$$E_p(x, t) = -\frac{\partial}{\partial x}\Phi(x, t) = E_m e^{i(kx-\omega t)}. \quad (1)$$

This field is screened by the mobile carriers depending on the local diagonal conductivity σ_{xx} and the effective field is then given by [2]

$$E_{eff}(x, t) = E_p(x, t) + E_{ind}(x, t) = \frac{E_p(x, t)}{1 + i(\sigma_{xx}/\sigma_m)}, \quad (2)$$

where E_{ind} is phase-shifted with respect to E_p by $\Phi = \text{arctg}(\sigma_{xx}/\sigma_m)$. Thus the generated local acoustoelectric current,

$$j_\alpha(x, t) = \sigma_{\alpha x} E_{eff}(x, t), \quad \alpha = (x, y) \quad (3)$$

gives rise to a modulated carrier density and thus a modulated local conductivity tensor:

$$N_S(x, t) = N_S^0 + \Delta N_S e^{i(kx-\omega t)}$$

and

$$\sigma(x, t) = \sigma_0 + \frac{\partial\sigma}{\partial N_S}\Delta N_S(x, t) \quad (4)$$

with an amplitude ΔN_S much smaller than the equilibrium value N_S^0. Using the continuity equation, the oscillating part of the charge density can now be related to E_{eff}:

$$\Delta N_S(x, t) = -\frac{k\sigma_{xx}E_{eff}(x, t)}{e\omega} = -\frac{\sigma_{xx}E_{eff}(x, t)}{ec}. \quad (5)$$

Here, c denotes the speed of sound, whereas the other symbols have their usual meaning. For $\Gamma_{xx} = \Gamma_m$ and an amplitude of the SAW $\mu_z = 0.1$ Å, $\Delta N_S/N_S^0 \approx 1 \times 10^{-3}$. The time average of the acoustoelectric current has two components.

$$\langle j_\alpha(x)\rangle_t = \left\langle\left(\sigma_{\alpha x}^0 + \frac{\partial\sigma_{\alpha x}}{\partial N_S}\Delta N_S(x, t)\right)E_{eff}(x, t)\right\rangle_t = -\frac{\partial\sigma_{\alpha x}}{\partial N_S}\frac{1}{ce}\langle(\sigma_{xx}^0 E_{eff}(x, t))E_{eff}(x, t)\rangle_t, \quad (6)$$

because $\langle\sigma_{\alpha x}^0 E_{eff}(x, t)\rangle_t = 0$ is zero and there is no phase shift between E_{eff} and ΔN_S. In other words, the acoustoelectric current is a quadratic function in E_{eff} thus representing the local quadratic response of the 2D electron system to the piezoelectric field of the SAW. On the other hand, the attenuation of the wave [1,2] and the relative dissipated power density are given by

$$\langle\Gamma\rangle_t = -\frac{1}{I}\frac{\partial I}{\partial x} = \frac{1}{I}\langle\sigma_{xx}E_{eff}^2(x, t)\rangle_t, \quad (7)$$

respectively. Here, I denotes the acoustic intensity of the wave. As $\Delta N_S \ll N_S^0$, the expressions (6) and (7) are identical and the acoustoelectric current can be expressed in terms of the attenuation Γ,

$$\langle j_\alpha(x)\rangle_t = -\frac{\partial\sigma_{\alpha x}}{\partial N_S}\frac{1}{ce}\langle I\cdot\Gamma\rangle_t\hat{e}_x = -\frac{\partial\sigma_{\alpha x}}{\partial N_S}\frac{1}{e}\langle Q\rangle_t\hat{e}_x. \quad (8)$$

Here, $Q = I\cdot\Gamma/c$ represents a "phonon pressure" proportional to both Γ and I, and $\hat{e}_x$ a unit vector in the direction of sound propagation. The acoustoelectric tensor $\mathbf{\Lambda}$ [5] defines the proportionality between the current and the phonon pressure $\mathbf{Q}$, namely $j_i = \Lambda_{il}Q_l$ and is in our model given by

$$\mathbf{\Lambda} = -\frac{1}{e}\frac{\partial\boldsymbol{\sigma}}{\partial N_S}. \quad (9)$$

This is the most important result of the above calculation. It is in contrast to Ref. [5] where $\mathbf{\Lambda}$ turns out to be directly proportional to the conductivity tensor $\boldsymbol{\sigma}$, whereas in our case it is given by its *derivative* $\partial\boldsymbol{\sigma}/\partial N_S$. Both quantities, however, converge for vanishing magnetic field since here the conductivity is linear in the carrier density. This non-linear relation between the acoustoelectric tensor and the carrier density is essential for the acoustoelectric effect in strong quantizing magnetic fields. Now, the field components E_x and E_y can be calculated:

$$E_x = \frac{I\cdot\Gamma}{ceN_S}\left(\nu\rho_{xy}\frac{\partial\sigma_{yx}}{\partial\nu} + \nu\rho_{xx}\frac{\partial\sigma_{xx}}{\partial\nu}\right);$$

$$E_y = \frac{I\cdot\Gamma}{ceN_S}\left(\nu\rho_{yx}\frac{\partial\sigma_{xx}}{\partial\nu} + \nu\rho_{yy}\frac{\partial\sigma_{yx}}{\partial\nu}\right), \quad (10)$$

where we express the carrier density N_S in terms of the Landau filling factor $\nu = N_S h/eB$ using

$$\frac{\partial \sigma}{\partial N_S} = \frac{\partial \sigma}{\partial \nu}\frac{\partial \nu}{\partial N_S} = \frac{\nu}{N_S}\frac{\partial \sigma}{\partial \nu}. \tag{11}$$

Eq. (10) can be regarded as an extension of the famous Weinreich relation [8] both taking into account the tensor nature of the conductivity as well as its nonlinear dependence on the carrier density of a 2DES in strong quantizing magnetic fields.

Experimentally, the resistivity tensor is easily accessible, and hence E_x and E_y can be calculated in order to compare the results with the experiments. This is shown in Fig. 1 (dotted lines) and in Fig. 1b only using the SAW intensity I as fit parameter. Especially for the transverse field E_y the agreement is very good. The bipolar peaks are well explained by the oscillating derivative $\partial\sigma_{xx}/\partial\nu$ which changes sign at integer filling factors. It should be noted, however, that standard DC measurements probe the conductivity of edge states rather than SAW experiments where the conductivity of the bulk of the 2DES is important whenever the sample size is larger than the SAW wavelength. This fact might be the origin of the deviations between the experiment and the calculations at present, e.g., in Figs. 1a and 1b around 8 T. The asymmetry of the double peaks of E_x in Fig. 1a is related to a well-understood asymmetry in the SAW attenuation caused by a sometimes unavoidable small inhomogeneity of the carrier density across the sample [2]. This asymmetry is less pronounced for the sample S2 as presented in Fig. 2.

In summary, we observe giant quantum oscillations in the sound-induced acoustoelectric fields caused by an interaction between a surface acoustic wave and a high mobility 2DES in a piezoelectric GaAs/AlGaAs heterojunction. The acoustoelectric effect in a 2DES under the conditions of the integer and fractional quantum Hall effect is quantitatively explained using a model that can be regarded as an extension of the Weinreich relation originally formulated for three-dimensional systems in the absence of a magnetic field. The important difference is the non-monotonic dependence of the diagonal component of the magnetoconductivity-tensor on the carrier density (or the Landau-level filling) in strong quantizing magnetic fields.

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