ACOUSTOELECTRIC STUDY OF LOCALIZED STATES IN THE QUANTIZED HALL EFFECT

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The acoustoelectric effect caused by momentum transfer from a surface acoustic wave to a two-dimensional electron system is employed to investigate the quantum Hall effect. Strong quantum oscillations of both the acoustoelectric fields and currents are observed and in part explained by a recent model, based on a local description of the conductivity. However, an unexpected bipolar acoustoelectric Hall voltage occuring at integer filling factors is related to localized electron- and hole-like states in the tails of Landau levels. A similar signal is also observed at filling factor $\nu = 5/2$.

In recent experiments it has been demonstrated, that the interaction of surface acoustic waves (SAW) with a two-dimensional electron system (2DES) confined in a piezoelectric semiconductor is sensitive to the dynamic magnetoconductivity of the 2DES in a way quite distinct from resistivity measurements. Since the attenuation of a SAW in a 2DES is strongest at comparatively low diagonal conductivities σ_{xx} transmission measurements have been particularly useful to study both the integer[1] and the fractional[2] quantized Hall effect (QHE). Whereas DC transport experiments in the QHE regime are now understood as being dominated by edge transport[3, 4, 5], the integrating nature of SAW experiments makes the latter more suitable to study the bulk magnetoconductivity[1, 6]. Here we report on initial experimental studies of the acoustoelectric (AE) effects in the QHE in which we investigate the currents and voltages induced by momentum transfer from the SAW to the electrons of the 2DES. Part of the experimental results can be well understood in terms of a semiclassical local description of the conductivity and acoustoelectric tensors[7]. The fact, however, that we observe a bipolar Hall voltage at even integer filling factors as well as at filling factor $\nu = 1$ is not predicted by the local model at all. We propose that SAW-induced hopping transport of localized electron- and hole-like carriers in the bulk of the 2DES is responsible for these bipolar Hall voltages.

The AE effect, predicted in 1953 by Parmenter[8] was first observed in 1957 by Weinreich and White[9] on bulk semiconductors. In our experiments we investigate the AE effect generated by a SAW within a high quality 2DES in the regime of the QHE. Our experimental setup is sketched in Fig. 1. The SAW is excited by means of interdigital transducers at a frequency of 144 Mhz.

Typically 100 µW RF power is fed into one of the transducers, resulting in an acoustic power of approximately 1 µW. The 2DES on a conventional AlGaAs/GaAs heterojunction is confined to a Hallbar geometry with ohmic contacts placed at both sides. Four-terminal magnetotransport measurements reveal an electron mobility of 60 T^{-1} and a carrier density of $2.4 \cdot 10^{15}$ m^{-2} at T = 2 K. The experiments are performed in two different configurations: *shorted* geometry, where the contacts 1 and 4 are externally shorted and *open* geometry, where all the contacts are left open. The AE voltages and currents are measured as a function of the magnetic field perpendicular to the sample surface employing standard lock-in techniques. The SAW is either AM or FM modulated at low frequencies. All data shown here are measured on the same sample, but essentially the same results have been obtained with various samples from different wafers.

Fig. 2 depicts results of such measurements in *shorted* geometry. In (a) we plot the AE current J_x^s and in (b) the corresponding AE Hall voltage V_y^s recorded simultaneously as a function of B. We observe strong quantum oscillations which are periodic in B^{-1}. The characteristic double peak structure of J_x^s at high magnetic fields reflects the maxima of SAW attenuation1. Whereas the AE current J_x^s is symmetric around integer filling factors the AE Hall voltage shows a clear asymmetry at $\nu = 2$ and $\nu = 4$. This

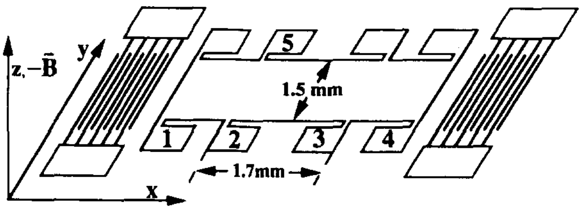

Fig. 1: Sketch of the experimental setup. The SAW propagates from left to right over the 2DES confined to a Hallbar geometry. The magnetic field is pointing downwards, as indicated. In shorted configuration the AE current is measured employing an I/V- converter between contacts 1 and 4. In open configuration all contacts are left open.

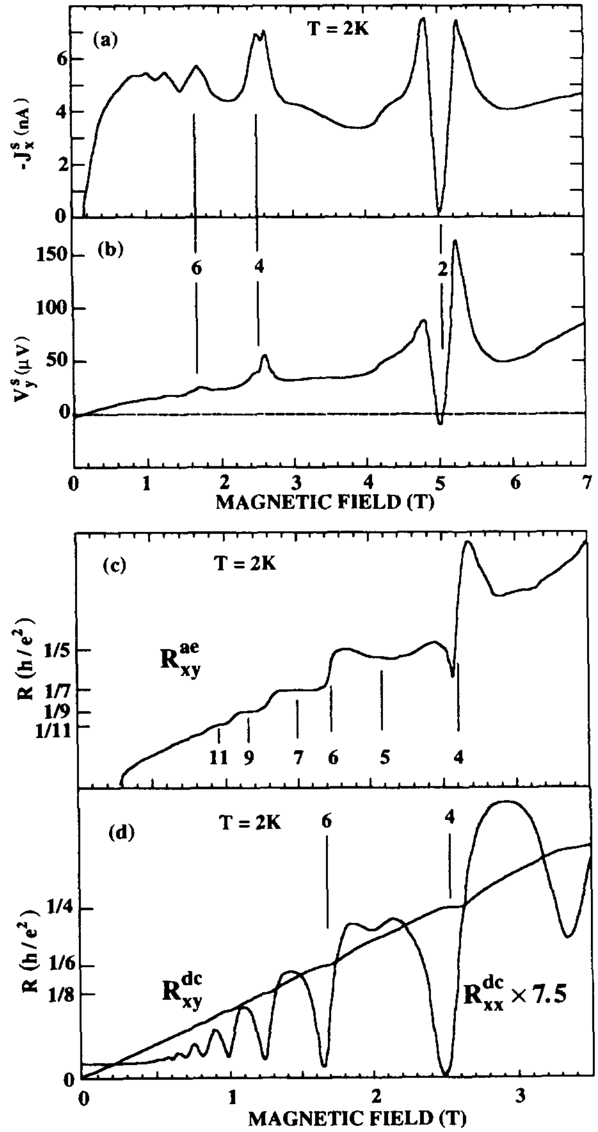

Fig. 2: Acoustoelectric effect measured in shorted geometry. In (a) the AE current and (b) the AE Hall voltage between contacts 2 and 5 are shown. In (c) the AE Hall resistance $R_{xy}^{ae} = -V_y / J_x$ is depicted as measured directly using an analog divider. At filling factor $\nu = 4$ (as at $\nu = 2$ and $\nu = 1$, but not shown in the figure for clarity) an asymmetric double peak structure is visible. Plateaus occur at filling factors $\nu = 5, 7, 9$, and 11, which are indicated by vertical bars. For comparison, R_{xx}^{dc} and R_{xy}^{dc} obtained from DC measurements on this sample, are shown in (d).

is also visible in Fig. 2c, where the AE Hall resistance $R_{xy}^{ae} = V_y^s / J_x^s$ is measured directly using an analog divider. At filling factor $\nu = 4$ and $\nu = 6$ an asymmetric signal can be recognized. At sufficiently large odd filling factors $\nu = 5, 7, 9$, and 11 plateaus in R_{xy}^{ae} occur at the quantized resistance values $R_{xy} = h/\nu e^2$. The DC Hall and longitudinal resistances R_{xy}^{dc} and R_{xx}^{dc}, respectively, as measured under identical conditions are shown for comparison in Fig. 2d. Note that, in striking contrast to R_{xy}^{ae}, no plateaus are observed at that odd filling factors in the DC Hall resistance.

Typical results obtained in the *open* geometry are shown in Fig. 3. No current can flow and an acoustoelectric voltage builds up in SAW propagation direction. The voltage V_x^o exhibits strong quantum oscillations at even integer filling factors and at $\nu = 1$ similar to the AE current in shorted geometry. In contrast the AE Hall voltage V_y^o at those filling factors shows bipolar peaks with their positions and polarities being the same as those of the asymmetric signals of R_{xy}^{ae} in shorted geometry (Fig. 2c). Unipolar signals in V_y^o are seen at filling factors $\nu = 3, 5$, and 7. In this particular experiment both voltage signals V_x^o and V_y^o appear to be partially quenched at the low field side of $\nu = 2$. After a different cooling cycle traces around $\nu = 2$ are observed quite similar to the ones around $\nu = 1$ in Fig. 3. Such behavior is characteristic for the sensitivity of SAW signals to small inhomogeneities of the carrier density across the sample[6], induced, e. g., by the cooling cycle. For the run shown in Fig. 3, however, at exactly $\nu = 5/2$ a minimum in V_x^o and a small bipolar signal in V_y^o is clearly seen, while DC transport experiments at the same temperature (T = 2K) do not reveal any structure. The signal at $\nu = 5/2$ is also observed on a second sample. All AE voltages measured are linear in the acoustic power over at least three orders of magnitude. We also find that for a given magnetic field both voltages V_x^o and V_y^o change sign with SAW propagation direction, as expected for purely sound induced signals. Reversing the magnetic field leaves V_x^o unaltered whereas V_y^o changes its relative polarity for a given |B| value close to an integer filling factor ν.

In order to explain our experimental results we basically follow the analysis of Efros and Galperin[7]. It has been shown[1], that the attenuation Γ of the SAW by a 2DES is given by a simple relaxation type expression and exhibits a maximum if the diagonal 2D conductivity $\sigma_{xx} = \sigma_m = 3.3 \cdot 10^{-7}\ \Omega^{-1}$ in the case of a [110] propagating SAW on (100) GaAs. A characteristic 'fingerprint' of the SAW attenuation in the QHE regime thus is the appearence of a double peak structure at integer and fractional Landau filling factors ν, when σ_{xx} drops to values smaller than σ_m. Whenever a SAW with intensity I is attenuated by the electron system, momentum Q is transferred to the mobile carriers, resulting in a DC current proportional to the rate of momentum transfer parallel to SAW propagation direction. In the local model the current density j_i in the presence of an electric field E_ℓ

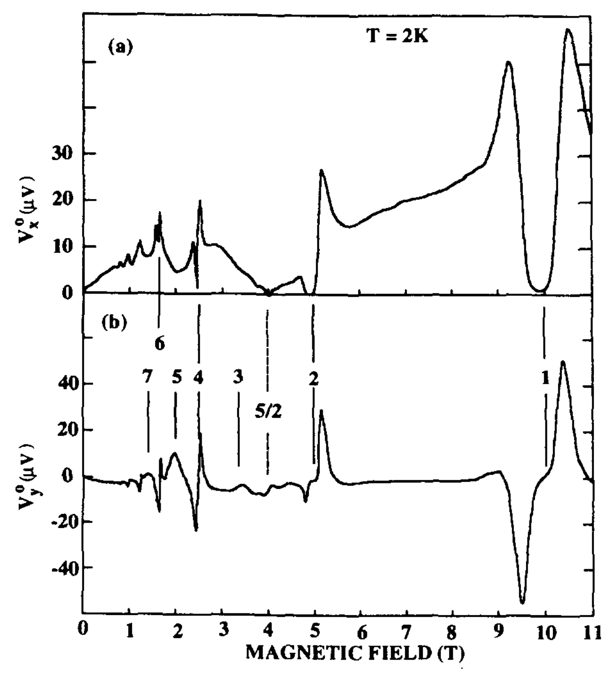

Fig. 3: Acoustoelectric voltages measured in open geometry. In (a) we show V_x^o between contacts 2 and 3. At even filling factors as well as at ν = 1 double peaks are visible. In (b) we depict the Hall voltage V_y^o between contacts 2 and 5. At ν = 1, 2, 4, 6, 8, and 5/2 bipolar and at ν = 3, 5, and 7 unipolar oscillations are observed. The low field peak of ν = 2 is probably quenched for reasons described in the text.

and a SAW field is given by[7]

$$j_i = \sigma_{i\ell} \cdot E_\ell + \Lambda_{i\ell} \frac{I \cdot \Gamma}{ven_s} \hat{k}_\ell \tag{1}$$

Here e is the elementary charge, n_s the 2D electron density, $\hat{k}$ a unit vector in SAW propagation direction, v the SAW velocity, and $\sigma_{i\ell}$ and $\Lambda_{i\ell}$ are the conductivity and acoustoelectric tensor components, respectively. The AE tensor Λ quantifies the current density generated if an average force $\dot{Q} = I \cdot \Gamma / vn_s$ is applied to each mobile carrier. Efros and Galperin have shown[7] from momentum conservation for negatively charged carriers at arbitrary magnetic fields that $\Lambda_{yx} = -\sigma_{yx}$ and that Λ_{xx} should be at least of the order of $-\sigma_{xx}$. In *shorted* configuration we can insert $E_x = 0$ and $j_y = 0$ into eqn. (1) and calculate:

$$j_x^s = -\frac{I \cdot \Gamma}{ven_s} \frac{1}{\sigma_{yy}} \left(\Lambda_{yx}\sigma_{xy} - \Lambda_{xx}\sigma_{yy} \right) \hat{k} \tag{2a}$$

$$E_y^s = -\frac{I \cdot \Gamma}{ven_s} \frac{\Lambda_{yx}}{\sigma_{yy}} \left(\hat{k} \times \hat{B} \right) \tag{2b}$$

Here, $\hat{B}$ represents a unit vector in the direction of the magnetic field. In the limit $|\sigma_{yy}| << |\sigma_{xy}|$, i.e., for high magnetic fields, the second expression in the parantheses of (2a) can be neglected. Then the AE Hall-resistivity is given by:

$$\rho_{yx}^{ae} = \frac{E_y}{j_x} = \frac{1}{\sigma_{xy}} \tag{3}$$

Thus ρ_{xy}^{ae} should be quantized[7]. This is indeed observed in our experiments, but only at the odd filling factors ν = 5, 7, 9, and 11. The fact, that we observe bipolar oscillations at ν = 1, 2, and 4, where we expect a plateau according to eqn. (3) is obviously in contradiction to the theoretical predictions based on a local conductivity model.

Here we like to stress again that the interaction between SAW and the 2DES is determined by the conductivity in the bulk of the 2DES whereas transport experiments are dominated by edge state properties[4,5]. As long as the conductivity is uniform over the whole sample the local model can be applied. In the plateau region of the QHE, however, the electrons in the bulk are localized and move on closed orbits around local potential extrema, the direction of which is determined by the slope of the impurity potential[3]. At exact filling factors this sense of rotation changes from electron-like to hole-like. We propose that the SAW field induces hopping of these localized carriers along percolation paths[10] resulting in an bipolar acoustoelectric Hall voltage around exact filling factors with sufficiently high quantization energy between the adjacent Landau or spin split levels. Due to the small spin splitting in GaAs the respective energy levels partially overlap even at relatively high magnetic fields and the local model may still be applicable.

In the local model one calculates the fields E_x^o and E_y^o for *open* geometry inserting $j_x = 0$ and $j_y = 0$ into eqn. (1):

$$E_x^o = \frac{I \cdot \Gamma}{ven_s} \frac{\Lambda_{yx}\sigma_{xy} - \Lambda_{xx}\sigma_{yy}}{\left(\sigma_{xx}^2 + \sigma_{xy}^2\right)} \hat{k} \tag{4a}$$

$$E_y^o = \frac{I \cdot \Gamma}{ven_s} \frac{\sigma_{yy} \cdot \Lambda_{xx}}{\left(\sigma_{xx}^2 + \sigma_{xy}^2\right)} \left(\frac{\sigma_{yx}}{\sigma_{yy}} - \frac{\Lambda_{yx}}{\Lambda_{xx}}\right) \left(\hat{k} \times \hat{B}\right) \tag{4b}$$

If the conductivity and acoustoelectric tensors were equal, as proposed by Efros and Galperin, we would expect from (4b) $V_y^o = 0$ independent of the magnetic field. This is consistent with the experimental results obtained away from exact filling factors, e.g., $1 < \nu < 2$ (Fig. 3b). The occurence of a bipolar voltage V_y^o, however, arises the question whether the above assumption holds in quantizing magnetic fields. The surprising sensitivity to the $\nu = 5/2$ state may be explained by the fact that only a small fraction of the carriers of the 2DES has to be localized to generate a V_y^o signal.

In conclusion, we observe strong quantum oscillations of acoustoelectric currents and voltages in both open and shorted geometries. The AE Hall voltage exhibits bipolar oscillations around low integer filling factors and to some extent around filling factor 5/2, which are not predicted by existing local theories. We propose that SAW induced hopping conductivity of localized electrons and holes in quantizing magnetic fields are responsible for this observation. At odd integer filling factors and magnetic fields not strong enough to establish quantization in transport experiments at a given temperature, plateaus of the acoustoelectric Hall resistance are observed. Because of its sensitivity to bulk properties the acoustoelectric effect appears to be a promising tool to also investigate the states of a 2DES in the extreme quantum limit[11].

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References

[1]A. Wixforth, J. P. Kotthaus, and G. Weimann, Phys. Rev. Lett. **56**, 2104 (1986)

[2]R. L. Willett, M. A. Paalanen, R. R. Ruel, K. W. West, L. N. Pfeiffer, and D. J. Bishop, Phys. Rev. Lett. **65**, 112 (1990)

[3]B. I. Halperin, Phys. Rev. **B25**, 2185 (1982)

[4]M. Büttiker, Phys. Rev. **B38**, 9375 (1988)

[5]R. Landauer, Z. Phys. **B68**, 217 (1987)

[6]A. Wixforth, J. Scriba, M. Wassermeier, J. P. Kotthaus, G. Weimann, and W. Schlapp, Phys. Rev. **B40** , 7874 (1989)

[7]A. L. Efros and Yu. M. Galperin, Phys. Rev. Lett. **64**, 1959 (1990)

[8]R. H. Parmenter, Phys. Rev. **89**, 990 (1953)

[9]G. Weinreich and H. G. White, Phys. Rev.**106**, 1104 (1957)

[10]Yu. M. Galperin, Anjun Jin, and B. J. Shklovskii, Phys. Rev. **B44**, 5497 (1991)

[11]H. W. Jiang, R. L. Willett, H. L. Störmer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **65**, 633 (1990)