Voltage tunable acoustoelectric interaction in GaAs/AlGaAs heterojunctions

C. Rocke, S. Manus, Achim Wixforth, M. Sundaram, J. H. English, A. C. Gossard

Angaben zur Veröffentlichung / Publication details:

Rocke, C., S. Manus, Achim Wixforth, M. Sundaram, J. H. English, and A. C. Gossard. 1994. "Voltage tunable acoustoelectric interaction in GaAs/AlGaAs heterojunctions." *Applied Physics Letters* 65 (19): 2422–24. https://doi.org/10.1063/1.112694.

Applied Physics Letters

Voltage tunable acoustoelectric interaction in GaAs/AlGaAs heterojunctions

Cite as: Appl. Phys. Lett. **65**, 2422 (1994); https://doi.org/10.1063/1.112694
Submitted: 01 July 1994 • Accepted: 08 September 1994 • Published Online: 04 June 1998

C. Rocke, S. Manus, A. Wixforth, et al.

Voltage tunable acoustoelectric interaction in GaAs/AlGaAs heterojunctions

C. Rocke, S. Manus, and A. Wixforth[a)]
Sektion Physik der LMU, Geschwister Scholl Platz 1, D-80539 München, Germany

M. Sundaram,[b)] J. H. English, and A. C. Gossard
Materials Department, University of California, Santa Barbara, California 93106

(Received 1 July 1994; accepted for publication 8 September 1994)

The interaction between surface acoustic waves and high mobility quasi-two-dimensional electron systems (2DES) in GaAs/AlGaAs heterojunctions with variable carrier density is investigated experimentally. In specially designed samples the strength of this acoustoelectric interaction can be controlled via the field-effect induced variation of the carrier density of the 2DES. Since the sensitivity of surface acoustic wave experiments is particularly high at very low conductivities, the proposed technique will be an especially valuable tool for the investigation of 2DES with extremely low sheet carrier densities. We demonstrate that the proper use of a metallic gate electrode does not conflict with the piezoelectric interaction between the mobile carriers confined in the heterostructure and the surface acoustic wave propagating on the piezoelectric substrate.

The interaction between surface acoustic waves (SAWs) and high-mobility quasi-two-dimensional electron systems (2DES) has recently attracted much attention.[1–3] SAWs proved to be a powerful tool for the investigation of the dynamical conductivity of such systems as they represent a highly sensitive dynamical probe which averages over the whole 2DES. SAW techniques have in the recent past been successfully applied to investigate the properties of a 2DES in the regimes of both the integer and the fractional quantum Hall effect at low temperatures and in high magnetic fields. In the extreme quantum limit of a spin-polarized electron system in the lowest Landau level SAW studies have revealed evidence for a Fermi surface[3] at a Landau filling factor $\nu=1/2$ which could be interpreted in terms of the so-called composite fermions.[4] Based on these new quasiparticles, a revolutionary model for the fractional quantum Hall effect has been proposed.[4,5] Meanwhile, several different elegant experiments[6] have uncovered many fascinating aspects of those novel particles and led to a new understanding of the nature of the electronic interaction at the half-filled Landau level.

The interaction between a SAW and a 2DES on piezoelectric semiconductors can be modeled using the dc conductivity $\sigma_{xx}(\omega=0)$.[1,7] In this simple theory, the interaction can be expressed using a relaxation time parametrized by the magnetoconductivity $\sigma_{xx}(B)$. The resulting attenuation Γ of the transmitted SAW intensity $I=I\ \exp(-\Gamma x)$ and the velocity shift $\Delta v/v_0$ are then given by

$$\Gamma=k\,\frac{K_{\rm eff}^2}{2}\,\frac{(\sigma_{xx}/\sigma_m)}{1+(\sigma_{xx}/\sigma_m)^2},$$
$$\frac{\Delta v}{v_0}=\frac{v_0-v(\sigma)}{v_0}=\frac{K_{\rm eff}^2}{2}\,\frac{1}{1+(\sigma_{xx}/\sigma_m)^2}. \tag{1}$$

Here, $k=2\pi/\lambda$ denotes the wave vector of the SAW, $K_{\rm eff}^2=6.4\times10^{-4}$ the effective electromechanical coupling coefficient of the (100)-GaAs surface, $v_0=2865\ {\rm ms}^{-1}$ the SAW velocity, σ_{xx} the sheet conductivity of the 2DES, and $\sigma_m=v_0(\epsilon_0+\epsilon_s)\approx3\times10^{-7}\Omega^{-1}$ a characteristic conductivity where maximum attenuation occurs. In this simple model, where the 2DES is assumed to be located on top of the crystal with no gate metallization present, σ_m is solely determined by the sound velocity and the dielectric constant of the substrate. At high sheet conductivities the attenuation vanishes as the conducting layer perfectly screens the electric field of the SAW. A peak in the attenuation occurs at $\sigma=\sigma_m$, where maximum power is absorbed. The sound velocity shows a steplike increase, indicating an additional term in the elastic constants which is called piezoelectric stiffening. Interestingly the interaction between a SAW and the 2DES is strongest if the sheet conductivity is comparatively low. This is the case, e.g., in the regimes of the integer and fractional quantum Hall effect where the magnetoconductivity σ_{xx} approaches zero at distinct magnetic fields. This results in giant quantum oscillations of both the SAW attenuation and the change in sound velocity as function of the magnetic field which have been observed for high mobility GaAs/AlGaAs heterojunctions.[1] On the other hand the interaction between a SAW and a 2DES leads to the occurrence of sound-induced currents and voltages in the 2DES which is called the 2D acoustoelectric effect.[8] It has recently been observed experimentally and described in terms of the local quadratic response of the 2DES to the piezoelectric field of the SAW.[9]

There have also been several attempts to detect the 2DES forming a magnetically induced electron solid in the extreme quantum limit at ultralow temperatures.[10] Although there are some indications for a phase transition consistent with the magnetic field induced Wigner crystal in these SAW experiments, more work has to be done to unambiguously answer this important question. For this reason, it would be highly desirable to be able to perform SAW experiments with tunable carrier density and hence Fermi level of the 2DES. Until now, however, the conductivity of the 2DES, which is the most important parameter of the described acoustoelectric interaction, could only be changed by the application of

[a)]Present address: Universität Regensburg, Universitätsstr. 31, D-93053 Regensburg.
[b)]Present address: Jet Propulsion Laboratory, NASA, 4800 Oak Grove Drive, Pasadena, CA 91109.

 0003-6951/94/65(19)/2422/3/$6.00

high magnetic fields in order to reach the very low value of σ_m.

Here, we would like to discuss and demonstrate a technique to control the sheet carrier density N_s of the 2DES by means of the field effect and simultaneously retain the possibility of using SAW to probe characteristic properties of the 2DES. To tune N_s, and hence the sheet conductivity $\sigma = eN_s\mu$ in a controlled manner, gate electrodes are usually employed. However, in the particular case of SAW experiments, a metal electrode shorts the piezoelectric field at the surface of the crystal thus destroying the major mechanism of interaction as long as the sheet conductivity of the metal exceeds σ_m. Unfortunately, metal electrodes of such low conductivity are not easily fabricated on a semiconductor sample. The screening of the surface lateral electric field due to the metallization, however, only weakly affects the predominately mechanical nature of the SAW. Therefore the piezoelectric potential recovers with increasing depth d into the substrate until at $d \approx \lambda/2$ it nearly reaches its original strength with no gate electrode.[11]

To enable a metal electrode to be used as a gate and simultaneously maintain an appreciable acoustoelectric interaction, this evidently implies that the ratio $\alpha = d/\lambda$ must be nonzero and preferably in the vicinity of 0.5. Heterojunctions yielding the highest quality 2DES are usually grown with a cap layer thickness of the order of 100 nm. In this case a maximum piezoelectric potential would be achieved using a SAW wavelength of only about 50 nm which corresponds to a frequency of approximately 60 GHz. Thus the feasibility of this approach is limited by the severe technological difficulties of producing the necessary interdigital transducers. An alternative route is to deposit a relatively thick spacer layer between the gate electrode and the 2DES to increase their spatial separation. In principle, this layer could consist of any material but the best results are expected if it is identical to the substrate piezoelectric material.

In our experiments, we used high quality modulation-doped GaAs/AlGaAs heterostructures where the 2DES is formed at a single interface 500 nm beneath the sample surface. The electron mobility at zero magnetic field is $\mu \approx 2.7 \times 10^5$ cm^2/V s with an areal density $N_s \approx 1.8 \times 10^{11}$ cm^{-2} at $V_g = 0$ V. The 2DES is shaped to form a conventional Hall bar structure using a wet chemical etching process. Six AuGe/Ni/AuGe ohmic contacts were diffused into the periphery of the mesa to measure both the longitudinal as well as the transverse resistance components and to monitor the acoustoelectric currents and voltages. The gate electrode consists of a 5 nm NiCr film deposited on top of the Hall bar. At both ends of the 3-mm-long mesa, lithographically defined interdigital transducers were evaporated directly onto the GaAs substrate. The interdigital electrode spacing of the transducer establishes the fundamental acoustic wavelength λ and center frequency $f = v_0/\lambda$, where v_0 is the sound velocity. The SAW is launched by the application of a short ($\approx$200 ns) rf pulse at the center frequency to one of the transducers. After passing the Hall bar and interacting with the 2DES it can then be detected at the other transducer using homodyne detection and standard time-resolved boxcar techniques. This can be done as a function of an applied

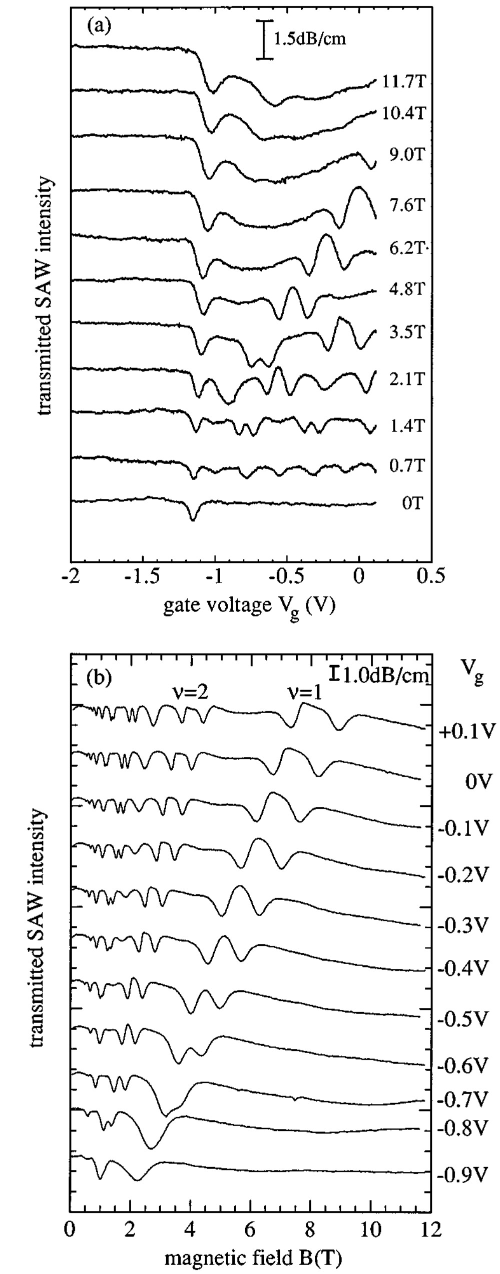

FIG. 1. (a) Transmitted intensity of an 840 MHz SAW after transmission through the mesa containing the 2DES for different magnetic field strengths at $T \approx 1.2$ K as a function of the applied gate voltage. Note that below $V_g \approx -1.15$ V, which is close to the threshold for depletion, the SAW intensity rises as σ_{xx} falls below the critical conductivity σ_m. (b) Magnetic field dependence of the SAW intensity for different gate bias at $T \approx 1.2$ K. The giant quantum oscillations of the SAW amplitude at integer filling factors shift to lower magnetic fields as the sheet carrier density is tuned to smaller values.

magnetic field[1] or—as presented in this work—as a function of the gate bias across the structure which is used to tune the carrier density in the heterojunction. From capacitance-voltage and magnetotransport measurements we know that the carrier density can be varied approximately linearly with increasingly negative gate bias and the 2D channel becomes depleted at around $V_g = -1.2$ V.

In Fig. 1(a) we show typical measurements of the transmitted SAW intensity as a function of the applied gate bias. The SAW frequency in this case is $f = 840$ MHz. The SAW

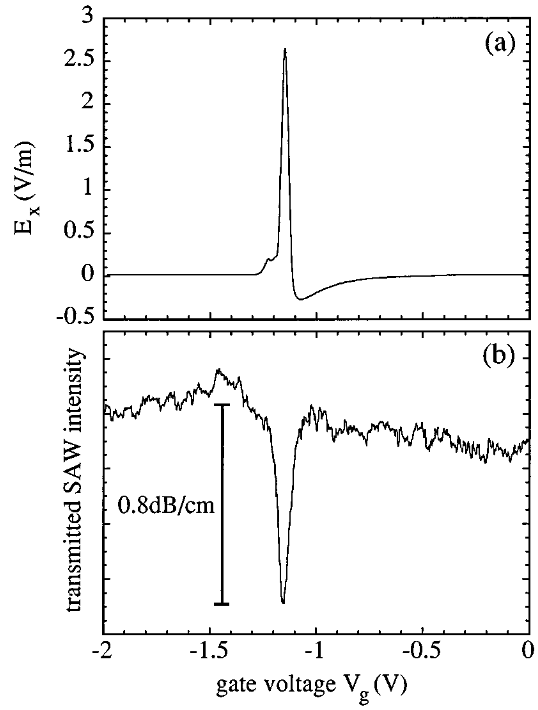

FIG. 2. Longitudinal acoustoelectric field (a) and SAW amplitude (b) vs the applied gate voltage at zero magnetic field. The sample had been kept in darkness during and after cooling at $T\approx 500$ mK. At $V_g\approx -1.15$ V where the sheet conductivity of the 2DES reaches σ_m, sharp peaks in the attenuation of the SAW amplitude and in the sound induced electric field E_x are measured.

potential at the depth of the 2DES is about 20% of the unscreened potential directly at the surface. As can be seen from Fig. 1(a), we observe the predicted peak [see Eq. (1)] of the attenuation for low carrier densities close to the threshold for depletion. Correspondingly, the sheet conductivity σ at this gate voltage is of the order of $\sigma_{xx}=\sigma_m$. At present, we cannot give a specific number for the carrier density at the gate bias of maximum attenuation, as the mobility of the system under these conditions is not well known. We estimate, however, that at the gate bias of $V_g=-1.15$ V the carrier density is as low as $N_s\approx 5\times 10^9$ cm^{-2}.

In Fig. 1(b), we depict the attenuation of the SAW as a function of a magnetic field applied normal to the sample surface for different gate bias V_g. Note the characteristic double-split features which arise whenever $\sigma_{xx}(B)$ falls below the critical value of σ_m and then rises again passing Γ_{max} twice. With increasingly negative V_g the 2DES becomes more and more depleted which can be seen by the shift of the oscillations that correspond to integer filling factors $\nu=hN_s/eB$ toward lower magnetic fields. If one traces an originally split oscillation to very negative bias (low densities) the splitting slowly disappears which indicates a disappearing of the quantum Hall effect at this low magnetic field due to an increased overlap of the respective Landau levels.

As a final example for the applicability of the gate controlled interaction we would like to demonstrate that the 2D acoustoelectric effect can also be observed in these GaAs/AlGaAs heterostructures. The result is shown in Fig. 2(a), where we plot the sound-induced longitudinal voltage V_x as a function of the gate bias V_g at zero magnetic field. We measure the voltage across two of the ohmic contacts along one side of the Hall bar, while all other contacts have been left open. In Fig. 2(b) we depict the simultaneously measured transmitted SAW intensity for comparison. The observation of the sharp peak in V_x at $\sigma=\sigma_m$ is the result of the proportionality between V_x and Γ which can be understood using a generalization of the Weinreich relation[12] as described in Ref. 9. Reversing the direction of SAW propagation reverses the polarity of the observed voltage hence indicating a truly SAW related phenomenon.

In summary, we have realized a technique to study the interaction between SAW and a two-dimensional electron system in a gated GaAs/AlGaAs heterojunction. The detrimental effect of the screening of the piezoelectric SAW fields by the metal gate electrode has been overcome by the design of special samples. Here, the distance between the sample surface and the 2DES has been largely increased as compared to conventional heterostructure samples. We demonstrate that the 2DES induced SAW attenuation is observable, even in the absence of magnetic fields and that the 2D acoustoelectric effect is also present in these structures. The investigation of the interaction between a SAW and a 2DES with tunable carrier density will certainly induce further work in the extreme quantum limit of a 2DES which might serve for a better understanding of the ground state of this interesting quantum system.

We thank A. Esslinger and J. Scriba for stimulating discussions, and H. P. Kiermeier, S. Kühn, and W. Kurpas for their technical expertise. This work was supported in part by the AFOSR under Grant No. AFOSR-91-02491 and by the National Science Foundation under the QUEST Science and Technology Center and in part by the Deutsche Forschungsgemeinschaft.

[1] A. Wixforth, J. P. Kotthaus, and G. Weimann, Phys. Rev. Lett. **56**, 2104 (1986); A. Wixforth, J. Scriba, M. Wassermeier, J. P. Kotthaus, G. Weimann, and W. Schlapp, Phys. Rev. B **40**, 7874 (1989).
[2] V. W. Rampton, K. McEnaney, A. G. Kozorezov, P. J. A. Carter, C. D. W. Wilkinson, M. Henini, and O. H. Hughes, Semicond. Sci. Technol. **7**, 641 (1992).
[3] R. L. Willett, R. R. Ruel, K. W. West, and L. N. Pfeiffer, Phys. Rev. Lett. **71**, 3846 (1993).
[4] B. I. Halperin, P. A. Lee, and N. Read, Phys. Rev. B **47**, 7312 (1993).
[5] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989); Phys. Rev. B **40**, 8079 (1989); **41**, 7653 (1990).
[6] W. Kang, H. L. Störmer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **71**, 3850 (1993); V. J. Goldman, Bo Su, and J. K. Jain, *ibid.* **72**, 2065 (1994); D. R. Leadley, R. J. Nicholas, C. T. Foxon, and J. J. Harris, *ibid.* **72**, 1906 (1994).
[7] A. R. Hutson and D. L. White, J. Appl. Phys. **33**, 40 (1962); P. Bierbaum, Appl. Phys. Lett. **21**, 595 (1972).
[8] A. L. Efros and Yu. M. Galperin, Phys. Rev. Lett. **64**, 1959 (1990).
[9] A. Esslinger, R. W. Winkler, C. Rocke, A. Wixforth, J. P. Kotthaus, H. Nickel, W. Schlapp, and R. Lösch, Surf. Sci. **305**, 83 (1994); A. Esslinger, A. Wixforth, R. W. Winkler, J. P. Kotthaus, H. Nickel, W. Schlapp, and R. Lösch, Solid State Commun. **84**, 939 (1992).
[10] M. A. Paalanen, R. L. Willett, P. B. Littlewood, R. R. Ruel, K. W. West, L. N. Pfeiffer, and D. J. Bishop, Phys. Rev. B **45**, 11342 (1992).
[11] S. Datta and B. J. Hunsinger, J. Appl. Phys. **49**, 475 (1978).
[12] G. Weinreich, Phys. Rev. **104**, 321 (1956).