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Angaben zur Veröffentlichung / Publication details:

Tilke, A., C. Rocke, and Achim Wixforth. 1997. "Frequency-dependent acousto-electric interaction in proximity-coupled piezoelectric-semiconductor hybrids." *Solid State Communications* 102 (9): 669–72. https://doi.org/10.1016/s0038-1098(97)00058-6.

FREQUENCY-DEPENDENT ACOUSTO-ELECTRIC INTERACTION IN PROXIMITY-COUPLED PIEZOELECTRIC-SEMICONDUCTOR HYBRIDS

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A quantitative analysis of the frequency-dependent acousto-electric interaction between a high-mobility quasi-two dimensional electron system in a semiconductor heterostructure and a surface sound wave propagating on a piezoelectric crystal is presented. We show that for this hybrid system a residual air gap between both partners strongly affects the acousto-electric interaction. Frequency-dependent measurement of the interaction enables us to determine the influence of the air gap on the strength of the interaction and the relevant parameters for the theoretical description. Our analysis might be of importance for the design of future acousto-electric experiments but also devices where strong interaction between the sound wave and the low dimensional electron system is required.

The interaction between surface acoustic waves and low-dimensional electron systems as present in semiconductor heterojunctions has attracted considerable interest over the past years [1–5]. This interaction has proven to be a powerful tool for the investigation of the dynamical conductivity $\sigma(\omega,k)$ of the low-dimensional electron system especially in high magnetic fields where quantum effects become important. Surface acoustic waves (SAW) of wavelengths in the (sub-) micron regime are propagated through the semiconductor containing the low-dimensional electron system where the mutual interaction leads to giant quantum oscillations in the propagation parameters of the wave that directly reflect the dynamical conductivity of the electron system. Particular examples are investigations of both the integer [1] and the fractional quantum Hall effect [2] under the presence of a surface acoustic wave. SAW transmission experiments as well as acousto-electric effects [6] being related to a phonon drag have been the subject of recent studies. One particular example for the power of this remarkable technique is the discovery of a new type of quasi-particles [3], the so-called composite Fermions that nowadays are believed to be responsible for the fractional quantum Hall effect. Recently, also experiments using quasi-one dimensional electron systems [7] and quantum point contacts [8] have been reported and revealed new and exciting aspects of the acousto-electric effects in low-dimensional electron systems.

For the experiments as described above, the usual arrangement is such that the sound wave and the electron system under investigation are present on the same (piezoelectric) semiconductor substrate like, e.g. GaAs. The interaction between the SAW and a quasi-two dimensional electron system (Q2DES) as confined in a semiconductor heterojunction could be shown to be of relaxation type. The SAW attenuation and the renormalization of the sound velocity caused by the interaction turned out to be given by [1]

$$\Gamma = \frac{K_{eff}^2}{2} k \frac{(Y)}{(1+Y^2)} \quad \text{and} \quad \frac{\Delta v}{v_0} = \frac{K_{eff}^2}{2} \frac{1}{(1+Y^2)}, \tag{1}$$

where $Y := \sigma/\sigma_m$ and $\sigma_m = v_0(\epsilon_0 + \epsilon_S) \approx 3.5 \times 10^{-7}\ \Omega^{-1}$ for GaAs denotes a critical conductivity where maximum attenuation $\Gamma_{max} = kK_{eff}^2/4$ occurs. $k = 2\pi/\lambda$ is the wave vector of the SAW, v_0 the sound velocity for a free surface and ϵ_S and ϵ_0 are the dielectric permittivities of the substrate and free space, respectively. The material parameter $K_{eff}^2 = 6.4 \times 10^{-4}$ for (1 0 0)-cut GaAs and a [1 1 0] propagating SAW determines the strength of the interaction. From equation (1) it is evident that the interaction is strongest for very small sheet conductivities $\sigma \approx \sigma_m$, indicating the importance for experiments in the quantum Hall regime. However, usual semiconductor substrates are only weak piezoelectrics. Thus, the achievable interaction is only a weak effect and a piezoelectric substrate with considerably higher K^2_{eff} would be desired for strong interaction between the sound wave and the electron system.

As pointed out earlier, this acousto-electric interaction is also a valuable tool for the non-destructive and contactless characterization of a semiconductor sample using a proximity coupling scheme as described in [9, 10]. One such system is for instance (*YZ*-cut) $LiNbO_3$, which provides an electro-mechanical coupling coefficient $K^2_{eff} = 0.048$ and thus bringing the strength of the interaction into even technologically interesting regions. The major problem, however, using the proximity coupling technique is the existence of a residual air gap between the piezoelectric and the semiconductor heterojunction under investigation.

Here, we would like to present our recent investigations regarding the influence of such a residual air gap on the strength of the interaction and the relevant parameters that are important for its description. For this purpose, we used a state-of-the-art multi-frequency SAW delay line on (*YZ*-cut) $LiNbO_3$ substrates on which a pair of split-4 interdigital transducers [11, 12] provided a whole set of operating frequencies between $f = 100$ MHz and $f = 2.35$ GHz on the same sample. Both $GaAs/Al_xGa_{1-x}As$ (sample B) as well as AlSb/InAs/AlSb (samples A and C) semiconductor structures containing high-mobility Q2DES are pressed face down on the piezoelectric to study the interaction in this sandwich system. As the technique described works on most semiconductor structures, a detailed description of the systems examined is omitted here for the sake of clarity. Experimentally, the sandwich is located in the center of a superconducting solenoid providing magnetic fields up to $B = 15$ Tesla at low temperatures $T \geq 2$ K. Short RF pulses ($\tau \approx 1\ \mu$s) at the desired operating frequency are supplied to one of the transducers and the transmitted SAW signal as a function of the applied magnetic field is analyzed in terms of intensity and sound velocity as described in detail in [1] using standard boxcar techniques.

In Fig. 1, we depict a set of experimentally obtained transmission spectra for different SAW frequencies as a function of the magnetic field. Clearly, the above mentioned giant quantum oscillations reflecting the Shubnikov–de Haas oscillations of the magneto conductivity $\sigma_{xx}(B)$ are observed. A characteristic fingerprint of the interaction between SAW and Q2DES is the splitting of the quantum oscillations at high magnetic fields [1]. Such a splitting arises whenever the magneto conductivity $\sigma_{xx}(B)$ falls below the value of σ_m, i.e. in the regime of the quantized Hall effect. The major observation in Fig. 1 is that this splitting of the high-field

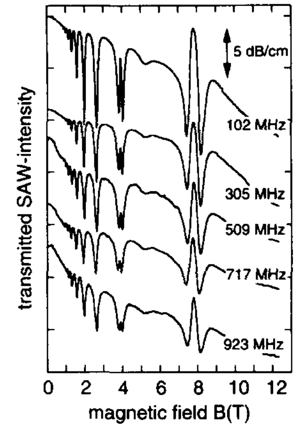

Fig. 1. Typical SAW transmission experiments for a heterostructure sample (sample B) in a magnetic field using the proximity coupling scheme and different frequencies. Giant quantum oscillations of the SAW intensity reflect the Shubnikov–de Haas oscillations of the diagonal magnetoconductivity σ_{xx} [1]. Both the maximum attenuation Γ_{max} as well as the critical conductivity σ_m decrease with increasing frequency.

oscillations decreases with increasing frequency. At the same time the maximum attenuation which occurs when $\sigma_{xx}(B) = \sigma_m$ decreases with increasing frequency. The characteristic lineshape can be well described using equation (1) only if one takes into account a sandwich-specific coupling constant $\tilde{K}^2_{eff}$ and a modified critical conductivity $\tilde{\sigma}_m$. Both quantities should obviously depend on the frequency or more specifically on the product *kd* where *d* is the width of the air gap. This dependence is caused by the fact that the time-varying electric fields accompanying the SAW at the speed of sound decay exponentially with the distance from the surface on which the wave propagates. As the piezoelectric and the semiconductor under consideration are usually acoustically mismatched, no wave is propagating on the semiconductor. This fact makes the theoretical description quite straightforward. As has been pointed out earlier by Schenstrom *et al.* [10] and more recently by Drichko *et al.* [13], the frequency dependence of both quantities $\tilde{\sigma}_m$ and $\tilde{K}^2_{eff}$ can be calculated analytically if one uses some of the above simplifying approximations. The critical conductivity $\tilde{\sigma}_m$ results in

$$\tilde{\sigma}_m(k, d) = v_0 \frac{(\epsilon_2 + \epsilon_0)(\epsilon_1 + \epsilon_0) - (\epsilon_1 - \epsilon_0)(\epsilon_2 - \epsilon_0)\,e^{-2kd}}{(\epsilon_1 + \epsilon_0) - (\epsilon_1 - \epsilon_0)\,e^{-2kd}}, \quad (2)$$

where ϵ_1 and ϵ_2 are the dielectric constants of the piezoelectric substrate and the semiconductor, respectively.

The effective coupling constant $\tilde{K}^2_{eff}$ can be expressed by the experimentally observable maximum attenuation

$$\Gamma_{max}(k,\, d) = \frac{K^2_{eff} k \epsilon_0^2 \epsilon_1^+ \mathrm{e}^{-2kd}}{[\epsilon_1^+ \epsilon_2^+ - \epsilon_1^- \epsilon_2^- \mathrm{e}^{-2kd}][\epsilon_1^+ - \epsilon_1^- \mathrm{e}^{-2kd}]}. \tag{3}$$

Here, the abbreviation $\epsilon_n^{+/-} := (\epsilon_n \pm \epsilon_0)$ has been used. Both quantities (2) and (3) depend exponentially on the parameter kd and on a properly averaged dielectric constant as indicated by $\epsilon_n^{+/-} := (\epsilon_n \pm \epsilon_0)$.

In Fig. 2, we plot the results of equation (2) for $\tilde{\sigma}_m$ and for Γ_{max} according to equation (3). The initial increase of Γ_{max} at low frequencies is caused by the proportionality of the attenuation and the SAW wave vector [cf. Equation (1)]. For higher frequencies, however, the exponential influence of the air gap gains importance which finally leads to a strong decrease of the maximum attenuation Γ_{max}. As Γ_{max} in a sense determines the maximum achievable interaction strength, this quantity is very useful for the estimate of potential experimental or device applications.

From our measurement of both $\tilde{\sigma}_m$ and Γ_{max} at different frequencies for the same cooling cycle and sample configuration, we are now able to deduce the size of the residual air gap of the specific experiment. In Fig. 3(a), we show the result of such an evaluation for three different sandwich systems. For the sake of this experiment, no special care was taken to reproduce a specific air gap for the three configurations. According to equation (3), we plot the expected relative maximum attenuation as a function of the size of the air gap for different frequencies (solid lines) together with the actual measurements for different frequencies and the three different samples (dashed lines). To be able to compare the results, all theoretical lines have been normalized to the one at $f = 102$ MHz. The crossing point (symbols) of the dashed and the corresponding solid lines indicates the average gap size for a given sandwich system. For high frequencies this gap size seems to be slightly smaller than for lower frequencies which we take as an indication that we are only able to determine an average size of the gap and for high frequencies the regions of the active sample area with small gaps contribute significantly to the interaction. Using this given gap size, the experimentally obtained maximum attenuation is well described by equation (3) over the whole accessible frequency range as it is demonstrated in Fig. 3(b) for sample B. Also, the frequency dependence of $\tilde{\sigma}_m$ is well described by the model as described by equation (2). Given the gap size d and using equation (2), we are able to reproduce (not

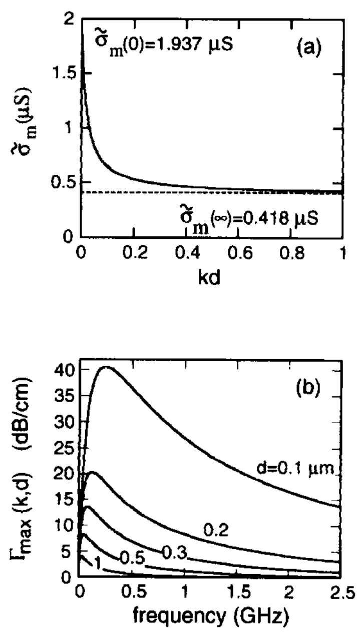

Fig. 2. (a) Theoretical plot of the critical conductivity $\tilde{\sigma}_m$ where maximum attenuation occurs as a function of the product kd. $k = 2\pi f/v_0$ denotes the SAW wave vector and d the size of the residual air gap. (b) Maximum attentuation $\Gamma_{max}(k, d)$ for a given air gap as a function of the frequency. For high frequencies $\Gamma_{max}(k, d)$ decreases according to the model calculation.

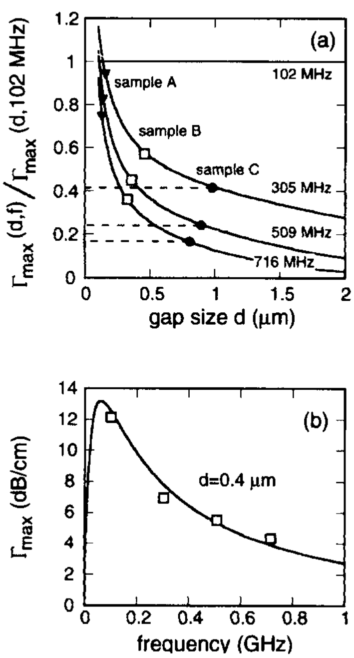

Fig. 3. (a) Experimentally obtained normalized maximum attenuation Γ_{max} (symbols) for three different frequencies and three different samples together with the theoretical predictions (solid lines). Comparison of theory and experiment results in the average size of the air gap for a given experiment (dashed lines). (b) Given the air gap of $d = 0.4$ μm for sample B (a), the behavior of the experimentally obtained maximum attenuation as a function of frequency is well described by the model.

shown) the size of the splitting and the actual line shape for split quantum oscillations at high magnetic fields.

In summary, we have investigated the acousto-electric interaction between a surface acoustic wave and a quasi-two dimensional electron system in a semiconductor heterostructure as a function of SAW frequency using a proximity coupling technique. The existence of a small residual air gap between the piezoelectric and the semiconductor containing the Q2DES leads to a frequency dependent strength of the interaction that can be described using simple models. We have studied this frequency dependence experimentally using multi-frequency SAW delay lines and different semiconductor structures. Excellent and quantitative agreement between our experiments and the theoretical model has been achieved.

Acknowledgements—We gratefully acknowledge fruitful discussions with M. Rotter and J.P. Kotthaus and thank S. Manus and W. Kurpas for technical support. The SAW delay lines have been kindly provided by Dr W. Ruile (Siemens AG, Munich). The semiconductor test structures are grown by Dr W. Wegscheider at the Walter-Schottky-Institut in Munich (sample B) and in the group of Prof. Kroemer in Santa Barbara, USA (samples A and C). We acknowledge financial support of the German-Israeli Foundation for Scientific Research (GIF) under contract No. I-328-248.07/93.

REFERENCES

1. Wixforth, A., Kotthaus, J.P. and Weimann, G., *Phys. Rev. Lett.*, **56,** 1986, 2104; see also Wixforth, A., Scriba, J., Wassermeier, M., Kotthaus, J.P., Weimann, G. and Schlapp, W., *Phys. Rev.*, **B40,** 1989, 7874.
2. Willett, R.L., Paalanen, M.A., Ruel, R.R., West, K.W., Pfeiffer, L.N. and Bishop, D.J., *Phys. Rev. Lett.*, **65,** 1990, 112.
3. Willett, R.L., Ruel, R.R., Paalanen, M.A., West, K.W. and Pfeiffer, L.N., *Phys. Rev.*, **B47,** 1993, 7344.
4. Shilton, J.M., Mace, D.R., Talyanskii, V.I., Galperin, Yu., Simmons, M.Y., Pepper, M. and Ritchie, D.A., *J. Phys.: Condens. Matter*, **8,** 1996, L337.
5. Willett, R.L. and Pfeiffer, L.N., *Surf. Sci.*, **361,** 1996, 38.
6. Esslinger, A., Winkler, R.W., Rocke, C., Wixforth A., Kotthaus, J.P., Nickel, H., Schlapp, W. and Lösch, R., *Surf. Sci.*, **305,** 1994, 83.
7. Nash, G.R., Bending, S.J., Boero, M., Grambow, P., Eberl, K. and Kershaw, Y., *Phys. Rev.*, **B54,** 1996, 8337.
8. Shilton, J.M., Talyanskii, V.I., Pepper, M., Ritchie, D.A., Frost, J.E.F., Ford, C.J.B., Smith, C.G. and Jones, G.A.C., *J. Phys.: Condens. Matter*, **8,** 1996, L531.
9. Wixforth, A., Scriba, J., Wassermeier, M., Kotthaus, J.P., Weimann, G. and Schlapp, W., *J. Appl. Phys.*, **64,** 1988, 2213.
10. Schenstrom, A., Qian, Y.J., Xu, M.-F., Baum, H.-P., Levy, M. and Sarma, Bimal K., *Solid State Commun.*, **65,** 1988, 739.
11. Engan, H., *IEEE Trans. Son. Ultrason.*, **SU-22,** 1975, 395.
12. Fleischmann, B., Ruile, W. and Riha, G., *Ultrason. Symp. Proc.*, 1986, pp. 163–167.
13. Drichko, I.L., Diakonov, A.M., Kagan, V.D., Kreshchuk, A.M., Kipshidze, G.D., Polyanskaya, T.A., Savel'ev, I.G., Smirnov, I. Yu and Suslov A.V., *Phys. Low-Dim. Struct.*, **10/11,** 1995, 275.