Resonances of piezoelectric plate with embedded 2D electron system

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Abstract. A thin GaAs/AlGaAs plate was studied by the resonant ultrasound spectroscopy (RUS) in the temperature range 0.3-10 K and in magnetic fields of up to 18 T. The resonance frequencies and linewidths were measured. Quantum oscillations of both these values were observed and were associated with the quantum Hall effect occurred in the 2D electron system. For an analysis the sample was treated as a dielectric piezoelectric plate covered on one side by a film with a field dependent conductivity. Screening of the strain-driven electric field was changed due to the variation of the electron relaxation time in the vicinity of the metal-dielectric transitions caused by the magnetic field in the 2D system. The dielectric film does not affect properties of GaAs and thus the resonance frequencies are defined only by the elastic, piezoelectric and dielectric constants of GaAs. A metallic 2D sheet effectively screens the parallel electric field, so the ultrasound wave velocities and resonance frequencies decrease when the sheet conductivity increases. Oscillations of the resonance linewidth reflect the influence of the 2D system on the ultrasound attenuation, which is proportional to the linewidth. A metallic film as well as a dielectric one does not affect this attenuation but at some finite nonzero value of the conductivity the linewidth approaches a maximum. In high magnetic field each oscillation of the conductivity produces one oscillation of a resonance frequency and two linewidth peaks. The observed phenomena can be described by the relaxation type equations and the resonant ultrasound spectroscopy opens another opportunity for contactless studies on 2D electron systems.

1. Introduction
The surface acoustic wave technique is an example of a probeless method for studying AC conductivity in low dimensional systems, see for example [1]. Often this technique is used for studying the Quantum Hall Effect. By contrast, in this research, another acoustic technique has been used. For the first time, the effect of a two dimensional electron system (2DES) on the vibration properties of a thin GaAs/AlGaAs plate was studied.

2. Experimental
Vibration of a GaAs rectangular plate with an AlGaAs layer grown on one of the plate surfaces was studied by Resonant Ultrasound Spectroscopy (RUS) [2]. A sample is placed between two piezoelectric lithium niobate transducers as shown in Fig. 1. One of the transducers is used to generate vibrations, while the second transducer acts as a vibration detector. Response of the detector is measured at the tone generator frequency \( f \). In general, this technique is used for measurements of elastic tensors. For this purpose, the frequency of the signal applied from the tone generator is swept in a broad range of frequencies. Thus, a set of the resonance
frequencies of the sample, the vibration spectrum, is measured. While analytic equations for resonance frequencies do not exist, these frequencies can be calculated by numeric methods for a sample with a simple shape if the symmetry, density and elastic tensor of the material are known, assuming free boundary conditions. The elastic constants, the fitting parameters of the theory, are calculated by fitting the calculated values to the experimentally obtained set of the resonance frequencies [2]. About 25 lowest resonances of a specimen are usually measured to obtain a good fit. These resonances lay in the frequency range of 100 kHz-2 MHz. The main resonance frequency of the transducers is much higher (about 10 MHz) and therefore transducer properties do not affect the experimental results.

**Figure 1.** Schematics of the experimental set up.

**Figure 2.** Relative change of the linewidth $\lambda$ and resonance frequency $f$ vs. magnetic field at different absolute temperatures. $f_0 = 840$ kHz.

The goal of this research is to study the influence of a conductive layer on the vibration of a piezoelectric plate. Thus, we investigated the relative change of the characteristics (frequency and linewidth) of a single resonance in a varying magnetic field rather than the whole acoustic spectrum. Measurements were performed on a GaAs/AlGaAs plate with dimensions $7.22 \times 6.4 \times 0.5$ mm$^3$ in the temperature range of 0.3-1.6 K in a magnetic field of up to 18 T applied perpendicular to the plate and to the conductive layer. Magnetic field dependencies of one of the resonance frequencies and of the linewidth of the corresponding resonance curve are presented in Fig. 2, where $\delta \lambda = (\lambda - \lambda_0)/\lambda_0$, $\delta f = (f - f_0)/f_0$. $\lambda_0$ and $f_0$ are the linewidth and the resonance frequency in zero field, respectively. Similar dependencies are observed for a resonance occurring at 964 kHz, while a resonance with frequency 107 kHz does not change in magnetic field. It is not clear yet if the magnetic field does not affect the 107 kHz resonance or the sensitivity of the experimental set up is not high enough to detect a magnetic field dependence at low frequency.

### 3. Discussion

Features associated with the Quantum Hall Effect, which occurs in two dimensional electron systems, are clearly seen on the presented curves. The changes of the resonance frequency are proportional to velocity changes of the bulk ultrasound waves in the sample. These velocity changes are associated with metal-dielectric transitions which befall in the two-dimensional system and are proportional to the electromechanical coupling factor. Changes of the resonance linewidth are proportional to the influence of the two-dimensional system on the attenuation.
of the bulk ultrasound waves in the sample. When the conductivity of the two-dimensional layer is zero or infinity, the layer does not affect the attenuation. Therefore, the maxima of the resonance linewidth occur at some finite but nonzero value of the conductivity.

Qualitatively, the observed dependencies are similar to the magnetic field dependencies of the velocity and attenuation of surface acoustic waves propagating in proximity to a two-dimensional electron system [1] and, neglecting electron diffusion, are described by the relaxation-type equations:

\[
\lambda - \lambda_0 = \alpha \frac{\sigma_{xx}(B)}{1 + \sigma_{xx}(B)/\sigma_m}^2, \quad \delta f = \beta \frac{1}{1 + \sigma_{xx}(B)/\sigma_m}^2,
\]

where \(\sigma_{xx}(B)\) is the conductivity of the 2D electron gas, \(\alpha\), \(\beta\), and \(\sigma_m\) are numeric coefficients dependent on dielectric permittivity of the piezoelectric and the electromechanical coupling constant, while the latter is different for different vibrating modes.

Theoretical aspects of vibrations of piezoelectric plates are of significant interest due to importance for applications. Nevertheless, studies of the electrode’s effect on the plate vibrations considered only a change of the density and the elastic constants of the contact layer from the properties of the resonator body [3, 4]. To the best of our knowledge, free vibrations of a crystalline piezoelectric plate with one or two sides covered by a conductive layer with a finite resistivity have never been studied theoretically.

We suppose that a simple model considering a bulk GaAs plate with a thin ”massless” conductive layer deposited on one of the surfaces would allow for an understanding of the experimental results presented above. Of course, such a model is oversimplified: (i) it does not take into account the layered nature of the real sample, (ii) the two-dimensional system is embedded inside the sample, instead of laying on its surface. On another hand, (i) it may be expected that the differences of the AlGaAs and GaAs properties (i.e., material density and the elastic constants) are not important due to relatively small concentration of the aluminum, (ii) the width of the protective layer grown on top of the AlGaAs is thin (usually several tens of nanometers), therefore the 2DES is located very close to the surface.

Due to the lack of any analytical or numerical model it is impossible to extract an absolute value of \(\sigma_{xx}(B)\) from the experimental data presented above. Thus, only one parameter of the 2DES was calculated, namely the electron density, which equals \(8.5 \times 10^{11} \text{ cm}^{-2}\).

In summary, this novel application of the RUS technique allows a new approach to the study of low dimensional electron systems. To enable calculations of the 2DES conductivity a theoretical model should be developed.

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