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Experimental setup for acoustical studies of the semiconducting heterostructures in the quantum Hall regime

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Introduction

Since the early 60-ies when the acousto-electronic phenomena in semiconductors were extensively studied, the interaction between high-frequency sound and the charge carriers has proved to be an efficient mean to obtain many significant semiconductor's parameters [1]. The acousto-electronic method is the more applicable in the case of the semiconducting heterostructures with a two-dimensional electron gas (2DEG). When using this method one does not need any electrical contacts attached to the sample, which circumstance considerably facilitates the measurement procedure. As it will be clear from the following, the acousto-electronic method provides several additional valuable possibilities.

If a sample with a two-dimensional conducting channel is placed at the nearest proximity of a piezoelectric medium in which a surface acoustic wave (SAW) is being propagated, the SAW undergoes additional attenuation and its velocity changes also. These phenomena are both due to the interaction between the high-frequency electric field of the piezoactive wave and the charge carriers in the two-dimensional channel of the heterostructure. Electric field of the wave produces currents and Joule losses therein leading to the attenuation of the acoustic wave. Elastic modules of a piezoelectric are generally stiffened due to the additional forces associated with the piezoelectric effect, but the charge carriers can screen the associated fields. If the conductivity of the channel changes, the screening changes also, that leading to the variation of the SAW velocity.

At least two experimental configurations for the measurement are possible.

The first one (Fig. 1, a) employs the fact that GaAs is a piezoelectric and a SAW is generated, launched and received directly on the surface of the substrate on which the heterostructure is grown. For this purpose a pair of interdigital transducers (IDT) is deposited on the substrate.

In the second experimental configuration (Fig.1,b) the sample under study is simply superimposed over a $LiNbO_3$ plate in which a SAW is excited and propagated. A pair of IDT's is also deposited on the plate to launch and register the SAW.

The problem of a SAW propagation in a layered system with two-dimensional electron gas has been considered by several authors [3,4,5]. As far as the magnetic field dependencies are concerned, attenuation Γ and velocity variation ΔV/V of a SAW could be expressed as follows:

$$\Gamma = A(C\sigma_1) / [(C\sigma_1)^2 + (1 + C\sigma_2)^2], \qquad (1)$$

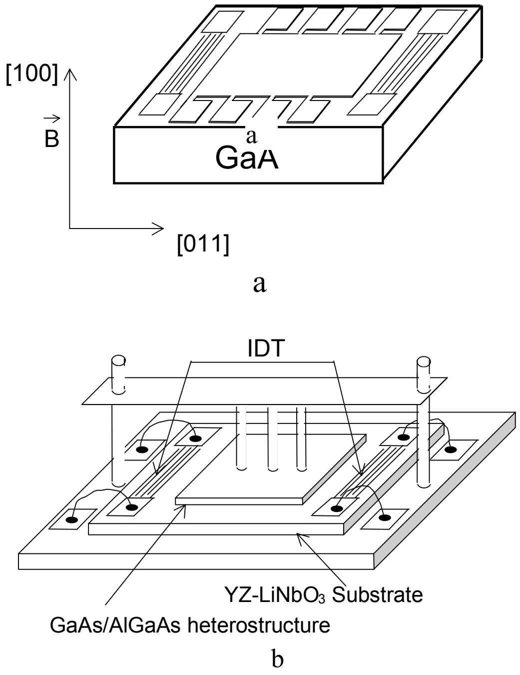


Fig. 1. **Possible sample assembly configurations [2]**

$$\Delta V/V = B(1 + C\sigma_2) / [(C\sigma_1)^2 + (1 + C\sigma_2)^2].$$

where σ_i is the respective (real or imaginary) part of the complex conductivity $\sigma_{xx}^{hf} = \sigma_1 - i\sigma_2$, V is the SAW velocity, $A(d,a,\omega)$, $B(d,a,\omega)$, $C(d,a,\omega)$ – factors that do not depend on a magnetic field, d is the embedding depth of the two-dimensional conductive layer, a is a clearance between the piezoelectric plate and the sample in the second experimental configuration, ω is the SAW frequency.

It follows from the above relations that both the attenuation and velocity variations of a SAW with a magnetic field are governed by the conductivity behavior, and that from the other hand, the both parts of the complex conductivity could be easily obtained from the SAW attenuation and velocity simultaneous measurements.

Our opinion is that the first experimental configuration has several drawbacks. Firstly, GaAs is a rather weak piezoelectric and the SAW excitation in this case is inefficient. Secondly, along with the electric field the propagating SAW introduces some mechanical stress.

The second configuration is accepted in our experiments. It proved to be preferable. $LiNbO_3$ is a strong piezoelectric and a SAW is excited very efficiently. Electric and mechanic forces in this case are separated. Electric field of the SAW simply penetrates into the 2DEG channel decoupled mechanically.

However, for the second configuration a certain problem arises associated with a clearance that inevitably appears between the sample and the piezoelectric platelet when mounting the sample.

One needs the exact value of a to calculate σ_{xx}^{hf} from the Eq. 1. It comes from [6] that to obtain a one has to measure Γ at two different frequencies in a sufficiently week magnetic field and perform the relevant calculations.

Wixforth and his team pioneered the acoustical studies of heterostructures [2]. In their experiments both discussed configurations have been used and the attenuation along with the velocity change of a SAW in a magnetic field in GaAs/AlGaAs heterostructures has been studied. In the analysis of the experiment the authors of [2] concluded that their results quantitatively agreed with the respective values which could be obtained from an equation similar to Eq.1 with σ_{xx}^{hf} taken from the direct-current measurements.

In an acoustical method by its very nature it is implied that the measured quantity is the high frequency conductivity σ_{xx}^{hf} which generally should be regarded as a complex quantity. In the quantum Hall regime the electrons are localized, and consequently, DC conductivity σ_{xx}^{DC}can not be equal to the high-frequency conductivity σ_{xx}^{hf}. For the direct-current conductivity to take place it is necessary that carriers do transfer via the entire sample from one edge to another, whereas the high-frequency conductivity can exist and manifest itself in a localized conducting area in a totally insulating sample. Our group was the first to notice [7] a striking difference between the conductivity value derived from SAW measurements and that coming from direct-current quantum Hall effect studies. In the quantum Hall regime when the real part of conductivity practically vanishes, imaginary part becomes of a primary significance. It follows from the discussion that to obtain both real and imaginary parts of the conductivity of the 2DEG one needs to measure the attenuation and velocity change of the surface acoustic wave interacting with the electrons in the two-dimensional channel of a heterostructure, and then use the Eq. 1.

So, experimentally the problem is reduced to the simultaneous measurement of both the attenuation and relative velocity changes of a SAW in a magnetic field.

Technical details and results

To perform this task a special experimental apparatus has been designed by our team. The apparatus consists of two main parts. The first one (Fig. 2) is a nitrogen-helium cryostat 1 with a superconducting solenoid 2. The heterostructure sample under study 3 is superimposed over a $LiNbO_3$ piezoelectric platelet 4 in which a SAW is launched with the aid of interdigital transducers 5 (see Fig 1, 2). The sample assembled in this way is then placed on a cold finger 6 in the pre-evacuated exchange gas chamber 7 of the cryostat. The He4 pressure with the adjustment of a manostat 8 controls the cryostat temperature.

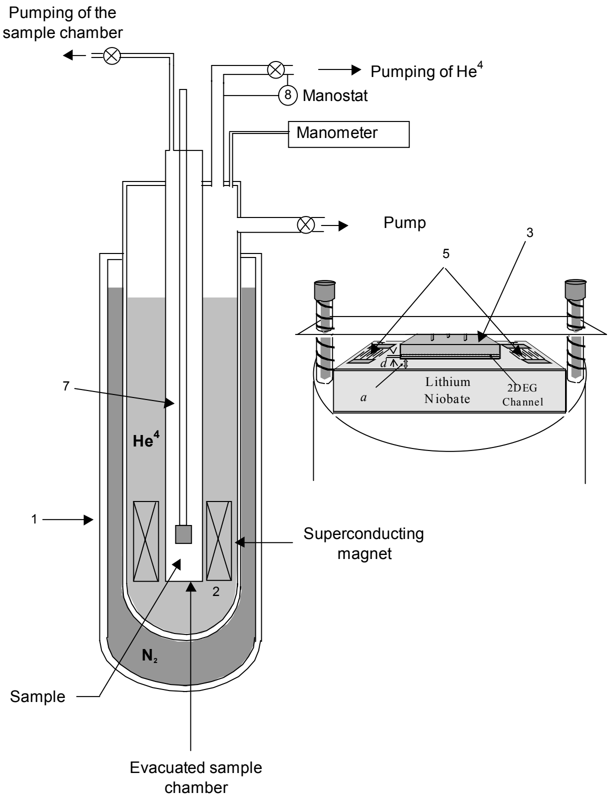
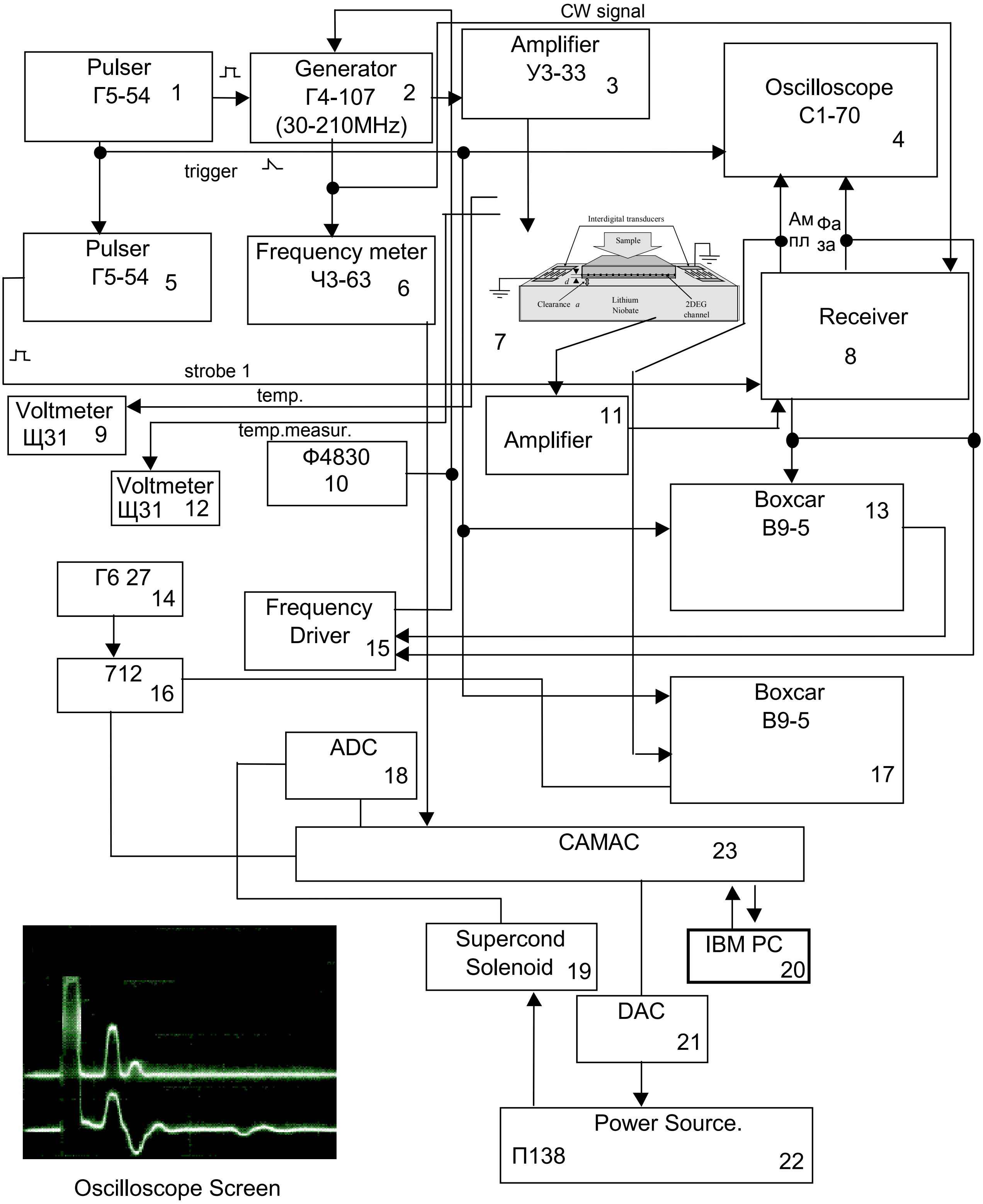


Fig. 2. **Cryostat and sample holder**

The second part of the apparatus is an electronic measurement system (Fig 3). Pulser 1 from its synch output provides timing clock pulses for all devices that need synchronizing. From its main output pulses are fed to the high-frequency oscillator 2 to produce high-frequency base pulses in the range 30-200 MHz and of approx. 1μs duration. The output base pulses of oscillator 2 via the amplifier 3 are applied to the transmitting transducer of the sample assembly 7. The amplifier 3 is needed mainly as a means of decoupling not very well matched transducer from the oscillator’s output. From the receiving transducer in 7 the signal propagated trough the sample structure is fed to the preamplifier 11 where the S/N ratio is enhanced. From the amplifier the signal comes to the input of the superheterodyne receiver 8.

Detailed block-diagram of the receiver is presented in Fig 4. This homemade receiver is based on some parts of a conventional TV-set. As a local oscillator and a mixer a standard SKM-23 tuner is used and the SMRK module stands for the IF amplifier. Both modules are modified a bit. Lowest frequency limit is tuned to 20 MHz. As it will be seen later, the receiver processes both the amplitude and phase of the signal. From its amplitude output the video pulse is fed to the boxcar (stroboscopic voltmeter) 17 to produce analog voltage proportional to the propagated SAW amplitude. The strobe delay in this the amplitude output of the receiver 8 is applied to the 1-st channel input of the oscilloscope 4. On the phase output of the receiver a video pulse is produced also. Both the sign and the amplitude of this pulse depend on the phase difference



Oscilloscope Screen

Fig. 3. **Block-diagram of the electronics**

between the base pulse carrier and that of the propagated SAW signal (the phase variation $\Delta\varphi = \omega\Delta\tau$, where $\Delta\tau$ is the propagated SAW pulse arrival time variation due to the sound velocity change in a magnetic field, ω is the SAW frequency). This phase-indicating pulse can be monitored at the second channel of the oscilloscope 4 (see photo in Fig 3). This pulse is fed to the another boxcar 13. Analog voltage from the output of this boxcar is an error signal for a servo combined of phase detector in 8, boxcar 13, frequency driver 15 and oscillator 2. In the first instant one adjusts the frequency of the oscillator 2 in such a way that the output of 13 be zero. When with the variation of the magnetic field the velocity of the SAW changes, the phase difference between the base pulse and the propagated

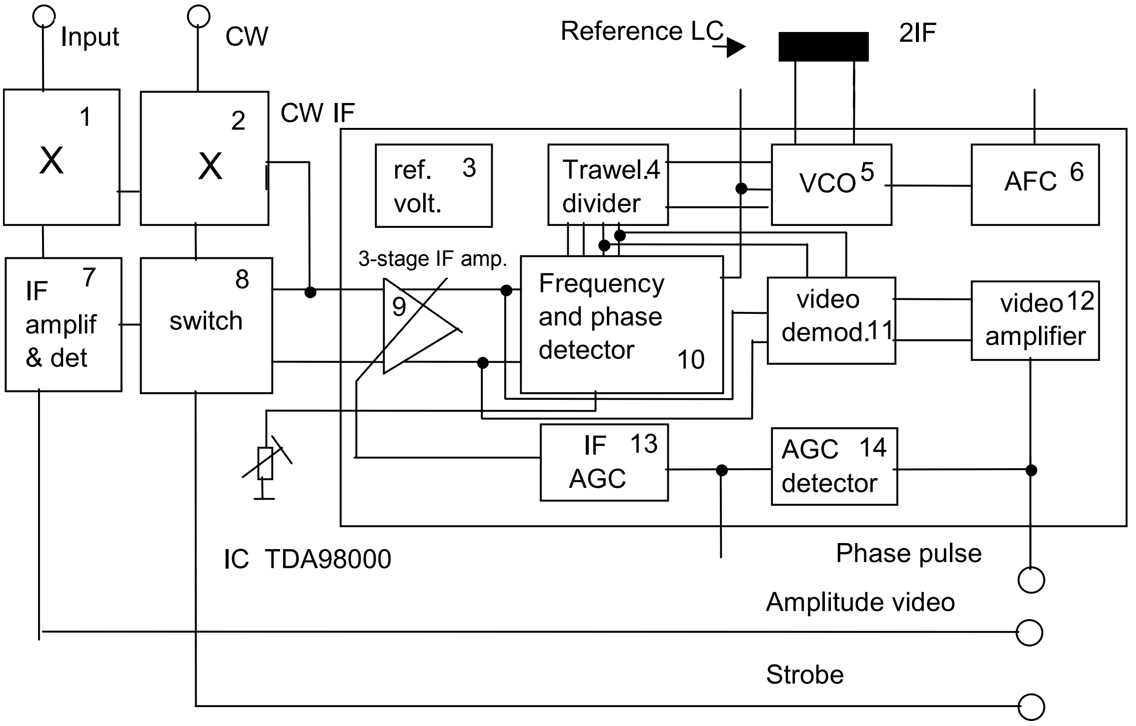


Fig. 4. **Detailed block-diagram of the receiver**

SAW signal changes also, that leading to the change of the amplitude and sign of the output of the boxcar 13.

One could directly use this output to tune the voltage - controlled oscillator 2 in order to compensate for the phase difference. In such a low-order servo there should always exist some residual error signal which is necessary to maintain the equilibrium. To avoid this problem and to rise the order of the servo a special block named “Frequency driver” has been introduced into the system. This block simulates a motor attached to the frequency control knob of the oscillator. Frequency driver incorporates two input comparators that produce commanding signals for up-or down counters according with the sign of the error voltage from the boxcar 13. As long as the error signal is present at the input of the driver 15, the respective counter therein is working and a DAC connected to the counter produces at the output of the driver a voltage which is applied to the oscillator 2 and tunes the latter until the phase difference becomes zero, then comparator signal vanishes and the counters stop. Counters do stop, but the output signal of the driver is not zero. It is just that value that is necessary to tune the oscillator 2 for zero phase difference between the base pulse and the propagated SAW signal. This output voltage of the driver 15 is being memorized until the appearance of the next error signal. Oscillator 2 frequency detuning which is necessary for the phase difference compensation is taken as a measure of the pulse delay variation associated with the change in the velocity of the SAW. Frequency variation of the oscillator 2 is monitored with a frequency meter 6 connected to the CW output of the oscillator 2.

In Fig.4 the receiver block-diagram is presented in more detail. The central place is occupied by a TV integrated circuit TDA9800 that is used here as a phase detector. Unlike the most frequently used TV phase-loop-locked (PLL) detectors this IC contains a voltage-controlled-oscillator (VCO) working at the twice IF which makes it very convenient for our purpose.

The receiver works as follows. With the aid of the continuous wave (CW) signal from the oscillator (2 in the main block diagram) and the local oscillator (LO) signal taken from the tuner 1 of the receiver, in the separate mixer 2 an intermediate frequency continuous wave (IF CW) signal is produced. This signal is fed to the input of the IC to lock the phase and frequency of the VCO 5. The signal picked from the receiving transducer is applied to the input of the tuner 1. It is mixed there with the LO signal to produce IF pulse at the input of the IF amplifier 7. This pulse is amplified in 7 and a rectified video pulse is taken out as an amplitude value. The IF amplified pulse is taken from the IF amplifier 7 and via the switch 8 is fed to the signal input of the IC. The switch is trigged off at the moment of the existence of the picked-up strong base pulse, and it is on when the propagated SAW pulse is registered. This helps to avoid an erroneous locking of the VCO 5 with the picked-up strong base pulse. The separate pulser (5 in the main block-diagram) provides the trigger pulse for the switch.

The propagated SAW IF pulse is phase-compared against the locked VCO signal and an error voltage pulse is generated at the video output of the IC.

An IBM PC computer 20 via a CAMAC system 23 controls the entire experiment. Everything is commanded by the magnetic field scanning process. With the aid of a DAC 21 incorporated in the CAMAC system, PC generates a ramp voltage that drives a superconducting solenoid power source 22. A signal from the current sensor in the solenoid circuit is measured with an ADC 18 and used as X-axis value for both the attenuation and SAW velocity registered dependencies.

There are usually about 1000 points per magnetic field scan. At every measuring point an amplitude value is taken from the output of the boxcar 17 by means of an ADC 16 (14 is a clock oscillator for the ADC 16). At the same point a frequency value is taken from the digital output of the frequency meter 6 with the aid of an input register of the CAMAC. Thus composed electronic table file is on-line plotted on the computer monitor by the simultaneously working “Origin “ software.

An example of the curves for SAW attenuation and sound velocity changes versus scanned magnetic field is presented in Fig. 5. The oscillating behaviour of the curves is associated with the Shubnikov-de Haas oscillations of the conductivity that occur at these temperatures and magnetic fields. Analysing the dependencies of Fig. 5 with the aid of the Eq. 1 one can study the magnetic field dependence of both real and imaginary parts of the high-frequency conductivity of a heterostructure [8] and also obtain some fundamental parameters of a system with the two-dimensional electron system [9].

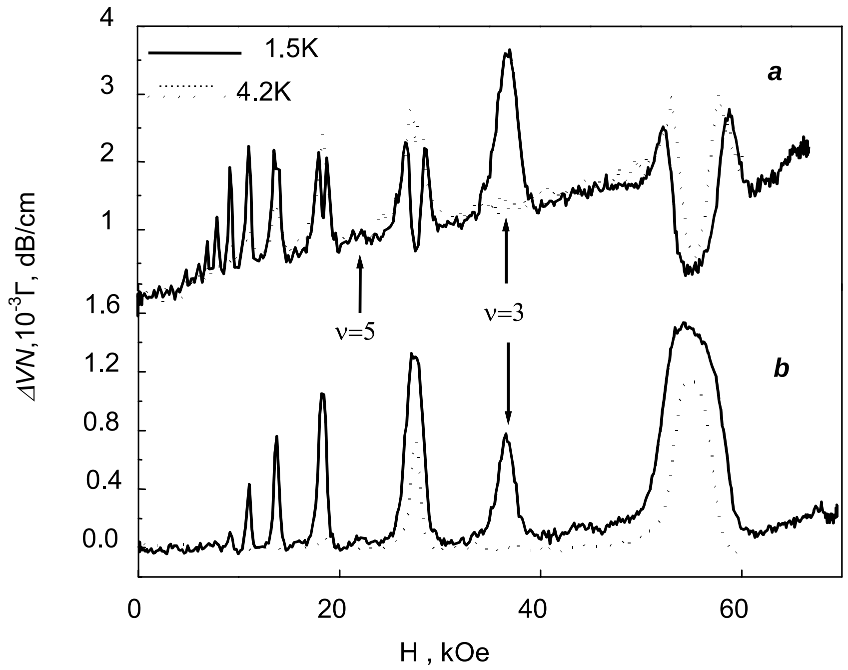


Fig. 5. **Experimental dependencies of the SAW attenuation factor Γ and velocity variation $\Delta V/V$ on a perpendicular magnetic field *H*, *f* = 30 MHz**

Conclusion

Based on the acousto-electronic interaction an experimental apparatus for the carrier kinetic studies in semiconducting heterostructures at low temperatures and strong magnetic fields has been designed and constructed. Extensive studies of the high-frequency conductivity in the GaAs/AlGaAs heterostructures were performed. Results were published elsewhere [6-11].

Specifications and precision

Frequency range: 30 –210 MHz
Oscillator output power: 1W,
usually attenuated by 40-60 dB
Receiver sensitivity: 10^{-11} W
Relative velocity change
measur. precision : 10^{-5}
Temperature range: 4.2 – 1.5 K
Magnetic field range: 0 – 7 T
Software environment: Windows 95, Origin 3.5

Acknowledgements

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Eksperimentinis įrenginys puslaidininkinių heterostruktūrų akustiniams tyrimams kvantiniu Hallo režimu

Reziumė

Sukurtas eksperimentinis įrenginys, pagrįstas akustine elektronine sąveika, puslaidininkinėms heterostruktūroms tirti esant žemoms temperatūroms ir stipriems magnetiniams laukams. Išmatuotas paviršinių akustinių bangų (30 200 MHz) slopinimas ir greičio pokyčiai. Remiantis šių matavimų duomenimis, nustatytas Ga As/Al Ga As heterostruktūrų aukštojo dažnio laidumas esant kvantiniam Hallo efekto režimui.

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