Interaction of surface acoustic waves with a two-dimensional electron gas in the presence of spin splitting of the Landau bands

I. L. Drichko\textsuperscript{a}, A. M. Diakonov\textsuperscript{a}, V. V. Preobrazenskii\textsuperscript{b}, I. Yu. Smirnov\textsuperscript{a}, and A. I. Toropov\textsuperscript{b}

\textsuperscript{a} A. F. Ioffe Physico-Technical Institute of Russian Academy of Sciences, Polytechnicheskaya 26, 194021, St.Petersburg, Russia;

\textsuperscript{b} Semiconductors Physics Institute of Siberian Division of Russian Academy of Sciences, Ak. Lavrentieva 13, 630090, Novosibirsk, Russia

(March 24, 2022)

The absorption and variation of the velocity of a surface acoustic wave of frequency $f = 30$ MHz interacting with two-dimensional electrons are investigated in GaAs/AlGaAs heterostructures with an electron density $n = (1.3 - 2.8) \times 10^{11}$ cm$^{-2}$ at $T = 1.5 - 4.2$ K in magnetic fields up to 7 T. Characteristic features associated with spin splitting of the Landau level are observed. The effective $g$ factor and the width of the spin-split Landau bands are determined: $g^* \approx 5$ and $A = 0.6$ meV. The greater width of the orbital-split Landau bands (2 meV) relative to the spin-split bands is attributed to different shielding of the random fluctuation potential of charged impurities by 2D electrons. The mechanisms of the nonlinearity manifested in the dependence of the absorption and the velocity increment of the SAW on the SAW power in the presence of spin splitting of the Landau levels are investigated.

PACS numbers: 73.40.Kp, 73.20.Dx, 71.38.+i, 73.20.Mf, 73.61.Ey, 63.20.Kr, 68.35.Ja, 71.70.Di

I. INTRODUCTION

In a magnetic field $B$ the energy spectrum of a two-dimensional (2D) electron gas represents a set of discrete levels with energies

$$E_N = (N + 1/2)\hbar \omega_c \pm (1/2)(g_0 \mu_B H + E_{\text{ex}}), \quad (1)$$

The first term describes the orbital splitting of the Landau levels $N$ enumerates the Landau levels, $\hbar \omega_c \equiv \hbar eH/m^*c$ is the cyclotron energy, $g_0 \mu_B H$ is the Zeeman splitting energy, $g_0$ is the $g$ factor in bulk GaAs, and $\mu_B$ is the Bohr magneton. In the 2D case electron-electron interactions increase the initial spin splitting relative lo the 3D case). As a result, (1) acquires an additional term $E_{\text{ex}}$, which describes the exchange interaction of electrons at the Landau level. The presence of exchange interaction is equivalent to an increase in the effective $g$ factor $g^*$

$$g^* \mu_B H = g_0 \mu_B H + E_{\text{ex}}(n \uparrow - n \downarrow).$$

It has been observed experimentally [3] that the $g$ factor in a GaAs/AlGaAs heterostructures is $|g^*| = 0.23$, which is an order of magnitude higher than the theoretical value $|g_0| = 0.44$ in bulk GaAs. An increase in the $g$ factor in 2D objects relative to their bulk counterparts has also been observed in Si/SiO$_2$ [3], GaInAs/GaAlAs [3], InAs/AlSb/GaSb [3], and AlAs [3] heterostructures.

It is evident from (1) that the energy $E_{\text{ex}}$ depends on the relative population of two spin states, therefore, if the Fermi level is situated between Landau levels of order $(N, \uparrow)$ and $(N, \downarrow)$ the difference $(n \uparrow - n \downarrow)$ is a maximum, and the quantity $g^*$ assumes a certain maximum value. But if the Fermi level is between Landau levels of order $(N, \downarrow)$ and $(N + 1, \uparrow)$, then $g^*$ assumes a minimum value equal to $g_0$. Consequently, the value of $g^*$ is an oscillating function of the magnetic field [4]. Indeed, oscillations of the $g^*$ factor in magnetic field have been observed in [3].

In this paper we report measurements of the absorption $\Gamma$ and velocity increments $\Delta V/V$ of surface acoustic waves (SAWs) in a piezoelectric material as a result of their interaction with 2D electrons in GaAs/AlGaAs heterostructures a magnetic field in the presence of spin splitting of the Landau levels.

II. EXPERIMENTAL PROCEDURE

The details of the procedure used to measure the SAW absorption are described in [5]. Here we mention only that the SAWs were generated by means of an interdigital transducer situated on the surface of a LiNbO$_3$ (lithium niobate) piezoelectric insulator, into which an rf pulse (30-150 MHz) of length 0.5 $\mu$sec and repetition rate 50 Hz was propagated. This pulse was chopped by the continuous output signal of a microwave oscillator. The signal transmitted through the sample was received by an analogous transducer formed on the same surface.

A modified version of the pulse-interference method was used to measure $\Delta V/V$. The duty phases of two pulses were compared in a phase detector the SAW-generating pulse on the lithium niobate surface and the pulse arriving at the receiving transducer, attenuated by interaction with 2D electrons. The error signal at the output of the phase detector was sent to the SAW-generating oscillator and thus altered its frequency in such a way as to reduce the difference between the duty phases of the indicated pulses to zero. This tracking system was operative throughout the entire experiment with
a frequency meter continuously tracking the phase difference between the indicated pulses. The frequency change recorded by this technique was converted into the corresponding velocity change.

The sample was held firmly against the lithium niobate surface by a spring, where the distance of the 2D channel from the lithium niobate surface was shorter than the SAW wavelength ($\lambda = 100\mu m$ at $f = 30 MHz$). With this mounting of the sample a random gap $a$ is formed between it and the lithium niobate surface, its width ($\sim 0.5\mu m$) most likely being governed by the roughness of the surfaces of the sample and the lithium niobate. The SAW-induced strain in the sample is not transferred in our experimental configuration. The alternating electric field accompanying the SAW penetrates into the channel carrying 2D electrons, inducing currents in the 2D channel and, accordingly. Joule losses, causing not only SAW energy to be absorbed, but also changing the velocity of the wave. The receiving transducer detects the amplitude of the SAW signal transmitted through the sample. This procedure can therefore be used to introduce an alternating electric field into the sample without having to use contacts. The absorption $\Gamma$ and velocity increment $\Delta V/V$ were measured in a vacuum chamber in a magnetic field up to 7 T at temperatures of 1.5-4.2 K in the linear regime (the acoustic power did not exceed $10^{-6}W$) and at $T=1.5K$ in the measurements, depending on the acoustic power.

The GaAs/AlGaAs heterostructures were fabricated by molecular-beam epitaxy with carrier densities $n = (1.3-2.8) \times 10^{11} cm^{-2}$ and mobilities $\mu = (1-2) \times 10^{6} cm^{2}/V \cdot s$. The density and mobility of 2D electrons were determined by a contactless acoustical method [6].

## III. EXPERIMENTAL RESULTS AND DISCUSSION

### A. Linear regime

In our experimental configuration the absorption coefficient $\Gamma$ and the velocity increment $\Delta V/V$ are given by the equations [2]

$$\Gamma = 8.68 \frac{K^2}{2} qa A \frac{(\frac{4qa}{\varepsilon_{s}V})t(q)}{[1 + (\frac{4qa}{\varepsilon_{s}V})t(q)]^2 + [\frac{4qa}{\varepsilon_{s}V}]^2 t(q)]^2},$$

$$\Delta V/V = \frac{K^2}{2} A \frac{(\frac{4qa}{\varepsilon_{s}V})t(q) + 1}{[1 + (\frac{4qa}{\varepsilon_{s}V})t(q)]^2 + [\frac{4qa}{\varepsilon_{s}V}]^2 t(q)]^2},$$

$$b(q) = [b_1(q)[b_2(q) - b_3(q)]]^{-1},$$

$$c(q) = [b_2(q) - b_3(q)]/[2b_1(q)],$$

where $K^2$ is the electromechanical coupling constant of LiNbO$_3$, $q$ and $V$ are the wave vector and velocity of the SAW, respectively, $a$ is the distance between the insulator and the investigated heterostructure, $d$ is the depth of the 2D layer, $\varepsilon_1$, $\varepsilon_0$, and $\varepsilon_s$ are the dielectric constants of lithium niobate, vacuum, and gallium arsenide, respectively, and $\sigma_1$ and $\sigma_2$ are the components of the rf conductivity of 2D electrons, which is complex-valued: $\sigma_{xx} = \sigma_1 - i\sigma_2$ [10]. These equations can be used to determine the values of $\sigma_1$ and $\sigma_2$ from the experimentally measured quantities $\Gamma$ and $\Delta V/V$.

It is evident from [4] that the dependence of $\Gamma$ and $\Delta V/V$ on the magnetic field $H$ is determined by the $H$ dependence of the components of the dissipative conductivity $\sigma_{xx}$, so that the quantization of the electron spectrum in a magnetic field, inducing Shubnikov-de Haas resistance oscillations, also generates oscillations in our measured effects. Figure 1 shows experimental curves of $\Gamma$ and $\Delta V/V$ as functions of the magnetic field for samples AG49 ($n = 2.7 \times 10^{11} cm^{-2}$), AG106 ($n = 1.3 \times 10^{11} cm^{-2}$), and BP92 ($n = 2.8 \times 10^{11} cm^{-2}$) at $T=4.2K$ and $1.5K$. It is evident from the figures that $\Gamma$ and $\Delta V/V$ oscillate in a magnetic field; additional peaks, nonexistent or faint at $T=4.2K$, are observed at $T=1.5K$ for $H=2.2T$ and $3.65 T$ (AG49), $H=2.4T$ and $4T$ (BP92), and $H=5.5T$ (AG106).

The emergence of these peaks is associated with spin splitting of the Landau zones, because for samples AG49 and BP92 their magnetic field positions correspond to occupation numbers $\nu = 3$ and $\nu = 5$, whereas for sample AG106 they correspond to $\nu = 1$, where

$$\nu = nch/eH,$$

c is the speed of light, $h$ is Planck’s constant, and $e$ is the electron charge. We are convinced that the SAW absorption peak in a magnetic field corresponding to spin splitting of the Landau level has been observed in [11], but was not identified by the authors.

Regarding the temperature dependence, in sample AG49 the absorption peaks corresponding to $\nu = 3$ are not observed at $T=4.2 K$ and begin to appear at $T = 3.2 - 3.7 K$ for different mountings of the sample, while the peak corresponding to $\nu = 5$ is observed only at $T=1.5K$. The energy of spin splitting of the Landau levels is $E_g = g'\mu_B H$, so that phenomena associated with spin splitting can occur only when the condition $E_g > kT$.
holds; consequently, the smaller the value of \( \nu \), the higher is the temperature at which they are observed.

The profile of the curves for \( \Gamma(H) \) in strong magnetic fields (splitting in two of the \( \Gamma \) peak in the vicinity of even occupation numbers) is attributable to the relaxation behavior of the absorption and is analyzed in detail in \( \text{[8]} \). Moreover, it is evident from Fig.1 that at \( T=1.5 \) K the value of the \( \Gamma \) peak for odd occupation numbers, \( \nu = 1 \) (AG106) and \( \nu = 3 \) (AG49) is higher (in spin splitting) than the maximum value of the absorption peak for even values \( \nu = 2, 4, 6 \), which correspond to orbital splitting. This fact is very important in regard to understanding the nature of the interaction of SAWs with 2D electrons in heterostructures in the regime of the quantum Hall effect. And indeed it has been reported in several papers (e.g., Refs. 11 and 12) that the experimentally measured value of \( \Gamma \) for all magnetic fields is given by an equation of the type \( \text{[2]} \), where the role of \( \sigma \) can be taken by the conductivity \( \sigma_{xx}^{dc} \) measured for a direct current. Here the maximum absorption \( \Gamma_{max} \) does not depend on \( \sigma_{xx} \), i.e., is universal. It has been shown \( \text{[8]} \) that the dependence \( \Gamma(H) \) is described by the conductivity determined from static measurements only when the 2D electrons are delocalized. In the regime of the integer-valued quantum Hall effect the Fermi level is situated halfway between two consecutive Landau levels, the electrons are localized, and the dc and ac conductivity mechanisms differ, so that \( \sigma_{xx}^{dc} > \sigma_{xx}^{ac} \approx 0 \). In this case allowance must be made for the fact that \( \sigma_{xx}^{ac} \) has a complex form. It is difficult to analyze the conditions for attaining the maximum \( \Gamma_{max} \) according to \( \text{[2]} \) as a function of the magnetic field in this case, but experiment shows that it is achieved when \( Re\sigma_{xx} = \sigma_1 \approx Im\sigma_{xx} = \sigma_2 \).

The maximum \( \Gamma_{max} \) can then be calculated according to \( \text{[2]} \) with \( \sigma_1 = \sigma_2 = \sigma \), and if, as experiment shows, \( 4\pi\sigma/\varepsilon_0V > 1 \), we then have \( \Gamma \approx 1/\sigma xx \); we now infer from \( \text{[8]} \) that the ratio of the absorption coefficients in these fields at two different frequencies for the same sample mounting (i.e., for the same gap) can be written in the form

\[
\frac{\Gamma(q_1)}{\Gamma(q_2)} = \frac{[q_1b(q_1)\ell(q_2)]e^{-(a+d)q_1}}{[q_2b(q_2)\ell(q_1)]}e^{-(a+d)q_2},
\]

Here \( q_1 \) and \( q_2 \) are wave vectors corresponding to two different SAW frequencies. In our experiments we have found that \( a \approx 0.5\mu m \) for different sample mountings.

Consequently, from acoustical measurements we have calculated \( Re\sigma_{sp} = \sigma_1 \) and \( Im\sigma_{sp} = \sigma_2 \), along with their dependences on the temperature, the magnetic field, and the SAW power. At \( T=1.5 \) K we find that \( \sigma_1/\sigma_2 \) has the values 9.7 (\( \nu=3 \)) for sample AG49, 17 (\( \nu = 3 \)) for BP92, and 0.9 (\( \nu = 1 \)) for AG106.

As mentioned, the maximum value of the absorption coefficient \( \Gamma_{max} \) is attained for \( \sigma_1 = \sigma_2 \). Consequently, if \( \sigma_1 > \sigma_2 \) in a magnetic field corresponding to the absorption peak, the maximum absorption \( \Gamma_{max} \) is still not attained. This case occurs in magnetic fields with \( \nu > 8 \) in all the samples, and in sample AG49 it also occurs for \( \nu = 3 \), even at \( T=1.5K \). Experiment shows that the conductivity \( \sigma_1 = \sigma_2 = \sigma \) at which the absorption attains its maximum value \( \Gamma_{max} \) is greater for even values of \( \nu \) than for odd values, which correspond to spin splitting, and since \( \Gamma_{max} \approx 1/\sigma \), the maximum absorption for spin splitting is found to be greater than for orbital splitting. This result is clearly evident in Fig.1 for sample AG106.

The temperature dependence of \( Re\sigma_{sp} = \sigma_1 \) (\( \nu = 3 \)) for all the samples in the investigated temperature range is well described by the law

\[
Re\sigma_{sp} = \sigma_1 \sim exp(-E_g/2kT).
\]

This law is confirmed by the linearity of the plots of \( ln\sigma_1 \) as a function of \( 1/T \) (\( f=30MHz \)) shown in Fig.2.
for all the investigated samples. From the slopes of these lines we have determined the activation energies $E_0 = g^* \mu_B$, which are determined by the spin splitting energy. The inset in Fig.2 shows the magnetic field dependence of $E_0$. It is evident that $E_0$ is a linear function of the magnetic field, so that the $g^*$ factor can be determined from the slope of $E_0(H)$, $g^* = 5$. This value agrees with the results of other studies [18]. It is evident from the figure that the $E_0(H)$ line does not pass through the origin when extrapolated to $H=0$, probably because the Landau level broadens as a result of the impurity fluctuation potential [15]. We have determined the width of the spin-split Landau levels from the intercept of the $E_0(H)$ line with the energy axis at $H=0$. $A=0.58$meV. We have previously [17] determined the widths of the bands in the case of orbital splitting for the same samples: $A \approx 2$meV (AG49). Consequently, the width of the Landau bands is greater in orbital splitting than in spin splitting. As mentioned above, the conductivity of the 2D electron system is always greater in spin splitting than in orbital splitting (for low occupation numbers). Accordingly, the greater the conductivity, the more effective is the shielding of the impurity fluctuation potential and, as a result, the smaller is the width of the band.

B. Nonlinear regime

Figure 3 shows the dependence of $\Gamma_{spin}$ on the rf source output power $P$ ($f=30$MHz) for samples AG49 ($\nu=3$) and AG106 ($\nu=1$) at $T=1.5$ K. It is evident from the figure that as the power is increased, the absorption associated with spin splitting of the Landau band, $\Gamma_{spin}$, decreases and becomes equal to zero at a certain power level. The relatively small value of $\Delta V/V$ for sample AG49 for $\nu=3$, in contrast with $\nu=2; 4$, implies that the conductivity of the 2D system is already fairly high, i.e., a large number of delocalized electrons is present. In this case the behavior of $\Gamma_{spin}(P)$ can be attributed to heating of the electron gas by the SAW electric field, where $\Gamma_{spin}(P) \rightarrow 0$ as $kT_e \rightarrow g\mu_B H$. To describe the heating of the electron gas, we need to know the electron temperature $T_e > T$ ($T$ is the temperature of the lattice), which can be determined by comparing the $\Gamma(P)$ and $\Gamma(T)$ curves. The SAW electric field that penetrates into the channel containing the 2D electron gas is given by the expression

$$|E|^2 = \frac{K^2 32\pi}{V} \frac{z e q e^{-2q(\alpha+d)}}{1 + (\frac{4\pi q}{\varepsilon_s V})^2} W, \quad (5)$$

$$z = [(\varepsilon_1 + \varepsilon_0)(\varepsilon_s + \varepsilon_0) - e^{-2q\alpha}(\varepsilon_1 - \varepsilon_0) \times (\varepsilon_s - \varepsilon_0)]^{-2}, \quad (6)$$

where $W$ is the input SAW power normalized to the width of the sound track. The energy losses in this case are $Q = \varepsilon_0 E^2 = 4W T_0$ [18]. The experimental plot of $Q(T_e)$ is shown in Fig. 4. It is found to be well described by the function $Q = A_0 (T_e^5 - T_0^5)$. A similar dependence has been obtained in an investigation of nonlinearities in weak magnetic fields, when the electrons exist in delocalized states [18], corresponding to the relaxation of energy at piezoacoustic phonons in the presence of strong shielding [19]. The value obtained for the coefficient $A_0$ from this experiment is $25$eV/($s \cdot K^5$), in contrast with the theoretical value determined from equations in [19] for this sample: $62$ eV/($s \cdot K^5$). The difference in the coefficients can be attributed to errors in the determination of the absolute value of the SAW power.

In sample AG106 ($\nu=1$) the same mechanism could not account for the behavior of $\Gamma_{spin}(P)$. Indeed, we can infer from the profile of the peak of the absorption coefficient and the increment $\Delta V/V$ that the conductivity in this sample at $T=1.5$ K is smaller than in sample AG49, where the splitting in two of the absorption peak indicates the localization of carriers situated in the upper band with an oppositely directed spin (relative to the lower band). In this situation we can assume that the nonlinear effects are associated with a decrease in the activation energy in the SAW electric field [20] for electrons existing in localized states at the Fermi level (Poole-Frenkel effect). Now the dependence of the real part of the conductivity on the SAW electric field is given by the expression

$$\sigma_1 = Re \sigma_{spin} \propto n(E) = n_0 \exp(2e^3/2E_{11}^1/2e_s^{-1/2}/kT), \quad (7)$$

where $n_0$ is the carrier density in the upper Landau band in the linear regime at $T=1.5$ K. The linear behavior of $ln\sigma_1$ as a function of $E_{11}/2$, with slope $10 \frac{cm}{s^2/\mu}$, corroborates this assumption (Fig.5). The slope calculated from (8) is $28 \frac{cm \cdot s^2/\mu}{g}$. We assume that both of the above-mentioned effects responsible for the dependencies $\Gamma(P)$ and $\Delta V/V(P)$ actually coexist, but when delocalized electrons dominate the upper, spin-split-off band, heating of the 2D electron gas plays a greater role; on the other hand, if free electrons are few in number, the dominant mechanism of nonlinearity at first is a reduction of the activation energy in the SAW electric field, causing the number of delocalized electrons to increase in the upper band of the spin-split Landau bands, which are heated by the SAW electric field.

IV. CONCLUSIONS

In our investigations of the absorption and velocity increment of surface acoustic waves ($f=30$MHz) due to interaction with two-dimensional electrons in GaAs/AlGaAs heterostructures (with electron densities $n = 1.3 \times 10^{11} \text{cm}^{-2}$, $n = 2.7 \times 10^{11} \text{cm}^{-2}$, and $n = 2.8 \times 10^{11} \text{cm}^{-2}$ at $T=1.5-4.2$ K in magnetic fields up to 7T, we have:
• observed peaks associated with spin splitting of the Landau levels;
• evaluated the effective g factor, $g^* = 5$.
• determined the width of the Landau bands associated with spin splitting: 0.6 meV, which is found to be smaller than the width of the Landau bands for orbital splitting: 2 meV; we have shown that the conductivity of the 2D electron system in spin splitting is always greater than in orbital splitting, so that the fluctuation potential of charged impurities, which governs the width of the Landau bands, is shielded more effectively in spin splitting;
• investigated the mechanisms of the nonlinearities manifested in the dependencies of the absorption coefficient and the SAW velocity increment on the SAW power in the presence of spin splitting of the Landau levels.

V. ACKNOWLEDGEMENTS

The authors are grateful to V. D. Kagan for many discussions, to A. V. Suslov for helping with the measurements, and to D. A. Pristinski for carrying out the numerical computations.

This work has been supported by grants from the Russian Fund for Fundamental Research, RFFI Grant No. 98-02-18280, and from the Ministry of Science, No. 97-1043.

[1] T. Ando and Y. Uemura, J. Phys. Soc. Jpn. 37, 1044 (1974).
[2] R. J. Nicholas, R. J. Haug, K. V. Klitzing, and G. Weimann, Phys. Rev. 37, 1294 (1988).
[3] F. F. Fang and P. J. Stiles, Phys. Rev. 174, 823 (1968).
[4] R. J. Nicholas, M. A. Brumnel, J. C. Portal, K. Y. Cheng, A. Y. Cho, and T. P. Pearsall, Solid State Common. 45, 911 (1983).
[5] E. E. Mendez, J. Nocera, and W. I. Wang, Phys. Rev. B 47, 13 937 (1993).
[6] S. P. Papadakis, E. P. de Poorte, and M. Shayegan, cond-mat/9805158.
[7] I. L. Drichko, A. M. Diakonov, A. M. Kreshchuk, T. A. Polyanskaya, I. G. Savel’ev, I. Yu. Smirnov, and A. V. Suslov, Fiz. Tekh. Poluprovodn. 31, 451 (1997) [Semiconductors 31, 384 (1997)]
[8] I. L. Drichko and I. Yu. Smirnov, Fiz. Tekh. Poluprovodn. 31, 1092 (1997) [Semiconductors 31, 933 (1997)]
[9] V. D. Kagan, Fiz. Tekh. Poluprovodn. 31, 470 (1997) [Semiconductors 31, 407 (1997)]
[10] I. L. Aleiner and B. I. Shklovskii, Int. J. Mod. Phys. B 8, 801 (1994).
[11] F. Guillion, A. Sachrajda, M. D’Iorio, R. Boulet, P. Coledige, Can. J. Phys. 69, 461 (1992).
[12] A. Wixforth, J. Scriba, M. Wassermeier, J. P. Kotthaus, G. Weimann and W. Schlapp, Phys. Rev. B 40, 7874 (1989).
[13] V. L. Gurevich, Fiz. Tverd. Tela (Leningrad) 4, 909 (1962) [Sov. Phys. Solid State 4, 668 (1962)]
[14] A. R. Hutson and D. L. White, J. Appl. Phys. 33, 40 (1962).
[15] A. Usher, R. J. Nicholas, J. J. Hams, and C. T. Foxon, Phys. Rev. B 41, 1129 (1990).
[16] D. R. Leadley, R. J. Nicholas, J. J. Hams, and C. T. Foxon, cond-mat/980534.
[17] I. L. Drichko, A. M. Diakonov, V. D. Kagan, I. Yu. Smirnov, and A. I. Toropov, Proc. of the 24th ICPS (Jerusalem, Israel) on CD-ROM, World Publishing, Singapore (1998).
[18] I. L. Drichko, A. M. D’yakonov, V. D. Kagan, A. M. Kreshchuk, T. A. Polyanskaya, I. G. Savel’ev, I. Yu. Smirnov, and A. V. Suslov, Fiz. Tekh. Poluprovodn. 31, 1357 (1997) [Semiconductors 31, 1170 (1997)].
[19] V. Karpus, Fiz. Tekh. Poluprovodn. 22, 439 (1988) [Sov. Phys. Semicond. 22, 268 (1988)].
[20] L. S. Stil’bans. Physics of Semiconductors (in Russian), Sov. Radio, Moscow (1967).
FIG. 1. Dependence of the SAW absorption coefficient $\Gamma$ (a) and the relative SAW velocity increment $\Delta V/V$ (b) on the magnetic field $H$ for different samples at temperatures of 4.2 K and 1.5 K; the SAW frequency is $f=30$MHz.
FIG. 2. Dependence of $\ln \sigma_1$ on $1/T$ for different samples. Inset: dependence of the activation energy $E_g$, on the magnetic field.
FIG. 3. Dependence of the SAW absorption coefficient $\Gamma_{\text{spin}}$ on the generator output power $P$ for samples AG49 and AG106 at $T \approx 1.5$ K.
FIG. 4. Dependence of the energy losses $Q$ on the electron temperature $T_e$ for sample AG49 at $T=1.5$ K.
FIG. 5. Dependence of $\ln \sigma_1$, on $E^{1/2}$ for sample AG106 at $T = 1.5$ K.