Nonlinearity of Acoustic Effects and High-Frequency Electrical Conductivity in GaAs/AlGaAs Heterostructures under Conditions of the Integer Quantum Hall Effect

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The absorption coefficient for surface acoustic wave $\Gamma$ and variation in the wave velocity $\Delta V/V$ were measured in GaAs/AlGaAs heterostructures; the above quantities are related to interaction of the wave with two-dimensional electron gas and depend nonlinearly on the power of the wave. Measurements were performed under conditions of the integer quantum Hall effect (IQHE), in which case the two-dimensional electron gas was localized in a random fluctuation potential of impurities. The dependences of the components $\sigma_1(E)$ and $\sigma_2(E)$ of high-frequency conductivity $\sigma = \sigma_1 - i\sigma_2$ on the electric field of the surface wave were determined. In the range of the conductivity obeying the Arrhenius law ($\sigma_1 \gg \sigma_2$), the results obtained are interpreted in terms of the Shklovskii theory of nonlinear percolation-based conductivity, which makes it possible to estimate the magnitude of the fluctuation potential of impurities. The dependences $\sigma_1(E)$ and $\sigma_2(E)$ in the range of high-frequency hopping electrical conductivity, in which case ($\sigma_1 \ll \sigma_2$) and the theory of nonlinearities has not been yet developed, are reported.

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I. INTRODUCTION

Studies of the kinetic effects in GaAs/AlGaAs heterostructures with two-dimensional (2D) electron gas in strong constant electric fields show that nonlinear effects are adequately accounted for by heating of electron gas. The main issue of controversy in the interpretation of the above results is related to identification of the relevant mechanism of electron-energy relaxation. The theory of electron-gas heating and the energy-relaxation mechanisms in the 2D case were considered in Ref. 5. In Ref. 6, the dependence of the coefficient of absorption of a surface acoustic wave (SAW) by 2D electron gas in a GaAs/AlGaAs heterostructure on the SAW intensity was also explained by heating of 2D electron gas by the SAW alternating electric field; it was also shown that the electron-energy relaxation time is controlled by energy dissipation at the piezoelectric potential of acoustic phonons under conditions of strong screening.

In the magnetic-field range where electrons are localized (i.e., under the conditions of IQHE), kinetic effects were also actively studied in a strong constant electric field. However, notwithstanding the fact that nonlinear dependences of current on voltage were similar in all cases, these dependences have not been unambiguously interpreted so far. Thus, these nonlinearities were explained by the heating of 2D electron gas by impurity breakdown in homogeneous electric fields, and by resonance tunneling of electrons between the Landau levels. In Ref. 7, another explanation was based on the theory of variable-range hopping conduction in a strong electric field. In Ref. 8, in order to explain the nonlinearities in the dependence of the width of the IQHE step on the current density in a GaAs/AlGaAs heterostructure at $T = 2.05$ K, the model of heating of 2D electron gas was used. It was found that the dependence of electron temperature $T_e$ on the current $I$ coincided with $T_e(I)$ measured in the absence of a magnetic field. As a plausible reason for this behavior, the authors of Ref. 9 could only suggest that it arose from the injection of hot charge carriers from near-contact regions where the Hall voltage was shorted out by the current contacts.

In connection with the above, the acoustic method seems to hold considerable promise for studying the nonlinear effects under the conditions of IQHE; this method is particularly convenient owing to the fact that there is no need for electrical contacts in such measurements.

In this work, we studied the dependences of $\Gamma(E)$ and $\Delta V/V$ on the velocity of SAWs in a piezoelectric due to the interaction of SAWs with 2D electron gas in GaAs/AlGaAs heterostructures on the SAW power $W$ absorbed in the sample (or on the SAW electric field $E$) under the conditions of IQHE ($T = 1.5$ K), which corresponds to the carrier-localization domain. The experimental dependences $\Gamma(E)$ and $\Delta V/V(E)$ were used to calculate the real and imaginary components of high-frequency electrical conductivity $\sigma_1(E)$ and $\sigma_2(E)$, as the high-frequency conductivity is written in the complex form $\sigma(E) = \sigma_1(E) - i\sigma_2(E)$ under the electron-localization conditions. The mechanisms of the nonlinearities were studied by analyzing the dependences of the components of the high-frequency electrical conductivity on the strength (i.e., on absorbed power) of a high-frequency electric field.

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II. EXPERIMENTAL METHODS AND RESULTS

In this work, the effect of the SAW power introduced into sample (f = 30 MHz) on the absorption coefficient Γ and on the relative variation in the SAW velocity ΔV/V was measured at T = 1.5K in magnetic fields corresponding to the midpoint of the Hall plateau (i.e., under the conditions of IQHE). We used the GaAs/AlGaAs heterostructures δ-doped with silicon; the density of electrons in 2D gas in the channel was n = (1.3 – 2.7) × 10¹¹ cm⁻² and their mobility was μ ≈ 2 × 10⁸ cm²/(V·s).

The heterostructures were grown by molecular-beam epitaxy and involved a spacer layer 4 × 10⁻⁶ cm in width. The experimental procedure was described in detail elsewhere. Here, we only note that the structure with 2D electron gas was grown on the piezoelectric (lithium niobate) surface over which the SAWs propagated. An alternating electric field having the frequency of SAW and accompanying the strain wave penetrates into the channel with 2D electron gas, induces electric currents and, correspondingly, introduces ohmic losses. As a result of such an interaction, the wave energy is absorbed.

Experimentally, we measured the absorption coefficient Γ and the relative variation in the SAW velocity ΔV/V in relation to the magnetic induction. Since the measured quantities Γ and ΔV/V are defined by the electric conductivity of 2D electron gas, electron-spectrum quantization resulting in the Shubnikov-de Haas oscillations brings about oscillations in the above effects as well.

Figure 1 shows the dependences of Γ and ΔV/V on the power P at the output of the RF generator (for a frequency of f = 30 MHz) for the filling numbers ν = 2; 4 and 6 for a sample with the 2D-electron gas density of n = 2.7 × 10¹¹ cm⁻² Here, ν = nch/eH, where H is the magnetic field strength. In the insert in Fig. 1, the dependences of Γ and ΔV/V on the magnetic field are shown for several values of the SAW power at a temperature of 1.5K. The form of the dependences of Γ on the magnetic field is analyzed in detail in Ref. 15: positions of the peaks in the Γ(H) and ΔV/V(H) curves are equidistant in 1/H; there, and the splitting of the Γ() peaks under the IQHE conditions is related to its relaxation origin. It can be seen from Fig. 1 that an increase in the supplied SAW power results invariably in a decrease in ΔV/V irrespective of the filling number, which corresponds to an increase in electrical conductivity. The form of dependences Γ(H) for dissimilar filling numbers is different: absorption increases with increasing P for ν = 2; whereas, for ν = 4 and 6, Γ increases initially as the SAW power increases, attains a maximum, and then decreases. The smaller the filling number, the higher the power corresponding to the maximum in Γ. It is also evident from Fig. 1 that the higher the magnetic field (the smaller the filling number), the higher is power P corresponding to the onset of the dependences Γ(P) and ΔV/V(P).

III. DISCUSSION OF THE RESULTS

In the experimental configuration of this work, the quantities Γ and ΔV/V are defined by the formulas

\[
\Gamma = \frac{K^2}{2qA} \frac{\Delta V}{V} \frac{(\frac{4\pi\sigma}{\varepsilon_0 c})t(q)}{[1 + (\frac{4\pi\sigma}{\varepsilon_0 c})t(q)]^2 + [(\frac{4\pi\sigma}{\varepsilon_0 c})t(q)]^2} \frac{dB}{cm},
\]

\[
A = 8b(q)(\varepsilon_1 + \varepsilon_0)c^2_0 e^{(-2q(\alpha+d))},
\]

\[
\Delta V = \frac{K^2}{2} \frac{A}{\Delta V} \frac{[\frac{4\pi\sigma}{\varepsilon_0 c})t(q) + 1}{[1 + (\frac{4\pi\sigma}{\varepsilon_0 c})t(q)]^2 + [(\frac{4\pi\sigma}{\varepsilon_0 c})t(q)]^2},
\]

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

\[
t(q) = [b_2(q) - b_3(q)]/[2b_1(q)].
\]
where the absorption coefficient $\Gamma$ is expressed in dB/cm; $K^2$ is the piezoelectric constant of LiNbO$_3$; $q$ and $V$ are the wave vector and the velocity of SAW, respectively; $d$ is the distance between the dielectric and the heterostructure under consideration; $\sigma_a$ is the depth of the position of the 2D electron-gas layer; $\varepsilon_1$, $\varepsilon_0$ and $\varepsilon_s$ are the permittivities of lithium niobate, vacuum, and gallium arsenide, respectively; and $\sigma_1$ and $\sigma_2$ are the components of the complex high-frequency electrical conductivity of 2D electron gas: $\sigma = \sigma_1 - i\sigma_2$. The necessity of considering both components of high-frequency conductivity was demonstrated in 14 and was related to localization of electrons under the conditions of IQHE. These formulas make it possible to determine $\sigma_1$ and $\sigma_2$ from the quantities $\Gamma$ and $\Delta V/V$ measured experimentally.

The filling numbers $\nu = 2$ and 1. It can be seen from Fig. 2 that, for $\nu = 2$ (orbital splitting), $\sigma_1$ and $\sigma_2$ initially increase with increasing electric field and, beginning with a certain $E$, $\sigma_2$ decreases rapidly while $\sigma_1$ continues to increase. In magnetic fields corresponding to the spin splitting ($\nu = 1$), $\sigma_1$ increases and $\sigma_2$ decreases with increasing $E$.

Figure 3 shows the dependences of $\sigma_1$ and $\sigma_2$ on the strength of high-frequency electric field $E$ for the sample with $n = 2.7 \times 10^{11} \text{cm}^{-2}$ for the filling numbers of $\nu = 2$; 4 and 6. It can be seen from Fig. 3 that, in the magnetic field $H$ amounting to 5.5T ($\nu = 2$), both components of high-frequency conductivity are independent of $E$ in a wide range of electric fields; for fields higher than a certain value $E_1$ these components increase with $E$. In a magnetic field of $H = 2.7$ T ($\nu = 4$), an increase in $\sigma_1$ and $\sigma_2$ sets in an electric field $E_2 < E_1$, and, for $H = 1.8$T ($\nu = 6$), $\sigma_2$ increases initially with increasing $E$, attains a maximum, and then decreases (similarly to what is shown in Fig. 2 for $H = 2.7$ T in the case of $\nu = 2$).

**FIG. 2.** Dependences of (a) real $\sigma_1$ and (b) imaginary $\sigma_2$ components of high-frequency electrical conductivity on electric field $E$ for sample AG106 ($n = 1.3 \times 10^{11} \text{cm}^{-2}$) at $T = 1.5$K.

**FIG. 3.** Dependences of the (a) real $\sigma_1$ and (b) imaginary $\sigma_2$ components of high-frequency electrical conductivity on electric field $E$ for sample AG49 ($n = 2.7 \times 10^{11} \text{cm}^{-2}$) at $T = 1.5$ K.
The high-frequency electric field of SAW is calculated here with the formula reported in Ref. 3. The only difference is that we have \( \sigma = \sigma_1 - i\sigma_2 \) i.e.,

\[
|E|^2 = K^2 \frac{32\pi}{V} (\varepsilon_1 + \varepsilon_0) \frac{z e^{-2q(a+d)}}{(1 + \frac{4\pi\sigma_0}{\varepsilon_s}t)^2 + (\frac{4\pi\sigma_0}{\varepsilon_s}t)^2} W, \tag{2}
\]

\[
z = [(\varepsilon_1 + \varepsilon_0)(\varepsilon_s + \varepsilon_0) - e^{-2q_n}(\varepsilon_1 - \varepsilon_0) \times (\varepsilon_s - \varepsilon_0)]^{-1},
\]

In order to explain the above dependences of \( \sigma_1 \) and \( \sigma_2 \) on \( E \), we should rely on the fact that, as was shown in Ref. 14, electrical conduction in the temperature range of \( T = 1.5-4.2 \) K is simultaneously governed by the following two mechanisms: (i) the Arrhenius-type mechanism related to activation of charge carriers from the Fermi level, where these carriers are in localized states, to the percolation level and (ii) the mechanism of hopping over localized states in the vicinity of the Fermi level. For \( T = 1.5 \) K, the contributions of these two mechanisms vary in relation to the filling number (the magnetic field). The smaller the filling number (the higher the magnetic field), the larger the activation energy defined by the value of \( 0.5\hbar\omega_c \) (\( \omega_c \) is the cyclotron frequency) and the smaller the Arrhenius contribution to the conductivity. In the case of hopping high-frequency conduction, the imaginary component has the value of \( \sigma_2 \approx 10\sigma_1 \gg \sigma_1 \) and begins to decrease with an increasing number of delocalized electrons as a result of the activation process. Thus, the ratio \( \sigma_1/\sigma_1 \) is a quantity characterizing the contribution of the above two mechanisms to conduction: if \( \sigma_1/\sigma_1 \approx 1 \), the hopping conduction is dominant, whereas, if \( \sigma_1/\sigma_1 \gg 1 \), the Arrhenius-law conduction is dominant and the hopping conduction may be ignored.

In view of the above, the nonlinearities should be analyzed separately for two different domains.

**A. Nonlinearities in the Region of Arrhenius-Type Conduction (\( \sigma_1/\sigma_1 \gg 1 \))**

The influence of a strong constant electric field on electrical conductivity stemming from activation of charge carriers to the percolation level of the conduction band distorted by random fluctuations of charged impurities was considered by Shklovskii in Ref. 18. In fact, we study here the influence of a strong electric field on conduction over the percolation level, with the role of the electric field limited to a reduction of activation energy, which may be interpreted as a lowering of the percolation threshold.

In this case, an increase in electrical conductivity in a strong electric field with decreasing activation energy is given by

\[
\sigma_1/\sigma_1^0 = \exp[(C\varepsilon V_0)^{1/(1+\gamma)}/kT], \tag{3}
\]

where \( \sigma_1^0 \) is the conductivity in the linear mode, \( E \) is the electric field strength, \( T \) is temperature, \( \gamma \) is a numerical coefficient, \( V_0 \) is the amplitude of fluctuations in the potential-relief pattern (the characteristic spatial scale of a potential), and \( \gamma \) is the coefficient that depends on dimensionality: \( \gamma = 0.9 \) for the three-dimensional (3D) case and \( \gamma = 4/3 \) for the 2D case.\(^{[9]}\)

Thus, in the 2D case under consideration, formula 3 can be rewritten as

\[
\sigma_1/\sigma_1^0 = \exp(\alpha E^{3/7}/kT), \tag{4}
\]

where

\[
\alpha = (C\varepsilon l_{sp}V_0)^{3/7}, \tag{5}
\]

and \( l_{sp} \) is the characteristic spatial scale of the potential, which may be taken as equal to the spacer thickness \( d_p \) in the heterostructures we studied (\( l_{sp} = 4 \times 10^{-6} \) cm).

In the experiment we performed, the following conditions were satisfied:

\[
ql_{sp} \ll 1, \omega \tau \ll 1. \tag{6}
\]

Here, \( q \) and \( \omega \) are the wave vector and frequency of SAW, respectively, and \( \tau \) is the electron-momentum relaxation time. Therefore, we may regard the wave as standing and we can use the formulas obtained for the constant electric field in the analysis of dependences of high-frequency conductivity on the alternating SAW electric field.

Figure 4 shows the dependences of \( \sigma_1/\sigma_2 \) on electric field strength \( E \) calculated according to 2 for two samples in different magnetic fields. It can be seen from Fig. 4 that the condition \( \sigma_1/\sigma_2 \) is met for sample AG106 alone; therefore, the dependences \( \sigma_1/\sigma_1^0 \) on \( E \) can be analyzed on the basis of 3 only for this sample. Figure 5 shows the dependence of \( \ln \sigma_1/\sigma_1^0 \) on \( E^{3/7} \). It can be seen that the dependence is linear; the slope of the corresponding straight line makes it possible to determine (to within a numerical factor) \( V_0 \) i.e., the amplitude of fluctuations in the potential relief pattern. We found that \( V_0 \approx 1.5 meV \).

Calculation of the fluctuation amplitude by the formula 3

\[
V_0 = (e^2/\varepsilon_s)/\sqrt{n}, \tag{7}
\]

where \( n \) is the density of ionized impurities equal in our case to the carrier density in the 2D channel with \( n = 1.3 \times 10^{11} cm^{-2} \) yields \( V_0 = 4.5 \) meV, which coincides by an order of magnitude with \( V_0 \) determined experimentally to within a numerical factor.
It is stated in Ref. [18] that the electric-field range in which formula 3 is valid is limited by the inequalities
\[ V_0 \gg eE_{\text{sp}} \gg kT \left( \frac{kT}{V_0} \right)^{4/3}. \]
(8)

Using the experimental value of \( V_0 \), we can estimate the quantities in this inequality:
- \( 1.5\text{meV} \gg 3 \times 10^{-3}\text{meV} \approx 5 \times 10^{-3}\text{meV} \) at the threshold of nonlinearities; and
- \( 1.5\text{meV} \gg 7 \times 10^{-3}\text{meV} > 5 \times 10^{-3}\text{meV} \) at the upper limit in our measurements.

Taking into account that the fluctuation amplitude is determined to within a numerical factor, we may consider that the inequality holds and we can use the theory \([18]\) to interpret nonlinearities arising in the case where the conductivity obeys the Arrhenius law.

B. Nonlinearities in the Region of High-Frequency Hopping Conduction (\( \sigma_1/\sigma_2 \approx 0.1 \))

In the case of electrical conductivity limited by activation, we could use the nonlinearity theory developed for constant fields to interpret the nonlinearities in high-frequency conductivity, because this theory described the influence of a strong electric field on the motion of quasi-free electrons activated to the percolation level. The mechanism of conduction in a constant electric field and that in a high-frequency field are found to be the same. However, in the case where the electrons...
are localized, the mechanisms of high-frequency hopping conduction and dc hopping conduction are different: in the dc mode, the conduction is accomplished by hops of electrons between two edges of the sample, whereas, in a high-frequency electric field with electrons localized at separate impurity atoms, conduction can be effected by hops of electrons between two impurity atoms separated by a distance smaller than the average one (within an impurity pair with a single electron); in this case, transitions of electrons between different pairs do not occur (a neighbor-site model). Therefore, it is understandable that the theory developed for nonlinearities in the mode of dc hopping conduction cannot be used to interpret the nonlinearities we observed in high-frequency hopping conduction (Figs. 2,3).

The dependences of resistivities \( \rho_{xx} \) and \( \rho_{xy} \), on the current density in a GaAs/AlGaAs heterostructure were observed under the IQHE conditions in the region of variable-range hopping conduction at \( T \ll T_\text{F} \). These dependences were analyzed using the theory \( 24 \) for variable-range hopping conduction in a strong electric field for 2D electron gas under conditions of the quantum Hall effect. An introduction of effective temperature for hopping conduction in terms of Ref. \( 22 \) makes it possible to use the above measurements to determine the value of localization length. However, it was found that the value thus obtained was by almost an order of magnitude larger than the localization length determined from the temperature dependence of \( \rho_{xx} \) in a linear conduction mode. This fact was related to non-uniformity in the distribution of the electric field.

The theory of nonlinear high-frequency electrical conduction was developed in Ref. \( 24 \) for the 3D case. However, the dependences \( \Delta \sigma_{12}^{nl}/\sigma_{12}^{nl} \propto W^2 \) we observed are stronger than those predicted in Ref. \( 24 \) (\( \Delta \sigma \propto W \)). Here, \( \sigma_{12}^{nl} \) is the conductivity in linear mode, \( \Delta \sigma_{12}^{nl} = \sigma_{1,2}(E) - \sigma_{1,2}^{nl}, \sigma_{1,2}(E) \) is the conductivity measured experimentally, and \( W \) is the SAW power absorbed in the sample. At present, the absence of a theory for the 2D case prevents us from analyzing the obtained results. The dependences of \( \sigma_f, \sigma_1 \) and \( \sigma_2 \) on the SAW electric field under conditions of hopping conduction set in under the electric field, which becomes lower as the magnetic-field increases; this fact is qualitatively well explained by assuming that the magnetic field affects the overlap integral for localized states at different impurities and, thus, brings about a depression of hopping conduction and a decrease in the relative nonlinear component \( \sigma_{12} \).

Dependence of absorptivity of SAW by 2D electron gas on the SAW power in GaAs/AlGaAs heterostructures was previously observed \( 24 \) in magnetic fields corresponding to small integer filling numbers when the Fermi level was in midposition between the neighboring Landau levels and when the electrons were localized. However, it is hardly possible to accept the interpretations \( 24 \) of these dependences as due to the heating of 2D electron gas, which, as was mentioned above, manifests itself only in the case where the electrons in 2D configuration are delocalized.

**IV. CONCLUSION**

We studied nonlinear dependences of absorptivity and variation in the SAW velocity induced by 2D electron gas on the intensity of sound under the conditions of the integer quantum Hall effect in GaAs/AlGaAs heterostructures. The nonlinearities were analyzed on the basis of high-frequency electrical conductivity that had a complex form and was calculated from experimental data. It is shown that the electric-field range corresponding to nonlinearities can be divided into two domains.

In the electric-field domain where \( Re\sigma = \sigma_1 \gg Im\sigma = \sigma_2 \), the dependence \( \sigma_1(E) \) is not only adequately accounted for by the Shklovskii dc nonlinearity theory describing the influence of a strong electric field on the motion of quasi-free electrons activated to the percolation level, but also makes it possible to evaluate the magnitude of the fluctuation impurity potential.

In the electric-field domain where \( Im\sigma = \sigma_2 \gg Re\sigma = \sigma_1 \), the 2D high-frequency hopping conduction apparently takes place; as of yet, the nonlinearity theory for this type of conduction has not been developed.

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