THE NONLINEAR EFFECTS IN 2DEG CONDUCTIVITY INVESTIGATION BY AN ACOUSTIC METHOD.

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Abstract

The parameters of two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure were determined by an acoustical (contactless) method in the delocalized electrons region ($B \leq 2.5\,\text{T}$).

Nonlinear effects in Surface Acoustic Wave (SAW) absorption by 2DEG are determined by the electron heating in the electric field of SAW, which may be described in terms of electron temperature $T_e$. The energy relaxation time $\tau_e$ is determined by the scattering at piezoelectric potential of acoustic phonons with strong screening. At different SAW frequencies the heating depends on the relationship between $\omega \tau_e$ and 1 and is determined either by the instantaneously changing wave field ($\omega \tau_e < 1$), or by the average wave power ($\omega \tau_e > 1$).

72.50, 73.40.
Acoustical method employs a SAW propagating on a surface of piezoelectric substrate \( [\text{LiNbO}_3] \), which is accompanied by an electric field with frequency \( \omega = 2\pi f \) equal to that of SAW, penetrating in the 2DEG channel, separated from the surface of a substrate by a vacuum gap \( a \). In experiments we measure the absorption of SAW by 2DEG. Since the SAW absorption coefficient \( \Gamma \) is determined by the conductivity of 2DEG, quantizing of the electron spectrum in the magnetic field should result in peculiarities in absorption of SAW.

We studied the magnetic field \( B \) dependence of \( \Gamma \) in GaAs/AlGaAs heterostructures in \( B \) up to 2.5T in \( f \) range 30-210MHz at \( T=1.4 \text{-} 4.2 \text{K} \) in the linear regime (input power \(< 10^{-7} \text{W} \) ) and at \( T=1.5 \text{K} \) for different SAW intensities. From previous studies \( [3] \) on the same samples we obtain the carrier density \( n = 6.7 \cdot 10^{11} \text{cm}^{-2} \) and the mobility \( \mu = 1.28 \cdot 10^{5} \text{cm}^{2} / \text{V} \cdot \text{s} \) at \( T=4.2 \text{K} \) (DC-data).

Curve 1 on figure 1 illustrates the \( \Gamma \) dependencies on the magnetic field \( B \) at \( T = 4.2 \text{K} \). The maxima of \( \Gamma \), as and minima of resistivity in a case of direct current measurements, are equidistant in inverse magnetic field. That allows one to find the carrier density, by the standard method, which yields \( n = 7 \cdot 10^{11} \text{cm}^{-2} \). From \( \Gamma(B), \sigma_{xx}(B) \) was determined using the formula for \( \Gamma(\sigma_{xx}) \) of \( [3] \), and using a value of \( n \) obtained in a way presented in \( [3] \).

It was shown in \( [3] \) that at \( B < 2.5T \), \( \sigma_{xx}^{DC} \) derived from the direct current measurements and \( \sigma_{xx}^{AC} \) derived from SAW absorption are equal, and we believe electrons to be delocalized there. In this case one can determine another parameters of the 2DEG in the heterostructure.

Curve 2 of figure 1 presents the dependence \( \sigma_{xx} \) on \( B \) derived from dependence of \( \Gamma(B) \).

In accordance with the Ando theory \( [3] \) \( \sigma_{xx} = \sigma_{xx}^{*} + \sigma_{xx}^{esc} \), where \( \sigma_{xx}^{*} = \sigma_{0} / (1 + \omega_{c}^{2} \tau_{p}^{2}) \) is the classical Drude conductivity, \( \tau_{p} \) is the transport lifetime, \( \omega_{c} = eB / m^{*} c \) is the cyclotron frequency, \( m^{*} \) is the effective mass, and \( \sigma_{0} \) is the zero-field conductivity. The oscillatory term is \( [3] \): \( \sigma_{xx}^{osc} \propto \sigma_{xx}^{*} D(XT) \exp(-\pi / \omega_{c} \tau_{q}) \cos(2\pi E_{F} / \hbar \omega_{c} - \pi) = \Delta \sigma_{xx} \cos(2\pi E_{F} / \hbar \omega_{c} - \pi) / 2, \) (1)

where \( D(XT) = X_{T} / \sinh(X_{T}) \), \( X_{T} = 2\pi^{2} T / \hbar \omega_{c} \), is determined by the temperature broadening of the Fermi level, \( E_{F} \) is the Fermi energy, \( \tau_{q} \) is the quantum lifetime, which is a measure of the collisional broadening of the Landau levels at the value of \( A = \hbar / 2\tau_{q} \), and \( \Delta \sigma_{xx} \) is the oscillation amplitude.

From the slope of \( \sigma_{xx} \) dependence \( 1 / B^{2} \) one obtains \( \mu_{0} \) at \( B = 0 \). The mobility \( \mu_{0} \) appeared to be equal to \((1.1 \pm 0.1) 10^{5} \text{cm}^{2} / \text{V} \cdot \text{s} \) (15 percent difference from the Hall mobility) and does not depend on temperature.

From the analysis of the maximal amplitude \( \Delta \sigma_{xx} \) value (fig.1) one can get the classical-to-quantum scattering time ratio \( \tau_{p} / \tau_{q} \), which is equal to \( 5.5 \pm 0.5 \) and corresponds to a case of dominance of screened-Coulomb scattering of electrons from ionized charge centers \( [3] \). The Dingle temperature is \( T^{*} = \hbar / 2\pi \tau_{q} = 1.5 \text{K} \). In accordance with \( [3] \) using the known ratio \( \tau_{p} / \tau_{q} \) and the carrier sheet density one can estimate the spacer thickness, which takes a value of \( \sim 30 \text{Å} \).

Let’s consider the nonlinear effects at relatively low \( B \). The dependences of \( \Gamma \) on \( T \) and SAW intensity were obtained from the experimental curves of the type presented in Fig.1. Fig.2a illustrates the temperature dependence of \( \Delta \Gamma = \Gamma_{MAX} - \Gamma_{MIN} \), where \( \Gamma_{MAX} \) and \( \Gamma_{MIN} \) are the values of an adjacent minimum and maximum of \( \Gamma \), measured in a linear regime at a frequency of 150 MHz. Fig.2b presents the \( \Delta \Gamma \) dependence on the output power \( P \) of the RF source of SAW at 150 MHz at \( T=1.5 \text{K} \). It is seen, that \( \Delta \Gamma \) decreases with the \( P \) and \( T \) increase.

It’s quite natural to consider the nonlinearity mechanism, which was investigated earlier on these structures using direct current \( [10] \), where it has been shown that the dependence of the resistivity on the current density can be explained by the 2DEG heating.

For a description of the electron gas heating using temperature \( T_{e} \), which differs from the lattice temperature \( T_{0} \), the condition \( \tau_{p} << \tau_{ee} << \tau_{e} \) is to be met \( (\tau_{ee}, \tau_{e} \) are the electron-electron collision time and energy relaxation time respectively). \( \tau_{p} \) can be derived from the value of \( \mu_{0} \) and is equal to \( \tau_{p} = 5 \cdot 10^{-12} \text{s} \). In \( [11] \) we obtained \( \tau_{ee} = 5 \cdot 10^{-10} \text{s}, \tau_{e} \simeq 3.3 \cdot 10^{-9} \text{s} \).
By analogy with \[10\] one can determine \(T_e\) - the temperature of 2DEG - comparing the dependence of \(\Delta \Gamma\) on \(P\) with its temperature dependence.

In order to find the energy losses \(Q\), we have made the following calculations: the electric field \(E\), corresponding to a SAW propagating in a piezoelectric, and penetrating in a 2D system, is:

\[
|E|^2 = K^2 \frac{32 \pi}{\nu} (\epsilon_1 + \epsilon_0) b \frac{k \exp(-2ka)}{1 + [(4 \pi \sigma_{xx}/\epsilon_s v)c(k)]^2} W,
\]

where \(K^2\) is the electromechanical coupling coefficient, \(\nu, k\) are the SAW velocity and the wave vector; \(\epsilon_0, \epsilon_1, \epsilon_s\) are the dielectric constants of vacuum, the piezoelectric and the sample respectively, \(W\) is the input SAW power in the sample per sound track width. The functions \(b\) and \(c\) are complex functions of \(\epsilon_0, \epsilon_1, \epsilon_s, k, a\). The energy losses per one electron \(Q = e \mu E^2\). Multiplying the both parts of Eq.(2) by \(\sigma_{xx}\), one obtains \(Q = 4WT/\eta\).

We have investigated the dependencies \(Q = f(T_e^3 - T_0^3)\), which in accordance with the results of \[14\] obtained for a DC, should correspond to the energy relaxation of electrons on piezoelectric potential of acoustic phonons (PA-scattering) in case of weak screening \[12\]. However, we find that our experimental curves can be fitted better by \(Q = A_5(T_e^5 - T_0^5)\) which corresponds to the case of PA-scattering with strong screening \[12\]. This is also in better accordance with our experimental situation, because the strong screening condition is fulfilled for the studied sample. Figure 3 shows the experimental points and theoretical dependencies \(Q(T_e^5 - T_0^5)\) for \(f=30\) and \(150\) MHz with \(A_5 = 3 \pm 0.5\) eV/sK\(^5\) and \(4.1 \pm 0.6\) eV/sK\(^5\), respectively.

Besides, it should be noticed that \(A_5\) takes different values for different frequencies. This difference is associated probably due to the fact that in the case of \(150\) MHz \(\omega \tau_e > 1\) the heating is determined by average wave power, whereas at \(f=30\) MHz and \(\omega \tau_e < 1\) the 2DEG heating is determined by the instantaneously changing wave field. That can lead to the different heating degree for the same energy losses.

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FIGURES

FIG. 1. The experimental dependences of the absorption coefficient $\Gamma$ (1) and of the 2DEG conductivity $\sigma_{xx}$ (2) on magnetic field at $T = 4.2K$ at frequency 30MHz.

FIG. 2. The $\Delta \Gamma$ dependence on temperature ($a$) and on power ($b$) at 150MHz for different magnetic fields $B$: 1-1.75T, 2-1.5T, 3-1.41T.

FIG. 3. The dependence of the energy losses $Q$ on the temperature $T_e$ for two frequencies (1-150MHz, 2-30MHz).
\[ \Gamma_\text{MIN} \]

\[ \Gamma_\text{MAX} \]

\[ \sigma_{xx} \] (10^{-4} \text{ Ohm}^{-1})

\[ 2\Delta\sigma_{xx} \]

\[ \sigma_{xx}^* \]

\[ B (T) \]

\[ \Gamma (\text{dB/cm}) \]
