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Impurity potential broadening of the Landau level as measured by an acoustoelectronic method

I. L. Drichko, A. M. Diakonov, V. D. Kagan and *I. Yu. Smirnov*
Ioffe Physico-Technical Institute, St.Petersburg, Russia

Abstract. In the quantum Hall regime the conductivity σ_{xx}, measured in a direct current experiment is equal to 0, whereas the alternative current conductivity σ_{xx}^{ac} has a finite value. It has been shown [1], that from the study of this *a.c.* conductivity one could obtain valuable characteristics of 2DEG and estimate the role of random fluctuation potential. As it has been demonstrated earlier, one of the best methods for the study of σ_{xx}^{ac} in semiconducting heterostructures is that of acoustoelectronic interaction of surface acoustic waves with 2DEG in a structure.

The SAW attenuation by the 2DEG was originally observed in [2]. If a sample is placed on the surface of a lithium niobate plate in such a way that the distance a between the 2DEG channel and the surface of $LiNbO_3$ is less than the SAW length, the 2-dimensional electrons find themselfs in an alternative electric field of SAW, which captures them and drags in the direction of propagation. The energy of the alternative electric field is absorbed, SAW is attenuated and its velocity grows because of of the additional piezoelectric stiffening of the propagation medium. The absorption coefficient of a SAW can be theoretically presented in the way [3]:

$$\begin{aligned} \Gamma &= 8.68\frac{K^2}{2}kA\frac{(4\pi\sigma_{xx}/\epsilon_s v)t(k)}{1+[(4\pi\sigma_{xx}/\epsilon_s v)t(k)]^2}, \ \frac{\text{dB}}{\text{cm}} \\ A &= 8b(k)(\epsilon_1+\epsilon_0)\epsilon_0^2\epsilon_s\exp(-2ka), \end{aligned} \tag{1}$$

where K^2 is the electromechanical coupling coefficient of piezoelectric substrate, k and v are the SAW wavevector and the velocity respectively, a is the vacuum gap width between the lithium niobate platelet and the sample, σ_{xx} is the dissipative conductivity of 2DEG, ϵ_1, ϵ_0 and ϵ_s are the dielectric constants of lithium niobate, vacuum and semiconductor respectively. b and t are complex functions of a, k, ϵ_0, ϵ_s and ϵ_1. When $(4\pi\sigma_{xx}/\epsilon_s v)t(k) = 1$, Γ achieves it's maximum Γ_m: $\Gamma_m = 8.68Ak(K^2/2)(1/2)$.

In our experiments we measure the absorption of SAW in a GaAs/AlGaAs heterostructure (mobility $\mu = 1.28\cdot 10^5$ cm/Vs, carrier density $n = 6.7\cdot 10^{11}$ cm^{-2}).

The measurements were carried out in a temperature range 1.5–4.2K, magnetic field up to 7 T, acoustic frequency 30–150 MHz. Two kinds of measurements were performed: for the first kind the acoustic power maintained low enough to provide the linearity of results, for the second kind a nonlinear behavior was studied intensively, at 1.5 K the dependence of 2DEG conductivity on acoustic power level (RF-generator output power P) was measured. In addition measurements of ρ_{xx} and ρ_{xy} were performed at magnetic fields up to 6 T and in a temperature range 0.65–4.2 K on a sample with similar parameters.

Fig. 1 illustrates the experimental dependences Γ on B. The linear behavior $\Gamma(T)$, as well as the $\Gamma(P)$ at $B < 3$ T has been studied in [4, 5]. In the present work

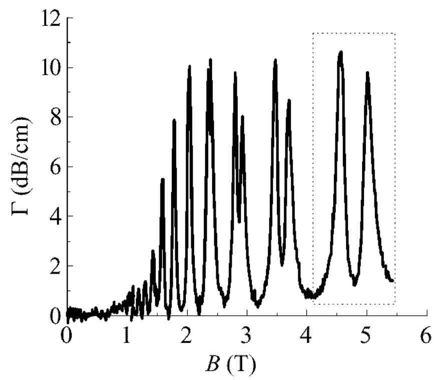

Fig. 1. The experimental dependences of Γ on B at $T = 1.5$ K, SAW frequency $f = 30$ MHz.

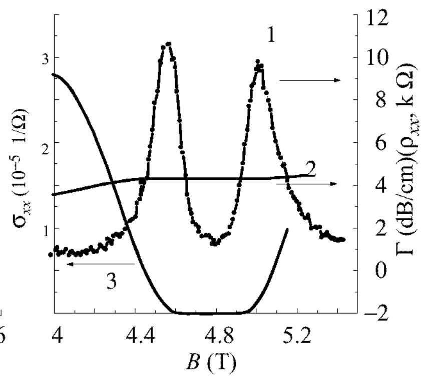

Fig. 2. The experimental dependences of $\Gamma(T)$ (1), ρ_{xy} (2) and σ_{xx} (3) on magnetic field at $T = 1.5$ K.

the experimental data for the magnetic fields corresponding to the middle of the Hall plateaus (quantum Hall regime) will be analyzed. It should be noticed that the analysis of the conductivity effects, performed in the present work, could be impossible in the framework of the conventional direct-current methods, because in the used magnetic field range DC conductivity is zero: the region of the Hall plateau. Meanwhile the absorption coefficient Γ behavior is characterized by dramatic peculiarities.

Fig. 2 (zoom-out of the part of Fig.1) illustrates the experimental dependences of Γ, σ_{xx} and ρ_{xy} on B, in the magnetic field region 4–5.5 T. Because σ_{xx} in this B region is very small, from (1) it follows that $\Gamma \propto \sigma$ therefore we can operate with Γ instead.

Fig. 3 illustrates the $\Gamma(T)$ dependences ($f = 30$ MHz) at magnetic fields corresponding to the attenuation minima (or the middle of the Hall plateau): 4.8, 3.6, and 2.9 T, which are deduced from the curves of the Fig. 1 type measured at different T and f. Similar curves were obtained for $f = 150$ MHz also. As one can see from the figure, as T grows, in a certain temperature range Γ does not depend on a temperature, but at higher temperature begins to grow exponentially; the stronger B, the higher T at which the growth starts.

Such a dependence of Γ on T could be explained, if one supposed that at these levels of a magnetic field the attenuation adds up from both the SAW attenuation (Γ_2) by the 2DEG thermally activated to the upper Landau level, and that (Γ_h) due to the hopping conductivity σ_h of electrons, localized on the impurities in the 3-dimensional layers or hopping conductivity of 2D electrons on the localized states near the Fermi level. Both hopping mechanisms have a weak dependence on temperature [6, 7]. If $\Gamma \propto \sigma$, $\Gamma = \Gamma_2 + \Gamma_h$.

As the temperature grows, more and more 2-dimensional electrons appears at the upper Landau level, due to their activation from the bound states at the Fermi level. This leads to the growth of the weight of Γ_2 in the total absorption, and therefore the T dependence of Γ becomes one of activation type.

The above speculations allowed us to obtain the value of SAW attenuation by merely subtracting Γ_h from the experimentally measured Γ. Γ_h is equal to the Γ in the temperature range where Γ is temperature-independent at the magnetic fields 4.8 and 3.6 T ($\Gamma_2 \ll \Gamma_h$). At $B = 2.9$ T, when there is no temperature flattening, Γ_h was obtained,

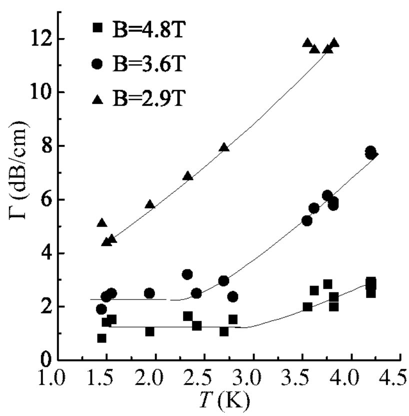

Fig. 3. The dependences of Γ on temperature at $f = 30$ MHz in the magnetic fields corresponding to the attenuation minima.

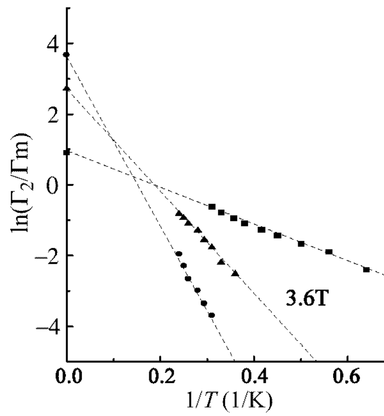

Fig. 4. The values of $ln\Gamma_2/\Gamma_m$ vs. $1/T$ in magnetic fields: 1—4.8, 2—3.6, 3—2.9 T at $f = 30$ MHz.

using the assumption that $\Gamma_h \propto 1/B^2$, which holds for 4.8 and 3.6 T, and has been observed in the case of 3-dimensional conductivity [6]. The values of Γ_2 obtained as a result of the subtraction were plotted as $\ln \Gamma_2/\Gamma_m$ (Γ_2 is devided by Γ_m in order to decrease the experimental error) versus $1/T$ (Fig. 4). When done for different magnetic fields and SAW frequencies such plots indeed confirm our earlier assumption and lead to the conclusion that SAW attenuation by the 2DEG in the upper Landau level is $\Gamma_2 \propto \sigma_2 \propto n \propto \exp(-\Delta E(B)/kT)$, where $\Delta E(B)$ is the energy gap between the Fermi level and the percolation level in the Landau band, widened by the random fluctuation potential. The dependence of ΔE on magnetic field, deduced from $\Gamma_2(1/T)$ for different SAW frequencies is presented in Fig. 5. Supposing $\Delta E = \hbar\omega_c/2 - A/2$, from the ordinate cut-off point of (crossing point) the $\Delta E(B) = 0$ curve for $B = 2.1$ T one could obtain A, the Landau band width, which appeared to be $A = 3.4$ meV. The slope of the $\Delta(B)$ line in Fig. 5 appeared to be 0.72 1/T, which by 10 percent differs from the $e/m^*c = 0.8$ 1/T, if $m^* = 0.07m_0$ for GaAs (m_0 — free electron mass). Hence, $\Gamma_2(T)$ behavior is governed by the activation of 2-D electrons from the bound states at the Fermi level to the upper Landau band, widened due to the fluctuation potential.

The dependence of Γ on the RF-generator output power P at the same magnetic field is shown in Fig. 6. As it can be seen from the figure, Γ increases with the increase of P. Keeping in mind that in the temperature range emploied, and at given magnetic fields the Γ_2 is determined by the activation of electrons to the upper Landau level from the Fermi level, Frenkel-Pool effect consisting in the activation energy decrease in electric field E of a SAW [8] could be considered as a model.

$$\Gamma_2 \propto \sigma_2 \propto n(T, E) = n_0 \exp(2e^{3/2}E^{1/2}\epsilon_s^{-1/2}/kT), \qquad (2)$$

where n_0 -carrier density in the upper Landau level at a linear approach at 1.5 K. An electric field E, in which 2D-electrons are when SAW propagates in a piezoelectric, is [5]:

$$|E|^2 = K^2 \frac{32\pi}{v}(\epsilon_1 + \epsilon_0) b_1(k) \frac{k \exp(-2ka)}{1 + [(4\pi\sigma_{xx}/\epsilon_s v)t]^2} W, \qquad (3)$$

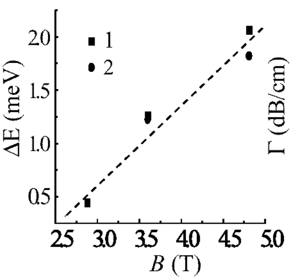

Fig. 5. The dependences of ΔE on magnetic field for different SAW frequencies: 1—30 MHz, 2—150 Mhz.

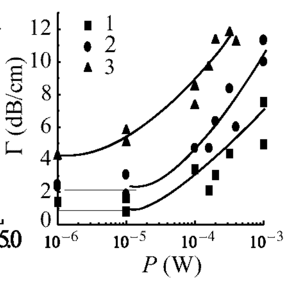

Fig. 6. The values of Γ ($f = 30$ MHz) vs. RF output power P in the magnetic fields corresponding to the Γ minima: 1—4.8 T, 2—3.6 T, 3—2.9 T.

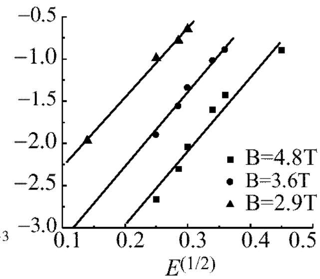

Fig. 7. The dependences of $ln\Gamma_2/\Gamma_m$ on $E^{1/2}$ for different B: 1—4.8 T, 2—3.6 T, 3—2.9 T at 30 MHz.

where W -the input SAW power in the sample per sound track width, $b_1 = 2b \cdot t$. Expression (2) has been obtained for a d.c. electric field, but it can be shown that it holds when E is the electric field of a SAW.

$Ln\Gamma_2$ plotted against $E^{1/2}$, where $\Gamma_2 = \Gamma - \Gamma_h$, and E is the electric field of SAW (Fig. 7) confirms our model. Indeed, this dependence could be presented by a straight line, with the slope $2e^{3/2}/\epsilon_s^{1/2}kT = 9(E^{-1/2}cgs)$. From (2) this slope comes equal to 26.

The discrepancy between the theoretical and experimental slopes could be due to several origins: lack of the precision in the determination of RF-power at the input of the sample, the assumption of the independence of Γ_h on E, and the neglect of the electron heating effects in the upper Landau level, when the input RF power is increased.

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