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**CONDENSED MATTER**

# Energy Relaxation of Two-Dimensional Electrons in the Quantum Hall Effect Regime

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**Abstract**—The mm-wave spectroscopy with high temporal resolution is used to measure the energy relaxation times $\tau_e$ of 2D electrons in GaAs/AlGaAs heterostructures in magnetic fields $B = 0–4$ T under quasi-equilibrium conditions at $T = 4.2$ K. With increasing $B$, a considerable increase in $\tau_e$ from 0.9 to 25 ns is observed. For high $B$ and low values of the filling factor $\nu$, the energy relaxation rate $\tau_e^{-1}$ oscillates. The depth of these oscillations and the positions of maxima depend on the filling factor $\nu$. For $\nu > 5$, the relaxation rate $\tau_e^{-1}$ is maximum when the Fermi level lies in the region of the localized states between the Landau levels. For lower values of $\nu$, the relaxation rate $\tau_e^{-1}$ is maximum at half-integer values of $\nu$ when the Fermi level is coincident with the Landau level. The characteristic features of the dependence $\tau_e^{-1}(B)$ are explained by different contributions of the intra-level and interlevel electron–phonon transitions to the process of the energy relaxation of 2D electrons. *© 2000 MAIK "Nauka/Interperiodica".*

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**1.** In the last decade, the electron–phonon interaction and the mechanisms of the energy relaxation of hot carriers were one of the most important problems of the physics of 2D structures. For the case of the scattering by acoustic and optical phonons in a wide temperature range in the absence of magnetic field, this problem has been solved by many authors, both theoretically (e.g., [1, 2]) and experimentally (e.g., [3, 4]). For a magnetic field perpendicular to the 2D layer, the electron–phonon interaction becomes essentially different because of the quantization of the carrier energy in the 2D plane.

A number of theoretical publications present the calculation of the energy relaxation rate of electrons in a real situation with allowance for the broadening of the Landau levels, as well as the appearance of a region of delocalized states near the center of the Landau level and localized states between the levels in the electron energy spectrum [5–8]. It was shown that, in a quantizing magnetic field, the spectrum of phonons involved in the interaction with electrons is essentially altered, which should result in a change in the energy relaxation rate.

Because of the dependence of the density of electron states on magnetic field, the energy relaxation rate should experience oscillations similar to the resistance oscillations in the Shubnikov–de Haas effect.

The energy relaxation may occur at the expense of the transitions both between the Landau levels and within them. The conditions of the experiment determine which of these two processes prevails. The object of most experimental studies is the spectrum of phonons involved in the interaction with electrons in magnetic field, as well as their angular distribution [6–9]. The measurements of the Landau level population by magnetic tunneling spectroscopy [10] provided the estimates of the energy relaxation time $\tau_e$ for the interlevel electron transitions. In magnetic fields $B \geq 4$ T, this quantity was found to be equal to ≈100 ns, which far exceeds the values of $\tau_e$ corresponding to zero magnetic field. As for the direct measurements of the energy relaxation times in magnetic field, no such experiments had been described in the literature.

**2.** We studied the inelastic relaxation of two-dimensional electrons in GaAs/AlGaAs geterostructures at the temperature $T = 4.2$ K in magnetic field 0–4 T perpendicular to the 2D plane. The measurements were performed under the weak heating conditions when the free carriers could be considered as quasi-equilibrium ones. We measured the relaxation time of the mm-wave photoconductivity caused by the nonresonance absorption of electromagnetic radiation in the regime of Shubnikov–de Haas oscillations of the resistance (the energy of the radiation quantum $\hbar\omega = 0.6$ meV was much less than $\hbar\omega_C$ for $B > 1$ T, where $\omega_C$ is the cyclotron frequency). For the measurements, we used GaAs/AlGaAs structures with the concentration $n_s \approx$

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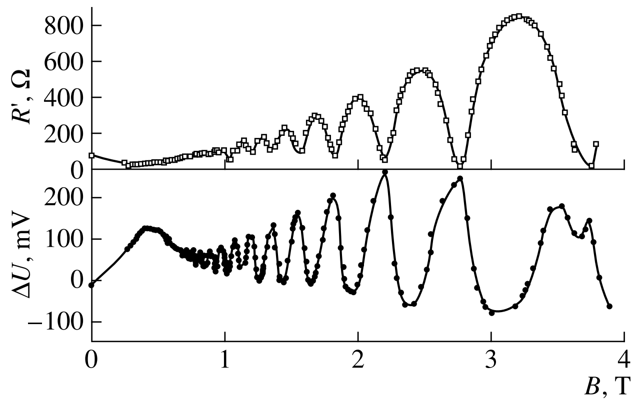


**Fig. 1.** (●) Photoconductivity signal in the mm-wave range $\Delta U$ and (□) the oscillatory contribution to the resistance of the sample $R'$ versus the magnetic field $B$. $R' = R - \Delta R(B)$, where $\Delta R(B)$ is the contribution of the magnetoresistance to the resistance of the sample; $\Delta R(B)$ linearly increases with increasing $B$.

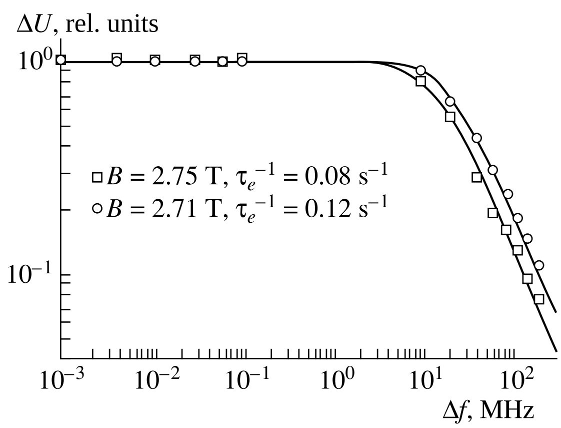


**Fig. 2.** Dependence of the signal magnitude on the modulation frequency for two close values of magnetic field: $B$ = 2.75 and 2.71 T. For low frequencies $\Delta f$, the values of $\Delta U$ are normalized to the photoconductivity signal at a frequency of 1 kHz.

$5 \times 10^{11}$ cm$^{-2}$ and the mobility $\mu = 2 \times 10^5$ cm$^2$/Vs at $T$ = 4.2 K. As in our previous experiments [4], for the direct measurements of the energy relaxation time, we used the mm-wave spectroscopy with high temporal resolution.

The specific feature of the case under study is that in magnetic field the energy relaxation time varies over wide limits, from $10^{-9}$ to $10^{-7}$ s. To measure small relaxation times $\tau_e < 10^{-8}$ s, we used a mm-wave spectrometer in which the electromagnetic radiation was incident on the sample from two backward-wave tube oscillators shifted in frequency by $\Delta f$. The absorption of electromagnetic radiation by free carriers or bonded carriers in the region of localized states leads to a variation in the sample resistance $\Delta R$ and the appearance of a photoconductivity signal $\Delta U$ at the frequency $\Delta f$. The relaxation time of the mm-wave photoconductivity signal is equal to the energy relaxation time of the carriers in the absence of the bolometric effect, and it is determined by the frequency dependence of the quantity $\Delta U$:

$$\Delta U(\Delta f) = \frac{\Delta U(\Delta f = 0)}{\sqrt{1 + (2\pi \Delta f \tau_e)^2}}.$$

The frequency stability of the backward-wave tube oscillators allows one to perform such measurements at frequencies $\Delta f > 10^7$ Hz ($\tau_e < 10^{-8}$ s). To measure large relaxation times, the electromagnetic radiation of a backward-wave tube oscillator is modulated by supplying a modulating voltage at the frequency $\Delta f$ to the anode circuit of the tube.

The measurements of $\tau_e$ in quasi-equilibrium conditions impose stringent requirements on the sensitivity of the measuring equipment because of the weak dependence of the resistance of the structure $R$ on the electron temperature. The sensitivity of the equipment used in our experiments allowed us to perform the measurements with the minimum electromagnetic radiation power incident on the sample and the dc power $P_{e\,\min} \approx 5 \times 10^{-17}$ watt per electron, which corresponds to an increase in the temperature of free two-dimensional carriers by $\Delta T_e \approx 0.1$–0.3 K; this value is quite suitable for the measurements at the temperature $T$ = 4.2 K.

**3.** The measurements of the nonresonant mm-wave photoconductivity $\Delta U$ showed that, in a magnetic field, the quantity $\Delta U$ exhibits oscillations similar to the Shubnikov–de Haas oscillations of the resistance (Fig. 1). The measured values of $\Delta U$ shown in the figure correspond to the low-frequency modulation of the mm-wave radiation ($\Delta f$ = 2 kHz). The signal is a bipolar one: in the vicinity of the resistance minimum in the Shubnikov–de Haas oscillations, $\Delta U$ corresponds to the growth of resistance with the absorption of electromagnetic radiation, and in the vicinity of the maximum in the resistance $R$ it corresponds to a decrease in the resistance. The first maximum observed in the signal at $B \approx$ 0.4 T corresponds to the cyclotron resonance at the frequency of the mm-wave radiation. The signal $\Delta U$ is asymmetric about zero: it is considerably greater at the minimum in the resistance $R$. The bipolarity of the signal is related to different mechanisms of photoconductivity (the electron gas heating near the resistance maximum and the hopping mechanism at the resistance minimum), and it was also observed in other experiments (e.g., [11]).

The photoconductivity signal $\Delta U$ was measured as a function of the frequency $\Delta f$ in magnetic fields from 0 to 3.6 T. As an illustration, in Fig. 2 we present the dependences of the photoconductivity signal $\Delta U$ on $\Delta f$ for two close values of $B$ ($B_1$ = 2.75 T and $B_2$ = 2.71 T) corresponding to the vicinity of the minimum in $R$. One can see that the frequency dependences noticeably differ from each other. From the measurements of $\Delta U(\Delta f)$, we obtained the values of $\tau_e^{-1}(B)$ (Fig. 3). The absence of the experimental values of $\tau_e^{-1}$ for $B$ = 2.9–3.3 and 2.3–2.5 T is related to the insufficient sensitivity of the experimental setup at high frequencies $\Delta f > 10^6$ Hz (in these intervals of magnetic fields $B$, the photoconductivity signal is too weak; see Fig. 1).

The experiment shows that, with increasing $B$, the electron–phonon interaction becomes less efficient ($\tau_e^{-1}$ decreases), and, at $B \approx 1.2$ T, the energy relaxation rate decreases by an order of magnitude relative to its value at $B = 0$. In the quantum Hall effect regime ($B > 1$ T, the filling factor $\nu = \epsilon_F/\hbar\omega_c < 8$), the dependence $\tau_e^{-1}(B)$ exhibits oscillations. The depth of these oscillations increases with increasing $B$. In Fig. 3, the arrows indicate the values of $B$ corresponding to the maximum photoconductivity signal (the minimum $R$). One can see that, for $B > 2.5$ T, the quantity $\tau_e^{-1}$ is minimum in magnetic fields $B$ corresponding to the resistance minimum, while, for $B < 2$ T, the minimum $\tau_e^{-1}$ corresponds to the resistance maximum.

**4.** We begin the analysis of our experimental results with some estimates. The measurements are performed at $T = 4.2$ K. The prevailing component of the electron–phonon interaction is the scattering due to the deformation potential; the wave vector of a thermal phonon $q = kT/\hbar S$ is of the order of the wave vector of a two-dimensional electron at the Fermi surface $k_F$ ($kT/\hbar S \approx k_F$). In the absence of magnetic field, the wave vectors of the phonons that take part in the electron–phonon interaction are limited in the direction perpendicular to the 2D layer by the transverse dimension of the layer $a_0$: $q_\perp < 1/a_0$, and, in the layer plane, according to the conservation laws, we obtain the limitation $q_\| < 2k_F$. Thus, all phonon states fill a cylinder of height $1/a_0 \approx 10^6$ cm$^{-1}$ for typical GaAs/AlGaAs 2D structures and of radius $q_\|$ (for the concentration of two-dimensional carriers $n_S \cong 5 \times 10^{11}$ cm$^{-2}$, we obtain $q_\| \approx 4 \times 10^6$ cm$^{-1}$ $\approx 1/a$). In a magnetic field, only the radius of the cylinder is changed; namely, $q_\|$ is limited by the magnetic length $l_B = \sqrt{\hbar/eB}$: $q_\| < 1/l_B$ ($1/l_B = 3.9 \times 10^5$ T$^{-0.5}$ cm$^{-1}$). For magnetic fields $B < 4$ T, we have $q_{\|B \neq 0} \ll q_{\|B = 0}$. These estimates show that, in the absence of magnetic field, the energy relaxation rate is determined by the emission of phonons with the energy $\approx kT$, while, in magnetic field, such phonons can be emitted only at low angles to the magnetic field direction, which considerably reduces the electron energy relaxation rate. Hence, the substantial decrease in $\tau_e^{-1}$ observed in the experiment in magnetic field can be attributed to the change in the spectrum of phonons involved in the electron–phonon interaction.

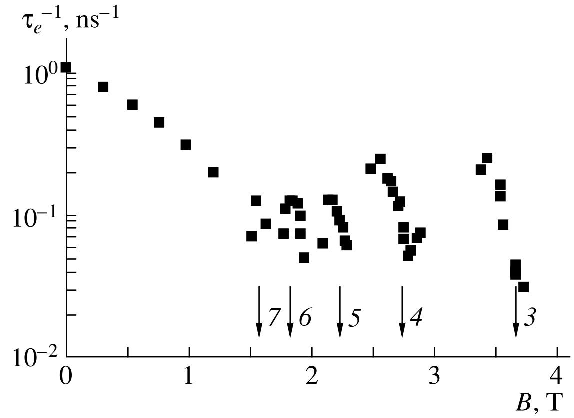


**Fig. 3.** Dependence of the inverse relaxation time of the photoconductivity signal $\tau_e^{-1}$ on the magnetic field $B$. The arrows indicate the values of $B$ at which $R$ takes its minimum values. The numbers near the arrows show the values of the filling factor $\nu$ corresponding to the given magnetic fields.

In a major part of the magnetic field range, the values of $\tau_e^{-1}$ obtained from our experiments describe the inelastic relaxation related to the electron transitions within the Landau levels. In fact, the energy of the mm-wave radiation quantum is $\hbar\omega = 0.6$ meV. For the maximum value of $B$, we obtain the estimate $\hbar\omega_C \approx 6$ meV; then, for magnetic fields $B > 1$ T, we have $\hbar\omega \gg \hbar\omega_C$. In the experiment, the temperature was $T = 4.2$ K, and $kT \approx 0.4$ meV. Since $kT \ll \hbar\omega_C$, in this magnetic field range the electrons occupy only the Landau levels with the energy $\epsilon \le \epsilon_F$. Therefore, the absorption of a radiation quantum with the energy $\hbar\omega \ll \hbar\omega_C$ can be accompanied only by the electron transitions within the last occupied Landau level. These transitions lead either to the carrier heating when $\epsilon_F$ is coincident with the energy of the Landau level in the region of delocalized states, or to nonresonant hopping between localized states when $\epsilon_F$ falls between the Landau levels in the region of localized states. In this case, the energy relaxation of excited carriers may occur only at the expense of the electron transitions within the Landau level. According to Kent *et al.* [9], the energy relaxation rate for the intralevel relaxation strongly depends on the density of states; i.e., the energy relaxation rate is maximum when the Fermi level coincides with the Landau level, and it is minimum when $\epsilon_F$ falls in the region of localized states. Only in low magnetic fields, in the transient region of $B$ where $kT < \hbar\omega_C$, interlevel transitions are possible owing to the presence of several partially filled Landau levels. As a result of the absorption of electromagnetic radiation, the heated carriers may emit phonons of both low energies $\epsilon_{ph} \ll \hbar\omega_C$ and high energies $\epsilon_{ph} \approx \hbar\omega_C$ (the interlevel ones). Although the probability of the emission of high-energy phonons is much less than that of the low-energy phonons, the former make a substantial contribution to the relaxation because of the large change in the electron energy in every event of emission. The energy relaxation rate for to these transitions is maximum when the Fermi level is in the region of localized states between the Landau levels [9]. In this case, the probability of the emission of phonons with the energy $\epsilon_{ph} \ll \hbar\omega_C$ is increased, since, for $kT < \hbar\omega_C$, the delocalized states at the Landau level with the energy $\epsilon > \epsilon_F$ are filled to a greater extent, and the delocalized states at the Landau level with the energy $\epsilon < \epsilon_F$ are filled to a lesser extent, as compared to the case of the Fermi level lying in the region of delocalized states.

The conditions corresponding to the energy relaxation at the expense of the intralevel transitions are fully realized in our experiment for $B > 2$ T: the quantity $\tau_e^{-1}$ exhibits two deep minima at the magnetic fields corresponding to the minima in the resistance $R$ ($\nu = 3$, 4). At $B = 3.6$ T, the value of $\tau_e^{-1}$ is an order of magnitude less than that corresponding to the maximum in $R$. Evidently, the depth of the oscillations should grow with increasing $B$ (at lower filling factors $\nu$) and with decreasing $T$. The oscillations of the quantity $\tau_e^{-1}$ are also observed for intermediate magnetic fields 1 T < $B$ < 2 T. However, at the values of $B$ corresponding to the minimum resistance $R$, a maximum in $\tau_e^{-1}$ is observed, which presumably testifies to the substantial contribution of the interlevel electron–phonon transitions to the energy relaxation of two-dimensional electrons. In this interval of magnetic fields $B$, the depth of the oscillations is much less than at low values of $\nu$.

Thus, we measured the energy relaxation times of 2D electrons in quasi-equilibrium conditions, in magnetic fields corresponding to the quantum Hall effect regime. We have shown that the quantization of the electron energy in magnetic field leads to a sharp decrease in the energy relaxation rate and to oscillations of the energy relaxation time that are similar to the Shubnikov–de Haas oscillations. Under weakly nonequilibrium conditions, the energy relaxation in high magnetic fields is determined by the electron–phonon transitions within the Landau level. The contribution of the electron–phonon transitions between the Landau levels manifests itself in intermediate magnetic fields.

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