Energy relaxation of 2D electrons at an AlGaAs/GaAs heterojunction

M. G. Blyumina, A. G. Denisov, T. A. Polyanskaya, I. G. Savel'ev, A. P. Senichkin, and Yu. V. Shmartsev
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

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Experiments reveal that the low-temperature heating of 2D electrons at an AlGaAs/GaAs heterojunction is caused by a piezoelectric scattering by acoustic phonons.

We have studied the Shubnikov–de Haas oscillations of the resistance in selectively doped $Al_{0.27}Ga_{0.73}As/GaAs$ heterostructures fabricated by molecular-beam epitaxy and described in Ref. 1. The present measurements were carried out with a direct current in double-cross-shaped samples over the temperature interval from 1.8 to 4.2 K. Figure 1a shows the temperature dependence of the oscillation amplitude ΔR_{SH} (normalized to the sample resistance R_0) at a fixed magnitude of the magnetic field, for two values of the electric field. The oscillations of the resistance over the field range studied $H \lesssim 10$ kG, are sinusoidal. The temperature dependence of the amplitude $\Delta R_{SH}/R_0$ for the case of an electric field which does not cause heating is described well by the theory of Ref. 2 with the effective mass $m^*/m_0 = 0.069 \pm 0.002$ for the 2D electrons. A comparison of the curve of $\Delta R_{SH}(E)$ (Fig. 1b) with the temperature dependence $\Delta R_{SH}(T)$ at $E = 0.02$ V/cm reveals the electron temperature T_e and its dependence on the electric field E.

In the "temperature approximation,"[3] the energy balance equation of 2D electrons which are interacting with acoustic phonons can be written

$$\langle Q \rangle = \alpha (T_e^\gamma - T^\gamma) = \alpha T^\gamma [(T_e/T)^\gamma - 1], \tag{1}$$

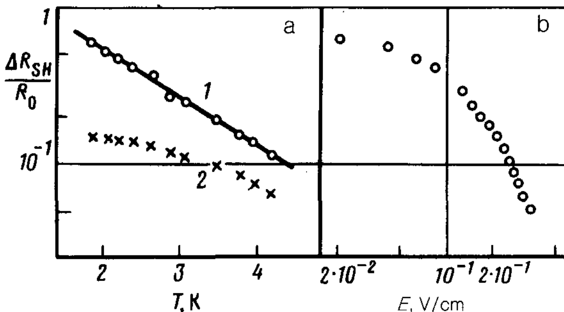

FIG. 1. Normalized amplitude of the Shubnikov–de Haas oscillations in sample No. 1 at a fixed magnetic field $H = 9.6$ kG. a: As a function of the temperature, for two values of the electric field E. 1—0.02 V/cm; 2—0.2 V/cm. b: As a function of the electric field at a lattice temperature $T = 1.86$ K.

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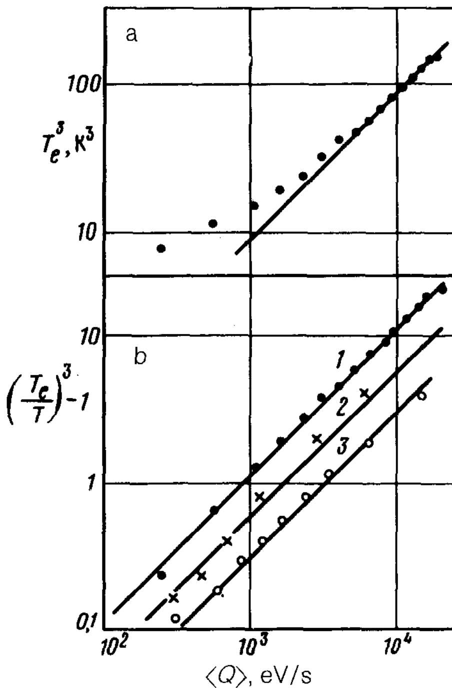

FIG. 2. a: Electron temperature T_e versus the supplied power $\langle Q \rangle$ at $T = 1.86$ K for sample No. 1. The straight line corresponds to $\langle Q \rangle \sim T_e^3$. b: The quantity $(T_e/T)^3$ versus the supplied power $\langle Q \rangle$. 1—Sample No. 1; 2—sample No. 2; 3—data of Ref. 9. The straight lines correspond to the behavior $\langle Q \rangle = A\,[(T_e/T)^3 - 1]$.

where $\langle Q \rangle = e\mu E^2$ is the Joule power per electron. Figure 2a shows the experimental dependence of the electron temperature T_e on the supplied power $\langle Q \rangle$. We see that in a strong field, $E > 0.2$ V/cm, in which we have $(T_E/T)^3 > 7$, the experimental dependence is described by an expression $\langle Q \rangle \sim T_e^3$. It can also be seen from Fig. 2b that the dependence becomes completely linear in terms of the coordinates $\langle Q \rangle$ and $[(T_e/T)^3 - 1]$; i.e., at the fixed value $T = 1.86$ K we have $\langle Q \rangle = A\,[(T_e/T)^3 - 1]$. Comparing curves 1 and 2 in Fig. 1a, we can find T_e as a function of the lattice temperature T at a fixed value of the electric field, and we can find the temperature dependence of the proportionality factor A: $A = \alpha T^3$ (Fig. 3). The balance equation in these struc-

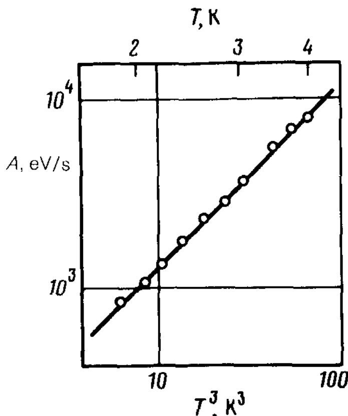

FIG. 3. The coefficient A versus the lattice temperature T for sample No. 1. The straight line corresponds to a function $A = \alpha \cdot T^3$.

tures is therefore described by expression (1) with $\gamma = 3$. Here we have $\alpha = 130$ eV/(s·K^3) for sample No. 1, with an electron density $n_\Box = 6.75\times10^{11}$ cm^{-2} and a mobility $\mu = 1.5\times10^5$ cm^2/(V·c), while we have $\alpha = 230$ eV/(s·K^3) for sample No. 2 with $n_\Box = 7.79\times10^{11}$ cm^{-2} and $\mu = 7.9\times10^4$ cm^2/(V·s).

For the energy balance equation of the 2D electrons as they interact with the strain energy of the acoustic phonons (DA scattering), in the low-temperature limit, $T < T_1 = 2\hbar k_F s$ (s is the sound velocity, and k_F is the wave vector of an electron with an energy ϵ_F), the theory predicts a value $\gamma_{DA} = 5$ if the screening of the electron scattering is ignored[4] or $\gamma_{DA} = 7$ if there is a strong screening.[5] A strong screening corresponds to the condition[6] $x \equiv q\lambda_q \ll 1$, where q is the phonon wave vector, and λ_q is the screening length. In a 2D gas in the long-wave limit ($q \approx T/\hbar s < k_F$) we would have $\lambda_q \simeq a_B/2$, where a_B is the Bohr radius of the electron ($a_B = 100$ Å for GaAs). In the same limit ($x \ll 1$) the value $\gamma_{PA} = 5$ was found in Ref. 5 for the interaction of 2D electrons with the piezoelectric potential of acoustic phonons (PA scattering). In the samples which were studied, the condition for the low-temperature limit is satisfied ($T_1 \simeq 15$ K $> T$), but the case of strong screening apparently does not hold because of the relation $x \simeq 1$. Consequently, the experimental value $\gamma = 3$ is not explained by the theory of Refs. 4 and 5. It was pointed out in Ref. 4, however, that in the low-temperature limit the difference between the energy loss rates of 2D and 3D electrons (if screening is ignored) would consist of only a change in the numerical factor in the expression for the energy balance. We thus considered it reasonable to use the results of the calculation of $\langle Q \rangle$ for PA scattering in a 3D electron gas given in the monograph by Gantmakher and Levinson[6] (see Table 6.1 in that monograph), where the values $\gamma_{PA} = 3$ and $\alpha = 1.8/\bar{\tau}_{PA}\epsilon_F^{3/2}(\hbar\omega_0)^{1/2}$. Here $\hbar\omega_0 = 421$ K and $\bar{\tau}_{PA} = 8\times10^{-12}$ s are characteristic parameters for GaAs (Ref. 6). This calculation yields the value $\alpha = 220$ eV/(s·K^3) for sample No. 1 and $\alpha = 170$ eV/(s·K^3) for sample No. 2. These values are close to the values found experimentally. However, according to the theoretical expression, the value of α should decrease with increasing electron density, while for the two samples studied we find the opposite behavior. This point remains unclear.

Interestingly, if we follow the previous approach (see the review by Ando *et al.*[7]) and plot $\Delta T = T_e - T$ versus the electric field E in logarithmic scale, we find that our data on sample No. 2 conform quite well to a straight line corresponding to the dependence[8] $\Delta T \sim E^{1.5}$. This behavior has been seen previously in silicon metal-insulator-semiconductor structures,[9] but it has not been explained, as was pointed out by Ando *et al.*[7] The data from Ref. 9 are shown in Fig. 2a; they are described well by (1) with $\gamma = 3$. This may be just a random coincidence, since no PA scattering occurs in silicon. However, other studies of silicon metal-insulator-semiconductor structures also fail to provide a complete agreement with the theory of scattering by a DA potential[4]—either in terms of the magnitude of the coefficient α (Ref. 10) or in terms of the exponent γ (Refs. 9 and 11).

The quantitative discrepancy between theory and experiment both in the present study and in Refs. 9 and 11 might be a consequence of the fact that the heating of the electrons was studied in the presence of a quantizing magnetic field. Since we have no theory for the heating of 2D electrons distributed among Landau levels (when a large

number of levels is filled), the effect of the magnetic field was ignored in the analysis of the experimental data, both in the present study and in the other studies.

For gallium arsenide, calculations show (e.g., Ref. 12) that at $T < 10$ K the primary mechanism for the interaction of electrons and phonons is a piezoacoustic scattering, in agreement with the results of the analysis which we are reporting here.

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