Electron energy relaxation in a 2D channel in AlGaAs–GaAs heterostructures under quasiequilibrium conditions at low temperatures

A. I. Verevkin, N. G. Ptitsina, G. M. Chulkova, G. N. Gol'tsman, and E. M. Gershenzon[1)]

Moscow Pedagogical State University, 119882 Moscow, Russia

K. S. Yngvesson

Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01003

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The energy relaxation time of 2D electrons, τ_ϵ, has been measured under quasiequilibrium conditions in AlGaAs–GaAs heterojunctions over the temperature range $T=1.5$–20 K. At $T>4$ K, τ_ϵ depends only weakly on the temperature, while at $T<4$ K $\tau_\epsilon^{-1}(T)$ there is a dependence $\tau_\epsilon^{-1}\sim T$. A linear dependence $\tau_\epsilon^{-1}(T)$ in the Bloch–Grüneisen temperature region ($T<5$ K) is unambiguous evidence that a piezoacoustic mechanism of an electron–phonon interaction is predominant in the inelastic scattering of electrons. The values of τ_ϵ in this temperature range agree very accurately with theoretical results reported by Karpus [Sov. Phys. Semicond. **22** (1988)]. At higher temperatures, where scattering by deformation acoustic phonons becomes substantial, there is a significant discrepancy between the experimental and theoretical results.

Electron–phonon interactions in the 2D electron gas in GaAs–AlGaAs heterostructures have been the subject of active research over the past decade. At low temperatures, experiments on electron heating are widely used, as in the bulk material. Although the mobility of 2D electrons in the better 2D structures is substantially higher than in the 3D case, it tells us essentially nothing about the electron–phonon interaction, since it is still limited by impurity scattering. The only method which has previously been used to study the electron energy relaxation at low temperatures has involved measuring the rate of the energy loss per electron, Q_e, as a function of the electron temperature T_e. Since there is a substantial heating of the electron gas under the conditions of these measurements,[1–3] it is not a simple matter to extract information about the kinetic times for energy and momentum relaxation under equilibrium conditions.

We have used a direct method to measure the energy relaxation time of 2D electrons in GaAs–AlGaAs heterostructures over the broad temperature range 1.5–20 K under quasiequilibrium conditions. The measurements were carried out on a millimeter-range spectrometer-relaxometer with a high time resolution. In this method, which has previously been used successfully to study superconductor structures,[4] the electromagnetic radiation from two backward-wave tubes, differing in frequency by an amount ΔF, is applied to the test sample. The absorption of the electromagnetic radiation by free carriers results in a heating of the electron gas and a change in the resistance, if the latter depends on the electron temperature. The change in the resistance of the sample, ΔR, at the frequency $f=\Delta F$ is determined from the change in the static bias voltage across the sample, ΔU. The relaxation time of the submillimeter-photoconductivity signal, which is equal to the energy relaxation time of free carriers in the absence of a bolometric effect, is found from the frequency dependence

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

Measurements of τ_ϵ under quasiequilibrium conditions ($T_e \approx T$) place several demands on the sensitivity of the measurement apparatus. The magnitude of the signal ΔU is small, because of the weak temperature dependence of the resistance of the sample. This temperature dependence is determined by the electron–phonon interaction. At low temperatures, on the other hand, the resistance is dominated by the temperature-independent impurity scattering. Even further requirements are imposed on the sensitivity because achieving quasiequilibrium conditions requires that the sum of the electromagnetic power $P_{e_\sim}$ and the dc power P_e absorbed by the sample be limited. The maximum permissible values of the sum ($P_{e_\sim}+P_e$) furthermore decrease with decreasing temperature, because of an increase in τ_ϵ (Ref. 5). The sensitivity of the measurement apparatus which we used was such that we could carry out measurements at $P_{e_{\min}} \approx 5\times 10^{-17}$ W/electron and $P_{e_{\sim\min}} \approx 10^{-17}$ W/electron. The test samples were prepared by molecular beam epitaxy. At $T=4.2$ K, they had a mobility $\mu \approx 7\times 10^5$ cm^2/V·s and an electron density $N_s \approx 4.2\times 10^{11}$ cm^{-2} in the 2D layer. The dimensions of the conducting layer were 200×50 μm. The measurements were carried out on a 2-mm-range spectrometer, as f was varied over the range 10^7–10^9 Hz, in the temperature range $T=1.6$–20 K.

Measurements of $\tau_\epsilon(P_e)$ at various lattice temperatures showed that a power $P_e=5\times 10^{-17}$ W/electron satisfies the conditions for a quasiequilibrium situation only at $T \geqslant 3$ K. The power of the electromagnetic radiation absorbed by the electrons, P_e, is low enough that the change which occurs in the electron temperature satisfies $\Delta T_e \ll T_e$, and the energy relaxation of the system can be described by a single value of $\tau_\epsilon(T_e)$, as under quasiequilibrium conditions. Extrapolating the measured behavior $\tau_\epsilon(P_e)$ to $P_e \to 0$, we find quasiequilibrium values of τ_ϵ at low temperatures.

Figure 1 shows the $\tau_\epsilon(T)$ dependence. The values of τ_ϵ found by extrapolation are shown by distinctive symbols in this figure. We see that at high temperatures, $T>4.2$ K, the time τ_ϵ is essentially independent of T, while at $T<4.2$ K it increases with decreasing temperature, approximately in accordance with T^{-1}. From the measurements of $\tau_\epsilon(P_e)$ we also found the dependence of τ_ϵ on the electron temperature T_e in the case of a pronounced heating by the static electric field, at various lattice temperatures. To determine the electron temperature T_e we measured Shubnikov–de Haas oscillations. Values of T_e were found in the standard way, by comparing the amplitudes of the oscillations in a magnetic field $B<1.5$ T corresponding to different values of P_e at a fixed lattice temperature and at various values of the temperature at a fixed low value of the power P_e ($P_e<10^{-17}$ W/electron). From the set of measurements of $\tau_\epsilon(T)$, $\tau_\epsilon(P_e)$, and

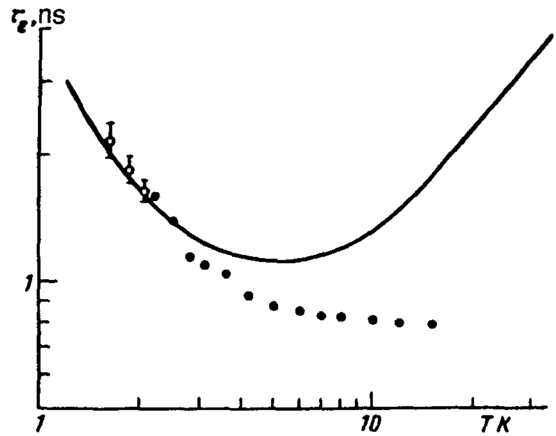

FIG. 1. Temperature dependence of τ_ϵ. Solid curve—Theoretical $\tau_\epsilon(T_e)$ calculated from the data of Ref. 6; ●—experimental data; ○—values of τ_ϵ found through an extrapolation of the experimental data to $P_e \to 0$.

the Shubnikov–de Haas oscillations we found that the energy relaxation time at sufficiently low temperatures ($T<5$ K) is determined exclusively by the electron temperature [$\tau_\epsilon(T)=\tau_\epsilon(T_e$ at identical values of T and T_e].

In theoretical studies[1,5,7] of the electron–phonon interaction in 2D structures, it has been customary to discuss either the temperature dependence of the mobility or the behavior of the energy loss rate Q_e as a function of T_e. It follows from those studies that, in the temperature range of interest here, the piezoacoustic (PA) and deformation (DA) scattering are comparable in magnitude; the DA scattering is predominant at high T, and the PA scattering at low T. Accordingly, it has become customary in the literature to carry out numerical calculations of $Q_e(T_e)$ and $\mu(T)$ incorporating both types of scattering. From a numerical calculation of $Q(T_e)$ for conditions of pronounced heating we find the values

$$\tau_\epsilon(T_e)=\frac{dE}{dQ(T_e)},$$

where dE is the change in the average energy of the carriers caused by a change in the power absorbed by the electrons, $dQ(T_e)$. For a degenerate 2D electron gas we have[1]

$$dE=\frac{\pi^2 k^2 T_e dT_e}{3\varepsilon_F \tau_\epsilon},$$

where ε_F is the Fermi energy, and k the Boltzmann constant. This situation is realized in our experiments when there is a pronounced heating by the static electric field ($T_e \gg T$), at a low level of the electromagnetic-radiation power absorbed. The most comprehensive analysis of electron–phonon scattering in 2D structures, including the most popular system—of electrons in a 2D channel on (001)GaAs (as we used)—was carried out in a series of studies by Karpus.[5] It follows from those studies that at $T \leqslant 6$ K the values of τ_ϵ should be determined exclusively by the electron temperature T_e, since in this temperature range ($T<\hbar k_F s/k$, where k_F is the electron wave vector at the Fermi surface, and s is the sound velocity) the primary mechanism for electron energy relaxation is spontaneous emission of acoustic phonons. This conclusion is supported by our own experiments, which show that we have $\tau_\epsilon(T_e)=\tau_\epsilon(T)$ for identical values of T and T_e.

The theoretical dependence $\tau_\epsilon(T_e)$ found by the method described above, from Fig. 3 in Ref. 6, is shown by the solid curve in Fig. 1 of the present paper. We see that the experimental results essentially coincide with the theoretical results at low temperatures. The linear $\tau_\epsilon^{-1}(T)$ dependence at low temperatures is unambiguous evidence that piezoacoustic scattering is predominant under these conditions. This conclusion is supported by the experiments of Ref. 2, in which a dependence $Q\sim T_e^3$, characteristic of piezoacoustic scattering, was found at $T=1.6$ K. At $T>4$ K, the experimental results on $\tau_\epsilon(T)$ and the theoretical results on $\tau_\epsilon(T_e)$ under strong-heating conditions are noticeably at odds. On the one hand, we should apparently not expect the values of $\tau_\epsilon(T)$ and $\tau_\epsilon(T_e)$ to be the same in this case, since in this transition region, with $T>\hbar k_F s/k$, a stimulated electron–phonon interaction should play a progressively greater role under quasiequilibrium conditions, leading to values of $\tau_\epsilon(T)$ which are smaller than $\tau_\epsilon(T_e)$. On the other hand, the heating experiments by Sakaki *et al.*,[1] carried out at $T=4.2$ K and $T_e=4.2$–20 K, yield a quadratic dependence $Q(T_e)$, which disagrees with the theoretical functional dependence found by Karpus[6] at $T>8$ K. The values of $\tau_\epsilon(T_e)$, which can be estimated from the $Q(T_e)$ measurements, yield $\tau_\epsilon\sim0.7$ ns, close to the values found in our experiments at $T=6-12$ K. Note that the error in the $Q(T_e)$ measurements is too large to allow us to extract the temperature dependence $\tau_\epsilon(T_e)$ from the experimental data.

The good quantitative agreement between our experimental data and the theory of Refs. 5 and 6 at low temperatures suggests that the accuracy of the $\mu(T)$ in Ref. 5 is quite high in this temperature region. Working from published measurements of the mobility μ of 2D electrons at low temperatures for the better GaAs–AlGaAs heterostructures (Ref. 8, for example), we can attempt to find the limiting mobility set by the electron–phonon interaction. To do this, we have to eliminate from the measured values of μ the contribution of impurity scattering, which actually limits μ at low temperatures. Although such estimates are not very accurate, they are consistent with our conclusion that the calculations of Ref. 5 agree with the experimental values of μ at low T.

In summary, we have measured the energy relaxation time of electrons in 2D GaAs–AlGaAs structures. The results show that in the Bloch–Grüneisen temperature region ($T<5$ K), in which we have $\tau_\epsilon\sim T^{-1}$, the piezoelectric mechanism for the electron–phonon interaction is predominant in inelastic electron scattering. The values of τ_ϵ in this region agree highly accurately with the results of calculations by Karpus.[5,6] At higher values of T (in the transition region), at which scattering by deformation acoustic phonons becomes important, we see a significant discrepancy between the experimental and theoretical results.

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[1)]e-mail: gershenzon@rpl.mpgu.msk.su

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