Energy relaxation rate of the two-dimensional hole gas in a GaAs/InGaAs/GaAs quantum well

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The nonohmic conductivity of two-dimensional hole gas (2DHG) in single GaAs$In_{0.2}Ga_{0.8}$AsGaAs quantum-well structures within the temperature range of 1.4–4.2 K, the carrier's densities $p = (1.5 - 8) \times 10^{15} m^{-2}$ and a wide range of conductivities $(10^{-4}$–$100)G_0$ ($G_0 = e^2/\pi h$) was investigated. It was shown that at conductivity $\sigma > G_0$ the energy relaxation rate $P(T_h, T_L)$ is well described by the conventional theory [P. J. Price, J. Appl. Phys. **53**, 6863 (1982)], which takes into account scattering on acoustic phonons with both piezoelectric and deformational potential coupling to holes. At the conductivity range $0.01G_0 < \sigma < G_0$ energy the relaxation rate significantly deviates down from the theoretical value. The analysis of $\frac{dP}{d\sigma}$ at different lattice temperature T_L shows that this deviation does not result from crossover to the hopping conductivity, which occurs at $\sigma < 10^{-2}$, but from the Pippard ineffectiveness.

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I. INTRODUCTION

In the case of conductivity over delocalized states (diffusive conductivity), the electric-field dependence of the conductivity originates from the heating of the two-dimensional hole gas (2DHG) up to temperature T_h, greater than lattice temperature T_L. In the stationary conditions T_h is determined by the balance between incoming energy rate P_{in} and energy relaxation rate P. Therefore, studying the nonohmic conductivity, one can find the energy relaxation rate P, its dependence on T_L, T_h, and determine the main mechanisms of the energy relaxation. Moreover, the study of nonohmic conductivity provides an opportunity to find the conditions in which the diffusion conductivity changes to hopping conductivity with the change of density, disorder, and temperature. It is possible due to the fact that in the hopping regime of conductivity $\sigma(E)$ dependence results not only from the change of the carrier distribution over energy, but also from the change in probability of hopes along the field.

Over the past 20 years there have been published a number of experimental papers, investigating heating of 2D electron gas in GaAs structures at high conductivities,[1–5] 2D hole gas in SiGe,[5] and a few papers studying heating of holes in GaAs,[6,7] but only for lattice temperatures below 100 mK. To the best of our knowledge, there is no experiment within a wide conductivity range at higher temperatures in GaAs. In the present paper, we investigate the dependence of the energy relaxation rate on the carrier density and the strength of disorder in InGaAs-based 2D hole structures in the temperature range of 1.4–4.2 K and a wide range of conductivities $(10^{-4}$–$100)G_0$. We have obtained the following results. It was shown, that at conductivities above G_0 the energy relaxation rate is well described in terms of scattering on acoustic phonons.[8] At lower conductivities $(3 \times 10^{-2} - 1)G_0$ the energy relaxation rate deviates down from the theory in Ref. 8, while the regime of conductivity remains diffusive. This deviation is associated with the Pippard ineffectiveness of electron-phonon interactions. It was shown that a crossover to the hopping conductivity with lowering of σ occurs at $\sigma \sim 10^{-2}$.

II. EXPERIMENTAL DETAILS

The structures investigated were grown by metalorganic vapor-phase epitaxy on a semi-insulating GaAs substrate and consist of a 0.2 mum thick undoped GaAs buffer layer, a 10 nm InGaAs quantum well, and a 0.2–0.3 mum cap layer of undoped GaAs. The Carbone δ layer was situated at the distance of 7 nm (samples 3855, 3857) or 15 nm (3953) from each side of the quantum well. The samples were mesa-etched into the standard Hall bars. The hole density was varied by applying voltage to the Al gate electrode, deposited by thermal evaporation. Nonohmic conductivity measurements on gated structures require special care: the voltage drop along the sample must be significantly lower than the gate voltage, otherwise the distribution of the carrier under the gate electrode would be non-homogeneous. To avoid this effect the sample surface was covered by a 3–5 mum thick dielectric (parylen) layer before depositing the gate electrode. With this layer $\frac{dp}{dV_g}$ was less than 5×10^8 cm^{-2}V^{-1} and we could apply gate voltage V_g up to 300 V (while the voltage drop along the sample was less than 0.5 V). The hole densities and conductivities at zero gate voltage and lattice temperature $T_L = 1.4$ K for the structures investigated are listed in Table I.

The hole effective mass $m = 0.16m_0$ was obtained from the temperature dependence of Shubnikov–de Haas oscillations.[9] The dependence $p(V_g)$ was obtained in a set of measurements with a long gate electrode, covering two pairs of Hall contacts (upper inset in Fig. 1). The heating experiments were taken with a shorter (Hall contacts remained uncovered) gate electrode (lower inset in Fig. 1) to avoid the rise in contact resistance at a high bias voltage. The current dependence of voltage drop between potential contacts 3–4 was measured during the current sweep while the lattice temperature remained constant. Temperature dependence of conductivity was measured in a linear regime of the response.

III. RESULTS AND DISCUSSION

Figure 1 shows the dependences of the conductivity on lattice temperature $\sigma(T_h)$ and electric field $\sigma(E)$ at lattice

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TABLE I. The parameters of the samples.

Sample	p, $\times 10^{11}$ cm^{-2}	$\sigma(1.4\,\mathrm{K}), G_0$
3855	5.4	44.2
3857	8.7	84
3953	4	100

temperature $T_L = 1.4$ K and $V_g = 0$ for sample 3855. The temperature dependence of conductivity of degenerate gas ($E_F \gg k_B T$, E_F is the Fermi level) at low temperatures is fully determined by the temperature dependence of quantum corrections to the conductivity. The corrections depend on nothing but the carrier temperature T_h [the dependence $\sigma(T)$ for similar structures was investigated in Ref. 10]. In this case, having compared the temperature dependence of conductivity in the ohmic regime and electric-field dependence of conductivity, we have reconstructed (follow the dashed line in Fig. 1) the electric field dependence of hole temperature T_h, and, then, we have calculated the incoming power $P_{\mathrm{in}} = jE = \sigma E^2$, required to heat the holes up to T_h.[11] In stationary conditions, P_{in} is equal to an energy relaxation rate $P(T_h, T_L)$. The temperature dependence of the energy relaxation rate $P(T_h, T_L)$, obtained at different lattice temperature T_L for sample 3855, is presented in Fig. 2. at conductivity $44.2 G_0$. Similar results were obtained for all the structures investigated over a wide conductivity range.

Let us compare our experimental data with the theory. As the mechanism governing a relaxation rate at low temperatures is scattering on acoustic phonons with both piezoelectric and deformational couplings, we use the theory from Ref. 8 for the quantitative analysis. The energy relaxation rate as a function of hole temperature T_h and lattice temperature T_L is written as a

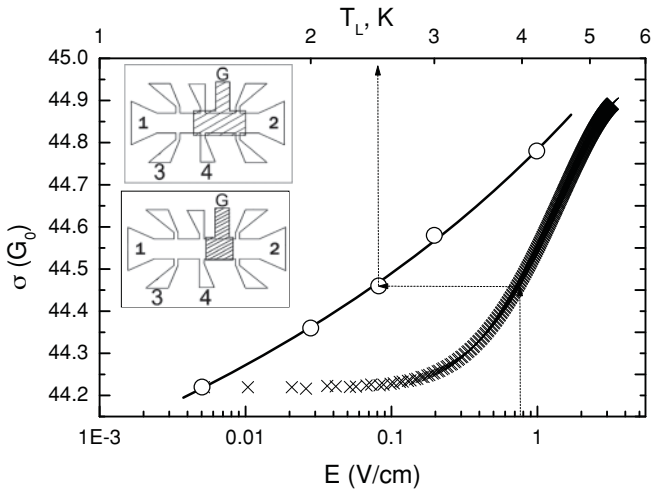

FIG. 1. The dependence of conductivity on lattice temperature in the ohmic regime (open circles), and on the electric field at $T_L = 1.4$ K (crosses). The solid line is the approximation of $\sigma(E)$ by a smooth function. Upper inset: Hall bar with a gate for $p(V_g)$ measurements. Lower inset: Hall bar with gate for heating experiments.

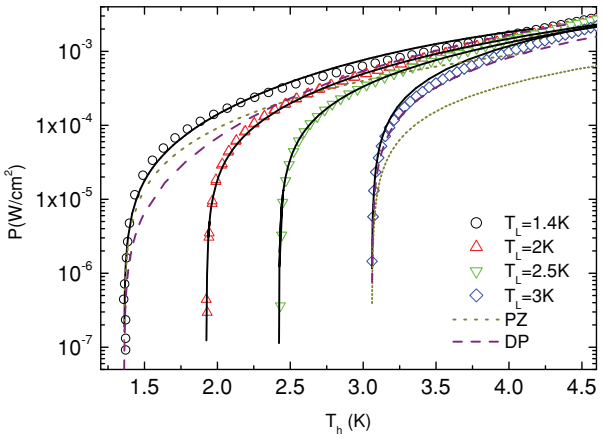

FIG. 2. (Color online) Hole temperature dependence of energy relaxation rate at different lattice temperatures for sample 3855 [$V_g = 0, p = 5.4 \times 10^{11}, \sigma(1.4) = 44.2 G_0$]. Dashed and dotted lines are the contributions from the coupling with deformation and piezoelectric potential, respectively, solid lines are their sums.

difference of two identical functions, where one term depends on T_h, and the other on T_L [Eq. (12) in Ref. 8]:

$$P(T_h, T_L) = \frac{p}{\hbar E_F}[F(T_h) - F(T_L)] \tag{1}$$

with

$$F(T) = \int dq |I(q)|^2 \overline{a[S(q)]^2 (\hbar w)^3 N(\hbar w / k_B T)}, \tag{2}$$

where $I(q) = \int_{-d}^{d} \rho(z) e^{iqz} dz$ is the form factor for the normal-direction wave function [$\rho(z) = \sqrt{\frac{1}{d}} \cos(\frac{\pi z}{2d})$]; $2d$ is the width of quantum well; $S(q)$ is a screening factor; $N(\hbar w / k_B T)$ is the phonon distribution function; a is a quantity, associated with the three-dimensional scattering matrix. In general $F(T)$

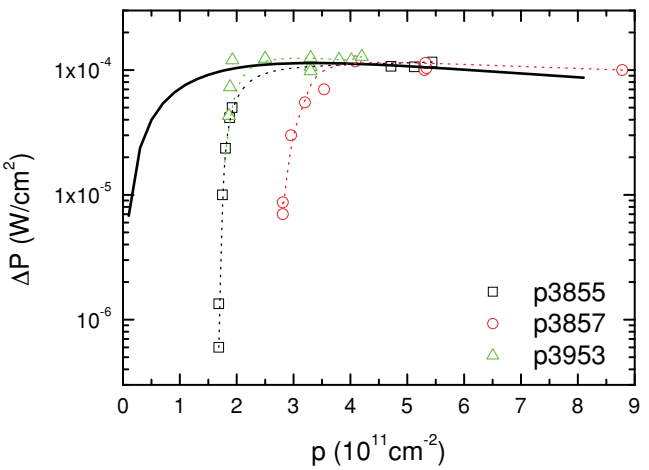

FIG. 3. (Color online) The power ΔP required to heat holes from lattice temperature $T_L = 1.4$ K up to $T_h = 1.9$ K as a function of concentration. The solid line is a theoretical curve in accordance with Eq. (1). Dotted lines are only to guide the eye.

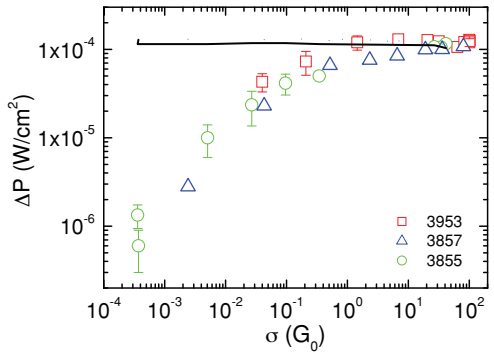

FIG. 4. (Color online) The power ΔP required to heat holes from lattice temperature $T_L = 1.4$ K up to $T_h = 1.9$ K as a function of conductivity at $T_L = 1.4$ K. Solid line is theoretical dependence $\Delta P(p(\sigma))$ for sample 3855.

is the sum of deformation-coupled and piezoelectric-coupled contributions:

$$F = F_{\mathrm{Ln}}^{DP} + F_{\mathrm{Ln}}^{PZ} + F_{\mathrm{Tr}}^{PZ},$$

where index Ln refers to the longitudinal component of the wave vector, and Tr to the transversal one. Then each component of a could be expressed as follows[3]:

$$a_{\mathrm{Tr}}^{PZ} = b_0 \frac{\alpha^2}{q^2+Q^2} \frac{8q^4Q^2+Q^6}{2(q^2+Q^2)^3}, \tag{3}$$

$$a_{\mathrm{Ln}}^{PZ} + a_{\mathrm{Ln}}^{DP} = b_0 \left(\frac{\alpha^2}{q^2+Q^2} \frac{9q^4Q^2+Q^6}{2(q^2+Q^2)^3} + 1 \right), \tag{4}$$

where $\alpha = \frac{eh_{14}}{\Xi}$, h_{14} is a piezoelectric coupling constant, Ξ is the deformation potential, q and Q are the components of the wave vector normal to and parallel to the heterolayer plane, respectively. The constant b_0 is equal to $\frac{m^*\Xi^2}{\hbar^2 2k_l}$, where k_l is an elastic constant equal to $\rho \cdot s_{\mathrm{Ln}}^2$ (ρ is the density of GaAs, s_{Ln}^2 is the longitudinal velocity of sound).

We have calculated temperature dependences of the energy relaxation rate using the following coupling constants: $h_{14} = 1.5 \times 10^9 V/m$ (Ref. 12), $\Xi = 8$ eV (Ref. 13), and the two-dimensional screening constant $p = (\frac{a_B}{2})^{-1} = 0.5$ nm^{-1}, where a_B is an effective Bohr radius.

The calculated curves $P(T_h, T_L)$ are presented in Fig. 2. The dashed and dotted lines are the contributions of the

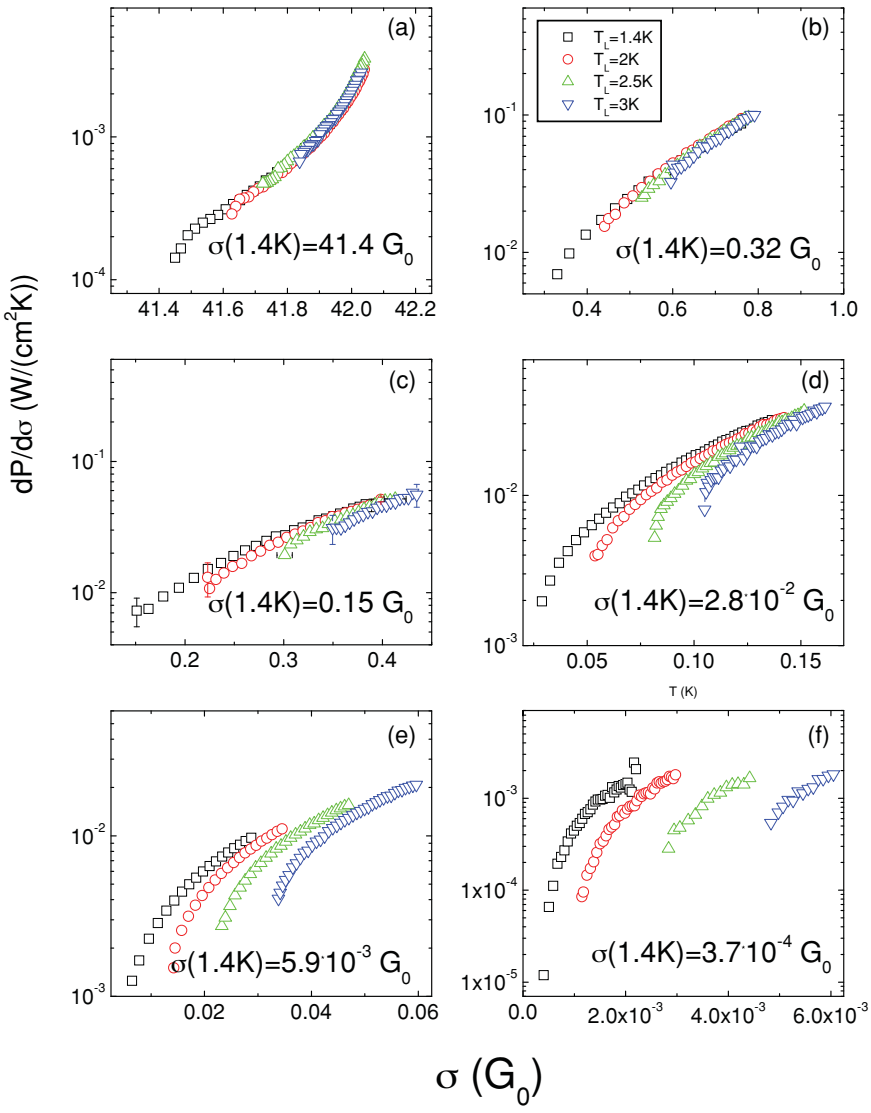

FIG. 5. (Color online) The derivative of energy relaxation rate with respect to σ at different lattice temperatures for sample 3855. The values of conductivities at $T_L = 1.4$ K are presented in the panels.

deformation and piezoelectric couplings, respectively. One can see that their contributions are comparable within the whole temperature range. The solid line is their sum. As seen from Fig. 2 the theoretical curves are in good agreement with the experimental data.

It is impossible to compare directly our experimentally obtained values of the energy relaxation rate with the results in Refs. 6 and 7, as they have been obtained at lower temperatures (below 100 mK). However, if we calculate $P(T_h, T_L)$ with the coupling constants, we used, we would get the energy relaxation rate only twice as large as the experimental value in Refs. 6 and 7. We believe that it is quite a good agreement for extrapolation from units of Kelvin down to milli-Kelvin temperatures.[14]

From Eq. (1) it follows that besides coupling constants, temperatures T_h and T_L, the only sample parameter which the energy relaxation rate depends on is hole density. Let us analyze the dependence of the power ΔP required to heat holes from lattice temperature $T_L = 1.4$ K up to $T_h = 1.9$ K, shown in Fig. 3. It is seen that at densities above a certain value (different for each sample), the experimental data are in agreement with the theory. At lower densities the experimental energy relaxation rate significantly deviates downward from the theoretical value significantly. Such divergence for all cases takes place when the conductivity of 2D gas falls below G_0 (Fig. 4).

A possible reason for such divergence could be the change of a conductivity mechanism (it is commonly believed that at $\sigma < \pi G_0$ conductivity is hopping), and in this case the above-described treatment with P is not valid anymore. To clarify the conductivity mechanism let us analyze the derivative $\frac{\partial P}{\partial T_h}$.[15]

From Eq. (1) it is seen that in a diffusive regime the derivative $\partial P/\partial T_h$ is independent of lattice temperature T_L. It means that experimental dependences $\frac{\partial P}{\partial T_h} = f(T_h)$, obtained at different T_L should fall on the universal curve.[15] This statement is valid when the change of σ with the electric field originates from the change of the hole temperature only. As a consequence, the set of curves $\partial P/\partial\sigma$ as a function of σ also has such a property. Besides, the treatment with $\partial P/\partial\sigma$ is more consequential because when the approximation of the hole temperature fails, $\partial P/\partial\sigma$ remains defined.

In the hopping regime, firstly, σ depends both on lattice and hole temperatures. Secondly, the change of conductivity with the electric field results not only from hole heating, but also from the change in the probability of hops. Finally, the energy distribution function of holes in the electric field can deviate from the Fermi-Dirac function. All these effects have to lead to a divergence of dependences $\frac{\partial P}{\partial\sigma} = f(\sigma)$ at different T_L.

Dependencies $\partial P/\partial\sigma$ for sample 3855, obtained experimentally, are depicted in Fig. 5. As seen from Fig. 3(a), the data taken at different lattice temperatures fall on one universal dependence when the conductivity of the 2D gas is relatively high $\sigma(1.4K) = 44.1G_0$. With decreasing conductivity this behavior remains until the conductivity reaches the value of $2.8 \times 10^{-2}G_0$ [Fig. 3(b,c)]. And only at $\sigma \approx 2.8 \times 10^{-2}G_0 \approx 10^{-2}\frac{e^2}{h}$ the curves begin to diverge, and with a decrease in conductivity they diverge drastically [Fig. 3(d,e,f)]. Such divergence indicates a crossover to a hopping regime of conductivity in the investigated structures.

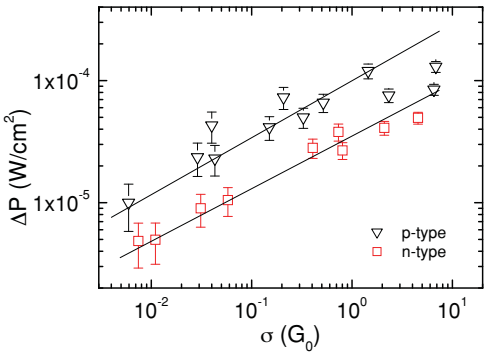

FIG. 6. (Color online) The dependence of power ΔP required to heat holes from lattice temperature $T_L = 1.4$ K up to $T_h = 1.9$ K as a function of conductivity for p-type and n-type structures.

Hence, the conductivity remains diffusive at $\sigma(1.4\,\mathrm{K}) > 3 \times 10^{-2}G_0$ and the drop in the energy relaxation rate at conductivity range $3 \times 10^{-2}G_0 < \sigma < 1G_0$ is not caused by a crossover to the hopping conductivity. We believe that it is caused by the Pippard ineffectiveness of the electron-phonon interactions,[16] which takes place under the following conditions: i) the number of carriers within the length of the thermal phonon is sufficient to introduce the local conductivity $\frac{q_t}{k_F} < 1$ (q_t is the wave vector of the thermal phonon), and ii) $q_t l < 1$, (l means free path). It was shown in Ref. 17, that the energy relaxation rate would decrease linearly in this regime. Indeed (see Figs. 4, 6), in the investigated structures the linear decrease of the energy relaxation rate is observed. It begins at $\sigma(1.4\,\mathrm{K}) \approx G_0$, when both conditions mentioned above are satisfied: $q_t l \approx 0.2$ ($q_t l = 1$ at $\sigma \approx 8G_0$). The parameter $\frac{q_t}{k_F}$ remains smaller than the unity within the whole range of temperatures. It should be noted that the analogous behavior was observed also on n-type structures (Fig. 6).[18]

IV. CONCLUSION

We have shown that in the diffusive regime at conductivities above G_0 the energy relaxation rate of 2D holes structures is well described in terms of inelastic scattering on acoustic phonons with both piezoelectric and deformational couplings to holes. It was shown that within the conductivity range of $(3 \times 10^{-2} - 1)G_0$ the conductivity remains diffusive, while the energy relaxation rate deviates from the theoretical prediction of Ref. 8 downward. Such a linear decrease results from the Pippard ineffectiveness for case $q_t l < 1$, $\frac{q_t}{k_F} < 1$. The analysis of $\partial P/\partial\sigma$ at a different lattice temperature shows that below $10^{-2}G_0$ the conductivity is hopping.

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