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Linear field dependencies of conductivity and phonon-induced conductivity of 2D gas in δ-doped GaAs

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Abstract. The electrical field dependencies of current I and its variation under phonon pulses $-\Delta I_{ph}$, were measured in δ-doped GaAs with $n = 5\times10^{11}$ cm^{-2}. It was shown that if $E< 1$ V/cm and $T = 2$ K, E/I, and E/I_{ph} linearly increase with E, and while the change in the first value was less than 5%, the second one increased by more than 3 times. The proposed explanation of experimental results is based on the nearness of the studied structure to a metal-insulator transition.

Keywords: quantum well, quantum localization.

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1. Introduction

Usually, a change in the semiconductor conductivity in the low electric field range is proportional to the square of the field strength, as it is due to electron heating. But there are other mechanisms of the electric field effect on conductivity, which lead to other field dependencies. For example, in a hopping conduction range, the electric field can result in delocalisation of energy states and decrease in activation energy of bond electrons. In this case, the conductivity change is proportional to the field strength [1–3]. It is known [2–3] that this effect increases near the Anderson-Mott transition in dielectric phase.

In the metal phase, for 3D states such mechanism of the conductivity change was observed in the only work [4] for Si:P under extreme conditions: $T < 40$ mK, $E <$ < 15 μV/cm, $(n - n_{cr})/n_{cr} = 3\cdot10^{-2}$ (n_{cr} – donor concentration at the transition point). In this work, $\sigma(E) = \sigma(0)+$ $+ a\sqrt{E}$ the square root dependence of conductivity on electric field was observed.

The Anderson-Mott transition is a special case of quantum phase transitions (QPT), in which at $T = 0$ properties of a system change qualitatively, when one of its parameter (magnetic field, the electron concentration in 2D gas, the chemical composition of a crystal and so on) achieves the critical value. For our structure, the corresponding parameter is the donor concentration, because at $n_d > n_{cr}$ there are free electrons in 2D gas. In 2D gas, the nonheating mechanism near QPT is stronger than in 3D case and, probably, has universal character [5], because it was found in rather different objects such as: quantum Hall effect [6], *a*-MoGe thin amorphous films near the superconductor-insulator transition [7] and pure Si near the metal-insulator transitions [8], although in the latter case the physics of the transition was not completely understood [9]. In all the cases this effect was observed on the both sides of transitions.

Quite formally, this phenomenon may be described by introducing the field-dependent electron effective temperature T_{el}, however, in such case T_{el} will not be connected with the electron average energy [5].

Should the nonheating mechanism be really universal, it must be observed in δ-doped GaAs, where the metal-insulator transition takes place at the doping concentration $n_d = 3\cdot10^{11}$ cm^{-2} [10]. Our purpose in the present work was to give experimental evidence of this effect in δ-doped GaAs.

2. Experimental results

Horizontal transport in δ-doped GaAs containing 7 quantum wells with $n_d = 5\cdot10^{11}$ cm^{-2} was investigated. The distance between the layers was 100 nm. All the layers were parallel to ohmic contacts. The distance between

them was 0.5 mm, the wide of 2D gas – 0.2 mm. Gold layer covered the opposite side of the sample. Heat pulses in GaAs were generated by Au film heated with 10ns-nitrogen laser beam, focused by lens to the spot with $d = 0.3$ mm. The sample structure and measurement technique were described in detail in [11,12]. First, the I-V and $\Delta I_{ph} - V$ characteristics of 2D gas were measured (where ΔI_{ph} is a change of I under the heat pulse). Then the resistance $R = V/I$, phonon-induced conductivity $\sigma_{ph} = \Delta I_{ph}/V$ and its inverse value $R_{ph} = 1/\sigma_{ph}$ were calculated. The temperature and field dependencies of these quantities were analysed. Similar experiments were made in [11,12], but the authors of these works did not investigate the field dependencies in low field range in detail.

Time dependence of phonon-induced current is shown in Fig. 1; where L and T peaks are formed by longitudinal and transverse ballistic phonons. The first peak in Fig. 1 is due to laser beam absorption in GaAs sample in the area between ohmic contacts, causing a change of the conductivity of the sample. The peaks were identified from their delays relative to the light pulse. For the first peak this delay must be equal to zero, for others – the time of flight between the source and detector for phonons of corresponding modes.

Field dependencies of R_{ph}, measured at 2K< T < 4 K at the moment of T-peak maximum, are shown in Figs 2 and 3 shows field dependencies of resistance R. In Fig. 4 temperature dependencies of R_{ph} and dR/dE in zero field, obtained by extrapolation of $R_{ph}(E)$ and $R(E)$, are shown.

The most interesting feature of these results is the linear character of field dependencies of R and R_{ph}, well seen in the Figs 2–3. For the forthcoming analysis, it is important to note some important features:

a) One may introduce an effective electron temperature $T_{ef}(E,T_0)$, defining it from the conditions $R_{ph}(E,T_0) = R_{ph}(0,T_{ef})$ or $R(E,T_0) = R(0, T_{ef})$. It is important to know to what extend T_{ef} differs from T_0, because our prime interest concerns the range where T_0 and T_{ef} are close to each other. Knowing $R_{ph}(E,T_0)$, one can get T_{ef} (1 V/cm, 2.0 K) = 3.6 K, and T_{ef} (1 V/cm, 2.5 K) = 3.9 K. Then, using $R(E, T_0)$ data, we obtain T_{ef}(1 V/cm, 2.0 K) = 3.5 K, and T_{ef} (1 V/cm, 2.5 K) = 3.8 K. It means, that at E < < 1 V/cm the condition $T_{ef} - T_0 < T_0$ is satisfied.

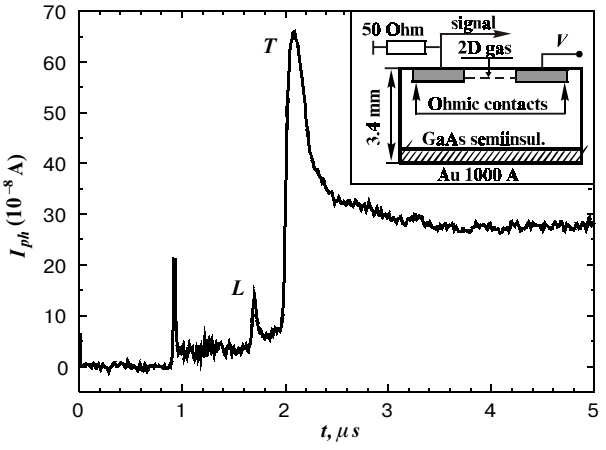

Fig. 1. Time dependence of phonon-induced current in 2D gas.

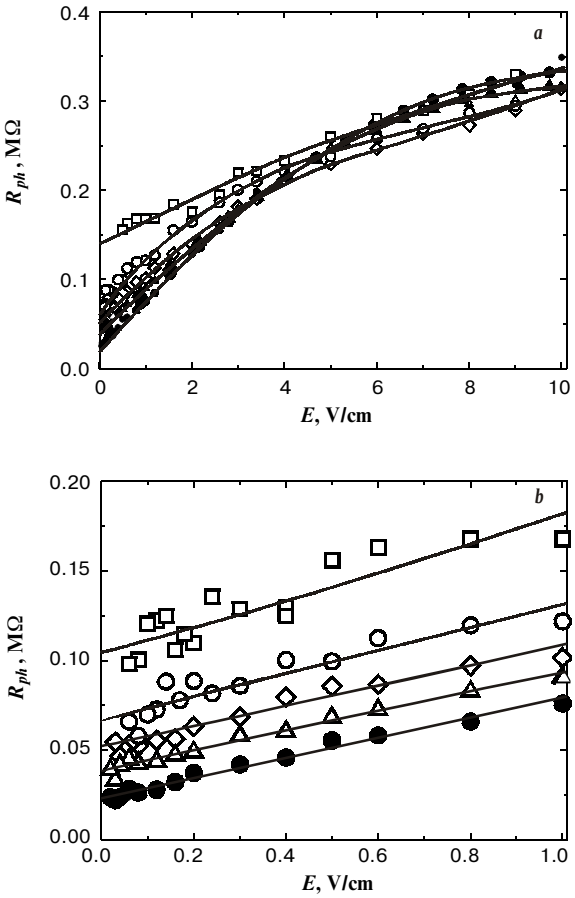

Fig. 2. Field dependencies of inverse phonon-induced conductivity in 2D gas, □ – T = 4K, ○ – T = 3.5 K, ◇ – T = 3K, △ – T = = 2.5K, ● – T = 2K.

b) The effect markedly decreases, if the temperature increases – R_{ph} increases, dR/dE in zero field becomes smaller, the range of linearity $R_{ph}(E)$ becomes narrower.

c) If E < 1 V/cm, the relative change of R_{ph} with field increasing is 30–40 times greater than the change of resistance.

3. Discussion

Let us assume that $R(E)$ and $R_{ph}(E)$ are due to the grow of the electron temperature T_e and try to define, how strong T_e changes at E <1 V/cm. In principle, a dependence $R(T)$ in zero field is due to the change of the energy distributions of both electrons and phonons, but for the investigated structure one can neglect the phonon contribution.

Magnetotransport measurements of the structure similar to investigated in this work were made in magnetic fields up to B = 14T/13/. It was found that 2D gas occupies two subbands with electron concentrations $n_1 = 4.9 \cdot 10^{11}\text{cm}^{-2}$, $n_2 = 0.93 \cdot 10^{11}\text{cm}^{-2}$ and mobilities

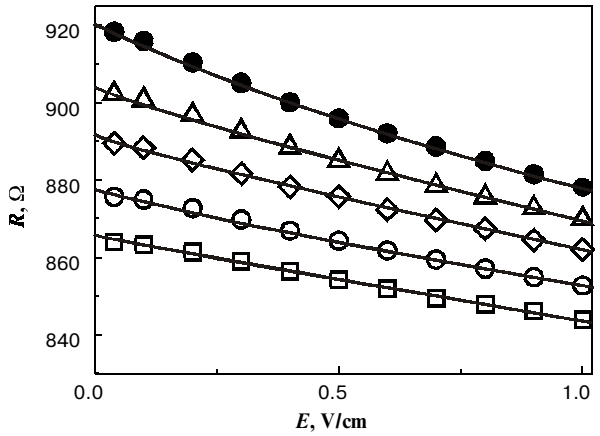

Fig. 3. Field dependencies of 2D gas resistance □ – T = 4K, ○ – T = 3.5 K, ◇ – T = 3K, △ – T = = 2.5K, ● – T = 2K.

$\mu_1 = 2.33 \cdot 10^3$ cm^2/Vs, $\mu_2 = 1.28 \cdot 10^4$ cm^2/Vs, and that these mobilities are determined by electron scattering from ionized donors. In this way one can estimate the middle electron mobility as $\mu = (n_1\mu_1 + n_2\mu_2)/(n_1 + n_2) \cong 4 \cdot 10^3$ cm^2/Vs. In pure GaAs structures, in which phonon scattering dominates, the mobility can rise up to $2 \cdot 10^6$ cm^2 /Vs at T = 5K [10]. Consequently, a relative change of the mobility, caused by the phonon scattering can not exceed of 0.2%, which is much less than observed value (see Fig. 3).

In this case, the temperature T_{ef}, defined previously, is simply equal to T_e, and we have $T_e - T_0 < T_0$ at $E <$ 1V/cm.

But at $\Delta T << T_0$ we must observe $R = R_0 + aE^2$, whereas in Fig. 3 we see the linear dependence. It compels us to refuse from the initial assumption and to find an nonheating mechanism to explane $R(E)$.

In principle, one can suggest that the quadratic dependence takes place at very low values $\Delta T/T$, and in Fig. 3 we observe the transfer between regions of low and high fields, which quite accidentally can be interpolated by a linear dependence. But observation of the same field

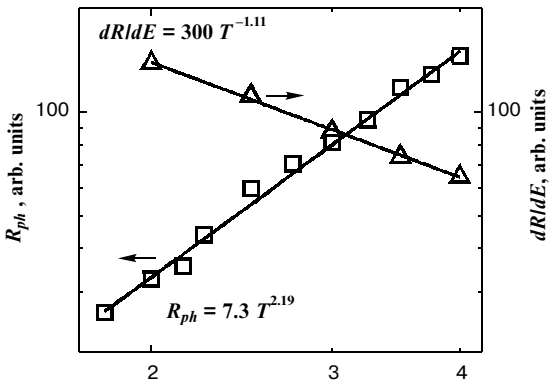

Fig. 4. The temperature dependencies R_{ph} – □ and dR/dE – △.

dependencies for two so different physical values as R and R_{ph} makes this assumption highly improbable because in general case the behaviour of $R(E)$, $R_{ph}(E)$ must be different in middle and strong fields.

Now we stand before the question: can these results be connected with the Anderson–Mott transition? In our δ-doped GaAs, this transition takes place at $n_{cr} = 3 \cdot 10^{11}$cm^{-2} [10], so we have $\Delta = (n - n_{cr})/n_{cr} = 0.67$. Usually, phase transition can significantly affect on the crystal properties if $\Delta << 1$. But in 2D case, QPT has strong effect on the same even at rather high values of Δ. In Si:P, field scaling relations were observed near the metal-insulator transition $-0.85 < \Delta < 0.25$ [8] and temperature one – at $-0.25 < \Delta < 0.45$ [14]. In a-MoGe, temperature scaling relations were observed near superconductor-insulator transition at $-0.4 < \Delta < 0.45$ ($\Delta = (H - H_{cr})/H_{cr}$) [7]. This point of view is confirmed by the analysis of electron mobility dependence on the donor concentration in δ-doped GaAs. At $n_{cr} < n < 5 \cdot 10^{11}$cm^{-2}, it is due to the transition from hopping conductor to the metal one [10]. In Si:P, the temperature scaling relations were observed at $0.2 < T < 3$ K [14]. It means that QPT influence can be significant at relatively high temperatures. All these facts give evidence for correlation between our results and the nearness of the investigated structure to QPT. Let us analyse the possible mechanisms of such influence.

Unfortunately, the mechanism of the conductivity field dependence in Si:P was not discussed in [8], but for other QPTs this effect was always attributed to delocalisation by electric field of elementary crystal excitations such as: electrons localized near the Landau levels, quantum vortex localized in a superconductivity phase and Cooper pairs localized in dielectric phase [6, 7].

Qualitative representation of the Anderson-Mott transition can be outlined by the percolation theory [15], according to which there are dielectric incorporations in metal phase and vice versa. Near the transition, the typical size of incorporations ξ approaches to infinity and the activation energy E_d of dielectric phase – to zero.

From this point of view, the phonon-induced conductivity is due to the absorption of phonons in dielectric incorporations, which leads to transitions of bound electrons into the conductivity band. The excitation of electrons has been made possible because E_d decreases near the transition and becomes less than the typical phonon energy. On the other hand, the temperature and field dependencies of R_{ph}, and R can be explained by destruction of dielectric incorporations under heating and electric field. It is important to notice that the dependence of resistance on field strength $\delta R = aE/T$, which was obtained in the 3D case for the hopping conductance range in [1–3], is well agreed with the similar dependencies obtained in the present work.

As it can be seen from Figs 2, 3, R_{ph} increases much stronger than R with increase of a field. In the context of the proposed theory, the sensitivity to dielectric incorporations can be due to the weakness of alternative mechanism – an electron heating by nonequilibrium phonons,

because the conductivity of δ-structure is almost independent of T.

Let us estimate the typical size ξ and activation energy E_d of the dielectric incorporations. Should E_d be of the same value for all incorporations, the dependence $R_{ph} \sim \exp(E_d/T)$ would be expected. Of course, there is a wide distribution of E_d in QPT, but nevertheless one can estimate its typical value. At $T_1 = 2$K we have $E_d = 5$K. According to [1], the delocalization occurs at $E_d = eE\xi$. Taking into account, that at $T = 2$K, the phonon-induced conductivity decreases twice at $E = 0.4$V/cm, we get $\xi = 15$ μm. The appearance of such capture centres not related to the QPT is scarcely probable.

4. Conclusions

The linear field dependencies of resistance and phonon-induced conductivity of 2D electron gas were observed. The analysis of the given data revealed that it is hard to explain them by electron heating, because at low fields this heating is only proportional to the field squared.

The alternative explanation of the results was proposed – the delocalisation of electrons with low activation energies by electric fields. The existence of such electrons in the sample is related to the nearness of the researched structure to the metal-insulator transition.

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