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EFFECT OF STRONG ELECTRIC FIELD AND IR RADIATION ON LONG-TERM RELAXATION OF PIEZORESISTANCE IN *p*-GaAs/AlGaAs

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Infrared radiation and strong electric field effects on uniaxial compression-induced long-term resistance relaxations of two-dimensional holes at the *p*-GaAs/$Al_{0.5}Ga_{0.5}As$ heterointerface at 4.2 and 77 K were measured. A sharp decrease in relaxation times under charge carriers heating by illumination and, at 77 K, by electric field was observed. At 4.2 K, an electric field over 200 V/cm did by itself cause sample switching to a metastable high-resistance state.

Long-term resistance relaxations induced by uniaxial compression have been recently observed [1] in *p*-GaAs/$Al_{0.5}Ga_{0.5}As$ heterostructures at temperatures below 160 K. For example, at 77 K, steady-state resistance values are attained in a time $\Delta t = 10^3$–10^4 s after loading or unloading. At 4.2 K, the relaxation time $\Delta t \gg 10^4$ s. The steady state can be reached by the sample heating to 200 K and its subsequent cooling to the measurement temperature. Earlier, similar phenomena accompanying uniaxial deformations were observed in bulk samples only (e. g., GaSb [2]).

In this work, at 4.2 and 77 K, we deal with strong electric field and IR radiation effects on uniaxial compression-induced long-term resistance relaxations of two-dimensional hole gas at the *p*-GaAs/$Al_{0.5}Ga_{0.5}As$ heterointerface doped with Be.

The 3 × 0.8 × 0.625 mm samples oriented along the [110] directions were prepared from the heterostructure [1] by cleavage along the (110) planes. The initial heterostructure was grown by molecular-beam epitaxy at the Niels Bohr Institute, Copenhagen University. It was comprised of a crystalline [001] GaAs substrate, a 1-μm buffer layer (nondoped GaAs), a 7-nm spacer (nondoped $Al_{0.5}Ga_{0.5}As$), a 50-nm active layer ($Al_{0.5}Ga_{0.5}As$, Be-doped in concentrations to 1×10^{18} cm^{-3}), and a 5-nm layer of GaAs Be-doped in concentrations to 2×10^{18} cm^{-3}. Contacts were made by deposition of Zn and Au layers followed by annealing in two configurations. In one configuration, the current and voltage contacts were four cross strips deposited directly on the sample. In the other, the standard Hall configuration was prepared. Contact quality was checked by measuring the voltage–current characteristics which were linear to at least 50 μA, whereas in the experiments, the 1–2 μA currents were used.

All effects described below are observed for samples with contacts of both types under IR illumination by both a GaAs-based diode with a maximum intensity at 0.92 μm and a microlamp used as a thermal radiation source. The samples and the light sources enclosed in a special copper screen were placed in liquid helium or nitrogen to eliminate direct thermal heating. Measurements in strong electric fields were taken with the use of a pulsed technique to avoid overheating. Rectangular 30–400 ns 1–100 Hz voltage pulses were produced by a mercury-relay generator. Uniaxial compression of samples in the [110] direction was effected as described in [3].

As in [1], we observed uniaxial compression-induced slow relaxations of two-dimensional hole gas resistance at the *p*-GaAs/$Al_{0.5}Ga_{0.5}As$ heterointerface (see time intervals *1*–*5* in Figs. 1 and 2). The

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relaxations manifested themselves as a slow resistance increase after loading or a decrease after unloading followed by attaining a steady-state value. The characteristic time of these relaxation processes exceeded 10^4 s at 4.2 K and rapidly decreased on heating [1]. Particularly, at 150–160 K, no noticeable difference occurred between resistance values in the steady and the loading-induced metastable state (Fig. 3). The steady-state resistance values could be attained by heating the sample to 200 K and then slowly cooling it to the measurements temperature [1].

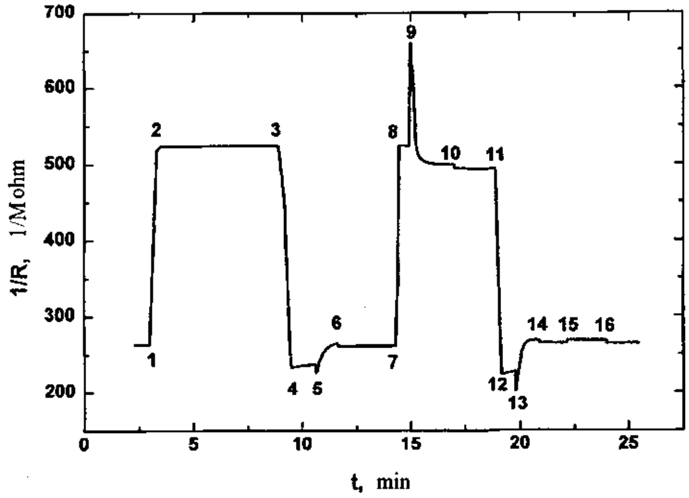

Fig. 1

Time dependence of sample conductivity $1/R$ at 4.2 K. Uniaxial compression $P = 1.04$ kbar applied during *1–2* and *7–8* and lifted during *3–4* and *11–12* time intervals; *5–6*, *9–10*, *13–14*, and *15–16* are time intervals of IR irradiation.

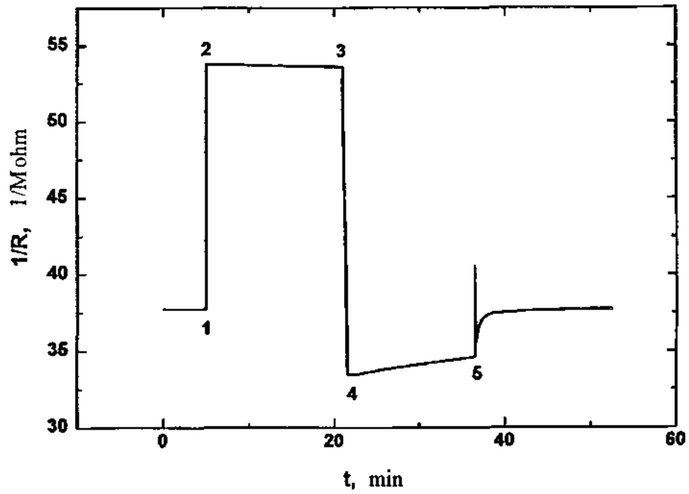

Fig. 2

Time dependence of sample conductivity $1/R$ at 77 K. Uniaxial compression $P = 1.47$ kbar applied during *1–2* and lifted during *3–4* time intervals. At time instant *5*, several strong ($E = 3000$ V/cm) electric field pulses were applied to the sample.

Figure 1 shows that IR illumination for 10–30 s is sufficient for attaining steady-state resistance values even at helium temperatures both after loading (interval *9–10*) and unloading (intervals *5–6* and *13–14*).

If compression is conducted under continuous illumination, long-term relaxations are not observed. It follows that illumination substantially accelerates relaxation processes and can be used instead of heating to 200 K [1] to get the steady-state resistance value. Note also that the samples photoconductivity kinetics is rather complex (the presence of positive and negative contributions) in metastable states induced by uniaxial compression (intervals *5–6*, *9–10*, and *13–14* in Fig. 1), whereas in the steady state, such anomalies are not observed (interval *15–16* in Fig. 1).

At 77 K, uniaxially compressed samples relax faster; they also relax under strong ($E \geq 3000$ V/cm) electric field (see Fig. 2). The spike detected at point *5* is due to a short overload of the instrumentation caused by high-voltage pulses.

At helium temperatures, fairly strong electric fields ($E \geq 200$ V/cm) do themselves switch samples to an IR-sensitive long-lived high-resistance state (Fig. 4). Field-induced resistance values are detectable at temperatures below 60–70 K (Fig. 5), whereas the critical temperature, at which the sample resistance values in the steady and uniaxial compression-induced metastable states become equal, amounts to 150–160 K (see Fig. 3). It is because of the difference of the effects critical temperatures that we can observe acceleration of strain-induced relaxations in strong electric fields at 77 K (see Fig. 2). The possibility of samples switching to a high-resistance state by pulses of different polarities (see Fig. 4) and the absence of noticeable nonuniformities in the relative effect values along the sample (see Fig. 5) show that the phenomenon can hardly be related to processes in the contacts.

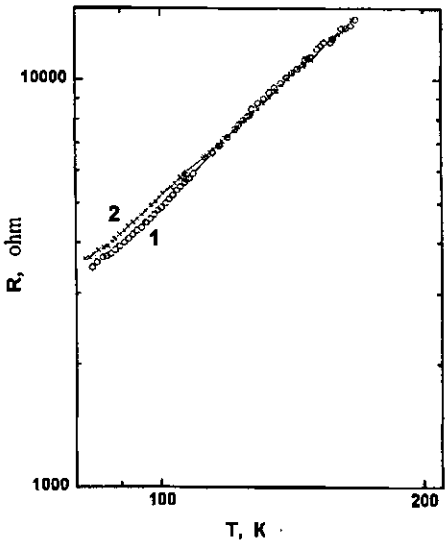

Fig. 3

Temperature dependences of sample resistance R in the initial steady state (*1*) and during heating after a loading-unloading cycle ($P = 1.04$ kbar) at 77 K (*2*).

Long-term resistance relaxations in bulk semiconductors are usually attributed to energy barriers of various nature [4]. Since the studied p-GaAs/Al$_{0.5}$Ga$_{0.5}$As structures are a model system with an artificial potential barrier, it would appear natural to apply these models. However, as mentioned in [1], long-term relaxation and a sharp decrease in resistance caused by uniaxial compression in a system of two-dimensional holes is not accompanied by a noticeable change in the concentration of charge carriers, as it would be if carriers were tunneled through barriers. According to the quantum Hall effect and the Shubnikov–de Haas oscillation measurements, a substantial redistribution of charge carriers between two spin-split subzones with different effective masses occurs under maximum loadings of $P = 2.5$ kbar, whereas the change in the total concentration of two-dimensional holes in the quantum well does not exceed 5–6% [5]. At the same time, resistance irreversibility after a loading-unloading cycle may amount to 50–60% [1].

Considering the subsystem of charge carriers only, we might attribute the long-term processes induced by uniaxial compression to redistribution of charge carriers between spin-split hole subzones. Spin flip

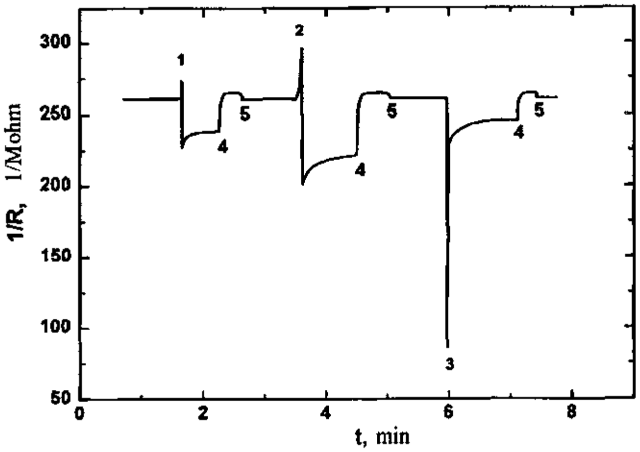

Fig. 4

Time dependence of sample conductivity $1/R$ at 4.2 K under application of separate strong electric field pulses; $E = 200$ (*1*) and 800 V/cm (*2*) (pulses of one polarity) and 1000 V/cm (*3*) (pulses of the other polarity). The sample was exposed to IR radiation during time intervals *4–5*.

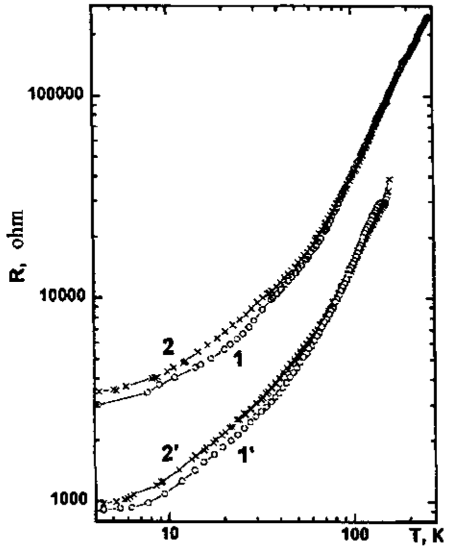

Fig. 5

Temperature dependences of resistance R of the whole sample (*1, 2*) and its middle part (*1', 2'*) in the initial steady state (*1, 1'*) and during heating after the application of strong electric pulses ($E = 3000$ V/cm) at 4.2 K (*2, 2'*).

being forbidden, such a redistribution may have long relaxation times. High sensitivity of this mechanism to external actions promoting processes that involve photons or many-particle transitions is in complete agreement with the results of this work. Nevertheless, exceedingly long characteristic times of the observed piezoresistance relaxations, for example, their complete quenching at 4.2 K, evidence that these relaxations are more likely related to processes in the lattice subsystem such as changes in the charge states of impurities or defects at the heterointerface or in the active layer. Large atomic weights and low temperatures make such processes very slow (relaxation times then have macroscopic values). Under these conditions, the scattering intensity on charged impurities changes, and relaxations are caused by changes in mobilities of two-dimensional carriers rather than in their concentration. In this case, illumination and strong electric fields can also induce relaxations, for instance, due to appearance of many phonons emitted by hot charge carriers. We used the procedure based on a comparison of the electric field and temperature dependences of resistance [6] to estimate the electronic temperature T_e. At $E \geq 3000$ V/cm, that is, at fields accelerating compression-induced long-term relaxations (see Fig. 2), we obtained $T_e \geq 150$–200 K at 77 K. Precisely these temperatures are critical for the observation of long-term piezoresistance relaxations (see Fig. 3). However, with rough T_e estimates, such a good agreement between the corresponding values should be considered fortuitous to some degree.

Switching to a high-resistance state in a system of two-dimensional electrons under the action of electric fields has been recently observed [7] for delta-doped GaAs heterostructures and attributed to transfer of carriers to *DX* centers, whose presence is substantiated by the observation of considerable delayed photoconductivity effects in the samples studied in [7]. So far as we know, there is no direct data on the existence of such centers (*AX* centers?) in the p-GaAs/$Al_{0.5}Ga_{0.5}As$-based heterostructures. There are, however, indications that Be admixtures form impurity states of various type [8] in $Al_xGa_{1-x}As$, including deep levels [9].

Most likely the mechanism of switching of a system of two-dimensional holes to a high-resistance state in the electric field differs from that of long-term resistance relaxations under uniaxial compression, because these effects are characterized by noticeably different critical temperatures (see Figs. 3 and 5). Also qualitatively different are the responses to IR illumination of samples in metastable states induced by uniaxial compression and electric field (see intervals *5–6*, *9–10*, and *13–14* in Fig. 1 and intervals *4–5* in Fig. 4). Combined data indicates, however, that the two phenomena could be expediently explained by studying the Be impurity states in $Al_{0.5}Ga_{0.5}As$ by photoluminescence and relaxation spectroscopy of deep levels in normal and strained states.

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