Long-term relaxation of the resistance of a 2D hole gas at a GaAs/$Al_{0.5}Ga_{0.5}As$ heterojunction induced by uniaxial compression

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An effect which might be called a "persistent piezoelectric," by analogy with persistent photoconductivity, has been observed in a system of 2D holes at a GaAs/$Al_{0.5}Ga_{0.5}As$ heterojunction during uniaxial compression. The effect is observed over the temperature range 4.2–160 K. A long-term relaxation of the resistance is observed during both the application and removal of a compressional stress. This relaxation exhibits a specific "memory." The relaxation rate increases with increasing temperature. The time evolution of this relaxation is of a two-step logarithmic nature. © *1995 American Institute of Physics.*

We have studied the electrical resistance of a 2D hole gas at a Be-doped GaAs/$Al_{0.5}Ga_{0.5}As$ heterojunction during uniaxial compression up to 2.5 kbar over the temperature range 4.2–200 K.

The energy spectrum in the quantum well at a GaAs/$Al_xGa_{1-x}As$ heterojunction is quite complex, and it is changed radically by anisotropic deformation. According to calculations[1] and experimental data obtained by optical methods,[2,3] uniaxial compression substantially shifts the sublevels of light and heavy holes in a quantum well. Even at a wave vector $\mathbf{k}=0$, it leads to a mixing of the states of heavy and light holes. To the best of our knowledge, only optical methods have been used to study the 2D hole gas in GaAs/AlGaAs and other 2D systems during uniaxial compression.[2,3] There has been no study of kinetic characteristics of the 2D carriers under these conditions. The long-term relaxation processes which were observed in the present study, and which were induced by an anisotropic deformation, have not previously been observed in heterostructures, although similar effects have occurred in gallium antimonide samples during the application and removal of an uniaxial load.[4]

The heterostructure which we studied was grown by molecular beam epitaxy at the Niels Bohr Institute of Copenhagen University. This heterostructure consists of a crystalline GaAs substrate, with [001] orientation along the growth direction, covered with an undoped layer of GaAs 1 μm thick (this is a buffer layer). After the buffer layer comes a spacer consisting of 70 Å of undoped $Al_{0.5}Ga_{0.5}As$. After this spacer comes the active layer, which is 500 Å of $Al_{0.5}Ga_{0.5}As$ doped with Be to a concentration of 1×10^{18} cm^{-3}. Finally, there is an $Al_{05}Ga_{0.5}As$ layer, 50 Å thick, doped with Be to a concentration of 2×10^{18} cm^{-3}. The samples were cleaved along [110] cleavage planes. They were parallelepipeds with dimensions of $3.0\times0.8\times0.625$ mm. The uniaxial compression was carried out along the [110] direction. Contacts were applied by depositing either Mg/Au or Zn/Au and then annealing. The contacts were in two configurations: 1) Four transverse stripes served as current and potential contacts (these were the samples of type PG). 2) The configuration was the standard Hall configuration (these were the PH samples). The quality of the contacts was monitored on the basis of the linearity of the current–voltage characteristics. This linearity prevailed up to at least 50 μA (the working current was 1–2 μA) at all pressures and temperatures studied. All the effects described below were observed equally clearly in the samples with both types of contacts (there were seven samples).

The least expected, most surprising effect observed in our study of the behavior of the resistance as a function of the uniaxial stress applied to the sample was a long-term relaxation. This relaxation occurred at sufficiently low temperatures ($T<160$ K), during both the application and the removal of the load. Figure 1 shows two cycles of loading and unloading of sample PH2 at $T=4.2$ K. Uniaxial compression to a pressure $P=0.36$ kbar at time point *1* results in a sharp decrease in the resistance of the sample (point *2*). This resistance then slowly increases over time (interval *2–3*), approaching a steady-state value R_{s2-3} (the dashed line in interval *2–3*). At liquid-helium temperatures, it is not possible to actually attain this equilibrium value during the experiment. When the load is removed from the sample, at point *3*, we observe the opposite behavior: The resistance of the sample increases sharply, running past its initial value R_0 to a value $R_4>R_0$ (point *4*) and then slowly relaxing to R_0 (the dot-dashed line in Fig. 1). A repeated loading (point *5*) to a higher pressure, $P=0.73$ kbar, results in similar processes at points *6*, *7*, and *8*. The magnitude of the change in resistance increases in the case of the greater load. At 4.2 K, the relaxation during the unloading is essentially "frozen." The only evidence that it occurs is the irreversibility of the resistance with respect to the initial value R_0. By analogy with persistent photoconductivity, this effect might be called a "persistence piezoelectric resistance."

Heating a sample to 200 K and then cooling it fairly slowly to 4.2 K in the absence of a load (time interval 9–10 in Fig. 1) completely restore the original resistance R_0 (point *10*). We can thus assume that the state of the sample after heating to 180–200 K, followed by a sufficiently slow cooling, is a steady state of the sample at the given pressure and the given temperature. One might expect that a corresponding thermal-cycling process under load would lead to a steady-state resistance of the sample in the loaded state. The steady-state values of the resistance, R_s, corresponding to these states are shown by the dashed lines in Fig. 1. Corresponding to the uniaxial compression $P=0.36$ kbar is R_{s2-3}, and corresponding to $P=0.73$ kbar is R_{s6-7}.

The transition of the system to a steady state during heating occurs because all the relaxation processes observed in this study accelerate with increasing temperature. As a parameter which roughly characterizes the dynamics of the relaxation, we adopt the time interval Δt^*, over the first half of which, after the beginning of the relaxation, the resistance of the sample reaches a value which remains constant, within the errors, during the second half. Using this parameter, we can demonstrate the temperature dependence of the relaxation rate at a qualitative level in the example of the data shown below for

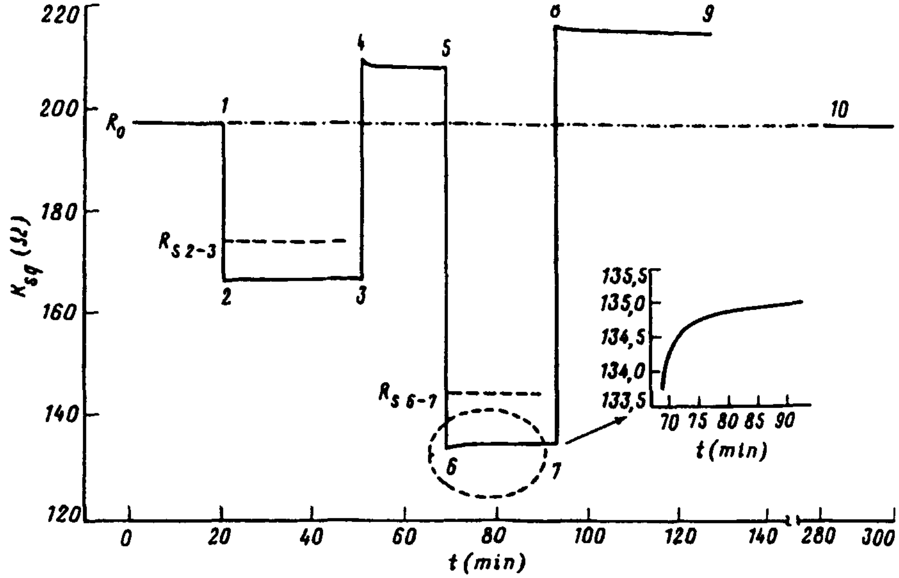

FIG. 1. The surface resistance $R_\square$ of sample PH2 versus the time t at 4.2 K and at various uniaxial compressions P: 0–1) $P=0$; 2, 3) $P=0.36$ kbar; 4–5) $P=0$; 6–7) $P=0.73$ kbar; 8–9–10) $P=0$. In interval 9–10, the sample is heated to 200 K and cooled slowly to 4.2 K.

sample PG-2. Here Δt^* is shown for various temperatures for two relaxation cases: a) after the application of a uniaxial compression $P=0.87$ kbar and b) after the removal of this compression.

Temperature	144 K	100 K	77 K
Δt^* after the application of a pressure of 0.87 kbar	0.5 min	3 min	>10 h
Δt^* after the removal of a pressure of 0.87 kbar	2 min	18 min	>10 h

The resistance of the GaAs/$Al_{0.5}Ga_{0.5}As$ test samples in the steady state and the transient state depends strongly on the magnitude of the compressional stress which is being applied (or removed). The long-term relaxation causes the load dependence of the resistance to depend on just how this behavior is found. Figure 2a shows one example of this behavior, which includes thermal cycling after each application and removal of the pressure. The open circles show the steady-state behavior of the resistance of the 2D-hole gas.

All the relaxation processes observed evolve in a very nonexponential way with the time. It is for this reason that we introduce the empirical parameter Δt^*. However, if we plot the time dependence of R as $\log(t)$, then many of the observed relaxation curves $R(t)$ can be described by a logarithmic time dependence with two linear regions, which differ in slope. The general shape of this dependence changes with increasing value of the pressure being applied or removed (Fig. 2b).

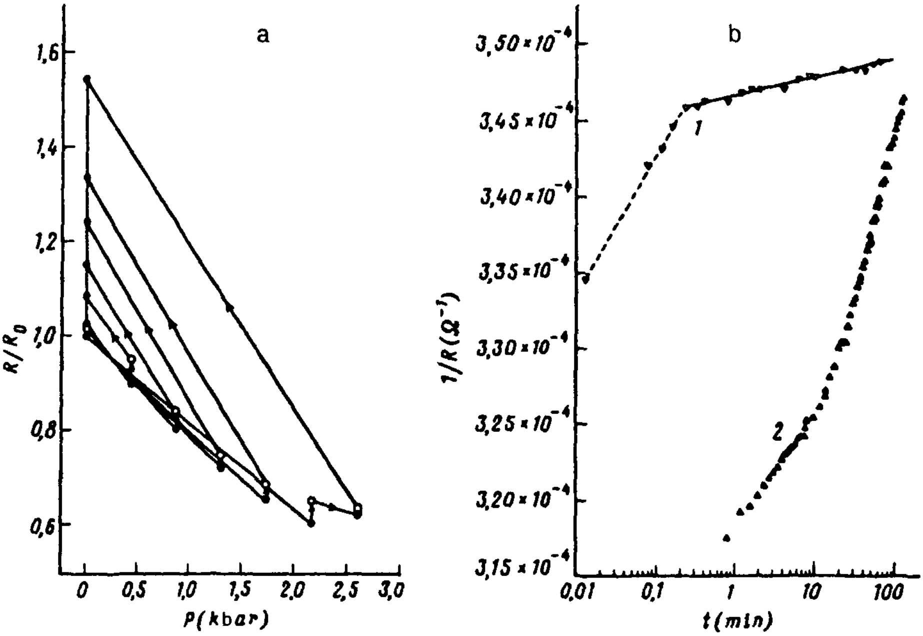

FIG. 2. a: Resistance of sample PG2 versus the pressure at 4.2 K. ●—The state 20 min after the application (or removal) of the pressure; ○—state after heating to 200 K and recooling to 4.2 K. The arrows show the order in which the experimental points were found. b: Conductance of sample PG2 versus the time at 77 K. 1—After the removal of a pressure of 0.86 kbar; 2—after the removal of a pressure of 1.72 kbar.

One of the most interesting aspects of the long-term relaxation observed here is a "memory" of previous cases of the loading and relaxation of the sample. For example, if the relaxation process after the removal of a load (interval *4–5* in Fig. 3) is interrupted by a brief cycle of the application and removal of a uniaxial perturbing stress of the same magnitude as in the prior cycle (*1-2–3–4*) (interval *5–6–7–8* in Fig. 3), then the resistance of the sample "remembers" its state up to the next loading cycle, and the next relaxation (*8–9*) is a continuation of the first relaxation (*4–5*). However, while the relaxation in the loaded state occurs for a fairly long time (*10–11*), the processes, after the removal of the load (*12–13*), are not a continuation of the relaxation (8–9). In other words, the resistance of the sample also "senses" the relaxation processes which occurred in the previous state.

The long-term relaxation of the resistance of the 2D-hole gas studied here has basically the same properties as the long-term relaxation in semiconductors, as described in a review by Sheĭnkman and Shik.[5] Specifically, the relaxation times are long, the relaxation rate increases with increasing temperature, there is a characteristic "memory," and there is a nonexponential time dependence. The long-term relaxation of the resistance was explained in Ref. 5 on the basis of a tunneling (thermal activation) of carriers across a potential barrier, from low-resistance regions to high-resistance ones, or vice versa, in a model of a nonuniform semiconductor. Since the GaAs/$Al_{0.5}Ga_{0.5}As$ heterojunctions

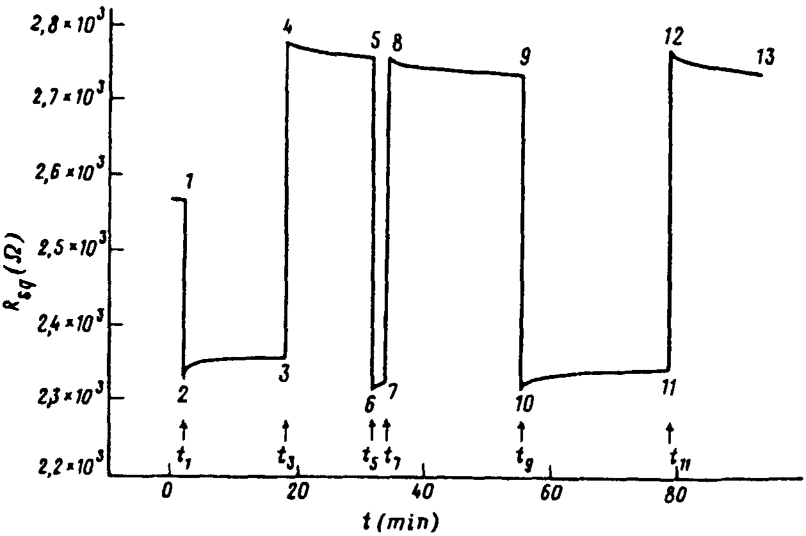

FIG. 3. Resistance of sample PG2 versus the time at 77 K. At times t_1, t_5, and t_9, a uniaxial compression $P=0.83$ kbar is applied; it is removed at times t_3, t_7, and t_{11}.

studied by us differ in no way from a macroscopic nonuniformity with an artificial potential barrier bounding a low-resistance region of 2D charge carriers (the case which was modeled), it is reasonable to suggest that the long-term relaxation processes which we observed are of the same nature.

It is important to note that the long-term relaxation processes induced in GaAs/$Al_{0.5}Ga_{0.5}As$ by a uniaxial compression are observed against the background of a pronounced decrease in the equilibrium value of the resistance of the 2D holes during the deformation. We believe that both of these effects are due to a restructuring of the spectrum of the 2D holes in a quantum well. If we assume that the Fermi level of the 2D holes during the uniaxial compression is lower than the Fermi level in AlGaAs, in which the acceptor impurities are concentrated, then the relaxation processes which occur during both the application and removal of the load can be explained on the basis of a tunneling (thermal activation) of nonequilibrium holes through a potential barrier. The logarithmic decay of these processes over time was studied in Ref. 6 for the relaxation of the photoconductivity in GaAs/AlGaAs. This logarithmic behavior was explained on the basis of a specific feature of the recombination of charge carriers which are separated spatially by a barrier; these carriers are 2D electrons and an ionized impurity in the bulk of the sample.

An exhaustive explanation of the long-term relaxation processes which have been observed will have to await data on the deformation-induced changes in the energy spectrum of the 2D holes in a quantum well, especially since the pronounced decrease in the resistance which is observed (Fig. 2a) occurs while the value of the Hall coefficient remains basically constant.

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