Persistent photoconductivity in hydrostatically compressed, selectively doped n-$Al_xGa_{1-x}As/GaAs$ structures

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A qualitative change in the nature of the persistent photoconductivity of n-$Al_xGa_{1-x}As/GaAs$ structures has been detected during hydrostatic compression. At high values of P (>8 kbar), the persistent photoconductivity disappears in the bulk $Al_xGa_{1-x}As$ layer, but it continues to be observed in the adjacent two-dimensional channel in the GaAs. The reason for the disappearance of the persistent photoconductivity from the $Al_xGa_{1-x}As$ is the descent of L or X valleys below the bottom of the Γ minimum.

1. The persistent photoconductivity in n-$Al_xGa_{1-x}As/GaAs$ heterostructures with $x > 0.2$ is attributed[1,2] to an unusual behavior of donor impurities in $Al_xGa_{1-x}As$. Any donor impurity that forms a simple shallow donor center in GaAs gives rise to relatively deep (>100-meV) so-called DX centers, distinguished by anomalously long scale times (τ_0) for the capture of free electrons at low temperatures. Two reasons for the large values of τ_0 have been discussed in the literature[1–4]: the specific local surroundings of the dopant in the $Al_xGa_{1-x}As$ (e.g., donor + vacancy),[4] and the structure of the conduction band, specifically, a small energy gap between minima at different points (Γ, X, and L) of the Brillouin zone. In an effort to distinguish between these two factors, we have applied hydrostatic compression, which changes the gap between the minima at Γ, X, and L but which does not affect the local surroundings of the dopant.

2. To describe the persistent photoconductivity in n-$Al_xGa_{1-x}As/GaAs$ structures, it is sufficient to obtain information on the electron densities separately in the $Al_xGa_{1-x}As$ layer and in the two-dimensional ($2D$) channel in the GaAs before and after illumination with light at various intensities. For this purpose we have measured the magnetoresistance ρ_{xx} and the Hall resistance ρ_{xy} in magnetic fields up to $H \sim 4$ T. Correct measurements of $\rho_{xx}(H)$ and $\rho_{xy}(H)$ at any intermediate illumination intensity were possible because after the illumination is turned off the values of ρ_{xx} and ρ_{xy} change only slightly (by less than 1%) over the first few seconds and then remain constant for many hours. All the measurements were taken at 4.2 K with an alternating current (20 Hz, 300 nA), which did not cause any heating of the carriers in the $2D$ layer in the GaAs.

For the measurements we used single selectively doped n-$Al_xGa_{1-x}As/GaAs$ junctions with $x \approx 0.3$ and with a Si dopant concentration in the n-$Al_xGa_{1-x}As$ of

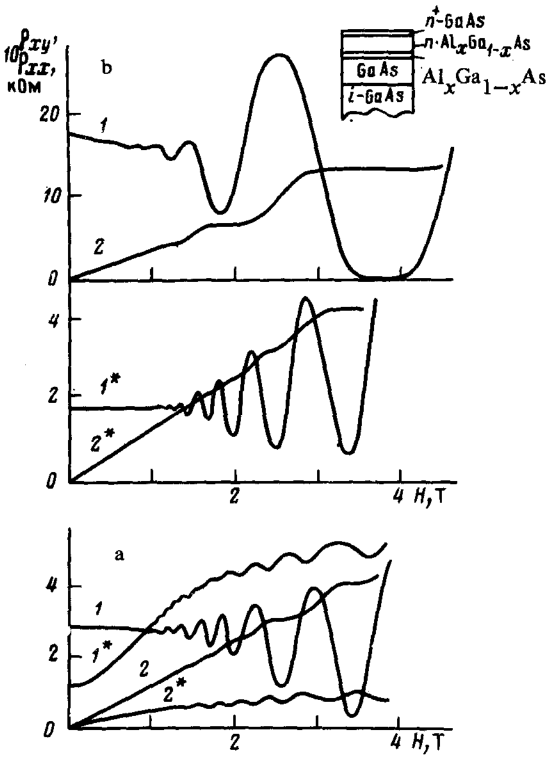

FIG. 1. Transverse magnetoresistance ρ_{xx} (1) and Hall resistance ρ_{xy} (2) versus the magnetic field H for n-Al$_x$Ga$_{1-x}$As/GaAs heterostructures at pressures $P = 0$ (a) and $P = 8.5$ kbar (b). The numbers without asterisks mean that the sample has not been illuminated; the asterisk means illumination to the point of saturation of the persistent photoconductivity. The structure is shown schematically at the top. The thickness of the n^+GaAs singular layer is 5 nm; that of the n-Al$_{x0.3}$Ga$_{0.7}$As is 50 nm; that of the Al$_{0.3}$Ga$_{0.7}$As is 10 nm; and that of the GaAs is 0.5 μm. The i-GaAs is the substrate.

about 10^{18} cm^{-3}. The samples were synthesized by molecular-beam epitaxy. Their structure is shown schematically in Fig. 1. A layer of Al$_x$Ga$_{1-x}$As, 120 Å thick, not deliberately doped, was used to increase the spatial separation of the free carriers in the 2D layer and of the ionized centers in the n-Al$_x$Ga$_{1-x}$As. The mobility of the 2D electrons at 4.2 K was $(4\text{–}15)\times 10^4$ cm^2/(V · s).

The hydrostatic compression of the structure was carried out in a self-contained, low-temperature, fixed-pressured chamber.[5,6] Illumination was provided by a GaAs light-emitting diode in the working volume of the chamber near the sample. The energy of the photons emitted by the diode increases with increasing pressure but always remains slightly smaller than the gap width of pure GaAs.

3. Figure 1 shows the measured results on $\rho_{xx}(H)$ and $\rho_{xy}(H)$ at $P = 0$ and 8.5 kbar before and after illumination to the point of saturation of the persistent photoconductivity. In structures that were not illuminated, these curves have the form corresponding to a 2D electron gas in GaAs, at all pressures.[7,8] There are no free carriers in the Al$_x$Ga$_{1-x}$As. The concentration n_s of the 2D electrons can easily be determined from the oscillation frequency on the $\rho_{xx}(H)$ curve (Fig. 2). At $P = 0$, the concentration of 2D electrons is 5×10^{11} cm^{-2}, or an order of magnitude lower than the total concentration of Si atoms in the Al$_x$Ga$_{1-x}$As per unit surface area. The Fermi level in the n-Al$_x$Ga$_{1-x}$As/GaAs structure coincides with the level of deep donors in the

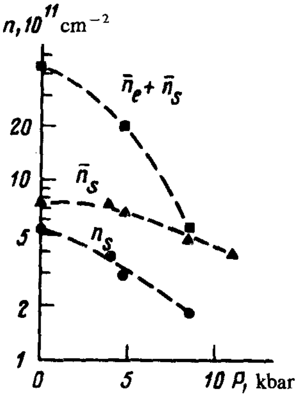

FIG. 2. Density of $2D$ electrons in the GaAs as a function of the pressure before (n_s) and after $(\bar{n}_s)$ illumination to saturation of the persistent photoconductivity. The curve of $(\bar{n}_e + \bar{n}_s)$ is the total electron density per unit surface area in the $2D$ layer in the GaAs and in the $Al_{0.3}Ga_{0.7}As$ under conditions corresponding to saturation of the persistent photoconductivity.

n-$Al_xGa_{1-x}As$ (Fig. 3). During hydrostatic compression of the structure (in all cases, carried out at room temperature), we observe a decrease in n_s (Fig. 2), indicating a lowering of the Fermi level with respect to the bottom of the Γ minimum (Fig. 3). This event is possible only if the level of the deep donors in $Al_xGa_{1-x}As$ "follows" the motion of the side minima in the conduction band.

The illumination of the uncompressed structures and of the slightly compressed ($P < 8$ kbar) structures leads to a substantial increase in the frequency of the oscillations on the $\rho_{xx}(H)$ curve, i.e., to an increase in the concentration (n_s) of $2D$ electrons in the GaAs (persistent photoconductivity in the $2D$ channel in GaAs). At higher illumination intensities, the $\rho_{xx}(H)$ and $\rho_{xy}(H)$ curves change qualitatively: In low fields, the magnetoresistance becomes positive, and minima appear on the $\rho_{xy}(H)$ curve (Fig. 1) in place of the plateaus corresponding to the quantum Hall effect. This

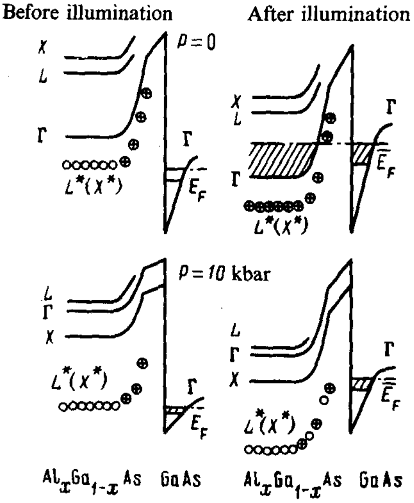

FIG. 3. Energy diagrams for the n-$Al_xGa_{1-x}As$/GaAs structure ($x \approx 0.3$) at (a) $P = 0$ and (b) $P = 10$ kbar before illumination (at the left) and under conditions of saturation of the persistent photoconductivity (at the right). The positions of the electron valleys, of the deep donor levels, and of the Fermi level are designated Γ, L, or X; $L^*(X^*)$; and E_F, respectively.

behavior is evidence of the appearance in the sample of carriers of a second type: electrons in a volume channel in the n-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ (persistent photoconductivity in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$; Ref. 1). The picture changes qualitatively at $P \gtrsim 8.5$ kbar. As can be seen from Fig. 1, in this case the illumination leads to simply an increase in the frequency of the oscillations on $\rho_{xx}(H)$, i.e., an increase in n_s. However, we still do not observe either a positive magnetoresistance or minima in place of the plateaus on the curve of ρ_{xy}; i.e., a persistent photoconductivity does not arise in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$. We wish to stress that we have observed a persistent photoconductivity in n-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ structures under conditions such that this persistent photoconductivity does not exist separately in either the GaAs or the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$.

The disappearance of the persistent photoconductivity from the $\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ at $P \gtrsim 8.5$ kbar coincides with the transition of the material from a direct-gap material to an indirect-gap material at this pressure.[9] Since the local structure of the impurity centers does not change under our experimental conditions, we conclude that the extremely long times required for the capture of the free electrons to impurity centers in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ with $x = 0.2$–0.4 is due to the particular features of the band structure, specifically, the position of the Γ minimum in the interval between the bottom of the side minima in the conduction band and the deep donor level associated with these minima.

4. The following mechanism for the persistent photoconductivity in n-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ structures emerges from these results. Some of the hot electrons that are photoexcited by the light ($\hbar\omega \sim 1.5$ eV) in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ with deep donors relax to the Γ minimum. Because of the short scale times for the tunneling of light Γ electrons through the narrow potential barrier at the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ interface, the systems of electrons in the GaAs ($2D$) and in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ ($3D$) are at a quasiequilibrium. Consequently, the illumination results in the appearance of a persistent photoconductivity first in the $2D$ layer in the GaAs. A persistent photoconductivity appears later in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$—after the Fermi quasilevel in the system rises above the bottom of the Γ minimum in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$. The decrease in the electron concentration in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ with increasing pressure occurs because the Γ electrons acquire the ability to relax to the L or X side minima in the conduction band which have dropped below the Fermi level of the electrons. This conclusion follows from the circumstance that the positions of the Fermi energy at various pressures in the illuminated samples, found from measurements of n_s, are always close to the bottom of these minima. We then find an obvious explanation for the existence of a persistent photoconductivity in the $2D$ layer in the GaAs at $P > 8.5$ kbar, where the persistent photoconductivity disappears from the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$: At the pressures studied ($P < 16$ kbar), the Γ minimum in the GaAs has not yet risen above the X minimum in the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ (Fig. 3). In the model outlined above for the persistent photoconductivity, there is yet another important question, related to the scale times for capture of electrons from the X and L valleys to deep centers. The appearance of the persistent photoconductivity in the $\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ at $P \gtrsim 8.5$ kbar, where the X valleys drop below the Γ extremum, is unambiguous evidence that the capture of electrons from the side valleys occurs in a relatively short time (clearly less than 1 s), in contrast with the capture of Γ electrons ($\tau > 10^6$ s).

In summary, the application of hydrostatic compression to n-$Al_xGa_{1-x}As$/GaAs structures reveals the nature of the persistent photoconductivity in both the $Al_xGa_{1-x}As$ and the two-dimensional channel in the GaAs. This study has shown (for the first time) that a persistent photoconductivity can occur in n-$Al_xGa_{1-x}As$/GaAs structures even if it is absent from the $Al_xGa_{1-x}As$ layer. At this point, we cannot explain the very large difference (>6 orders of magnitude) in the scale times for the capture of X and Γ electrons at a relatively deep donor center.

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