# Negative persistent photoconductivity in GaAs($\delta$-Sn) structures

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The effect of illumination with various wavelengths $\lambda$ (770 nm$<\lambda<$1120 nm) on the conductivity of GaAs structures with tin $\delta$-doping of the vicinal faces was investigated in the temperature range 4.2–300 K. Negative persistent photoconductivity was found in strongly doped samples. It was shown on the basis of the results of investigations of the Hall and Shubnikov–de Haas effects that the negative photoconductivity is due to a large decrease in the electron mobility with increasing electron density. The decrease of electron mobility is explained by ionization of DX centers, which destroys the spatial correlation in the distribution of positively charged donors and negatively charged DX centers. © *1999 American Institute of Physics.* [S1063-7761(99)01912-5]

## 1. INTRODUCTION

Delta-doped semiconductors, where the impurity atoms are located in a layer one or several atomic monolayers thick, are now an object of intense experimental and theoretical investigations.[1] The charges of the dopants in the $\delta$ layer create a potential well, as a result of which a structure with two-dimensional electrons is formed. In $\delta$-doped structures with a high impurity density, electrons fill many size-quantization subbands. The behavior of two-dimensional electrons in such systems in electric and magnetic fields is much more complicated than in ordinary low-dimensional structures with a single filled subband. Intersubband electron scattering is important, and electron mobilities in each subband are different.

Interest in the study of $\delta$-doped semiconductors is justified not only from the scientific standpoint but also by the possibility of practical applications of such materials. Delta-doping is an example of an extremely narrow doping profile which gives high current-carrier densities. Even though high dopant concentrations are important in nanoelectronics, the mechanisms limiting the maximum achievable free-electron density at high doping levels are still not completely understood.

It should be noted that ordinarily silicon is used to produce *n*-type $\delta$-layers in gallium arsenide, and it is important to investigate and compare the electronic properties of $\delta$-layers with different dopants, for example, tin. As a donor impurity, tin is less amphoteric than silicon,[2] and the use of tin should make it possible to obtain higher densities of two-dimensional electrons in a $\delta$-layer.

Quasi-one-dimensional and one-dimensional electronic systems, produced on the basis of two-dimensional systems, are now being investigated increasingly more actively.[3] Quantization of the conductivity as a function of the width of the conducting channel, quantum oscillations of a new type in a magnetic field, and other fundamental effects are observed in such systems. Ordinarily, submicron electron lithography is used to limit the lateral size in two-dimensional systems.[3] To obtain systems with quasi-one-dimensional electronic channels several tens and less nanometers in size, a promising method is to grow structures on the vicinal surface of gallium arsenide,[4–10] i.e., on a surface tilted from the basal plane [for example, (001)] by a small angle, as a result of which it becomes stepped.

An important experimental fact is that, usually, persistent positive photoconductivity is observed in structures with $\delta$-doped layers at low temperatures, i.e., under illumination the conductivity of the structures increases and remains for a long time.[11] Various models of persistent photoconductivity exist. One model involves the photoionization of deep levels, called DX centers. It is believed that a DX center is a negatively charged localized state, which traps two free electrons.[12–15] In a different model, the separation of photoionized electron–hole pairs, so that the electrons remain in the $\delta$ layer while the holes escape into the interior volume, is taken into account. In this case, a logarithmic decay of the persistent photoconductivity is expected.[16,17] Conductivity anisotropy[4–6,18] and positive photoconductivity and its quenching by a strong electric field[19,20] are observed in GaAs structures with tin $\delta$-doping of the vicinal face.

In the present paper we report the results of an investigation of negative persistent photoconductivity, which we observed in GaAs structures with tin $\delta$-doping of the vicinal faces, in a wide range of photon energies in the temperature range 4.2 K$<T<$300 K. Mechanisms of negative and positive persistent photoconductivity in $\delta$-doped GaAs structures are discussed.

 

TABLE I. Resistivity $\rho$, Hall density $n_H$, and Hall mobility $\mu_H$ of electrons and the sum $\Sigma n_{SdH}$ of the electron densities in all subbands, which is determined from the Shubnikov–de Haas effect, at temperature $T=4.2$ K.

| Sample No. | Form of illumination | $\rho$, Ω | $n_H$, $10^{12}$ cm$^{-2}$ | $\mu_H$, cm$^2$/(V·s) | $\Sigma n_{SdH}$, $10^{12}$ cm$^{-2}$ |
|---|---|---|---|---|---|
| | In dark | 202 | 31.5 | 981 | 26.2 |
| 1 | $\lambda=791$ nm | 198 | 31.6 | 1000 | 26.3 |
| | $\lambda>850$ nm | 232 | 30.4 | 886 | 27.9 |
| | In dark | 374 | 25.8 | 648 | 25.9 |
| 2 | $\lambda=791$ nm | 367 | 24.9 | 683 | 26.0 |
| | $\lambda>850$ nm | 417 | 26.0 | 576 | 29.6 |
| | In dark | 1330 | 8.03 | 586 | 8.28 |
| 3 | $\lambda=791$ nm | 1173 | 8.62 | 618 | 8.39 |
| | $\lambda>850$ nm | 1235 | 8.81 | 574 | 8.38 |

## 2. SAMPLES AND MEASUREMENT PROCEDURE

The experimental structures were grown by molecular-beam epitaxy. A 0.45 $\mu$m thick undoped GaAs buffer layer was grown on a semi-insulating GaAs{Cr} substrate, disoriented by 3° from the (001) plane toward to the (110) plane. A system of steps formed on the vicinal face of the crystal. A 1 ML high step is 5.3 nm wide. Next, growth was stopped and a definite quantity of tin was precipitated onto the surface. After the tin was deposited, a 40 nm thick gallium arsenide layer was grown at low epitaxy temperatures $\approx$450 °C, which should make it possible to preserve a nonuniform distribution of tin. Then a 20 nm thick GaAs layer, doped with silicon to $2\times10^{18}$ cm$^{-3}$, to fill the surface states was grown.

Samples in the form of double Hall bridges with the conducting channel oriented along the [110] direction and along the [−110] direction were prepared for resistivity and Hall effect measurements. In all samples the resistivity in the [110] direction was less than in the [−110] direction. At the same time, the influence of illumination of the conductivity was qualitatively independent of the direction of the conducting channel, so that in the present paper we report the results obtained for samples with the conducting channel oriented along the [110] direction. To investigate the photoconductivity the samples were illuminated with an incandescent lamp through a monochromator, which extracted radiation with wavelength ranging from 770 nm to 1120 nm with spectral linewidth 2.6 nm, and through various filters. Certain parameters of the experimental samples at $T=4.2$ K are presented in Table I.

## 3. EXPERIMENTAL RESULTS

The photoconductivity of the experimental samples depends on the wavelength of the incident light. In addition, the irradiation intensity was found to be important for observing negative photoconductivity with reasonable durations of the experiment. The typical dependence of the resistivity of sample 1 on the illumination time is displayed in Fig. 1. As one can see in this figure, when the sample is irradiated with $\lambda=791$ nm light (curve *2*), at first positive photoconductivity is observed and then, under further illumination, it changes to negative. For $\lambda\geqslant1120$ nm (curve *1*) only negative photoconductivity is observed. The dependence of the change in the resistivity as a function of the wavelength of the incident light for various radiation intensities for sample 1 is presented in Fig. 2. The same dependence is observed for sample 2. The resistivity of these samples, after cooling in the dark to temperature 4.2 K and illumination with monochromatic light with wavelength less than 835 nm and intensity less than 20–70 nW/cm$^2$, decreases (positive photoconductivity) and saturates in $\approx$30 min (points *1*, Fig. 2). Under further illumination of the same samples with radiation with wavelength 786 nm$<\lambda<$796 nm and intensity $I\approx10$ $\mu$W/cm$^2$, the resistivity at first decreases to a minimum (point *3* in Fig. 2), and then starts to grow, reaching at saturation a value (point *4* in Fig. 2) greater than the value in the dark (negative photoconductivity). Under continuous irradiation with light with wavelength greater than 835 nm and intensity $I\approx20$ nW/cm$^2$ (this intensity of light is obtained by illuminating through a monochromator) the resistivity of the samples remains unchanged for

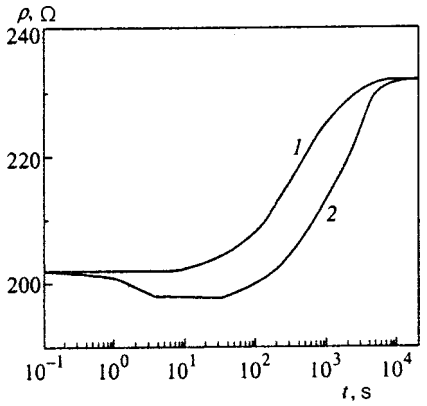


FIG. 1. Resistance of sample 1 versus the irradiation time for light with wavelength $\lambda\geqslant1120$ nm (*1*) and $\lambda=791$ nm (*2*) and illumination intensity 10 $\mu$W/cm$^2$.

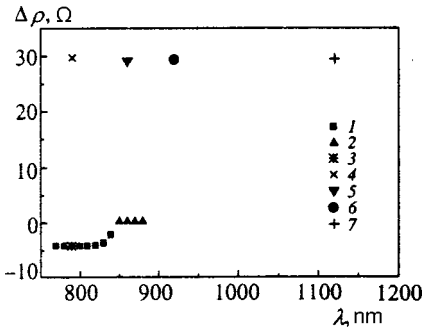


FIG. 2. Resistivity change $\Delta\rho$ of sample 1, measured from the dark resistivity, versus the wavelength $\lambda$ of the incident radiation: *1*—illumination through a monochromator with intensity $I\approx70$ nW/cm$^2$ for 1 h; *2*—illumination through a monochromator with intensity $I\approx20$ nW/cm$^2$ for 1 h; *3*—illumination through a filter 786 nm $<\lambda<$796 nm with $I\approx10$ $\mu$W/cm$^2$ (minimum value of the resistivity); *4*—illumination through the same filter and with the same intensity $I\approx10$ $\mu$W/cm$^2$ to saturation; *5*—$\lambda>850$ nm filter to saturation, $I\approx60$ $\mu$W/cm$^2$; *6*—920 nm $<\lambda<$930 nm filter to saturation, $I\approx10$ $\mu$W/cm$^2$; *7*—$\lambda\geqslant1120$ nm filter, $I\approx60$ $\mu$W/cm$^2$ to saturation.

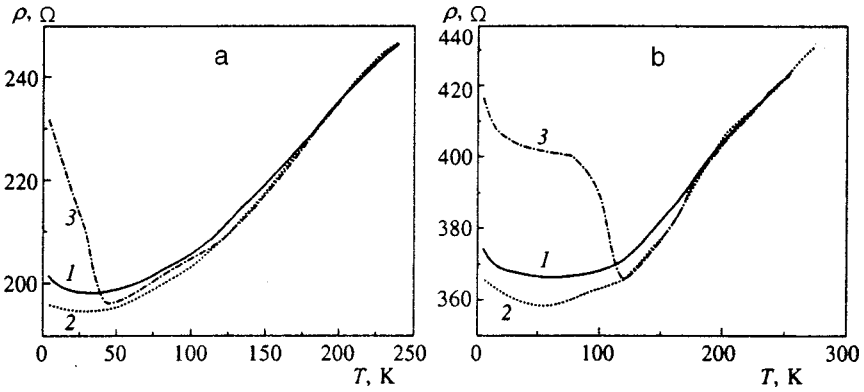


FIG. 3. Temperature dependences of the resistivity of samples 1 (a) and 2 (b) in the dark (curve *1*) and after illumination at $T=4.2$ K with $\lambda=791$ nm light (curve *2*) (the illumination was switched off after the minimum resistivity was reached) and $\lambda>1120$ nm light (curve *3*) (the illumination was switched off after resistivity saturation was reached).

at least 5 hs (points *2* in Fig. 2). When the samples 1 and 2 are illuminated with radiation with wavelength greater than 850 nm and intensity $I\approx 10-60$ $\mu$W/cm$^2$, the resistivity increases from the dark value and reaches at saturation (points *5*, *6*, and *7* in Fig. 2) the same value as for illumination with intense light with wavelength less than 835 nm. In this case an initial decrease of the resistivity is not observed. In the negative photoconductivity regime, the resistivity remains unchanged for at least 5 h after the illumination is switched off at temperature 4.2 K, i.e., negative persistent photoconductivity is observed. The critical photon energy corresponding to wavelength 835 nm is approximately 35 meV less than the GaAs band gap. This corresponds to the energy required to transfer electrons from shallow acceptors into the conduction band.[21]

The temperature dependences of the resistivity $\rho$ of heavily doped samples 1 and 2, measured in the dark and after various forms of illumination at $T=4.2$ K and heating at a rate of 3 K/min, are presented in Fig. 3. When sample 1 is heated, after illumination at $T=4.2$ K (up to saturation of the resistivity) through a filter transmitting light with wavelength greater than 1120 nm, as the temperature increases, the resistivity decreases and crosses the dark curve $\rho(T)$ at $T\approx 40$ K (Fig. 3a). For sample 2 the heating curve, after illumination with ''long-wavelength'' radiation (we shall call radiation with energy less than the band gap in gallium arsenide long-wavelength radiation) crosses the dark temperature dependence at $T\approx 120$ K. After crossing the dark dependence $\rho(T)$, the resistivity curve after illumination with ''long-wavelength'' radiation lies somewhat above the resistivity curve after illumination with ''short-wavelength'' radiation (radiation with photon energy greater than the band gap in gallium arsenide), switched on at the moment when the resistivity reaches its minimum value. In all samples persistent photoconductivity exists up to temperatures $\approx 180$ K.

For the less heavily doped sample 3 the resistivity decreases after illumination with ''short-wavelength'' and ''long-wavelength'' radiation, but the values of the resistivity at which saturation occurs are different for these two forms of illumination—the resistivity decreases more strongly for illumination with ''short-wavelength'' radiation. After illumination at temperature 4.2 K is switched off, the resistivity of this sample slowly returns to the dark value in several hours. The temperature dependences of the resistivity of sample 3, which were measured in the dark, and with heating after irradiation at $T=4.2$ K with light with various wavelengths are presented in Fig. 4.

Besides the temperature dependences of the resistivity, in the present work we investigated the Shubnikov–de Haas effect to determine the electron density in the size-quantization subbands. The magnetoresistivities for samples 1 and 2, respectively, at $T=4.2$ K measured in the dark (curves *1*) and after various forms of illumination (curves *2* and *3*) are displayed in Figs. 5(a) and 6(a), and the Fourier spectra corresponding to the oscillations are displayed in Figs. 5(b) and 6(b). The Shubnikov–de Haas effect showed that for positive persistent photoconductivity the frequencies (proportional to the two-dimensional electron densities in the size-quantization subbands), observed in the Fourier spectrum of the magnetoresistivity oscillations, remain practically unchanged (curves *2* in Figs. 5 and 6), while for negative persistent photoconductivity the frequencies increase (curves *3* in Figs. 5 and 6) compared with the dark values (curves *1* in Figs. 5 and 6). The quantum electron mobilities[22] in the size-quantization subbands in the presence of positive persistent photoconductivity increase by 10–20% (primarily in the upper subbands) compared with the dark values, and in the presence of negative persistent photoconductivity they decrease strongly (by a factor of 1.5) in the lower subbands. This change of the quantum electron mobilities affects the height and width of the peaks in the Fourier spectrum: For illumination with ''long-wavelength'' radia-

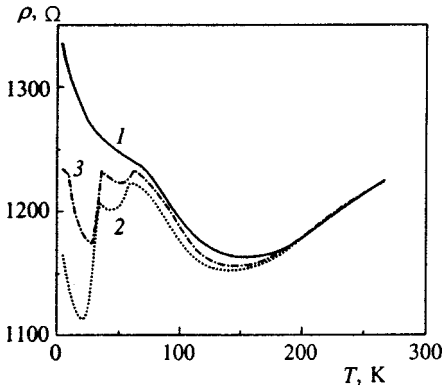


FIG. 4. Temperature dependences of the resistivity of sample 3 in the dark (curve *1*) and after illumination at $T=4.2$ K with $\lambda=791$ nm light (curve *2*) and $\lambda=850$ nm light (curve *3*). The illumination was switched off after resistivity saturation was reached.

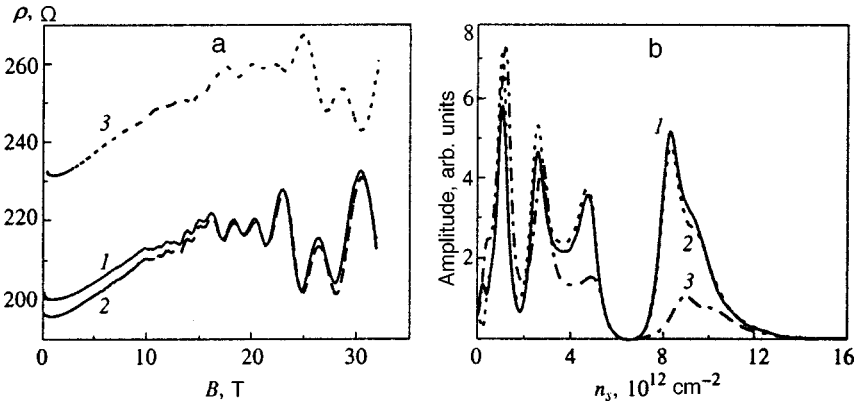


FIG. 5. (a)—Magnetoresistivity oscillations of sample 1 at $T=4.2$ K in the dark (*1*) and after irradiation with $\lambda=791$ nm light (*2*) (the illumination was switched off after the minimum resistivity was reached) and $\lambda>850$ nm light (*3*) (the illumination was switched off after resistivity saturation was reached). (b)—Amplitude of the Fourier transform of the Shubnikov–de Haas oscillations versus the density of two-dimensional electrons for sample 1 in the dark and after a corresponding illumination.

tion the height of the peaks corresponding to the lower subbands is much smaller and the width is much greater than in the dark [Figs. 5(b) and 6(b)]. The Hall effect investigations confirmed that the change in the resistivity of the samples after illumination is determined primarily by the change in the electronic Hall mobilities (see Table I). For illumination with ''short-wavelength'' radiation the Hall mobility averaged over all subbands increases, and the ''long-wavelength'' mobility decreases compared with the values in the dark.

#### 4. DISCUSSION

The long-time character of the negative photoconductivity observed in the heavily doped samples 1 and 2 gives a basis for inferring that this effect is associated with filling and emptying of DX centers. The increase in the total electron density, determined from the Shubnikov–de Haas effect, under illumination is 6.5% for sample 1 and 14% for sample 2 (see Table I). This appears to be due to the ionization of filled DX centers.[12] It is believed that a DX center is a negatively charged localized state, trapping two free electrons.[13–15] The Coulomb interaction between the positively charged shallow donors and DX centers gives rise to a correlation in the spatial distribution of charged impurity atoms and decreases scattering of electrons by them.[23–27] Ionization of DX centers by the light destroys the correlation and this should decrease the electron mobility[23,28] and lead to the above-described negative persistent photoconductivity effect. It should also be noted that, possibly, the filled tin DX centers in GaAs are still neutral (they contain one electron each)[29] and weakly scatter electrons, while under illumination the tin atoms become positively charged, and the observed decrease of the electron mobility is simply due to increase in the number of scattering centers.

The positive persistent photoconductivity can be explained as follows. Under illumination with ''short-wavelength'' radiation, electron–hole pairs are produced, and they are separated by a weak electric field which exists at equilibrium in the *i*-GaAs buffer layer between the substrate and the $\delta$-layer. In the process, the electrons slide down into the $\delta$-layer, and the holes neutralize the charged acceptors, which are present in small quantities in *i*-GaAs, or slide down into the substrate. The characteristic acceptor density in *i*-GaAs is $4\times10^{14}$ cm$^{-3}$, which for buffer layer thickness $d=0.45$ $\mu$m corresponds to a two-dimensional density $1.8\times10^{10}$ cm$^{-2}$. As a result of the spatial separation of the electrons and holes in the buffer layer, an additional electric field arises and completely compensates the initial field, the bands are rectified,[11] and the electron–hole pairs no longer separate. The additional charge-carrier density required for such a nonequilibrium situation to arise is approximately

$$\Delta n_s=\frac{\varepsilon_0\varepsilon}{ed}\Delta V,$$

where $\Delta V=0.75$ V is the potential corresponding to a deep chromium level in the substrate[30] and $d=0.45$ $\mu$m is the buffer layer thickness in the experimental structures. The

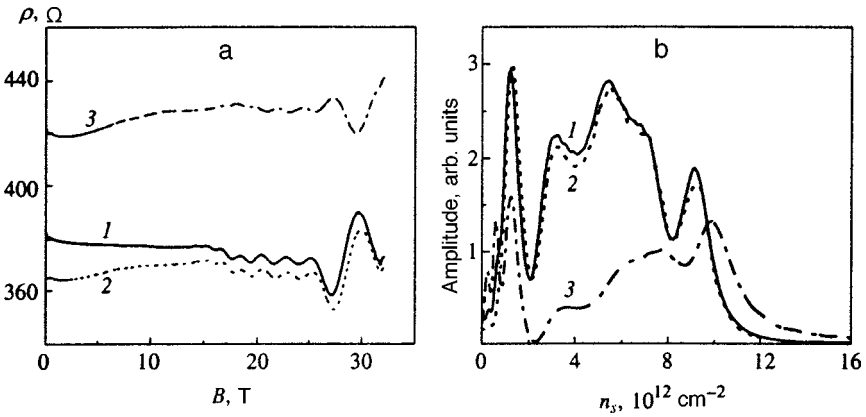


FIG. 6. (a)—Magnetoresistivity oscillations of sample 2 at $T=4.2$ K in the dark (*1*) and after irradiation with $\lambda=791$ nm light (*2*) (the illumination was switched off after the minimum resistivity was reached) and $\lambda>850$ nm light (*3*) (the illumination was switched off after resistivity saturation was reached). (b)—Fourier spectrum of the Shubnikov–de Haas oscillations for sample 2 in the dark and after corresponding illumination.

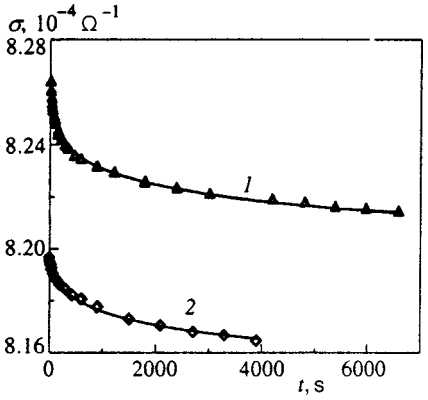


FIG. 7. Temporal relaxation of the positive photoconductivity of sample 3 after illumination at $T=77$ K with $\lambda=791$ nm light (*1*) and $\lambda>1120$ nm light (*2*. Solid lines—fit of the formula (1).

value of $\Delta n_s$ obtained in this manner is $1.2\times10^{11}$ cm$^{-2}$, which corresponds to a small increase of the Shubnikov electron densities in the samples (for example, $\Delta n_s$ for sample 3 is $1.1\times10^{11}$ cm$^{-2}$). The rectification of the conduction band bottom increases the effective width of the quantum well. At the same time, the wave functions of the electrons are concentrated farther away from the charged donors of the $\delta$-layer. This decreases the electron scattering and increases the electron mobility. This should affect the electron mobility most strongly precisely in the upper subbands, since it is the wave functions of electrons in the upper subbands that are most sensitive to such an increase in the width of the potential well.[22]

Under ''long-wavelength'' illumination, together with ionization of DX centers, the electrons are excited from deep levels of chromium in the substrate and slide down into the $\delta$-layer. At the same time, neutralization of the acceptors in the *i*-GaAs buffer layer by holes, just as with ''short-wavelength'' illumination, does not occur. The neutralization of charged acceptors under illumination with ''short-wavelength'' radiation results in an additional increase of the electron mobilities in the upper subbands,[22,31] and for this reason in the present case the resistivity of the samples decreases more strongly than for illumination with ''long-wavelength'' radiation.

The fact that positive persistent conductivity arises because of the spatial separation of the photogenerated electrons and holes is confirmed by measurements of the temporal relaxation of the photoconductivity. The decrease of the conductivity with time after illumination is switched off is described well by a logarithmic time dependence, which is characteristic for spatial charge separation.[16,17] Figure 7 displays the relaxation of the positive persistent photoconductivity in sample 3 and a fit of the function

$$\sigma(0)-\sigma(t)=A\ln(1+t/\tau), \tag{1}$$

obtained in Ref. 16 and valid for the initial time interval, to this photoconductivity. The relaxation parameter $\tau$ for sample 3 illuminated with ''short-wavelength'' radiation at $T=77$ K is 19 s, while for illumination with ''long-wavelength'' radiation it is 68 s. At $T=4.2$ K the relaxation parameter increases and is 23 s for ''short-wavelength'' radiation and several tens of minutes for ''long-wavelength'' radiation. Neutralization of charged acceptors under illumination with ''short-wavelength'' radiation results in faster relaxation of the positive persistent photoconductivity than for illumination with ''long-wavelength'' radiation, because of the recombination of the electrons in the $\delta$-layer and the close-lying acceptors. In heavily doped samples 1 and 2, in the regime of positive persistent photoconductivity, the relaxation times of the photoconductivity are close to the relaxation times in sample 3.

## 5. CONCLUSIONS

In summary, we have investigated for the first time negative persistent conductivity in GaAs structures with tin $\delta$-doped vicinal faces. This effect is observed only in samples with a high level of doping. An increase in resistivity is accompanied by an increase in the electron density and a substantial decrease of electron mobility, which is what determines the negative sign of the photoconductivity. The increase in electron density is a consequence of the ionization with deep metastable levels—DX centers. The decrease of the mobility could be due to breakdown of the spatial correlation in the arrangement of positively charged donors and negatively charged DX centers as well as to an increase in the density of positively charged scattering centers, if the DX centers were neutral before ionization.

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