Persistent relaxation processes in proton-irradiated $4H$-SiC

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The processes of long-term (persistent) conductivity relaxation in n-type silicon carbide irradiated with protons in a wide range irradiation temperatures Ti from 23 to 500°C are studied. It is shown for the first time that as a result of the proton irradiation with the fluence of $10^{14}\,\mathrm{cm}^{-2}$, two „competing"long-term processes of conductivity relaxation can be observed. The characteristics of both processes significantly depend on the irradiation temperature and bias, at which the dynamics of conductivity changes is studied. After applying a relatively small constant voltage to the sample, the decrease in current during persistent relaxation process is replaced by persistent increase in current and establishing of the steady state. Both processes are characterized by a very wide range of time constants. When irradiation is performed at room temperature ($T_i = 23^\circ$C), the time constants range from milliseconds to hundreds of seconds. When the samples are irradiated at elevated temperatures, the time constants are in the range from milliseconds to hundreds of milliseconds. The higher the bias applied, the faster the decrease in current is replaced by its increase. The possible nature of the observed effects is discussed.

Keywords: silicon carbide, proton irradiation, high temperature irradiation, persistent relaxation processes.

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1. Introduction

The effect of proton irradiation on the properties of semiconductors and semiconductor devices is important both from an applied point of view and from the point of view of studying fundamental physical issues of defect formation [1–4]. Such studies for silicon carbide and devices based on it has been conducted in a number of papers (see, for example, [1.5–10] and references in these papers). The main attention in these studies was paid to the study of the spectrum of defects formed in SiC depending on the proton energy and radiation dose, changes in the concentration of primary carriers due to the formation of local trapping centers, and a decrease of the life of minority carriers.

The proton irradiation causes the occurrence of a long-term (persistent) decrease of conductivity in a number of semiconductors (see, for example, [11–16] and the respective references in these papers). Such processes serve as an extremely sensitive indicator of the presence of structural imperfections in semiconductors and semiconductor devices can be caused by the formation of capture levels resulting from irradiation [17], spatially inhomogeneous energy barriers [18], the formation of a „tail" density of states exponentially decreasing into the depth the band gap (see, for example, [19]).

In all these studies, the process of establishment of stationary conductivity was characterized by a monotonous long-term current drop after applying a voltage pulse to the sample. A nonmonotonic character of steady state establishment was observed for the first time in proton-irradiated silicon carbide of n-type in this paper. After application of the voltage the current drop, characterized by a very wide range of time constants (persistent process), is replaced by an increase of current, which is also characterized by a very wide range of time constants. The effect of proton irradiation temperature on the processes of nonmonotonic long-term conductivity in silicon carbide of the n-type is investigated in this paper. The possible nature of the observed effects is discussed.

2. Experimental conditions

Schottky SiC diodes JBSCPW3-1700-S010B with a blocking voltage of 1700 V, the concentration of carriers (electrons) in the base $n_0 \approx 3.4 \cdot 10^{15}\,\mathrm{cm}^{-3}$ and the thickness of the base of $W \approx 20\,\mu$m were studied. The irradiation was carried out with protons with an energy of 15 MeV in a pulsed mode. The pulse repetition rate was 100 Hz; the pulse duration was 2.5 ms. The temperature T_i at which the diodes were irradiated was in the range of $23-500^\circ$C. The accuracy of temperature regulation during irradiation was $\pm 5^\circ$C. The radiation dose of Φ was $10^{14}\,\mathrm{cm}^{-2}$ for all values of T_i.

The average free path length of protons with an energy of 15 MeV calculated using the SRIM [20] software is 1 mm. Thus, the density of the defects introduced by irradiation can be considered homogeneous with high accuracy with the thickness of the base of the diodes $W \approx 20\,\mu$m.

The volt-ampere characteristics and the dynamics of changes of the conductivity of the samples were studied at room temperature in an isothermal mode. Measurements were carried out using direct current with a base resistance of $R_b \geq 10^3$ Ohms. At $R_b \leq 10^3$ Ohm, measurements were carried out in the pulse mode with the duration and duty cycle of the pulses which guaranteed the isothermal conditions.

3. Experimental results and discussion

Figure 1 shows the static direct volt-ampere characteristics of structures irradiated with protons with an energy of 15 MeV with a dose of 10^{14} cm^{-2} at four temperatures.

The dependences shown in Figure 1 are reasonably consistent with the results obtained in [15] in case of irradiation at room temperature with protons with the same energy and the same dose of SiC Schottky diodes with a blocking voltage of 1200 V, i. e. with a slightly higher initial electron concentration.

As has been repeatedly shown earlier, irradiation has a relatively weak effect on the exponential section of the volt-ampere characteristics when most of the applied voltage U_F falls on the forward biased Schottky barrier [22,23]. When the value of the forward voltage exceeds the so-called „cut-off voltage“ U_c, the vast majority of the applied voltage drops at the base of the diode. Although the value of U_c somewhat depends on the dose Φ and temperature T_i, it does not exceed ~ 1.0 V in the entire range of values of these parameters [23].

Figure 1 shows that the current value in the non-irradiated diode is 14 A with the reference value of the forward voltage $U_F = 2$ V. Irradiation with a dose of $\Phi = 10^{14}$ cm^{-2} at room temperature ($T_i = 23°$C) reduces the current value at $U_F = 2$ V to $I \approx 3.4 \cdot 10^{-8}$ A, i.e by ~ 9 orders of magnitude. The radiation resistance of the material monotonously increases with increasing T_i. The value of current I at $U_F = 2$ V and with the same dose is $5 \cdot 10^{-7}$ A at $T_i = 150°$C, $2.2 \cdot 10^{-4}$ A at $T_i = 300°$C and $3.3 \cdot 10^{-2}$ A at $T_i = 500°$C. The presented data obviously demonstrate that the stationary concentration of radiation defects accounting for the compensation for the conductivity of the base decreases with the irradiation temperature. A qualitative analysis of this temperature dependence was performed in [23].

Figure 2 shows the dependence of current on time at three values of direct DC voltage U_F applied to a structure irradiated with a dose of $\Phi = 10^{14}$ cm^{-2} at 23°C. The voltage rise rate dU_F/dt in the range from zero to U_F was 10^2 V/s.

The decrease of conductivity can be traced in the range of time constants from milliseconds to hundreds of seconds (cf. with data in [15].) Figure 2 shows the most important time interval of the transient process, which allows tracing the occurrence of a second long-term transient with an increase of bias.

Figure 2, *a* shows that the current decreases over time up to $t \approx 100$ s at $U_F = 3$ V, after which it is practically saturated at the provided scale. In reality, however, a very slow increase of current begins at $t \geq 100$ s. The values of current I are equal to $5.849 \cdot 10^{-8}$, $5.905 \cdot 10^{-8}$ and

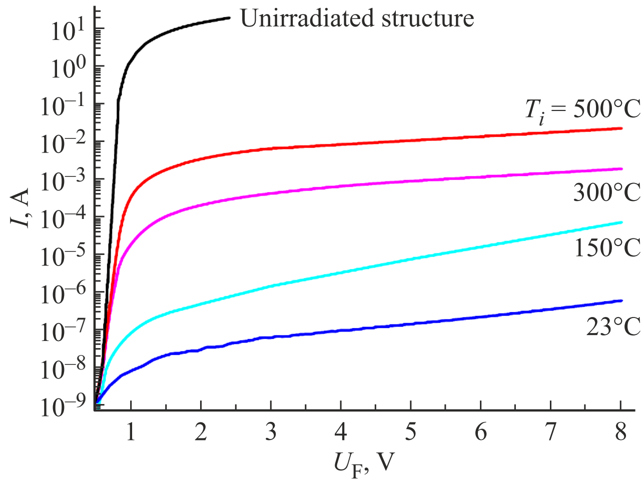

Figure 1. Static direct volt-ampere characteristics of structures irradiated with protons with an energy of 15 MeV at a dose of 10^{14} cm^{-2} at four irradiation temperatures T_i. The upper curve corresponds to the volt-ampere characteristic of the non-irradiated sample [21].

$5.94 \cdot 10^{-8}$ A at $t = 100$, 200 and 300 s respectively. The steady-state current value at $U_F = 3$ V is $5.99 \cdot 10^{-8}$ A.

At $U_F = 5$ V (Figure 2, *b*), the current drop at $t \approx 50$ s is replaced by an obvious process of current rise, which, like the process of current decline, is long-term (persistent) character. The non-exponential nature of the current increase in Figure 2, *b* during an additional experiment was traced up to the value of $t = 600$ s. The current values of I were $1.322 \cdot 10^{-7}$ and $1.348 \cdot 10^{-7}$ A at $t = 300$ and 600 respectively. The steady-state current value at $U_F = 5$ V is $1.44 \cdot 10^{-7}$ A.

The current drop time decreases with a further increase in the bias voltage. At $U_F = 8$ V (Figure 2, *c*) the current reaches a minimum value at $t \approx 25$ s, after which the current increases, tending to a stationary of value $I_{st} = 6.85 \cdot 10^{-7}$ A. At $t = 100$, 200, 300 and 600 s the values of current I are equal to $6.68 \cdot 10^{-7}$, $6.72 \cdot 10^{-7}$, $6.75 \cdot 10^{-7}$ and $6.80 \cdot 10^{-7}$ A accordingly.

It should be noted that despite very high resistivity of the irradiated material, the observed times of long-term transients are many orders of magnitude higher than the Maxwell time of dielectric relaxation $\tau_d = \varepsilon\varepsilon_0/\sigma_x$, where $\varepsilon = 9.66$ — dielectric constant SiC, $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m — dielectric constant of vacuum, σ — specific conductivity of the irradiated material.

Indeed, the resistance of the sample before irradiation is equal to ≈ 0.1 Ohms (Figure 1). At the same time, with the electron concentration before irradiation of $n_0 \approx 3.4 \cdot 10^{21}$ m^{-3} and mobility of $\mu_n = 0.8$ m^2/(V $\cdot$ s) [24] the value of the specific conductivity in a non-radiated sample will be $4.3 \cdot 10^2$ Ohm^{-1}m^{-1}.

This situation corresponds to the τ_d value $2 \cdot 10^{-13}$ s. Irradiation increases the resistivity by 9 orders of magnitude. Thus, the value of τ_d in the irradiated sample will be ≈ 0.2 ms. Taking into account the dependence of

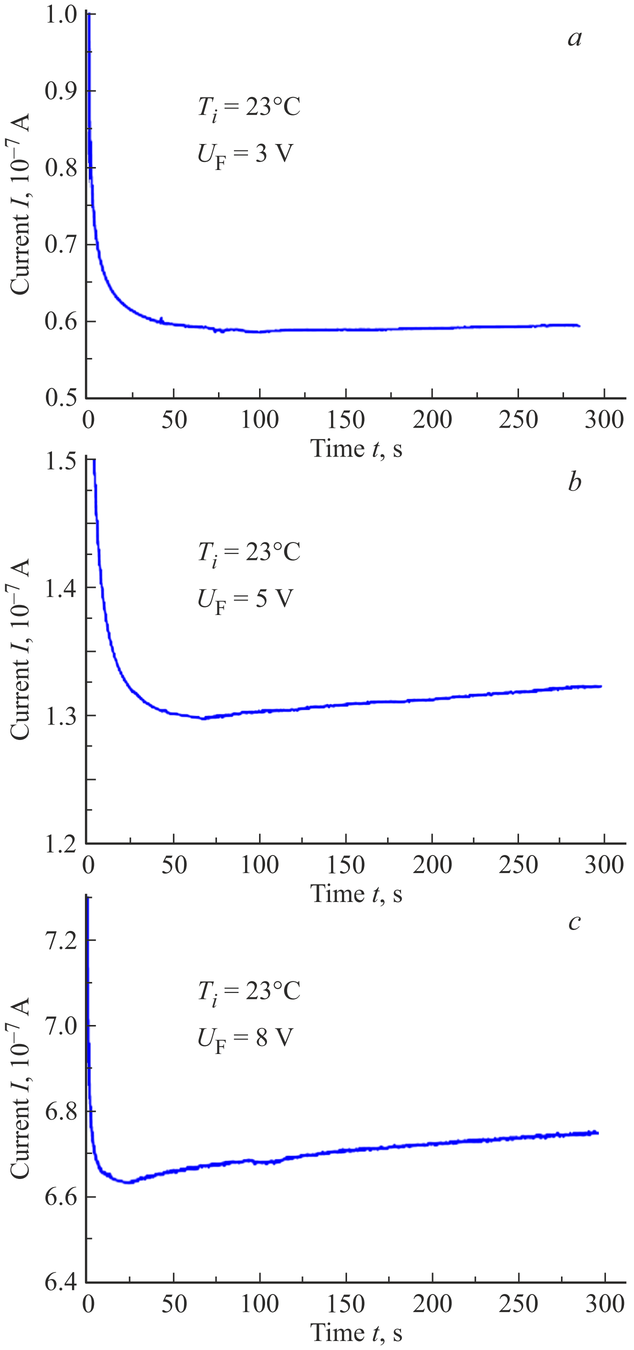

Figure 2. A long-term transient process of establishment of a stationary state in case of application of pulse voltage with an amplitude of U_F to a sample irradiated with a dose of $\Phi = 10^{14}\,cm^{-2}$ at $T_i = 23°C$. Voltage U_F, V: *a* — 3, *b* — 5, *c* — 8. Voltage rise rate $dU_F/dt = 10^2$ V/s.

mobility on the concentration of introduced defects [24] has almost no effect on the result.

Irradiation at a relatively low temperature 150°C, which does not exceed the maximum operating temperature of the devices [21], reduces the resistivity of the sample after irradiation approximately by an order of magnitude compared with the case of irradiation with protons with the same dose at room temperature (Figure 1). (The value of direct current I at a reference value of $U_F = 2$ V in diode irradiated at 23°C is $\approx 3.4 \cdot 10^{-8}$ A; in a diode irradiated at 150°C, the value of I is equal to $\approx 5 \cdot 10^{-7}$ A). However, the characteristic times of both persistent relaxation processes decrease by almost 3 orders of magnitude (Figure 3).

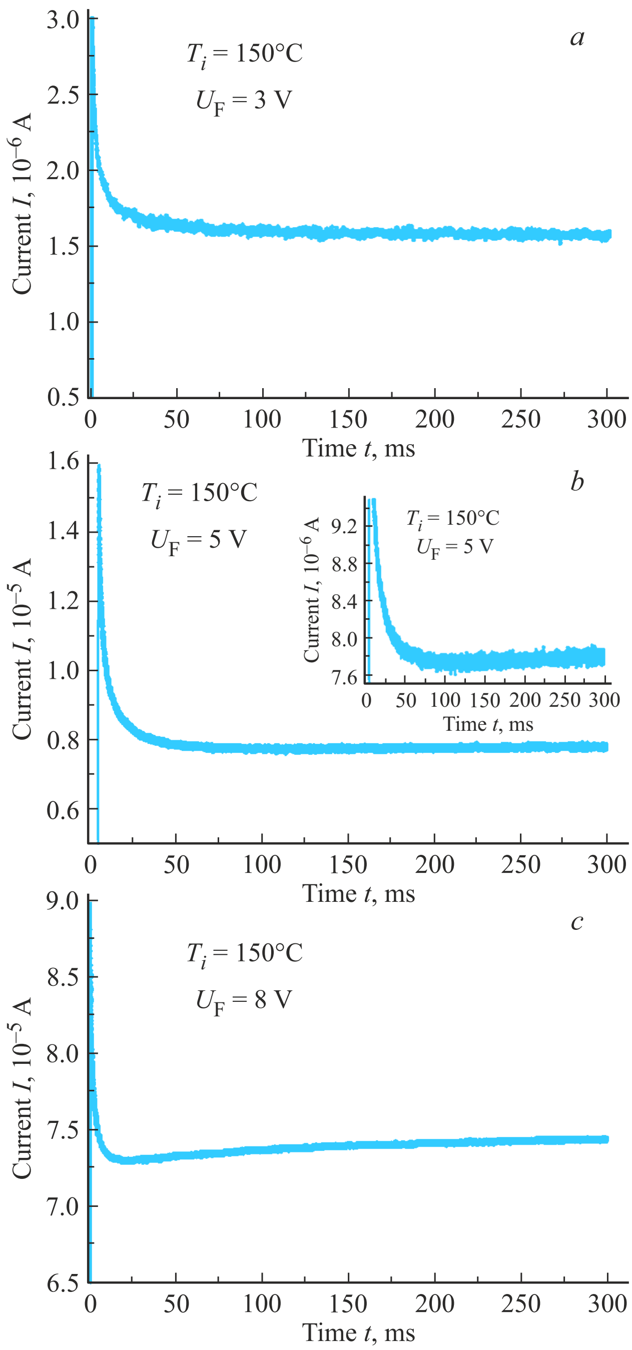

Figure 3. A long-term transient process of establishment of a stationary state in case of application of pulse voltage with an amplitude of U_F to a sample irradiated with a dose of $\Phi = 10^{14}\,cm^{-2}$ at $T_i = 150°C$. Voltage U_F, V: *a* — 3, *b* — 5, *c* — 8. The dependence $I(t)$ is shown with a high resolution of current I in the box to Figure 3, *b*. Voltage rise rate $dU_F/dt = 2 \cdot 10^3$ V/s.

At $U_F = 3$ V (Figure 3, *a*) the current decreases over time up to the value of $t \approx 60$ ms, after which it is practically saturated at the provided scale. In reality, however, the current continues to decrease very slowly. At $t \approx 300$ ms the current value is equal to $I = 1.57 \cdot 10^{-6}$ A. Steady-state current value is $I_{st} = 1.52 \cdot 10^{-6}$ A.

At $U_F = 5$ V (Figure 3, *b*) the current decreases until the moment $t \approx 120$ ms, after which a very slow current growth begins, also of a persistent nature. The value of I at the minimum was $7.76 \cdot 10^{-6}$ A. At $t = 300$ s the value of current I was equal to $\approx 7.77 \cdot 10^{-6}$ A. The steady-state current value at $U_F = 5$ V is equal to $7.8 \cdot 10^{-6}$ A.

At $U_F = 8$ V (Figure 3, *c*) the minimum current value is reached at $t \approx 25$ ms. At $t \geq 25$ ms current begins to increase. At $t = 100$, 200, 300 ms, the values of current I are equal to $7.36 \cdot 10^{-5}$, $7.38 \cdot 10^{-5}$ and $7.395 \cdot 10^{-5}$ A respectively. The steady-state current value at $U_F = 8$ V is equal to $7.4 \cdot 10^{-5}$ A.

Thus, the processes of persistent relaxation turn out to be significantly more sensitive to a relatively small increase of the irradiation temperature than the conductivity of the base (Figure 1).

An increase of the irradiation temperature to 300°C results in a significant increase of stationary current with the same dose of $\Phi = 10^{14}$ cm^{-2}. At a reference value of $U_F = 2$ V the value of I_{st} increases by ~ 400 times compared with the case of irradiation at $T_i = 150$°C (Figure 1). At the same time, the time scale of persistent processes changes relatively slightly: the characteristic scale of these processes remains in the range of tens of milliseconds. However, with the value of the voltage rise rate $dU_F/dt = 2 \cdot 10^3$ V/s unchanged in comparison with the data presented in Figure 3, the amplitude and time dependences of the current in the processes of current drop and rise change very significantly (Figure 4).

Comparing Figure 3, *a* and 4, *a*, it is easy to see that if in Figure 3, *a* a noticeable drop of current was observed at $t \geq 60$ ms, and then the current was almost saturated, while in Figure 4, *a* a noticeable drop of current can be traced up to $t = 300$ ms. Steady-state current value $I_{st} = 7.5 \cdot 10^{-4}$ A.

At $U_F = 5$ V (Figure 4, *b*) the current monotonously drops to a stationary value $I_{st} = 1.04 \cdot 10^{-3}$ A. The second persistent process is manifested only at $U_F = 8$ V (Figure 4, *c*): an increase of current over time. Interestingly, at $U_F = 8$ V and $T_i = 300$°C, the minimum current is observed even slightly earlier than with the same value of U_F at $T_i = 150$°C (Figure 3, *c*).

In case of the irradiation temperature of 500°C the process of a persistent current rise is not observed even with the voltage of $U_F = 8$ V (Figure 5).

The presented experimental data allow formulating a hypothesis about the physical nature of the observed persistent processes. As noted in the Introduction, the appearance of a persistent monotonous drop of conductivity after proton irradiation has been observed in many cases. The possible mechanisms of this effect were discussed, in particular, in [17–19]. A general condition that makes it possible to

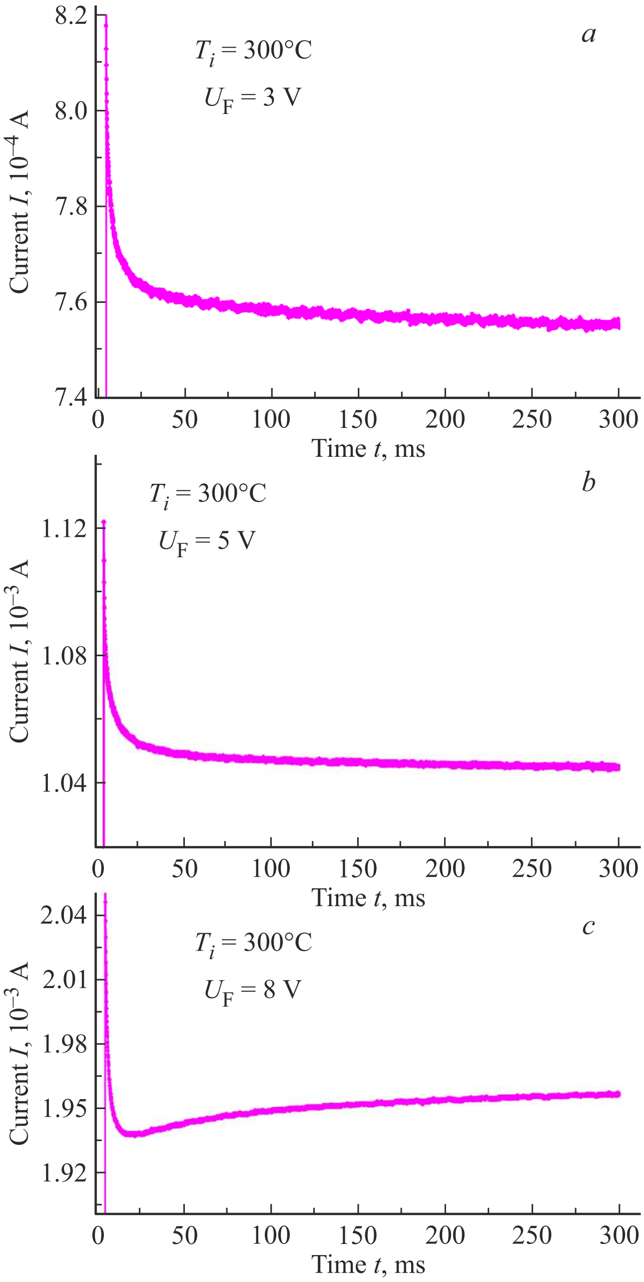

Figure 4. A long-term transient process of establishment of a stationary state in case of application of pulse voltage with an amplitude of U_F is applied to a sample irradiated with a dose of $\Phi = 10^{14}$ cm^{-2} at $T_i = 300$°C. Voltage U_F, V: *a* — 3, *b* — 5, *c* — 8. Voltage rise rate $dU_F/dt = 2 \cdot 10^3$ V/s.

interpret the effect of the occurrence of a persistent drop of conductivity is the formation of a continuous spectrum of capture levels as a result of irradiation, characterized by an exponentially broad set of capture times τ. The maximum values of τ can be extremely large (see, for example, [19,25]).

The presented results, however, convincingly demonstrate that in the discussed situation there are not one, but two regions of a continuous spectrum of levels with an exponen-

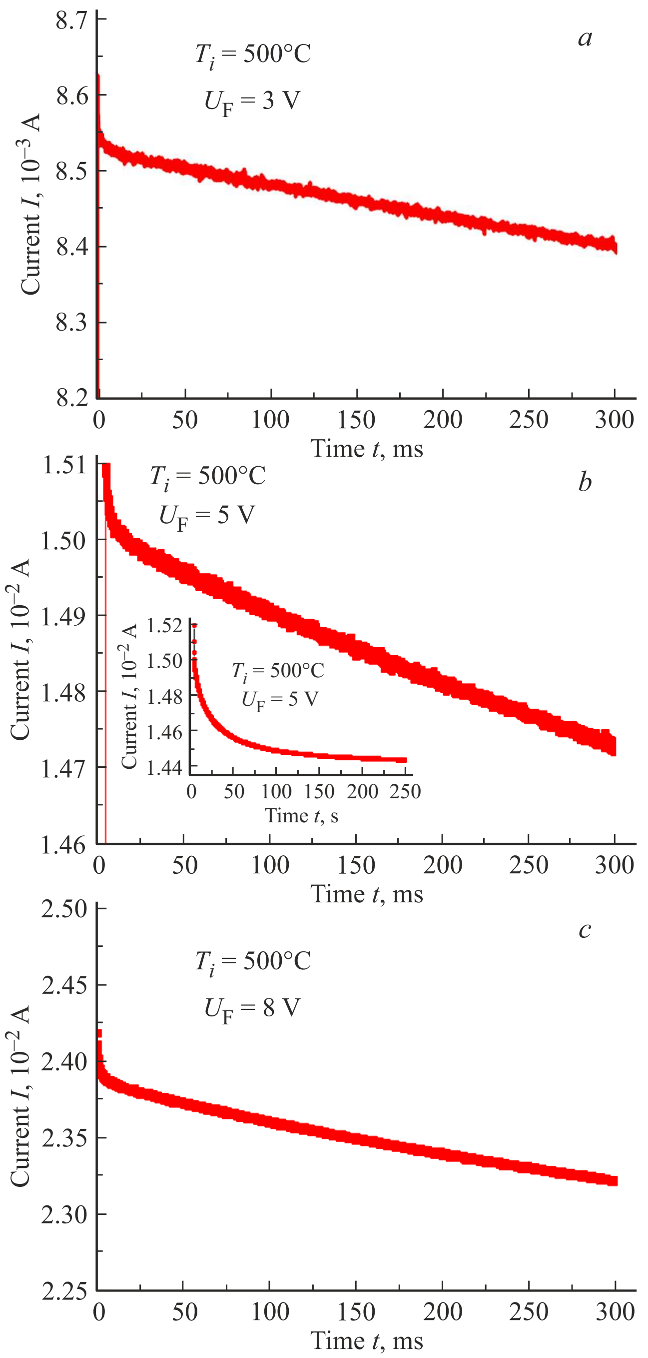

Figure 5. A long-term transient process of establishment of a stationary state in case of application of pulse voltage with an amplitude of U_F to a sample irradiated with a dose of $\Phi = 10^{14}\,\text{cm}^{-2}$ at $T_i = 500^\circ$C. Voltage U_F, V: *a* — 3, *b* — 5, *c* — 8. The dependence $I(t)$ is traced in the time range of hundreds of seconds in the box to Figure 5, *b*. Voltage rise rate $dU_F/dt = 2 \cdot 10^3$ V/s.

tially broad set of relaxation times τ_1 and τ_2. Nonequilibrium electrons arising in a sufficiently high-resistance material under the impact of rapidly increasing voltage dU_F/dt are „distributed" between these two regions [26].

Before analyzing the dynamics of the behavior of these nonequilibrium electrons, we note first of all that in case of application of a direct voltage to the studied JBS structures irradiated with protons, any effect of holes can be ignored, despite the fact that a significant part of the area of such structures is occupied by „embedded" *p*-regions. In non-radiated structures, the presence of such regions with forward bias leads to effective injection of holes into the base of the structure (with biases exceeding $U_F \approx 1$ V). However, this situation is realized only under the condition of $W/L_p \approx 1$, where L_p is the diffusion length of holes in the base of the structure.

Proton irradiation with a dose of $\Phi = 10^{14}\,\text{cm}^{-2}$ radically reduces the lifetime and diffusion length of holes. The dependence of the hole lifetime on the dose of electron irradiation in JBS structures similar to those studied in this paper was studied in [27]. The decrease of the lifetime under the impact of irradiation is described by the expression $1/\tau_p = 1/\tau_0 + K_T\Phi$, where τ_0 — the initial lifetime of holes before irradiation, τ_p — the lifetime of holes after irradiation, K_T a coefficient describing the degradation of lifetime under the impact of radiation. In case of irradiation with electrons with an energy of 4.5 MeV $K_T = 3 \cdot 10^{-7}\,\text{s}^{-1} \cdot \text{cm}^2$ [27]. The efficiency of introduction of the main recombination acceptor centers $Z_{1/2}$ and $EH_{6/7}$ in case of irradiation with SiC protons with an energy of 15 MeV is in ~ 400 times higher than in case of irradiation with electrons with the specified energy [15]. Thus, in the considered case $K_{Tp} \approx 1.2 \cdot 10^{-4}\,\text{s}^{-1} \cdot \text{cm}^2$, and with a dose of $\Phi = 10^{14}\,\text{cm}^{-2}$, the lifetime of holes after irradiation will be $\tau_p \approx 1/K_{Tp}\Phi \approx 10^{-10}$ s. At the same time, the diffusion length of the holes $L_p = (D_p\tau_p)^{1/2} \approx 1.6 \cdot 10^{-5}\,\text{cm} = 0.16\,\mu$m (here D_p —the diffusion coefficient of the holes, for evaluation set to $10^2\,\text{cm}^2$/s [24]). Thus, the ratio W/L_p is ≈ 125 in the studied irradiated structures.

In addition, the absence of any hole effect is directly seen from the volt-ampere characteristics of irradiated diodes (Figure 1). No features of the volt-ampere characteristics of irradiated diodes are observed even at biases U_F, significantly exceeding 1 V. Thus, the observed persistent processes are caused only by nonequilibrium electrons injected into the base at high values of dU_F/dt [26].

Some of the „excess" nonequilibrium electrons that emerged at relatively high values of dU_F/dt are quickly captured at the levels of one of the regions of the continuous spectrum of levels. This process is not detected in the experiments described above. Excess electrons, for which no free states were found in this region, slowly relax to an equilibrium state with an exponentially broad set of relaxation times τ_1. This process corresponds to the initial current drop observed in all experiments (Figures 2–5, see also [11–16]). It should be emphasized that, as far as we know, only qualitative considerations have been expressed in the literature for the case of monopolar relaxation of conductivity unlike the processes of persistent relaxation of photoconductivity, for which there are several adequate models (see, for example [18]).

Some of the excess nonequilibrium electrons, quickly captured after the application of the pulse, gradually begin to be released. This process, which is also characterized by an exponentially broad set of relaxation times τ_2, corresponds to the areas of current rise convincingly observed in Figures 2, *b, c*; 3, *b, c* and 4, *c*. In all cases, the higher the applied voltage U_F, the faster the current drop is replaced by a rise, followed by the establishment of a stationary state corresponding to the static volt-ampere characteristic shown in Figure 1.

In case of irradiation at 23°C (Figure 2), the persistent decrease and subsequent increase of conductivity can be traced on a scale of hundreds of seconds. This means that in the process of increase of the current the carriers „are released" from sufficiently deep levels or sufficiently deep pits of potential relief resulting from irradiation [18,19]. The fact that the higher the applied voltage, the faster the decrease of conductivity is replaced by an increase, may be due to the well-known Poole–Frenkel effect [28]. In case of application of the electric field, the height of the energy barrier holding the electron in the quantum well decreases, facilitating thermal emission from a deep level. Note that the average electric field strength of ~ 4 kV/cm corresponds to the bias voltage of $U_F = 8$ V with the base thickness of $W = 20\,\mu$m.

On the other hand, no ncrease in current is observed in case of irradiation at $T_i = 500°$C (Figure 5) even with the highest applied voltage. The current monotonously decreases over time. This may mean that the potential relief formed at $T_i = 500°$C as a result of irradiation either does not form at all, or is characterized by a low height of potential barriers. As can be seen from Figure 5, *b*, in this case, even at the highest possible irradiation temperature, the process of conduction drop can be traced to time constants of the order of hundreds of seconds.

There are two possible scenarios explaining the effects of hot irradiation on the conductivity of irradiated samples as noted in [23,29], in which the impact of the irradiation temperature T_i on the processes of defect formation in SiC at elevated temperatures („hot irradiation") was studied for the first time. The first scenario assumes that the spectra of radiation defects are the same, both in case of fairly well-studied irradiation at room temperature („cold" irradiation, see, for example, [15,30]) and in case of hot irradiation. Then, the proportion of primary Frenkel pairs simply decreases with the growth of T_i and these pairs further dissociate into separate components forming the levels $Z_{1/2}$ and $EH_{6/7}$.

An alternative scenario assumes that high irradiation temperatures radically change the spectrum of secondary radiation defects. This is exactly the scenario that is realized with hot irradiation of GaAs and InP [31].

It seems that a comparison of the persistent relaxation processes observed at irradiation temperatures of 23 and 500°C is a serious argument in favor of the second scenario. Another argument in favor of this scenario is a comparison of the processes of persistent relaxation at room temperature and at $T_i = 150°$C (cf. Figure 2 and 3). A relatively small change of T_i leads to a decrease of the characteristic times of both processes of persistent relaxation by 3 orders of magnitude.

4. Conclusion

Two persistent conduction relaxation processes were observed for the first time in silicon carbide of *n*-type irradiated with protons with an energy of 15 MeV. The processes of long-term relaxation were traced in the irradiation temperature range T_i from 23 to 500°C. When a relatively small voltage U_F is applied to irradiated samples, following the initial current drop, characterized by a very wide range of time constants, a subsequent current increase is observed, which also has a persistent character and ends with the establishment of a stationary state. The characteristics of both relaxation processes critically depend on T_i. At $T_i = 23°$C, the time constant range of the processes of the drop and subsequent rise of the current can be traced in the range from milliseconds to hundreds of seconds. This means that the process of current rise is accountable for the „release" of carriers from sufficiently deep levels forming a continuous spectrum of states, or the release of carriers from sufficiently deep wells of potential relief.

Irradiation at $T_i = 150°$C reduces the resistivity by approximately an order of magnitude compared to the case of irradiation at $T_i = 23°$C. At the same time, the characteristic times of both long-term processes decrease by ~ 3 orders. An increase of T_i to 300°C, on the contrary, leads to a very significant increase in the steady-state current. At the same time, the characteristic times of both processes change slightly compared to the case of $T_i = 150°$C. Finally, only the first of the long-term processes is observed at $T_i = 500°$C: the current decreases monotonously over time.

In all cases where two long-term current relaxation processes are observed, the greater the applied voltage U_F, the faster the current drop is replaced by the rise. This result may be attributable to the Pool–Frenkel effect. The absence of a current rise process at $T_i = 500°$C may mean that the spectrum of levels accountable for the current rise either has a low activation energy or is not formed at all.

The results obtained serve as a cogent argument in favor of the conclusion that high irradiation temperatures radically change the spectrum of secondary radiation defects.

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Conflict of interest

The authors declare that they have no conflict of interest.

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