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The effect of maintaining a high conductivity state in high-voltage GaAs diodes switched-on in the delayed avalanche breakdown mode

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Received June 3, 2022
Revised June 29, 2022
Accepted June 30, 2022

It is experimentally established that high-voltage GaAs diodes maintain conducting state with low residual voltage after switching to the conducting state in the delayed impact-ionization mode. The duration of the constant current in the reversely-biased structure is determined by the duration of the applied rectangular voltage pulse (up to 100 ns) and significantly exceeds drift extraction and recombination times. The discovered effect of self-supporting conducting state resembles the „lock-on" effect in optically activated GaAs semiconductor switches and S-diodes with deep centers. The effect can be explained by shock ionization in narrow collapsing Gann domains.

Keywords: high-voltage GaAs diodes, „lock-on" effect.

DOI: 10.21883/TPL.2022.08.55065.19271

For GaAs structures, the effect of self-sustaining of high-conductivity state was previously observed in GaAs structures with deep sites (S diodes) [1,2] and switches with optically triggering based on semi-insulating GaAs [3,4]. In switches with optical triggering this phenomenon is known as the „lock-on" effect: the conducting state surprisingly persists for a long time (more than 100 ns) after the end of the optical pulse [3,4]. In GaAs S diodes with deep sites, a separate branch is observed on the reverse current-voltage characteristic, corresponding to the conducting state [1,2]. Thus, for both classes of GaAs devices the conduction state is self-sustained in a weak average electric field (~ 4 kV/cm). After many years of studies, a possible physical mechanism of the lock-on effect in optically triggered switches [5,6] was established, based on the generation of electron-hole plasma in narrow collapsing strong field domains [7] spontaneously arising due to the bipolar Gunn effect. The appearance of ionizing domains of this type was first predicted in GaAs avalanche transistors [7] and is possible at ultrahigh current density ($J \sim 1$ MA/cm^2), which is achieved due to the current localization in narrow channels [7]. The mechanism of the conducting state in GaAs S diodes, explained for many years by the re-charge of deep sites [1,2], was revised in recent years and is also related to collapsing domains [8–10].

This paper presents experimental evidence of long-term self-sustaining of the conducting state in a reverse-biased GaAs $p-p_0-n_0-n$ structure with a low concentration of deep sites. Avalanche switching to the conducting state was initiated by a fast (~ 3 kV/ns) rise of the reverse voltage and occurred in the mode of delayed impact-ionization breakdown, previously implemented in GaAs diodes in [11–13]. It is shown that after a subnanosecond switching, the reverse-biased GaAs diode conducts current of about 10 A for tens of nanoseconds without showing any signs of recovery of the $p-n$ junction. Self-sustaining of the conducting state is observed at residual voltage ~ 90 V, which is by many times lower than the steady-state breakdown voltage (~ 400 V). Note that the anomalous dynamics of the residual voltage in GaAs diode under similar conditions of avalanche switching was discovered by us earlier in [13], where we already suggested the possibility of lock-on effect and the role of collapsing domains. However, in [13] the bell-shaped pulse applied to the diode had a half-width of about 2 ns, comparable to the drift extraction time of non-equilibrium carriers. The short pulse duration did not allow us to experimentally confirm the effect of self-sustaining of the conducting state. In the present paper the pulse width reaches 100 ns.

Fig. 1, a shows the electrical circuit of the experimental unit, in which the holder of the diodes under study was part of the coaxial measuring path. The voltage across the diode connected in series with load of 50 Ω was set by the charging voltage U_2 of the capacitor C and the impulse voltage of the generator U_1. A high-voltage generator of square pulses based on photon-injection pulsed thyristor [14] and a coaxial charging line was used, the line length set the duration (up to 100 ns). The rise time of the generator pulse amplitude at the leading edge t_r did not exceed 0.3 ns at a repetition frequency of 1 kHz (Fig. 1, b). The shape of the pulses was recorded by digital two-channel oscilloscope Agilent Technologies DS06102A with sampling rate of $f_d = 4$ GHz (20 pic/ns). When measuring the voltage $U_R(t)$ at the channel input 50 Ω *1*, a set of broadband attenuators was used. The voltage $U_\Sigma(t)$ across the diode and the load was measured using a high-voltage probe connected to the output of the measuring path (channel *2*). The oscillograms taken in channels *1* and *2* determined the time dependences of current $I(t) = U_R(t)/R$ and voltage $U_D(t) = U_\Sigma(t) - U_R(t)$.

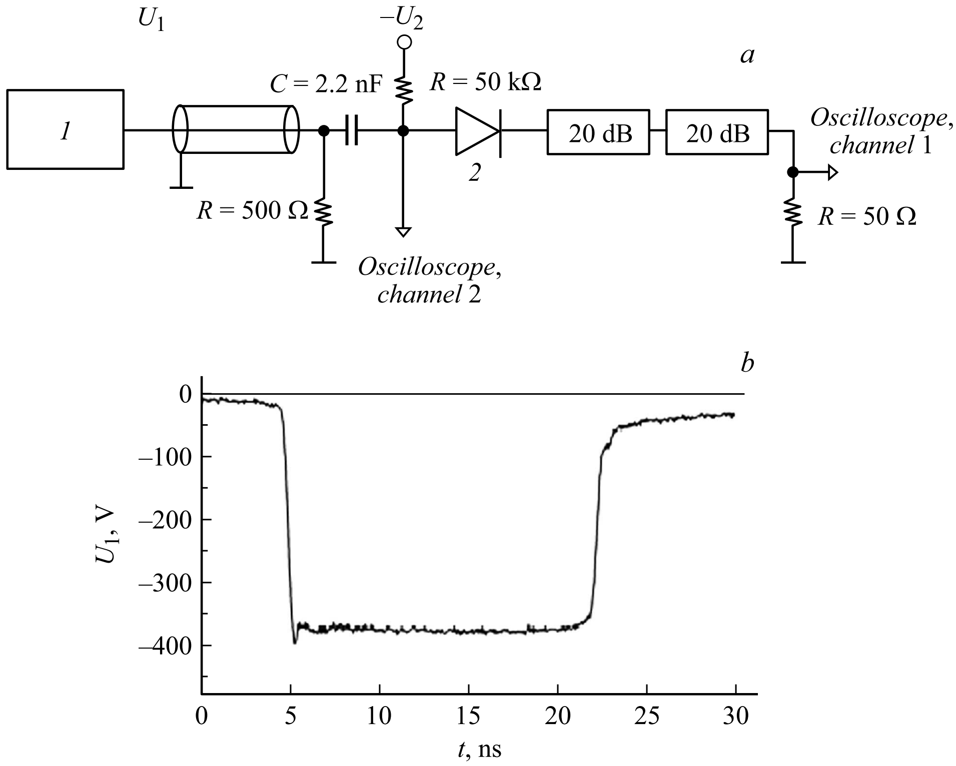

Figure 1. Electrical diagram of the experimental set-up (*a*) and the shape of the initial pulse (*b*) generated by the generator *1*to load of 50 Ω. *2* — investigated diode structure.

GaAs $n^+-n-i-p-p^+$ diode structures with low concentration ($< 10^{16}\,\mathrm{cm}^{-3}$) of residual acceptor (Si) and donor (O) impurities were fabricated by liquid-liquid-phase epitaxy on Zn-doped *p*-type substrates. The base region had a thickness of $\sim 45\,\mu$m. The depth of the $p-i$- and $n-i$-junctions with respect to the substrate was 15 and $30\,\mu$m, respectively. The doping level of the i region did not exceed $10^{14}\,\mathrm{cm}^{-3}$. Diodes with a mesostructure diameter of $d = 500\,\mu$m were formed using deep ($h \gg 45\,\mu$m) chemical etching. The lifetime of non-equilibrium carriers did not exceed 100 ns. The stationary breakdown voltage U_b for a batch of diodes of the same type was in the range from 380 to 410 V.

Fig. 2 shows the time dependences of the current and voltage across the diode. Fig. 2, *a* corresponds to „subcritical" mode, in which the avalanche breakdown begins, but switching to the conducting state with a low residual voltage does not occur. During the rise time of the voltage pulse $U_1(t)$, the field strength in the diode structure exceeds the impact-ionization breakdown threshold, avalanche generation and the flow of the avalanche current begin (Fig. 2, *a*, curves *1*, initial offset $U_2 = 120$ V). With the initial bias increasing on U_2 diode from 120 to 200 V, the avalanche current flows in the mode of generating UHF oscillations with a frequency of ~ 1.5 GHz (Fig. 2, *a*, curves *2*). Such self-oscillations in Si-diode were previously observed in the paper [15]. The oscillation mechanism is associated with the generation of an electron-hole plasma packet in the region of a strong electric field near the $p-n$ junction and the subsequent decrease in the field strength below the impact ionization threshold due to field distortion by this packet [15]. The period ($t \leqslant 0.5$ ns) approximately corresponds to the duration of the drift extraction of carriers from the base region of the diode structure.

Fig. 2, *b* shows the time dependences of the current and voltage for a larger pulse amplitude U_1, sufficient to switch the structure to a high conductive state. The threshold value of the switching voltage for batch of diodes of the same type is in the range of 750–800 V. Measured by the signal level 0.1–0.9, the rise time of the current amplitude (t_r) is ~ 300 ps and is limited by the time resolution of the measuring unit. The current amplitude immediately after switching reaches $I_m = 8-10$ A (Fig. 2, *b*), i.e. by 5–10 times more than in „subthreshold" mode (Fig. 2, *a*). The current value in the on state is mainly determined by the series resistance. The conducting state of the reverse-biased diode after avalanche switching is quasi-stationary (Fig. 2, *b*). Indeed, the state duration of the high reverse conductivity significantly exceeds the drift extraction time (by about nanosecond). The stationary conducting state was observed by us for pulses with a duration of up to 100 ns, however, at a duration of 100 ns there were cases of irreversible degradation of the structure after a series of pulses. With a pulse duration of 15 ns (Fig. 2), the diodes withstood long-term operation at a repetition rate of 1 kHz without degradation. The residual voltage across

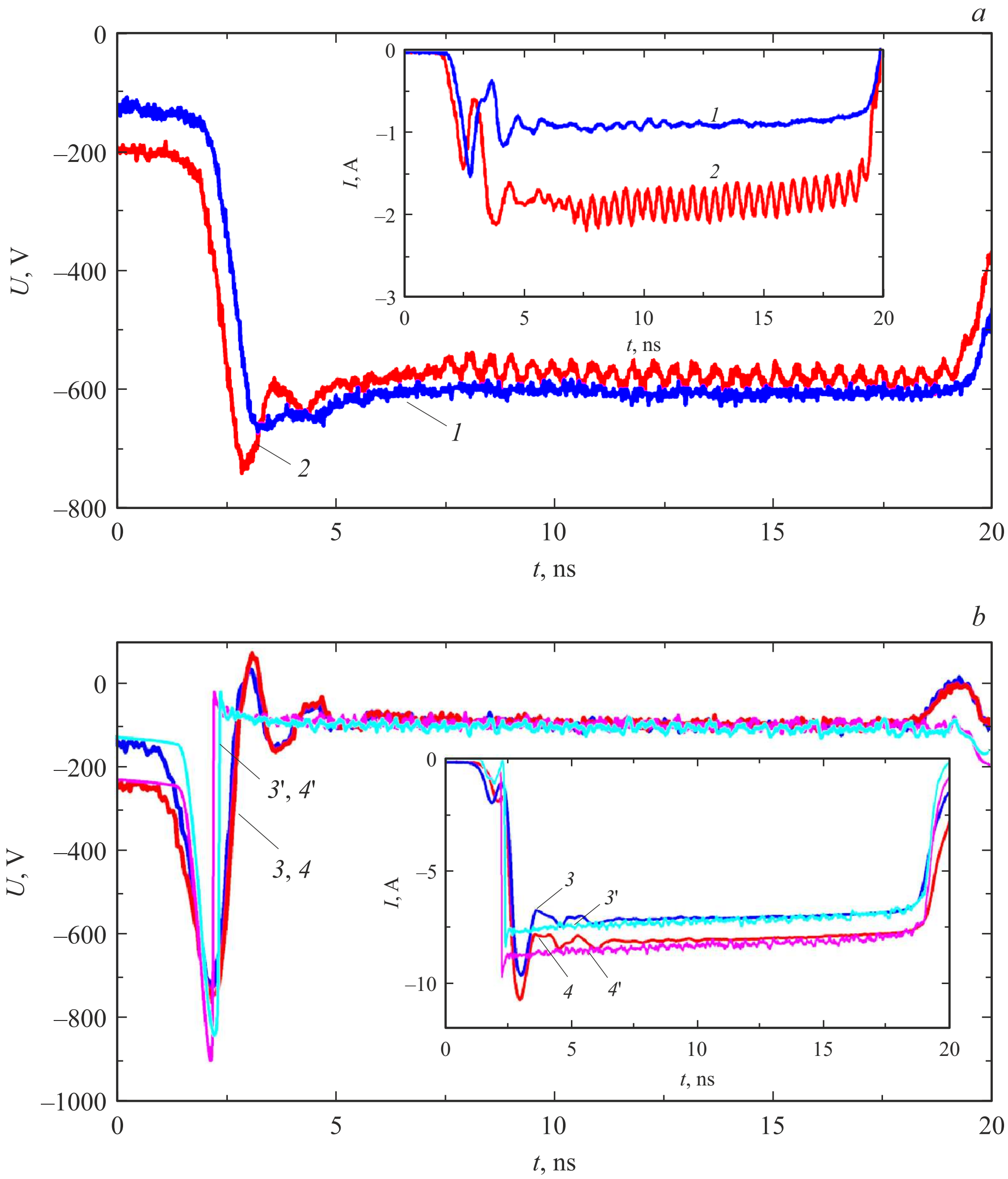

Figure 2. Voltage and current oscillograms (on inserts) in the absence of switching to highly conductive state (*a*) and during an avalanche switching of the diode to a highly conductive state (*b*) in the voltage pulsed rise mode. The amplitude values of the applied reverse pulse U_1(in V) and the initial reverse bias of the diode structure U_2 (in V) for the recording modes are, respectively: *1* — 300 and 120, *2* — 300 and 200, *3* — 400 and 120, *4* — 400 and 220. Curves *3'* and *4'* are the results of a numerical calculation corresponding to the values $U_1 = 400$ V, $U_2 = 120$ V and $U_1 = 400$ V, $U_2 = 220$ V respectively.

the diode after switching ~ 90 V is by many times less than the stationary avalanche breakdown voltage, does not change throughout the entire pulse and does not depend on the current value (Fig. 2, *b*). Thus, self-sustaining of the conducting state in the reverse-biased GaAs diode structure is observed in the experiment.

At residual voltage ~ 90 V the average value of the electric field strength in the base regions of the diode is by many times less than the impact ionization threshold (~ 300 kV/cm), but exceeds the threshold value (~ 3.5 kV/cm) of negative electron mobility, i. e. the Gann instability condition is satisfied [5–7]. It is known that bipolar Gunn domains are observed during the formation of narrow current channels, the current density in which exceeds 1 MA/cm^2 [3–7]. To check the presence of such channels, the recombination radiation was recorded with the infrared camera. When switching to quasi-stationary conducting state, narrow channels of current localization were found on the side bevel of the structure (Fig. 3). At this stage of studies, it was not possible to determine the moment of the beginning of the formation of narrow current channels and to establish a relationship between the current rise rate and the number and cross section of the channels. However, the established dimensions of the current channels

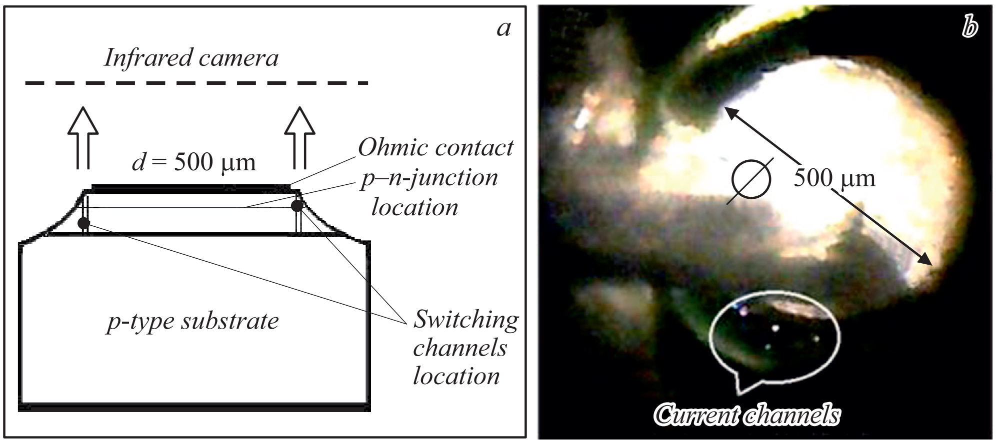

Figure 3. Scheme of the mutual arrangement of the diode structure and the infrared radiation detection chamber (a) and the spatial distribution of current channels over the area of the diode structure (b) during subnanosecond switching to the state of high conductivity (the diameter of the metallization region is $500\,\mu$m).

($d = 2-5\,\mu$m) and the density of their distribution over the area of the structure made it possible to roughly estimate the total area of the conductive region as $S < 2 \cdot 10^{-5}\,\mathrm{cm}^2$, which corresponds to the current density $J \sim 1\,\mathrm{MA/cm}^2$. Thus, the physical conditions for the formation of collapsing domains in the GaAs diode under study are close to those in optically switched GaAs structures, in which the lock-on effect was observed earlier [3–6]. Fig. 2, b shows the preliminary results of numerical calculation performed in the diffusion-drift approximation for the area of the current conductive region $S = 2 \cdot 10^{-5}\,\mathrm{cm}^2$. Agreement with experiment is good. The calculation confirms the hypothesis about the collapsing domains occurrence in the device. The results of numerical simulation will be shown in detail separately.

Thus, the effect of self-sustaining of the conducting state, initially created by dynamic avalanche breakdown under double overvoltage conditions, was found in GaAs diodes based on $p-p_0-n_0-n$ structures, which differ from $\pi-\nu-n$- and $n-\pi-\nu-n$ structures of S diodes by a low concentration of deep sites (less than $10^{16}\,\mathrm{cm}^{-3}$) [16]. A quasi-stationary conducting state is observed in $p-p_0-n_0-n$-structures in the absence of electron injection. Such electron injection from $n-\pi$-junction or metal contact occurs in S diodes based on $n-\pi-\nu-n$- and $\pi-\nu-n$-structures respectively [17].

In addition to pulsed electronics, the practical prospects of the discovered phenomenon can be associated with subterahertz radiation. It is known that collapsing domains are an effective source of such radiation, which was first experimentally discovered when switching GaAs-avalanche transistors (AT) [18]. However, the peak power values ($\ll 1\,\mathrm{mW}$) achieved in practice are significantly below the calculated values ($\sim 1\,\mathrm{mW}$) [19]. One of the possible reasons for the low radiation efficiency is related to the design features of the LT: the metallization boundaries of the emitter and base electrodes narrow the radiation output region [18,19]. Besides, the time interval of LT emission is limited to a few nanoseconds required to turn it on [18,19]. Diode structures can provide a more efficient output of radiation and, in the lock-on mode, provide a longer generation time. The high-frequency radiation of avalanche GaAs diodes in the detected lock-on mode will be the subject of our further studies.

Finally, note that the paper presents experimental evidence of long-term (up to 100 ns) self-sustaining of conducting quasi-stationary state with low residual voltage in high-voltage reverse-biased GaAs diode structure after avalanche switching in the mode of delayed impact-ionization breakdown. The discovered effect can be potentially applied to create compact sub-terahertz sources based on pulsed avalanche GaAs diodes.

Conflict of interest

The authors declare that they have no conflict of interest.

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