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Collapsing Gunn Domains as a Mechanism of Self-Supporting Conducting State in Reversely Biased High-Voltage GaAs Diodes

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Received July 28, 2022
Revised September 1, 2022
Accepted September 1, 2022

Switching of a high-voltage GaAs diode to the conducting state in the delayed impact-ionization mode is simulated and the results are compared with experimental data. It is shown that the effect of long-term (up to 100 ns) sustaining of the conducting state of the diode after switching is due to the appearance of narrow (of the order of a micrometer) ionizing Gunn domains, the so-called collapsing domains, in the electron-hole plasma. Impact ionization in collapsing domains and in the edge (cathode and anode) domains of a strong electric field (~ 300 kV/cm) maintains a high concentration of nonequilibrium carriers ($\geqslant 10^{17}\,\mathrm{cm}^{-3}$) during the entire duration of the applied reverse polarity voltage pulse.

Keywords: high-voltage GaAs diodes, impact ionization, subnanosecond switches, Gunn effect, lock-on effect.

DOI: 10.21883/TPL.2022.10.54803.19326

The effect of self-maintenance of a conducting state in GaAs structures, which is known as the lock-on effect, has been observed earlier in optically activated solid-state switches based on semi-insulating GaAs [1] and diode structures with deep centers (S-diodes) [2]. We have recently discovered this effect in experiments with reverse-biased high-voltage GaAs $p^+{-}p^0{-}n^0{-}n^+$ structures, the switching of which into a conducting state was initiated by a rapidly rising voltage pulse in the delayed impact-ionization mode [3]. Following the avalanche switching, the diodes remained in a conducting state with a low residual voltage for several tens of nanoseconds, carrying a current of around 10 A. The detection of recombination radiation allowed us to determine the size of current channels (diameter $d = 2{-}5\,\mu$m) and the density of their distribution over the structure area. The obtained data were used to estimate the current density, which was found to be $\sim 0.5\,\mathrm{MA/cm^2}$ [3].

In the present study, the physical mechanism of self-maintenance of a conducting state is established via numerical simulations. It is demonstrated that narrow ionizing Gunn domains emerge spontaneously in a GaAs diode under the conditions of experiment [3]. These bipolar domains have been discovered by Vainshtein, Yuferev, and Kostamovaara in the examination of a bipolar transistor and have been called collapsing domains (CDs) [4].

Numerical modeling was performed for a GaAs $p^+{-}p^0{-}n^0 - n^+$ structure with a stationary breakdown voltage of about 400 V and area $S{=}2\cdot 10^{-3}\,\mathrm{cm}^{-2}$ (the doping profile is presented in Fig. 1, a). In accordance with the experimental conditions [3], a quasi-rectangular voltage pulse (with a leading-edge rise time of 300 ps and a duration of about 15 ns) was applied to the studied diode and a 50 Ω series load via a coaxial line (see the inset in Fig. 1, b). A detailed description of the structure and the experimental setup was provided in [3]. The internal diode dynamics was modeled in the drift–diffusion approximation with impact ionization, optical and Auger recombination, and Shockley−Read recombination taken into account. The approximation proposed in [4] and the standard approximation [5] were used for the dependences of the drift velocity of electron carriers in GaAs and the impact ionization coefficients, respectively. The recharge kinetics of deep levels and the „photon recycling" were neglected. The grid pitch was 25 nm. The current-carrying area was set to $S_a = 2 \cdot 10^{-5}\,\mathrm{cm}^{-2}$ (following the estimate from [3]). In accordance with the well-known method for modeling a spatially inhomogeneous switching [6,7], the „active" and „passive" structure parts were regarded as two parallel diodes with cross-section areas S_a and $S - S_a$, respectively, at zero coefficients of impact ionization in the „passive" part. The propagation of a generator pulse in a coaxial line and its reflection off the diode [8] were characterized by telegraph equations in the same way as it was done recently in the simulation of avalanche switching of a silicon avalanche sharpening diode (SAS) in [7]. Self-consistent characterization of the internal diode dynamics and non-stationary wave processes in a coaxial line was implemented this way.

The simulation describes accurately the effect of self-maintenance of a conducting state: current $I(t)$ and diode voltage $U(t)$ agree with the experimental dependences (Fig. 1). The diode carries a current of about 8 A, which is set by a generator pulse and the load resistance, for more than 15 ns, preserving a constant residual voltage of approximately 100 V that is much lower than voltage U_b of stationary avalanche breakdown. The difference between calculated (~ 50 ps) and experimental (~ 300 ps)

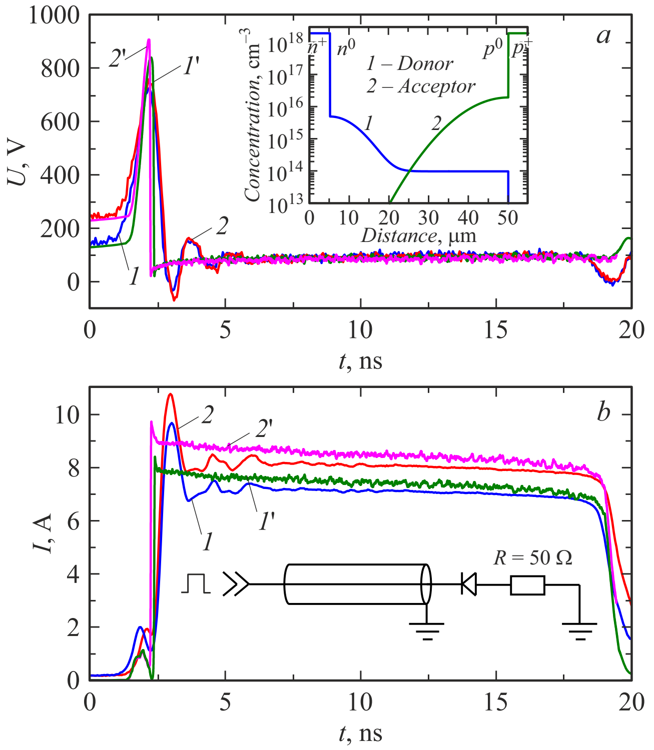

Figure 1. Voltage $U(t)$ across the studied diode (a) and current $I(t)$ (b). Doping profile of the GaAs $p^+-p^0-n^0-n^+$ structure and diagram of the experimental circuit are shown in the insets in panels a and b, respectively. Curves *1* and *2* illustrate the results of experiment [3] at an initial reverse bias of 120 and 220 V, respectively, applied to the diode structure and at a reverse pulse amplitude of 400 V; curves *1'* and *2'* represent the corresponding numerical calculations.

times of switching to a conducting state is attributable to the fact that the measurement circuit has a limited time resolution [3]. The results of simulation demonstrate that carrier concentration $n_{\max}$ immediately after avalanche switching exceeds $10^{18}\,\mathrm{cm}^{-3}$. Note that the total number of nonequilibrium carriers (NECs) in the p^0-n^0 region with thickness $W = 45\,\mu$m is $2S_aWn_{\max} \approx 2 \cdot 10^{11}$, where S_a is the area of local channels, at this concentration. The measured current (8 A [3]) has the capacity to extract the corresponding charge for approximately 4 ns (with recombination being neglected). This estimate clearly indicates the presence of a concealed mechanism of generation of nonequilibrium carriers that sustains the conducting state.

The nature of this mechanism may be clarified by analyzing the distributions of the electric field and the carrier concentration in the diode (Fig. 2). Immediately after avalanche switching, the NEC concentration starts decreasing due to optical recombination and the formation of extraction fronts [9] that reduce the plasma concentration at the edges of the weakly doped p^0-n^0 region (Fig. 2, $t = 2960$ ps). CDs form first in the p^0 region, where the plasma concentration decreases to $\sim 10^{17}\,\mathrm{cm}^{-3}$ due to the motion of the electron extraction front. A quasi-stationary cathode domain, which acts as a source of avalanche injection of electrons, emerges at the p^+-p^0 junction. The distributions of the electric field and the NEC concentration at later times, which correspond to the steady-state quasi-stationary regime, are also shown in Fig. 2. The plasma concentration averaged over the p^0-n^0 region does not vary with time in this regime, and the average electric field strength exceeds the threshold of negative differential electron mobility (~ 3.5 kV/cm). Narrow regions of a strong electric field in the p^0-n^0 region correspond to CDs moving against the field with a velocity on the order of 10^7 cm/s. Three close time points ($t = 17\,016, 17\,026, 17\,036$ ps) were chosen to be reproduced in Fig. 2 so as to illustrate the evolution of individual CDs. New CDs detach one by one from the cathode domain, move through the p^0-n^0 region, and collapse. Owing to a high field strength, CDs are ionizing. The chaotic spatiotemporal dynamics of CDs corresponds to the scenario portrayed in pioneering studies of GaAs avalanche transistors [4] and later studies into optical switches [10].

An anode domain (Fig. 3) emerges near the n^+-n^0 junction (the potential site of formation of a hole extraction front [9]). The generation of NECs in the anode domain compensates the drift extraction of plasma in the n^+-n^0 junction region. The anode domain amplitude in the studied structure with an abrupt epitaxial n^+-n^0 junction varies quasi-periodically within the 280–350 kV/cm interval (Fig. 3, a): the domain „breathes.“. The results of calculations for the structure with a graded ($\sim 5\,\mu$m) n^+-n^0 junction reveal that an anode domain emerges and vanishes quasi-periodically approximately every 100 ps; the average domain existence time is close to 10 ps (Fig. 3, b). Dependences $U(t)$, $I(t)$ and the NEC concentration in this case are the same as those for the structure with an abrupt n^+-n^0 junction; i.e., the n^+-n^0 junction sharpness has not influence on the lock-on effect. The mechanism of anode domain oscillations is likely to be related to a negative differential electron mobility and warrants further study.

Impact ionization in CDs and edge domains compensates completely the drift extraction and recombination of NECs, maintaining a constant average carrier concentration. Apparently, the time of self-maintenance of a conducting state is limited only by the rate of Joule self-heating of a conducting channel, which is estimated at 5 K/ns at a current density of $0.5\,\mathrm{MA/cm}^2$. The results of our calculations indicate that the dependence of current $I(t)$ and voltage $U(t)$ on area S_a at $K = S/S_a$ varying within an interval of 50–500 is very weak. At the same time, the quasi-stationary plasma concentration increases linearly with K (i.e., current density) and exceeds $10^{18}\,\mathrm{cm}^{-3}$ at $K = 500$.

It is important to note that CDs in the already studied GaAs $n^+-p-n^0-n^+$ structures of high-speed avalanche transistors [4] and $n-\pi-\nu-n$ structures of S-diodes with deep levels [2,10–12] emerge under the conditions of electron injection from an n^+ emitter, while the injection of holes is avalanche in nature. The injection of both types of carriers in the lock-on mode is effected by

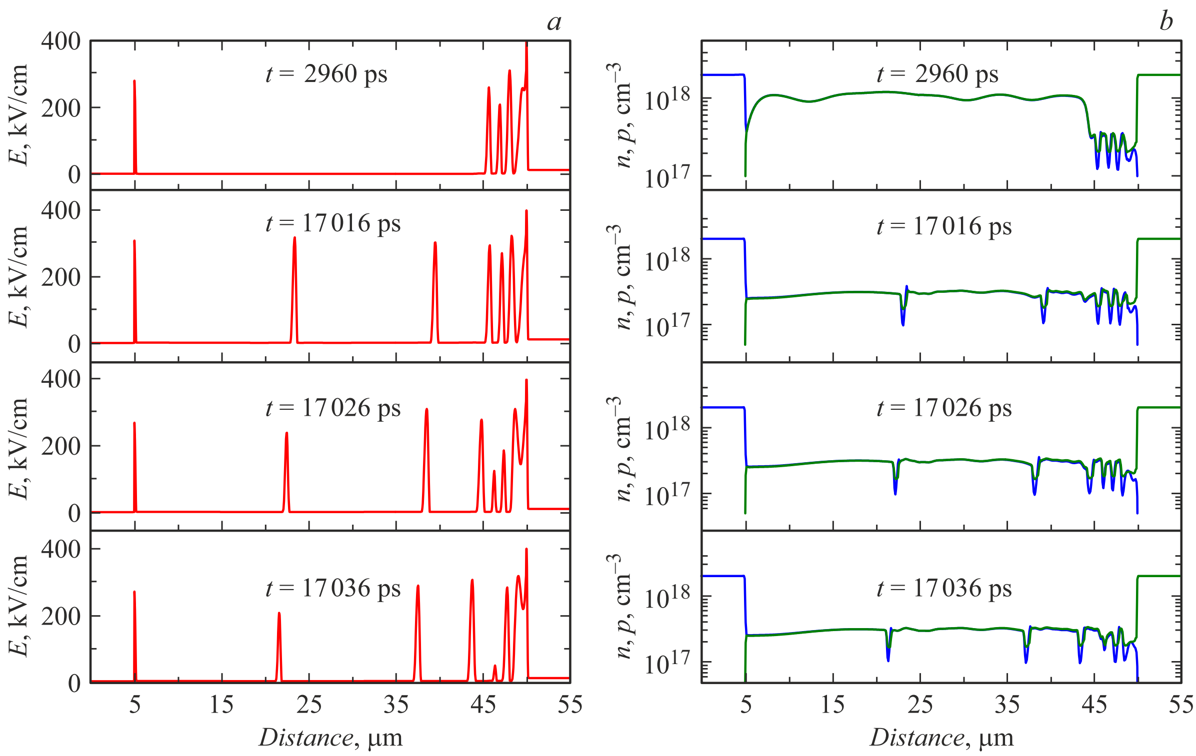

Figure 2. Spatial distributions of the electric field (*a*) and the carrier concentration (*b*) in the structure immediately after switching ($t = 2960$ ps) and in the steady-state regime ($t = 17\,016$, $17\,026$, $17\,036$ ps).

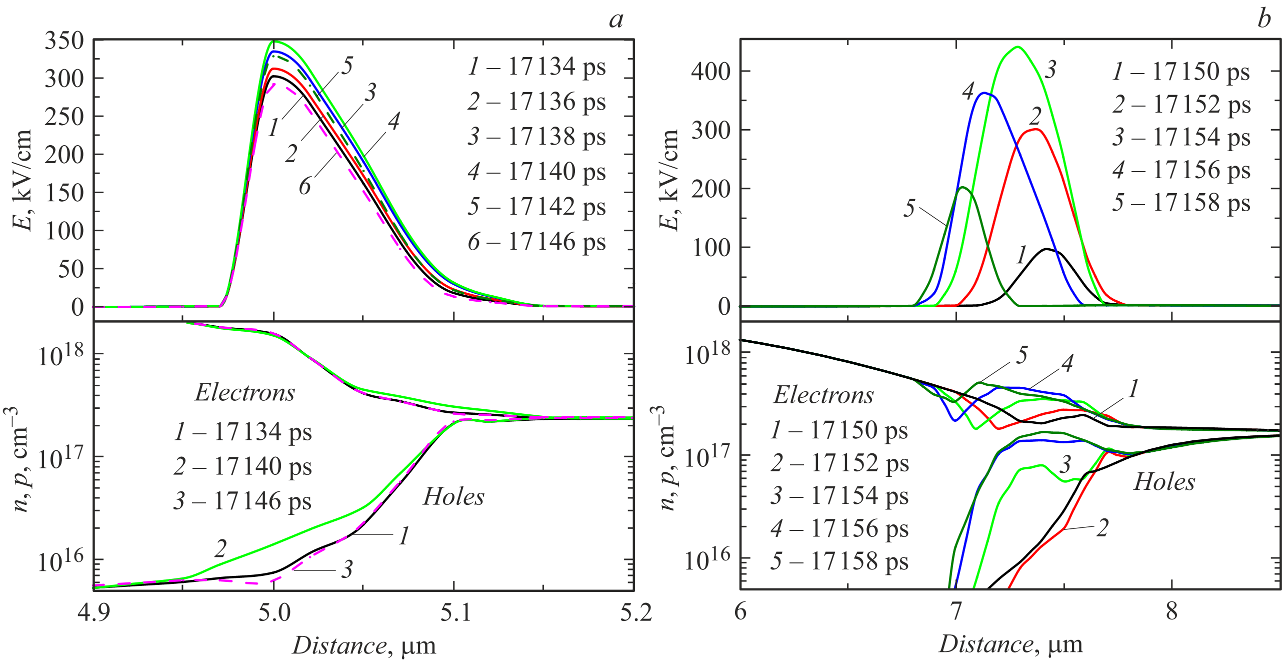

Figure 3. *a* — Spatial distributions of the electric field and the carrier concentration under small-amplitude oscillations of an anode domain in the structure with an abrupt $n^+{-}n^0$ junction; *b* — emergence and vanishing of an anode domain in the structure with a graded $n^+{-}n^0$ junction (diffusion $\sim 5\,\mu$m).

impact ionization only in the $p^+{-}p^0{-}n^0{-}n^+$ reverse-biased structure examined in the present study. It is evident that a predominant generation of holes in the $n^+{-}n^0$ junction region and electrons in the $p^+{-}p^0$ junction region is needed to maintain a constant concentration of the electron–hole plasma. This is achieved due to the fact that electrons are generated in the cathode domain and CDs, while holes are generated in the anode domain and as a result of isolated CD transits through the entire p^0-n^0 region. A high NEC concentration at the initial stage ($> 10^{18}\,\mathrm{cm}^{-3}$) is established by dynamic avalanche breakdown under two-fold overvoltage [3].

Thus, the experimentally observed effect of self-maintenance of a conducting state in a reverse-biased GaAs diode [3] is attributable to impact ionization in collapsing Gunn domains and avalanche injection from cathode and anode domains. Collapsing domains emerge spontaneously in electron–hole plasma due to a negative differential mobility of electrons in GaAs and are characterized by a high field strength ($\sim 300\,\mathrm{kV/cm}$), small sizes ($\sim 1\,\mu\mathrm{m}$), intense impact ionization, and irregular chaotic spatiotemporal dynamics. The effect of self-maintenance of a conducting state is closely related to the lock-on effect in optically activated switches [1], which has also been attributed to collapsing domains [10], and the effect of emergence of a conducting state in S-diodes with deep levels [11–13].

Conflict of interest

The authors declare that they have no conflict of interest.

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