ISSN 1063-7850, Technical Physics Letters, 2018, Vol. 44, No. 2, pp. 160–163. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © V.I. Brylevskiy, I.A. Smirnova, N.I. Podolska, Yu.A. Zharova, P.B. Rodin, I.V. Grekhov, 2018, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2018, Vol. 44, No. 4, pp. 66–73.

Experimental Observation of Delayed Impact-Ionization Avalanche Breakdown in Semiconductor Structures without *p–n* Junctions

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Received October 18, 2017

Abstract—We have experimentally studied the dynamics of impact-ionization switching in semiconductor structures without *p–n* junctions when subnanosecond high-voltage pulses are applied. Silicon $n^+–n–n^+$ type structures and volume ZnSe samples with planar ohmic contacts exhibit reversible avalanche switching to the conducting state within about 200 ps, which resembles the well-known phenomenon of delayed avalanche breakdown in reverse-biased $p^+–n–n^+$ diode structures. Experimental data are compared to the results of numerical simulations.

DOI: 10.1134/S1063785018020177

High-voltage pulses with steep fronts are used to initiate avalanche breakdown and create conducting electron–hole plasma in systems of two types: semiconductor diode structures with planar contacts [1–3] and semiconductor crystals with "point" contacts [4]. Semiconductor diode structures switched by short high-voltage pulses are also called "pulse sharpeners." The switching of a pulse-sharpening diode takes less than 100ps and starts at a voltage significantly exceeding that of steady-state breakdown [1, 5]. This phenomenon, known as the "delayed impact-ionization avalanche breakdown of semiconductor diode structures" [1], was originally discovered in silicon-based and arsenide–gallium structures [6, 7] and used in pulsed power electronics [2, 3, 8–10]. The transverse size of a pulse-sharpening diode significantly exceeds the distance between planar contacts, so that the electric field that provides ionization avalanche in the *n*-base is quasi-uniform over the area of the structure and the avalanche generation of carriers can occur (at least in principle) over the entire volume of the structure. In contrast, a high-voltage pulse with a steep front in semiconductors with point contacts initiates the formation and propagation of streamers [4], that is, the generation of dense electron–hole plasma within narrow filamentary regions. Previous investigations [4] were aimed at creating impact-ionization lasers.

The present work was devoted to the first experimental investigation of impact-ionization avalanche breakdown in semiconductor structures without *p–n* junctions. The experiments were performed with silicon structures of $n^+–n–n^+$ type and volume zinc selenide (ZnSe) samples with planar ohmic contacts. It was established that a high-voltage pulse with a steep front in these systems initiates ultrafast (within about 200 ps) switching to the conducting state. A comparison of experimental data to the results of numerical simulations leads to the conclusion that nonequilibrium electron–hole plasma is generated in the most part structure volume.

Silicon $n^+–n–n^+$ diode structures were manufactured from *n*-type silicon with dopant concentration $N = 1.7 \times 10^{14}$ cm^{-3} by the same diffusion technology as that used previously in obtaining $p^+–n–n^+$ structures for pulse-sharpening diodes [5] with similar dimensions: diameter of about 1 mm and total thickness of about 200 μm. The thickness of n^+ layers formed using phosphorus diffusion was ~10 μm. In addition, a series of $n^+–n–n^+$ diode structures were manufactured with ~60-μm-thick n^+ layers and 80-μm-thick *n* layers. Zinc selenide samples were manufactured from ZnSe(111) plates with a thickness of 450 μm and 0.5–1-μm-thick indium ohmic contact layers [11] formed by two-stage deposition with intermediate annealing. The samples were cut out in the form of disks with a diameter of 1 mm.

The experimental setup comprised the generator of bell shaped pulses with nano- and subnanosecond rise time, the resistive coupler, two measuring circuits with high-voltage attenuators, and a 20-GHz stroboscopic oscilloscope. The resistive coupler also played the role of a sample holder, where the structure was

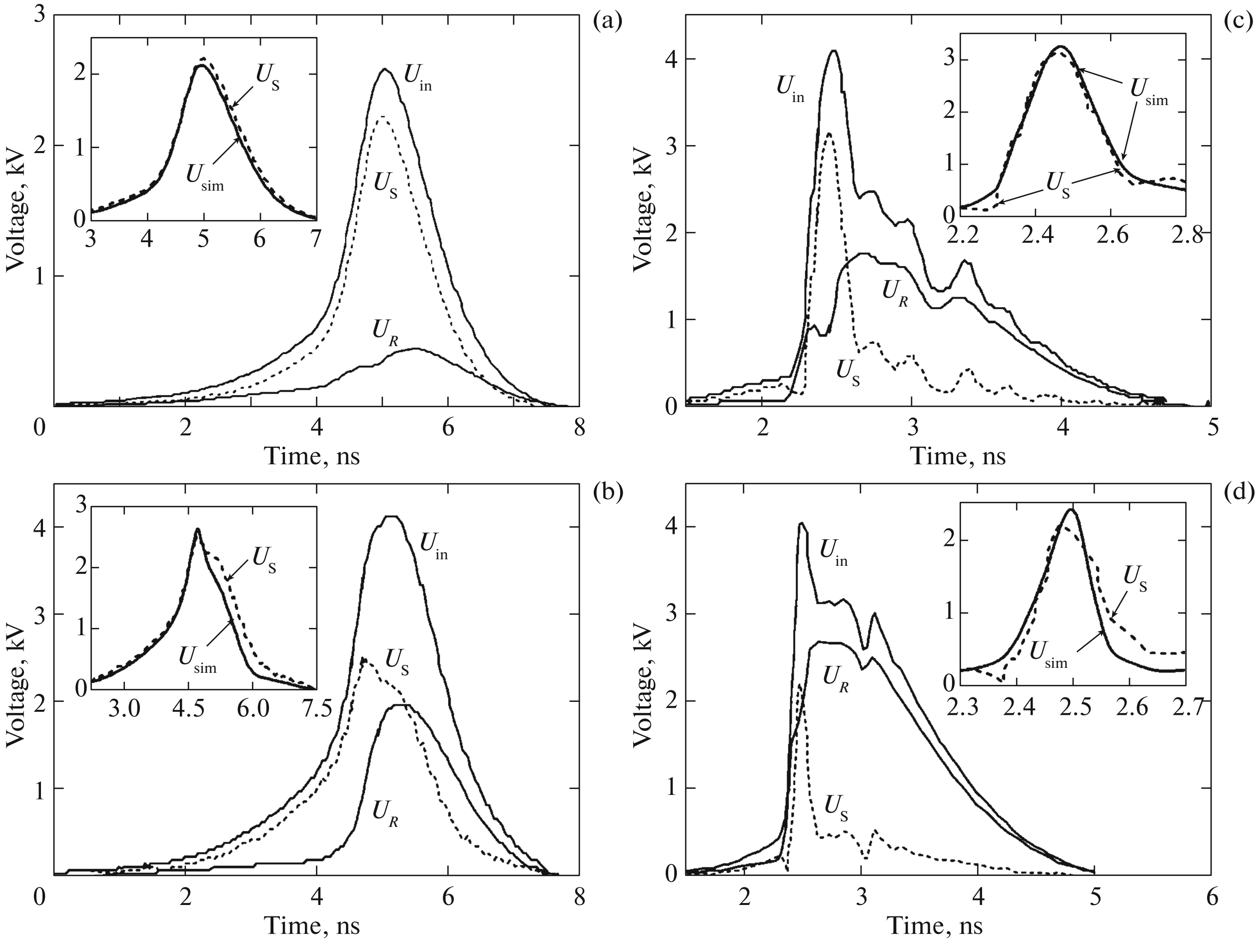

Fig. 1. Waveforms of voltages U_S on the $n^+–n–n^+$ structure, U_R on the series load resistance $R = 50$ Ω, and total U_{in} on the structure with the series load resistance for the samples with (a–c) 10-180-10-μm layer thicknesses (at various applied pulses) and (d) 60-80-60-μm layer thicknesses, respectively. The insets compare the experimental U_S (dashed line) waveforms to the simulated curves U_{sim} (solid line).

placed inside a gap of the central wire of a coaxial line. The experimental setup provided simultaneous and independent measurements of voltage U_R on a series load resistance $R = 50$ Ω and total voltage U_{in} on a sample structure with the series load resistance (i.e., measurements of sample current $I_S = U_R/R$ and sample voltage $U_S = U_{in} - U_R$) at a temporal resolution of no worse than 50 ps. The setup has been described in more detail elsewhere [5].

Figure 1 presents typical results of measurements, showing the waveforms of voltage U_R on the series load resistance $R = 50$ Ω (i.e., the sample current is $I_S = U_R/R$) and voltage U_S on the sample structure for various amplitudes and shapes of applied pulses. Let us first consider the case (Fig. 1a) of a bell-shaped high-voltage pulse with full width at half-maximum (FWHM) ~ 1.5 ns and amplitude 2.6 kV, which ensured successful ultrafast avalanche switching of the reverse-biased diode structures [5]. In the case of $n^+–n–n^+$ structures, U_S waveform closely follows the applied voltage U_{in} (Fig. 1a).

The response of the sample structure somewhat changes as the applied pulse amplitude is increased to 4.1 kV at the same rise time (Fig. 1b). In this case, U_S curve ceases to follow U_{in} and starts decreasing at $t = 4.76$ ns (Fig. 1b), which is indicative of a significant increase in the concentration of free carriers due to impact ionization. This also leads to the current simultaneous growth in the series load resistance, but ultrafast switching of the diode to the conducting state does not take place.

A qualitative change in the response dynamics is observed upon a sharp decrease in the rise time (increase in steepness) of the applied voltage pulse (Fig. 1c), which was achieved with the aid of silicon-based sharpening diodes. In this case, ultrafast switching of the diode begins at $t = 2.46$ ns and U_S drops from 3.17 to ~0.63 kV within about 200 ps, while the current increases up to I_S ~ 35 A. After switching, the

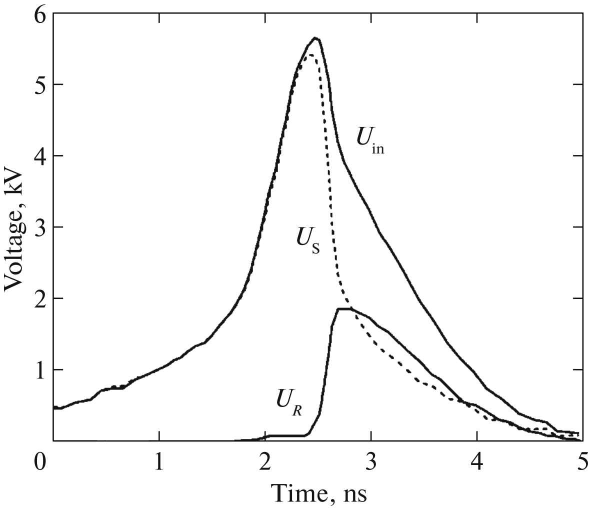

Fig. 2. Waveforms of voltages: U_{in} on a ZnSe structure with serially connected 50-Ω load, U_R on the 50-Ω load, and U_S on the ZnSe structure.

U_S value varies but slightly over the applied voltage pulse. Analogous ultrafast switching was observed in n^+–n–n^+ structures with layer thicknesses about 60–80–60 μm, respectively (Fig. 1d). At $t = 2.48$ ns, the voltage drops from $U_S = 2.22$ to ~0.45 kV within about 155 ps and the current increases to greater than 50 A. Thus, we have experimentally discovered ultrafast avalanche switching of the silicon n^+–n–n^+ structures to the conducting state.

To achieve ultrafast switching in ZnSe-based structures, the pulse amplitude was increased to 5.7 kV at FWHM = 1.2 ns (Fig. 2). The switching of this system is accompanied by a rapid drop of U_S and growth of the current I_S in the series load resistance within ~200 ps. The applied pulse amplitude was close to the maximum possible values for the available generator of the experimental setup, which hindered more detailed study of the switching process.

All samples were studied at a pulse-repetition frequency of 300 Hz. After operation in the continuous regime for several minutes, no changes in the pulse shape and/or electrical parameters of the structures were observed. This circumstance is evidence of the fully reversible character of avalanche breakdown in the studied diode structures.

The insets in Fig. 1 compare the experimental data to the simulations carried out in the one-dimensional approach using the SILVACO software package [12]. Simulations were obtained for the n^+–n–n^+ structures with the area $S = 1.2$ mm^2 and layer thicknesses 10–160–10 and 55–90–55 μm, respectively. These parameters were treated as fitting parameters and varied within an interval based on the technological tolerance known for manufacturing real structures. Good agreement between the one-dimensional simulations and experiments indicates that the impact-ionization processes occur quasi-homogeneously over the structure area. In addition, the simulations show that nonequilibrium carriers generated due to impact ionization are also quasi-homogeneously distributed in the direction of current passage. According to the simulations the carriers concentration for experiments illustrated in Fig. 1c and Fig. 1d, is of the order of 10^{15} cm^{-3}, being equal for electrons and holes. Thus, the electron–hole plasma generation during the impact-ionization avalanche switching is evidently homogeneous in the entire volume of n^+–n–n^+ structure.

For these simulations, the coefficients of the impact ionization were described using the of model [13] instead of that of [14] that was used previously [15]. It turned out that some differences between approximations [13] and [14] in the region of electric fields from 10^5 to 3×10^5 V/cm led to the qualitatively different results. In the last model [14], the impact ionization begins at a greater applied voltage, which does not admit agreement between experiment and calculations. The influence of the chosen approximation for the impact ionization coefficients on the switching process will be studied later.

As a result, we have experimentally demonstrated the possibility of the ultrafast avalanche impact-ionization switching to the conducting state in semiconductor structures without p–n junctions while the subnanosecond high-voltage pulse is applied. Comparison of the obtained experimental data to the simulations leads to the conclusion that the avalanche impact ionization initiated by high-voltage pulses with steep fronts in n^+–n–n^+ silicon structures leads to the quasi-homogeneous generation of electron–hole plasma in the entire volume of a structure.

Acknowledgments. This study was supported in part by the Russian Science Foundation, project no. 14-29-00094.

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Translated by P. Pozdeev