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Subnanosecond Impact-Ionization Switching of Silicon Structures without *p–n* Junctions

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Abstract—It is shown that an application of a fast-rising high-voltage pulse to an n^+–n–n^+ silicon structure leads to subnanosecond avalanche breakdown, generation of electron–hole plasma throughout the entire structure, and structure switching to the conducting state in a time of about 100 ps. The predicted effect is similar to the delayed avalanche breakdown of reverse-biased p^+–n–n^+ diode structures; however, it is implemented in a structure without *p–n* junctions.

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An application of a voltage pulse with a high (>1 kV/ns) rise rate to a high-voltage diode structure in the reverse direction is known to lead to a delayed impact-ionization breakdown [1–3]. The key features of this physical effect are as follows: (i) breakdown at a voltage exceeding the stationary breakdown voltage by a factor of about 2; (ii) transition of the structure to the conducting state for a time less than 100 ps, which is an order of magnitude shorter than the drift time of carriers with saturated velocity $v_s \approx 10^7$ cm/s through the diode base (~1 ns for a characteristic base thickness of ~100 μm); and (iii) a deterministic character, which manifests itself, in particular, in a negligible (<10 ps) jitter [1–3]. The delayed impact-ionization breakdown is the fastest nonoptical method for generating large amounts of electron–hole plasma in semiconductors. Currently, this effect is mainly used in pulsed electronics [2, 4, 5]; however, impact-ionization lasers also have a great potential [6]. Optical applications require passing from silicon to direct-gap semiconductors, among which ZnSe and CdS are promising materials. [6]. Since the technology of *p–n* junction formation is absent for both these materials, it is important to consider the fundamental possibility of applying impact ionization for controlled generation of electron–hole plasma in semiconductor structures without *p–n* junctions (including bulk semiconductor samples with planar ohmic contacts). The character of dynamic avalanche breakdown of these samples at a high rise rate of applied voltage is also of general interest for semiconductor physics.

In this Letter, we report the results of a numerical simulation of the physical processes occurring at a fast rise of applied voltage $V(t)$ by an example of n^+–n–n^+ silicon structure. It is shown that an ultrafast (for about 100–200 ps) avalanche transition to the conducting state, which is somewhat similar to the delayed avalanche breakdown of diode structure, occurs in a structure without a *p–n* junction if the rise rate dV/dt and the high pulse amplitude are sufficiently high.

We consider an n^+–n–n^+ Si structure connected in series with load R = 50 Ω. The structure area is S = 0.01 cm^2, and the thickness of the *n* region is W = 100 μm; the doping of the *n* region ($N_d = 1.7 \times 10^{14}$ cm^{-3}) corresponds to silicon with a resistivity of 30 Ω cm. The n^+ layers (adjacent to ohmic contacts) have a Gaussian doping profile with the maximum donor concentration of 10^{20} cm^{-3} and a width of 7 μm. The parameters of the n^+–n^+ structure were chosen to be similar to those of the p^+–n–n^+ diode structure investigated in recent experiments [7]; that structure had the same area, thickness, and doping level of the *n* base. Voltage pulse $V(t)$ applied to the structure is approximated by piecewise-linear dependence $V(t) = At$ at $t < V_m/A$ ($V(t) = V_m$ at $t > V_m/A$, where A is the voltage-rise rate). The dynamics of electrons and holes in the structure was modeled in the one-dimensional approximation within the drift-diffusion model by solving the Poisson and continuity equations jointly with the Kirchhoff equation for the external circuit.

Figure 1 shows voltage $U(t)$ across the n^+–n–n^+ structure and applied voltages $V(t)$ at different voltage-rise rates A and pulse amplitude U_m= 7 kV. At the initial stage, the duration of which decreases with an increase in A, voltage across the structure $U(t)$ increases at the same rate as applied voltage $V(t)$ (Fig. 1) and the load

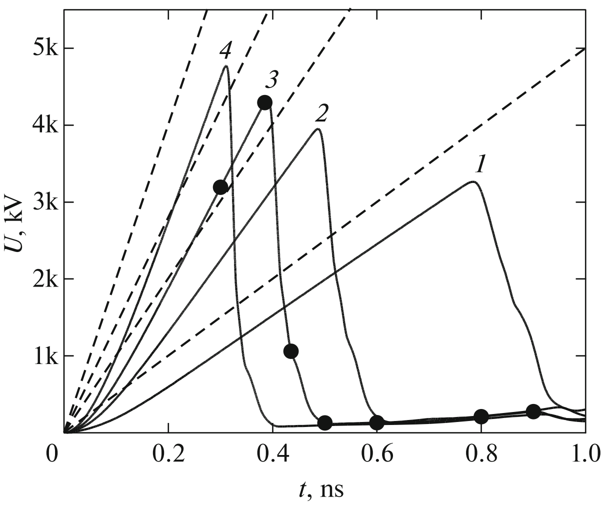

Fig. 1. Voltage across the n^+–n–n^+ structure $U(t)$ (solid lines) and applied voltage $V(t)$ (dashed lines). Curves *1*, *2*, *3*, and *4* correspond to the rates of rise of the applied voltage A = 5, 10, 14, and 20 kV/ns, respectively. Voltage $V(t)$ grows to the value U_m = 7 kV and then remains constant. The circles on curve *3* indicate instants t = 300, 385, 435, 500, 600, 800, and 900 ps for which the field and carrier distributions in the structure are shown in Fig. 3.

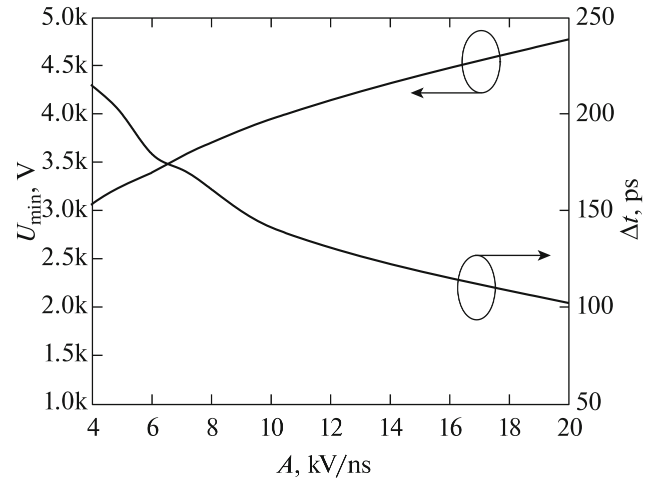

Fig. 2. Dependences of minimum amplitude U_{min} of pulse $V(t)$ that is necessary for the switching and switching time Δt on the rise rate of applied voltage A.

current $I(t) = U_R(t)/R$ is the bias current in the n^+–n–n^+ structure. This current increases from 10 to 30 A with an increase in A from 5 to 20 kV/ns. Then the avalanche breakdown begins, and the structure passes to the conducting state. With an increase in A from 5 to 20 kV/ns, the switching time is reduced from 200 to 100 ps (Fig. 2). Thus, the avalanche switching results in the pulse sharpening effect: pulse $U_R(t)$ formed in the load has a rise rate several times higher than that of the applied pulse. Residual voltage U_{res} equals several hundred volts and increases with a decrease in A. Due to the relation $U_{res} \ll U_m$, the current after switching can be determined with a good accuracy as $I = U_m/R \approx$ 140 A.

Figure 3 shows the spatial distributions of electric field $E(z, t)$ and concentrations of electrons $n(z, t)$ and holes $p(z, t)$ for A = 14 kV/ns at different instants. The initial electron concentration is determined by the n-base doping level, and the initial concentration of equilibrium holes is insignificant. An increase in the electric field in the structure in the initial stage is due to the formation of two space charge layers. A narrow (several micrometers thick) layer of positive charge is formed in the heavily doped left n^+ layer due to the extraction of main carriers (Fig. 3). The negative-charge layer on the right-hand side of the n base is formed by the injection of electrons into the base from the right n^+ layer. The formation of this layer is clearly illustrated by the profile $n(z, t)$ corresponding to the instant t = 300 ps at which the avalanche carrier multiplication is still insignificant (Fig. 3).

The negatively charged layer has a thickness of ~10 μm. A decrease in A increases this value, along with the switching-delay time. The electric-field spatial nonuniformity on the right-hand side of the n base is related specifically to the electron space charge in this layer. Significant impact ionization of electrons begins at an electric-field strength of more than 200 kV/cm and clearly manifests itself in an increase in the hole concentration (t = 385 ps). The field strength reaches ~500 kV/cm (t = 385 ps) by the onset of rapid switching. The subsequent avalanche switching develops almost uniformly throughout the entire n region. For a time of ~100 ps, the electron and hole concentrations become equal, reaching a value of 10^{16} cm^{-3}, and the electric-field strength in the larger part drops to less than 10 kV/cm (t = 500 ps). Thus, one can say that there is generation of conducting electron–hole plasma. A narrow (~10 μm) region of strong field is retained near the n^+–n boundary after switching (t = 500–900 ps); however, the impact ionization in this region does not affect the structure conductivity.

Simulations show that, while the voltage rises, spatial nonuniformity of the field $E(z)$ increases with a decrease in A. The reason is that the switching delay increases with a decrease in A; therefore, the electrons injected from the right n^+ layer penetrate more deeply into the n layer and distort more strongly the field distribution. Thus, the trapezoidal "prebreakdown" profile $E(z)$ (see, for example, Fig. 2, t = 385 ps) is gradually transformed into an almost triangular one with a decrease in A. In turn, this fact leads to a decrease in the switching voltage and less efficient ionization. As a consequence, with a decrease in A, the concentrations of nonequilibrium electrons and holes after switching decrease (to ~5 × 10^{15} cm^{-3} at A = 5 kV/ns) and the electric-field strength increases. Note that current

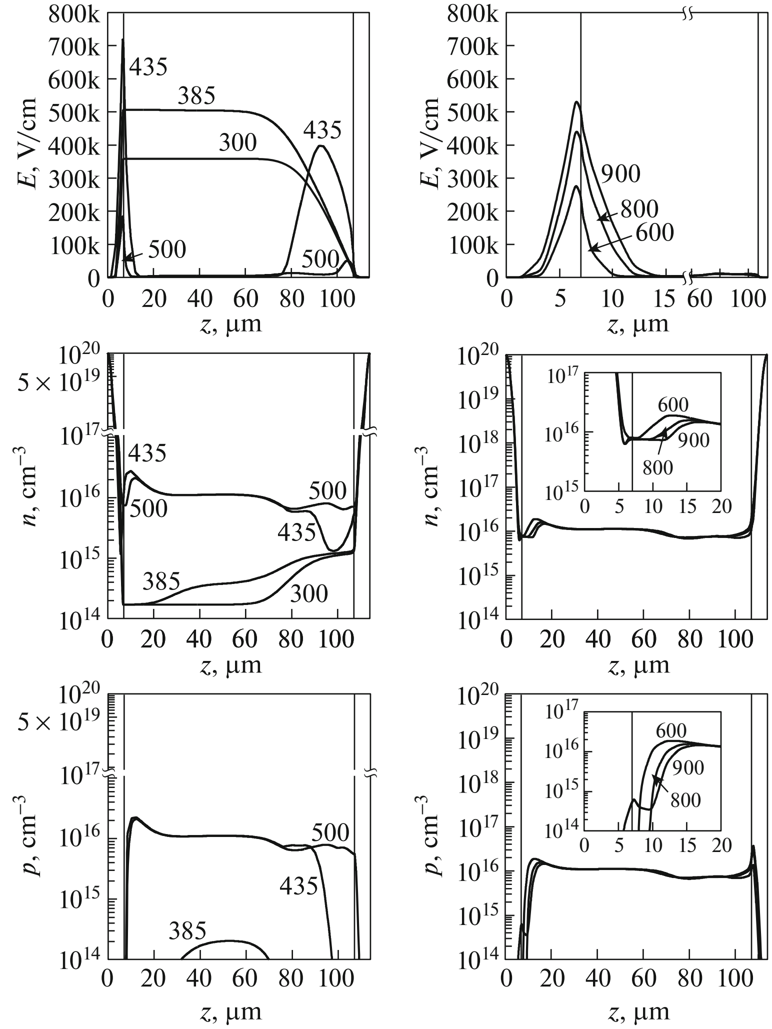

Fig. 3. Spatial distributions of the electric field and electron and hole concentrations at different instants for A = 14 kV/ns. The instants (in picoseconds) to which the curves correspond are indicated.

density $j = U_m/(RS)$ = 14 kA/cm^2, which is unambiguously specified by the pulse parameters, load value R, and cross-sectional area, requires the concentration of nonequilibrium carriers in the structure to be no less than $n = p = j/qv_s = 5 \times 10^{15}$ cm^{-3}. When the nonequilibrium concentration drops below this value, the metastable conducting state after switching becomes impossible. The minimum rate of voltage rise A, which is necessary for successful structure switching, is determined by the described above effects and equals to A = 4–5 kV/ns for the chosen structural parameters. This value is several times higher than that for the comparable p^+–n–n^+ diode structure.

The minimum pulse amplitude, which is necessary for switching the n^+–n–n^+ structure, can be estimated as voltage $V(t)$ corresponding to the switching onset. This value equals 3–5 kV and increases with an increase in A (Fig. 2). The comparable p^+–n–n^+ diode structure has a lower switching voltage: ~2 kV [7].

Let us consider the major differences between the above-described ultrafast avalanche switching of the n^+–n–n^+ structure and the known effect of delayed impact-ionization breakdown of diode p^+–n–n^+ structures. First, in the diode structure, the process of fast switching begins in a completely depleted reverse-biased structure due to the multiplication of few initial carriers, the source of which was not unambiguously established [8]. On the contrary, in the n^+–n–n^+ structure, there is initially a considerable concentration of major carriers. Second, the electric field in the depleted p^+–n–n^+ structure is significantly inhomogeneous and has a maximum near the p–n junction. This fact may cause a wave-type breakdown, which originates in the strong-field region and then moves through the n base as an impact-ionization wave [2, 3]. On the contrary, the electric-field distribution in the n^+–n–n^+ structure during the voltage rise is significantly spatially nonuniform and the avalanche breakdown does not have a wave character. According to our simulations, this is not a hindrance for achieving a subnanosecond switching time. Third, the ultrafast avalanche switching of the n^+–n–n^+ structure requires a much higher amplitude and rise rate of the voltage pulse than the corresponding parameters for a comparable diode structure.

Thus, we demonstrated the fundamental possibility of subnanosecond impact-ionization generation of large (~10^{-3} cm^3) amounts of electron–hole plasma in semiconductor structures without a *p*–*n* junction using a rapidly rising kilovolt voltage pulse. The switching to the conducting state takes 100–200 ps and is accompanied by sharpening of the applied pulse.

The simulation was performed using the SILVACO software [9], and the model [10] was chosen for the impact-ionization coefficient. We are planning to continue this study to determine the influence of the approximation for the impact-ionization coefficients on the switching characteristics.

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