Quasi-streamer mode of delayed avalanche breakdown initiated by technological imperfections

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Abstract. Numerical simulations of spatially non-uniform picosecond-range switching of high-voltage silicon diodes with technological imperfections have been performed. It is shown that spatially inhomogeneous distribution of process-induced deep-level centers that trigger ionization process easily provoke current localization. A fluctuation of concentration with a relative amplitude of 10% leads to almost complete localization of current. The switching time sharply decreases (from ~100 ps to ~10 ps) with the increase of the amplitude of the inhomogeneity and the decrease of its size.

1. Introduction

Propagation of the superfast impact ionization TRAPATT-like front represents one of the possible mechanisms of the delayed avalanche breakdown in high-voltage p^+–n–n^+ structures [1]. This phenomenon underlies the operation of picosecond range pulse power electronics semiconductor devices [2] and manifests itself in superfast switching of a diode structure from a blocking to a conducting state on condition of a rapid growth of the reverse voltage applied to the structure. A plane TRAPATT-like front is unstable with respect to small perturbations [1], which makes the spatio-temporal dynamics of the switching very sensitive to small technological inhomogeneities of the diode structure. The subsequent current localization can play a constructive role reducing the switching time [3]. The aim of this study is to investigate the influence of the technological inhomogeneity responsible for the generation of initial carriers that trigger avalanche ionization process in overvoltaged diodes on the switching dynamics.

2. The model

We consider a reversely biased p^+–n–n^+ structure connected in series with a load $R = 50\ \Omega$. The circuit and the structure are schematically presented in figure 1. A steep voltage ramp must be applied to the diode to achieve the delayed avalanche breakdown mode [1]. In our simulations the external voltage is approximated as a linear voltage ramp $V(t) = V_0 + At$, where $V_0 = 1$ kV is the initial bias and $A = 2$ kV/ns. The parameters of the structure are taken as follows: the diameter of the structure $d = 1$ mm, n-base length $W = 100$ μm, base doping level $N_d = 10^{14}$ cm^{-3}. These structure and circuit parameters roughly correspond to those in recent experiments [4].

Numerical simulations are performed under an assumption that initial free carriers are generated by field-enhanced thermionic electron emission from deep electron traps (thermal defects) as it has been suggested in [5]. Amongst all possible technological inhomogeneities, the inhomogeneity of concentration N_{PI} of these deep-level centers over the cross section of the device is expected to be the most important because these centers influence the very beginning of the front propagation process.
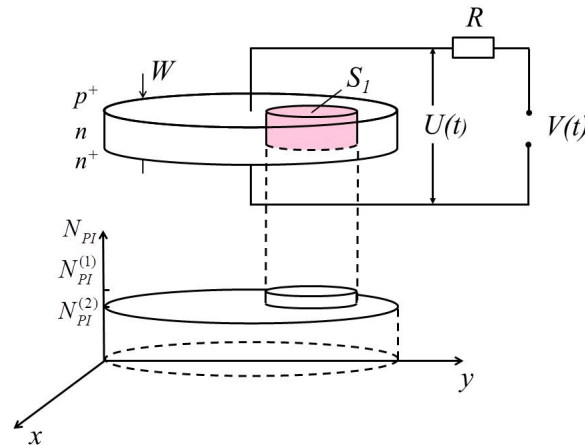

Figure 1. Sketches of p^+–n–n^+ structure with the external circuit and thermal defects distribution over the cross section of the structure.

Taking into account that the structure width W is much smaller than the diameter, we neglect possible inhomogeneity of the thermal defects concentration N_{PI} along the cathode-anode direction and model the spatial inhomogeneity of N_{PI} by dividing the structure cross section into two parts. These are a part with higher concentration $N_{PI}^{(1)} = N_{PI}^{(0)}(1+\delta)$ and area S_1, and a part with lower concentration $N_{PI}^{(2)} = N_{PI}^{(0)}(1-\delta)$ and area S_2. In the following we refer to these parts as to the "active" part and the "passive" part, respectively. In the framework of the long-wavelength approximation, it is equivalent to connecting two diodes with these parameters in parallel. The long-wavelength approximation is valid as far as $\sqrt{S_1} > W$, so S_1 cannot be chosen arbitrary small. The average value of the deep centers concentration is chosen as $N_{PI}^{(0)} = 10^{12}\,\text{cm}^{-3}$. Parameter δ is the
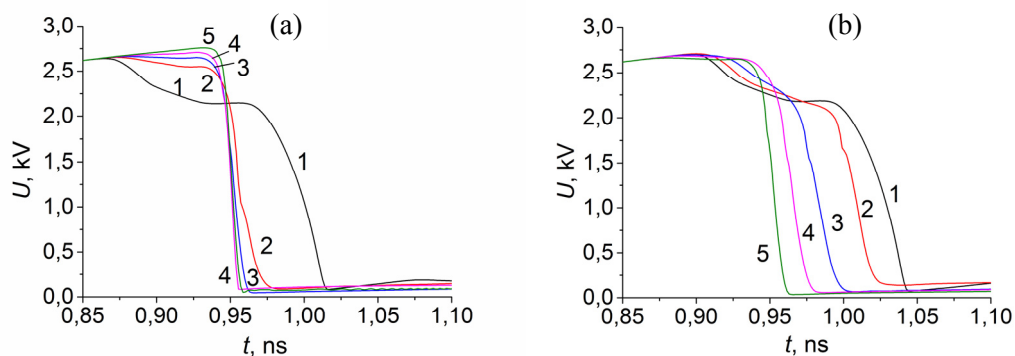

Figure 2. Voltage across the structure $U(t)$ versus time at $K = 1, 4, 8, 16, 64$ (curves 1–5, respectively) and fixed $\delta = 0.5$ (a); and at $\delta = 0, 0.1, 0.2, 0.3, 0.5$ (curves 1–5, respectively) and fixed $K = 8$ (b).

relative amplitude of the inhomogeneity. Another important parameter is the inverse relative size $K = (S_1 + S_2)/S_1$ of the inhomogeneity.

3. Results

The dependences of the voltage across the device $U(t)$ on parameters K and δ are shown in figure 2. At $t < 0.85$ ns the voltage increases linearly, following the external voltage applied to the structure and the load. It is readily seen that the switching process becomes much faster with the increase of either K or δ.

   Numerical simulations do not agree with experiment as far as we assume that switching is homogeneous. Namely, the non-monotonic voltage waveforms $U(t)$ predicted by numerical simulations at low values of K and δ (e.g. curve 1 for the uniform switching in figure 2) correspond to slow switching process and are not observed in experiments. In contrast, for higher values of K and δ the results of numerical simulations and experiments [4] are in good agreement (e.g. curves 3,4,5 in figure 1). It is an argument in favour of the inhomogeneity of the switching. The switching time rapidly decreases with the increase of K and δ, which is shown in figure 3(a). This dependence saturates when the relative amplitude of the fluctuation δ reaches ~0.3 and K reaches ~6. Localization of current in the "active" part of area S_1 is even more sensitive to the value of δ: inhomogeneities with $\delta > 0.1$ lead to almost complete current localization irrespective of their size K (figure 3(b)). In figure 3(b) the current through the "active" part S_1 at the moment when the external voltage reaches 4 kV is shown. Note that the total current through the structure is mostly determined by the load $R = 50$ Ω and equals ~80 A. It implies the winner-takes-it-all character of the competition between the "active" part of the structure, where the ionizing front has better starting conditions, and the lagging ionizing front in the "passive" part.
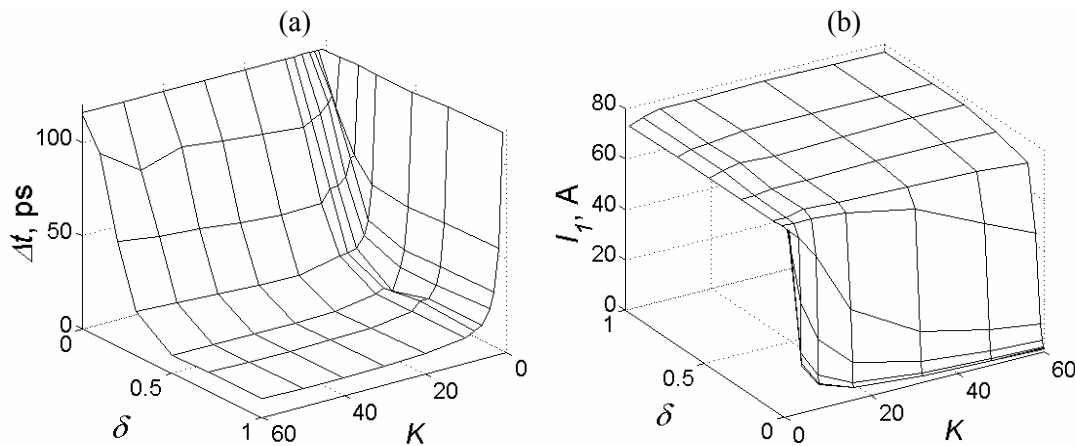

Figure 3. Dependence of the switching time (a) and the current in the conducting channel (b) on K and δ.

   Our simulations reveal that current localization induced by technological inhomogeneity leads also to a significant change in the conductivity modulation mechanism. Namely, the switching process becomes divided into two stages. The first stage is the propagation of the impact ionization front in the "active" part of the structure (figure 4(a)). This stage is similar to the homogeneous switching scenario, but the voltage does not drop during the front passage. As a result, the electric field behind the front increases (figure 4(a), curves 3, 4). The front starts in the "passive" part as well, but it starts later, fails to spread through the whole base length and stops in the middle of the structure. Thus, the "passive" part of the device effectively plays a role of a parallel capacity. At the second stage of switching, the discharge of this capacity, associated with the "passive" part, through the conducting

channel formed by the front passage in the "active" part, occurs. At this stage, the secondary avalanche breakdown of the "active" part takes place (figure 4(b)). It is accompanied by the rapid voltage drop on the device. Obviously, the second stage is not observed for the homogeneous switching process that is finished when the ionizing front passed across the diode base.
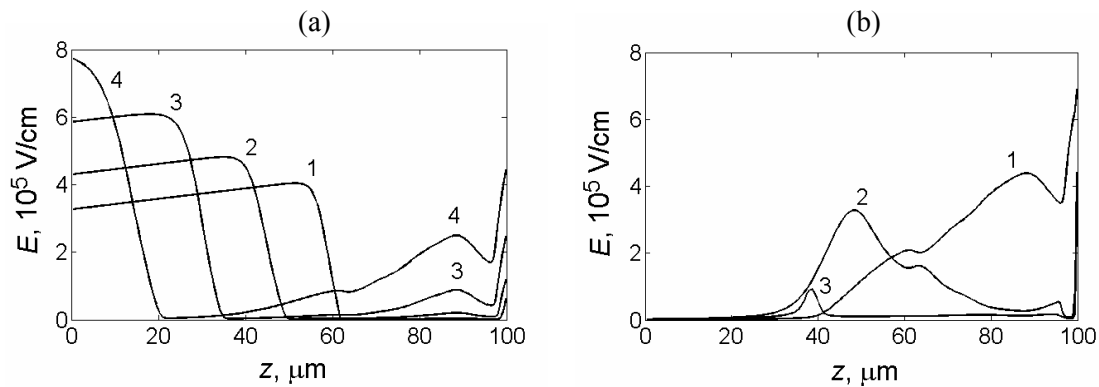

Figure 4. Electric field $E(z,t)$ at the front propagation stage (a) and at the secondary breakdown stage (b). Curves 1–4 in section (a) correspond to time moments $t = 0.97, 0.985, 0.993$ and 0.997 ns (a), curves 1–3 in section (b) correspond to $t = 1.0, 1.01$ and 1.02 ns. Parameter values are $K = 8$ and $\delta = 0.1$, which corresponds to curve 2 in figure 2(b).

4. Conclusions

The presence of technological imperfections qualitatively changes the switching scenario and reduces the switching time of picosecond-range avalanche diodes operating in the delayed avalanche breakdown mode. Instead of homogeneous switching due to propagation of the TRAPATT-like ionizing front over the whole cross-section of the device, our numerical simulations predict localization of current in the area with a higher concentration of deep electron traps responsible for triggering impact ionization. Although the ionizing front is triggered over the whole area of the device, its lagging part fails to compete with the leading part. This winner-takes-it-all dynamics eventually leads to formation of a conducting channel only in the location of the technological inhomogeneity. Nearly total localization of current in this area occurs if the relative amplitude of the inhomogeneity exceeds 10% (figure 3(b)), and it is not sensitive to the relative size of the inhomogeneity. Switching in such a spatially inhomogeneous quasi-streamer mode is faster than uniform switching, but a significant decrease of the switching time requires higher relative amplitude of the inhomogeneity and a smaller relative size than those required for current localization (figure 3(a)). The decrease of the switching time occurs not because the ionizing front propagates faster, but because switching occurs after the front passage during the secondary avalanche breakdown. At this stage, the "passive" part of the device, where the front passage has been terminated, recharges through the conductive channel formed by the front passage in the "active" part of the device. It implies that technological imperfections may play a constructive role leading to a faster switching process.

References

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