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SIMULATION OF SILICON n^+np^+, p^+pn^+ AND SCHOTTKY TRAPATT DIODES

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The plasma formation and extraction processes in silicon n^+np^+, p^+pn^+, and Schottky TRAPATT (TRApped Plasma Avalanche Triggered Transit) diodes were simulated. The drift-diffusion model was chosen for the simulation of the processes. We show that the minority carrier storage depends on the TRAPATT diode structure. The most intensive minority carrier storage takes place in the n^+np^+ diode, where holes accumulate in the n^+ region and electrons in the p^+ region. The extraction of electrons from the p^+ region is more rapid due to higher electron mobility compared to holes. Thus, the initial current for the next oscillation period is the hole current. In the p^+pn^+ diode the accumulation of holes in the n^+ region is inferior to that in the n^+np^+ diode due to a higher electric field in the pn^+ interface. The initial current in p^+pn^+ diodes is lower and the voltage oscillation is almost periodic. The most efficient structure in respect to low minority carrier storage is a pm-type Schottky diode. In this structure the initial conditions in all voltage oscillation periods are the same and there is a quite periodic oscillation in a very wide region of the diode total current density. We show that periodic oscillation can be achieved even in the n^+np^+ diode with optical generation of the carriers during the plasma formation and extraction period.

Keywords: simulation, avalanche diodes, diffusion, minority carrier storage

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1. Introduction

TRAPATT diodes were invented in [1] as high-power microwave devices working with high efficiency. The best achieved result on efficiency (75 percent) was reported in [2]. The peak power output of 1.2 kW at 1.9 GHz with 24% efficiency from five series-connected diodes was obtained in [3]. Very important results on powerful TRAPATT diodes were reported in [4] (300 kW at 6 GHz). The physical mechanism of the new avalanche diode operation mode was described in [5] by computer simulation. The analytical model of the TRAPATT diode was proposed in [6, 7]. It was shown that, contrary to the transit time mode, the main role in achieving high efficiency is played by the space charge of the carriers generated during the short in time but extremely intensive avalanche process in the whole active region of the diode. If the total current density is sufficiently high, the space charge density of free carriers exceeds the density of the ionized impurity several times and defines the electric field shape in the active region. The generated electrons and holes move in opposite directions. This causes the electric field to drop to a very low value during several picoseconds. As a result, we have electron-hole-ionized impurity plasma in the active region of the diode. The plasma extraction period (up to several hundred picoseconds) in a low electric field follows the plasma formation process. Due to a relatively long plasma extraction period the frequency of the TRAPATT generator is several times lower than in the transit time mode. The maximum frequency of the TRAPATT generator obtained experimentally is in the X-band [8, 9]. TRAPATT diodes are suitable for phased-array radar systems [10].

Because of a very strong nonlinearity of the TRAPATT diode, current and voltage contain high-order harmonics of up to 7 or 10. As a consequence, in [11–13] it was shown that TRAPATT diodes are useful not only for generating sinusoidal oscillation, but also for generating triangular pulses with sub-nanosecond duration. This feature of the TRAPATT diode may be utilized in modern radar systems with a non-sinusoidal carrier. Our experiments show that a typical TRAPATT diode with a static breakdown voltage of about 90 V and a p^+n junction diameter of 250 μm generates triangular pulses with a 100 V amplitude and a 0.3 ns duration with the repetition rate of about 1–2 GHz on a 50 ohm load [12, 13]. On the load of 5 ohm the generator provides a current of 6.3 A. This feature is very useful for the direct modulation of a powerful laser diode with a gigabit per second rate. The TRAPATT diode is very sensitive to the optical signal. Optical synchronization, amplification, frequency, and amplitude modulation were demonstrated experimentally [14–16].

Another important utilization of TRAPATT diodes is kilovolt pulse with kHz repetition rate sharpening. Experimental results demonstrate pulse generation with the amplitude of 2000 V into a 50 Ohm load and a rise time of 200 ps using a single diode and a power MOSFET driving circuit [17]. The diodes for pulse sharpening are called SAS (silicon avalanche sharpers) and DDB (diodes with delayed breakdown) [18–21]. The switching mechanism in these diodes is similar to the conventional TRAPATT diodes: a very fast electron-hole plasma formation in the active layer due to the dynamic avalanche breakdown.

Due to the above-mentioned advantages TRAPATT diodes have been useful for microwave power generation up to now. But these diodes have several disadvantages. One of them is a start-up jitter when using TRAPATT diodes for microwave pulse generation in modern radar systems. This is mainly due to oscillation aperiodicity during the transient period. As it will be demonstrated in this paper, oscillation aperiodicity may be reduced substantially by using p-type Schottky TRAPATT diodes. We carefully inspected the literature on TRAPATT diodes and have not found any papers with experimental or theoretical investigation of Schottky TRAPATT diodes.

The main processes in the TRAPATT diode are: electron-hole plasma formation due to very intensive impact ionization in a high electric field and plasma extraction in a low electric field. The plasma formation process and the resulting plasma density depend on the n^+n interface steepness [22, 23], on the electron diffusion coefficient in the high electric field [23], and on the dynamic minority carrier storage [24, 25]. Because of the dynamic minority carrier storage the initial conditions for the first and the second oscillation period are not the same. During the plasma extraction period holes accumulate in the n^+ region and electrons in the p^+ region due to the carrier diffusion process. As a result, the residual hole density in the active layer for the second oscillation period is several orders greater than that for the first oscillation period. The impact ionization process begins earlier, the diode voltage maximum becomes lower, and the electron-hole plasma density becomes lower as well. We have aperiodic oscillation which may be the reason of oscillation jitter in the real external circuit of the TRAPATT generator. In [24] the dynamic minority carrier storage was obtained for the first time in the n^+np^+ diode. In [25] a comparison between n^+np^+ and p^+pn^+ diodes was made, but with the assumption that the carrier diffusion coefficient is independent of the electric field and the doping density. Thus, we can consider these results as qualitative results, because the carrier diffusion coefficient dependence on the electric field affects strongly the plasma formation process in the TRAPATT diode [23].

The main purpose of our work is the quantitative comparison of the dynamic minority carrier storage in n^+np^+, p^+pn^+ type TRAPATT diodes and p^+pm, n^+nm, pm, nm type Schottky TRAPATT diodes. In addition, we propose the equalization of the initial conditions in all oscillation periods by optically generated carriers.

2. The TRAPATT diode model

The doping distribution in the modelled TRAPATT diodes is shown in Fig. 1. Donor $N_d(x)$ and acceptor $N_a(x)$ distribution is approximated by a well-known function erfc(x) [23], where x is distance, donor and acceptor density at the contacts $N_{d0} = N_{a0} = 5 \cdot 10^{18}$ cm^{-3}, donor (acceptor) density in the active layer $N_{d1}(N_{a1}) = 2.4 \cdot 10^{15}$ cm^{-3}, total length of the $n^+np^+(p^+pn^+)$ diodes $w = 4.5$ μm and of the n^+nm (p^+pm) Schottky diodes $w = 3.5$ μm. We also investigated a simplified Schottky diode without a $n^+(p^+)$ region. This diode consists of only an active n(p) region and a Schottky barrier on the right of it. The total length of the simplified diode $w = 2$ μm. Because of the diode simplicity it is not shown in Fig. 1.

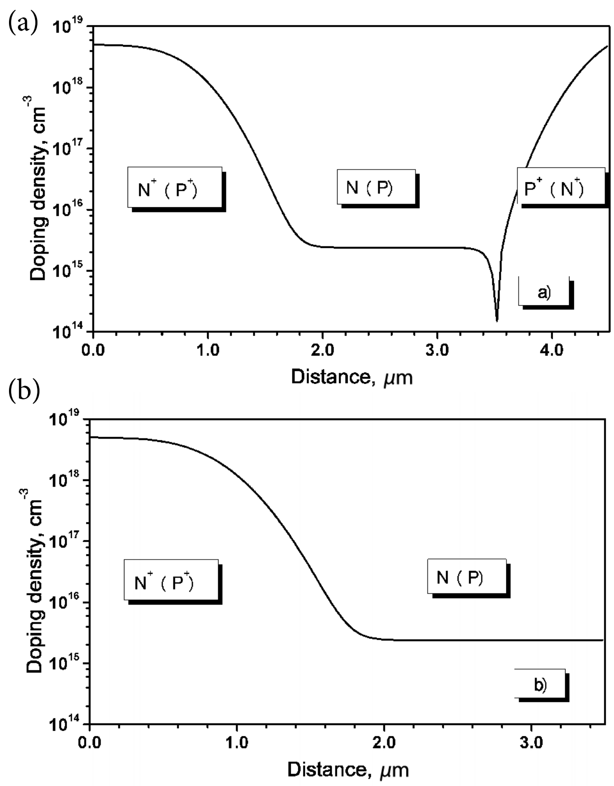

Fig. 1. Doping distribution of simulated (a) n^+np^+ (p^+pn^+) diodes and (b) n^+nm (p^+pm) Schottky diodes.

In all p-type diodes the electric field and the diode voltage are negative but in all our Figures we displayed these variables as positive ones. In such case the comparison of n-type and p-type diodes is better understood.

For computer simulation of the TRAPATT diodes we used a one dimension drift-diffusion model based on continuity equations for electrons and holes and Poisson's equation:

$$\frac{\partial n}{\partial t} - \frac{\partial J_{\mathrm{n}}}{\partial x} = G - R + A(x,t), \tag{2.1}$$

$$\frac{\partial p}{\partial t} + \frac{\partial J_{\mathrm{p}}}{\partial x} = G - R + A(x,t), \tag{2.2}$$

$$\frac{\partial E}{\partial x} = \frac{q}{\varepsilon\varepsilon_0}\left(p - n + N_{\mathrm{d}}(x) - N_{\mathrm{a}}(x)\right), \tag{2.3}$$

where t is time, n is electron density, p is hole density, E is electric field intensity, J_{n}, J_{p} is electron and hole current density normalized to electronic charge, G is charge generation term due to impact ionization, R is hole electron generation and recombination term, $A(x,t)$ is charge generation term due to optical effect, q is electronic charge, $\varepsilon = 12$, $\varepsilon_0 = 8.85 \cdot 10^{-14}$ F/cm.

$$J_{\mathrm{n}} = nv_{\mathrm{n}}(E, N_{\mathrm{d}}, N_{\mathrm{a}}) + \frac{\partial}{\partial x}\left(D_{\mathrm{n}}(E, N_{\mathrm{d}}, N_{\mathrm{a}}) \cdot n\right), \tag{2.4}$$

$$J_{\mathrm{p}} = pv_{\mathrm{p}}(E, N_{\mathrm{d}}, N_{\mathrm{a}}) - \frac{\partial}{\partial x}\left(D_{\mathrm{p}}(E, N_{\mathrm{d}}, N_{\mathrm{a}}) \cdot p\right), \tag{2.5}$$

where v_{n} is electron drift velocity, v_{p} is hole drift velocity, D_{n} is electron diffusion coefficient, D_{p} is hole diffusion coefficient. For v_{n}, v_{p}, and R we used the expressions described in [23]. For D_{n}, D_{p} we used the second approach and for G the first approach from [23]. At the $n^+(p^+)$ boundary, it is assumed that the surface-state density is high enough so that the surface recombination velocity is infinite and the semiconductor is very extrinsic. Hence, the particle density at the boundary is [23]:

$$n(0) = N_{\mathrm{d}}(0), \quad p(0) = \frac{n_{\mathrm{i}}^2}{N_{\mathrm{d}}(0)}, \tag{2.6}$$

$$p(w) = N_{\mathrm{a}}(w), \quad n(w) = \frac{n_{\mathrm{i}}^2}{N_{\mathrm{a}}(w)}, \tag{2.7}$$

where n_{i} is intrinsic particle density.

Our calculations show that final results are quite insensitive to boundary conditions for electrons and holes. Because of that we choose very simple boundary conditions for electrons and holes at n-type Schottky contact:

$$n(w) = N_{\mathrm{c}} \exp(-q \cdot \varphi_{\mathrm{k}} / K \cdot T), \tag{2.8}$$

$$\frac{\partial p(w)}{\partial x} = 0, \tag{2.9}$$

where N_{c} is effective density of states in the conduction band, $\varphi_{\mathrm{k}} = 0.75$ V is contact potential difference, K is Boltzmann constant, T is temperature.

For p-type Schottky contact,

$$p(w) = N_{\mathrm{v}} \exp(-q \cdot \varphi_{\mathrm{k}} / K \cdot T), \tag{2.10}$$

$$\frac{\partial n(w)}{\partial x} = 0, \tag{2.11}$$

where N_{v} is effective density of states in the valence band.

The electric field on the left or the right boundary is calculated by solving the total current equation using the iteration method:

$$J(t) = \varepsilon\varepsilon_0 \frac{\partial E}{\partial t} + qJ_{\mathrm{n}} + qJ_{\mathrm{p}}. \tag{2.12}$$

All calculations were made assuming a constant total current.

3. The computer simulation method

In this numerical method, a well-known time-space mesh [26] is chosen to derive the difference equations. The diode is divided into i_{w} partitions. If needed, $\Delta x_i = x_{j+1} - x_j$ varies in space. The electron density, hole density, and doping density are defined at both ends of each partition at points j. There are $j_{\mathrm{w}} = i_{\mathrm{w}} + 1$ such points. In the middle of the two j points, there are i points. The electric field intensity, particle current density, and those material parameters which are functions of the electric field intensity are defined at these i points.

The continuity equations for electrons and holes derived in difference form according to the time-space mesh were solved using the flow sweep method [27, 28]. For flow variables we used particle currents $J_{\mathrm{n}i}$ and $J_{\mathrm{p}i}$. When solving the continuity equation for electrons at the $(k+1)$th time step we used the hole density and the electric field intensity from the kth time step. After that we used the calculated electron density at the $(k+1)$th time step to obtain the hole density at the same time step. Finally we used the calculated electron and hole density to obtain the electric field intensity at the $(k+1)$th time step by solving Poisson's equation. A self-consistent solution for the electron and hole density and the electric field intensity at the $(k+1)$th time step is obtained after finishing the iteration process. Usually 2–4 iterations are needed.

4. Computer simulation results

The typical voltage oscillation on the n^+np^+ (p^+pn^+) TRAPATT diode (total current density $J = 3$ kA/cm^2) is shown in Fig. 2. The carrier density in the depletion region at the beginning of the first oscillation period (Fig. 3) is very low, about 10^3–10^4 cm^{-3}. Thus, almost the whole current is a displacement current and we have the electric field increasing at a constant rate. As we can see in Fig. 2, the diode voltage increases linearly until very intensive impact ionization begins. The carrier density increases rapidly. Near the voltage maximum point the carrier density becomes much larger than the donor (acceptor) density in the active layer and according to Poisson's equation the carrier density defines the electric field shape. In the active layer the electric field decreases with time. The diode voltage decreases as well. In the time interval of about several picoseconds the diode voltage decreases to a very low value (1–2 V). We have a very high carrier density

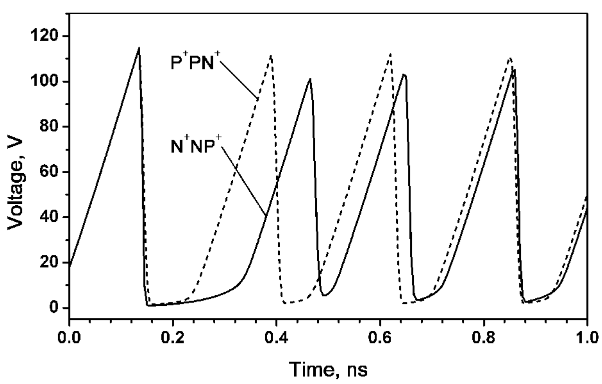

Fig. 2. Voltage oscillation on the n^+np^+ and on the p^+pn^+ TRAPATT diode. Total current density $J = 3$ kA/cm^2.

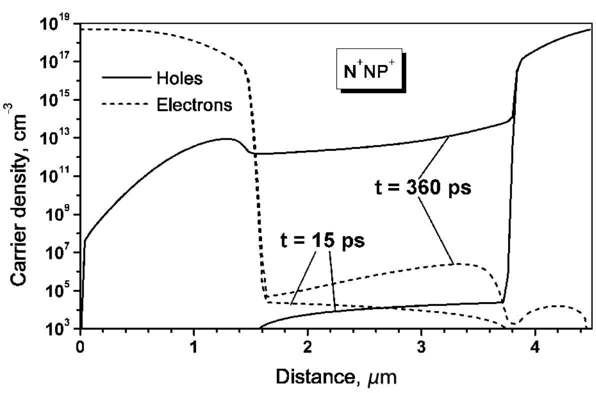

Fig. 3. Carrier density in the n^+np^+ TRAPATT diode at the beginning of the first oscillation period (t = 15 ps) and at the beginning of the second oscillation period (t = 360 ps). Total current density $J = 3$ kA/cm^2.

(above 10^{16} cm^{-3}) in a low electric field (600–700 V/cm). Almost in the whole active region $n - p = N_d$, which indicates electron-hole-ionized donor plasma. The next process is the plasma extraction in the low field. During this process (100–150 ps) the diode voltage increases from 1–2 V to about 10 V. The carrier density in the active region is very low after plasma extraction (Fig. 3). So, almost the whole current is a displacement current. The diode voltage increases again and the next oscillation period begins. The oscillation period depends on the plasma extraction time. It depends on the carrier density in plasma and the applied total current density. Larger current density leads to a more rapid increase of diode voltage, a higher voltage maximum, and a more intensive impact ionization process. As a result, we have denser electron-hole plasma and a prolonged plasma extraction process. Thus, the first oscillation period increases with the total current density increase.

In Fig. 2 we can see two main differences between the n^+np^+ and p^+pn^+ TRAPATT diodes. The first difference is a strong voltage oscillation aperiodicity of the n^+np^+ diode and a quite periodic voltage oscillation of the p^+pn^+ diode. This difference may be explained as follows. The diode voltage maximum and plasma density depend on the initial particle current density at the beginning of the impact ionization process. A more intensive initial particle current density leads to a diode voltage maximum and plasma density decrease. A comparison the curves in Fig. 3 show that there is a dramatic difference of the carrier density at the beginning of the first and the second period of the voltage oscillation in the n^+np^+ diode (10^4 cm^{-3} at t = 15 ps and 10^{13} cm^{-3} at t = 360 ps). The corresponding difference of the carrier density in the p^+pn^+ diode is sufficiently less (10^4 cm^{-3} at t = 15 ps and 10^7 cm^{-3} at t = 275 ps). The relatively high carrier density at the beginning of the second voltage oscillation period is due to intensive hole diffusion to the n^+ region during the plasma extraction period. The initial conditions for hole diffusion are not the same in the n^+np^+ and in the p^+pn^+ diodes. In the n^+np^+ diode (Fig. 4) the electron-hole plasma density is higher and occupies more space than in the p^+pn^+ diode (Fig. 5). There is an electric field maximum on both sides of the active region (Figs. 4, 5). The higher the electric field peaks the lower the minority carrier diffusion and their storage in the n^+ and p^+ regions. The electric field peak in the n^+n interface (Fig. 4) is considerably lower than in the pn^+ interface (Fig. 5). As a result, we have more hole storage in the n^+ region of the n^+np^+ diode than in the p^+pn^+ diode. The electron storage in the p^+ regions is inferior to the hole storage in the n^+ regions in both diodes due to a higher electric field peak in the p^+p and np^+ interfaces. Also, the electron mobility

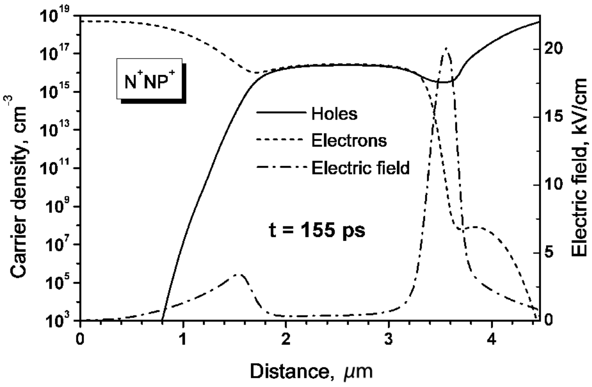

Fig. 4. Carrier density and electric field distribution in the n$^+$np$^+$ TRAPATT diode at the beginning of the plasma extraction period (t = 155 ps). Total current density J = 3 kA/cm^2.

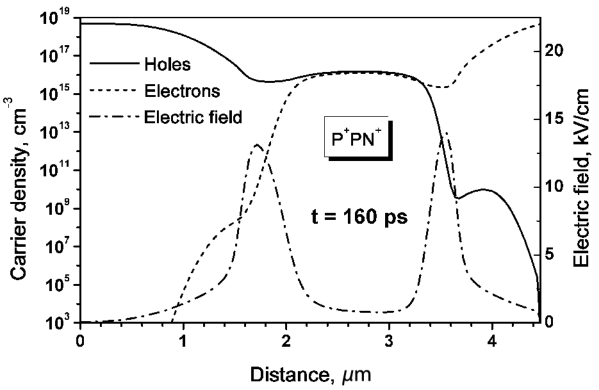

Fig. 5. Carrier density and electric field distribution in the p$^+$pn$^+$ TRAPATT diode at the beginning of the plasma extraction period (t = 160 ps). Total current density J = 3 kA/cm^2.

is considerably higher than the hole mobility. So, the electron extraction from the p$^+$ region is more rapid than the hole extraction from the n$^+$ region. Thus, the initial current at the beginning of the second voltage oscillation period is almost a hole current.

The second difference between the n$^+$np$^+$ and p$^+$pn$^+$ TRAPATT diodes is the duration of plasma extraction time in the first voltage oscillation period, which is two times greater in the n$^+$np$^+$ diode than in the p$^+$pn$^+$ diode (compare curves in Fig. 2). This difference may be explained as follows. In silicon the impact ionization coefficient of electrons $\alpha(E)$ is about ten times greater than the corresponding coefficient of holes $\beta(E)$. At the beginning of the first voltage oscillation period the electron and hole density in the active region of both diodes is almost the same. Thus, the electrons play the main role at least in the beginning of the impact ionization process. The generation rate for electrons $G = \alpha(E)|J_n|$, where $\alpha(E)$ depends exponentially on the electric field. In the n$^+$np$^+$ diode the electron density decreases but the electric field increases with distance. So, the generation rate maximum is near the middle of the active layer. In the p$^+$pn$^+$ diode the electron density and the electric field increases with distance and the generation rate maximum coincides with the electric field maximum in the pn$^+$ interface. As a result, the generation rate in the p$^+$pn$^+$ diode is much higher than in the n$^+$np$^+$ diode at the same diode voltage. The early impact ionization in the p$^+$pn$^+$ diode leads to a lower diode voltage maximum, lower carrier density in the electron-hole plasma, which occupies less space in the active region of the diode. As a result, the plasma extraction period is two times shorter than in the n$^+$np$^+$ diode (Fig. 2). In Fig. 6 we have the electric field distribution in both diodes during the plasma formation period. According to the above-mentioned conclusions, the electric field collapse in the n$^+$np$^+$ diode begins in the middle of the active layer and the ionization wave propagates to the left and to the right until the electron-hole plasma occupies the whole active region. In the p$^+$pn$^+$ diode the electric field collapse begins in the pn$^+$ interface and the ionization wave propagates to the

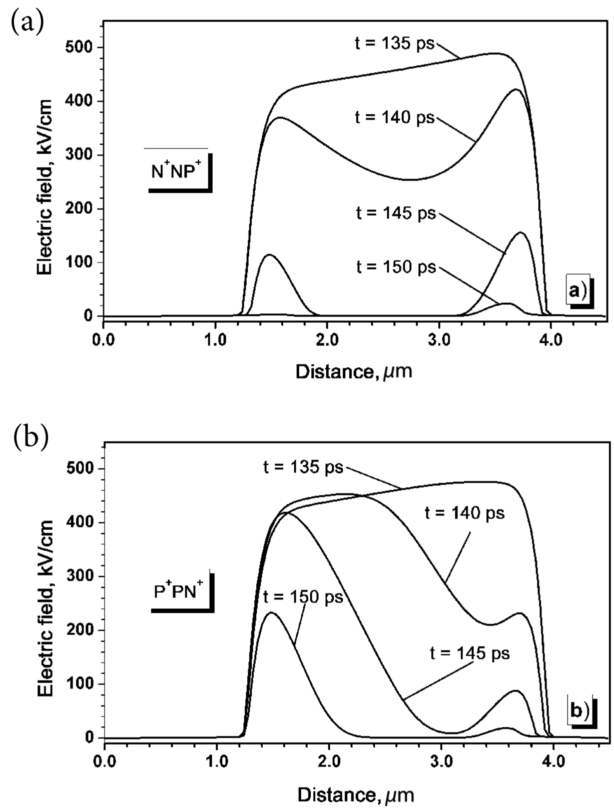

Fig. 6. Electric field distribution in (a) n$^+$np$^+$ and (b) p$^+$pn$^+$ TRAPATT diode during the electron-hole plasma formation period. Total current density J = 3 kA/cm^2.

left, so the electron-hole plasma occupies only part of the active region.

Periodic voltage oscillation on the p$^+$pn$^+$ diode exists only in a limited range of the total current density (J < 3 kA/cm^2). Increasing the total current density leads to the aperiodic voltage oscillation and the p$^+$pn$^+$ diode has no superiority against the n$^+$np$^+$ diode. The aperiodicity of voltage oscillation is due to the dynamic hole storage in the n$^+$ region. Thus, one must eliminate the n$^+$ region from the TRAPATT diode. This is possible in the p$^+$p-type TRAPATT diode with Schottky barrier (p$^+$pm diode) instead of the n$^+$ region. Our calculations show that the n$^+$nm Schottky diode works very similarly to the n$^+$np$^+$ diode. Voltage oscillation on the p$^+$pm Schottky diode is absolutely periodic at the total current density J = 3 kA/cm^2 and almost periodic even at J = 6 kA/cm^2. The superiority of the p$^+$pm Schottky diode is obvious. So, we will take a closer look at the physical processes in the p$^+$pm Schottky diode. First, we compare the initial conditions at the beginning of the first voltage oscillation period and the second period (Fig. 7). Electron density in the right side of the active region is the same in both cases. Since the charge generation rate maximum coincides with the electron density and the electric field (Fig. 7) maximum, we have identical voltage oscillation periods. The hole storage does not exist. The negligible electron storage in the p$^+$ region has no effect on the subsequent plasma formation process. The plasma extraction period begins at t = 160 ps (Fig. 8). The plasma exists in the active region where $p-n-N_a = 0$. The holes move to the left and the electrons to the right. The electric field has two peaks at the edges of the active region (Fig. 8). The peak at the right edge of the active region (about 33 kV/cm) prevents hole diffusion to the p-metal interface. Another peak (about 13 kV/cm) significantly reduces the electron diffusion to the p$^+$ region. In the active region, occupied by plasma, the electric field is very low (Fig. 8). The electron velocity in such low electric field is about three times greater than the hole velocity. So, the left edge of the plasma moves to the right much faster than the right edge to the left (Fig. 9). The left peak of the electric field increases but the right peak remains almost the same (Fig. 9). After some time (t = 230 ps) the plasma disappears but the hole density in the active region is significant (Fig. 10). The electric field is high in the whole active region (Fig. 10). At the end of the first diode voltage oscillation period we have the same initial conditions as in the beginning and the diode voltage oscillation

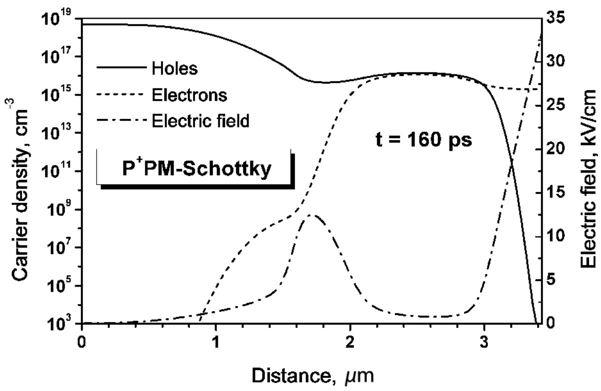

Fig. 8. Carrier density and electric field distribution in the p$^+$pm Schottky TRAPATT diode at the beginning of the plasma extraction period (t = 160 ps). Total current density J = 3 kA/cm^2.

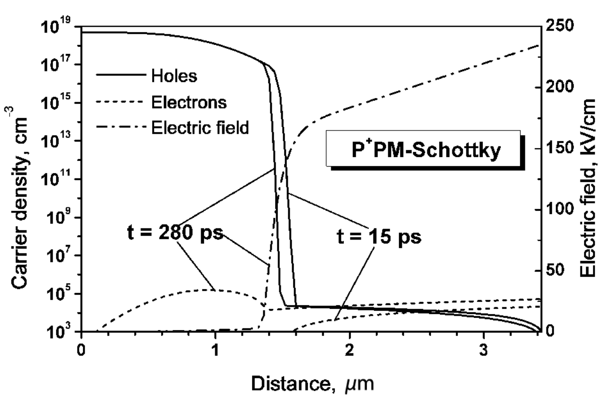

Fig. 7. Carrier density and electric field distribution in the p$^+$pm Schottky TRAPATT diode at the beginning of the first voltage oscillation period (t = 15 ps) and the second voltage oscillation period (t = 280 ps). Total current density J = 3 kA/cm^2.

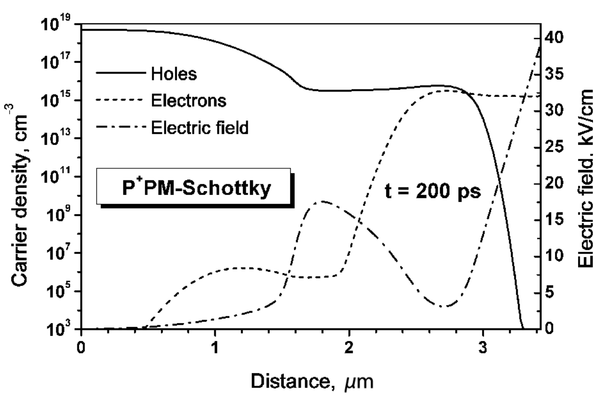

Fig. 9. Carrier density and electric field distribution in the p$^+$pm Schottky TRAPATT diode during the plasma extraction period (t = 200 ps). Total current density J = 3 kA/cm^2.

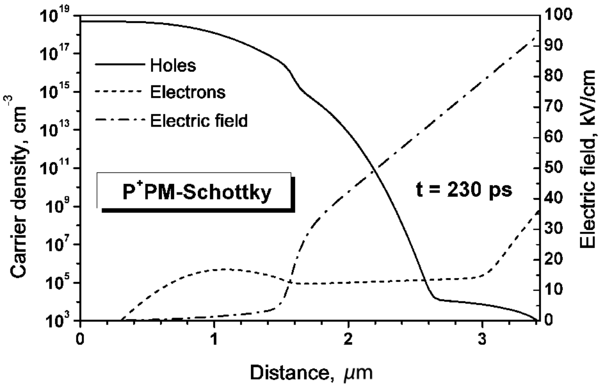

Fig. 10. Carrier density and electric field distribution in the p$^+$pm Schottky TRAPATT diode after the plasma extraction period (t = 230 ps). Total current density J = 3 kA/cm^2.

is periodic. The situation changes in the case of the total current density J = 6 kA/cm^2. The electron storage in the p$^+$ region is about three orders higher than in the case of J = 3 kA/cm^2. Thus, the existence of the p$^+$ region leads to the diode voltage aperiodicity.

A further improvement of the Schottky TRAPATT diodes may be achieved by eliminating the n$^+$ region from the n$^+$nm simple-structure Schottky diode and the p$^+$ region from the p$^+$pm Schottky diode. The calculations of these TRAPATT diodes were done (Figs. 11, 12). The differences between nm-type and pm-type Schottky diodes still exist. However, we can see a great improvement of voltage oscillation on the nm Schottky diode even at the high total current density (J = 6 kA/cm^2) against the n$^+$nm Schottky diode at J = 3 kA/cm^2. At the extremely high current density of 12 kA/cm^2 the voltage oscillation becomes aperiodic again (Fig. 11). The voltage oscillation on the pm Schottky TRAPATT diode is periodic at J = 6 kA/cm^2 and quite periodic even at the extremely high total current density J = 12 kA/cm^2 (Fig. 12). The superiority of the pm Schottky diode is obvious.

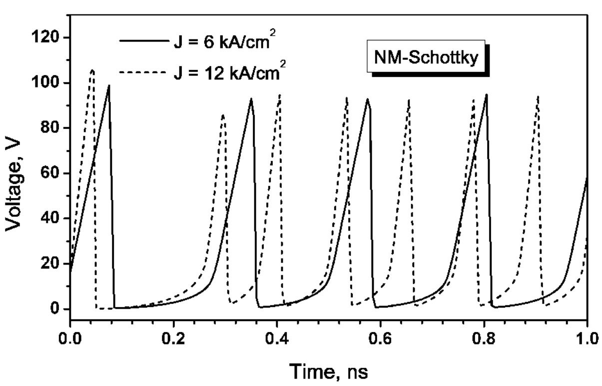

Fig. 11. Voltage oscillation on the nm Schottky TRAPATT diode at the total current density J = 6 kA/cm^2 and J = 12 kA/cm^2.

The next part of our investigation concerns the effect of optical charge generation in TRAPATT diodes. Our calculations show that periodic voltage oscillation can be achieved even in the n$^+$np$^+$ TRAPATT diodes by optical charge generation. In Fig. 13 we can see the dependence of voltage oscillation periodicity on the optical charge generation rate $A(x,t)$. A significant voltage periodicity enhancement can be achieved with $A(x,t)$ = 10^{18} cm^{-3}/s. Increasing $A(x,t)$ from 10^{19} cm^{-3}/s and above gives us periodic voltage oscillation (Fig. 13). The plasma extraction period decreases and, as a result, the voltage oscillation frequency increases. So, we have frequency modulation by optical charge generation in the TRAPATT diode.

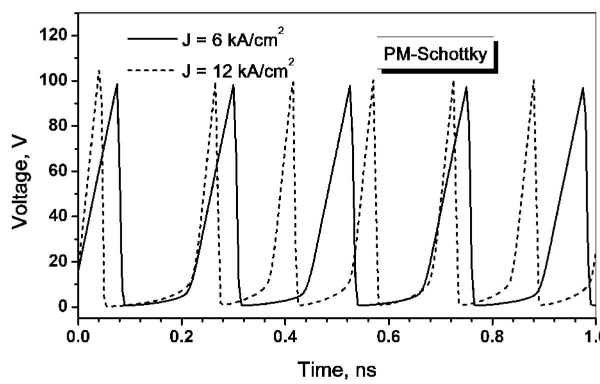

Fig. 12. Voltage oscillation on the PM Schottky TRAPATT diode at the total current density J = 6 kA/cm^2 and J = 12 kA/cm^2.

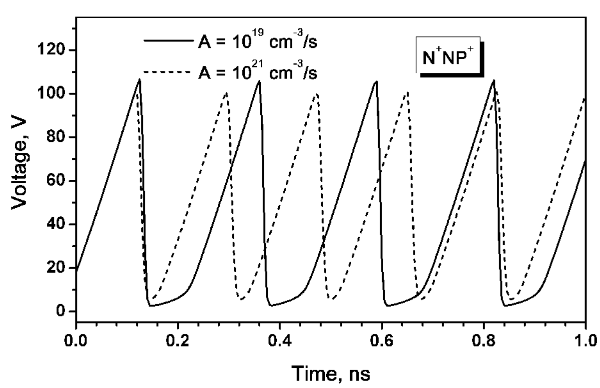

Fig. 13. Voltage oscillation on the n$^+$np$^+$ TRAPATT diode with optical charge generation. Charge generation rate A = 10^{19} cm^{-3}/s and 10^{21} cm^{-3}/s. Total current density J = 3 kA/cm^2.

5. Conclusions

Plasma formation and extraction processes in silicon n^+np^+, p^+pn^+ TRAPATT diodes and n^+nm, p^+pm, nm, pm Schottky TRAPATT diodes were simulated. The main focus was on the dynamic minority carrier storage in the n^+ and p^+ region of the TRAPATT diodes. The minority carrier storage affects initial conditions in the second voltage oscillation period. The difference in the initial conditions for the first and the second oscillation period leads to voltage oscillation aperiodicity. The most aperiodic voltage oscillation exists in the n^+np^+ diodes. The aperiodicity increases with the total current density increase. Periodic diode voltage oscillation appears in the p^+pn^+ diode in a limited range of the total current density ($J < 3$ kA/cm^2). There are no sufficient differences between the voltage oscillation on the n^+np^+ diode and on the n^+nm Schottky diode. The p^+pm Schottky diode has a two times higher total current range ($J < 6$ kA/cm^2) in which the periodic diode voltage oscillation exists. The most periodic voltage oscillation appears on the pm Schottky diodes in a very wide total current density range ($J < 12$ kA/cm^2). The periodic voltage oscillation can be achieved even in the n^+np^+ TRAPATT diodes by optical charge generation. Increasing the optical charge generation rate from 10^{19} cm^{-3}/s and above generates periodic voltage oscillation. The plasma extraction period decreases and, as a result, the voltage oscillation frequency increases. So, we have frequency modulation by optical charge generation in the TRAPATT diode.

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SILICIO n^+np^+, p^+pn^+ IR ŠOTKIO TRAPATT DIODŲ MODELIAVIMAS

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Santrauka

Darbe pateikti plazmos susidarymo bei išsiurbimo procesų n^+np^+, p^+pn^+ ir Šotkio silicio TRAPATT (TRApped Plasma Avalanche Triggered Transit) dioduose modeliavimo rezultatai. Procesų modeliavimui buvo pasirinktas dreifinis-difuzinis modelis. Parodyta, kad šalutinių krūvininkų kaupimas priklauso nuo TRAPATT diodo sandaros. Intensyviausias šalutinių krūvininkų kaupimas vyksta n^+np^+ diode, kur skylės kaupiasi n^+ srityje, o elektronai – p^+ srityje. Dėl didesnio judrio elektronų išsiurbimas iš p^+ srities vyksta greičiau negu skylių iš n^+ srities. Dėl to pradinė srovė kitame virpesių periode yra skylių srovė. p^+pn^+ diode skylių kaupimas n^+ srityje yra mažesnis negu n^+np^+ diode (dėl didesnio elektrinio lauko np^+ sandūroje). Pradinė srovė p^+pn^+ dioduose yra mažesnė, o įtampos virpesiai praktiškai yra periodiniai. Efektyviausias mažo šalutinių krūvininkų kaupimo požiūriu darinys yra pm tipo Šotkio diodas. Šiame darinyje pradinės sąlygos visiems įtampos virpesių periodams yra vienodos, ir virpesiai praktiškai yra periodiniai plačiame pilnosios srovės tankio diapazone. Parodyta, kad periodiniai virpesiai gali egzistuoti netgi n^+np^+ diode optiškai generuojant krūvininkus plazmos formavimosi ir išsiurbimo metu.