A study of the influence of forward bias pulse duration on the switching process of a 4H-SiC drift step recovery diode

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Abstract. The results of simulation of the switching process in a silicon carbide drift step recovery diode with various times for injecting non-equilibrium carriers are presented. The inefficiency of a long injection time is demonstrated.

1. Introduction
Silicon-based drift step recovery diodes (DSRD) are widely and successfully implemented in high-voltage pulse generators as superfast opening switches. The main principle underlying a typical DSRD operation cycle is based on the superfast recovery effect that occurs in a p-n junction after injection of non-equilibrium charge carriers into the base region of the structure with a short forward current pulse and their subsequent removal with reverse current [1].

In [2, 3] the results of the design of silicon carbide DSRDs are presented. The designed diodes demonstrate outstanding performance, providing voltage rise velocities of 2.5 - 3.5 V/ps, which is unachievable for a silicon DSRD because its switching velocity is limited by the value of 1 V/ps. In [4, 5] the results of the design of the voltage pulse generators with 4H-SiC DSRDs implemented as superfast opening switches are demonstrated; they are capable of shaping voltage pulses with subnanosecond rise times.

However, despite the existence of experimental results and theoretical works [6-8], many questions relating to 4H-SiC DSRD operation remain unanswered. In order to improve the efficiency of these switches and to reach a voltage rise velocity of up to 10 V/ps that is theoretically achievable for 4H-SiC [1], it is necessary to conduct further studies of the electrical and thermal properties and, in particular, dynamic characteristics of these diodes. Thus, the objective of the present paper is to study the influence of forward bias pulse duration on charge losses in a silicon carbide drift step recovery diode.

2. Simulation
The study was conducted by simulation in Synopsys Sentaurus TCAD software in the drift-diffusion approach with the following effects accounted for: bandgap narrowing at high doping levels, avalanche generation in high fields, incomplete dopant ionization, which is a very specific effect for 4H-SiC, Shockley-Read-Hall and Auger recombination mechanisms, and various mobility models including mobility lowering in heavily doped regions and carrier velocity saturation at high fields.

The examined diode has a $p^+\!-\!p\!-\!n^+$ structure with epilayer thicknesses of 2, 18 and 350 um, respectively. The concentrations of acceptors (Al) and donors (N) in p-type and n-type layers are $2\cdot10^{19}$ cm$^{-3}$, $5\cdot10^{15}$ cm$^{-3}$, and $10^{19}$ cm$^{-3}$, respectively. The area of the top contact is 1 mm$^2$. The doping profile of the structure is presented in figure 1. Based on an approximate breakdown analysis involving solution of the Poisson equation with calculation of ionization integrals, the static
The breakdown voltage of the structure (and hence the reverse voltage the diode is to switch) is estimated to be 1800 V. The operation of the diode has been studied in a circuit containing a voltage source $V_1$, a 4H-SiC-DSRD $D_1$ and a 50 Ω load resistor $R_1$. This circuit is presented in figure 2.

A typical transient in the circuit the diode was studied in is presented in figure 3. During the time $T_P$, the diode is biased forward with a linearly rising voltage pulse, which is accompanied by injection of non-equilibrium carriers into the base region of the structure. After that, the voltage at the source changes its polarity and remains constant while the voltage drop at the diode is low as the injected carriers are extracted; the latter process lasts for time $T_D$. By the time the non-equilibrium carriers have been fully removed, the majority carriers are extracted from the base with saturated velocities, which goes along with a fast voltage rise at the diode and corresponds to superfast switching.

Figure 1. The doping profile of the drift step recovery diode (marked line) and ionized doping distribution (red line).

Figure 2. The circuit that the 4H-SiC ultrafast diode was examined in.

The results of several transient simulations described above with various values of $T_P$ are presented in figure 4. In order to estimate the times $T_D$ correctly, the endings of the forward bias pulses are shifted to the moment of time $t = 0$. Since the full charge that is injected into the structure and the extracted charge are, respectively:

$$Q_+ = \int_0^{T_P} \frac{U}{R_1} dt \approx \frac{1}{2} I_{D_1} T_P;$$

$$Q_- = \int_{T_P}^{T_D} \frac{U}{R_1} dt \approx I_{D_1} T_D,$$

where $I_{D_1}$ is the current flowing through the diode, we may introduce the relation between $Q_-$ and $Q_+$ as the percentage between the injected and extracted charge. So if $Q_- / Q_+$ is less than 100%, one can observe a loss of the injected charge. The quantified charge losses for various durations of the forward bias pulse $T_P$ are summarized in table 1.

| $T_P$, ns | 1  | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|-----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|-----|
| $T_D$, ns | 0.5| 1.8| 3  | 3.9| 4.5| 5.2| 5.8| 6.3| 6.8| 7.7| 8.6| 9.3| 9.9| 11 | 11  |
| $Q_+$, nC | 18 | 90 | 180| 270| 360| 450| 540| 630| 720| 900| 1080| 1260| 1440| 1620| 1800|
| $Q_-$, nC | 18 | 67 | 110| 140| 164| 188| 208| 228| 244| 276| 308| 335| 357| 382| 401 |
| $Q_- / Q_+$, % | 100| 74 | 61 | 52 | 46 | 42 | 39 | 36 | 34 | 31 | 29 | 27 | 25 | 24 | 22  |
Figure 5 demonstrates that the concentrations of the injected non-equilibrium holes and electrons in the base region of the structure rise with the increase of the forward bias pulse duration. This evidences that the absolute amount of the charge stored in the diode’s base region increases as well, and is limited by the maximum injection ability of $p^+p$ and $n^+p$ junctions [10].

It is also worth noting that the absolute value of the charge stored in the structure is relatively small compared to the injected charge at times $T_P$ higher than 40 nanoseconds.

**Figure 3.** Typical transient in the circuit the diode has been studied in (black and red lines represent the voltages of the voltage source $V1$ and the studied diode $D1$, respectively).

**Figure 4.** The switching processes of the studied diode at various durations of the forward current pulse.

**Figure 5.** Distribution of holes (coloured lines) and electrons (dashed lines) at the end of the injection process (the marked line represents the ionized doping distribution).
3. Results and conclusion

It is shown that the losses of the injected charge increase with an increase of the duration $T_P$ of the forward bias pulse injecting non-equilibrium carriers into the diode base region.

Based on the shapes of the dependences obtained in figure 4 and briefly stated in table 1, one can conclude that biasing the diode forward for a time longer than 40 ns is impractical due to the limited value of the charge that can be stored in the diode structure. Therefore, long injection times lead to vast loss of the injected charge. It can also be clearly seen that with an increase in $T_P$, the efficient part of the diode's switching process shrinks up to 10% at the end of it.

In figure 5, one can also observe that the electrons and holes are accumulated in the $p^+$ and $n^+$-regions, which undoubtedly shows that conservation of the injected charge is possible not only by the accumulation of non-equilibrium carriers in the base region, but also by the accumulation of minority carriers in passive heavily doped regions of the diode.

We assume that the loss of the injected charge is caused by recombination of minority charge carriers (electrons) at the ohmic contact to the $p^+$ emitter. Since the thickness of this region is much smaller than the electron diffusion length, a certain amount of electrons injected into a $p^+$ emitter diffuse towards the ohmic contact to this layer, where the recombination rate is infinite, so the loss of these electrons occurs. This mechanism of charge loss may only be enhanced by incomplete dopant ionization, which is a very common phenomenon for wide bandgap semiconductors such as 4H-SiC. Thus, incomplete dopants ionization may result in an increase in mobility of minority carriers in heavily doped regions and a consequent rise in their diffusion lengths.

According to the results presented in this paper, in order to improve the accumulation of electrons in a $p^+$ emitter and hence to reduce charge losses in the diode structure, an increase of doping ionization degree is of practical interest and will be the subject of our future research.

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