Investigation of the temperature effect on the dynamic parameters of ultrafast silicon carbide current switches

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Abstract. The results of a theoretical and experimental study of temperature effect on a switching process of a 4H-SiC drift step recovery diode are presented. The effect of the injected charge losses lowering at high temperatures is demonstrated.

1. Introduction
Drift step recovery diodes (DSRDs) are the most popular high power superfast semiconductor switches that may be implemented in nano- and subnanosecond pulse generators amongst others. The DSRDs usage is very common due to their reliability, high switching velocities, relatively simple manufacturing process and the possibility of combining the diodes into high voltage stacks [1]. 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 carries into the base region of the structure with a short forward current pulse and their further removal with reverse current. It is widely known that silicon-based DSRDs are capable of switching voltages of kilovolt orders at 1 V/ps switching velocity.

Yet in [2, 3] it was shown experimentally that implementation of silicon carbide (4H-SiC) in DSRDs fabrication leads to a major increase of switching velocities up to 3-4 V/ps. Apart from gaining high switching velocities 4H-SiC DSRDs are able to operate at high repetition frequencies up to dozens of megahertz, which results in heavy heating of the diode structure. One of the main advantages of 4H-SiC is its high thermal conductivity, which determines the upper temperature limit at which the diode’s operation is stable, thus 4H-SiC DSRDs have huge perspectives of their implementation in high voltage pulse generators with subnanosecond rise times working at high pulse repetition frequencies.

However, at the moment both the maximum temperatures the diodes can operate at, and the temperature affection on the parameters of the voltage pulses shaped have not been studied. In addition, despite 4H-SiC provide the major switching velocity gain, one of the general issues the 4H-SiC DSRDs suffer is a vast loss of injected charge [4, 5] which may constrain the maximum switching velocity and decrease the energy efficiency of the device. Also, being a distinctive effect for 4H-SiC, incomplete dopants ionization may lead to severe losses of charge at room temperature. All the conditions listed above determine the relevance of our study of the temperature effect on the dynamic parameters of the superfast 4H-SiC current switches and, in particular, on the injected charge losses.
2. Instrumentation
The diodes under examination have \( p^+ - p - n^+ \) structure with the thickness of the epilayers, respectively: 2, 18 and 350 \( \mu m \). Aluminum and nitrogen were used as dopants with concentrations in epilayers respectively: \( 2 \times 10^{19} \), \( 5 \times 10^{15} \) and \( 5 \times 10^{18} \) cm\(^{-3} \).

The theoretical study was carried out by simulation in Synopsys Sentaurus TCAD software with the following effects accounted for: bandgap narrowing at high doping levels, Shockley-Read-Hall and Auger recombination, impact ionization at high fields, incomplete dopants ionization and several mobility models including carriers scattering on ionized impurities and carrier velocity saturation at high fields.

The 4H-SiC DSRDs’ operation has been studied in a proprietary stand, which consisted of an ultrashort pulse generator with inductive energy accumulation with the diodes implemented as opening switches, a set of microwave attenuators (Aeroflex-Weinschel and Barth Electronics) and a stroboscopic oscilloscope Tektronix DAS8300 with a 20 GHz band.

The heating of the diode structure was carried out by setting a high pulse repetition rate whilst the cooling was executed by using non-flammable circuit freeze spray. The temperature of the diode was observed by the means of non-contact measurements of injection electroluminescence spectra technique during the diode’s operation [6]. A mobile optical spectrometer [7] was used in order to define the temperature of the structure by spectral maximum wavelength detection.

3. Results and discussion
The diode’s operation had been studied by its recovery process simulation in a circuit containing a voltage source, the diode under examination and a 50\( \Omega \) load connected in series. For 70 nanoseconds the diode is biased forward with a linearly rising voltage pulse up to 1800 V, 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 extraction takes place. By the end of non-equilibrium carriers removal the extraction of majority carriers from base with saturated velocity occurs simultaneously with a fast voltage rise at the diode, which corresponds to its switching. The results of simulation of the diode’s recovery processes at different temperatures are presented in Figure 1.

![Figure 1. The DSRD under examination switching processes at various temperatures](image-url)

If we define the loss of charge as the relation \( Q_-/Q_+ \) between the extracted non-equilibrium charge \( Q_- \) and injected charge \( Q_+ \), which are defined by the areas under current transient response at different stages of the diode’s recovery process [5]. One can clearly observe that the temperature rise leads to
better charge accumulation in the structure. The percentage of ionized impurities in $p^+$- and $n^+$-emitters increases with temperature from 3% at 233 K to 27% at 573 K, which outcomes in a significant growth of $p^+-p$ and $p^- n^+$ junctions injection ratios. Hence the higher the temperature is, the more charge may be injected into the base region of the structure and the longer it takes to extract it, which is approved by the shapes of non-equilibrium electron-hole plasma distributions at different temperatures at the end of the injection stage (Figure 2). The charge losses estimation is presented in Table 1.

![Figure 2. Distributions of holes (coloured lines) and electrons (dashed lines) at the end of the forward current pulse at various temperatures](image)

**Table 1.** Injected charge losses estimation at various operating temperatures

| T, K  | 233 | 293 | 373 | 423 | 473 | 523 | 573 |
|-------|-----|-----|-----|-----|-----|-----|-----|
| $T_D$, ns | 6,48 | 11 | 16,85 | 19,6 | 22,3 | 24,4 | 26 |
| $Q_-$, nC | 233 | 396 | 606 | 705 | 802 | 879 | 936 |
| $Q_+/Q_-$, % | 19 | 31 | 48 | 56 | 64 | 70 | 74 |

The diode’s performance had been observed in the ultrashort pulse generator circuit (Figure 3). The operation principle of the circuit is described in detail in [8]. A power MOSFET was implemented as the S1 switch whereas the DSRD D1 under examination was used as the opening switch. It is also worth noting that during the experiment the MOSFET was set to a heat sink in order to exclude its overheating, so the S1 voltage pulse shape was stable.

During the diode’s operation in pulse generators it is essential to implement minimal forward current pulses durations in order to diminish the charge losses. In case of the following study the forward current pulse duration was defined by the characteristics of the circuit and set up to 70 nanoseconds. The values of capacitances and inductances in the circuit were chosen to guarantee non-equilibrium carriers’ extraction to end at the same moment the diode current reaches its maximum value, the latter process being accompanied by superfast switching of the diode.

In the Figure 4 the comparison between the results of theoretical and experimental study is given. The time dependence $U_{S1}$ represents the voltage pulse shaped at the MOSFET S1. The results of the simulations and the experimentally obtained voltage pulses are shown in Figure 4 as well. The difference between the amplitude of the voltage pulse obtained in the experiment (1400 V) and the one the examined DSRD may provide (1800 V) is determined by the parameters of the attenuators array.
implemented as the 50Ω load: the first attenuator in the array was the high power Aeroflex-Weinschel (model 49-40-34) with 40 dB attenuation and 5 kW maximum input peak power. With the voltage pulse amplitude 1400 V the peak power the 50Ω load is to dissipate is 39 kW, which exceeds the maximum allowable power by nearly 8 times, so in order to prevent damaging the attenuator the voltage pulse amplitude was not raised higher than 1400 V.

**Figure 3.** The ultrashort pulse generator circuit the diode was examined in

As one can observe from Figure 4, the rise of temperature affects the diode’s operation in the same way it was demonstrated in simulation (Figure 1): in case of high temperatures the higher it is, the better the injected charge is stored, which results in the prolonged period of carriers’ extraction from the base region; in case of low temperature the charge accumulation is the worst. Therefore, the moment the superfast switching should occur is offset in case of any other temperature than 293 K concerning the optimum when the diode current reaches its peak value. The amplitude of the generated voltage pulse decreases from 1400 V at room temperature to 650 V at 573 K and the mean switching velocity lowers from 2 to 0.7 V/ps.

**Figure 4.** The results of simulations (solid lines) and experimentally observed voltage pulses (markers) at different temperatures
It is also worth noting that during the experiment all the parameters of the circuit were constant, but it is possible to achieve the optimal moment of time for the diode to switch at various temperatures by adjusting the circuit parameters. Thus, for every duration of the charge extraction process it is essential to tune the circuit.

4. Conclusion

The analysis given in the following paper establishes the fact that the vast loss of injected charge usually observed in 4H-SiC drift step recovery diodes strongly depend on the percentage of ionized doping. The results of the simulation demonstrated that at high temperatures the injection of non-equilibrium carriers occurs more effectively, which outcomes in better charge accumulation in the diode structure. The results of the experiments approve both the adequacy of the model and the theoretical statements concerning temperature affection on charge losses in 4H-SiC DSRDs.

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