A study of 4H-SiC diode avalanche shaper

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Abstract. The results of the simulation of an ultrashort pulse generator with a 4H-SiC diode avalanche shaper implemented as a superfast closing switch are presented. The possibility of shaping a voltage pulse with an amplitude of 3300 V and 19 picosecond rise time is demonstrated.

1. Introduction

A study of the impact ionization phenomenon in reverse-biased silicon junction diodes resulted in the discovery of the superfast switching effect [1], which occurs at extremely high voltage rise velocities at $p$-$n$ junctions ($dU/dt > 10^{12}$ V/s). The voltage drop across the diode may reach values exceeding its static breakdown voltage up to two times, and, after that value is reached, it decreases in a very short time (less than 100 ps). This process is accompanied by a significant growth of the current through the diode and links with a superfast transition to a conductive state. In fact, it has been shown in [2] that such a transition may be possible as a result of the formation and propagation of a delayed shockwave front. Based on this unique idea the silicon avalanche shapers capable of switching powers up to hundreds of kilowatts at short times (70…100 picoseconds) were designed [3].

A detailed analysis of this superfast switching effect is undoubtedly of both practical and fundamental interest as is the problem of the design of a superfast closing switch based on new and perspective materials, such as 4H-SiC. For instance, the results of the design, simulation and experimental studies of the nano- and subnanosecond opening switches (the drift step recovery diodes, or DSRDs) based on 4H-SiC that are reported in [4…6] approve the possibility of a qualitative improvement of the 4H-SiC devices over silicon devices.

The following paper states for the first time the prospects of shaping voltage pulses with 20…30 picosecond rise times and magnitudes of kilovolt orders in an ultrashort pulse generator with the 4H-SiC diode avalanche shaper implemented as a superfast closing switch.

2. Simulation

The examined diode avalanche shaper has a $p^+–p–n^+$ structure with the thicknesses of the epilayers, respectively: 10 um, 10 um and 100 um. The concentrations of acceptors (Al) and donors (N) in $p$-type and $n$-type layers are, respectively: $10^{19}$ cm$^{-3}$, $8 \cdot 10^{14}$ cm$^{-3}$ and $10^{19}$ cm$^{-3}$. The area of the top contact is 0.1 mm$^2$, likewise in [7]. The doping profile of the structure is presented in Figure 1. The static breakdown voltage of the following structure is 1500 V. The operation of the avalanche shaper had been studied in the ultrashort pulse generator circuit with inductive energy accumulation shown in Figure 2.
The simulation has been carried out using Synopsys Sentaurus TCAD software in the drift-diffusion approach with the following effects accounted: bandgap narrowing at high doping levels, avalanche generation in high fields, incomplete dopants ionization, Shockley-Read-Hall recombination, Auger recombination and various mobility models including mobility lowering in highly doped regions and carrier velocity saturation at high fields.

The simulation had been executed in the mixed mode in order to combine the actual physical simulation of the diodes D1…D3 and D4 and the SPICE simulation of the ultrashort pulse generator circuit with the avalanche shaper D4 implemented as a superfast closing switch.

![Figure 1. Doping profile of the avalanche shaper (marked line) and ionized doping distribution (dashed line)](image1)

![Figure 2. The ultrashort pulse generator circuit](image2)

In the Figure 2 the D1…D3 diodes stand for a high-voltage diode stack consisting of three single-crystal drift step recovery diodes (DSRDs) – the ultrafast opening switches. It was shown in [4] that it is possible to implement single-crystal 4H-SiC DSRDs in ultrashort pulse generators. The magnitudes of the generated pulses may reach the values varying from 1500 V to 2000 V with rise times less than 500 picoseconds. The article [4] also deals with information on the possibility of assembling single-crystal DSRDs into the high-voltage diode stacks in order to raise the switching voltages keeping the same subnanosecond rise times.

The implemented DSRDs D1…D3 have $p^+\text{-}p\text{-}n^+$ structures with the thicknesses of the epilayers respectively: 5 um, 8 um and 100 um. The concentration of acceptors and donors in $p$-type and $n$-type layers are respectively: $10^{19}$ cm$^{-3}$, $10^{16}$ cm$^{-3}$ and $10^{19}$ cm$^{-3}$. The areas of the top contacts are 0.9 mm$^2$. The static breakdown voltage of a single DSRD in a stack is estimated 1000 V, so the whole stack’s static breakdown occurs at 3000 V.

The operation principle of the generator circuit is described below. At the initial moment of time the C2 capacitor is charged to the potential of voltage difference between the V1 and V2 sources, so when the switch S1 is closed, the diode stack D1…D3 is biased forward with a current pulse duration of $T_+$ (50 ns). The period $T_+$ is defined by the values of L2 inductance and C2 capacitance. Throughout the $T_+$ period the injection of the non-equilibrium carriers into the base regions of D1…D3 diodes occurs, so the whole diode stack is in a conductive state.

By the end of the forward current pulse the switch S1 opens and the period of oscillations in the circuit is now defined by the values of L2 inductance and C1, C2 capacitances. The L2 coil accumulates energy, which is proportional to the reverse current flowing through the diode stack D1…D3. The voltage at the stack changes its polarity, so that the extraction of the non-equilibrium carriers could begin, so for the $T_-$ period the voltage drop at the stack is low.
By the end of non-equilibrium carriers extraction the diodes’ D1…D3 recovery process begins: majority carriers are being synchronously extracted from the structures’ base regions with saturated velocities in a short time $t_F$, which is followed by a significant rise of the whole stack’s resistance and accompanied by shaping an impulse with a very steep front at the load resistor R3. The amplitude of the impulse greatly exceeds the power supply voltage $V_1$.

The switching process of the avalanche shaper D4 is presented in Figure 3. The voltage pulse shaped at the D1…D3 stack acts as a driving pulse for the avalanche shaper D4. By the end of the slow part of the driving pulse the base region of the shaper D4 is fully depleted with majority carriers, so at the stage of the steep voltage rise at the diode stack the current at the shaper is defined by only the displacement current and by the time $t = 64.93$ ns the voltage at the structure is $U_{D4\text{MAX}} = 2620$ V, which is 1.75 times greater than the static breakdown voltage. After the voltage at D4 has reached its peak value the propagation of the shockwave in the base region of the structure is initiated and during the following 19 picoseconds the device is switching to a conductive state, the latter process being accompanied by shaping the voltage pulse at the R3 load resistor with the same rise time as that of the D4 switching.

The V3 source is implemented with the purpose of biasing the avalanche shaper D4 in the reverse direction in order to speed up its recovery into a non-conductive state after the switching.

![Figure 3. The process of the D4 shaper switching (red line) with the driving pulse at the DSRD stack D1…D3 (black line)](image)

**3. Results and conclusion**

In the following study we have successfully demonstrated the 4H-SiC diode avalanche shaper’s operation in an ultrashort pulse generator circuit where the device has been implemented as a superfast closing switch. The simulation results are presented in Figures 4 and 5.

The voltage pulse shaped at the DSRD stack D1…D3 (Figure 4, black line) is of 3400 V amplitude and 160 ps rise time measured at $(0.2 - 0.9)U_{\text{STACK MAX}}$. 

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A mentioned earlier, the process of the shaper’s transition into a conductive state goes along with a very steep voltage rise at the R3 load resistor (Figure 4). The amplitude of the voltage pulse at R3 made up to 3300 V. The rise time at (0.2 – 0.9)ULoad Max is estimated as 19 picoseconds.

While the pointwise derivation of the impulse (Figure 5, dashed line) demonstrated that the shaper’s switching velocity is time dependent, the mean voltage rise velocity at the efficient part of its switching process is of 121 V/ps.

References
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