ANALYSIS OF CARRIER LIFETIME EFFECTS ON HV SIC PIN DIODES AT ELEVATED PULSED SWITCHING CONDITIONS

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Abstract

Future Army power systems will require utilizing high-power and high-voltage SiC devices in order to meet size, weight, volume, and high power density for fast switching requirements at both component and system levels. This paper presents the modeling and simulation of a high voltage (>12kV) silicon carbide PiN diode for high action pulsed power applications. A model of a high power PiN diode was developed in the Silvaco Atlas software to better understand the extreme electrical stresses in the power diode when subjected to a high-current pulse. The impact of carrier lifetime on pulsed switching performance of silicon carbide (SiC) PiN diode was investigated.

I. INTRODUCTION

High-power and high-voltage diodes are essential for robust and reliable protection of active and passive components in continuous and pulsed power systems. Silicon carbide (SiC) high-voltage bipolar diodes have attracted great attention as an alternative solution to silicon diodes for various Army high-power continuous and pulsed power applications. SiC’s superior material properties make it a more viable candidate than its silicon (Si) counterpart for higher action (I²t) applications. These enhanced material properties include: high critical electric field, low intrinsic carrier concentration, and high thermal conductivity, high saturation velocity, high Young’s Modulus compared to its silicon counterpart [1-3].

The U.S. Army Research Laboratory is investigating the electro-thermal effects of carrier transport in high voltage SiC devices subjected to extreme (>1kA/cm²) pulsed power conditions at unique time-scales in the microsecond and millisecond regimes through physics-based modeling and simulation. This paper discusses the effects of ambipolar carrier lifetime on the performance of high voltage SiC PiN diodes under elevated pulsed current switching conditions. The numerical modeling and two-dimensional (2D) simulation of the high power PiN diode structure was implemented in the Silvaco Atlas software. The carrier lifetime models implemented in the device simulator are a function of carrier doping concentration and temperature. The ambipolar lifetime analysis values used in the Atlas simulator was based on the spatial lifetime variation ranges (0.5μs to 2.0 μs) that have been reported for thick n-type 4H-SiC [4-7]. The details of the device structure, the modeling approach, and simulation results depicting carrier lifetime effects on the electro-thermal performance of a high voltage SiC PiN diode will be presented in the following paper.

II. DEVICE MODELING APPROACH

It is essential to implement accurate SiC physics-based models to characterize the transient characteristics of the SiC devices appropriately under extreme pulsed conditions. The primary physics-based models employed in the numerical simulator Atlas includes: a low and high-electric field mobility model which accounts for phonon scattering and ionized impurity scattering of carriers due to elevated temperature and doping concentration, respectively [8], low and high level injection carrier recombination model (SRH and Auger) [9], and an impact ionization model which accounts for the carrier generation due to high electric fields [10]. The carrier lifetimes are modeled as a function of doping concentration and temperature [11-12]. For this research, the electron carrier lifetime (τₑ) is assumed to be five times higher than the hole lifetime (τₕ) [12-13]. Since the electron mobility in 4H-SiC is typically eight to ten times higher than the hole mobility, the electron diffusion coefficient (Dₑ) and diffusion length (Lₑ) will be much higher than the hole diffusion coefficient (Dₕ) and diffusion length (Lₕ) implying that electron lifetime would be much higher than the hole lifetime [5]. Furthermore, the values of τₑ and τₕ are measured in the lightly doped region of the device and then scaled down to the square root as the doping concentration increases. This clearly implies that carrier lifetime decrease with an increase in doping concentration [12-13].
Temperature dependent SiC material models such as thermal conductivity and volumetric specific heat were accounted for in this work to portray an accurate electro-thermal behavior of the device under extreme pulsed-switching conditions [14-16]. Fig. 1 depicts thermal conductivity of SiC at various temperatures. Accurate modeling of the material thermal conductivity is essential for steady-state simulation of the device. Furthermore, accurate modeling of the volumetric specific heat is imperative for transient simulation of the device.

![Figure 1. Comparison of model vs. measured data of the thermal conductivity of SiC](image1)

The expression used to model the thermal conductivity of SiC is shown in Eq. (1), where TC.A, TC.B, and TC.C are material dependent fitting parameters and $T_L$ is the lattice temperature [11].

$$\kappa(T) = \frac{1}{(TC.A + (TC.B)*T_L^2 + (TC.C)*T_L^2)}$$ (1)

The expression used to model the volumetric specific heat of SiC is shown in Eq. (2). In the volumetric specific heat equation, HC.A, HC.B, and HC.C are material dependent fitting parameters and $T_L$ is the lattice temperature [11].

$$C = HC.A + HC.B*T_L + HC.C*T_L^2 + \frac{HC.D}{T_L^2}$$ (2)

Fig. 2 depicts volumetric specific heat of SiC with respect to temperature.

![Figure 2. Comparison of model vs. measured data of the volumetric specific heat of SiC](image2)

When high-level carrier injection occurs in the drift region of a bipolar device such as a PiN diode, the ambipolar lifetime ($\tau_a$) is a summation of the electron carrier lifetime ($\tau_e$) and hole carrier lifetime ($\tau_h$) because lifetime is independent of recombination traps. An analytical temperature-dependent carrier lifetime model was implemented in the Atlas simulator. The temperature dependent electron lifetime model is shown in Eq.3. In the following equation below, $T_L$ is the lattice temperature, $\tau_{no}$ is the initial electron lifetime at room temperature, and $LT_{\tau n}$ is the temperature dependent electron lifetime coefficient. $LT_{\tau n}$ has to be greater than zero in order to enable the temperature dependent lifetime model in the simulator. For this work, the temperature dependent electron lifetime coefficient was 1.5. The temperature dependent hole lifetime expression correlates with expression shown in equation 3[11].

$$\tau_n = \tau_{no} \left( \frac{T_L}{300} \right)^{LT - \tau n}$$ (3)

A plot of carrier lifetime with respect to temperature is shown in Figure 3. As mentioned previously, the electron carrier lifetime ($\tau_{no}$) was five times larger than the hole carrier lifetime ($\tau_{po}$) as shown in Fig. 3. Fig. 3 also depicts a plot of an ambipolar lifetime of 1 μs at ambient temperature and the contribution of the electron lifetime and hole lifetime. The power law increase in lifetime with temperature in Fig. 3 is equivalent for all the ambipolar lifetimes investigated in this research.
Figure 3. Plot of carrier lifetime temperature dependent model with respect to temperature

All the physics-based models and parameters implemented in these simulations are realistic values based on what have been reported in literature for 4H-SiC [8-13].

III. HV SiC PIN DIODE DEVELOPMENT

A two-dimensional, numerical-based simulation was performed to understand the physical phenomena that occur in the SiC PiN diode when pulsed under extreme conditions. This discovery and understanding is essential in developing optimized devices with improved performance for a range of high power applications. The diode structure implemented in the physics-based numerical simulator is displayed in Fig. 4.

Figure 4. Cross section view of high voltage SiC PiN diode

The diode structure implemented in Atlas had a drift region thickness of 120 microns with a doping concentration of 2e14 cm⁻³. The drift region thickness and doping concentration provides the device with sufficient hold-off voltages capability greater than 12kV. Both the anode and cathode region of the diode was heavily doped p-type and n-type, respectively. The anode region had a thickness of 2 micron to minimize the total on-resistance of the diode while enhancing the hole carrier injection on the topside of the diode. The doping concentration and drift region thickness used in the simulation are typical values that have been reported for high voltage SiC PiN diodes [7, 17-18]. The active area of the diode implemented in Atlas was approximately 0.5cm². To account for the die active area of approximately 0.5cm², the current flowing through the diode was scaled accordingly in the z-axis (quasi 3D). The mesh width in the z-direction was 1.3e6 microns.

IV. DEVICE SIMULATION APPROACH

The simulation of the conduction of the SiC PiN diode under extreme conditions was implemented by replicating a voltage pulse waveform equivalent to the forward voltage drop across the high voltage diode to circumvent the implementation of various passive components in a more complex mixed-mode circuit simulation. High-current, wide-pulse diode evaluations previously conducted at the U.S. Army Research Laboratory utilized a circuit like the one shown in Fig. 5, where the SiC diode is represented as the DUT [18-19]. To mimic identical electrical stress on the modeled diode without incorporating the passive components, the high current through the diode was simulated by a pulsed voltage profile. With the appropriate capacitance, inductance, and resistive load, the pulse evaluation circuit depicted in Figure 5 can produce a 1-ms pulse current waveform that may be required in high action applications. The SiC diode (DUT) is in-line with a GTO device that is triggered into the ON-state with a fiber-optic transmitter once the capacitor has been charged up to the desired voltage of choice with a power supply. The discharged capacitor produces the current flow across the switch and DUT. The current waveform is shaped by the inductor and resistive load in the pulse circuit [18-19].

Figure 5. Capacitor discharge circuit schematic

A transient voltage pulse was applied to the PiN diode structure implemented in Atlas as illustrated in Fig. 6. This transient voltage pulse induced current flow into the device. The current flowing in the device was equivalent to a pulse current that would be generated by the capacitor.
discharge circuit shown in Fig. 5. The amount of current flow in the diode structure is primarily dependent on the conductivity (resistance) of the drift region or i-layer. The simulation approach utilized in this work evades the cumbersome implementation of transient mixed-mode circuit simulations by eliminating the implementation of both active and passive components in the pulse circuit and primarily focusing on the device under test. The approach implemented is much more efficient and produces faster solutions based on the forward voltage characteristics of the device under test at a given peak pulse current rating. The 1-ms current pulse is the baseline transient current for the carrier lifetime investigation of the SiC PiN diode.

![Figure 6. Simulation approach used to generate elevated pulse current flow across diode](image)

V. SIMULATION RESULTS

The simulation of the forward characteristics of a high voltage (>12kV) SiC PiN diode at various ambipolar lifetimes is displayed in Fig. 7. The simulation of the HV diode forward characteristic emulates the pulsed I-V characterization of a SiC PiN diode that would be acquired from a Tektronix 371 curve tracer in pulse mode [7]. Based on the results in Figure 7, the ambipolar lifetime has a drastic impact on the forward voltage drop of SiC PiN diode at the given current level of 560A (Anode current density \( J_F \)=1160A/cm\(^2\) based on active area).

The results imply that a high ambipolar lifetime enhance the conductivity modulation of the SiC PiN diode significantly. Furthermore, there is a drastic increase in the ambipolar diffusion length with an increase in ambipolar lifetime as illustrated by the forward characteristics of the diode in Fig. 7.

Table 1. Pulsed I-V simulation of high voltage diode electro-thermal performance with respect to ambipolar lifetime at a given current rate of 560A \( (J_F=1120A/cm^2 \) based on active area)

<table>
<thead>
<tr>
<th>Lifetime (μs)</th>
<th>Current (A)</th>
<th>Forward Voltage (V)</th>
<th>Maximum Power (W)</th>
<th>Maximum Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>560</td>
<td>10.2</td>
<td>5712</td>
<td>314</td>
</tr>
<tr>
<td>1.0</td>
<td>550</td>
<td>7.5</td>
<td>4200</td>
<td>310</td>
</tr>
<tr>
<td>2.0</td>
<td>560</td>
<td>6.5</td>
<td>3640</td>
<td>308</td>
</tr>
<tr>
<td>4.0</td>
<td>560</td>
<td>6.1</td>
<td>3416</td>
<td>306</td>
</tr>
</tbody>
</table>

![Figure 7. Pulsed I-V simulation of high voltage diode with respect to ambipolar lifetime](image)

Figure 8 depicts the peak current capability the modeled SiC PiN diode at a given peak forward voltage of 18.5V. The plot shows a drastic increase of peak pulse current with an ambipolar lifetime of 4 μs compared to 0.5 μs. A peak current of 3.1kA is obtained with an ambipolar lifetime of 4 μs compared to peak current of 2.2kA with an ambipolar lifetime of 0.5 μs.

![Figure 8. Pulse current at various ambipolar lifetime at a given pulse voltage (note: peak pulse voltage was 18.5V)](image)
The simulation results illustrated in Figure 9 suggest excess heating and temperature rate of change of greater than 150°C at elevated 1-ms, 2kA peak current level within 2kA for ambipolar lifetimes ranging from 0.5μs to 2μs. It is projected that SiC can operate at junction temperatures greater than 300°C. However, high power packaging technology must be improved to enable SiC bipolar power devices to operate at their full potential. These simulation results suggest that the packaging methodology used to package PiN diodes for pulsed applications is extremely essential. Furthermore, it should be noted that the maximum temperature in the diode occurs well after the peak pulse current and it is primarily attributed to recombination heating induced by the high level injection of holes and electrons in the drift region. At maximum steady-state levels the power dissipated across the device is due to carrier recombination in the bulk region of the device. At peak elevated surge levels however, the power dissipated is due to surface recombination and is also dominated by the effects of ohmic or joule heating [13].

Figure 9. Maximum device temperature for the 1-ms pulse duration considering different ambipolar lifetime values

VI. SUMMARY

The diode is the basic building block for bipolar devices such as bipolar junction transistor (BJT), insulated gate bipolar transistors (IGBT), gate turn-off thyristors (GTOs), and mos-controlled thyristors (MCTs). The following research investigated the pulse current handling capability of high voltage SiC PiN diodes for high action applications utilizing physics-based simulation with Silvaco Atlas software.

The primary purpose of the pulse analysis was to evaluate the electro-thermal behavior of the SiC PiN under extreme pulse-switching conditions. This work also investigated the impact of carrier lifetime on the electro-thermal performance of high voltage SiC PiN diodes. The simulations implemented in Atlas was of a high voltage (>12kV) SiC PiN diode. It was determined by simulation that carrier lifetime not only minimizes the on-resistance at a given current density but it also reduces the maximum peak temperature at a given current density which could potentially extend the lifespan of the device under extreme pulsed switching operation.

VII. REFERENCES


[16] Rohm and Hass company, CVD SILICON CARBIDE™ Datasheet, September 2000

