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US Army Research Laboratory

Simulation of a High-Voltage Silicon Carbide (SiC) Power Diode under High-Action Pulsed Operation

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14. ABSTRACT

Future Army pulsed-power applications require semiconductor devices that will meet high-power, low-weight and volume, and fast-switching-speed constraints. This report details the pulse evaluation and corresponding modeling and simulation of 10-kV silicon carbide PiN diodes. The diode conducted a pulse current of 2.6 kA at a 1-ms pulse width with an instantaneous power dissipation of 26 kW. 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. Simulation of the on-state current and voltage across the diode closely matched measured data. Current density distribution through the device was analyzed and areas of localized high current density were identified.

15. SUBJECT TERMS

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1. Introduction

The US Army Research Laboratory (ARL) is interested developing and using modeling and simulation of the inner workings of high-power silicon carbide (SiC) devices that are subjected to elevated current densities at unique timescales in the microsecond and millisecond regime. Accurate physics-based SiC models will enable better optimization of SiC device designs leading to enhanced device performance. These physics-based SiC models will also enable the prediction of device performance at various extreme pulsed conditions, expanding the application space of SiC power devices. This research presents the modeling of a SiC power diode at extreme pulsed power densities and shows direct correlation between measured high-power characterization and simulated current and voltage waveforms. SiC PiN diodes are slated to replace current silicon (Si) diodes used in various pulsed-power applications. These high-power diodes are critical in various pulsed systems to protect both active and passive components from reverse voltages and currents. SiC's electrical, thermal, and mechanical properties make it a more viable candidate than its Si counterpart for high-action pulsed-power applications.[1,2]

A series of pulse evaluations were conducted with SiC PiN diodes in this work. The diodes were used for reverse voltage blocking in series connection with a Si super-gate-turn-off (SGTO) thyristor device in a high-energy, under-damped system. Details of the Si SGTO's design[3,4] and pulsed-power capabilities have been reported in literature.[5]

2. SiC PiN Diode Structure

The device evaluation and simulation presented in this work are based on a 10-kV, 1-cm^2 SiC PiN diode designed and fabricated by Cree Inc. The SiC diodes used in this work were fabricated from low-defect wafers with a 90-µm drift layer and 4° off-ward cut. The 600-µm multi-zone junction termination structure further enables these devices to reliably block voltage up to 10 kV with less than 100 µA of leakage current. The cross-sectional view of the SiC diode is displayed in Fig. 1. An image of the diode with a metallization and polyimide overlay with a 30-mm^2 contact opening is shown in Fig. 2.

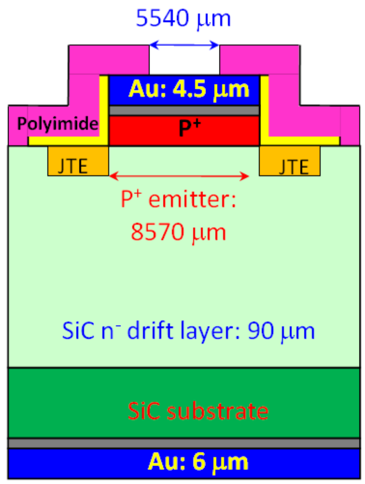


Fig. 1 Cross-sectional view of the 1.0-cm², 10-kV SiC PiN diode

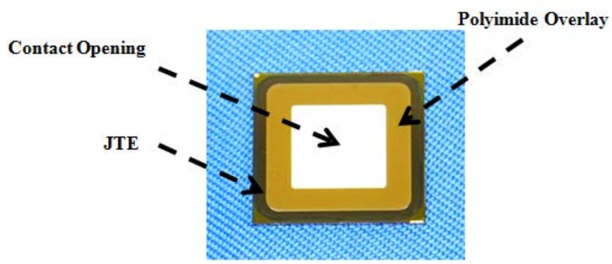


Fig. 2 Image of the diode with a metallization and polyimide overlay with a 30-mm² contact opening

The die area of the PiN diode is 1.0 cm². Pulsed analysis of the diode's behavior in a small-scale module has been reported at the IEEE Power Modulator and High Voltage Conference.[6]

3. 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 include 1) 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;[7–10] 2) low- and high-level injection carrier recombination models (Shockley-Read-Hall Recombination and Auger);[9] and 3) an impact ionization model, which accounts for the carrier generation due to high electric fields.[8–10] The carrier lifetimes are modeled as a function of doping concentration and temperature.[10,11] For this research, the electron carrier lifetime (τ_{no}) is assumed to be five times higher than the hole lifetime (τ_{po}).[12,13] Since the electron mobility in 4H-SiC is typically 8 to 10 times higher than the hole mobility, the electron diffusion coefficient (D_n) and diffusion length (L_n) will be much higher than the hole diffusion coefficient (D_p) and diffusion length (L_p), implying that electron lifetime would be much higher than the hole lifetime.[12–14] Furthermore, the values of τ_{po} and τ_{no} 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 the carrier lifetime decreases with an increase in doping concentration.[13]

Temperature-dependent SiC material models, such as thermal conductivity and volumetric specific heat, were accounted for in this work to portray an accurate electrothermal behavior of the device under extreme pulsed-switching conditions.[10] Figure 3 depicts the 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.

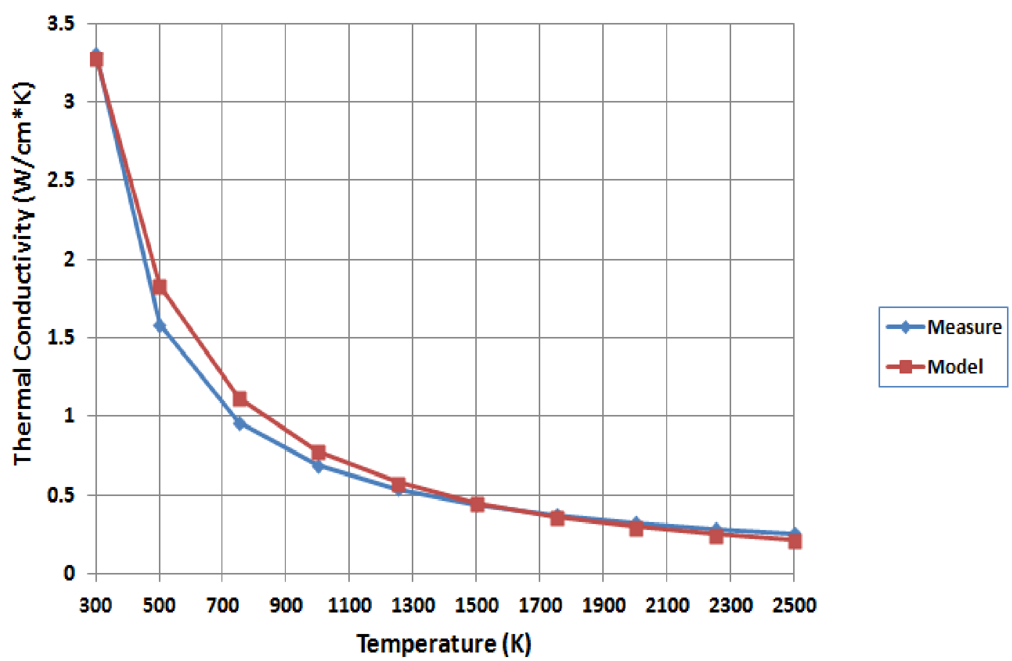


Fig. 3 Comparison of model vs. measured data of the thermal conductivity of SiC

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.[10]

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

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.[10]

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

Figure 4 depicts the volumetric specific heat of SiC with respect to temperature.

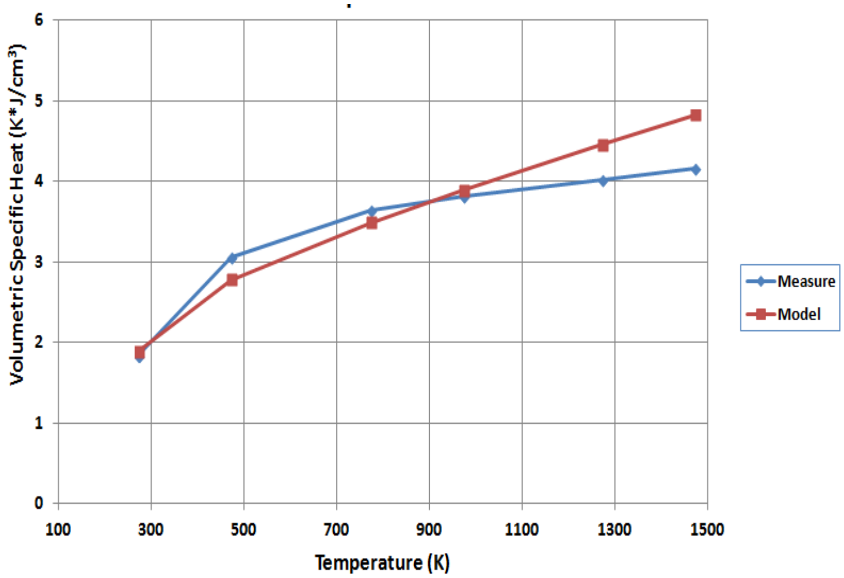


Fig. 4 Comparison of model vs. measured data of the volumetric specific heat of SiC

When high-level carrier injection occurs in the drift region of a bipolar device such as a PiN diode, the ambipolar lifetime (τ_a) is a summation of the electron carrier lifetime (τ_n) and hole carrier lifetime (τ_p), 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, where T_L is the lattice temperature, τ_{no} is the initial electron lifetime at room temperature, and LT_τn is the temperature-dependent electron lifetime coefficient. LT_τn has to be greater than zero 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 Eq. 3.[10]

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

A plot of carrier lifetime with respect to temperature is shown in Fig. 6. As mentioned previously, the electron carrier lifetime (τ_{no}) was five times larger than the hole carrier lifetime (τ_{po}), as shown in Fig. 5. Figure 5 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 characteristics in Fig. 5 is equivalent for all the ambipolar lifetimes investigated in this research.

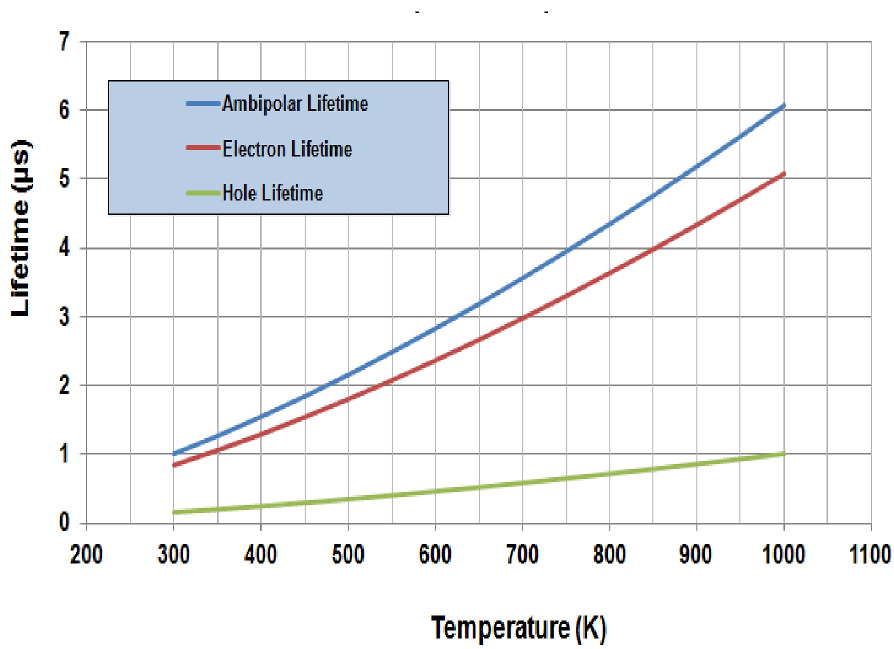
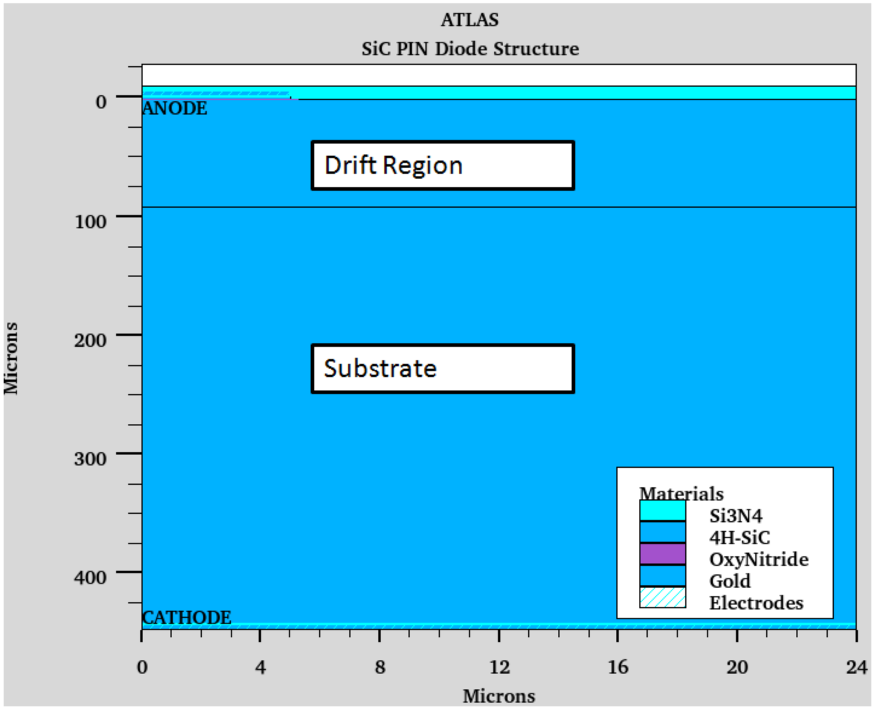


Fig. 5 Plot of the 1-µs ambipolar carrier lifetime temperature-dependent model with respect to temperature.

The ambipolar lifetime value used in the simulation was 2 µs based on the spatial variation lifetime range (<0.5 to 2.1 µs) that has been reported for thick n-4H-SiC utilizing various optical measurement techniques.[14] 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.[7–12]

4. High-Voltage (HV) SiC PiN Diode Development

A 2-D 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. 6.



Fig, 6 Cross-sectional view of the HV SiC PiN diode

The diode structure implemented in Atlas had a drift region thickness of 90 µm with a doping concentration of 2e14 cm^{-3}. The dimensions and doping profile are based upon the PiN design fabricated by Cree. The drift region thickness and doping concentration provides the device with a sufficient hold-off voltage capability greater than 9 kV. Both the anode and cathode regions of the diode were heavily doped p- and n-types, respectively. The anode region had a thickness of 2 µm 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 HV SiC PiN diodes.[6] The active area of the diode implemented in Atlas was approximately 0.72 cm^2. To account for the die active area of approximately 0.72 cm^2, the current flowing through the diode was scaled accordingly in the z-axis (quasi 3-D). The mesh width in the z-direction was 3.0e6 µm.

5. 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 HV 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 ARL used a circuit like the one shown in Fig. 8, where the SiC diode is represented as the device under test (DUT). The SiC diode (DUT) is connected in series with a Si SGTO 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 evaluation circuit had a custom-made inductor with an inductance of approximately 180 µH. The capacitors used in circuit were three 175-µF General Atomics metalized capacitors rated for 22 kV in a parallel configuration; a total charge capacitance of 525 µF and a load resistance of 200 mΩ were used in the pulsed circuit. The primary purpose of the anti-parallel Solidtron Si diode was to mitigate the reverse voltage recovery that the Si SGTO must endure after being subjected to an elevated-current pulse. To emulate the 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 Fig. 7 can produce a 1-ms pulse current waveform, which may be required in high-action applications. The pulse current and on-state voltage measurements obtained from the evaluation circuit were used to assist the model development and validity of the physics-based simulations.

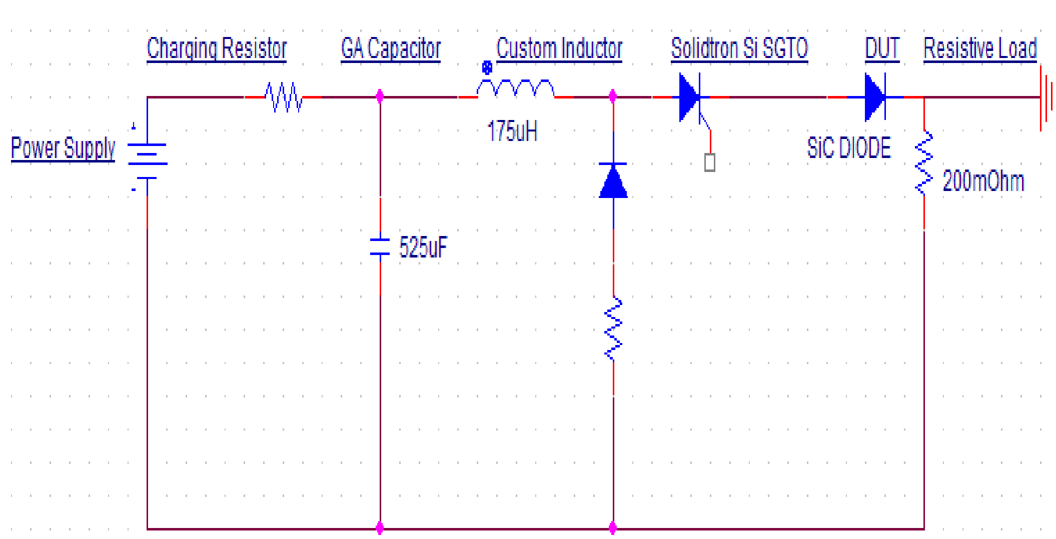


Fig. 7 Circuit schematic used to evaluate the HV SiC PiN diode (DUT)

A transient voltage pulse was applied to the PiN diode structure implemented in Atlas, as illustrated in Fig. 8. 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. 8. 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 used 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 DUT. The approach implemented is much more efficient and produces faster solutions based on the forward voltage characteristics of the DUT 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.

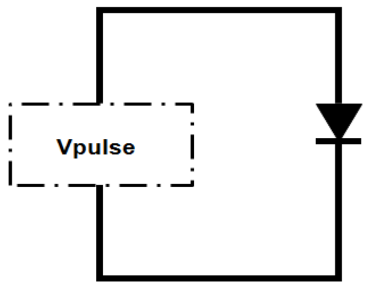


Fig. 8 Simulation approach used to generate an elevated pulse current flow across the diode

6. Results and Discussion

At elevated pulse current levels, the conductivity of the drift region is enhanced drastically due to the excess of hole and electron concentrations in that region. The conductivity modulation in the drift region reduces the diode's total on-state resistance and enables the device to withstand large surge currents and power. As the current density increases, the anode voltage increases due to excess carriers colliding with each other (carrier–carrier scattering) and thermal vibrations in the lattice, which drastically reduces the carrier mobility of the device. Figure 9 illustrates an overlay of the model results and measured pulse data of the diode at 2.6 kA, respectively. The high localized current density near the anode edge (as labeled later in Fig. 11) is induced by current crowding and creates a lateral voltage drop across the anode region.

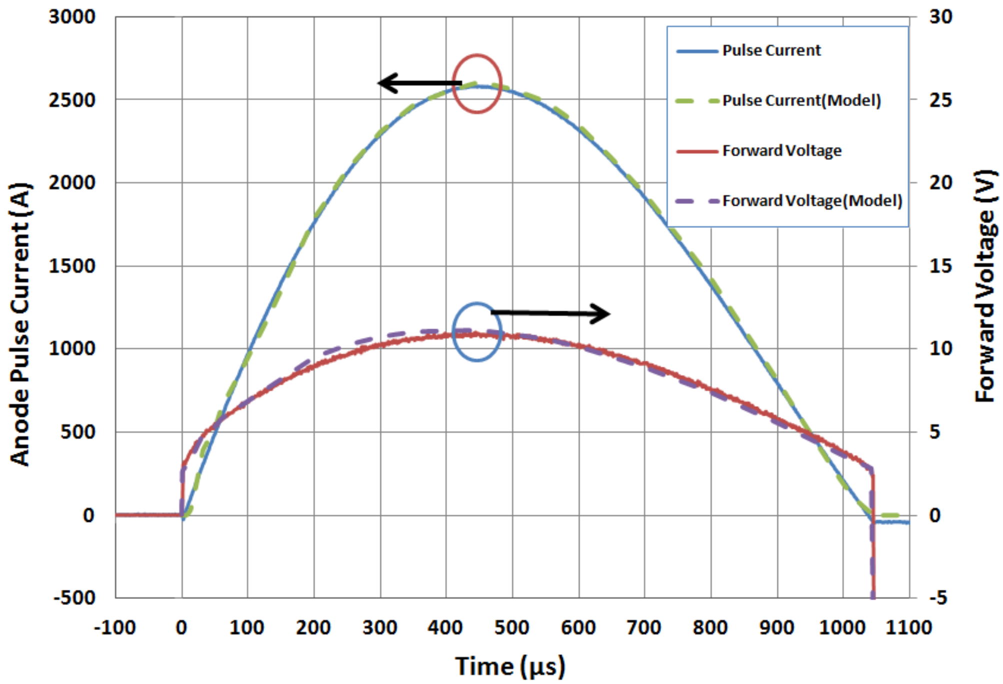


Fig. 9 The 10-kV SiC PiN diode transient electrical model vs. experimental results at a 1-ms peak pulse current of 2.6 kA

Based on the pulse analysis, the SiC PiN diodes are able to withstand instantaneous peak powers greater than 26 kW. These results clearly highlight SiC's enhanced thermal conductivity capability. 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. The simulation result illustrated in Fig.10 shows that localized current density at a peak pulse current of 2.6 kA is about 22 kA/cm^2, nearly nine times the global pulse current magnitude near the anode edge. This corner effect near the anode generates hotspots, which could eventually lead to the catastrophic failure of the device. 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.

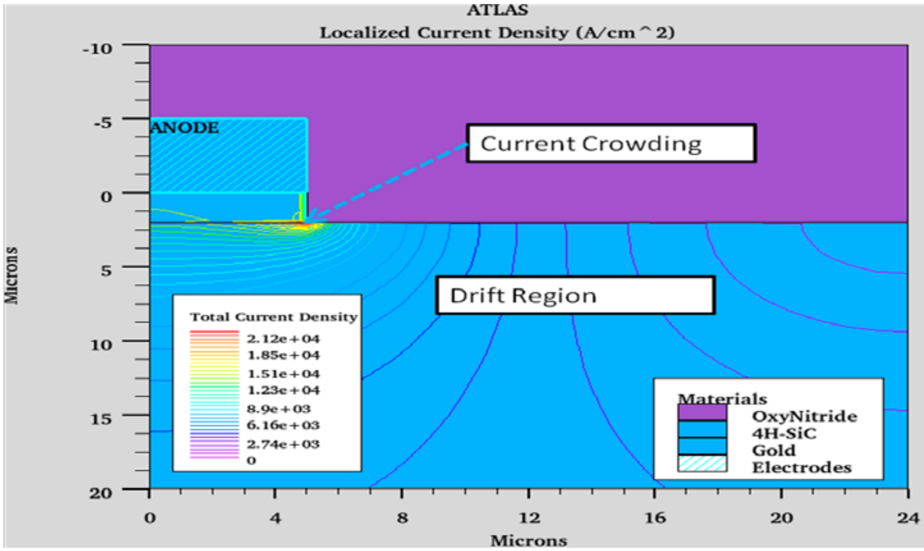


Fig. 10 Localized current density of the SiC PiN diode at a peak pulse current of 2.6 kA

The simulation results illustrated in Fig. 11 suggest excess heating and a temperature rate of change of greater than 200 °C at the elevated 1-ms, 2.6-kA peak current level. 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. Furthermore, it should be noted that the maximum temperature in the diode occurs well after the peak pulse current and 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 power levels, however, the power dissipated is due to surface recombination and is also dominated by the effects of ohmic or joule heating.

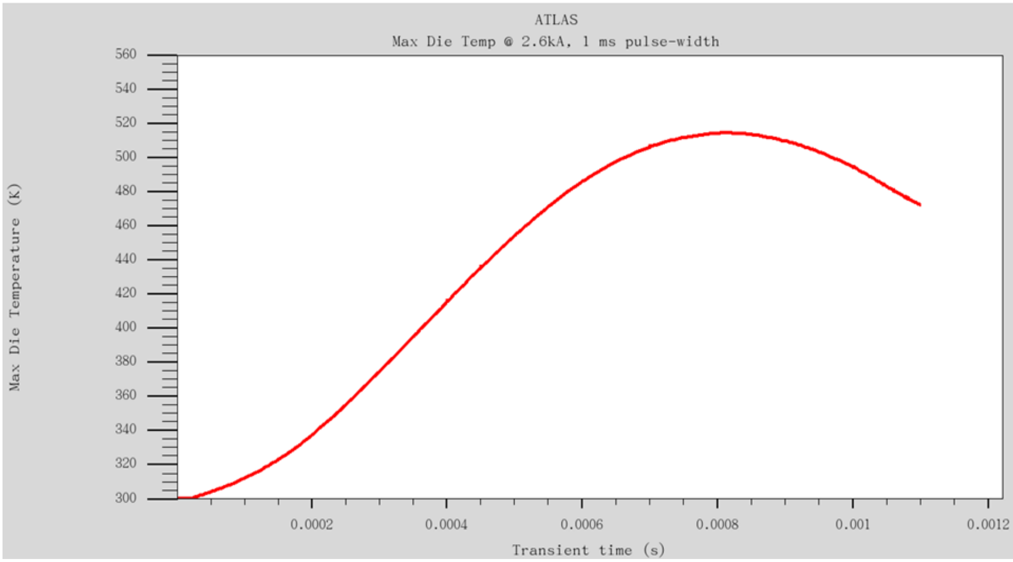


Fig. 11 Device temperature at 2.6 kA for the 1-ms pulse duration

7. Summary and Conclusion

This work presents the successful simulation of a 4H-SiC PiN diode under extreme pulsed conditions. The simulation reveals localized current density near the anode edge at elevated pulse current levels, which could generate hotspots, potentially causing the device to degrade drastically with time. The diode is the basic building block for bipolar devices such as a bipolar junction transistor, insulated gate bipolar transistor, and thyristors. The simulation results from this work also provide insight to how the SGTO conducts in the on-state when subjected to extreme pulsed conditions. Overall, the 10-kV, 1-cm^2 SiC PiN diodes are very robust devices that can be reliably pulsed at current levels up to 2.6 kA with a 1-ms pulse width. The thermal transients that result from operating these devices at extreme pulsed conditions was also investigated and reported in this work.

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ARL	US Army Research Laboratory
DUT	device under test
HV	high voltage
SGTO	super-gate-turn-off
Si	silicon
SiC	silicon carbide

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