Electro-Thermal, Transient, Mixed-Mode 2D Simulation Study of SiC Power Thyristors Operating Under Pulsed-Power Conditions†

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Abstract

An electro-thermal, transient device simulation study of Silicon Carbide (SiC) power thyristors operating in a pulsed-power circuit at extremely high current density has been carried out within the drift-diffusion approximation and classical heat generation and transport theory using MEDICI* [1]. The convergence problems normally associated with Technology Computer-Aided Design (TCAD) simulations of SiC bipolar devices were overcome without artificially increasing the free carrier concentration by optical carrier generation, or by increasing the initial temperature (thermal carrier generation). The simulation results closely predict the actual operating conditions of the SiC thyristor in the pulsed-power circuit and are used to interpret the results of experimental failure limit studies [2]. It is shown that TCAD simulations can realistically predict the electrical and thermal properties of complex SiC bipolar semiconductor devices operating under fast transient, pulsed-power conditions.

1 Introduction

SiC is a wide-bandgap compound semiconductor material with 4H-SiC (the SiC poly-type most commonly used in power device applications) having a band-gap of 3.26 eV, a breakdown electric field of 2.2 x 10^6 V/cm (> 7x Si) and a thermal conductivity of 4.5 W/cm K @ 300 K (>3x that of Si). These material properties give SiC devices a number of advantages over Si: higher blocking voltage, higher radiation tolerance, higher switching speed, lower switching power losses, higher operating temperature, and better heat and current handling capabilities. These properties are of particular importance for devices used in pulsed-power applications because they enable pulsed current densities up to 50 times higher than with silicon [2].

Due to the wide bandgap of SiC, equilibrium free carrier concentrations at room temperature are extremely low. The low free carrier concentration has long been an obstacle for realistic physical-based modeling of SiC minority-carrier (bipolar) semiconductor devices, due to numerical convergence problems. To achieve convergence for SiC bipolar devices, it is common practice to increase the lattice temperature (typically to 700 °C to 800 °C) or to include a light source in order to artificially increase the concentration of free carriers. These methods for achieving convergence represent a large departure from the actual device operating conditions. The SiC numerical simulations described in this paper are performed without artificially increasing the concentration of free carriers and are used to evaluate the capabilities and failure limits of SiC power thyristors for extremely high current density, pulsed-power conditions [2].

*Any mention of commercial products within this paper is for information only; it does not imply recommendation or endorsement by the National Institute of Standards and Technology.

2 Device simulations

This section presents a selection of results from a comprehensive electro-thermal, transient, mixed-mode 2D MEDICI [1] simulation study of epitaxially manufactured 4H-SiC power thyristors operating under pulsed-power conditions. The device parameters and the circuit used for the simulations are similar to those of the existing 1.2 kV SiC thyristors and circuits being evaluated at the US Army Research Laboratory (ARL) [2].

The simulations were carried out within the framework of the drift-diffusion approximation and classical heat generation and transport theory. Convergence problems due to the low equilibrium concentration of free carriers in SiC were overcome by a simultaneous optimization of several aspects of the simulation. A triangular mesh of varying density able to resolve large gradients was manually constructed. The mesh density distribution was optimized not only to resolve the thyristor physical properties under electrostatic conditions (i.e., high density of mesh points at pn junctions), but also in the regions of the device expected to exhibit large gradients in physical properties during dynamic conditions. The simulation initial conditions, as well as the conditions prior to switching, solution methods, time-steps, and number of iterations, were all manually selected and optimized while keeping error tolerance settings constant. The numerical stability of the solutions was tested for a large range of conditions, including impact-ionization avalanche and temperatures far beyond the range of validity of the physical models used.

The simulated thyristor structure and impurity concentration profile are shown in **Figs. 1a** and **1b**, respectively. The thyristor has an active area of 0.07 cm^2. The abrupt gradients in dopant concentration are a result of the epitaxial method of fabrication used to manufacture the thyristor and can, by themselves, lead to convergence problems.

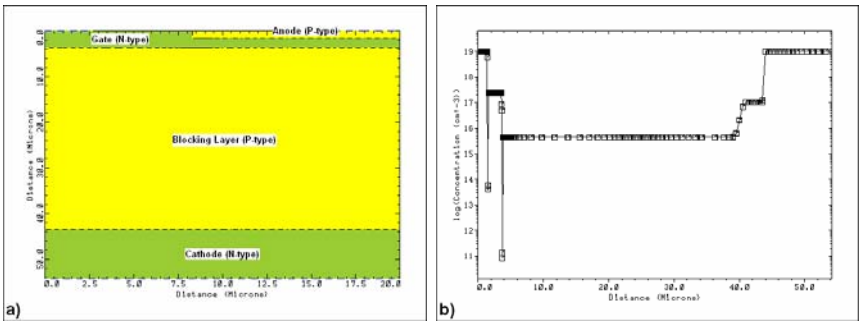

Fig. 1 a) SiC power thyristor simulated structure, showing the anode and gate regions at the top and the cathode at the bottom, **b)** Doping profile of the simulated device. The five impurity layers, from left to right, are: anode, gate, blocking-layer, buffer-layer, and cathode (P^+-N^+-P^--P^+-N^+ type, respectively).

Fig. 2a shows the pulsed-power ring-down circuit used in the simulations and in laboratory experiments. The simulation begins by charging the capacitor "CS" using the voltage power supply "VAA" for 850 μs to reach the initial condition desired on the capacitor before triggering the thyristor. During this time, the power thyristor is in the off-state, blocking the voltage building up across the CS capacitor. **Fig. 2b** shows a 3D plot of the electric field distribution inside the thyristor during the voltage-blocking off-state. The upper left edge of the plot corresponds to the anode-gate region of the thyristor, while the lower right edge is the thyristor cathode. The position of the anode-gate and cathode remains unchanged in all subsequent 3D plots shown in this paper. The width of the

voltage blocking depletion region (about 12 μm) is approximately 15 times less than what it would be in a Si device of equivalent rating, blocking the same voltage [3].

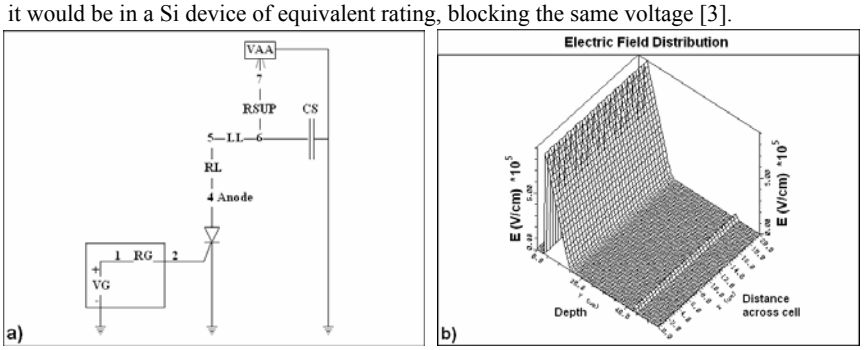

Fig. 2 a) Diagram of the ring-down electric circuit used in the simulations, **b)** Electric field distribution inside the SiC thyristor during the voltage-blocking off-state.

Fig. 3 shows the thyristor gate current and anode voltage waveforms on a 0.3 μs scale during the turn-on phase. At time t=850 μs, a negative 13 A current pulse with a rise time of 20 ns is applied to the thyristor gate. The simulations predict voltage oscillations and a trigger delay (the time between the application of the gate pulse and the fall of the anode voltage). Lower gate currents result in less oscillation but longer trigger delays and more device heating. After a turn-on delay of approximately 0.3 μs, the thyristor becomes conductive and the anode voltage drops to near 10 V. **Fig. 4** shows the anode current ring-down pulse that occurs after the device is triggered and becomes conductive; this is shown on a longer time scale of 2.5 μs as compared to the 0.3 μs time scale of **Fig. 3.**

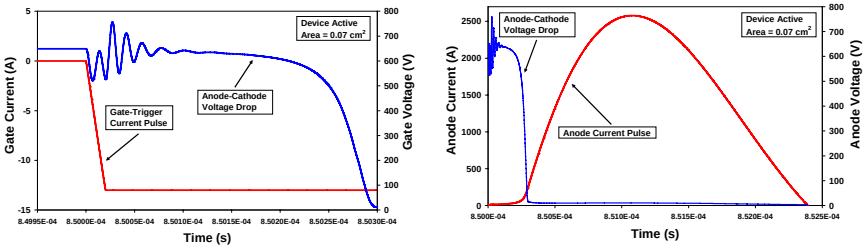

Fig. 3 Gate current and anode voltage waveforms (0.3 μs scale) during the thyristor turn-on phase indicating the negative 13 A current pulse that is applied to the gate at time 850 μs. The capacitor is charged to approximately 650 V prior to the gate trigger pulse.
Fig. 4 Anode voltage and anode current waveforms (2.5 μs scale) during the trigger phase and the subsequent ring-down current pulse for the same simulation as **Fig. 3**. There is approximately a 0.3 μs turn-on delay from gate turn-on up to the point where the thyristor becomes conductive. The half-max anode current pulse width is 1.353 μs, and the peak anode current is 2579 A.

The limitations of SiC for pulsed power applications are determined by the peak temperature and current density that occur inside the device during the pulse. **Fig. 5** shows the current density distribution in the device at the time instant when the peak anode current occurs. The peak current density is approximately 2.2 x 10^5 A/cm^2 in the anode region, while the average current density in the remainder of the active device is approximately 3.7 x 10^4 A/cm^2. The peak temperature increase (ΔT) inside the device shown in **Fig. 6** is approximately 100 °C over the initial temperature of 298 K (room

temperature) and occurs at a different point in time than the peak anode current (t_{Imax}= 851.077 μs and t_{Tmax}=851.640 μs, respectively). The time evolution of the temperature at the anode and cathode electrodes is shown in **Fig. 7.**

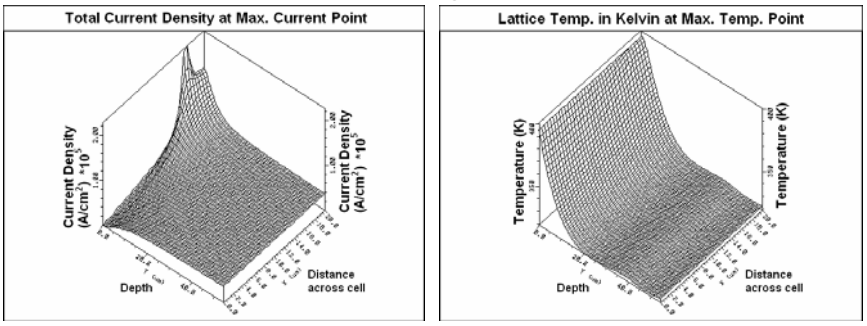

Fig. 5 3D plot of the total current density at the time instant when the peak anode current occurs (t_{Imax}= 851.077 μs). The peak current density is 2.2 x 10^5 A/cm^2 in the anode region, while the average current density in the remainder of the active device is approx. 3.7 x 10^4 A/cm^2.

Fig. 6 3D plot of the temperature distribution inside the thyristor at the time instant when the peak temperature occurs (t_{Tmax}=851.640 μs). The peak temperature increase (ΔT) over room temperature in the anode-gate region of the thyristor is almost 100 °C (T_{peak} =397 K).

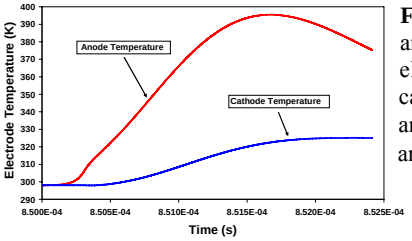

Fig. 7 Time evolution of the temperature at the anode and cathode electrodes. The initial electrode temperature is 298 K. The anode and cathode temperatures reach approximately 395 K and 326 K; an increase of approximately 97 °C and 28 °C above room temperature, respectively.

3 Conclusions

Physics-based TCAD simulations have been used for the electro-thermal study of SiC power thyristors operating under high-current, pulsed-power conditions. All convergence problems normally associated with TCAD simulations of SiC bipolar devices have been solved without artificially increasing the free carrier concentrations. It is demonstrated that TCAD simulations can realistically predict the electrical and thermal properties of complex SiC bipolar semiconductor devices operating under fast pulsed-power transient circuit conditions, with extremely high-current densities. The use of electro-thermal, physics-based device and circuit modeling is fundamental in the study of the operating limits of SiC power devices.

References

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