Physics-based Numerical Simulation for Design of High-Voltage, Extremely-High Current Density SiC Power Devices

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Optimization of SiC power devices requires the use of physics-based numerical modeling to predict the behavior of new device designs in realistic circuit conditions. Realistic transient, electro-thermal numerical modeling of bipolar-type SiC power devices has proven particularly challenging due to numerical convergence problems resulting from the low equilibrium free carrier concentrations in SiC at room temperature. To achieve convergence in numerical simulations of bipolar-type SiC devices, it is common practice to increase the initial equilibrium free carrier concentrations by either increasing the lattice temperature or by including an external light source to generate electron-hole pairs. These artificial methods for achieving numerical convergence introduce a large departure from the actual operating conditions of power devices in most applications. The numerical simulation results presented in this paper are obtained using MEDICI without artificially increasing the initial equilibrium free carrier concentrations to facilitate numerical convergence [1].

This paper presents a selection of results from numerical studies addressing various problems highly relevant to the operation of SiC power devices in power systems such as the speed optimization of high-voltage SiC PiN diodes and the operation of SiC thyristors under extremely-high-current pulse-power conditions. Various methods used to optimize the reverse-recovery performance of 4H-SiC PiN power diodes are studied, including base life time control, emitter efficiency reduction, and regional lifetime control. Pulse-power thyristors are also simulated to determine the limits of reliable performance due to self-heating-induced failure.

Reduction of reverse recovery time and peak current in SiC PiN power diodes are essential to decrease power losses and to improve reliability for the diode and the complementary switching device, as well as for increasing the operating frequency of the systems. **Fig. 1 a)** shows the effect of varying P^+ emitter dopant concentration on the reverse recovery performance of a 10 kV 4H-SiC PiN power diode. Lower P^+ dopant densities result in low reverse recovery time and peak current. However, the on-state voltage drop also increases as shown in **Fig. 1 b)**, making evident the need for a design trade-off. The effect of inserting a low carrier lifetime region (adjacent to the P^+ emitter) within the N^- layer of a 10 kV 4H-SiC PiN power diode is shown in **Fig. 2**, where **a)** shows the effect on reverse recovery performance and **b)** shows the effect on the on-state voltage. The low lifetime layer and/or P^+ emitter dopant concentration reduction provide a more favorable trade-off as compared to uniform lifetime reduction in the entire N^--region. However, the P^+ emitter dopant concentration reduction is also limited as P^+ emitter dopant concentration approaches that of the N^- layer. Simulations that accurately model carrier lifetime and mobility in the various regions of the device are essential to optimize device performance using lifetime-engineered structures.

Fig. 3 shows a transient electro-thermal numerical simulation of a SiC pulse-power thyristor turn-on process, where **Fig. 3 a)** shows the anode voltage and anode current transient response as a square current pulse is applied to the thyristor gate and the device transitions from the voltage-blocking off-state to the current-conducting on-state. These simulations are particularly challenging due to the combination of the initial low free carrier concentration typical of SiC devices, the abrupt dopant concentration gradients, the rapid rate-of-change of voltage and current at turn-on, and the extremely high current density gradients (**Fig. 3 b**). As in the case of the high voltage PiN diode, accurate modeling of the operating conditions as well as of the SiC material properties are essential for the optimization of device performance and safe-operating-area. For further details on the physics-based modeling of SiC Pulsed-Power Thyristors, see reference [1].

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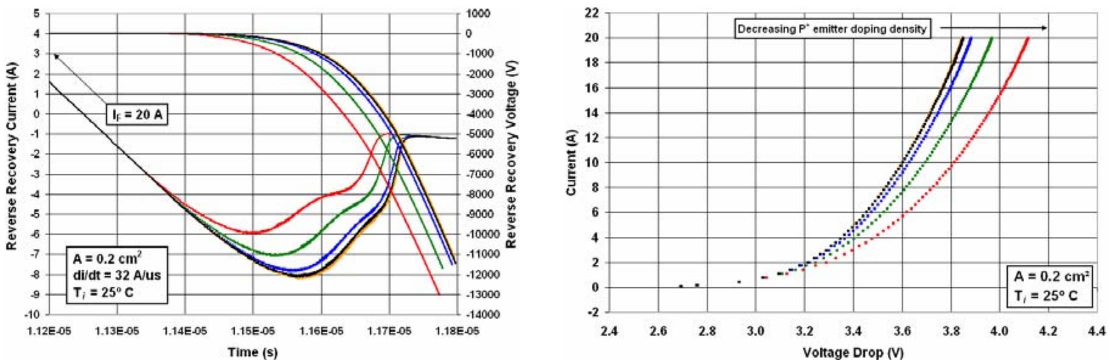

Fig. 1 Effect of varying P$^+$ emitter dopant concentration in a 10 kV 4H-SiC PiN power diode: **a)** (**left**) reverse recovery current and voltage waveforms and **b)** (**right**) forward conduction characteristics. The reverse recovery current and time decrease and the on-state voltage drop increases with decreasing P$^+$ emitter dopant concentration.

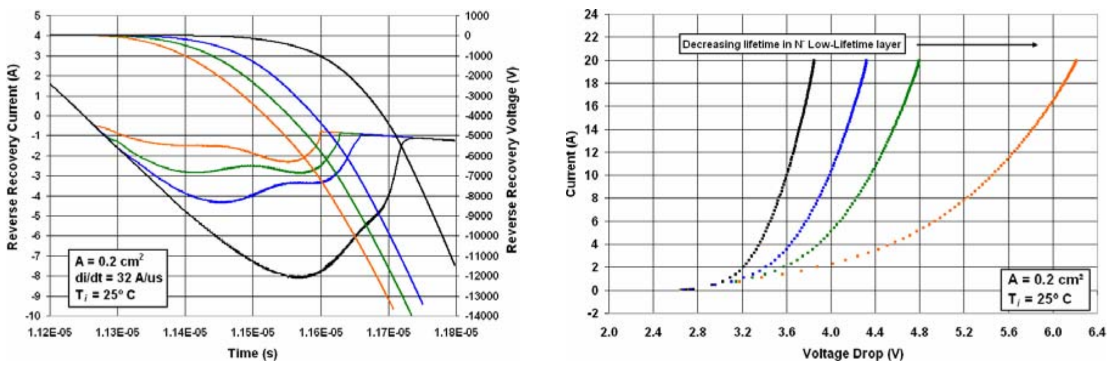

Fig. 2 a) (**left**) Effect of lifetime engineering on the reverse recovery performance and **b)** (**right**) on the forward conduction characteristics of a 10 kV 4H-SiC PiN power diode.

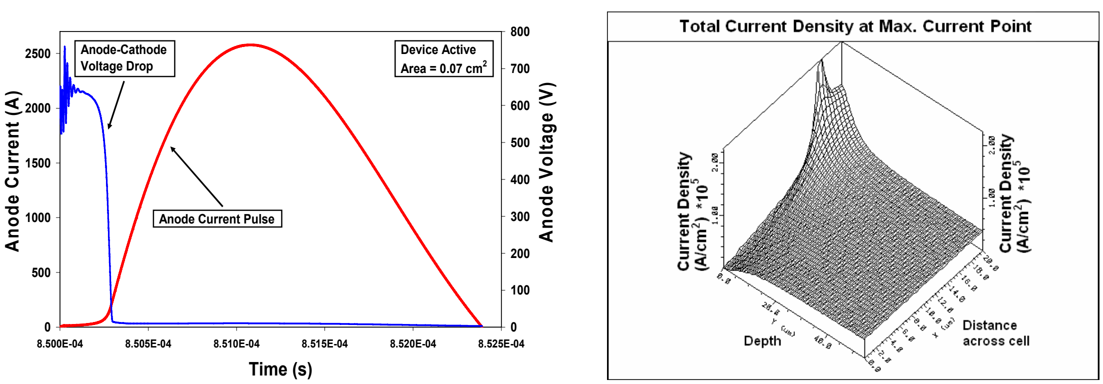

Fig. 3 a) (**left**) SiC thyristor pulse-power anode voltage and current transient response. Following the application of a square current pulse to the thyristor gate the thyristor transitions from the voltage-blocking off-state to the current-conducting on-state and then the pulse-power ring down circuit discharges, **b)** (**right**) Current density distribution inside the thyristor at the peak of the anode current pulse.

References

[1] L. M. Hillkirk, A. R. Hefner, R. W. Dutton, S. B. Bayne, H. O'Brien, "Electro-Thermal, Transient, Mixed-Mode 2D Simulation Study of SiC Power Thyristors Operating Under Pulsed-Power Conditions," ***IEEE Proceedings of the 12th International Conference on Simulation of Semiconductor Processes and Devices 2007*** **(SISPAD 2007), Vol. 12, pp. 181-184, Sept. 2007, Vienna, Austria.**