3D TCAD Mixed-Mode Simulation of Current Filaments in IGBT Multicell Array under Short-Circuit Condition

Background
A power IGBT (Insulated Gate Bipolar Transistor) is conventionally made up of a repetitive array of homogenous IGBT cells. Such a homogenous configuration renders a uniform current flow across the active surface area of the IGBT chip when the IGBT is turned on. Under a short-circuit condition, however, the IGBT being turned on is exposed to a very high collector-to-emitter voltage. In this condition, the IGBT conducts a very high collector current, leading to correspondingly high power dissipation in the form of heat flowing uniformly across the chip. If the heating of the chip exceeds a critical level during a short-circuit operation, the device may fail or even get destroyed by local overheating in conjunction with the establishment of current filaments in a localized area, or the hot spots, within the device.

Modeling and Simulation
In cell mode of Victory Process an IGBT array consisting of 8 cells, as shown in Figure 1, is generated by joining 8 copies of the IGBT single cell together. This IGBT multicell array is uniform along its width of 40 µm. Each IGBT single cell is 20 µm long and features a 1.3 kV trench-gate design with a fieldstop layer (n-buffer) that consumes 16 µm out of the n-drift region thickness of 134 µm. For the sake of convenience, the doping profiles of the cell structure are modeled with analytic functions.

For simulation of filament formation, the multicell IGBT is tested with the test circuit pictured in Figure 2. The collector-to-emitter terminals are supplied with a constant voltage source of 600 V while the gate is pulsed from 0 V to 15 V in 10 ns with a pulse length of 10 us.

Continued on page 2 ...
During the short-circuit test the IGBT is assumed to be mounted on a heat sink maintained at an ambient temperature of 300 K. This can be modeled in Victory Device by adding a thermal contact with a thermal resistance of 0.3 cm².K/W to the heat sink to the bottom collector electrode.

To predict the short-circuit behavior in the multicell array, Victory Device takes the following physical models into account: (1) low-field mobility dependent on doping and perpendicular electric field, (2) parallel-electric-field dependent mobility (velocity saturation), (3) Shockley-Read-Hall and Auger recombination, (4) impact ionization and (5) self-heating effects.

Victory Device self-consistently solves the drift-diffusion transport equations, along with the heat flow and the circuit equation, using an MPI-based parallel direct solver referred to as the PAS solver [1]. The great advantage of PAS is its speed and robustness. For 226,000 mesh points in the simulated IGBT multicell array, the required simulation time is only 4.5 days on a machine with 12 CPUs.

**Simulation Results**

The simulated short-circuit waveforms of the 8-cell IGBT in Figure 3(a) indicate that the device can withstand the power pumped into it for 5.57 μs before it fails. Furthermore, a peak in the current waveform at \( t = 0.48 \) μs and a kink at \( t = 4.5 \) μs suggest two possible occasions of nondestructive filament formation prior to device burn-out. Figure 3(b) captures the 3D electron current density distribution.
distribution at the failure point in time \( t = 5.57 \, \mu\text{s} \). At that time, the hot spot current filaments are concentrated mainly on the emitter side of the eighth cell to the right of the multicell array and the current density is non-uniformly distributed across the device from the hot spots.

To illustrate how current filaments evolve shortly before excessive heat burns out the device, the same 8-cell IGBT with a reduced width of 1 \( \mu\text{m} \) is simulated. Such a 1 \( \mu\text{m} \) wide multicell array can be thought of as a quasi-3D multicell array. Similar behavior can be observed in the short-circuit waveforms of the quasi-3D 8-cell IGBT shown in Figure 4(a). The quasi-3D multicell array fails at a short-circuit turn-on time of 5.24 \( \mu\text{s} \). Figure 4(b) displays cross-sectional views of current filament evolution in the quasi-3D 8-cell IGBT for a number of selected points in time prior to and upon device failure at \( t = 5.24 \, \mu\text{s} \). It is evident that, in the vicinity of the failure point, the filament formation is so intense that the current crowding occurs at the right edge of the multicell array. The current filaments are gradually widened and, simultaneously, establish a front that moves towards the left edge of the multicell array, starting from the collector side, until the device is burnt out.

**Summary:**

With the combined advanced features of Victory Process and Victory Device including:

- 3D rapid prototyping
- Electrothermal computation in 3D
- Mixed-mode 3D device and circuit simulation
- Fast and robust 3D direct solver using MPI

Silvaco’s 3D TCAD tools make it possible for large complex power semiconductor structures to be efficiently handled. More importantly, the 3D device simulator demonstrates for the first time that current filamentation phenomena in a 3D IGBT multicell array subject to a short-circuit condition can be simulated in days and not weeks or months. This clearly facilitates the use of 3D TCAD simulation for understanding of physical processes in power devices, as well as optimization and prediction of device characteristics.

**References:**