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Electrothermal Simulation of an IGBT

V. Axelrad, R. Klein*
Technology Modeling Associates, Palo Alto, California, USA
*Laboratoire d'Electronique de Technologie et d'Instrumentation, Grenoble, France

Self heating effects are of importance in several types of semiconductor devices. One of the most obvious cases is power applications, where high electric fields and high current densities can be present at the same time. Self-consistent simulation of the electrothermal problem is a challenging task, since the governing equations nonlinearly depend on the temperature of the crystal lattice. If lattice heating is significant, the heat flow equation is tightly coupled to the current continuity equations, making relaxation schemes divergent. In most interesting cases a fully coupled solution is required. In addition, the actual geometry of the device including such large scale details as position and material properties of heat sinks is usually of great importance and cannot be neglected in the simulation if lattice heating is significant.

Device Structure

In this work an insulated gate bipolar transistor (IGBT) is investigated using the general-purpose numerical device simulator MEDICI [1]. The device is a combination of a bipolar junction transistor with a MOSFET. The device structure and an equivalent circuit of the device are shown is Fig. 1. The IGBT possesses many advantageous properties for power applications [2]. Among these is low forward voltage drop comparable to that of a thyristor and high-impedance control over the current flow, in particular the possibility to switch off the device under high forward bias conditions.

A potential problem in the operation of the device is the possible latch-up of the four layer thyristor-like structure (Source of the MOSFET - Collector - Base - Emitter). In this case the device cannot be switched off any more, which can lead to catastrophic breakdown of the circuit and its destruction. The device designer can optimize the IGBT in order to suppress the latch-up effect by e.g. modifying the doping profiles [2]. However, the discussed example shows that the latch-up behavior cannot be modeled accurately without incorporating self-heating effects in the simulation.

The simulated device structure is shown in Fig. 1. The bipolar device is vertical with the collector at the top, connected to the source of the n-MOSFET. The drain of the MOSFET injects electrons into the base of the bipolar transistor.

As thermal boundary conditions for the simulation, a heat sink held at $300K$ was attached to the bottom of the device via a lumped thermal resistance of $10K/W\mu m$. More thermal contacts and additional layers of material at the bottom or at the sides can be easily handled by MEDICI [1] if required.

Simulation

Figure 2 shows the current-voltage characteristics of the IGBT with a gate bias of $25V$. The current rises exponentially with V_E up to about $0.8V$ leveling off for higher biases. For current levels up to about $10^3 A/cm^2$ there is no significant self-heating of the device, hence no difference is observed between the conventional simulation including Poisson's and current continuity equations only (dashed line) and the more complete set of equations including the heat flow equation in addition.

As we approach higher biases, the lattice temperature in the device increases, finally leading to a latch-up of the thyristor structure at about $5V$ forward bias (Fig. 2). The I-V curve snaps back with the voltage drop reaching as low as about $2V$ (this part of the simulation was performed using current boundary conditions). The actual thermal destruction of the device with lattice temperature rising beyond $1000K$ is indicated by the second snap-back visible in the upper part of the curve. If constant lattice temperature of $300K$ is assumed as in conventional simulation (Fig. 2, dashed line) no latch-up is observed until about $30V$.

Figures 3-4 show the carrier concentrations and the internal lattice temperature distributions in the device at two bias points indicated as A, B in the I-V curve Fig. 2. In case A, Fig. 3 the device is in normal forward bias operating condition before the onset of latch-up. Case B, Fig. 4 demonstrates the developing latch-up with increasing electron concentration in what was the collector-base space-charge region at lower current levels. The second snap-back finally leading to very high lattice temperatures and the destruction of the device (Fig. 2) is characterized by the further spread of high carrier concentration

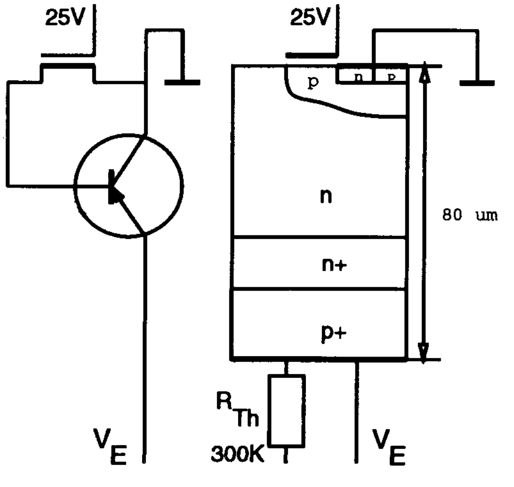

Figure 1: Device structure and an equivalent circuit.

into the higher doped p-type region under the p^+ contact, i.e. the latch-up of the vertical $n-p-n-p$ structure.

To improve the breakdown voltage of the device, the designer might take steps to decrease the thermal resistance between the device and the heat sink. This would shift the I-V curve towards the limiting case of constant lattice temperature in the device (dashed line in Fig. 2).

Conclusions

Realistic simulation of power semiconductor device requires an accurate description of self-heating effects. This can be only done using a advanced device simulator including a fully coupled simultaneous solution of Poisson's, carrier continuity and heat flow equations as well as realistic boundary conditions.

Self-heating has a dramatic effect on the forward bias performance of the discussed IGBT lowering the snapback voltage from $30V$ to about $5V$.

References

[1] Technology Modeling Associates, Inc., Palo Alto, California, USA. *MEDICI user's manual*, Jan 1992.

[2] B.J. Baliga, M.S. Adler, R.P. Love, P.V. Gray, and N.D. Zommer. The insulated gate transistor: A new three-terminal MOS-controlled bipolar power device. *IEEE Trans. on Electron Devices*, ED-31(6), June 1984.

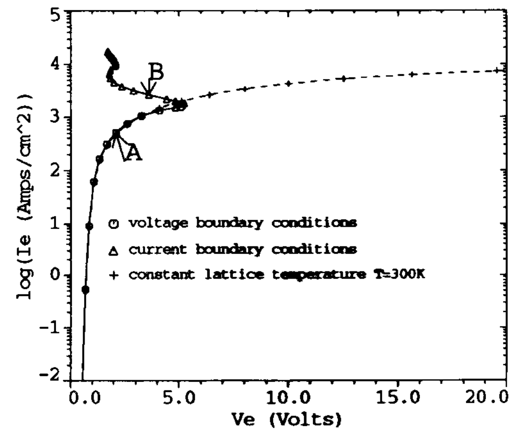

Figure 2: Current-Voltage characteristics of the IGBT.

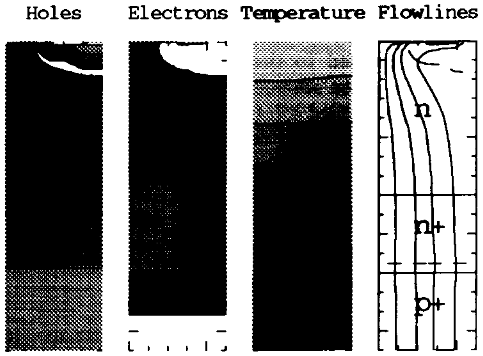

Figure 3: Electron, hole contours ($\Delta log_{10}n, p = 1$), temperature contours ($T_{max} = 326K, \Delta T = 0.5K$) and current flow lines in the IGBT at the bias point A indicated in Fig. 2 (lighter color → higher value).

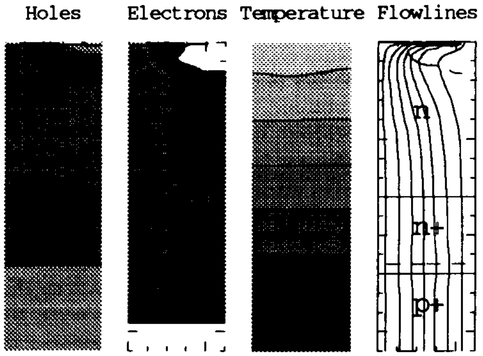

Figure 4: Electron, hole contours ($\Delta log_{10}n, p = 1$), temperature contours ($T_{max} = 564K, \Delta T = 10K$) and current flow lines in the IGBT at the bias point B indicated in Fig. 2 (lighter color → higher value).