Advanced Electro-thermal SPICE Modelling of Large Power IGBTs

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Abstract. A novel IGBT electro-thermal model is implemented for the first time in PSpice for the simulation of steady state and transient temperature dependent IGBT operation including self-heating and latchup. A thermal circuit representing the characteristics of the IGBT package is developed and validated against a finite element model and experimental results. A novel electrical IGBT model based on the Kraus model is developed to account for the electrical impact of instantaneous junction temperature variations due to self-heating. The resulting electro-thermal model is validated against experimental dc and transient FBSOA measurements.

INTRODUCTION

The increasing trend of integrating power devices with low voltage MOS logic circuits which are all designed and tested with software packages using the Spice language has generated a great demand for a fully coupled electro-thermal IGBT model in Spice. At the present time, the most advanced IGBT models are only incorporated within expensive and mutually incompatible programs such as Eldo or Pacte because they allow a high-level language description [1].

A novel fully coupled electro-thermal IGBT model based on the Kraus model [2] is developed here for the study of dynamic performance variations due to self-heating effects and the prediction of the temperature dependent FBSOA and SCSOA. This complete model has been implemented in PSpice for the first time and now allows researchers the capability of investigating thermal imbalances between parallel IGBTs in power modules. Results are compared to temperature dependent SOA measurements on 1.7kV Dynex IGBT modules and FEMLAB and MEDICI simulations.

THERMAL MODELLING

Heat Source. The heat density in W/cm$^3$ of a Dynex 1.7kV IGBT cell is calculated and plotted in MEDICI (fig. 1). The heat source is found to be strongly localized in the channel and accumulation regions, justifying the use of a point heat source situated at the oxide-semiconductor interface.

Steady-state thermal analysis of the package. A 1-dimensional dc thermal circuit representation of the Dynex DIM800DDM17 module package built using package material properties is developed by modelling each layer with an equivalent thermal RC circuit. The total junction to case equivalent thermal resistance is found to be 20.0K/kW.

A 2-dimensional thermal finite element analysis in FEMLAB is also performed. It is determined that lateral thermal interference between adjacent IGBTs only has a 4% impact on the junction temperature. The junction to case equivalent thermal resistance is found to be 19.4K/kW. Both the circuit and FEMLAB approaches do not consider the 3-dimensional nature of the heat flow profile in the package and therefore yield conservative thermal resistance results when compared to the worse case experimental measurement of 18K/kW.

Dynamic thermal analysis of the package. The IGBT junction temperature response to an applied power pulse is analysed in FEMLAB. According to...
the experimental thermal transient impedance curve and the on-state current measurements, it is calculated that the temperature reaches its overheating threshold of 125°C after a 50µs pulse of 81kW. Initial results with the SPICE RC thermal circuit show a discrepancy due the lack of discretisation in the silicon drift region. Additional RC stages are added so that the first node of the thermal circuit representation corresponds to the IGBT junction. Optimal results are reached with a total of 16 stages. Good agreement is then reached between experimental predictions, PSpice, and FEMLAB (fig. 2). The small 4% difference can be attributed to the lateral heat flow not taken into account in the one-dimensional PSpice model.

A novel self-heating Spice IGBT model. A new temperature pin is added to the Kraus IGBT model. Since PSpice does not allow dynamic variations of parameters between bias point calculations, each semiconductor parameter is translated to a voltage at a node inside separate subcircuits that depend on the voltage at the temperature pin (fig. 3). The anode-base junction diode in the Kraus model can account for temperature variations only through the global temperature setting in PSpice. Replacing the diode by a current source controlled by the temperature voltage accounts for the dynamic temperature dependence of the anode-base junction current. A large resistor is added in parallel for convergence during the PSpice initial bias point analysis.

The lifetime dependent RC stage inside the base charge subcircuit models recombination in the base. A lifetime dependent resistor is constructed through a controlled current source to achieve temperature dependent recombination. The current source is the ratio of the voltage across the source to the variable lifetime and temperature dependent resistance expression: \( I_r = \frac{VC}{\tau(T)} \) where C is the charge storage capacitance in the base charge subcircuit.

The equations governing the Kraus model are adapted recursively to incorporate the temperature dependence of each semiconductor parameter based on its respective subcircuit.
On-state characteristics. Comparing the DC current simulation results obtained with the original Kraus model and this fully coupled electro-thermal model (figs 5a and 5b) shows that the increased temperature due to self heating leads to a reduction in the injection efficiency and in the channel mobility thereby leading to the earlier saturation of the I-V curves and a subsequent reduction in current levels deeper in the saturation region. Note that the DC current is however not significantly affected below $V_a=5V$.

The p-well resistance responsible for latchup is calculated from MEDICI simulations by plotting the hole quasi-fermi level and the hole current density throughout the p-well. At room temperature, a value of $R_s=75\mu\Omega$ is found. The feedback effect leading to latchup is achieved by measuring the parasitic n-p-n BJT current and feeding it to the charge accumulation subcircuit so that the n-p-n latchup current leads to a reduced base resistance, thereby increasing $I_{pc}$. This feature allows one to model the thyristor action leading to temperature dependent latchup.

The FBSOA is simulated based on both the junction overheating limit of 125ºC and on temperature dependent latchup (figs. 6a and b).

Steady-state Forward Bias Safe Operating Area modelling. A current source controlled by the temperature pin voltage is added between the cathode and the base to model the parasitic n-p-n BJT effect taking into account the temperature dependent BJT threshold voltage and the increasing p-well resistance due to lower mobilities at higher temperatures.

It is found that in steady-state operation the IGBT module will always reach overheating well before reaching latchup. Thus the FBSOA is limited by the thermal resistance of the package rather than by the p-well resistance. As can be seen from fig. 6a, very good agreement is reached between the thermally limited FBSOA simulation and the experimental measurements. The temperature dependent latchup simulation results in fig 6b are consistent with the
SCSOA measurements showing typical latchup temperatures in the order of 420ºC.

**Transient Forward Bias Safe Operating Area Modelling.** Using the electro-thermal IGBT model, the transient temperature response of the IGBT under short circuit conditions for the different pulse times of 50µs, 100µs and 1ms is simulated. Having determined that the module reaches overheating before latchup, dynamic thermal feedback is implemented to sweep the anode and gate voltages deep within the saturation region to determine the maximum allowable value of \( V_a \) for a given \( V_g \) for which the overheating limit is reached. The results are in good agreement with the transient FBSOA experimental measurements as shown in fig. 7.

![Figure 7. Steady state and transient FBSOA simulation results vs. experimental measurements](image)

**CONCLUSION**

The thermal behaviour of a Dynex 1.7kV IGBT module package was modelled in the form of an RC circuit validated by a thermal finite element 2-dimensional heat flux model of the package. Good agreement was reached with the experimental equivalent junction to case thermal resistance. Dynamic thermal simulations were performed to determine the necessary level of discretisation in the RC circuit so as to reach good agreement with FEMLAB dynamic simulations.

A novel electrical IGBT model based on the Kraus model was developed. We are able for the first time to model the dynamic variations of semiconductor parameters through the subcircuit approach. A new temperature pin is implemented to affect the parameters during steady state and transient simulations according to the instantaneous junction temperature of the IGBT.

Linking of the thermal and electrical models yields a fully coupled thermo-electric IGBT model able to simulate for the first time in PSpice the effects of self-heating on the on-state characteristics of the IGBT. Consistently with device physics, it was found that self-heating impacts significantly the saturation region of operation.

The temperature dependent parasitic n-p-n BJT current was implemented with an active feedback to the base resistance to simulate the steady-state FBSOA based on both overheating and latchup. Having determined that the module reaches overheating before latching up, the electro-thermal model was also used to model the transient FBSOA based on overheating of the IGBT junction. Very good agreement was reached with the experimental results. Simulating power pulses at \( I_c = I_{sat} \) also allows designers to assess the module’s SCSOA as limited by latchup.

Coupling the novel IGBT model to the thermal circuit model allows an accurate and reliable analysis for the first time in SPICE of both IGBT performance variations due to self-heating and temperature imbalances between independent IGBTs. The temperature imbalances affect the current sharing capability of large power IGBT modules due to the thermal properties of the package.

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