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Large Scale Thermal Mixed Mode Device and Circuit Simulation

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Abstract

The thermal mixed-mode capabilities of the device and circuit simulator DESSIS are presented. The mode allows both electrical and thermal netlists to interconnect physical and circuit devices. As an example, the full electrothermal simulation of IGBT power module is presented.

A thermal mixed-mode extension to the DESSIS device and circuit simulator has been developed to simulate thermoelectric systems of yet unprecedented complexity. The originality of this work lies in its generality. Whereas existing mixed-mode simulators make a distinction between the use of temperature in physical semiconductor devices versus SPICE-like circuit devices, DESSIS does not, and allows full thermal coupling between any type of device. Links between the electrical and thermal networks can be done either through physical devices (with either thermodynamic or hydrodynamic transport models) or through circuit devices.

Fig. 1 shows how the existing versions of DESSIS (formerly SIMUL[1]) was extended. The new addition to the simulator are the support for thermal netlists and mixed thermoelectric circuit models. These improvements build upon the programs existing features, such as, the capability of mixing 1D, 2D and 3D physical and circuit devices (using circuit models from BONSIM [2]), advanced physical models and an extensive set of solvers.

	Electrical	Thermal	Thermo-electric
Device	Iso-thermal devices	Die, heat sync, packaging	Self-heating high-power devices
Circuit	Electrical netlist	Thermal netlist	Coupling of T-E netlists

Figure 1: New thermal mixed mode features added to DESSIS(shaded)

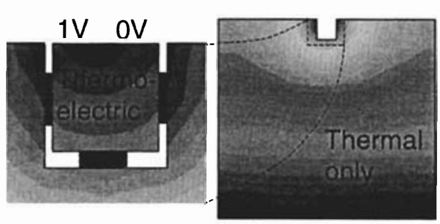

Figure 2: Thermoelectric simulation of a resistive device

An important use of the thermal mixed mode is to reduce the work necessary to simulate the large thermal environment of power devices. A typical elementary power device is many times smaller than its package size. While electrically it makes sense to limit the range of the device simulation and use circuit models for most of the devices, this simplification is much more difficult for a realistic thermal simulation because of the much larger range in the thermal interactions. The thermal mixed mode solves this problem in two ways. First, a large device that could formerly only be computed with a total thermoelectric simulation can be subdivided into a thermoelectric part and a thermal only part. A simple example of this is shown in fig. 2 where a resistive device is simulated with the full set of thermoelectric equations over a small device which is thermally connected through three thermal links to a much larger device where only the thermal equation is computed.

Another way the thermal mixed mode can be used is to connect the physical devices and the circuit devices through a thermal network. Fig. 3 shows the two ways this type of connection can be done in DESSIS, by directly coupling to temperature variables in the circuit models or by using an interface device to access the temperature parameter of the models. This latter method is valid in most cases because the temperature usually varies quite slowly.

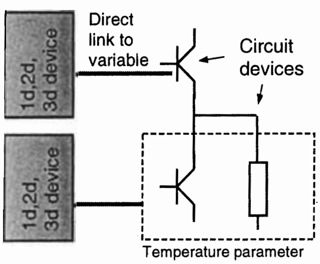

Figure 3: Thermal connection between physical devices and circuit device can be done in two ways

The definition of the system to be simulated is straightforward with only a small extension over the previous DESSIS input syntax: the thermal nodes of the netlist must be declared as such. This allows both electrical nodes and thermal nodes to share physical device contacts. Whether the connection is electrical or thermal is determined by the type of the node.

Fig. 4 shows how the thermal mixed mode can be used to simulate a large power module with an IGBT and SPEED diode. Here the module structure is broken down into four parts: the IGBT and SPEED diode device simulated as 2d physical devices (1415 and 568 vertices) using the thermodynamic model, the gate control circuitry is simulated with circuit models and the package is simulated with a 2d device (150 vertices) with only thermal models. Only a very rough approximation of the geometry of the package was considered with as size of 6x4x4cm.

The thermal connectivity of this example is done as follows: The IGBT is connected thermally to the package directly through its collector and resistively through its emitter. The SPEED diode is connected in a similar manner. Each circuit element can be thermally connected to specific point of the package but for the sake of simplicity all circuit element were attached to a single thermal contact in the package. During the solve process, a decoupled iteration is done between the full coupling of the temperature related equations and the Poisson, continuity and circuit equations.

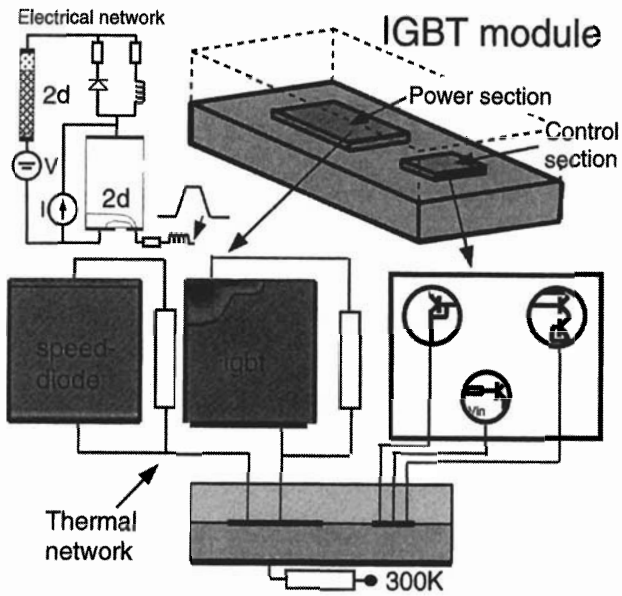

Figure 4: IGBT module structure simulated with thermal mixed mode

The following preliminary results are given for the study of the turn-on turn-off behaviour of a 800V IGBT. A first transient simulation was run starting with a general temperature of 300K. Given the size of the package a large number of cycles would be necessary to reach thermal steady state, thus only one cycle was simulated from which a mean power loss was extracted (about 200W). This value was used to re-initialize the package by computing its temperature distribution subject to a fixed heat supply. A new transient simulation was recomputed with this new initial solution resulting in the following results: Fig. 5 shows the temperature distribution through the package. Of interest is the temperature at the substrate of the IGBT ($\approx$400K) and the gradient of the temperature over the control circuit section. Note that these values are realistic but will be improved with a more exact description of the package. Both Fig. 6 and 7 show the behaviour of the IGBT for a turn-on, turn-off cycle. Fig. 6 shows the short circuit thermal failure that results when the the IGBT is fixed to 800V and the pulse is long (80μs). Fig. 7 shows the behaviour of the IGBT when connected to the SPEED diode and subject to a fixed 75A load. Here a longer pulse will fail to turn off due to the heating of the device.

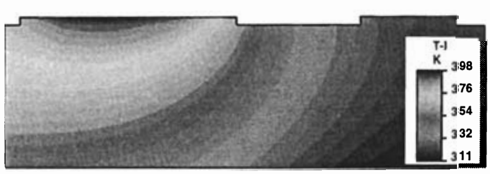

Figure 5: Near steady state distribution of temperature in package

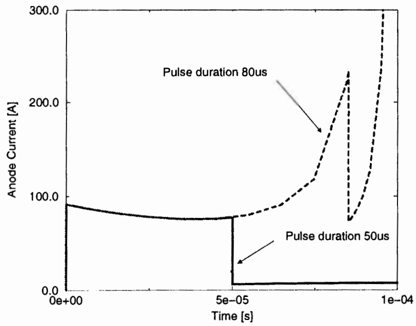

Figure 6: Short-circuit thermal runaway of the IGBT

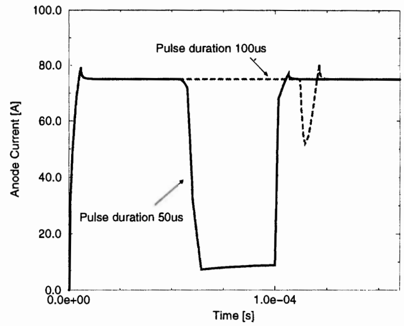

Figure 7: Turn-off failure of the IGBT

In a general, a full electrothermal simulation of such a large system is not necessary because of the the fundamentally different time spans between the thermal and electrical equations. Solving the thermal equation for the package during the transient computation is not necessary because its temperature varies very much more slowly in the package than in the power devices. On the other hand, resolving the package adds no noticible amount of CPU time. In practice, to efficiently obtain the asymptotic solution it is best to iterate between solving the package in steady-state and the devices in transient.

Work still needs to be done to ease the creation of the thermal devices and networks. A layout to circuit tool approach [3] is necessary to assure a precise thermal modeling. On the numerical side work can be done to take advantage to the fundamentally different time spans between the thermal and electrical equations.

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References

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