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Thermal Management of Space Power Electronics using TLM-3D

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***Abstract*—**When designing satellites, one of the major issues aside for designing its primary subsystems is to devise its thermal. The thermal management of satellites requires solving different sets of issues with regards to modelling. If the satellite is well conditioned all other parts of the satellite will have higher temperature no matter what. The main issue of thermal modelling for satellite design is really making sure that all the other points of the satellite will be within the temperature limits they are designed.

The insertion of power electronics in aerospace technologies is becoming widespread and the modern electronic systems used in space must be reliable and efficient with thermal management unaffected by outer space constraints. Many advanced thermal management techniques have been developed in recent years that have application in high power electronic systems.

This paper presents a Three-Dimensional Modal Transmission Line Matrix (3D-TLM) implementation of transient heat flow in space power electronics. In such kind of components heat dissipation and good thermal management are essential. Simulation provides the cheapest tool to investigate all aspects of power handling. The 3D-TLM has been successful in modeling heat diffusion problems and has proven to be efficient in terms of stability and complex geometry. The results show a three-dimensional visualisation of self-heating phenomena in the device affected by outer space constraints, and will presents possible approaches for increasing the heat dissipation capability of the power modules.

***Keywords*—**Thermal Management; Conduction; Heat dissipation; CTE; Ceramic; Heat spreader; Nodes; 3D-TLM.

I. Introduction

MODERN electronic systems used in space must be reliable and efficient with thermal management unaffected by outer space constraints. The space environment produces different heating and cooling conditions that are inherently different based on the positioning of the spacecraft, its orbit, etc...

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Thermal analysis of electronic components has been one of the primary areas of application of advanced heat transfer techniques. One significant area where thermal management has played a crucial role is in the area of power electronics. Devices of this type are usually used on a large scale where the heat flux levels are much greater than microelectronics. In many cases, catastrophic failure is a result of steep temperature gradient in the localized temperature distribution. The local heat transfer characteristics are complex, as the heat dissipated in the chip is conducted into the substrate and then transferred by some combination of thermal conduction to the outer surface through numerous components [1].

The thermal management efforts develop, demonstrate, and make transition technologies to improve the performance, flexibility, and ground testability of on-orbit assets while reducing the mass and heater power requirements of the satellite thermal management subsystem [2]. The space power efforts cover the development of all required components for satellite power subsystems including power generation and energy storage and include growth and lattice compatibility of advanced semiconductor materials for multi junction and low-cost, feasibility and reliability of space-qualified, solid-state components and circuits [3].

Thermal failures such as mechanical stresses, thermal de-bonding and thermal fracture become many of the possible breakdowns of electronics components. Mismatch of the thermal coefficient expansion (CTE) between two different materials, especially at the interface conditions, could result in the separation of interfaces and bonds between different parts in a module. In addition, fatigue in the solder connections and cracking in substrate are common failures in electronics components in the space environment.

The IGBT, a hybrid of a MOSFET and a turn/off bipolar junction transistor (BJT), is a MOS-gated device. It requires minimum cooling, if is more reliable, experiences reduced voltage spikes at turn-off, and exhibits improved thermal life.

The IGBTs modules are constituent parts of electronic converters which permeate space power systems [4]. A power electronic system can comprise a modular power electronic subsystem (PESS) connected to a source and load at its input and output power ports, respectively. The third port of PESS is connected to the system control, as shown in Fig. 1 [5].

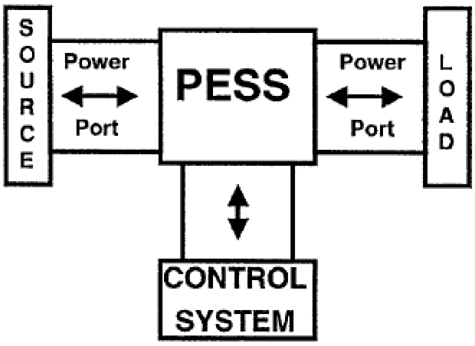


Fig. 1 Three-Port Power Electronic System Structure schema

An IGBT module will typically contains more individual IGBT devices, plus their associated protection diodes. The exact temperatures of each device will therefore depend on the arrangement of the devices within the package and 3D modelling techniques are necessary in order to evaluate the exact temperatures which all of the die will operate at.

In this paper, thermal analysis of an IGBT module was investigated and analysed using the 3D-TLM method. In this work, we wrote our own software based on the TLM technique. It calculates the junction temperature for a given input power and localises hot spots then visualises the thermal behaviour of the device under space conditions.

II. TLM TECHNIQUE

The simulations are based on the transmission line matrix (TLM) method. The TLM method is intrinsically a discrete approach, which directly models a physical process. It has been shown that an electrical pulse on a transmission-line matrix obeys Maxwell's curl equation for propagation in lossy medium, which has the form of telegrapher's equation [6]:

$$\nabla^2 \Phi = A R_d C_d \frac{\partial \Phi}{\partial t} + B L_d C_d \frac{\partial^2 \Phi}{\partial^2 t} \quad (1)$$

Where Φ is the potential, Rd, Cd and Ld are distributed resistance, capacitance and inductance, respectively. The A and B are constants. If the first time derivative term on the right-hand side of equation (1) dominates the second term, the network models the diffusion equation described by the equation:

$$\nabla (k_t (T) \quad \nabla T(x,y,z,t)) = \rho c_p \frac{\partial T(x,y,z,t)}{\partial t} \quad (2)$$

Where, T is the temperature, Cp is the specific heat, ρ is the density and Kt is the thermal conductivity. Therefore, it should be possible to model the thermal wave heat flow in terms of lumped RLC network where temperature will be represented by voltage. The capacitor/ inductor combinations are replaced by loss-free transmissions-lines, of impedance Z, which connect each node to its neighbours and carry voltage pulses between the nodes in finite time Δt.

According to the fundamental transmission line theory [7], the impedance is related to C and L through:

$$Z = \sqrt{\frac{L}{C}} = \frac{a \ \Delta t}{C} = \frac{L}{a \ \Delta t} \quad (3)$$

Where, the capacitor models the heat capacity of the material. The TLM parameters R and Z can be evaluated from:

$$2R = \frac{1}{K_t \ \Delta x} \quad \text{and} \quad Z = \frac{a \ \Delta t}{\rho \ c_p \Delta x^3} \quad (4)$$

Where Δx is the length of the cubic elemental volume, the parameter a represents as well the number of link lines in each elemental volume. In TLM modelling, the system is divided in small unit volumes. Each element is represented by a node that will represent a unit of Line Transmissions. The Fig.2 presents a 3D TLM node.

A TLM solution is obtained by repeatedly considering delta voltage (temperature) pulses to be incident simultaneously on all parts of all nodes. These incident pulses are scattered instantaneously into reflected pulses which, during the time step Δt, travel along link transmission lines to become incident upon neighboring nodes. The TLM routine operates on the traveling, scattering and connecting of these pulses in the network. The transmissions line in the model in the model act as delay lines, with the node impulse population being the discrete solution at each time step [8].

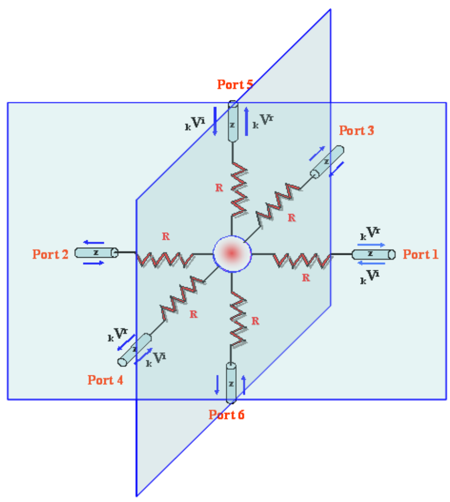


Fig. 2 Equivalent 3D-TLM node

The transient heat equation can be solved in a TLM framework by iterating the following steps [9], [10] and [11]:

Nodal temperatures: At each node N, the temperature at the time step k, $_kV(N)$, is calculated from the local sources and the incident temperature pulses, $_kV_j^i(N)$. For a three-dimensional node such as that illustrated in Fig. 2 nodal temperature is:

$$ {}_kV(N)=\left[\frac{2\left({}_kV_1^i+{}_kV_2^i\right)}{R_x+Z}+\frac{2\left({}_kV_3^i+{}_kV_4^i\right)}{R_y+Z}+\frac{2\left({}_kV_5^i+{}_kV_6^i\right)}{R_z+Z}\right]\frac{1}{Y} \quad (5) $$

Where $Y=\frac{2}{R_x+Z}+\frac{2}{R_y+Z}+\frac{2}{R_z+Z}$ and ${}_kV_m^i$ are incident pulses, at the Kth iteration.

Scattered pulses: Reflected pulses ${}_kV_j^r(N)$ are calculated according to:

$$ {}_kV_{1,2}^r=\frac{1}{R_x+Z}\left[Z\,{}_kV+\left(R_x-Z\right)V_{1,2}^i\right] \quad (6) $$

$$ {}_kV_{3,4}^r=\frac{1}{R_y+Z}\left[Z\,{}_kV+\left(R_y-Z\right)V_{3,4}^i\right] \quad (7) $$

$$ {}_kV_{5,6}^r=\frac{1}{R_z+Z}\left[Z\,{}_kV+\left(R_z-Z\right)V_{5,6}^i\right] \quad (8) $$

Incident pulses: At the (k+1) iteration, incident pulses given by:

$$ {}_{k+1}V_j^i(x,y,z)=\Gamma_j\,{}_kV_j^r(x,y,z)+\left(1-\Gamma_j\right){}_kV_{j'}^r(u,v,w) \quad (9) $$

Where (x, y, z) are node N co-ordinates and Γj is the reflection coefficient in direction (j) given by:

$$ \Gamma_j=\frac{Z(u,v,w)-Z(x,y,z)}{Z(u,v,w)+Z(x,y,z)} \quad (10) $$

The corresponding values of j', u, v, w for j=1, 2 ... for equations (9) and (10) are listed in following Table I.

TABLE I
THE VALUES OF J, J', U, V, AND W USED

j	j'	U	v	w
1	2	x-1	y	z
2	1	x+1	y	z
3	4	x	y-1	z
4	3	x	y+1	z
5	6	x	y	z-1
6	5	x	y	z+1

Implementation of a TLM routine consists solely of repeated application of equation (5) to (10). As argued by Kronberg [12], boundary conditions express the interaction of the system at hand with its surroundings. Boundaries are part of the transport model and thus should be consistent with the description of the heat transport inside the medium.

III. THE POWER SEMICONDUCTOR DEVICES

The space power systems have a considerable real estate of power usage and has emerged as a 'driver' for developing MET's (More Electric Technology). This has increased the use of power electronic converters to condition and control power in the related systems [13].The advent of MET for space systems, has focused attention on insertion of electronic modules in space technologies. The key elements for MET are its power electronics, the materials used and their weight and size considered. The IGBT module will typically contains more individual IGBT devices, plus their associated protection diodes. The exact temperatures of each module will depend on the arrangement of the devices within in and 3D modelling techniques are necessary in order to evaluate the exact temperatures which all of the die will operate at. It is however possible to estimate their temperatures fairly accurately using the TLM method. The TLM is used to estimate the thermal requirements for a proposed IGBT structure. The total power dissipation is spread equally over a number of IGBTs and their maximum allowable continuous junction temperatures are changed. Devices are mounted on the package baseplate using an alumina DBC substrate. The heatsink is assumed to be cooled by air and the power is dissipated uniformly over the junction region on the top faces of the IGBTs.

There are numerous electronic substrate materials but perhaps only a few that are suitable for a high power and space application. Three popular substrate materials were identified as potential candidates for the thermal design; these were alumina (Al2O3), beryllium (BeO), and aluminum nitride (AlN). Diamond was also recognized as being suitable for power applications. Though its mechanical, thermal and electrical insulating properties are far superior to any of the other substrate materials, the cost of diamond currently makes its use somewhat restrictive. The use of AlN for space power devices seems quite clear due to its superior thermal conductivity, matched coefficient of thermal expansion to silicon, high strength, and low toxicity. Alumina resulted in unacceptably high surface temperatures. Beryllium and diamond were considered but discounted primarily due to toxicity and cost, respectively [15, 16].

To meet these requirements present power modules use a layered construction, as shown in Fig.3. The IGBT and diode die are soldered to a Direct Bonded Copper (DBC) substrate with an upper copper layer patterned to form the electrical connection to the die. The heat spreader is mechanically attached to the external cold plate. In modest power applications, the external cold plate may be a bonded-fin, air-cooled cold plate. In higher power applications, an aluminum or copper swaged-tube cold plate is used.

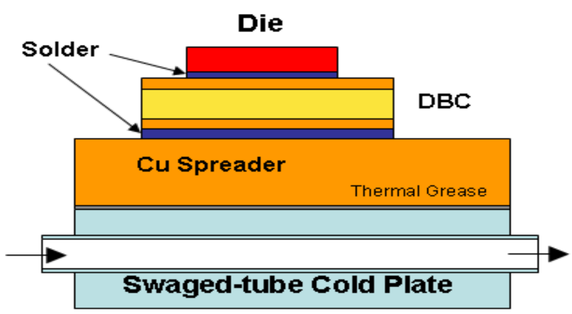


Fig. 3 Schematic of IGBT with thermal management

The simulated structure is presented in Fig.3. A range of materials commonly used in IGBT construction is shown in Table II. These materials are normally chosen based on either Kt or their thermal diffusivity and CTE [17]. The temperature rises are calculated using TLM. For all simulations, a program was written in MapleV language in order to evaluate the temperature at every node within the device as function of time and others parameters.

TABLE II
MATERIAL PROPERTIES USED IN IGBT MODULES

Material	ρ(Kg/m3)	Kt(W/m.K)	Cp(J/Kg.K)
Top plate	10220	138	255
Silicon	2320	148	700
Copper	8960	393	276
Substrate	3260	170	669
Solder	7400	40	160
Base plate	2980	180	722

IV. SIMULATIONS AND RESULTS

The thermal behavior of IGBT power module can be illustrated by using three-dimensional views of distribution using TLM method. The simulation results for a 6-chip in-line arrangement are shown in Fig.5. Although this layout has the benefit of ensuring that all the chips experience cooling air of the same temperature, it is however found to lead to a higher spread in the peak junction temperatures of the devices.

The simulations were run with AlSiC base plate and AlN as substrate. Based on the profile of the figure, we can deduce:

- The results show clearly that the IGBT modules are capable of self-generating under the outer space constraints that affected and decrease device lifetime.
- The heat flows from the operating hot regions to the base plate. The hottest spot temperature is observed in and around the centers of the IGBTs.
- The ceramic substrate and the base plate act as a heat spreader to dissipate the temperature.
- the heat sink thickness plays an important role to control the thermal performance and maintains a constant temperature for total module.

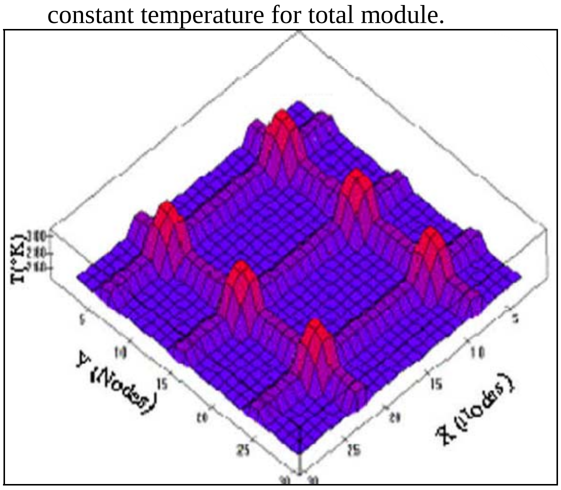


Fig. 4 The thermal profile along the vertical axis

Simulations can be done by representing the structure of the IGBT module mounted on the heat sink, and by calculating the solid and flow temperatures simultaneously.

In the Fig.5, the thermal behaviour of the total system is displays.

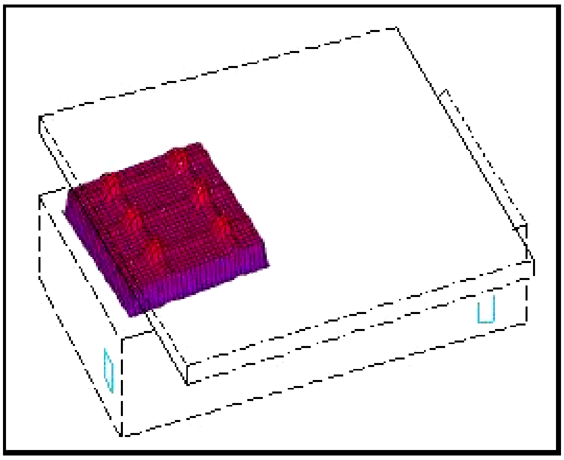
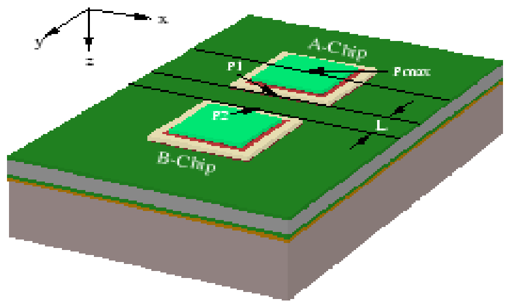


Fig. 5 Thermal Simulation for the Total System

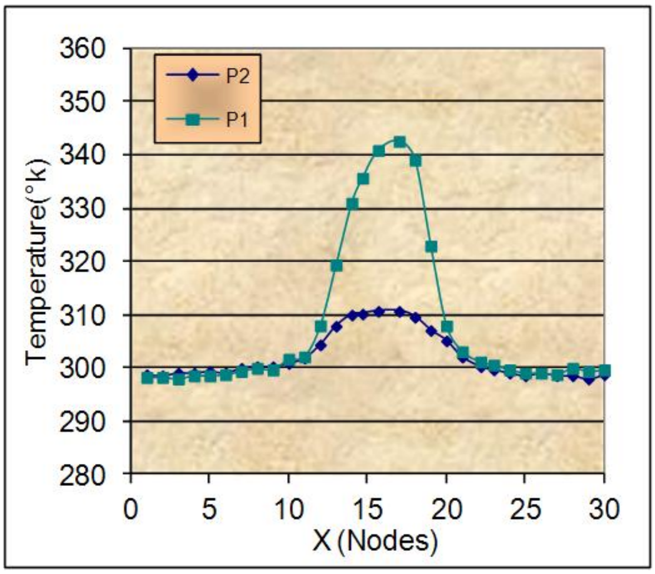
The lateral heat spreading effect causes the thermal interference between the IGBTs and diodes.

Fig. 6(b) shows the temperature profiles along three cross sections at two different points along X-directions. They are extracted through the P1 and P2 points with 100W power dissipation in the A-chip. Even though there is no heat source in the B-chip, the maximum temperature rise of approximately 10°K occurs through the P2 line.

This is evidently caused by the heat source in the A-chip. Normally this contributed temperature at the P2 line varies with the applied power of the remote chip and the chip-to-chip distance, while the self generated temperature at the P1 line depends on the applied power only. So, to predict the accurate temperature rise of silicon chips, the chip thermal interference effect should be considered carefully.



(a)



(b)

Fig. 6 Simple Structure for the thermal interference analysis.
(a) Simplified structure
(b) The temperature profiles along three cross sections at points P1 and P2 along X-directions

So, the insertion of power electronics in space technologies will become widespread. The application of semiconductor devices and electronic modules includes satellite power system, motor drives and reusable launch vehicles. Dual-use electronic modules should reduce system development cost.

The TLM has been successful in modelling heat diffusion problems and has proven to be efficient in terms of stability and complex geometry. The three-dimensional results show that method has a considerable potential in space power devices thermal analysis and design.

V. Conclusion

A three-dimensional TLM analysis has been presented in this paper to investigate the thermal effect in IGBT device. The results show clearly that the IGBT modules are capable of self-generating heat under the outer space constraints that affected and decrease device lifetime. Increasing use of power electronic modules will require consideration of device ratings, bi-directionality or otherwise of power flow, power density requirements and degree of integration, when developing space systems. So, thermal management should be an important and necessary part of any concurrent design and must be reached in the coming years. As a consequence of such a physical limit, design rules become very important in achieving reliable temperature predictions and better thermal solutions without costly redesign or over design. This paper has also demonstrated that it is relatively simple to use the three-dimensional TLM method for thermal analysis of various space device structures. We believe that the unconditionally stable nature of the method and the ease with which complex geometry can be handled good with the TLM technique. So a comprehensive thermal analysis is possible for any power devices with complex geometry and fabricated with many different materials.

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