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Transient Electrothermal Simulation of Power Semiconductor Devices

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Abstract—In this paper, a new thermal model based on the Fourier series solution of heat conduction equation has been introduced in detail. 1-D and 2-D Fourier series thermal models have been programmed in MATLAB/Simulink. Compared with the traditional finite-difference thermal model and equivalent RC thermal network, the new thermal model can provide high simulation speed with high accuracy, which has been proved to be more favorable in dynamic thermal characterization on power semiconductor switches. The complete electrothermal simulation models of insulated gate bipolar transistor (IGBT) and power diodes under inductive load switching condition have been successfully implemented in MATLAB/Simulink. The experimental results on IGBT and power diodes with clamped inductive load switching tests have verified the new electrothermal simulation model. The advantage of Fourier series thermal model over widely used equivalent RC thermal network in dynamic thermal characterization has also been validated by the measured junction temperature.

Index Terms—Electrothermal modeling, Fourier series, insulated gate bipolar transistor (IGBT), transient thermal characterization.

I. INTRODUCTION

THE ELECTRICAL behavior of power semiconductor devices is greatly dependent on package design. A good package of switching power devices should provide not only solid electrical isolation from semiconductor chip to supporting baseplate but also good thermal performance to limit the junction temperature rise. The solid electrical isolation is achieved by having the isolator integrated into the package. Thermal performance is related with specific structure and the material used in the package design. Thermal performance is one of the most crucial issues of package technology for power semiconductor devices. According to some research [1], nearly 60% of failures are temperature-induced, and for every 10 °C temperature rise in the operating environment, the failure rate nearly doubles. The thermal performance of packaging technology is simply evaluated by the maximum temperature rise in the semiconductor

chip under certain power dissipation levels with designed heat sink. The lower the chip temperature, the better performance the package shows.

The traditional design of power electronics packages involves thermal cycling tests, but few, if any, studies of transient power cycling exist. For example, an extension of the traditional RC network for the junction-to-case system to a case-to-ambient (via a heat sink) system has been shown to adequately describe steady-state and long-pulse operation in insulated gate bipolar transistor (IGBT) modules [2]. However, this macroscopic lumped-element model limits the usefulness under short electrical transient pulses, typical in modern converter operations. To find an exact thermal solution under transient power dissipation is difficult. Most research uses finite-element methods (FEMs) to achieve the exact solution [3]–[6]. The FEM can provide high precision at the cost of slow computing speed. One of the major disadvantages of using an FEM package for thermal simulation is that it is not easy to create a cosimulation with an electrical circuit simulator, which could predict the transient power dissipation from power electronic devices instantaneously.

Another method to solve transient temperature problems is to set up a thermal network based on the thermal resistance of different package materials [7], [8]. In this way, the junction temperature can be estimated instantly with the help of circuit simulators, such as PSpice. The methodology used in [9] provides a typical way in which temperature profiles are determined. A minor drawback of this method was the use of temperature-independent thermal conductivity and heat transfer coefficient values (so as to linearize the heat-flow diffusion equation). This would slightly impact the accuracy of the proposed method in [9] due to local heating from adjacent die as well as material property changes due to self-heating. In addition, the method is cumbersome due to the need to measure energy losses during switching and conduction, perform a polynomial fit to the energy loss versus current measurements, and then use the fitted polynomials to generate the heat-source terms used in the heat-flow equation. Nowhere in this methodology are temperature changes used to modify the electrical switching behavior of the device. This results in a decoupling of electrical and thermal behavior and limits the usefulness for self-consistent physics-based circuit simulation models of power semiconductor devices and modules. Other drawbacks of 1-D equivalent RC thermal networks are the discrepancy in high-frequency or high-dissipation conditions [10], [11]. Extensive 2-D and 3-D ladders of RC cells can be used for thermal representation of power modules. The number of cells is typically limited by convergence problems in the simulation. Inherent

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limitations from the complexity and suspect relation to physical quantities may be overcome using the diffusive representation (state-space model) described in [12]. Related to thermal and electrical model complexity are the amount of relevant physics captured and accurately described by various model levels and compact models. A comprehensive discussion of this topic is provided in [13]–[18].

An IGBT model based on semiconductor physics has provided our approach for finding the analytical solution of transient thermal response. The approach of this new IGBT model is to solve the ambipolar diffusion equation (ADE), describing the dynamic charge, with the Fourier-series-based solution method [19], [20]. This method also results in a similar solution as proposed in [21]. The number of nodes required in our method is typically lower than the number of effective time constants (equivalent to nodes) proposed in [21], though the resulting electrical equivalent circuit is the same in both thermal models, an equivalent *RC*-ladder network with associated current sources. Another disadvantage described in [21] is the need to use FEM simulations of heating curves (thermal impedances) to create the necessary model matrix used in the circuit simulations. Our method does not require any simulated or experimental data, but only knowledge of the package system materials and physical dimensions.

Since carrier diffusion in semiconductor material and heat conduction behavior obey very similar differential equations, in this paper, the Fourier series expansion is used to solve the heat diffusion equation in different packaging materials [22]. Because of the similarity of the ADE and the heat conduction equation, an electrical and thermal model can easily be integrated into one comprehensive electrothermal model that includes the device or module package, heat sink, and ambient environment. To prove the viability of the method, the simulated results and experimental temperature measurement of a 600-V 50-A IGBT module are compared.

II. FOURIER-SERIES-BASED ELECTRICAL MODEL

The similarity of governing physical equations for both electrical and thermal behavior has provided a new approach to thermal analysis. In order to introduce the new thermal model, the electrical model will be discussed briefly at first. The Fourier-series-based electrical model for power devices is one analytical model, in which the ADE is solved by Fourier series expansion. An equivalent *RC* network is established based on the Fourier solution of this ambipolar equation that is easily implemented in circuit-simulation software. Compared with other analytical models, the Fourier-series-based model provides a better trade-off between simulation speed and accuracy [23].

In this paper, Fourier-series-based electrical model for a non-punch-through IGBT is used as an example. The carrier distribution in 1-D view is illustrated in Fig. 1. The carrier distribution is determined by an ambipolar equation. In high-level injection, assuming a quasi-neutral condition in carrier storage region, the ADE is described as

$$D \frac{\partial^2 p(x, t)}{\partial x^2} = \frac{p(x, t)}{\tau} + \frac{\partial p(x, t)}{\partial t} \quad (1)$$

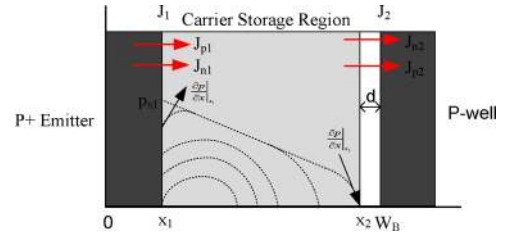


Fig. 1. 1-D carrier distribution in IGBT.

where D is the ambipolar diffusion coefficient, τ is the high-level carrier lifetime within the drift region, and $p(x, t)$ is the excess injected carrier concentration.

The Fourier series solution of the excess carrier distribution can be written as

$$p(x, t) = p_0(t) + \sum_{k=1}^{\infty} p_k(t) \cos \left[\frac{k\pi(x - x_1)}{x_2 - x_1} \right]$$

$$p_0(t) = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} p(x, t) dx$$

$$p_k(t) = \frac{2}{x_2 - x_1} \int_{x_1}^{x_2} p(x, t) \cos \left(\frac{k\pi(x - x_1)}{x_2 - x_1} \right) dx. \quad (2)$$

Substituting the carrier concentration in Fourier series form into the ADE, the amplitude of Fourier series $p_k(t)$ can be determined by a group of the first-order differential equations. Details of the solution are derived in [24]. After finding the excess carrier concentration, the voltage drop over carrier storage region is also known. The electric field and voltage drop in drift region is determined by

$$E = \frac{J}{q\mu p(x, t)} + \frac{DV_T}{q} \frac{dp(x, t)}{dx}$$

$$V = \int E dx. \quad (3)$$

The voltage drops across the junction and depletion region are also related to the injected carrier concentration at two boundaries of the carrier storage region. The total voltage is then determined.

III. FOURIER-SERIES-BASED THERMAL MODEL

A. Heat Conduction in Packages

In order to find the solution of transient heat conduction problems, it is necessary to review the geometry of typical package of power semiconductor devices. Direct bond copper (DBC) technology is frequently used in modern power electronic packaging. The copper is directly bonded to a ceramic substrate, such as AlN [25]. Fig. 2 illustrates a structure view of a typical DBC package. The geometry is based on a commercially available IGBT module.

Due to the symmetrical structure, it is possible to consider half of a chip with an appropriate boundary condition along the axis of symmetry. The simulated domain is given in Fig. 3.

The heat generated in a silicon chip is dissipated through the package structure to a baseplate and heat sink (usually copper).

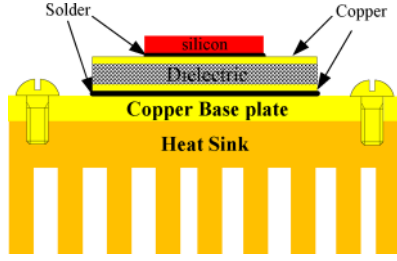


Fig. 2. Structure view of the DBC package.

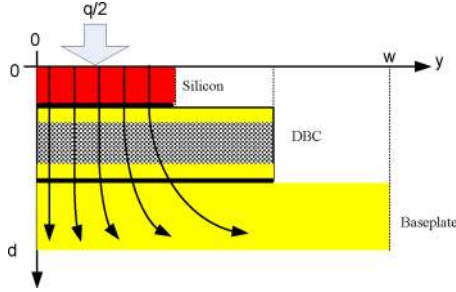


Fig. 3. Simulation domain of DBC.

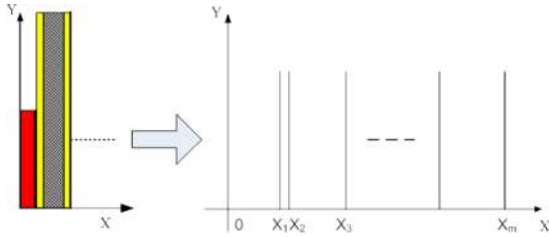


Fig. 4. 1-D heat conduction in DBC.

The general form of heat diffusion equation can be written as [26]

$$\nabla(K \cdot \nabla T(x, t)) + G = \rho c \frac{\partial T(x, t)}{\partial t} \quad (4)$$

where K is the thermal conductivity, ρ and c are the mass density and specific heat of different material respectively, and G is the heat generation function, which is usually known for thermal analysis.

B. 1-D Fourier Series Thermal Model

The 1-D model of heat conduction behavior in DBC geometry is illustrated in Fig. 4. For 1-D heat conduction, the equation can be simplified as

$$\alpha_i \frac{\partial^2 T_i(x, t)}{\partial x^2} + G'_i(x, t) = \frac{\partial T_i(x, t)}{\partial t}, \quad i = 1, \dots, m \quad (5)$$

where α_i is the thermal diffusivity of each layer.

To solve (5), certain boundary conditions are necessary. At each interface between different layers, perfect thermal contact

is assumed, giving

$$T_i(x_{i+1}, t) = T_{i+1}(x_{i+1}, t) \quad (6)$$

$$k_i \frac{\partial T_i(x, t)}{\partial x} \bigg|_{x=x_{i+1}} = k_{i+1} \frac{\partial T_{i+1}(x, t)}{\partial x} \bigg|_{x=x_{i+1}} \quad (7)$$

Assuming the heat source to be located only on the top of the silicon chip, this can be expressed as

$$\frac{\partial T_1(x, t)}{\partial x} \bigg|_{x=x_1} = q(t). \quad (8)$$

At the boundaries without heat flux input, the convection surface boundary condition can be written as

$$k_m \frac{\partial T_m(x, t)}{\partial x} \bigg|_{x=x_{m+1}} + h(T_m(x_m, t) - T_0) = 0. \quad (9)$$

The 1-D form of heat conduction equation can be solved by assuming that the solution of the temperature distribution in Fourier series form is written as in (10a)–(10c). Alternative basis functions such as exponentials could be used for the series solution instead of cosines. However, the use of trigonometric functions is equivalent to exponentials and results in a similar equivalent circuit representation, described in (10) and (11). Further, the use of cosine functions provides a solution methodology that is identical to that used for the charge carrier dynamics and allows software simplification for our full electrothermal device models

$$T(x, t) = T_0(t) + \sum_{k=1}^n T_k(t) \cos \left[\frac{k\pi(x - x_1)}{x_m - x_1} \right] \quad (10a)$$

$$T_0(t) = \frac{1}{x_m - x_1} \int_{x_1}^{x_m} T(x, t) dx \quad (10b)$$

$$T_k(t) = \frac{2}{x_m - x_1} \int_{x_1}^{x_m} T(x, t) \cos \left[\frac{k\pi(x - x_1)}{x_m - x_1} \right] dx \quad (10c)$$

where x_m represents the total depth of the simulated domain and x_1 is the starting position of silicon chip. For a general simulation, the boundary conditions are arbitrary and are coupled to the electrical device/module behavior as well as the external circuit in which the device/module is inserted. One difference in treating the heat flow as compared to charge-carrier distribution is that the spatial boundaries of the heat-flow domain remain fixed (moving depletion region edges affect the carrier distribution in device operation). Therefore, only time variations of the boundary conditions need be considered for the thermal model. Boundary thermal gradients (7)–(9) may be obtained from the knowledge of the input heat source, assumed here to be distributed uniformly across the silicon die surface area. This time-varying heat source is determined from the instantaneous electrical power dissipation during the dynamic operation of the module. Full electrothermal simulation includes feedback from the electrical power dissipation to the thermal behavior to calculate the instantaneous junction temperature that is then used to update the material and device physical parameters for the next time step in the circuit simulation.

The temperature distribution of whole DBC structure is in the form of Fourier series. The amplitude of harmonics of Fourier

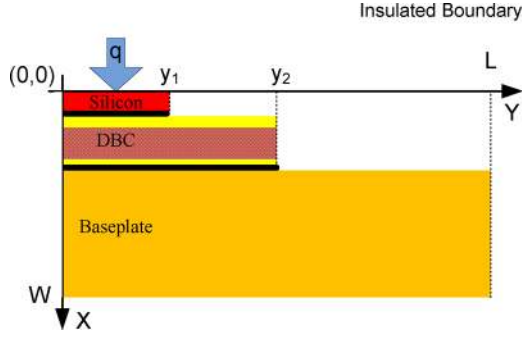


Fig. 5. Simulation domain for 2-D heat flow.

series $T_k(t)$ is determined by (10). To find the solution of (5) with certain boundary and internal conditions (6)–(9), (5) can be rewritten in matrix form as

$$\frac{d\bar{T}}{dt} + A \times \bar{T} = B \quad (11)$$

where \bar{T} is a vector of Fourier series harmonics amplitude $[T_0, T_1, \dots, T_n]$, which is varied dynamically. A is a transfer matrix and B is an input matrix that is related to the known heat generation function and boundary conditions. The detailed derivation of Fourier series solution can be found in [22]. The amplitude of each harmonic is obtained based on the solution of (11). After the inverse Fourier series transformation, the transient temperature distribution in the package is determined simultaneously.

C. 2-D Fourier Series Thermal Model

Although 2-D heat conduction is much more complicated than 1-D heat flow, more accurate prediction of the junction temperature requires 2-D thermal characterization, especially in the design of integrated power electronics module (IPEM), which contains multichips packaged into one heat sink to reduce the volume.

The simulated geometry of 2-D heat conduction in DBC package is illustrated in Fig. 5. The insulated boundary keeps heat dissipation only in the DBC packages. For 2-D heat conduction problems, heat conduction equation is written as

$$\alpha_i \left(\frac{d^2 T_i(x, y, t)}{dx^2} + \frac{d^2 T_i(x, y, t)}{dy^2} \right) + G'_i(x, y, t) = \frac{dT_i(x, y, t)}{dt}, \quad i = 1, \dots, m \quad (12)$$

$$T(x, y, t) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} T_{mn}(t) \cos \frac{m\pi x}{W} \cos \frac{n\pi y}{L} \quad (13)$$

where

$$T_{mn} = \frac{4}{WL} \int_{x=0}^W \int_{y=0}^L T(x, y, t) \cos \left(\frac{m\pi x}{W} \right) \cos \left(\frac{n\pi y}{L} \right) dy dx, \quad m \neq 0 \quad n \neq 0$$

$$T_{m0} = \frac{2}{WL} \int_{x=0}^W \int_{y=0}^L T(x, y, t) \cos \left(\frac{m\pi x}{W} \right) dy dx, \quad m \neq 0 \quad n = 0$$

$$T_{0n} = \frac{2}{WL} \int_{x=0}^W \int_{y=0}^L T(x, y, t) \cos \left(\frac{n\pi y}{L} \right) dy dx, \quad m = 0 \quad n \neq 0$$

$$T_{00} = \frac{1}{WL} \int_{x=0}^W \int_{y=0}^L T(x, y, t) dy dx, \quad m = 0 \quad n = 0. \quad (14)$$

The 2-D Fourier series form of solution of (12) can be written in the form shown in (13). The amplitude of each harmonics is defined by (14). Using the method in 1-D solutions, (12) can be transformed into a form similar to (11). Although the input matrix and transfer matrix will be much more complicated, the amplitudes of harmonics are solved based on (14).

The increasing complexity of transfer matrix and input matrix requires powerful mathematical tools for fast calculation. MATLAB/Simulink is adopted as the simulation tool, which is a dynamic simulation tool with graphical interface to various MATLAB's numerical methods to solve ordinary differential equation (ODE) [27]. The Fourier-series-based thermal model can be easily programmed in Simulink environment. The drawback of Simulink is its lack of circuit-based simulation. So it is suitable only for simple circuit simulations with a limited node number [28].

Boundary conditions are important under parameter extraction procedures, whether a global approach is used [21] or based on terminal behavior [12]. The method described in this paper tends to be more similar to that used in [21]. Knowledge of the package system materials and physical dimensions is required, but not experimental or higher order modeling (e.g., FEM analysis). However, it has been shown that material nonlinearities produce important second-order effects, particularly for temperature excursions above 80 °C [29], which noted that an exponential temperature dependence of the thermal conductivity (could often be approximated as linear) and an approximation of temperature independence of the heat capacity provided excellent results. It should also be noted that interface states at material layer boundaries can introduce discrepancies between measured results and simulations.

IV. COMPARISON OF THERMAL MODELS

In this section, to prove the availability of the new thermal model, the simulation results of thermal model based on finite-difference method (FDM), Fourier series thermal model, and traditional equivalent RC thermal ladder are compared.

A. Thermal Model Based on Finite-Difference Solutions

The FDM is frequently used in thermal calculations for steady-state and transient conditions. FDM can provide high precision at the cost of slow computing speed. Normally, the FDM thermal model is widely used as a result verification tool because of its high accuracy. In transient thermal analysis, FDM is not a good choice because of slow speed and high memory storage.

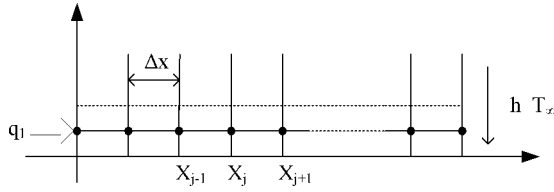


Fig. 6. Schematic view of discrete nodes for the 1-D thermal model.

The basic idea of FDM thermal model relies on transforming the partial differential equations into a group of approximate and soluble algebraic equations. For 1-D thermal model, as shown in Fig. 6, at first, the whole geometry is divided into a mesh of discrete nodes. The accuracy of the calculation depends strongly on the number of nodes. The larger the number of nodes, the more accurate the solution will be, but at the cost of a slower calculation speed.

There are explicit and implicit forms of finite-difference equations. Relative to the explicit method, the implicit formulation has the advantage of being unconditionally stable [26]. So, in this model, the implicit method has been used. For the simple 1-D model illustrated in (5), the implicit finite-difference form of the differential equation can be written as

$$-\frac{\alpha_i}{\Delta x^2} * T_{m+1}^{p+1} + \left(\frac{2\alpha_i}{\Delta x^2} + \frac{1}{\Delta x \Delta t} \right) T_m^{p+1} - \frac{\alpha_i}{\Delta x^2} * T_{m-1}^{p+1} = \frac{1}{\Delta t} T_m^p + g' \quad (15)$$

where p is introduced to represent a discrete time step, $t = p \times \Delta t$. The time derivative is expressed in terms of the new $(p+1)$ and previous p times. Hence, the solution must be performed at every time interval Δt .

After a nodal network has been established, the finite-difference form of equations can be written for each node. The next step is to find the solution of these equations. There are direct and iterative methods to solve the equations. The direct method is used for a small number of nodes. Considering the simple shape of the coefficient matrix, the temperature at the center node is only related to the temperature of neighboring nodes; so, the tridiagonal matrix algorithm (TDMA) method is used for higher calculation speed [30].

FDM thermal model can be easily developed into a 2-D form for more accurate temperature distributions. The finite-difference model can also easily include the temperature dependence of material constants, such as thermal conductivity. A previous work [7] has provided a partial coupled FEM method to speed up the simulation. One of the major drawbacks of using an FDM model for thermal simulation is that it is not easy to create a cosimulation with an electrical circuit simulator, which could calculate the transient power dissipation from power electronic devices instantaneously. In order to run concurrently with circuit simulator tools properly and efficiently, some improvement should be added.

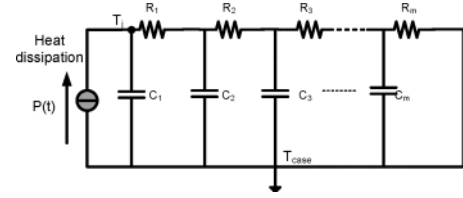


Fig. 7. Schematic for equivalent thermal RC ladders.

B. Equivalent RC Thermal Ladder

Another method for transient thermal analysis is to build an equivalent RC thermal network based on the experimental curve of thermal impedance provided by the manufacturer. A typical schematic of this equivalent RC thermal network is shown in Fig. 7. The resistances are lumped representation of the thermal resistance, while the capacitances are lumped representation of heat capacitance. The value of the thermal resistance and capacitance can be obtained through curve-fitting method based on the transient impedance curve. The experimental thermal impedance curve can usually be found in the datasheet.

C. Simulated Results Comparison

To validate the Fourier series thermal model, it is first compared with the finite-difference thermal model for a step thermal response. A constant heat input at the silicon surface approaches 100 W/cm^2 . The duration of the power dissipation is 1 ms. Because of the short duration of the power input, it is reasonable to neglect the thermal dependence of most material constants.

The result of 1-D heat conduction simulation is shown in Fig. 8 at two different times: 0.5 and 1 ms. The maximum difference between the two models is within 5%, which is acceptable in practical simulations. The speed of calculation is dependent on the number of Fourier series harmonics. In this paper, the number of Fourier series harmonics is chosen to be 20 for whole DBC geometry. The total computation time of the Fourier-series-based thermal model under constant heat input for 1 ms is less than 10 s. However, the 1-D finite-difference model for the same system, when the time step is chosen to be $1 \mu\text{s}$ and the total number of nodes as 300, results in a total computation time of about 2 min. The weakness of this Fourier series thermal model is that it is not convenient for representing the imperfect thermal contact between different layers, which differs from the actual temperature distribution. The assumption of perfect thermal contact between material layers will lead to some inaccuracy, though the use of constantly updated heat source (from feedback with the electrical/circuit behavior) ensures that the time variations are accurate.

To characterize 2-D heat conduction, the thermal step response of DBC structure under constant heat dissipation is presented. The heat dissipation is up to 100 W/cm^2 . The duration of power dissipation is 1 ms. The results of 2-D finite-difference thermal model and Fourier series thermal model have been compared in Fig. 9. Because of the short heating duration, only the top three layers with distinctive temperature changes are plotted.

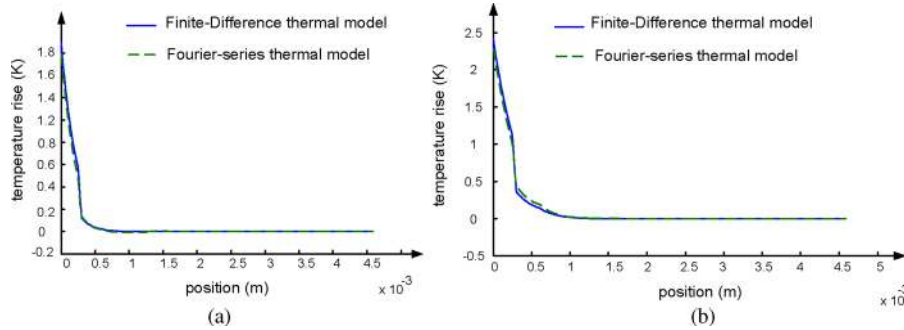


Fig. 8. Comparison of the 1-D Fourier series thermal module and a finite-difference thermal model at different times: 0.5 and 1.0 ms.

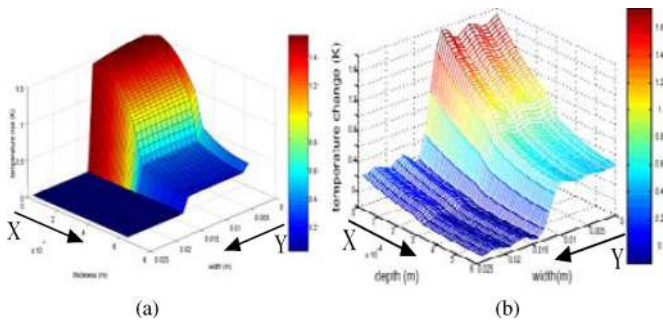


Fig. 9. Results of the 2-D heat conduction in DBC structure under constant heat dissipation of 100 W/cm^2 for 1 ms. (a) 2-D FDM. (b) 2-D Fourier series thermal model. Due to the short heating duration, only the top three layers with distinctive temperature changes are plotted.

For 2-D finite-difference model, there is a tradeoff between the size of elements and the required accuracy of thermal calculation. The mesh size in this case is chosen to be $10 \mu\text{m}$ in the thickness (vertical) direction and 1 mm in the width (lateral) direction. When the time step is chosen to be $1 \mu\text{s}$, the simulation time could be up to 10 min. The maximum temperature rise is 1.5 K . For 2-D Fourier series thermal model, the number of harmonics is also chosen based on the tradeoff between simulation speed and accuracy. In this paper, the number of harmonics in the x -axis is 50 and number harmonics in the y -axis is 10. The maximum temperature rise in 2-D Fourier series thermal model is 1.7 K , which is close to that of the FDM thermal model under the same heat dissipation. The total simulation time of Fourier series thermal model is less than 60 s with the same computer that is only one-tenth of that consumed by finite-difference thermal model. The simulation results of a step thermal response using an equivalent RC thermal ladder model from the manufacturer's datasheet has been compared with the Fourier model. If the heating duration is less than 0.1 s , the calculated temperature in the equivalent RC thermal model is at least 30% less than that of the Fourier-series-based thermal model. The steady-state results are similar, however, and show the expected convergence of the results over time.

These comparison examples from Figs. 8 and 9 and the datasheet RC -impedance model highlight the accuracy of the Fourier method while being inherently simpler in form than a full FEM or finite-difference description.

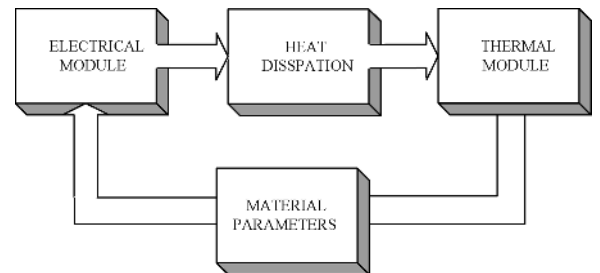


Fig. 10. Schematic of the complete electrothermal model.

A complete description of a typical power module would require a full 3-D model, which is beyond the scope of this paper. The number of harmonic terms needed would increase in the z -direction from 10 to 50. The accompanying increase in simulation time will start to negate the benefits of the Fourier method in favor of optimized finite-element models.

V. ELECTROTHERMAL MODELING

For a complete simulation model, the thermal issue cannot be neglected since most of the primary parameters of semiconductor material are strongly temperature-dependent. Generally, the modification of semiconductor material parameters should be included based on thermal feedback. A schematic description of the complete electrothermal simulation model is illustrated in Fig. 10. The electrical and thermal model is connected through estimation on self-heat dissipation, which is achieved by electrical behavior simulation.

The electrical model employed in this paper is the Fourier-series-based electrical model, which has been reported in [19]–[24]. The thermal model can be varied from FEM or FDM thermal model, Fourier-series-based thermal model, and traditional equivalent RC thermal network. Since the complexity of the FEM or FDM thermal model limited its use in dynamic thermal analysis, Fourier series thermal model and equivalent RC thermal network are implemented and compared in this paper.

A. Temperature-Dependent Parameters

The results of power device simulation greatly depend on the physical parameters of semiconductor materials, e.g., intrinsic concentration, carrier mobility, minority carrier lifetime, etc.

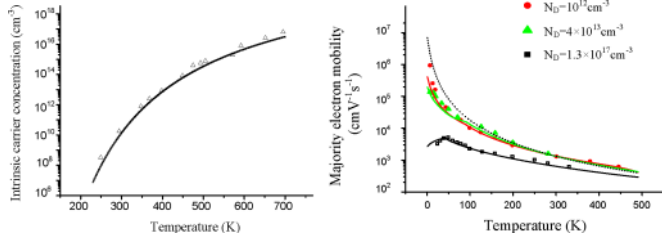


Fig. 11. Material parameters as a function of temperature.

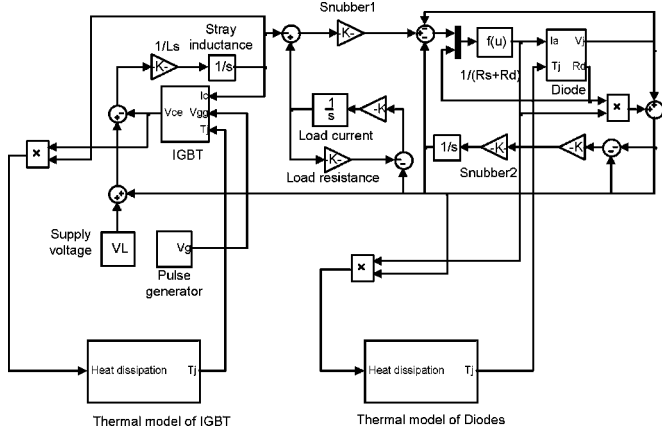


Fig. 12. Electrothermal module of IGBT and power diode under inductive load test.

Most of these parameters are strongly dependent on junction temperature of semiconductors.

In the complete electrothermal simulation model, the temperature-dependent parameters are modified through empirical formulations, which are usually obtained by curve-fitting on the experimental measurement. Fig. 11 shows the intrinsic carrier concentration and carrier mobility changing with temperature. The dots are experimental data from [31] and [32]. In the proposed electrothermal models, every temperature-dependent parameter has been considered. The details about modeling temperature-sensitive parameters of semiconductor material have been reported in [33].

B. Electrothermal Model in Simulink

The electrothermal model has been implemented in MATLAB/Simulink environment. The electrothermal simulation block diagram of IGBT and power diode for inductive load switching in Simulink is shown in Fig. 12. The circuit schematic of inductive load switching is shown in Fig. 13. The thermal model is to determine the junction temperature based on transient heat dissipation calculated from the electrical model. The electrical model contains an extra input, which, for the junction temperature, is calculated by thermal models.

The temperature-sensitive parameters are a function of the predicted junction temperature. The simulation model of IGBT with temperature-dependent parameter set has been shown in Fig. 14. The temperature-dependent parameters have been calculated in the function block and then transferred into other simulation function blocks. Due to the convergence problem, the

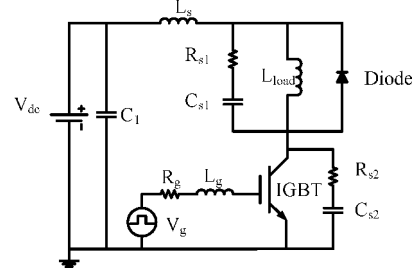


Fig. 13. Circuit schematic of the inductive load switching test.

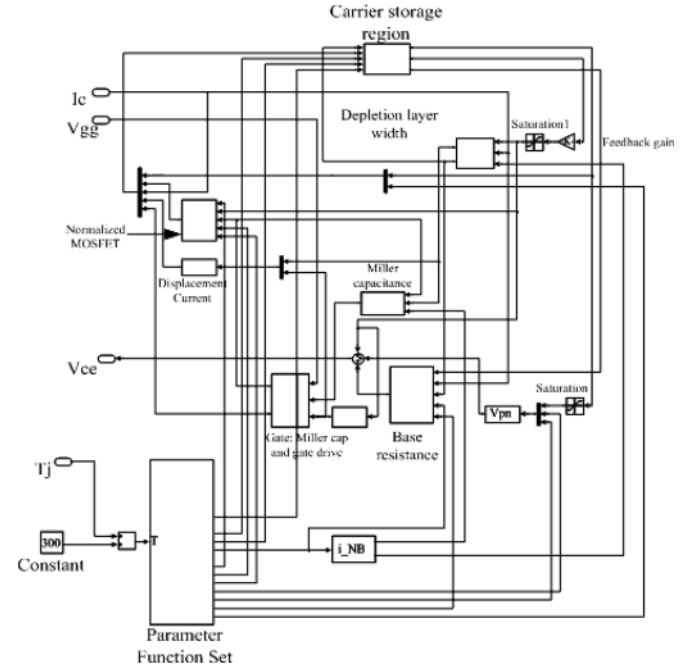


Fig. 14. Electrothermal module of IGBT with temperature-sensitive parameter.

small time step is usually required when simulating the electrical behavior. The electrical response is usually much faster than the thermal response, especially in the case of high switching frequency. It is reasonable to assume that the junction temperature is uniform within several time steps. So, in the electrothermal models, in order to accelerate the simulation speed, the modification of temperature-sensitive parameters is implemented in multi-time steps within which junction temperature change is distinctive.

Simulink is one of many tools by which circuit simulation models can be developed, though it is limited in its ability to move between model levels (levels of abstraction), and so, other tools may be more useful for prototyping. A software tool called ModLyng allows the designer to create models from the perspective of what the model does rather than what the model language needs to be [17]. The key concept behind the approach is to consider the model structure and key elements, and then for the software to automatically export the format that is appropriate for the design in question. This allows numerous analyses to be performed. For example, if the simulation environment is Saber, then the model is exported in a MAST format; however, if the

TABLE I
PARAMETERS OF CIRCUIT COMPONENTS

Load (μH)	V _g (V)	R _g (Ω)	Snubber I	Snubber II	C1 (μF)	Ls (μH)
310	-5-15	12	10 Ω /10nF	10 Ω /10nF	300	0.54

model is required in Verilog-AMS or VHDL-AMS, then crucially the same model can be exported without alteration into the alternative formats. Another interesting slant to this approach is to extend from the normal modeling approach of creating a library of individual elements and then creating schematics in a specific format, to an approach of hierarchical modeling, a bit-like macromodeling, from which single models can be exported. This can greatly streamline the design process of complex systems in multiple platforms.

Certify is a companion parameter extraction tool with a user-friendly graphical user interface [18]. Unlike many commercial model characterization tools, Certify is focused on making the parameter extraction definition and execution easier, and is able to be applied to any model: behavioral, physics-based device models, etc. It is an intuitive, flowchart-oriented tool that allows the user to capture model characterization recipes, save and reuse them (including simulator settings), import data, and perform parameter extraction and curve-fitting. Certify is currently integrated to work with the Saber and Spectre simulators; therefore, it supports MAST, VHDL-AMS, and Verilog-A models, respectively.

VI. EXPERIMENTAL MEASUREMENT

In order to validate transient thermal analysis on the proposed electrothermal module, a clamped inductive load circuit has been established for electrical and thermal measurement. The simplicity of inductive load circuit makes it easier to be simulated in Simulink environment. The circuit schematic is shown in Fig. 13. In this circuit, the inductive load L_1 , charged by a voltage source, can be treated as a current source in the circuit analysis. The current commutation occurs between the freewheeling diode and the IGBT. R_s and C_s are the snubber resistance and capacitance, respectively. R_g and L_g represent the resistance and inductance in the gate control circuit. L_s is the stray switching loop inductance in test circuit. The model of IGBT is FS50R06YL4 from ABB, rated at 600 V 50 A. The diode model is CS241210 from Powerex, rated at 1200 V 100 A. The parameters of main circuit component have been listed in Table I.

To measure the temperature of the IGBT module, several thermocouples need to be attached to the surface of the silicon chip, the module base, and the heat sink. Since transient thermal measurements require a fast time response, the adopted thermocouples are type K unsheathed fine gauge microtemp thermocouples from OMEGA. The model is CHAL-0005 with 0.013 mm diameter wire and 200 mm lead. When heated from 0 °C to 100 °C, these thermocouples can provide response time on the order of several milliseconds [34]. The layout of

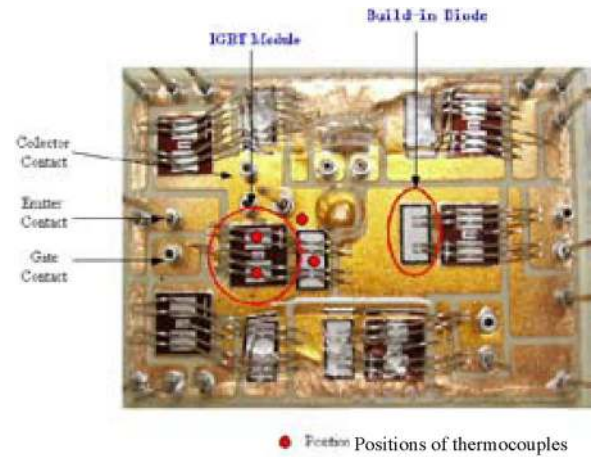


Fig. 15. Layout of the positions of thermocouples.

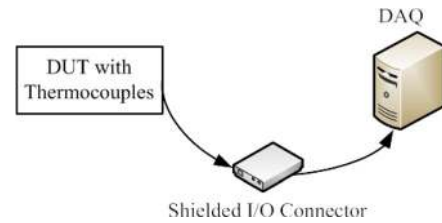


Fig. 16. Diagram of the thermal measurement system.

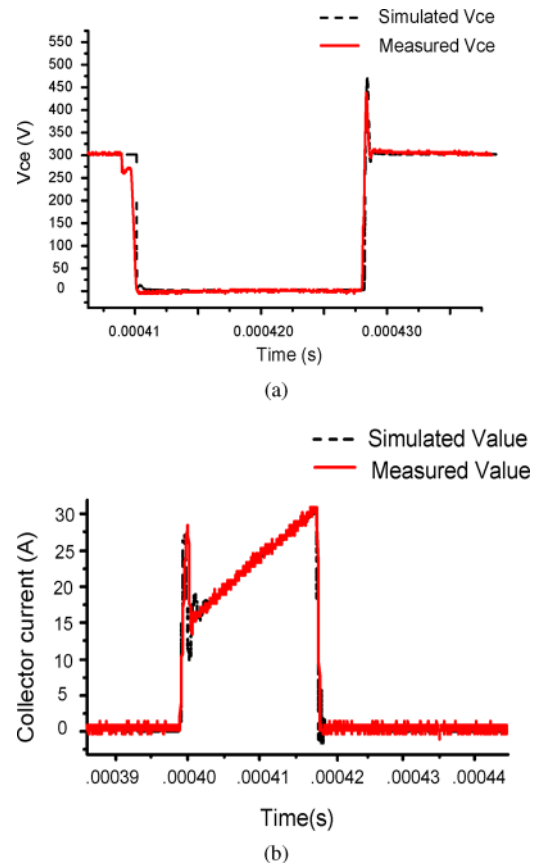


Fig. 17. Simulated and measured collector-emitter voltage and current. (a) Vce. (b) Ic.

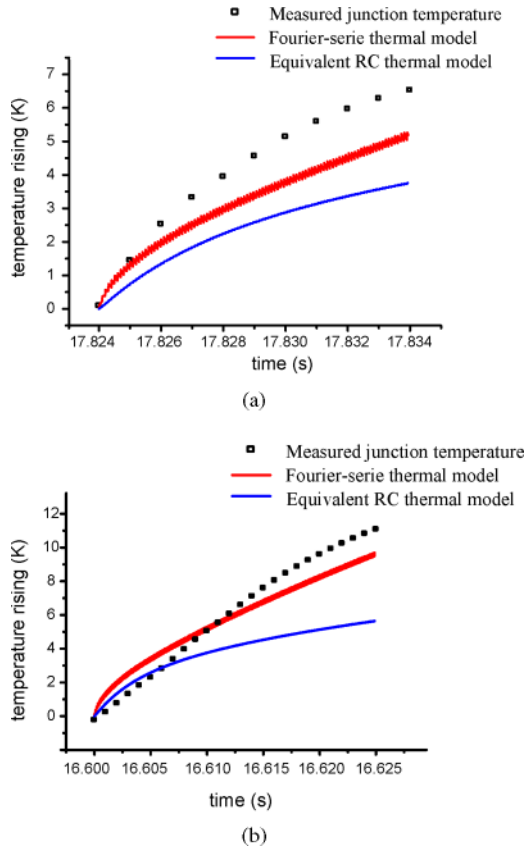


Fig. 18. Comparison of measured junction temperature and simulated results under different switching cycles. (a) 100 cycles. (b) 250 cycles. The switching frequency is 10 kHz and dc bus voltage is 300 V.

thermocouples placed on the top of IGBT and power diode is demonstrated in Fig. 15.

The proposed thermal measurement system includes thermocouples, shielded I/O connector, and a remote workstation containing NI 7831R devices from National Instruments. The diagram of measurement system is presented in Fig. 16. The NI 7831R is a reconfigurable I/O (RIO) device. The NI 7831R has eight independent, 16-bit analog input (AI) channels, eight independent, 16-bit analog output (AO) channels, and 96 digital I/O (DIO) lines. This device is integrated with a user-reconfigurable field-programmable gate array (FPGA) that controls the digital and analog I/O lines [35].

The measured output voltages of thermocouples are usually nonlinear. The Seebeck coefficients can vary by a factor of 3 or more over the range of thermocouples operating temperature. Here, in order to obtain the real temperature from measured voltage difference of K-type thermocouples, polynomial approximation on temperature versus voltage curve of K-type thermocouples has been programmed [36]

$$T = a_0 + a_1 V + a_2 V^2 + \dots + a_n V^n \quad (16)$$

where V is the measured output voltage from thermocouples and a_0, a_1, \dots, a_n are the coefficients that are specific to K-type thermocouple.

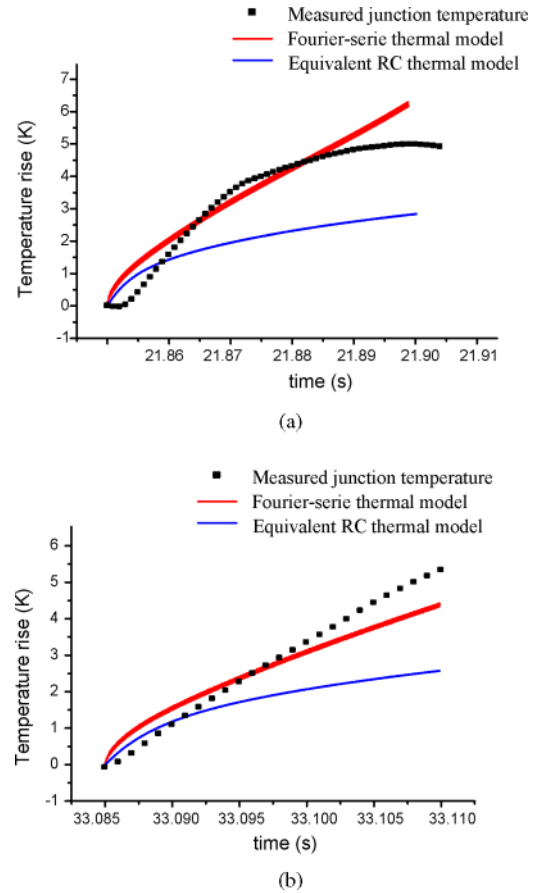


Fig. 19. Comparison of measured junction temperature and simulated results under different switching frequencies. (a) 5 kHz. (b) 10 kHz. The number of switching cycles is 250 and dc bus voltage is 200 V.

VII. RESULTS AND DISCUSSION

The results of electrothermal simulation are compared with experimental measurements. During the switching measurement, the IGBT drain-source voltage and drain current are recorded for comparison with simulated results. Fig. 17 shows the voltage and current waveforms of the IGBT module during one switching cycle at room temperature. The dc voltage bus is set to be 300 V. The switching frequency is 10 kHz with a duty ratio of 0.1. The switching waveform of IGBT matches well with the simulated result, which validates the electrical simulation model.

To check the accuracy of transient thermal analysis based on the proposed thermal model, the junction temperature calculated by electrothermal simulation has been compared with actual measured value. In order to achieve measurable temperature rise, the IGBT is switched for a certain number of cycles with low duty ratio.

Also, in order to evaluate the new thermal model, Fourier series thermal model and equivalent RC thermal network are employed in the electrothermal simulations. The fourth order of equivalent RC thermal network has also been adopted as thermal models.

Figs. 18–20 show the measured junction temperature rise and simulated temperature rise using two different thermal models:

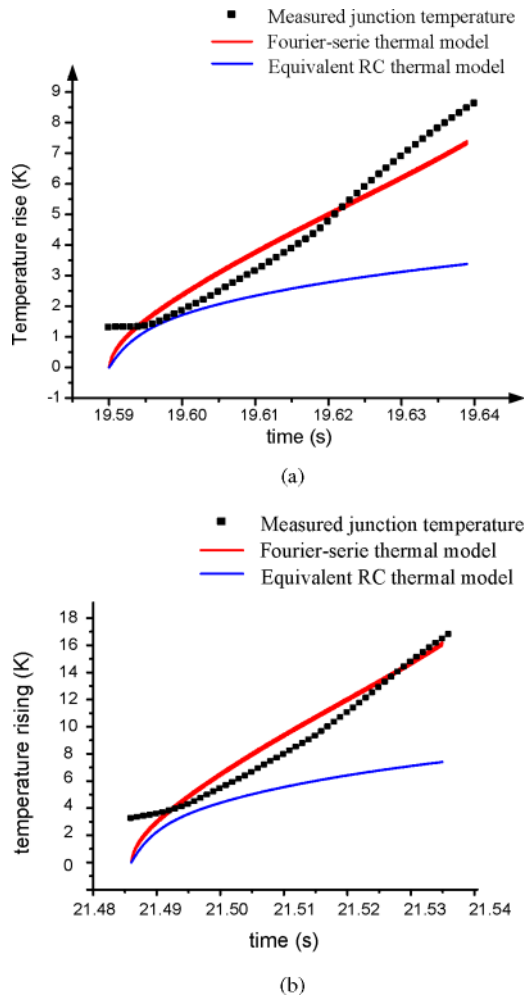


Fig. 20. Comparison of measured junction temperature and simulated results under different voltages. (a) 200 V. (b) 300 V. The number of switching cycles is 500 and the frequency is 10 kHz.

the proposed Fourier series model and the equivalent RC thermal network. Fig. 18 shows the comparison of measured junction temperature evolution under different number of switching cycles. The dc bus voltage is set to be 300 V and the switching frequency is 10 kHz. The simulation result and the measured result under different switching frequencies are shown in Fig. 19. The voltage of dc bus is set to be 200 V. The number of switching cycles is chosen to be 250. Fig. 20 shows the measured junction temperature rise while switching from 300 V and 200 V dc bus value. The switching frequency is 10 kHz. The total number of switching cycles is 500.

From these comparisons of simulated and measured junction temperature, it is seen that the error is within a range of a few degrees or less. The better performance of Fourier series thermal model over equivalent RC thermal model has been illustrated with a closer match to the measured junction temperature. The switching times displayed in Figs. 18–20 cover 10–50 ms of the transient thermal response of the silicon. The Fourier method presented provides a closer match to the measured junction temperature in each case than does a simple fourth-order RC -transient impedance representation. Both

models and the measurements should originate from the same initial temperature and then diverge as several switching events occur. All models converge again after several seconds of operation, as has been confirmed previously [28].

Although the simulation time is shorter for equivalent RC thermal model compared with Fourier series thermal model, the equivalent RC thermal network usually underestimates the junction temperature, especially for high voltage and with a high number of switching cycles. The reduced number of Fourier series coefficient can speed up the total simulation speed at the cost of less accurate calculation. Due to the multilayer structure of DBC package, the total number of Fourier series coefficients is suggested to be at least 40 (about 5 to 7 per layer) to obtain the affordable precision of thermal simulation. This is fewer than, but on the order of, the number of terms described in [21]. The total simulation time for 500 cycles at 10 kHz switching frequency is around 8 min using a computer with Pentium 2.8 GHz processor and 1 GB RAM.

VIII. CONCLUSION

In this paper, a new thermal model based on Fourier series transformation has been introduced. The fast speed and high accuracy of Fourier series thermal model has been validated by finite-difference thermal model for both 1-D and 2-D heat conduction in typical DBC package structures. Compared with traditional equivalent RC thermal ladder, a more accurate result has been proved using the new thermal model. A complete electrothermal simulation model of IGBT and power diode under inductive load switching test has been implemented in MATLAB/Simulink. The dynamic electrothermal simulation of IGBT and power diode has been completed under various switching conditions. The experimental setup and thermal measurement system have been introduced in detail. Experimental measurement has proven that the thermal model based on Fourier series transformation provides better prediction of junction temperature than the traditional equivalent RC thermal network, which tends to underestimate the junction temperature.

This integrated electrothermal power device model is not appropriate for reliability analysis. More extensive mechanical material parameters (i.e., coefficient of thermal expansion for stress and strain) would be necessary for a complete physical description of the package system. Predictions based on thermal cycling of the silicon would also not be typically relevant because of the computational time required (our model is not compact enough). However, the strength of this demonstrated model is the seamless integration of the electrical and associated thermal behavior of the device and package, and the ability of the model to appropriately adjust its device and material parameters based on circuit operation in a physically valid and meaningful way. Ultimately, the circuit designer can have confidence that simulation results will indicate a potentially dangerous operating mode if the junction temperature exceeds some prescribed limit.

REFERENCES

- [1] P. M. Fabis, D. Shun, and H. Windischmann, "Thermal modelling of diamond-based power electronics package," in *Proc. 15th Annu. IEEE Semicond. Therm. Meas. Manage. Symp.*, 1999, pp. 98–104.

- [2] Z. Luo, H. Ahn, and M. A. El Nokali, "A thermal model for insulated gate bipolar transistor module," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 902–907, Jul. 2004.
- [3] J. Lohan and M. Davis, "Transient thermal behavior of a board-mounted 160-lead plastic quad flat pack," in *Proc. 1994 InterSociety Conf. Therm. Phenom. Electro-Syst.*, 1994, pp. 108–116.
- [4] S. J. Ham, M. S. Cho, and S. B. Lee, "Thermal deformation of CSP assembly during temperature and power cycling," in *Proc. Int. Symp. Electr. Mater. Pack.*, 2000, pp. 350–357.
- [5] M. Thoben, W. Staiger, and J. Wilde. (2000). Modeling and experimental investigations on degradation of microcomponents in power cycling [Online]. Available: http://ansys.net/ansys/papers/mw/2000_1031.pdf
- [6] A. Syed, "Predicting solder joint reliability for thermal, power and bend cycle within 25% accuracy," in *Proc. 51st ECTC*, 2001, pp. 255–263.
- [7] E. R. Brown and M. C. Shaw, "Thermomechanics of power electronics packages," in *Proc. 2000 InterSociety Conf. Therm. Phenom.*, pp. 270–278.
- [8] F. P. Incropera and D. P. Dewitt, *Heat and Mass Transfer*. New York: Wiley, 2002.
- [9] Q. Chen, X. Yang, Z. Wang, L. Zhang, and M. Zheng, "Thermal design considerations for integrated power electronics modules based on temperature distribution cases study," in *IEEE PESC Rec.*, Orlando, FL, Jun. 17–21, 2007, pp. 1029–1035.
- [10] A. Ammous, K. Ammous, H. Morel, B. Allard, D. Bergogne, F. Sellami, and J. P. Chante, "Choosing a thermal model for electrothermal simulation of power semiconductor devices," *IEEE Trans. Power Electron.*, vol. 14, no. 2, pp. 300–307, Mar. 1999.
- [11] A. Lakhsasi and Y. Hamri, "Transient thermal analysis of fast switching devices by partially coupled FEM method," in *Proc. IEEE CCECE/CCGEI*, Ottawa, ON, May 2006, pp. 1098–1103.
- [12] S. M'Rad, "An experimentally verified compact transient electro-thermal modeling procedure for power systems," in *EPE Conf. Rec.*, Aalborg, Denmark, Sep. 2–5, 2007, pp. 1–8.
- [13] E. Santi, J. L. Hudgins, and H. A. Mantooth, "Variable model levels for power semiconductor devices," presented at the Soc. Model. Simul. Int. Conf. Rec., San Diego, CA, Jul. 2007, Session W13, Paper 3.
- [14] E. Santi, L. Lu, Z. Chen, J. L. Hudgins, and H. A. Mantooth, "Simulating power semiconductor devices using variable model levels," presented at the Soc. Model. Simul. Int. Conf. Rec., San Diego, CA, Jul. 2007, Session W13, Paper 4.
- [15] A. T. Bryant, P. A. Mawby, P. R. Palmer, E. Santi, and J. L. Hudgins, "Exploration of power device reliability using compact device models and fast electro-thermal simulation," *IEEE Trans. Ind. Appl.*, vol. 44, no. 3, pp. 894–903, May/Jun. 2008.
- [16] A. T. Bryant, P. R. Palmer, E. Santi, J. L. Hudgins, and P. A. Mawby, "Review of advanced power device models for converter design and simulation," in *Proc. IET Inf. Commun. Tech. Electr. Sci. (ICTES) Conf. Rec.*, Chennai, India, Dec. 20–22, 2007, pp. 85–90.
- [17] P. R. Wilson, H. A. Mantooth, E. Santi, and J. L. Hudgins, "Model creation for all electric ship (AES) power systems," presented at the Soc. Model. Simul. Int. Conf. Rec., London, U.K., Jun. 2008.
- [18] W. Li, Y. Feng, P. R. Wilson, H. A. Mantooth, E. Santi, and J. L. Hudgins, "Certify: A parameter extraction tool for power semiconductor device models," presented at the Soc. Model. Simul. Int. Conf. Rec., London, U.K., Jun. 2008.
- [19] P. R. Palmer, E. Santi, J. L. Hudgins, X. Kang, J. C. Joyce, and P. Y. Eng, "Circuit simulator models for the diode and IGBT with full temperature dependent features," *IEEE Trans. Power Electron.*, vol. 18, no. 5, pp. 1220–1229, Sep. 2003.
- [20] P. Leturcq, O. Berraies, J. L. Debrie, P. Gillet, M. A. Kallala, and J. L. Massol, "Bipolar semiconductor devices models for computer-aided design in power electronics," in *Proc. 6th Eur. Conf. Power Electron.*, 1995, vol. 2, p. 84.
- [21] Y. C. Gerstenmaier, A. Castellazzi, and G. K. M. Wachutka, "Electrothermal simulation of multichip-modules with novel transient thermal model and time-dependent boundary conditions," *IEEE Trans. Power Electron.*, vol. 21, no. 1, pp. 45–55, Jan. 2006.
- [22] B. Du, J. L. Hudgins, A. T. Bryant, E. Santi, and P. R. Palmer, "Expanded thermal model for IGBT modules," *IEEE IAS Annu. Meeting Conf. Rec.*, vol. 2, pp. 777–784, Oct. 2006.
- [23] X. Kang, "Characterization and modeling of trench gate IGBT," Ph.D. dissertation, Dept. Electr. Eng., Univ. South Carolina, Columbia, Dec. 2002.
- [24] A. Bryant, "Simulation and optimization of diode and IGBT interaction in a chopper cell," Ph.D. dissertation, Univ. Cambridge, Cambridge, U.K., Jan. 2005.
- [25] C. Van Godbold, V. A. Sankaran, and J. L. Hudgins, "Thermal analysis of high-power modules," *IEEE Trans. Power Electron.*, vol. 12, no. 1, pp. 3–11, Jan. 1997.
- [26] F. P. Incropera and D. P. Dewitt, *Heat and Mass Transfer*. New York: Wiley, 2002.
- [27] The MathWorks, Inc. (2008). [Online]. Available: <http://www.mathworks.com/products/simulink/description1.html>
- [28] B. Du, J. L. Hudgins, A. T. Bryant, E. Santi, P. R. Palmer, and H. A. Mantooth, "Transient thermal analysis of power devices based on Fourier-series thermal models," in *IEEE PESC Rec.*, Rhodes, Greece, Jun. 22–26, 2008, pp. 3129–3135.
- [29] M. Rencz and V. Szekely, "Studies on the nonlinearity effects in dynamic compact model generation of packages," *IEEE Trans. Compon. Packag. Technol.*, vol. 27, no. 1, pp. 124–130, Mar. 2004.
- [30] S. D. Conte and C. deBoor, *Elementary Numerical Analysis*. New York: McGraw-Hill, 1972.
- [31] H. D. Barber, "Effective mass and intrinsic concentration in silicon," *Solid-State Electron.*, vol. 10, pp. 1039–1051, May 1967.
- [32] C. Jacoboni, C. Canali, G. Ottaviantand, and A. A. Quaranta, "A review of some charge transport properties of silicon," *Solid-State Electron.*, vol. 20, pp. 77–89, Jul. 1977.
- [33] A. Caiafa, X. Wang, J. L. Hudgins, E. Santi, and P. R. Palmer, "Cryogenic study and modeling of IGBTs," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2003, vol. 4, pp. 1897–1903.
- [34] OMEGA Inc., *Manual of Unsheathed Fing-Gage Thermocouples*. (2007). [Online]. Available: www.omega.com/ppt/pptsc.asp?ref=IRCO_CHAL_P13R_P10R
- [35] National Instruments Corp. Austin TX, *Getting Started With NI 783xR*. (2006). [Online]. Available: <http://www.ni.com/pdf/manuals/370489d.pdf>
- [36] T. Ferguson, "Measuring temperature with thermocouples—A tutorial," National Instruments Corp., Austin, TX, Appl. Note 043, 1996.

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