High Speed IGBT Module Transient Thermal Response Measurements for Model Validation[1]

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Abstract--- **A test system is introduced and applied for validation of dynamic electro-thermal models of multi-chip insulated gate bipolar transistor (IGBT) modules. The test system operates the IGBT in a pulsed high power active mode with controlled current and voltage. The gate-cathode voltage is used as a time-dependent temperature sensitive parameter (TSP). The TSP is calibrated versus temperature with a temperature controlled test fixture using short pulses that do not result in self heating. It is shown that the temperature calibrations for the TSP must be performed on the same IGBT, and under the same conditions for which a transient measurement is to be made. Heating transient measurements are made for both multiple paralleled chips and for a single isolated chip in the same module. Comparisons between measurements of the single IGBT chip and paralleled chips indicate that current sharing is adequate for high-current, low-voltage heating conditions but is not adequate for high-voltage, low-current conditions. Model validation results indicate good performance of a previously developed IGBT electro-thermal model for the range of heating rates tested.**

I. INTRODUCTION

The electrical characteristics and reliability of integrated power electronic modules (IPEMs) can be greatly influenced by the temperature distribution inside the module. To evaluate IPEM thermal performance, it is important to have accurate measurements of chip heating under high-power transient conditions. These measurements can then be used to validate the performance of models that are used to predict the electro-thermal behavior of the IPEMs.

In previous work, a model was developed and experimentally validated for the transient heating of an IPEM and heatsink system [1], [2]. In the previous work, measurements were compared with model results for long-term system heating under relatively low power (150 W) continuous heating. The previous system is capable of validating thermal time constants of 10 s and above. A combination of device temperature sensitive parameters (TSPs) including forward diode voltage and gate-cathode (threshold) voltage, as well as thermocouples, were used to collect the data.

The purpose of this paper is to extend this previous work by developing measurement methods suitable for extracting transient thermal data for short-term (100 µs through 1 s), high-power, heating conditions and to use the data to validate model predictions for these short-term events. For these short-term events, the IGBT silicon chips in which the heat is generated, the direct bond copper (DBC) layer, and the baseplate of the IPEM need to be considered. The heatsink is held at a constant temperature during these fast high-power heating pulses.

II. TEST CIRCUIT

The test circuit used for the measurements is shown in Fig. 1a, and a sketch of the test-circuit waveforms is shown in Fig. 1b. The test circuit maintains the IGBT under test in its active region with a fixed anode to gate voltage and pulses the cathode current from a small bias current to large a heating current. These two currents are shown in the top waveform in Fig. 1b and are designated as the “heating phase” and “cooling phase”. The TSP used to measure the IGBT chip transient temperature response in this work is the gate-cathode threshold voltage and is shown as the middle waveform in Fig. 1b. The initial portion of this waveform indicates a constant voltage in response to the constant bias current and the IGBT being at thermal equilibrium. When the cathode current is switched to a high value during the heating phase, the cathode voltage responds by becoming more negative and then decreases as the device heats. When the heating interval ends, the cathode voltage initially responds by becoming less negative than the initial cathode voltage was before the heating interval began, but then returns towards its initial pre-heating value as the IGBT cools.

Referring once again to Fig. 1a, the gate terminal of the IGBT is referenced to ground through a 470 Ω resistor. The TSP is labeled “Cathode-Gate Voltage” and is shown as a negative number in the results to follow. The IGBT module used is indicated in the dashed outline and contains two multi-chip IGBTs and two multi-chip anti-parallel diodes. For the results shown, only one IGBT is used to obtain the thermal response measurements. Either IGBT1 or IGBT2 can be used; the unused device is disabled by connecting its gate and cathode terminals together as shown for the unused IGBT1. Neither diode is forward biased during the measurements.

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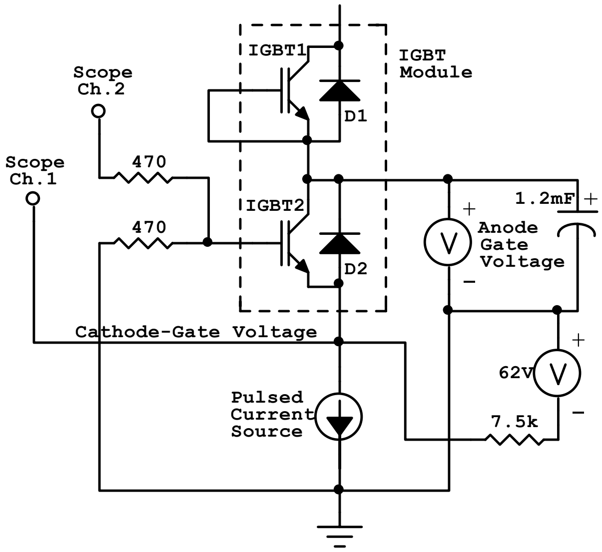

Fig. 1a. High-speed IPEM thermal transient test circuit for measuring the TSP for IGBT2.

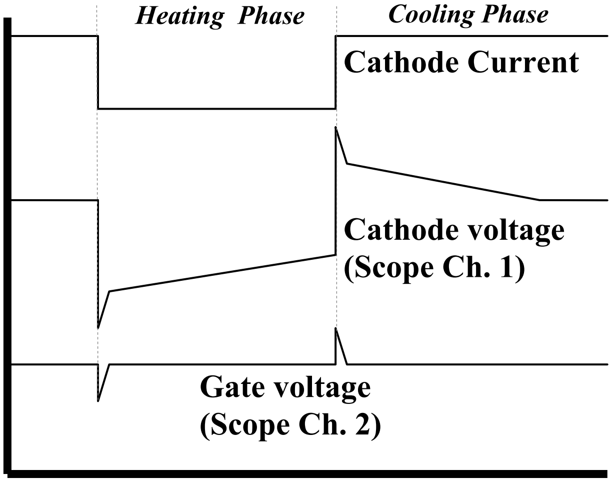

Fig. 1b. Sketch showing test circuit waveforms vs. time.

The cathode of IGBT2 is connected to a pulsed constant current source that is referenced to ground, and the anode of the IGBT2 is connected to a heavily bypassed voltage supply, also referenced to ground. The pulsed current source is a custom-made precision current source that features high-speed gating and current control in 0.1 A increments up to 25.5 A. The 470 Ω gate resistor serves as a damping resistor to prevent oscillation. The small auxiliary current source comprised of a 62 V voltage supply and 7.5 kΩ resistor supplies the bias current and limits the amplitude of the measured switching voltage that appears on the cathode. This bias also provides for the capability of using the TSP measurement during the cooling phase.

The cathode voltage is applied to channel 1 of a digitizing oscilloscope, and the gate voltage is applied to channel 2 of the scope through an additional 470 Ω resistor. The data acquisition is configured to provide a differential gate-to-cathode measurement because a substantial common mode voltage spike appears on the gate and cathode during switching as shown in the middle and bottom waveforms in Fig. 1b. This is due to gate-charging current interacting with the gate resistor used to prevent oscillation.

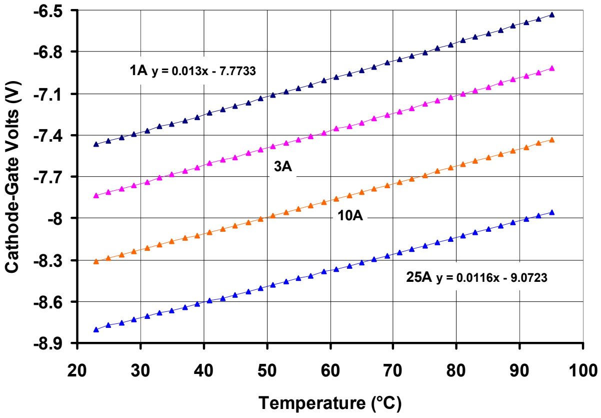

Fig. 2. Calibration curves for different anode currents at gate to cathode voltage of 200 V.

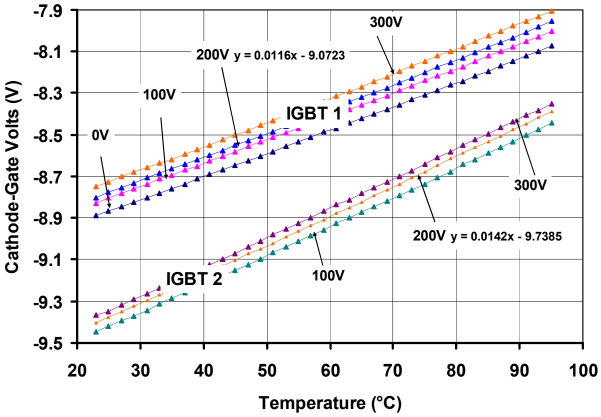

Fig. 3. Calibration curves for two different IGBTs at various voltages at an anode current of 25 A.

III. MEASUREMENT PROCEDURE

The measurement of the IGBT transient heating requires two parts. First, a calibration consisting of the measurement of the cathode to gate voltage, the TSP, must be made at known IGBT operating conditions and at a series of known temperatures. Second, with the heatsink at a fixed and known temperature, the IGBT is subjected to a longer transient heating pulse. The same test circuit shown in Fig.1 is used for both calibration and transient heating measurement; the difference between these is determined by the pulse width and by the way the data is handled. For both the calibration and the transient heating measurement, the duty cycle is made to be low so that the chip temperature settles to the known heatsink temperature before the next IGBT current pulse begins.

For the calibration curve, the operating conditions that need to be specified include anode to cathode voltage and anode current. Known temperatures are provided by having the IGBT module mounted on a temperature controlled heatsink. The pulse width is very short for the TSP calibration so as to avoid significant chip heating. The result of the calibration is an established relationship between chip temperature and the TSP value.

For the heating measurement, the same anode current and voltage conditions are used for the transient heating pulse as for the TSP calibration pulse. During the transient heating pulse, the IGBT chip increases in temperature, and the heat propagates through the chip and through the various DBC layers to the baseplate. The transient heating pulse is not long enough for the heat to propagate all the way through the baseplate to the heatsink. The TSP value is recorded during the transient heating pulse as a function of time, and the voltage waveform is mapped into temperature as a function of time by using the calibration data. Each IGBT and operating condition requires a new calibration.

Section A below further describes the calibration procedure and gives examples of calibration curves obtained for various conditions and shows how these typically change with different devices. Section B shows how the measurement of the transient heating is made by using the calibration data.

A. IGBT TSP Calibration

The measurements for TSP calibration are taken with the aid of a Labwindows/CVI^{TM} [2] virtual instrument user interface program that obtains data from the oscilloscope and controls the temperature of the heatsink upon which the IGBT is mounted. The TSP measurement is implemented by pulsing the IGBT on for a short interval with a known anode voltage and current while holding the heatsink at a fixed temperature.

The TSP calibration curve is obtained by measuring the cathode-gate voltage versus heatsink temperature for a given set of conditions. For given IGBT voltage and current conditions, the oscilloscope is manually set to select a suitable window for data averaging. The window is chosen to begin after the net electrical switching transients have ended. The window is chosen to end before a significant change in cathode-gate voltage due to self-heating is observed. For example, the optimum choice for a 25 A, 300 V calibration on the device under test in our system requires waiting about 40 µs after switching for the switching transients to diminish and the window width is 16 µs.

This setup needs to be performed only at the lowest, or start, temperature rather than at each temperature. Once the oscilloscope is set, the measurement sequence is initiated from the Labwindows/CVI user interface. The program averages the channel 1 minus channel 2 data points in the oscilloscope window to obtain the cathode-gate voltage for the given heatsink temperature. The program then increases the heatsink temperature in increments and obtains a cathode-gate voltage for each temperature.

Fig. 2 shows a set of calibration curves for an IGBT taken with 200 V anode to gate at various currents in two-degree increments. The equations of the linear fits for the 1 A and 25 A data sets are shown. For these two conditions the TSP changes at a rate of 13 mV/°C and 11.6 mV/°C, respectively. As expected, less gate-cathode voltage is needed to maintain higher anode currents as temperature is increased due to threshold voltage decrease with temperature.

Fig. 3 shows sets of calibration curves for two different IGBTs at various anode voltages, taken at a 25 A anode current. The data shows that the two IGBTs have a different gate-cathode TSP voltage for identical measurement conditions, likely caused in part by a different threshold voltage. The two IGBTs also show different slopes for the TSP, IGBT 1 having a slope of 11.6 mV/°C at 200 V and IGBT 2 having a slope of 14.2 mV/°C at 200 V. This difference is due to dissimilarities in transconductance between devices. For a given IGBT, the slopes for the TSP are nearly the same, although there is a TSP voltage offset difference for different anode voltages. The voltage offset difference is primarily due to the device current saturation region output conductance. One of the calibration curves for IGBT 1 is shown for 0 V. It should be noted that this is 0 V anode to gate. The actual anode to cathode voltage ranges from 8.9 V to 8.1 V as the heatsink temperature is raised from 23 °C to 95 °C. For the other labeled test voltages, the true anode to cathode voltage is also higher by the corresponding gate-source voltages.

B. Measurement of transient heating

For the measurement of the temperature transient of the IGBT, the heatsink temperature is fixed, normally at 25°C. Another Labwindows/CVI virtual instrument user interface program is used to measure the cathode to gate voltage and to determine the chip temperature as a function of time. This program begins by using the difference between the channel 1 and 2 waveforms to obtain the differential TSP voltage waveform. The program then uses the user-selected calibration curve data that matches the applied measurement current and voltage conditions to generate a temperature-transient curve.

Fig. 4 shows both the measured cathode-gate voltage waveform and the corresponding temperature waveform for an example of a heating transient. The transient heating pulse begins near the 2 ms point and ends after the 5 ms point. The TSP waveform indicates a cathode

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[2] LabWindows/CVI^{TM} is a trademark of National Instruments, Inc. Certain commercial products or materials have been identified in order to specify or describe the subject matter of this paper adequately. This does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that these products are necessarily the best for the purpose.

to gate voltage that is approximately a constant negative 6.6 V before the heating pulse. This voltage is established by the IGBT threshold voltage reacting with the current supplied by the 62 V power supply connected in series with the 7.5 kΩ resistor (Fig. 1). The temperature of the IGBT is equalized to the heatsink temperature during this time interval. From near the 2 ms time point to slightly after the 5 ms time point, a large and constant heating current is forced through the IGBT. During this time interval, the TSP voltage rises, due to the threshold voltage falling. Upon termination of the heating pulse, the current through the IGBT returns to that established by the 62 V supply with the 7.5 kΩ resistor at the elevated temperature. The TSP voltage then decays as the IGBT cools.

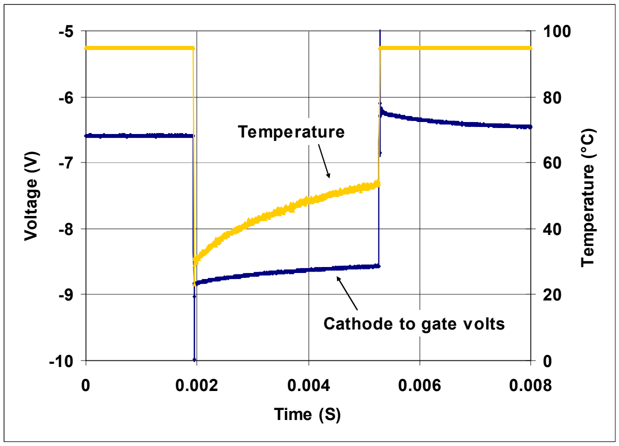

Fig. 4. Measured cathode to gate voltage mapped to temperature. Portions of the temperature waveform are truncated to 95 °C.

The temperature waveform in Fig.4 is mapped from the TSP waveform using the Labwindows/CVI program and the calibration data. Because the calibration data is taken over a finite temperature range, the program gives the user the choice of truncating the temperature at the highest or lowest temperature for which calibration data is taken or extrapolating the temperature based on a best fit to a straight line derived from the calibration data available. In this example, the calibration data cover the range from 23 °C to 95 °C. It is important to realize the calibration is made for the same IGBT current as that applied during the heating pulse, and the calibration does not apply before or after the heating pulse. In this example, truncation is chosen, and the program has assigned a constant temperature of 95 °C both before and after the heating pulse. The indicated IGBT temperature rises from about 30 °C to about 55 °C during the heating pulse.

The software and measurement test circuit provide the opportunity to measure the transient cooling of the IGBT. To make a transient cooling measurement, calibration data must be taken for the condition whereby only the current supplied by the 62 V supply and 7.5 kΩ resistor is used. This calibration data would then be used to calculate the cooling temperature waveform from the changing TSP in Fig. 4 after the termination of the transient heating pulse. The temperature waveform would also properly indicate the heatsink temperature before the heating pulse begins.

IV. RESULTS AND DISCUSSION

Part *A* of this section describes the physical parameters of the IGBT module that is used to model and measure the transient heating for the model validation described in this work. In part *B* of this section, results are given comparing transient thermal measurements with thermal simulations for the multi-chip IGBT module. Finally, in part *C*, issues of individual IGBT chip current sharing for these multi-chip modules are brought to light.

A. Module physical parameters

A module was broken open in order to make dimensional measurements for the purpose of modeling the transient thermal characteristics. In order to model the IGBT module, parameters such as IGBT chip thickness and size and thermal layer attributes must be known. Fig. 5 shows a sketch of a portion of the IGBT module. The important dimensional parameters used in the model are given in Table 1. Lateral dimensions not given in the table scale approximately to the sketch. The portion shown is the high-side switch, comprising three IGBT chips wired in parallel and four anti-parallel diodes wired in parallel with the IGBT chips. The module includes cathode sense connections that are not shown in the sketch.

Table 1. Physical module parameters.

Parameter	**Dimensions**
IGBT chips, 3 each	1.2 cm by 1.2 cm each
Diode chips, 4 each	0.6 cm by 0.8 cm each
IGBT chip center to center spacing	approx. 2.3 cm
Diode chip center to center spacing	0.67 cm
Baseplate width	7.2 cm
AlN layer 1 width	6.75 cm
CU chip carrier width	6.4 cm
AlN insulator thickness	0.082 cm
Copper chip carrier thickness (Cu 1)	0.03 cm
IGBT chip thickness	0.0375 cm
Solder 1 thickness	0.005 cm
Cu 2 thickness	0.013 cm
Solder 2 thickness	0.005 cm

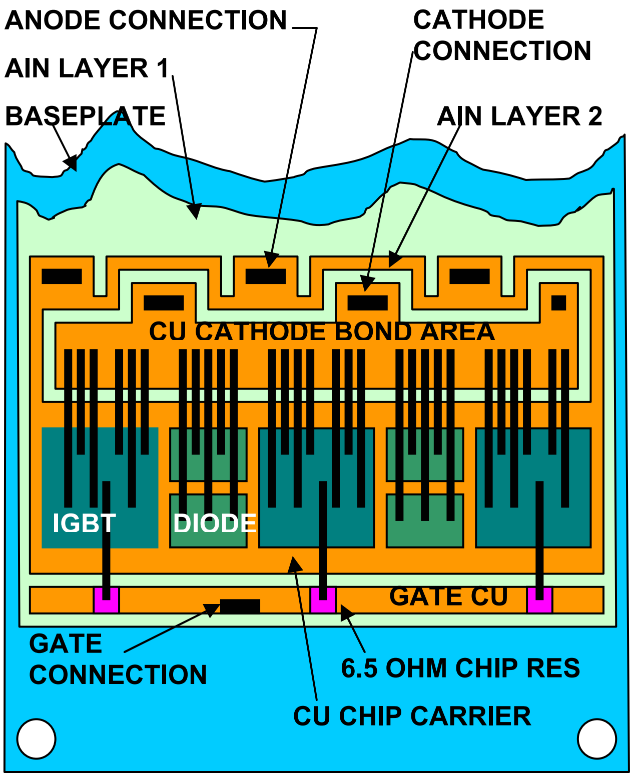

Fig. 5. Sketch showing component parts of high-side portion of IGBT module.

Table 2. Material properties for model.

	Specific Heat J·kg^{-1}·K^{-1}	Thermal Conductivity W·m^{-1}·K^{-1}	Density kg·m^{-3}
Cu	390	400	8900
Solder (Sn60Pb40)	150	50	8500
AlN	820	150	3250
Chip	700	150	2330

Each IGBT chip in Fig. 5 has a 6.5 Ω chip gate resistor mounted on a common copper gate contacting strip as shown. A bond wire then connects from the top of each resistor to its respective IGBT chip. All seven semiconductor chips are solder scrubbed onto a common copper plate. This plate serves as the anode connection for the IGBT chips as well as the cathode connection for the anti-parallel diode chips. Three heavy connections are brought vertically upward from this plate to make the module package anode connection terminal for the high-side IGBT.

Multiple bond wires are used to connect the cathodes of the IGBT chips and the anodes of the anti-parallel diodes to a common copper plate that is used for the cathode connection of the high-side IGBT. This plate also has three heavy connections that extend vertically upward to make the module package connection for both the cathode of the high-side IGBT as well as the anode of the low-side IGBT. The low-side IGBT is not shown in the sketch, but its construction is similar to that of the high-side switch. The anode of the low-side switch is joined to the vertically extending connections for the cathode of the high-side switch inside the module.

Two aluminum nitride (AlN) insulating layers are shown in Fig. 5. A large insulating layer labeled AlN layer 1 is bonded to copper and solder scrubbed to the baseplate to provide electrical isolation between the baseplate and all module components. In actuality, there are two AlN insulators placed side by side to make up the insulating layer. The high-side IGBT chips with diode chips are mounted on one insulator and the low-side IGBT chips with diodes are mounted on the other. Both the copper chip carrier for the high-side switch and the gate connection copper strip are in turn bonded to the top surface of this AlN layer to isolate these nodes electrically as shown. An additional AlN layer, labeled AlN layer 2, is bonded to the top surface of the copper chip carrier plate. The copper cathode bond-area plate is in turn bonded to the top surface of this second insulator layer.

Fig. 6 is a sketch showing the vertical DBC layer structure of the IGBT module. This sketch is not drawn to scale. Vertical dimensions used in the modeling are included in Table 1. The material properties for the various layers are given in Table 2. The thermal conductivity of AlN has been the subject of much research over the years and has been enhanced over earlier values. Thermal conductivity is controlled by the internal structure of the grains, such as the presence of oxygen solute atoms, rather than grain size in the AlN [3]. The value of thermal conductivity used in Table 2 reflects these improvements. Other physical material properties given in Table 2 are available from various databases [4]-[6].

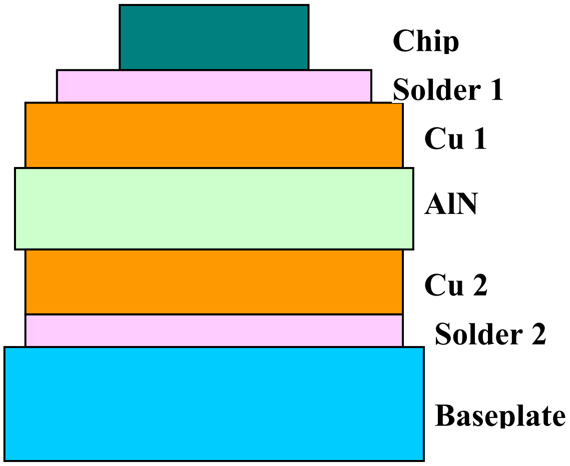

Fig. 6. DBC layers for the model.

B. Measured and simulated results

Fig. 7 shows measured and simulated transient heating curves for the multi-chip IGBT under various pulsed heating power conditions ranging from about 1080 W to about 7700 W. These power values take into account the anode to cathode voltages, rather than the anode to gate voltages used for identification in Figs. 2 and 3.

The simulations are run in Saber^{TM} [3] using a constant power pulse source connected to the IGBT thermal module model [1]. A constant temperature source is connected to the base plate of the module representing the constant heatsink temperature used in the experiment. The power level and pulse times are the same as those used in the experiment. The simulated temperatures shown in Fig. 7 are the chip junction temperatures representing the temperature measured by the TSP.

During the measurements, it was found that the IGBTs can be taken to the highest temperatures when the largest currents are used. A number of devices were destroyed when making lower current measurements for longer times, even though the indicated temperature was well below the temperature that achieved for the high current conditions. There is generally a notable deviation between the measured and simulated waveforms near the peak temperature, prominently shown for the higher-power curves in Fig. 7, in that the measured temperature shows a transition to an upward concavity after an initial downward concavity. It is likely that the current is constricting and one or more regions of localized high temperature are forming. The upward concavity in heating and the observed device failures for the low current, high voltage conditions are consistent with typical forward-bias safe-operating area (FBSOA) failure limits.

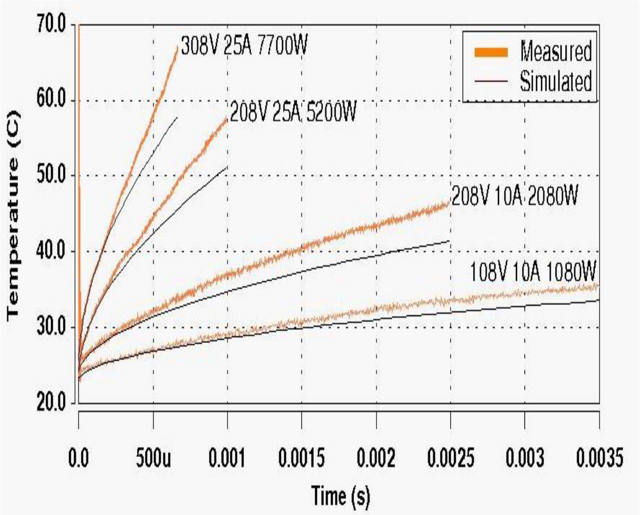

Fig. 7. Transient heating curves for various power conditions for the multi-chip module.

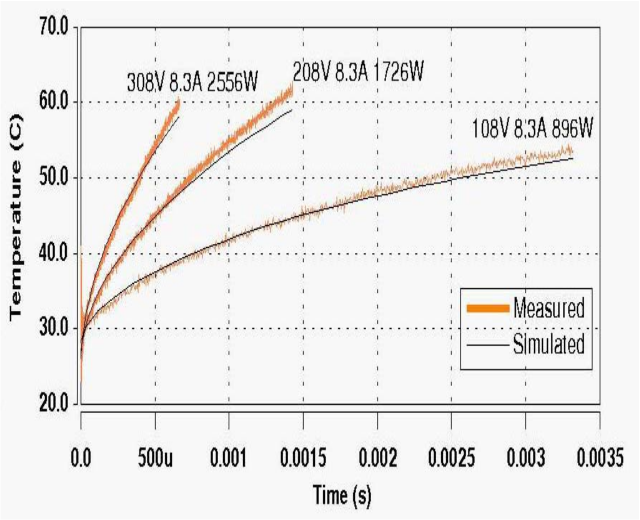

Fig. 8. Transient heating curves for various power conditions for a single isolated chip.

C. IGBT chip current-sharing issues

Operating a multi-chip IGBT in an active mode presents potential problems with current sharing between the individual chips. This can occur because the threshold voltage decreases with temperature and any chip in a multi-chip IGBT that has a lower threshold voltage will tend to hog the current. In a switching application, this is generally not a problem because the applied gate voltage is well above the threshold voltage. However, with the active mode operation used to provide the heating power, the multi-chip IGBT is operated close to its threshold voltage. For the lower current heating conditions, the gate voltage is operated closer to the threshold voltage resulting in a larger current nonuniformity and the observed FBSOA failures.

Multi-chip IGBT module current constriction has major implications in thermal model validation when threshold voltage is used as a TSP. The measurement of the TSP indicates a temperature that is dominated by the hot chip, and the remaining chips contribute less significantly. The thermal model used in this work assumes a fixed chip area and uniform current conduction through that area. In reality, the effective chip area is shrinking dynamically during the application of the heating pulse. As a result of this phenomenon, it should be expected that the measured temperature will indicate a higher level than the simulated temperature, especially toward the end of the heating pulse. This is in fact what is observed in Fig. 7, whereby the simulation initially agrees well with the measurement, but diverges as the heating pulse progresses.

To investigate the current sharing influence on the validation of the thermal model, one IGBT chip was isolated from the others by grinding the copper gate connecting metal so that the left-hand IGBT chip in Fig. 5 can be powered by itself. The cathode bond area copper was also ground so as to separate the cathode connection of the same chip. The test circuit is now applied to only one IGBT chip and measurements are made at one third the power

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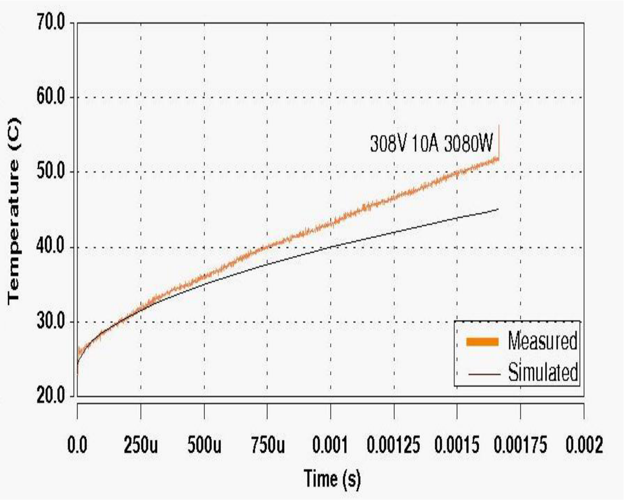
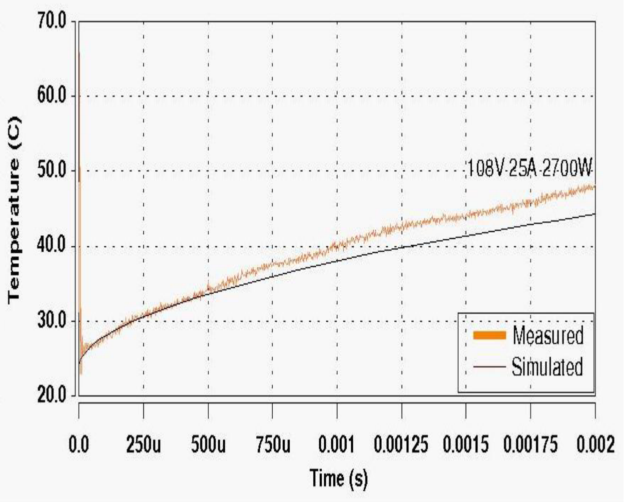
[3] Saber is a trademark of Synopsys, Inc., previously Avant!, Inc., previously Analogy, Inc., Beaverton, OR.

level as that previously used for the three-chip IGBT. The chip area in the simulation is reduced to one third accordingly. Fig. 8 shows a comparison between the measured and simulated results. The agreement now is quite good, with only a slight deviation between the measurement and simulation as the heating pulse progresses. This minor deviation could be the result of further current constriction on the chip itself.



(a)



(b)

Fig. 9. Effect of different current and voltage parameters on current sharing in multi-chip module for similar power levels. (a) Higher voltage, lower current. (b) Lower voltage, higher current.

Returning once again to the comparisons between the measured and simulated results on the three-chip IGBT, it appears that the use of lower voltage and higher current for a given power level is advantageous. Fig. 9a shows the measured and simulated results for a 308 V, 10 A heating pulse, representing a heating power of 3080 W. This can be compared with Fig. 9b which shows the measured and simulated results for a 100 V, 25 A heating pulse, representing a heating power of 2700 W. Although the power level for these two cases is similar, the agreement between measurement and simulation is better for the lower voltage, higher current case. The IPEM module used for all of the measurements in this paper is rated for an anode current of 300 A. It is likely that thermal transient measurements of the type described in this work made on multi-chip IGBT modules become less subject to the problems relating to current sharing when performed at currents closer to the rated current for the module.

V. CONCLUSIONS

A measurement system suitable for extracting transient thermal data for short-term, high-power heating conditions is developed and used for the validation of fast thermal transient model predictions of multi-chip IGBT modules. It is found that the gate-cathode voltage can be used as a time-dependent temperature sensitive parameter during intervals of high power dissipation in the active mode. Temperature calibrations must be performed on the same IGBT, and using the same conditions under which a transient measurement is to be made. Model validation results indicate good performance of a previously developed IGBT electro-thermal model for a tested range of heating times of 100 µs through 1 s.

Operating the multi-chip IGBT module in the active mode results in well controlled high power heating but also results in current nonuniformity that can influence the measurements. Good agreement between measured and simulated transient heating is obtained for the initial portion of a heating pulse, but the measurement concaves toward a higher temperature than the simulation as the heating progresses. Measurements and simulations on a single IGBT chip isolated from the others in the multi-chip module demonstrates better current sharing and good agreement with the electro-thermal model for the full range of temperature and heating currents. Improved current sharing between chips in a multi-chip module occurs when higher currents and lower voltages are used in the transient thermal model validation measurement.

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[4] http://www.memsnet.org/material/

[5] http://www.chipscalereview.com/issues/0700/miller5.htm

[6] http://www.aluminumnitride.com