An Effective Heat Propagation Path-Based Online Adaptive Thermal Model for IGBT Modules

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***Abstract*—The information of junction temperature is crucial for operation management of IGBT modules. In practice, junction temperature is typically estimated by using an electrothermal model. IGBT modules are subject to various aging processes during operation, some of which, e.g. substrate solder crack, changes the thermal impedance of an IGBT module. However, in the literature little work has included the aging effects into online thermal behavior modeling of IGBT modules. This paper proposes an Effective Heat Propagation Path (EHPP)-based online adaptive thermal model for IGBT modules, where the EHPP is proposed to quantify the impact of substrate solder cracks on the heat propagation inside the IGBT modules. A straightforward relationship between substrate solder crack and the degree of nonuniformity of case temperature distribution is established. Based on the EHPP, the parameters of a thermal network, e.g., a Cauer thermal network, are adjusted online to track the thermal behavior changes of the IGBT modules caused by substrate solder cracks, leading to an adaptive thermal model. The proposed adaptive thermal model is validated by comparing with finite element analysis (FEA) simulation results for a commercial IGBT module.**

I. INTRODUCTION

The information of junction temperature T_j is crucial for operation management of IGBT modules in real world applications. Accurate junction temperature estimation can be used to prevent over temperature [1] and estimate the remaining useful life [2] for an IGBT module. In practice, junction temperature is typically estimated by using an electrothermal model, which consists of power loss estimation, a power module thermal model, and a cooling system thermal model. Much work [2]-[6] has been done on computationally efficient thermal behavior modeling for power semiconductor devices when the devices are healthy.

However, IGBT modules are subject to various aging processes during operation. For example, substrate solder crack is a major aging mechanism in IGBT modules [7] and will lead to the degradation of heat propagation inside an IGBT module. As a consequence, the thermal resistance of the IGBT module will increase, leading to a higher T_j when the operating point and cooling condition remain the same. In this case, using a thermal model developed for a healthy IGBT will result in an underestimation of T_j. Therefore, a thermal model which is adaptive to the aging of IGBT modules is desired for effective operation management of the IGBTs in real world applications. However, in the literature little work has included the aging effect into the thermal behavior modeling of IGBT modules. Due to the difficulty in characterizing the change of the heat propagation inside an IGBT module caused by aging and the lack of an effective online thermal model parameter adaption scheme, it is still an open issue to develop a thermal model for an IGBT module which is adaptive to the aging of the device online.

To develop a thermal model adaptive to the solder aging of an IGBT module, this paper proposes a new concept of Effective Heat Propagation Path (EHPP) to interpret the effect of the substrate solder crack on the heat propagation inside an IGBT module. First, the non-cracking area in the substrate solder layer of an IGBT module for heat flow propagation is estimated through an Inverse Heat Conduction Problem (IHCP) using the measurable nonuniformity of case temperature distribution. Then, the EHPP can be approximated using a thermal spread angle method. Finally, based on the approximated EHPP, the resistances and capacitances of a thermal network model can be adjusted online during the substrate solder aging process, leading to an adaptive thermal model. The proposed method and adaptive thermal model are validated by comparing with finite element analysis (FEA) simulation results for a commercial IGBT module.

II. EHPP-BASED THERMAL BEHAVIOR CHARATERIZATION FOR IGBT MODULES

Due to the complexity of the geometry and differences in the materials' properties, the heat propagation inside an IGBT module is a complex, dynamical process. In this section, a new concept of EHPP is introduced to effectively quantify the impact of substrate solder cracks on the thermal behavior of IGBT modules. Then, the paper will show that the change of

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the thermal resistance from junction to case of an IGBT module caused by substrate solder cracks can be interpreted by the change of the EHPP, which can be quantified by the degree of the nonuniformity of the case temperature distribution.

The EHPP is defined to be the thermal path in an IGBT module through which most heat flows, as illustrated in Fig. 1. During the operation of the IGBT, the heat can be assumed to be generated at the top surface of a die and spreads down through different layers to the bottom of the baseplate, which is cooled by a heat sink or a cold plate. Compared to the top surface of the die, the EHPP covers a larger area at the bottom surface of the baseplate, which is called the baseplate hot area A_{hot}. The temperature inside A_{hot} is much higher than that in the remaining area of the bottom surface of the baseplate. A_{hot} can be viewed as the thermally effective contact to the heat sink or the effective heat removal area. The following paragraphs will describe how the EHPP and A_{hot} change with substrate solder aging and derive the relationship between the change of the case temperature distribution and the remaining non-cracking solder area in the substrate solder layer.

A crack usually initializes from the edge of the substrate solder layer and then propagates to the center [8]-[10]. The crack will not significantly affect the heat propagation inside the module or the thermal resistance of the module until it encroaches the EHPP. In this case the IGBT module is in a dangerous status in which the heat flows are forced to concentrate to the remaining non-cracking portion of the substrate solder layer, as illustrated in Fig. 2. Both the EHPP and A_{hot} shrink, resulting in the increase of the IGBT module's thermal resistance and the degradation of heat removal at the bottom surface of baseplate.

Assuming that the same amount of heat is generated at the top surface of the chip, the shrink of the A_{hot} can be indicated by an increase in the difference between the case temperature (i.e., T_{c_die}) at the location right beneath the die (i.e., in the middle of the A_{hot}) and the case temperature (i.e., T_{c_side}) at the location inside the A_{hot} but near the edge of the A_{hot}. If the A_{hot} shrinks, T_{c_die} will increase due to more concentration of the heat flows; while T_{c_side} will drop as its location tends to move out of the A_{hot} or away from the main EHPP. Obviously, it is important to choose appropriate locations at the bottom surface of the baseplate to acquire the information of the nonuniformity of the case temperature distribution related to the change of the EHPP.

However, it is still not straightforward to establish the relationship between the difference of T_{c_die} and T_{c_side}, the remained non-cracking area A_r in the substrate solder layer, and the change of the EHPP caused by substrate solder cracks, because an IGBT module involves multilayer thermal conduction and heat storage and spreading. To establish an effective relationship, this paper simplifies the problem to a baseplate layer IHCP, which utilizes the measurable case temperatures to inversely estimate the remaining non-cracking solder area. By neglecting the heat spreading in the thin substrate solder layer, the heat flux flowing through the substrate solder layer to the baseplate is perpendicular to the baseplate top surface. Then, the A_r in the substrate solder layer is equivalent to the heat flux area on the top surface of the baseplate.

Fig. 3 shows the change in the heat flux on the baseplate top surface due to the aging of the substrate solder. Assume that the cooling condition is stable such that the boundary condition on the bottom surface of the baseplate is stationary. Since the heat flux is concentrated at center and the total heat propagating through the EHPP at a certain operating condition is specific, the IHCP solution, A_r, is unique. Thus, a look-up table can be conveniently built via a numerical method, such as FEA, to relate ($T_{c\_die} - T_{c\_side}$) to A_r for various operating conditions for online applications.

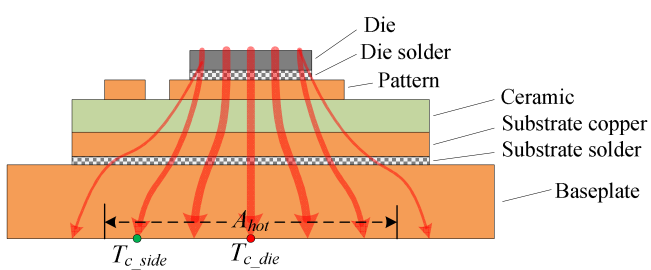

Fig. 1. The EHPP in a healthy IGBT module.

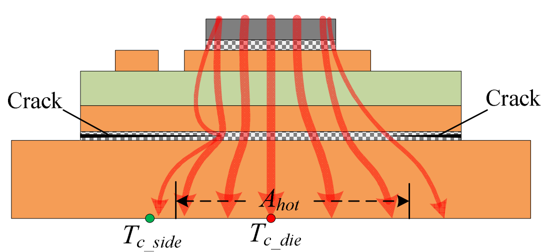

Fig. 2. The EHPP in an IGBT module when cracks developed from the edge to the center in the substrate solder layer.

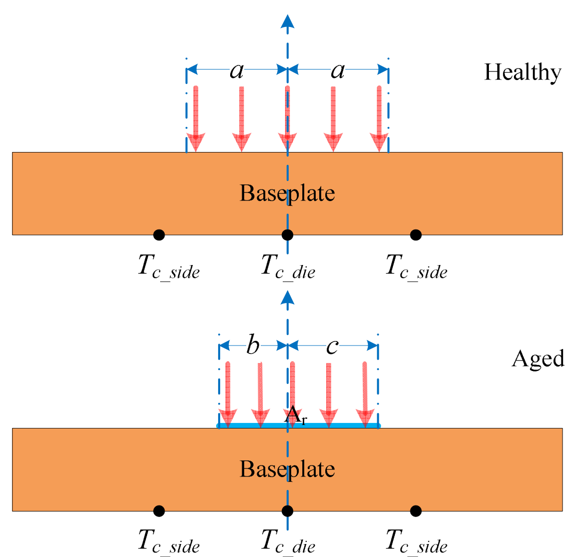

Fig. 3. IHCP using case temperature to estimate the effective heat flux area.

III. The EHPP-Based Online Adaptive Thermal Model for IGBT Modules

Once the health condition of the substrate solder of an IGBT module is quantified online using A_r, the next problem is how to model the thermal behavior of the IGBT module adaptively by taking into account the substrate solder aging effect. The FEA method can provide a high-fidelity thermal model, which, however, requires extensive time and memory to implement. This paper proposes an EHPP-based online adaptive resistor-capacitor (RC) thermal network model for IGBT modules. In the proposed model, a traditional RC thermal network, e.g., a Cauer thermal network, is used to physically represent each layer of the EHPP inside an IGBT module The EHPP shown as the dashed-line area in Fig. 4 is approximated by using the heat spreading angle technique [11]. The impact of substrate solder cracks on the thermal behavior of the IGBT module is interpreted via the change of the EHPP. Assuming that only the EHPP through the substrate solder layer and its two adjacent layers, i.e., the substrate copper layer and baseplate layer, is altered by the substrate solder cracks, then the area A_c of the EHPP through the bottom surface of the ceramic layer is constant.

The heat spreading angles θ_i in degree in the pattern layer and the ceramic layer can be calculated by [12]:

$$\theta_i = 90 \tanh\left\{0.355\left(\frac{\pi K_i}{180}\right)^{0.6}\right\} \qquad (1)$$

where K_i is the thermal conductivity in W/(m ℃) of the material of the pattern or ceramic layer. The heat spreading angle in the substrate solder layer is neglected owing to the relatively low thermal conductivity of solder and the relatively thin thickness of the substrate solder layer. The heat spreading angle in the baseplate is cooling-condition dependent and is expressed as a function of the ratio between the total thickness of all the heat-spreading layers beneath the chip and the side length of the chip [13]. Therefore, only the heat spreading angle α_{adj} in the substrate copper layer needs to be determined according to the status of the substrate solder crack. Once the value of A_r in the substrate solder layer is obtained, α_{adj} can be calculated using the geometry information A_c and A_r, and the thickness $d_{pattern}$ of the substrate copper layer.

The thermal resistance of each layer is calculated by:

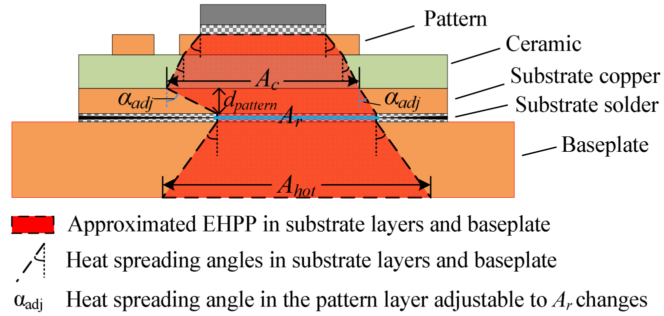

Fig. 4. The approximated EHPP for an IGBT module with substrate solder cracks.

$$R_i = \int_0^{d_i} \frac{1}{K_i \cdot A_i(z)} dz \qquad (2)$$

where R_i, d_i, K_i, and z are the thermal resistance, thickness, thermal conductivity of the material, and vertical distance from the top surface to the bottom surface of the ith layer, respectively; and $A_i(z)$ is the horizontal cross section area at the distance z, which is calculated according to the geometry information, including the heat spreading angle, of the layer. The calculation for the thermal capacitance of each layer, however, is not straightforward. The detailed information on the calculation of thermal impedances of electronic packaging can be found in [3], [14].

The approximated EHPP in the substrate solder layer and the adjacent copper layer and baseplate is adjusted according to A_r. Based on the approximated EHPP, the RC parameters of the three layers can be adjusted for the Cauer thermal network, leading to an adaptive thermal model. The schematic of the proposed online adaptive thermal network model is illustrated in Fig. 5, where I_C, f_{sw}, PF, P_{loss}, and T_a are the collector current, switching frequency, power factor, power loss, and ambient temperature of the IGBT module, respectively.

IV. Simulation Validation

A commercial IGBT module CM1400DU-12NF made by POWEREX is studied to validate the proposed EHPP-based adaptive RC thermal network model. The geometry information of the module is provided by POWEREX. The IGBT module is in a half-bridge configuration. Each IGBT

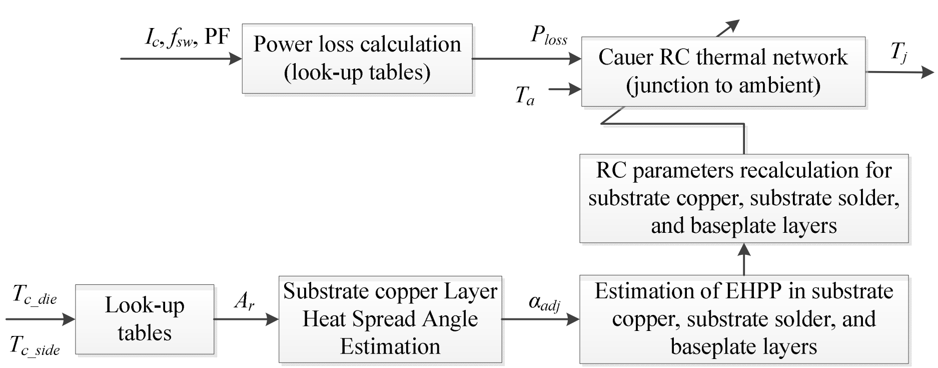

Fig. 5. Schematic of the proposed online adaptive thermal network model.

switch consists of 9 parallel dies placed on three direct bond copper (DBC) transistor stacks. Taking the advantage of the symmetry of the stack layout, one sixth of the module (41.5mm×75mm), i.e., a thermal stack with 3 IGBT dies, is built in ADINA, which is a commercial FEA software platform, as shown in Fig. 6. The cold plate is simplified to an aluminum block with the bottom surface temperature being set to be the inlet coolant temperature. The thermal interface between the baseplate and the cold plate is a thermal grease layer with a thickness of 0.1 mm.

The substrate solder is assumed to have a uniform crack from the edge to the center. Fig. 7 illustrates the geometry of the module viewing from the baseplate with the locations of the case temperature measuring points. Since the three dies are connected in parallel in one switch, the power losses in the three dies are assumed to be the same. The EHPP of the center die is assumed unchanged during the substrate solder cracking process. The approximated EHPPs of the three dies, as shown in Fig. 8, are separated by dashed lines. It should be noted that Fig. 8 is only for illustration purpose and does not reflect the real geometry of the module.

The effectiveness of using the nonuniformity of the case temperature distribution ($T_{c\_die} - T_{c\_side}$) as an indicator of substrate aging is evaluated for three solder crack cases at two specific operating conditions by the FEA method. The first operating condition is a constant load (i.e., constant power loss) case, where the test IGBT conducts long enough to reach a steady-state temperature. The second operating condition is a dynamic load case, where the test IGBT is operated as a leg in a three-phase inverter with the collector current I_c = 450 A, switching frequency f_{sw}=2 kHz, and power factor PF = 0.85. The AC output frequency of the inverter is selected to be 1 Hz, where an accurate thermal modeling of the IGBT module is important, owing to the fact that the IGBT undergoes a more severe thermal stress under a low-frequency load [15]. The power loss profiles of one die for the two load conditions are shown in Fig. 9, where the power loss is averaged over each switching period in the dynamic load case. Fig. 10 shows the changes of the nonuniformity of the case temperature distribution ($T_{c\_die} - T_{c\_side}$) and the changes of the maximum junction temperature T_{jmax_side} of the side die for different solder crack cases with respect to those of the healthy case. The case temperature is measured after the maximum junction temperature is reached while considering the phase delay between the power loss and the measured case temperatures.

It can be seen that the nonuniformity of the case temperature distribution and the junction temperature increase with the development of the substrate solder crack in both constant and dynamic load conditions. The increases in (T_{c_die} - T_{c_side}) and T_{jmax_side} in the 1.75-mm solder crack case are not noticeable. However, in the other two cases where the solder cracks become more severe, both (T_{c_die} - T_{c_side}) and T_{jmax_side} increase more noticeably. These results prove that (T_{c_die} - T_{c_side}) is a sensitive indicator of the substrate solder aging process.

The thermal resistance R_{side_ja} of the side die is a key

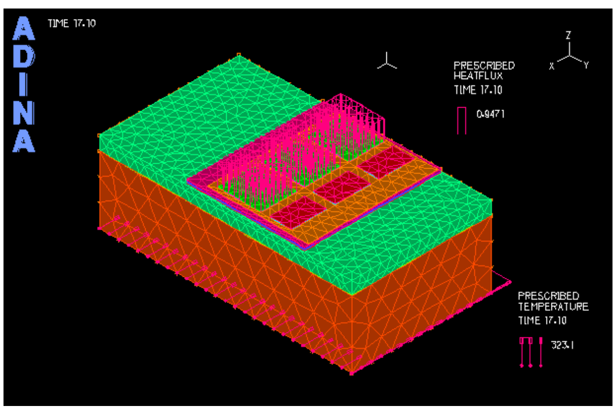

Fig. 6. The model of one sixth of a CM1400 IGBT module built in ADINA.

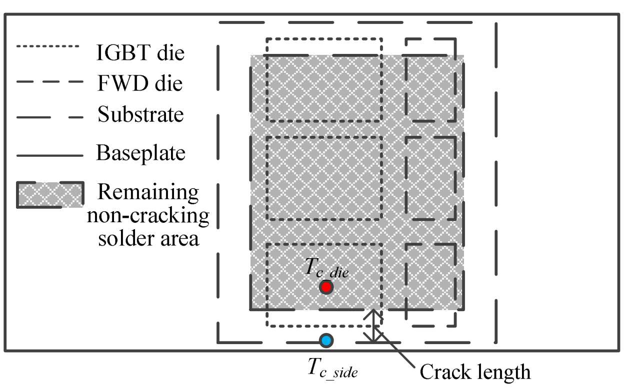

Fig. 7. Baseplate side view of the IGBT module.

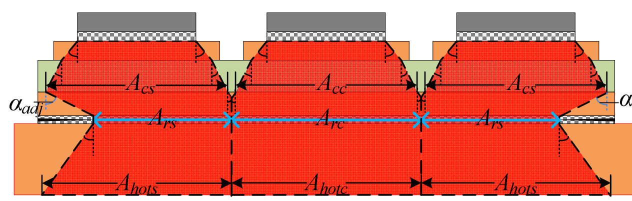

Fig. 8. EHPPs of the side dies and the center die (separated by dashed lines).

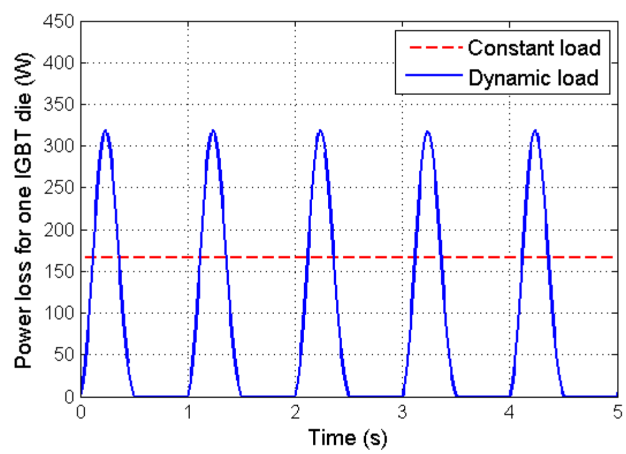

Fig. 9. Power loss profiles of constant load and dynamic load cases for one IGBT die.

concern, since the solder crack will first encroach the EHPP of the side die. Using the proposed method, the value of R_{side_ja} is calculated. The thermal resistance of the thermal grease layer is also calculated by using (2). However, the heat spreading in the thermal grease layer is neglected and, therefore, the cross section area is equal to A_{hot}. The change in thermal resistance of the cold plate is not considered due to its negligible impact on the total thermal resistance. Fig. 11 compares the values of R_{side_ja} calculated by the FEA method and the proposed model. The results show a good match between the two models, where the error between the two models is less than 2%.

To examine the performance of the proposed model for adaptive dynamic junction temperature estimation, the results obtained from the FEA method, the proposed adaptive model, and the traditional Cauer thermal network model without parameter adaption (i.e., using the fixed parameters extracted for the IGBT in the healthy condition) are compared in Fig. 12 under the dynamic load condition for the 3.5-mm crack and 5-mm crack cases. The relative error is defined to be the ratio between the absolute error of the junction temperature estimated by the proposed model or the traditional Cauer thermal network model with respect to that obtained from the FEA method and the mean value of the temperature rises from coolant to junction estimated from the FEA method. The maximum error between the proposed model and the FEA model is less than 4℃, and the relative errors are within 5% during most times of the simulation in both cases. On the other hand, the maximum error between the traditional Cauer thermal network model and the FEA model is more than 7 ℃, and the relative errors are much larger than those of the proposed model. These results clearly show that the proposed adaptive thermal model is much better than the traditional thermal network models for junction temperature prediction by including the substrate solder aging effect suing the proposed EHPP method.

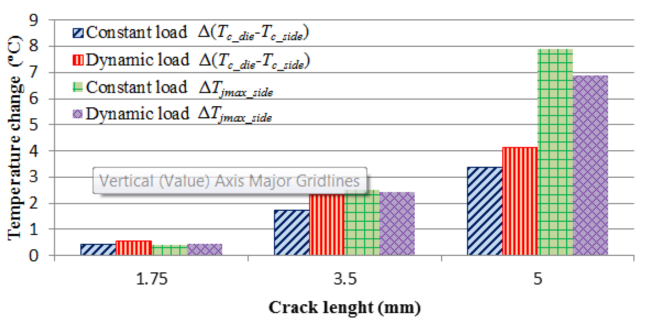

Fig. 10. Changes of the nonuniformity of the case temperature distribution and maximum junction temperature in the three substrate solder crack cases in constant and dynamic load conditions.

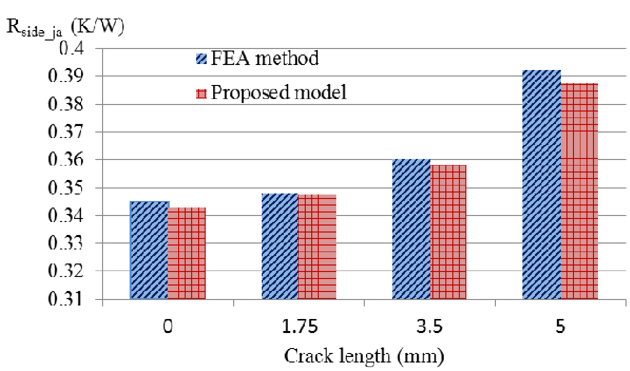

Fig. 11. Comparison of R_{side_ja} calculated by the FEA method and the proposed model.

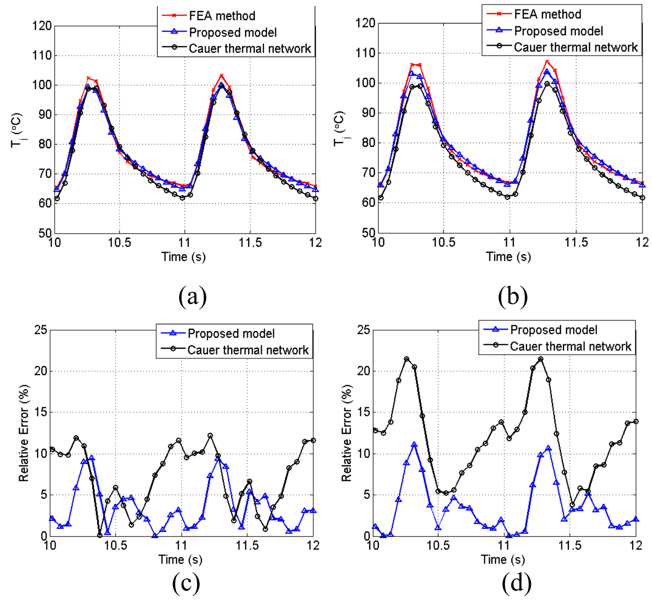

Fig. 12. Comparison of different models for the cases of 3.5-mm solder crack and 5-mm solder crack under the dynamic load condition: (a) junction temperature (3.5-mm solder crack); (b) junction temperature (5-mm solder crack); (c) relative error (3.5-mm solder crack); and (d) relative error (5-mm solder crack).

V. CONCLUSION

This paper has presented an EHPP-based RC thermal network model for IGBTs, where the parameters have been made adaptive online to substrate solder cracks inside the IGBT modules. The concept of EHPP has been introduced to effectively characterize the thermal behavior of IGBT modules using the heat spreading angle technique. The impact of substrate solder cracks on the thermal behavior of IGBT module has then been interpreted by using the change of the EHPP approximated based on the change of the nonuniformity of the case temperature distribution. The approximated EHPP has then been used to adapt the RC parameters of the thermal network online. Numerical simulation studies have validated the effectiveness of using the nonuniformity of the case temperature distribution to indicate the severity of substrate solder cracks and the effectiveness of using the proposed adaptive thermal model to achieve improved junction temperature estimation with respect to traditional thermal network models. The proposed model can be used for effective online condition monitoring, control, and thermal and health management of IGBTs and associated power electronic systems.

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