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Thermal Management on IGBT Power Electronic Devices and Modules

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ABSTRACT As an increasing attention towards sustainable development of energy and environment, the power electronics (PEs) are gaining more and more attraction on various energy systems. The insulated gate bipolar transistor (IGBT), as one of the PEs with numerous advantages and potentials for development of higher voltage and current ratings, has been used in a board range of applications. However, the continuing miniaturization and rapid increasing power ratings of IGBTs have remarkable high heat flux, which requires complex thermal management. In this paper, studies of the thermal management on IGBTs are generally reviewed including analyzing, comparing, and classifying the results originating from these researches. The thermal models to accurately calculate the dynamic heat dissipation are divided into analytical models, numerical models, and thermal network models, respectively. The thermal resistances of current IGBT modules are also studied. According to the current products on a number of IGBTs, we observe that the junction-to-case thermal resistance generally decreases inversely in terms of the total thermal power. In addition, the cooling solutions of IGBTs are reviewed and the performance of the various solutions are studied and compared. At last, we have proposed a quick and efficient evaluation judgment for the thermal management of the IGBTs depended on the requirements on the junction-to-case thermal resistance and equivalent heat transfer coefficient of the test samples.

INDEX TERMS Power electronics, IGBT, thermal management, cooling, qualifications.

I. INTRODUCTION

Power electronic (PE) systems have been widely applied in both industrial and domestic applications in modern society for use of controlling and converting electrical energy [1]. Besides, the usage of PE systems have resulted in energy savings and compact structures on electric cars, trains, automated manufacturing systems, power generation, and etc. [2] With the characteristics of excellent performance, low cost, high reliability, low weight and size, power semiconductors including insulated-gate bipolar transistors (IGBTs) dominate the market of power converters [3], [4]. As one of the most important power converter devices, the IGBTs have been invented in 1982 [5] and accelerated the applications of bipolar devices to the high voltage and current markets. Since appearance of the first commercial product in 1988 [6], [7], IGBTs have gained significant importance as one of major carrier devices in both discrete and module markets. It is expected that the IGBT market will be booming from 2014 to 2020, archiving 6.6 billion US$, at a Compound Annual Growth Rate 10% in the segmentation of renewable energy, UPS, motor drive, rail traction, motor drive, EV/HEV, consumer electronics, and others (Figure 1). These trends have exacerbated issues pertaining to the increasing demands from consumer electronics, low carbon emission system, acceleration of replacement of petrol vehicles and deployment of smart grids.

IGBTs are required for applications operated over a broad spectrum of current and voltage levels as shown in Figure 2. The current ratings for the IGBTs increase with the increasing voltage rating in these applications except for the smart grid. The smart grid application is unique in requiring very high voltage devices with low current ratings. In the case of silicon

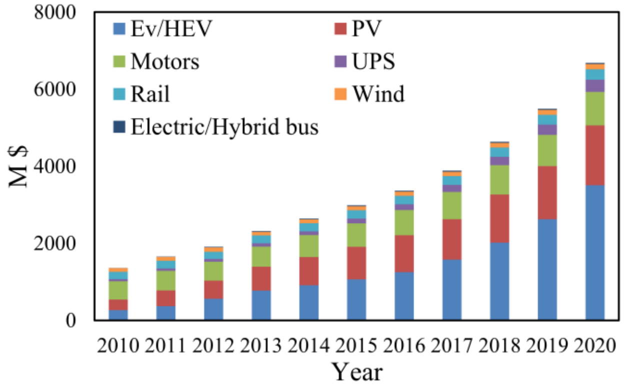

FIGURE 1. IGBT market split by applications [8], [9].

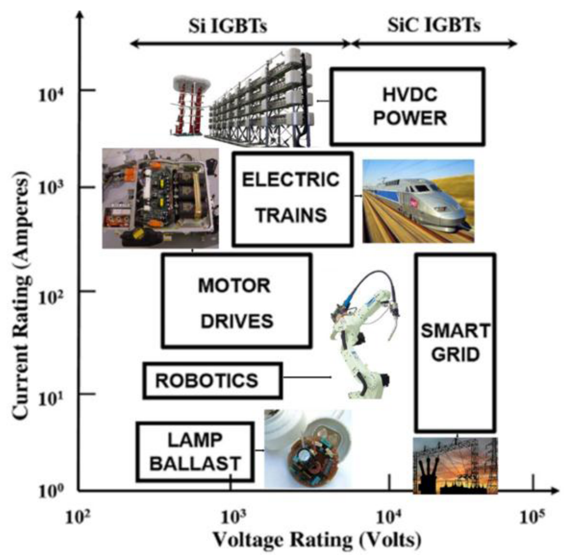

FIGURE 2. Application spectrum for IGBTs [10].

IGBTs, this issue is tackled by resorting to multichip press-pack modules. A more advanced solution is to use SiC-based IGBTs which can operate at higher frequencies than their silicon counterparts. Rapid evolution of the IGBTs technology enhances induces high power density on the chips, with higher and higher speed and compact package. Typically, more complex and bulky cooling solutions are significantly required.

A. DEVELOPMENT OF IGBTs

The IGBT technical progress and development trend for industrial applications is primarily driven by five aspects influenced among each other to an extent, which are operating temperature, efficiency, dimension, reliability and cost, in the last thirty years. The power density of the IGBTs is lifted from 35 kW/cm^2 from the very beginning to 250 kW/cm^2 expected in 2020s as shown in Fig.3, thanks to innovative assembly and interconnection techniques. On the other hand, as a result of a high voltage and current, the total heat dissipation is continued to increase as well. Nowadays, the power outputs

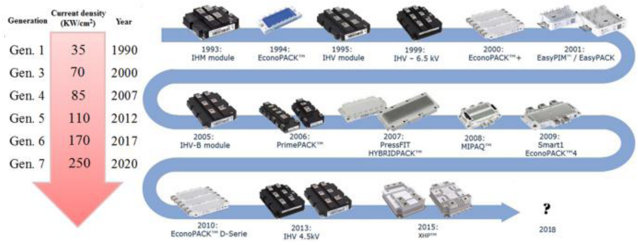

FIGURE 3. Development power density in generation of IGBTs.

of typical commercial IGBTs are reaching an extremely high value of more than ten thousand watts. IGBTs of 600V/650V up to currents of 600 A, 1200 V up to currents of 3600 A, 1600V/1700V up to currents of 3600 A, 3300 V up to currents of 1500 A, 4500 V up to currents of 1200 A and 6500 V up to currents of 750 A have been shown on the market today and those more than 10 kV device are under test [11]. Shown as an example, features of the commercial IGBTs from Fuji Electric, Fairchild Semiconductor, STMicroelectronics, Infineon Technologies, Mitsubishi Electric, and IXYS Power are illustrated in Figure 4. In future, the semiconductor industry is expected to continuously raise the power outputs of IGBTs owing to new developments. Similarly, for reliability reasons, the cooling technology will also be advanced to catch up with the development of IGBTs.

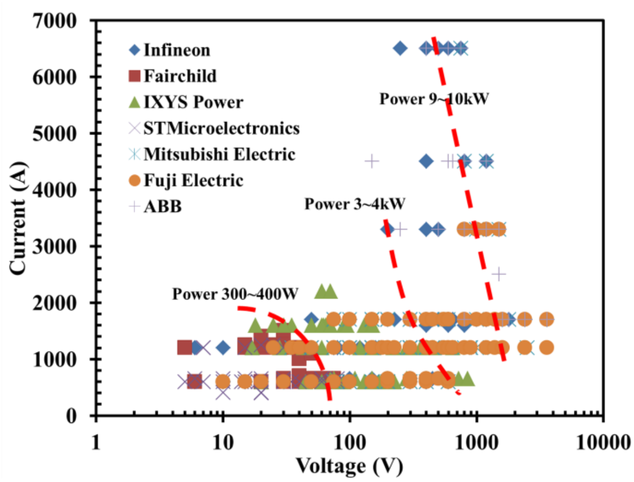

FIGURE 4. Power range of commercially available IGBTs.

B. THERMAL CHALLENGES OF IGBTs

Thermal management and cooling solutions is a growing concern for IGBTs due to the increased heat losses in their widely applications [12]–[16]. These heat losses can be further divided into two categories, i.e. conduction losses and switching losses. The conduction losses occur during the on-state voltage drop across the IGBTs depending on the conducted current. Whereas the switching power losses occur during on and off stages of the IGBTs depending on the current, duty cycle, switching voltage and switching frequency. Figure 5 demonstrates a typical IGBT heat flux

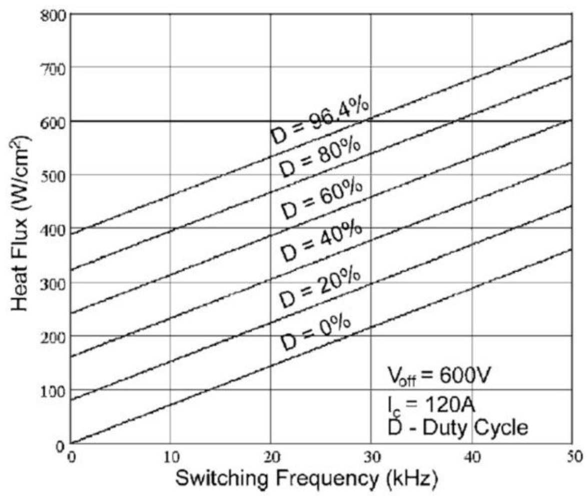

FIGURE 5. Heat flux versus switching frequency in different duty cycle for a typical IGBT (V_{off} = 600 V, I_c = 120 A) [18].

caused by the power loss in terms of frequency in different duty cycles with careful analysis on the turn-on and turn-off curves. The height of the total setup amounts to about 9 mm within a 1.2 × 1.2 cm^2 test sample of a thermal resistance of 0.087 K/W [17].

Currently, IGBT chips can dissipate no more than 10 kW of power and are associated in parallel in a single package to obtain desired rated current and the module (Figure 4). The heat flux of the IGBT used in hybrid electric vehicles is now at the level of 100-150 W/cm^2 during normal situation. With increasing current capacity and switching frequency, a heat flux up to 500 W/cm^2 is definitely expected in the future [19]–[23]. As to temperature junction, the limit value for silicon IGBT devices is ~150 °C for 6 kV voltage [24], [25], but wide band gap semiconductors such as SiC and GaN can survive from higher temperatures. However, with consideration of structural components, solder materials, reliability and costs, the junction temperature is limited to ~175 °C constrained with the available packaging technologies [16], [26], [27]. Thus generating major discussions on the alternative liquid cooling, two-phase cooling, micro channeling cooling, impinging jets, spray cooling and other novel solutions in an attempt to mitigate such issues. Several reports have been published in recent years to review the state of the art of power electronics including IGBTs and the thermal management challenges in power electronics are involved. Lostetter *et al.* [3] explained the concept of Integrated Power Modules (IPMs). A single compact standardized module includes the electronic control circuitry and the converter for high power electronics, with the baseplate for supporting, cooling and electric interconnecting. Sheng *et al.* [28] focused on the different electro-thermal models based on various circuit conditions, structures and thermal considerations which are the basis for thermal management of IGBTs. Mohammed *et al.* [7] briefly reviewed the applications for power systems, in which IGBT is most common used power electronic devices. SiC, having low thermal resistance, was approved to be the future materials for realizing high temperature operation and better thermal management.

TABLE 1. Thermal failure sites, causes, stresses, modes, and mechanisms of IGBT packages.

Failure sites	Causes	Stresses	Modes	Mechanisms
Bond pad	High temperature	Thermal overstress	Open circuit	Metallization reconstruction[30]
Bonding wire: bond	CTE mismatch between die and wire by temperature excursion	Thermomechanical stress	Bond wire liftoff	Fatigue [31]
Bonding wire: heel	Expansion and contraction of bond wire due to temperature change	Thermomechanical stress	Bond wire heel cracking	Fatigue [32]
Bonding wire: body	High temperature	-Thermoelectrical stress -Thermomechanical stress under corrosive environment	-Open wire -Wire burnout	-Electromigration [33] -Stress corrosion - Joule heating
Solder joint	-CTE mismatch by temperature excursion -Transformation in solder microstructure at high temperature	Thermomechanical stress	Solder joint cracks	Fatigue or grain growth [34][35]
Ceramic substrate	Thermal shock	Thermomechanical stress	Delamination	Delamination of metallization [36]

C. THERMAL FAILURES OF IGBTs

Long term failures of power modules which are operating within their predesigned range are caused by thermal problems. A variety of failures such as solder joint cracks, delamination of bonded surfaces, heel cracks and lift-off of wire bonds emerge gradually with the increase of power cycle counts. These types of failures are exacerbated by thermal cycling. As the failure grows, for example a crack propagated from a solder joint edge, the conduction of heat through the layered stack deteriorates due to less area available for heat transfer. This results in an increase in the thermal resistance between the device and the cooler. The higher component operating temperature results in thermal cycles of larger amplitude, leading to high thermal-mechanical stresses and crack growth rates, ultimately the total failure of the IGBT by overheating [29]. Table 1 summarizes potential failure sites, causes, stresses, modes, and mechanisms of IGBTs. Most frequently reported failure mechanisms are fatigue, latch-up, electrostatic discharge, radiation-induced effect, and ceramic substrate fracture as a result of high temperatures. Thus, it is urgent to achieve good thermal management for long term reliability. In those reports, emphasis is placed upon the applications and developing trends of IGBTs and it is lack of direct investigations on thermal management.

Several hundred papers have been published on thermal analysis and management of IGBTs since the 1990s [37]–[40]. In this paper, the work on thermal management of IGBTs are reviewed, analyzed, compared and organized. Firstly, in Section II, to estimate the semiconductor rating, evaluate the long-term reliability and archive efficient heat sink design strategy, those different approaches include analytical, numerical, and RC models to perform thermal analysis are given. Secondly, Section III presents the thermal resistance on IGBTs which is the one of the most design parameters for thermal management. We have discussed the different available and future thermal solutions in Section IV and compared the thermal effectiveness of them. Finally, the concluding remarks of our reviewing research are given in Section V.

II. THERMAL MODELS FOR IGBTs

The thermal analysis of PE systems is imperative as the power density and switching frequency continuously increase. Consequently, optimization of thermal performance of IGBTs is required by effective and robust electro-thermal models. An electro-thermal analysis is attractive to predict heat generation in IGBTs. Especially, the dynamic electro-thermal model gives in-situ evaluation for the potential of electric changes, consisting of the resistivity, dielectric constant, dissipation factor, material properties and elucidation of structure. In those analyses, the thermal models are important to calculate the junction temperature under certain power dissipation with the input of thermal power of the IGBTs.

Most of the thermal models in electro thermal analysis published since 1993 are listed chronologically in Table 2 with the first author and publication year. Numerous modeling and analysis methods have been established during the past decades. Typically, three types of methods are used to build the thermal model of PEs. The first category ''analytical models'' are based on the heat diffusion equations including device chips, packages, modules and heat sinks and solving those physics equations with mainly discretization of analytical expressions describing each component. To emulate IGBT behaviors, the expressions are widely implemented into various simulators with integrating of the electric equations for various applications. Those methods, which mainly provide a Fourier series solution by solving the heat diffusion equations, are much quicker than numerical methods. Moreover, the imperfect contact has not been considered which may induce considerable prediction errors. The second method is related to numerical models, which mainly include the computational fluid dynamics (CFD) and the finite-element method (FEM) for steady and transient thermal analysis. Those numeric models simulate the thermal performance with boundary conditions and heat resources by a large number of finite elements which has higher accuracy with the detailed material properties and the exact physical dimensions than the analytical model but requires much more time.

TABLE 2. Thermal analysis in electro-thermal models for IGBTs.

Method category	First author	Year	Merits	Limits and drawbacks
Analytical models	Dorkel [41] Khatir [42] Hocine [43] Ishiko [44] Ibrahim [45] Castellazzi [46] Du [47][48] Musallam [49] Reichl [50] Sarkar [51]	1996 2001 2003 2007 2007 2008 2008,2010 2010 2015 2017	•Improved trade-off between the accuracy and computing speed compared to the numerical methods	•Simplified assumption for boundary and initial conditions •Not suitable to implement in real-time simulator •Do not consider the imperfect contact
Numerical models	Lakhsasi [52] Drofenik [53] Dehbi [54] Riccio [55]-[57] d'Alessandro [58] Wu [59] Greco [60] Xu [61]	2001 2007 2008 2010,2011,2012 2013 2014 2014 2016	•Exact solution •Modeling any device geometry •Good for structure optimization •Fatigue analysis	•Time consuming •Evaluating the junction temperature variation under arbitrary load profiles
Thermal network models (i.e. compact thermal models)	Hefner [62]-[64] Mantooth [38][65] Turkes [65] Ammous [66] Igic [68] Yun [69] Rodríguez [70] Carubelli [71] Azar [72] Kojima [73]-[75] Luo [76] Ciappa [77] Trigkidis [78] Castellazzi [79]-[83] Zhou [84] Senturk [85][86] Gragger [87] Moussodji [88][89] Yin [90] Nejadpak [91] Wang [92] Alnajjar [93] Batard [94] Alavi [95] F. D. Napoli [96]	1990, 1993,1994 1993,1997 1998 2000 2001 2001 2002 2003 2004 2004, 2006,2007 2004 2005 2006 2006,2007,2008 2008 2011,2012 2012 2013 2013 2013 2015 2015 2015 2017 2017	•Easy to integrate into existing circuit simulator •Short calculation time •Easy to include temperature-dependent properties	•Less accuracy than numerical models especially for those models with complex 3D structure

Therefore, they are nearly impossible to be applied for evaluating the junction temperature variation under arbitrary load profiles or under a real duty cycle in the operating condition, which are more important for the reliability analysis of the system. Also, these methods cannot coexist with an electrical simulation, making dynamic electro-thermal models impossible. The last, and also most widely used method is the thermal network model (also called compact thermal model), derived by a resistor-capacitor (RC) thermal network. It produces an accurate and computationally efficient thermal model that can be easily realized in circuit simulators to estimate the instantaneous junction temperature in a long-term dynamic simulation. The thermal network model discretizes the whole structure of IGBTs into a network of heat diffusion elements and convection heat transfer elements, and then calculate the temperatures of network nodes by using heat diffusion and convection equations.

A. ANALYTICAL MODELS

Several early thermal models of IGBTs were based on mathematical equations, for fast thermal modeling and integrated power circuits, and this kind of method was continually developed until recent years. Dorkel *et al.* [41] built efficient computation tools by implementing the two-port network theory with the fast Fourier transform algorithms with highly efficiency in calculating for temperature and heat flux distributions in plane multilayered systems. They gave several examples to calculate the temperature rise and heat flux map with assumed effective thermal conductivity for the interface under cooper and assumed heat transfer coefficient of water cooling. In 2001, the analysis method was proposed by Khatir and Lefebvre [42], which used the boundary element method (BEM) to simulate a high power IGBT (i.e. 3300V-1200A) with power cycling. The BEM significantly reduced the geometrical complexity and solved the transient heat conduction in packages with complex multilayers. Hocine *et al.* [43] conducted the thermal analysis for an IGBT with 1200 A, 3.3 kV by 3D Transmission Line Matrix which was based on the differential equation of heat conduction. This method was approved to be accurate with comparing of the results by experiments, semi-numerical 3D thermal simulation and FEM. Ishiko *et al.* [44] proposed a compact calculation method of dynamic electro-thermal behavior of IGBT PWM inverter modules. Ibrahim *et al.* [45] published the work on the IGBTs with the electro thermal simulation, using VHDL-AMS language to couple electrical and thermal models. Their approach for the thermal model is the ''Diffusive Representation'' method for the dynamic thermal analysis. Castellazzi and Ciappa [46] explored a coupled 3D electro-thermal modeling approach to construct the details such as chip, substrate, heat sink, aspect ratio and shape integrating analytical compact models. Their work was widely used in general purpose circuit simulators (e.g., Saber, Simplorer) and the realistic control and drive signals were added, enabling a more accurate and in-depth characterization of assembled devices. More recently, Du *et al.* [47], [48] developed the new thermal model based on Fourier series expansion method for dynamic thermal analysis. It is approved that their model has high accuracy and efficiency compared to FEM. Moreover, it is favorable dynamic thermal characterization caused by the high switching. A real-time reduced-order compact thermal model was developed by Musallam and Johnson [49] . In their work, the internal behavior of the electro-thermal effects of the PEs was in situ monitored and can be utilized as part of a prognostic tool for thermal cycling assessment and health management of PEs together with the thermo-mechanical wearout models. The 3D Finite difference methods (FDM) were also used to solve the heat conduction equation for multilayer, and multichip thermal component model by Reichl *et al.* [50]. Sarkar and Issac [51] investigated the heat transfer mechanism inside the Thermal Interface Material (TIM) layer in between an IGBT and heat sink by developing a heat propagation speed model within the TIM layer. By virtue of their model, it is possible to optimize the TIM geometry based on operating conditions of the IGBT and heat dissipation properties of the heat sink.

B. NUMERICAL MODELS

Finite Element Method (FEM), as a numerical simulation method, obtained high accurate temperature distribution of the simulated models based on the detailed structure and material properties. It was applied more frequently on the electro thermal model of IGBTs in recent years as the rising calculation ability of the computers. The power loss and operation temperature of IGBT PWM (Pulse-Width Modulation) was predicted by Lakhsasi *et al.* [52] using partially coupled approaches for estimation of accurate peak junction temperature under dynamic operation. Drofenik *et al.* [53] demonstrated a 3D FEM model of a 3300V/1200A HiPak IGBT power module and analyzed the sensitivity of model parameters on the simulation results. Dehbi *et al.* [54] used ANSYS Workbench to develop an accurate 3D FEM thermal model and simplified the model by employing MOR and finally performed electro thermal simulation in CASPOC circuits simulator. A series of researches on IGBTs were proposed by Riccio *et al.* [55]–[57], based on two coupled systems: a three dimensional thermal simulator and a one dimensional temperature-dependent electrical-physical model of single IGBT cell. The electro thermal simulations were performed in unclamped inductive switching conditions of a high power trench IGBT. d'Alessandro *et al.* [58] presented accurate, 3-D simulation strategy devised for the Unclamped Inductive Switching analysis of multicellular power transistors with very fast 3-D simulations by FEM through adoption of smart mesh-refinement strategies. Wu *et al.* [59] used ANSYS/Icepak FEM with an advanced physics-based PSpice model to simulate the electro thermal performance of IGBTs, achieving an unprecedented fast and accurate method. It is successfully archived that considerable faster computational speed and high accurate results compared to the traditional double physics simulations according to this method. Greco *et al.* [60] studied the electro-thermal model to retrieve voltages and temperatures with PSpice-like simulator. The thermal layer synthesis process was performed via a PSpice-like circuit which was generated by using an Electronic Design Automation tool. Xu *et al.* [61] proposed a thermal analysis method consisting of two steps. Firstly, power losses of each key components in the IGBT were analytically calculated respectively. Then these information was imported as inputs to a finite element model of the IGBT to perform an accurate thermal simulation for an optimization design of the cooling fan.

C. THERMAL NETWORK MODELS

The thermal network model was widely used for steady-state and dynamic thermal analysis for power electronics with the basic elements of thermal resistance (R) and thermal capacitance (C). Since 1990, Hefner Jr [64] firstly developed a complete 1D analytical, charge controlled model suitable for circuit simulator implementation of IGBTs. The electro thermal behavior of PE circuits and systems was then studied [62], [63]. In the thermal network models, the R and C are based upon a discretization of the heat diffusion equation for various 3D coordinate system symmetry conditions and the simulator calculate the temperature distribution over the semiconductor devices, packages, and heat sinks in analogy with the calculation of currents and voltages over the electrical network. The thermal network was also coupled to the electrical network through the electro thermal models for the IGBTs with instantaneous power dissipation and boundary conditions. This method boosted for its advances of easy connection to electric network and external thermal network, accurate results with temperature depended parameters, and fast dynamic calculations.

Mantooth and Hefner Jr [38], [65] reported the work on thermal network models in the electro thermal modeling of IGBTs. The Saber circuit simulator was used to model the electric performance and coupled the thermal network models for the power device silicon chips, packages, and heat sinks. The dynamic thermal response was shown and the thermal response of the silicon chips determined the IGBT temperature rise during the device switching cycle. Turkes and Sigg [66] proposed a methodology for the development of physics based models of PEs. The thermal network of IGBTs was derived from the physical structure and the parameters which were strongly dependent on the temperature were extracted by experiments. Rodríguez *et al.* [70] developed the thermal component models for (IGBT) PE modules which were associated high-power converter heat sinks. The models were parameterized in terms of structural and material parameters and were supposed to be developed a library of component models for the various commercially available PE modules. An accurate thermal network model of IGBT chip was done by Azar *et al.* [72]. The silicon drift region was decomposed into slices and each slice was modeled as an individual R-C stage, and the optimized results were achieved with a total of 16 stages. The electrical model needs to consider the temperature variation, in order to accurately predict the power loss density in IGBTs. Trigkidis *et al.* [78] predicted the temperature variation of the device under transient condition to within 3°C with the developed thermal network models.

A high power IGBT models (4500V-1800A press-pack pairs) were applied in the wind turbine described by Senturk *et al.* [85], [86]. The static thermal model was based on the physical placement of the press-pack IGBT diode pairs, the aluminum nitride-ceramic cooling plates and the cooling plates supplying double-sided cooling by water flows. Moussodji *et al.* [88], [89] presented a new distributed electro-thermal model to analyze the electrical and thermal mappings of PEs during critical operations. The thermal model was based on a nodal method with a three dimensional RC thermal network. Material layers were discretized into volume elements which are characterized by the thermal capacitance and the thermal resistances in 3D. Yin *et al.* [90] proposed the Foster RC network which was used for thermal modeling and coupled with the electrical modeling by the interaction between the power loss and the junction temperatures. Depending on the measurement and the parameters extraction of datasheets, both static and dynamic models are formulated by the curve fitting. Wang et al. [92] proposed the thermal network model with the substrate solder cracks inside the IGBTs. The effective heat propagation path was used to adapt the RC parameter of the thermal network to qualify the impact of the substrate solder cracks. Recently, Alnajjar and Gerling [93] established the loss model of the three level neutral point clamped rectifier to calculate the exact conduction losses and switching losses of IGBT. The temperature distribution of the IGBTs and the diodes were calculated based on the RC equivalent equations which represented the temperature differences between the junctions of the devices and the heat sink that used the liquid cooling. A lumped three dimensional thermal network was developed by Batard *et al.* [94], which consisted of a three dimensional network of RC cells constructed for time dependent operation, to precisely determine the temperature excursion of the diodes and transistors subsequent to time-dependent the power losses. Alavi et al compared the thermal impedances of a 600V/150A IGBT calculated by using Foster and Cauer RC networks [95]. They confirmed that the time dependent thermal impedance curves calculated by one-order Cauer network model and four-order Foster network model were almost the same, but the one-order Cauer network model saved a lot of computational time. Napoli *et al.* [96] developed a situ junction temperature measurement technique for an IGBT device. And based on the on-line measured junction temperatures they proposed a dynamic compact thermal model (DCTM) to calculate the time dependent thermal impedance curves of the IGBT. As a real time processing method, their model can be further used in on-line health monitoring of IGBTs.

The models to establish the thermal networks were depended on the physical properties of the inner parts of the IGBTs. however, it was impossible to dismantle the IGBTs to analyze the thermal resistance and the thermal capacitance. To conduct non-destructive method to build the thermal network models, there were mainly two ways: experimental methods and numerical simulations. Igic *et al.* [68] presented the electro thermal models by transforming the electric device models to the thermal node. They used a deconvolution method to extract the RC thermal network parameters form the thermal transient response function of the device. Besides, the FEM was also applied to obtain the thermal transient response. Kojima [73]–[75] proposed a novel thermal network model of IGBT modules for the automotive applications. They introduced a simple parameter model for PEs by thermal impedance. Besides, the thermal resistance and thermal capacitance were also calculated by using the transient heat FEM.

An extraction method that relied on transient thermal impedance from junction to case and transient thermal impedance from case to ambient to determine the thermal network parameters introduced by Luo *et al.* [76]. The thermal aspects in the electro thermal modeling were experimentally analyzed by Castellazzi *et al.* [79]–[83]. The junction-to-ambient thermal impedance was used to characterize the IGBT components or system and to generate the thermal equivalent network model. They also developed two different approaches for simulations on a short time scale and for simulations on larger time scales. Each node of the thermal network corresponded to a physical location of the chip and the 3.3 kV, 6.5 kV IGBTs, different temperature dependencies were introduced for the equations describing different regions of the IGBTs and diodes. Gragger *et al.* [87] simulated the junction temperature of the inverter module with thermal networks representing an IGBT and a diode placed on common substrates with the cooling systems. The thermal impedances between junction and case of the semiconductors were used by collecting in the data sheet of the inverter module.

The thermal networks based on the finite element method (FEM) were widely applied due to the high accuracy of FEM and low time consuming of the RC networks. Ammous *et al.* [67] developed the two-dimensional thermal networks equivalent to a discretization of the heat equations by the FEM and coupled to the electric model to give an adequate model of the IGBT. Yun *et al.* [69] analyzed the static and dynamic thermal behaviors of IGBTs mounted on a water cooling heat sink. They extract thermal resistances and time constants for a thermal network from the FEM results. It was approved that the dynamic behavior predicted by the thermal network was equivalent to numerical solutions of the FEM and RC network quickly offered insight into the physical layers of the components and provided useful information in a few minutes. An implementation of a thermal modeling method applied to a multichip module used as a power converter was presented by Carubelli and Khatir [71]. From the 3D thermal simulations and experimental validations using direct chip temperature measurements, the analytical functions of thermal impedances were developed. Ciappa *et al.* [77] made a new approach to extract accurate thermal network models from FEM of the converter including the module and the heat sink for fast electro thermal simulations of IGBTs using for hybrid electric vehicles. The FEM model was calibrated by static experiments and the transient 3D FEM simulation was used to extract the thermal impedance. Their methods brought advantages in terms of increased reliability, reduction of the costs, and shortening of the design cycle with the adapted treatment of thermal systems with a non-negligible lateral heat spreading. Zhou *et al.* [84] shown a compact thermal model of a three-phase IGBT inverters which was assembled from R and C according to the data extracted from FEM by FLOTHERM. Nejadpak and Mohammed [91] presented an algorithm to simulate the temperature dependent characteristics of SiC IGBTs. In this method, parameters of the model were extracted from the 3D FEM for computation of the transient thermal impedance.

III. THERMAL RESISTANCE ON IGBTs

In order to solve the junction temperature limitation, a huge improvement has been made on the thermal management to reduce the junction temperature or enhance the heat dissipation from the chip, package, module up to assembly over the past two decades [97]–[103]. At first, industry has pushed

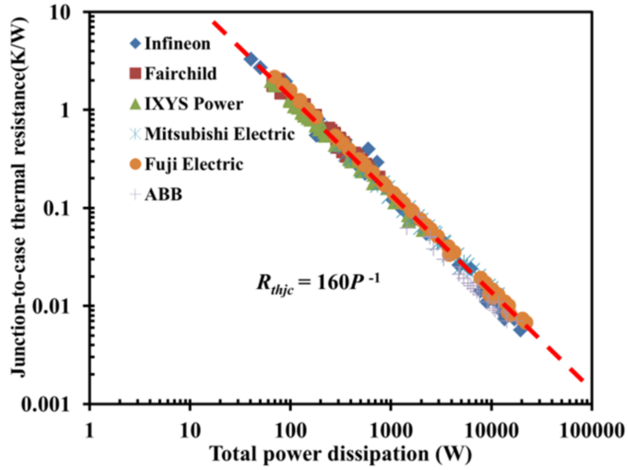

FIGURE 6. Typical thermal appearance of commercial IGBT modules.

power devices with decreasing thermal resistance from low power to high power [104]. The junction-to-case thermal resistance (R_{thjc}) is the most important key parameter for thermal management on the module level. Figure 6 shows a general trend on thermal resistances of the current commercial IGBTs as a function of total power dissipation. It is very interesting to find that the R_{thjc} is decreasing reversely with the rise of power dissipation. The higher dissipated power requires lower thermal resistance, pushing the industry to keep improving the thermal performance of IGBTs to reach the desirable junction temperature. However, it is a real challenge for the chip design, packaging material and etc. as the total power is continuously increasing. Besides, the technology of die and substrate attach, interconnection and encapsulation are also facing challenge.

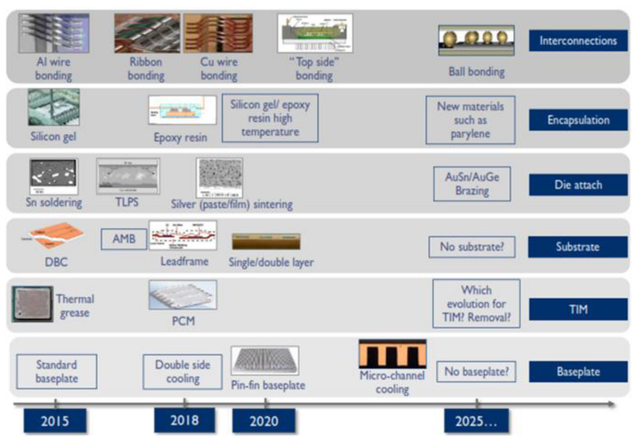

FIGURE 7. The development of packaging technology for IGBT modules [9].

Advanced packaging and cooling have also been developed to improve the thermal performance designs for the IGBT modules (in Figure 7). New products have been conducted to increase the yield and reliability of PE modules, especially for the common failure locations, die and substrate attach, interconnection and encapsulation. Shown as examples, the soldering technology is progressively losing the market share, replaced by the nanosintering materials, in order to improve the interfaces. Standard wire bonding has been evolved as well using ribbon or ball bonding to increase the contact surface. As the high temperature needed for the PEs, encapsulation technologies must be improved to handle high operating temperatures. And new materials which can bear high temperature are also needed to replace the standard silicone gel or epoxy.

IV. THERMAL MANAGEMENT ON IGBTs

A. COOLING SOLUTIONS

1) AIR COOLING

There are a wide variety of passive cooling options for IGBTs among which air cooling is the simplest and reliable one with low cost. Normally, to suit the applications, bulk materials with high thermal conductivities, like aluminum or copper, and fin arrays or other extruded surfaces are used to exchange the heat between dies and environment. The passive cooling also includes more complex systems with phase change and natural convection. The use of these complex passive systems is to reduce the thermal resistance between the IGBTs and the ambient. Most of the passive cooling solutions choose the air cooling plan to release the heat to ambient, by transporting heat from the heat sources within the IGBT to the surface where the heat can be taken away via air convection. Then the heat exchange between the solid materials and air is mainly depended on the contact area. For the case that the heat spreading area to exchange and dissipate heat is small, there will be a bottleneck between the terminal heat sink and the ambient. Therefore, no such a complex solution will help to avoid the use of active cooling in this case.

Another reason why air is a less favorable option in many cases is because it provides a much lower cooling efficiency compared to the liquid counterparts such as water [105]. However, in some cases forced air may still be a good choice, where water is limited. The heat transfer of forced air cooling can be enhanced in much the same ways as with water. For instance, Howes *et al.* [106] utilized an air-cooled extruded aluminum heat sink whose equivalent heat transfer coefficient is about 1406 $W/m^2 \cdot K$ to cool the IGBT. Castagno *et al.* [12] tested an IGBT-stack prototype with 6 1200 V rated IGBTs in series. Cooling has been provided by forced air (approximately 100–200 Cubic Feet per Minute airflow at 25 °C) between the heat sinks for a horizontal cross flow with the equivalent heat transfer coefficient about 328 $W/m^2 \cdot K$. The design for heat sink depends not only on the architectures but also the materials which are very attractive with low cost, low density, high thermal conductivity and high surface area.

2) DIRECT LIQUID COOLING

A number of single-phase or two-phase liquid-cooling solutions, including the micro-channel heat sink cooling solution, spray cooling solution, jet impingement cooling solution etc., are capable to provide very high heat transfer

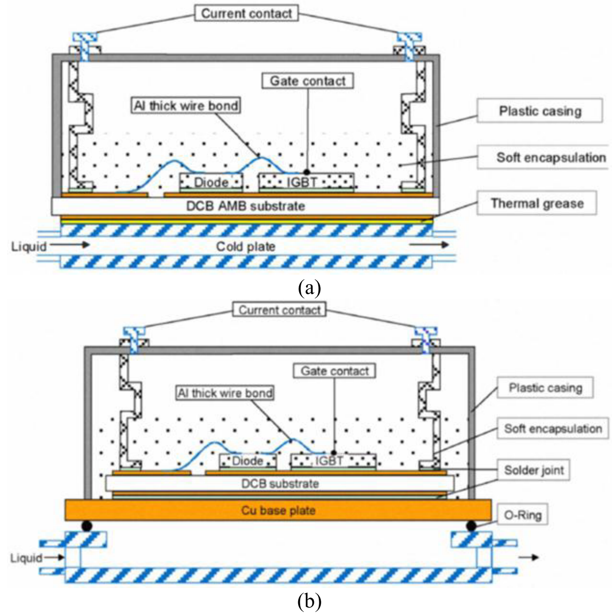

FIGURE 8. (a) Indirect liquid cooling versus (b) direct liquid cooling [108].

coefficients and low thermal resistances to the IGBT [4]. Conventional power module is mounted to the heat sink with the thermal grease. Most of heat from chip loss is dissipated from the bottom through the direction of the undersurface of chip to heat sink. There is relatively big thermal resistance of the insulating substrate and thermal grease in such a heat dissipating path. Since heat dissipation is limited by the contact part of the module and the heat sink, it becomes difficult to attain a downsizing even if it makes thermal resistance of the module itself small [16]. Therefore, direct cooling structure has been widely used to replace the conventional indirect cooling way. The direct cooling structure discards a base plate and the adhering thermal grease compared to the indirect cooling structure as shown in Figure 8 [111]. Some papers [14], [16], [107] found the thermal performance of IGBTs has improved significantly through direct liquid cooling. The direct cooling structure is capable to reduce thermal resistance up to 30% compared to the conventional indirect liquid cooling type.

3) MICRO-CHANNEL HEAT SINKS

A micro-channel heat sink boast for many unique attributes, such as superior cooling characteristics, compactness, and minimal coolant usage. They are ideally suitable for cooling electronics, especially when the phase change of the coolant occurs in the heat sink. The micro-channel heat sinks are well-suited to many electronic applications due to the ability of removing a large amount of heat from a small area. In Figure 9, the typical micro channel heat sink design is designed to use an integral structure that incorporates the micro channels into the bottom copper layer of the ceramic substrate as a direct liquid cooling [109]. Yun *et al.* [69] analyzed the thermal performance of the total

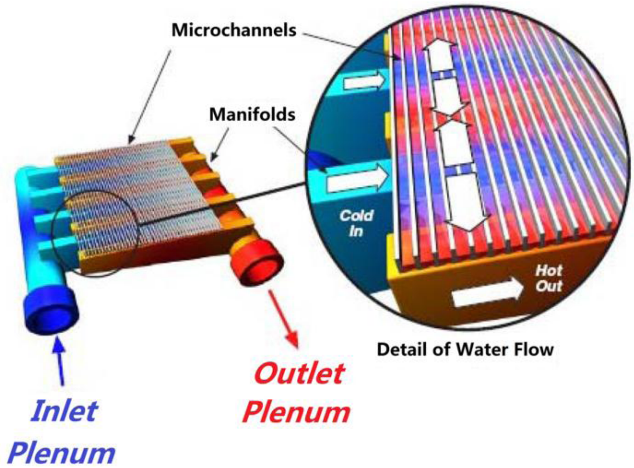

FIGURE 9. Schematic view of a heat sink design with micro channels, including micro-channels, manifolds and plenums [109].

system, which consists of 1200 A, 3.3 kV IGBT and the cooling system. The module has 6 subassemblies on the common base plate, which was mounted on the heat sink. While the heat sink was cooled by forced water convection through the micro channels. The equivalent heat transfer coefficient of the cooling system was about 557.6 W/m^2 K. Liu *et al.* [110] studied the thermal effects of IGBT power module with direct liquid cooling design. The micro-channel cold plate, bonded with direct bonded copper (DBC) substrate directly, was used in direct liquid cooling. It can reduce thermal resistance and cooler size of IGBT power module effectively due to its high equivalent heat transfer coefficient of about 2951 W/m^2 K. In addition, the micro-channel cold plate contributed to decrease the warpage and increase reliability of IGBT power module.

4) TWO-PHASE FORCED CONVECTION COOLING

Two-phase cooling designs offer significant advantages compared to their single-phase counterparts in the heat sinks, since the single-phase heat sinks have the key drawback of large temperature gradient. Two-phase heat sinks are capable to increase the convective heat transfer coefficient inside the heat sink and helps maintain device surface temperature uniformity which is based on latent heat exchange and decided mostly by the coolant saturation temperature. Using PF-5060 as the working fluid of two-phase spray cooling, the heat transfer coefficient can reach to 24 000 W/m^2 K [111]. Two-phase systems and comparative performance data were illustrated for air-, water-, and vaporizable dielectric fluid-cooled systems by using fluids of water, FC-72, R-134a and similar refrigerants in pumped [23], [110], [112], [113]. Use of such high-efficiency two-phase liquid cooling systems provided improvements in space utilization by reducing needed physical volumes, allowing for more compact system designs, and improving efficiency of waste heat removal for higher overall system performance.

There are a number of studies dealing with two-phase flow in micro channels. Gillot *et al.* [40] assessed the feasibility of single and two-phase micro heat exchangers applied to the cooling of IGBTs. The experimental measurements were compared to the predictions of the thermal and hydraulic performance with water and the inert fluorocarbon liquid as coolant fluids. Lee and Mudawar [114], [115] designed an R134a-cooled two-phase micro-channel heat sink which is capable of providing a heat transfer coefficient up to 50 000 W/m^{2}K. However, appreciable pressure drop and corresponding increase in power consumption was undesirable in electronic systems due to the small hydraulic diameter of a micro-channel.

5) JET IMPINGEMENT AND SPRAY COOLING

The jet impingement cooling is to incorporate the jet nozzles to form liquid jet on the surface of the base plate. This technology provides high heat transfer coefficients as well as eliminates the presence of thermal resistance between the chips and the cooling fluid. It can achieve very low thermal resistances (generally $10^{-5} - 10^{-6}$ K m^2/W) [116] through the usage of impinging liquid jets. Because of the very thin thermal boundary layer, which is formed in the stagnation zone and extends radially outwards from the jet, the jet impingement cooling is capable of extracting a large amount of heat. For the thermal management of an inverter module in a hybrid vehicle, Bhunia and Chen [117] presented a study of liquid jet impingement cooling technique and its system level implementation. The thermal analysis results showed that more than 10% of the total heat dissipation at 1600 W level through impingement cooling, and approximately 1.8 times improvement over forced convection liquid cooling in the most advanced pin fin cold plate. Natarajan and Bezama [118] developed that a single-phase water submerged jet that reached an equivalent heat transfer coefficient as high as 52000 W/m^2 K. Parida *et al.* [119] illustrated the direct liquid jet impingement cooling of power converter module in Figure 10. There were several structures with the separating walls to enhance the effective surface area and the jet nozzles to attain a much higher heat transfer rate.

Over the last decade, jet impingement has become one of the best cooling solutions for high-powered electronic and photonic modules. It is always desirable to use an array of jets to cool larger surfaces due to the heat transfer coefficient decreases rapidly with distance from the jet. But it may arise disturbances when water from one jet meets the water from the neighboring jet, which is difficult to be modeled accurately but have been shown to decrease the overall heat transfer drastically [120], [121]. Spray cooling is the other attractive technology explored for high heat flux applications, which is shown in Figure 11. The structure of the spray cooling can fully make use of the ability of the phase change process to remove large heat loads via the latent heat of vaporization of the liquid [122], which is mainly affected by the forced convection, impinging spray droplets and the boiling of the liquid on the sprayed surface [123].

In 1989, Tilton *et al.* [124] proved that evaporative spray cooling can handle high heat fluxes of 1000 W/cm^2 with only

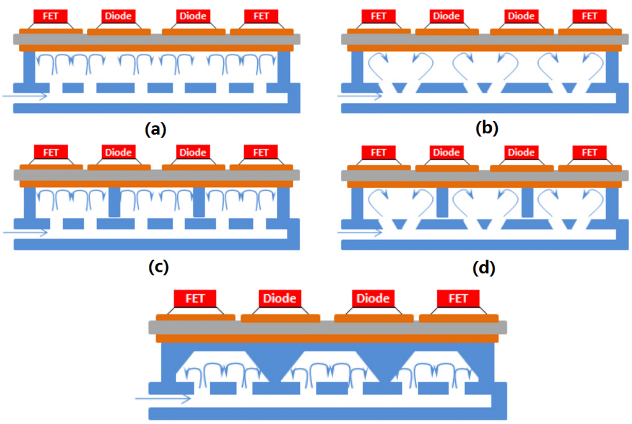

FIGURE 10. Liquid jet impingement cooling of power converter module [119]. (a) Conventional normally impinging jet based design. (b) Inclined impinging jet based design. (c) Conventional jet impingement on a finned base-plate based design. (d) Inclined jet impingement on a finned base-plate baseed design (Swirl-Impingement-Fin based design). (e) Conventional jet impingement on an angled base-plate based design.

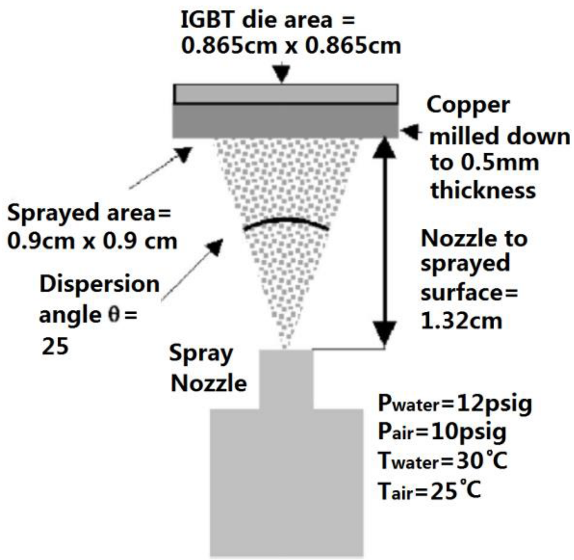

FIGURE 11. Principle behind spray cooling [18].

a relatively small temperature difference between the sprayed surface and the liquid from experiments. It demanded lower mass flow rates of liquid than that of single phase convective cooling. Fabbri *et al.* [125] demonstrated that a single-phase spray-cooling system with the water as the working fluid can achieve a heat transfer coefficient of 15000 W/m^2 K. In 2002, Shaw *et al.* [126] used spray cooling techniques to cool the IGBTs by using high powered AC motors driven by IGBTs with high-power dissipation achieved flux density as high as 130 W/cm^2 at the die with the very low water flow rates. Besides, three types of cooling were explored in this investigation by Mertens' group [18]: single-phase convection with water, spray cooling with air-water and spray cooling with steam-water. The clear advantages of air-water spray cooling IGBTs over other cooling technologies were showed by experiments.

6) HYBRID SOLID AND LIQUID COOLING

When the high heat flux cooling solutions mentioned above applied on the back side of the DBC substrate and designed for thermal management of the entire IGBT, these cannot solve the problem of the non-uniform temperature distribution on the individual IGBTs [127]. Therefore, it has to be found a new and novel cooling solution into the high power PE system for isothermalization of IGBTs. More and more advanced technologies focusing on the high-flux cooling solutions for the microprocessors and electro-optic components have been taken into great consideration. Such as, advanced thermoelectric (TE) solid-state cooling technology, based on polycrystalline miniaturized TE cooler (TEC) [128], [129], minicontact enhancement technology [130], [131], silicon and germanium substrate self-cooling [132], [133], and nanostructured superlattice TEC [134], [135]. Wang *et al.* [4] integrated the cold plate liquid and TE solid-state cooling technologies together to propose a hybrid solid/liquid cooling solution for a 10 × 10 mm^2 IGBT chip at a heat flux of 100∼200 W/cm^2. As shown in Figure 12, the heat in the IGBT module is majorly dissipated through the cold plate in which the thin-film TEC was placed for isothermalization of the individual chips. The results demonstrated that the hybrid solid and liquid cooling with thin-film superlattice TEC works perfectly by eliminating 94% of the temperature nonuniformity for the 100 W/cm^2 IGBT chip and 91% for 200 W/cm^2 IGBT chip.

7) DOUBLE-SIDE COOLING

Most of the conventional packages of power modules are based on DBC substrate technology. But some parts of module, like brazed layers, interfaces and heat exchange between heat sink and ambient represent a great part of the total thermal resistance. There are reliability problems such as breaking, crack, or fatigue of the wire bonds due to thermal cycling. Therefore, Gillot *et al.* [136] developed a new technique for the packaging of IGBTs, in which the components were sandwiched between two DBC substrates with AlN and wire bonds were replaced with flip chip solder bumps. This structure allowed cool components on both sides for better thermal managements. Micro-channel heat sinks were directly integrated in the package to decrease the thermal resistance of the module from both sides, increasing power dissipation by 76% compared to one-sided cooling. Steiner and Sittig [17] experimented with double-sided cooling using micro-channels with water coolant and direct surface contact with the IGBT die to achieve 312 W/cm^2 per side and 624 W/cm^2 at the base. The junction-to-case thermal resistance was reduced from 0.312 K/W to 0.087 K/W.

B. DISCUSSION

Cooling of power semiconductor devices is imperative when to design automotive, electrical vehicle systems using IGBT. The cooling system should be appropriate to keep the cell temperature low as well as uniform, but be simple

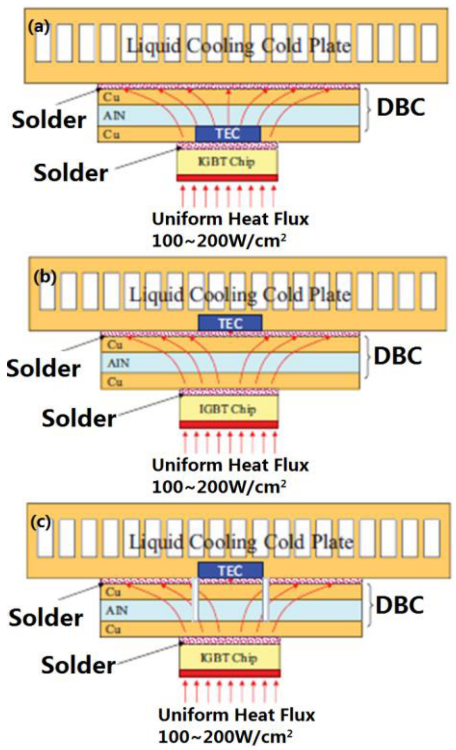

FIGURE 12. Hybrid solid- and liquid-cooling designs for IGBT isothermalization. (a) Thin-film TEC embedded in the copper layer of the DBC substrate. (b) Thin-film TEC embedded in the cold plate base. (c) Thin-film TEC embedded in the cold plate base and enhanced with trench structure in the DBC substrate [4].

and reliable. An overview of various methods that can be employed for cooling of IGBTs is presented in this works. The major thermal design considerations for cooling of IGBTs are one side cooling and double side cooling. Compared to the one-side cooling solution, more than 76% of the heat can be dissipated by the double-sided cooling solution. However, the normal used wire bond chips can hardly be fit to the requirement of double-side cooling. Therefore, the press-pack IGBT are the most suitable candidates with their high reliability and high thermal conductivity from the both sides [85], [86]. Currently, most of the cooling solutions, such as the passive system, forced air cooling and single-phase liquid cooling, are applied on one-side cooling. A wide variety of passive cooling options are available, but if the area available for heat spreading is small, no such complex solutions will help to avoid the use of active cooling. Single-phase or two-phase liquid-cooling solutions, such as micro-channel heat sink cooling, spray cooling, and jet impingement cooling, can provide very high heat transfer coefficients and low thermal resistance. Besides, the hybrid solid/liquid cooling solution, which combine cold plate liquid cooling and TE solid-state cooling can successfully isothermalize IGBT chip.

In order to compare the efficiency of each cooling method directly, we compare the equivalent heat transfer coefficient of each cooling apparatus. The equivalent heat transfer coefficient h is calculated through (1).

$$h = \frac{Q}{A \times (T_s - T_\infty)} = \frac{q}{(T_s - T_\infty)}. \tag{1}$$

where Q is heat transfer rate (W), or thermal power per unit area $q = \mathrm{d}Q/\mathrm{d}A$ (W/m^2), h is heat transfer coefficient (W/(m^2 K)), (T_s-T_∞) is the difference in temperature between the solid surface and surrounding (fluid) area (K) and A is the heat spreader area or the module bottom contact the cooling solutions rather than the chip size or the heat sink surface. The calculated h of different ways of heat dissipation in references are listed in Table 3 and Table 4. It is obviously found that the spray cooling has a great potential for use in IGBTs.

TABLE 3. Cooling solutions and the effective heat transfer coefficient.

Authors	Description	Way of Heat dissipation	Power (W)	Heated area	Equivalent h (W/m^2 K)
Liu et.al [15]	600 V, 450 A IGBT power module	Liquid cooling with AlN DBC and Cu plate	1250	9.8 cm × 5.1 cm	6252.5
Ishiko et al. [137]		Aluminum alloy cooling block + water	700	(Chip) 1cm^2	12000
Castagno [12]	1200 V and 60 A NPT-type IGBT	Forced air cooling (100–200 CFM)	180	5.15 in × 3 in	328
L. Dupont [138]	600 V, 200 A INFINEON IGBTs (SIGC100T6 0R3)	Water cooling	93.7	9730µm × 1023 µm	11074
Howes et al. [106]	1200 VAC, 450 A IGBT devices	Air-cooled extruded aluminum heat sink, common geometry	600	122 mm × 62 mm	1406
		Water-cooled standard extruded aluminum liquid cold plate	736	N/A	2592
		Water-cooled aluminum liquid cold plate, custom; tubing circuit aligned to die locations	1070	N/A	3777
		Water-cooled aluminum liquid cold plate, custom design	1040	N/A	3573
		VDF-cooled copper cold plate, custom design (450A devices).	1461	N/A	14689
		VDF-cooled copper cold plate, custom design (225A devices)	1184	N/A	16526
Lee [139]	600 V, 600 A	Liquid cooling	1200	9.8 cm × 5.1 cm	6002
Liu et al. [110]	600V, 450A	Indirect Liquid Cooling	1250	N/A (ASSUMED 122mm in length and 62mm in width)	2015
		Direct liquid cooling with microchannel			2951
T. Hitachi et al.[14]	N/A	Round pin fin	289*6	105 mm × 108 mm	1996
		Square pin fin			2153
Morozumi et al. [140]	N/A	Direct Liquid Cooling	230*6	97 mm × 99 mm	1690
		Indirect Liquid Cooling			1481
Gillot et al.[136]	1600 V, 50 A	One-sided cooling	1200	N/A	100000
		Two-sided cooling			100000*2
Ayadi et al.[141]	1200 V, 75 A	Water-cooling	N/A	120 mm × 45 mm (assumed)	N/A
Turek et al.[122]	450 VDC, 400 A	50/50 WPG spray cooling	N/A	N/A	61111
Ivanova et al. [142]	N/A	Water cooling	110	(Heat pipe) 80 mm × 30 mm	5000
Steiner et al.[17]	N/A	Micro-heat sink for double sided fluid cooling	900	13.4 cm^2	8395

TABLE 4. Cooling solutions and the effective heat transfer coefficient – cont'D.

Authors	Description	Way of Heat dissipation	Power (W)	Heated area	Equivalent h (W/m^2 K)
Gillot, et al.[40]	600 V, 450 A	Water(30ml/min)	300	N/A	23750
		Water(60ml/min)			25840
		FC 72 (300ml/min)			13320
		FC 72 (600ml/min)			15490
Xu et al.[143]	N/A	Water ethylene glycol (WEG) cooling loop	6000	57 mm × 57 mm	21553
Mertens et al.[18]	650 V, 70 A	Water 228 l /h	300 W/cm^2	0.9 cm × 0.9 cm	57692
		Water-steam spray cooling 5.65 l /h	510 W/cm^2		98076
		Air-water spray cooling water 5.65 l/h;air 567 l/h	587W/ cm^2		234800
G. Mitic et al.[144]	600 V, 180 A	Spray cooling	1371	7.368 cm^2	34079
		Spray cooling without polymide on chips	1393		44695
		Direct liquid baseplate flow convection	1198		29243
Yun et al.[69]	N/A	N/A	223.57	15 cm × 11 cm	557.6
Wang et al.[23]	N/A	R134a-cooled two-phase cold plate	2400	216 mm × 81 mm	4157
		Ethylene glycol (EGW)-cooled single-phase cold plate			3015
Saums et al.[113]	1700 V, 450 A	Air cooled aluminum extruded heat sink	600	N/A	N/A
		Water-cooled extruded aluminium cold plate	736	N/A	N/A
		Water-cooled aluminium cold plate with copper cooling circuit aligned to die locations	1070	N/A	N/A
		Water-cooled vacuum-brazed high performance aluminum cold plate	1040	N/A	N/A
		VDF pumped R-134a convoluted copper cold plate	1461	N/A	N/A
Vasiliev et al.[145]	N/A	N/A	900	N/A	N/A
Wang et al.[4]	N/A	Hybrid solid-and liquid-cooling	100 W/cm^2	N/A	10000
			200 W/cm^2		10000
Campbell et al. [112]	N/A	two-phase cooling method using the R134a refrigerant	1201	N/A	N/A

In opposite to the junction-to-case thermal resistance in Figure 6, the equivalent heat transfer coefficient of different ways of heat dissipation in references is increasing exponentially by rising the power density in Figure 13. To maintain the performance and reliability of IGBT, it is indispensable to have exponentially decreasing thermal resistance and exponentially increasing cooling ability of thermal solutions by the rising heat dissipation. It is obvious that air cooling can rarely be used and liquid cooling are widely applied on IGBT. The spray cooling solutions can handle very high heat flux according to the experimental results.

For making sure the IGBT could work stably under practical operating conditions for a long term, the thermal management is usually conservatively designed with a large margin. For instance, a larger heat sink, a reduced driving current or a reduced switching frequency will be considered when designing the IGBT module. However, all these choices

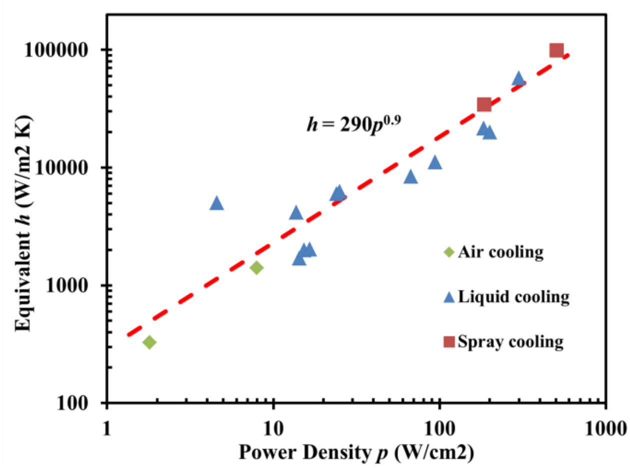

FIGURE 13. The equivalent h of different ways of heat dissipation in references.

that reduce the performance of the system increase the price of IGBT on the other hand. For reaching a more optimal balance between the IGBT performance and price, one should have a precise understanding on the temperature distribution inside the IGBT under existing operating conditions. For this reason, thermal analysis within electro-thermal modeling can be regarded as a fundamental step to design the power conversion systems. Along with the thermal analysis, thermal management of the IGBT and cooling solutions is the next requirement. Then a number of design variants such as long term reliability, functionality of the device, structural optimization and heat sink determination can be further performed based on the thermal analysis results. According to this review, we have proposed relative simple judgment for fast estimating and designing. To achieve an effective thermal management for IGBT, the two rules should be simply followed:

1) The junction-to-case thermal resistance (R_{thjc}, K/W) of IGBT on a heat spread is on or below the line of the following equation.

$$R_{thjc} = 160P^{-1}. \tag{2}$$

where P is the total thermal power (W).

2) The equivalent heat transfer coefficient (h, W/m^2 K) of the integrated metal plate of IGBT is on or above the line of the following equation.

$$h = 290P^{0.9}. \tag{3}$$

where p is the power density (W/cm^2).

V. CONCLUSION

In this paper, researches of thermal management of IGBT published in literature are reviewed, analyzed, discussed and classified into different categories. The thermal analyses using analytical models, numerical models and thermal network models are discussed respectively. Those thermal models are part of electro-thermal models to accurately calculate the dynamic heat dissipation which is one of the most important parameters for overall thermal design. The thermal network models can obtain the tradeoff between the computational time and dynamic performance, and therefore gain the most attention in the electro-thermal analysis that couples electric behavior and temperature-dependent properties.

As to the current cooling studies for IGBTs, single-phase or two-phase liquid-cooling solutions, such as micro-channel heat sink cooling, spray cooling, and jet impingement cooling, can provide very high heat transfer coefficients and low thermal resistances of the modules. With the double-sided cooling technique, an improvement of 76% power dissipation can be achieved compared to the one-sided cooling technique. Moreover, the relationship between the junction-to-case thermal resistance and total power dissipation and the growing trend between the equivalent heat transfer coefficient and the power density are obtained based on the investigation in this paper.

At last, we conclude a relative simple strategy for fast estimating and designing for an effective thermal management of IGBT by two parameters, which are the junction-to-case thermal resistance (R_{thjc}, K/W) and equivalent heat transfer coefficient (h, W/m^2 K) respectively.

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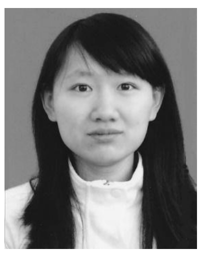

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