A Review of Insulation Challenges and Mitigation Strategies in (U)WBG Power Modules Packaging

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***Abstract*— In the ever-growing landscape of electrical power demand, the future of power electronics module packaging lies in the realm of wide-bandgap (WBG) materials, including silicon carbide (SiC), gallium nitride (GaN), and cutting-edge ultra WBG (UWBG) materials like diamond, aluminum nitride (AlN), and hexagonal-boron nitride (h-BN). These materials offer superior properties to traditional silicon-based devices, promising higher power density, reduced weight, and increased operating temperature, voltage, and frequency. However, pushing the boundaries for power electronics modules presents challenges in insulation systems as the encapsulation material and the ceramic substrate may not withstand the functional parameters, potentially leading to unfavorable conditions like high field stress and partial discharge (PD), ultimately resulting in insulation failure. This paper presents a thorough analysis of the characteristics of the electrical insulation materials used in power electronics devices based on the research in WBG packaging conducted in recent years. The significance of maximum electric field stress at triple points (TPs) is examined. Furthermore, the paper reviews the strategies and techniques employed to mitigate the challenges related to maximum field stress and PDs in both encapsulation and substrate materials. It is concluded that the mitigation strategies are promising in improving insulation systems for packaging, but the studies lack their implementation under actual operating conditions of WBG power modules.**

Keywords—WBG power module packaging, high voltage, insulation, high power density, partial discharge, electric field reduction, triple points, partial discharge inception voltage, high temperature

I. Introduction

In recent years, there has been a trend towards more and all electric appliances, fueled by the goal of achieving net zero emissions [1], which will inevitably raise the demand for electrical power. As increasing the current to meet power demand results in voltage drop and power losses, operating the apparatuses at higher voltages is the only feasible solution. The higher voltage application, combined with the desire to reduce the weight and size of the modules, leads to the high voltage, high power density concept [2].

To tackle the issue of operating power modules at higher voltages and higher power densities, modules based on WBG materials (e.g., SiC, GaN) and UWBG materials (e.g., diamond, AlN, h-BN) are the most promising solutions. The blocking voltage of devices based on WBG materials is higher than that of conventional Si-based devices. One prime significance of WBG materials is their suitability to operate under high slew rates (dv/dt) and high-frequency repetitive voltage pulses [3]. But, with the operation of compact-sized power modules at high-frequency voltages, electric field stress is increased. Insulation systems are impacted the most by the increment in field stress, which leads to the possibility of PDs, accelerated aging, and ultimately, premature insulation failure within the power module [4]. Thus, significant attention has been given to reducing the electric field stress and increasing the partial discharge inception voltage (PDIV) of insulation materials within the system [5-7].

Ceramic substrate, which electrically isolates the chips and extracts the generated heat, and encapsulation materials, which protect substrate, connections, and semiconductors from moisture, dirt, and vibrations, are the insulation systems within the power electronics module. Due to the suitability of WBG power electronics modules to operate at high temperatures (>200ºC), the insulation materials are exposed to temperatures higher than their withstand capacity, further increasing the probability of insulation damage. However, there are only a few papers dealing with thermal stress in power modules [3]. It has been suggested that thermal conductivity alone is an inadequate criterion for deciding whether a polymer is a good packaging material. Other properties also evaluate the thermal performance of insulation systems, like the coefficient of thermal expansion (CTE), glass transition temperature (T_g), and thermal degradation temperature. So, the review of the insulation system needs to be holistic [8].

Several factors influence the phenomenon of high electric field stress and PD in insulation systems of power module. This paper reviews the influence of temperature and frequency on electric field stress at triple points (TPs) and PDIV. Also, this paper analyzes several mitigation methods used to address the issue of high electric field (especially at TPs) and PD phenomenon. It was suggested in [3] that in the future, the goals of PDIV improvement and electric field reduction should be addressed under actual operation conditions of WBG power module, i.e., high frequency and temperature, and the possibility of replacing silicone gel with other polymers as encapsulation should be investigated. Therefore, more recent

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papers that were not reviewed in [3, 9, 10] are discussed here to evaluate the techniques of power module packaging focusing on insulation properties.

II. Triple Points (TPs) and Their Significance in Electric Field Evaluation

Fig. 1. shows a typical schematic of a metalized ceramic substrate for power module packaging. This is a well-established technology where metallization layers are soldered into a ceramic substrate with active metal brazing and encapsulated by silicone gel (SG). TPs, formed by the junction of ceramic substrate, encapsulation material, and metallization layers, are the archils heels of the power module packaging, as the electric field is maximum around at these points, and the interface between packaging material and ceramic substrate serves as a weak area of insulation [12].

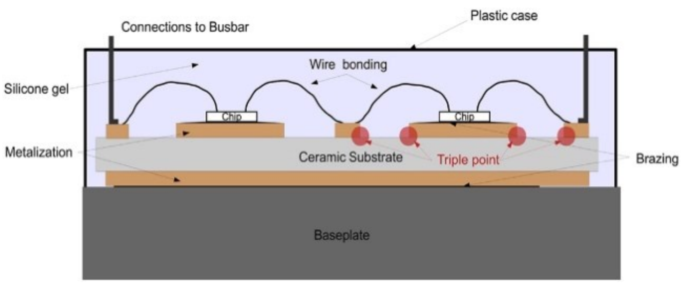

Fig. 1. A schematic of an IGBT/diode showing triple points [11].

Several studies have shown that field stress at TPs is always the highest, and it's this junction that initiates PD within power modules [13, 14]. In [14], the electric field at TP was calculated through the finite element method (FEM) in COMSOL Multiphysics. The simulation was done for 1.72×10^{-11} and 10^{11} S/m electrical conductivity of AlN substrate and silicone gel with their permittivity of 9 and 2.7, respectively, 2 mm and 0.25 mm thickness of substrate and metal layer, and 2 mm trench distance between two electrodes. The results in Fig. 2. show that the electric field value at TP is 65.34 kV/mm, which is way higher than the criterion field intensity of 21 kV/mm. As TP is a singularity point with an infinite electric field, the field calculation is done at some distance away from the triple point. The distance should be selected such that the accuracy of the field stress calculation isn't compromised.

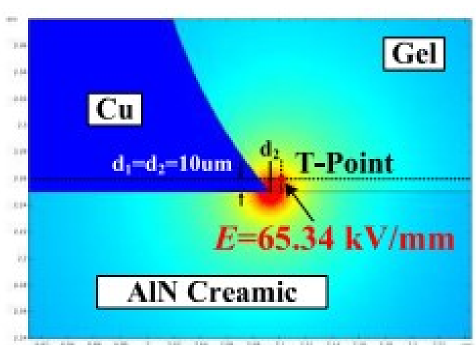

Fig. 2. Electric field distribution of the power module showing a high field stress value at triple point [14].

III. Silicone Gel as a Packaging Material

Silicone gels (SGs) are the most commonly used encapsulation materials in power module packaging due to their excellent electrical properties, high elasticity, easy processability, and, above all, their self-healing properties [15, 16]. The self-healing characteristics of SG were investigated at different temperatures, frequencies, and component ratios [17]. The effect of temperature and frequency on their self-healing property was examined through fractal dimension, expansion coefficient, and duty ratio, and for example, it was ascertained that SG with 50% of a special component has the best self-healing degree of electrical treeing. However, in this study, the maximum frequency of the applied voltage was only 18 kHz, and the maximum investigation temperature was 100ºC, below the numbers targeted for (U)WBG power modules.

B. Zhang et al. evaluated the insulation properties of three commercial SGs for power module packaging [18]. The differential scanning calorimetry (DSC) experiments showed the T_g of all three gels to be around -120ºC and the thermal degradation temperature above 400ºC for gels 1 and 3. Furthermore, all three gels were stable for DSC analysis up to 250ºC. Considering the dielectric loss, breakdown field strength, volume resistivity, and thermal stability, gel 3 stood out as the best encapsulation material. However, the self-healing characteristics of SG3 should be investigated due to its resemblance of adhesion characteristics and electrical treeing morphology to elastomers.

Despite having no issues with T_g, the negative aspect of SG is its operating temperature limit (<200ºC) because of high coefficient of thermal expansion (CTE) which causes CTE mismatches with other module components and leads to thermos-mechanical stress in the system at elevated temperature operations [19]. Thus, several papers have proposed using alternative packaging materials to improve the thermal performance of insulation systems.

IV. Mitigation Methods Implemented to Reduce Electric Field Stress and Improve PDIV

The distinct methods used to reduce the maximum electric field intensity at TP and increase the PDIV involve geometrical techniques to redesign the structure of the substrate, replacing SG with high-temperature encapsulation materials, and the addition of either nonlinear field-dependent conductivity (FDC) coating, high dielectric strength materials or field dependent permittivity (FDP) materials around TPs [20, 21].

A. Structural Redesigning of Ceramic Substrates

H. Hourdequin et al. designed a mesa structure, a trench burrowed in the ceramic between two electrodes, to reduce the maximum electric field value at TP [11]. They found that with a 0.6 mm trench height and 0.5 mm trench width on a 1 mm thick AlN substrate encapsulated by SG, the maximum field intensity at TP was reduced by 57% compared with the conventional structure. It was also found that the PDIV increased from 7.2 kV to 9.2 kV with a 10 pC PD threshold.

The effectiveness of using protruding substrate to reduce the maximum field stress at TP was studied in [22] and it was identified that the maximum field intensity on SG and ceramic substrate at TP were 80.33 and 39.22 kV/mm. Though the field stress reduction in the ceramic substrate is significantly higher than SG, both values (17 kV/mm and 25 kV/mm) are greater than the criterion values. Thus, it is evident that the protruding substrate design isn't adequate to achieve desirable dielectric performance.

In [23], a stacked ceramic substrate design was proposed where instead of one substrate, two or more substrates with a cumulative thickness equal to that of the case are used. The maximum electric field intensity at the AlN substrate and SG were within criterion values (15.18 and 17.48 kV/mm, respectively). However, the thermomechanical stability of the substrate must be investigated because joining substrates with bond lines of a low structural defect and low interfacial thermal resistance requires a reliable process.

F. Yan et al. recommended a new design of ceramic substrate to separate the interface of insulating materials (weak insulation area) from the metal edge (high electric field stress) [24] and showed that a field reduction of 26.56% and 48.85% are achieved on the metal edge and substrate-gel interface, respectively. A conclusion was drawn that increasing the silicone gel height and reducing the ceramic substrate height under the upper metallization layer remarkably reduces the electric field enhancement.

B. *Replacement of SG with Alternative Materials*

Fig. 3. shows the desired properties of polymeric encapsulation materials to be used in envisaged high-voltage, high-power-density WBG power modules. The properties, possibilities, and limitations of encapsulation materials for use in high-temperature power modules are discussed in [19]. Epoxy resin-cyanate ester (EP-CE) blend system with fillers of Al_2O_3 and concurred with polyimide (PI), fluoric phthalonitrile resin, benzo-polymers, and especially bio-based epoxy systems show promise due to their high T_g, lower CTE, high dielectric constant, and increased thermal conductivity (T_C). But still, much exploration is needed to analyze their processability, compatibility with electronic materials, and dielectric properties.

Y. Wang et al. [25] investigated the effect of adding micro-sized and nano-sized boron nitride (BN) and silicon carbide (SiC) on silicone elastomer and discovered that the more the fillers content, the more the reduction in the CTE, increment in thermal conductivity and the increase in PDIV is up to 36%.

Q. Wang et al. [26] found that despite reducing the maximum field intensity and increasing the thermal performance of elastomers, m-SiC fillers decrease the tensile strength of the composite due to the introduction of defects on the interface of matrix and large-sized fillers. Therefore, the best way to achieve the desired objectives would be to use n-AlN/m-SiC/silicone elastomer hybrid composite.

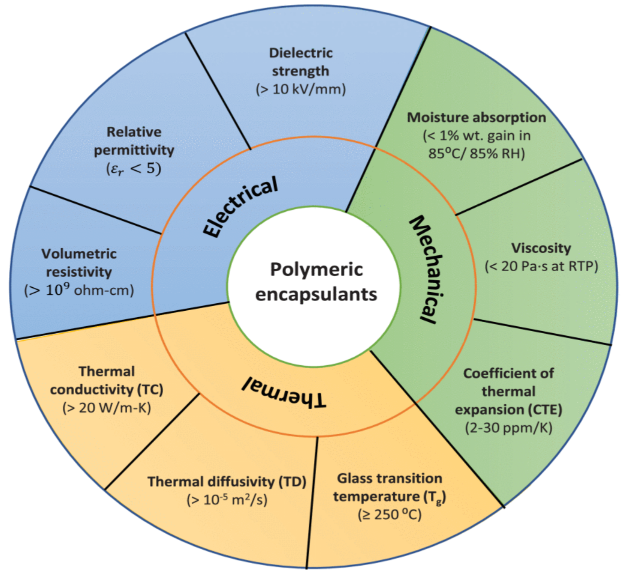

Fig. 3. Required electrical, thermal, and mechanical properties for next-generation polymeric encapsulation materials [8].

Epoxy resins (EPs) are widely used encapsulants due to their high adhesion strength, chemical resistance, low CTE, and high Young's modulus. However, their glass transition temperature (T_g) is lower, thus limiting their performance to temperatures below operating conditions. The most used method to improve the thermal properties of these encapsulants is to add fillers with high thermal conductivity [27-29]. X. Chen et al. [29] studied T_g enhancement of EPs by adding AlN nanofillers for a 15 kV SiC-IGBT module under the square and high-frequency sinusoidal voltage. T_g was calculated through DSC, and the results showed that T_g first increased for EP2 (2 wt% of AlN) and then decreased. This is because the excessive addition of nanocomposites results in interfacial defects and reduces the cross-linking degree between the filler and the polymer matrix. The AC breakdown strength of EP2 was 25% more than pure EP, and the field stress under AC and square voltage became lower with the increase of nano-AlN content and frequency. In a similar investigation but with SiC composites on EP [28], they found that T_g of EP2 was the highest (136.8ºC), and it decreased with additional filler content. Also, the breakdown strength of EP1 was the highest, and it fell with adding more fillers, the increase in space charge density and electric field distortion can explain it. Although T_g was higher with filler content in these experiments, the operating temperature was still limited to 150ºC, suggesting that further examinations must be conducted to see if the thermal stability persists for higher temperatures (>200ºC).

Y. Zhang et al. [27] used BN/EP composite for electric tree evaluation at higher frequencies and discovered that the addition of BN sheets increases the tree inception voltage at all frequencies, which is more than 7 kV at 130 kHz compared to 5.7 kV of pure EP. Also, the maximum and minimum tree lengths observed at 400 Hz and 130 kHz are 51.2% and 18.0% less than pure EP. Contrary to what was expected, the inhibition in electrical tree initiation and growth wasn't due to thermal conductivity, as it increased by only 15% with 0.1 wt% BN sheet. Instead, it was due to the blocking effect of BN sheets and deeper traps at the BN/EP interface. The effect of temperature on the performance of adding BN sheets to the polymer should also be examined before utilizing it as an encapsulation material.

C. Nonlinear Field-Dependent Permittivity (FDP) Materials

Ferroelectric materials (e.g., $BaTiO_3$) are incorporated as fillers in polymer composites (e.g., EP) to create FDP materials, which help in electric field reduction with their high non-linear dielectric constant and high electrical breakdown field [30]. But, compared to nonlinear FDC materials, the research on nonlinear FDP materials is limited. The reason is the disappearance of field dependent permittivity feature of these materials after a specific temperature, called curie point. The curie point in the combination of SG and $BaTiO_3$ (BTO) crystals was 135ºC, which is lower than the operating temperature of the next-generation power modules.

F. Yan et al. found that partially coating high permittivity $BaTiO_3$ materials in silicone gel reduces the electric field intensity at TP, as shown in Fig. 4, and inhibits the formation of electrical treeing in insulating material (SG) due to the formation of silicone/$BaTiO_3$ interfaces [31]. However, with the increase in temperature and frequency, the permittivity value is reduced, so further experiment needs to be conducted for curie points greater than 200ºC and higher frequencies. In a similar experiment conducted in [6], it was examined that even though 33 vol% BTO concentration minimized E_{max} by 15% compared with pure EP due to increased ε_r to 11.7, the viscosity rose to more than 8000 mPa-S. This increased viscosity makes it difficult for the material to flow in power modules and, during the manufacturing process, may introduce defects due to not filling voids and cavities correctly. Thus, the insulation performance of the encapsulation materials is compromised.

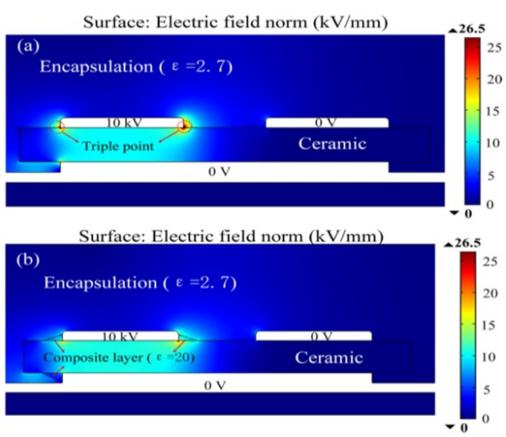

Fig. 4 Electric field distribution, (a) For silicone gel with ε_r=2.7. (b) addition composite with ε_r=20 as a coating at TP [31].

It's evident from all the research conducted till now that the field stress needs to be decreased more at TPs and their vicinity, compared to other areas in the insulation system. Therefore, S. Diaham et al. developed an electrophoresis process to deposit functionally graded materials (FGM) for power module packaging [32]. These materials, shown in Fig. 5, prepared by the composite mixture of strontium titanate ($SrTiO_3$) particles with EPs, achieve higher permittivity towards the area with higher electric field intensity and gradually decrease in areas where the field stress is less. They performed simulations for pure epoxy, homogeneous epoxy/$SrTiO_3$ composite, and FGM composites and found that the field reduction was more than 50% for optimal permittivity range ($15 \leq \varepsilon_{layer} \leq 50$) of FGM layer [33]. Moreover, a breakdown voltage improvement of 68% was achieved compared to pure EP. This is a promising result considering the electrical properties, but complementary investigations should be carried out to observe the influence of FGMs on thermal and mechanical properties.

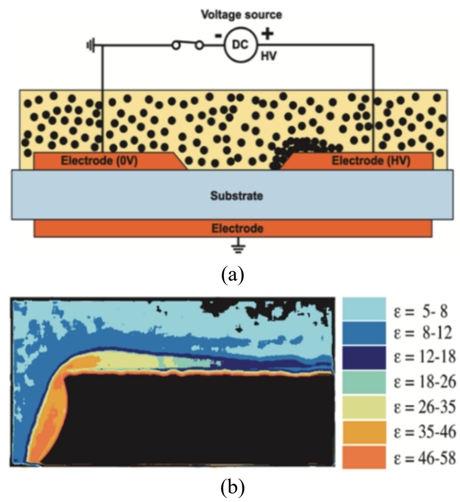

Fig. 5. (a) Electrophoresis application to DBC substrate, (b) Permittivity distribution around the accumulated particle layer showing higher permittivity layers around triple point [33].

D. Nonlinear field-dependent conductivity (FDC) coatings

Nonlinear FDC composites consist of high-conductivity filler particles (e.g., zinc oxide microvaristors) in a polymer matrix (SG or EP) [34]. The nonlinear conductivity nature of these composites changes with variations in electric field, allowing the conductivity to increase in high-field stress areas to uniformly distribute the electric field and prevent breakdown from occurring [35-39]. Nonlinearity coefficient, α, of these composites should be > 10, and the switching field (E_b) should be taken as the maximum applied voltage per layer length. Research on nonlinear FDC materials has been going on for decades, and considerable progress has been made to solve the issues of high electric field and PD [23, 41-42]. To reduce the electric field at TP, but also not to increase field value at the new sharp edge of the interface between silicone gel and substrate, the following are desired properties of the coating:

Switching field value, E_b (kV/mm)	Applied Voltage (U_{peak})/Trench Distance (d)
Nonlinearity coefficient (α)	10
Relative permittivity (ε_r)	5
Low-field conductivity, σ_0 (S/m)	1.4×10^{-9}
Coating coverage at each sharp edge of electrode (m)	10 to 25%

A nonlinear FDC coating at TP of the upper metal electrode was designed in [22] and it was found that even though the field stress around SG and AlN substrate is within criterion values, it is increased around the ground electrode. This is because, for $E>E_b$, the field stress around the HV electrode gets transferred to the ground electrode due to FDC coating. Therefore, they proposed a protruding substrate design with a bridging nonlinear FDC layer, where the field stress was within criterion values (17 kV/mm and 25 kV/mm for SG and substrate, respectively). They concluded that increasing E_b reduces the field more, and the design works for frequencies up to 100 kHz. In a similar simulation in [23], they identified that designing protruding substrate to both metallization layers and combining with a bridging nonlinear FDC coating, which fully covers the area between substrate and baseplate, results in the maximum field reduction (Fig. 6).

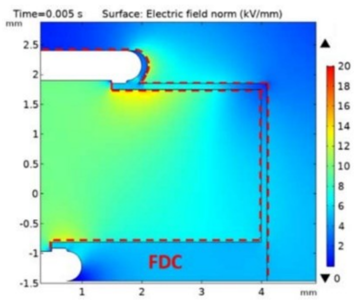

Fig. 6. Electric field distribution for bridging nonlinear FDC coating fully covering the bottom region combined with protruding substrate on both electrodes [23].

K. Li et al. found that using a nonlinear FDC coating with 10% SiC nanofillers in the EP matrix led to a 73% reduction in field intensity at TP [40]. This was due to the combined effects of the temperature-dependent conductivity of EP and electric field-dependent conductivity of SiC nanoparticles, enhancing the field optimization at higher temperatures. Phase-resolved partial discharge (PRPD) patterns showed that PD pulse amplitudes decreased from 1000 pC to less than 10 pC for coated substrates and the PDIV increased from 7.8 kV to 10.4 kV, a 33.3% enhancement. Thermo-mechanical properties of nonlinear FDC layers are crucial for determining their suitability in high-voltage, high-density power modules at high temperatures. So in [41], a polyimide-based FDC (PI-FDC) layer with SiC nanofillers was used, and it was seen that 50 phr (parts per hundred parts of resin) PI-FDC with 500 nm SiC particles have higher values of E_b, and α, lower field intensity, and higher PDIV. The coating retained the nonlinear conductivity aspect even after 120 hours of aging at 200ºC compared to 24 hours for FDC coating on EP and SG matrix. The TGA curves validated this analysis as 5% weight loss wasn't observed up to 537.5ºC. The lower Young's modulus of the layer caused less thermal stress when subjected to thermal shocking tests, proving its thermos-mechanical reliability.

Most of the works mentioned above were performed either under DC voltage or power frequency (50/60 Hz) sinusoidal voltage, but future WBG power modules will operate under square voltages of high slew rates and higher frequencies [43-45]. Thus, further research in this area must be carried out to validate the improvement of insulation systems with these mitigation strategies under actual conditions.

V. Conclusions and Future Recommendations

This paper discussed the recent efforts implemented to address the issue of high electric field stress and partial discharge in insulation systems of next-generation high voltage, high-power-density WBG modules. The significance of triple point (TP) in field stress reduction was presented, and the merits and limitations of silicone gel as an encapsulation were analyzed. As the envisioned WBG power modules will be exposed to higher operating temperatures, the thermal stability of possible alternative materials in place of silicone gel was assessed. Finally, the papers focusing on the application of redesigned substrate structure (mesa structure, protruding substrate, and stacked substrate), nonlinear field-dependent permittivity (FDP) materials, and nonlinear field-dependent conductivity (FDC) coatings for achieving reduced electric field were reviewed. It was highlighted that most of the investigations were performed for temperatures less than 200ºC (which is much less than the envisaged 500ºC operation) and under DC and power frequency sinusoidal AC voltages. The PD behavior under fast-rise high-frequency square wave voltages is different from power frequency sinusoidal voltages. So, the existing standard cannot predict the insulation performance of power electronics modules under real-world situations of high temperature, high slew rate, and repetitive voltage pulses and a new standard needs to be introduced. Therefore, future research must focus on these areas to evaluate the effectiveness of mitigation methods.

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