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Partial Discharges and AC Breakdown Voltage Tests on Thick Metallized Aluminum Nitride Substrates for High Voltage Power Modules

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Abstract— In order to take full advantage of the new wide bandgap semiconductor devices such as silicon carbide (SiC) power devices, new power modules need to reach higher voltage ratings (> 10 kV). The electrical stresses carried over the main insulation, consisting of a ceramic substrate and an encapsulating silicone gel, are significantly increased. Consequently, a better understanding of both the breakdown mechanisms and the partial discharge phenomena for the whole system is needed. In this study, AC breakdown voltage (BV) and Partial Discharge Inception Voltage (PDIV) tests were performed on thick metallized aluminum nitride (AlN) substrates, which represent a simplified model for the passive part of a high voltage power module. The impact of the encapsulating material and of different types of metallization are analyzed. The results show that the nature of the metallization has little to no influence on AC BV but PDIV is affected. Both AC BV and PDIV are strongly impacted by the encapsulating material, which suggests that the underlying mechanisms might be different depending on the surrounding medium. Finally, this study shows that the design challenges stemming from a rise in the operating voltage of future power modules cannot be simply solved by increasing the thickness of the metallized substrate, even if the induced thermal dissipation problems could be solved by other means.

Keywords— High voltage power module, ceramic substrate, dielectric strength, partial discharge inception voltage

I. INTRODUCTION

The emergence of wide bandgap semiconductor devices, particularly the silicon carbide (SiC) ones, theoretically enables an increase in the voltage ratings of the power modules, which could well exceed 10 kV. This increase in voltage, together with an increase in the switching frequency, allows for higher power densities while inducing stronger electrical stresses on the power module insulation system. The latter generally consists of a metallized ceramic substrate and an encapsulating silicone gel.

It is therefore crucial to understand the behavior of this insulating system when submitted to such higher voltage stress both in terms of AC breakdown voltage (BV) and from a Partial Discharges Inception Voltage (PDIV) point of view. Partial discharges (PD) are initiated in areas where the electric field is high enough, such as around the so-called “triple point”, which is the junction between the silicone gel, the ceramic substrate and the edge of the metallization. PD are detrimental to the insulators, especially to the silicone gel [1, 2], and can eventually lead to an electrical breakdown and a failure of the entire system. In a power module, the outer edge of the metallization is regularly prone to discharges [3, 4] but, depending on the metallization technology used, discharges can also occur underneath the metallization [5] or within the ceramic substrate [6], even if less intense and inducing no significant degradation in these cases.

Due to its high dielectric breakdown strength (more than 30 kV/mm even at temperatures around 200 °C) and its relatively high thermal conductivity (from 140 to 200 W.m⁻¹.K⁻¹)[7], the aluminum nitride (AlN) ceramic substrate is a good candidate for insulating power chips with voltage ratings higher than 10 kV. This study focuses on AC BV and on PDIV of metallized AlN substrates with higher thicknesses (ranging from 1 mm to 3 mm) than those used in the current lower voltage power modules. Moreover, two types of metallization processes (copper Active Metal Brazing (AMB) and gold sputtering), and two types of encapsulation materials (silicone gel and dielectric liquid) are considered in order to analyze their influences on the mechanisms observed during BV and PDIV tests. To ensure a valid comparison approach, all the ceramics were sourced from CeramTec company and were manufactured with the same method and initial powders.

II. EXPERIMENTAL SETUP AND MATERIAL

A. Test Samples

The samples are AlN ceramic substrates (55 x 55 mm²), elaborated by CeramTec with four different thicknesses (1 mm, 1.5 mm, 2 mm, and 3 mm). They are provided with an upper metallization area of 20 x 20 mm², for connection to the high voltage and a lower metallization of 40 x 40 mm², to be connected to ground. Two types of metallization were realized: either AMB-Cu electrodes using 300 μm-thick copper sheets or thin sputtered gold (S-Au) electrodes of 120 nm thickness. The electrical contacts are made using a screw attached to a soldered nut in the AMB-Cu case and neodymium magnets with a conductive coating (nickel) in the S-Au case.

The substrates with their contacts are encapsulated either with a Perfluoropolyether dielectric liquid (Galden® HT55) or a soft silicone gel (WACKER SilGel® 612). The silicone gel was polymerized within each test cell after being mixed in 1:1 ratio and placed under vacuum in order to remove all the bubbles. The gel was cured at atmospheric pressure and room temperature during 24 h. These insulator properties are summarized in Table 1. The liquid dielectric strength was measured using an oil breakdown tester (Baur DPA 75 C) with 12.5 mm diameter spherical electrodes spaced of 2.5 mm. For the silicone gel case, spherical 14 mm electrodes spaced of 2 mm were used. The voltage ramp-up speed was 2 kV/s in both cases.

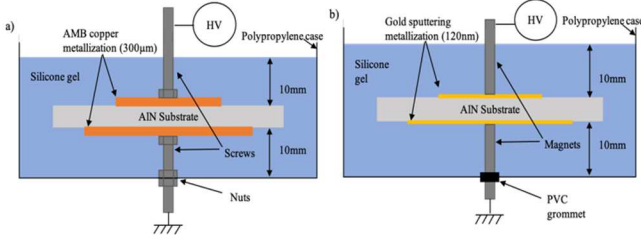


Fig. 1. Schematic of the test-cell and electrical connexions for a) AMB-Cu and b) S-Au metallized substrates, in the case of silicone gel encapsulation.

TABLE I. PROPERTIES OF THE DIELECTRIC LIQUID AND THE SILICONE GEL USED FOR ENCAPSULATION AT ROOM TEMPERATURE

Material	Dielectric constant	Dielectric strength (kV/mm)	Volume resistivity (Ω.cm)	Thermal conductivity (W/m.K)
PFPE dielectric liquid	1.86*	14.7**	1.10 ¹² *	0.065*
Silicone gel	2.70*	32.5**	1.10 ¹⁵ *	0.200*

* Manufacturer specifications. ** Measured values.

B. AC Breakdown Voltage Test

The AC BV bench consists on a step-up transformer (100 kV maximum voltage) connected to a control bay with a motorized autotransformer to create the voltage ramp. A 50 Hz AC voltage ramp of 2 kV/s is applied. For each sample configuration, ten samples were tested and the results were analyzed following the Weibull distribution, which is widely accepted for processing dielectric breakdown results [8]. We quote α as the scale parameter which represents the BV value with a 63 % probability of occurrence, and β as the shape parameter indicating the data dispersion.

C. Partial Discharge Inception Voltage Test

PDIV measurements were realized using a commercial PD detection system from Power Diagnostix (ICMcompact). A 50 Hz AC voltage is applied on the sample and raised progressively until the inception of partial discharges. The maximum voltage that can be applied is 40 kV and the background noise level is below 0.3 pC. Five samples are tested for each sample configuration. For each sample, the PDIV value is measured eight times successively and a Phase Resolved Partial Discharge (PRPD) spectrum is recorded during 20 s at PDIV.

III. RESULTS

A. AC Breakdown Voltage

A comparison of the BV values (i.e. α scale parameter values) for each sample configuration is presented in Fig. 2. The black bars represent the 95 % confidence interval calculated using the shape parameter β [9]. The metallization method does not have a significant influence on BV unlike the encapsulating material. Indeed, BV is higher for the substrates in silicone gel than in dielectric liquid (between 40 % and 50 % higher), except for the thicker ones (with AlN thickness of 3 mm), for which the BV values in liquid are reaching the ones in gel (however with a higher observed dispersion).

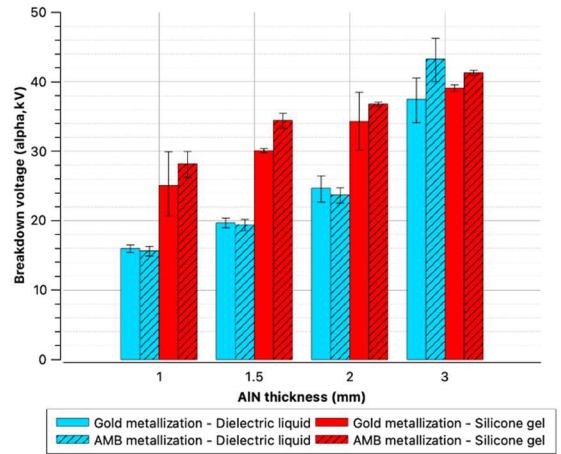


Fig. 2. BV (scale parameter α) for both types of metallization in dielectric liquid and in silicone gel.

The nature of the insulating encapsulation has an impact on the involved breakdown mechanism as well. For all AlN substrates immersed in dielectric liquid, the breakdown occurs through the AlN bulk, leaving a visible track at the AlN surface and a hole through the ceramic layer near the top electrode, as illustrated on typical examples in Fig. 3. For the AlN substrates embedded in silicone gel, the breakdown occurs through the AlN bulk near the metal electrode, as for the liquid encapsulation case, only for the thinnest samples (1 mm-thick). For all the others, the breakdown occurs by bypassing the substrate along the silicone gel/AlN interface. Fig. 4 shows typical profiles and top views of samples in silicone gel after the breakdown test.

Fig. 4 allows to observe the resulting track and perforation mark for a 1 mm-thick ceramic substrate, and the resulting bypassing channel for a thicker one (2 mm-thick in the shown case).

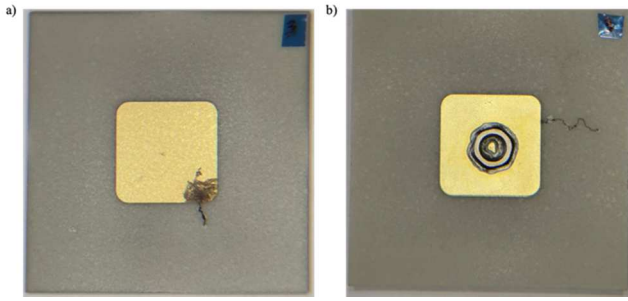


Fig. 3. Top view photos of 3 mm-thick samples with a) S-Au and b) AMB-Cu metallizations, after the breakdown test in dielectric liquid.

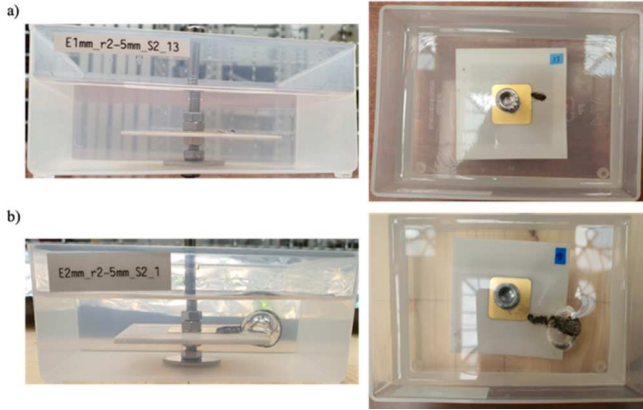


Fig. 4. Top views and profile views of AMB-Cu samples embedded in silicone gel with a) 1 mm-AlN thickness showing breakdown degradation through the ceramic bulk and b) 2 mm-AlN thickness showing breakdown degradation along the AlN/silicone gel interface.

B. Partial Discharges Inception Voltage

For samples in dielectric liquid, the successive eight measurements per sample are quite reproducible, and the PRPD graphs recorded at PDIV are typically as those presented in Fig. 5 a) and b) for both types of metallization. The observed charge amplitudes generally remain below 50 pC, and no degradation marks are detected by eye, neither within the liquid nor on the sample after the whole test sequence. Fig. 6 shows the dependence of the PDIV average value (over 8 tests per sample and 5 samples per thickness) on the substrate thickness, for both electrode natures. Except for the 1 mm-thick sample case, PDIV is higher with the thin gold metallization than with the thick copper metallization.

On the contrary, for AlN substrates in silicone gel, two kinds of behaviors are observed. In fact, either similar PRPD as for the liquid encapsulation case are observed (see Fig. 5 c) and d)), exhibiting low quantities of small discharges (named Type I behavior), or the detected discharges are of higher number and of higher level (with amplitudes exceeding 1 nC), as shown on the PRPD in Fig. 7. Often, the latter phenomenon (named Type II behavior) can be detected during the very first measurement of a sample, especially for AlN substrates of large thickness (as 2 mm or 3 mm). The subsequent measurements then show lower PDIV values, as illustrated in Fig. 8 (example of a series of 2 mm-thick AlN samples with AMB-Cu electrodes). This type II PD behavior can be observed for both types of substrate metallization. Moreover, but only for S-Au samples, a visible

black mark situated at the edge of the top electrode could be observed resulting from the PDIV test, probably because of the fragility of such a thin conductive layer and the high level (of the order of 1 nC) of the PD activity involved in such cases.

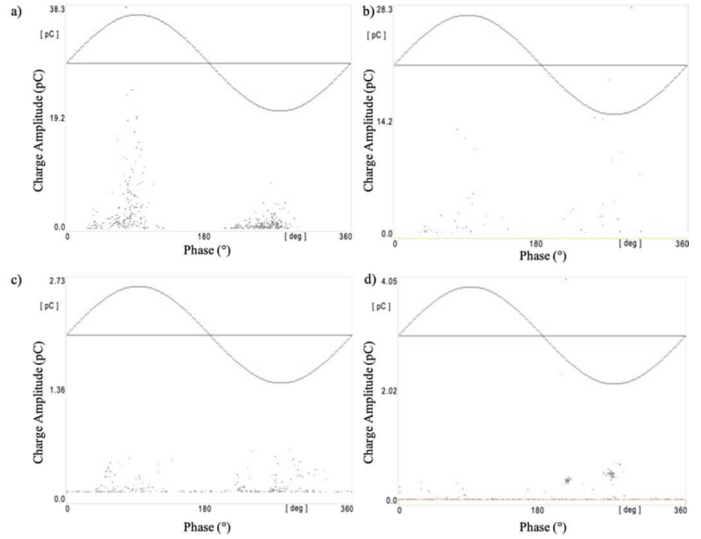


Fig. 5. PRPD recorded at PDIV for 3 mm-thick samples a) Dielectric liquid, S-Au, 11 kV ; b) Dielectric liquid, AMB-Cu, 11.3 kV ; c) Silicone gel, S-Au, 10.3 kV, d) Silicone gel, AMB-Cu, 9.5 kV.

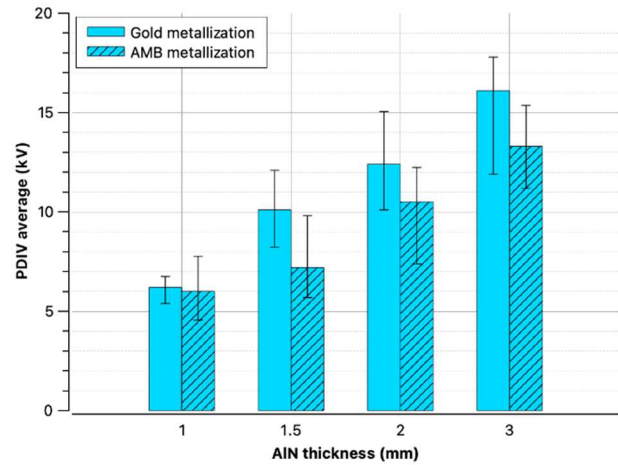


Fig. 6. Comparison of mean PDIV value between both types of metallization for all substrate thicknesses in dielectric liquid. The black bars represent the difference between the maximum and the minimum values of each distribution.

In order to compare the impact of the metallization nature for the gel encapsulation case, Fig. 9 shows the average PDIV from the first recorded measurement only (over five samples) versus the substrate thickness. The metallization has an influence on the PDIV first measurement value, which is lower with AMB-Cu than with S-Au. It can be said also that this first measurement average PDIV value in gel is higher than the average PDIV evaluated in liquid on equivalent samples (Fig. 6). On the contrary, it is observed that the average PDIV values (not shown here) measured in silicone gel subsequently to a type II PD phenomenon are lower compared to the ones in the liquid.

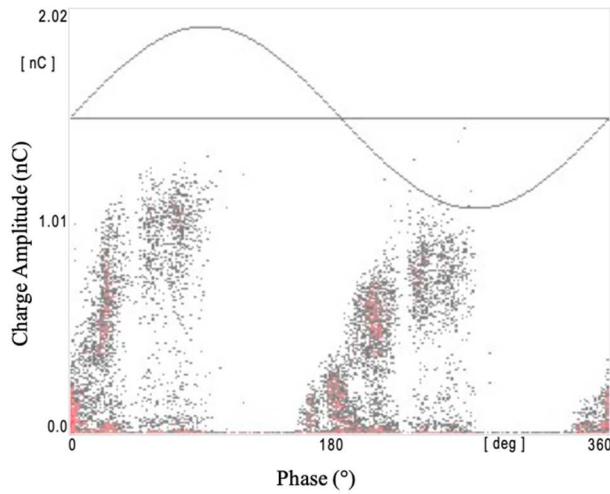


Fig. 7. PRPD recorded at PDIV (8.95 kV) of the 1st measurement for 2 mm-thick samples with AMB copper metallization embedded in silicone gel.

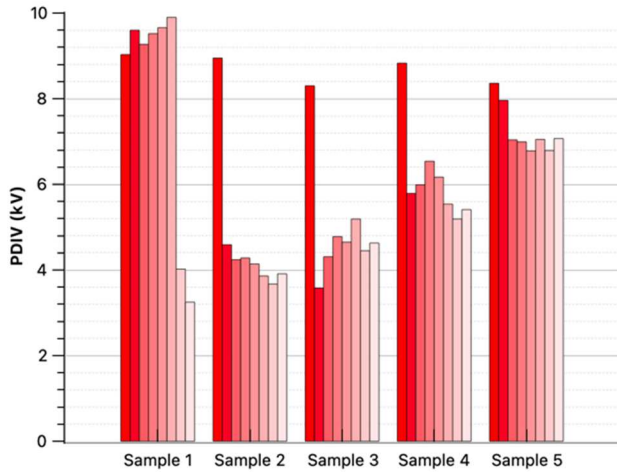


Fig. 8. The eight successive PDIV measurements (from left to right) for a 2 mm-thick AlN substrate with AMB metallization embedded in silicone gel.

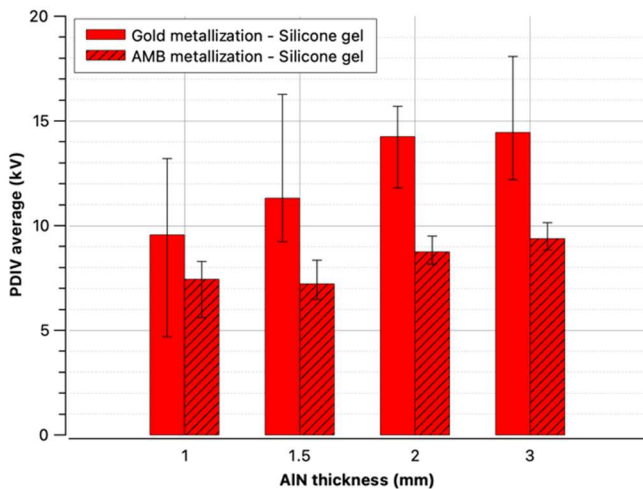


Fig. 9. Comparison of mean PDIV value of the 1st measurement between both types of metallization for all substrate thicknesses in silicone gel. The black bars represent the difference between the maximum and the minimum values of each distribution.

IV. DISCUSSION

The experimental results show that a modification of the encapsulating material has a strong effect on the AC BV and on the PDIV measurements. They highlight the different behaviors between these two materials under electrical stress and comply with already reported investigations on thinner substrates. Even if the silicone gel handles internal streamer formation in a similar way than other dielectric liquids such as hydrocarbon and silicone liquids, it is unable to recover after discharges, leading to permanent defects [5, 10]. The weak point in this configuration is the AlN/silicone gel interface where surface discharges appear before the breakdown [2]. In the case of an AlN substrate, these discharges can increase the surface conductivity and so elongate the cavity stopping length under high electric fields [11]. This phenomenon can explain that with a silicone gel encapsulant, the breakdown occurs along the silicone gel/AlN interface for substrates of 1.5 mm thickness or more, despite the high distances, whereas with dielectric liquid encapsulation, a lower BV occurring through the ceramic bulk is observed. The silicone gel seems to reduce the electrical constraint on the AlN substrate at breakdown, but to become the weakest point of the insulating system under high electric field, with regards to partial discharges.

The type of metallization does not affect the dielectric strength (see Fig.2). On the contrary the PDIV value is affected by the kind of metallization. A copper AMB metallization decreases the PDIV compared to the thin gold metallization, whatever the encapsulation nature. This could be explained by the sharp metallic edges of the AMB metallization or the presence of voids between the ceramic substrate and the AMB copper, that are assumed to be less present or inexistent with a conformal gold sputtered metallization. From PRPD, it can be noted that discharges occur between zero and the maximum voltage (between 0° and 90° phase) and are symmetrical, which can lead to the conclusion that discharges occur in voids in the bulk of the ceramic substrate or the silicone gel [3, 12, 13]. The presence of a black mark at the edges of the gold metallization after PDIV measurements for samples in silicone gel indicates that discharges occur in the gel near the triple point where the electric field is higher.

V. CONCLUSION

In this study, the electrical behavior of simple structures of metallized AlN substrates with a thickness up to 3 mm was highlighted both in liquid dielectric and silicone gel encapsulations. The breakdown voltage is found higher for substrates embedded in silicone gel than in PFPE liquid, with a breakdown occurring along the silicone gel/AlN interface for a substrate thickness of 1.5 mm or more, and not through the AlN bulk like with the dielectric liquid. Furthermore, during PDIV tests, samples with silicone gel are permanently degraded by the discharges, leading to lower values for the following PDIV measurements, and also lower values than PDIV values in dielectric liquid. Besides, the study of the impact of the nature of the metallization on the PDIV shows a detrimental impact of AMB-Cu electrodes comparing to more perfect sputtered thin Au electrodes, whereas the BV is not affected (for a given substrate thickness). It arises from the study that even if increasing thickness of the AlN substrate (up to 3 mm) increases

the BV and PDIV levels, this solution is far from being sufficient to reach power module operating voltages of 20 kV or more (for example, PDIV measured for 3 mm-thick AMB AlN substrates embedded in silicone gel is only around 8 kV). Even if new design packaging solutions may enhance the thermal power dissipation [14], and so theoretically enable the use of a thicker ceramic substrate, new geometries as those proposed in [15] and [16] are currently under investigation in ARCHIVE project, in order to further reduce the electric field reinforcement at the edges of the substrate upper metal electrodes.

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