[Technical Paper]

Partial Discharges in Ceramic Substrates – Correlation of Electric Field Strength Simulations with Phase Resolved Partial Discharge Measurements

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Abstract

High voltages and the edges of the metallization on ceramic substrates (AMB, DBA, DBC, HTCC, LTCC) lead to high electric field strengths. In the vicinity of the metal edges these high electric field strengths induce partial discharges in the ceramic insulation and in the potting and thereby represent one key degradation mechanism of power modules. In this work the correlation of the simulated electric field strength with phase resolved partial discharge (PRPD) measurements has been investigated. For the simulation of the electric field strength a new method was used to bypass numerical artifacts. The simulated values show that it is possible to reduce the electric field strength by an adaption of the metallization structure. There the distance of the upper and the lower metallization to the rim of the ceramic was changed relative to each other. Due to this variation a reduction of the electric field strength of about 30% can be reached by choosing the optimum distance compared to state of the art design. In PRPD measurements for insulating ceramic substrates (AlN/Al₂O₃ by DCB) we examined whether the electric field strength reduction leads to higher partial discharge inception voltages (PDIV). The measurements were executed on layouts with different dimensions of the upper and lower metallization relative to each other as well as for 3 different thicknesses of the ceramic insulation layer. An increase from 20% to 35% of the PDIV was measured for layouts designed according to the findings from the simulation with respect to electric field strength reduction. Finally, the calculated electric field strength and the measured PDIV were correlated.

Keywords: Ceramic Substrate, Mechanical Design and Reliability, Potting, PD Testing, Substrate Technologies, Partial Discharge, Electric Field Strength, DBC

1. Introduction

The demands on power modules have increased regarding power electronics for energy transmission systems. Longer lifetimes, rough environments, and higher temperatures and higher voltages are aimed. Especially the electrical insulation realized by ceramic circuit boards such as DBC (direct copper bonded), AMB (active metal brazed), or DAB (direct aluminum bonded) substrates will have to withstand higher voltages beyond 6.5 kV (i.e., for SiC devices) in the future.

Starting with the development of ceramic substrates the electrical insulation as well as the partial discharge behavior of substrate and coating became of interest. In the last 20 years some research has already been done by different research groups, shortly summarized in the following.

Altogether, the research that was done up to now local-

ized the highest electric field strength in power modules at the metallization edge of the ceramic substrates.[1–3] In consequence, PD takes place in voids of the ceramic, in the coating or potting, in the dielectric interlayer between metallization and ceramic (only DBC/solderless DAB), and/or on the surface between coating and ceramic. The localizations of the PD were identified by optical, acoustical, and PRPD measurements.[4–11] Also upcoming cracks or defects due to aging[12–14] as well as penetrating moisture, increasing temperature, or decreasing pressure[15] increase the PD activity and decrease the PDIV. Simulation was mostly used for the localization or for a rough description of possible improvements to the peak electric field strength. The discussed improvements include a coating of the edge (non-linear resistive materials, high-resistive materials, etc.), 3D-integration, embed-

ding of the metallization, and stacking of substrates. [16–21] Furthermore, the PDIV can be increased by inert fluids instead of potting like silicone gels with the same permittivity and with increased permittivity of the fluids. In addition, optimized manufacturing processes, for instance for etching or polishing, as well as a rounded shape of the metallization layout can contribute to the reduction of PD.[22, 23] Many tests were done on the localization of the critical sections in the module and the electrical insulation itself. Also many optimizations have been carried out. However, only a few of those optimizations are yet implemented or were completely discussed and the simulation itself did lack of a broad study and an evaluation procedure. A quantitative comparison of simulations and experiments based on correlating the simulated electric field strength and the PDIV is still lacking. In order to be able to predict PDIV based on simulations, we performed a broad study including simulations and measurements. In particular, we correlated the simulated electric field strength with the PDIV.

2. Simulation

2.1 General information on the simulation

The simulation process itself is summarized in Fig. 1. First, parts of the structure were idealized to elementary geometric structures and constructed for electrostatic simulation in ANSYS Maxwell. Especially the idealization concerns the sidewalls of the metallization that in reality has an etch profile due to the production process. Also the interlayer (if there is one) between ceramic and metallization was neglected. This can be justified as for DBC technology the interlayer that attaches the copper metallization on the ceramic material by copper oxides during the manufacturing has only a thickness of some micrometers. For the electrostatic simulation, a voltage load of 10 kV is applied on the upper metallization whereas ground potential is applied to the baseplate on which the lower metallization is located. The relative permittivity of the covering material was set to 2.0 representing the inert fluid used for the PRPD measurements. The ceramics, AlN and Al₂O₃, have a relative permittivity equal to 9.0 and 9.8, respectively. The simulated distribution of the potential and the electric field strength are shown in Fig. 1. Here as well as in literature[1, 4, 8, 11, 16, 18] it can clearly be seen that the highest electric field strength occurs in the vicinity of the metallization edge.

However, the 3D simulation is not that easy-to-handle or even necessary and therefore was reduced to a 2D model.

The rounding of the lateral edge has an effect on the electric field strength. This effect is quite high for an exclusive view of this spot only. But, regarding the whole electrical insulation the ratio of the corner length to the total length of the edge is very small. Therefore, as partial discharge is a statistical process, the electric field strength at the rounding of the metallization can be neglected. Furthermore, the simulation was always based on ideal structures and a rectangular metallization layer. The real shape of the metallization depends on the etching process and is frayed. At the bottom of the metal edge, where the metal is in contact with the ceramics, a sharp metal edge is generated as the result of the wet etching process used for structuring of the metal layer. The radius of this edge is much smaller than the radius of the layout rounding. In consequence, the shape of the sharp edge of the metal is the most important quantity in terms of high electric field strength and PD. 3D effects due to the layout are of second order. A 2D

Fig. 1 Star-shaped DBC sample layout (top), simplified (middle) and electrostatically simulated (bottom; the left simulation picture shows the distribution of the electric field strength on the ceramic and the right simulation shows the electric equipotential surfaces in the dielectric material).

simulation is sufficient to study the effect of the geometry of the sharp metal edge.

2.2 2D Simulation and the evaluation procedure

The 2-dimensional structure that was simulated is shown in Fig. 2 where also dimensions are named to describe the structure as well as 4 measurement points (MP1 to MP4) are defined. In all simulations and samples measured the upper and lower metallization thickness was $300\text{ }\mu\text{m}$ which is a common value for ceramic substrates. The combinations of thickness and ceramic material that were simulated (and measured) are listed in Table 1. The constraints to the electric potential are already mentioned before.

However, the simulated values for the electric field strength cannot be easily evaluated at the critical edge of the metallization at the triple point (1 conducting and 2 dielectric materials in touch). The triple point itself or the sharp edge of the metallization is a numerical singularity of the calculation where no physical meaningful interpretation of the simulated values can be achieved for the electric field strength. Linear measures that refer to a length or an area will become infinite because of the further decreasing reference length or reference area at a corner or edge of the geometric structure. This means that singu-

larities always occur if a geometrical detail is not or could not be correctly taken into account. If there is a singularity a physically meaningful statement on mechanical stresses or strains, thermal fluxes, or electric field strength is not possible (unlike deformations, temperatures, or voltages). Those critical locations in models mostly are problematic in praxis, too.

The singularities in simulations cause increasing values with increasing refinement of the mesh. Nevertheless, these critical spots shall be evaluated. Therefore the electric field strengths for 3 different refinements of the mesh were exemplary studied on a line starting from the critical edge and ending in the measurement points. In Fig. 3 the electric field strength on a line from the edge to MP1 is illustrated. Along the line a good matching between the different mesh sizes (difference below 1%) is reached after a distance of $10\text{ }\mu\text{m}$ to the edge. This shows that the electric field strength in a certain distance to the triple point can be evaluated based on a defined refinement of the mesh. Because of that the MP1 to MP4 were introduced to describe the electric field strength behavior in the vicinity of the singularity in a distance of $50\text{ }\mu\text{m}$. For each edge two points were defined, one for the covering and one for the ceramic. This procedure, using measurement points in the vicinity of the singularity for the analysis and not the peak value at the metallization edge, was already introduced and is further specified in.[24]

2.3 Simulation results

The simulations were carried out for the different combinations of ceramic and thickness (type A to D; Table 1) as well as for a variation of the relative distance of the upper and lower metallization to the rim of the ceramic material, the here-called offset r_{off} (Fig. 2). The offset r_{off} is

Fig. 2 Cross-section of the rim of a DBC structure; the measurement points are marked with MP1 to MP4 and the location of the upper and lower metallization is depicted by the lengths r_U and r_L (yielding to the offset r_{off}).

Table 1 Named combination types A, B, C, and D of thickness and ceramic that were simulated and measured.

Ceramic	Thickness in mm		
	1.0	0.63	0.38
AlN	Type A	Type B	–
Al ₂ O ₃	–	Type C	Type D

Fig. 3 Electric field strength along a measurement line away from the edge of the metallization for 3 different upper mesh limits.

Fig. 4 Simulated electric field strength in MP1 to MP4 as a function of the offset for the type D with a minimum of the electric field strength of all measurement points that is slightly negative and close to zero (here between offset values of -0.1 mm and -0.2 mm).

defined as the difference of the upper metallization length r_U and lower metallization length r_L :

$$r_U - r_L = r_{off} \quad (1)$$

For all types (types A to D), the resulting electric field strength of MP1 to MP4 exhibits a minimum of the electric field strength for an offset value that is slightly negative and close to zero (for type D between offset values of -0.1 mm and -0.2 mm; Fig. 4). Furthermore, as reported earlier, another finding is that by varying the thickness of the ceramic the electric field strength does not follow the equation of a plate capacitor: a doubling of the thickness (1 mm to 2 mm) reduces the electric field strength in MP1/2 only by about 30% and not by 50%. [24]

3. Measurement of the PDIV

For the PD measurements samples of type A (Fig. 5) to D were available and within each type the offset was varied. For every combination the offset values studied were -1 mm, -0.45 mm, 0 mm, 0.25 mm, 1 mm, and 2 mm. On each side the metallization layer was $300 \mu\text{m}$ thick.

The 'Mess-&Pruefsysteme Teilentladungsmessgeraet' MPS TMG 20 partial discharge meter was used for the PD measurements. With this measuring instrument tests according to IEC 60270 are possible. In the measuring chamber the samples were placed onto a copper baseplate and contacted by two electrodes (Fig. 6). The contacts and the whole measurement arrangement were covered by Galden® HS240 (Fig. 6), an inert fluid with a relative permittivity of 2.0. The HV electrode carried the measurement signal according to Fig. 7. The voltage was increased

Fig. 5 Isometric view on a DBC sample of type A.

Fig. 6 Experimental setup for PRPD measurements: the sample on the baseplate in an inert fluid has two contact electrodes.

Fig. 7 Increasing measurement voltage used for the PD measurements at a frequency of 50 Hz.

with a rate of 50 V/s. After the first PD exceeding 10 pC (according to IEC 61287) the voltage was increased by 1% to maintain the discharge. The discharge itself was recorded for 5 s. The first measured PD higher than 10 pC marks the PDIV. Altogether the PRPD measurements result in one PDIV value for each layout and type that will be later on correlated with the electric field strength values of MP1 to MP4 of the simulation.

The PRPD signal measured (Fig. 8) indicates the origin of the discharges in voids or on the surface according to literature. [1–3] The usual densification of Al_2O_3 and AlN ceramic samples in this application is about 95% and 97%, respectively, which provides information on the porosity. [25] All measurements for the different types A to D and all different offset variations were done on at least 5 samples to reach a statistical meaningful number of mea-

Fig. 8 Typical recorded phase distribution for the PD detection.

Fig. 9 Normal distribution of 20 measurements at a significance level of 95% of one type C sample with an offset of 2 mm.

measurements. The measurement error is given by the standard deviation. Even though many measurements were carried out to reach a meaningful result it was not always possible to generate a standard deviation below 1 kV. It is also important to mention that there is a high variation between each production charge and therefore the measurements were only compared for the same ceramic master card. However, it is possible to give reliable information on any variation in the PDIV that is higher than 5%. The use of the standard deviation as error postulates a Gaussian distribution curve of the measurement results rightly (Fig. 9).

Altogether, the experiments resulted in a peak PDIV for the samples with an offset of zero for all types (i.e., type D see Fig. 10). It was also found that there was no significant difference between samples of type B and C. Further results on the influence of the structure or of the dielectric

Fig. 10 PDIV and standard deviation (SD) of the type D layouts as a function of the offset of the metallization.

materials used (ceramic, potting) on the PDIV are given elsewhere.[26, 27]

4. Correlation

In this section selected measured PDIV values are correlated with the simulated electric field strength values to study their functional dependency. For the correlation all values of the experiments with the offset samples of all types are taken into account. For that only the higher value of MP1 and MP4 as well as of MP2 and MP3 is chosen due to the assumption that these are the critical values for the discharge process. Combining the calculated maximum electric field strength in the two measurement points of each edge the PDIV was plotted as a function of the arithmetic as well as the geometric mean (Fig. 11 and Fig. 12). The mean values of the electric field strength in the inert fluid and in the ceramic were used for a better representation of the critical electric field strength in the vicinity of the edge. Furthermore, the correlation of the mean values is slightly better than the single maxima.

Thereby a linear interconnection of these variables can be observed. Although the measurement error of the PDIV measurements is high and the simulation result only shows one factor in the partial discharge process a linear correlation is possible. Even if the dependency is not proved in each point and for each studied layout (all variations in offset and type), a trend can be clearly seen between both variables which also justifies previous works on ceramic substrates in which simulations have been carried out. The correlation of the arithmetic and the geometric mean of the simulated electric field strength with the measured PDIV values was statistically analyzed with Minitab® 17.2.1 (Table 2). The Pearson's correlation evalu-

Fig. 11 PDIV as a function of the arithmetic mean of MP1 to MP4 (the first two measurements of type A in the diagramm are most exemplary for a negative offset in the measurements).

Fig. 12 PDIV as a function of the geometric mean of MP1 to MP4 (the first two measurements of type A in the diagramm are most exemplary for a negative offset in the measurements).

ates the linear relation of two continuous variables. If those variables are completely correlated the absolute value of the Pearson coefficient is equal to 1. The positive or negative sign of the coefficient provides information on the gradient of the correlation. Furthermore, if the p-value is smaller than 0.05 the correlation is statistically significant.

Analyzing the correlation yields to the result that MP1 and MP2 are slightly linear correlated with the PDIV while MP3 and MP4 are not. The maximum values as well as their arithmetic and geometric means have a strong linear correlation with the PDIV. The statistical meaningful dependency can be described by the linear equations in Table 3.

Altogether, the reduction of the partial discharge pro-

Table 2 Correlation of simulation results and PDIV: Pearson's correlation.

Correlation	Correlation quality	
	Pearson coefficient	p-value
MP1	-0.617	0.001
MP2	-0.615	0.001
MP3	-0.061	0.775
MP4	-0.050	0.818
max(MP1, MP4) = maxA	-0.935	0.000
max(MP2, MP3) = maxB	-0.962	0.000
Arithmetic mean [maxA; maxB]	-0.952	0.000
Geometric mean [maxA; maxB]	-0.951	0.000

Table 3 Coefficients of the function describing the linear dependence of the PDIV on the simulated electric field strength.

Correlation	Linear function $y(x) = t - m \cdot x$	
	y-intercept t in kV	Slope m in $kV/(kV/mm)$
max(MP1, MP4) = maxA	20.4	0.33
max(MP2, MP3) = maxB	20.2	0.37
Arithmetic mean [maxA; maxB]	20.4	0.35
Geometric mean [maxA; maxB]	20.4	0.25

cess to the factor of the electric field strength seems sufficient using the previously discussed evaluation procedure. The y-intercept also seems physically meaningful because it is about 20 kV which is only by chance the breakdown strength of the inert fluid for 1 mm. But if the measurement points were closer to the edge the function would be simply shifted to higher simulated values that would also shift the y-intercept. However, the slope provides more information on the function. In the evaluation procedure a reduction of the simulated values at the measurement points of about 3 kV/mm to 4 kV/mm leads to an increase of about 1 kV regarding the PDIV. This conclusion is based on variations in the DBC design. In Figs. 11 and 12, it can be seen that the type A measurements of the layouts with negative offset (corresponding to the low values of the simulated electric field strength) do not perfectly fit the

simulation results. Also type B and C layouts with negative offset slightly deviate from the expected behavior. This could be due to manufacturing deviations, a not completely sufficient evaluation procedure, a preferred lower edge due to the partial discharge, or the simplified simulation model. Perhaps an evaluation by integrating the electric field strength in changing sections where the partial discharge will likely occur adapted to each geometric variation would help. However, when neglecting the measurements for the negative offsets the Pearson's coefficient can be further improved to -0.987 .

5. Conclusion

In this work the behavior of the electric field strength in commonly used ceramic insulation substrates as well as its influence on the partial discharge was studied. It is now possible to describe the electric field strength in the vicinity of the metallization edge neglecting the singularity of the calculation at sharp conducting edges. Based on those results PDIV measurements on DBC samples were performed resulting in the fact that no relative distance between upper and lower metallization is best. The simulations and measurements have been evaluated in terms of establishing a correlation of the calculated electric field strength and the measured inception voltage of the PD. It turned out, that the maximum electric field strengths are the most important factor influencing PD with respect to the evaluation procedure used. A linear dependence of the PDIV on the simulated electric field strength quantitatively described our observations. For samples with negative offset deviation from this behavior is seen. However, neglecting these samples leads to Pearson correlation coefficients close to -1 . The extracted formulas predict that a reduction of the electric field strength of about 3 kV/mm to 4 kV/mm leads to an increase of the PDIV of about 1 kV .

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