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# Partial Discharges and Electroluminescence Measurements on Power Electronic Substrates Embedded in Liquids

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**Abstract** — This paper presents an experimental study of partial discharges (PD) and electroluminescence properties of dielectric liquids (dibenzyltoluene & silicone oil) embedding a Silicon Nitride ( $\text{Si}_3\text{N}_4$ ) ceramic substrate. With silicone oil partial discharges appear above 3 kV whereas no PD activity is recorded with dibenzyltoluene up to 6 kV. This indicates that with this  $\text{Si}_3\text{N}_4$  substrate, partial discharges actually originate from the liquid, contrary to previous similar measurements carried out with other ceramics ( $\text{Al}_2\text{O}_3$ , AlN). Optical light detection and visualization also shows that DBT is highly electroluminescent. Silicone oil and  $\text{Si}_3\text{N}_4$  show no electroluminescence, making it possible to study PD activity with a high sensitivity via measurement of emitted light. Since light measurements can be done whatever the shape of voltage wave, contrary to electrical PD recording, the detection of PDs with fast rise voltage becomes possible.

**Keywords**—Partial discharge, power electronic modules, substrates, insulating liquid, electroluminescence.

## I. INTRODUCTION

In a power electronics module, switching components such as IGBTs, MOSFETs and Diodes are mounted on a substrate and embedded in an insulating material called encapsulant. The substrate is usually based on ceramic materials such as Alumina ( $\text{Al}_2\text{O}_3$ ) and Aluminium Nitride (AlN). These materials exhibit high dielectric strength and high thermal conductivity, suitable for high voltage insulation and cooling of semiconductors. Soft materials such as silicone gel are most commonly used as encapsulant to suppress partial discharges (PDs) occurring in high field areas (e.g., at the edges of metallized tracks over substrates), as well as physical protection of the switching components.

In the case of high voltage modules (e.g., 4H-SiC IGBTs offering blocking voltage  $> 10$  kV) [1], the electric field around metallized tracks may become high enough to induce PDs in the gel as well as in the substrate material itself. PDs in the gel rapidly induce irreversible degradation (cavities) which is not favourable for high voltage applications [2]. PD measurements under ac were made previously with various substrates (AlN,  $\text{Al}_2\text{O}_3$ , Epoxy) and encapsulant materials: either liquids (silicone oil, dibenzyltoluene, ester, etc.), or gel (silicone gel). PDs recorded with AlN are rather stable and

reproducible, and does not vary when the encapsulant is changed, indicating that PDs do occur within the substrate [3]. Ceramic materials contain many pores of  $\mu\text{m}$  size, which may explain such internal PDs. This conclusion was also supported by the fact that PD patterns are totally different from those recorded in point-plane gap with liquids, showing large dissymmetry between positive and negative polarities, and marked instability. In  $\text{Al}_2\text{O}_3$  (Alumina) substrates, results are almost identical as in AlN [3, 4].

In contrast, very few PDs were recorded with epoxy substrates, and showing typical features of discharges in liquids (dissymmetry and instability). Unfortunately, PDs with epoxy substrates occurred at high voltage, very close to its breakdown voltage, which prevented to carry out many measurements [3].

The optical detection of light emitted by PDs along the edges of metallized tracks was also made with AlN and  $\text{Al}_2\text{O}_3$  substrates with silicone oil encapsulant [5]. This measurement intended to detect PDs with fast rise impulse voltage, typical of real conditions within power modules. However, the results obtained remained rather questionable with AlN, since it emits light under high field (electroluminescence). This explained why strong light emission under ac was recorded at voltages well below PDIV [5].  $\text{Al}_2\text{O}_3$  substrates did not show such electroluminescence, making it possible to detect PDs in silicone oil as encapsulant from optical measurements. Measurements under impulse voltage showed lower PD inception voltages compared to ac [5].

The objective of this paper is to present both PD measurement and optical detection under ac with another ceramic material (Silicon Nitride,  $\text{Si}_3\text{N}_4$ ) which has good thermal and mechanical performance. The experiments will be done with both dibenzyltoluene (DBT) liquid showing excellent thermal and PD suppression properties [6], and silicone oil showing lower PD suppression capability but no electroluminescence.

## II. MATERIALS AND EXPERIMENTAL SETUP

### A. Substrate and encapsulant

$\text{Si}_3\text{N}_4$  substrates exhibit good thermal and electrical properties making them suitable for applications in high

voltage power electronic (Table 1). It also shows good properties at high temperature, and excellent mechanical resistance to thermal cycling. A commercially available  $\text{Si}_3\text{N}_4$  substrate was used, with two square copper upper metallization (18 x 18 x 0.3 mm), constituting electrodes connected to high voltage HV. Only one electrode was used for all measurements presented here, in order to be able to properly compare results obtained in different conditions (liquid nature, frequency) without changing the substrate. The lower copper metallization (26 x 54 x 0.3 mm) was used as ground electrode as shown in Fig.1. The substrate includes two  $\text{Si}_3\text{N}_4$  layers of equal thickness (0.32 mm) in series, with an intermediate copper electrode between them. During measurements, this intermediate electrode, as well as other electrodes on the substrate, were floating. Considering the capacitances between lower, intermediate, and upper electrode, the intermediate electrode potential was 24 % of applied voltage.

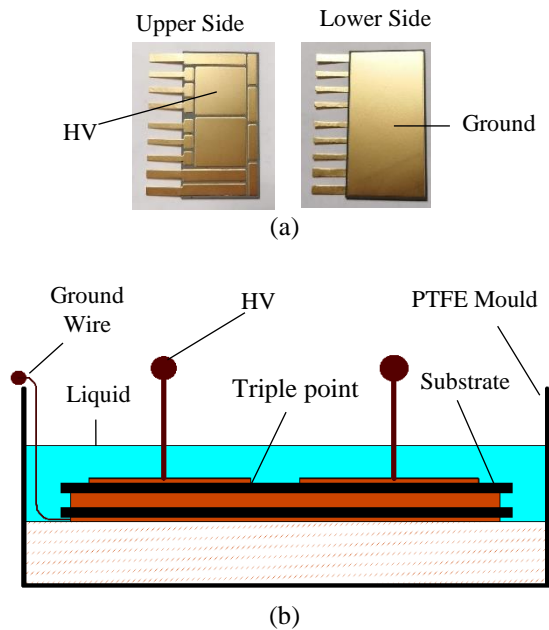


Fig.1. (a)  $\text{Si}_3\text{N}_4$  substrate sample, (b) Structure of test cell

This substrate was immersed in silicone oil (47V50) or dibenzyltoluene liquid (DBT). The liquid level was maintained 5 mm above the surface of HV electrode. After filling with the liquid, the test cell was placed under vacuum for 2 hours to remove trapped air bubbles in the liquid and at the liquid/substrate interface. The thermal and electrical properties of these two liquids are shown in table 1.

Table 1. Properties of encapsulant liquids and substrate at 25°C [7]

	47V50	DBT	$\text{Si}_3\text{N}_4$
Relative Permittivity	2.8	2.6	7.8
Loss Factor ( $\times 10^{-4}$ )	1	1.5	4
Volume resistivity ( $\Omega \text{ cm}$ )	$\sim 10^{15}$	$\sim 10^{14}$	$\sim 10^{14}$
Breakdown field ( $\text{kV} \cdot \text{mm}^{-1}$ )	16	60	15
Thermal conductivity ( $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ )	0.15	0.13	85

## B. Low noise PD and light measurement system

The test cell was placed in a Faraday cage to reduce noise during PD measurements as shown in Fig.2. The cage also provides a dark enclosure for sensitive optical detection and visualization of light. The cage is equipped with a photomultiplier (PM, Burle™ 8575), and a very sensitive camera constituted by a CCD image sensor coupled to a double stage image intensifier (Hamamatsu™ C4274).

The high voltage ac source is constituted by a transformer, PD free up to 20 kV, fed by a low noise and low distortion ac signal provided by a linear power amplifier. A Power Diagnostix ICMSys™ phase-resolved partial discharge analyser (PRPD) was used to record PD patterns at different frequencies (20, 50, 100, 200 Hz). Thanks to the very good shielding and the low-noise HV power supply, the background noise during measurements was around 0.2 pC (corresponding to the noise level of the PRPD system). The PD rejection threshold during measurements was set to 0.3 pC in order to avoid recording noise. Therefore, PD's smaller than this threshold (if existing) were ignored during measurements. All recorded positive and negative PDs were numerically stored for a 1-minute duration, and this procedure was repeated 6 times for each condition.

From these measurements, an equivalent average PD current ( $I_{pd}$ ) could be calculated, by summing all positive and negative PD charges, divided by recording time.

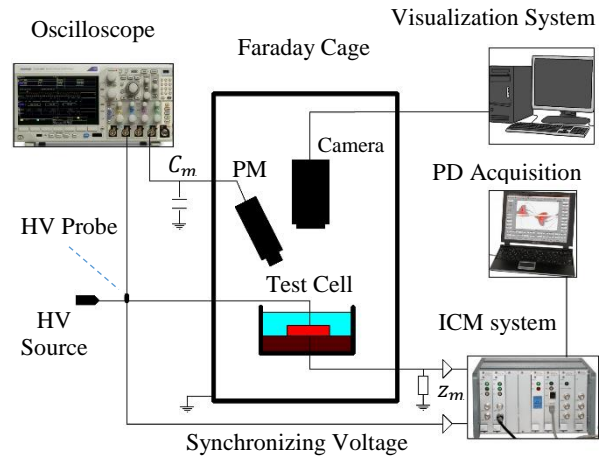


Fig.2. Test set-up for PD and optical measurements

The light emitted was measured in terms of PM current ( $I_{pm}$ ). With almost no ambient light entering the Faraday cage, the background average PM noise was stable, and reduced to a very low level (0.5 nA) corresponding to the “dark current” of the PM itself. This stable noise was subtracted from all measurements presented here.

Depending on the required light measurement features, the PM (that constitutes a current source) was connected to different impedances ( $RC$  parallel circuit), providing various trade-off between bandwidth and sensitivity:

- With  $R = 0.5 \text{ M}\Omega$  in parallel with  $C = 346 \text{ nF}$ , a measurement time constant  $\tau_m = RC = 0.17 \text{ s}$  was obtained. This allowed integrating all the light emission for a duration much longer than the voltage period, and provided the highest measurement sensitivity;

- With  $C$  reduced to 0.4 nF, the time constant reduces to  $\tau_m = 0.2$  ms, allowing time-resolved measurements of light intensity (with ac voltage maximum frequency of 200 Hz).

The light emission at the edges of high voltage electrode is visualized by the sensitive camera placed directly above the test cell. This camera also has background noise, which results in random bright dots on images. To reduce the camera noise, the average of 50 consecutive images was calculated by a frame grabber, which provided an equivalent exposure time of 2s. This helped to reduce noise considerably and produced better images of stable light sources (e.g., repetitive PD occurring at a fixed location). However, unstable, intermittent PDs could not be captured in this way.

### III. EXPERIMENTAL RESULTS

#### A. PD measurements and average light intensity

PD measurements were made with both Silicone oil and DBT using a single  $\text{Si}_3\text{N}_4$  substrate. With Silicone oil, the Partial Discharge Inception Voltage (PDIV, defined by the occurrence of more than 10 PD's during 1 minute duration) was around 3 kV<sub>rms</sub>. No PD was detected with DBT when voltage was increased up to 6 kV<sub>rms</sub>. With further increase of voltage, the substrate got permanently damaged due to breakdown of the ceramics. Therefore, PD measurements with Silicone oil were limited to 5 kV<sub>rms</sub>. The large influence of the liquid nature clearly shows that PDs originate from the liquid rather than from substrate, contrary to previous measurements with AlN and  $\text{Al}_2\text{O}_3$  substrates [3, 4].

Typical PRPD recording in silicone liquid with  $\text{Si}_3\text{N}_4$  substrate can be seen in Fig.3. More PD's occur in negative polarity, in agreement with typical PD recording carried out in Silicone oil with point-plane electrode system [3]. In contrast, quasi symmetrical PRPDs were obtained with AlN and  $\text{Al}_2\text{O}_3$  ceramic substrates [4]. This further confirms the hypothesis that PDs originate from the silicone oil when  $\text{Si}_3\text{N}_4$  substrate is used.

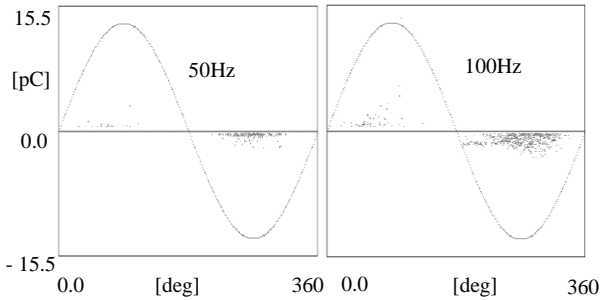


Fig.3. Typical PRPD at 5 kV<sub>rms</sub> in Silicone oil with  $\text{Si}_3\text{N}_4$  Substrate (1 minute recording)

The PD count (number of recorded PD's/minute) at fixed voltage (5 kV<sub>rms</sub>) shows that more PDs are recorded in negative polarity. The PD number rapidly increases versus ac voltage frequency as shown in Fig.3. However, no variation of PDIV and maximum PD charge were observed at various frequencies. However, an important drawback on such measurement must be pointed: from the recorded PD distributions (Fig. 3), it is clear that many PD's with amplitudes lower than the detection threshold (0.3 pC) do

exist, but are ignored in recordings. Therefore, the PD number is probably underestimated.

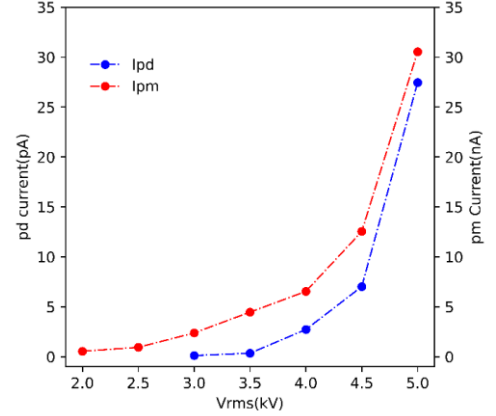


Fig.4.  $I_{pd}$  and  $I_{pm}$  ( $\tau_m = 0.173$ s) measured at 50Hz in silicone oil with  $\text{Si}_3\text{N}_4$  substrate

Fig. 4 shows the average PM current ( $I_{pm}$ ) and the average PD current ( $I_{pd}$ ) measured in silicone oil.  $I_{pd}$  is calculated from the sum of all PD charge recorded for 1 minute, divided by time. Although  $I_{pm}$  and  $I_{pd}$  show some correlation at high voltage, some low-level light ( $\sim 0.1$  nA) is still recorded at voltages below PDIV. Assuming that both silicone oil and  $\text{Si}_3\text{N}_4$  substrate show no electroluminescence, the light recorded below PDIV probably comes from low amplitude PD's, not detected with electrical measurements. A similar result was observed with  $\text{Al}_2\text{O}_3$  embedded in silicone oil [5]. Since the maximum PD charge shows no marked increase with voltage, the increase of both  $I_{pm}$  and  $I_{pd}$  versus voltage is mainly attributable to the increase of PD number.

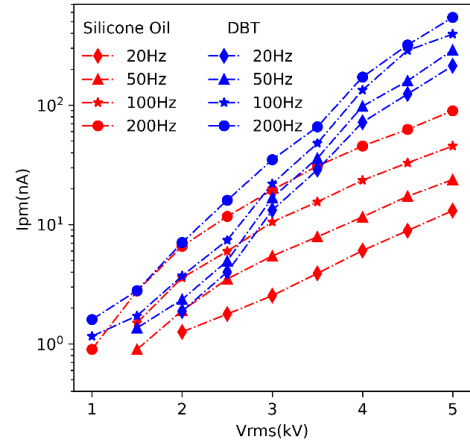


Fig.5.  $I_{pm}$  measured at different frequencies in Silicone oil and DBT with  $\text{Si}_3\text{N}_4$  substrate ( $\tau_m = 0.173$ s)

With silicone oil, an increase of  $I_{pm}$  with the frequency and voltage can be observed (Fig.5).  $I_{pm}$  shows an exponential increase versus voltage, and is roughly proportional to frequency at fixed voltage. Such variation is consistent with an increase of PD number proportional to frequency, i.e., a feature frequently observed in PD measurements (e.g., in cavities).

In DBT, where no PDs are recorded,  $I_{pm}$  due to liquid electroluminescence increases more rapidly with voltage, and

is not proportional to frequency. This evidences that different physical mechanisms are involved in light emission.

### B. Time-resolved light detection

The time resolved light measurement ( $\tau_m = 200 \mu s$ ) in Silicone oil (Fig. 6) shows higher light intensity in negative polarity, in agreement with PD recordings (Fig. 3). Recordings also show ‘spikes’ around the maximum intensity, probably related to PDs. In DBT, light due to electroluminescence mainly occurs in negative polarity, and is considerably larger (about 20 times at 5 kV<sub>rms</sub>) than in silicone oil. The trace is smoother than in Silicone oil, indicating no PD activity.

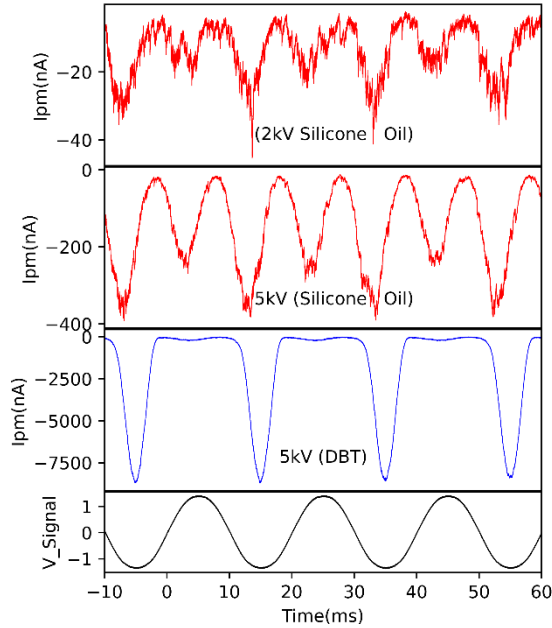


Fig.6. Time-resolved recording of  $I_{pm}$  with  $Si_3N_4$  at 50Hz

### C. Visualization of light

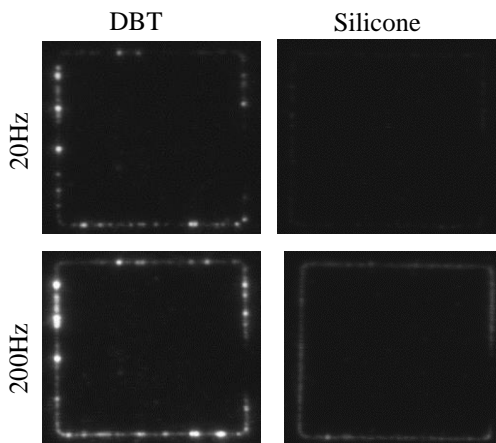


Fig.7. Light visualization in Silicone Oil and DBT with  $Si_3N_4$  Substrate (5 kV<sub>eff</sub>, Average of 50 images, total exposure time 2s)

Very low light level, evenly distributed along the electrode edge is recorded with the camera in silicone oil (Fig. 7). The even light distribution indicates that PDs equally occur at different locations. In DBT, images show bright light

intensity concentrated at several spots, probably indicating the presence of “defects” where the field is enhanced.

## IV. CONCLUSION

PD measurements with  $Si_3N_4$  substrate embedded in liquids show that PDs originate from the liquid, and not from the substrate. Under ac, DBT shows better PD suppression properties compared to silicone oil. Light emission in silicone oil is attributable to PDs only, and provides a promising very sensitive way to detect PDs. This measurement can also be done whatever the shape of the voltage (e.g., with impulse voltage). Due to electroluminescence, DBT is not suitable for such measurement.

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