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Electrical and Optical PD Measurements with Si₃N₄ Power Electronics Substrate Embedded in Silicone Oil

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Abstract- This paper presents an experimental study of partial discharges (PD's) carried out with a Silicon Nitride Si₃N₄ substrate embedded in silicone oil. Optical PD detection is feasible with such non-electroluminescent materials, and can be done whatever the shape of applied voltage (dc, ac, fast impulses), whereas conventional electrical PD measurements can be obtained only with ac or dc. Optical PD recordings show that PD inception is greatly favoured under fast rise impulse compared to ac. The influence of pulse risetime and dc prestress shows that PD inception is strongly influenced by space charge injection, in the case of slow high voltage waves such as ac or dc.

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 built with ceramic materials such as Alumina (Al₂O₃) or Aluminium Nitride (AlN). Such 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 (PD's) from occurring in high field areas (e.g. at the edges of metallized tracks over substrates), and to provide protection to semiconductors against dust, humidity, etc.

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 PD's in the gel, as well as in the substrate material itself. PD's in the gel rapidly induce irreversible degradation (cavities) [2]. PD measurements under ac were previously carried out with various substrates (AlN, Al₂O₃, Epoxy) and various encapsulant materials: either liquids (silicone oil, dibenzyltoluene, ester, etc.), or gel (silicone gel). PD's recorded with AlN and Al₂O₃ are rather stable and reproducible, and does not vary when the encapsulant is changed, indicating that PD's do occur within the substrate [3, 4]. Ceramic materials contain many pores of μm size, which may explain such internal PD's.

In contrast, with epoxy substrates PD's occur only in the encapsulant [3]. PD's in such substrates appear at high voltage close to their breakdown voltage. With liquids encapsulant, Phase Resolved recordings (PRPD) show typical features similar to those recorded in point-plane gap: large dissymmetry

between positive and negative polarities, and marked instability.

The optical detection of light emitted by PD's along the edges of metallized tracks was also made with AlN and Al₂O₃ substrates using silicone oil encapsulant [5]. This intended to develop a method able to detect PD's with fast rise impulse voltage, typical of real conditions existing within power modules. Optical PD detection with high sensitivity can be made with any type of applied voltage, whereas electrical PD measurements are hardly possible with fast rise voltage impulses. However, the results obtained with AlN remained rather questionable, since this material also emits light under high field (electroluminescence), that can hardly be distinguished from that due to PD's. This explained why light emission under ac with AlN was recorded at voltages well below Partial Discharge Inception Voltage (PDIV) [5]. Al₂O₃ substrates did not show such electroluminescence, making it possible to detect PD's from optical measurements, with silicone oil as encapsulant.

More recently, experiments carried out under ac voltage with a silicon nitride substrate (Si₃N₄) and silicone oil as encapsulant showed no electroluminescence [6]: the light emitted is only due to PD's. These materials are therefore favorable to carry out optical PD measurements with impulse voltage. The objective of this paper is to present PD measurements carried out with these materials, using both electrical and optical PD detection under ac, and optical detection with impulse. The influence of injected space charges on PD is evidenced by changing the impulse rise time, and also by adding a dc prestress.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Si₃N₄ Substrates

A Si₃N₄ substrate was used, with rectangular copper upper metallization (20 x 44 mm, 0.3 mm in thickness) connected to high voltage. The lower copper metallization (60 x 68 x 0.3 mm³) was used as ground electrode as shown in Fig.1(a). The metallization has thin silver coating. The substrate includes one Si₃N₄ layer, 0.3 mm in thickness. It was immersed in silicone oil (47V50) with 50 cST viscosity. The liquid level was maintained 5 mm above the surface of HV electrode. After filling, 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 properties of the insulating materials are shown in table 1.

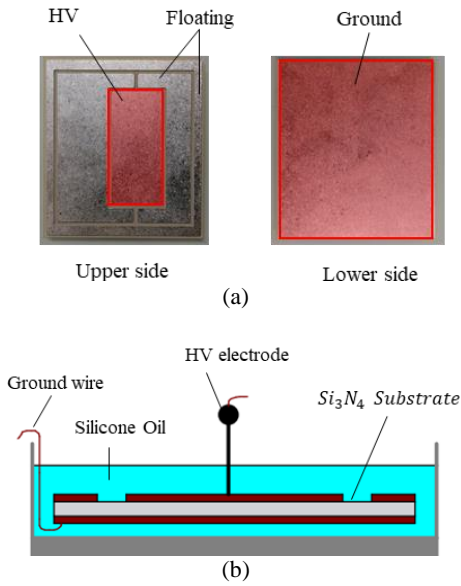


Fig.1. (a) Single layer silicon nitride substrate with silver finish copper metallization. (b) Test cell structure

TABLE I

PROPERTIES OF SILICONE OIL AND Si₃N₄ AT 25°C [7]

	47V50 Silicone oil	Si ₃ N ₄
Relative Permittivity @ 1MHz	2.8	7.8
Volume resistivity ($\Omega \cdot cm$)	$\sim 10^{15}$	$\sim 10^{14}$
Breakdown field (kV. mm ⁻¹)	16	15

B. Electrical and Optical PD Measurement Systems

The test cell was placed in a Faraday cage to reduce noise during PD measurements (Fig.2). The cage also provides a dark enclosure for sensitive optical detection and visualization of light. It 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 linear power amplifier. This allows obtaining low noise and low distortion ac high voltage, with variable frequency F from 20 to 200 Hz. A phase-resolved partial discharge analyzer (PRPD, Power Diagnostix ICMSystem™) was used to record PD patterns. The background noise of PD charge measurement q during measurements was around $q = 0.2$ pC, corresponding to the noise level of the PRPD system. The PD rejection threshold during recordings was set to $q = 0.3$ pC in order to avoid recording noise. Therefore, PD's smaller than this threshold were ignored during measurements. PD's were recorded for 1 minute, and this procedure was repeated 6 times for each condition. From PRPD measurements, an equivalent average PD current I_{pd} could be calculated, by adding all positive and negative PD charges q , and dividing by recording time.

For measurements with rectangular impulse voltage, a generator constituted by a high voltage dc source, and a push-pull high voltage switch (Belhke™ HTS 301-03 GSM) was used. The lowest pulse width was 100 ns, and the highest repetition frequency reached 10 kHz. The minimum rise and fall time of pulses t_r was 280 ns. It can be increased up to more than 5 ms by adding a resistor in series with the test cell. A dc bias voltage (positive or negative) could be added to impulse voltage. In this way, a variety of voltage conditions could be achieved. In the following text, impulse and ac voltages are quoted as peak – peak values V_{pp} .

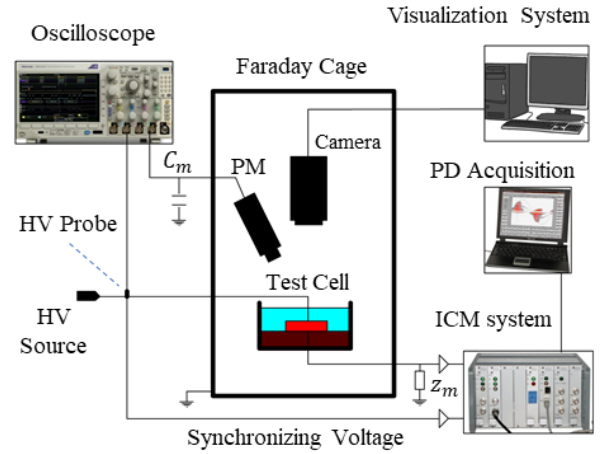


Fig.2. Test set-up for electrical PD measurements under ac, and optical measurements

The light emitted was measured in terms of photomultiplier signal U_{pm} . The PM constitutes a current source proportional to light intensity, and was connected to different impedances (RC parallel circuit), providing various trade-off between bandwidth and sensitivity. With $R = 0.5$ M Ω and $C = 400$ nF, a long measurement time constant $\tau = RxC = 0.2$ s was obtained. This allowed integrating the PM current for a duration much longer than the voltage period (at 50 Hz), and obtaining the average current $I_{pm} = U_{pm}/R$ that provided the highest measurement sensitivity. With no light entering the Faraday cage, I_{pm} shows a low-level background signal (about 0.5 nA) corresponding to the “dark current” (i.e., noise) of the PM. This stable noise was subtracted from all I_{pm} measurements presented here. With C reduced to 0.6 nF (due to stray capacitances of PM, cables, and oscilloscope), the time constant reduces to $\tau = 300$ μ s, allowing to observe and compare the light emission occurring during positive and negative half waves of ac, as well as following rise and fall of impulses. PM signals appear as negative signals on oscilloscope recordings.

The camera also has some background noise, which results in random bright dots on images. To reduce noise, the average of 50 consecutive images could be calculated by a frame grabber, providing an equivalent exposure time of 2 s. This helped obtaining better images of stable light sources (e.g., repetitive PD's occurring at a fixed location). However, unstable intermittent PD's could not be captured in this way.

III. EXPERIMENTAL RESULTS

A. PD detection under ac and bipolar impulse voltage

Under ac voltage, PD's larger than the threshold value ($q = 0.3$ pC) occurred above 4.2 kV_{pp}. This value was lower than in previous similar measurements [2 – 6], due to the lower thickness of Si₃N₄ ceramics (0.3 mm). The PRPD recorded at different frequencies ($F = 20$ Hz – 200Hz) show that most PD's occur before the peak voltage Fig.3(a). Time resolved light recording with $\tau = 300$ μ s (Fig.4) also shows similar phase shift (the maximum of light emission occurs before the voltage peak), and also a larger light emission during negative half-cycle. These observations are similar to those obtained with another type of Si₃N₄ substrate in [6]. The larger light emission in negative polarity is correlated with a larger number of PD's (60%) in this polarity. From experiments carried out with another liquid (dibenzyltoluene DBT), it was concluded in [6] that with Si₃N₄ substrate PD's do occur in the encapsulant, unlike the results of ceramic substrate such as AlN (embedded in DBT) where PD's appear within the ceramic.

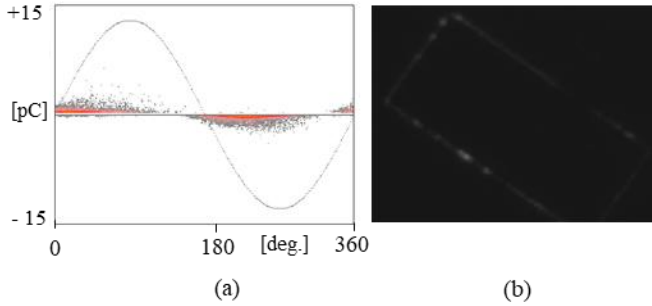


Fig.3. Typical recording at 11.3 kV_{pp} 50 Hz (a) PRPD recorded for a duration of 1 min, (b) Average integrated light for 2 s along the edge of HV electrode

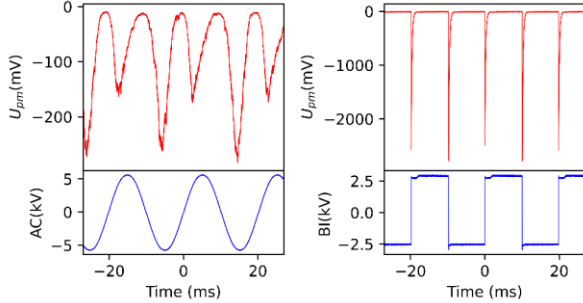


Fig.4. Time resolved light recording ($\tau = 300$ μ s) at $F = 50$ Hz with ac (11.3 kV_{pp}) and symmetrical bipolar impulses (BI) (5 kV_{pp}).

With symmetrical bipolar impulses (BI), light is detected during a short duration immediately following the rise and fall of voltage (Fig. 4). With a fast risetime ($t_r = 280$ ns), PD light emission occurs for a typical duration of 10 μ s after voltage rise (or fall), and ceases thereafter. The peak PM signal U_{pm} recorded with bipolar impulses of 5 kV_{pp} amplitude is 10 times larger and of much shorter duration than with ac at 11.3 kV_{pp}. However, due to the very different time duration of light emission, compared to the measurement time constant ($\tau = 300$ μ s), both measurements do not have the same meaning:

- Under ac 50 Hz, light is emitted during several ms at each halfwave. U_{pm} provides the PM current, proportionnal to light intensity ($I_{pm} = U_{pm} / R$);
- Under fast impulse, light is emitted during about 10 μ s, and the peak value of U_{pm} provides the integrated PM current ($Q_{pm} = U_{pm} \times C$), proportionnal to the total amount of light emitted after voltage rise (or fall).

With both waves, a very small amount of light from PD's can be seen with the camera along the edge of HV electrode, with several brighter spots (Fig.3(b)), depicting non-uniformity of PD activity along the edge.

With ac voltage ($F = 50$ Hz), Fig.5 shows the comparison between electrical measurements (average PD current I_{pd} calculated from PRPD recording), and optical measurements (average PM current I_{pm} recorded with low bandwidth, $\tau = 0.2$ s). Both signals are not proportionnal to each other over the whole voltage range. A possible explanation is as follows: close to PDIV (4.2 kV_{pp}), many small PD's of charge q below 0.3 pC (threshold of charge detection) probably exist, but are not recorded. I_{pd} is therefore underestimated at low voltage. In contrast, I_{pm} resulting from analog integration of U_{pm} by the RC circuit includes all discharges, whatever their amplitude. This probably explains why the ratio I_{pm}/I_{pd} increases at low voltage.

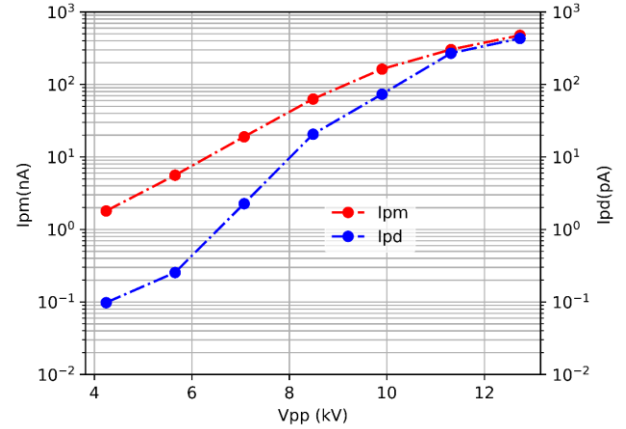


Fig.5. Average PD currents I_{pd} (1 minute recording) and average PM current I_{pm} ($\tau = 0.2$ s) at 50Hz under ac

B. Influence of pulse rise time (t_r) on PD activity

The rise and fall times t_r of symmetrical bipolar impulse voltage (BI) was increased by adding resistors in series with the test cell, from $t_r = 0.28$ μ s (no resistor) to 7.5 μ s (40 k Ω resistor), 135 μ s (1.5 M Ω), 2.85 ms (10 M Ω). With fixed frequency ($F = 50$ Hz), a significant increase in I_{pm} (measured with $\tau = 0.2$ s) is observed for shorter rise time (i.e., higher dV/dt), see Fig.6. This effect can be attributed to the influence of space charge injection: with fast dV/dt, time is too short for injected ions to propagate and attenuate the maximum field at the electrode edge. With long risetime, space-charge limitation of the field occurs, and PD activity decreases. Similar effects were previously observed in liquids with point-plane gap [7]. Logically, with $t_r = 2.85$ ms, light emission is close to sinusoidal ac. PD activity considerably increases when large dV/dt impulses are involved, which corresponds to practical situations

existing in power modules. Compared to sinusoidal ac, the voltage required to induce a similar PD activity with fast risetime impulses is at least two times lower. Low level light measurements are limited by the PM noise to about $I_{pm} = 1$ nA. With short rise time impulses, light can be detected above about 1.5 kV_{pp}, instead of 4.2 kV_{pp} under 50 Hz ac. Similarly, the peak PM signal recorded as in Fig. 4 shows a significant decrease with increased rise time.

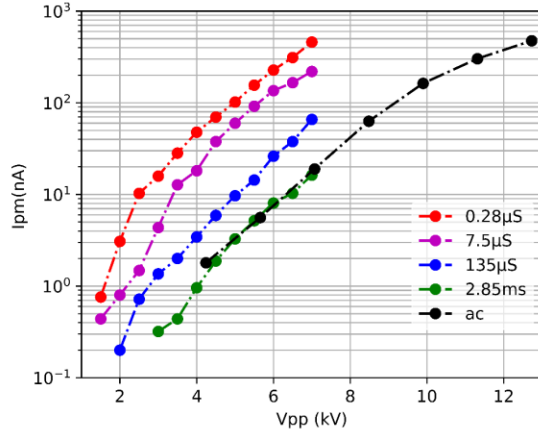


Fig. 6. Variation of I_{pm} ($\tau = 0.2$ s) with different voltage rise and fall times of bipolar impulse, and comparison with ac (50 Hz).

C. Influence of dc prestress with impulse voltage

To further evidence the major influence of injected space charges on PD activity, experiments with a dc prestress V_{dc} added to impulses were carried out (Fig. 7).

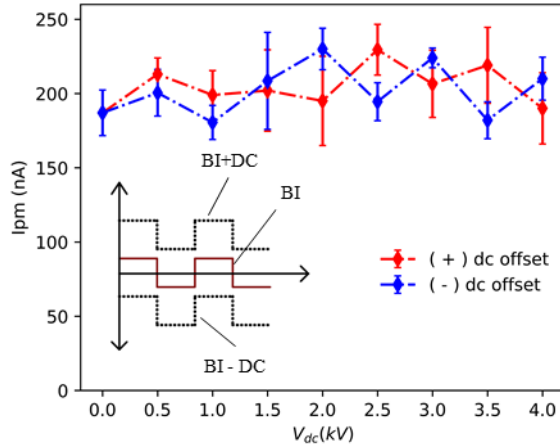


Fig.7. I_{pm} ($\tau = 0.2$ s) measured with dc prestress V_{dc} superposed to 6kV_{pp} bipolar impulses ($t_r = 0.28$ μ s, $F = 50$ Hz).

Positive or negative V_{dc} from -4 kV to 4 kV were added to symmetrical bipolar impulses of fixed amplitude (6 kV_{pp}). In extreme cases, the applied voltage switched between +1 and +7 kV (with $V_{dc} = +4$ kV), -3 to +3 kV (with $V_{dc} = 0$ kV), and -7 to -1 kV (with $V_{dc} = -4$ kV). In measurements, no significant fluctuation of average current I_{pm} occurred. The statistical variation of I_{pm} (Fig.7) recorded with various prestress compare with those measured without dc prestress. PD's under repetitive impulse voltage are dependent on the peak-peak

amplitude, and do not change with imposed dc offset. Under dc only, no PD activity was recorded up to $V_{dc} = 5$ kV. This confirms that under dc, the actual field at the electrode edge is strongly reduced by injected space charges, induced by the very high field at the electrode edge. Under 50 Hz ac, since PD's do occur, one may conclude that the attenuation of field due to space charges is not as large as under dc. However, some attenuation of field obviously occurs, as evidenced by the lower PD activity under ac compared to fast rise impulses (Fig. 6), and also by the influence of pulse risetime.

III. CONCLUSION

Metallized Si₃N₄ ceramic substrate embedded in silicone oil provides an interesting opportunity to study partial discharges via optical measurements, since both materials are non electroluminescent. The recorded light only comes from PD's occurring at the sharp edges of metallization. Optical measurements allow PD detection whatever the high voltage wave used, including pulses with fast rise. The comparison of light emission between ac voltage and impulses of variable risetimes shows that PD inception is greatly favoured by fast risetime. This effect is attributable to injected space charges that attenuate the field in the case of ac, dc, and impulses with slow risetime. Adding a dc prestress to impulse voltage does not influence PD occurrence, and further evidences the major influence of space charges.

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