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# Breakdown Properties of Epoxy and Ceramic Substrates Embedded in Liquids at High Temperature

J. Muslim<sup>1,2</sup>, O. Lesaint<sup>1</sup>, R. Hanna<sup>1</sup>, N. I. Sinisuka<sup>3</sup>

<sup>1</sup> Univ. Grenoble Alpes, CNRS, Grenoble INP, G2Elab, F38 000 Grenoble, FRANCE,

<sup>2</sup> PLN Indonesia, Jakarta 12160, Indonesia,

<sup>3</sup> Institut Teknologi Bandung (ITB), Bandung 40132 Indonesia

**Abstract-** Surface breakdown is investigated with substrates made either from standard glass/epoxy PCB board or Alumina ceramic, and embedded in silicone gel or dibenzyltoluene (DBT) high temperature liquid. Depending on the substrate nature and gap distance, breakdown may occur either above the surface within the encapsulant material, or below within the solid substrate. In the case of ceramic substrate with liquid encapsulation, which could be tentatively used at high temperatures above 200°C, the weakest material is the ceramic, which shows irreversible degradation (cracks) after a single breakdown. Therefore, such insulating structure does not benefit from the self-healing character of liquids. Breakdown voltages also show a marked decrease at high temperature.

## I. INTRODUCTION

High temperature power electronics has become possible with the recent development of wide bandgap semiconductor materials. To take full advantages of these devices, packaging materials operating under high temperature and high voltage are required. Silicone gel is used widely to encapsulate modules, mainly to provide a mechanical protection and to suppress partial discharges when high voltage is used. However, the use of silicone gel is limited to about 175°C.

A large electric field appears at the edge of metallization on substrates, where a triple junction is present between ceramic, metallization, and encapsulant. Local high field can induce PDs, and ultimately breakdown. PDs in silicone gel quickly reduce its insulation capabilities due to formation of permanent cavities [1-3]. PD measurements carried out with liquids instead of gel [4] evidenced the fact that embedding substrates in a high temperature liquid such as Jarytherm®DBT provides good PD properties at high temperatures, up to 350°C with Alumina substrates, i.e., far higher than the maximum temperature limit of silicone gels.

This study constitutes a continuation of these studies with liquids, with the objective to investigate breakdown phenomena. Depending on the field geometry, breakdown may occur either across the ceramic substrate itself, or between metallized tracks along the ceramic/liquid interface. The latter case is considered here. The occurrence of surface breakdown between adjacent metallized tracks constitutes a key question for high voltage modules. Two types of voltage exist within a power module: DC and impulse voltages with fast rise time due to switching. The case of DC will be considered here.

DC breakdown measurements between tracks are carried out with 2 substrates materials: a standard epoxy/glass PCB board, and Alumina ceramic. Epoxy, although it is not used in real modules, constitutes a simple and cheap way to build breakdown samples, and also provides the opportunity to evidence the differences existing between ceramic and polymer materials. Substrates were embedded either in DBT high temperature liquid, or in silicone gel for comparison.

## II. EXPERIMENTAL TECHNIQUES

The thickness of Alumina ceramic substrates was 630  $\mu\text{m}$ , and that of copper metallization was 100  $\mu\text{m}$ . Epoxy substrates were 1500  $\mu\text{m}$  in thickness, with 35  $\mu\text{m}$  copper metallization. Substrates were etched chemically in order to obtaining 8 breakdown gaps on a single sample (Fig. 1a). During measurements, the central electrode and 7 outer electrodes were connected to ground, while the remaining outer electrode was connected to high voltage to induce surface breakdown. Different breakdown gap distances  $d$  between central and outer electrodes were obtained by etching. Due to the etching process used, some variation of  $d$  occurred among the 8 breakdown gaps on a single sample, and the exact distance of each gap was precisely measured with a microscope. For measurements in silicone gel, substrates with connecting wires were placed in a metallic cup and embedded under vacuum in DowCorning Sylgard™527 gel (Fig. 1b). For measurements in liquid, substrates were attached to a PTFE holder (Fig. 2), immersed in a beaker containing the liquid, and placed under vacuum to remove trapped gases prior to measurements.

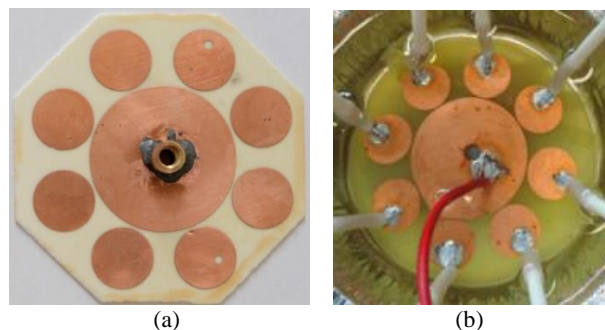


Fig. 1. (a) Alumina substrate containing 8 surface breakdown gaps. Grounded central electrode: 28 mm diameter, outer high voltage electrodes: 12 mm diameter, (b) epoxy substrate embedded in silicone gel.

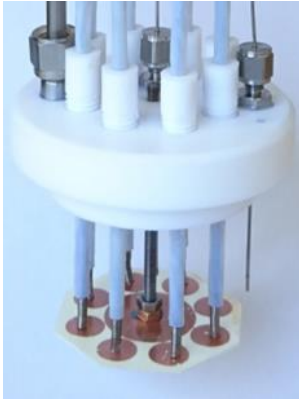


Fig. 2. PTFE substrate holder, and connections for breakdown measurements in liquids.

Breakdown measurements were done under a DC ramp (1 kV/s) with a 44 k $\Omega$  series resistor to limit the breakdown current, at a temperature up to 160°C in silicone gel, and 200°C in DBT.

### III. EXPERIMENTAL RESULTS WITH EPOXY

#### A. Epoxy substrate in DBT: repeatability tests

In order to check the self-healing character with liquid encapsulation, up to 20 consecutive measurements on a single breakdown gap were carried out at different distances and room temperature (RT = 20 °C). The rest time between each measurement was > 3 minutes.

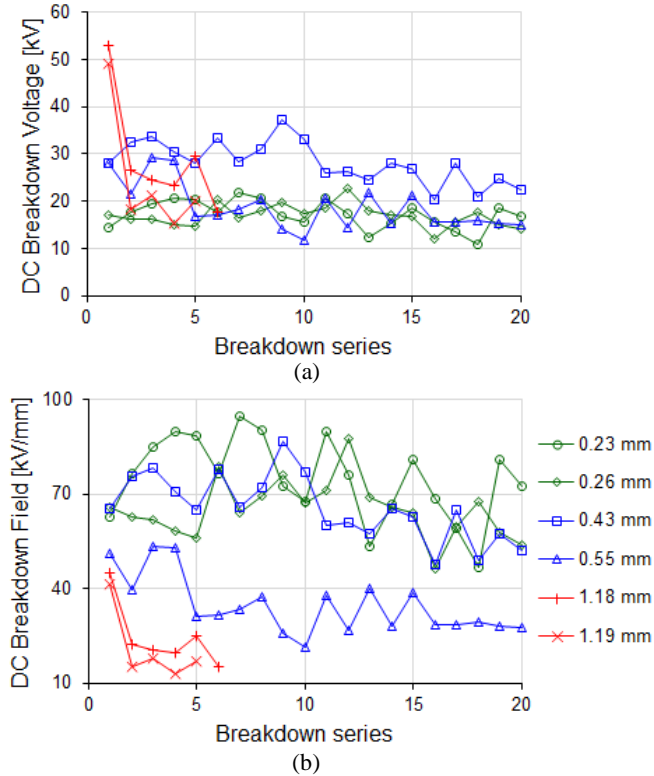


Fig. 3. DC breakdown voltage series of epoxy substrate embedded in DBT at 20°C: (a) Breakdown voltage  $U_{BD}$  (b) Corresponding average breakdown field  $E_{BD} = U_{BD}/d$

Fig. 3(a) shows typical DC breakdown test series with different breakdown gap distances. With the shortest gaps ( $d \approx 0.2$  mm) and correspondingly lowest breakdown voltage  $U_{BD}$ , measured values are fluctuating while remaining rather repeatable around some mean value. Fig. 3(b) shows the corresponding average breakdown field  $E_{BD} = U_{BD}/d$ , which reached very high values about 60 kV/mm in short gaps. In medium gaps ( $d \approx 0.5$  mm) a progressive degradation was observed, and at largest gaps ( $d \approx 1.2$  mm)  $U_{BD}$  immediately dropped after the first shot. The corresponding average breakdown field  $E_{BD}$  decreases when  $d$  is increased, both for first and subsequent breakdown. Degradation above 0.5 mm occurred when the first breakdown voltage exceeded typically 25 kV.

Fig. 4 shows images of the irreversible degradation of epoxy induced by breakdown at the largest gaps. Permanent cracks and carbonization are seen. The breakdown arc partly propagated through the liquid (right side) and epoxy (left side). In short gaps, with typical first breakdown voltages below 20 kV, no similar degradation was observed: breakdown occurred through the liquid, and the system showed a self-healing character.

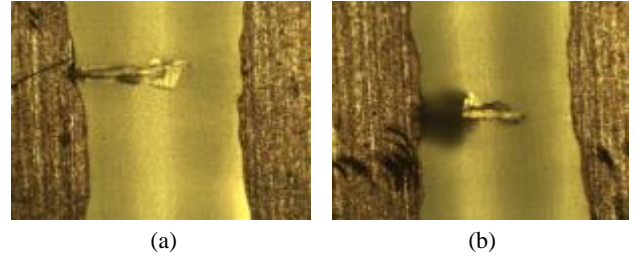


Fig. 4. Final epoxy condition after breakdown tests with DBT: (a) 1.18 mm gap (b) 1.19 mm gap

#### B. Breakdown series with Epoxy in DBT

A typical series of measurements with  $d \approx 0.37$  mm is presented in Table 1. Ten shots were carried out with each testing electrode. After tests, no trace of irreversible degradation could be seen on the substrate. The mean  $E_{BD}$  based only on first measurements is 42.1 kV/mm, scattering from 24.4 kV/mm to 54.1 kV/mm. Mean  $U_{BD}$  and  $E_{BD}$  of 1<sup>st</sup> shots is only 1% higher than mean of all series, showing that no modification of the substrate occurred.

TABLE 1  
Breakdown voltage of epoxy substrate in DBT.  $d \approx 0.36$  mm

Electrode N°	1	2	3	4	5	6	7	8
Gap [ $\mu$ m]	364	362	364	375	357	347	376	410
$U_{BD}$ [kV] 1 <sup>st</sup> shot	8.9	14.8	9.8	18.8	19.2	18.8	16.4	17.6
$U_{BD}$ [kV] mean of 10 shots	7.8	15.0	12.8	17.6	18.5	16.6	17.1	18.6

A similar series with  $d \approx 1.1$  mm is presented in Table 2. The mean  $E_{BD}$  based only on 1<sup>st</sup> measurements is 36.3 kV/mm, scattering from 24.4 kV/mm to 54.1 kV/mm. Mean  $U_{BD}$  and

$E_{BD}$  of 1<sup>st</sup> shots is  $\approx 20\%$  higher than mean of all series. Traces of epoxy degradation can be seen on all samples.

TABLE 2  
Breakdown voltage of epoxy substrate in DBT.  $d \approx 1.1$  mm

Electrode N°	1	2	3	4	5	6	7	8
Gap [ $\mu$ m]	1059	1089	1090	1097	1117	1096	1089	1067
$U_{BD}$ [kV] 1 <sup>st</sup> shot	28.1	41	33.8	43.2	40.8	40	46	43.2
$U_{BD}$ [kV] mean of 10 shots	31.3	32.8	25.4	25.8	33	34	43	35.2

Fig. 5 shows the breakdown voltage  $U_{BD}$  and average field  $E_{BD}$  at different distances.  $E_{BD}$  remains nearly constant versus distance, but the scatter is quite large at short gaps, with minimum values down to 20 kV/mm.

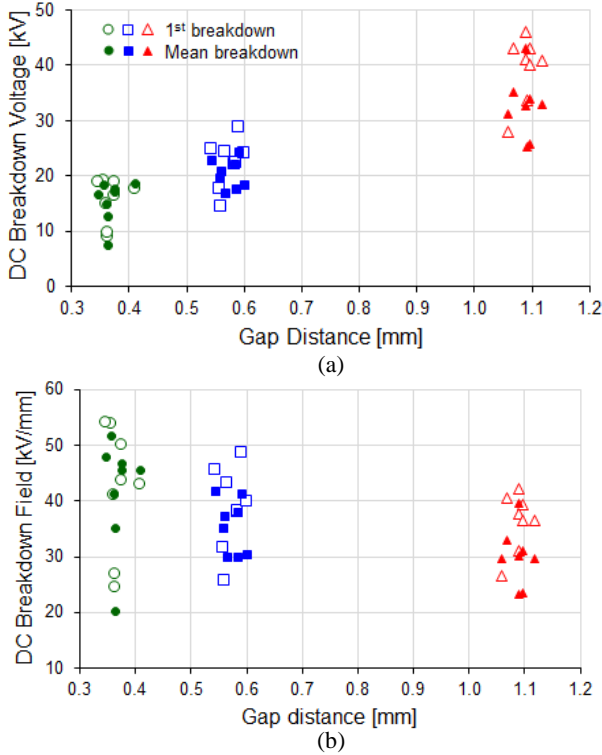


Fig.5. DC breakdown on epoxy substrates in DBT at various gap distance. RT = 20°C. (a) breakdown voltage  $U_{BD}$  (b) breakdown electric field  $E_{BD}$

### C. Breakdown of Epoxy in silicone gel

For epoxy substrates embedded in silicone gel, only one DC breakdown measurement was carried out with each testing electrode. Breakdown occurred in the gel and produced immediate irreversible degradation, evidenced by black residues and cavities forming “tunnels” in the gel between electrodes (Fig. 6). The subsequent measurements resulted in almost zero breakdown voltage, indicating that breakdown created a permanent short circuit.

Fig. 7 shows the breakdown voltage and field at various gaps in silicone gel. On average, the breakdown field shows slightly larger values than in DBT, and decreases with distance.

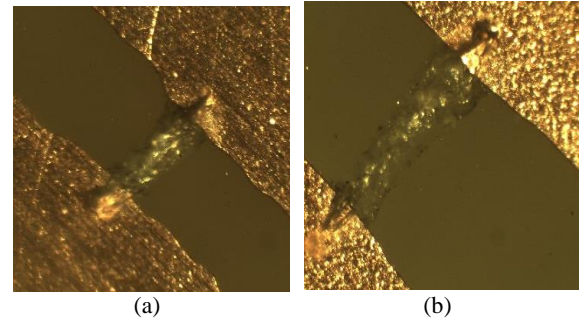


Fig. 6 Permanent degradation of silicone gel after a single breakdown: (a) 0.36 mm, (b) 0.58 mm

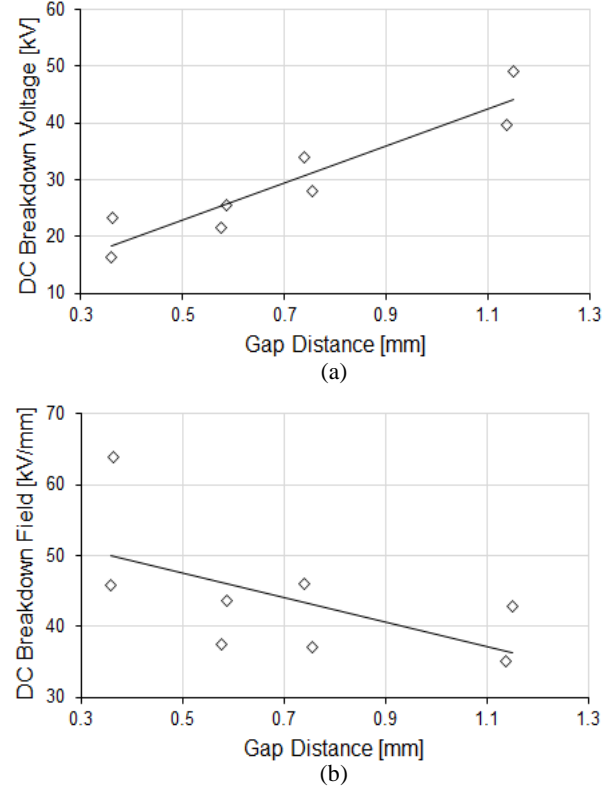


Fig.7. DC breakdown on epoxy substrates embedded in silicone gel at various gap distances. RT = 20°C. (a) breakdown voltage  $U_{BD}$  (b) breakdown field  $E_{BD}$

### D. Influence of temperature

For epoxy substrates embedded in DBT, a single sample with  $\approx 0.3$  mm gap was used at 20°C, 80°C and 160°C by applying 4 breakdown shots at each temperature. Maximum temperature was limited to 160°C due to the thermal limit of epoxy substrate. After 160°C measurements, the sample was again tested at 20°C to ensure that no substrate ageing occurred.

Fig. 8 shows that the average breakdown field (taken from all shots at corresponding temperature) slightly dropped at high temperature, but remained larger than 30 kV/mm.

Similar measurements carried out with silicone gel (Fig. 9) show a larger reduction of breakdown voltage at 160°C, with minimum values falling below 20 kV/mm.

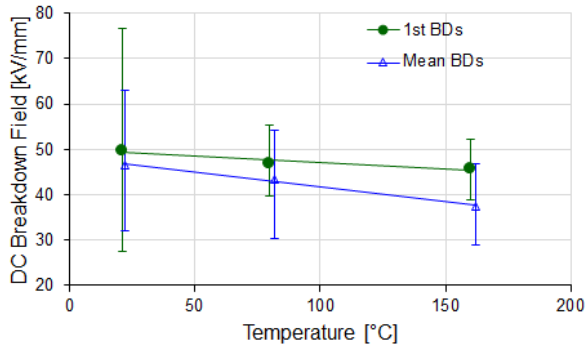


Fig. 8 1<sup>st</sup> and mean DC breakdown field on epoxy substrates embedded in DBT at various temperature.  $d \approx 0.3$  mm.

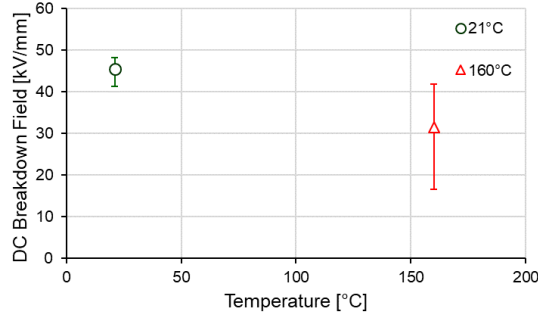


Fig. 9. DC breakdown voltage on epoxy substrates embedded in silicone gel at various temperature.  $d \approx 0.3$  mm.

#### IV. EXPERIMENTAL RESULTS WITH ALUMINA SUBSTRATES

With Alumina, irreversible degradation occurred after the first breakdown in silicone gel or DBT, whatever the distance. Following the first breakdown,  $U_{BD}$  immediately dropped to low values, and only the first value recorded can be considered. Taking into account the lower availability of ceramic samples compared to epoxy samples (which manufacturing is much easier at lower cost), less results could be obtained with Alumina.

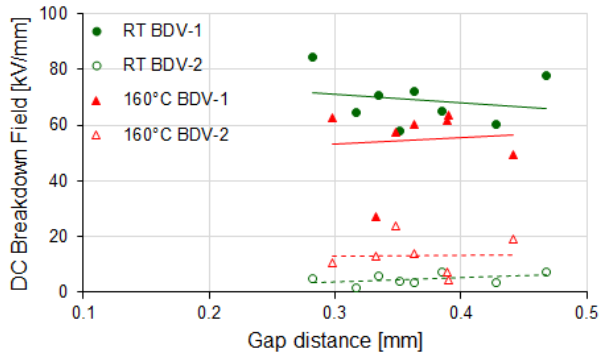


Fig. 10. DC breakdown field of alumina substrate embedded in silicone gel at RT and 160°C

Fig. 10 shows measurements obtained with silicone gel with an average gap distance  $d \approx 0.37$  mm, at two temperatures (room temperature RT = 20°C, and 160°C). The breakdown field measured at the second shot (BDV-2) is considerably reduced as compared to the first one (BDV-1). Values recorded at 160°C are slightly reduced compared to

room temperature. These values are slightly higher than those recorded with epoxy at the same distance at room temperature, and much higher at 160°C.  $E_{BD}$  at 160°C with epoxy may drop below 20 kV/mm (fig. 9), and remains larger than 50 kV/mm with alumina. In DBT (Fig. 11), the average breakdown field  $E_{BD}$  is also high at room temperature (40 to 50 kV/mm), although lower than with the gel encapsulation. At 200°C a significant decrease is observed in DBT, with a large scatter of measurements and minimum values down to 20 kV/mm. Such values are about half those recorded in gel at 160°C (Fig. 10)

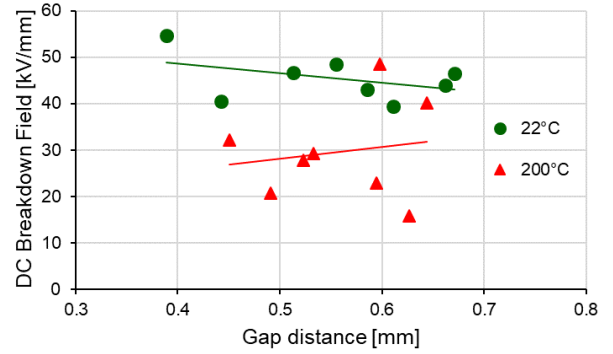


Fig. 11. DC breakdown field of alumina substrate embedded in DBT at RT and 200°C

#### V. CONCLUSION

Embedding ceramic substrates with a high temperature insulating liquid such as DBT can constitute a solution for high voltage and high temperature applications above 200°C. However, regarding surface breakdown properties, such arrangement does not benefit from the self-healing properties of liquids. The ceramic constitutes the weakest material and provides the preferred path for the breakdown arc. Irreversible degradation of the ceramic occurs after a single surface breakdown. The design rules (insulation distances between tracks) should also be adapted to account for the reduction of surface breakdown field at high temperatures.

#### ACKNOWLEDGMENTS

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