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# Application of Field Grading Material for Power Device Insulation in PCB Embedded Environment

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**Abstract-** This paper presents the development of a Field Grading Material (FGM) to be applied for the insulation of high voltage wide bandgap power device embedded in printed circuit board (PCB) technology. This composite encapsulant is made up with an epoxy resin matrix and high permittivity particles (barium titanate: BaTiO<sub>3</sub>). The permittivity gradient is obtained through a gradient of particle concentrations achieved by the way of an electrophoresis process (i.e., application of a DC electric field to drift particles around the high potential electrode). The characterizations carried out include digital microscope and scanning electron microscope (SEM) observations to determine the morphology of the FGM layers and their particle density. The breakdown voltage of a test structure made with two FGM-encapsulated copper tracks on top of a FR4 prepreg was also evaluated and has shown an insulation enhancement compared to control test chip (full FR4 or epoxy).

## I. INTRODUCTION

The current dual trend in power electronics packaging is to increase the operating voltage and reduce the size and weight of power electronics modules by embedding new wide-bandgap power devices (e.g., SiC or GaN) in PCB technology while simultaneously improving the electrical efficiency. To enable the increase in the operating voltage, from 650V up to 1200V for GaN power devices, or beyond for SiC power devices, this implies new requirements in terms of polymer-based insulating encapsulation material performances due to a significant increase in the electric field in this kind of assemblies [1]. These module assemblies are subject to very high electrical stresses, as the insulation between the different Cu conductive layers is downscaled and this can lead to electrical failure in critical areas of the packaging like around the die top edges or in between two Cu foils separated by a FR4 prepreg in the PCB structure, as shown in Fig. 1.

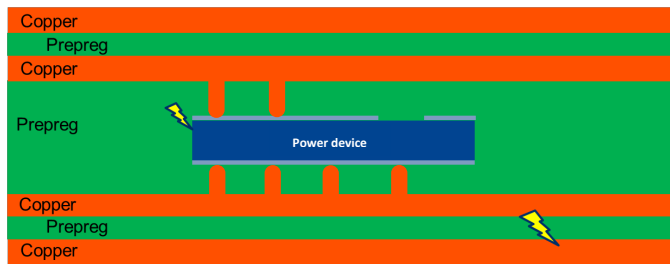


Fig. 1. Illustration of the dielectric breakdown locations in PCB embedded packages.

In the recent years, several studies have been carried out with the aim to find new solutions to reduce the electric field at the triple point (or in critical areas around components). Among them, one original way has been involving to create a permittivity gradient functionality within a composite polymer-based encapsulant [3]. This solution was enabled by adding particles with high permittivity (high-k), such as barium titanate (BaTiO<sub>3</sub>) or strontium titanate (SrTiO<sub>3</sub>) and arrange them in a graded concentration throughout the bulk by using an electrophoresis process [4-6]. The objective of this paper is to evaluate how structuring locally FGM composite materials with permittivity gradient by electrophoresis in PCB integrated technology can affect the breakdown voltage around the high electric field regions (i.e., Cu track edges) of the prepreg-Cu packaging assemblies.

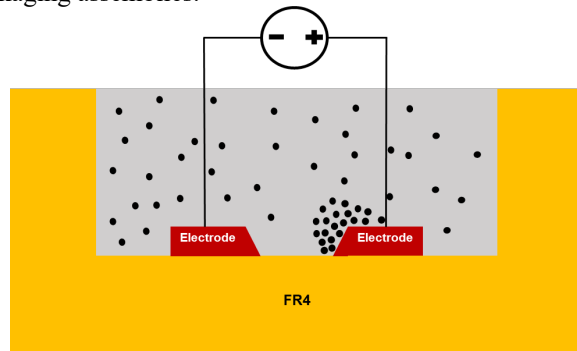


Fig. 2. Principle of the electrophoresis process under lateral sharp electrode profile configuration on PCB substrate to induce a divergent electric field.

## II. EXPERIMENTAL PART

### A. Materials

In this study, to realize the FGM composite compound, commercially sourced BaTiO<sub>3</sub> particles (660 nm in diameter) were mixed with a commercial DGEBF epoxy resin specially used for power electronic components encapsulation. The density of the BaTiO<sub>3</sub> particles is 6.08 g.cm<sup>-3</sup> and the densities for the epoxy are 1.29 g.cm<sup>-3</sup> and 1.17 g.cm<sup>-3</sup> for parts A and B, respectively. To transfer the FGM into PCB, Cu foils and FR4 prepreg sheets made up with glass-reinforced epoxy with high T<sub>g</sub> were used and assemble by the mean of a dedicated technology platform.

## B. Sample preparation

The PCB is composed by a core composed by a stack-up of four FR4 prepreg sheets laminated on top of each other. The core is manufactured by a thermo-compression cycle of three sheets of FR4 prepreg, 80  $\mu\text{m}$  thick each, together with a 35  $\mu\text{m}$ -thick copper foil. Once pressed, the copper tracks are chemically etched to the desired patterns and dimensions. This chemical etching consists of several process steps. The first step is to apply a photosensitive film to the laminate, which is patterned according to a mask. This step is followed by a revelation step to remove the film that has not been insulated, so that the copper can be etched with iron perchloride. At a final development step, the uninsulated film is removed.

Then, four sheets of prepreg with a total thickness of 320  $\mu\text{m}$  are trimmed by a milling machine to produce the same patterns. These sheets were then assembled on the fabricated final laminate. This assembly creates the cavity where the composite FGM will be deposited (see Fig. 3).

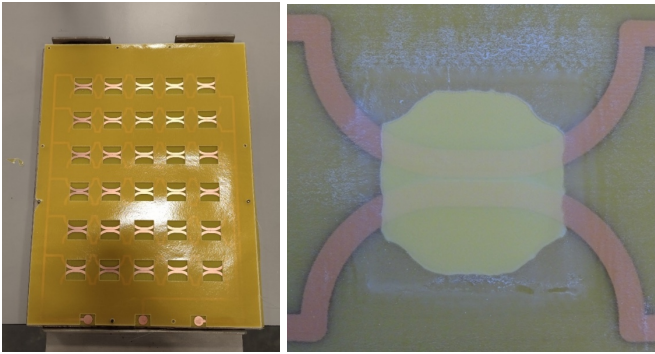


Fig. 3. Image of the sample before the lamination process to create the cavities (a) and final image of a cavity filled with composite material (b).

To study the influence of the gradient permittivity on the electrical breakdown of the assembly, a protocol is set up to create reproducible samples using the same process. First, it is important to obtain a homogeneous composite mixture of  $\text{BaTiO}_3$  and epoxy particles using a planetary mixer, without the presence of particle agglomerates. The particles are mixed with the resin under a primary vacuum for 3 min at 800 rpm and 1 min at 1800 rpm. The initial particle's concentration was selected at 2%vol. The resulting mixture was deposited into the different cavities of the previously fabricated PCBs before being pressed at room temperature. Then, an electrophoresis process under 100V DC voltage was applied between the copper tracks via electrical connections on dedicated pads. As  $\text{BaTiO}_3$  particles are sensitive to the electric field, they move into the liquid epoxy resin to build up a layer with a higher concentration of particles around the high-voltage tracks during the manufacturing process. Once the concentration gradient is achieved, the composite material is cross-linked at 100°C for 1 h to 'freeze' the particles.

## C. Electrical characterization

To electrically characterize the samples, AC breakdown voltage testing (50 Hz) has been carried out using a high voltage source up to 75  $\text{kV}_{\text{rms}}$  applied between two Cu tracks in a PCB board. The samples were placed into a container filled with a fluorinated insulating liquid to avoid any risk of flashover. The amplitude of the AC voltage was increased with a ramp between 1  $\text{kV}_{\text{rms}}/\text{s}$  and 2  $\text{kV}_{\text{rms}}/\text{s}$  to achieve breakdown between 10 seconds and 20 seconds, complying with the international ASTM D149 standard. The breakdown data was processed assuming a Weibull distribution to extract the characteristic parameters of the cumulative probability of failure, such as  $\alpha$  (the scale factor at 63.2%) and  $\beta$  (the shape factor). Furthermore, reference samples where the coating is made by pre-impregnated FR4 sheets or pure epoxy were manufactured and characterized for comparison purposes.

## III. RESULTS AND DISCUSSION

### A. Particle distribution in the FGM samples

To characterize the electrophoretically deposited FGM layer, the samples were firstly analyzed under a scanning electron microscope (SEM) coupled with an image post-analysis method developed using MATLAB®. The first step is to analyze the gray level of homogeneous samples of known concentration, in order to establish a reference (see Fig. 4).

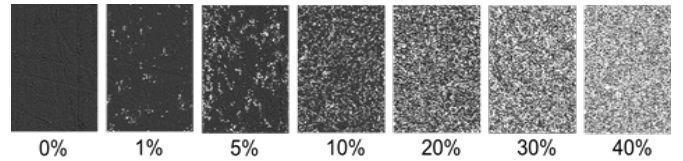


Fig. 4. SEM images of different concentrations of homogeneous materials used as references to determine the concentration in the FGM composites.

Based on the homogeneous samples, a grayscale is created to determine the concentration of the different regions of the FGM layers deposited around the HV electrode. A Gaussian blur is applied on the analyzed image in order to minimize the hot spots representing the particles. The Gaussian blur calculates the weighted average of the values of the surrounding pixels for each pixel, and then links these pixel values to a particle concentration.

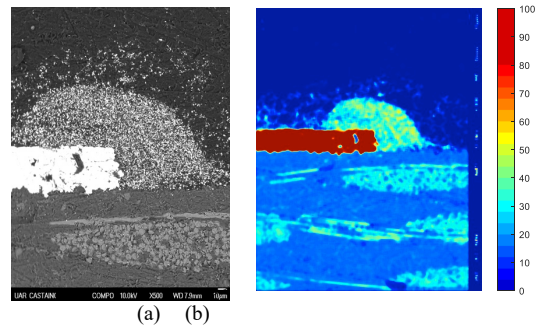


Fig. 5. SEM images of FGM composite samples containing initially 2%vol  $\text{BaTiO}_3$  particles and density of particles mapping after image processing for a 30 min (a, b) electrophoresis process.

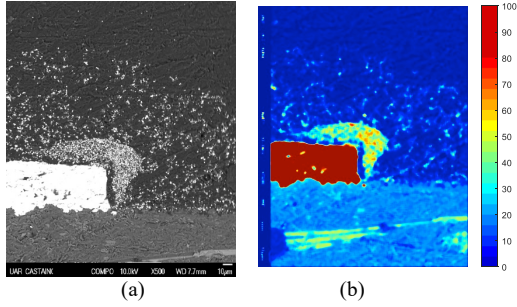


Fig. 6. SEM images of FGM composite samples containing initially 2%vol BaTiO<sub>3</sub> particles and density of particles mapping after image processing for a 60 min (a, b) electrophoresis process.

In order to compare the results, SEM images of the homogeneous samples and the samples containing the FGMs are taken at the same time on the same support, in order to have the same backscattered electron intensity, the same brightness and the same magnification. In addition, a filter is used to average the pixels in order to reduce the intensity of hot pixels. For samples with initially 2%vol particles (Fig. 5), the FGM layer for 30 min of electrophoresis has a concentration of around 35%vol to 40%vol for a thickness of 70  $\mu$ m between the electrodes. For the samples where the electrophoresis lasted for 60 min (Fig. 6), the layer exhibits a higher concentration around 40%vol to 45%vol.

### B. FEM modeling of electric field distribution

Finite element modeling (FEM) has been used to determine the electric field distribution within the fabricated samples. ANSYS Maxwell software was used in that purpose. All the parameters used in the simulations are extracted from the previous experimental results. The main parameters are the geometry of the fabricated samples and the permittivity of the various materials. Then, 2D geometries featuring two copper tracks assembled on a prepreg layer and further insulated by prepreg, epoxy or FGM are studied. In addition, an adaptive mesh is used to enhance simulation accuracy in critical areas such as the corners of the tracks or the triple points. The input parameters used for the simulations are reported in Table 1.

Table 1. Values of main permittivities used on simulations.

Material	Permittivity $\epsilon$
Prepreg FR4	4.5
Neat epoxy	5
Epoxy/BaTiO <sub>3</sub> FGM layer @40% vol.	35

The electrical boundary conditions for the simulations are a voltage of 1200V (application target) on the right track and 0V on the left track, with an inter-track distance of 280  $\mu$ m. As a first step, a simulation is performed considering that the copper tracks are fully embedded in prepreg (see Figure 6). The electric field is maximum at the corners of the copper tracks, with a maximum value of 73.9 kV/mm.

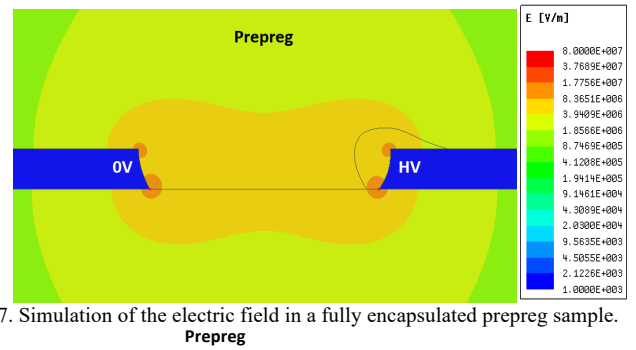


Fig. 7. Simulation of the electric field in a fully encapsulated prepreg sample.

Through the two simulations results shown in Fig. 7, it represents the same geometry with two different configurations: the first one considers the sample with an initial 2%vol of particles without electrophoresis and the second one represents the sample with electrophoresis of 60 minutes as previously obtained experimentally. The maximum electric field value is slightly reduced down to 68.2 kV/mm without electrophoresis whilst it is significantly mitigated down to 39.3 kV/mm with electrophoresis. The high field regions are reduced compared to the pre-impregnated FR4 sample. A high field region appears in the substrate (in the “non treated” laminate) and is located at the interface between the FGM layer, the homogeneous epoxy/BaTiO<sub>3</sub> composite region and the prepreg substrate laminate. The presence of this high field region will likely have an impact on the sample’s dielectric strength. Indeed, depending on the spreading of this electrical stress at the track edge, it will accelerate the internal electrical aging within the PCB board. The impact of the FGM layer is significant in reducing the electrical stresses at the corners and triple point, even though it creates other electrical stresses in the sample closer to the ground-connected track.

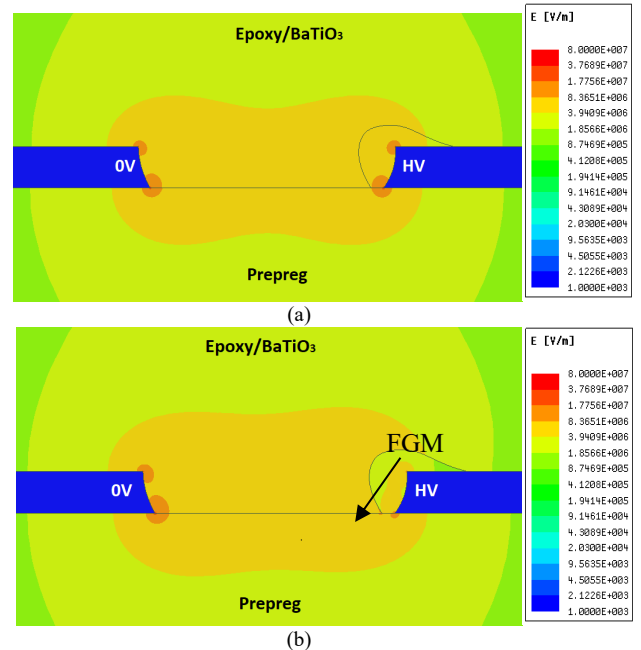


Fig. 8. Simulations of the electric field in an FGM sample with 2%vol of particles without (a) and with an electrophoresis time at 100V of 60 min (b).

### C. Breakdown voltage testing

To evaluate the benefit of the proposed solution in PCB board, an electrical breakdown voltage analysis of the FGM layer of material with permittivity gradient has been conducted (Table 2 and Fig. 8). The breakdown voltage of the neat epoxy used is higher than for the pre-impregnated materials (27.3 kV<sub>rms</sub> compared to 25.6 kV<sub>rms</sub>, respectively). After adding 2%vol of BaTiO<sub>3</sub> particles, the breakdown voltage is significantly higher with the creation of FGM layer accompanied with a higher improvement in terms of first to fail data point.

Table 2. Values of  $\alpha$  and  $\beta$  for different conditions.

Material	Voltage breakdown (kV)	$\beta$ value
Prepreg FR4	25.6	20.4
Neat epoxy	26.7	17.0
Epoxy/BaTiO <sub>3</sub> @2% vol.	32.4	9.6
Epoxy/BaTiO <sub>3</sub> @2% vol. with FGM 60 min	33.8	18.2

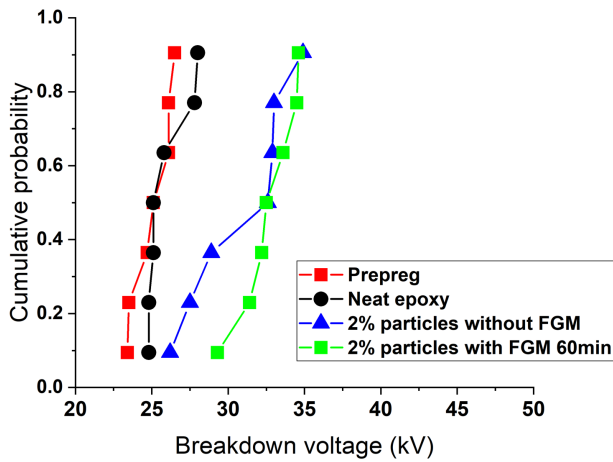


Fig. 9. Representation of Weibull's law for different composite material conditions

These experimental results confirm the FEM E-field simulations where the FGM layer spread efficiently the field reinforcement at the Cu track edge and make the PCB board more electrically robust in terms of HV insulation. Ongoing complementary results will be presented in a near future.

## IV. CONCLUSION

This study demonstrates that composite materials containing a FGM layer built by electrophoresis have a significant impact on the high voltage withstand of PCBs. These FGM materials help to mitigate the electrical stress at the corners of the Cu tracks and at the triple points. However, they can also create new stresses that may weaken the PCB and decrease its voltage withstand if the FGM layer is not well optimized. This study

highlights the significant potential of incorporating FGM layers in PCB assemblies to enhance the voltage withstand between copper tracks and paves the way for a new approach to improving their electrical reliability at high voltage for integrated power electronic applications.

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