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Original design of field grading materials for high voltage power module applications

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Abstract- One of the main goals in aeronautic industry is to increase the total electrical power in on-board systems. The first approach is to increase the voltage while reducing the volume of converters. However, this approach induces very high electrical constraints on the insulating materials used for power module. These local high electric fields can cause premature failure, by partial discharge activity and insulation breakdown. In order to efficiently reduce the electrical stresses in high voltage power modules, the design of new stress-control encapsulating composite materials with graded properties has been developed using the particles electrophoresis auto assembling technique. It is a promising solution since it does not impact the volume of the power module and has a negligible impact on the overall mass. The aim of this paper is to evaluate different strategies to achieve such field grading encapsulating composite with local high relative permittivity ($\epsilon_r > 10$), tailored around critical areas where the electric field is high. The present paper mainly proposes two processes to enable the electrodeposition of a field grading layer within a composite encapsulation to cover multiple electrodes of a direct bonded copper (DBC) substrate with a complex layout. The first approach consists in adding a new and fixed electrode on the layout of DBC substrate that will not be polarized or used during normal operation of the module. The second method consists in adding a removable top electrode above the substrate. Results show that the latter approach is potentially the best choice to enable the electrodeposition of a homogenous thickness of field graded layer on a complex DBC layout with multiple adjacent copper tracks.

I. INTRODUCTION

One of the main challenge toward the hybrid or electrical aircraft is the increase of the total electrical power in on-board systems. Among the plausible approaches to increase the power density of electrical systems, the use of higher voltages and the reduction of converter volumes seem to be very promising. However, both approaches will induce very high electrical constraints on the insulating materials used in the electrical systems, including the power module ones. In the power module packaging, these high electrical fields are strengthened by the geometry imposed by the design, the fabrication process as well as the packaging methods. One of the most critical regions is located at the junction of two insulating materials, namely the ceramic substrate and the encapsulation, with the metallic track

on top of the ceramic substrate. This region is known as the “triple point”. The sharp geometry of the electrodes combined with the different dielectric permittivities of the insulating materials induce non-homogeneous and divergent local electric fields. Any defects present in these regions could be the source of potential premature failure of the insulation materials, particularly the polymer materials used for encapsulation that are more vulnerable to PDs than the substrate ceramics [1][2]. The partial discharge activity can lead to electrical treeing and insulation breakdown and can cause short circuit in the power module [3]-[10].

The aforementioned degradation mechanism become a serious issue for power module due to two main trends:

i) The reduction of the insulation distances to achieve high integration level

ii) The steadily increase over time of semi-conductor devices voltages specially with Silicon carbide SiC-based Metal Oxide Semiconductor Field Effect Transistor (MOSFET) [11][12].

The Fig. 1 shows a schematic cross-section view of a power module where some of the triple points are highlighted in red circles.

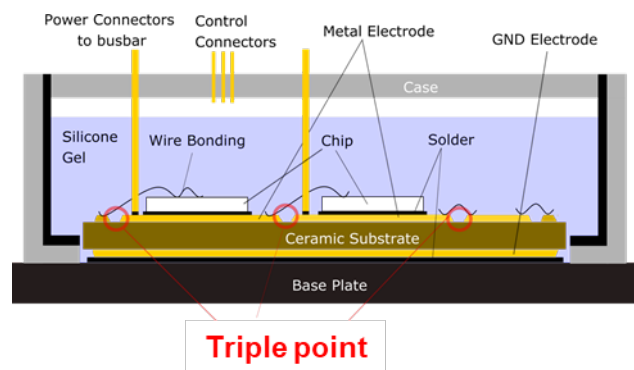


Fig. 1. Cross section of power electronic module with various triple points at the gel-ceramic-electrode contact.

Keeping the target of high-power densities, a performance improvement is needed to increase the voltage of such power module designs. This can be achieved by a radical change on the metallization geometry or by an improvement of the withstanding capabilities of encapsulation materials. In the

latter strategy, it is possible to reduce the local electrical fields at the triple point by modifying the encapsulation material electrical properties. This is known as electrical stress-control or field-grading. This can be achieved by applying different layers of materials with different intrinsic properties or by building a graded material (or Functionally Graded Material, FGM).

II. FUNCTIONALLY GRADED MATERIALS

Electrical stress-control can be achieved by locally changing the dielectric permittivity of the surrounding region around the triple point. Recently, we have proposed a method to apply such FGM materials at the metallization edges of a DBC as used in power modules [13][14]. The proposed method uses the electrophoretic phenomena to displace high permittivity particles within a liquid epoxy, closer to the high electric field regions just before solidifying the matrix.

The general approach to produce FGM between two copper tracks requires to create a DC voltage difference between the two tracks. In our process, the particles will accumulate on the high positive electrode following a specific profile, creating a high permittivity region surrounded by a lower permittivity one (polymer matrix with lower particle concentration). More details can be found in previous publications [13][14][15]. If the described method is applied onto face-to-face electrodes on top of a DBC, the obtained FGM composite covers only one of the electrodes (Fig. 2).

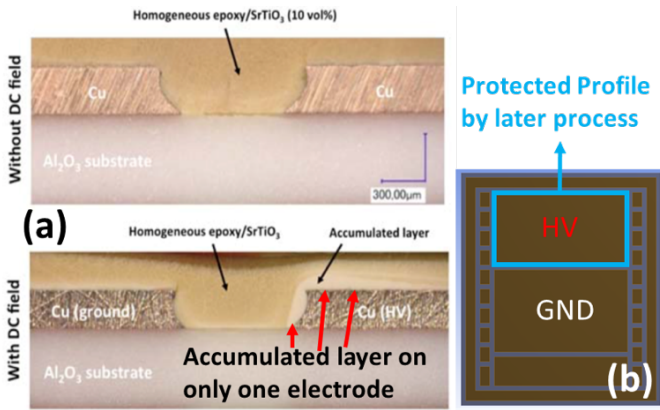


Fig. 2. a) Deposition of a high-permittivity composite (FGM) around one of a DBC copper metallization edges (triple point) by electrophoresis [13]. b) inset shows a scheme the protected region by FGM.

This configuration can increase the withstand voltage on track-to-track surface breakdown by at least 70% when compared to a neat epoxy encapsulation [13]. Nevertheless, in real power modules, several copper tracks are used in a single DBC substrate. Hence, this field-grading method, would only prove its applicability if more complex metallization geometries can be covered with such high-permittivity FGM.

The next sections will describe how we applied such FGM materials to complex DBC structures by using electrophoretic phenomena. Two methods are proposed in order to cover the main triple points in the tested DBC structures.

III. APPLICATION OF FGM TO COMPLEX DBC STRUCTURES

A. Materials and methods:

For all experiments, we use a di-glycidyl ether of bisphenol F (DGEBF) thermosetting epoxy resin system (EP 630, Polytec PT GmbH). The hardener is an amine type one with a ratio of 10:1 (resin: hardener). After curing, the epoxy has a density of 1.23 g/cm^3 . Micron size strontium titanate (SrTiO_3) particles with a density of 5.11 g/cm^3 were added at 10 vol% and homogenized in a planetary mixer. This mixture is then poured on top of the DBC structures before applying DC voltage. Once the voltage application protocol is finished, samples are put in an oven at 150°C for 10 minutes to achieve full polymerization of the epoxy resin.

Two basic strategies are explored to apply the FGM on the DBC copper tracks. The first one consists to use directly the available DBC layout in order to try to cover most of the triple points by the FGM. In the second approach, we authorize ourselves to add an external electrode on top of the DBC substrate to use only during the FGM application. This external electrode could be removed prior to the curing process of the polymer composite.

B. Additional electrodes in the DBC layout

The main challenge is to cover both two facing electrodes of a more complex substrate layout with FGM. This remains unresolved by using the method described in section II. Electrodeposition of the particles is driven by electric field and even if the latter were low, theoretically, it would be possible to cover the two facing electrodes, as long as they are polarized (positively) compared to other neighboring electrode. With this in mind, we prepared a DBC layout adding external electrodes on the top surface of the substrate as illustrated in Fig. 3.

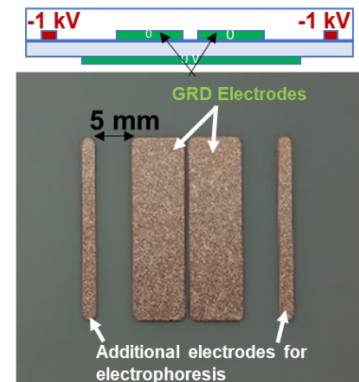


Fig. 3. a) Configuration with two additional electrodes on the top of a DBC structure. b) Only the central (GRD) electrodes are intended to be covered with the field-grading FGM.

The external electrodes are then connected to the high negative voltage ($-1 \text{ kV}_{\text{DC}}$), while the rest of the electrodes are grounded (0 V_{DC}). The FGM profile obtained after applying $-1 \text{ kV}_{\text{DC}}$ for 60 minutes is shown in Fig. 4. This technique allows depositing the high permittivity composite layer on both inner copper tracks and the inter-space between the two

grounded electrodes is well covered (Fig. 4. a). Nevertheless, the layer thickness is not homogeneous and not identical on the grounded electrode sides. The FGM layer thickness facing the external electrodes becomes very thick and the layer can detach from the electrode either prior curing or during sample preparation (Fig. 4. b).

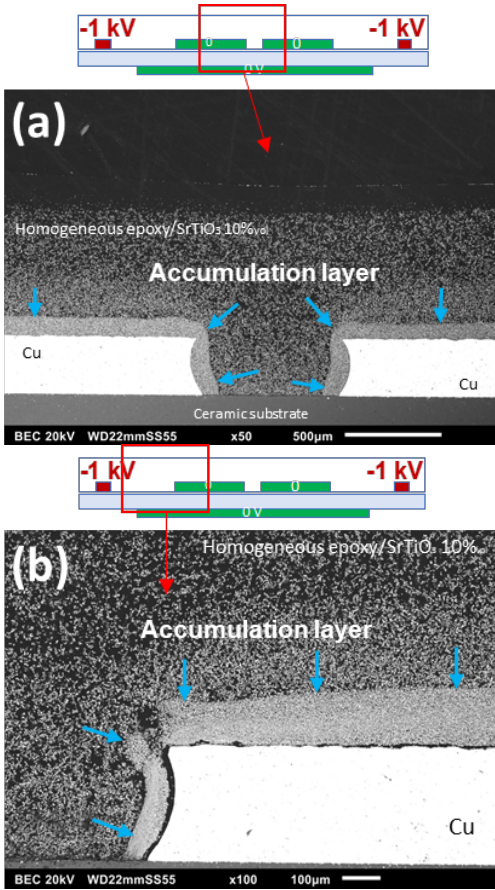


Fig. 4. An image of a cross section of the sample after curing (SEM-BE, scanning electron microscopy, backscatter electrons), showing the a) inner space between GND electrodes and b) the external side of the central electrodes, facing the high voltage additional copper electrodes.

This approach seems to be applicable to structures that are more complex as the one in Fig. 3. Nevertheless, the added external electrode would need to be very far from some required zones to be protected by the FGM. This would increase the time required for the process to several hours as well as the footprint of the power module.

C. Removable electrode on the top of the DBC layout

In the following approach, the main idea is to use a “removable electrode” on top of the DBC substrate copper tracks. The distance between the removable electrode and the substrate was fixed at 5 mm. This technique does not require any modification in the DBC layout. Once the FGM layer has been deposited, the removable electrode can be withdrawn while the epoxy resin is still in a liquid state, just prior to the curing process.

Electrophoresis process is applied for 30 minutes under 250 V_{DC} in a two-track DBC configuration. The Fig. 5. shows an image (SEM-BE) of the sample cross-section. A homogenous layer of particles (65-89 μm) was deposited overall copper tracks of the DBC substrate. This layer exhibits a conformal-like geometrical profile, covering the external and the internal track-to-track spaces.

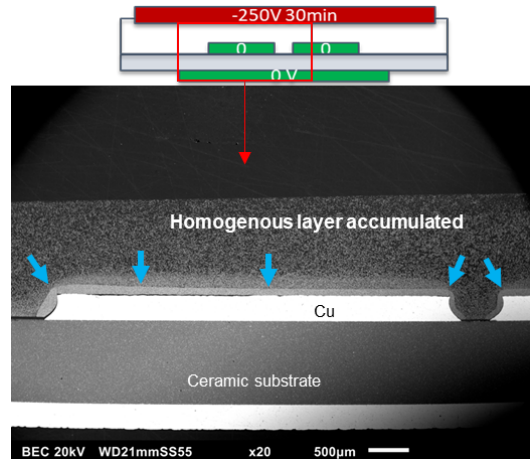


Fig. 5. Configuration with additional electrodes and cross section of the sample after curing (SEM-BE, scanning electron microscopy, backscatter electrons).

Samples of known homogeneously distributed particle concentrations ranging from 10 to 60 vol% were analyzed, by SEM-BE, side-to-side to the sample in Fig. 5. After creating a calibration curve of particle concentration vs. grayscale tone, it is possible, by image treatment, to obtain an image composition with the volume concentration in each region of the FGM layer.

The particle concentration (vol%) for the removable electrode process when applying 250 V_{DC} for 30 minutes is shown in Fig. 6. The layer closer to the removable electrode, on top of the copper tracks, shows a filler ratio higher than 40 vol%. The corresponding permittivity of the composite at 40 vol% is about $\epsilon_R=22$. For the case of the track-to-track spacing and external profile of the electrodes, the maximum particle concentration near the electrodes is about 35-40 vol% corresponding to a dielectric permittivity of $\epsilon_R=18-22$ [14].

We can identify several advantages of this processing method:

- i. This process can be very versatile because in one single step all electrodes in the DBC are covered.
- ii. Adding a removable electrode for the electrophoresis phase, does not require any special modification on DBC substrate layout.
- iii. Since lower voltages and shorter duration are needed, compared with the first process, the control of the electrodeposition and hence the layer thickness can be more easily and rapidly achieved.
- iv. The layer thickness is more homogeneous than for the process described in section III.B.

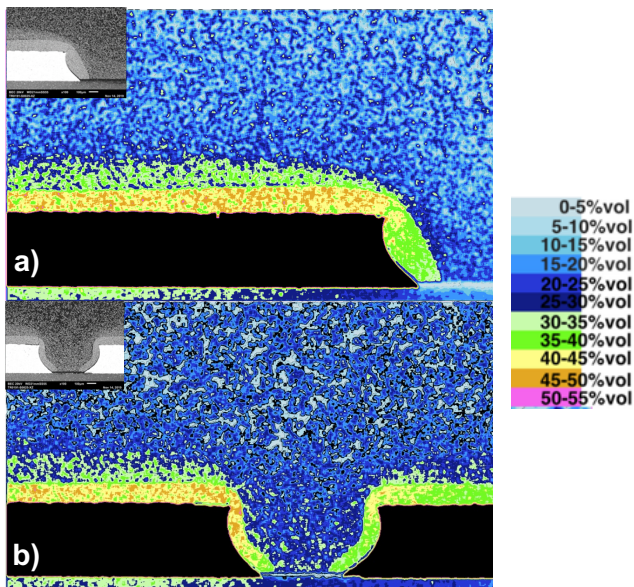


Fig. 6. Digital image composition of the cross-cut sample after the process using a removable electrode, applying 250V for 30min shows a homogenous layer with more than 40 (vol%) on external electrode profile a) and b) inter-electrode profile

IV. CONCLUSION

In this paper, two new processes to build a Functionally Graded Material with high dielectric permittivity were presented. These FGM layers were applied on complex DBC substrates, with the purpose of covering all existing electrodes. The first method consists in an additional copper track that must be added to the DBC layout. The FGM layer obtained can be applied to the targeted triple point regions of the DBC. However, layer thickness is not homogeneous among the analyzed zones, the process duration can be long and the footprint of the substrate is increased.

In the case where a removable electrode (on the top) is applied only for the electrophoresis step, all triple points in the DBC are covered with homogeneous thickness FGM layer. This work represents a necessary step towards the development of advanced insulation systems based on field grading strategies for power modules. Further works need to be carried out to verify the gain in performance obtained when applying these FGM into a functional prototype.

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