Electric Field Distribution in High Voltage Power Modules Using Finite Element Simulations

Zhao Wang¹, Yaoning Liu²

¹ R&D Center, CRRC Yongji Electric Co., Ltd., Xi’an, 710018, China
² Semiconductor Branch, CRRC Yongji Electric Co., Ltd., Xi’an, 710018, China
E-mail: wangz_crrc@163.com

Abstract. With the development of the high voltage insulated gate bipolar transistor (IGBT) power module, it leads to serious problems concerning the electric field insulation. The electric field capabilities of the silicone gels used in the power module encapsulation directly affect the module insulation. Some solutions have been developed to optimize the electric field and reliability. In this letter, the finite element simulation was used to analyze and localize the maximum electric field position; solutions were proposed to improve the module insulation. It’s demonstrated that BaTiO₃ silicone composite is a promising insulation material for high voltage power device.

1. Introduction

In recent years, power semiconductor IGBT modules are used as switching devices for power conversion in a wide variety of applications such as high speed railway, automobiles, and robotic control. Blocking voltage has reached 6.5 kV, which leads to higher demands on electrical insulation capabilities as well as partial discharge (PD) resistance, referring the insulating materials inner the module [1]. Silicone gels are used as a soft encapsulation within IGBT modules, in order to prevent electrical discharges in air from occurring, and also to protect semiconductors, substrates, and connections against humidity, dirt and vibration. Gels present unusual properties with features reminiscent of both liquids and solids. They consist of a chemically cross linked silicone polymer network, which gives the gel its elastic characteristics. Gels are able to return to their original shape after a large deformation. The study of prebreakdown processes (formation of cavities and propagating “streamers”) show that gels have properties very close to viscous liquids at ambient and high temperature up to 180°C. In such conditions, some “self healing” capability of this material subjected to PDs can be observed. Silicone gels are frequently used to ensure the electrical insulation within IGBT modules thanks to their good thermal, mechanical, and electrical properties. However, at high voltage the electric field may become locally large enough to induce PDs in the gel. Experiments and simulations show that PDs mainly occur at the sharp edges of metallization on ceramic substrates [2-5]. Two main research directions have been developed to solve this problem. One way is the development of new dielectric gels and substrate with higher capabilities [6-8]. The other is the study and the localization of the field reinforcement and the maximum values generated. Some solutions can be developed to limit the electric field and stay above the dielectric material characteristics [9-11].

There are mainly three main dielectric systems within a power electronic module. One is the ceramic substrate, typically made of aluminum nitride or aluminum oxide. The second is the silicone gel which is used as an encapsulant. This fills the entire module housing and prevents partial discharges or...
breakdowns developing within the module. The final dielectric system is formed at the interface of these two components and it is this that is often the weakest point in a power module [12-15]. The qualities of ceramics and silicone gel definitely influence the PDs in the module, however, it could be proved that the electrical field strength reaches its peak at the edge of substrate metallization. In consequence, partial discharges will most likely start at this location [16]. In this letter, we propose to use finite element simulation method, in order to optimize the electric field distribution in IGBT module using BaTiO$_3$ doped silicone gel encapsulation.

The development of prototype is very long and expensive, and sometimes not representative of industrial production. In addition, field measurements are tricky. Therefore, simulation seems an attractive way to help in the design process. Finite element methods are well known for their ability to simulate electrical fields. The aim of this paper is to validate this method in this particular application, by comparison with effective measurements.

Obviously, it’s not possible to account for several manufacturing imperfections in such simulations, such as voids, polymerization problems. The main objective is to get a global field map of the module, in order to know where the electrical field is the highest. It is assumed that local defaults in these particular locations will result in local field reinforcement, what will induce partial discharge. The same defaults in other location would not have such important effects.

2. Electric field simulations
By means of finite element simulations, it is possible to have an insight on the electric field inside the power module and to evaluate the effect of modifications of the insulation system on the electric field distribution. These simulations can be used for layout optimization and deliver quantitative results. The simulations can represent the power electronic module in its entirety and therefore usually model the substrate with its copper metallization, the base plate and the soft silicone that encapsulates the whole module. Solutions could be investigated to limit the electric maximum field value according to the simulation results, which can be of great use in reducing the product development cost.

The software used are Ansoft Maxwell 3D for the global study of substrate configuration. It is not semiconductor simulation software, but is used for general purpose electromagnetic analysis. For the finite element analysis software, the most important step is the mesh. The division structure of thin layer grid is not easy, the corners of the mesh size must be small in order to avoid convergence problems, at the same time, the divided total number of tetrahedron could not be too much. Therefore, the simulation conditions is based a certain reasoning and judging ability.

The cross-section view of high voltage IGBT module was shown in Figure 1. The model of direct bonding copper (DBC) was built as follows: metalized ceramic substrates (AlN), 630 μm in thickness and 50 mm x 50 mm in size were used to build a model. 300 μm thick copper metallization bonded on both sides spreads to 48 mm x 48 mm size. Figure 2 shows the DBC figure of structure and simulation model.

![Figure 1. Typical cross section view of IGBT module](image-url)
For the electric field simulation in IGBT module, the whole module was simplified as DBC substrate with silicone gel, which is because Maxwell 3D software could not perform professional semiconductor characteristics simulation. When the chips above DBC were regarded as just silicon with dielectric constant and impedance, the electric field intensity on the surface of chips and copper layer were almost the same. Obviously, this is a relatively ideal simulation state, which ignores some special chip structures.

3. Results and discussion

In the test, the collector of the substrate metallization is connected to high voltage while the emitter is connected to earth. Simulation works under the frequency of 50 Hz. This provides a more realistic test than is used once substrates are populated with devices as the collector emitter gap is stressed as well as the outer edge of the metallization.

Taking the 6.5 kV IGBT module as an example, when the applied voltage of 6.5 kV in the collector, the emitter grounded. Figure 3 shows the surface electric field distribution of DBC substrate by finite element analysis. It can be directly seen that the electrical field strength reaches its peak at the edge of substrate metallization. In consequence, partial discharges will most likely start at this location. This result clearly matches that of other researchers as discussed in the introduction section.

The peak at the edge of substrate metallization could lead to eventual failure of partial discharge test. Therefore, an effective method to reduce the edge electric field is using modified silicone gel or new dielectric materials to improve the reliability of power. According to recent researches, new materials with nonlinear dielectric properties (permittivity depends on the applied electric field) may be a good choice to alleviate the electric field peak in the edge of substrate metallization [17-19].
It was found that silicone gels filled with barium titanate could reduce the electric field enhancement at the edge of substrate metallization. Their functionality as a stress relieving material relies on enhanced polarization mechanisms (spontaneous domain alignment) occurring in the ferroelectric filler particles at elevated electrical field strengths. These enhanced polarization effects then give the composite dielectric an enhanced permittivity at elevated electrical field strengths. However, such spontaneous domain alignment would disappear above Curie temperature. Fortunately, the Curie temperature of barium titanate filled silicone gel is above the maximum junction temperature of IGBT devices of 150 °C. Meanwhile, the enhanced polarization effects are only realizable under ac fields, which is suitable for power module working condition.

In this paper, barium titanate was chosen as the filler material. The inclusion of barium titanate into the silicone gel does not significantly disturb the curing characteristics of the gel and nor does it significantly affect the adhesive qualities [6]. Before filled silicone gel was poured into the module, the dielectric properties of the composite were tested and analyzed. At room temperature, the dielectric constants of silicone gel and barium titanate are 2.9 and 1700, respectively; then the theoretical permittivity formula for 0-3 composite dielectric material is:

\[
\ln \varepsilon_{	ext{eff}} = f \ln \varepsilon_i + (1 - f) \ln \varepsilon_m
\]

\(f\) is the volume ratio of mixing, and \(\varepsilon_i\) is the permittivity of ceramic powder, and \(\varepsilon_m\) is the permittivity of silicone gel. As the barium titanate ceramic powders with 15% volume ratio were evenly mixed with silicone gel, a theoretical permittivity \(\varepsilon_{	ext{eff}}\) 5.42 of the composite silicone gel was obtained by calculating. The composite silicone gel system is actually tested by bias voltage, and the dielectric constant depends on the variation of the electric field strength as follows [6],

\[
\varepsilon_r(E) = 6.4 + 1.3E
\]

Accordingly, as the filled silicone gel is fit in a higher bias field, its dielectric constant also increases.

The dielectric constant of pure silicone is ~2.9, however, It leads to an increased permittivity of ~15, due to the high electric field at the edge of substrate metallization in the silicone gel mixed with barium titanate powder. In order to identify the differences between pure silicone and filled silicone, the simulation of electric field distribution under the two silicone gels were simulated using the Maxwell 3D software. Figure 4 illustrates the electrical field distribution on the substrate surface in the test configuration used in the experimental measurements of the filled gel performance. It could be clearly observed that the potential diffusion in the filled silicone is more rapid, meanwhile, the electric field strength at the edge of substrate metallization decreased obviously. It indicates that filled silicone can effectively improve the electric field distribution in the power module.
Figure 4. (a) Voltage distribution map for pure silicone (b) electric field distribution map for pure silicone (c) Voltage distribution map for filled silicone (d) electric field distribution map for filled silicone

Figure 5 shows the surface electric field strength curve across the DBC substrate. The simulation results of pure silicone and silicone composite model show that the maximum electric field strength at the edge of substrate metallization decreased from 9.96 kV/mm to 8.16 kV/mm, the electric field intensity peak is reduced by up to 18%. It directly improves the electrical insulation and partial discharge performances and the reliability of power modules. Compared with pure silicone, the filled silicone exhibits non-linear dielectric permittivity, significantly reduction on the electric field at the edge of substrate metallization. It is demonstrated to be one of the commercial trends of the IGBT power module.

Figure 6 shows a test cycle defined by the International Electro-technical Committee (IEC 1287). The electric insulation test must be carried out at AC voltages up to

\[ U_{p,\, max} = \frac{2U_m}{\sqrt{2}} + 1000 \text{ V} \]

for one minute, where \( U_m \) is the highest permissible blocking voltage of the IGBT module. For a 6.5 kV IGBT module, an endurance voltage of 10.2 kVac and a partial discharge inception voltage of at least 5.1 kVac are required. During the last 5 s of the test cycle, the partial discharge is measured at 5.1 kVac. It must be less than 10 pC. Since the thickness of the insulation substrate is no more than 1.0 mm due to heat-resistance limitations, the above requirement for voltage endurance means an average electric field of 10 kV/mm, which is an extremely severe voltage from an insulation point of view. Likewise, the above partial discharge inception voltage results in an average test electric field of 5.1 kV/mm. To suppress partial discharge under the presence of higher electric fields at the edge of electrode patterns, there is a need for advanced manufacturing-process technology and insulation.
design technology.

4. Conclusion
By using the finite element analysis method, the maximum electric field in IGBT power modules was found at the edge of substrate metallization. It also proposed the use of silicone gel filled with barium titanate to solve the problem of high local electric field peak. The filled silicone exhibits non-linear dielectric permittivity, significantly reduction on the electric field at the edge of substrate metallization. It directly improves the electrical insulation and partial discharge performances and the reliability of power modules. It’s demonstrated that BaTiO3 silicone composite is a promising insulation material for high voltage power module.

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