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Design and Analysis of a 15-kV Package for Wide Bandgap Semiconductor Devices

by Dimeji Ibitayo and C. Wesley Tipton

ARL-TR-3225 **May 2004**

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
May 2004	Final	

4. TITLE AND SUBTITLE
Design and Analysis of a 15-kV Package for Wide Bandgap Semiconductor Devices

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Dimeji Ibitayo and C. Wesley Tipton

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-SE-DP
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-3225

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The development of wide bandgap semiconductor materials such as silicon carbide (SiC) has made possible devices that exceed the voltage ratings of conventional component packaging schemes. As such, a new class of high voltage packages must be developed to realize the full potential of these technologies. We report on the electrostatic analysis and design of a 15-kV ceramic package using the ANSYS[1] Multiphysics software. To baseline our work, a standard ceramic package was characterized and modeled for high voltage operation. With this information, a new package geometry was designed, and additional SiC die requirements were identified via finite element simulations.

[1]Not an acronym.

15. SUBJECT TERMS
15 kV package, SiC, ANSYS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UL	18	Dimeji Ibitayo
Unclassified	Unlcassified	Unclassified			19b. TELEPHONE NUMBER (*Include area code*) 301-394-5514

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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1. Introduction

This analysis was performed in support of the Defense Advanced Research Projects Agency Wide Band-gap Initiative High Power Electronics program. One of the goals of this program is to demonstrate silicon carbide (SiC) technology for use in high voltage applications. The U.S. Army Research Laboratory performed a series of electrostatic analyses to determine the appropriate package geometry for 10- to 15-kV devices. In these analyses, the operating ambient was assumed to be at 25 °C. These finite element analyses were coupled with high voltage experimentation for validation purposes.

2. Modeling/Design

The primary tool used in these analyses was ANSYS[1]. ANSYS is a finite element analysis modeling software package used in a variety of engineering applications. An electrostatic field analysis was performed to determine the electric field distribution caused by applied voltage. The procedure for doing the electrostatic analysis consisted of three main phases using a combination of the ANSYS graphical user interface (GUI) and commands: (1) build the model, (2) apply loads and obtain solution, and (3) review results.

To build the model, the preferences were set for an electric analysis: This was done to ensure that the elements needed for the analysis were available. Once the electric preference was set, the ANSYS preprocessor (PREP7) was used to define the element type, the material properties, and the model geometry. These tasks are common to most analyses. The element type used was PLANE121, the ANSYS 2-D, eight-node electrostatic element. For an electrostatic analysis, the permittivity (PERX) material property must be defined. Table 1 provides the permittivities of the materials used in the simulations as well as their corresponding breakdown, electric field strengths.

Table 1. Material properties.

Material	Relative permittivity	Field strength (MV/m)
Air	1.0001	3
Alumina	9.5	16.9
*Epoxy	4.0	22
Fluorinert	1.98	15.75
SiC	10.2	300
SF_6†	1.0021	9

*Duralco 4460
†Sulfur hexafluoride

[1]Not an acronym.

Figure 1 shows a comparison of a "standard" design as modeled in ANSYS. The light blue areas represent the ambient environments that were varied among several materials including air, epoxy, Fluorinert, and SF_6. These materials were evaluated as encapsulants. The white areas are alumina, the orange areas are metals (lead, bond wires, and base plate), and the black area is the silicon carbide die. The silicon carbide die had a metallized top surface, the extent of which was varied. After the areas were created, they were meshed.

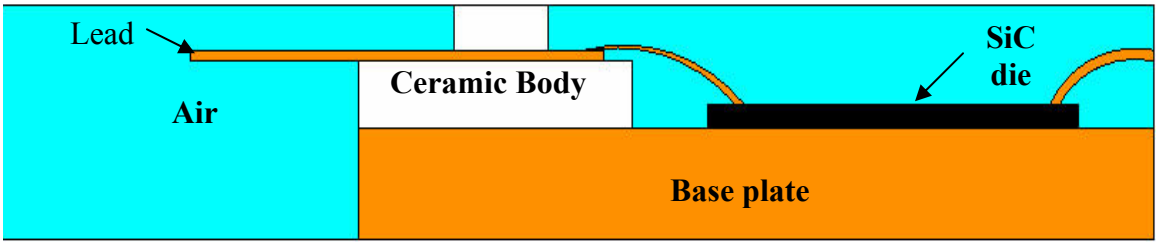

Figure 1. Standard package geometry.

When the meshing procedure was complete, the second step of the analysis was to apply loads and solve. Voltage loads were applied in these analyses. Voltage loads of 10 to 15 kV were applied to the metal lead, the wire bonds, and the metallized top surface of the die. The base plate was at zero potential with an applied voltage of 0 V. After the loads were applied, the solution was obtained.

The final step of the analysis was to review results. The ANSYS finite element analysis program generated electric field plots of the various geometrical and material configurations. Figure 2 shows the simulations results for the package shown in figure 1. In the simulations, package failure occurs if the critical field of the dielectric (air) is exceeded so that a high-field path exists between two conductors. Figure 2 shows that a high electric field (>3 MV/m for air) exists between the package lead and base plate.

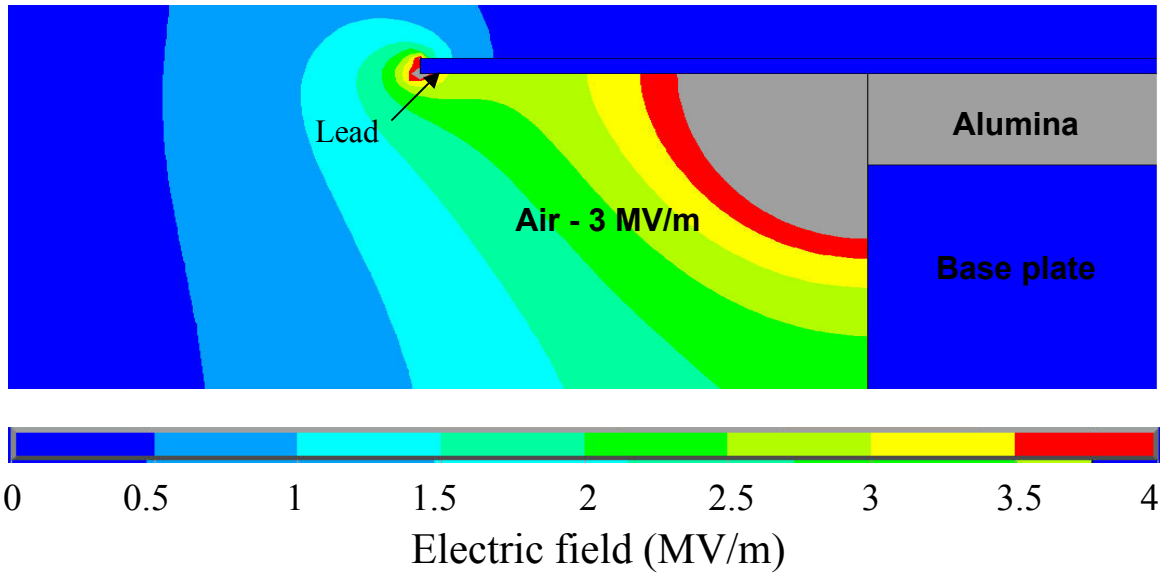

Figure 2. Electric field plot at the lead region of the standard package.

In order to eliminate the continuous breakdown region, a new package was designed with the ceramic body extended beyond the base plate. Figures 3 and 4 show the geometry of the new high-voltage package design and the electric field plot, respectively. The extended body simulation of figure 4 shows that the continuous breakdown region has been eliminated.

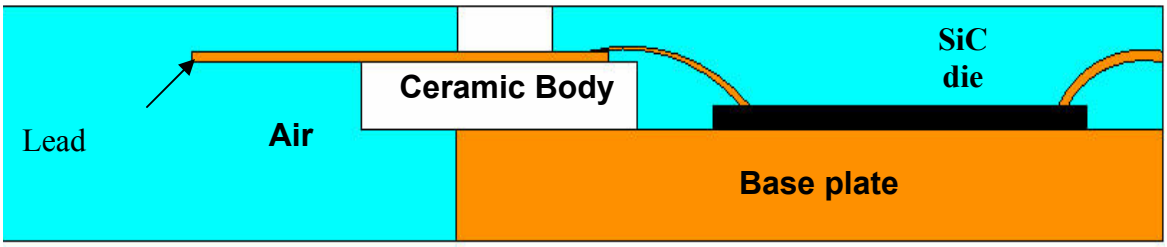

Figure 3. High-voltage package geometry.

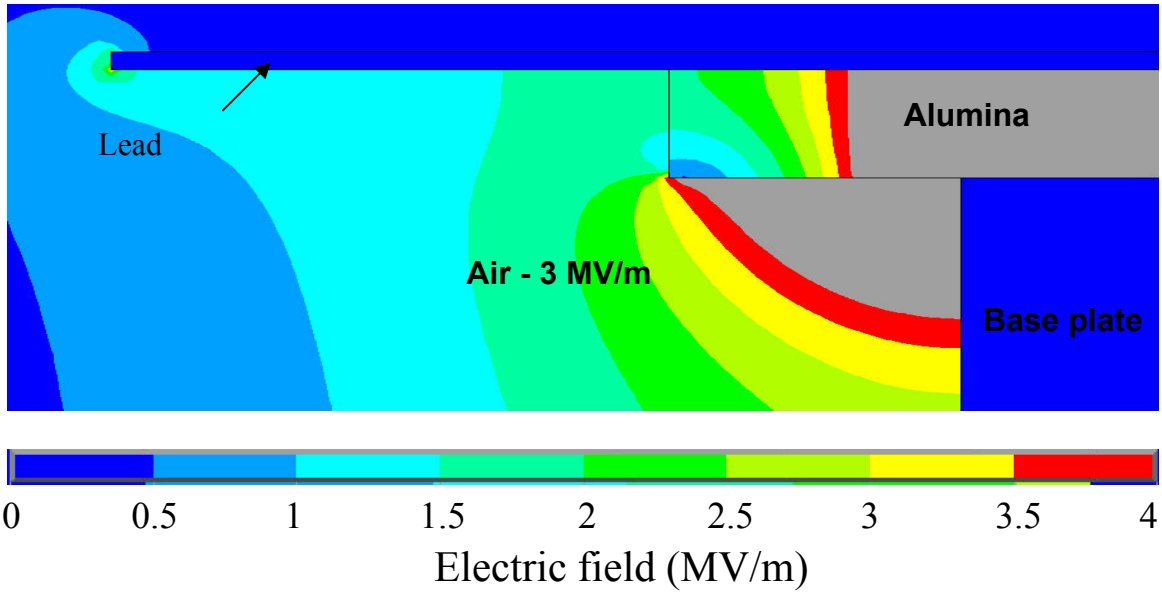

Figure 4. Electric field plot at the lead region of the high-voltage package.

Although it was possible to design the lead region of the package for high-voltage operation in air, the same was not the case for inside the package cavity. Extensive finite element analysis was conducted, but it was discovered that the high-voltage package required encapsulants with significantly higher dielectric strengths than air to successfully operate at voltages of 10 to 15 kV. The extent of potential termination from the edge of the die was also a crucial factor. Simulations were conducted with 0.2- and 0.5-mm termination spacing. Figure 5 shows the electric field near the silicon carbide die at an operating voltage of 15 kV. In this simulation, Fluorinert was used as an encapsulant and the potential was terminated 0.2 mm from the edge of the die. Figure 6 shows the electric field distribution under the same conditions as figure 5 except that the potential is terminated 0.5 mm from the die edge. With Fluorinert's electric field strength of approximately 15 MV/m, the simulation indicates that the potential on the die should be terminated greater than 0.2 mm from the edge to prevent breakdown at 15 kV.

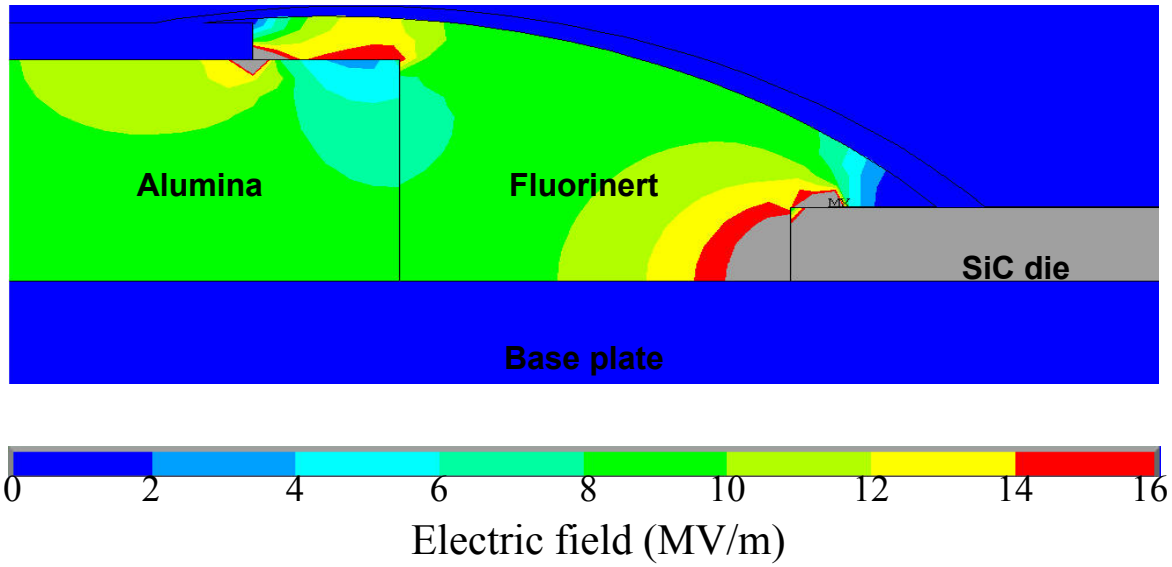

Figure 5. Electric field plots showing the performance of Fluorinert under an applied voltage of 15 kV with surface potential terminated 0.2 mm from the edge of the die.

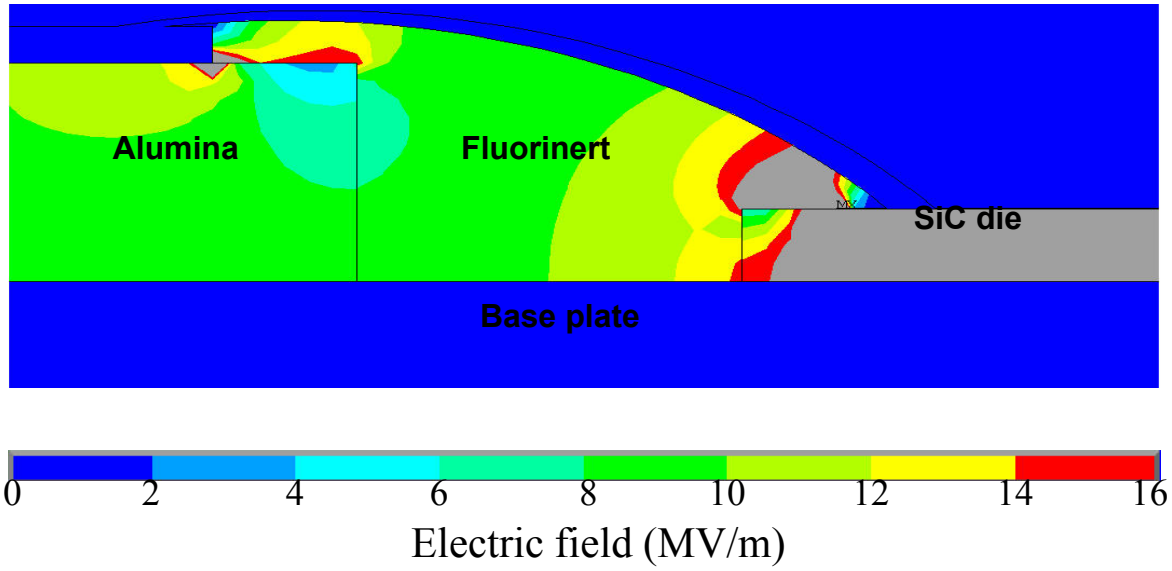

Figure 6. Electric field plot showing the performance of Fluorinert under an applied voltage of 15 kV with surface potential terminated 0.5 mm from the edge of the die.

Figure 7 shows the electric field near the silicon carbide at an applied voltage of 15 kV and with the epoxy encapsulant. The potential was terminated 0.2 mm from the edge of the die. Figure 8 shows the electric field distribution under the same conditions as figure 7 except that the potential was terminated 0.5 mm from the die edge. With an electric field strength of approximately 22 MV/m, the result indicates that the epoxy provides for a reasonable dielectric breakdown margin at a termination spacing of 0.2 mm.

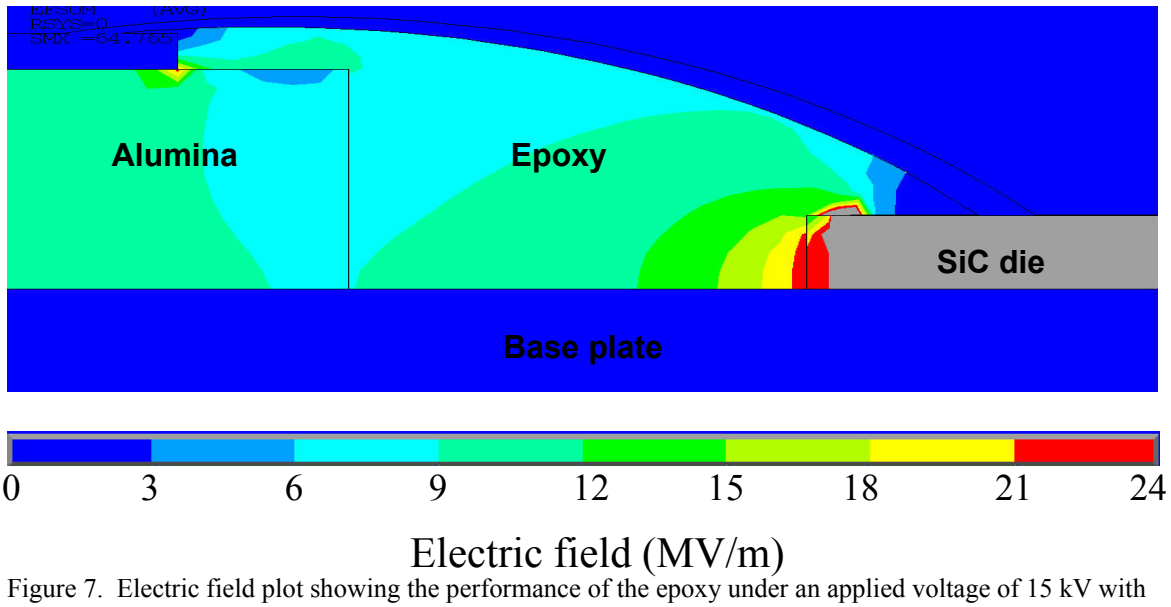

Figure 7. Electric field plot showing the performance of the epoxy under an applied voltage of 15 kV with surface potential terminated 0.2 mm away from the edge of the die.

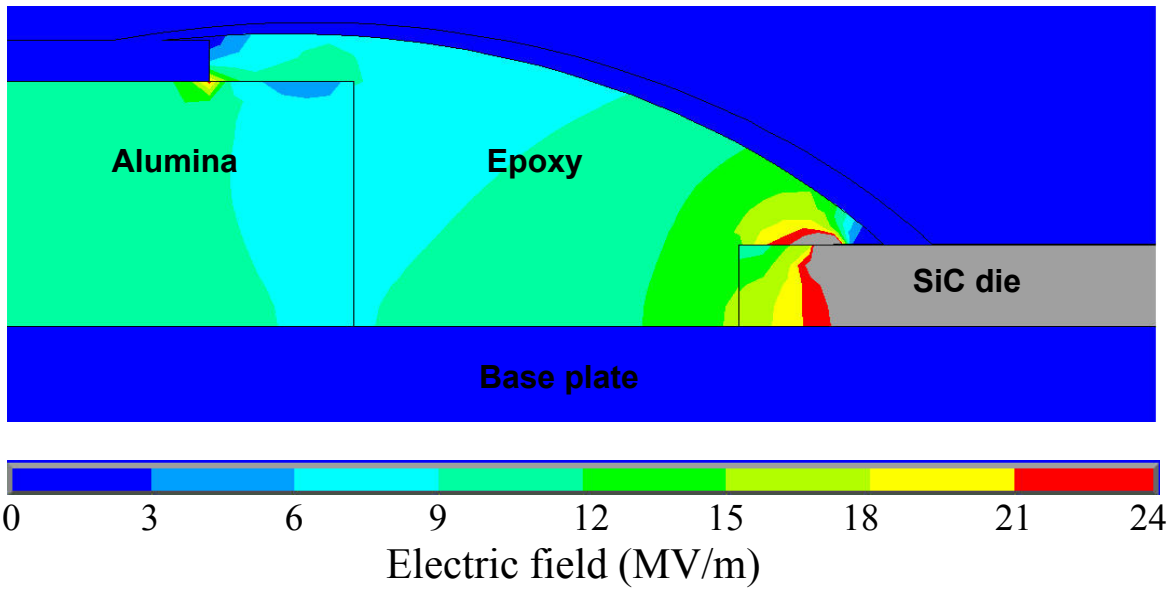

Figure 8. Electric field plot showing the performance of the epoxy under an applied voltage of 15 kV with surface potential terminated 0.5 mm away from the edge of the die.

Figures 5 through 8 show that when the surface is terminated approximately 0.2 mm from the edge of the die at 15 kV, the epoxy alone can be successfully used as the encapsulant. Fluorinert will also be effective at this voltage if the termination is 0.5 mm or farther from the edge of the die. However, it was discovered from further analyses that materials that have considerably lower dielectric strengths than Fluorinert (e.g., SF_6 at 9 MV/m) cannot be considered as encapsulants for this package at 15 kV.

The package was also simulated at 10 kV. Figure 9 shows the electric field near the silicon carbide die at an applied voltage of 10 kV. In this simulation, Fluorinert was used as an encapsulant and the potential was terminated 0.2 mm from the edge of the die. With Fluorinert's electric field strength of approximately 15 MV/m, it provides for a reasonable dielectric breakdown margin at a termination spacing of 0.2 mm.

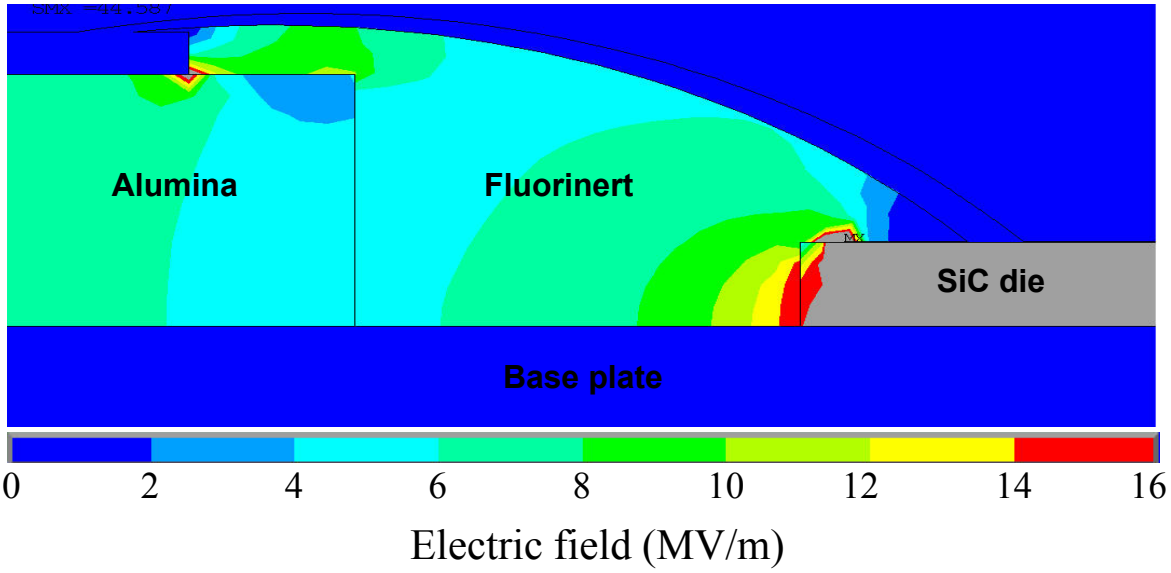

Figure 9. Electric field plot showing the performance of Fluorinert under an applied voltage of 10 kV with surface potential terminated 0.2 mm from the edge of the die.

The performance of SF_6 was also investigated at 10 kV. SF_6 is one of the most popular insulating gases with a breakdown strength of about 3 times that of air. It is important to note that this gas is fairly inert at normal temperatures, but it presents hazards at elevated temperatures because it can decompose to form fluorine, which is highly reactive. Figure 10 shows that at a termination spacing of 0.2 mm, SF_6 is not able to protect against breakdown at 10 kV. However, as seen in figure 11, it does provide a reasonable breakdown margin with a 0.5-mm termination spacing.

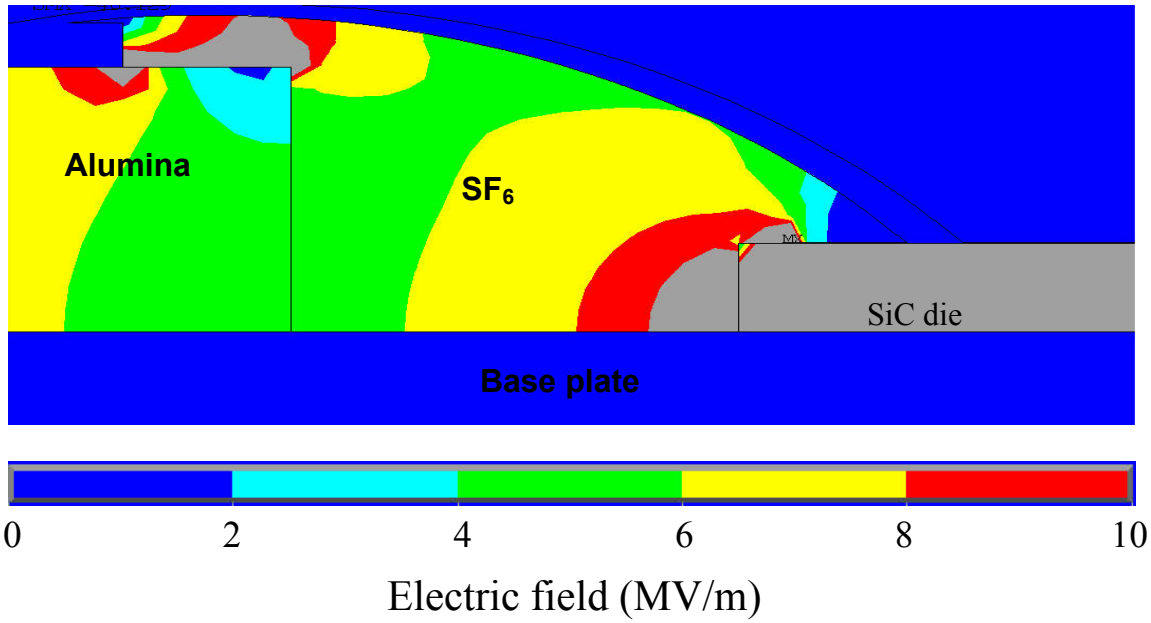

Figure 10. Electric field plot showing the performance of SF_6 under an applied voltage of 10 kV with surface potential terminated 0.2 mm away from the edge of the die.

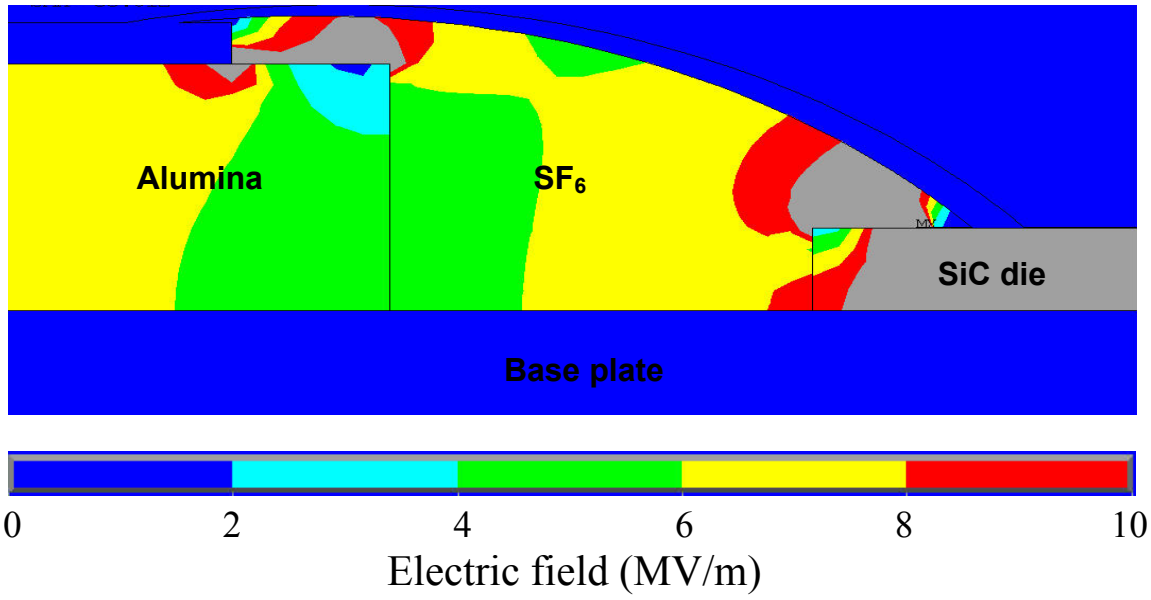

Figure 11. Electric field plot showing the performance of SF_6 under an applied voltage of 10 kV with surface potential terminated 0.5 mm away from the edge of the die.

3. Experimentation

In order to validate the electrostatic finite element analysis, several standard ceramic packages were characterized for high voltage operation. The first ceramic package from Vendor A was rated at 2 kV. When the package was characterized under a curve tracer in the operating ambient, it failed at 1.5 kV. For this same package, ANSYS results indicate that breakdown will occur at approximately 1.8 kV. Figure 12 shows the ANSYS simulation for this particular package at 1.8 kV. The lead and cavity regions are shown on the same plot.

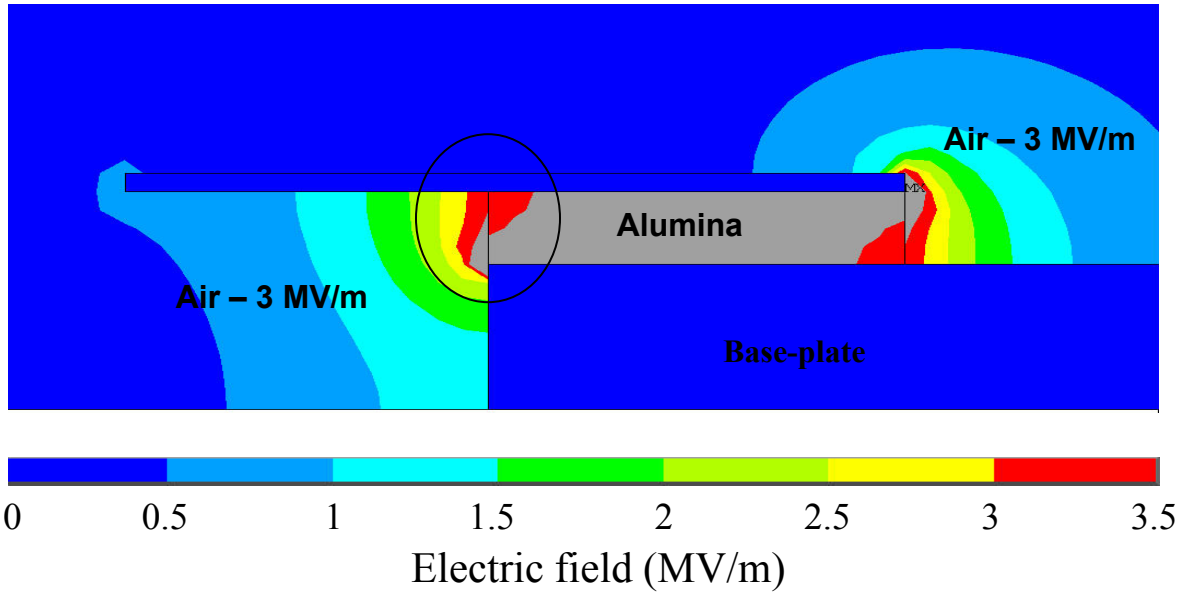

Figure 12. Electric field plot of Vendor A package showing failure at 1.8 kV.

A ceramic package from Vendor B was also characterized for high voltage operation. This package is a slightly different design from the Vendor B package, and the ceramic body is 5 times thicker. The characterization of this package was conducted with a 10-kV power supply in a nitrogen atmosphere. The package failed at 7.8 kV because of arcing between the metal lead and the metallized backside surface of the ceramic ring as shown in figure 13.

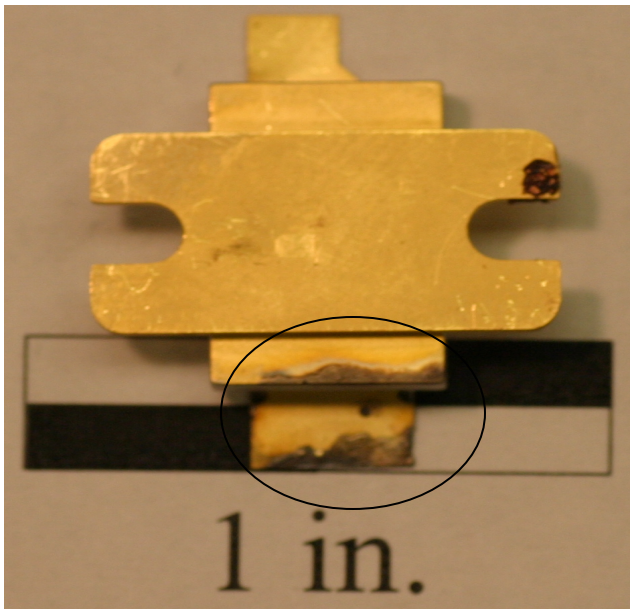

Figure 13. Photograph of Vendor B package showing where arcing occurred.

ANSYS results show that dielectric breakdown will take place at around 8 kV, based on figure 14. Analysis error for this package is calculated to be 2.56 %.

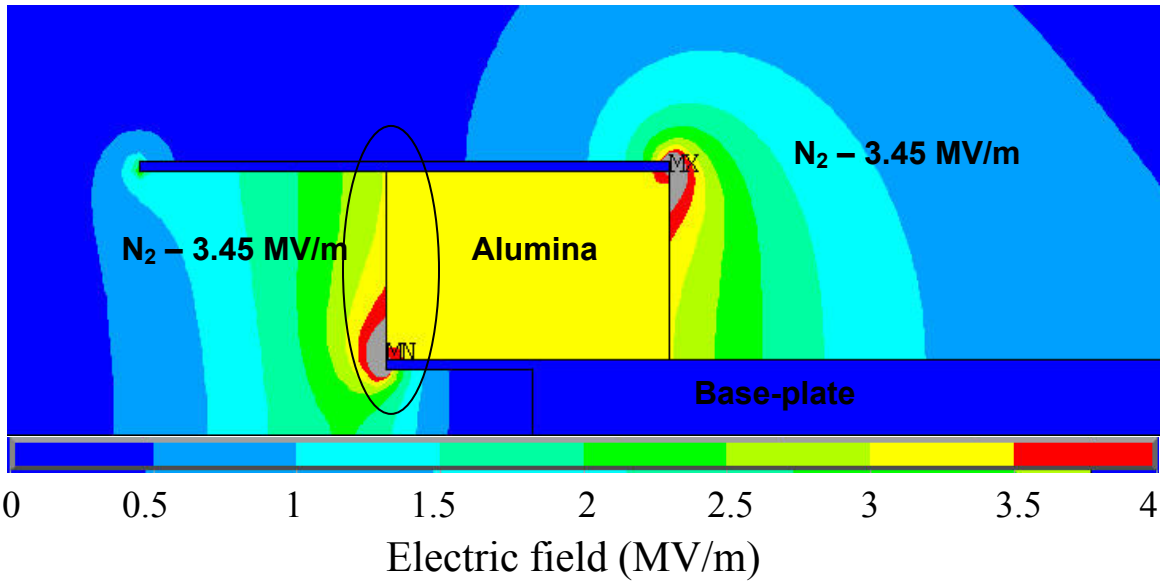

Figure 14. Electric field plot of the Vendor B package under 8-kV operation.

4. Summary

In summary, we have used finite element, electrostatic modeling to design a ceramic package for the next generation of high voltage semiconductor components. This new package is designed to operate at 15 kV, which is more than 5 times higher than conventional ceramic package designs. Our results show that this package will perform successfully without arcing at the lead region and with proper encapsulation and potential termination at the edge of the die, critical electric fields are not exceeded within the die cavity.

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