Co-Designed High Voltage Module

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ABSTRACT

Co-design and co-engineering have the potential to significantly advance the state of the art of electronics packaging. A co-designed approach moves away from a sequential design approach (electrical layout, then a mechanical module design, and finally the addition of a heat sink) and replaces it with an approach where the electrical, thermal, and mechanical domains are all simultaneously designed for during the initial design. This paper demonstrates how a co-design approach can be used to design an electronics module. This work shows the design and fabrication of a 30 kV module using two aspects of co-design: (1) multi-functional components (MFCs) and (2) quick parametric analysis. There is a need for advanced high voltage electronics packages due to the recent development of high voltage (15-30 kV) single-die silicon carbide (SiC) power devices to realize their full potential. This paper describes a 30 kV module with integrated heat sinks, double sided device cooling, and an air cooled heat sink which removes heat from four sides of the module. The module has numerous MFCs allowing a compact form factor and efficient design. In addition, the geometry and materials selections were based off a co-design tool which allows quick parametric analysis for both thermal and stress. This paper demonstrates the capabilities and benefits of moving away from a traditional design approach and implementing a co-design methodology.

KEY WORDS: co-design, high voltage, co-engineering, power module, multi-functionalization, double sided cooling

INTRODUCTION

The Army is moving to a more electric force with a number of high voltage applications. State-of-the-art 4H-SiC power semiconductor devices are currently under development for an increasing number of Army applications including microgrids, communications, survivability, and lethality systems. To support this transition, there have been a number of efforts to develop high voltage (15-30 kV) single die 4H-SiC bipolar switches and diodes [1-5]. However, packaging these high voltage devices has proven to be challenging since standard packaging methods cannot withstand the high voltages in a compact form. For example, a standard 25 mil thick aluminum nitride (AlN) direct bond copper (DBC) substrate can only withstand 10 kV. Therefore, alternative packaging methods are necessary. The current high voltage package for silicon carbide (SiC) high voltage switches are large and bulky, and two 15 kV SiC diodes must be attached in series to achieve a 30 kV module. When the diodes are assembled in a planar fashion on a substrate, they take up a substantial amount of board real estate. Therefore, this work develops modules with improved size, weight, and power density by stacking diodes.

The authors have previously fabricated two high voltage modules which stack two 15 kV power diodes. The first module, shown in Fig. 1, could withstand 30 kV but was limited in its ability to dissipate heat due to an encapsulant surrounding the devices [6]. The second module, shown in Fig. 2, had an integrated dielectric cooled heat sink but due to the dielectric fluid limitations, it could only withstand 21 kV [7].

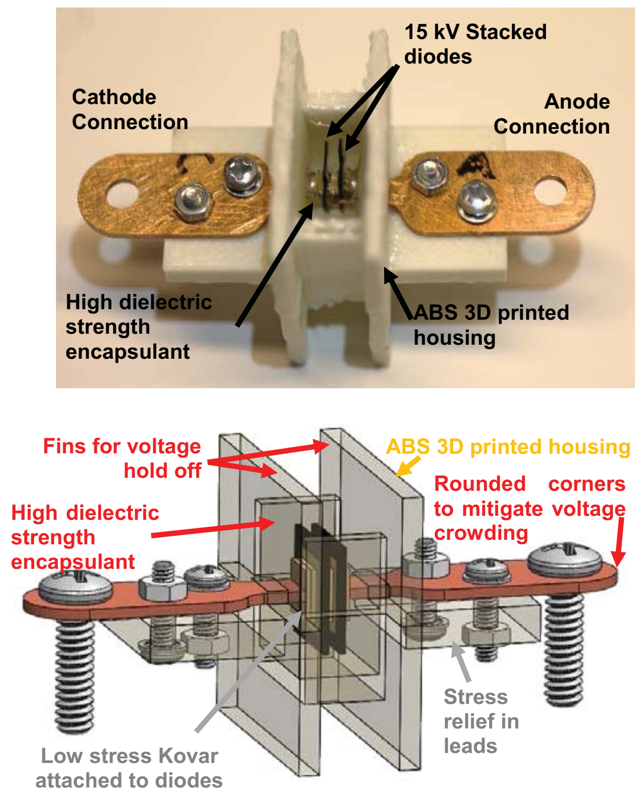


Fig. 1. Previously completed stacked diode assembly (a) fabricated module (b) Schematic with red text indicating the high voltage aspects, grey text represents the reliability advantages and gold text shows the cost benefits. [6]

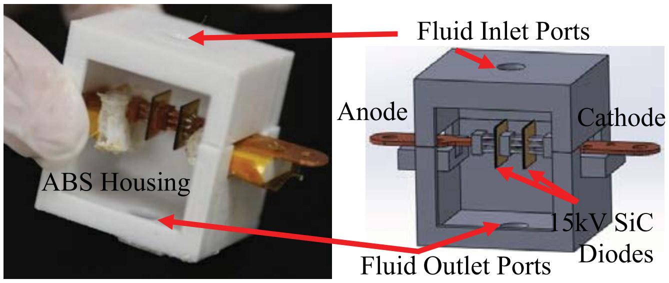


Fig. 2. Fabricated high voltage module with integrated cooling. Image shows location of fluid ports as well as the cathode and anode of the diodes, stacked in series. [7]

This paper discusses using a co-design methodology to design the next iteration of the high voltage power modules, shown in Fig. 3, to create a module that can withstand 30 kV while also allowing heat removal through internal AlN fins. The complete module is depicted in Fig. 3c and consists of two end caps (labeled) with an air (or liquid cooled) heat sink surrounding the other four sides. The interior of the module, shown in Fig. 3a and b consists of a five layer structure with alternating layers of heat sinks/electrical contacts and devices. The devices are 15 kV silicon carbide Schottky diodes. The heat sinks/electrical contacts consist of 3 mm thick machinable AlN with a copper pillar inserted into a hole in the middle of the AlN fins. The perimeter of the AlN is attached to copper heat sinks and endcaps are placed on each side. A full fabrication sequence is described further in the paper with the mostly assembled module shown in Fig. 3d.

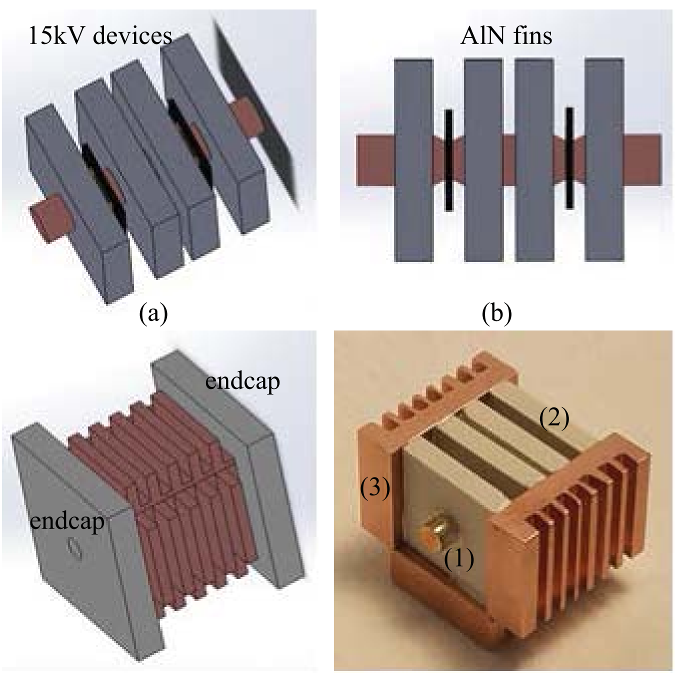


Fig. 3. Co-designed high voltage module (30kV) (a) perspective of the interior stack (b) side view of the interior stack (c) completed module with heat sink on all four sides and (d) fabricated module

This paper demonstrates the complete process flow utilizing co-design methods. It starts with multi-functional components (MFCs) in the initial design, then it uses a co-design tool to understand the design space and quickly narrow in on a design, then finally building and testing the module.

CO-DESIGN: MULTI-FUNCTIONAL COMPONENTS

The first aspect of a co-designed module is to understand the relationship between the electrical, thermal and mechanical domains. This requires the electrical engineer, mechanical/packaging engineer and the thermal engineer to work together during the initial design phase to understand the requirements and opportunities for improvement across the domains. Furthermore, in order to create a fully integrated package, multi-functional design is desired. The authors have previously shown two modules that have incorporated multi-functional components including a half bridge module [8] and a previous high voltage module [7]. In both cases the modules showed >10X reduction in size as well as better thermal performance than standard power modules. The new module, shown in Fig. 3, expands on that previous work.

Multi-functional components (MFCs) are package parts that eliminate single function elements. A single function component (SFC) is any part of a package that performs a single primary function. A heat sink, for example, is a SFC because in most modules it is attached to the backside of a heat spreader and the only function it performs is to remove heat (thermal domain). The ceramic in the direct bond copper (DBC) substrate is another example of a SFC because its primary purpose is to block the voltage (electrical domain). In addition, the ceramic actually hinders the ability to remove heat from the module and is a primary thermal resistance in the thermal stack of a power module [9]. The ceramic is also a primary failure location due to the coefficient of thermal expansion (CTE) mismatch between the copper and ceramic. Therefore, the ceramic is necessary to block the voltage in a standard planar power module; but, from a thermal and mechanical perspective, it is an impediment.

Taking this into consideration, modules should be designed to benefit all domains and this happens through cross-domain design, eliminating SFCs and replacing them with MFCs. The module in this paper has incorporated a number of multi-functional aspects, each of which is numerically labeled in Fig. 3:

- Center copper pillars act as electrical, thermal and mechanical connections simultaneously (1)
- Ceramic fins act as both thermal connections and voltage isolation (2)
- Copper exterior acts as both the housing of the module and the heat sink (3)

CO-DESIGN: PARAMETRIC MODELING

The second aspect of a co-designed module is a parametric study of potential geometries to understand their impact on the electrical, thermal and mechanical domains. This parametric analysis was performed using a tool that was co-developed by the Army Research Laboratory and the Naval Academy called ParaPower. ParaPower allows quick parametric multi-modal design analysis on most rectilinear module designs. The model uses a 3D thermal resistance network to quickly calculate the temperatures and stresses in a generic module structure [10, 11]. Previous work by the authors compared the ParaPower tool to standard finite element analysis (FEA) showing <5C temperature difference and <30% error in stress while allowing >100X faster solution times. The tool was used to determine the geometry of the module and the materials. A brief summary of how the ParaPower tool works is shown in Fig. 4. The tool allows layer-by-layer input of any rectilinear geometry. Each layer can have multiple materials and heat sources. The tool then generates nodes and creates a 3D network of thermal resistors. A nodal summation is performed around each node and the equations are placed into a matrix. The power vector [Q] is also generated and a [T] vector is solved which equates to the temperatures in each node.

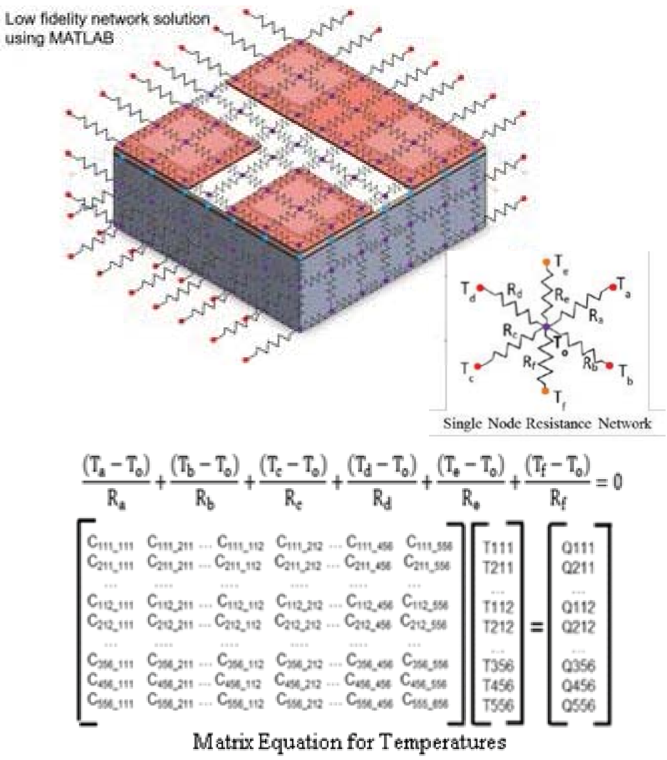


Fig. 4. 3D thermal resistance network used in the ParaPower tool. A nodal summation is performed at each node and placed into a matrix equation. The matrix equation solves the temperature at each node based on the power input.

The module presented in this paper is the first module that has been fully designed using the ParaPower tool. A complete analysis was performed on the module but in the interest in space, a small subset of the analysis is shown here.

A critical determination of how effectively the module will be able to remove heat is through the design of the ceramic fins. A parametric analysis was performed to determine the number of fins between each device, the thickness of the fins, and the overall fin dimensions.

Fig. 5 shows the results from varying the number of fins and their thickness. Based on these results 4 fins each with a thickness of 3 mm was chosen. Going beyond these sizes gives diminishing reduction in temperature and causes the overall module size to increase. This is the type of analysis that would take hours using a typical FEA code but can be done in minutes using a co-design code. Both the computer-aided design (CAD) and meshing have been eliminated which saves a significant amount of time, training, and computational resources.

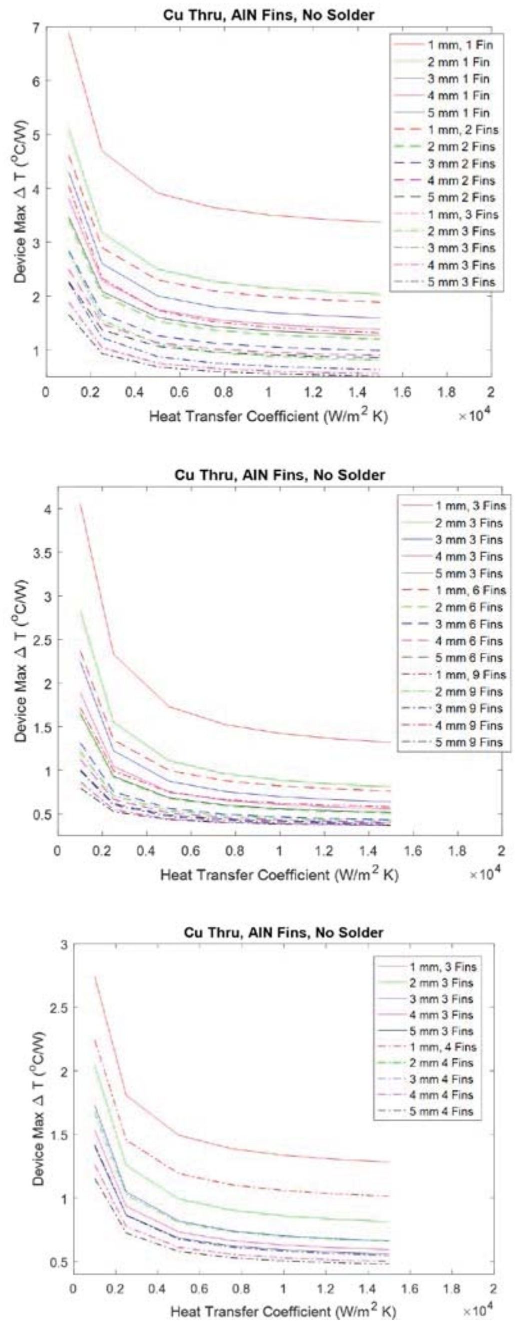


Fig. 5. ParaPower results varying the fin thickness between 1 to 5mm and the number of fins between 1 and 9 fins.

The y-axis of the plots are shown normalized for power (°C/W) such that the temperature can be approximated based on any input power to the diodes. Typically SiC devices can operate at 150-175°C but the allowable rise in temperature (device ΔT) would depend on the ambient conditions. For example, if the coolant fluid is at 100°C and the chip is rated to 150°C, then the allowable device ΔT is ~50°C. If the package performed at 1°C/W, then the package could handle 50 W of power dissipation. In addition, we neglected the effect of solder in the models since initial modeling showed it had very little impact on the final results. A constant heat transfer coefficient (h) was applied to the four exterior heat dissipating walls of the package. The h was varied between 1,000 – 15,000 W/m^2K to account for most thermal solutions that will be of interest for the application space. As can be seen in Fig. 5, heat transfer coefficients >15,000 W/m^2K will not significantly affect the die temperatures and should not be used. Also, heat transfer coefficients <1,000 W/m^2K should not be used due to their temperature sensitivity such that small changes in heat transfer will equate to large temperature fluxuations.

When choosing a fin material, moving to machinable AlN as opposed to the standard AlN allowed for both a simpler fabrication procedure and an easier purchasing option. But the machinable version has much lower thermal conductivity; 100 W/mK for the machinable AlN versus 160 W/mK for standard AlN. Therefore, a quick model was run to determine the impact of the ceramic thermal conductivity on performance. Alumina was also added to the comparison (thermal conductivity of 25 W/mK) which could be chosen if cost is of greater concern than performance. Quickly being able to perform "what-if" and trade-off studies is a prime reason to move into the co-design modeling approaches. In this case, the benefits of moving to the machinable ceramic outweighed the slight performance degradation and therefore, we chose to move forward with the machinable version.

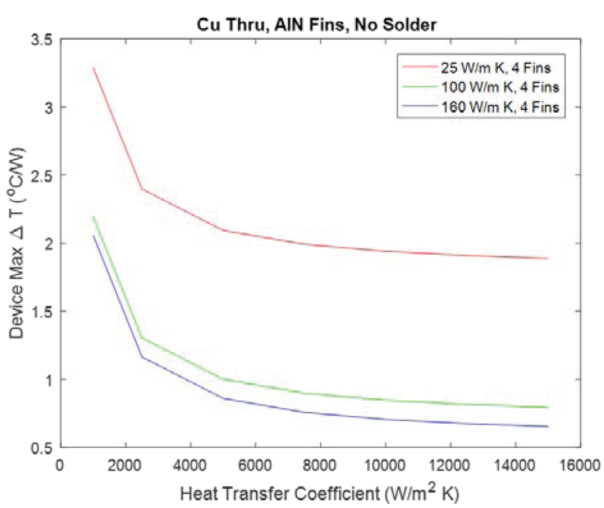


Fig. 6. ParaPower results showing the effect of fin material on the device temperature.

FABRICATION

Fabrication of the final package is detailed below:

Step 1: Fabricate and clean all parts of the module including the copper pillars, ceramic fins, and external copper fins. Each of these three components is considered an MFC. The copper pillars are both electrical contacts and are used to conduct heat away into the fins. The ceramic fins act as both voltage isolators and thermal conductors. The external copper fins act as both the module housing and the heat sink. The copper pillars and the ceramic fins are shown in Fig. 7. As can be seen in Fig. 7, the copper pillars are designed with a slight constriction on the sides in contact with the device. This was a design decision based on the parametric modeling such that the thermal performance was improved by making the copper pillars thicker however the ends had to be designed small enough to fit inside the active area of the die.

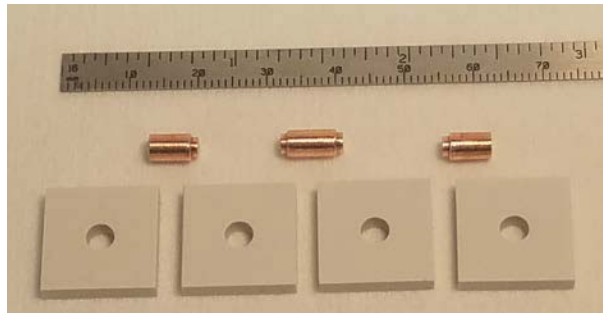
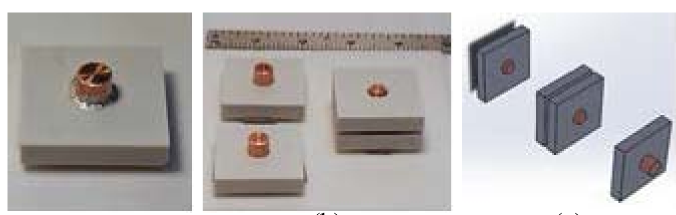


Fig. 7. Machined ceramic fins and copper pillars.

Step 2: Bond the copper pillars into the ceramic fins. A high thermal conductivity thermal epoxy, EPO-TEK EK1000, was chosen to attach the copper pillars to the ceramic fins. One millimeter spacers were placed under and between each of the ceramic fins to ensure proper vertical alignment on the copper pillars. The attachment was made by coating the interior of each ceramic hole with the epoxy, then the alumina was placed onto the spacers ensuring the spacers were not located under the hole. At that point, the copper pillar was carefully dropped into place and then wiggled to encourage good adhesion. Additional epoxy was then added at the top to ensure good thermal and mechanical contact between the two parts, shown in Fig. 8a. The epoxy was then cured in the oven according to the datasheet to maximize the thermal and electrical properties. This process was repeated for each of the three sections, shown in Fig. 8b and c.



(a) (b) (c)

Fig. 8. Images of the package segments bonding the ceramic fins to the copper pillars.

Step 3: Align the complete stack and bond. The five layer stack is created by placing each layer on top of each other in a vertical fixture, as shown in Fig. 9. As shown in Fig. 9a, one of the vertical 90 degree alignment angles is fixed and one is allowed to move to aid in proper placement of each layer. Ceramic alignment parts are placed to allow proper placement of the chips on each layer and weights are placed against the movable vertical angle to ensure it does not move during processing. The same silver epoxy is used to attach the copper pillars to each side of the die. This creates the electrical and thermal contact between the ceramic fins and copper pillars.

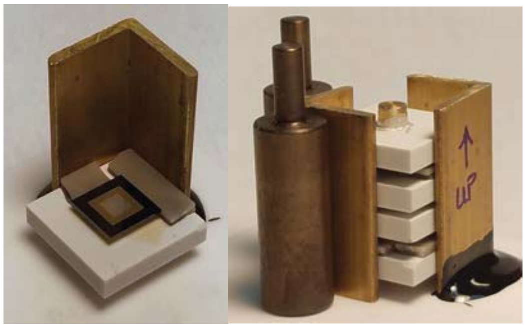


Fig. 9. Alignment fixture for attachment of the entire stacked assembly.

The complete stack is shown in Fig. 10 including the four ceramic fins and two 15 kV diodes with copper pillars creating the thermal and electrical contacts.

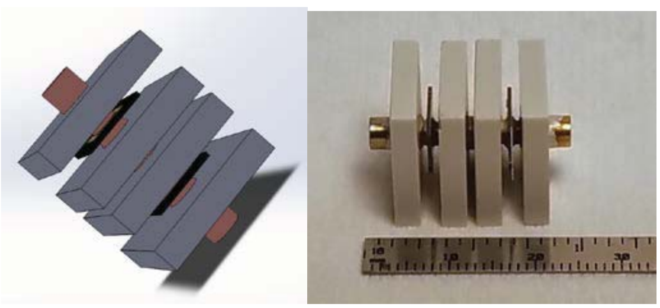


Fig. 10. Complete stack assembly with four ceramic fins and two high voltage diodes as well as the electrical contacts connecting them in a series arrangement.

Step 4: Connect exterior copper fins to AlN interior fins. In order to ensure good thermal contact but minimize the stress between the perimeter fins and the ceramic fins, a ceramic based thermal interface material (TIM) was used. It was spread evenly and generously along the perimeters of each of the ceramic fins then the copper fins were pushed into place. Two of the ceramic fins were cut even with the edge of the ceramic and the other two were cut slightly larger to give a little overlap. The edges were then sealed with a high temperature epoxy. Initially, only three sides are completed to allow access for the encapsulation.

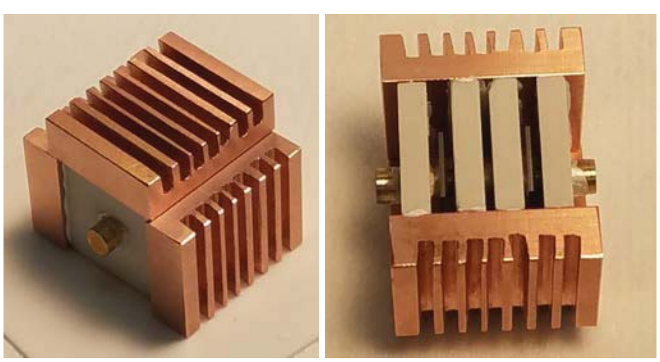


Fig. 11. Attachment of three of the perimeter copper fins leaving the forth one off to allow access for encapsulation.

Step 5: Apply endcaps. The endcaps are additively manufactured out of ABS plastic and then sealed with a high temperature epoxy such that they are no longer porous. They are then placed onto both ends of the module and sealed into place using the same epoxy as was used on the fins. High voltage wires are soldered onto the copper ends which are located slightly inside the endcaps to reduce potential stress on the copper pillars.

Step 6: Encapsulate and apply final exterior fin. The final step is to encapsulate the devices. This was done by using a thin tipped syringe to inject the encapsulant into each of the cavities as is shown in Fig. 12 such that both sides of each of the ceramic pieces are coated. Sylgard 527 was chosen due to its dielectric properties. The encapsulant was deaerated before curing to ensure no trapped air is left in the module which can be detrimental to voltage hold-off.

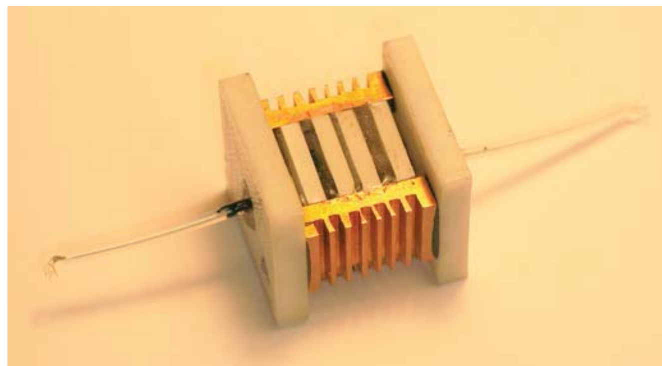


Fig. 12. Final stacked assembly showing locations of the encapsulant deposition.

After the encapsulant is cured, the final heat sink is then placed on and the edges are secured into place using a high temperature epoxy. This allows heat sinks on four of the six sides of the module thus increasing heat transfer. In addition, the heat sinks are electrically isolated such that any heat sink fluid can be used (air, water, dielectric, etc.).

EXPERIMENTAL RESULTS

After the fabrication was completed, the devices were tested for functionality and voltage breakdown. The first set of tests performed included forward-conduction tests, the results of which is shown in Fig. 13. The forward-conduction I-V characteristics were measured using a Tektronix 371B high-power curve tracer and indicate the diode assembly performs as expected and the diodes function properly.

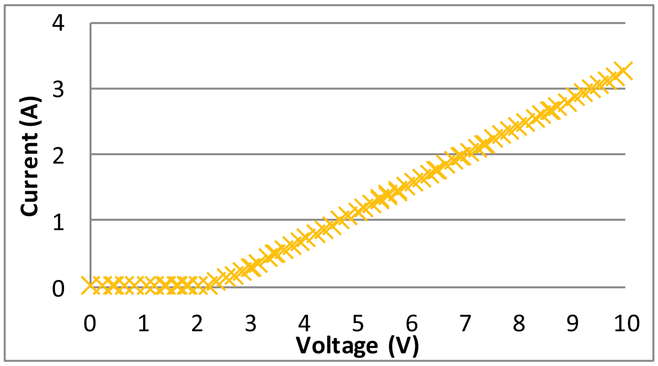


Fig. 13. Forward-conduction IV plot for the assembled module

In the pulsed dielectric breakdown test, the voltage was stepped up carefully until the semiconductor goes into avalanche breakdown, the package material breaks down, or its current reaches a predetermined compliance limit. This high potential (hi-pot) test was performed using a Spellman MP30 high voltage power supply which has a 30 kV maximum voltage rating, a 300 µA maximum current limit, and a programmable feedback control interface that connects to a LABVIEW computer. The results from the hi-pot test are shown in Fig. 14. The current starts to increase at around 27kV but this increase is still significantly less than the compliance limit of 20µA; therefore, it passes the hi-pot test and no failures are observed.

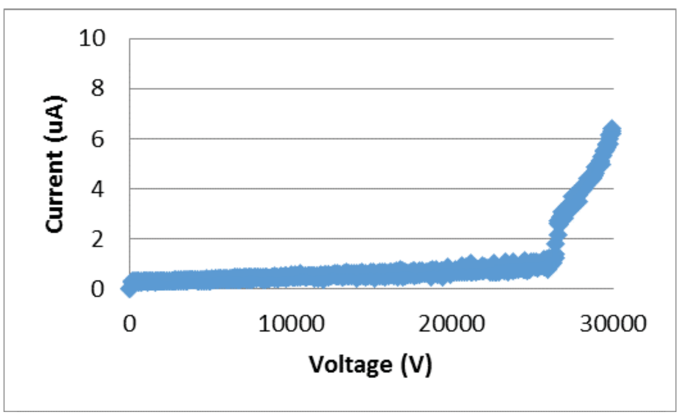


Fig. 14. Experimental hi-pot results showing voltage breakdown of >30 kV.

The results are shown in Table 1 comparing a discrete diode package, the uncooled stacked module (Fig. 1), the cooled stacked module (Fig. 2) and the co-designed module presented in this paper. The second column of Table 1 shows the results of the continuous-blocking test indicating the voltage at which each of the four modules could block for 5 minutes. The third column of Table 1 shows the voltage at which the threshold current of 20 µA was reached during a hi-pot test. This module has expanded on the work from the first two modules to create a module that can withstand 30 kV as well as effectively remove heat. As high voltage SiC devices become more prevalent, the need for advanced high voltage packaging increases. This work presents examples of high voltage modules that moves away from the traditional planar packaging which limits performance.

Table 1: Summary of results for dielectric breakdown tests

Device:	Continuous (kV)	Failure @ 20 µA (kV)	Failure mode:
Discrete Diodes	20	21.25	Package
Uncooled Stacked	25	29.25	Avalanche
Cooled Stacked	20	20.36	Package /Fluid
Co-design Module	25	30	No Failure

CONCLUSIONS

Co-design and co-engineering have the potential to significantly advance the state of the art of electronics packaging. This paper shows how such a design approach can be used and a type of module that can be achieved by implementing this approach. The module presented in this paper shows the type of compact, high performing module that can be created with the two main aspects of codesign: (1) multi-functional components (MFCs) and (2) quick parametric analysis. This paper demonstrates the capabilities and benefits of moving away from a traditional design approach and implementing a co-design methodology. This paper presents a specific module but the methodology is universal.

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