

Fabrication of High-Voltage Bridge Rectifier Modules for Pulse Power Applications

by Dimeji Ibitayo, Gail Koebke, Damian Urciuoli, and C Wesley Tipton

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Fabrication of High-Voltage Bridge Rectifier Modules for Pulse Power Applications

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14. ABSTRACT <p>The advancement of wide bandgap semiconductor materials such as silicon carbide (SiC) has made possible devices that exceed the voltage ratings of conventional packages and modules. Therefore, novel high voltage packages and modules must be developed to realize the full potential of these technologies. We report on the fabrication of multiple versions of a 15-kV bridge rectifier module for pulsed-power applications.</p>					
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1. Introduction

Fifteen-kV full-bridge rectifier modules are a custom component developed and fabricated by the US Army Research Laboratory (ARL) in order to demonstrate 15 kV, 3-A, and 6-A silicon carbide (SiC) junction barrier Schottky rectifier modules in application circuits. Such high voltage, high-speed rectifiers help reduce power conversion volume while increasing efficiency. This development also serves to identify challenges associated with high voltage semiconductor packaging. The SiC junction-barrier Schottky (JBS) diodes used in the module were state-of-the-art devices developed and fabricated by CREE Inc. under the Defense Advanced Research Projects Agency's Wide Bandgap Semiconductor Technology Initiative. The 3-A rated die are 8 mm × 8 mm in total area, and the 6-A rated die are 10 mm × 10 mm.

2. Module Implementation (Version 1)

Three versions of the 15 kV bridge rectifier modules were fabricated at ARL for various applications. A total of 12 modules have been fabricated to-date, using a multi-step packaging and assembly process. Version 1 (V1) was developed for a 40-kV converter and used the 3-A SiC JBS diodes mounted on a Curamik Electronics aluminum nitride (AlN) direct bond copper (DBC) substrate material (0.3 mm Cu/0.6 mm AlN/0.3 mm Cu). For all versions of the module, the DBC substrate was patterned to meet electrostatic simulation criteria and to accommodate devices, bond wires, and terminals on the top side. An exploded view of V1 is shown in Fig. 1, and a photograph of a completed module is shown in Fig. 2. As shown in Fig. 1, a pocket was cut into the top face of the copper heat sink. The bottom-side copper on the substrate was also removed within the pocket region but remained outside the pocket region to allow for soldering of the substrate to the heat sink. A set of holes was drilled through the heat sink to allow the resulting pocket to be partially filled with encapsulant for high voltage operation following solder bonding.

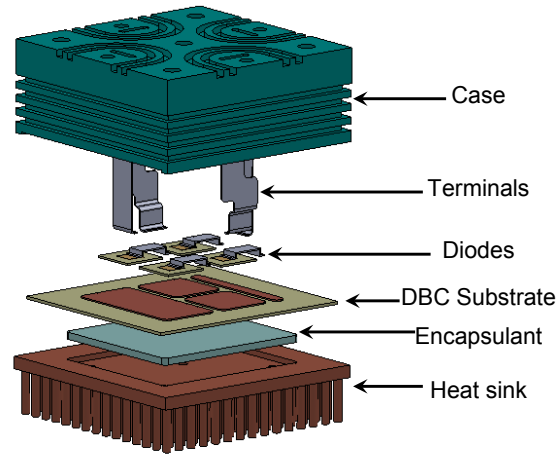


Fig. 1 Exploded view of Version 1, 15 kV full-bridge rectifier module

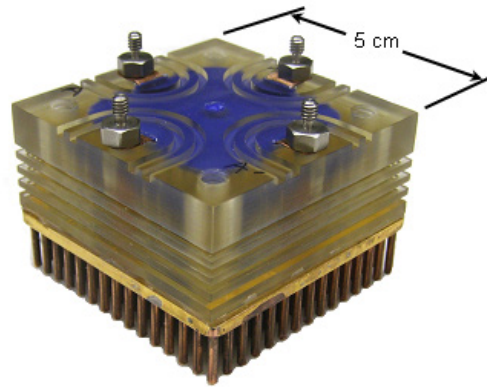


Fig. 2 Completed Version 1, 15 kV full-bridge rectifier module

Solder bonding at the diode-to-substrate and substrate-to-heat sink interfaces was performed using a single-step process in a vacuum reflow oven to achieve low voiding within the solder. A Sn-Ag-Cu alloy solder was used on both interfaces, and the process temperature profile was tailored to reduce mechanical stress in the final assembly. However, cracks were formed as a result of thermomechanical stresses within the DBC substrate after the soldering process. After the die, substrate, and heat sink were bonded, the die interconnects were made using 0.25 mm aluminum bond wires. Finally, 4 copper terminals were attached to the substrate using a Sn-Pb alloy solder.

The plastic case was constructed from Ultem PEI having a maximum working temperature of 168 °C. In addition to its high temperature rating, this material has a voltage breakdown rating in excess of 20 MV/m and low moisture absorption. The height of the case and terminal locations was specified to provide sufficient separation of all conductors, including the heat sink, to prevent voltage breakdown in air. Grooves were machined into the outside surfaces of the case to mitigate voltage creep. The case was attached to the substrate assembly using room-temperature

vulcanizing (RTV) silicone. Because the module was designed to have the heat sink at a floating potential, the case has 4 threaded holes for module mounting. Similar to the heat sink, a hole was placed in the top of the case to allow approximately three-quarters of the die cavity to be filled with an encapsulant, Dow Corning Sylgard® 527. This product was chosen because encapsulants with high curing temperatures entrapped many voids. The remainder of the cavity was filled with Cotronics Duralco® 4537N epoxy to bind the terminals. The encapsulant was cured under a partial vacuum. Both the encapsulant and epoxy were cured at 27 °C.

3. Module Implementation (Version 2)

The Version 2 module (V2) was developed for the same application as V1 in order to address thermomechanical concerns that arose during the assembly of V1. In the case of V2, a CarbAl™ baseplate was used in place of the copper pin fin heat sink. CarbAl™ is a carbon-based nanocomposite comprised of a 20% dispersed aluminum in 80% carbon. The coefficient of thermal expansion (CTE) of CarbAl™, as shown in Table 1, is significantly lower than that of copper and is a closer match to the AlN DBC substrate and silicon carbide. The cracking of the DBC substrate that occurred in the construction of V1 was not experienced with the change from copper to CarbAl™. CarbAl™ also possesses a high thermal conductivity.

Table 1 Thermal properties of materials

Material	Thermal conductivity (W/m·K)	Coefficient of thermal expansion (ppm/°C)
SiC	120	3.5–5.0
AlN	185	4.5
Copper	385	16.6
CarbAl-N™	350–400*	6.60–7.44

* k_z , compared to $k_{x,y} = 150\text{--}200$ W/m·K

A photograph of the completed V2 module is shown in Fig. 3. The DBC substrate was soldered directly to an electroless nickel immersion gold (ENIG) plated CarbAl™ baseplate. Cotronics Duralco® 4525N epoxy was used for binding the terminals due to its lower moisture absorption and higher strength. All of the other materials and processing were identical to what was used in V1.

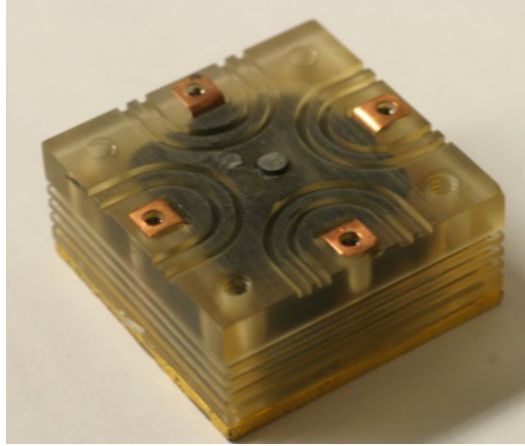


Fig. 3 Completed Version 2, 15 kV full-bridge rectifier module with CarbAI™ baseplate

4. Module Implementation (Version 3)

ARL provided the design and Stellar Industries Corporation was responsible for photo-patterning, copper etching, and electroless nickel immersion gold (ENIG) plating on a Curamik Electronics DBC substrate material (0.3 mm Cu/1.0 mm AlN/0.3 mm Cu). The availability of the thicker ceramic layer allowed for 15 kV operation without the requirement of the dielectric pocket used in the previous 2 versions. Additionally, aluminum was used as the base-plate material, and Gap Pad® VO Ultra Soft was used for heat transfer between the substrate and base-plate in order to dampen vibration. Size 4-40 screws were also used in order to secure the case to the base-plate. Noryl PPO plastic was used instead of Ultem as the case material due to its opacity and reduced cost. Although both plastics have suitable electrical, mechanical, and thermal properties, they are susceptible to stress-cracking in the presence of some common organic compounds such as acetone, gasoline, and kerosene. Both Ultem and Noryl also exhibited stress-cracking when exposed to Loctite 242 Threadlocker®, which was, therefore, eliminated from the module mounting process. As before, the substrate was designed to meet electrostatic simulation criteria and to accommodate devices, bond wires, and wire terminals on the top side. The use of wire terminals extending from the package simplified module fabrication, while effectively eliminating voltage creep at the module case. To reduce strain normal to the substrate, an inner lid was sealed into the case forming an air pocket above the encapsulant to accommodate its thermal expansion. Cotronics Duralco® 4525N epoxy was used to fill the remainder of the open cavity and to bind the wire terminals. An exploded view of the version 3 module is depicted in Fig. 4.

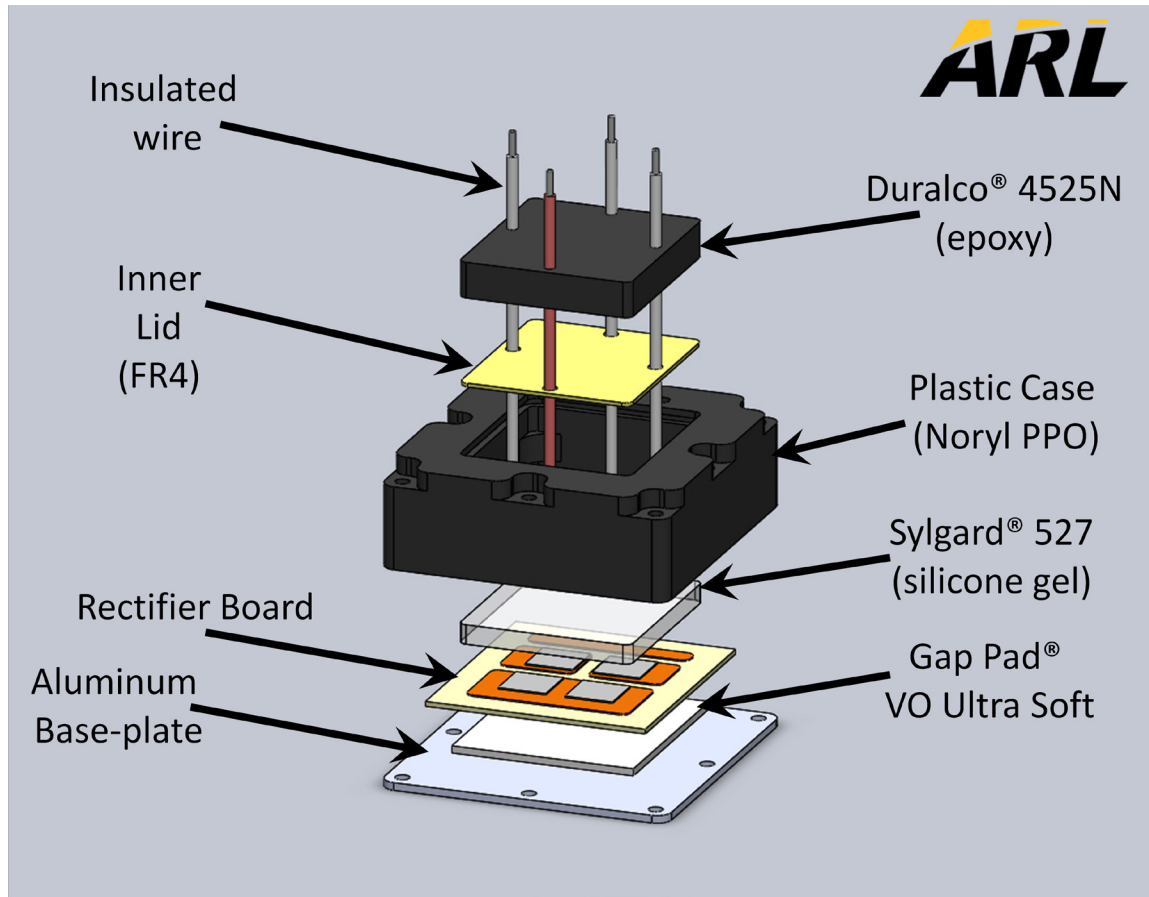


Fig. 4 Exploded view of Version 3, 15 kV full-bridge rectifier module with aluminum baseplate

The following is a step-by-step procedure for the assembly of the V3 module:

Step 1: Moisture bake out of module components

- Place H.V. rectifier board, inner lid, case, and insulated wire in oven
- Subject components to a 24-h bake-out at 100 °C to remove moisture

Step 2: Cutting and cleaning diodes and gold-tin (80Au20Sn) solder preforms

- Cut AuSn preforms (0.002 in. thick) for each diode to ~90% of the device size using preform cutter as in Fig. 5
- Soak preforms in acetone and ultrasonic clean for 1 min
- Rinse each preform with isopropyl alcohol (IPA) and blow dry with nitrogen
- Clean diodes with IPA, ensuring cleanliness of backsides
- Rinse with IPA and blow dry with nitrogen



Fig. 5 Solder preform cutter designed and 3D printed at ARL

Step 3: Bonding of SiC JBS diodes to H.V. rectifier board in vacuum-pressure furnace

- Use the graphite tooling to assemble all the module components as in Fig. 6
- Place the DBC substrate on the tooling base plate
- Place the thin graphite template on top of the DBC
- Place the AuSn preforms on the DBC in the windows of the template
- Place the JBS diodes on top of the preforms
- Place the top portion of the tooling over the tooling base plate
- Carefully lower the weights through the holes in the tooling
- Place the tooling assembly in the vacuum furnace and run AuSn reflow profile ($T_{\text{peak}} = 310\text{ }^{\circ}\text{C}$; $t_{\text{AL}} = 1:10\text{ sec}$)

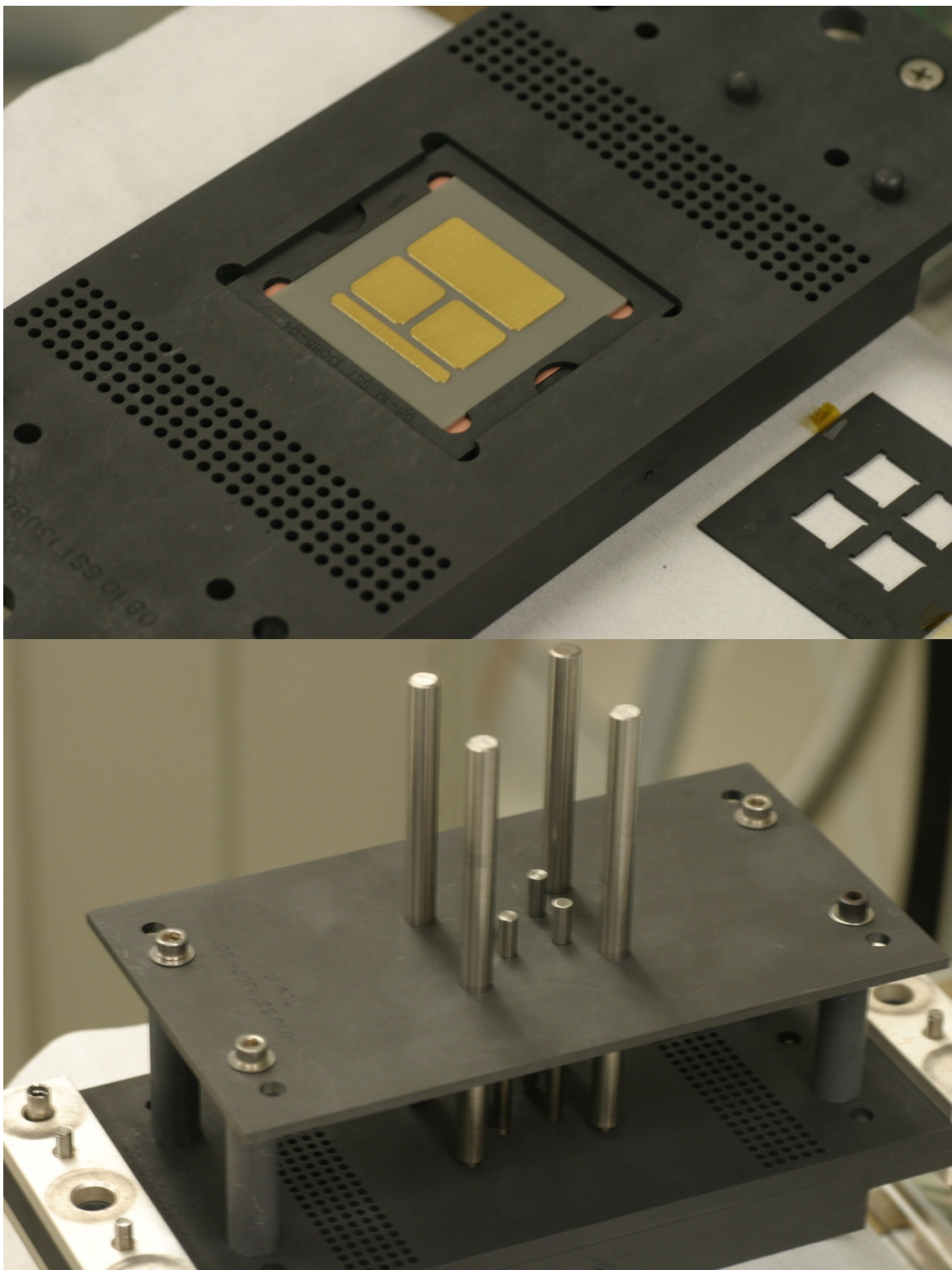


Fig. 6 Tooling used to assemble module components, including inserts, weight assembly, and weights

Step 4: Soldering insulated wires onto the DBC substrate using tin-lead (63Sn37Pb) RMA solder

- Use H.V. rectifier inner lid as a locator guide to solder wire leads onto DBC pads
- Solder a 12 in. long red wire to DC positive pad, and 12 in. white wire to the other 3 locations as shown in Fig. 7
- Thoroughly clean all flux residue from the wire, DBC, and devices
- Ensure that wire insulation will extend below the top surface of the encapsulant when added

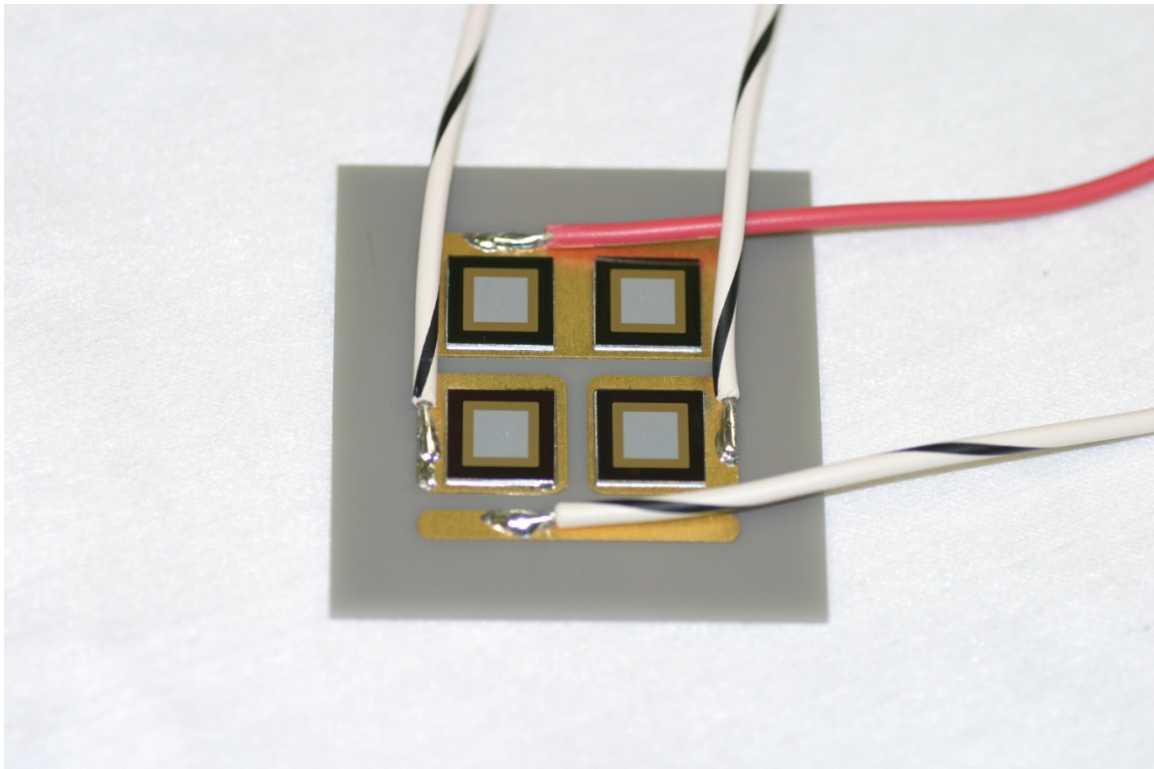


Fig. 7 Photograph of H.V. rectifier board after die attach and soldering of insulated wires

Step 5: Wire bonding devices to DBC

- Wire bonds were made using Orthodyne® Model 20 Ultrasonic bonder
- Aluminum wire (0.25 mm) used for all wire bonds as seen in Fig. 8
- Three wire bonds were placed on each device

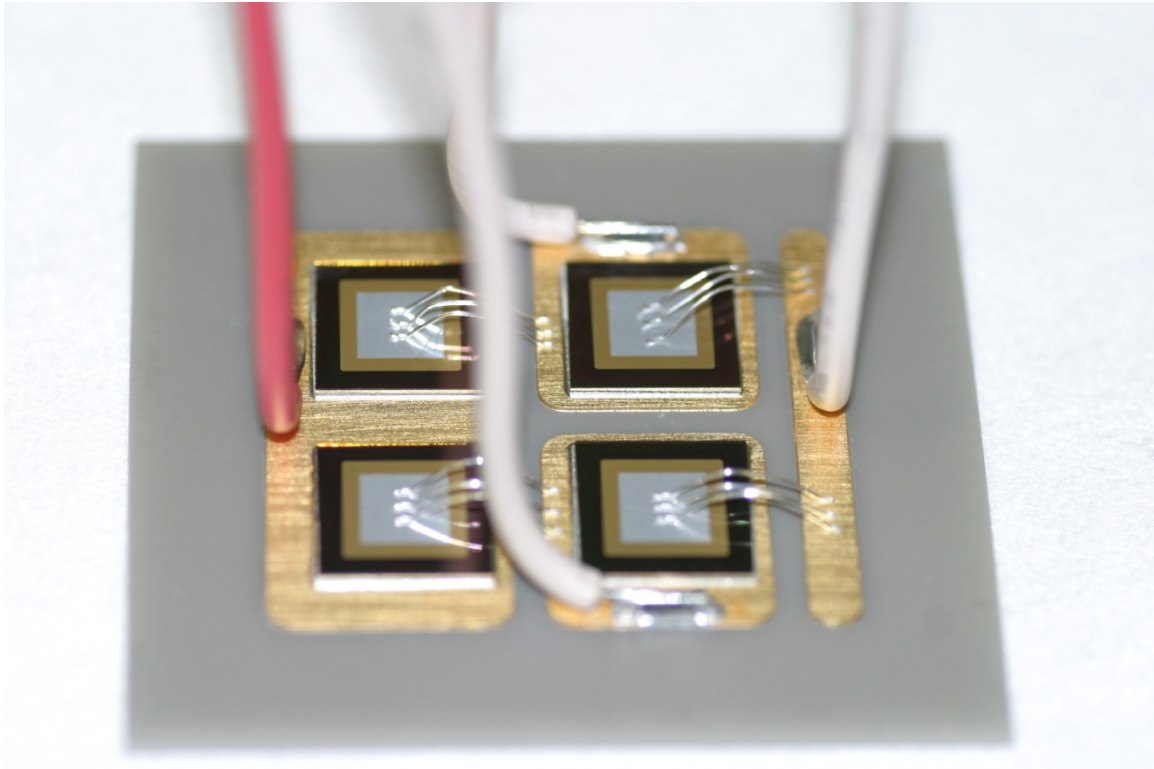


Fig. 8 Die interconnects made using 0.25 mm aluminum wire with an ultrasonic bonder

Step 6: Sealing H.V. rectifier board to H.V. rectifier case

- Apply thin coat of Dow Corning® 3140 RTV and press board firmly to case
- Place module upside down with weight on the backside of the DBC as shown in Fig. 9
- Allow 24 h for RTV to cure at 27 °C

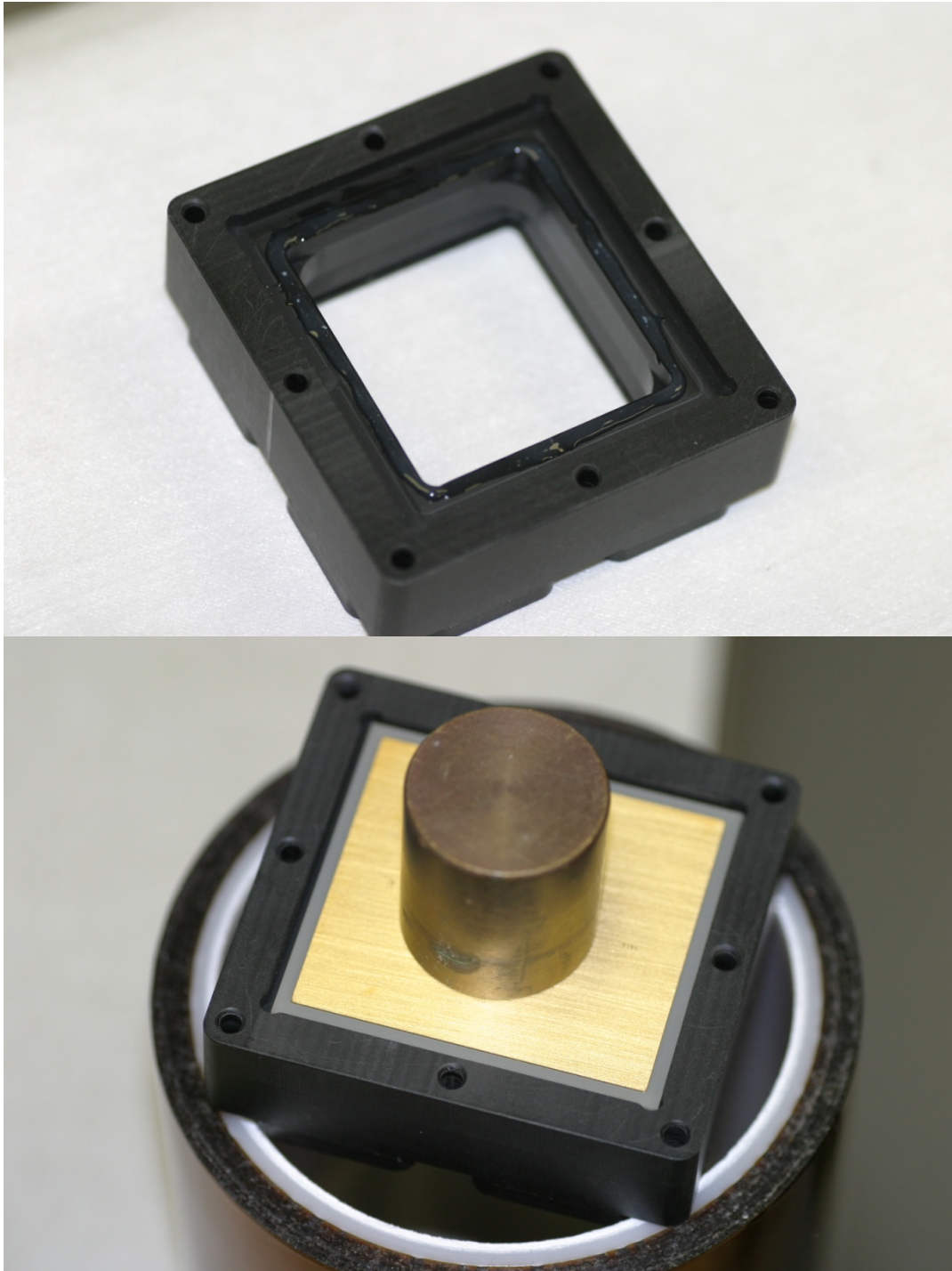


Fig. 9 Photographs depicting process of sealing of H.V. rectifier board to rectifier case using Dow Corning® 3140 RTV coating

Step 7: Attach aluminum baseplate to module

- Cut 1.5 mm Bergquist Gap Pad® VO Ultra Soft using template (38 mm × 42 mm) and remove blue film
- Apply the gap pad to the exposed backside of the DBC ensuring that it is centered as in Fig. 10
- Fasten aluminum baseplate to the case using size 4-40 machine screws, nuts, and washers
- Securely tighten the screws to compress the gap pad so there is no space between the aluminum plate and the case

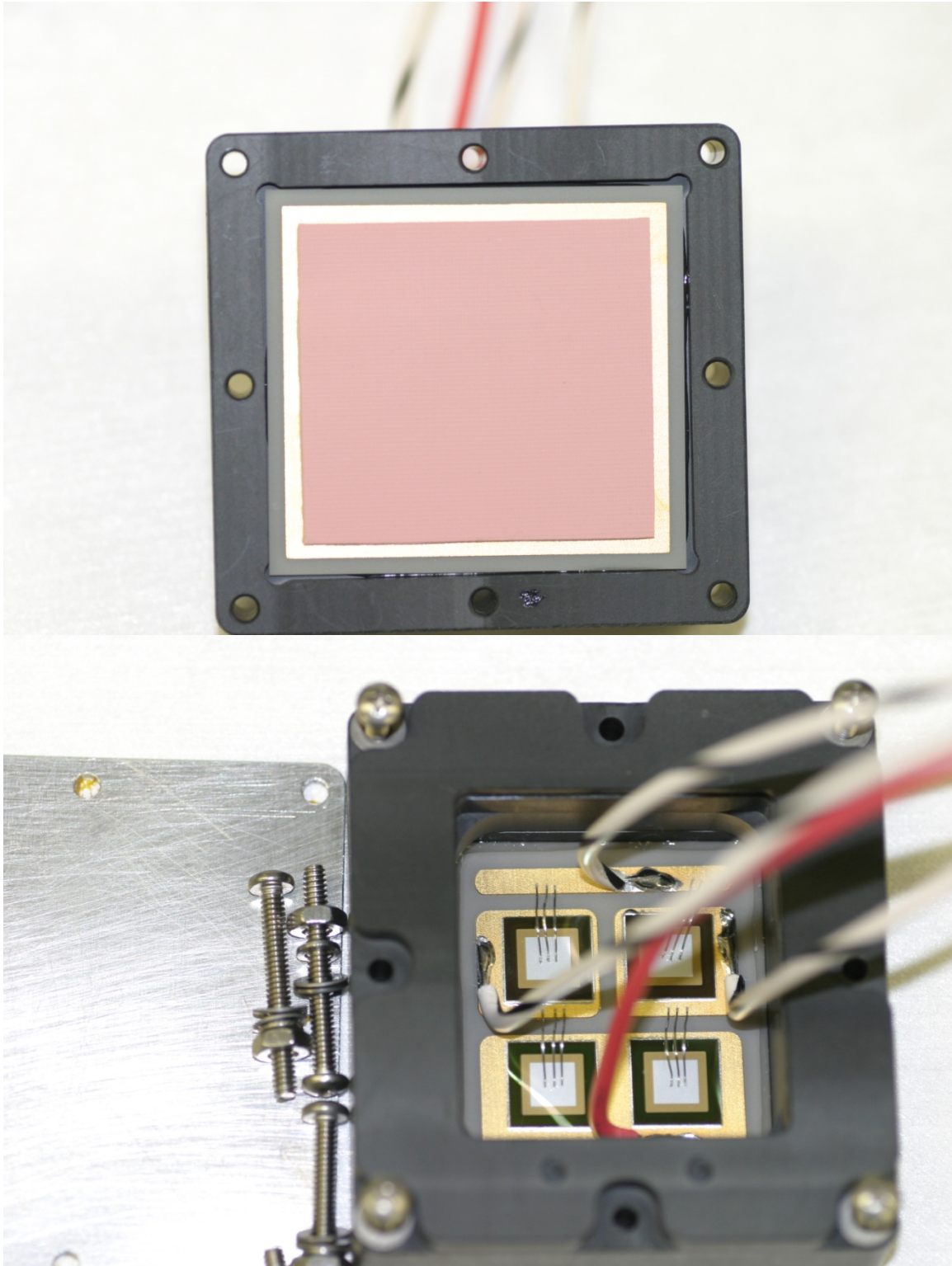


Fig. 10 Photographs depicting attachment of aluminum baseplate to module using Bergquist Gap Pad® VO Ultra Soft and size 4-40 machine screws

Step 8: Encapsulate die cavity using Sylgard® 527 A&B Silicone Dielectric Gel

- Mix 1:1 ratio of Sylgard® 527 A&B Silicone Dielectric Gel
- Degas under vacuum to ensure a void-free protective layer
- Dispense the gel into the die cavity (see Fig. 11) below top of corner webs in case
- Inspect for void entrapment
- Allow 24 h for gel to cure at 27 °C

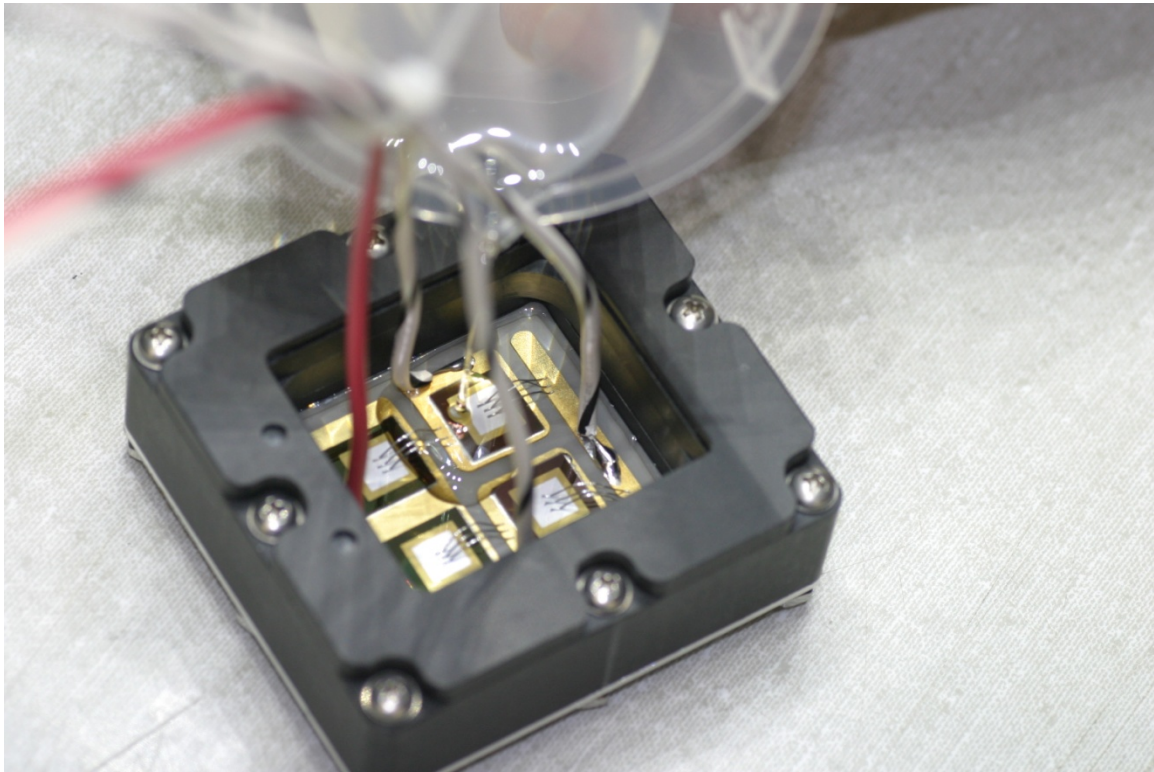


Fig. 11 Photograph depicting filling of module cavity with Sylgard® 527 A&B Silicone Dielectric Gel

Step 9: Seal inner lid to case using Dow Corning® 3140 RTV Coating

- Slide inner lid onto wires and seat on top of case corner webs
- Seal inner lid to case and around wires for a liquid tight seal using RTV coating as seen in Fig. 12
- Avoid applying excessive RTV on the inner side walls of the case and wires where they come through the lid
- Allow 24 h for RTV to cure at 27 °C

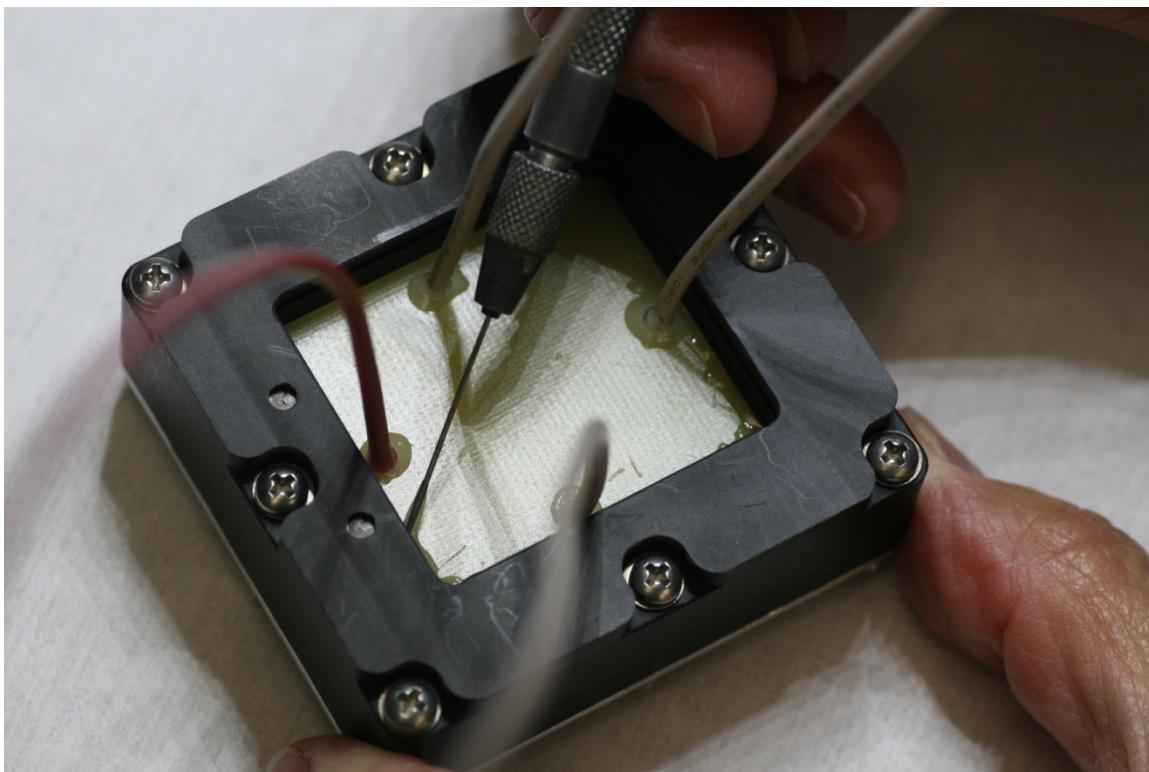


Fig. 12 Photograph depicting sealing of the inner lid using Dow Corning® 3140 RTV coating

Step 10: Seal top of case with Cotronics Duralco® 4525N to provide strain relief to wires

- Fill case cavity with Duralco® 4525N epoxy as in Fig. 13, ensuring the epoxy runs into upper side wall groove
- Allow 24 h for epoxy to cure at 27 °C

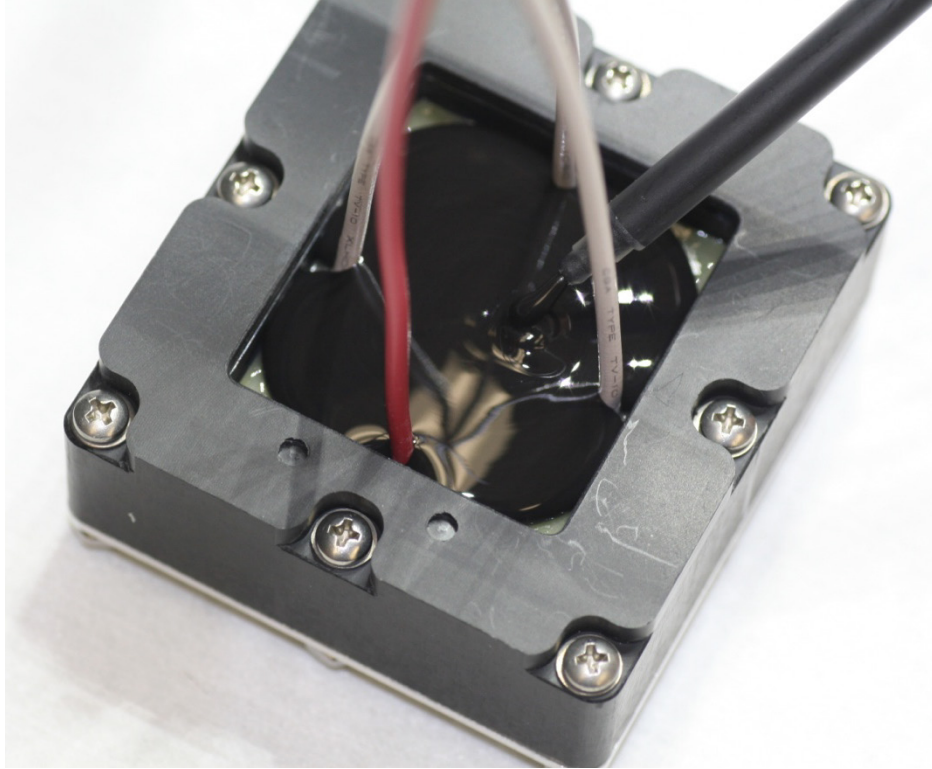


Fig. 13 Photograph depicting fill of case cavity with Cotronics Duralco® 4525N

Table 2 presents properties of the various encapsulants and adhesives used for fabricating the Version 3 module. Figure 14 is a photograph of the completed module.

Table 2 Version 3 module encapsulants & adhesives

Material	Maximum temp. (°C)	Hardness	Appearance	Cure	Purpose	Dielectric strength (Volts/mil)
Dow Corning Sylgard® 527 A&B	150	Silicone gel (soft)	Clear	Room temp	Die cavity	425
Cotronics Duralco® 4525N	200	Epoxy (hard)	Black	Room temp	Bind terminals (wires)	450
Dow Corning® 3140 RTV	200	Hard	Clear	Room temp	DBC & Inner Lid to Case	385
Bergquist Gap Pad® VO US	200	Ultra Soft	Mauve/ Pink	N/A	DBC to Al baseplate	--

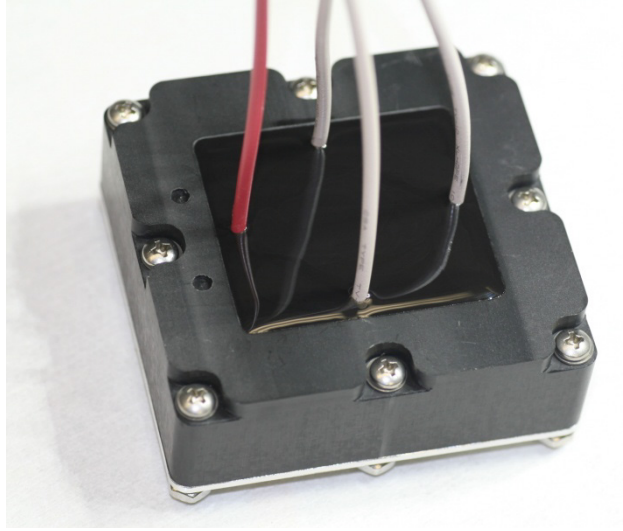


Fig. 14 Completed Version 3, 15 kV full-bridge rectifier module with aluminum baseplate

5. Conclusions

The advent of SiC devices capable of operating well beyond the voltage regimes of COTS packages has given rise to the need for the development of custom modules for ultra-high voltage operation. Three versions of a high-voltage bridge rectifier module have been developed and fabricated at ARL for pulsed-power applications. Version 2 improved upon Version 1, with the copper baseplate being replaced with a low-CTE CarbAl™ baseplate material, doing away with the issue of crack formation in the ceramic during soldering. The availability of the thicker ceramic layer served to eliminate the requirement of the dielectric pocket for Version 3.

List of Symbols, Abbreviations, and Acronyms

AlN	aluminum nitride
COTS	commercial off-the-shelf
CTE	coefficient of thermal expansion
DBC	direct bonded copper
ENIG	electroless nickel immersion gold
H.V.	high voltage
IPA	isopropyl alcohol
JBS	junction-barrier Schottky
RTV	room temperature vulcanization
SiC	silicon carbide

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