Abstract—High current and voltage handling capabilities are desired in many high-performance power electronic modules. One of the main challenges when integrating a power module is having a high-voltage insulation material that is reliable at all operating temperatures. In this work, the use of a polyamide imide (PAI) material as the high-voltage passivation for the power electronic modules was investigated. The power modules were integrated with a two-step passivation-encapsulation process using the PAI material. The fabricated modules were tested up to 10 kV to evaluate the material insulation properties.

I. INTRODUCTION

With the advent of wide-bandgap power semiconductor devices such as those made from silicon carbide, the demand for power electronic modules with a voltage handling capability greater than 10 kV will be increasing when high-voltage devices are used in electric utility applications. The ability to withstand voltages of 10 kV or greater for power electronic modules poses great challenges in terms of insulation materials and module design. At high voltages, the module insulation/encapsulation material is susceptible to electrical “treeing” due to high electrical stresses and partial discharge (PD) phenomena originating from local electrical stress enhancements [1-2]. To mitigate the electrical treeing and PD phenomena, the maximum electric field should be reduced below the critical breakdown threshold through careful module design and/or utilize insulation materials with high dielectric breakdown strengths. Methods to reduce the electric field intensity include depositing a resistive layer on the top of the substrate; modifying the shape of the metallization edges; and making use of a three-dimensional module layout approach [3-4]. Commercially available encapsulation materials listed in Table I offer a very narrow selection of breakdown dielectric strength within 15~36 kV/mm.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Temperature Range (°C)</th>
<th>Dielectric Strength (kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-60NC Hysol</td>
<td>~</td>
<td>21.7</td>
</tr>
<tr>
<td>3-4190 Dow Corning</td>
<td>-45 to 150</td>
<td>19.7</td>
</tr>
<tr>
<td>3-6635 Dow Corning</td>
<td>-80 to 200</td>
<td>20.5</td>
</tr>
<tr>
<td>Sylgard 567</td>
<td>-45 to 200</td>
<td>20.7</td>
</tr>
<tr>
<td>TSE3051</td>
<td>~</td>
<td>18</td>
</tr>
<tr>
<td>Nusil CF2186</td>
<td>-65 to 240</td>
<td>35.4</td>
</tr>
</tbody>
</table>

In this work, a polyamide imide (PAI) thin film was developed to serve as the high-voltage passivation material for power electronics modules. Nano silica particles were embedded into the PAI film to further improve its breakdown behavior [5]. To further improve the insulation reliability of the power modules, a two-step passivation-encapsulation process was introduced. In this process, a thin layer (e.g., 20 µm) of the PAI passivation material is first coated on top of the power module followed by another layer of conventional encapsulation as shown in Figure 1. This passivation material, with good adhesion and outstanding electrical/mechanical properties, has been shown to improve the breakdown capability of the power electronic modules.
II. MATERIAL AND CHARACTERIZATION

The PAI has an imide functional group (O=C–N-C=O) as well as an amide functional group (=C-O-N-HR) as shown in Fig. 2. The imide group gives the film high thermal stability. The coated PAI gives a high dielectric strength of 100 - 280 kV/mm [6-7]; exceptional high heat capability from cryogenic temperature -200°C up to 260 °C [8]; an outstanding surface adhesion to many different materials including metals, and a broad chemical resistance. In this work, a PAI polymer was prepared using a sol-gel method via an isocyanate route with trimellitic acid anhydride and di-isocyanatodiphenyl methane. Silica nano particles were first functionalized with tetraethoxysilane (TEOS) for a uniform dispersion. Metal-Insulator-Metal capacitors were formed on the top of a metalized silicon wafer for breakdown dielectric strength measurements. A Valhalla 5880A Dielectric Analyzer was used to test the dielectric breakdown strength. The voltage ramp rate was set at 100 V/s and the target voltage was held for 10 s. The breakdown voltage was recorded when an arc discharge occurred or a maximum current of 0.1 µA was reached. The breakdown dielectric strengths for a PAI film with a 6% silica nano material (by weight) are shown in Table II. The 6% silica by weight was chosen to optimize the mechanical and electrical characteristics for the UA PAI silica nano films even though PAI film with 10% silica content was reported to have the optimum dielectric strength [5]. As shown, the dielectric breakdown strength of the film decreases with increasing thickness of the PAI nano-composite films. This is because more defects are incorporated into the film as its thickness increases. As a comparison, a dielectric breakdown strength of 300 kV/mm has been reported for a 1.4 µm PAI nano-composite film [6]. However, the breakdown voltage for thin PAI films is in practice usually less than its theoretical values because of processing defects. For this reason, a 20 µm PAI film was chosen as the passivation thickness for the power modules. Figure 3 illustrates the dielectric breakdown strength of the PAI films with and without nano silica particles at 25 °C and 200 °C.

<table>
<thead>
<tr>
<th>Film Thickness(µm)</th>
<th>Average Breakdown Voltage(kV)</th>
<th>Dielectric Breakdown Strength(kV/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.5</td>
<td>300</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
<td>200</td>
</tr>
<tr>
<td>45</td>
<td>6.6</td>
<td>120</td>
</tr>
<tr>
<td>60</td>
<td>7</td>
<td>118</td>
</tr>
</tbody>
</table>

As can be seen, the PAI films with silica nano particles have higher dielectric breakdown strengths compared to those PAI films without the silica nano particles. In general, the dielectric breakdown strength of the PAI films decreases with increasing temperatures.

III. EXPERIMENTAL PROTOTYPES

Power electronics modules, passivated with the PAI nano hybrid material, have been fabricated to demonstrate the passivation concept. Figure 4(a) shows the wire-bonded power module with a silicon carbide (SiC) super gate-off thyristor (SGTO) in series with a SiC diode. This device configuration enables us to verify both the forward and reverse blocking capabilities since the SGTO conducts in the forward direction while the diode blocks the reverse voltage in the reverse direction. The single-switch power module has been demonstrated as an effective way to evaluate material and fabrication process [9]. A bond wire was implemented to exacerbate the electric field intensification between the bond wire and the substrate. The wire-bondless power module with DBC lead-frame shown in Fig. 4(b) was also fabricated for comparison. The SGTO and diode were attached onto the DBC substrate using a 95.5 Pb 3.5 Sn 1 Ag solder ribbon; the power connectors were attached using a SAC405 solder paste.
Interconnection between SGTO and diode were achieved using multiple 5 mil aluminum bond wires.

The assembled modules were first cleaned with acetone and then dipped into a 10% hydrochloric acid solution for 3 minutes followed by rinsing in de-ionized water. The modules were then dried and dipped into the PAI material and spun at sequential speeds of 200, 800 and 1500 rpm. After spinning, the power modules were baked at 80 °C in a vacuum oven. To reduce pin holes defects as well as to achieve the desired thickness of 20 µm, the spin and soft bake processes were repeated three times. After passivation, the power modules were then encapsulated using commercially available encapsulation materials. After a cure process, the power modules were ready for evaluation. The module assembly process is shown in Fig. 5.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Several test configurations were performed to evaluate the integrity of the passivation material under high voltage operation as shown in Fig. 6. These configurations include: A – SGTO is series connected to the diode; B – the SGTO is shorted to test the diode only; and C – the diode is shorted to test the SGTO only.

The wire-bonded power modules built for test configurations A, B, and C are shown in Fig. 7. To test the forward and reverse blocking voltages of the SGTO/diode configuration, a 10-kV voltage is applied between terminals T1 and T2 as indicated. The circles shown in modules B and C are bond wires that short the diode or SGTO, respectively.

The configurations A, B and C of wire-bondless modules are shown in Figure 8. The SGTO in power module B and diode in module C were shorted using a bond wire. During test, a 10-kV bias was applied between terminals T1 and T2.

The blocking voltage test circuit is shown in Fig. 9. A programmable 10-kV power source with a ramp rate of 100V/s is set to test the breakdown voltage of the
power modules. A 10MΩ current limit resistor is serially connected with the power module under test (PUT) as shown in Fig. 9. The test voltage was held constant for 10s after reaching 10 kV. The leakage current is recorded using a high resolution current meter. The reverse voltage blocking test was also performed in a similar manner.

![Voltage blocking test circuit](image)

Fig.9 Voltage blocking test circuit

The test results are shown in Table III. With passivation, all the wire-bonded power modules A, B, and C were able to withstand a 10kV operation voltage in both the forward and reverse directions. The wire-bondless modules A and B were also able to withstand a 10kV operation voltage in both the forward and reverse directions. However, the wire-bondless module C can only withstand a forward and reverse voltage of 9.2kV. Above 9.2kV, an arc discharge was observed under the DBC lead frame.

**TABLE III. Power module breakdown test result**

<table>
<thead>
<tr>
<th>Module Passivation</th>
<th>Power module under test</th>
<th>Module A</th>
<th>Module B</th>
<th>Module C</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Passivation</td>
<td>wirebond module</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td></td>
<td>wirebondless module</td>
<td>Pass</td>
<td>Pass</td>
<td>breakdown at 9.2kV</td>
</tr>
<tr>
<td>No Passivation</td>
<td>wirebondless module</td>
<td>breakdown at 7kV</td>
<td>breakdown at 7kV</td>
<td>breakdown at 7kV</td>
</tr>
</tbody>
</table>

All wire-bondless power modules without passivation failed the breakdown voltage test below 7kV. Thus, it shows that the passivation improves the power module breakdown voltage. The breakdown voltage enhancement is probably due to these factors: first, the passivation layer has a higher dielectric strength than the encapsulation material; second, the PAI solution is low in viscosity. It could enter the small gaps under the DBC lead-frame while the encapsulant with a relatively high viscosity usually cannot penetrate; third, a thin passivation layer formed in each subsequent coating prevents micro-voids from forming. The improvement of the module breakdown voltage would enhance the module reliability by delaying the initiation of partial discharge [10].

The passivated wire-bonded power module was also tested to verify the blocking capability at high temperatures. During test, a 10kV DC bias was applied across terminals T1 and T2 of the module and the module was heated up to 195°C. The passivation worked well without breakdown. The leakage current is recorded as shown in Fig. 10.

![10kV power module heating up blocking test](image)

Fig.10 10kV power module heating up blocking test

In summary, polyamide imide embedded with nano material has been shown to be an effective passivation layer for the improvement of the breakdown voltage of the power modules. A two-step passivation and encapsulation process has been introduced in this research work. The PAI material and process have been tested using wire-bonded and wire-bondless power modules up to 10kV. Wire-bonded module with passivation passed the high temperature 10kV blocking test without breakdown.

**V. CONCLUSIONS**

Polyamide imide embedded with silica nano material was demonstrated to be an effective passivation for the power electronics modules. A two-step passivation and encapsulation process was implemented on the prototyped power electronic modules which were able to withstand a breakdown voltage of 10 kV.

**VI. FUTURE WORK**
The reliability of the passivation layer under high temperature and high voltage stresses is being investigated. It was reported in [11-12] that nano composite material would increase the partial discharge inception voltage and delay the tree initiation.

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REFERENCES


