

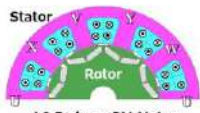
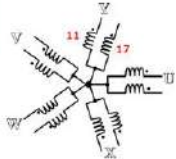
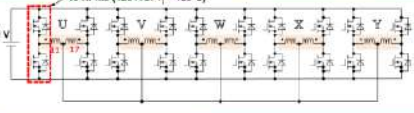
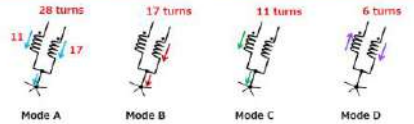
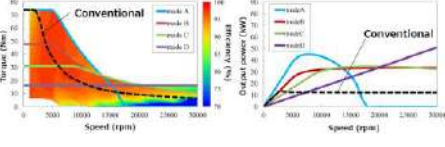
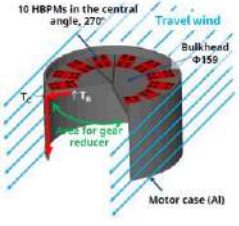
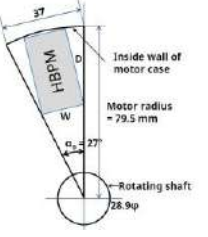
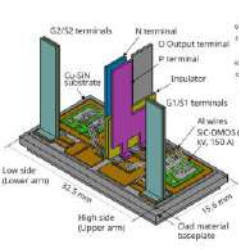

■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

<p>先端パワーエレクトロニクス技術体系講座 Advanced Course</p> <hr/> <p>～次世代SiCインバータ～ <b>EV機電一体パワーモジュール</b></p> <p>福島SiC応用技研株式会社 (FSiC) 谷本智 (Satoshi TANIMOTO, Ph.D.) satoshi.tanimoto@fukushima-sic.co.jp</p>																			
<p>Global Urgent Problems &amp; Issues YNU 横浜国立大学</p> <ul style="list-style-type: none"> <li>Exhaustion of fossil fuels</li> <li>Resource capture</li> <li>Exhaust gas pollution</li> <li>Nuclear fuel waste (Fukushima disaster!)</li> <li>Global warming (? Scientifically debatable)</li> </ul> <p style="text-align: center;">↓</p> <ul style="list-style-type: none"> <li>Energy saving</li> <li>Renewable energy creation</li> </ul>																			
<p>Power Conversion Systems YNU 横浜国立大学</p> <table border="0"> <tr> <td style="border: 1px solid black; padding: 5px;"> <b>Requirements</b>                  Higher efficiency                  Smaller size                  Lighter weight                  Air cooling                  More robustness                  Lower cost             </td> <td style="text-align: center; vertical-align: middle; font-size: 2em;">→</td> <td style="border: 1px solid black; padding: 5px;"> <b>Solution</b>                  SiC/GaN unipolar devices                  +                  Higher current density                  +                  Higher <math>f_{sw} &gt; 20</math> kHz                  +                  Extended <math>T_{jmax} &gt; 200^{\circ}C</math> </td> </tr> </table> <p style="text-align: center; border: 1px solid green; padding: 5px; margin-top: 10px;">Smaller size results in lower cost.</p>	<b>Requirements</b> Higher efficiency Smaller size Lighter weight Air cooling More robustness Lower cost	→	<b>Solution</b> SiC/GaN unipolar devices + Higher current density + Higher $f_{sw} > 20$ kHz + Extended $T_{jmax} > 200^{\circ}C$																
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<p>Major Properties of SiC YNU 横浜国立大学</p> <table border="1" style="width: 100%; border-collapse: collapse; text-align: center;"> <thead> <tr> <th>Physical Property</th> <th>Si</th> <th>4H-SiC</th> </tr> </thead> <tbody> <tr> <td>Band gap (eV)</td> <td>1.12</td> <td>3.26</td> </tr> <tr> <td>Breakdown Field (MV/cm)</td> <td>0.3</td> <td>2.8</td> </tr> <tr> <td>Electron mobility (cm/s)</td> <td>1350</td> <td>1000</td> </tr> <tr> <td>Thermal conductivity (W/cmK)</td> <td>1.5</td> <td>4.9</td> </tr> <tr> <td>Intrinsic temperature (K)</td> <td>600</td> <td>1400</td> </tr> </tbody> </table>	Physical Property	Si	4H-SiC	Band gap (eV)	1.12	3.26	Breakdown Field (MV/cm)	0.3	2.8	Electron mobility (cm/s)	1350	1000	Thermal conductivity (W/cmK)	1.5	4.9	Intrinsic temperature (K)	600	1400	
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<p>Scenario of Size Reduction YNU 横浜国立大学</p>																			

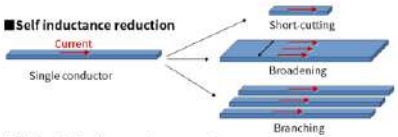
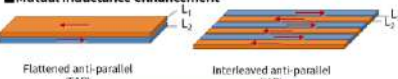
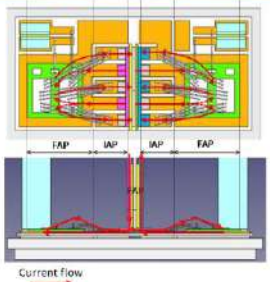
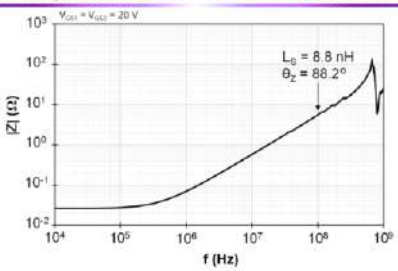
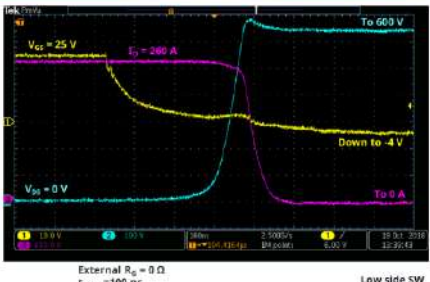
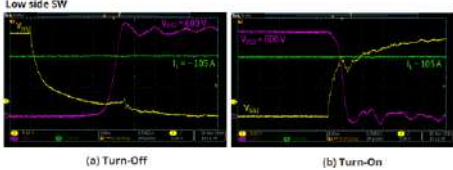
■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

<p><b>Inverter Comparison</b> YNU 横浜国立大学</p>  <p>Commercial Si-IGBT Inverter (11 kW)</p> <p>SiC Inverter "NIJI" (10 kW@50 kHz, 15 kW@20 kHz)</p>											
<p><b>70 kW/L SiC Inverter</b> YNU 横浜国立大学</p>  <table border="1" data-bbox="159 795 343 896"> <tr><td>Input</td><td>600 V (DC)</td></tr> <tr><td>Output</td><td>2φ ~80 V, 25 kW</td></tr> <tr><td>Size</td><td>105 × 80 × 40 mm (350 mL)</td></tr> <tr><td>Power density</td><td>70 kW/L</td></tr> <tr><td>Frequency</td><td>50 kHz</td></tr> </table> <p>Assembly diagram</p>	Input	600 V (DC)	Output	2φ ~80 V, 25 kW	Size	105 × 80 × 40 mm (350 mL)	Power density	70 kW/L	Frequency	50 kHz	
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<p><b>AC 50 Hz 20 kW Output Waveform</b> YNU 横浜国立大学</p>  <p>Line voltage (AC 400 V)</p> <p>Phase current (AC 34.5 A)</p> <p>Power factor = 0.82, <math>f_{sw} = 50</math> kHz</p>											
<p><b>Continuous Output Test</b> YNU 横浜国立大学</p>  <p><math>T_c</math> (fins) = 160°C  <math>T_j</math> = 180°C (Calc.)      Dissipation = 100 W/module</p>											
<p><b>EV In-Wheel Motor</b> YNU 横浜国立大学</p>  <p>40 kW Motor and Inverter</p> <p>gear reducer</p> <p>16 inch front wheel</p> <p>Built in Inverter</p> <p>Motor</p> <p>HBPMS</p> <p>Drive circuit</p>											

■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

<p><b>In-Wheel Motor Concept</b> YNU 横浜国立大学</p> <p><b>Features</b></p> <ul style="list-style-type: none"> <li>• applicable to 16-inch front wheels</li> <li>• high-safety five-phase AC motor drive</li> <li>• high torque and high efficiency</li> <li>• natural air cooling</li> </ul>  <p>AC 5 phase PM Motor</p>  <p>Wiring configuration</p>	
<p><b>Virtual Transmission</b> YNU 横浜国立大学</p> <p>10 HBPMs (120 A at <math>T_1 = 120^\circ\text{C}</math>)</p> <p>DC 400 V</p>  <p><b>Mode A (Low)</b></p> <ul style="list-style-type: none"> <li>• Steer assist</li> <li>• 28 (= 17+11) turns</li> <li>• Maximum torque</li> </ul> <p><b>Mode B (2nd)</b></p> <ul style="list-style-type: none"> <li>• City drive</li> <li>• 17 turns</li> </ul> <p><b>Mode C (3rd)</b></p> <ul style="list-style-type: none"> <li>• Outer city cruise</li> <li>• 11 turns</li> </ul> <p><b>Mode D (4th)</b></p> <ul style="list-style-type: none"> <li>• Highway drive</li> <li>• 6 (= 17-11) turns</li> </ul>	
<p><b>Performance</b> YNU 横浜国立大学</p>  <p>Mode A Mode B Mode C Mode D</p>  <p>Conventional</p> <p>Mode A Mode B Mode C Mode D</p>	
<p><b>Grand Design</b> YNU 横浜国立大学</p>  <p>10 HBPMs in the central angle, <math>270^\circ</math></p> <p>Travel wind</p> <p>Bulk head <math>\phi 159</math></p> <p>Motor case (Al)</p>  <p>Inside wall of motor case</p> <p>Motor radius = 79.5 mm</p> <p>Rotating shaft <math>\phi 28.9\text{p}</math></p>	
<p><b>Final Design and Actual HBPM</b> YNU 横浜国立大学</p>  <p>Low side (lower arm) 22.5 mm</p> <p>High side (upper arm) 15.4 mm</p> <p>Clad material: copperplate</p>  <p>W26 x D.37 x H7</p>	

■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

<p><b>L<sub>s</sub> Reduction Strategy</b> YNU 横浜国立大学</p> <p>■ Self inductance reduction</p>  <p>■ Mutual inductance enhancement</p>  <p><math>L_s = L_1 + L_2 - 2k\sqrt{L_1 + L_2}</math> (<math>0 &lt; k &lt; 1</math>)</p>	
<p><b>L<sub>s</sub> Reduction Design</b> YNU 横浜国立大学</p>  <p>Current flow</p>	
<p><b>Actual L<sub>s</sub> Reduction</b> YNU 横浜国立大学</p>  <p>Impedance between P and N terminal</p>	
<p><b>High Current Turn-off Transient</b> YNU 横浜国立大学</p>  <p>External <math>R_G = 0 \Omega</math>  <math>T_{turnoff} = 100 \text{ ns}</math></p> <p>Low side SW</p>	
<p><b>SW Transient at 250°C</b> YNU 横浜国立大学</p>  <p>(a) Turn-Off (b) Turn-On</p>	

■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

### Heat Release Calculation

Component	Material	TC K (W/mK)	CTE (ppm/K)	SH (C) (J/gK)	SG (v) g/cm3	Thickness t (mm)
Power die	SiC	293	4.5-6.6	0.69	3.21	0.3
Die attach	AuGe	44	12	0.15	14.67	0.02
AMB Cu	Cu	401		0.38	8.93	0.3
SiN sub	SiN	120	6.5	0.86	3.32	0.32
AMB Cu	Cu	401		0.38	8.93	0.3
Sub attach	Al	237	24.3	0.27	2.70	0.2
Baseplate	CPC141	220	7.6	0.32	5.92	3

### R<sub>th</sub> and Heat Spreading

### Thermal Response (LTspice Sim)

### Thermal Stress Design

CTE Matching and Use of Ductile Al sub-attach

### Die Attachment Reliability

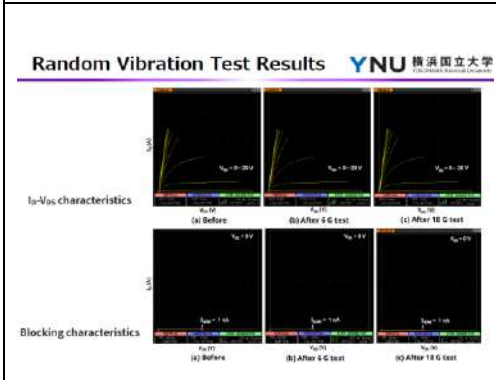
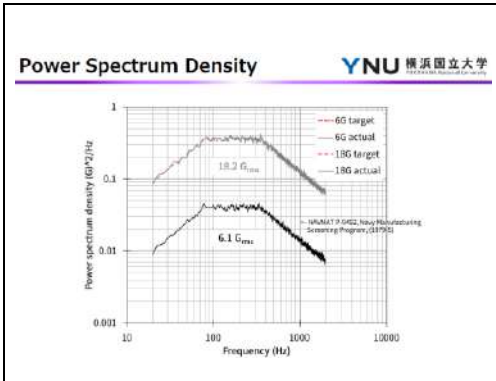
■ A3 【パワーデバイスと実装（自動車系）】 谷本講師

<p><b>Sub/BP after -40 to 200°C TCT</b> YNU 横浜国立大学</p> <p>0 cycles</p> <p>3000 cycles</p> <p>Cu-SiN/Al Al/Base plate</p> <p>SAT images</p>	
<p><b>X-SEM Analysis of Sub/BP</b> YNU 横浜国立大学</p> <p>0 cycles</p> <p>3000 cycles (-40 to 200°C TCT)</p>	
<p><b>X-EDS of Al/BP after TCT</b> YNU 横浜国立大学</p> <p>TCT:          • -40 to 200°C          • 3000 cycles</p> <p>① CuAl<sub>2</sub>          ② CuAl          ③ CuAl (x &lt; 1.0)</p>	
<p><b>Tj Dependence of Al Wire Bonds</b> YNU 横浜国立大学</p> <p>Temperature dependence</p> <p>Test sample</p> <p>Fracture occurred:          - on the beam or at the heel for Tj &lt; 50°C          - at the heel for Tj &gt; 50°C</p>	
<p><b>Wire Bond Reliability</b> YNU 横浜国立大学</p> <p>TCT between -40 and 250°C</p> <p>PwCT for Tjmax=200°C, ΔTj=165°C</p>	

■ A3 【パワーデバイスと実装（自動車系）】 谷本講師

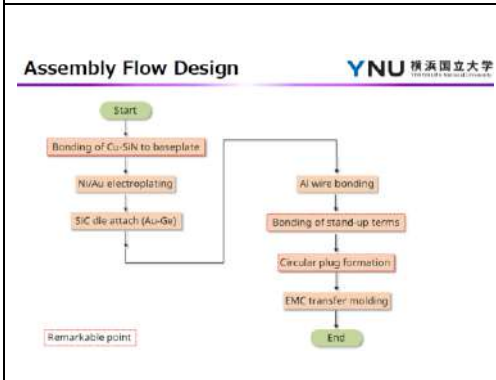
<p><b>Test Results for Storage at 250°C</b> YNU 横浜国立大学</p> <p><b>Uninterrupted storage tests for 3000 hours</b></p> <table border="1"> <thead> <tr> <th>Storage time &amp; temperature</th> <th>0 hour</th> <th>250°C</th> <th>3000 hours</th> </tr> </thead> <tbody> <tr> <td>Pull strength (gF)</td> <td>241</td> <td>180</td> <td>194</td> </tr> <tr> <td>Relative strength (%)</td> <td>100</td> <td>75</td> <td>68</td> </tr> <tr> <td>Ratio to IEC 60749-22</td> <td>3.4</td> <td>2.6</td> <td>2.3</td> </tr> </tbody> </table> <p>Storage for 1000 hours at 250°C</p>	Storage time & temperature	0 hour	250°C	3000 hours	Pull strength (gF)	241	180	194	Relative strength (%)	100	75	68	Ratio to IEC 60749-22	3.4	2.6	2.3	
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<p><b>Encapsulation* Reliability for Storage at 200°C</b> YNU 横浜国立大学</p> <p>Change of <math>V_{BD}</math> and <math>V_T</math> of SiC-SBD</p> <p>EMC/SiC-SBD X-SEM after 3000 Hours</p>																	
<p><b>TCT Reliability of Encapsulation*</b> YNU 横浜国立大学</p> <p>Change of <math>V_{BD}</math> and <math>V_T</math> of SiC-SBD</p> <p>EMC/SiC-SBD X-SEM after 3000 cycles</p>																	
<p><b>Vibration Test</b> YNU 横浜国立大学</p> <p>EMC PCS-BL104MJ, EMC F-1R00/BOH/LA16</p> <p>HSPM (x axis), HSPM (y axis), HSPM (z axis)</p>																	
<p><b>Resonant Characteristics</b> YNU 横浜国立大学</p> <p>Acceleration rate (<math>G_{rms}</math>) vs Frequency (Hz)</p> <p>0.1 <math>G_{app}</math></p>																	

■ A3 【パワーデバイスと実装（自動車系）】 谷本講師



### Yield Rate

Property	6 G <sub>rms</sub> Test (30H)		18 G <sub>rms</sub> Test (30H)	
	Arm	Leg	Arm	Leg
Output	0/6	0/3	0/6	0/3
Blocking	0/6	0/3	0/6	0/3
Total	0/6	0/3	0/6	0/3



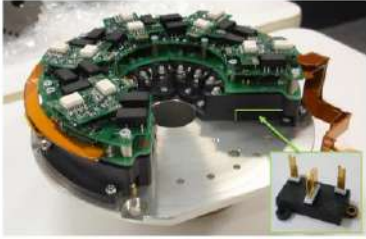

### Comparison\* with Market Products

Issues	Market Products**	Dur module	Innovative Factor
Total Volume V (cc)	100	5	1/20
Thermal Resistance R <sub>th,jb</sub> (K/W)	0.16	0.18	comparable
Parasitic Inductance L <sub>p</sub> * (nH)	15	8.8	1/2
Junction temperature T <sub>jmax</sub> (°C)	150	200 (250***)	50°C higher, More than 200°C
Thermal Excursion ΔTj (°C)	190	340 (260***)	50°C greater

\*1.2kV 120A class HBPM, \*\*Combination of best values, \*\*\*Short range in time.



■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

<p>Practical 5-Phase Inverter <span style="float: right;">YNU 横浜国立大学</span></p> 	
<p>EV IWM equipped with Inverter <span style="float: right;">YNU 横浜国立大学</span></p> 	
<p>Summary <span style="float: right;">YNU 横浜国立大学</span></p> <p>Extremely compact full SiC HBPMs built in a real EV IWM have been designed, prototyped and characterized.</p> <p>The prototyped HBPMs are extremely compact in size and capable of withstanding junction temperatures up to nearly 200°C and steadily switching 260 A at DC 600 V.</p> <p>They have better CTE matching and low thermal resistance, resulting in superior reliabilities.</p> <p>An assembly process of the HBPM encapsulated with thermoset EMC has been proposed and finally completed.</p>	
<p>Acknowledgement <span style="float: right;">YNU 横浜国立大学</span></p> <p>This work was supported in part by the Strategic Innovation Promotion Program (SIP) directed by the New Energy and Industrial Technology Development Organization (NEDO) of Japan.</p> <p>The authors gratefully thank Prof. Kan Akatsu (Shibaura Institute of Technology), Dr. Masaki Nakano and Dr. Yoshinori Murakami (Nissan Motor, Japan) for the design and fruitful discussions with regard to the IWM described here.</p>	
<p style="text-align: center;"><b>Thank you for your kind attention.</b></p>	