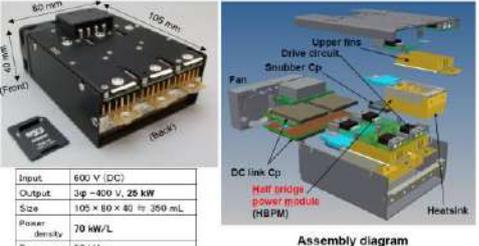
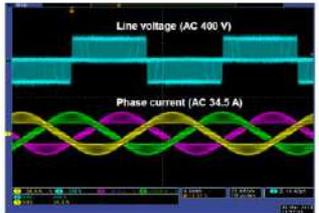
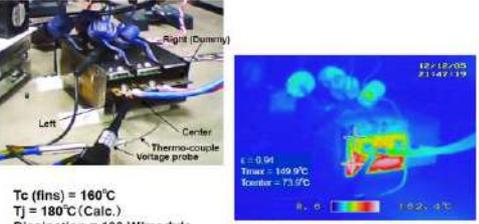
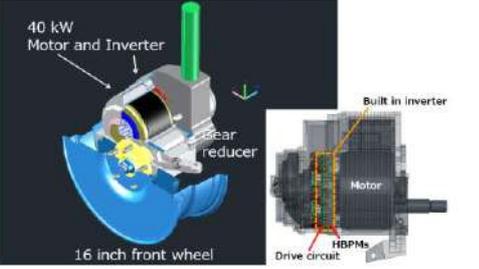


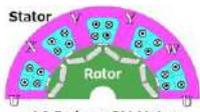
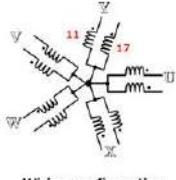
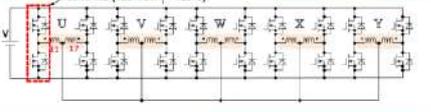
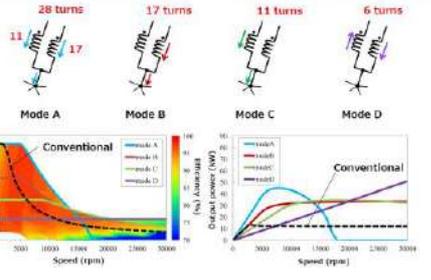
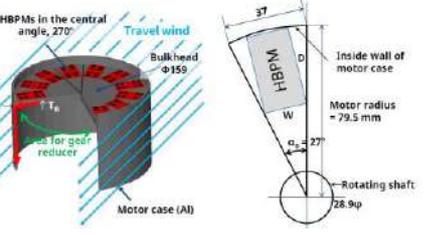
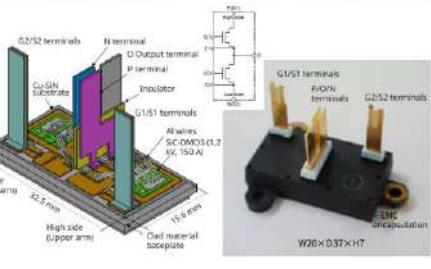
■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

<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～ EV機電一体パワーモジュール</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 & Issues YNU 横浜国立大学</p> <ul style="list-style-type: none"> Exhaustion of fossil fuels Resource capture Exhaust gas pollution Nuclear fuel waste (Fukushima disaster!) Global warming (? Scientifically debatable) <p style="text-align: center;">↓</p> <ul style="list-style-type: none"> Energy saving Renewable energy creation 																			
<p>Power Conversion Systems YNU 横浜国立大学</p> <table border="0"> <tr> <td style="border: 1px solid black; padding: 5px;"> Requirements 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;"> Solution SiC/GaN unipolar devices + Higher current density + Higher $f_{sw} > 20$ kHz + Extended $T_{jmax} > 200^\circ\text{C}$ </td> </tr> </table> <p style="text-align: center; border: 1px solid green; padding: 5px; margin-top: 10px;">Smaller size results in lower cost.</p>	Requirements Higher efficiency Smaller size Lighter weight Air cooling More robustness Lower cost	→	Solution SiC/GaN unipolar devices + Higher current density + Higher $f_{sw} > 20$ kHz + Extended $T_{jmax} > 200^\circ\text{C}$																
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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>																			

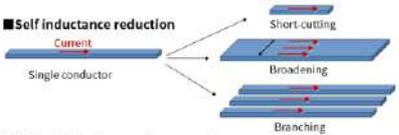
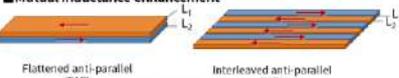
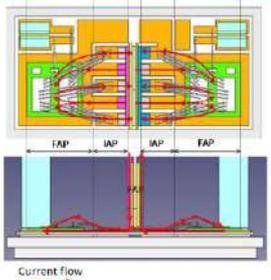
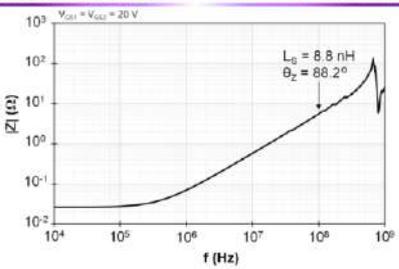
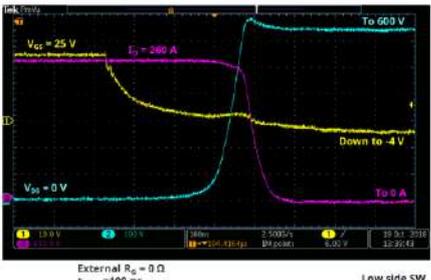
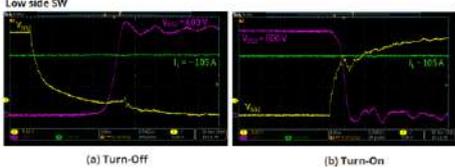
■ A3 【パワーデバイスと実装 (自動車系)】 谷本講師

<p>Inverter Comparison 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>70 kW/L SiC Inverter YNU 横浜国立大学</p>  <table border="1"> <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>AC 50 Hz 20 kW Output Waveform 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, $f_{sw} = 50$ kHz</p>											
<p>Continuous Output Test YNU 横浜国立大学</p>  <p>Right (Dummy)</p> <p>Left</p> <p>Center</p> <p>Thermocouple voltage probe</p> <p>T_c (fins) = 160°C T_j = 180°C (Calc.) Dissipation = 100 W/module</p> <p>$\epsilon = 0.91$ $T_{max} = 169.9^\circ\text{C}$ $T_{center} = 73.0^\circ\text{C}$</p>											
<p>EV In-Wheel Motor 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>In-Wheel Motor Concept YNU 横浜国立大学</p> <p>Features</p> <ul style="list-style-type: none"> • applicable to 16-inch front wheels • high-safety five-phase AC motor drive • high torque and high efficiency • natural air cooling  <p>AC 5 phase PM Motor</p>  <p>Wiring configuration</p>	
<p>Virtual Transmission YNU 横浜国立大学</p> <p>10 HBPMs (120 A at $T_c = 120^\circ\text{C}$)</p> <p>DC 400 V</p>  <p>Mode A (Low)</p> <ul style="list-style-type: none"> • Steer assist • 28 (= 17+11) turns • Maximum torque <p>Mode B (2nd)</p> <ul style="list-style-type: none"> • City drive • 17 turns <p>Mode C (3rd)</p> <ul style="list-style-type: none"> • Outer city cruise • 11 turns <p>Mode D (4th)</p> <ul style="list-style-type: none"> • Highway drive • 6 (= 17-11) turns 	
<p>Performance YNU 横浜国立大学</p>  <p>28 turns (Mode A), 17 turns (Mode B), 11 turns (Mode C), 6 turns (Mode D)</p> <p>Conventional</p>	
<p>Grand Design YNU 横浜国立大学</p>  <p>10 HBPMs in the central angle, 270°</p> <p>Travel wind</p> <p>Bulk head $\phi 159$</p> <p>Motor case (Al)</p> <p>Inside wall of motor case</p> <p>Motor radius = 79.5 mm</p> <p>Rotating shaft $\phi 28.9\text{p}$</p>	
<p>Final Design and Actual HBPM YNU 横浜国立大学</p>  <p>G2/52 terminals</p> <p>Al terminal</p> <p>Output terminal</p> <p>P terminal</p> <p>Insulator</p> <p>G1/51 terminals</p> <p>Al wires</p> <p>SiC MOS (1.2 μs, 150 A)</p> <p>Clad material</p> <p>substrate</p> <p>Low side (lower arm) 22.5 mm</p> <p>High side (upper arm) 15.6 mm</p> <p>G1/51 terminals</p> <p>600V terminals</p> <p>G2/52 terminals</p> <p>EMC suppression</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>L_s Reduction Strategy YNU 横浜国立大学</p> <p>■ Self inductance reduction</p>  <p>■ Mutual inductance enhancement</p>  <p>$L_s = L_1 + L_2 - 2k\sqrt{L_1 + L_2}$ ($0 < k < 1$)</p>	
<p>L_s Reduction Design YNU 横浜国立大学</p>  <p>Current flow</p>	
<p>Actual L_s Reduction YNU 横浜国立大学</p>  <p>Impedance between P and N terminal</p>	
<p>High Current Turn-off Transient YNU 横浜国立大学</p>  <p>External $R_G = 0 \Omega$ $T_{Gate} = 100 \text{ ns}$</p> <p>Low side SW</p>	
<p>SW Transient at 250°C 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
SiC sub	SiC	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_{th} 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>Sub/BP after -40 to 200°C TCT 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>X-SEM Analysis of Sub/BP YNU 横浜国立大学</p> <p>0 cycles</p> <p>3000 cycles (-40 to 200°C TCT)</p>	
<p>X-EDS of Al/BP after TCT YNU 横浜国立大学</p> <p>TCT: • -40 to 200°C • 3000 cycles</p> <p>① CuAl₂ ② CuAl ③ CuAl (x < 1.0)</p>	
<p>Tj Dependence of Al Wire Bonds YNU 横浜国立大学</p> <p>Bond pull strength (gf)</p> <p>Temperature (°C)</p> <p>Temperature dependence</p> <p>Test sample</p> <p>Al wire: 200 μm in thickness SiC-SBD: 2 X 2 mm</p> <p>Fracture occurred: - on the beam or at the heel for Tj < 50°C - at the heel for Tj > 50°C</p>	
<p>Wire Bond Reliability YNU 横浜国立大学</p> <p>Bond pull strength (gf)</p> <p>Number of cycles</p> <p>TCT between -40 and 250°C</p> <p>Bond pull strength (gf)</p> <p>Number of cycles</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>Test Results for Storage at 250°C YNU 横浜国立大学</p> <p>Uninterrupted storage tests for 3000 hours</p> <table border="1"> <thead> <tr> <th>Storage time & 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>Encapsulation* Reliability for Storage at 200°C YNU 横浜国立大学</p> <p>Change of V_{BD} and V_T of SiC-SBD</p> <p>EMC/SiC-SBD X-SEM after 3000 Hours</p>																	
<p>TCT Reliability of Encapsulation* YNU 横浜国立大学</p> <p>Change of V_{BD} and V_T of SiC-SBD</p> <p>EMC/SiC-SBD X-SEM after 3000 cycles</p>																	
<p>Vibration Test 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>Resonant Characteristics YNU 横浜国立大学</p> <p>Acceleration rate (G_{rms}) vs Frequency (Hz)</p> <p>0.1 G_{app}</p>																	

■ A3 【パワーデバイスと実装（自動車系）】 谷本講師

<p>Power Spectrum Density YNU 横浜国立大学</p>																									
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<p>Yield Rate YNU 横浜国立大学</p> <table border="1"> <thead> <tr> <th rowspan="2">Property</th> <th colspan="2">6 G_{rms} Test (30H)</th> <th colspan="2">18 G_{rms} Test (30H)</th> </tr> <tr> <th>Arm</th> <th>Leg</th> <th>Arm</th> <th>Leg</th> </tr> </thead> <tbody> <tr> <td>Output</td> <td>0/6</td> <td>0/3</td> <td>0/6</td> <td>0/3</td> </tr> <tr> <td>Blocking</td> <td>0/6</td> <td>0/3</td> <td>0/6</td> <td>0/3</td> </tr> <tr> <td>Total</td> <td>0/6</td> <td>0/3</td> <td>0/6</td> <td>0/3</td> </tr> </tbody> </table>	Property	6 G _{rms} Test (30H)		18 G _{rms} 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	
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<p>Comparison* with Market Products YNU 横浜国立大学</p> <table border="1"> <thead> <tr> <th>Issues</th> <th>Market Products**</th> <th>Dur module</th> <th>Innovative Factor</th> </tr> </thead> <tbody> <tr> <td>Total Volume V (cc)</td> <td>100</td> <td>5</td> <td>1/20</td> </tr> <tr> <td>Thermal Resistance R_{th,jb} (K/W)</td> <td>0.16</td> <td>0.18</td> <td>comparable</td> </tr> <tr> <td>Parasitic Inductance L_p* (nH)</td> <td>15</td> <td>8.8</td> <td>1/2</td> </tr> <tr> <td>Junction temperature T_{jmax} (°C)</td> <td>150</td> <td>200 (250***)</td> <td>50°C higher, More than 200°C</td> </tr> <tr> <td>Thermal Excursion ΔTj (°C)</td> <td>190</td> <td>340 (260***)</td> <td>50°C greater</td> </tr> </tbody> </table> <p>*1.2kV 120A class IGBT, **Combination of best values, ***Short range in time.</p>	Issues	Market Products**	Dur module	Innovative Factor	Total Volume V (cc)	100	5	1/20	Thermal Resistance R _{th,jb} (K/W)	0.16	0.18	comparable	Parasitic Inductance L _p * (nH)	15	8.8	1/2	Junction temperature T _{jmax} (°C)	150	200 (250***)	50°C higher, More than 200°C	Thermal Excursion ΔTj (°C)	190	340 (260***)	50°C greater	
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■ A3 【パワーデバイスと実装（自動車系）】 谷本講師

<p>Practical 5-Phase Inverter YNU 横浜国立大学</p> 	
<p>EV IWM equipped with Inverter YNU 横浜国立大学</p>  <p style="text-align: center;">Inverter (10 HBPMs)</p>	
<p>Summary YNU 横浜国立大学</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 YNU 横浜国立大学</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;">Thank you for your kind attention.</p>	