Wide Bandgap for Aerospace Applications

Dr Suresh Perinpanayagam
• Overview of Cranfield Power Electronics Capabilities
• Towards All-Electric Aircraft
• SiC MOSFET Case Study
• Developing failure models for Wide Bandgap
• Prognostics development for Wide Bandgap
Welcome to Cranfield

We are an exclusively postgraduate university that is a global leader for education and transformational research in technology and management.

We provide:

- Impact and influence
- Premier learning
- Transformational research.
Impact and influence

We work with 750+ businesses and governments around the world

**Aerospace:**
we have strategic relationships with global companies such as Airbus, BAE Systems, Boeing and Rolls-Royce

**Defence and Security:**
we are one of the world’s largest providers of postgraduate defence and security education

**Environment:**
working with all UK water utility companies and advising major government departments such as Defra

**Leadership and Management:**
we work with major international businesses such as Jaguar Land Rover, L’Oréal and Shell, developing high performance leaders across the world

**Manufacturing:**
leading two and key partners in an additional four EPSRC Centres for Innovative Manufacturing.
Global reach
Cranfield's world-class facilities include clean rooms, laboratories and test/fabrication services through to prototype component manufacture, with extensive analysis, modelling, synthesis and characterisation capability.
Towards All-Electric Aircraft

- Novel architecture for generation and distribution of loads
- Thermal management and thermal exchange
- Flight-proven electrical equipment systems, including environmental conditioning and protection

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Electrical Distribution Architecture for Regional Aircrafts

DC/DC cellular converter
Comparison between a Si IGBT and a SiC MOSFET

A comparison of the overall losses between a Si IGBT and a SiC MOSFET with similar nominal ratings

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# Inverter for Ground Power Units

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Link Voltage</td>
<td>500</td>
<td>VDC</td>
</tr>
<tr>
<td>Output Voltage - Line to Line</td>
<td>232</td>
<td>VAC</td>
</tr>
<tr>
<td>Output Frequency</td>
<td>400</td>
<td>Hz</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Nominal Output Power</td>
<td>45</td>
<td>kW</td>
</tr>
<tr>
<td>400% Overload value</td>
<td>180</td>
<td>kW</td>
</tr>
<tr>
<td>Switching Frequency at Nominal Load</td>
<td>16</td>
<td>kHz</td>
</tr>
<tr>
<td>Switching Frequency at Overload</td>
<td>4</td>
<td>kHz</td>
</tr>
<tr>
<td>Heatsink Thermal Resistance</td>
<td>0.017</td>
<td>K/W</td>
</tr>
<tr>
<td>Maximum Junction Temperature</td>
<td>150</td>
<td>°C</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>40</td>
<td>°C</td>
</tr>
</tbody>
</table>

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Effect of Junction Temperature

Junction temperatures of switching devices under nominal load and overload conditions. Note the reduction in temperature which corresponds with the reduction in switching frequency.
Comparison of Losses

- 67% reduction in losses can be expected.
- 1.6% increase in efficiency if the IGBT4 module with SiC diodes is used.
- 2.3% increase if the SiC MOSFET module is used.
Standard IGBT4 technology reaches its limit at a 55kW nominal load. SiC-based devices would be able to increase the nominal rating of the power assembly to 95kW, which represents a 72% increase in power density. SiC-based devices have the potential to double the power density of typical 3-phase inverters.
Power Electronics Reliability Studies

- Repeated heating and cooling leads to repetitive mechanical stress and eventual failure.
- Exposure to sustained high temperatures drives diffusion-related mechanisms (creep, intermetallic growth, annealing).
- Mismatch in CTE causes fatigue failure (debonding) of bond wires and soldered interfaces.
Physics-of-Failure Applied in Design

Mission Profile

I(t)

(1) Thermal Profile Generator

T\text{interface}\,(t)

(2) Rain-Flow Analysis

\Delta T\text{interface} vs No. of Cycles

(3) Damage Profile Generator and Lifetime Prediction

Electrical systems:
- Trains, Planes & Automobiles
- Renewable power sources
- Power generation & distribution
- Industrial processes

Interfaces:
- Wire-bonds
- Chip solder
- Substrate solder

- Power-electronics process
- Switching strategy
- Device electrical models
- Device thermal models

- Failure models
- POF/Empirical
- Statistical models
- Weibull
Electro-Thermal and Thermo-Mechanical Models

Thermo-Mechanical Model

Electro-Thermal Model
Wire bond wear-out models

\[ N_f = \frac{K}{\Delta T_J^n} \exp \left( \frac{T_a}{T_{ref}} \right) \]

- \( K = 2.13 \times 10^{14} \)
- \( n = 5.33 \)
- \( T_a = 126 \, ^\circ C \)

\[ N_f = (1.4 \times 10^{11}) \Delta T^{-3.597} \]

- \( N_f \) is the material number of cycles to failure
- \( \Delta T \) is temperature variation.

Reliability life-time models for IGBT bond wire interconnect.
IGBT Reliability

Comparisons between Junction Temperature Estimates and Measurements

- Infra-Red Measurements

CEDIP Titanium high frame rate camera

IGBT (G2) junction temperature estimates (°C)
IGBT (G2) junction temperature measurements (°C)
Diode (D1) temperature estimates (°C)
Diode (D1) temperature measurements (°C)
T ambient (°C)

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Integrated Vehicle Health Management

Vehicle Maturation/New Product

Design Engineering Manufacturing
- Production, certification & testing
- Total ownership costs
- System & life cycle
- Requirements
- FMECAs
- Design models
- Failure modes/models
- System test data

Maintenance & Logistics
- Operational Demand
- Fleet Availability
- MR & O leading
- Maintenance Scheduling
- Spares Supply
- Asset Tracking
- Maintenance Execution

Operational Control
- Operational Schedule
- Operational Effectiveness

Operational Control
- Health Status
  - Current
  - Predicted

Acquire
- Health Status
- Transfer
- Maintenance & Logistics
- Operational Control

Data Repository & Ground Processing
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Repeated heating and cooling leads to repetitive mechanical stress and eventual failure.

Exposure to sustained high temperatures drives diffusion-related mechanisms (creep, intermetallic growth, annealing).

Mismatch in CTE causes fatigue failure (de-bonding) of bond wires.

CTE mismatch causes fatigue failure at soldered interfaces.

<table>
<thead>
<tr>
<th>Failure Mechanism</th>
<th>Precursor Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-dependent dielectric breakdown</td>
<td>$V_{GE(th)}$, $I_{ge}$</td>
</tr>
<tr>
<td>Latch-up</td>
<td>$V_{CE(ON)}$, $I_{CES}$</td>
</tr>
<tr>
<td>Wire bond flexure fatigue, solder die attach fatigue, die attach voiding</td>
<td>$V_{CE(ON)}$</td>
</tr>
</tbody>
</table>

Elements of the heat transfer path of the power electronic module

Silicon Die
Die bond
Solder
Substrate
Substrate Solder
Copper base plate
Thermal Grease
Heatsink

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Power Cycling Ageing Test

The power cycling ageing test provides monitoring and measurements of temperature and electrics.

- On-state collector emitter voltage (Vce) changes with different power cyclings.
- The junction temperature and the collector-emitter are measured and recorded constantly until the IGBT fails in accelerated ageing experiments.
- The failure mode involves wire bond lifting off and progressively ending before reaching the open circuit.

- The Vce (on-state) parameter indicates any increases in a non-monotone fashion and shows discrete steps with noise invasion until the IGBT fails.
- The Vce (on-state) voltage precursor indicates a sudden fall at the end of the ageing process when the IGBT fails after more than 4,500 time units.
Noise Filtering

First IGBT data set after filtering

All IGBT run-to-failure data sets after filtering

First IGBT data set after filtering

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<table>
<thead>
<tr>
<th>IGBT No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1^st   Phase</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2^nd Phase</td>
<td>109</td>
<td>132</td>
<td>61</td>
<td>117</td>
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<tr>
<td>3^rd phase</td>
<td>1245</td>
<td>955</td>
<td>1069</td>
<td>1561</td>
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<td>4^th phase</td>
<td>1440</td>
<td>1429</td>
<td>1940</td>
<td>1296</td>
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<tr>
<td>5^th phase</td>
<td>656</td>
<td>866</td>
<td>317</td>
<td>341</td>
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<tr>
<td>6^th phase</td>
<td>88</td>
<td>164</td>
<td>645</td>
<td>480</td>
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<tr>
<td>7^th phase</td>
<td>521</td>
<td>879</td>
<td>266</td>
<td>394</td>
</tr>
<tr>
<td>8^th phase</td>
<td>282</td>
<td>94</td>
<td>145</td>
<td>331</td>
</tr>
<tr>
<td>9^th phase</td>
<td>45</td>
<td>78</td>
<td>209</td>
<td>85</td>
</tr>
<tr>
<td>10^th phase</td>
<td>111</td>
<td>6</td>
<td>17</td>
<td>91</td>
</tr>
<tr>
<td>IGBT Life</td>
<td>4498</td>
<td>4605</td>
<td>4671</td>
<td>4698</td>
</tr>
</tbody>
</table>
Using analytical maximum likelihood estimation (MLE) method to estimate best fit of the modelling parameter $\lambda$ for Poisson distribution

$$P(x_i|\lambda) = \frac{\lambda^{x_i} e^{-\lambda}}{x_i!}, x_i \geq 0$$

$$\hat{\lambda}_{MLE} = \frac{1}{n} \sum_{n=1}^{N} x_n$$

### MLE for Poisson Probability Distribution

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\lambda$</th>
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<tbody>
<tr>
<td>Model 1</td>
<td>2</td>
</tr>
<tr>
<td>Model 1</td>
<td>98</td>
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<tr>
<td>Model 1</td>
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<tr>
<td>Model 1</td>
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<tr>
<td>Model 1</td>
<td>211</td>
</tr>
<tr>
<td>Model 1</td>
<td>126</td>
</tr>
<tr>
<td>Model 1</td>
<td>70</td>
</tr>
</tbody>
</table>
Results from RUL Estimation Using Weibull Model

Constructed Markov model & Monte Carlo simulation for RUL prediction
Conclusions

• Reliability and maintenance-free power solutions are important for wide adaption of Wide Bandgap technology.
• Cranfield could assist industry to develop reliability models for Wide Bandgap applications.
• Cranfield could develop prognostics capabilities for Wide Bandgap applications.
• This will enable safety-conscious industry, such as electric aircraft, to adapt Wide Bandgap.