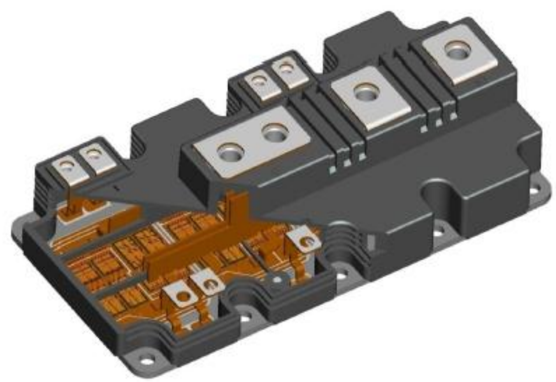
Analysis of innovation trends in packaging for power modules

7th European Advanced Technology Workshop on Micropackaging and Thermal Management

February 1st & 2nd – IMAPS 2012



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iMAPS

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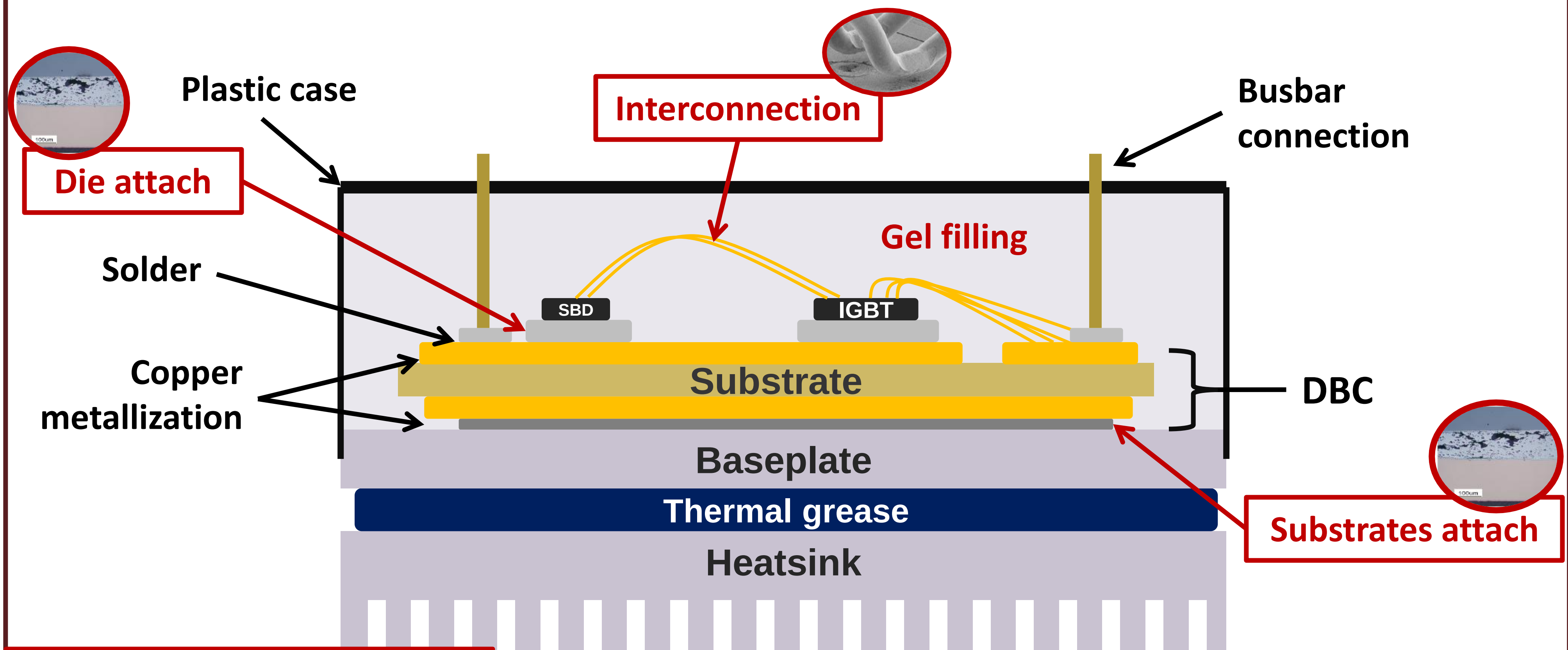
Introduction

Standard module package cross section drawing

- Common failure in a power module is caused by thermal cycling. Mismatching CTEs (coefficient of thermal expansion) incur adhesion issues, cracks. Some filling gels cannot handle high temperatures

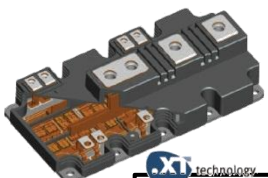


In red: Common failure locations

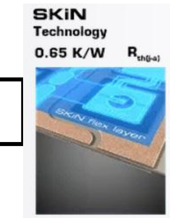
Introduction

Key innovation areas in packaging, with examples

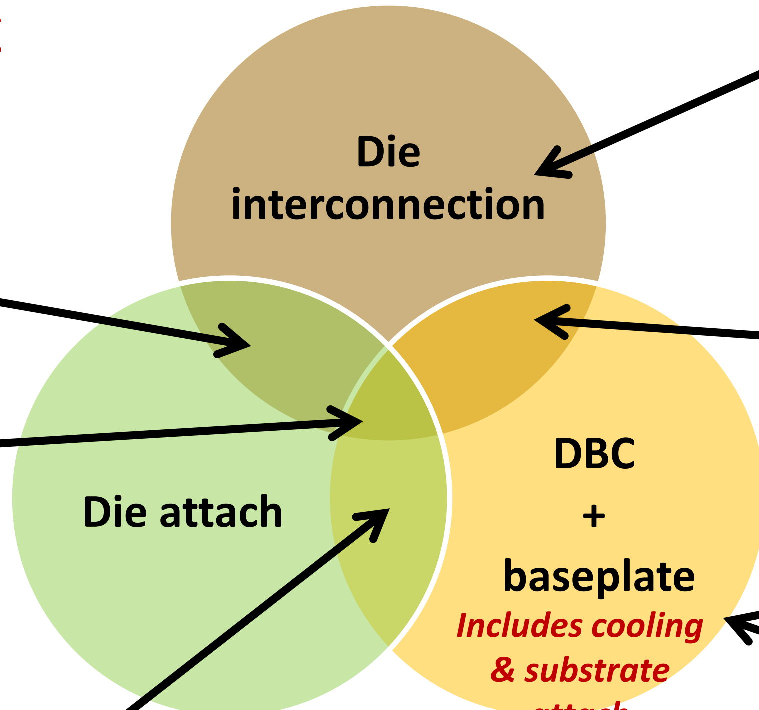
All applicable to Si and SiC



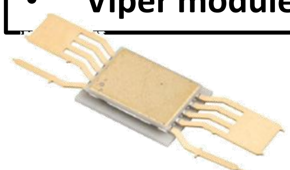
Infineon .XT



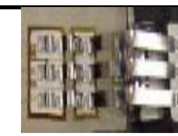
Semikron Skin

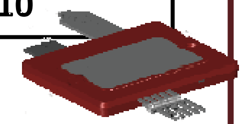


- GE power overlay
- Viper module

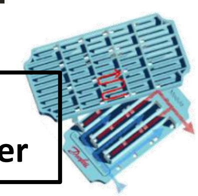


Lexus/toyota modules:
LS 600h
Prius 2010

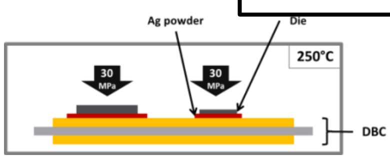




Danfoss
Shower power

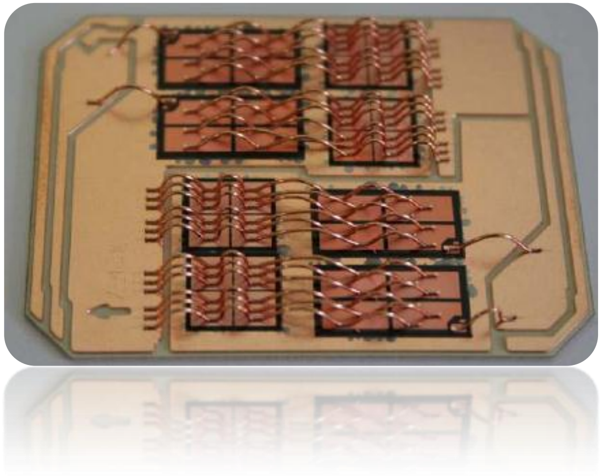


Semikron Ag sintering



Improvements in packaging can be made along 3 different axis:

- **Die interconnection,** which is searching for innovative wire bonding or no-wires connection for better lifetime and reliability
- **Die attach**, which uses new materials for better lifetime
- **DBC+baseplate**, which uses new materials and suppress layers for improved cooling and smaller size



Die interconnection

Die interconnection

Available solutions

➔ **Targets for improvements in interconnection**

- Electrical conductivity
- Thermal conductivity
- Lifetime (thermal cycles impact)

TODAY

- **Al wirebonding is a fast, cheap and easy process**
  - Equipment is widely available
  - It is a historical method since the beginning

  ➔ Wire count and thickness is limited
  ➔ Limited reliability : detaching wires

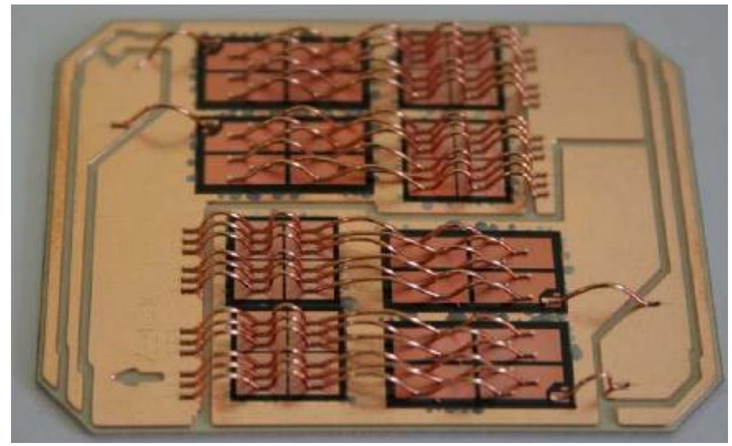
	Al wire bonding	Al ribbon bonding	Copper wire bonding	Semikron Skin
Electrical conductivity	Taken as reference	same	40% better	Same (current density is improved)
Thermal conductivity		same	2x better	Almost the same
Lifetime		Improved (larger pads)	Improved thermal performance	70x better (Ag sintering)
Status		In production, still expensive	Already in mass volume prod for general semiconductor packaging	Close to mass production

Die interconnection

Case study - Infineon .XT

- **Infineon introduced mass production of copper wirebonding power modules**

Copper wire bonding is the next standard. Biggest are working towards this technology.
Equipement is ready as copper wire bonders are widely used for low power and signal
It is not expensive and easy to produce in mass compared to gold wires or flip-chip
➔ *Remaining issue is die metallization*
➔ *Most important players are already working towards this standard*



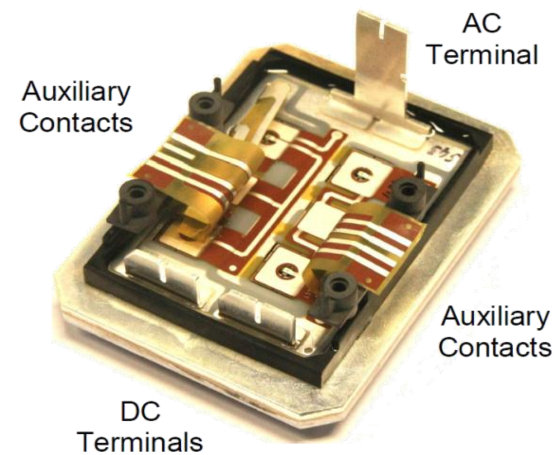
Source: Infineon

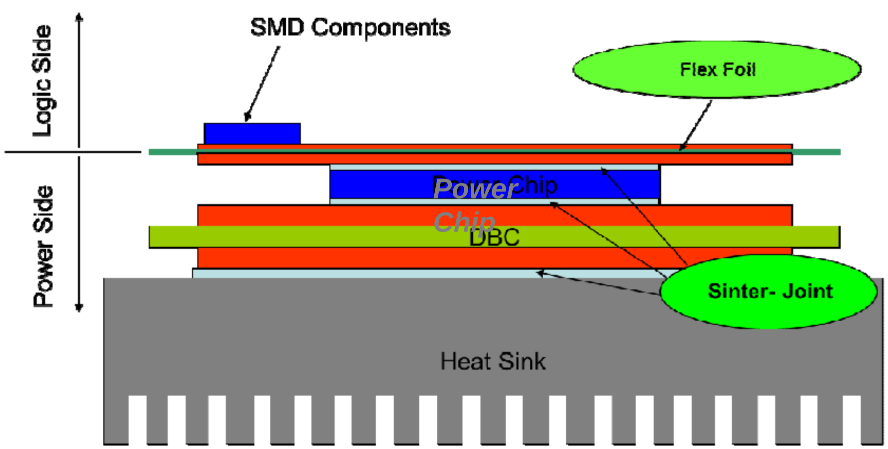
	Copper	Aluminum
Electrical resistivity	*1,7µΩ.cm*	*2,7µΩ.cm*
Thermal conductivity	*400W/m.K*	*220W/m.K*

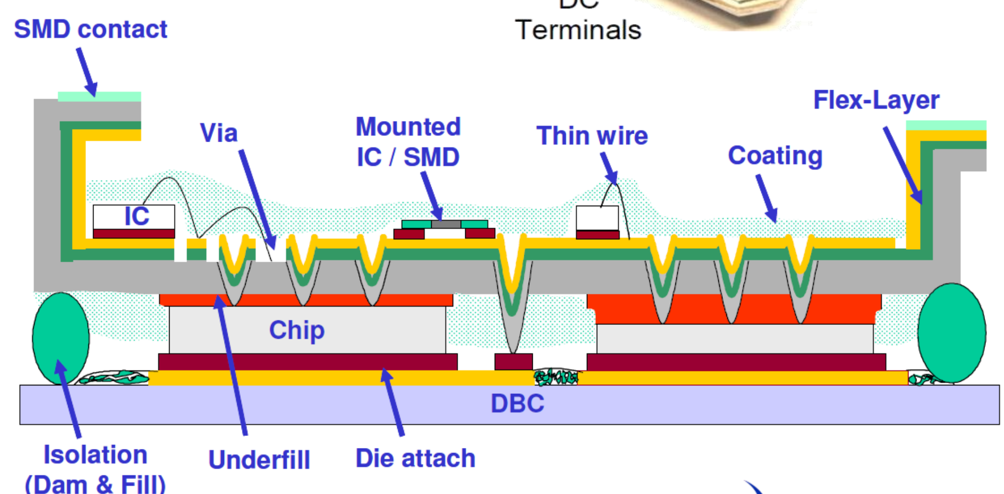
Die interconnection

Case study – Semikron SkiN technology

- Semikron has revealed in 2011, its **innovative interconnection technology** using flexible 'PCB'
  - Made of Ag/Cu/polyimide layers and Ag sintered to the chips
  - Flexible foil is replacing wires
  - Power cycling performance estimated to be 70 times better





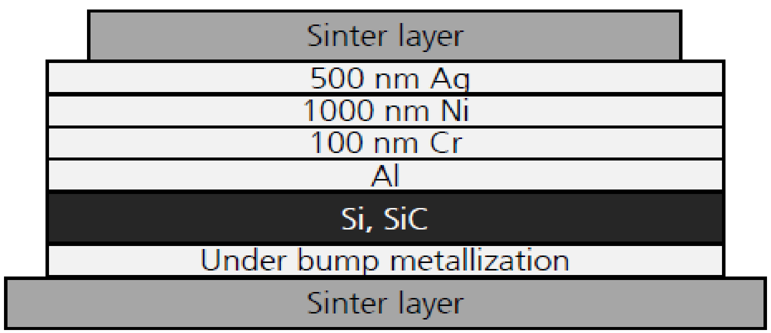


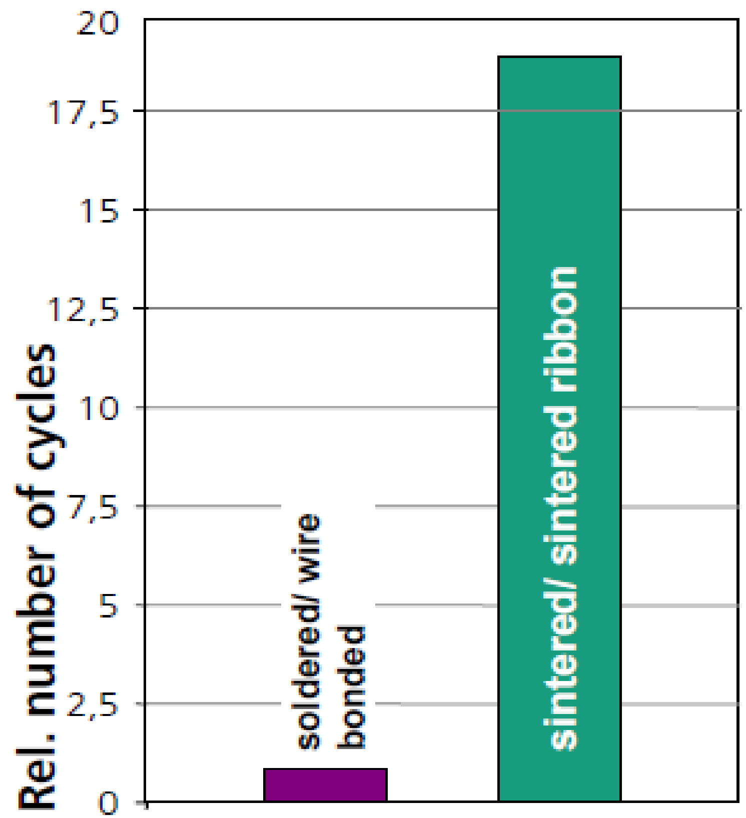
Source: Semikron

Die interconnection

Case study – Fraunhofer – Ag sintered bonding

- Fraunhofer developed and tested Ag sintered ribbon bonding and Ag sintered dies
- They presented and tested the reliability
- Metallization must be specific, which is an issue for production
- This technology has an interest for long lifetime (Wind, rail traction and energy production, some industrial motor drives)



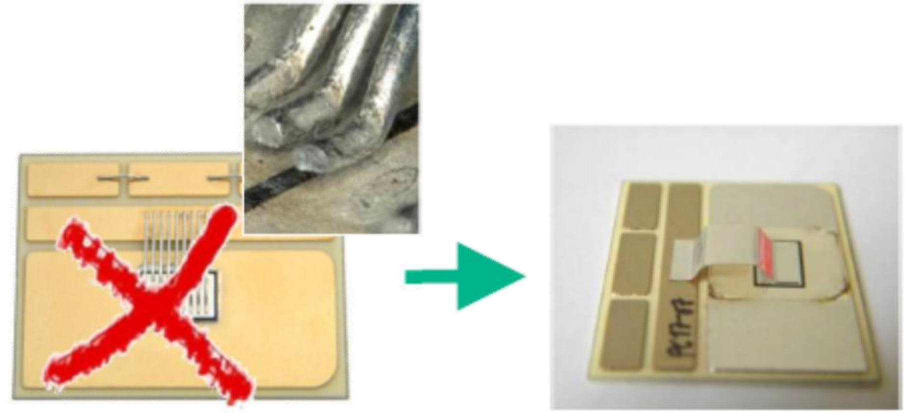


Die interconnection

Case study – Fraunhofer – Ag sintered bonding

- **Sintering at low pressure allows:**
  - Double sided sintering
  - No bond wires
- **It implies the use of Ag nano-powder**

- **There are three parameters when Ag sintering:**
  - Time
  - Temperature
  - Pressure
- **Each of these parameter have a linked influence on the results, i.e, we can reduce the time or the pressure, if we increase the temperature proportionally. Reverse way is possible**



Ribbon bonding solution from Fraunhofer

„Classical":	„nano-scale":
t = 60..120 s	t = 60..120 s
T = 230..250°C	T = 220..275°C
p = 30..50 MPa	p = 1..5 MPa

Silver sintering characteristics regarding the type of paste

Die attach

Die attach

Available solutions

➔ **Targets for improvements of die attach**

– Thermal cycling capability
– Temperature of operation
– Manufacturability (impacting cost)

TODAY

- **Soldering is a fast, cheap and easy process**
  – They use a paste or a gel for soldering
  – Historically, it is an alloy of Tin (Sn) and Lead (Pb)
  – But **Pb is to be abandoned due to RoHS:**
  ➔ Pb-free solution is Sn/Ag (Tin/Silver) soldering

  ➔ Soldering is not suitable for high temperature or multiple steps manufacturing

  T° max is 180°C – T° melting is 220°C

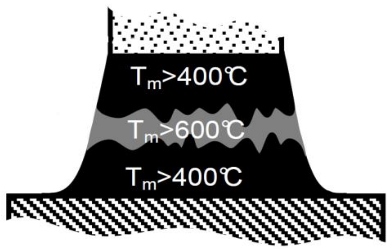
	Sn soldering	Eutectic soldering Cu/Sn	Ag sintering µ-powder	Ag sintering Nano-powder
Thermal cycling	Taken as reference	7x to 10x better	7x to 10x better	Minimum 7x to 10x better
Temperature		Up to 400°C	Up to 400°C	Up to 400°C
Manufacturability		In mass production	In mass production Difficult to produce (pressure+temperature)	At R&D stage Nano-particules regulation issues Will be easier to manufacture

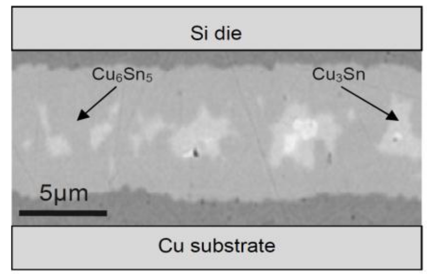
Die attach

Case study - Infineon .XT & Semikron skinter

- **Transient Liquid Phase Bonding (TLPB) → Eutectic soldering**
  - They stack layers of Tin (Sn) and Copper (Cu), and the first melts and diffuse through the other. Result is an alloy of Cu/Sn with progressive percentage. This method is also called **Eutectic soldering**

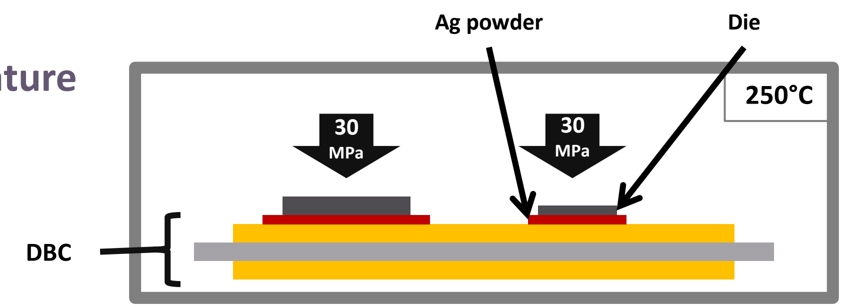
$T°_m$(Cu/Sn) > 400 °C





Used by Infineon in its "*.XT modules*" in 2010

- **Sintering process is now in mass production for Semikron, manufacturing process is as following:**
  - An Ag (Silver) powder is compressed at high temperature
  - Compression:
    - 30MPa to 40MPa
    - at 250°C
    - 60sec. to 120sec. duration
  - Used by Semikron since 2008
  - Ag silver paste in provided by companies like DOWA…



Ag sintering process: Pressure applied at 250°C

Die attach
Silver sintering

- **Nano particles sintering**
  - Same principle as Ag micro particles sintering
  - Using nano size particles allows a better result with a simpler process :
    - Temperature is much lower ➔ down to 20°C
    - Pressure and time are also reduced ➔ faster thus cheaper process
  - This technology is still at R&D development
    - Issues from the migration of Ag particles at high temperature still need to be overcome
  - Time-to-market : 2012 (Nano-paste is already available)

„Classical“:	„nano-scale“:
t = 60..120 s	t = 60..120 s
T = 230..250°C	T = 220..275°C
p = 30..50 MPa	p = 1..5 MPa

Silver sintering characteristics regarding the type of paste

DBC, Baseplate and encapsulation

DBC+Baseplate

Available solutions

➔Targets for improvements in **DBC+Baseplate assembly**

- Cooling capabilities
  - Thermal resistance
  - Thermal path
- Reliability (CTE matching with die)
- Size and volume reduction

TODAY

- DBC is the standard – $Al_2 0_3$ or Si_3N_4:
  - The DBC and baseplate materials depend on required performance and cost, in each application
  - Main issue is to match the CTE of the different layers, keeping the highest thermal conductivity

➔ We are now looking for improved lifetime and temperature performance

➔ Integrated cooling solutions will probably be the next step (baseplates are abandoned with DBC in direct contact with cooling system)

➔ AlN benefits from fast increasing volumes of high power LEDs : cost decreasing

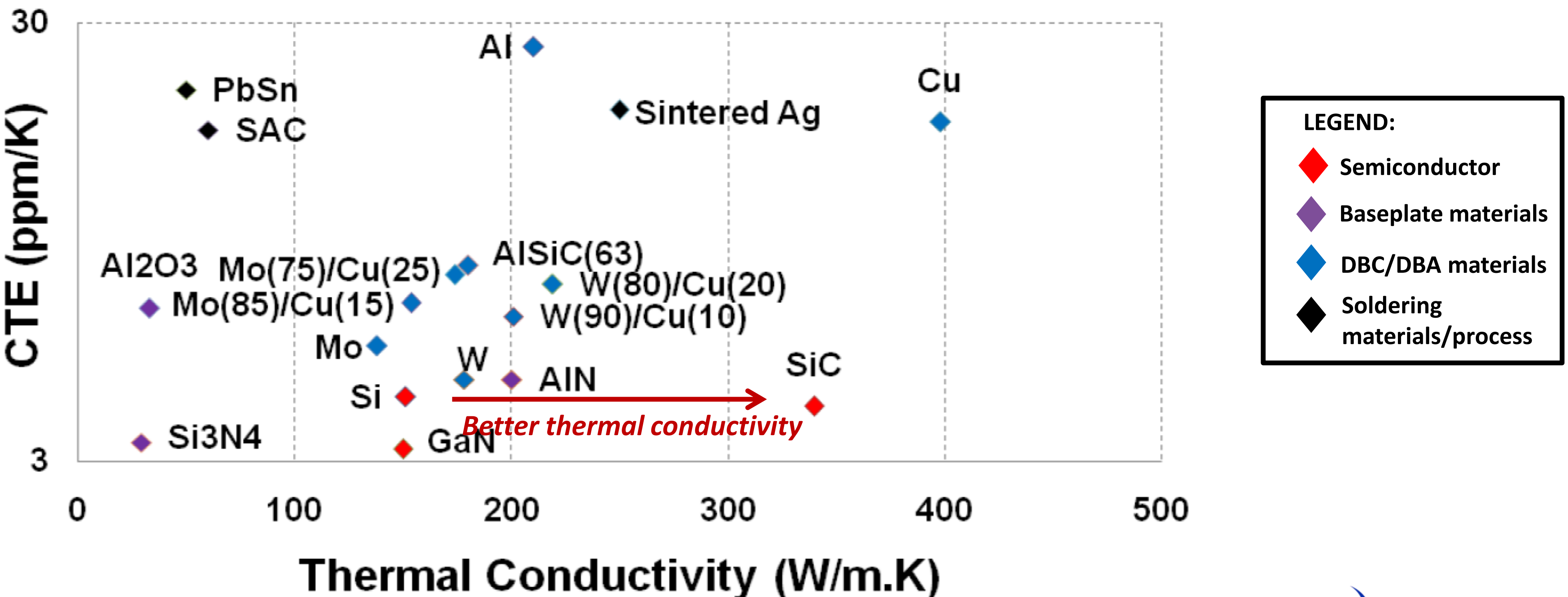
DBC ceramic materials

	Al_2O_3	Si_3N_4	AlN	AlSiC
Thermal conductivity	Taken as reference	same	Approx. 7x better	Better (depending on alloy ratio)
CTE matching		Close to Si CTE	Closest to Si CTE	depending on alloy ratio

DBC+Baseplate

Material choice is key

- **Materials properties is key for packaging. It is all about a trade-off between:**
  - CTE: coefficient of thermal expansion can mismatch between layers
  - Thermal conductivity: It improves cooling efficiency
  - Cost
  - ➔ **But suppressing layers is equal to suppressing issue sources**



Encapsulations

Gel filling

Parylene HT vs. Gel solution

Today's solution

Silicone gel

- Silicone gel max temperature is 200°C
- There are not many solutions to overcome the issue for now

Gel	Manufacturer	Dielectric strength (kV/mm)	CTE (ppm)	Max temperature
Elastosil RT 745S	*Wacker*	*23*	*N/A*	*?*
Nusil R2188	*Nusil silicone*	*17.7*	*N/A*	*240°C*
Sylgard 567	*Dow corning*	*21*	*300*	*200°C*

For very high temperature

– **Coating solution → Parylene HT**
  - Air fills the empty parts of the module
  - Achieve 400°C
  - Only one company propose it : Specialty Coating Systems
  - Parts must be sent to the company to be coated → highly protected process

FOCUS ON EV/HEV

Focus on EV/HEV

Power module packaging trend in EV/HEV

Introduction

- EV/HEV is one of the biggest market for power electronics in 2020, according to all forecasts
- The main challenges will include **manufacturability, reliability** and **lifetime**, but also **integration** and **weight**
- Module packaging is already a great challenge in EV/HEV:
  - *The market is potentially large enough to involve large development efforts*
  - *The level of integration will lead to custom solutions and all integrated inverters*
  - *Footprint, size, weight and cost and all are strong technical drivers*

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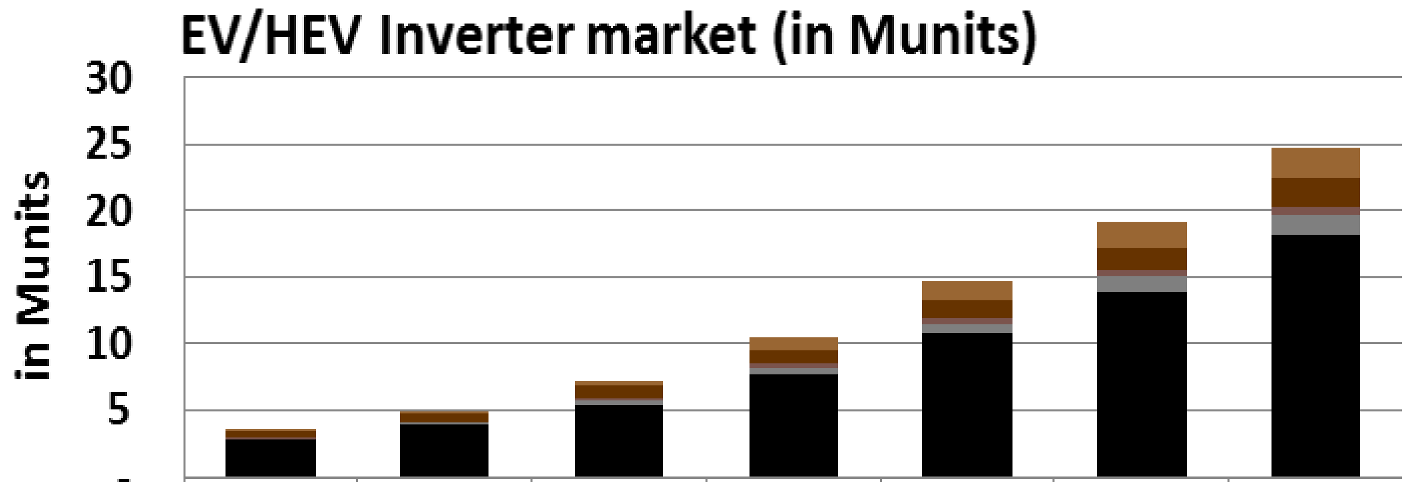
EV/HEV inverter market forecasts Munits

- **40% compound annual growth rate aver the 2010-2016 period!**

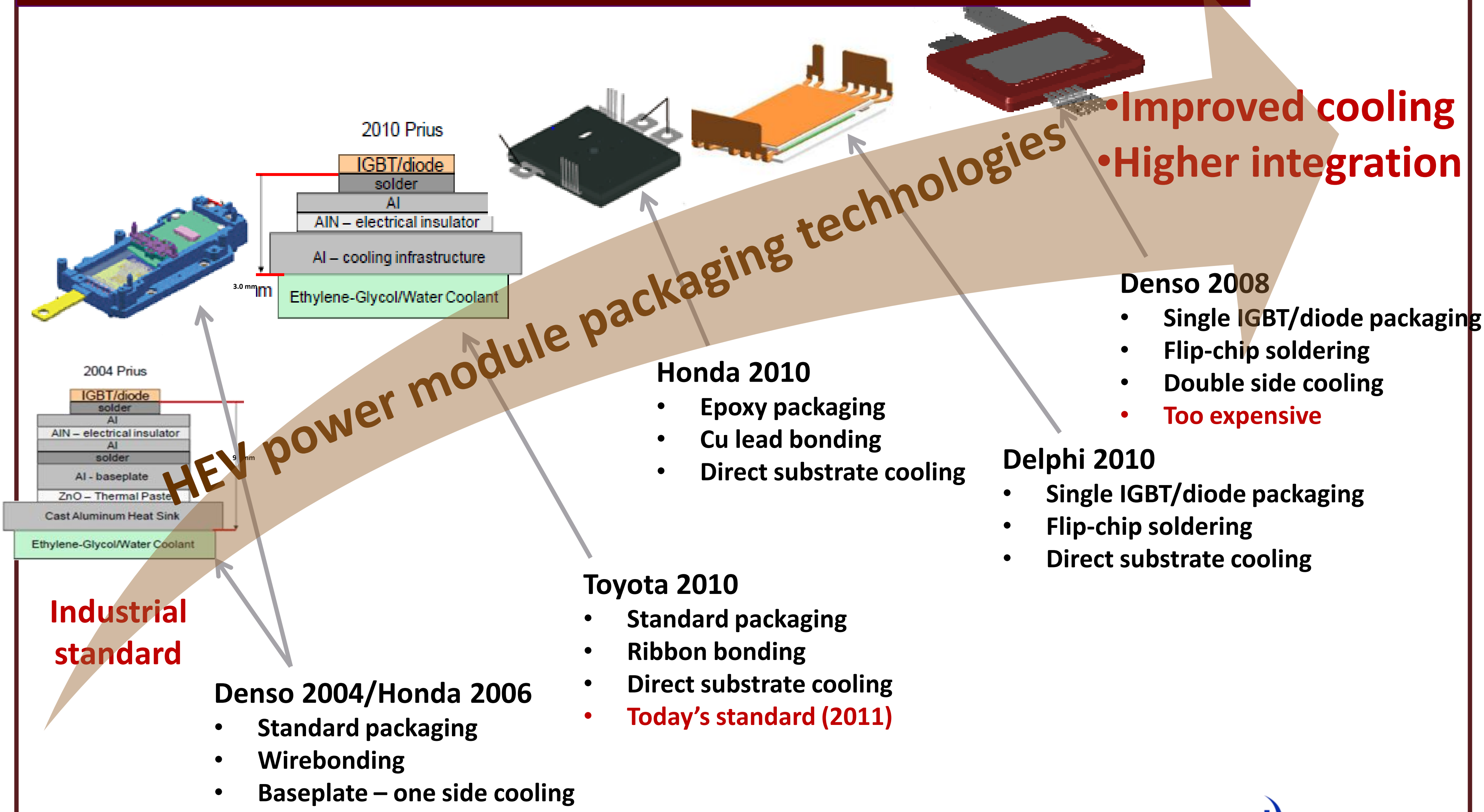


	2010	2011	2012	2013	2014	2015	2016
Plug in HEV / EV	0.0	0.2	0.5	1.0	1.6	1.9	2.3
Full HEV	0.5	0.7	0.8	1.1	1.3	1.6	2.1
Mild HEV	0.1	0.1	0.2	0.3	0.4	0.6	0.7
Micro mild HEV	-	0.1	0.3	0.5	0.8	1.0	1.4
Micro HEV	2.8	3.9	5.5	7.7	10.8	14.0	18.2

Focus on EV/HEV

Power module packaging trend in EV/HEV

Introduction

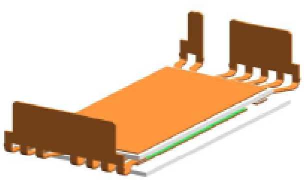


Case study

Delphi – Viper module project

- **Single IGBT/diode packaging**
- **Flip-chip soldering**
- **Direct substrate cooling**

- **Viper power module is at pre-production stage**
  - **Wirebondless package**
  - **Double sided cooling – 30% lower thermal resistance**
  - **Original roadmap planned release in 2008, they just entered pre-production 2010**



IGBT and Diode Co-packaged
Discrete Power Package

Single Device
Discrete Power Package

VIPER modules

Power board

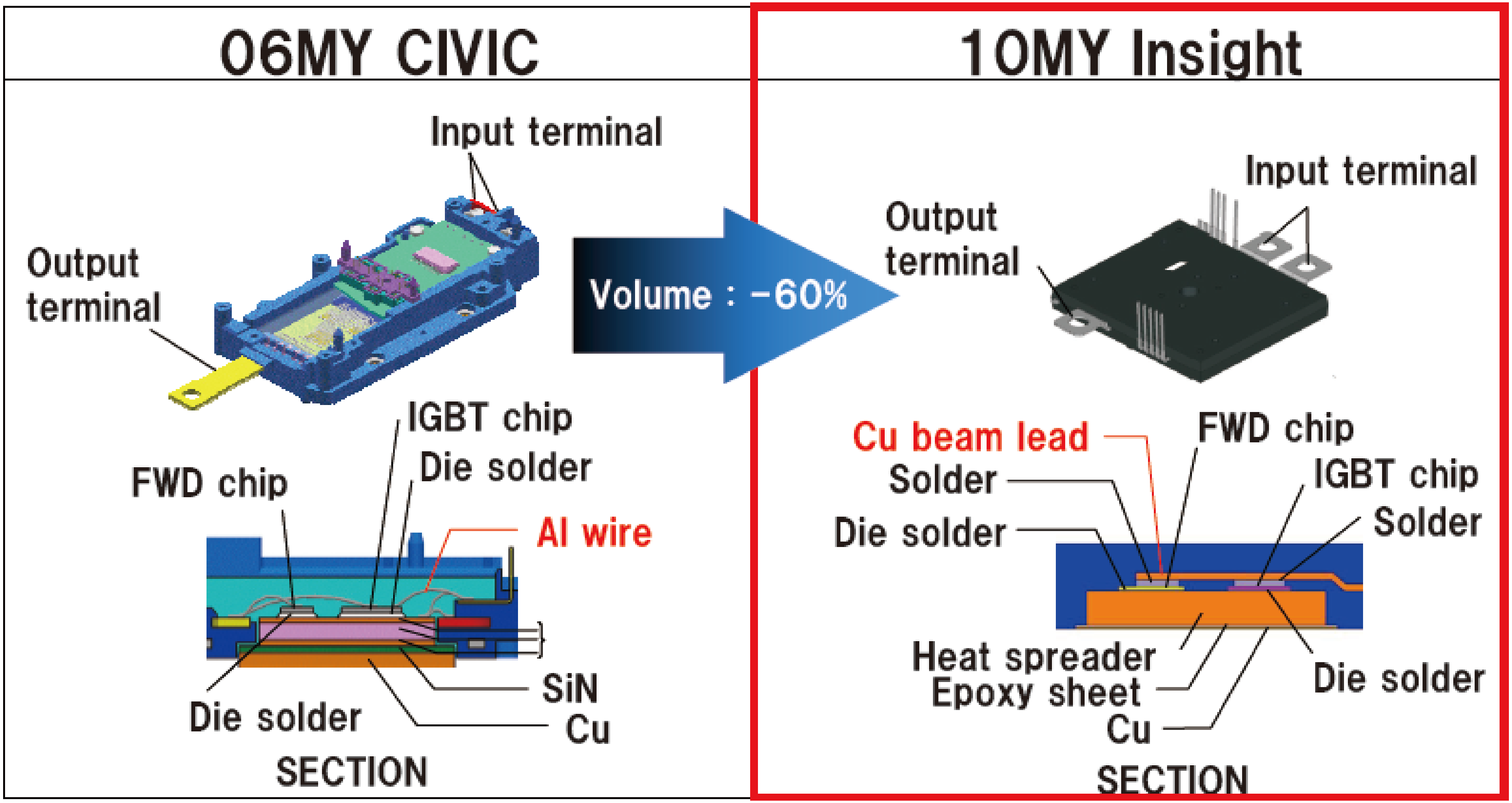
Inverter

Case study

Honda – Improvement from 2006 to 2010

Honda 2010

- **Epoxy packaging**
- **Cu lead bonding**
- **Direct substrate cooling**



Source: Honda

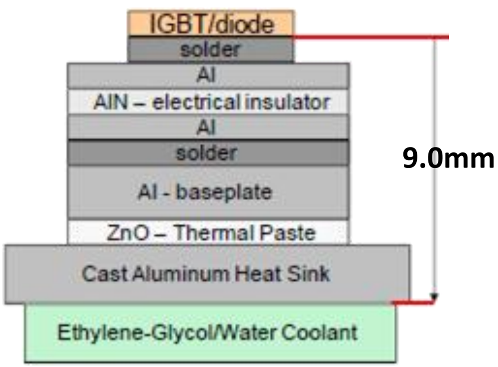
Case study

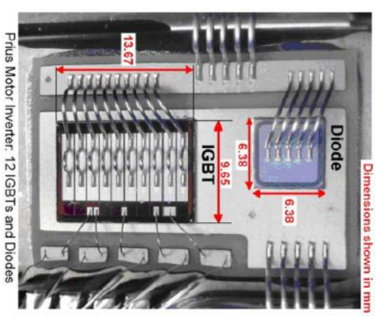
Denso Prius 2004 – Improvement from 2004 to 2010

- **Cost effective basic packaging – 2004**
  - Al wirebonding
  - Al baseplate + Al heatsink
  - Similar to industrial standard

- **Improved packaging - 2010**
  - Denso made cooling improvements
    - Al ribbon bonding replace wires
    - Heatsink is suppressed – cooling is in direct contact with the baseplate
    - Cost effective improvements

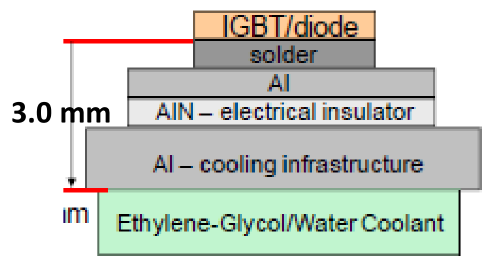
2004 Prius

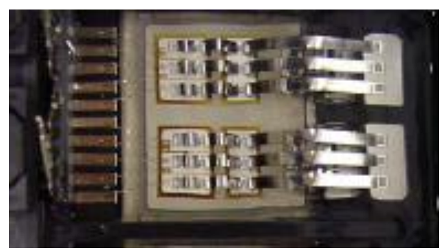




Source: ORNL

2010 Prius





Source: ORNL

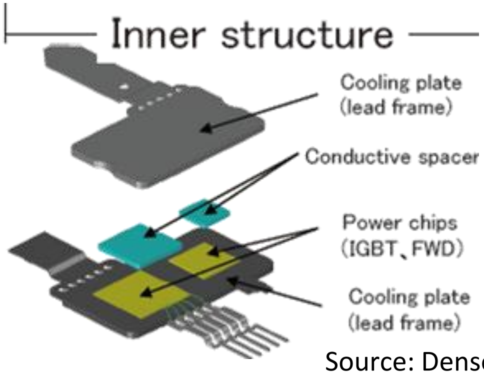
Toyota 2010

- Standard packaging
- Ribbon bonding
- Direct substrate cooling
- Today's standard (2011)

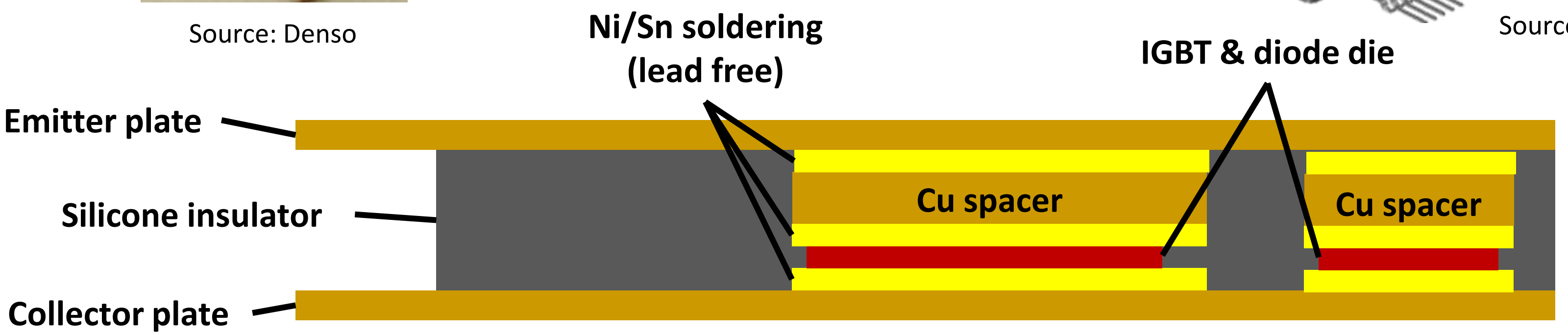
Case study
Denso – Lexus LS 600h

- **Most advanced packaging for HEV inverter. It has been introduced on Lexus LS 600h model 2008**
- **The power module is wirebondless, and mounted for double sided cooling**
- **Modules are stacked with liquid coolant going in between**
- **This packaging is costly, and only for luxury Toyota cars (Lexus brand)**

Source: Denso



Source: Denso

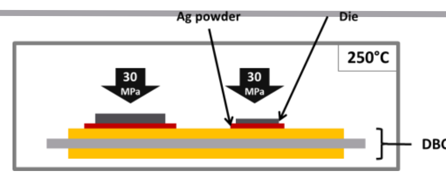


Lexus LS 600h – IGBT/diode module

Conclusions

Analysis of innovation trends in packaging for power modules

<u>Conclusions</u>: Trends in power module packaging

	Current solutions *Widely used by all players*	***Emerging technos*** *At mass production and growing in market shares*	***Potential breakthrough*** *At R&D stage. Still too expensive*
Interconnection	 Al wire bonding	Al ribbon bonding  Copper wire bonding 	Foil sintering Foil ultrasonic wedge bonding 
Die attach	Pb/Sn alloy Or SAC alloy	 Silver micro powder sintering	Nano powder sintering (no heating and pressure for attach process)
Baseplate Cooling	Baseplate + heatsink AlSiC for long lifetime Al2O3 for cost	Thermal exchange improvements:  • Shower power • DBC to heatsink (no baseplate)	 Micro-channel cooling

DBC on both sides:
flip chip
+ Sintering on both sides
+Cooling on both sides

Analysis of innovation trends in packaging for power modules

Conclusions

- **The main improvements aspects are each leading to different technologies, but some breakthrough technologies are promising to solve all these issues at the same time:**
  - Using double side DBC, with integrated cooling could solve all the potential issues at the same time. But production process is not cost effective as of today, and no standard is emerging yet

- **Several technologies are closer in time or already used in high-end packaging:**
  - Direct cooling is becoming a standard and widely used, especially for EV/HEV. There is no clear trend in wirebonding:
    - Copper wires seems on its way to become a standard, being developed by several players including Infineon
    - Semikron pushes for Ag sintering applied to interconnection, but we have to wait and see for the results
    - Denso is putting ribbon Al bonding in Toyota Prius modules
  - Die attach solutions are on the same trends, between copper and Ag sintering

- **The innovation is going to be increasingly driven by EV/HEV players. They need better power electronics conversion systems to gain in added value. Smaller and easier to cool are the two drivers.**

Your contacts at YOLE

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BACKUP SLIDES

Assembly and design

HEV/EV power electronics applications

Device types and power levels

	Micro HEV	Mild HEV	Full HEV	Plug in HEV	EV
1. Start/stop module + DC/DC booster option	MOSFET 1.5 to 10 kW Av: 3.5 kW				
2. DC/DC converter 14V			MOSFET – 1.5 / 3 kW – Av: 2.25 kW		
3. DC/AC inverter + DC/DC booster option		IGBT 5 /20 kW Avg: 15 kW	IGBT – 20 / 80 kW Avg: 50 kW		
4. Battery charger				MOSFET - 3/6 kW – Av: 4.5 kW and then IGBT - 10 / 20 kW – Av: 15 kW	
Total average power / car	3.5 kW	17.25 kW	52.25 kW	56.75 to 102.5 kW (for a single motor setup)	

Source: Yole Développement

Here are the applications that are specific to HEV/EV. Standard ICE power device applications are not considered (oil pump, steering, braking, HVAC….).

Auxiliary inverters have not been considered due to the small amount of power devices.

Introduction

Power Range of the targeted applications