TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Elektrotechnik und Informationstechnik Institut für Aufbau- und Verbindungstechnik der Elektronik

36th International Spring Seminar on Electronics Technology, Alba Julia
"Automotive Electronics"

"Reliable Power Electronics for Electric Vehicles"

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May 9th 2013

DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

- **Introduction**
- Trends in Power Electronics Packaging
- Challenges and Solution for Soldered Interconnects
- Summary

Electro mobility - a 100 year old vision

Figure 45. Fred Allison and the 1913 Ford experimental car. (From the collections of Henry Ford Museum & Greenfield Village, neg. 0-1923)

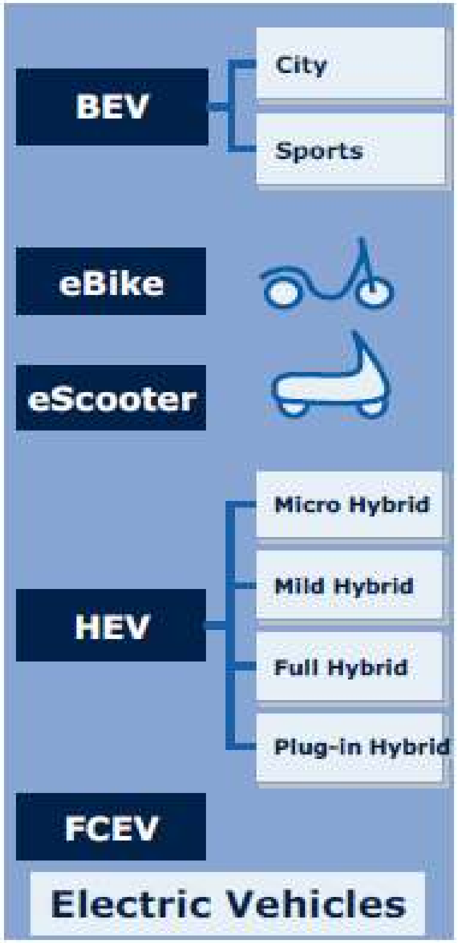
Images Source : Ford

Mega Trends in future global development:

- Demographic Change
- Globalization
- Lack of resources
- Climate change
- **Urbanization**

  The future impact of the city development on mobility, working life and societies is going to be tremendous.
- **Mobility**

  Electric Vehicle (EV) is a major trend that will impact the mobility of people and will change the Automotive, Auto-component and related industries.



BEV: Battery EV, HEV: Hybrid EV, FCEV: Fuel Cell EV

Source : Infineon

Urban	**Interurban**	**Long distance**
		

ICE – mild hybrid (15 % fuel reduction) **/ ICE - full hybrid** (25 % fuel reduchtion)

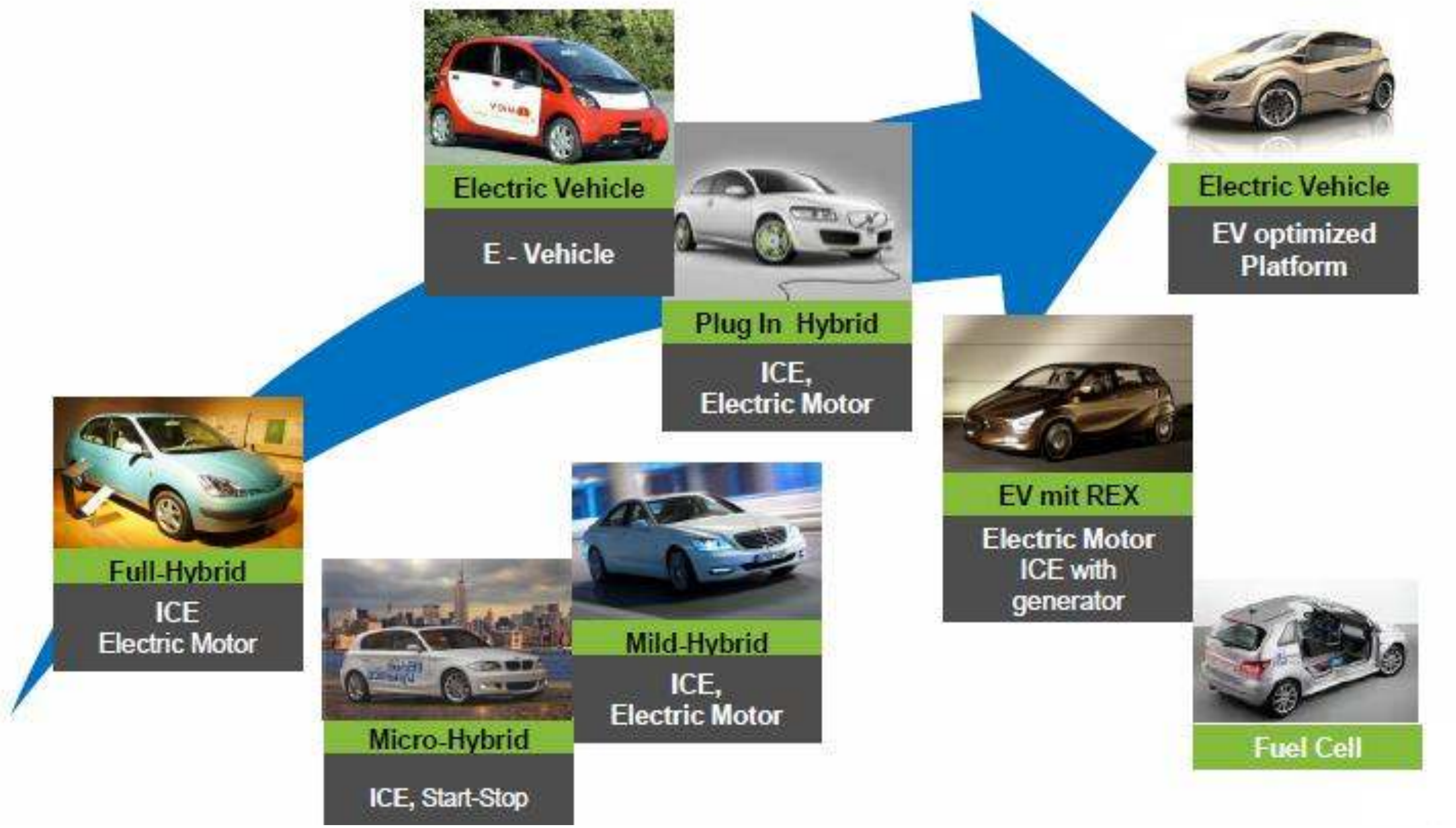
(ICE- Internal Combustion Engine)

Plug in hybrid (65 % fuel reduction)

Battery Electric Vehicle

Fuel cell range extended Electric Vehicle

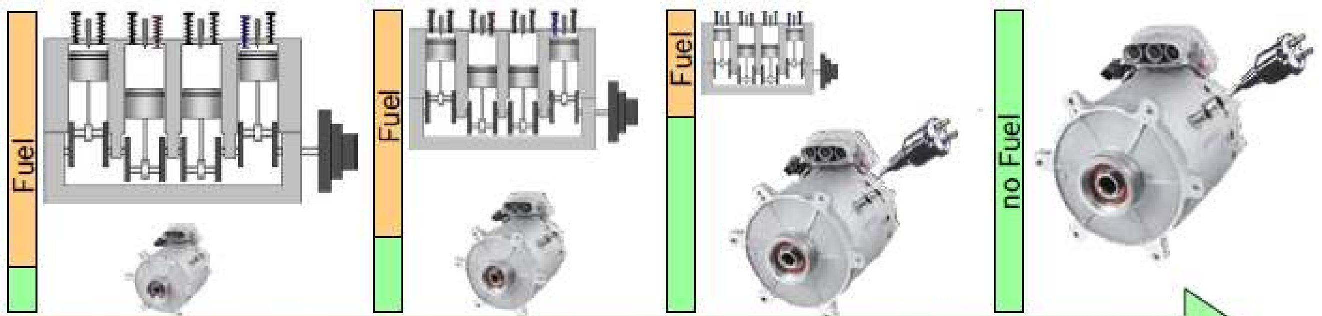
Images Source : Magna



Images Source : Magna

Intermediate Steps to pure Electric Driving

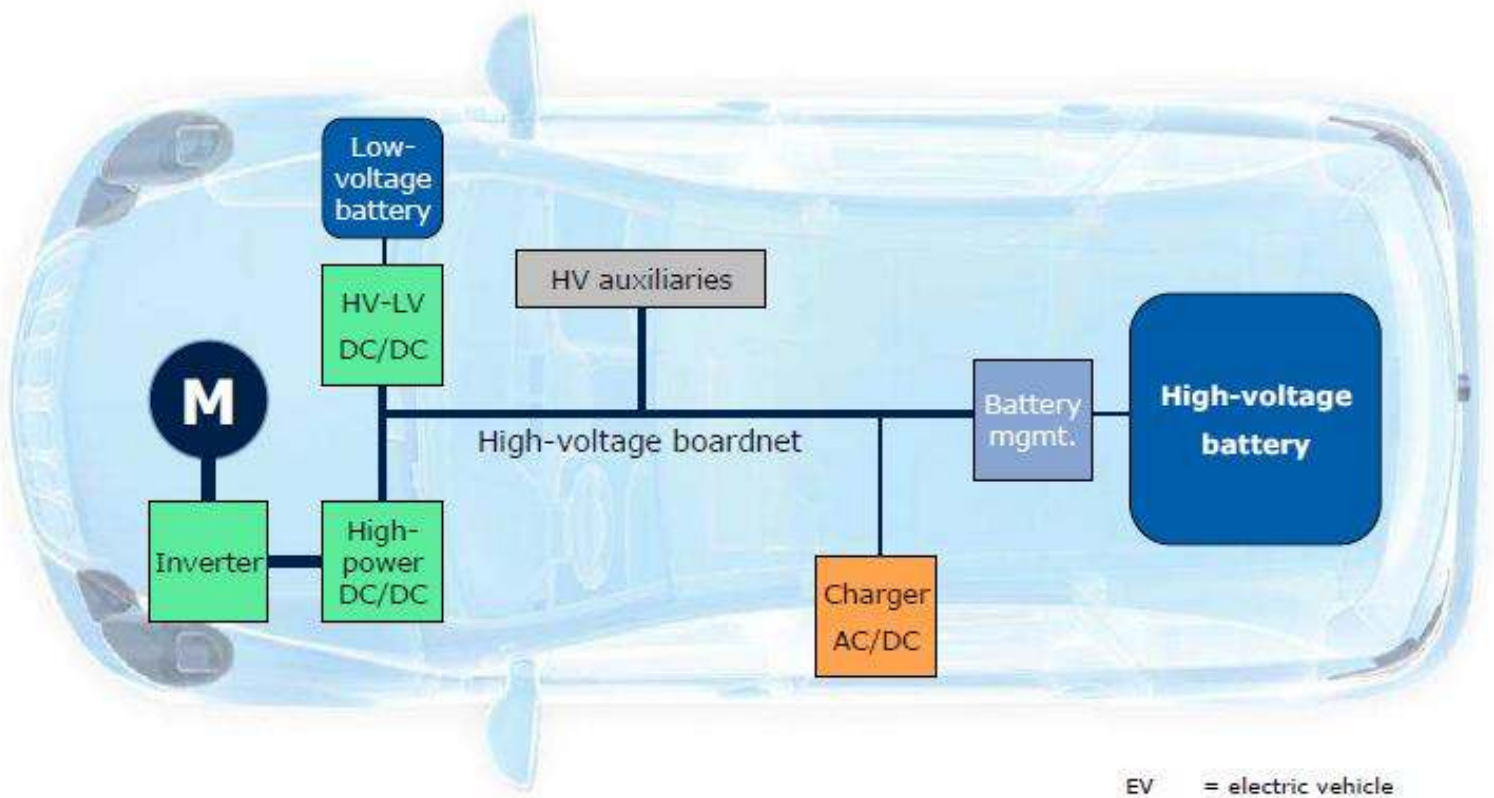
	Mild Hybrid	Strong Hybrid	Plug-In Hybrid	Electric Vehicle
Electric Power	**5 – 15 kW**	**20 – 60 kW**	**40 – 80 kW**	**15 – 150 kW**
Voltage	**100 – 150 V**	**250 V**	**350 V**	**400 V**
Battery type	**medium power**	**high power**	**high energy**	
Energy	**0,6 – 1,8 kWh**		**5 – 15 kWh**	**> 15 kWh**
Cell size	**5 Ah**		**20 – 40 Ah**	**40 – 60 Ah**
Function	Start/Stop regenerative braking, torque support **→ fuel reduction 15%**	same as Mild HEV + El.-driving **→ fuel reduction 25%**	same as Strong HEV + grid charging **→ fuel reduction 65%**	**pure electric driving**



Hybrid Vehicles are Bridge Technology from Conventional to Electric Vehicle

Source : BOSCH

Components of Battery Electric Vehicle



EV	= electric vehicle
HEV	= hybrid electric vehicle
HV	= high-voltage
LV	= low-voltage
AC	= alternating current
DC	= direct current

Source : Infineon

	2009 EV 1. generation	2015 1. Gen evolution	2020 EV 2. generation
Battery capacity	**24 kWh**	**24 kWh**	**24 kWh**
Battery weight	**300 kg**	**160 kg**	**120 kg**
Energy density (Battery system)	**80 Wh / kg**	**150 Wh / kg**	**200 Wh / kg**
Range	**100 km**	**150 km**	**200 km**
Battery price	**very high**	**high**	**moderate**
Market phase	**Development phase**	**Market expansion**	**Penetration**

Source : BOSCH

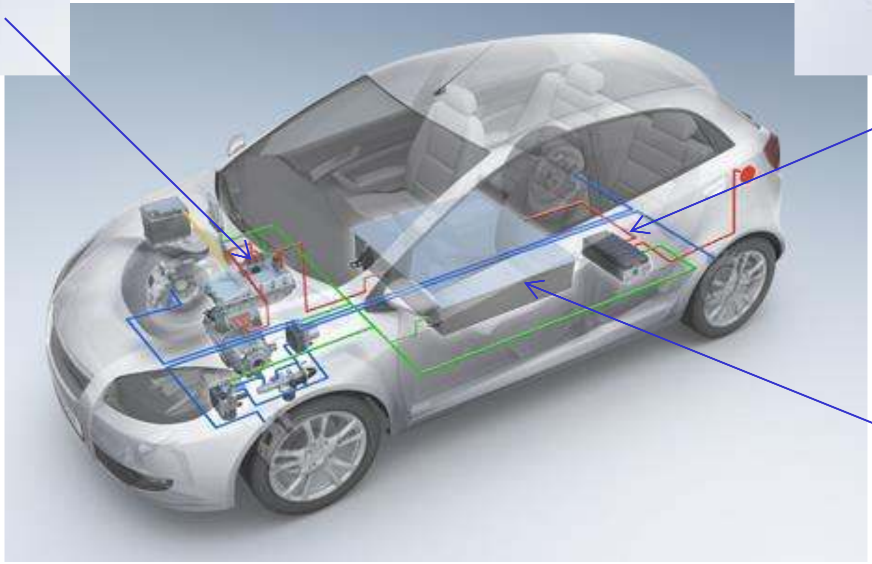
Location of Components

Inverter

Battery Charger

AC/DC-Converter

DC/AC-Converter



Lithium Battery

Images source : BOSCH

VISIO M/BMW for Urban Traffic

Passengers: 2
Trunk: 500 Liter
Range: 160 km
Prize: as compact car

Market: Europe

Speed: 120 km/h
Power: 15 kW (cont.)
Weight: 400 kg +
100 kg Battery

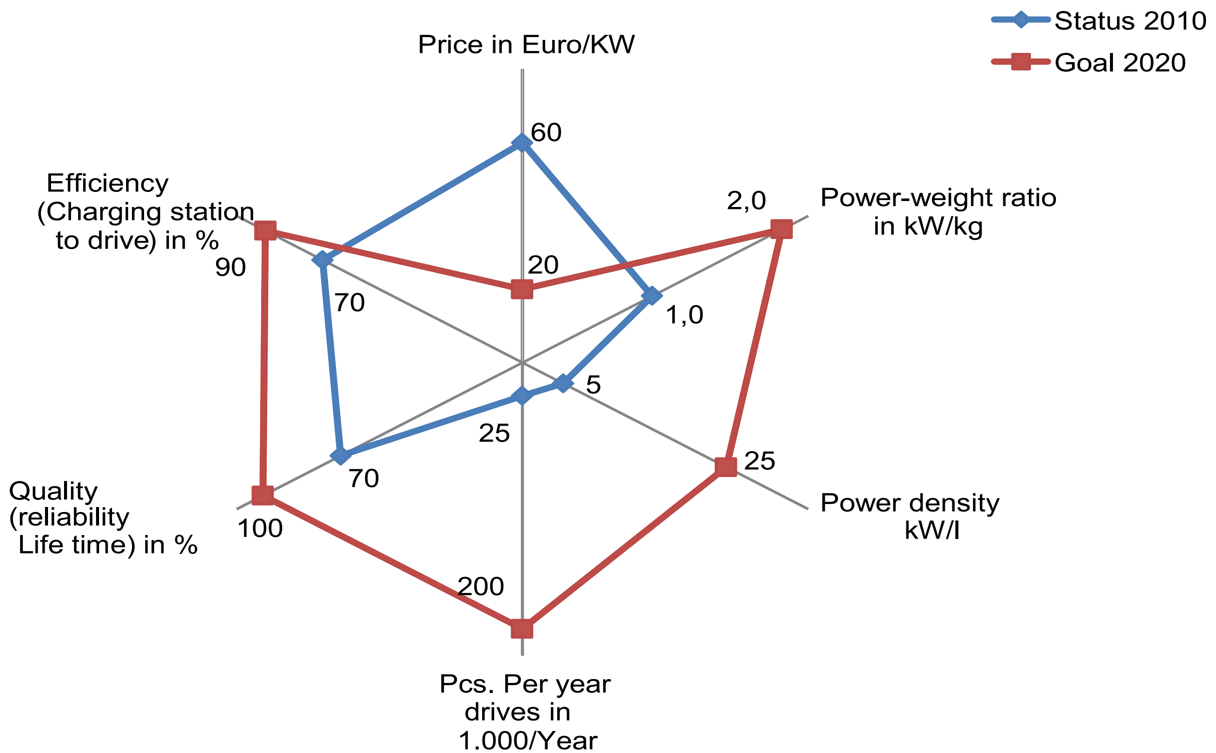
Image Source : BMW

- **ProPOWER is the project funded by**
- **Timeline: Jan. 2012 to Dec. 2014**
- **Partners in the project:**

Federal Ministry of Education and Research

SIEMENS, BOSCH, Infineon, OSRAM, eesy-id, VIA electronic, andus ELECTRONIC, HOFMANN LEITERPLATTEN, F&K DELVOTEC, Heraeus, Seho, GÖPEL electronic, Danfoss, Audi, FAPS, KIT Karlsruher Institut für Technologie, Fachhochschule Kiel University of Applied Sciences, TU berlin, Fraunhofer ENAS, Fraunhofer IISB, AVT

ProPower Project – Goals of Drive Systems



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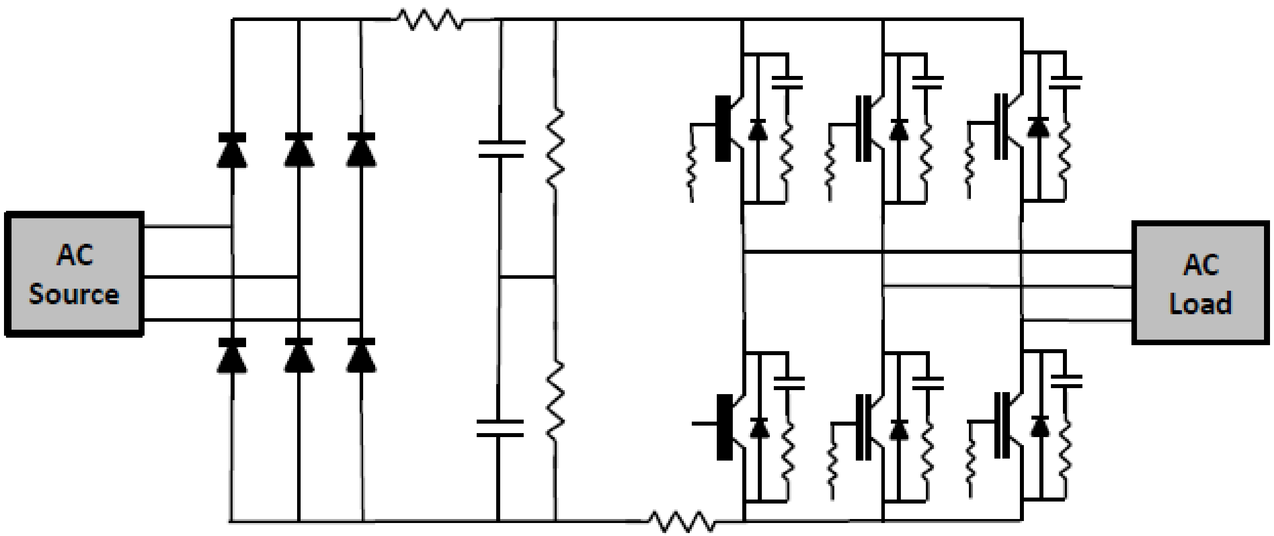
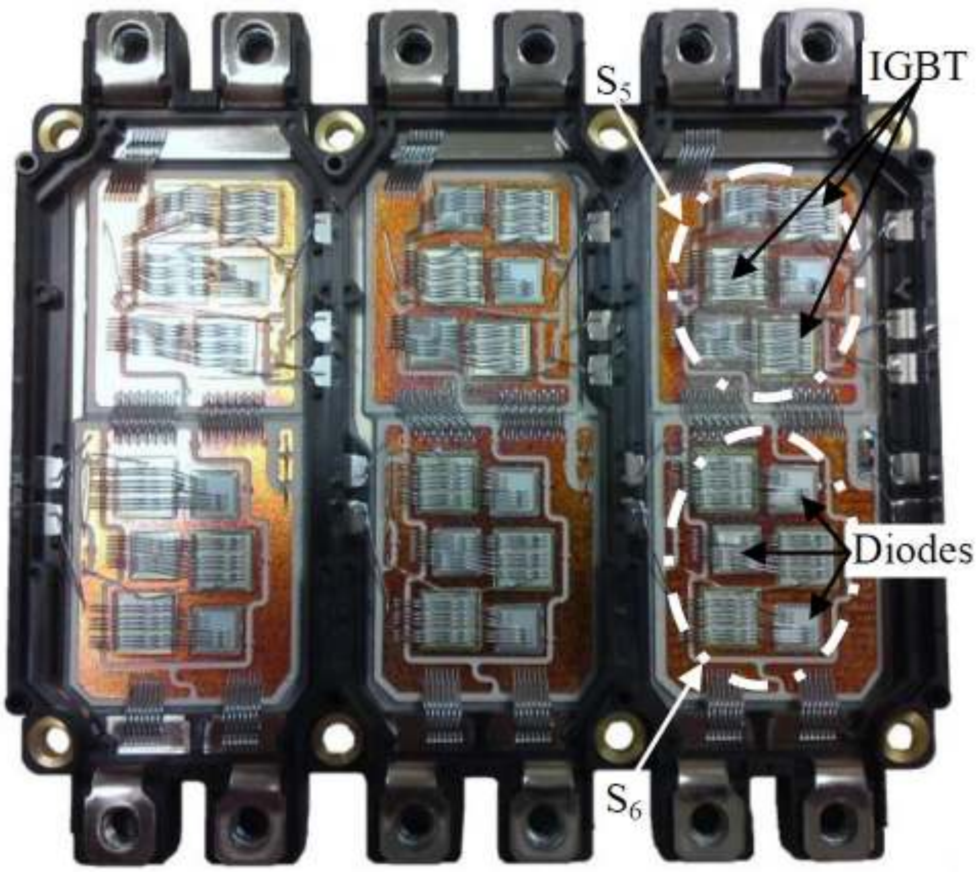
- Generic schematics of an inverter



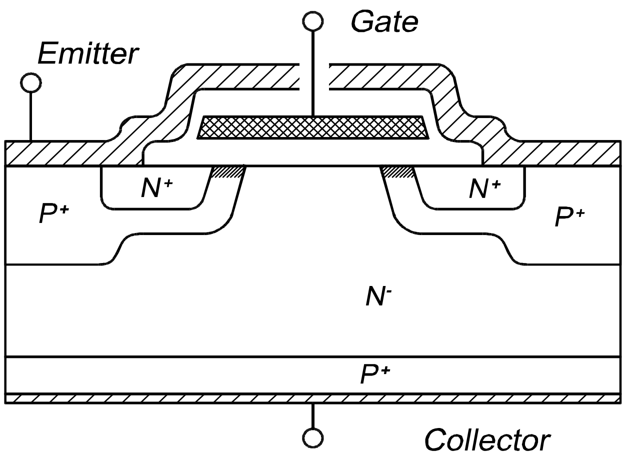
- An inverter is used for power conversion, with two main purposes:
  - Electricity conversion for transportation, distribution or storage
  - Motion for electric motors: conversion if from electricity to another type of energy (mechanics basically)

Source: Yole 2012

Typical IGBT-Module

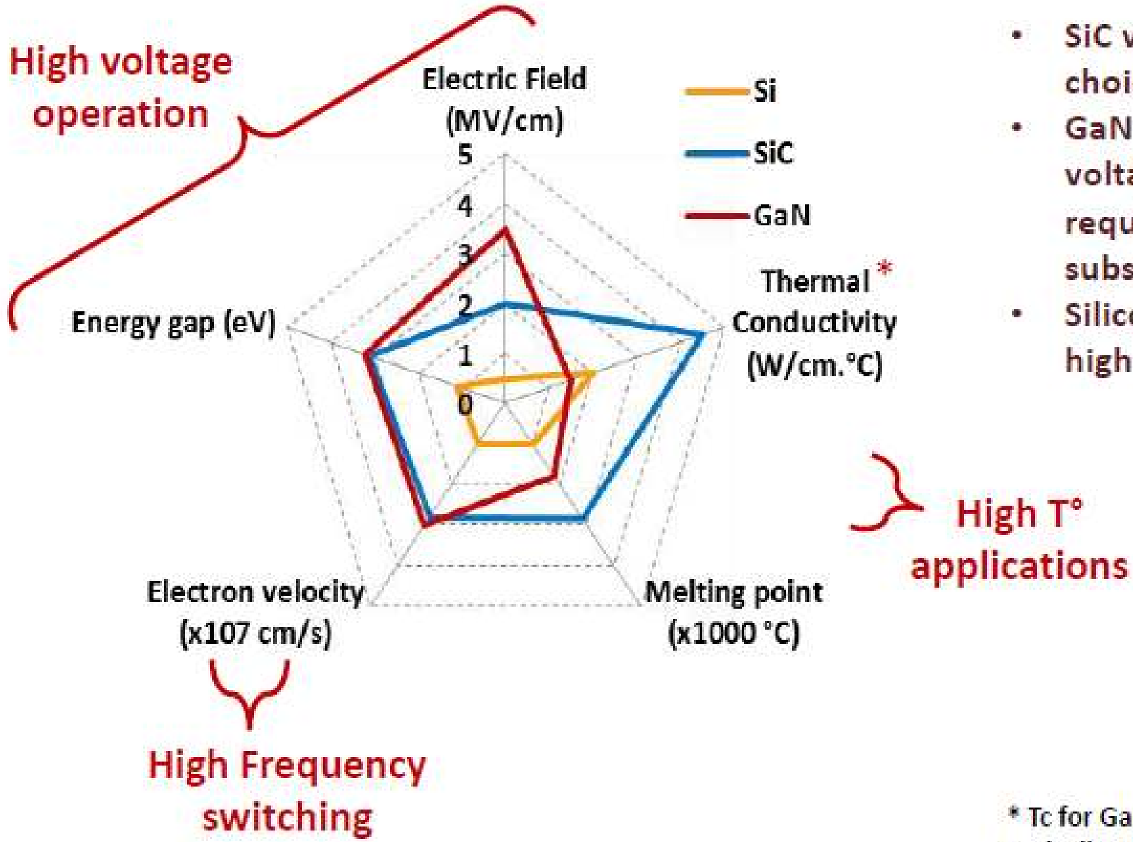


IGBT – Insulated Gate Bipolar Transistor



Source: Antonios et. al.

Comparision of Semiconductor Materials

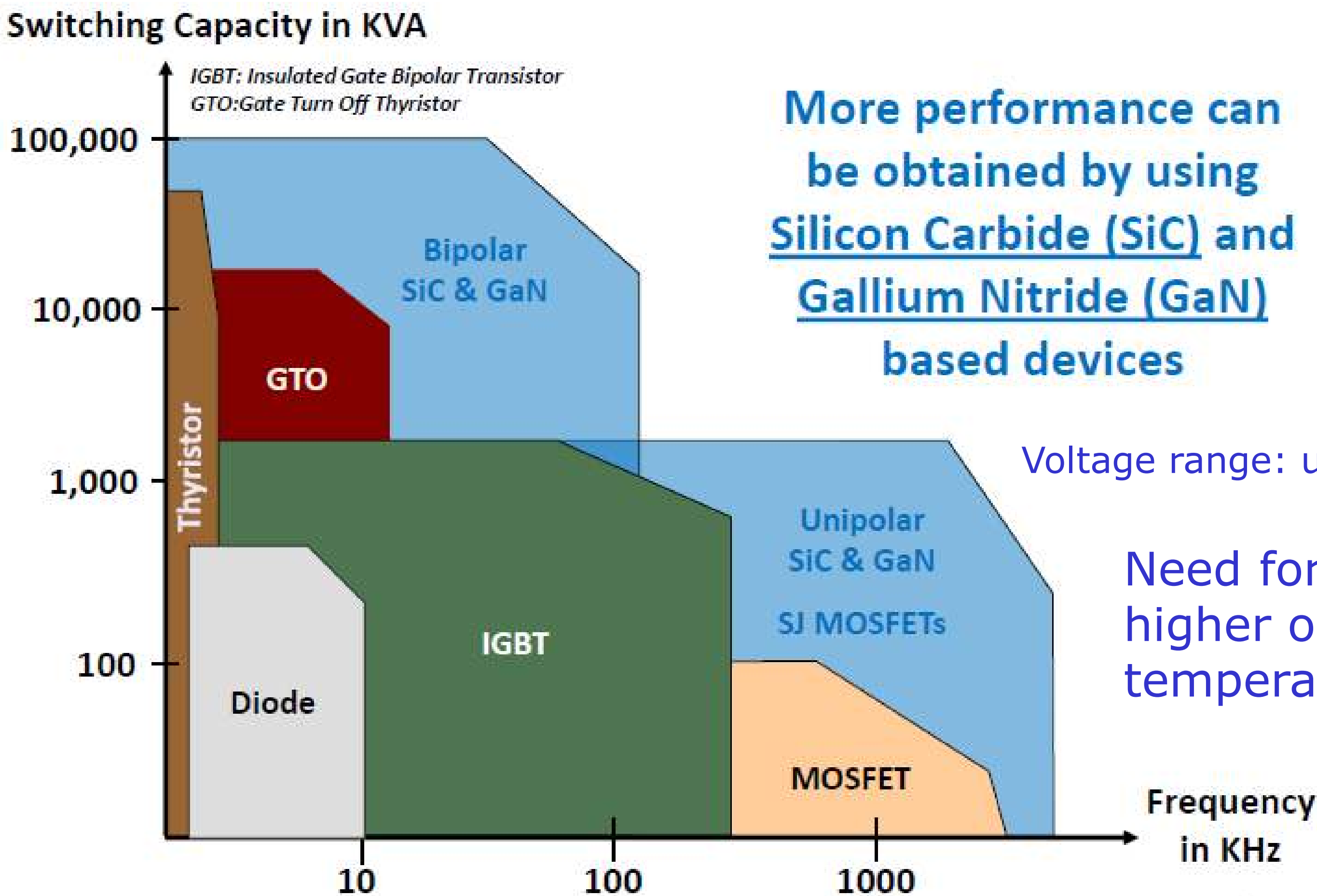


- SiC will stay the preferred choice for high T° application
- GaN could possibly reach high-voltage values but thus will require bulk-GaN as the substrate.
- Silicon cannot compete at the high-frequency range

* Tc for GaN is given here for GaN-on-Si typically. It has been demonstrated that Tc of bulk GaN could reach 4 W/cm.°C

Source: Yole 2012

Expanding Device Family

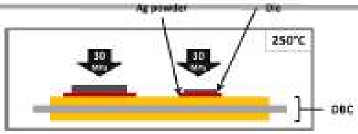
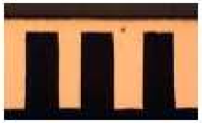


More performance can be obtained by using Silicon Carbide (SiC) and Gallium Nitride (GaN) based devices

Voltage range: up to 6,5 kV

Need for packages for higher operating temperatures

Source: Yole 2012

	Current solutions *Widely used by all players*	***Emerging technos*** *At mass production and taking up 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 	DBC on both sides: flip chip + Sintering on both sides +Cooling on both sides
Die attach	Pb/Sn alloy	 Silver micro powder sintering	Nano powder sintering (no heating and pressure for attach process)	
Baseplate Cooling	Baseplate + heatsink AlSiC for long lifetime Al_2O_3 for cost	Thermal exchange improvements:  • Shower power • DBC to heatsink (no baseplate)	 Micro-channel cooling	

Source: Yole 2012

➔ Targets for improvements in interconnection
- Resistivity
- 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

➔ Number of wires and thickness is limited

➔ Reliability and lifetime is caused by wires detaching

	Al wirebonding	Al ribbon bonding	Copper wire bonding	Semikron Skin
Resistivity	Taken as reference	same	40% better	Same (current density is improved)
Thermal conductivity		same	2x better	Almost the same
Lifetime		Improved (larger pads)	Improved from thermal performance	70x better (Ag sintering)
Status		In production, still expensive	Close to mass production	Close to mass production

Source: Yole 2012

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 step manufacturing

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

➔ Targets for improvements die attach

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

	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	More than 400°C	More than 400°C
Manufacturability		In mass production	In mass production Difficult to produce (pressure + temperature)	At R&D stage Nano-particle regulation issues Will be easier to manufacture

Source: Yole 2012

➔ Targets for improvements in DBC + Baseplate assembly

- Cooling capabilities
  - Thermal resistance
  - Thermal path
- Size and volume reduction

TODAY

- DBC is the standard – Al_2O_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

	Al_2O_3	Si_3N_4	AlN	AlSiC
Thermal conductivity	Taken as reference	same	40% better	Same (current density is improved)
CTE matching	Taken as reference	same	2x better	Almost the same
CTE matching	Taken as reference	Improved (larger pads)	Improved from thermal performance	70x better (Ag sintering)

Source: Yole 2012

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Need for Thermal Management

Electric Motor Efficiency

5% Inverter losses

- Ohmic losses
- Junction losses
- Switching losses

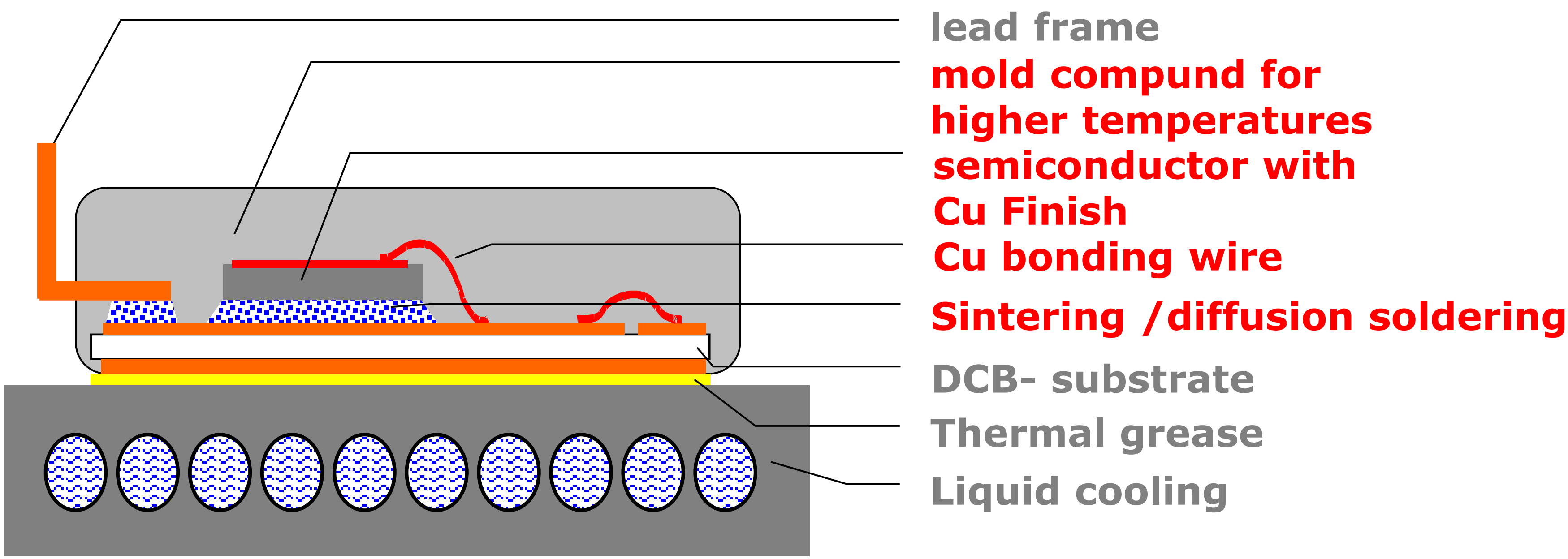
5% Motor losses

- Ohmic losses
- Magnetic losses
- Friction losses

Electric Power for EV	Inverter losses (5%)
15 kW	750 W
60 kW	3000 W
80 kW	4000 W
150 kW	7500 W

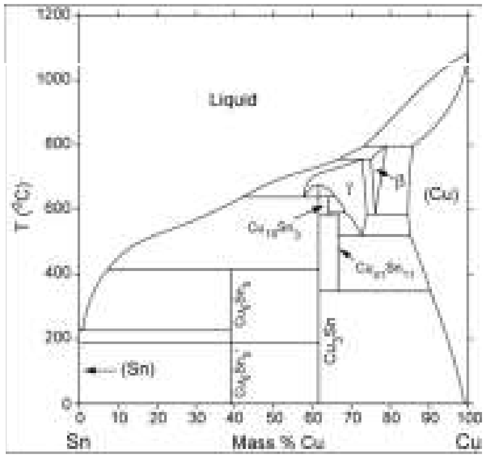
Source: Infineon

Example of innovative power module with improved reliability for increased operating temperatures



Source: M. Kock, Danfoss, modified

The Sn-Cu-System for soldered Die Attach



	Liquidus for soldering	electrical conductivity in 1/ohm cm	thermal conductivity in W/cm K	Young`s Modulus in GPa	Temperatur for re-melting
SnCu0,7 (Sn99Cu1)	227°C	0.80×10^5	0,660	49,90	227°C
Cu_6Sn_5	-	0.57×10^5	0.341	85.56	415°C
Cu_3Sn	-	1.12×10^5	0.704	108.30	638°C

values taken from: Journal of Non-Cristalline Solids;
Lee et.al @ 2007 Electronic Components and Technology Conference;
Indium Corp.

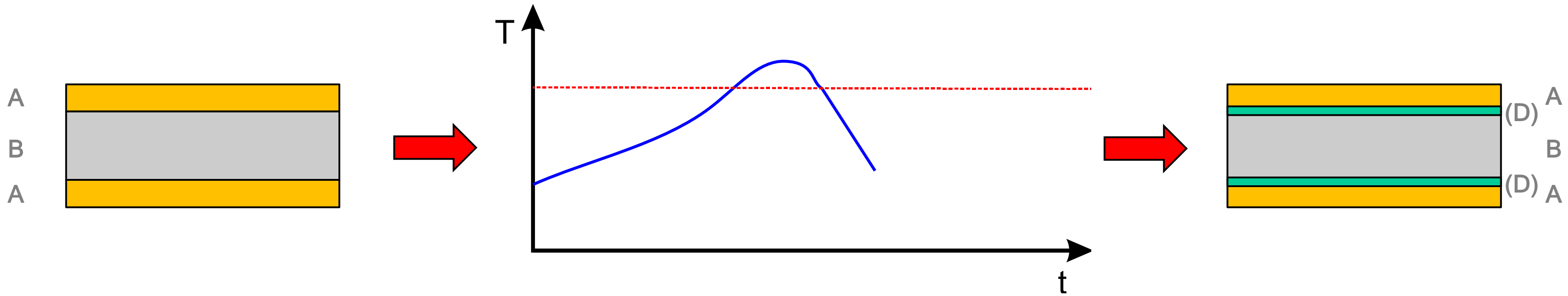
Homologous temperature: $T_H = T_{op}/T_{mp}$ (both temperatures in K)

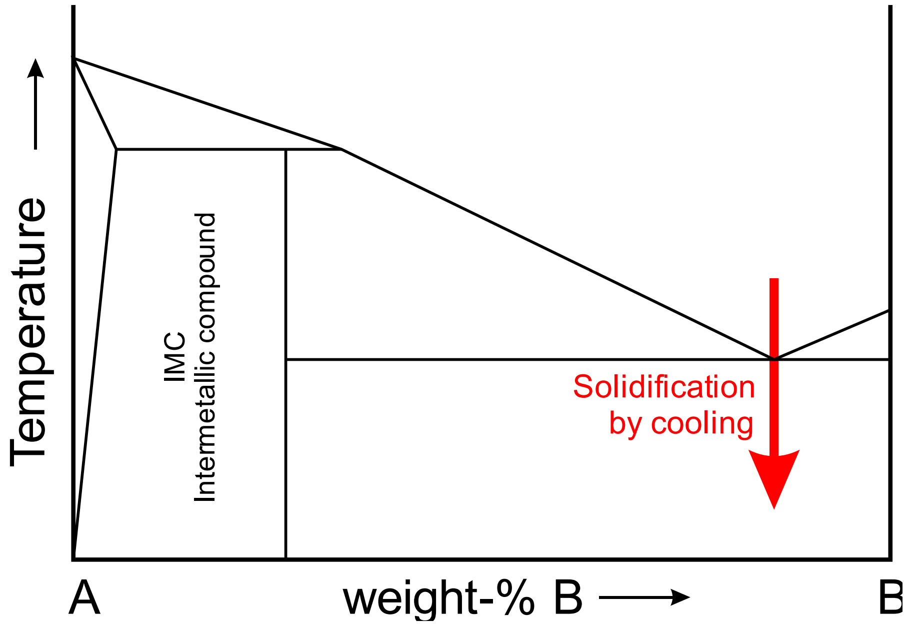
$T_H < 0.4$ … no or small influence on materials behavior
$T_H > 0.4$ … creeping
$T_H > 0.7$ … strong decrease of mechanical strength

Homologous temperature of SnAg solder vs. SnCu IMP and Ag:

Material	SnAg3,5	Cu_6Sn_5	Cu_3Sn	Ag
Melting temperature [°C]	221	415	638	961
T_H for 125°C	0,81	0,58	0,44	0,32
T_H for 150°C	0,86	0,61	0,46	0,34
T_H for 200°C	0,96	0,69	0,52	0,38
T_H for 250°C	1,06	0,76	0,57	0,42

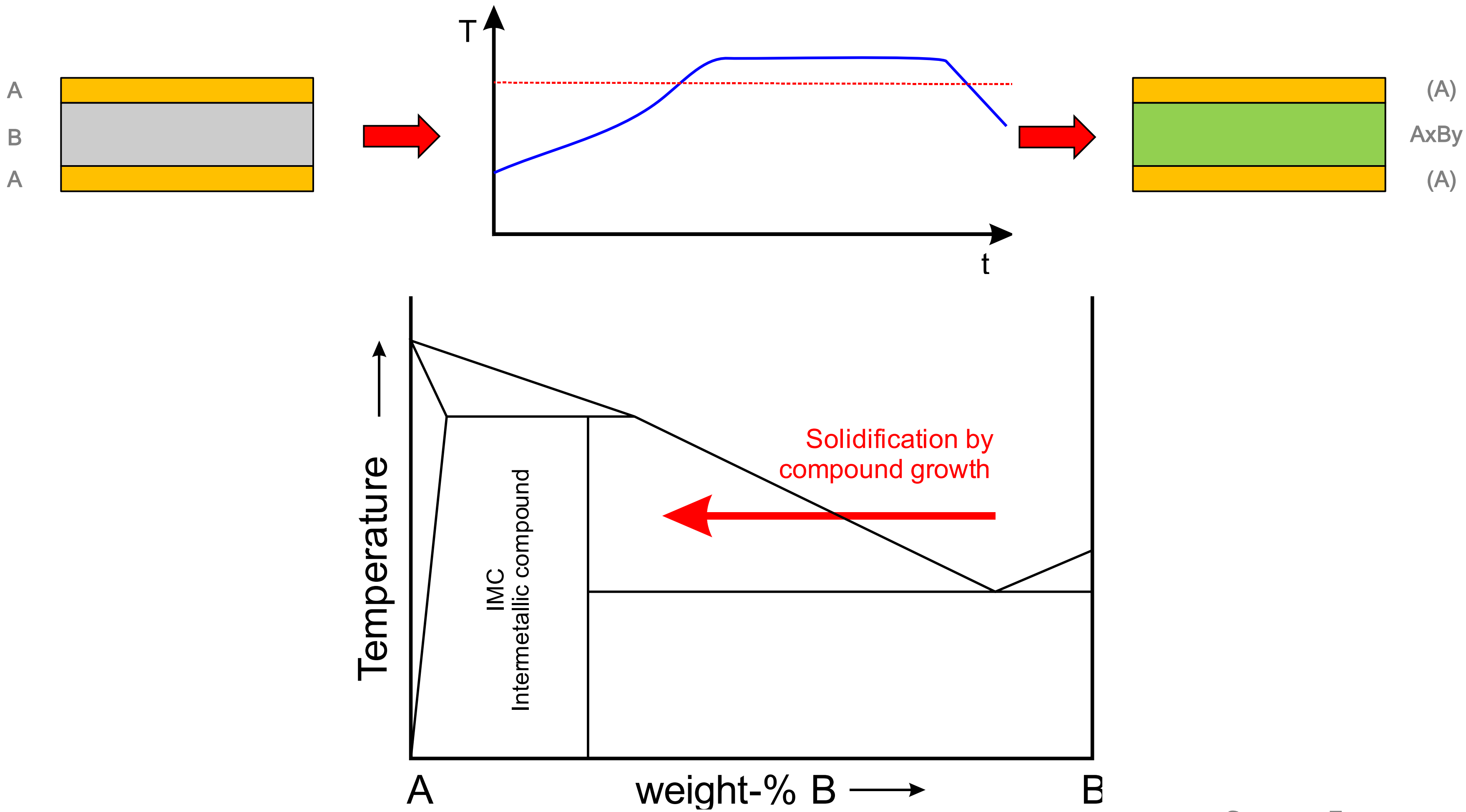
Solidification during soldering (I)





Source : Zerna

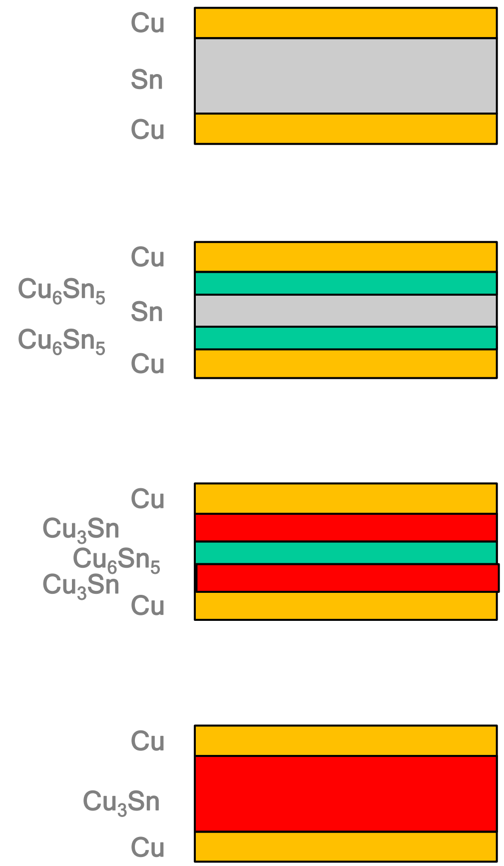
Solidification during soldering (II)



Source : Zerna

Isothermal solidification of Cu-Sn-Cu stack

- During initial stages both Cu_6Sn_5 and Cu_3Sn phases grow.
- After consumption of all available Sn, the Cu_3Sn phase grows reactively at the expense of Cu and Cu_6Sn_5.
- Finally, we obtain solder joints consisting of only Cu_3Sn.



Source : Zerna

Possible realizations

Option 1:

- Use layer stack of solid metals/alloys between components
- Forming interconnection with temperature and maybe pressure
- Interconnecting material becomes temporarily liquid

→ SLID: Solid Liquid InterDiffusion

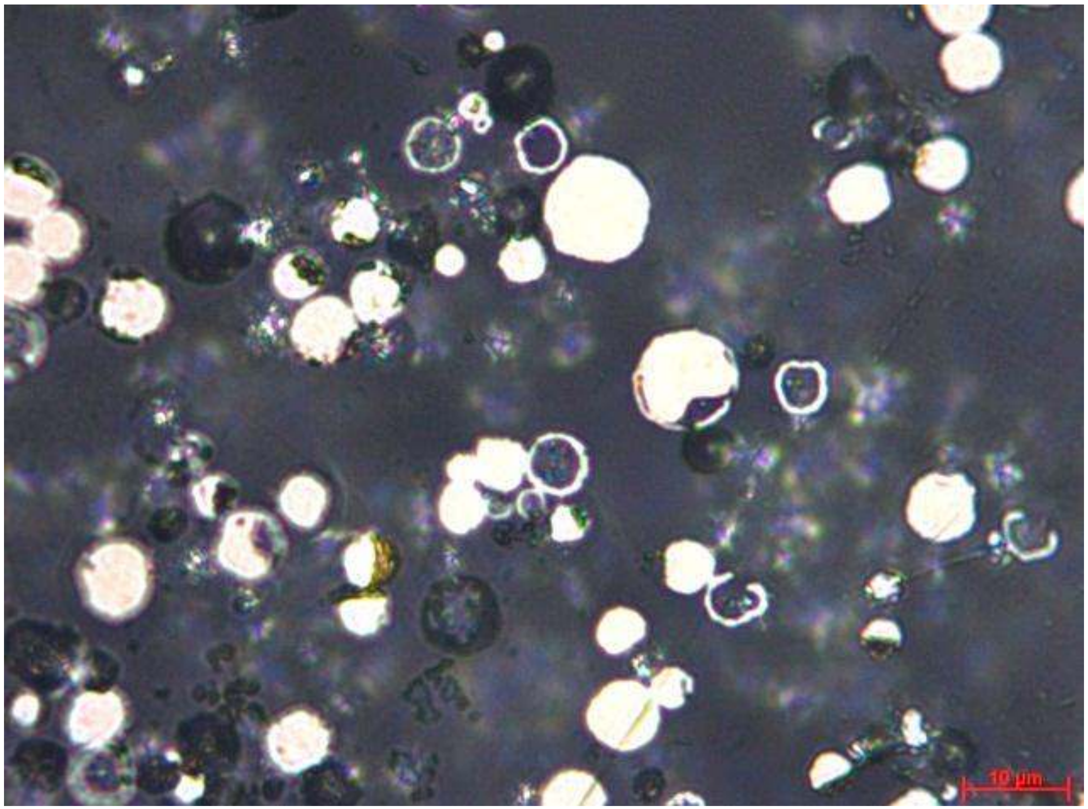
Option 2:

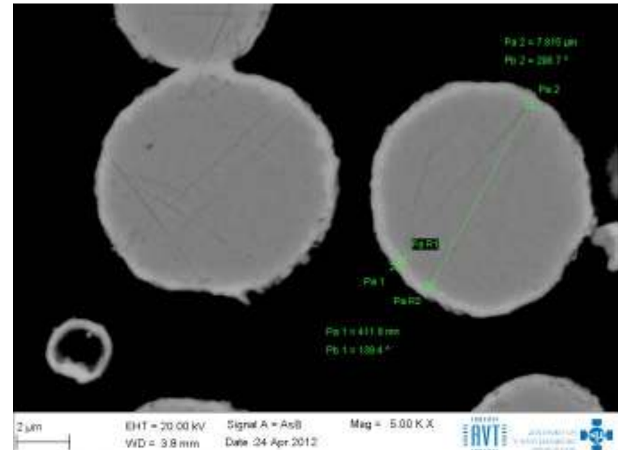
- Use interconnecting material in paste-like state
- Remelt paste (reflow soldering) and keep temperature until IMC growth is completed

→ Diffusion soldering

Source : Zerna

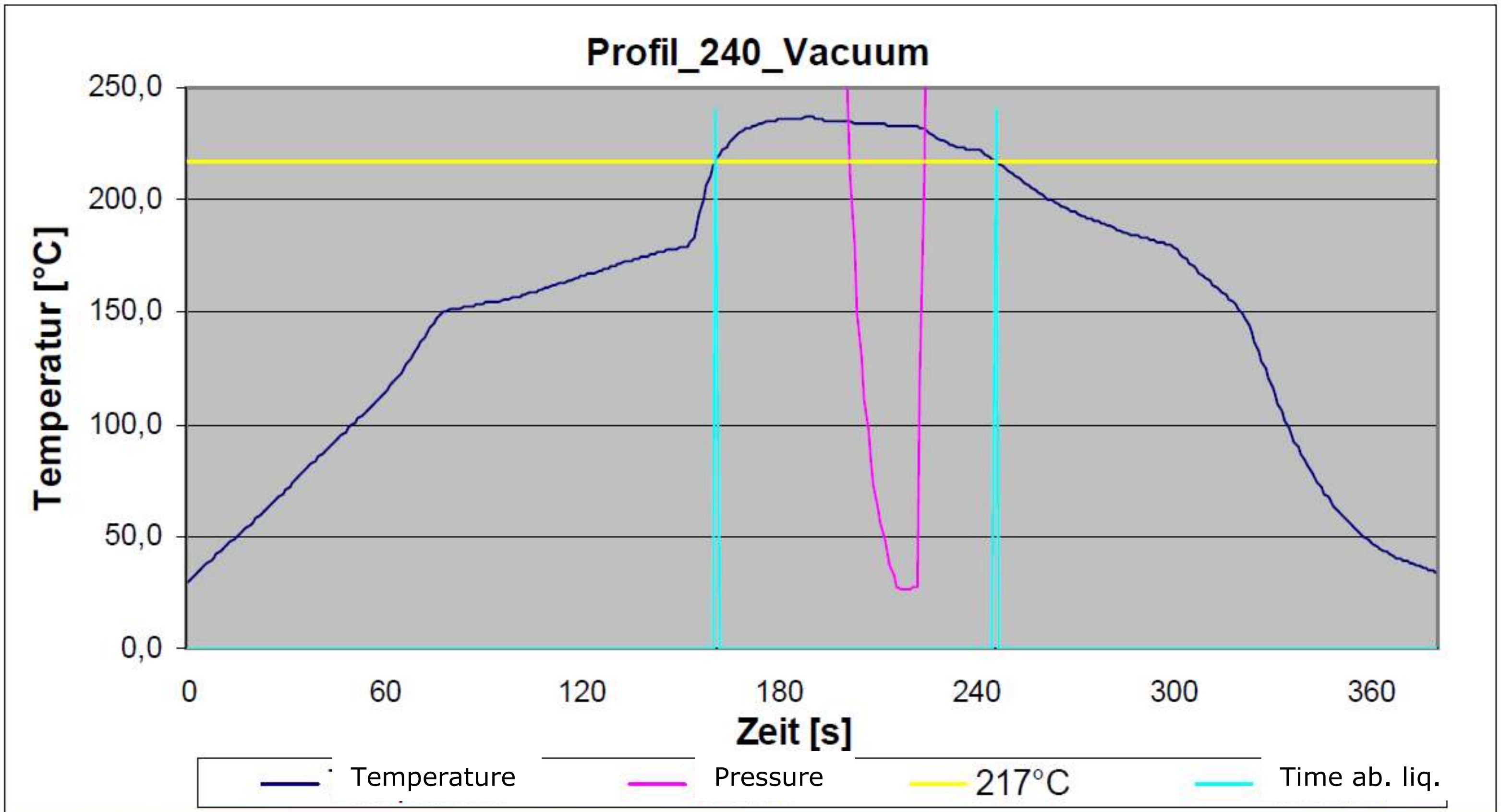
- **Cross section SEM**





Source : Zerna

Combination of vapor phase soldering and vacuum (CONDENSO)

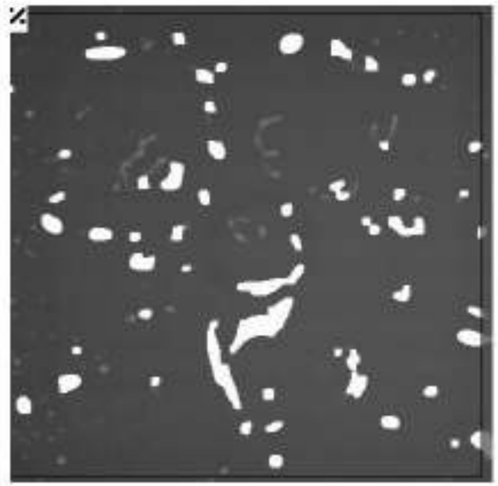


Source: Rehm Thermal Systems/IAVT

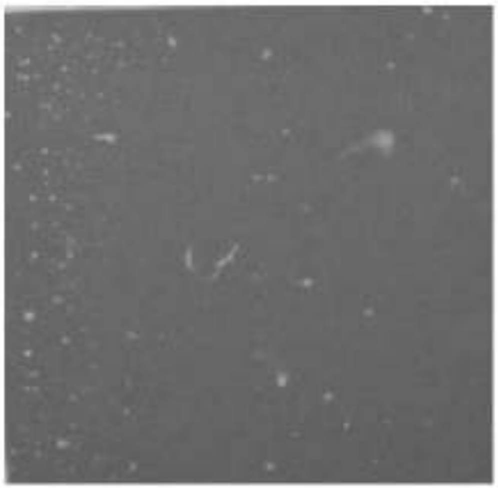
Approach I to „avoid voids“

Si-Chip, Paste: SnAgCu

Convection soldering with N_2



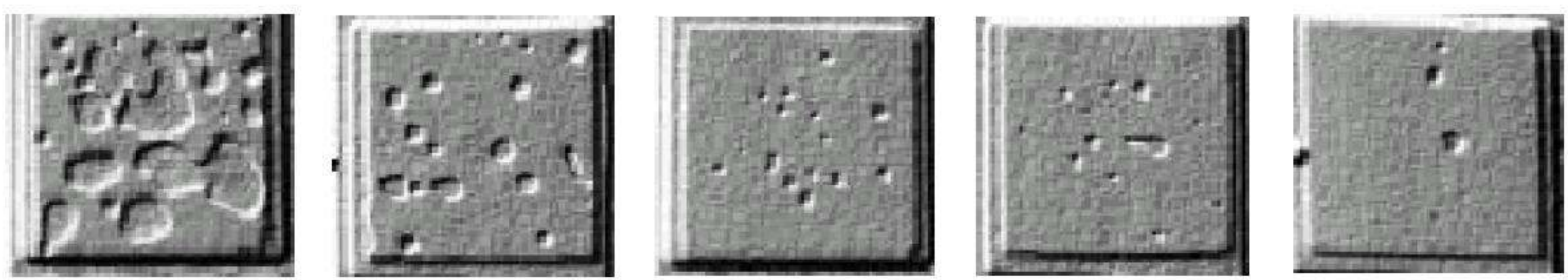
Condenso Paste thickness 125 µm



Condenso Paste thickness 180 µm

Source: Rehm Thermal Systems/IAVT

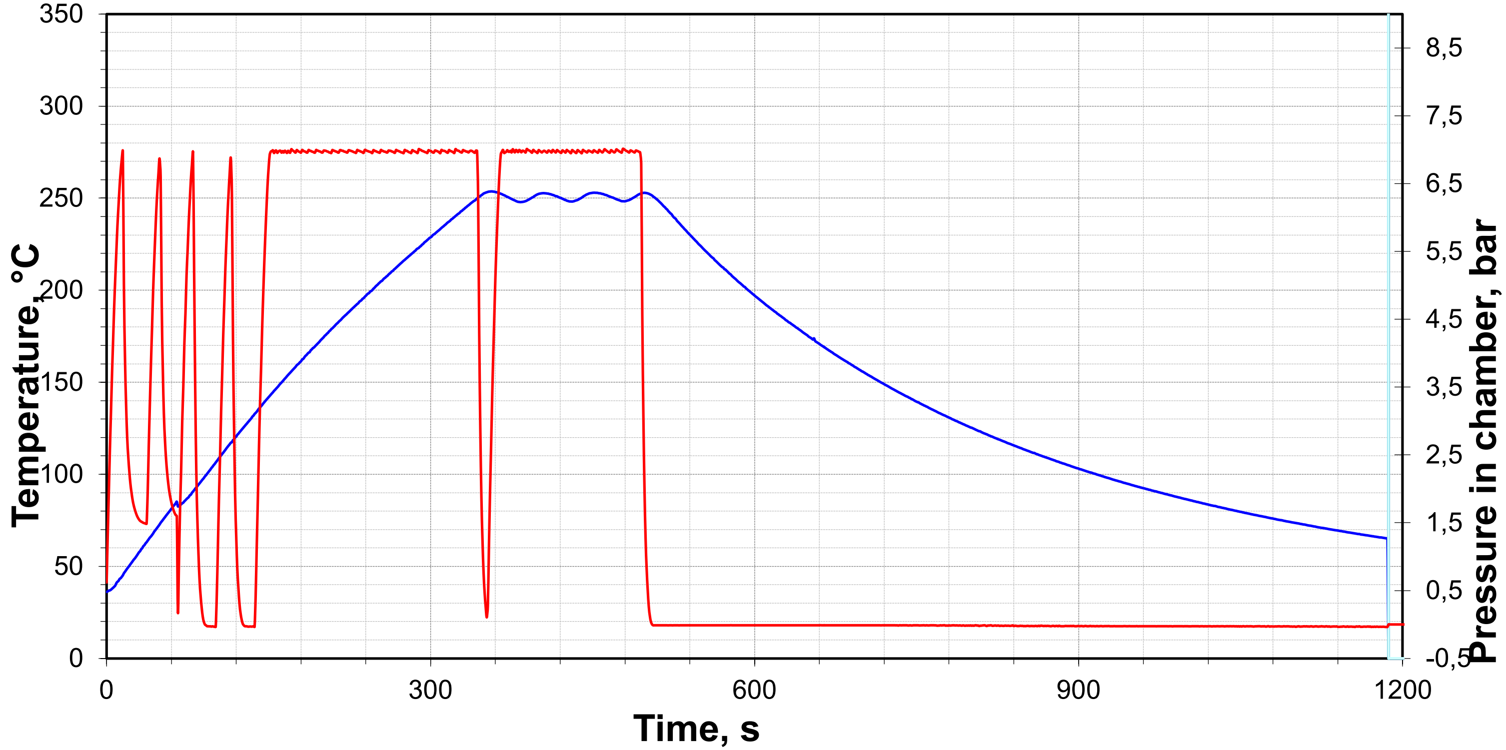
Influence of vacuum pressure



1 bar **200 mbar** **20 mbar** **2 mbar** **0,2 mbar**

Source: Rehm Thermal Systems/IAVT

Combination of convection soldering and temporary high pressure



Source : Seho/Zerna

Summary and outlook

- Reliable power electronic devices require emerging packaging technologies for higher operating and ambient temperatures
  - Copper wire bonding
  - Diffusion soldering or
  - Micro Ag-sintering for die attach
  - DBC for baseplate.

- Solder joints with intermetallic compounds growth can be a solution for high temperatures die attach.

- Challenges for diffusion soldering are long process time, voiding in area soldering and brittleness of IMC.

- Future packaging technologies for power electronic devices will require
  - Foil sintering and foil ultrasonic wedge bonding
  - Nano Ag-sintering for moderate heating and pressure for die attach
  - Micro channel cooling in DBC baseplate.