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3D-FE electro-thermo-magnetic modeling of automotive power electronic modules - Wire-bonding and Copper clip technologies comparison

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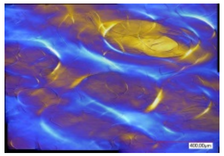
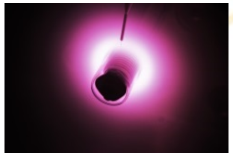
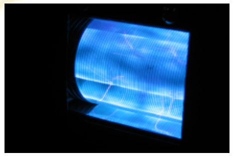
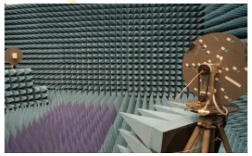
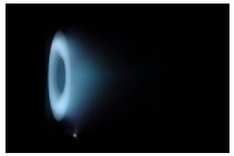
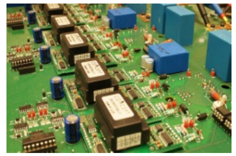




Contents

Introduction

Conventional improvment

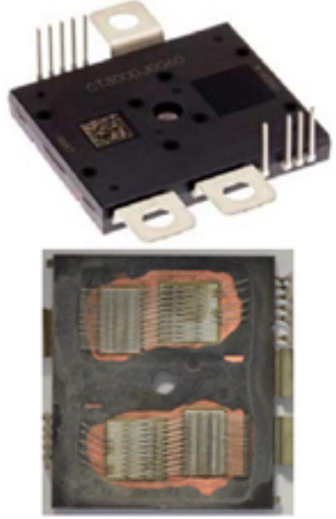
- Direct-Lead-Bonding (DLB) with thick copper clips at the top of chips
- Use large diameter copper wires bonding (WB) in parallel

Comparison study by finite elements (electro-thermal modeling)

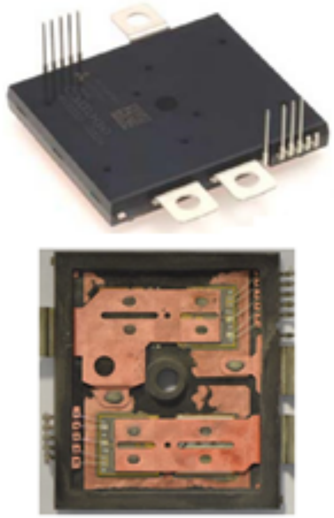
- Electromagnetic simulations in AC (20kHz) and DC
- Thermal study in steady and transient

Using wire-bonding (WB) power modules for high current applications (typically up to 600A DC @ Tcase=25°C for a 15x15mm² chip size) **requires interconnection** with **low resistance** and **inductance** values to **reduce voltage drop** and **additional losses**.

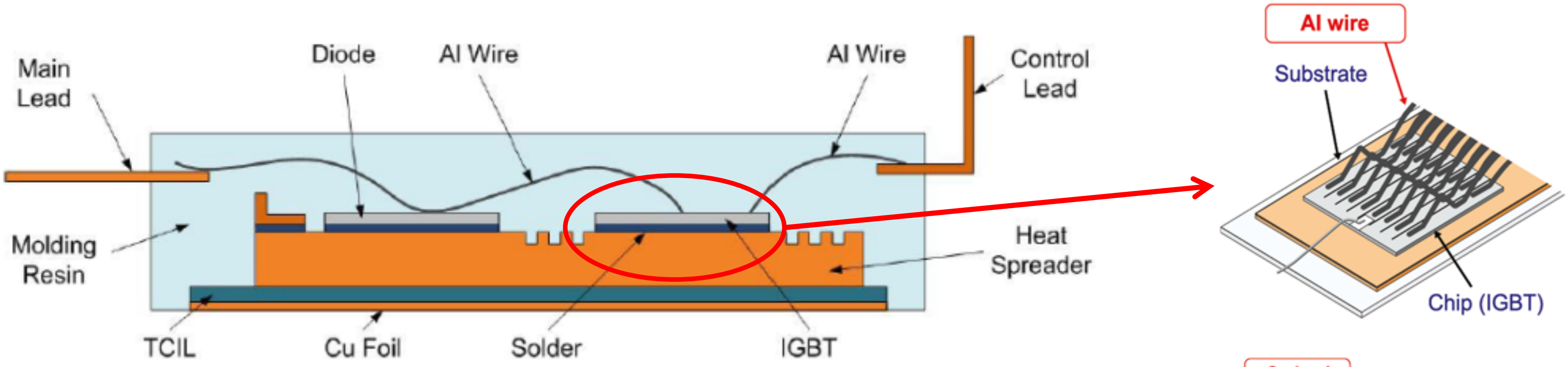
Mitsubishi CT300DJB060
WB (Al)
I_C *300A*
V_{CES} *600V*

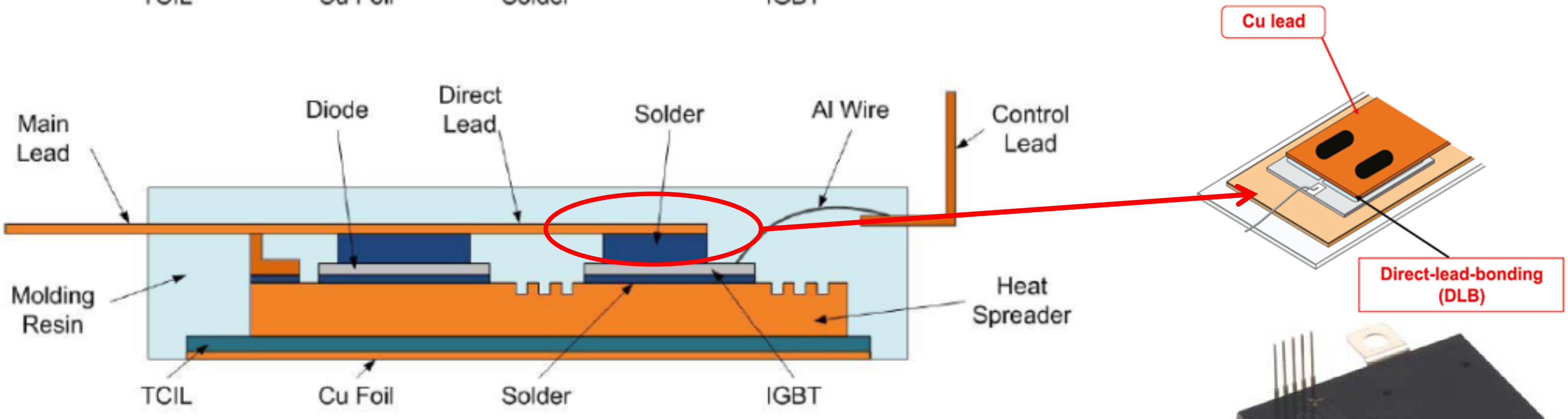


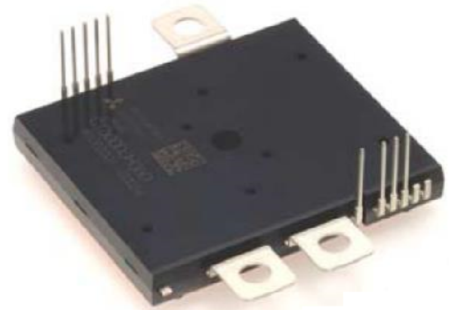
Mitsubishi CT600DJH060
DLB (Cu)
I_C *600A*
V_{CES} *600V*



Design



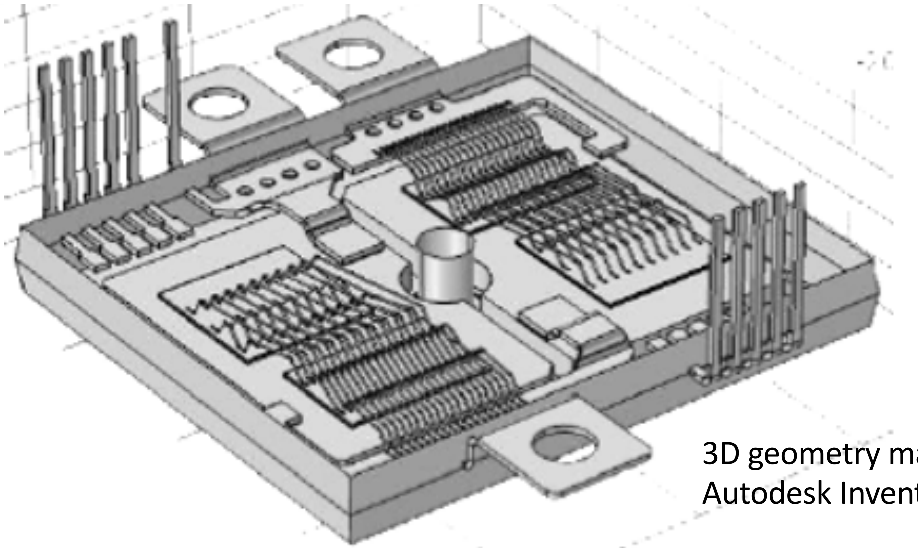


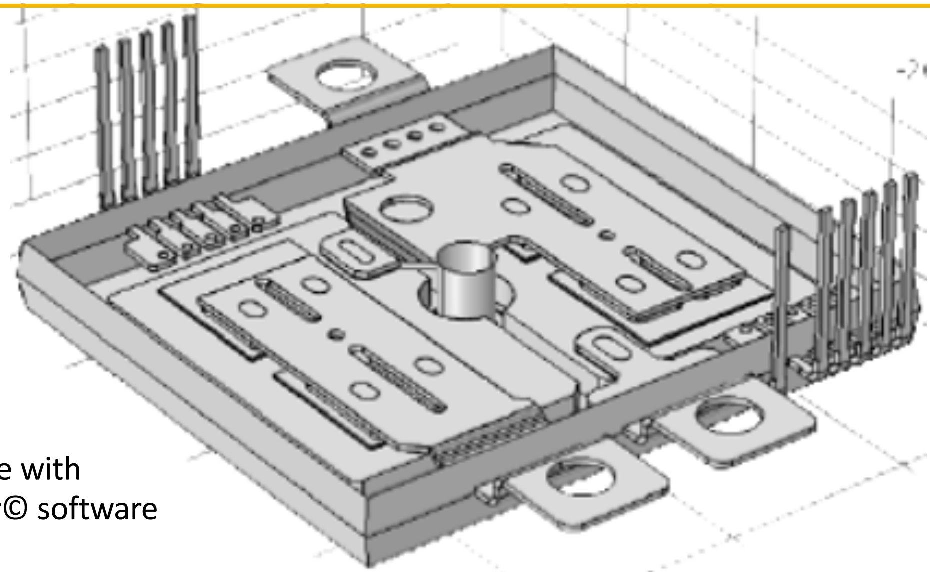


We have same materials in these two configurations

a compact epoxy molded case have been used.

Modeling geometry

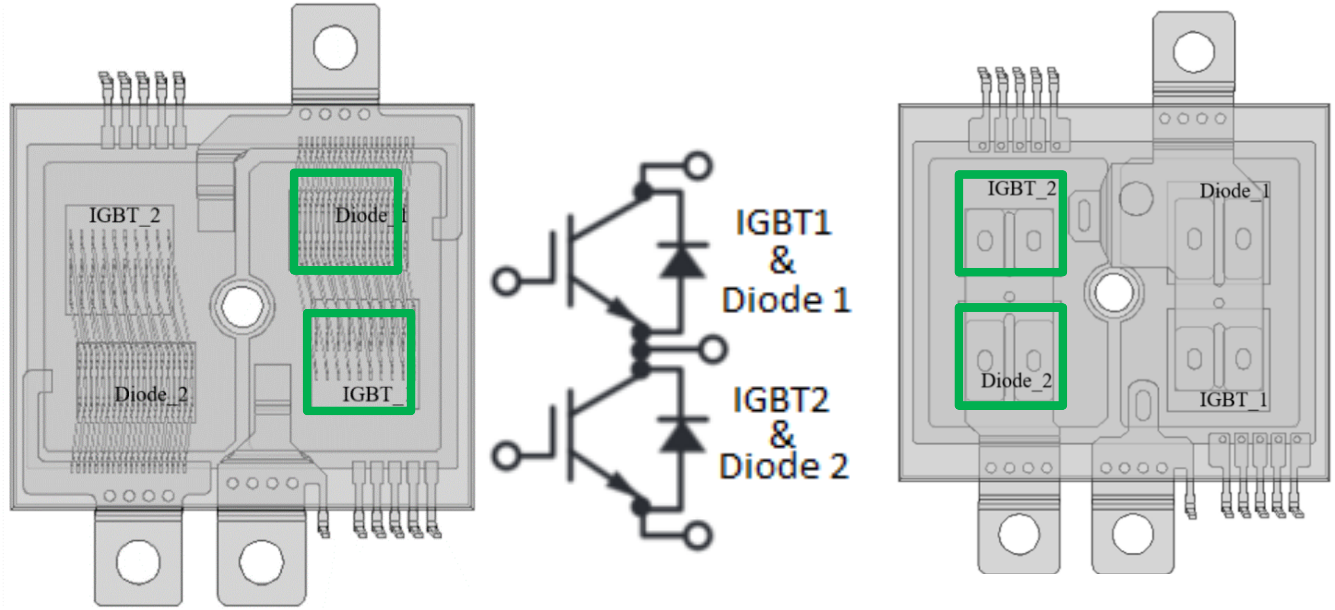




3D geometry made with
Autodesk Inventor© software

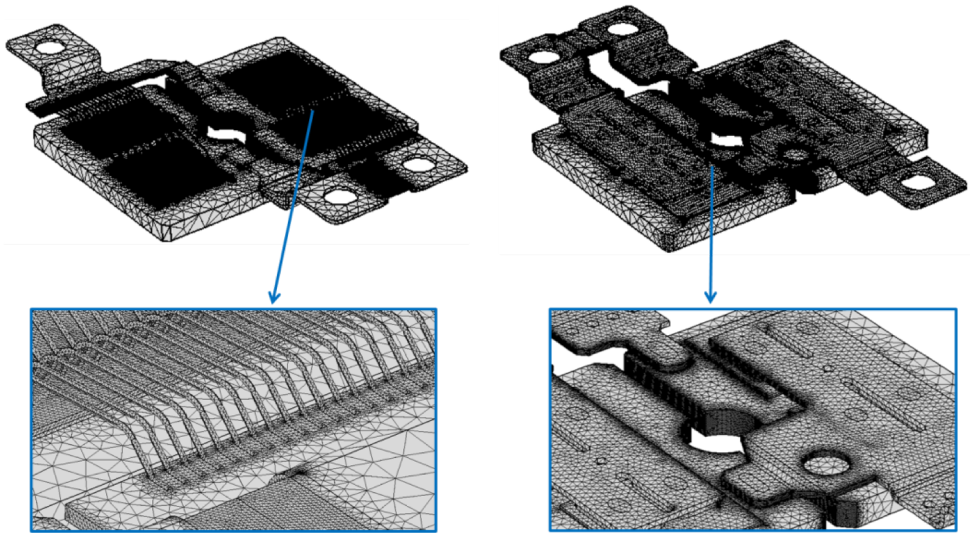
- A 2D has its limits to better understand the impact of WB and DLB interconnections from an electromagnetic and thermal point of view.
- A complete 3D modeling is necessary for a realistic way.
- To avoid overloading the model, some parts not needed for the study were removed.
- The very thin layers of deposited materials have been reduced to zero-thickness (2D)
- The effective thickness of these layers is still considered in the calculations by means analytical relations

Electromagnetic study



- Calculations have been done with Comsol Multiphysics© software
- We have coupled electrical, magnetic and thermal problems in 3D.
- For AC mode, special attention must be given to the mesh according to the objectives of the study.
- Stray electrical resistances and inductances have been calculated by activating one switching-cell by means of IGBT1 and Diode2.

AC mode : meshing



This leads to :

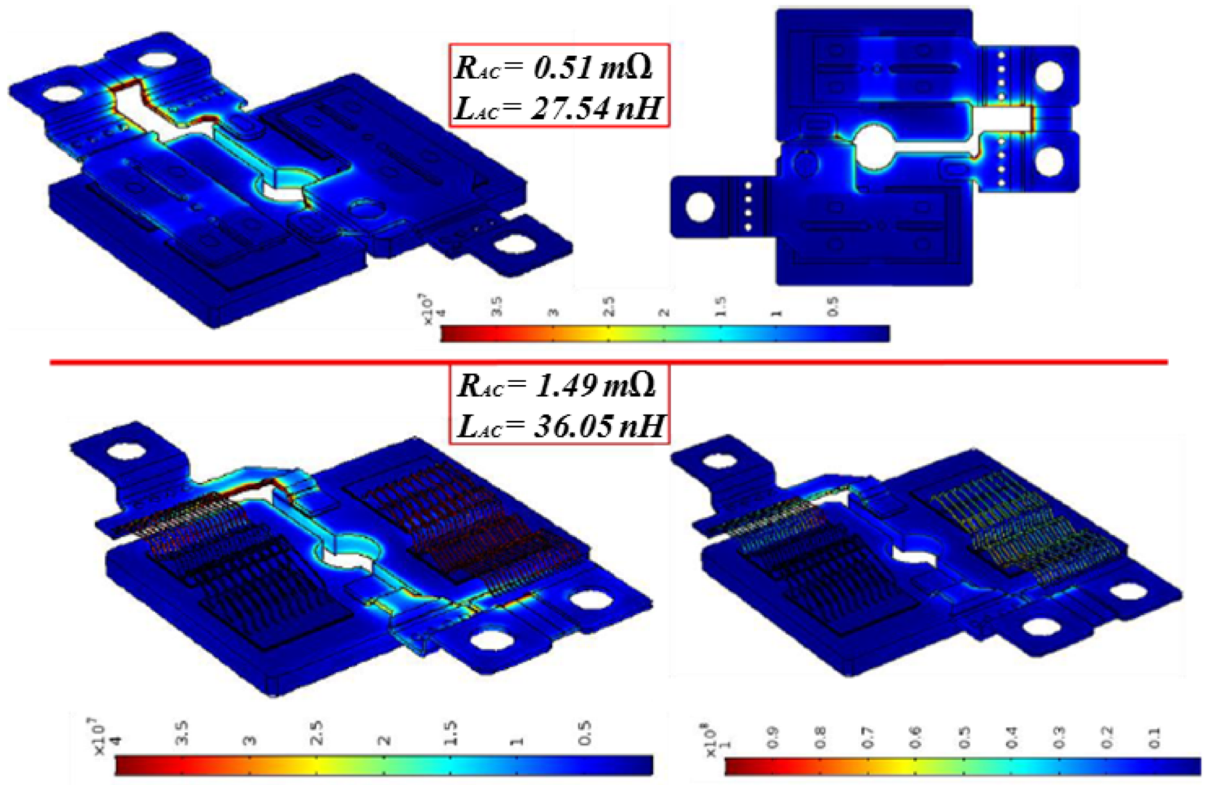
- 2639739 elements and 17981231 DoF for the WB module
- 1824095 elements and 12087973 DoF for the DLB module.

- Attention must be paid to the mesh to consider the frequency effects (**skin and proximity effects**) that modify the current distribution in the electrical conductors.

- The mesh must be refined in these constriction zones to properly evaluate the current gradients. ,

- We have adopted the method of imposing in these zones finite elements whose **size is less than half the theoretical skin thickness in copper at 20 kHz.**

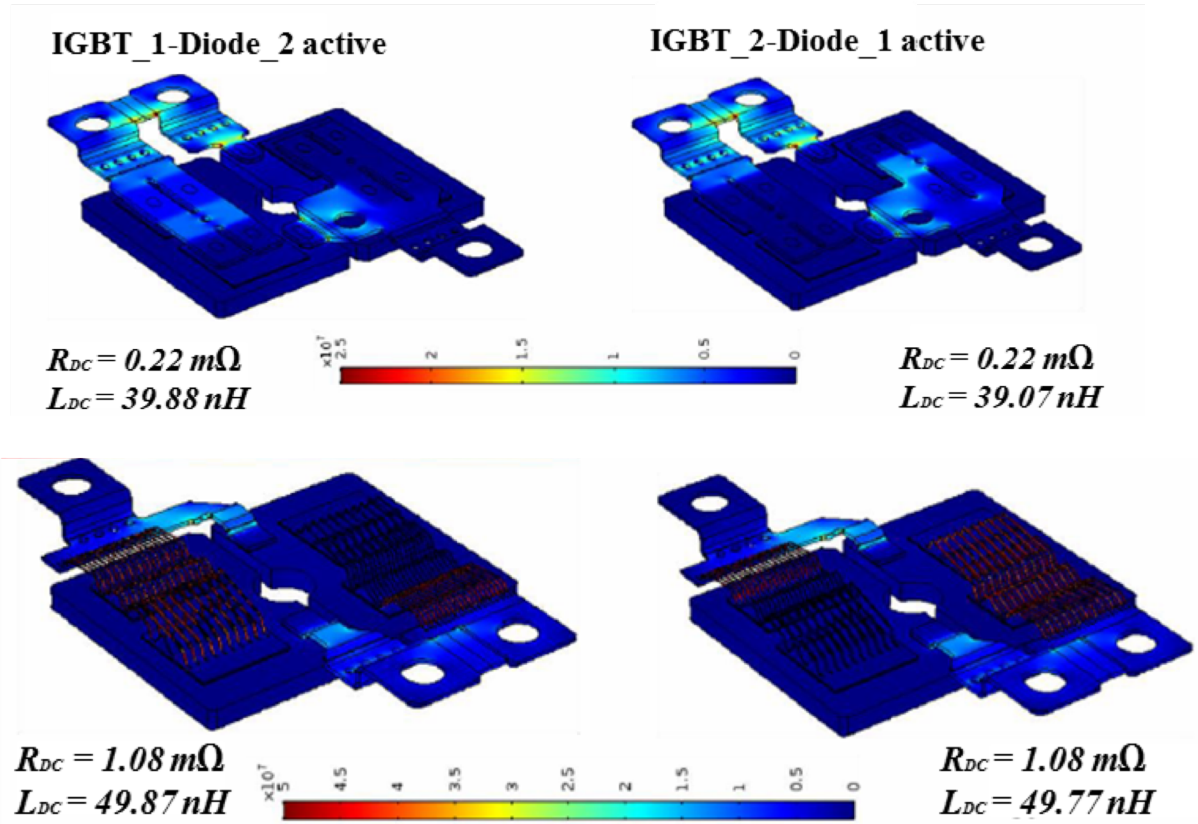
Current density in AC and impedance values



➢At 20 kHz, the current lines are tightened towards the center of the module due to the proximity effect between the two coppers clips of the IGBT and diode chips.

- ➢ For this operating point, We verify that the DLB solution offers better values than the WB one.
- ➢ The copper clips allow **reducing the R_{AC} value by one third** compared with the wire-bonding reference.
- ➢ The L_{AC} value is only reduced by 25%. These values are consistent with those calculated or measured elsewhere [4-5].

Current density in DC and (RDC, LDC)



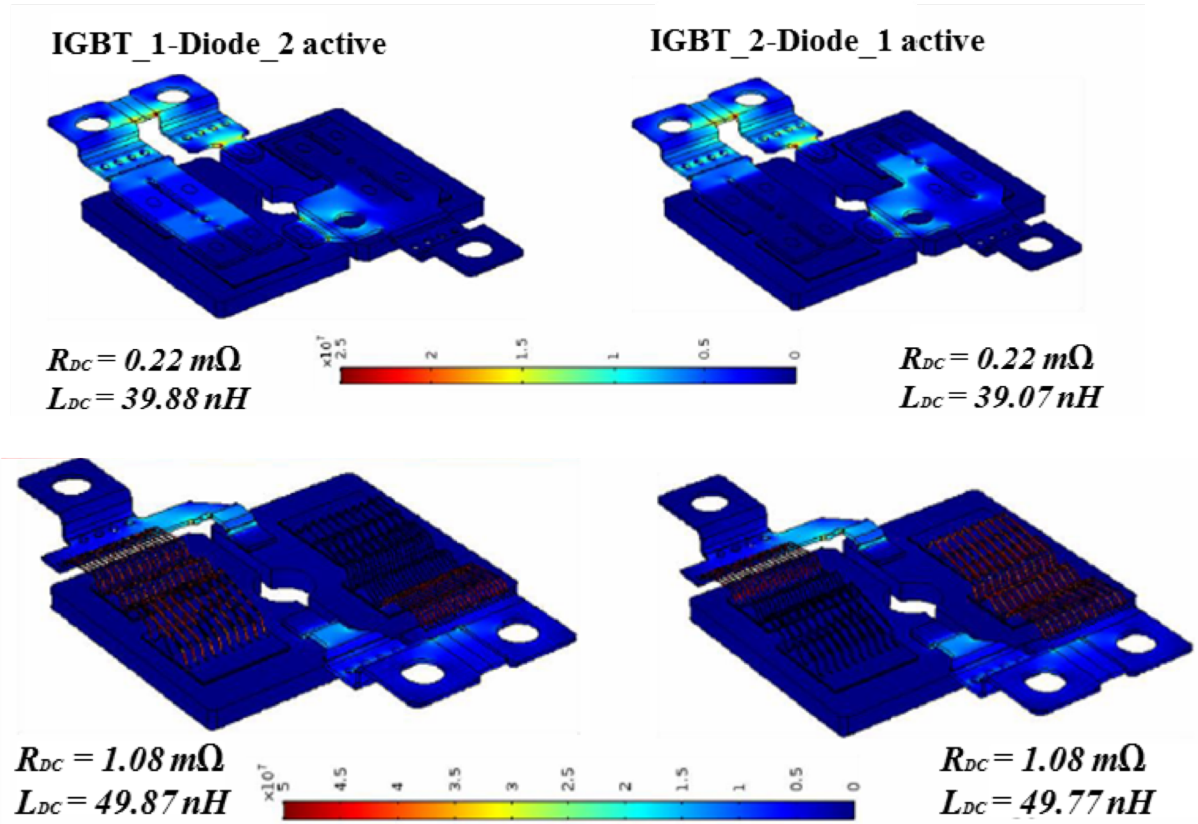
- Frequency phenomena are no longer present =>The mesh can be simplified

- The current flows this time in the entire conductors and that the values obtained have logically evolved downward for the resistors and upward for the inductors.

- The DLB solution is better than the WB one.

- R_{DC} value is four times lower than the reference module.

Current density in DC and (RDC, LDC)



- Frequency phenomena are no longer present =>The mesh can be simplified

- Given the geometrical symmetry of the modules, the dual operating mode (IGBT2 & Diode1) gives us the same results.

- The DLB module is more sensitive to the frequency effect than the wire-bonding module: its R_{AC} increases by 130% at 20kHz while it only increases by 38% for wire-bonding module.

Thermal study

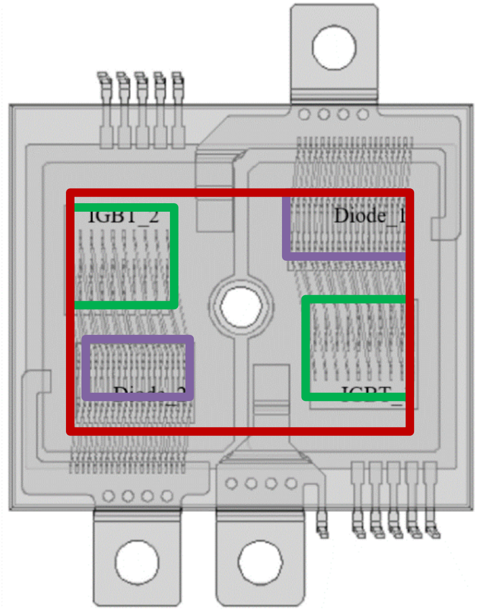
- The objective => Thermal management of the power modules in a realistic operating mode.

- In our case,
  - the module operates => PWM voltage inverter mode,
  - switching frequency => 20 kHz
  - modulation index => 0.9
  - Connection on the DC side => 300V voltage source and supplies an inductive load (power factor equal to 0.8) at 200A peak-current.

- Under these conditions, off-line analytic calculations gives:
  - An effective equivalent RMS (or DC) current of 90A injected through IGBT1&2 chips and 44A through Diode1&2 chips.

- Heat losses calculated only for a constant temperature Tj=125°C.
  - IGBTs (190W)
  - Diodes (73W

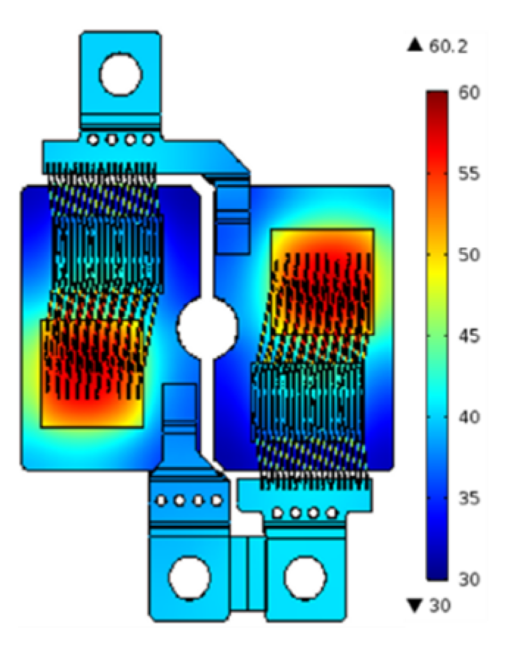
Thermal study: conditions



- Thermal conditions at the boundaries of the domain:
  - the convective and radiative exchanges to the ambient => **h=10 W.m^{-2}.K^{-1}**
  - For the interface with the heatsink on the back side, we imposed a constant temperature of **16 °C** corresponding to that of the cooling water.

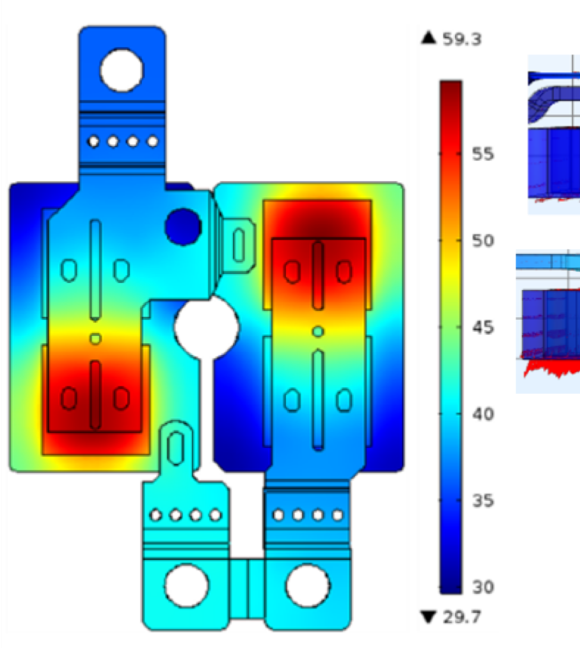
- Calculation methodology : Superposition on three steps
  1. The IGBTs are in on-state => The electric power density distribution due to **90A** is calculated
  2. The Diodes are in on-state In a second time, the electric power density distribution due to **44A** circulating current is calculated
  3. The global power density as the sum of these two contributions without forgetting to impose realistic losses in the **IGBTs (190W)** and the **Diodes (73W)**.

Thermal study : Steady state mode



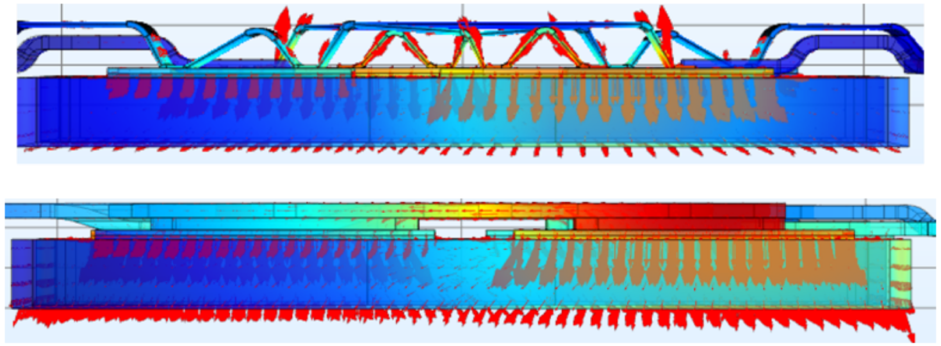
Tm_IGBT = 53.5°C
Tm_Diode = 39.7°C

Tmax = 60.2°C



Tm_IGBT = 55.4°C
Tm_Diode = 40.1°C

Tmax = 59.3°C



- The two configurations (clip and WB) have **approximatively the same temperature field**.
- The maximum temperature reached in WB is slightly higher than the clip one localized in the IGBT chip
- The maximum temperature points are localized inside the IGBT for the DLB module, and on the wire bonding for WB module.

Heat flux and Thermal resistance

Flux direction	Value of the flux
IGBT to baseplate	185.6 W
IGBT to clip	3.95 W
IGBT to epoxy	0.12 W
Diode to baseplate	76.5 W

Heat flux proportions (DLB module)

Flux direction	Value of the flux
IGBT to baseplate	186.26 W
IGBT to wires	-0.34 W (reverse flux)
IGBT to epoxy	0.02 W
Diode to baseplate	60.8 W

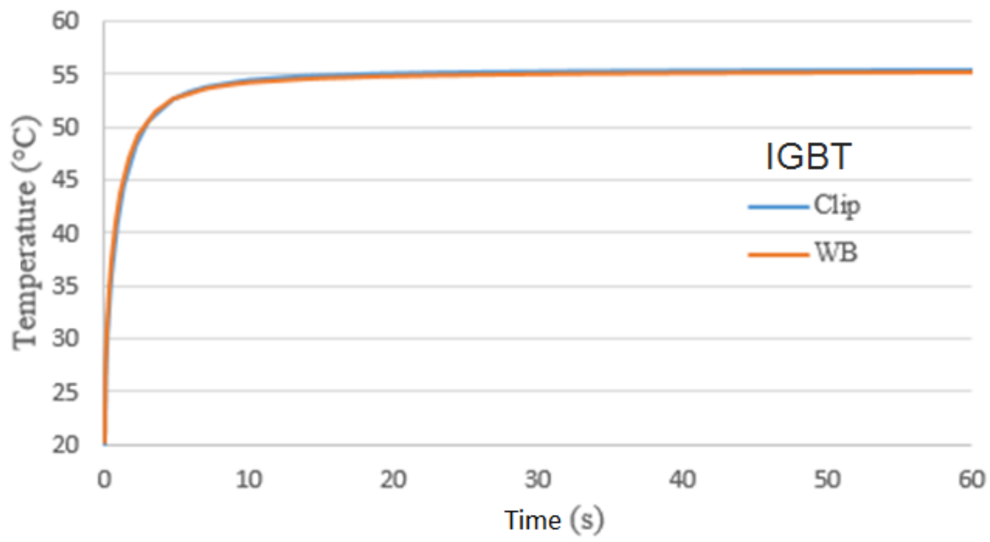
Heat flux proportions (WB module)

- The majority of the thermal transfer takes place well from the chips to the cooler system but the spreading effect of the copper clip is also visible
- The clip drain and WB inject heat

	Clip		WB	
	IGBT	Diode	IGBT	Diode
Tm (K)	328.1	313.1	327.7	315.9
Thermal resistance (K/W)	0.21	0.31	0.2	0.35

- Thermal resistance have been calculated between each chip and the cooling baseplate.
- These values are very close because the assemblies of the chips on their substrate and the cooling system are almost identical between the two modules.

Thermal study : Transient mode



- The transient study was carried out with a **time step of 1ms** with the **same power conditions**.
- The **temperature evolution** are **quite identical** for both configurations

- The time-domain evolution of the average temperature of the chips is almost the same for the two modules.
- The 95% steady state temperature is reached in less than 10 seconds.
- DLB module has **a slight higher thermal inertia due to the presence of the copper clip** which plays the role of thermal capacitance.
- The effect is minor because few heat flux is injected through this clip and the thermal filtering is very reduced.

Conclusions

➢We have compared two technological solutions for electrical chips interconnections WB and DLB by finite

➢Stray electrical (DC and AC) resistance and inductance values for DLB modules have been significantly reduced compared to the WB one.

➢DLB module presents more frequency dependence due to its more bulk connections compared with WB ones.

➢This leads to a reduction of the electrical losses and to an improvement of the commutations with using DLB module.

➢From a thermal point of view, the differences are not significant.

➢The steady-state temperatures and the thermal time constants are equivalent.

Futur works

➢**In the future:**

▪Optimize chip assembly techniques in modules,

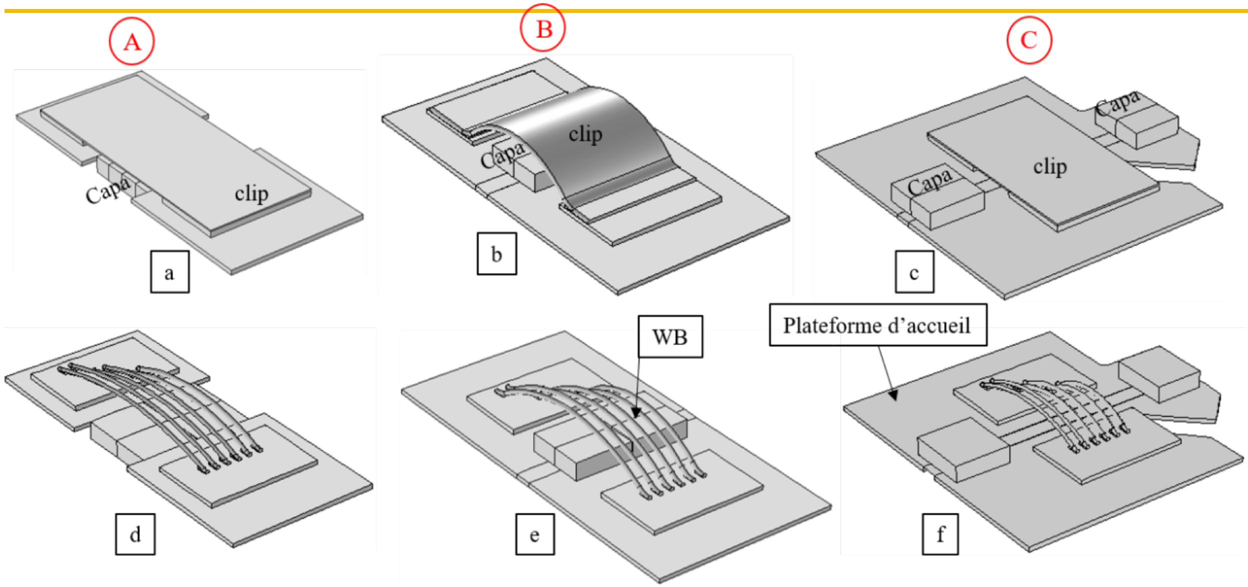
▪Optimize thermal behavior and electrical interconnections. It might be interesting to study a technological evolution of the DLB structure by introducing a double cooling, above and below the chip.

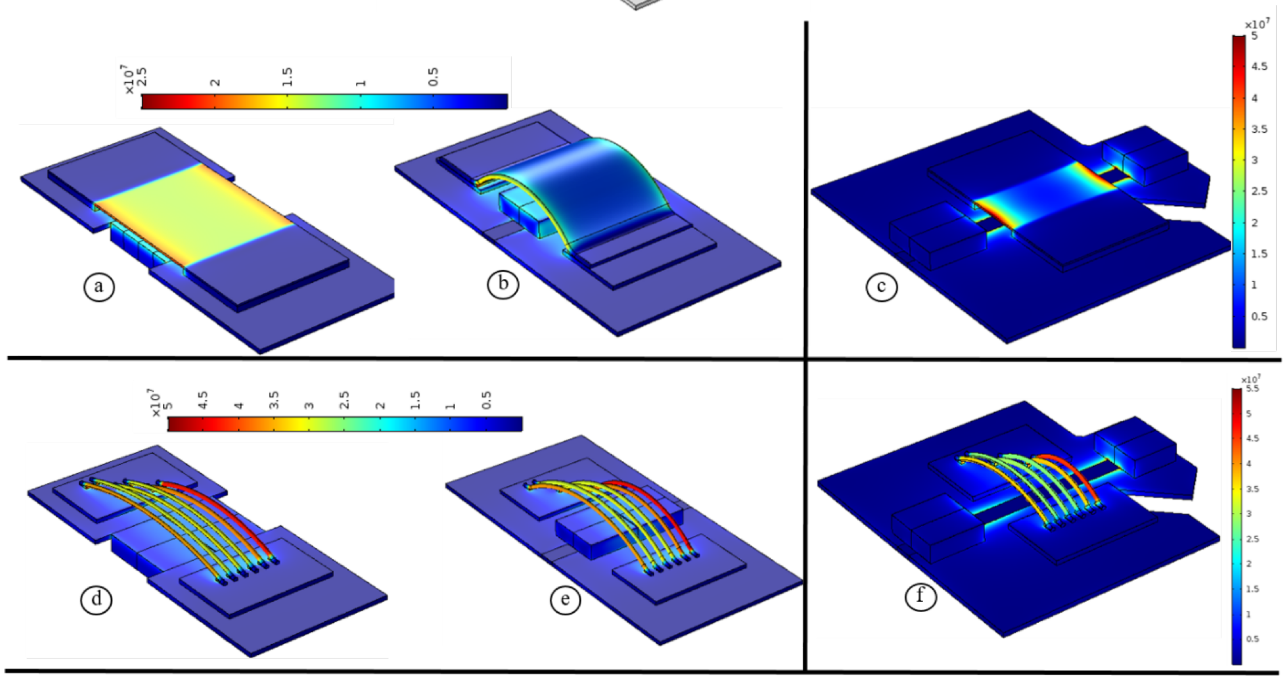
▪Modified DLB for use integration

▪3D DLB power switching loop with partial flip-chip interconnection

Thank you for your attention

Annexes


A
B
C
Capa
clip
a
b
c
WB
Plateforme d'accueil
d
e
f


×10^7
2.5
2
1.5
1
0.5
a
b
c
×10^7
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
d
e
f
×10^7
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5

Annexes

		Inductance Lac		
	configuration et alimentation	**Version (A)**	**Version (B)**	**Version (C)**
Simulation COMSOL	WB_2_capas	**2,36 nH**	**2,67 nH**	**2,4 nH**
	WB_Capa_Droite	2,97 nH	3,02 nH	4,00 nH
	WB_Capa_Gauche	2,97 nH	3,03 nH	3,88 nH
	Clip_2_capas	**0,58 nH**	**1,43 nH**	**1,2 nH**
	Clip_Capa_Droite	0,94 nH	1,78 nH	2,34 nH
	Clip_Capa_Gauche	0,94 nH	1,77 nH	2,29 nH
Mesure fréquentielle	WB	2,6 nH	2,89 nH	2,78 nH
	WB (corrigée)	**2,2 nH**	**2,49 nH**	**2,38 nH**
Caractérisation double-impulsion	Mesure brut	1,11 nH (clip)	4,2 nH (Filaire)	
	Mesure corrigée	0,71 nH	3,8 nH	
		Erreur relative par rapport à la mesure fréquentielle corrigé (cas WB)		
		7,27%	7,23%	0,84%

		Résistance Rac		
		Version (A)	Version (B)	Version (C)
Simulation COMSOL	WB_2_capas	**0,74 mΩ**	**0,78 mΩ**	**0,61 mΩ**
	WB_Capa_Droite	0,84 mΩ	0,83 mΩ	0,86 mΩ
	WB_Capa_Gauche	0,83 mΩ	0,82 mΩ	0,79 mΩ
	Clip_2_capas	**0,27 mΩ**	**0,21 mΩ**	**0,29 mΩ**
	Clip_Capa_Droite	0,38 mΩ	0,25 mΩ	0,54 mΩ
	Clip_Capa_Gauche	0,38 mΩ	0,25 mΩ	0,49 mΩ