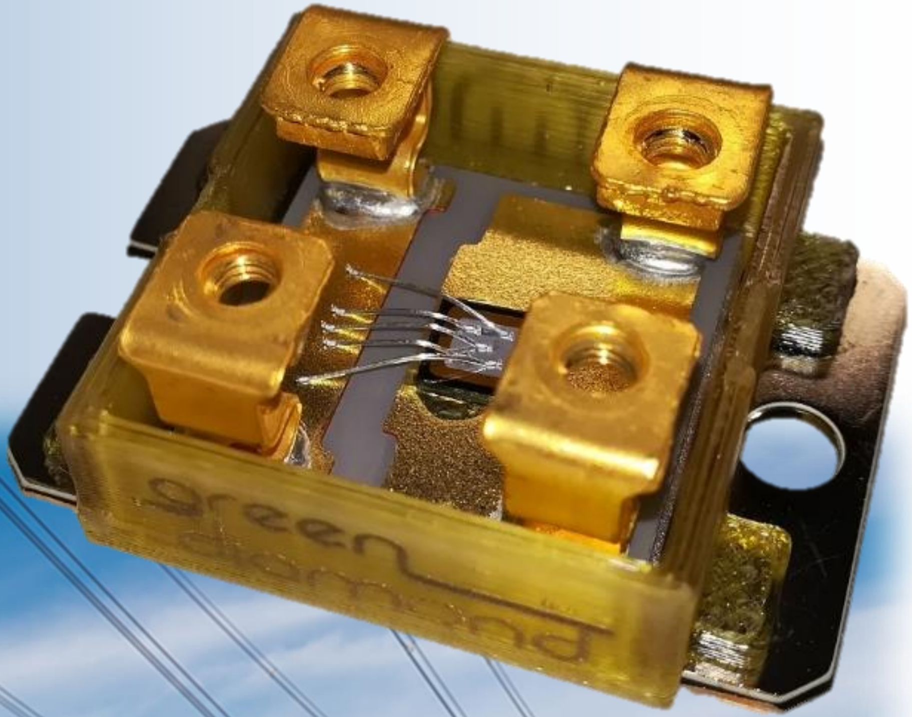
Wide and Ultra-wide bandgap power devices

Key technologies to undertake the electrification and decarbonisation challenge



X. Jordà, P. Godignon, O. Aviñó, X. Perpiñà, M. Vellvehi

Centro Nacional de Microelectrónica CSIC

PDS Power Devices and Systems

S. Busquets

UPC

J-C. Crebiere

G2E Lab Grenoble Génie Electrique Grenoble Electrical Engineering

E. Gheeraert

NÉEL institut cnrs

Motivation

Power electronics is a key enabling technology in the new energy transition scenario using:

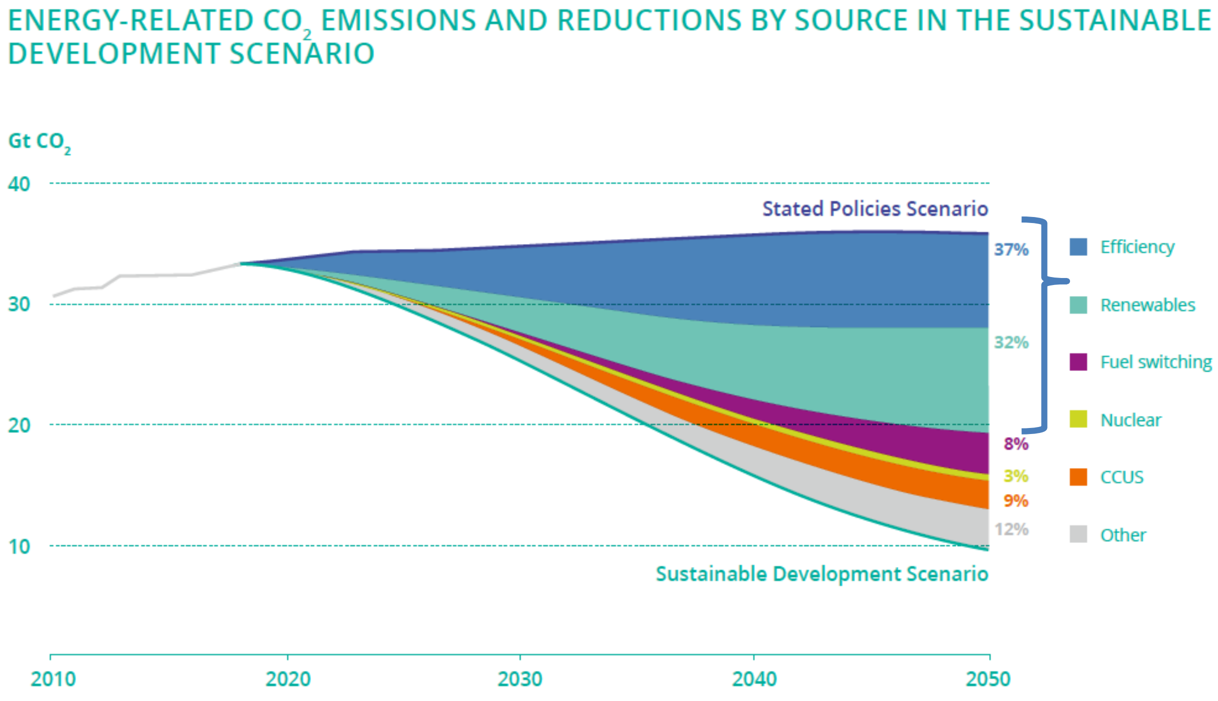
- Renewable sources
- Deep electrification

Barcelona and Grenoble research groups have been collaborating in this field for years

We will show some relevant recent examples turning around WBG/UWBG semiconductors

Decarbonisation objectives for 2050 based on different approaches

Transition to <u>renewable</u> sources and improvement of <u>efficiency</u> allow major CO_2 reductions



Efficiency and renewables provide most CO_2 emissions reductions. (Source: IEA World Energy Outlook 2019)

<u>Electrification</u> (replacement of fossil fuels by electric energy) is an optimum way for implementing this transition in more efficient systems

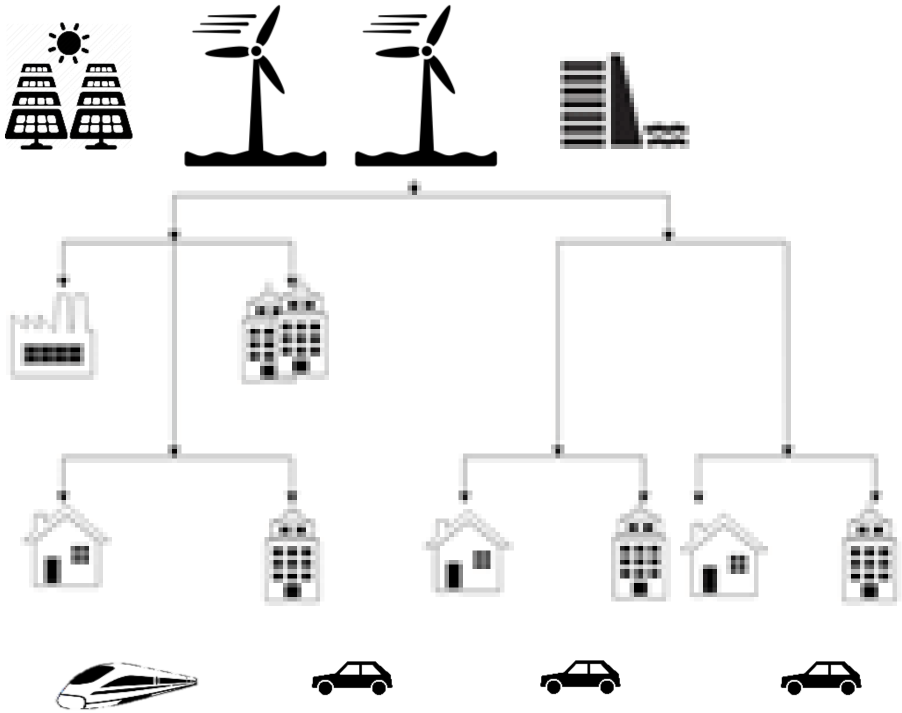
Replacement of fossil fuel based power plants in traditional power grids is not the solution…

Renewables are distributed and can be scaled from kW to MW plants

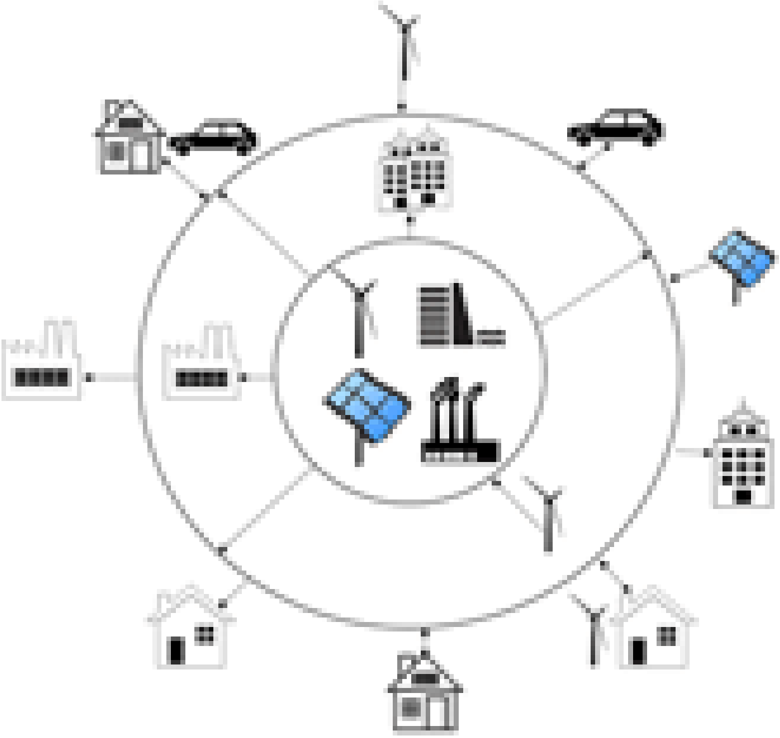
Bidirectional power flow is required for managing renewables fluctuations

Electrified processes require more flexibility ⇒ Smart-Grids

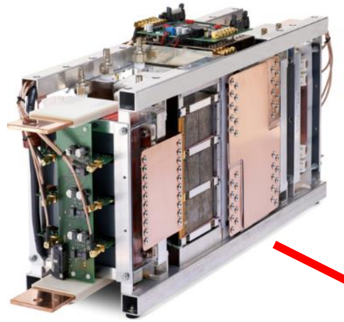
Centralised demand-driven power grid

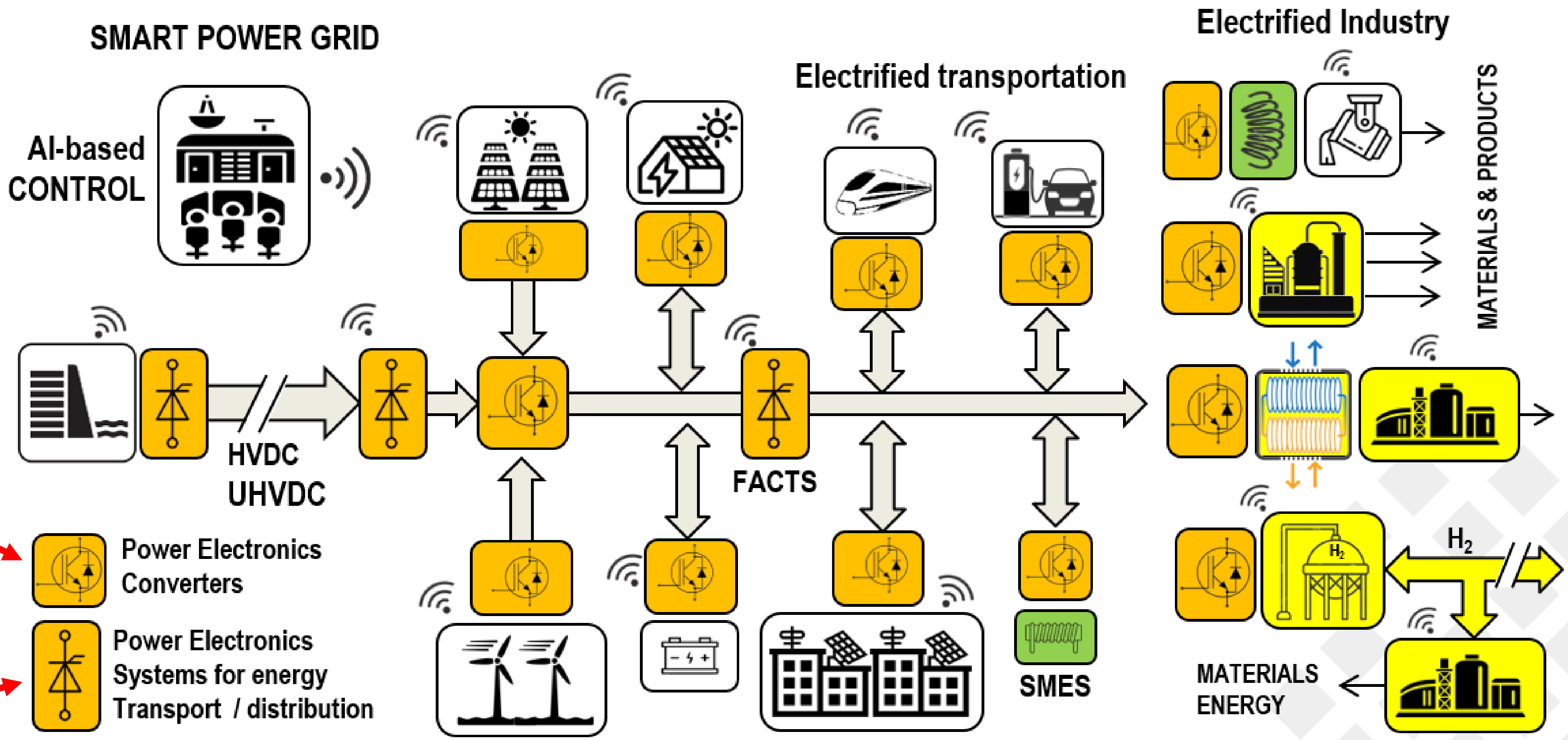


Multi-modal decentralised smart-grid

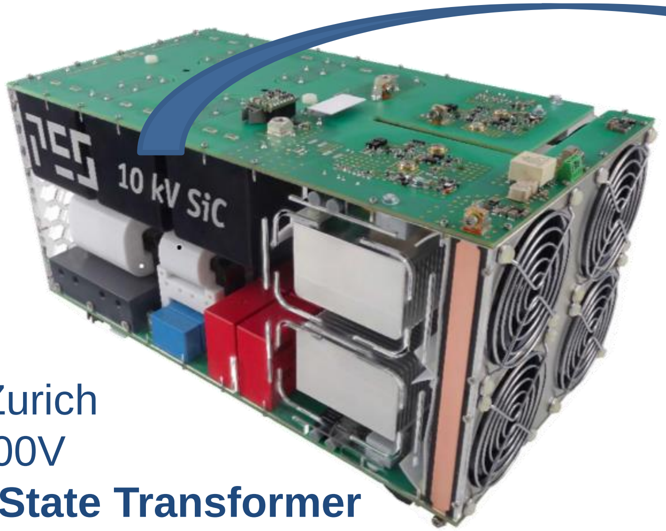


Power electronics circuits are found in the smart-grid between all the required conversion interfaces of the *__generation - transport / distribution - use__* value chain

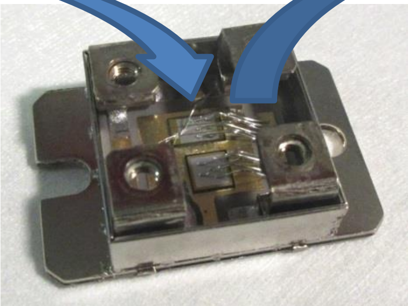




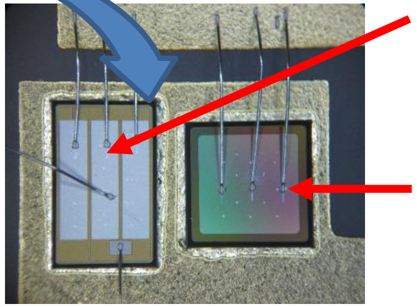
Semiconductor power devices are the key elements of power converters
They operate in switching mode at relatively high switching frequencies



ETH-Zurich
7kV-400V
Solid State Transformer



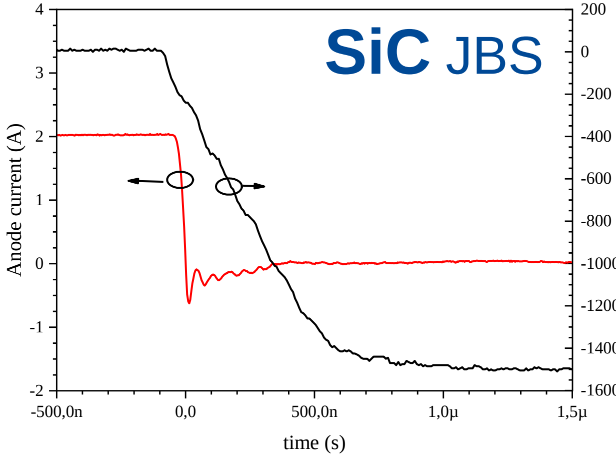
Power module

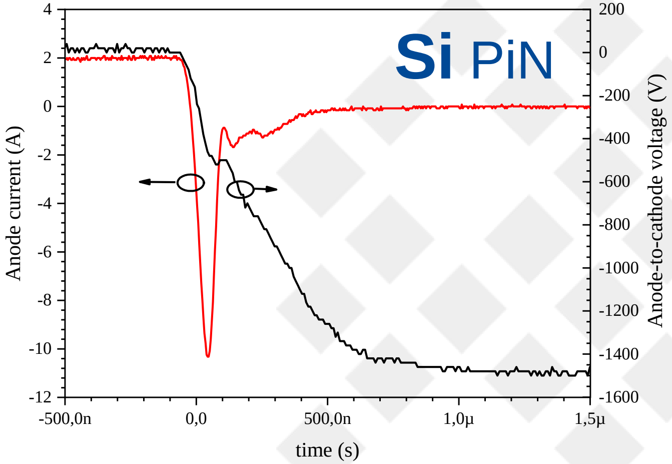


SiC MOSFET die

SiC diode die

Diodes turn-off process at 1500V – 2A





<u>Wide bandgap</u> (WBG, such as SiC and GaN) and <u>ultra-WBG</u> (Diamond, Ga_2O_3) semiconductors have broken the limits of Silicon in terms of switching speed, breakdown voltage, temperature, etc.

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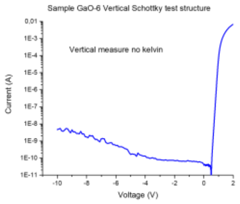
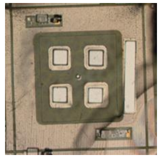
Wide Band-Gap Semiconductors at PDS

Power Devices and Systems

2020

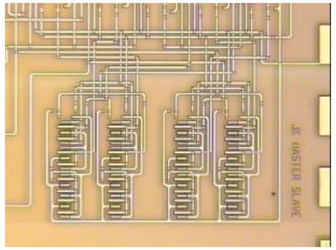


Ga_2O_3 Technology

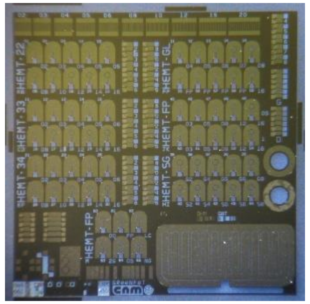


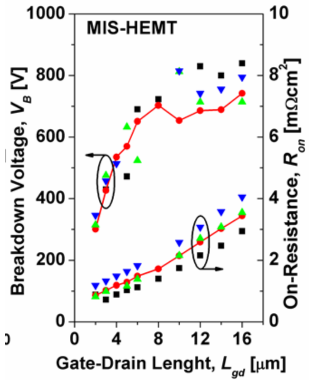
Diamond Devices

High temperature IC and diodes



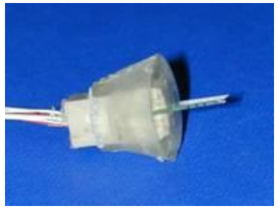
SiC flight components for space applications

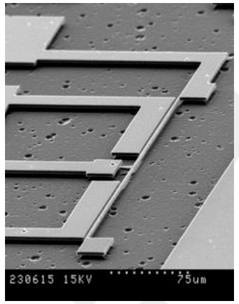


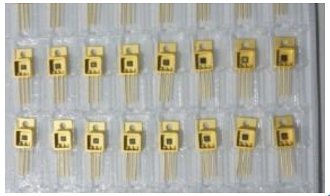


GaN-on-Si process development

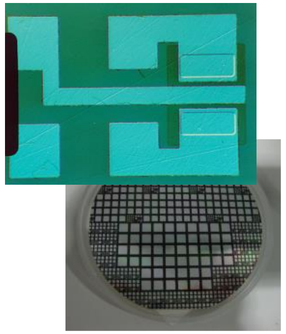
SiC sensors development & fabrication





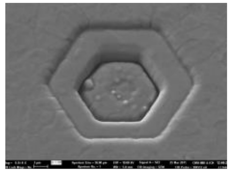


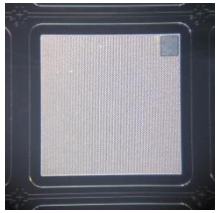
SiC power devices fabrication

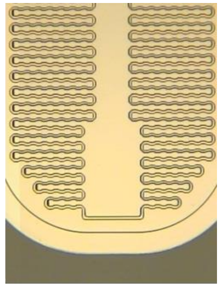


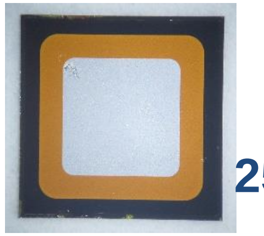
SiC process developement

1993





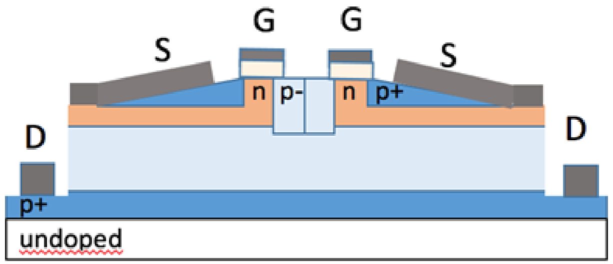


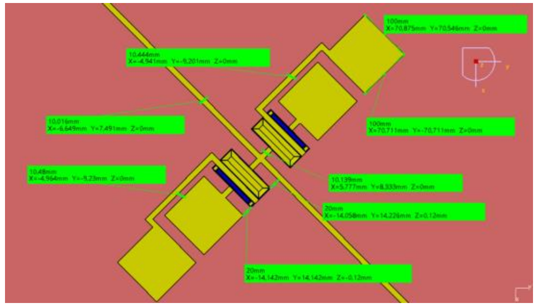


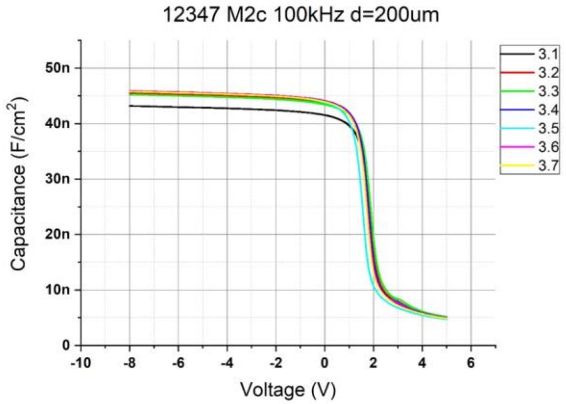
25 mm^2 >6kV SiC diodes

Present UWBG activities…

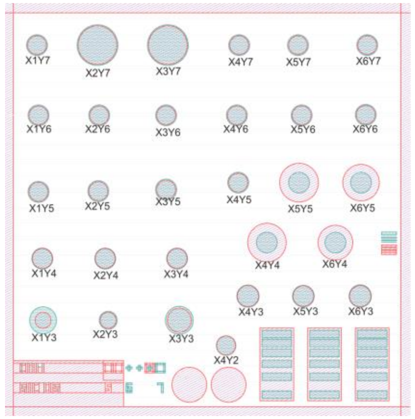
Patented MOSFET based on lateral Diamond growth

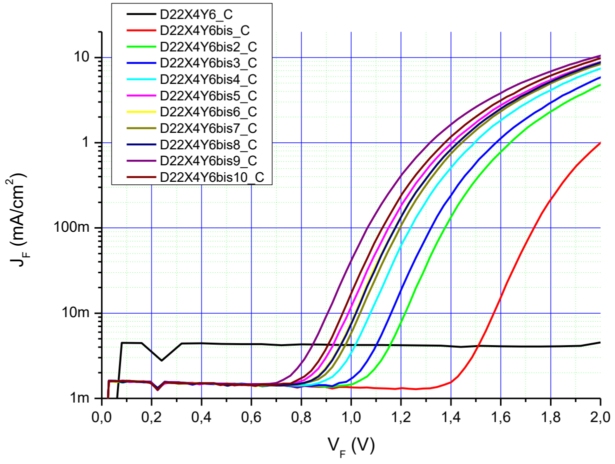


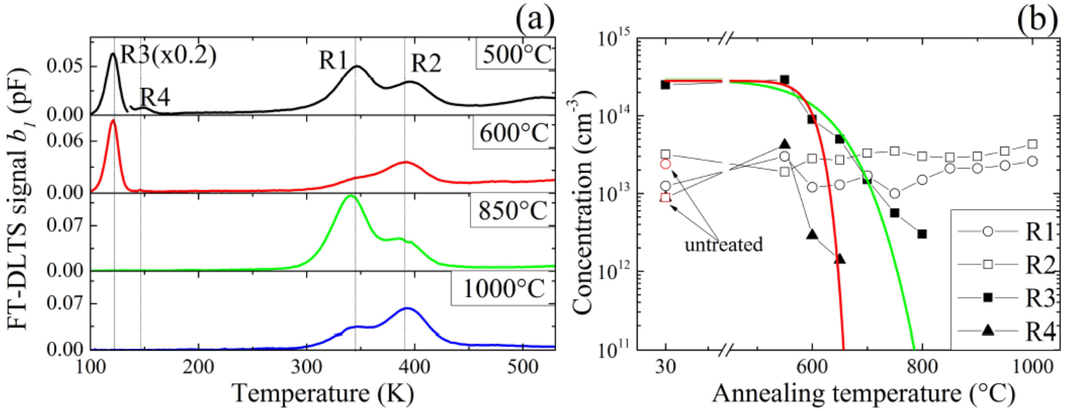




Vertical Schottky diodes on epitaxied <100> Ga_2O_3 (Ni Schottky contact)







RIE/ICP of Ga_2O_3 : identification of a new defect

Diamond power devices

green diamond

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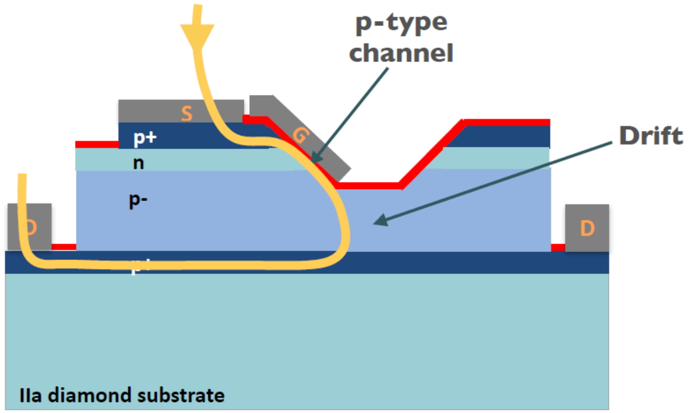
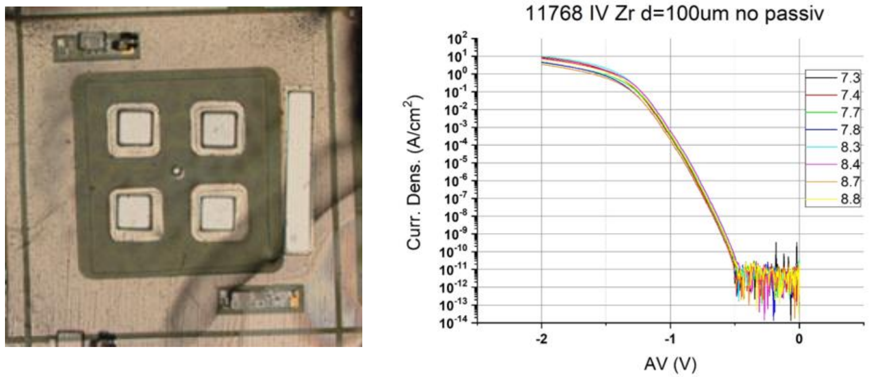
H2020 "Low Carbon Energy" Project
4M€
15 partners from 5 countries
2015 - 2020

Development of diamond-based power devices (MOSFETs, Schottky), their packaging, characterization tools, industrialisation issues and final applications. Analysis of the different technological bottlenecks at each level



Quasi-vertical power MOSFET concept studied

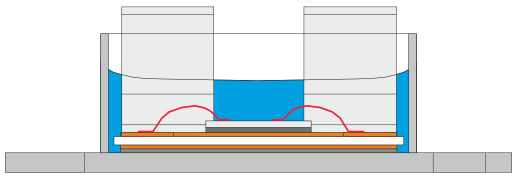


Complete (passivated) Schottky diodes

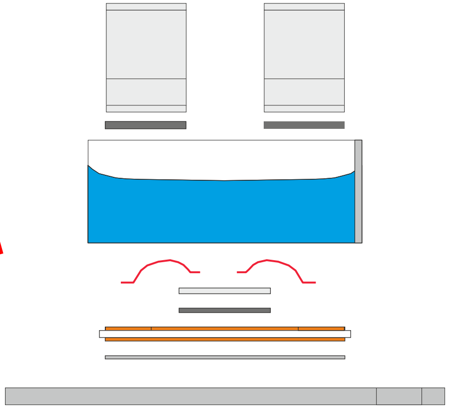
Packaging of WBG and UWBG power devices: the GreenDiamond case

Providing mechanical, termal and electrical interface to the devices

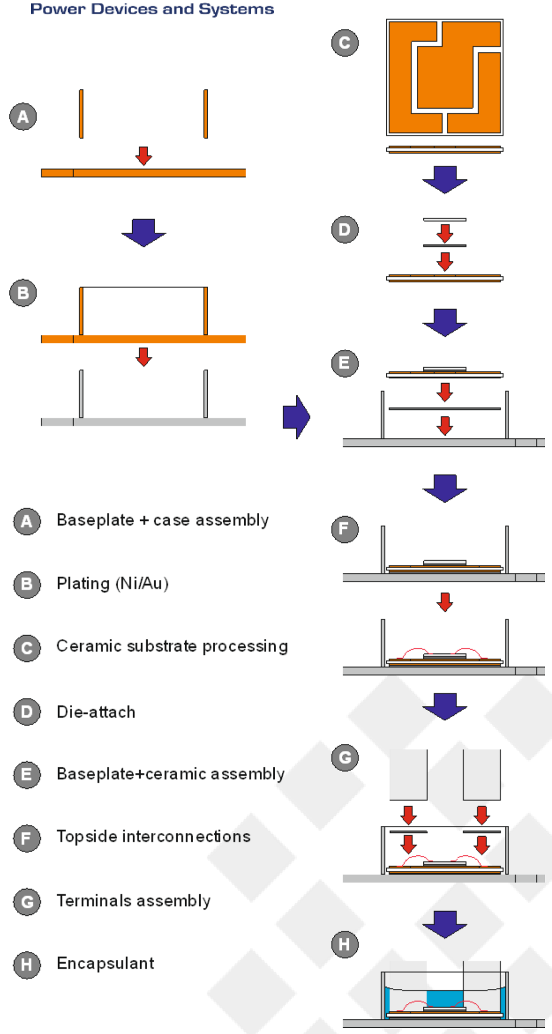
Power module



Cross-section



Main parts



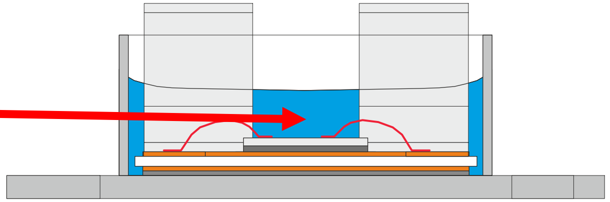
Assembling sequence

Main characteristics:

- High voltages (~10kV)
- High temperatures (250-300ºC)
- Low termal resistance
- CTE mismatches
- Cost-effective

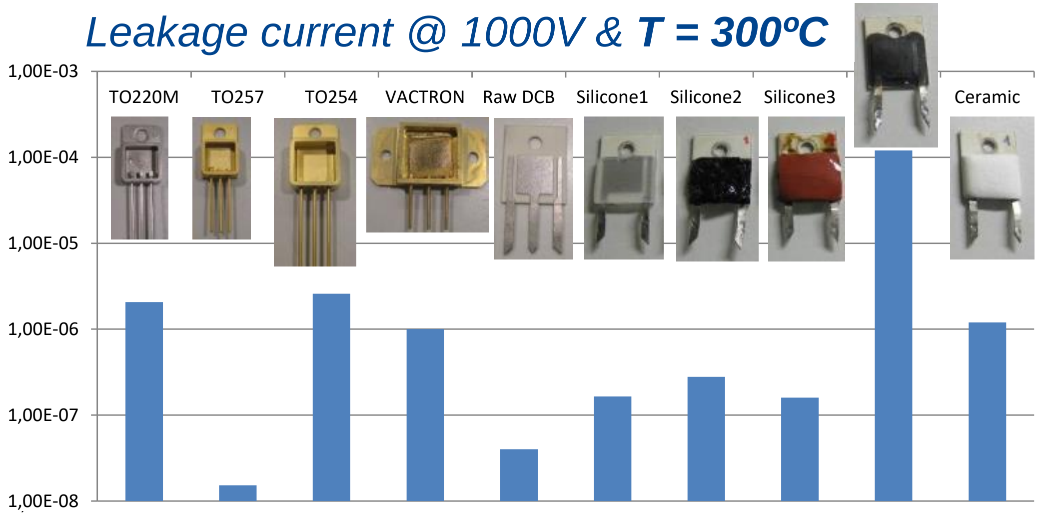
Not-limiting semiconductor performances!

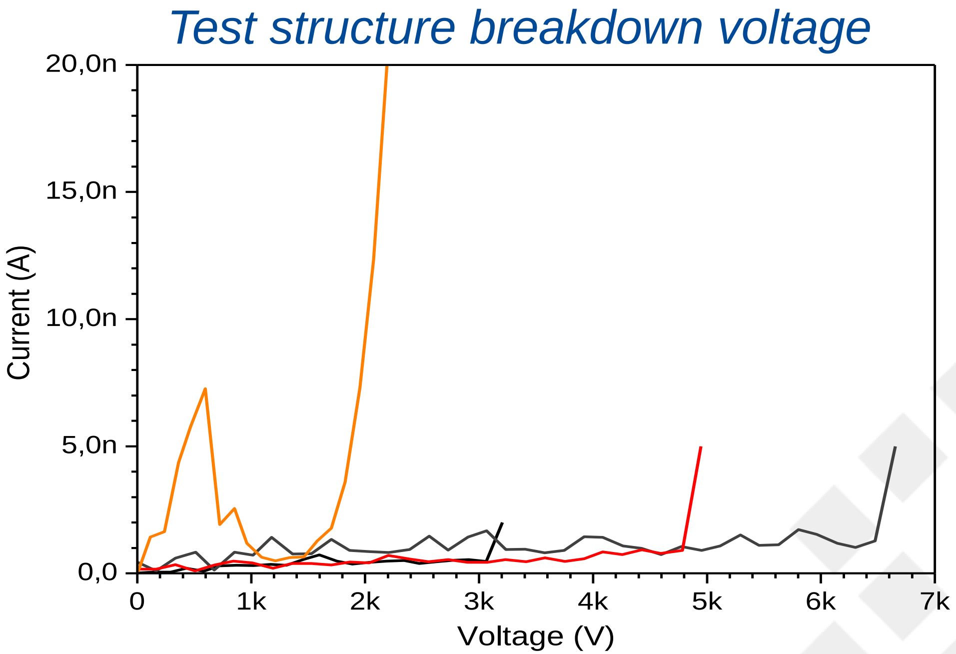
Example of a critical material: the encapsulant



Dielectric filler to protect the die and top contacts

Lack of suitable materials for HV/HT applications such as WBG/UWBG packaging

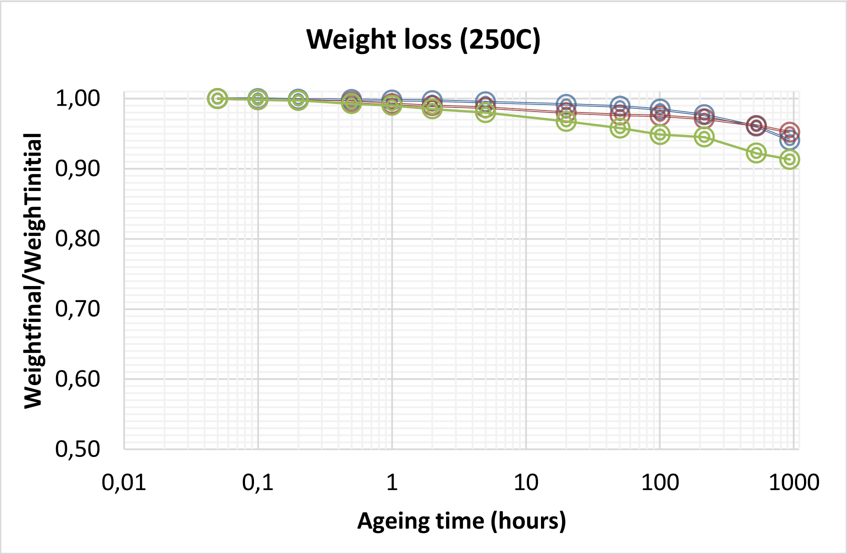


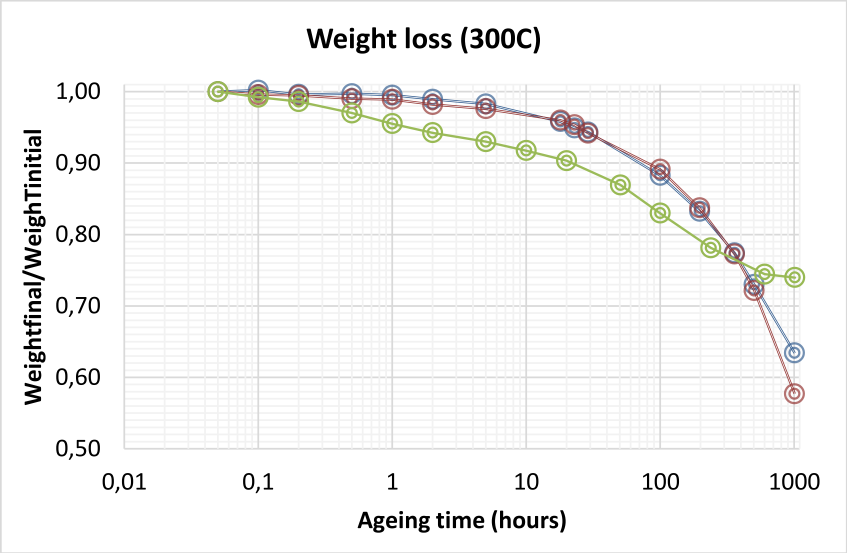


Silicones are a promising cost-effective solution…

… but there are critical issues to be considered in terms of:

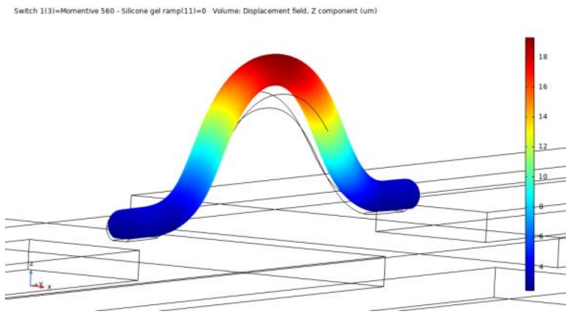
Aging

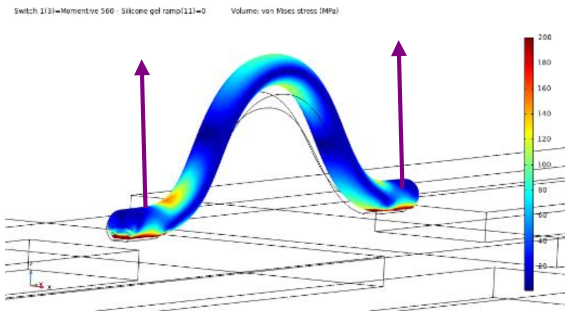




Thermo-mechanical behaviour (thermally induced stress to the wire-bondings)

Displacement

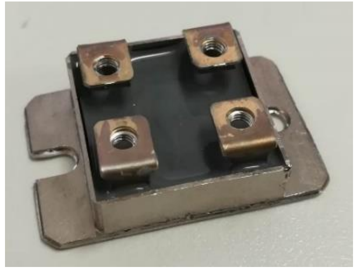


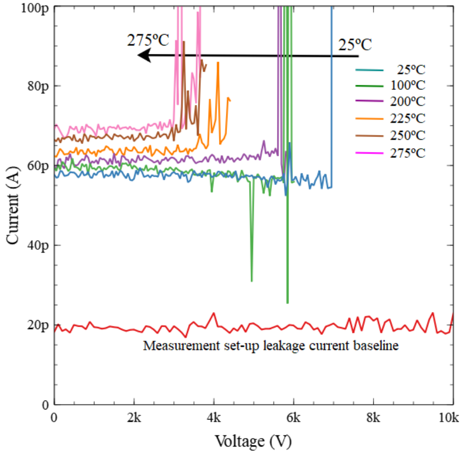


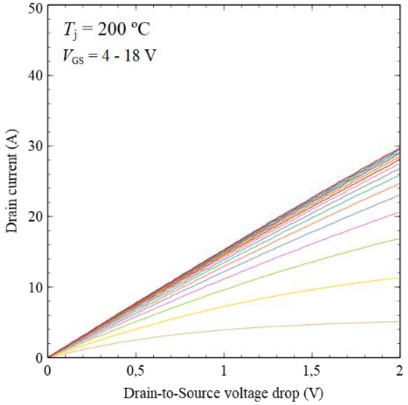
Stress

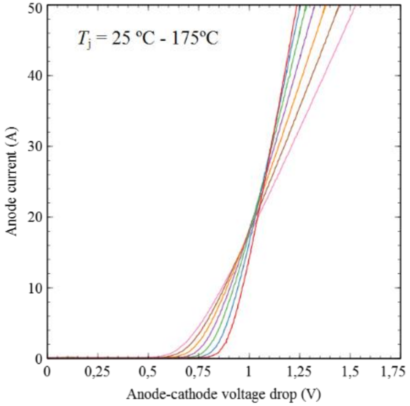
In the framework of GreenDiamond we developed two families of HV/HT packages

2.5 kV – 250ºC

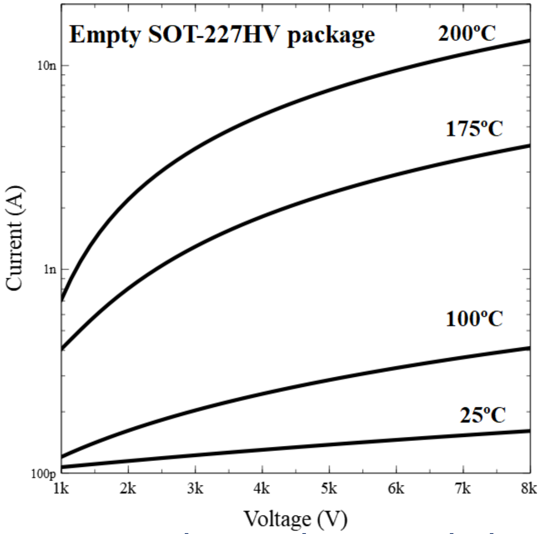




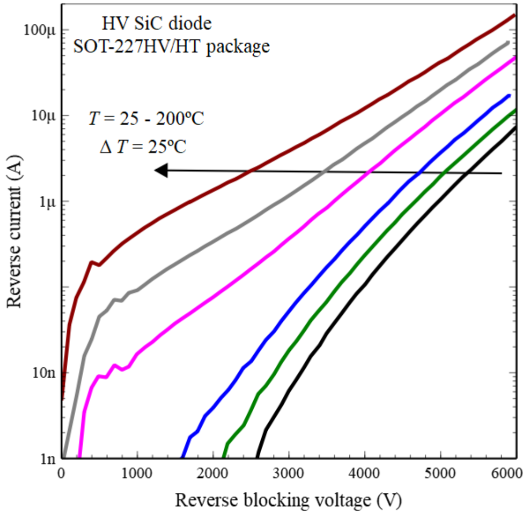




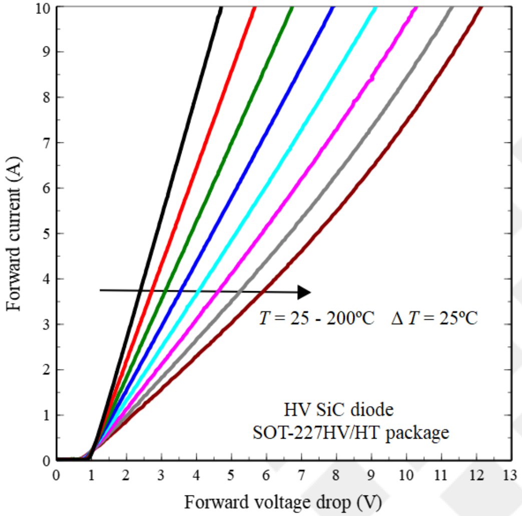
>6 kV – 210ºC: developed from 6 kV 25 mm^2 SiC diodes manufactured at IMB-CNM



Empty package characteristics



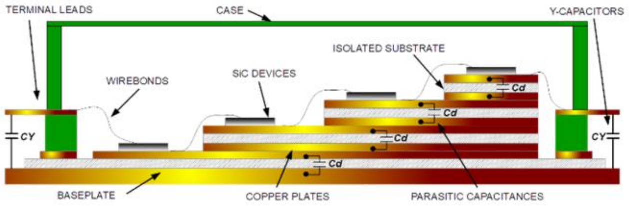
SiC diode blocking characteristics

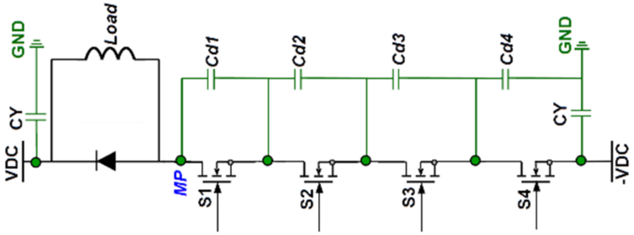


SiC diode conduction characteristics

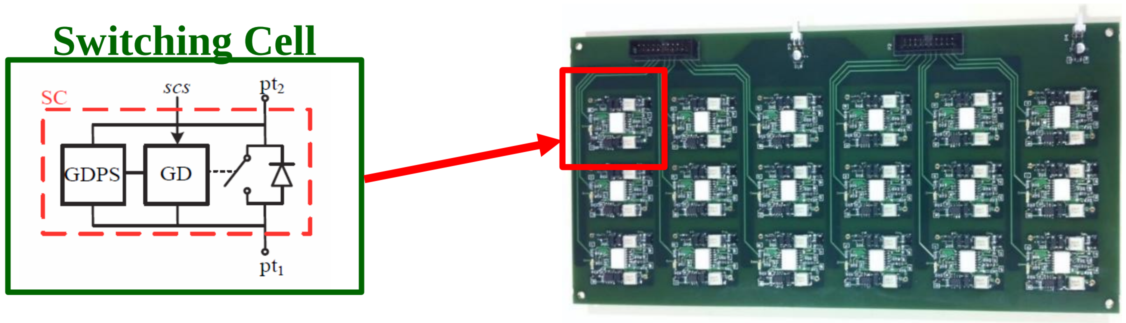
Other approaches for implementing power converters in grid applications with LV devices:

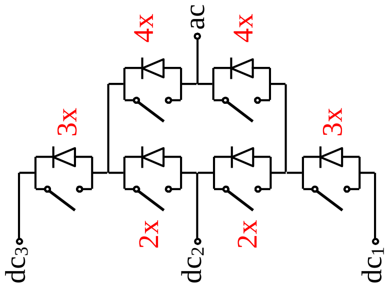
Multi-step Packaging Concept developed by G2ELAB: "smart" series connection of devices (managing parasitic C's)



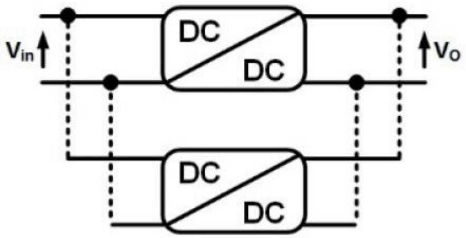


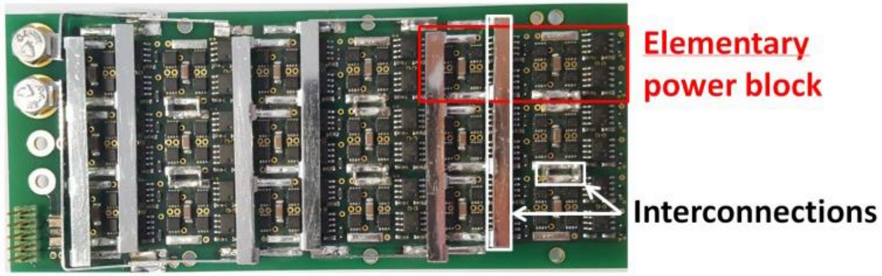
Switching Cell Array approach: Building converter legs from an array of standard cells (multi-level converters)





Building converters by series/parallel association of elementary Power Electronics Building Bloks (PEBB)





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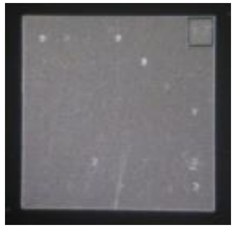
Reliability issues in WBG materials ⇒ <u>specific characterization tools</u> available at IMB-CNM

Example: Gate Oxide Degradation of SiC MOSFET in Switching Conditions

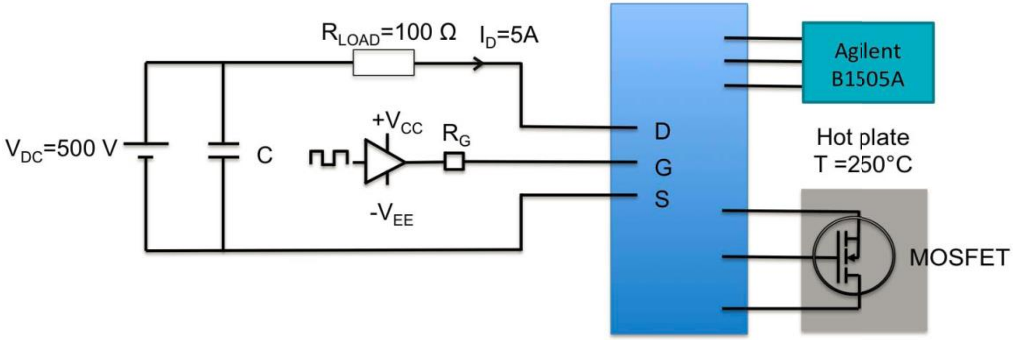
Ampère

THALES



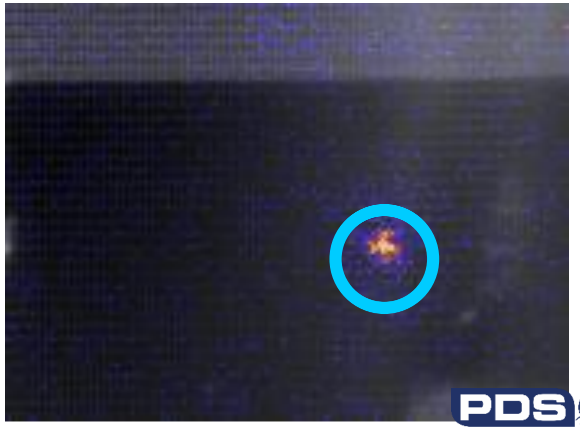
*1.2 kV **SiC MOSFETs***

***Test:** switching at 10 kHz under 500 V / 250-300ºC*



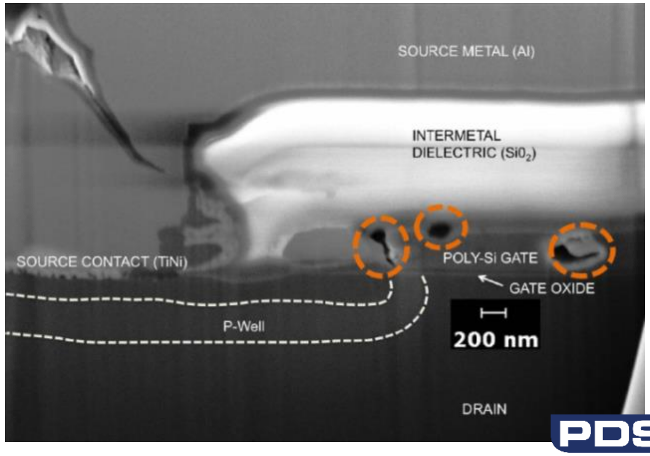
PDS

***IR-LIT** detects physical failure signature (V_{DS} homodinally modulated, V_{GS}=0V)*



PDS

Failure physical signature located

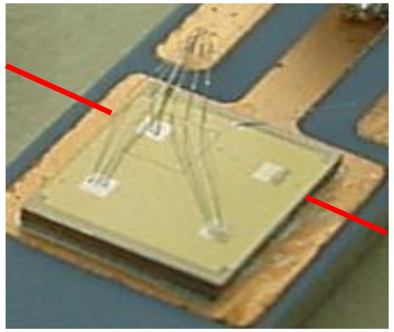


PDS

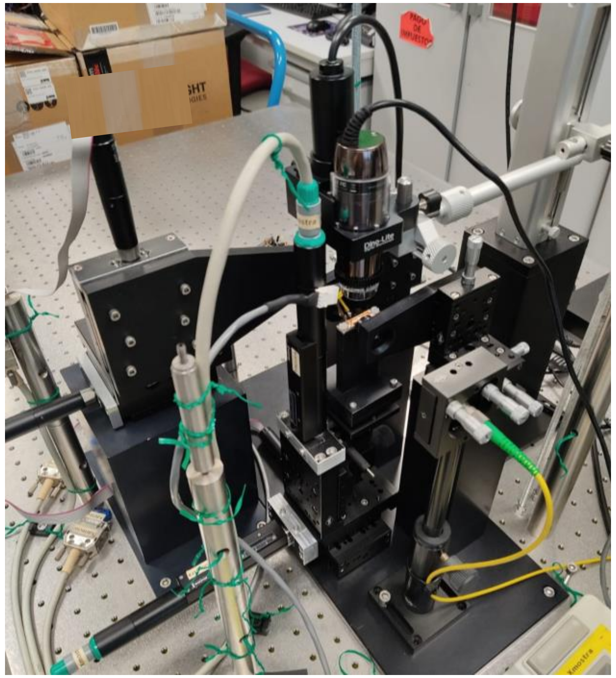
Physical failure signature: gate oxide local breakdown (FIB Millings and SEM)

Advanced characterization optical techniques for depth-resolved analysis at chip level

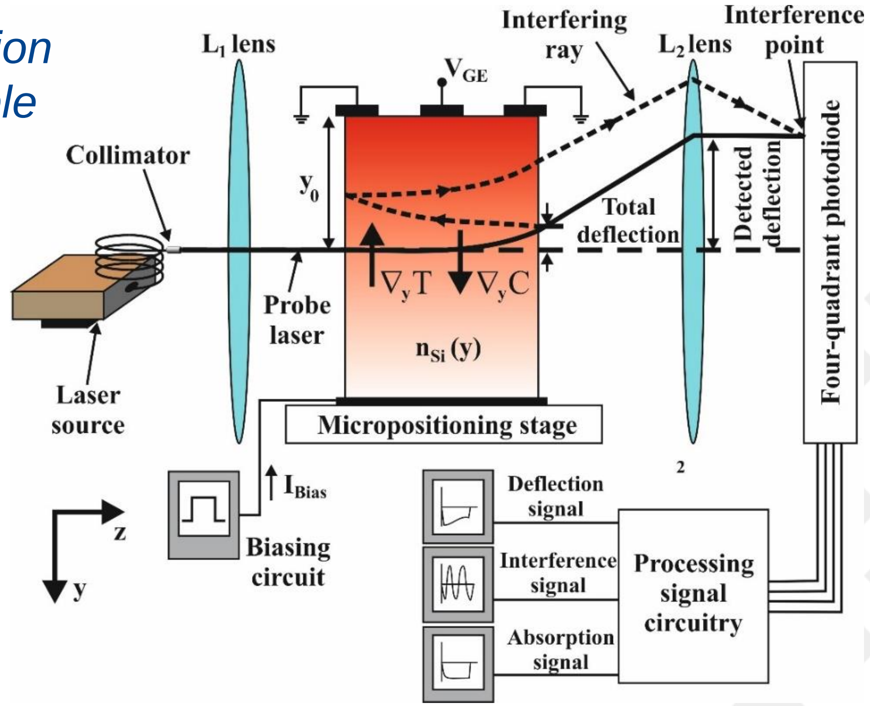
- Based on an IR laser probe beam through the device under test
- Advanced optical techniques for depth-resolved electro-thermal characterization:
  - ✓ Internal IR-laser Deflection (IIR-LD): thermal gradients determination (heat flux)
  - ✓ Fabry-Perot Interference thermometry (FPI): temperature measurements
  - ✓ Free-Carrier Absorption (FCA): free-carrier concentration measurements



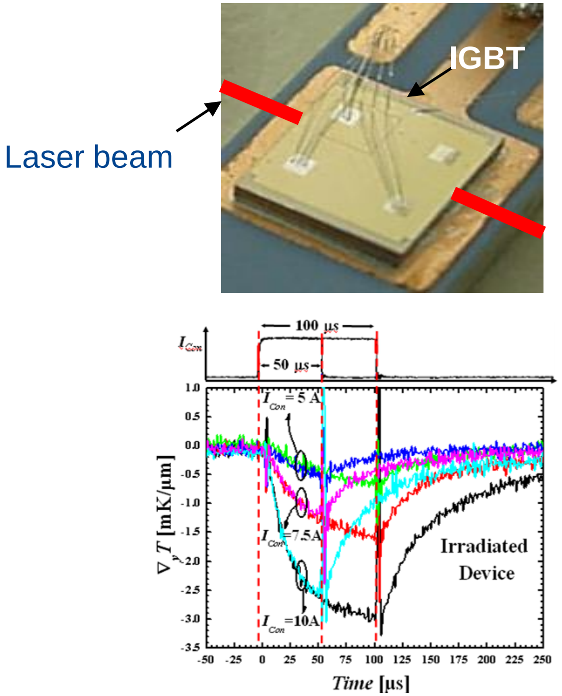
Automated setup view



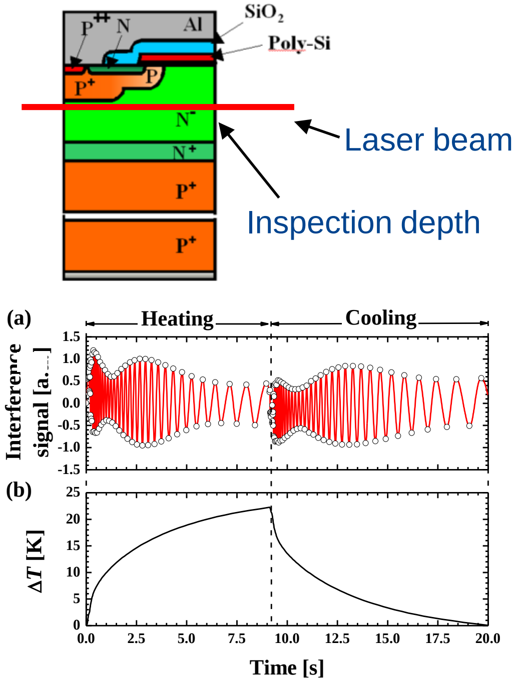
Operation principle



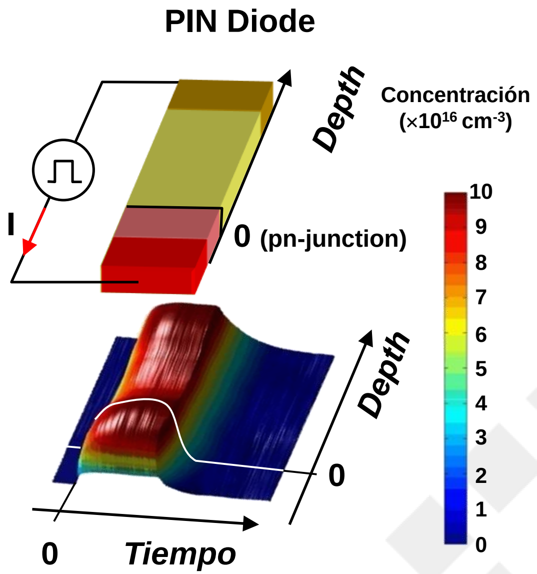
- Advanced optical techniques for depth-resolved electro-thermal characterization:
  - ✓ Internal **IR-laser Deflection** (IIR-LD): thermal gradients determination (heat flux)
  - ✓ **Fabry-Perot Interference thermometry** (FPI): temperature measurements
  - ✓ **Free-Carrier Absorption** (FCA): free-carrier concentration measurements



Free-carrier & thermal Gradient measurements by ***IIR-LD***



IGBT temperature profile Measurement by ***FPI***



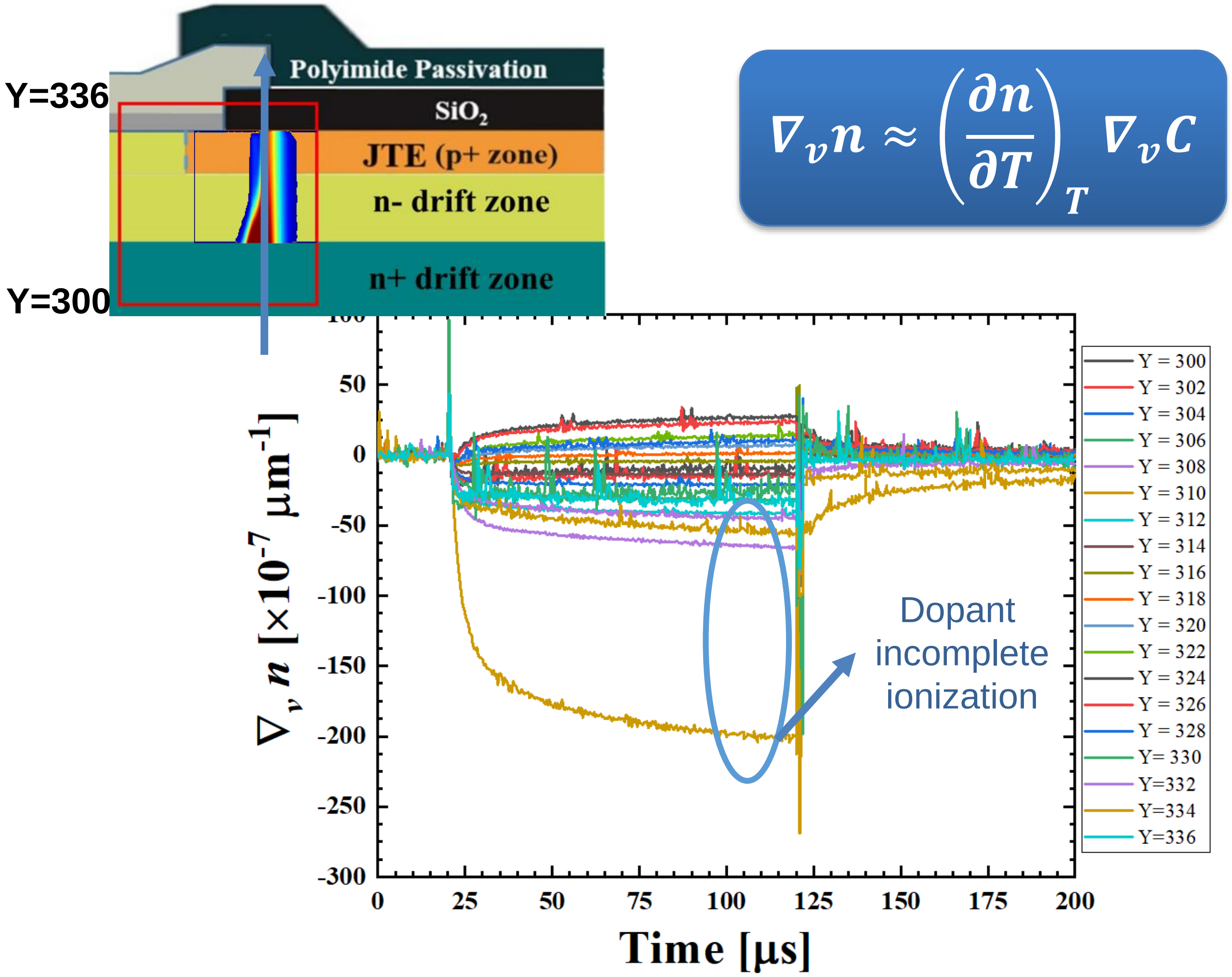
Free-carrier concentration ***measurement*** *by* ***FCA***

Application to WBG semiconductors: IIR-LD SiC Schottky diodes

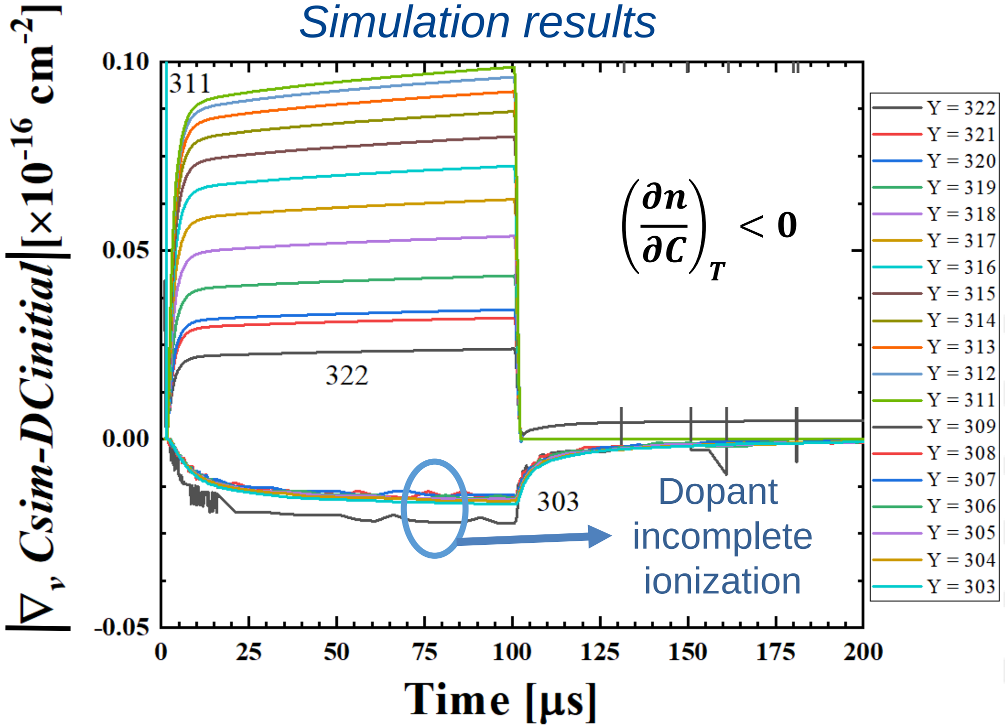
Singular phenomena not observed in Silicon

$$\nabla_v n \approx \left(\frac{\partial n}{\partial T}\right)_T \nabla_v C$$

under dopant incomplete ionization,
$\boldsymbol{\nabla_v n < 0}$



Simulation results



Conclusions

Power electronics is a key enabling technology allowing the implementation of efficient smart-grids, which are crucial for a deep electrification of industry, transportation, buildings, etc.

This electrification is one of the main tools for achieving the decarbonisation and a neutral carbon society for the 2050 horizon

There is a very complementary combination of research groups in Grenoble and Barcelona focusing their efforts on investigating more efficient and reliable power devices and converters

Strengthening their collaboration and including new groups from other fields (materials, electrical and magnetic systems, EMC, transportation, etc.) will result in one of the most singular research poles in Europe

Thanks for your attention

C/ del Til·lers s/n
Campus de la Universitat Autònoma de Barcelona (UAB)
08193 Cerdanyola del Vallès (Bellaterra)
Barcelona · Spain

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