# The Wide Band-gap Semiconductors, a New Trend of Power Semiconductor Devices Development


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***This presentation talks about contributions of the Microelectronic Institute of Barcelona to the WBG power devices development, focused on SiC devices .***

# Power Devices and Systems

## Wide band-gap group

### Researchers

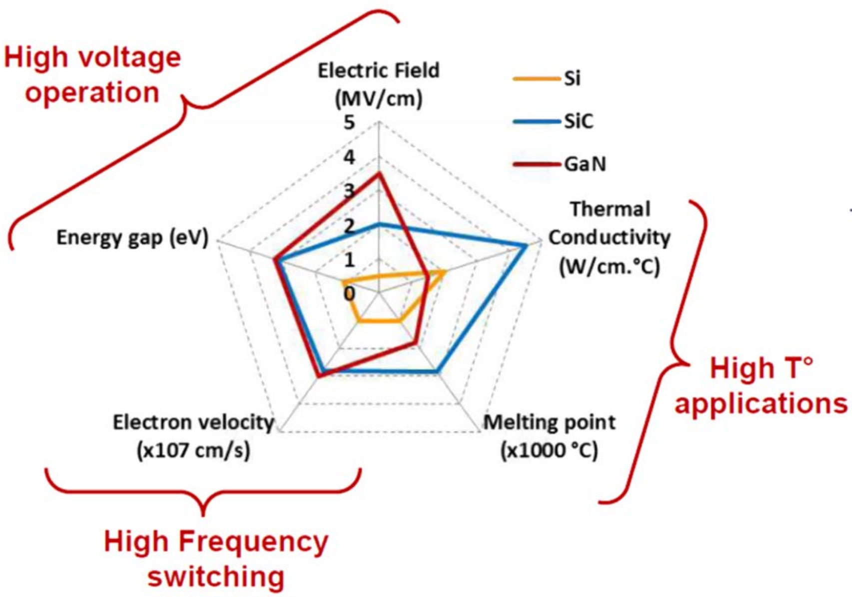
- **Professor Dr. Philippe Godignon (group leader)**
- Dr. Josep Montserrat
- Dra. Gemma Rius
- Dr. José. Rebollo

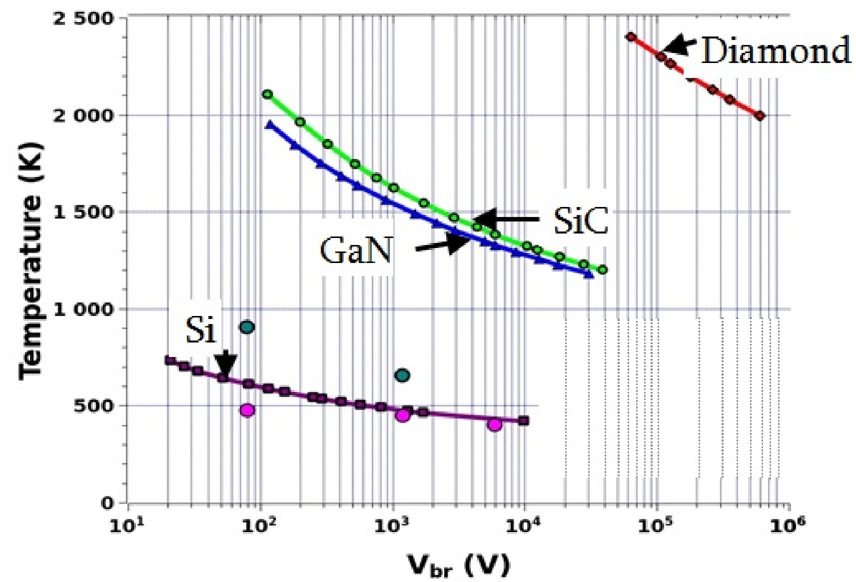
### Technical staff

- Viorel Banu
- David Sánchez
- Raphaela Tkatchenko

### PhD Students

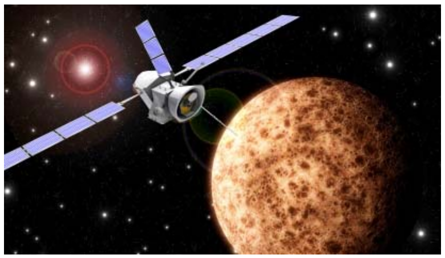
# Wide Band Gap (WBG) material properties compared to Silicon




*Compared to silicon, the WBG semiconductors have superior properties in terms of maximum temperature, break down voltage and switching frequency.*

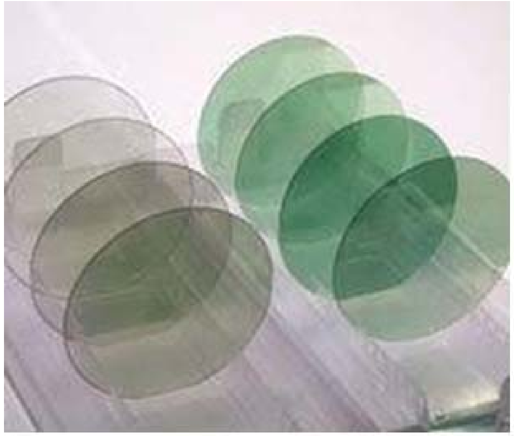
# High Voltage and Temperature Applications



*The high temperature and high voltage power devices are now demanded by the industry for new projects.*

# Wide band-gap semiconductors studied at IMB-CNM

- Silicon Carbide (SiC)
- Gallium Nitride (GaN)
- Diamond
- Gallium Oxide ($Ga_2O_3$)



# WBG Devices developed at IMB- CNM

- **Power devices**
  - **Diodes**
    - **Schottky** (SiC, Diamond, $Ga_2O_3$)
    - **JBS (Junction Barrier Schottky )** (SiC, $Ga_2O_3$)
    - **PiN** (SiC)
  - **Switches**
    - **JFETs and MESFETs** (SiC)
    - **MOSFETS and HEMTs** (SiC and GaN)
    - **BJT** (SiC)
- **Integrated Circuits for Intelligent Power**
  - **MESFETs** (SiC)
  - **CMOS** (SiC)

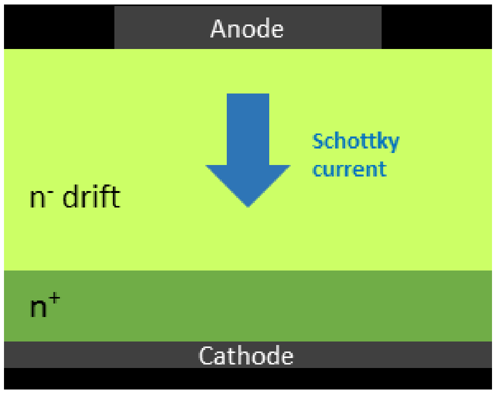
# Challenges for Wide Band-gap devices

| Issue | Solutions |
|---|---|
| Limited surge current capability | • Design<br>• Package |
| High temperature operation | • Package<br>• Materials |
| Reliability | • Materials<br>• Package,<br>• Technology |
| Test & Measurement | • New test methods<br>• New specific instruments |
| Ringing oscillations and EMI (due to high switching speed) | • Package with low stray inductance<br>• Smart power integration |

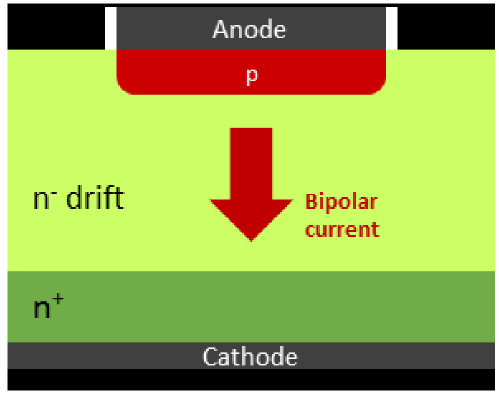
*Despite the massive presence on market of WBG devices, some challenging issues remain to be solved.*

# SiC Diodes

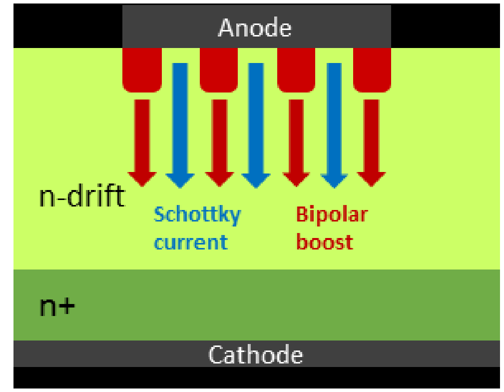
# SiC Diodes




Schottky Barrier Diode

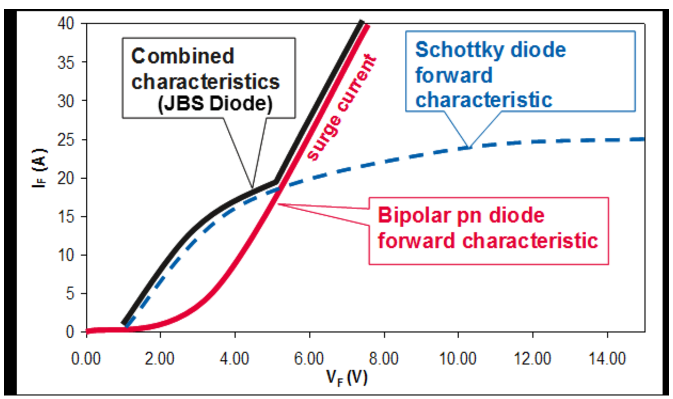



PiN diode



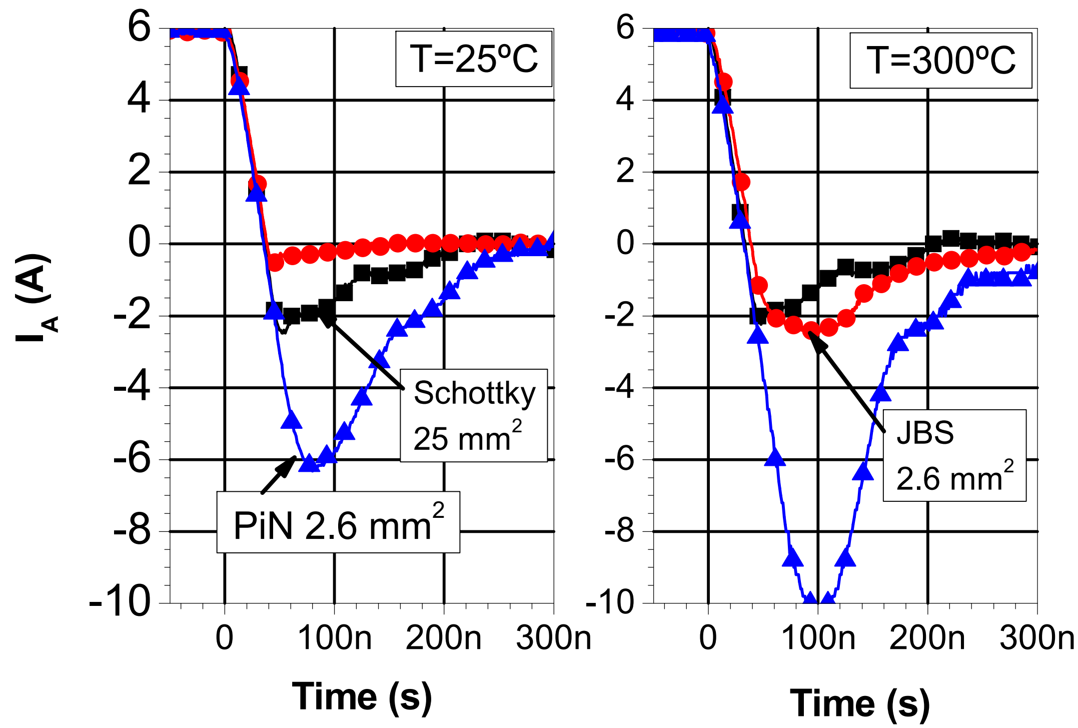

JBS cross-section

- **SBD: high switching speed and low on-state losses, but lower blocking voltage and high leakage current.**
- **PiN diodes: high voltage operation and low leakage current, but higher reverse recovery time during switching.**
- **JBS (or MPS) diodes: Schottky-like on-state and switching characteristics and PiN-like off-state performances.**




**Typical forward I(V) characteristic of a SiC JBS rectifier (Infineon)**

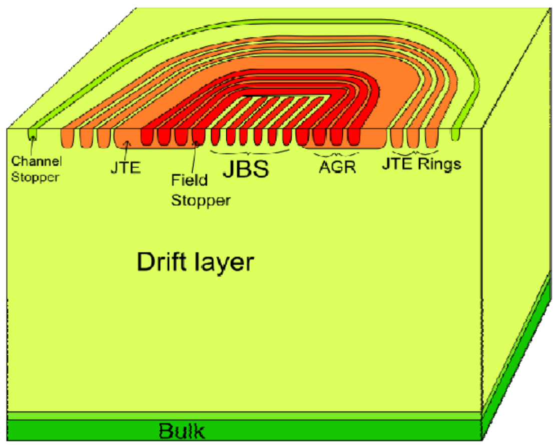
# SiC Diodes



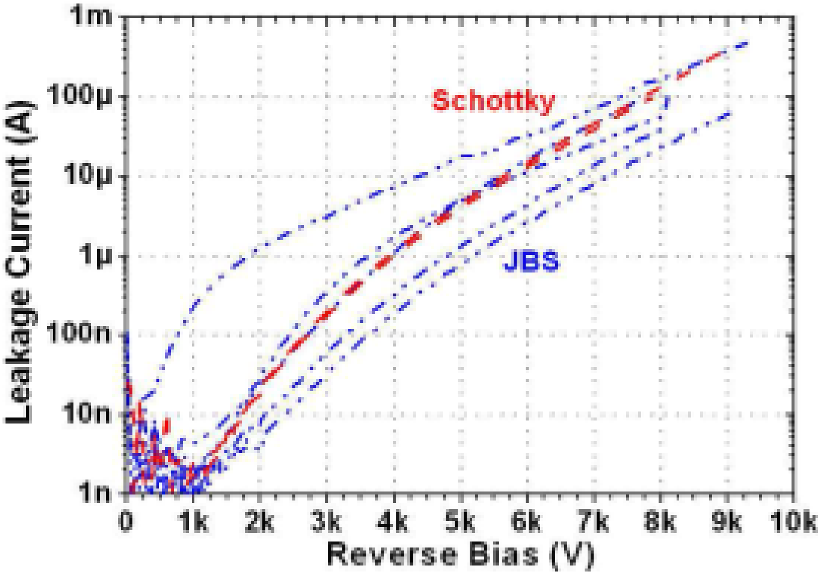

Turn-off current waveforms for **3.3 kV SiC diodes** in the 25°C-300°C temperature range (CNM)

*The best switching behavior even at high temperature, belong to Schottky diodes, followed by JBS and PiN diodes.*

# 9kV SiC Diodes




Schematic view of a JBS diode with the 10kV edge termination. Epilayer: 90µm, $5 \cdot 10^{14} cm^{-3}$

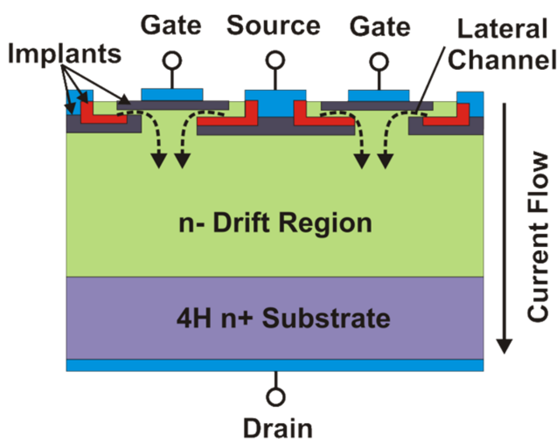



Reverse characteristics of 9kV JBS diodes measured at room temperature in a Galden bath.

# SiC Switches

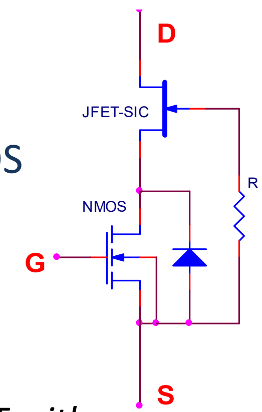
# SiC Switches: JFETs +Si MOSFET

Normally ON




SiC JFET

Cascode SiC JFET + Si NMOS

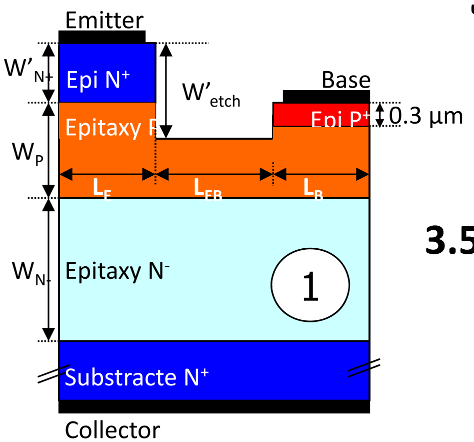



Normally OFF

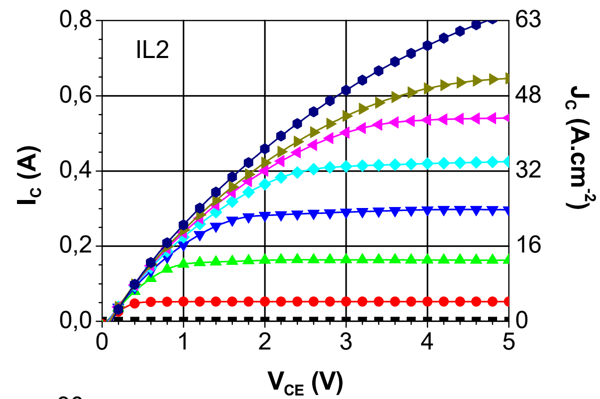
*Combining normally ON SiC JFET with low voltage Si MOSFET, a normally OFF device is obtained.*

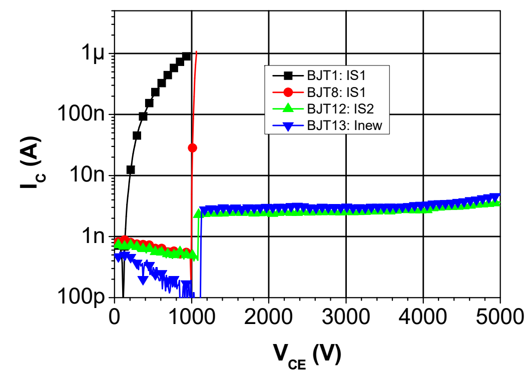
- **SiC unipolar switches allow on-state conduction losses'reduction compared to Si IGBTs.**
- **Internal body diode can replace the freewheeling diode.**
- **Single SiC JFET also used for circuit protection (current limitation)**

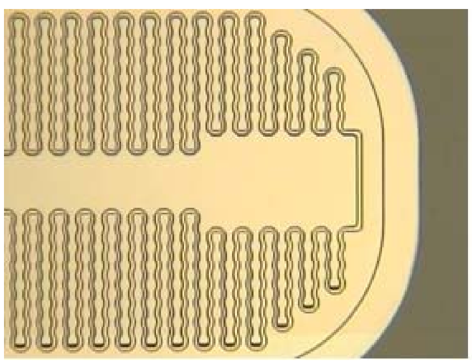
# SiC Switches: Bipolar Transistor

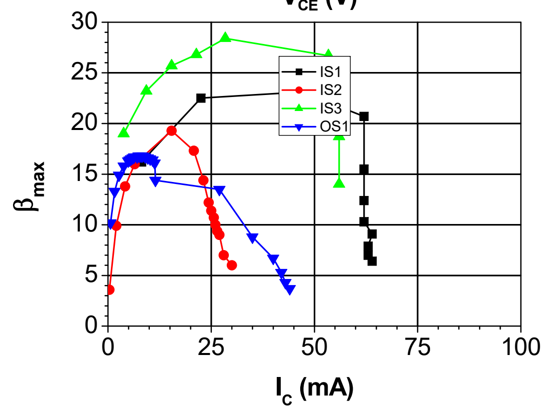


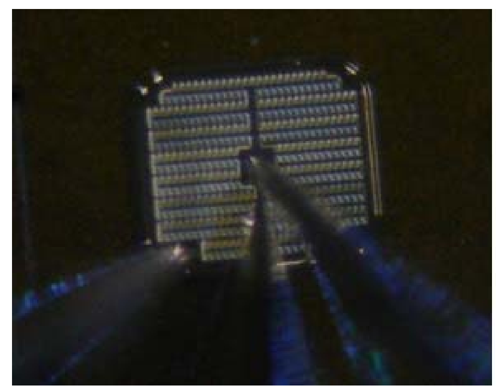

**3.5kV – 5kV**



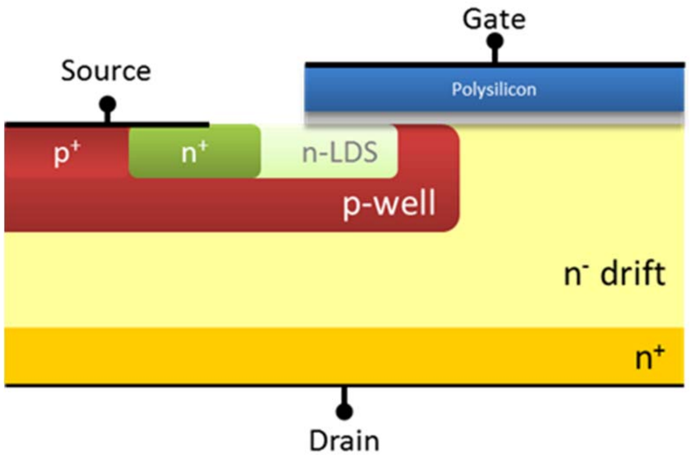





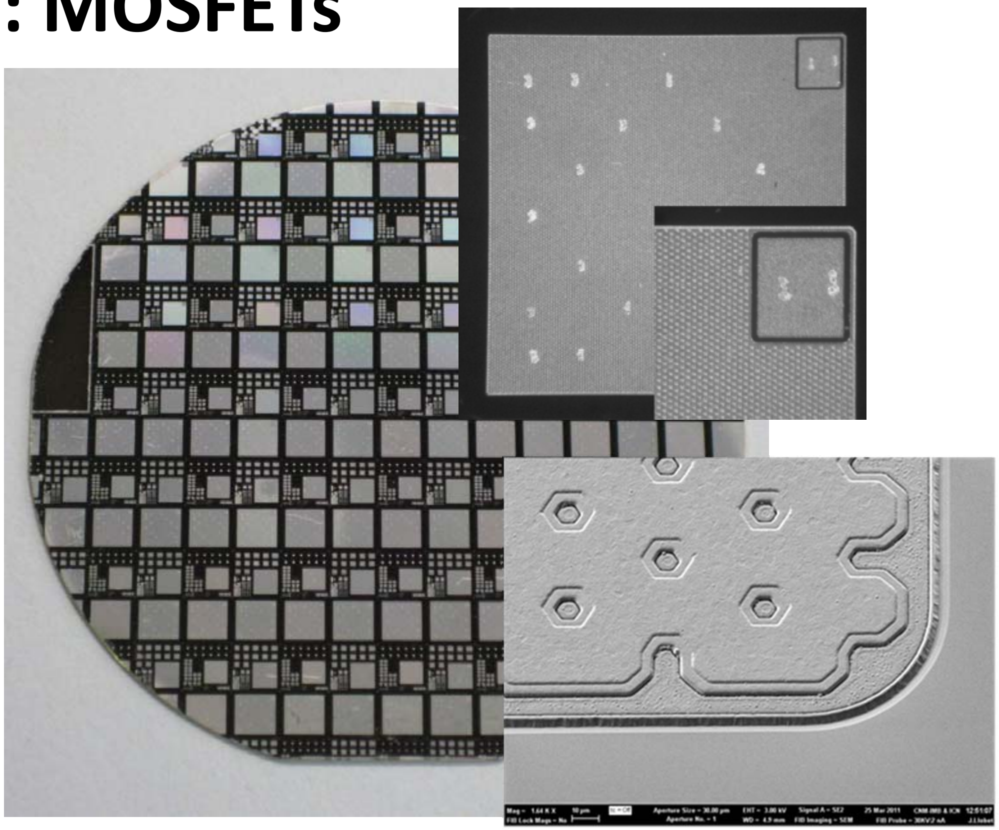
*BJTs are able to sustain high voltage breakdown and high currents. However the presence of BE surface recombination reduce the transistor gain. Surface recombination remains a big issue to be solved.*

# SiC Switches: MOSFETs



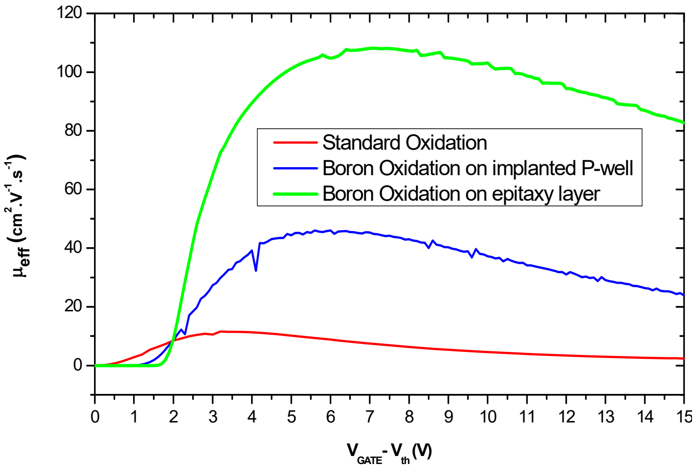

Schematic cross-section of a SiC planar VDMOS half-unit cell

- **SiC MOSFETs have relatively poor body diode.**
- **Body diode operation may cause bipolar degradation by expansion of stacking faults in the SiC-MOSFET.**
- **Monolithic integration of a Schottky structure as a freewheeling diode are also explored.**

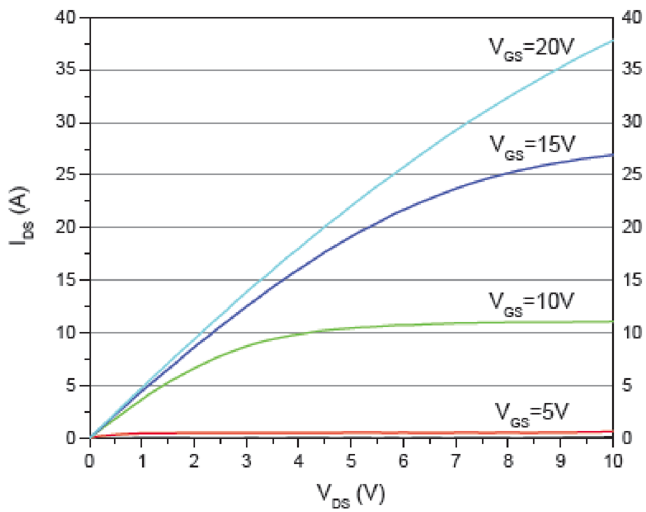


*Important efforts are focused to solve the remaining issues of SiC MOSFETs.*

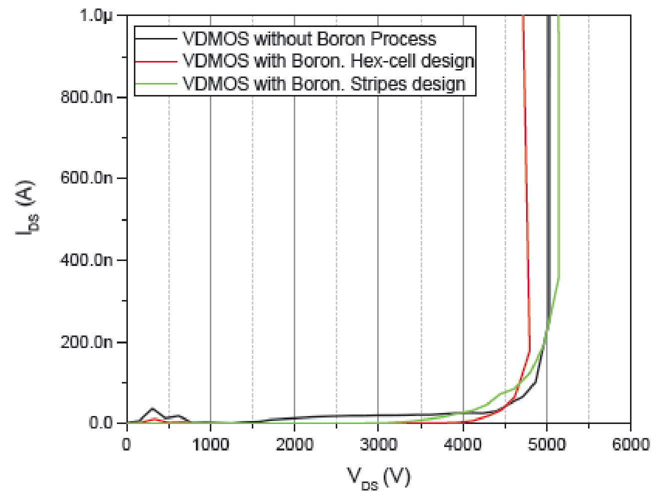
# SiC Switches: MOSFETs




Experimental effective channel mobility extracted from a novel batch of N-MOSFETs test structures with an optimized Boron treatment.



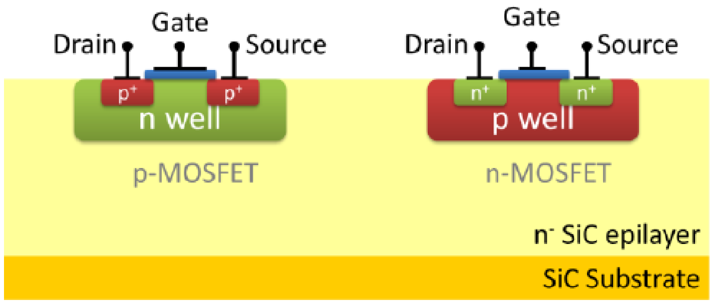

Experimental output characteristics of fabricated 25mm² VDMOS



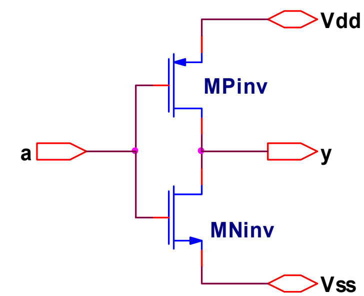

Blocking characteristics of fabricated VDMOS with hexagonal and stripe designs.

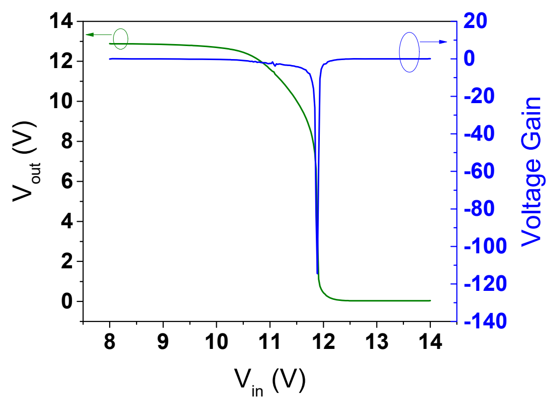
*The low effective mobility of the channel is now a problem solved. The actual MOSFETs reach tens of Amps and more than 5kV breakdown voltage.*

# SiC CMOS Inverter



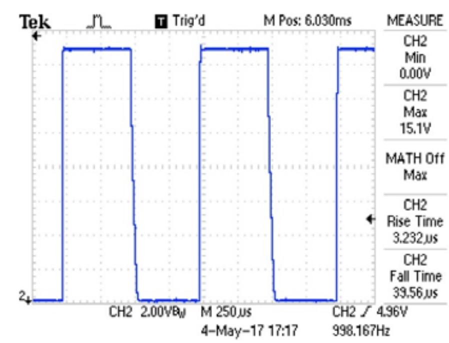

Cross-section of CMOS on SiC in twin tub technology




Voltage-transfer characteristic and associated gain

*The SiC CMOS technology is under development and SiC CMOS inverter was already demonstrated in our lab.*



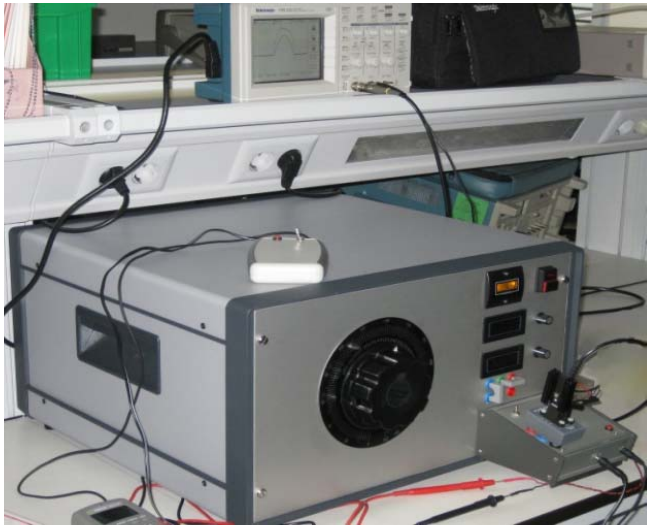

Switching performance of the SiC CMOS inverter

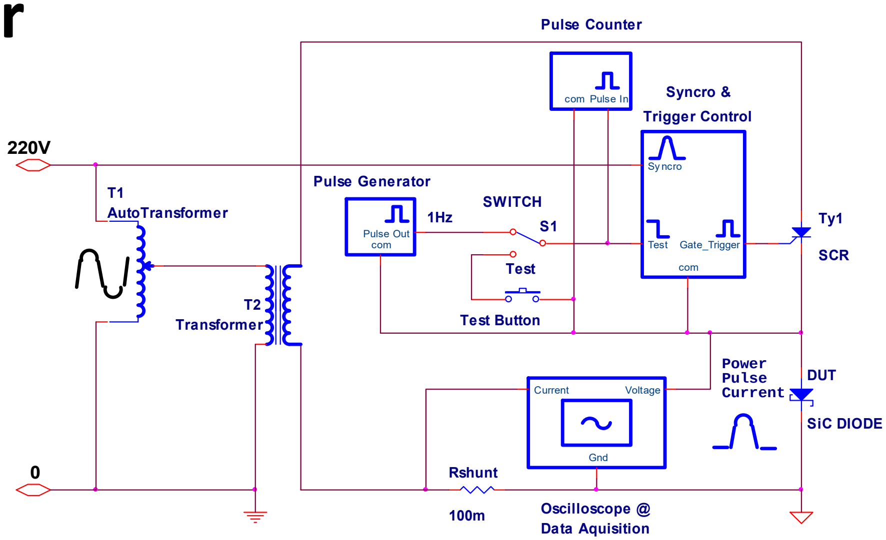
# Proprietary Test Instruments

***Developing the new generation of WBG devices requires specific instruments that are not still available on the market.***

***Various specific test instruments were developed by our group.***

# 500A/10ms sine Surge Current and Power Cycling Tester

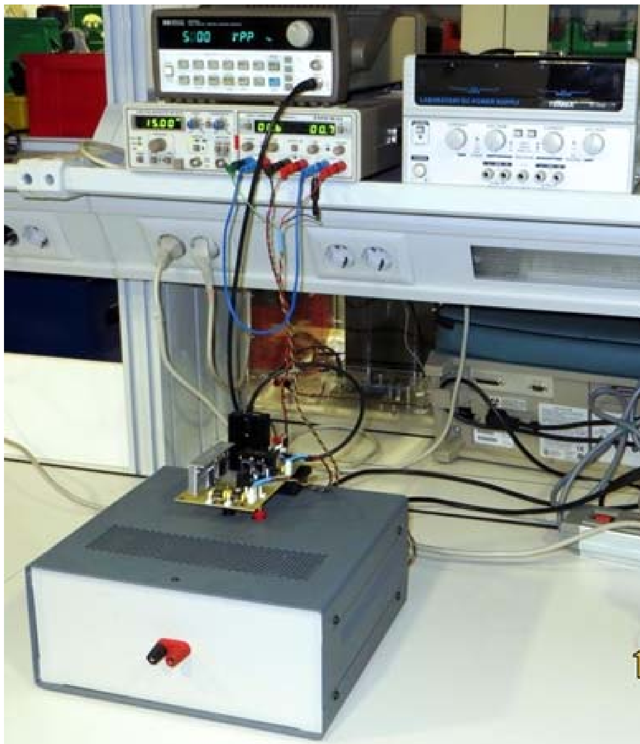





- The instrument is able to provide 10ms half sinus current pulses up to 500A peak.
- The frequency is tuneable in the range of 0.5Hz to 5Hz.
- The preferred frequency is 1Hz.

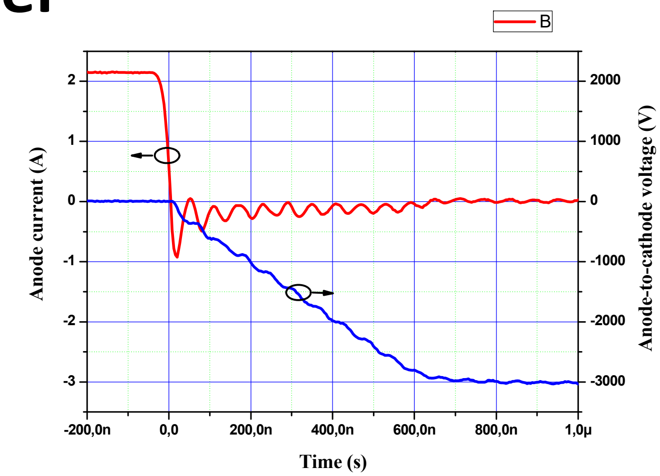
*Our lab developed a proprietary Surge Current and Power Cycling instrument that uses 10 ms sine waveform.*

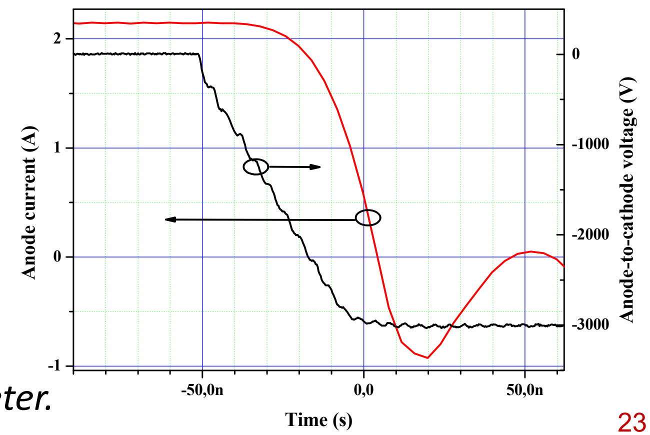
# 200A/100µs Rectangular Pulse Surge Current Tester




*We also have built a Surge Current tester using 100 µs to 10ms rectangular waveform.*

# 4kV Reverse Recovery Time Meter

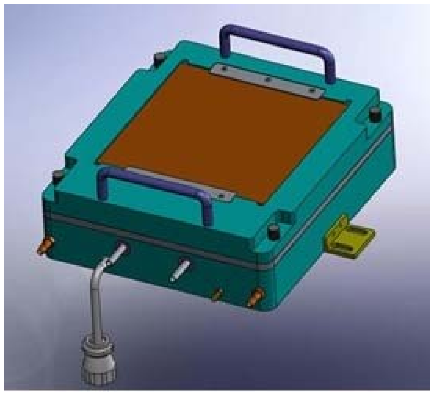


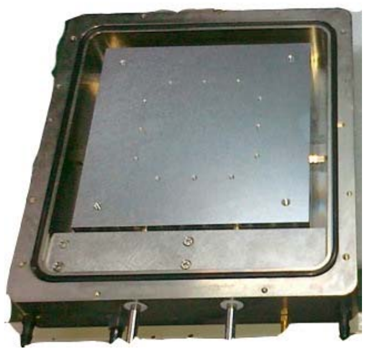

*Another proprietary instrument developed in our lab is the 4 kV reverse recovery time meter.*

# Hot-Cold Thermal Cycling System

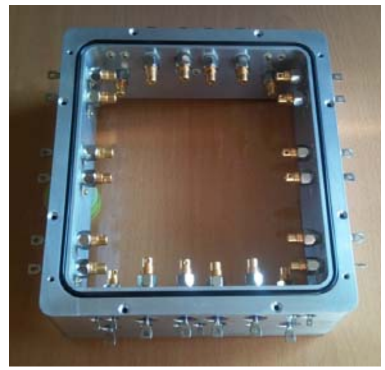
***In cooperation with INSTEC Inc. And MAG.ABC-SRL***



Hot-Cold Plate with cover



Hot-Cold Plate



Insertion with electrical feedthrough

*A hot-cold thermal cycling system was developed for extreme temperature cycling from -180 °C to +300 °C.*


Temperature Controller


LN2 Pump

LN2 Dewar


Water Pump

# Clamping Device for Free Floating Press Pack Measurements

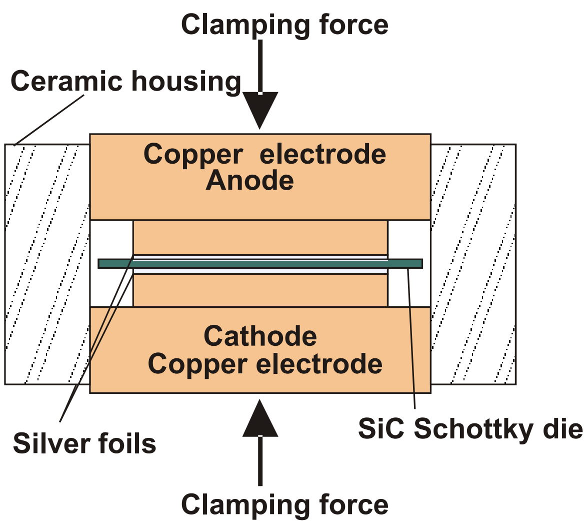

Clamping device with pressure calibration and parallelism compensation for free floating press pack SiC diodes tests.

*For the studies dedicated to free-floating press pack technology we have designed and fabricated a clamping device with pressure calibration and parallelism compensation.*

Clamping device for free floating press pack SiC diodes tests in measuring configuration.

# Novel Test Methods for Power SiC Devices

# Free Floating Press Pack Diode Tests

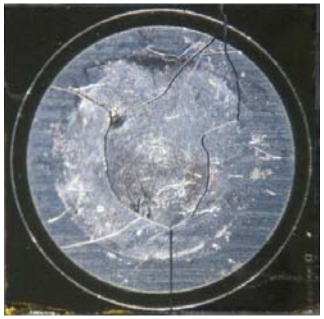


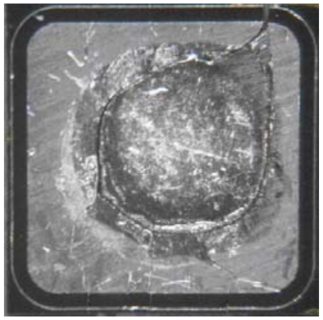

Floating Press Pack Diode

*We have reported for the first time experimental results about power cycling and surge current capability for the SiC Diodes using free-floating press pack technology.*

Clamping device

# Surge Current Results for Free Floating Press-Pack Contact

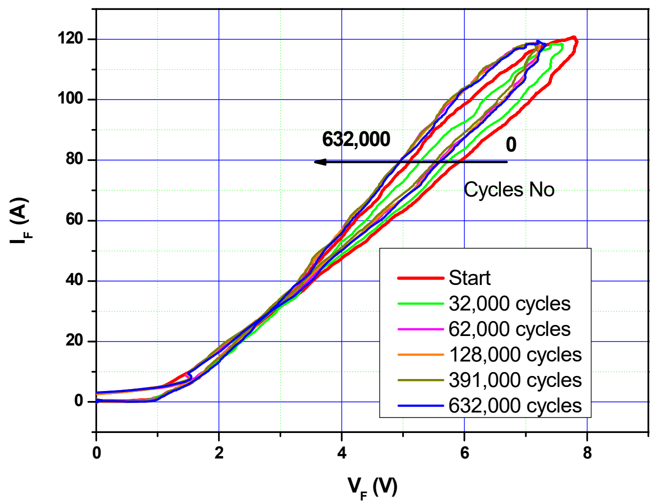




| 1200V Schottky Diodes | |
|---|---|
| Diode bonding and die attach interconnection | Destruction Current Density ($A/mm^2$) |
| press-pack interconnection | 24 |
| 10 wires, 50µm gold ball bonding | 13.75 |
| Al wedge bondings | 12.5 |

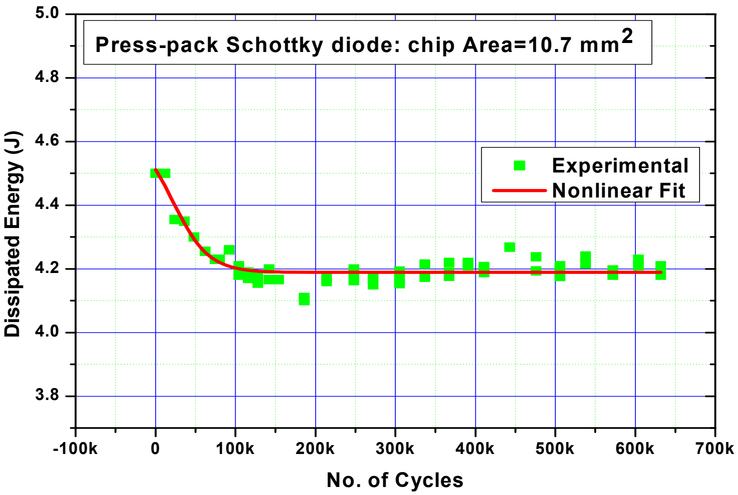
*We have demonstrated the doubling of surge current capability by using free floating press- pack technology compared to classic package.*

# Accelerated Power Cycling Results for Free Floating Press-Pack Package



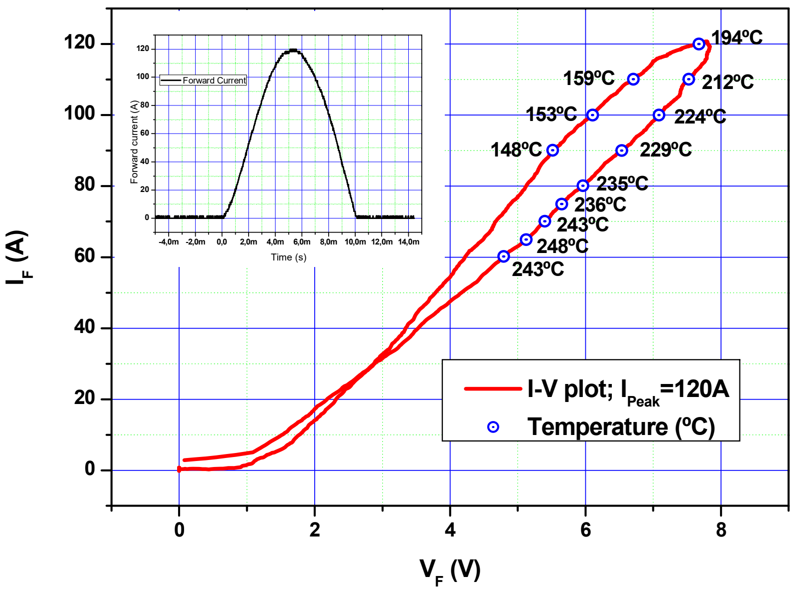

$I_F$-$V_F$ plot of a press-pack SiC Schottky diode for an increasing number of power cycles
Current density $J_F$=1.12 KA/cm$^2$

*For shortening the reliability tests time, an accelerated power cycling method was developed using the concept of global dissipated energy evolution. The free floating press pack technology demonstrated unparalleled robustness, no changes occurred even after 1 million cycles at 120 A peak current and temperatures sweep from 36 °C to 250 °C.*



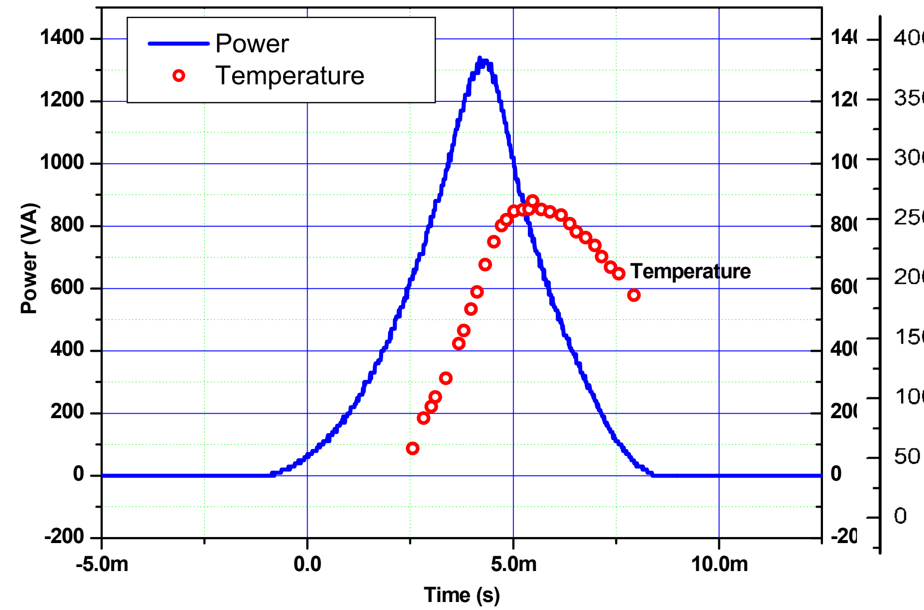

Dissipated energy evolution of tested SiC Schottky diodes with press-pack contact: $E_{d0}$ =4.5 J, S=10.7mm$^2$

# Estimated temperature swing and phase



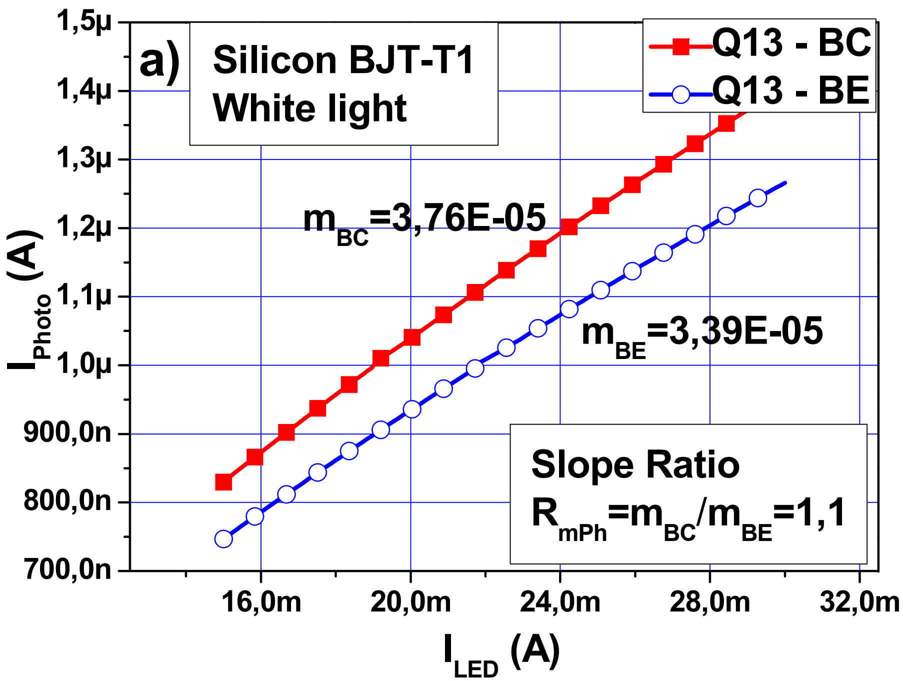

Instantaneous temperatures during 120 A half sine current pulse applied to free-floating press pack SiC diode

*An original method was elaborated for determining the instantaneous temperature and phase during the 10 ms half sine current pulse.*



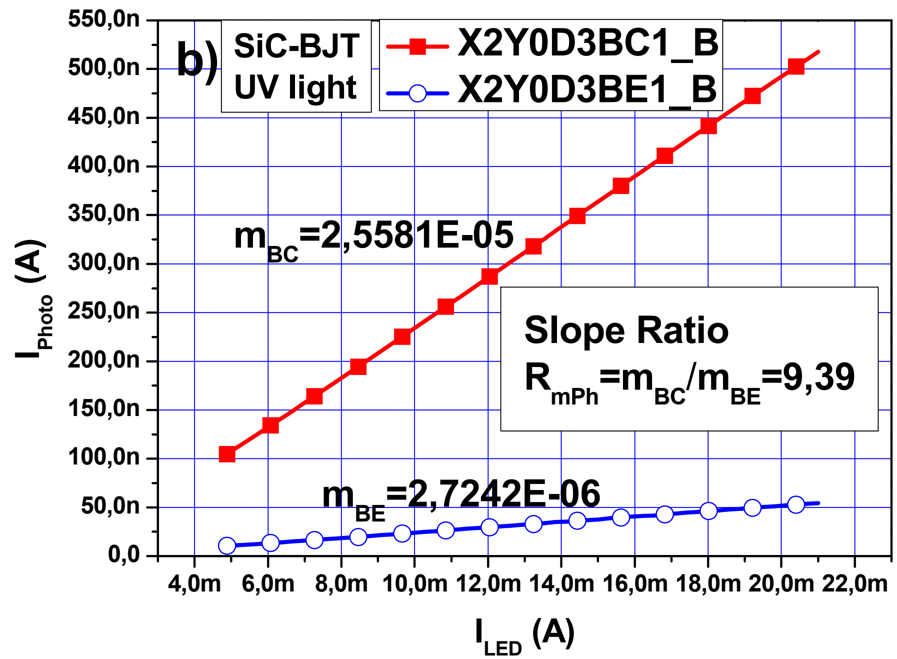

Temperatures phase during 120 A half sine current pulse applied to free-floating press pack SiC diode

# Electro-Optical method for evaluation very short minority carrier lifetime in SiC BJT




*For surface recovery evaluation in SiC devices we have developed a novel electro-optical method.*

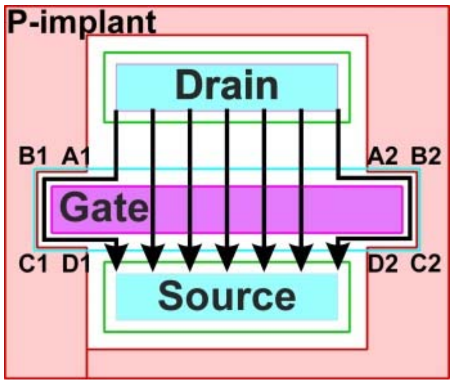
$$\frac{m_{BC}}{m_{BE}} = B_A\sqrt{\frac{\tau_{BC}}{\tau_{BE}}}$$



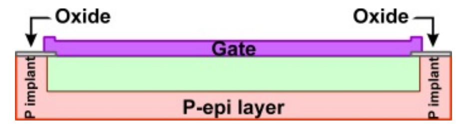
# Integrated Circuits for Intelligent Power

***Integration of driver circuits in the vicinity of the SiC power devices is required in order to reduce the switching ringing of power device and the associated power loss and electromagnetic interference (EMI). Integrated circuits based on SiC MESFETs were designed, fabricated and tested.***

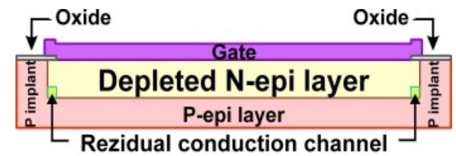
# Finger Gate MESFET




Basic finger gate MESFET layout and current flow distribution

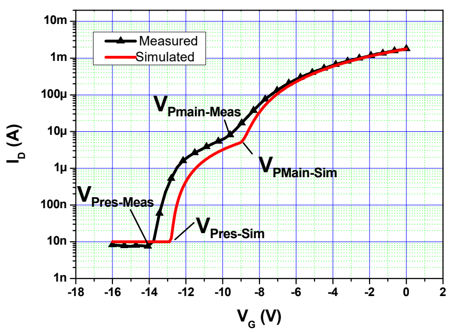



Cross section through the non depleted gate

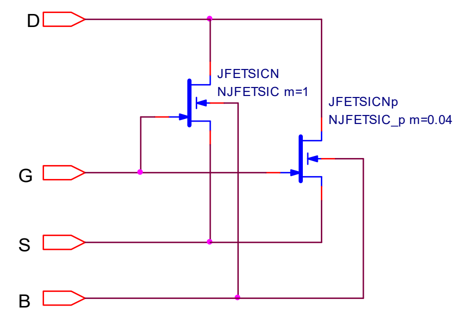



Cross section through depleted gate of the main transitor and residual channel @ $V_{GS}= V_{pinch\text{-}off}$, $V_{DS}=0$

*We have designed an original scalable finger- gate MESFET having implanted isolation rings. It was further used for the integrated circuits design and fabrication.*

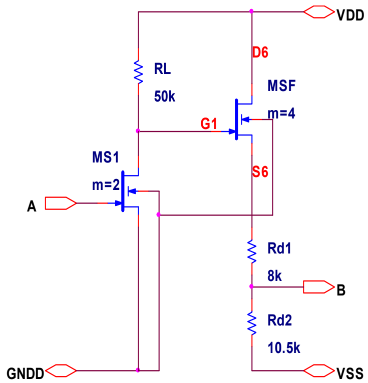



$I_D$-$V_D$ characterisics of planar finger gate MESFET

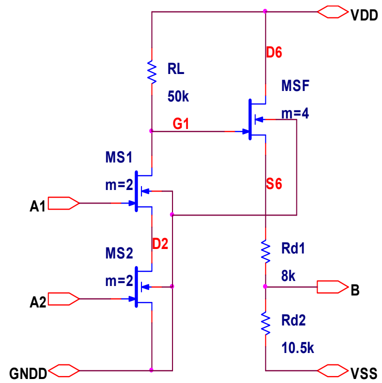



Electrical equivalent circuit of the composed MESFET

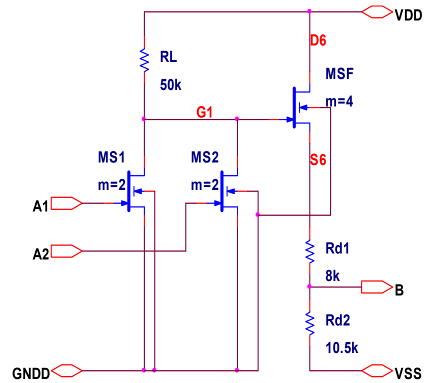
# Basic digital gates schematics with MESFETs



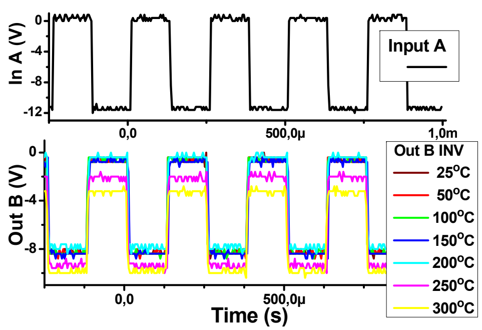

NOT(inverter)

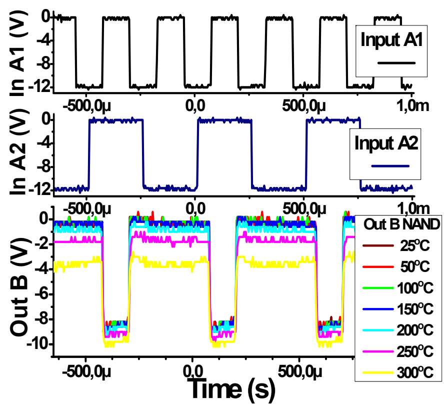


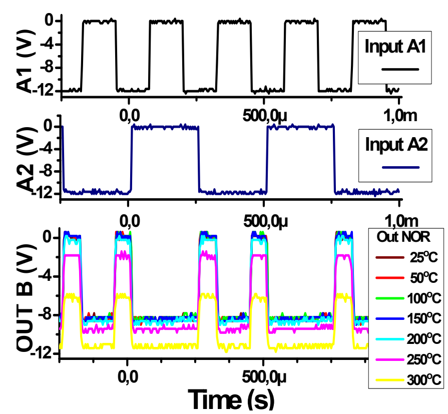

NAND

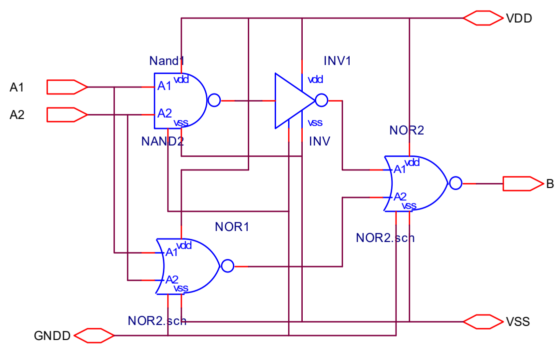


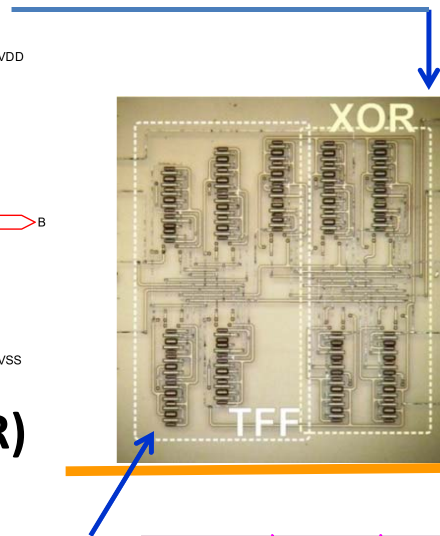

NOR

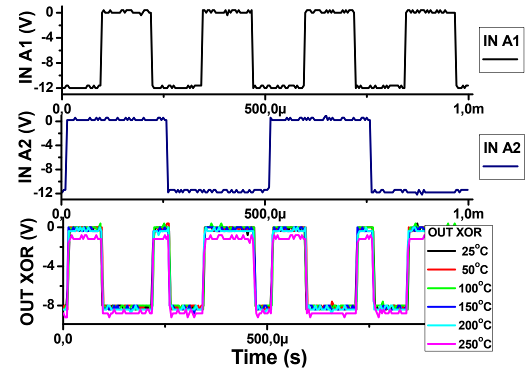


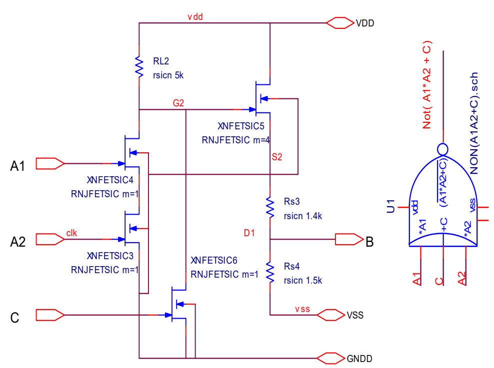



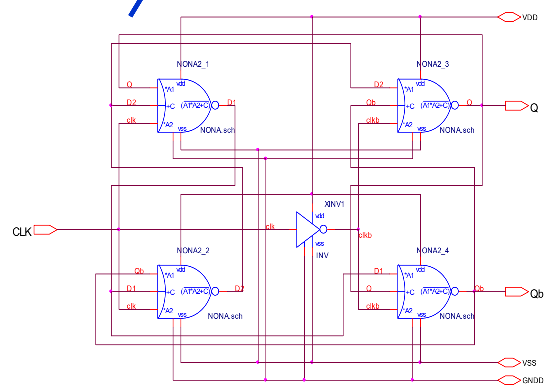


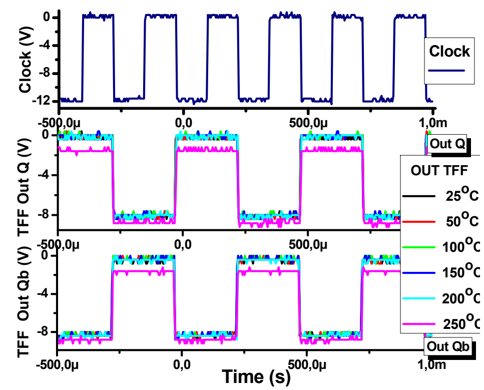



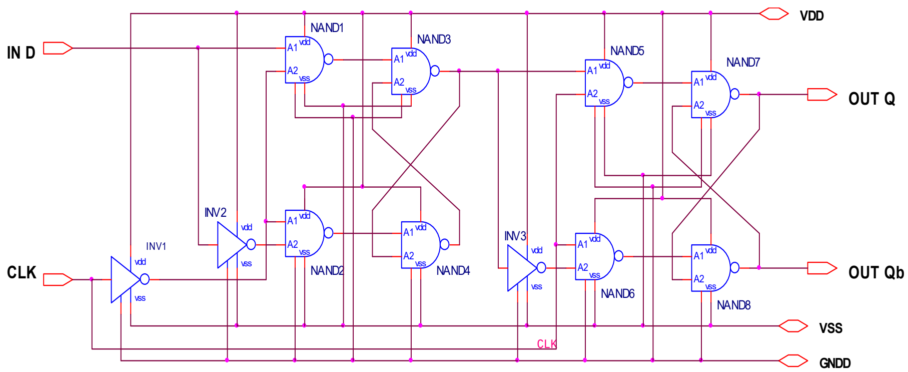

## Exclusive OR gate (XOR)

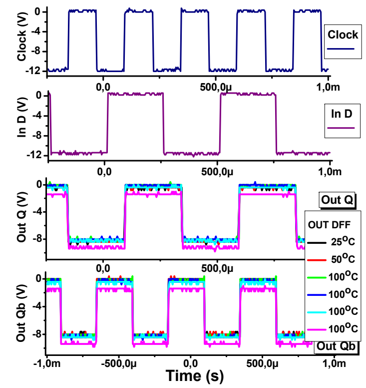


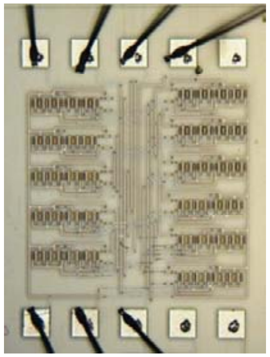



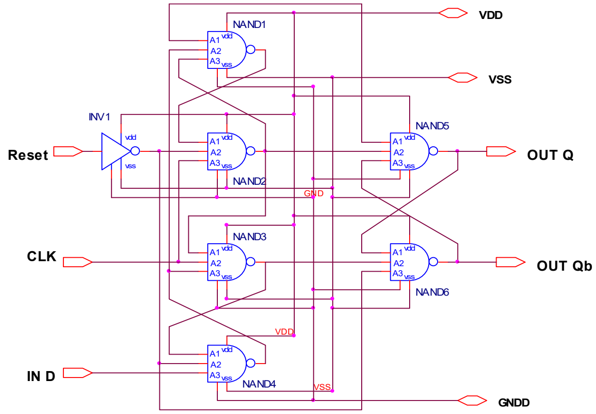

## Toggle Flip-Flop (TFF)

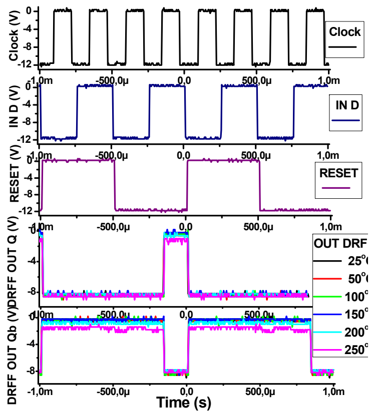


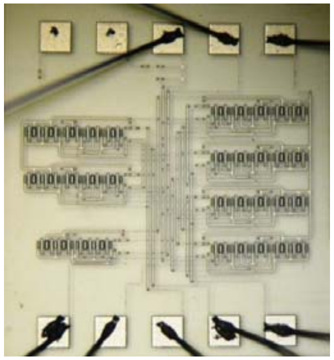



# Data Master-Slave Flip-Flop (DMSFF)

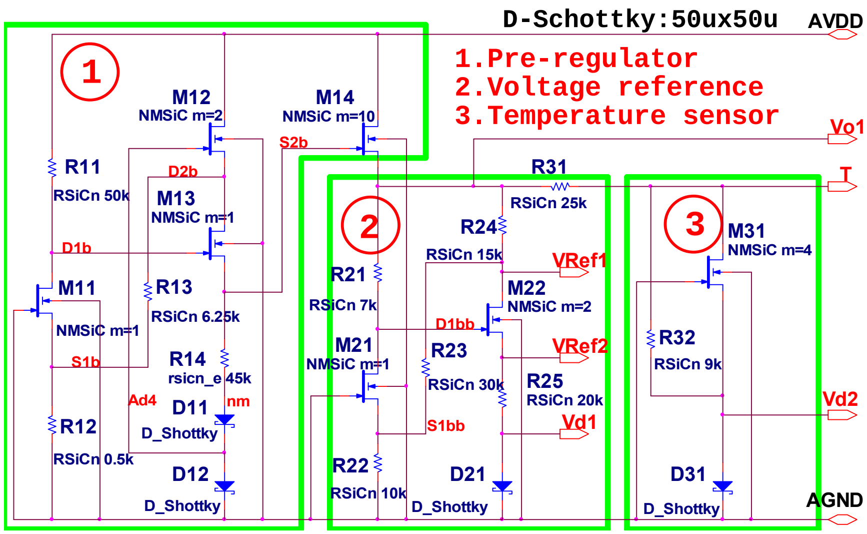


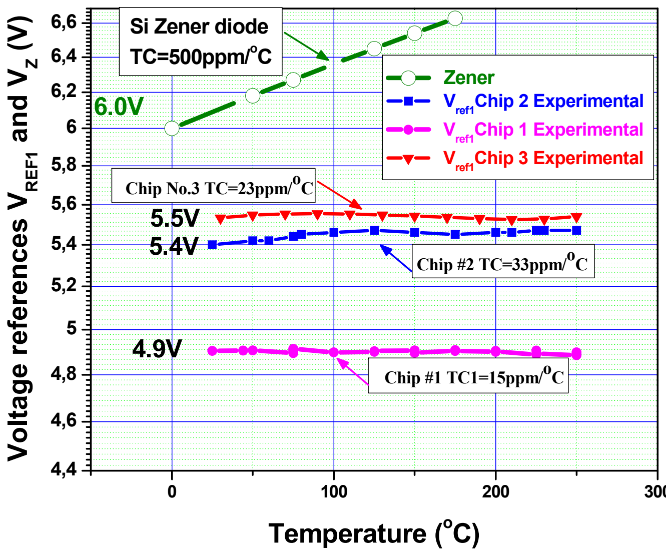



# D-Reset Flip-Flop (DRFF)

# Voltage Reference Integrated Circuit on SiC



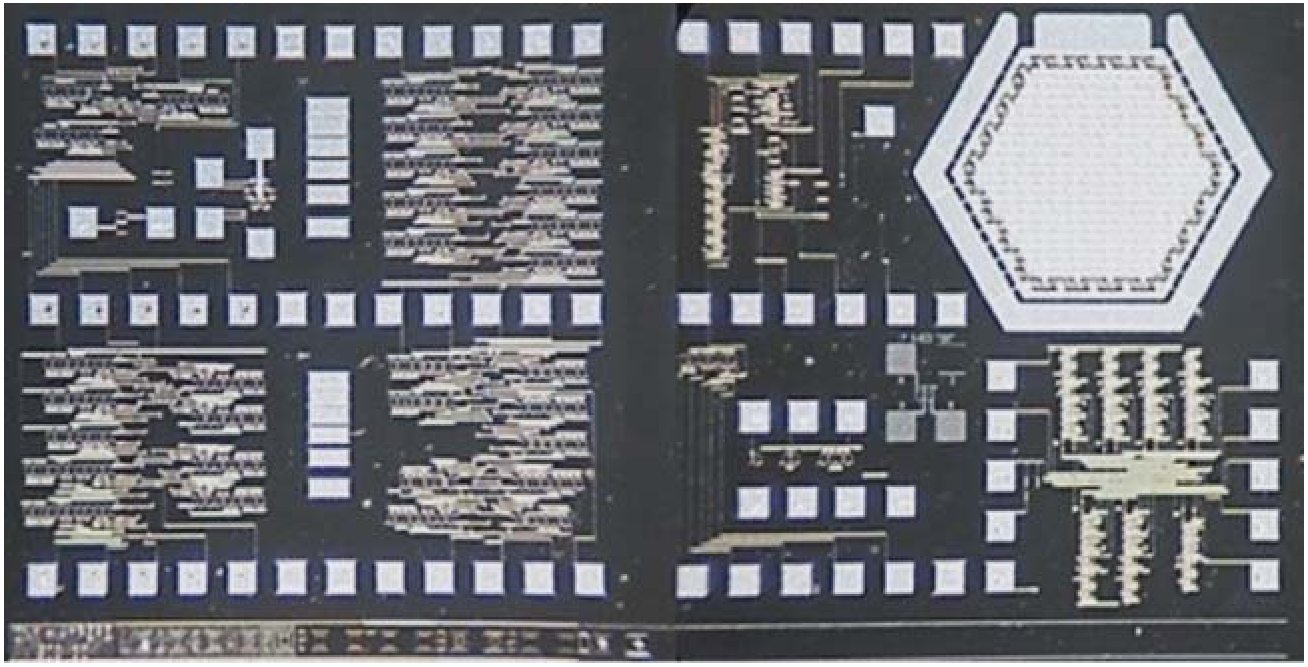

Voltage reference schematic




Voltage reference versus temperature

*On the same chip was fabricated a high temperature voltage reference having a decent temperature coefficient (TC), in a range from 15 to 33 ppm/K.*

# Monolithic integration on a single die

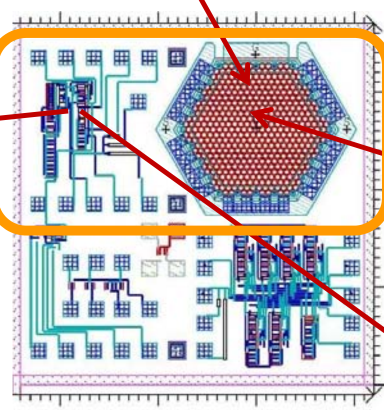


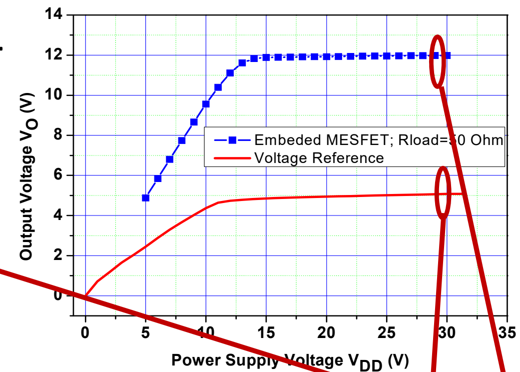
*A micrograph optical capture of monolithic integrated digital gates, voltage reference and power MESFET on the same die.*

# Monolithic Smart Power Demonstration on 4H-SiC

200V Embedded power MESFET

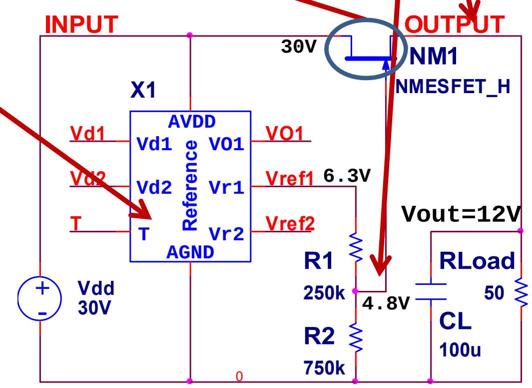
SiC Voltage Reference micrograph






*Using the integrated elements, a 12 V voltage regulator for smart power applications was demonstrated.*

**Embedded Voltage regulator implemented with SiC voltage reference and power SiC MESFET**




Simple schematic application 12V voltage regulator

# Schottky Diodes for BepiColombo Space exploratory mission

# Schottky Diodes produced by Instituto de Microelectrónica de Barcelona, IMB-CNM (CSIC)
# BepiColombo Mission: Exploring Mercury

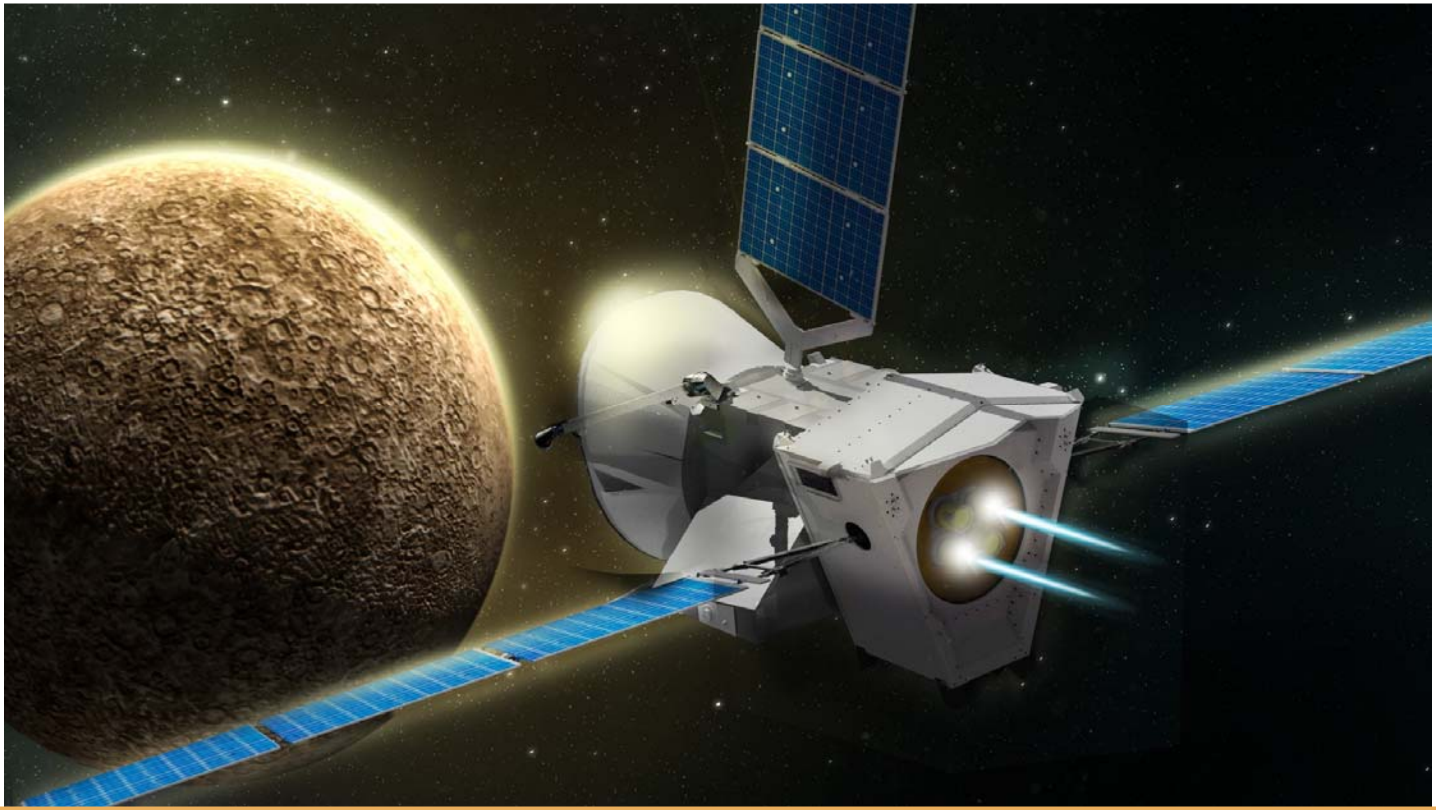

*The last but not the least contribution is our participation to the space mission BepiColombo.*

*We have participated to the space mission BepiColombo as high temperature diodes supplier, used in solar panels. The same high temperature diodes were also delivered for use in Solar Orbiter Mission scheduled in 2020.*

European Space Agency

bepicolombo

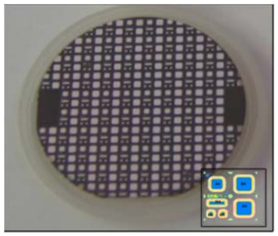
Japan Aerospace Exploration Agency



*BepiColombo is a joint endeavour between ESA and the Japan Aerospace Exploration Agency, JAXA. It is the first European mission to Mercury and the first to send two spacecraft to make complementary measurements of the planet at the same time.*

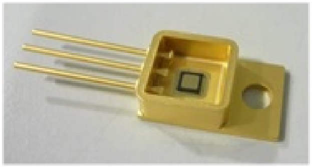
# Diodes Fabrication and Selection

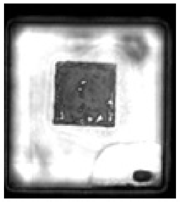
**Wafer processing**



**1st diodes selection**
On-wafer electrical mapping
Reverse current measurement at 300V

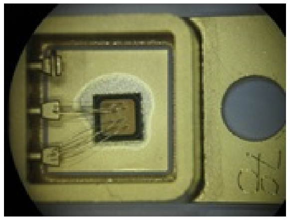
**Dicing and Die attach of the selected diodes**

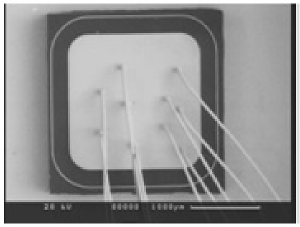




**2nd control (die attach )**
C-SAM (Confocal Scanning Acoustic Microscopy) evaluation
Void density <10%

**Wire Bonding**





**3rd diodes control & selection**
Bond pull and die shear on sampling
Optical inspection following ESA rules (ESCC2045000)

**Hermetic sealing**

# Diodes Fabrication and Selection

**Screening / preconditionning step**

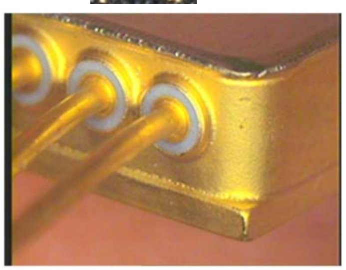
**Final diodes selection**

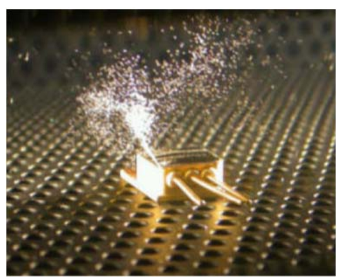
1. Forward voltage at nominal current
2. Reverse current at 300V
3. Schottky barrier height and ideality factor

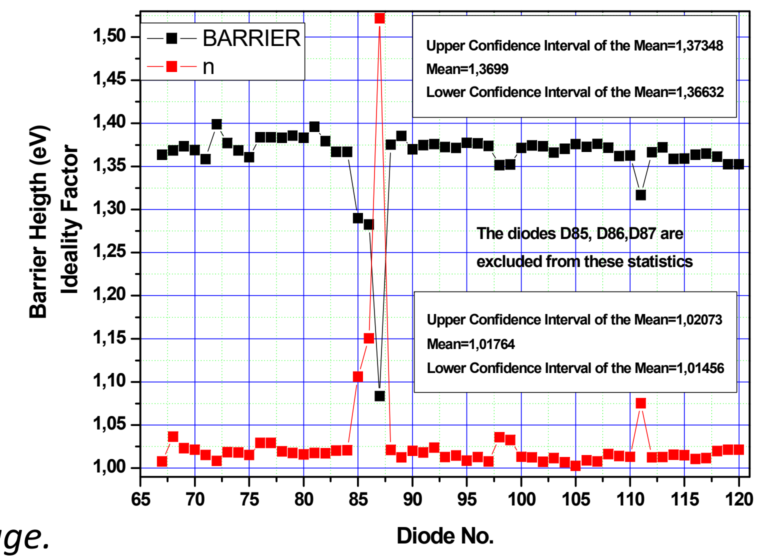
**Final yield: 55% approx.**

**Hermetic sealing**

**4th control & selection**
Gross and fine leak test in a freon bath
RGA on sampling
PIND test





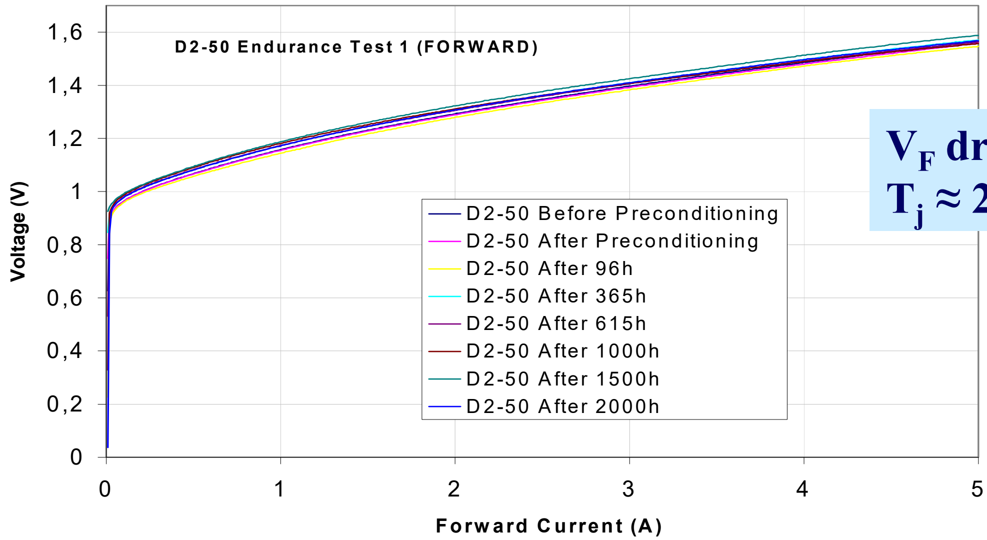



*A crucial test is the gross and fine leak of the hermetic sealing of the package.*

# Diodes Stability Tests

**Test Condition**: Static forward mode; $I_F$=5 A, $N_2$ flux, 10 diodes in series
Tcase=285ºC 2,000 hours
Tcase=300ºC 1,000 hours
Tcase=330ºC 500 hours

**Test procedure:** $V_{forward}$ @ $I_F$=5A is measured every hour, and
$I_{reverse}$ @ Vr=300V is checked regularly

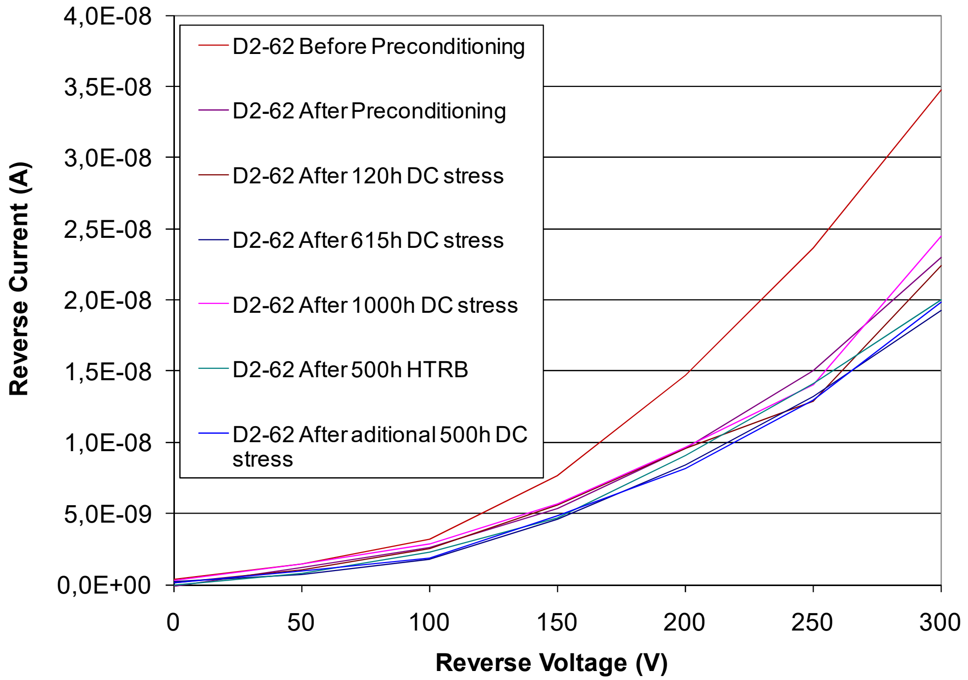



**$V_F$ drift with time @ Tcase= 285ºC**
**$T_j$ ≈ 297ºC**

*From every final batch, some diodes were submitted to hard reliability tests at extreme temperatures. The stability is perfect.*

# Diodes HTRB Tests

HTRB stress: 500 hours at 280ºC




*Excellent results are also obtained for high temperature reverse bias stress test (HTRB) after 500 hours at 280 ºC.*

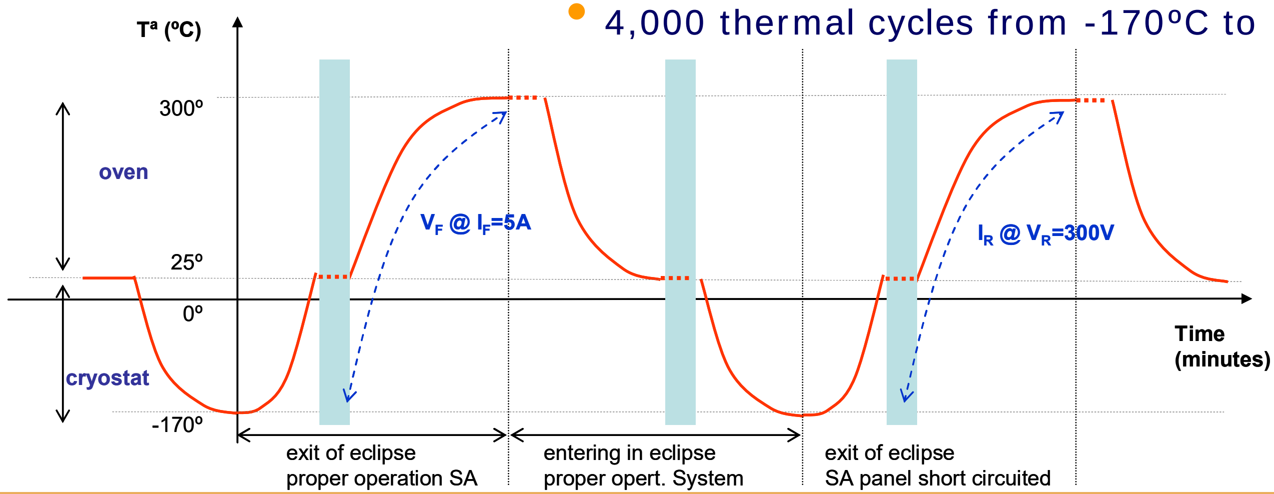
Drift after preconditioning. No extra drift after HTRB and DC bias stress

# Thermal cycles

## Protection Diodes Specifications

- Operation temperature range: -170ºC / +280ºC.
- Breakdown voltage >**300 V** over full temperature range.
- Reverse current < **1 mA** @ 300 V and 280ºC.
- Nominal DC output current: **5 A** over full temperature range.
- Maximum forward voltage drop at nominal current and 280ºC: **1.7 V.**
- Packaged diode weight < 5 g.

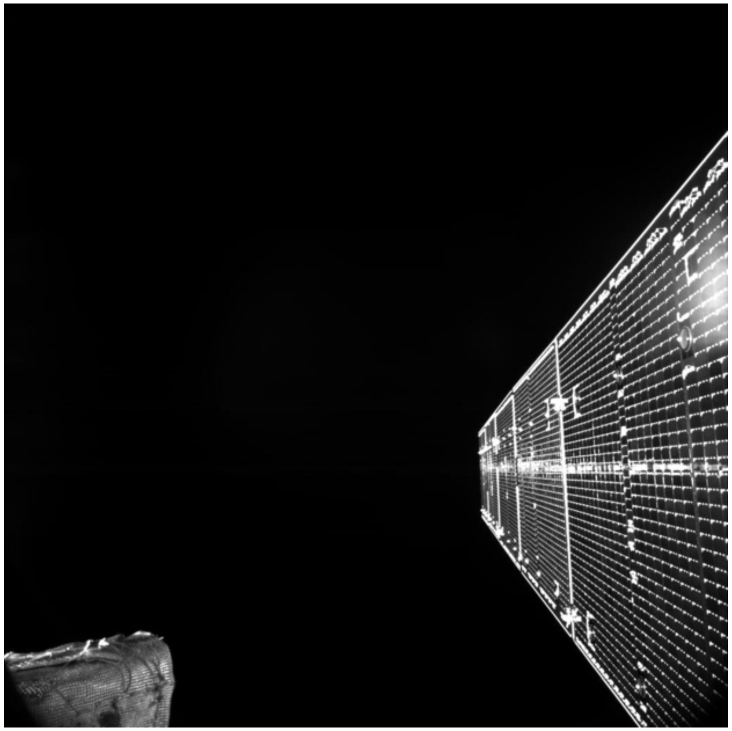
- 4,000 thermal cycles from -170ºC to +280ºC




*The thermal cycles in the extreme temperature range, from -170 ºC to +280 ºC also revealed a very good stability of the diodes.*

***The CNM's Schottky diode is the first high reliability/high temperature SiC device certified by the European Space Agency (ESA).***

# BepiColombo Spacecraft Launched on 20 Oct 2018 at 01:45:28 GMT (03:45:28 CEST)

*BepiColombo spacecraft sent its first selfies in which one of the solar panels is displayed, which means that the SiC diodes are working properly.*

# Summary

- **State of the art**
  - Progresses in manufacturing high quality WBG materials in the last decade enabled the development of WBG devices.
  - A large variety of SiC and GaN devices occurred on the market replacing step by step silicon power devices in the new projects.
  - Issues to be solved in the future for the new generation of WBG power devices
- **The reply of WBG team from Power Devices and Systems, IMB-CNM CSIC, Barcelona** to the WBG development challenges:
  - High voltage diodes, MOSFETs, JFETs, BJT, Integrated Circuits for smart power;
  - Specific test instrumentation;
  - New test methods conception;
  - IMB-CNM is the first certified supplier by European Space Agency for a SiC semiconductor device : high temperature Schottky diode used in the solar panels of space mission BepiColombo to Mercury.

# Thank you for your attention!

**Centre Nacional de Microelectrònica (CNM)**