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Silicon Carbide for Sensing: a Continuous Challenge

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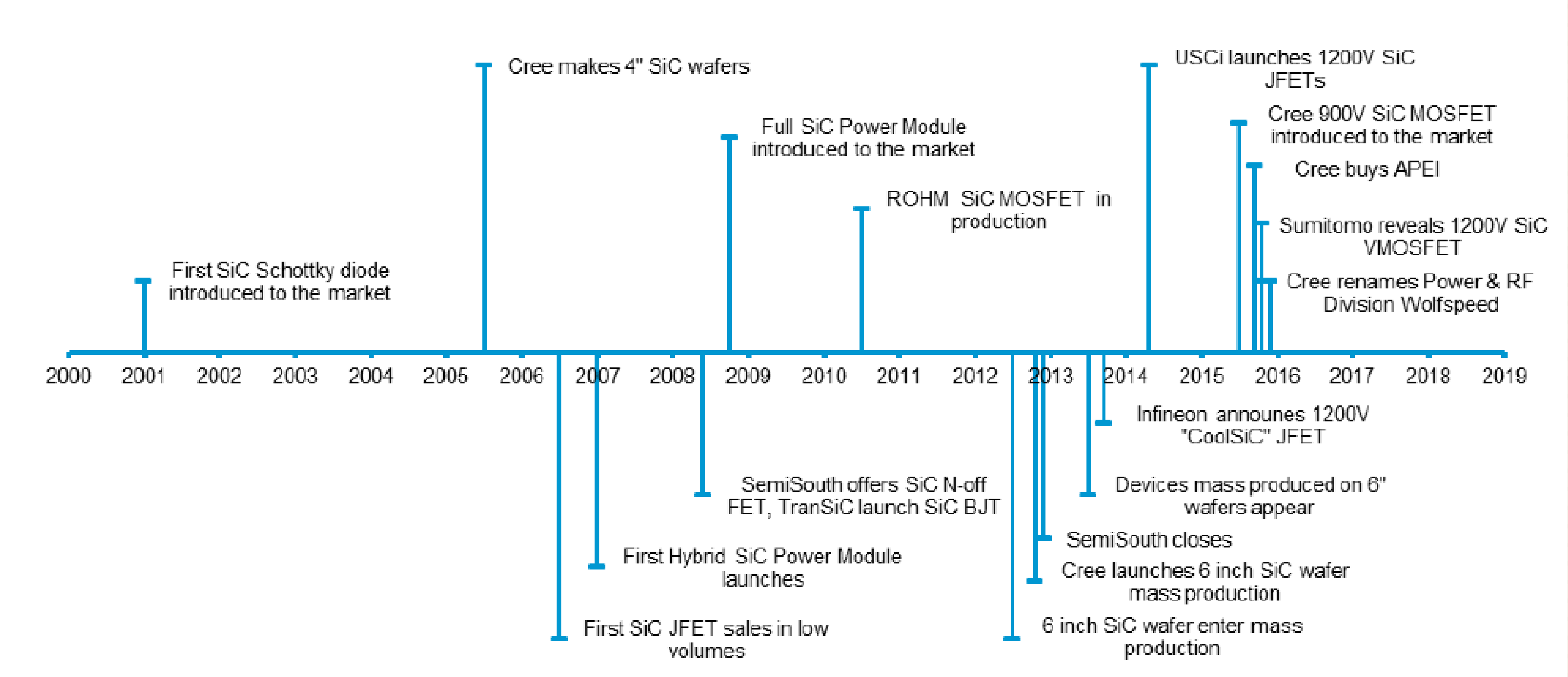
Outline

- Silicon Carbide(SiC)
- SiC Devices in Romania
- Sensor Sample Preparation
- High Temperature SBD Sensor
- MOS Capacitor Gas Sensor
- Conclusions

SiC – Power Electronics - Time line



- Cree SiC wafer: 4” (2005) 6” (2012)
- SiC Devices: Schottky diode (2001) JFET (2007) MOS (2010)
- SiC Power Module: Hybrid (2007) Full (2009)

SiC – Properties vs Applications

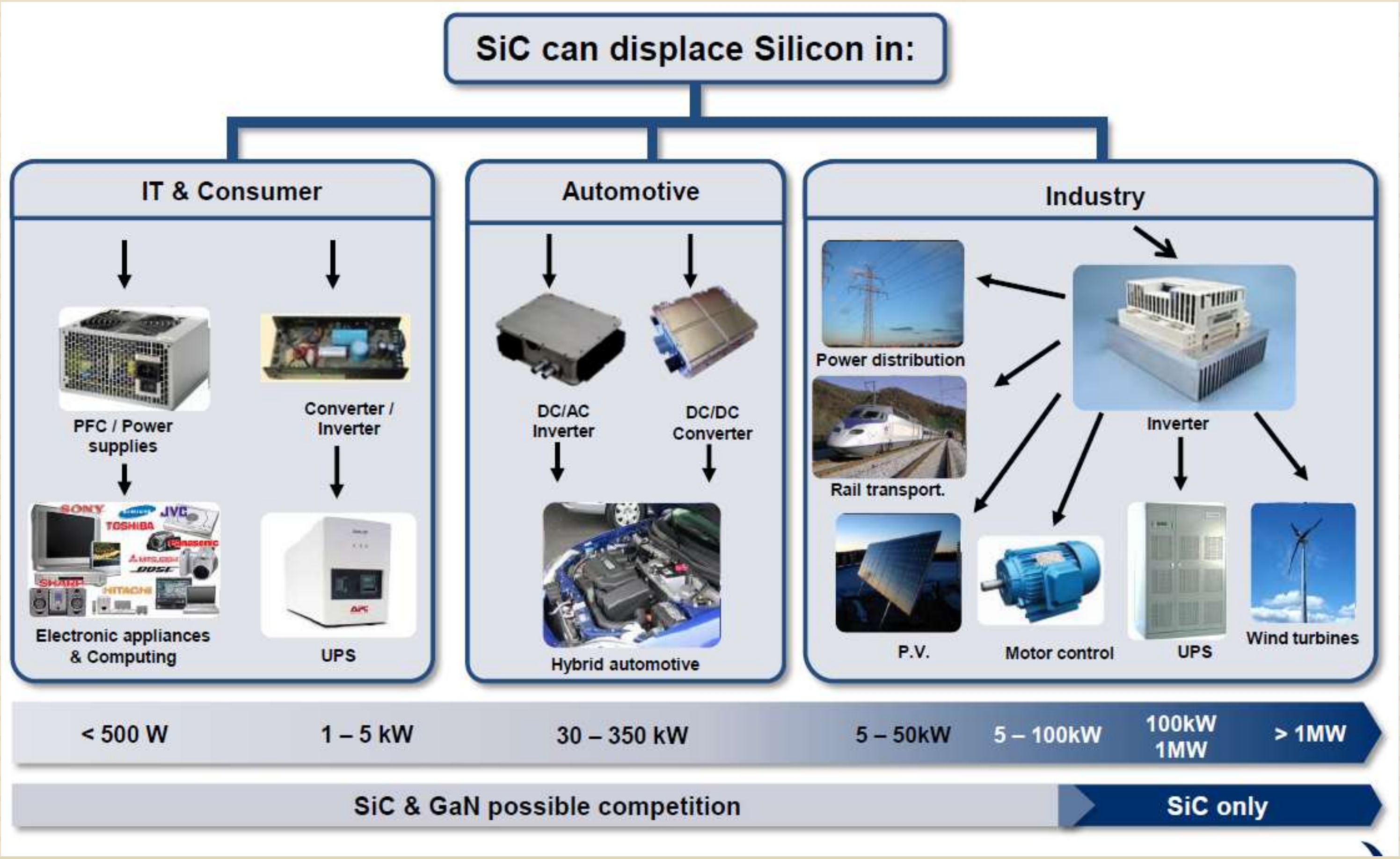
	Si	**4H-SiC**	GaN	Diamond
Breakdown field (MV/cm)	0.3	**3**	5	10
Saturation velocity ($x10^7$ cm/s)	0.9	**2.0**	2.5	2.0
Bandgap (eV)	1.1	**3.26**	3.45	5.45
Thermal conductivity (W/cmK)	1.5	**4.9**	1.3	24
Yield Strength [GPa]	7	**21**	10.2	53
Thermal Expansion Coefficient [°C·10^{-6}]	2.6	**0.8-5.4**	3.1-5.59	0.8
Chemical Stability	Fair	**Excellent**	Strong	Fair

Applications:
- High frequency
- High voltage

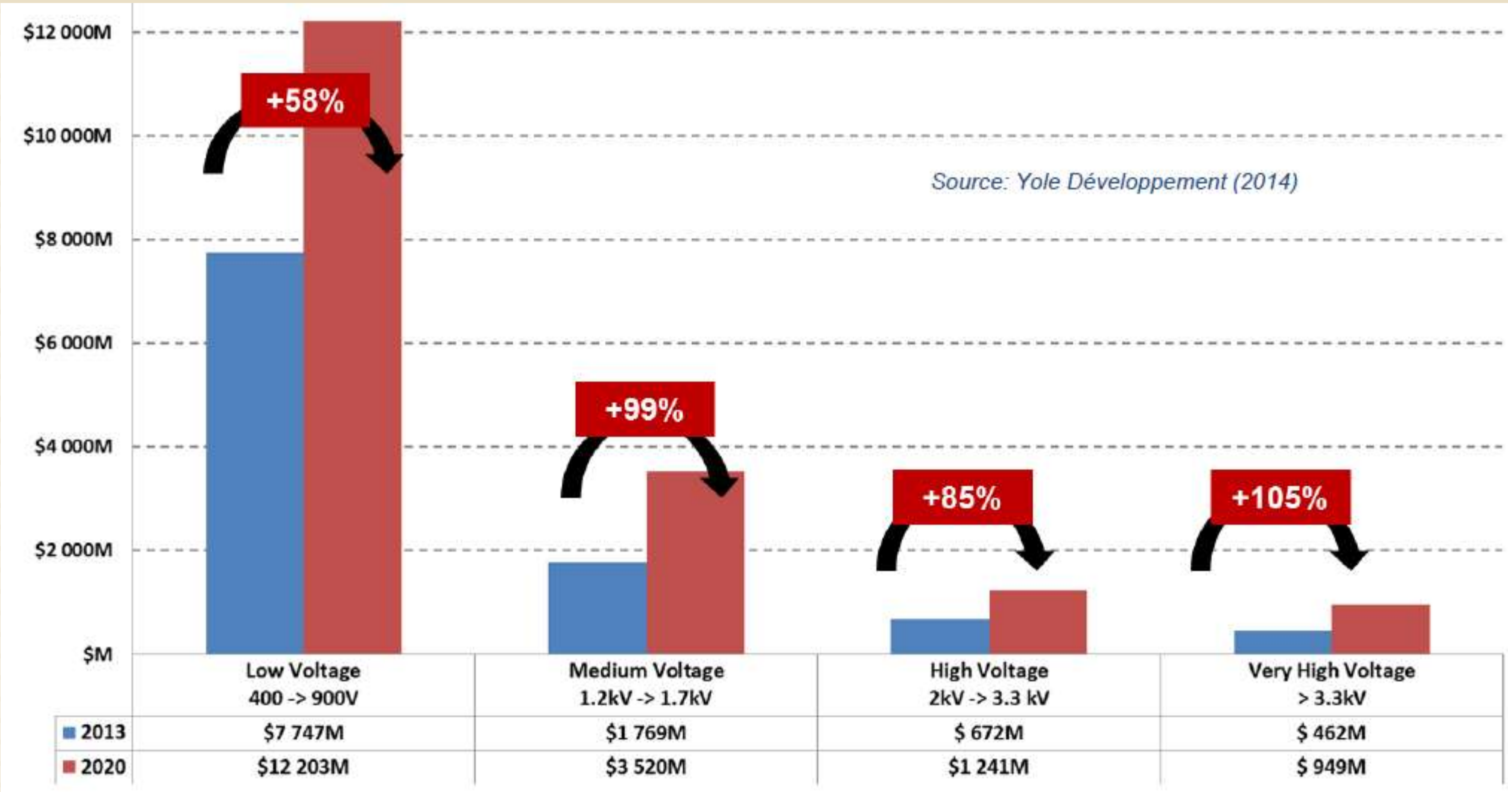
Applications:
- High temperature
- High power

Applications:
- Harsh environment (corrosive, radiative high vibration, etc.)

SiC Power Applications



Power Electronics Evolution



- 2013 -2020
- Market size evolution
- Voltage comparison

Silicon Carbide Market

Major players in the market:

- Infineon Technologies A (Germany)
- CREE Inc. (Wolfspeed) (US),
- ROHM Semiconductor (Japan),
- STMicroelectronics (Switzerland),
- ON Semiconductor (US),
- United Silicon Carbide, Inc. (US),
- General Electric (US),
- GeneSiC Semiconductor Inc. (US)

SiC Devices

Most commercially successful SiC Devices:

Schottky Barrier Diode:

- Very low forward conduction losses for increased efficiency
- Low switching losses for reduced size and cost of the power converter
- Soft switching behavior (low EMC impact), simplifying certification and speeding time-to market
- High forward surge capability for increased robustness and reliability
- High power integration (dual diodes) for reduced PCB
- High-temperature capability with T_j max = 175°C

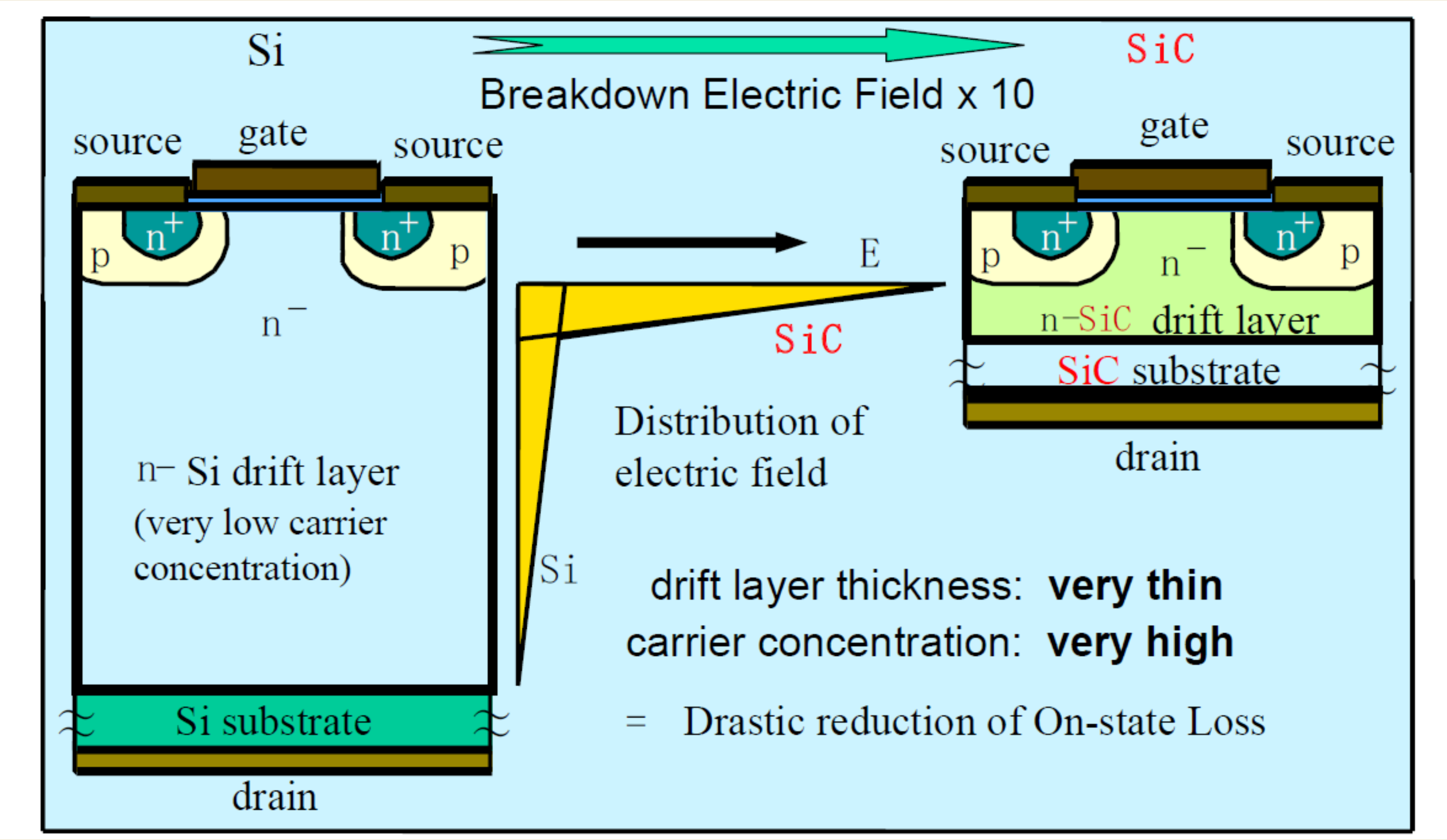
SiC Devices

Most commercially successful SiC Devices:

MOSFET:

- Industry’s highest operating junction temperature of 200°C for reduced cooling requirements and heatsink (**STMicroelectronics)**
- Low on-state resistance over the entire temperature range to 200°C for reduced cooling requirements with a higher system efficiency
- Extremely low power losses
- Small increase of on-resistance versus temperature
- Very easy to drive (resulting in smaller component count)
- High operating frequency for reduced switching losses and smaller and lighter systems
- Very fast and robust intrinsic body diode

SiC – MOS Structures comparison

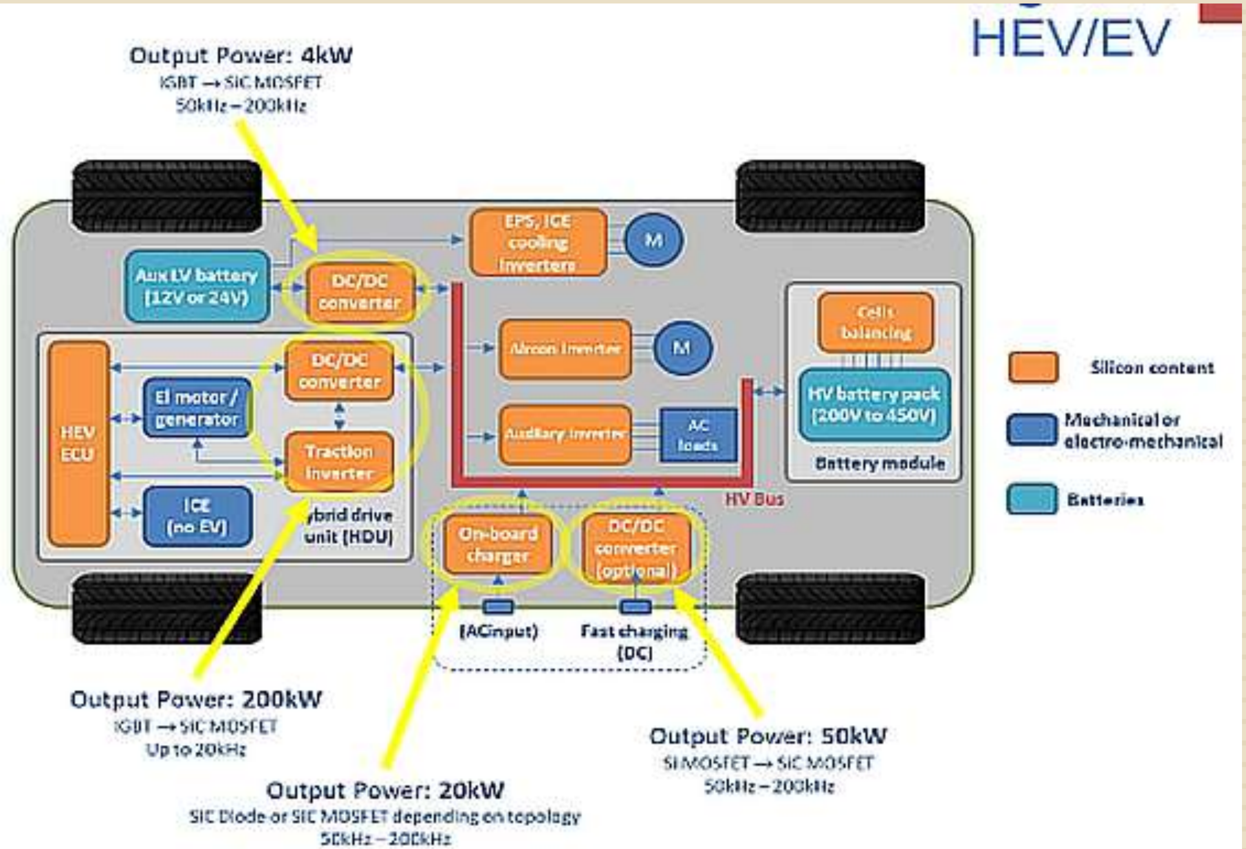


SiC – First Semiconductor Device

1907

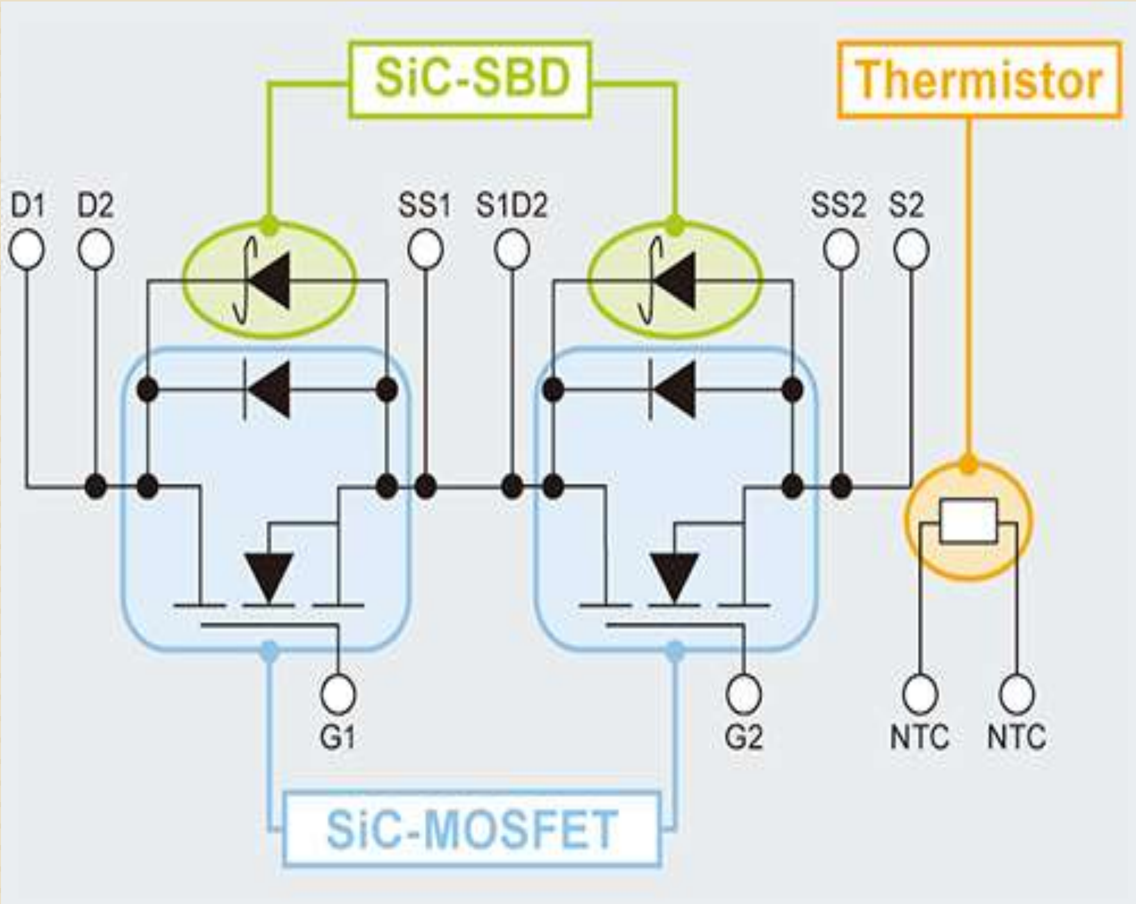
- First Light Emitting Diode (LED) on SiC
- 10V between two contacts placed on a SiC crystal
- Yellow, green & orange luminescence
- Electroluminescence phenomena was proven

E-Vehicle – Power Block diagram



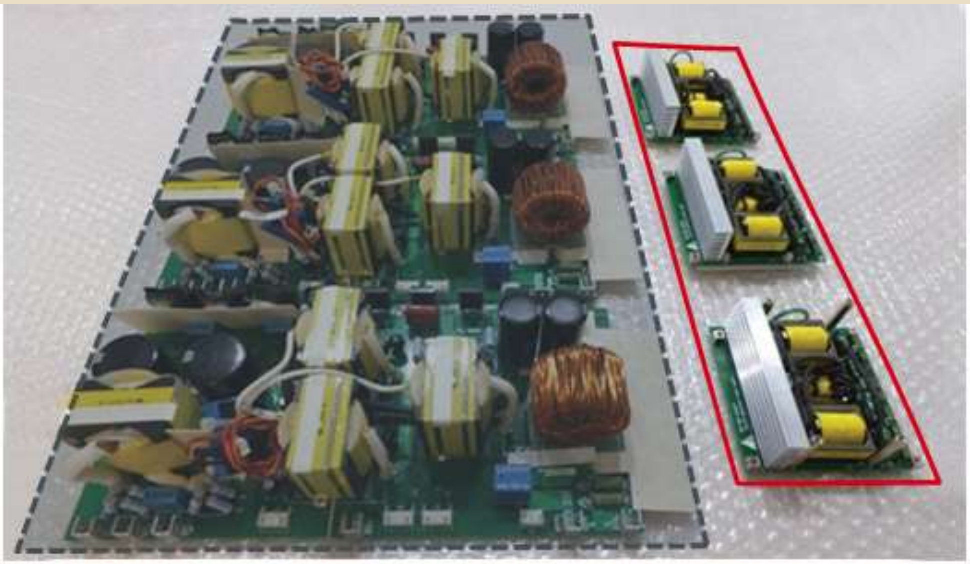
- Traction inverters for the wheel motors (200 kW/up to 20 kHz)
- AC-input on-board charger (20 kW/50 kHz to 200 kHz);
- Optional fast-charging (50 kW/50 kHz to 200 kHz)
- Power for auxiliary functions: driver's console, battery management, air conditioning, GPS, (on the order of 4 kW/50 kHz to 200 kHz)

SiC – Inverters



- Power module: Converters/Inverters
- Rohm's 1200V/300A SiC - schematic

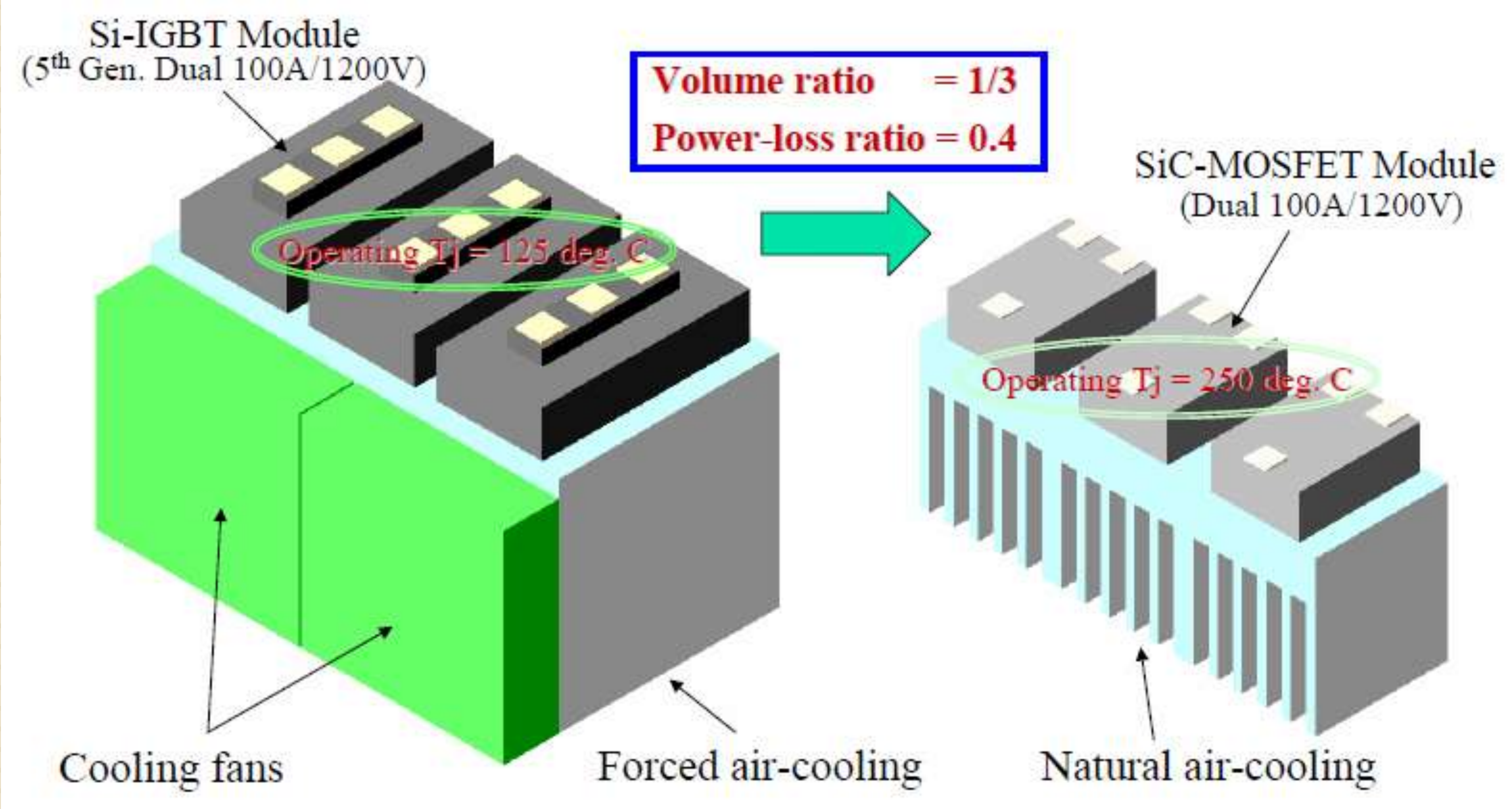
SiC – Converters/Inverters



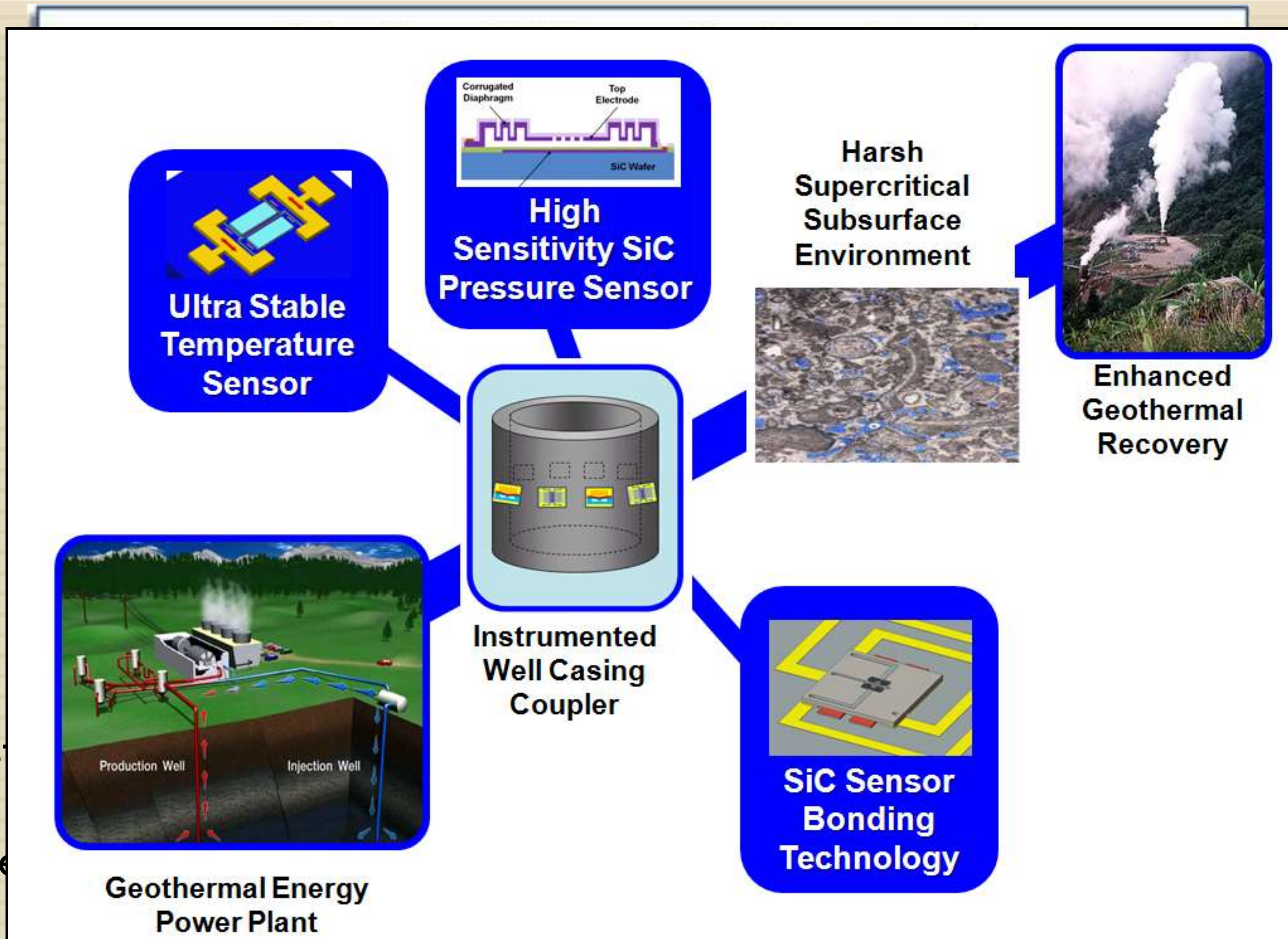
	System with Si IGBT	System with SiC
Weight	7 kg	0.9 kg
Volume	8.775 cc	1.350 cc

- Si IGBT vs SiC MOS for:
  DC-DC Converters/Inverters
- 1200V/300A
- Switching frequency increases:
  from 25kHz to 160kHz (*6x higher*)
- Weight and Volume: *9x lower*
- Chip size 1/4

SiC – Converters/Inverters



SiC – Sensors - High Temperature Applications



- Indus
- Tempe
- Increase efficiency, reliability / reduce pollution

SiC Sensors - NASA

- JFET ICs, MEMS based pressure sensor and Schottky diode based gas chemical / temperature sensors
- **500°C / 5000h –SiC MEMS sensors have been proved**
- Applications include aerospace engine control and long term Venus probes
- Packaging system needed for device application and long term test.

SiC Sensors?

- **A single type of commercial SiC sensor**
  - UV SiC photodiodes (Boston Electronics)
  - Prices from 26 USD

Typical responsivity at peak wavelength	**0.13 A/W**
Wavelength of max spectral response	280 nm
Broadband - Responsivity range (R=0.1 x Rmax)	221 to 358 nm
Package	TO-18
Active area	0.06mm^2
Operating temperature	-55 to 170°C

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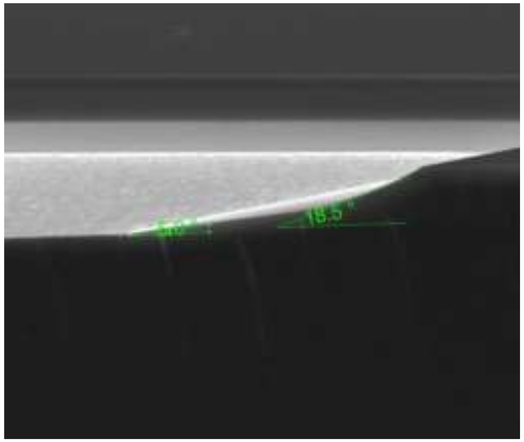
Romanian SiC-Group Contributions

- First SiC / diamond devices fabricated in Romania:
  - power JBD (400V/10A) - 1997
  - power SBD (1100V/1A) - 2000
  - UV photodetectors - 2003
  - Temperature SBD sensors - 2010 -2018
  - Gas MOS capacitors sensors - 2012 - 2018
- Research Laboratory:

  Advanced Electron Devices and Circuits- 1995

- A new SiC field plate edge termination:
  - based on simple technology with T<1000°C
  - offers a nearly ideal breakdown
  - has no effect on specific resistance
  - patented, simulated and experimented in Romania;



Romanian SiC-Group Papers

- 9 Invited Papers
- 41 Papers in ISI Periodicals:
  - *IEEE Transactions on Electron Devices*
  - *Solid State Electronics*
  - *Journal of Applied Physics*
  - *Applied Physics Letters*
  - *Microelectronics Journal*
  - *Material Science Forum*
  - *Material Science and Engineering*
  - *Diamond and Related Materials*

Romanian SiC-Group Papers

- 90 Papers at Conferences Proceedings:
  - International Conference of Silicon Carbide and Related Materials (**ICSCRM**)
  - European Conference on Silicon Carbide and Related Materials (**ECSCRM**)
  - Diamond, Diamond-Like Materials, Nitrides and Silicon Carbide Conference (**DIAMOND**)
  - International Semiconductor Conference (**CAS**)
  - Yugoslav Conference on Microelectronics (**MIEL**)
  - International Symposium on Power Semiconductors Devices and ICs (**ISPSD**)

Romanian SiC-Group Projects

- 6 International Projects Founded by:
  - European Community
  - Royal Society
  - N.A.T.O.
- In cooperation with:
  - Cambridge University, U.K.
  - Centro Nacional de Microelectronica, Spain
  - FORTH Crete Greece
- 12 National Projects

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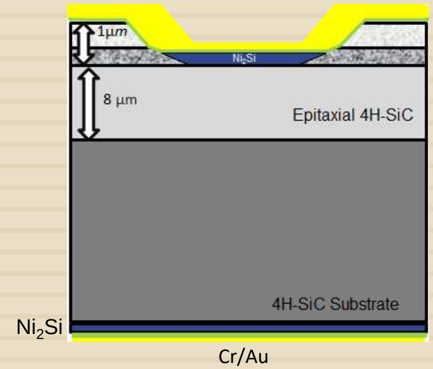
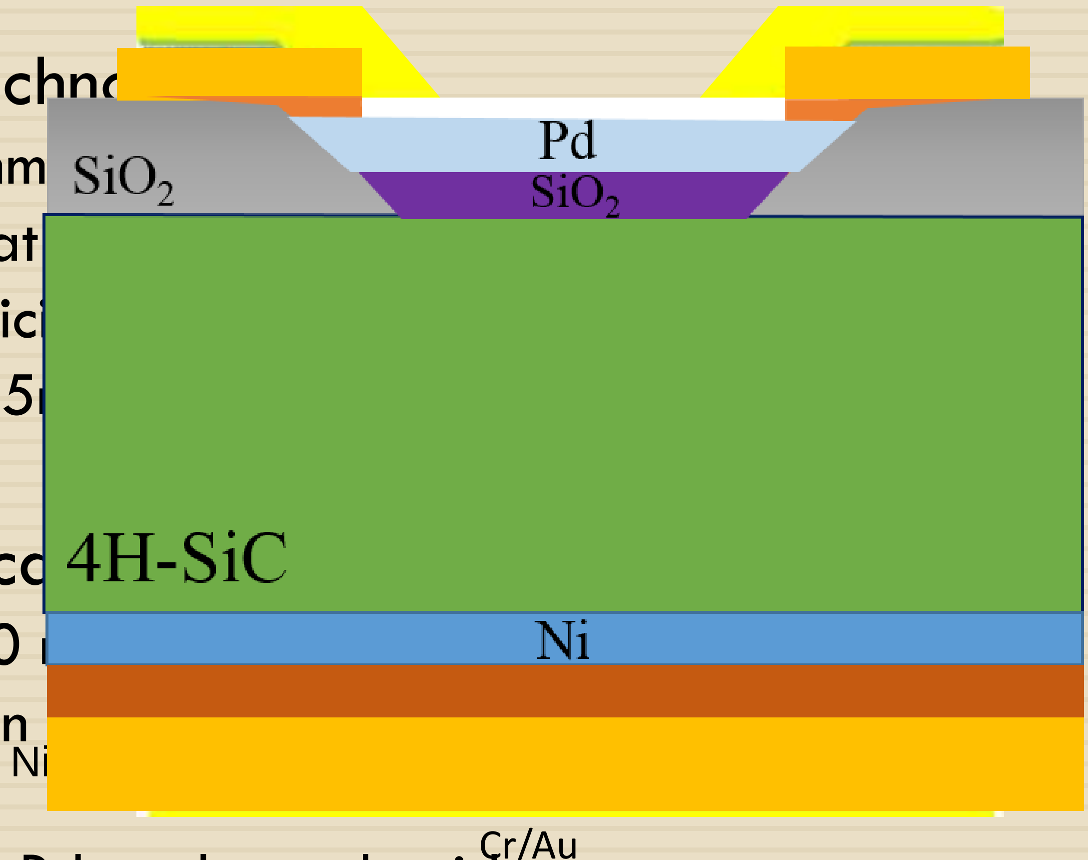
Temperature and Gas SiC SensorsTechnology (II)

SBD techn

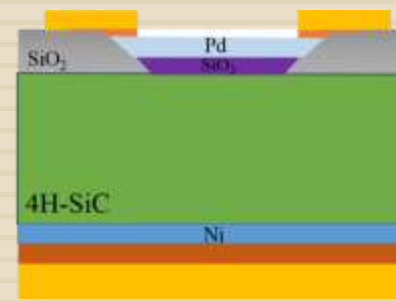
- 150nm
- RTA at
- Ni-silic
- Cr (15 pad



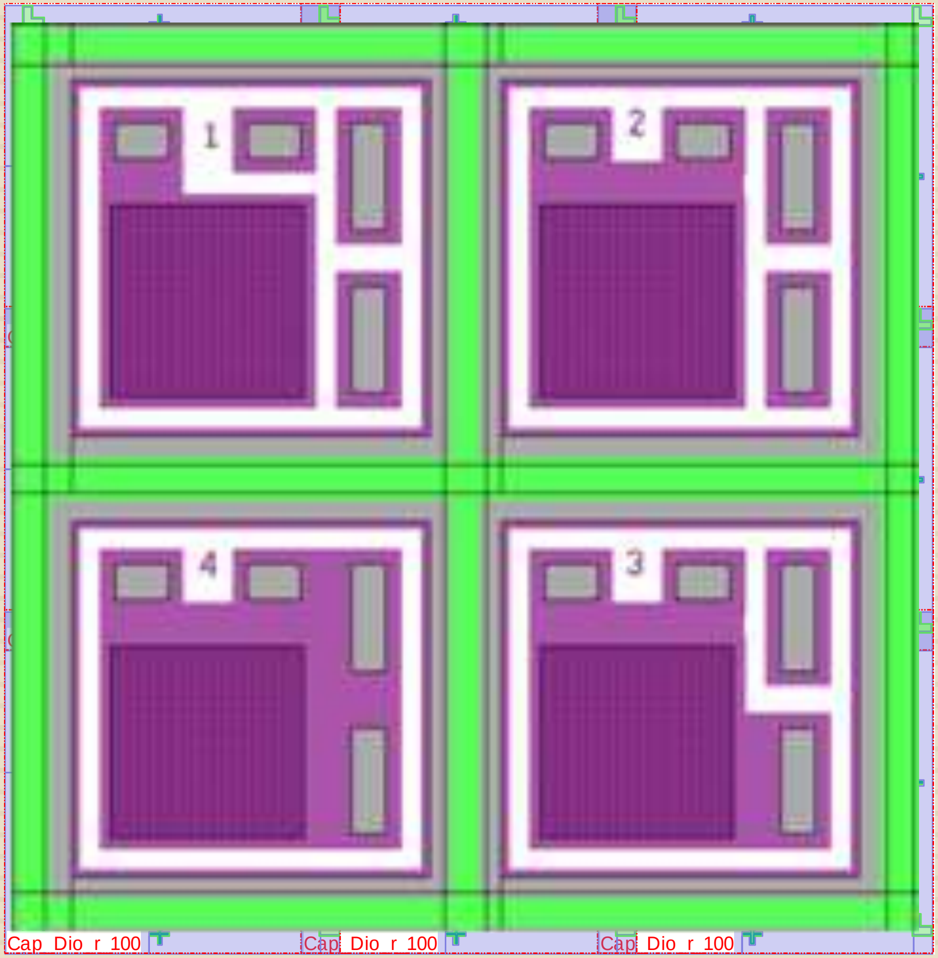


MOS c

- 30-40
- Grown area
- 50nm Pd on thermal oxide
- Cr (15nm)/Au (100nm) stack on Pd and pad



Sensor Layout



- Some layouts were designed for sensors
- 200, 300 and 400µm circular windows for active area
- A large area pad for the electrical connection with the package terminals
- Pad can be connected to one or up to 3 windows for different structure areas

Sensor Packaging

- Two packaging techniques
- Sensor operation up to 400°C in a cement factory
- Partially electrically isolated package with a gold wire(TO39)
- Fully isolated solution with metallic piston and pressure contacts

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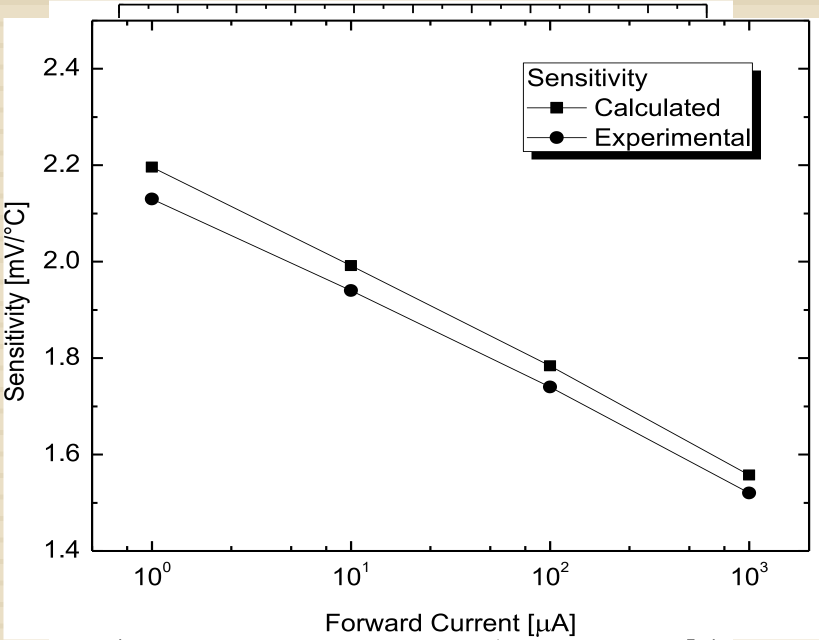
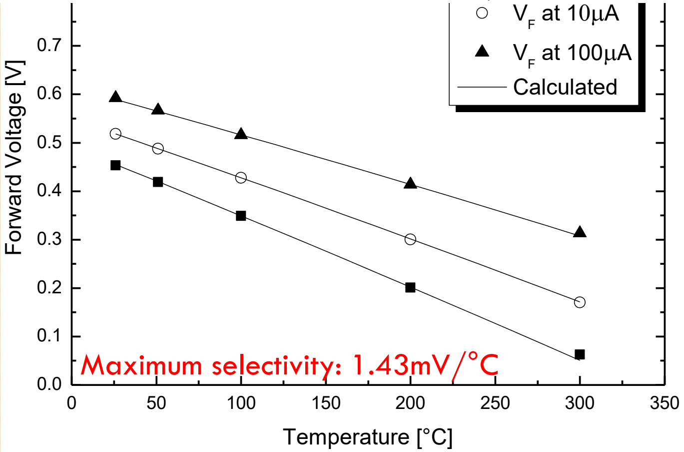
SiC SBD High Temperature Sensors





- SBD forward biased at constant current

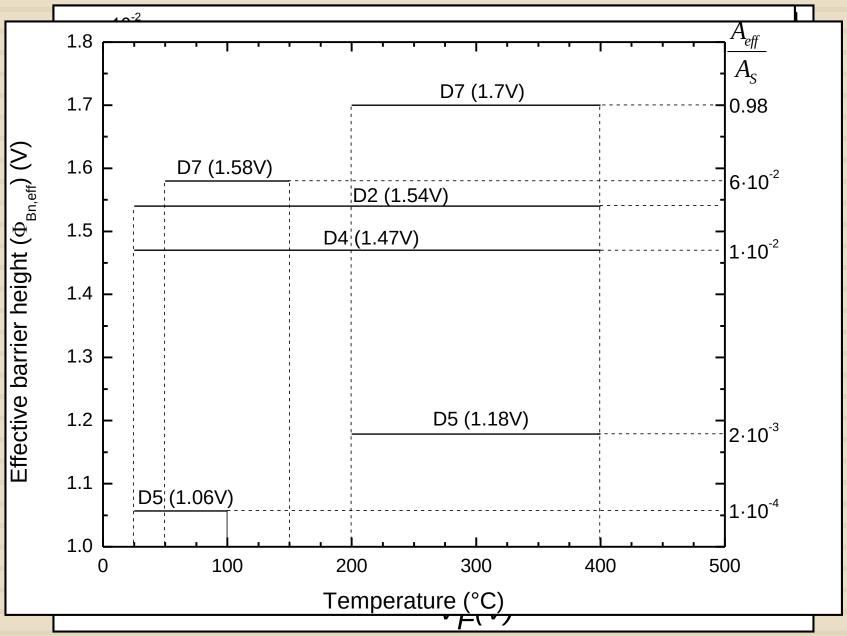
$$V_F(T) = n\varphi_{Bn} - [n\varphi_{Bn} - V_F(T_0)]\frac{T}{T_0}$$

- Sensor detection selectivity

$$S = \frac{n\varphi_{Bn} - V_F(T_0)}{T_0}$$

- High $n\Phi_{Bn}$ – high selectivity

SiC Schottky Barrier Diodes (SBD)
Ni Schottky Contact Non-Uniformity



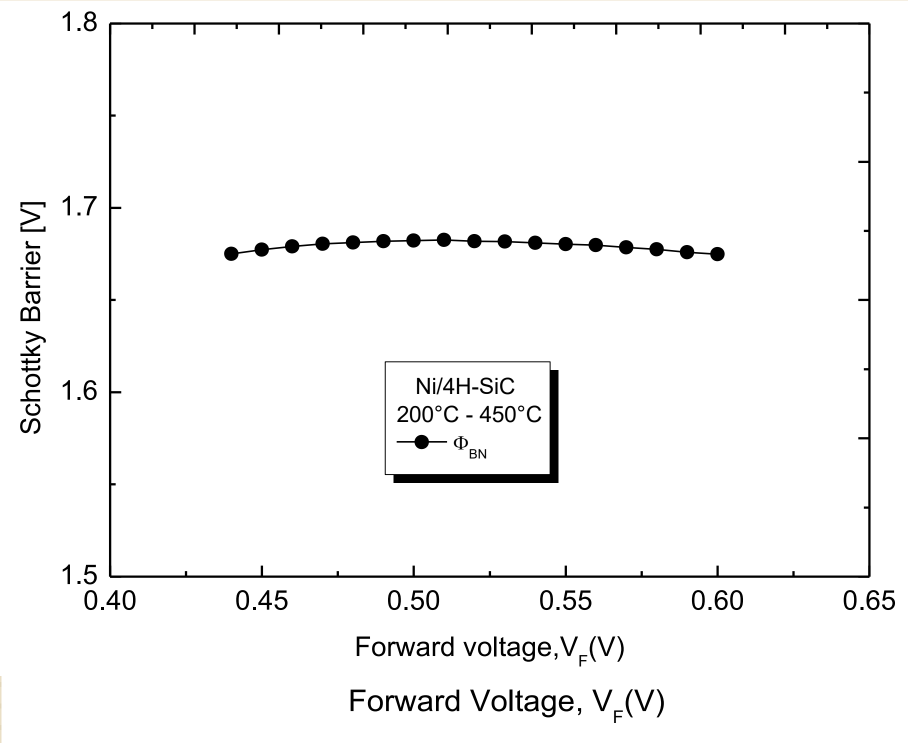
- Barrier non-uniformity on Schottky contact
- Large zones covered in Ni_2Si
- High barrier – $\Phi_{Bn} > 1.65V$
- Ni patches with a lower barrier $\Phi_{Bn} = 0.8V$
- Modeling – original non-uniformity parameter

$$\varphi_{Bn,T} = \varphi_{Bn} + \frac{k}{q} pT$$

$$\ln\left(\frac{I_F}{A_n A T^2}\right) = -p - \frac{\varphi_{Bn} - \frac{V_F(T_0)}{n}}{V_{th0}} \cdot \frac{T_0}{T}$$

- An effectve methodology to determine temperature and bias intervals, where inhomogeneous SiC SBD operate predictably, as a sensor, with a stable barrier

SiC – Ni Uniform Schottky Contact



- RTA at 800°C/ 5min
- Thick, uniform metallic Ni_2Si layer
- Exponential current increase up to 450°C
- $n < 1.04$
- Temperature constant n
- Slight barrier increase with temperature

$$\varphi_{Bn,T} = \varphi_{Bn} + \frac{k}{q} pT$$

- Low non-uniformity parameter
- p between 2.05 and 2.21

$$\ln\left(\frac{I_F}{A_n A T^2}\right) = -p - \frac{\varphi_{Bn} - \frac{V_F(T_0)}{n}}{V_{th0}} \cdot \frac{T_0}{T}$$

- High effective Schottky barrier (Φ_{Bn} = 1.69V)

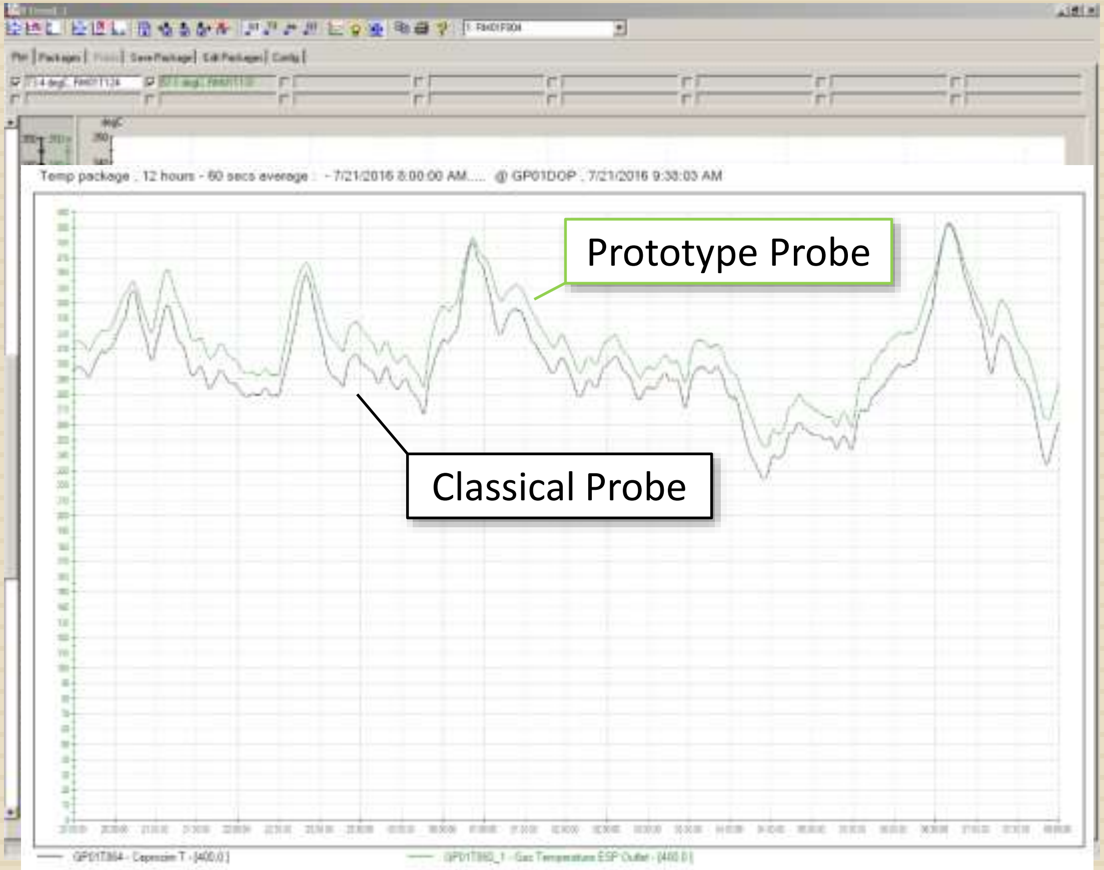
SBD output signal processing circuit

- Excitation and offsetting block:
  - ✓ SBD constant source (I_1=100μA)
  - ✓ Offset current source (I_2=100μA)
- Amplifier:dual single-supply operational amplifiers
- Voltage - current converter for connection with the standard industrial acquisition system
- *p*MOS high output resistance

Temperature Probe with SiC SBD Sensor (V)

- Signal processing circuit
- Smart sensor connection
- Temperature probe
- Temperature probe placed on a furnace of Fieni cement factory

Temperature Probe - Operation



- Furnace temperature monitoring
- Cement factory
- *T*= 290°C many months
- < 5% differences between factory standard sensors and temperature probe
- *T* range of 220°C – 390°C

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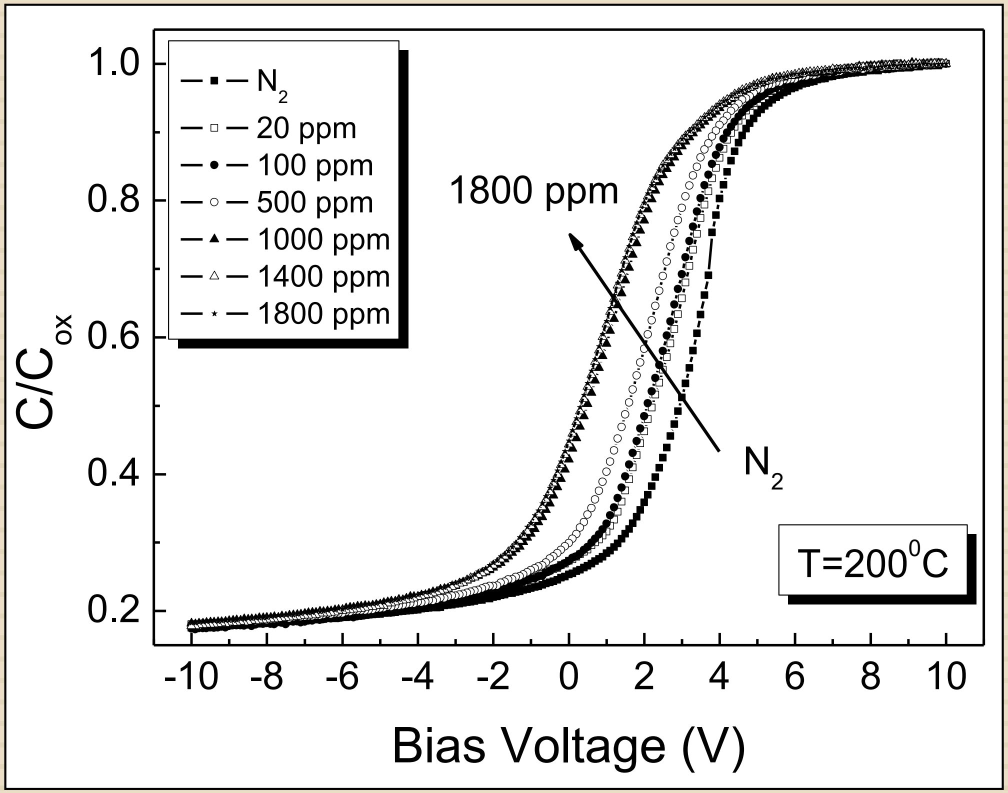
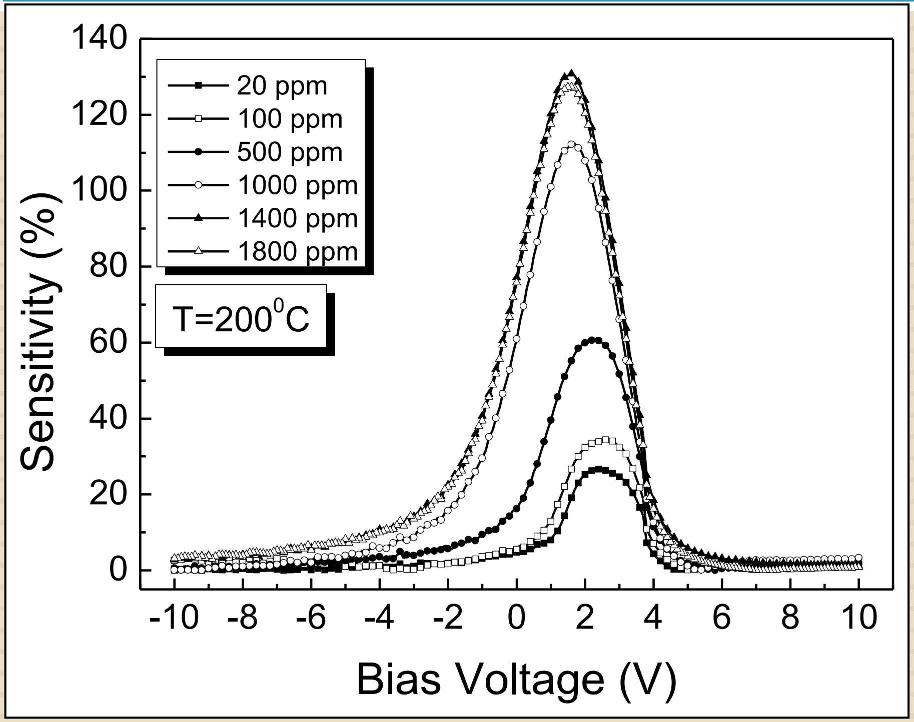
High Frequency C-V Curves



- Pd catalytic metal
- H-induced dipole layer at the metal–oxide interface
- High frequency (*1MHz*) C-V measurements
- C-V curve shifts to lower gate voltages with H_2 concentrations increase
- Displacement is strong up to 1000 ppm

SiC MOS Sensor Response



$$R(\%) = \frac{C_{H2} - C_{N2}}{C_{N2}} \cdot 100$$

- Capacitance shift at constant voltage (T= 200°C)
- A peak sensitivity at around 2V
- Peak value is saturated over 1000 ppm

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Conclusions

- A review of:
  Silicon Carbide - SiC on power applications and sensors
- Similar technology process has been used
- SiC SBD temperature sensor was tested up to 450^0C
- The temperature sensitivity is in range of 1.52 - 2.12mV/^{0}C, in good agreement with the calculations
- Temperature probe based on SiC SBD was designed, implemented and tested in a cement factory
- Temperature monitoring (up to 390°C) yields data consistent with factory standard thermocouple
- SiC MOS capacitor:high sensitivity & selectivity for H_2
- Operating up to 250°C

SiC – Trend to Top