SCHOTTKY DIODE ON SILICON CARBIDE (SIC) IDEAL DETECTOR FOR VERY WIDE TEMPERATURE RANGE SENSORS

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Outline

- Silicon Carbide(SiC) – Power Applications
- SiC Devices in Romania
- SiC Schottky Barrier Diode (SBD)
- SBD non-uniform forward characteristic modeling
- Temperature sensors with SiC SBDs
- Conclusions

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

SiC – Properties vs Applications

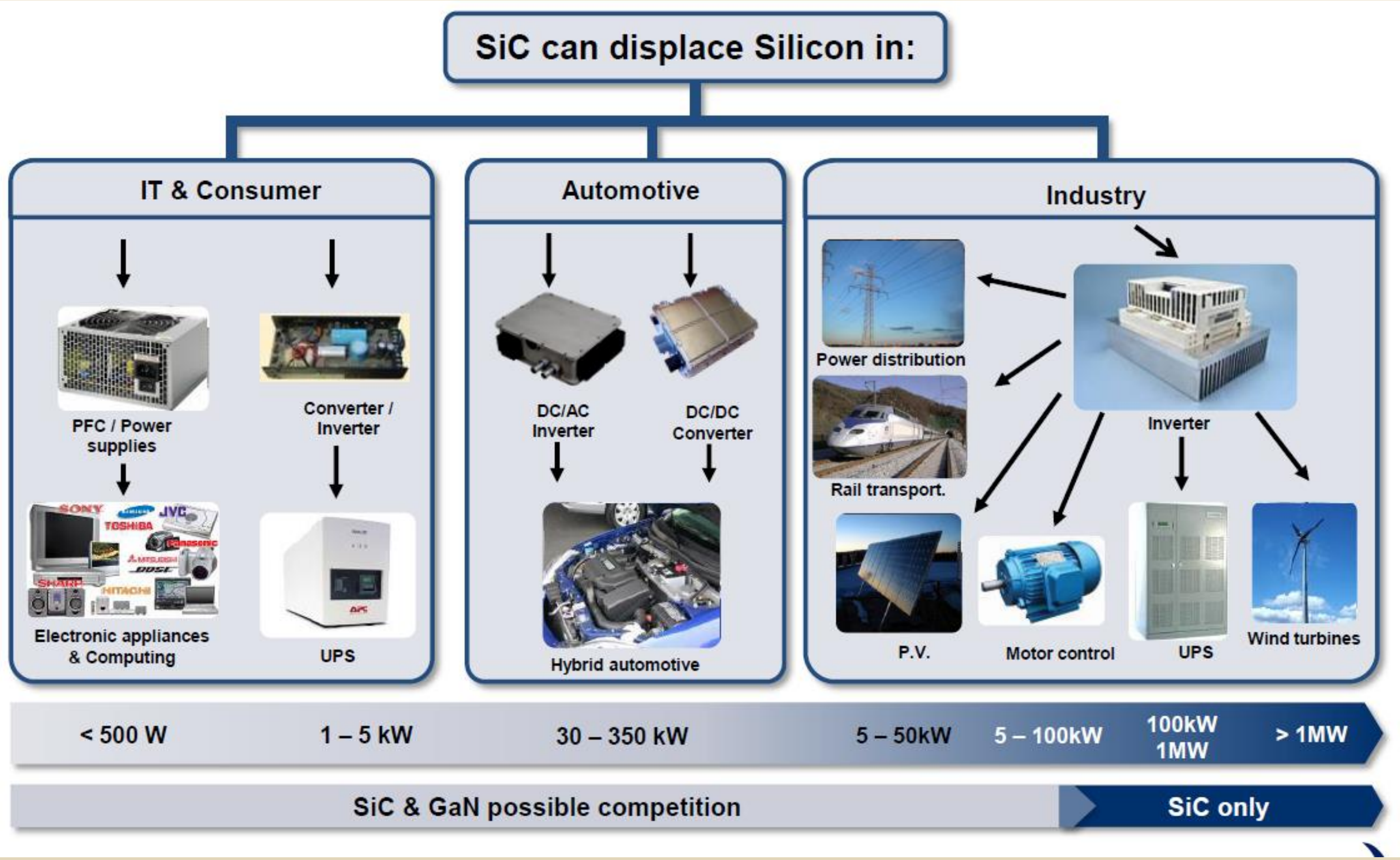
	Si	**4H-SiC**	GaN	Diamond
Breakdown field (MV/cm)	0.3	**3**	5	10
Saturation velocity ($x10^7$ cm/s)	0.9	**2.0**	2.5	2.0
Bandgap (eV)	1.1	**3.26**	3.45	5.45
Thermal conductivity (W/cmK)	1.5	**4.9**	1.3	24
Yield Strength [GPa]	7	**21**	10.2	53
Thermal Expansion Coefficient [°C·10^{-6}]	2.6	**0.8-5.4**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



SiC can displace Silicon in:

IT & Consumer

PFC / Power supplies

Electronic appliances & Computing

Converter / Inverter

UPS

Automotive

DC/AC Inverter

DC/DC Converter

Hybrid automotive

Industry

Power distribution

Rail transport.

Inverter

P.V.

Motor control

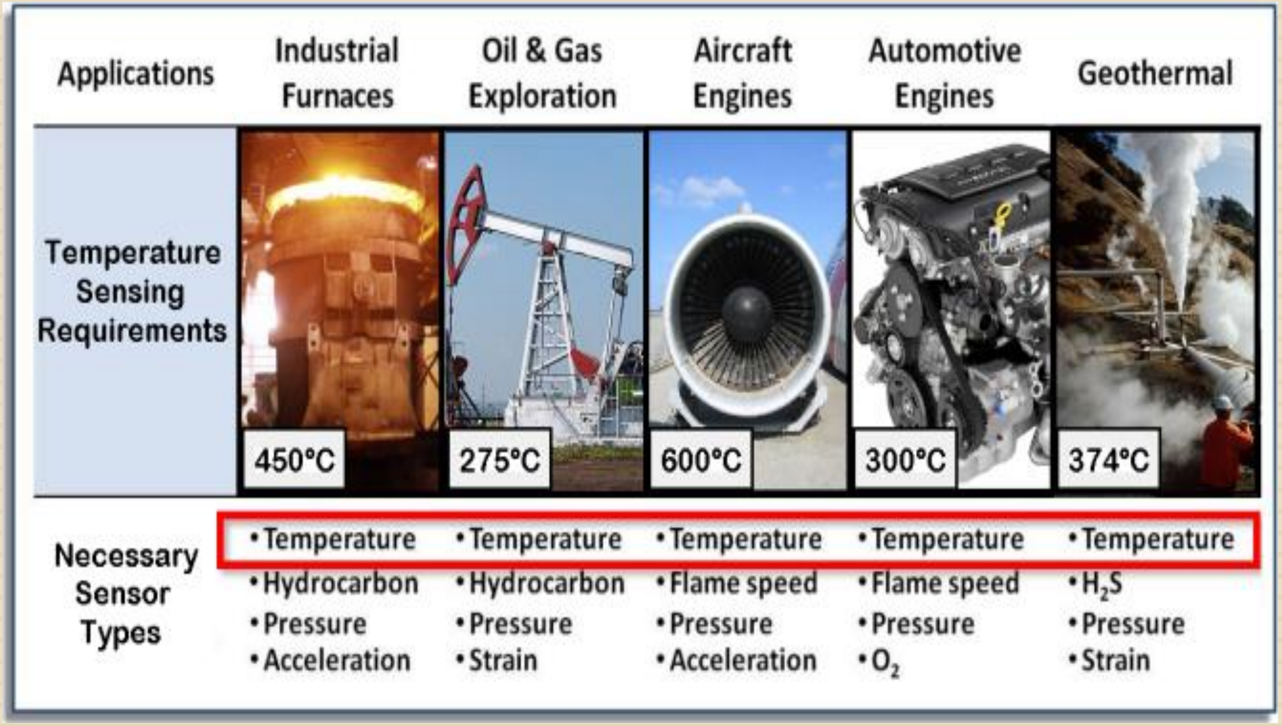
UPS

Wind turbines

< 500 W | 1 – 5 kW | 30 – 350 kW | 5 – 50kW | 5 – 100kW | 100kW 1MW | > 1MW

SiC & GaN possible competition | SiC only

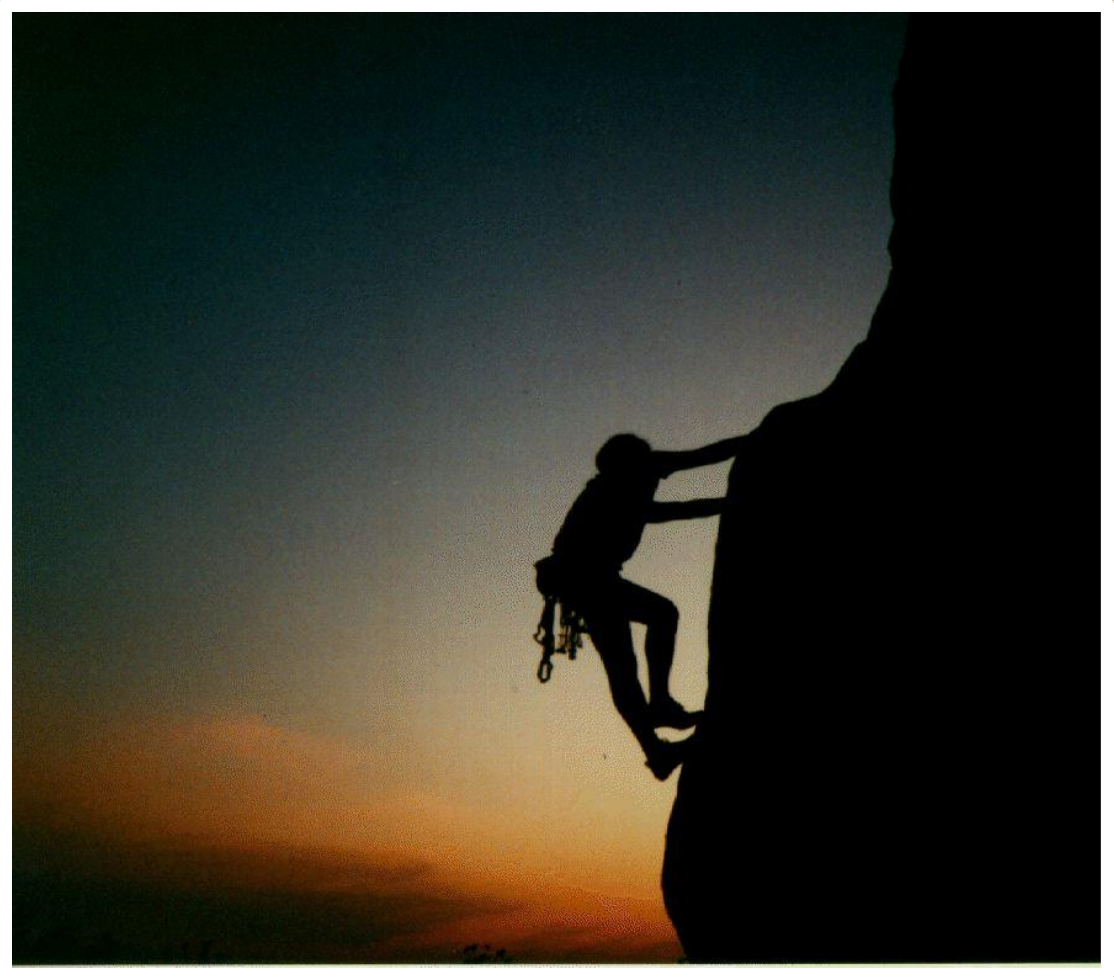
SiC - Sensors
High Temperature Applications



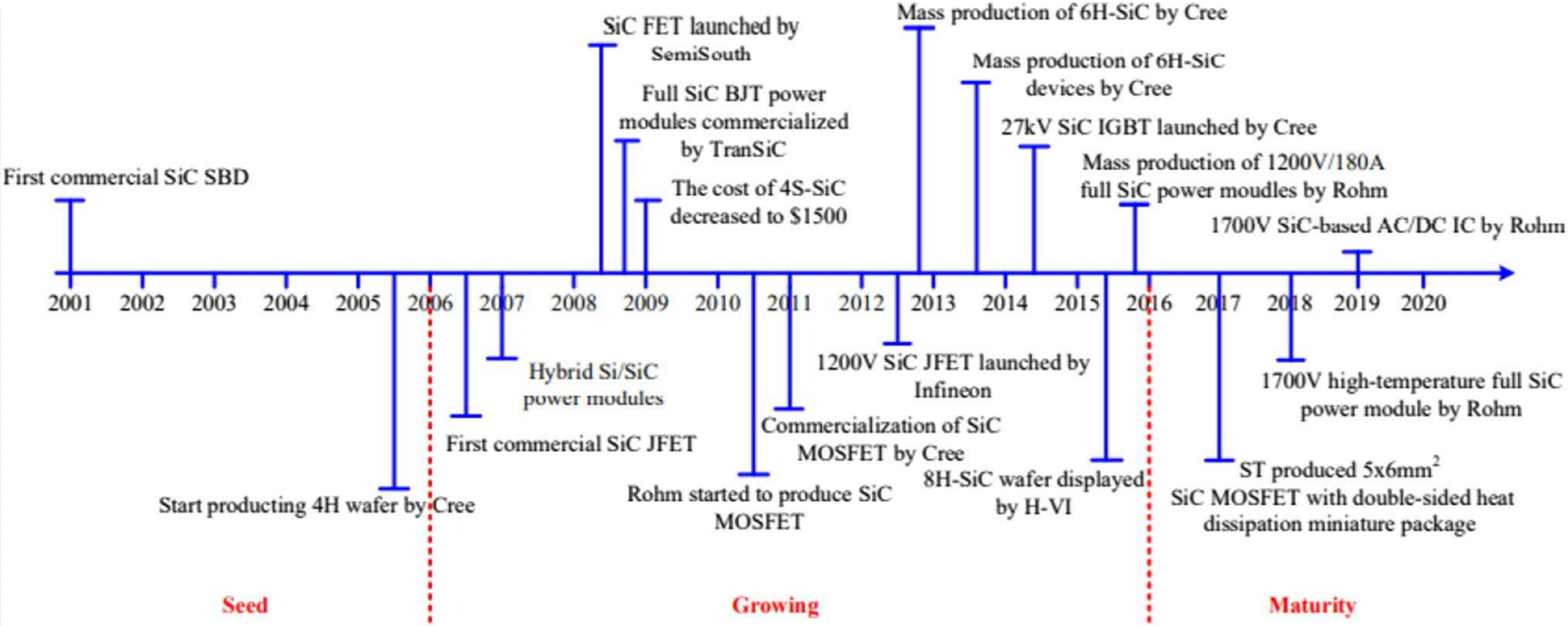
Applications	Industrial Furnaces	Oil & Gas Exploration	Aircraft Engines	Automotive Engines	Geothermal
Temperature Sensing Requirements	450°C	275°C	600°C	300°C	374°C
Necessary Sensor Types	• Temperature • Hydrocarbon • Pressure • Acceleration	• Temperature • Hydrocarbon • Pressure • Strain	• Temperature • Flame speed • Pressure • Acceleration	• Temperature • Flame speed • Pressure • O_2	• Temperature • H_2S • Pressure • Strain

- Industrial furnace - cement factory
- Temperature monitoring / Gas sensing
- Increase efficiency, reliability / reduce pollution

SiC -Trend to top



SiC power devices and wafer production
Time progress



- 2001 – Start - first commercial SiC SBD
- 2006 – Growing - first commercial SiC JFET
- 2011 – first commercial SiC MOS (1.2kV) CREE/RHOM
- 2014 – SiC MOS 15kV / 2018 – *pn* diode 30kV
- 2016 – Maturity - SiC power module 1700 V/180A

Silicon Carbide Market

Major players on the market:

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

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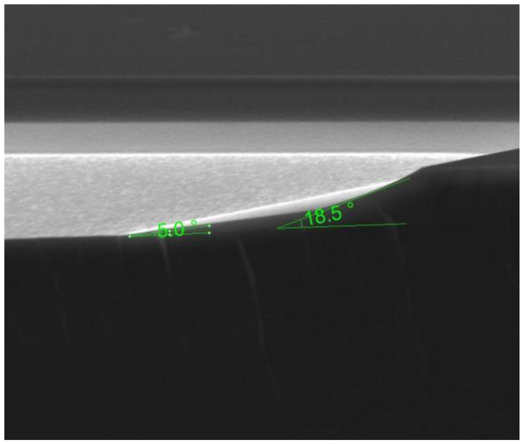
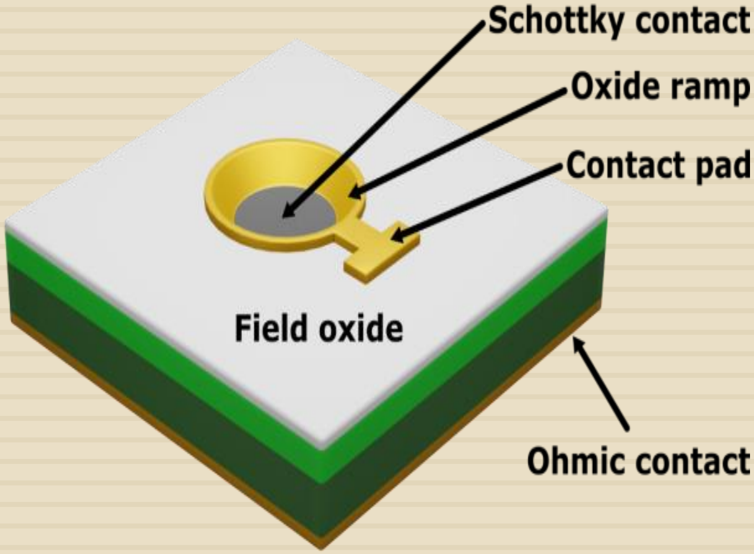
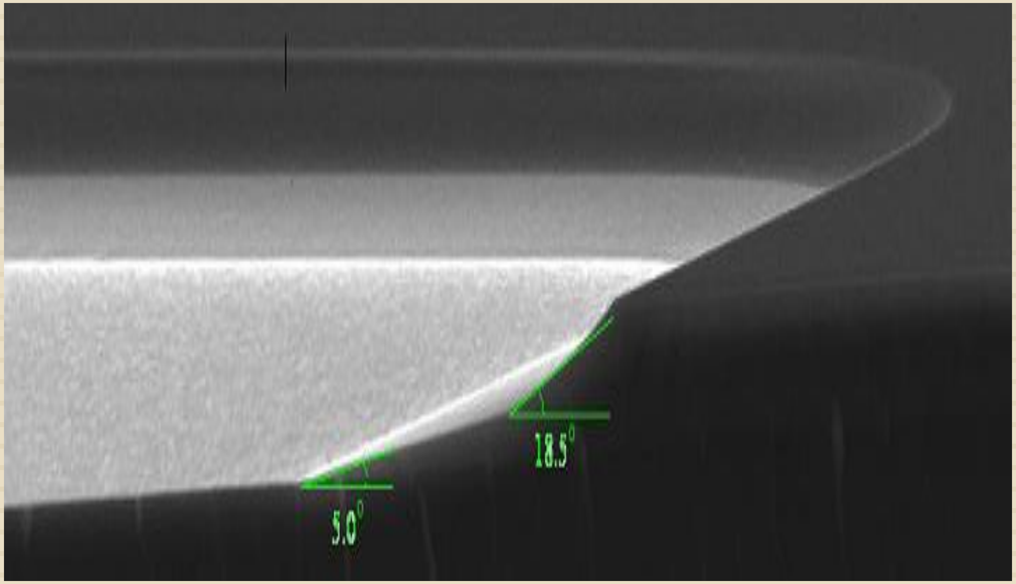
Romanian SiC-Group Contributions

- Research Laboratory: ***Advanced Electron Devices and Circuits (DCE-SA)*** ERIF-2000-000M-2131 1995
- First SiC / diamond devices fabricated in Romania:
  - power JBD (400V/10A) - 1997
  - power SBD (1100V/1A) - 2000
  - UV photodetectors - 2003
  - Temperature SBD sensors - 2010 -2023
  - Gas MOS capacitors sensors - 2012 - 2023
- 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;



SiC SBD technology





- n-4H-SiC Cree wafer with 8 µm/ 10^{16}cm^{-3} epi layer and 200 µm /5.10^{18}cm^{-3} substrate
- Deposition of two oxide layers with different annealing treatments (1µm total thickness)→
- anisotropic etching →
- oxide profile with two low-ramp angles (5° and 18.5°) →
- uniform current distribution

Romanian SiC-Group Papers

- 10 Invited Papers
- Over 50 Papers in WOS 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*
  - *Material Science Semiconductor Processes*
  - *Sensors Journal*

Romanian SiC-Group Papers(2)

- 100 Papers in 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

- 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
- 20 National Projects

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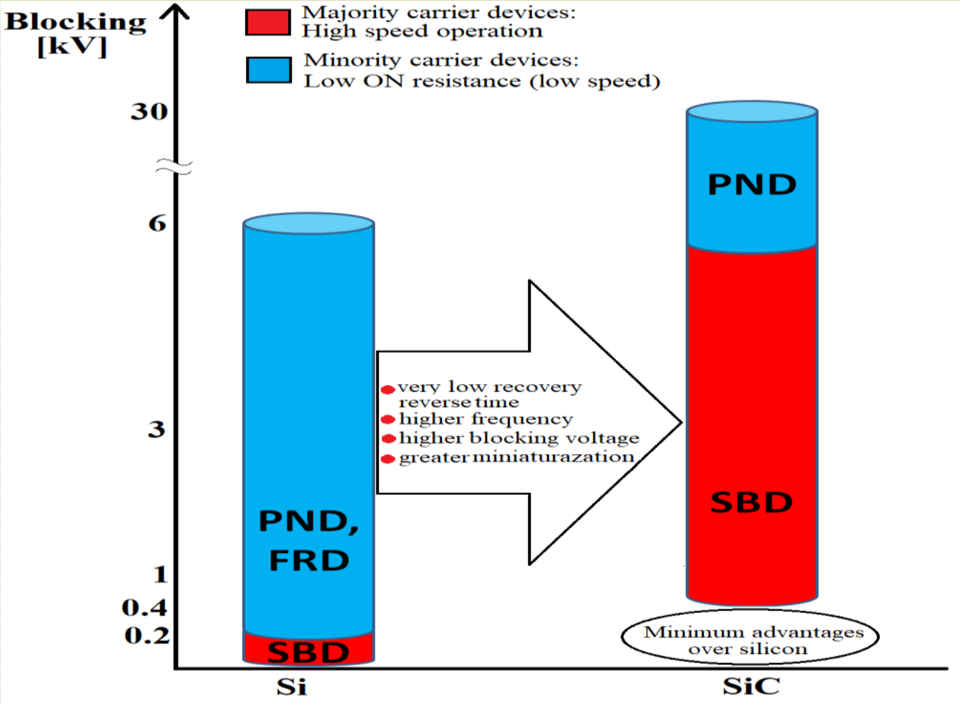
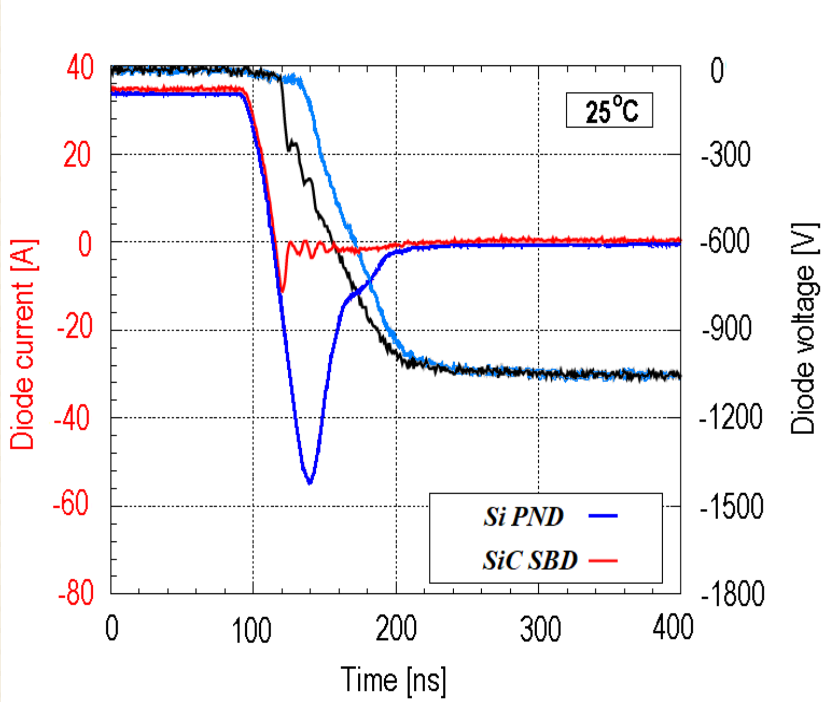
SiC- Schottky Barrier Diode (SBD)

- Most commercially successful SiC Devices
- 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 footprint
- High-temperature capability with $T_{j,max}$ = 175°C
- SiC SBD typical applications: power factor correction circuits, power supplies, photovoltaic inverters and sensors.

Schottky Diode(SBD) vs pn Diode(PND)





Diode	Si	SiC
V_R - *SBD*	200V	6kV
V_R - *PND*	6000V	30kV

- SBD - majority carrier device
- PND - minority carrier device
- SBD - no reverse recovery current/time
- Turn $\mathrm{OFF}_{\mathrm{SBD}}$ < Turn $\mathrm{OFF}_{\mathrm{PND}}$

SBD for applications

- *Based on uniform Schottky contact*
- *Main parameters:*
  - Φ_{Bn} - Schottky barrier
  - R_s - series resistance
  - A_{eff} - active contact area
  - n - ideality factor
- *Characteristics*
  - $n < 1.05$
  - Temperature independence for Φ_{Bn}, A_{eff} and n
  - Full characterization through simulations / measurements at different temperatures and over the entire bias range

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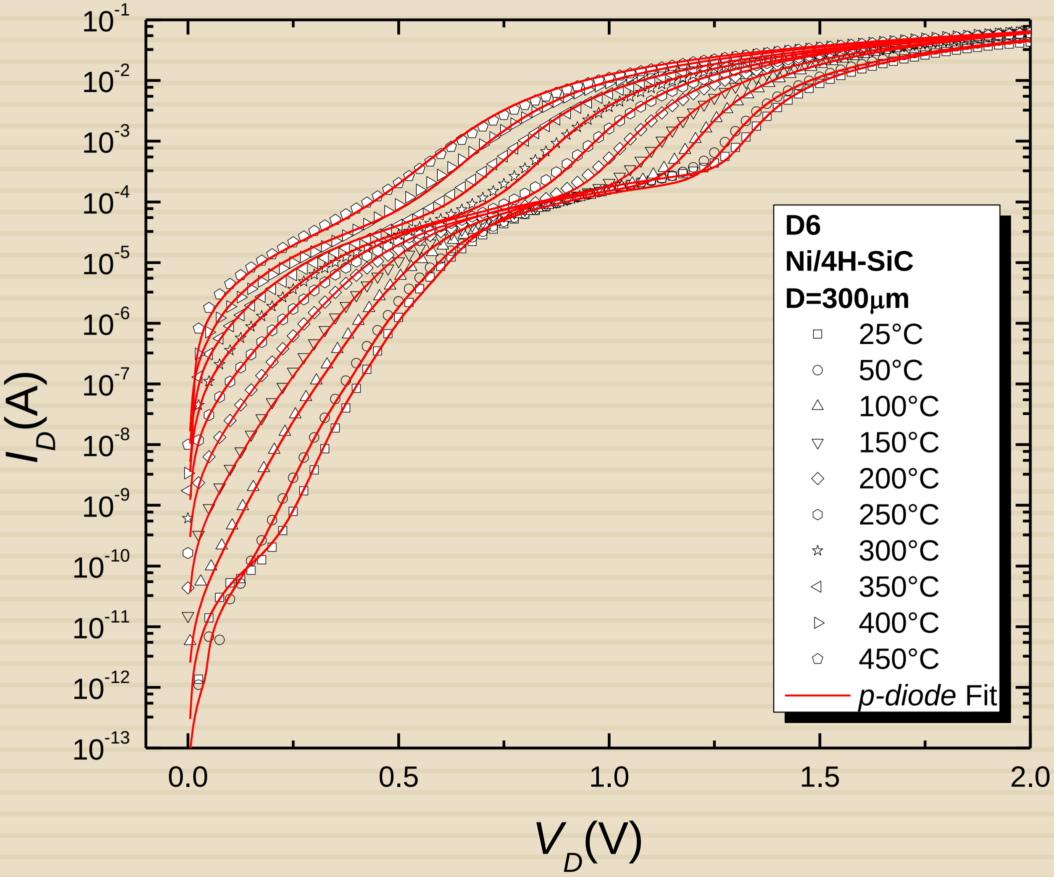
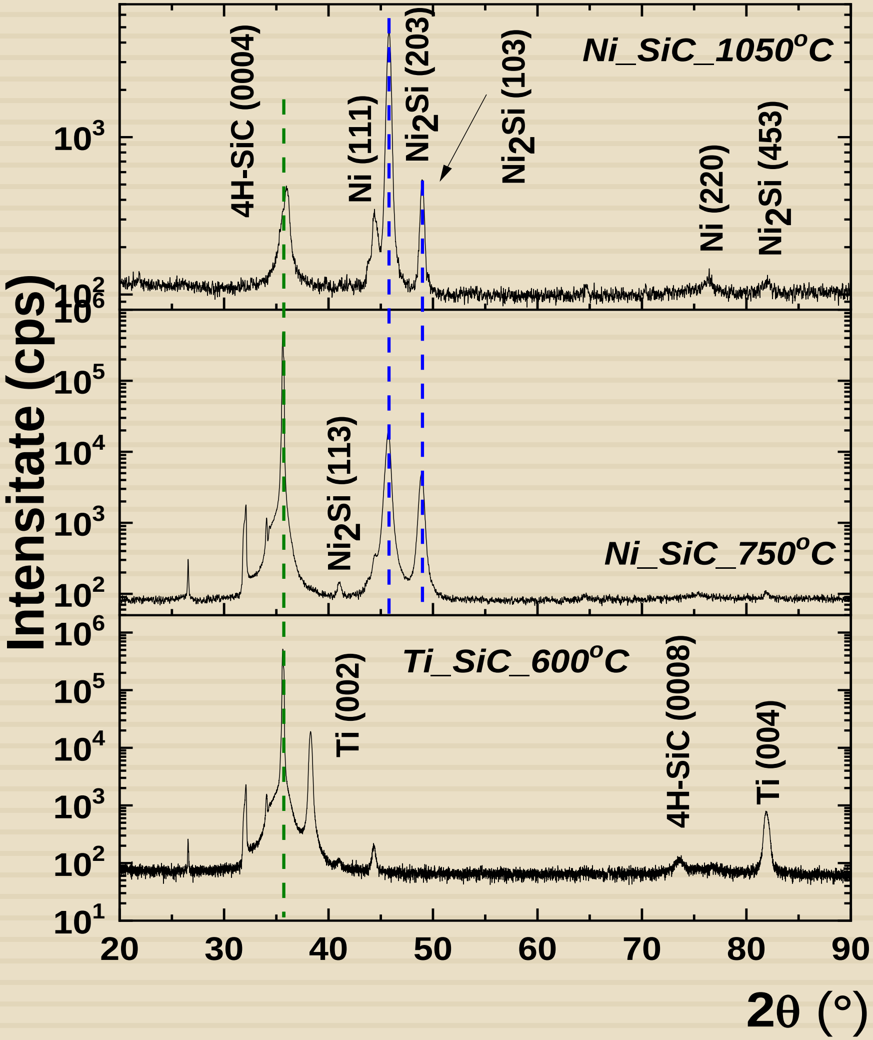
SiC SBD nonuniform Characteristics



- Ni/4H SiC SBD measured over 25°C - 450°C
- Deviation from exponential I_F (V_F) dependance over entire temperature range
- Annealing of Ni/4H SiC → *Ni_2Si* /4H SiC Schottky contact

X-ray Diffraction Analysis



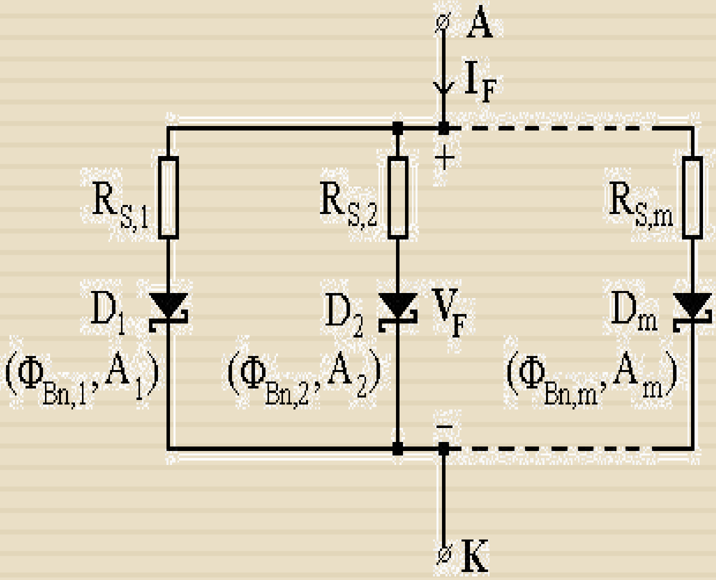
- Annealing at 1050°C →
- *Ni_2Si* ohmic contact

- Annealing at 750°C →
- *Ni_2Si* Schottky contact

- Annealing at 600°C →
- *Ti* Schottky contact

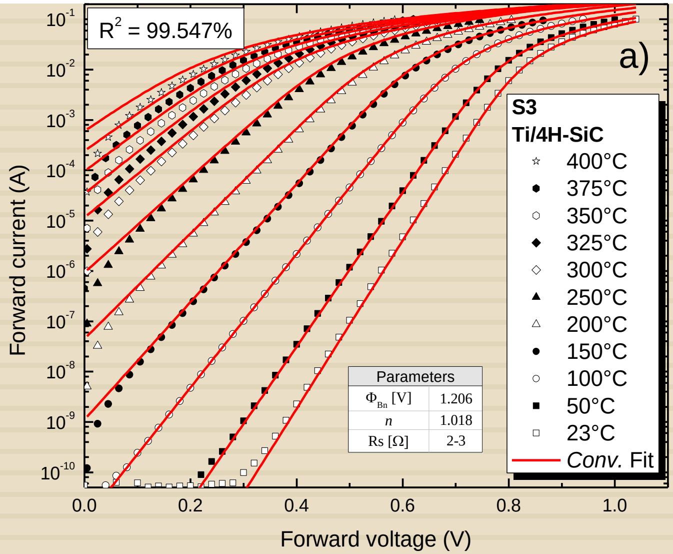
p - diode Model for non-uniform Schottky contacts

$$I_F = \sum_{i=1}^{m} I_{F,i} = \sum_{i=1}^{m} A_n A_S T^2 \exp\left(\frac{-\Phi_{Bn,i}}{V_{th}} - p_{eff,i}\right)\left[\exp\left(\frac{V_F - R_{S,i} I_{F,i}}{n V_{th}}\right) - 1\right].$$

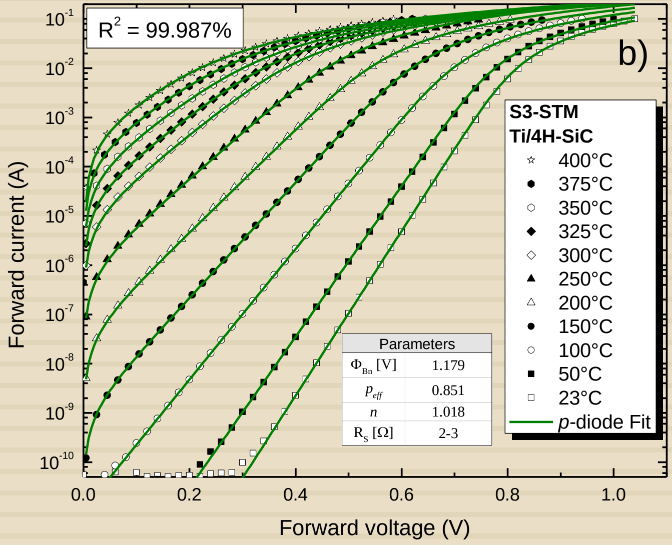


- Well-known parallel conduction concept
- *m* diode area regions which influence current over investigated temperature and bias range →
- *m* parallel diodes with parameters:
- $\Phi_{Bn,i}$ - Schottky barrier
- $R_{s,I}$ - series resistance
- $p_{eff,i}$ - Schottky contact inhomogeneity degree
- *n = 1.03* ideality factor

Ti/4HSiC Schottky contact - uniform



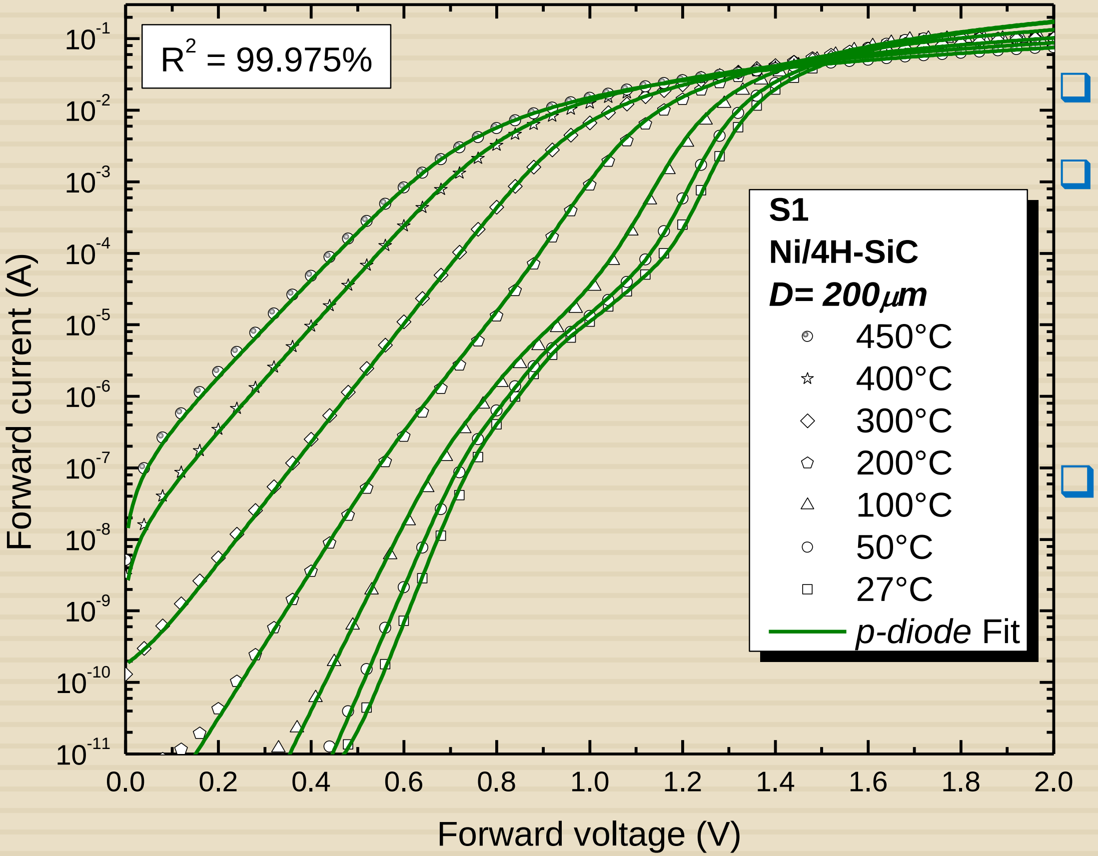
- Classical model
- $A_s = A_{eff}$ $(p_{eff}=0)$
- Good matching up to 200°C
- Data sheet: $T_{max} = 175°C$



- *p-diode* model
- $A_{eff} = 0.43 \cdot A_s$
- Good agreement up to 400°C

$A_{inactive} = 0.57 \cdot A_s$ $\Phi_{Bn} > 1.18$

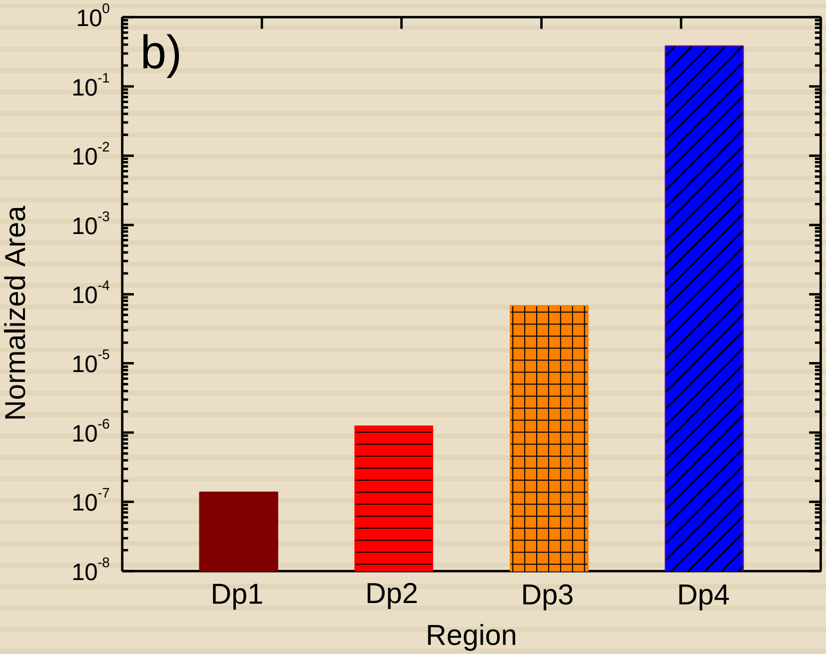
Ni/4HSiC Schottky contact - non uniform



- S1 - *Ni*$_2$Si Schottky contact
- Measured curves below 200°C, exhibit pronounced abnormal behavior with two discernable exponential portions.
- m=4 excellent agreement experimental / *p*-diode model (R^2 = 99.975%)

S1 - Ni_2Si /4H SiC Schottky contact

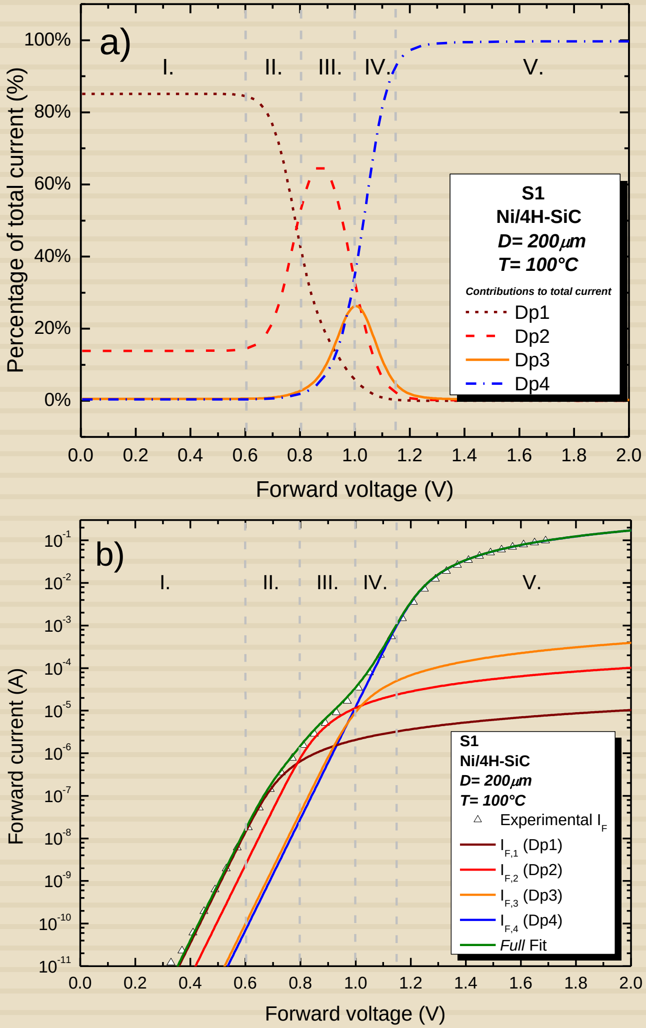
Parallel diode	Φ_{Bn} [V]	p_{eff}	n
Dp1	0.936	15.80	1.03
Dp2	1.064	13.60	
Dp3	1.296	9.60	
Dp4	1.585	0.96	



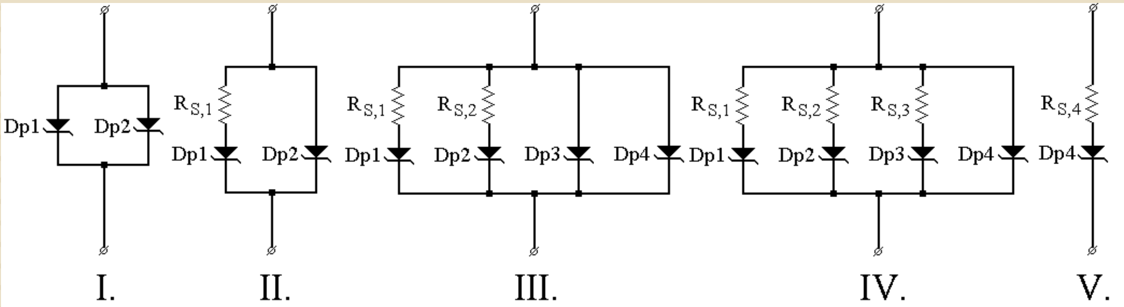
- ❑ Table parameters are rigorously constant over the entire temperature and bias range

- ❑ A_{eff}/A_s for all parallel diodes
- ❑ Very large difference between $A_{eff,i}$

S1 - Ni_2Si /4H SiC Schottky contact



- D_{p1} …D_{p4} percentage contributions to total current



- Bias range – 5 domains
- Individual forward characteristics
- D_{p4} - dominates conduction above 1.1V and high temperature T> 200°C

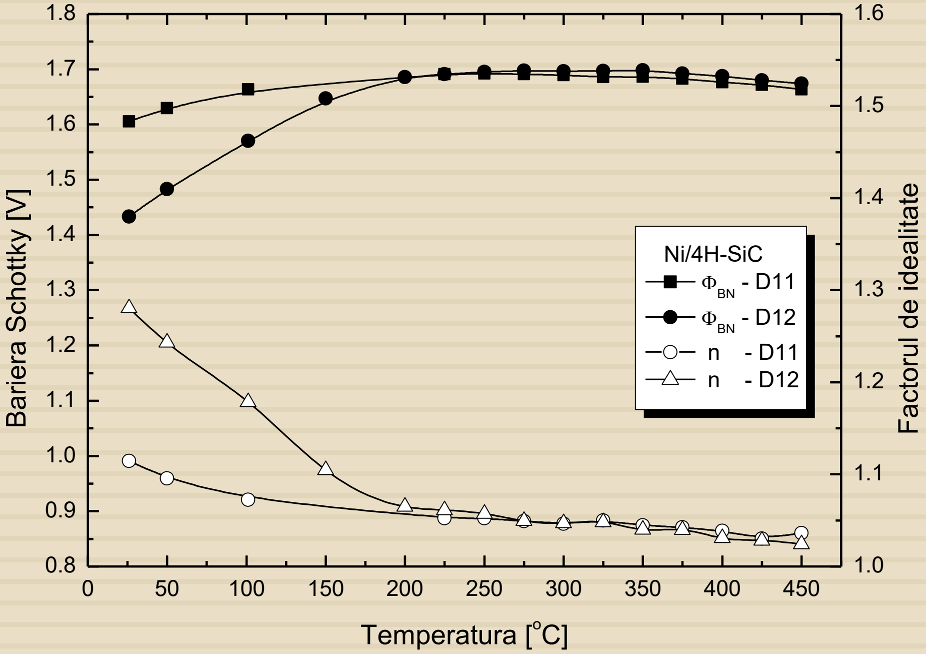
S1 - Ni_2Si /4H SiC Schottky contact

- *S1* Schottky contact – non-uniform at room temperature
- High temperature (T > 200°C)
- S1 – ideal SBD (D_{p4}):

$A_{eff,4} = 0.38 \cdot A_s$

Φ_{Bn} = 1.6V

$n = 1.03$



- *D11* and *D12* similar behavior to S1
- T > 200°C

Φ_{Bn} = 1.55V

$n < 1.05$

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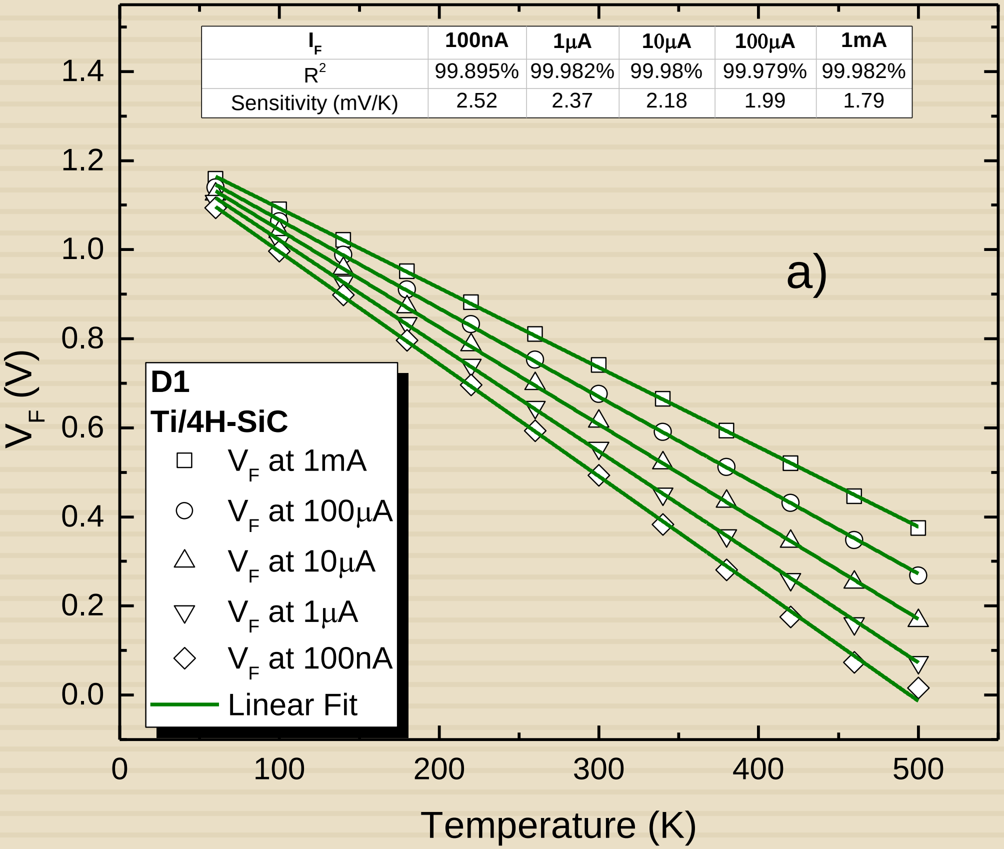
CTAT technique – Ti contact

$$V_F(T) = n\Phi_{Bn,T} - \left[n\Phi_{Bn,T} + 2nV_{th0}\ln\left(\frac{T}{T_0}\right) - V_F(T_0)\right]\frac{T}{T_0},$$

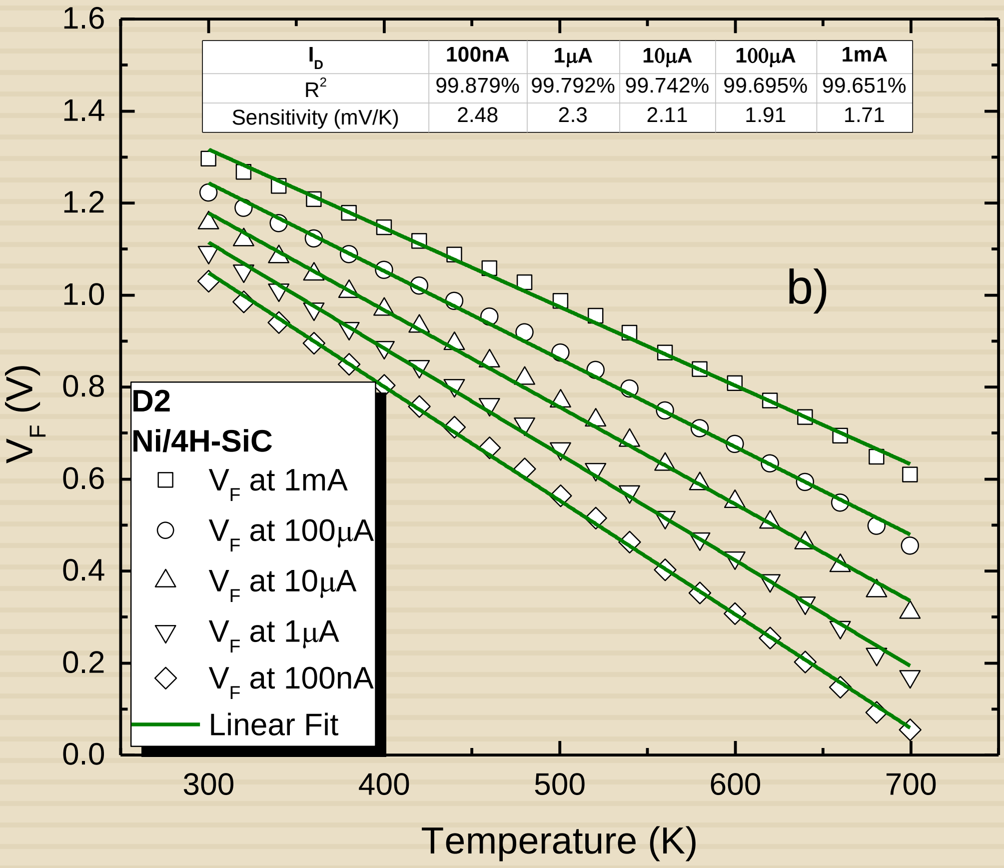


I_F	100nA	1µA	10µA	100µA	1mA
R^2	99.895%	99.982%	99.98%	99.979%	99.982%
Sensitivity (mV/K)	2.52	2.37	2.18	1.99	1.79

- V_F decreases with T at I_F=const.
- Ti/ 4H-SiC uniform contact →
- T = 60K….500K
- Very good linearity, R^2 >99.9%
- $\Phi_{Bn,T}$ = 1.19V for entire T range
- Sensitivity ↘ with I_F

CTAT technique – Ni contact

$$V_F(T) = n\Phi_{Bn,T} - \left[n\Phi_{Bn,T} + 2nV_{th0}\ln\left(\frac{T}{T_0}\right) - V_F(T_0)\right]\frac{T}{T_0},$$



I_D	100nA	1μA	10μA	100μA	1mA
R^2	99.879%	99.792%	99.742%	99.695%	99.651%
Sensitivity (mV/K)	2.48	2.3	2.11	1.91	1.71

- Ni/ 4H-SiC non-uniform contact →
- Barrier fluctuations
- T = 300K…700K →

  $\Phi_{Bn,T}$ = 1.62V…1.71V
- Linearity progressively degrades with I_F (R^2 ↘)

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Conclusions

- **A review** of: *Silicon Carbide - SiC on power applications and sensors*
- **SiC SBDs** - most commercially successful SiC Devices
- ***p*-diode model** → evaluating performances of Schottky contacts
- Difference between a mere Schottky contact and a SBD.
- Problems with Ti/4H- SiC and Ni/4H-SiC Schottky contacts

  - Ti/4H- SiC uniform contact but $A_{eff} < A_s \rightarrow$ SBD

  - Ni/4H- SiC essentially non-uniform contact →

  - SBD at high temperature and $V_F > 1V$ only
- SiC-SBD sensors – **Romanian technological processing and packaging**
- Ti/4H-SiC SBD → temperature sensor over 60 – 500K
- Ni/4H-SiC → adequate as sensors up to 700K