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# SiC Power MOS technology evolution

## Sustainable and efficient energy conversion in DC grids

SEMICON Europa 2021, Munich

November 19<sup>th</sup> 2021

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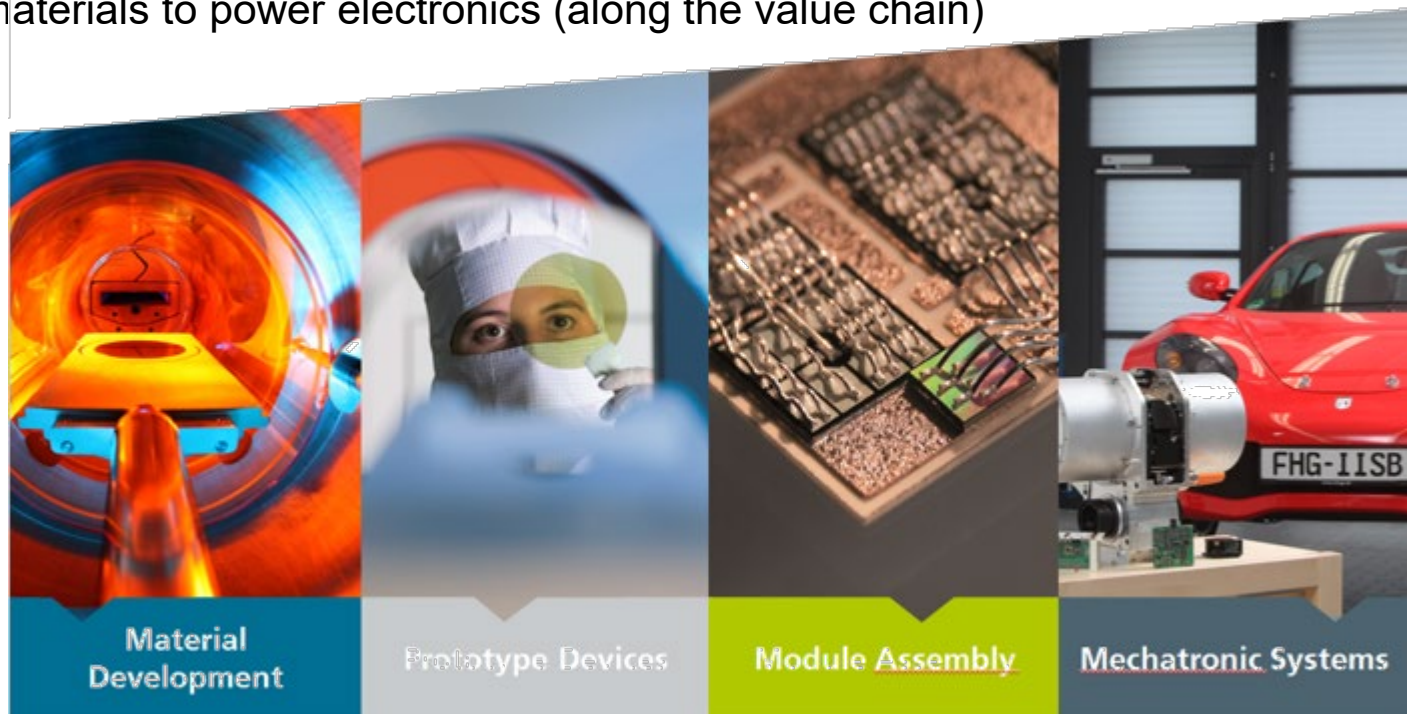
T. Erlbacher

Fraunhofer Institute for Integrated Systems and Device Technology IISB  
Erlangen, Germany



# Fraunhofer IISB: Wide-bandgap for Power electronics

- Research and Development in Applied Science (Non-profit organization)
  - From materials to power electronics (along the value chain)



- On the go from R&D through Prototypes to Small volume fabrication
  - R&D activities along vertically integrated value chain (internal customers!)
  - 150mm SiC CMOS technology platform with qualified process modules

# Content

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- Sustainability through energy efficient DC grids
  - CO<sub>2</sub> neutrality: Reduction and energy efficiency
  - Motivation, competition and market situation for SiC devices
  - SiC Devices: From electric vehicles to DC grids infrastructure
- Evolution of SiC Power MOS technology
  - Planar technology, wafer material and unit cell optimization
  - Trade-offs between performance, reliability and yield
  - Challenges for further advancements and moving targets
- Possible goals for further tool optimization
  - High temperature processing: Oxidation, implantation, high-temperature annealing
  - Lithography, SiC Trench etching ohmic contacts, Wafer thinning
- Opportunities and Conclusion

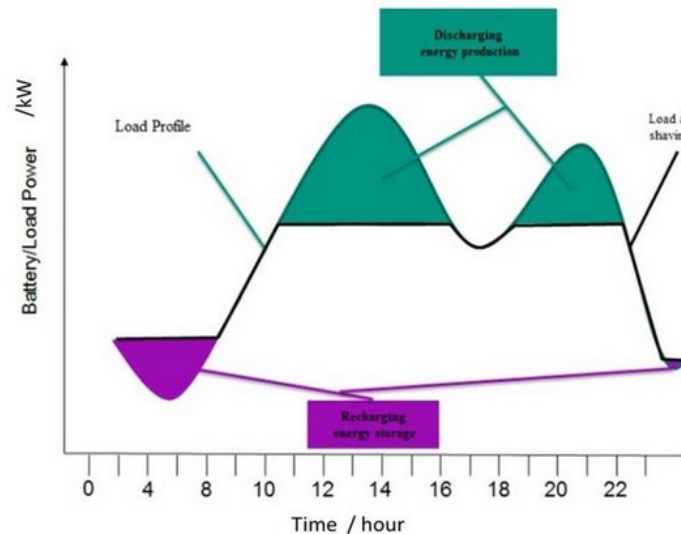
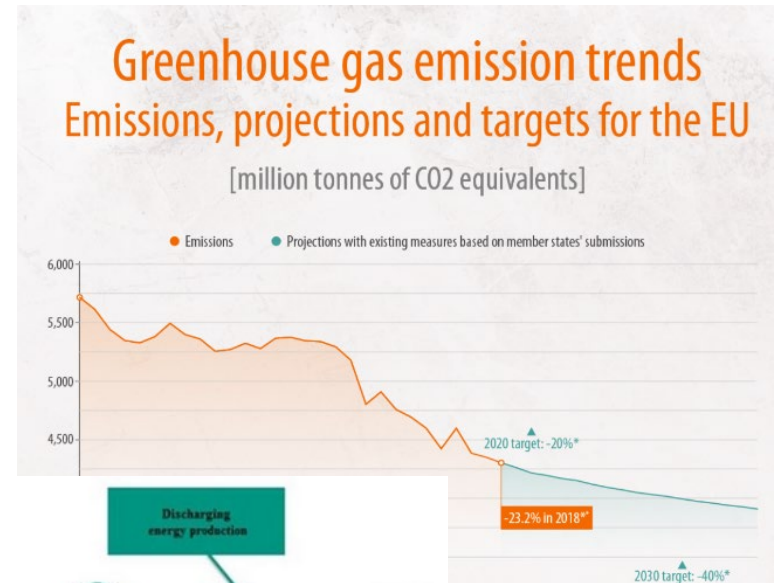
# Content

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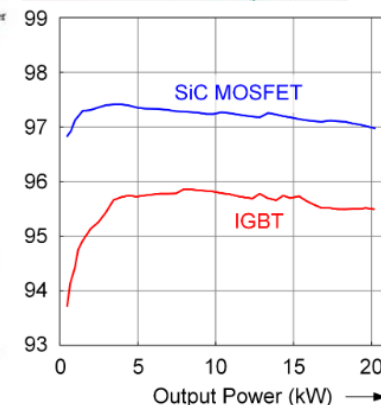
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# Sustainability through energy efficient DC grids

- Energy efficiency contributes to EU's CO<sub>2</sub> goals
  - Ecological and economical implications
    - Laws and regulations (compare Monitors)
    - Prestige and responsibility for companies
- SiC (WBG) converters offer excellent partial load properties
  - Up to 10% more efficiency compared to silicon topologies
  - Every time energy is transferred
    - Generation
    - Storage (Recuperation)
    - Consumption
  - Applicable to any source of electrical energy consumption (broad range)



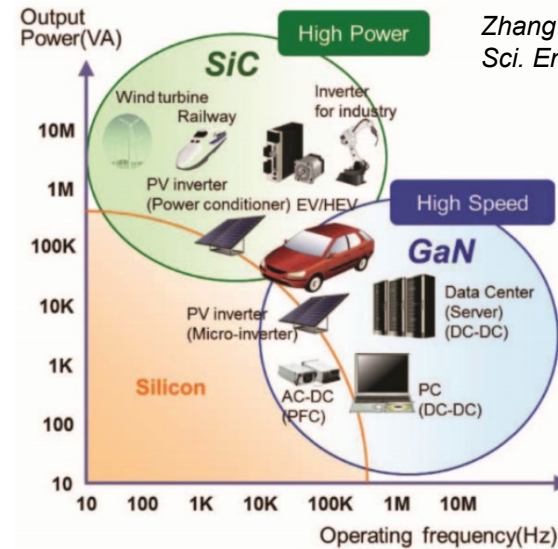
Boyounk N. et al., ISGT-Europe 2018, Sarajevo



M. Nitzsche et al.,  
PCIM 2019, Nuremberg

# Sustainability through energy efficient DC grids

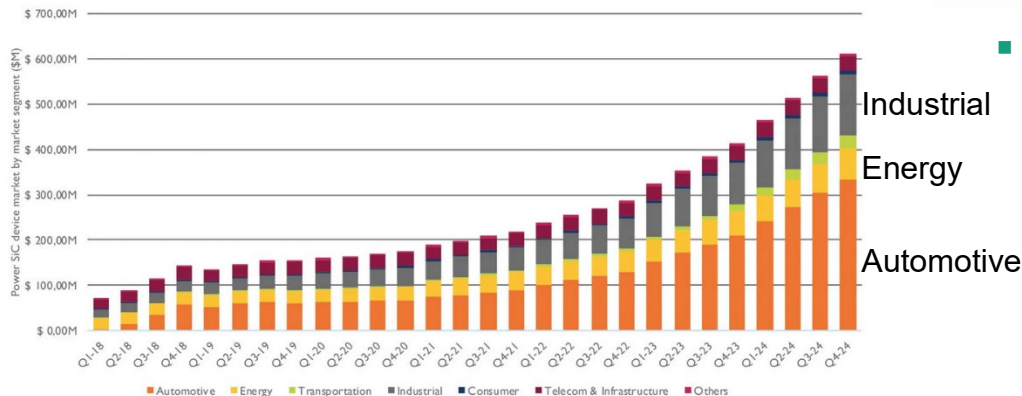
- Motivation, competition and market situation for SiC devices
  - Competition zone Si/SiC/GaN
    - SiC excels at 600V and above
    - High reliability demonstrated
    - Reduction of fabrication cost



Zhang Y., Mater. Sci. Eng. 738 012004

## Power SiC device market Forecast by segment

(Source: CS Market Monitor, Yole Développement, Q4 2019)

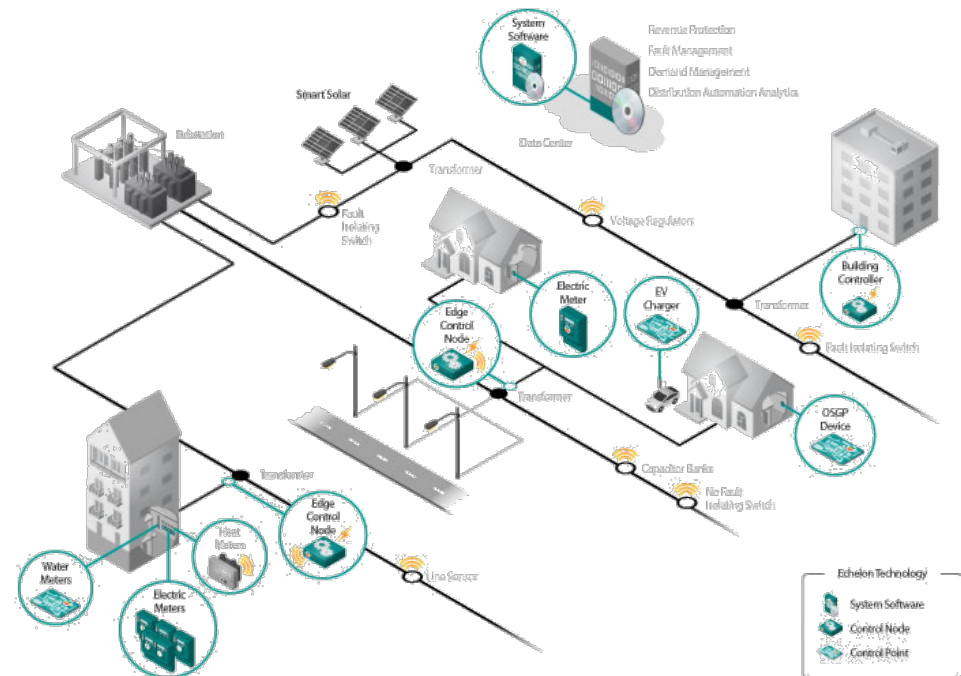


- This figure represents the estimated market for SiC devices, including both open and captive markets.
- The ramp up of automotive market in 2018 was mainly due to Tesla's adoption of SiC in its main inverter.
- Similar to automotive application, other applications such as industrial, energy and transportation are expected to grow.

- Power SiC market trends
  - Ramp-up is imminent
    - Tesla and Toyota kicked it off
    - OEMs are following now
  - Increase in Fab capacity
    - Fab extensions (150/200mm) & Pure-play foundries
  - “Crazy China”

# Sustainability through energy efficient DC grids

- Reduction of transmission losses using SiC-based switch-mode power supplies
  - Automotive traction inverters and converters are paving the way...
  - Broad range of generation and consumption for DC grids
    - PV and Wind Power
    - Electrical storage
    - EV Charging infrastructure
    - Manufacturing tools / factories (regulated motors)
    - H2 generation (hydrolysis)
    - Lighting
- Usually partial load conditions
  - Peak loads are the exception
    - Converter designed for peaks
  - Load shifting or Peak shaving?



# Content

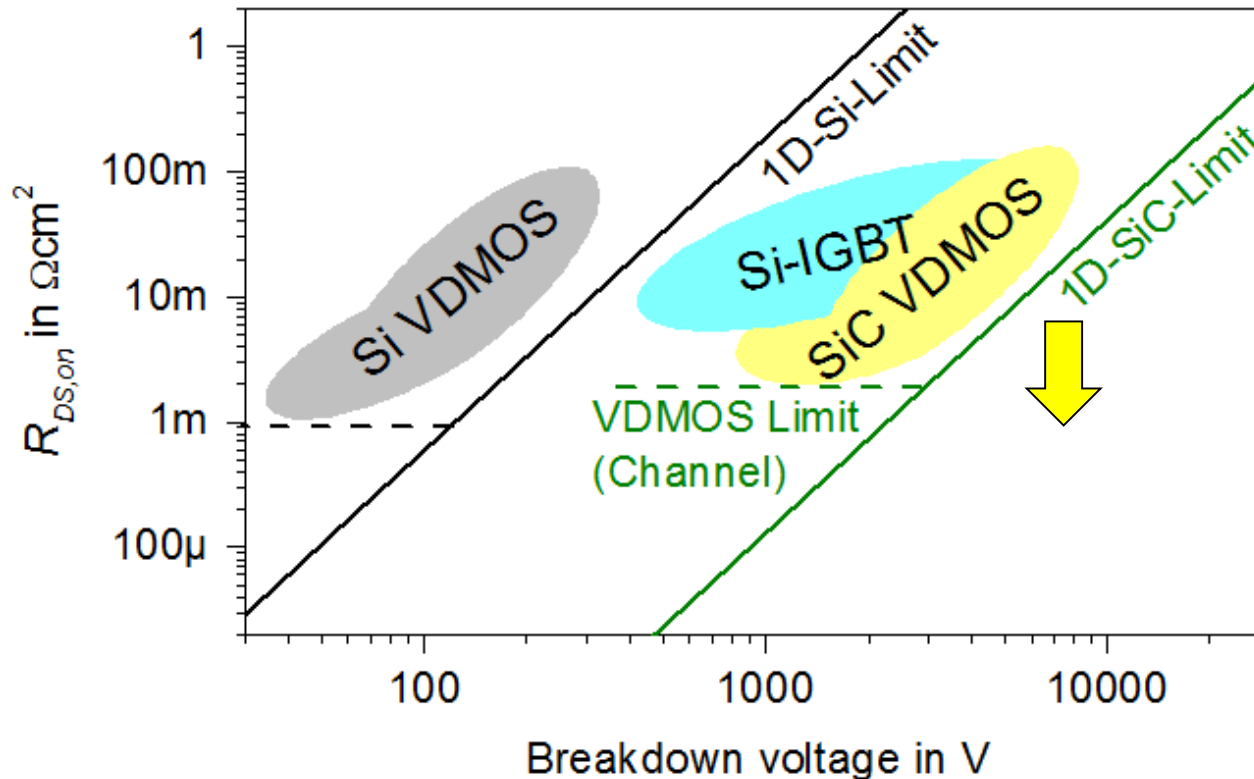
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# Evolution of SiC Power MOS technology

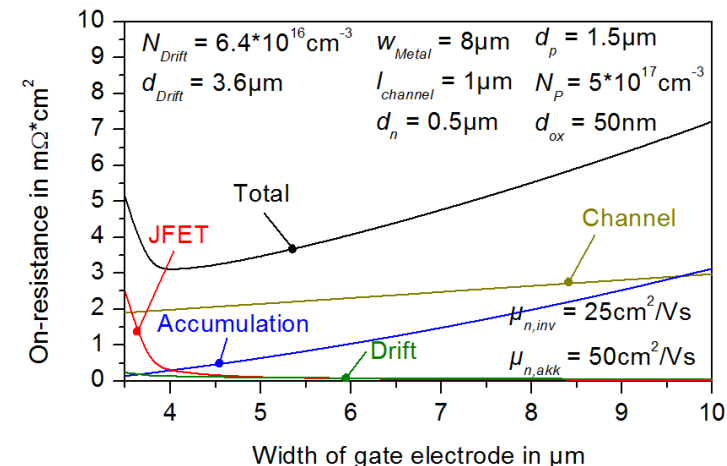
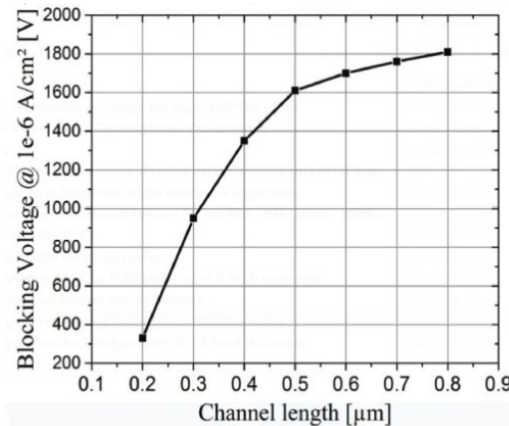
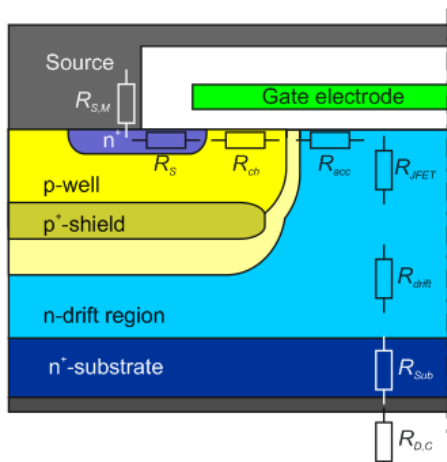
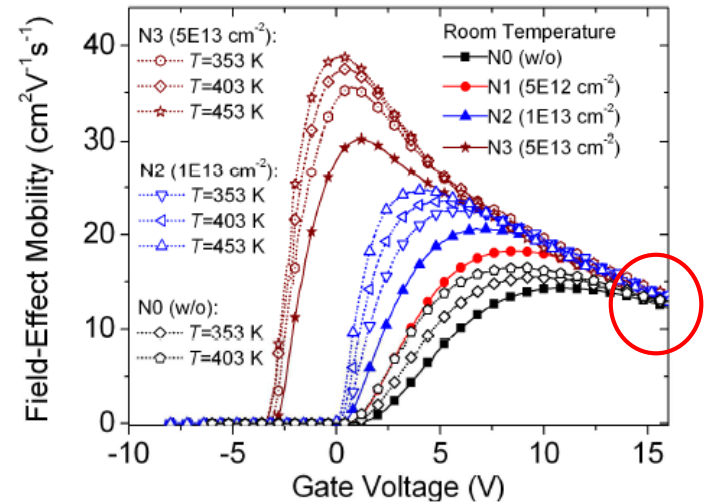
- Task 1: Reduction of On-State resistance to minimize die size/cost
  - Technology development depends on voltage rating



# Evolution of SiC Power MOS technology

Strenger et al., Mat. Sci. Forum 740–742 (2013), 537

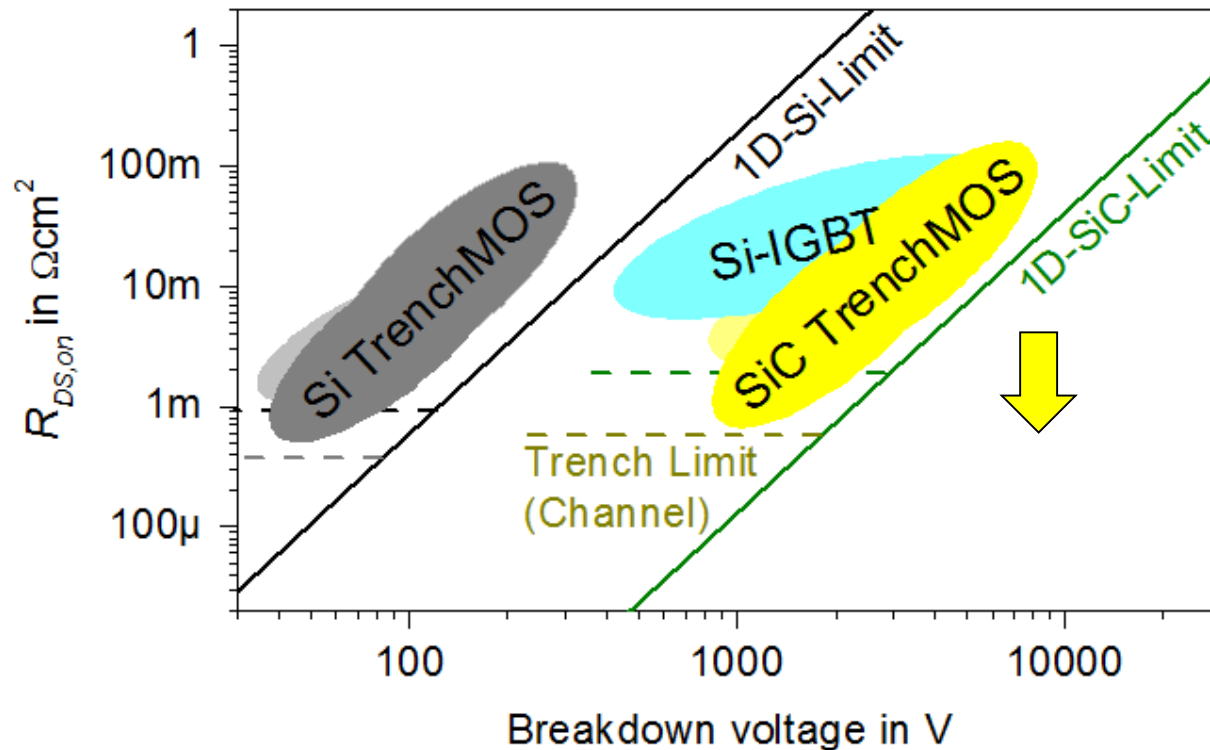
- Task 1: Reduction of On-State resistance
  - Improvements in channel mobility
    - Reduction of interface states by POA at 1300°C in NO
    - Channel mobility gradually increased to 20 cm<sup>2</sup>/Vs at  $V_{gs,max}$
  - Shielding of gate oxide required: p<sup>+</sup>-shield
  - Shrinking of unit cell: e.g. reduced channel length, JFET implantation



H. Schlichting et al., Mat. Sci. Forum 963 (2019) 763-767

# Evolution of SiC Power MOS technology

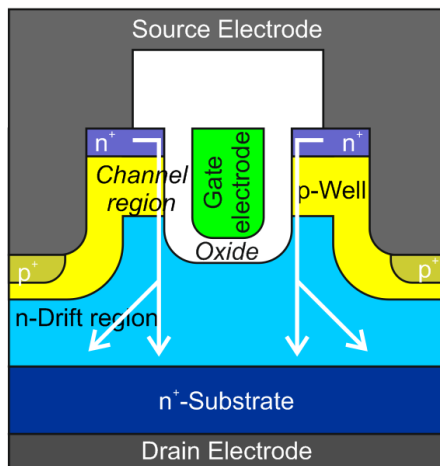
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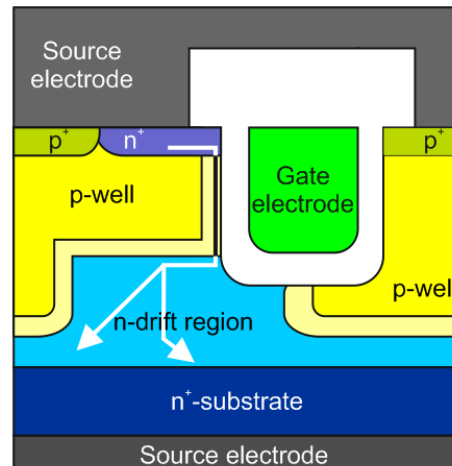
# Evolution of SiC Power MOS technology

- Task 1: Reduction of On-State resistance
  - Implementation of trench gates
    - Increased channel mobility along (1 1 -2 0) orientation
    - Vertical channel → Pitch reduction compared to VDMOS
  - Shielding of trench bottom oxide vital!

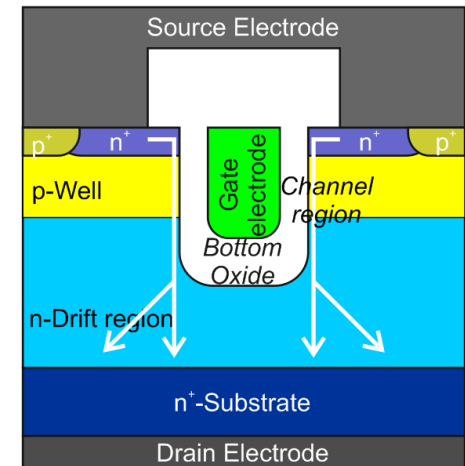
## Examples of practical SiC Trench MOS concepts



*Rohm / MaxPower Double Trench*



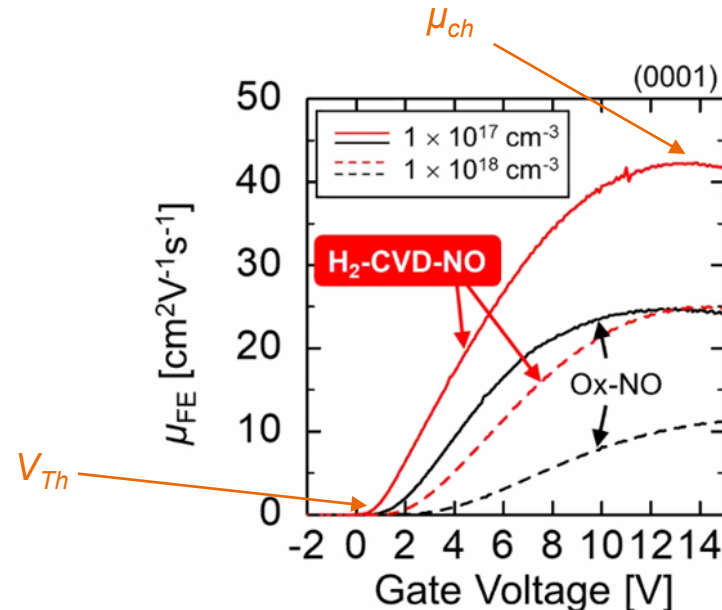
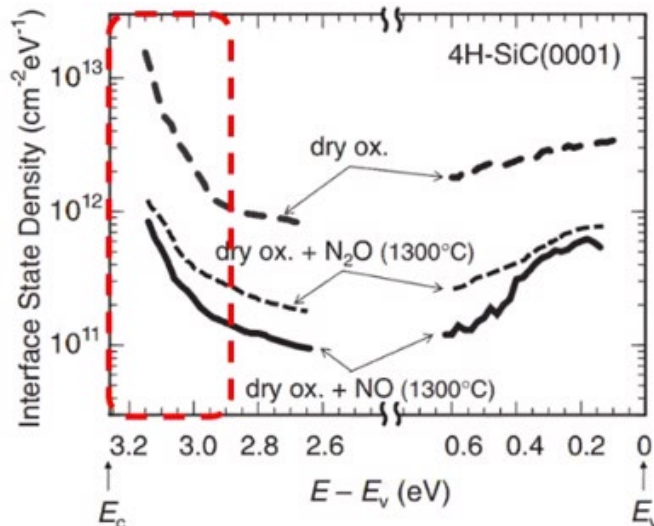
*Peters et al., Power-Mag 3 (2017)*



*Banzhaf et al. MSF 858 (2016) 848-851*

# Evolution of SiC Power MOS technology

- Task 2: Design for Reliability, Manufacturability and Ruggedness
  - On-state resistance can be “traded off” to achieve application specific goals
  - Example: Gate oxide reliability
    - Choice of gate oxide affects channel resistance (thickness, mobility,  $V_{th}$  etc.)
      - Oxide capacitance & Maximum gate voltage

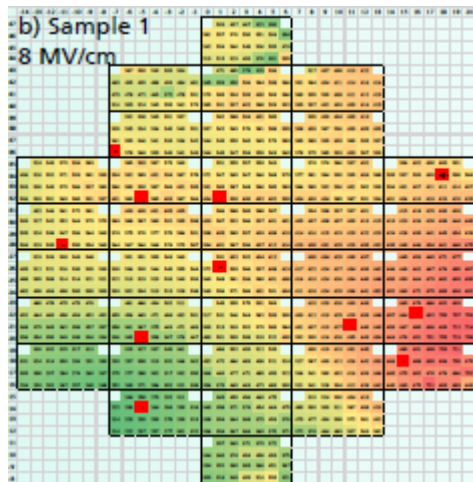


K. Tachiki et al., ECSCRM 2021

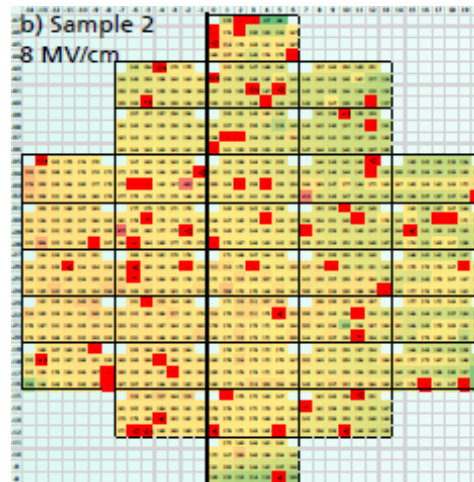
# Evolution of SiC Power MOS technology

- Task 2: Design for Reliability, Manufacturability and Ruggedness
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  - Example: Gate oxide reliability
    - Choice of gate oxide affects channel resistance (thickness, mobility,  $V_{th}$  etc.)
      - Oxide capacitance & Maximum gate voltage
    - Gate oxide thickness also affects lifetime and Defect density, which can be traded-off against Yield (Burn-in)

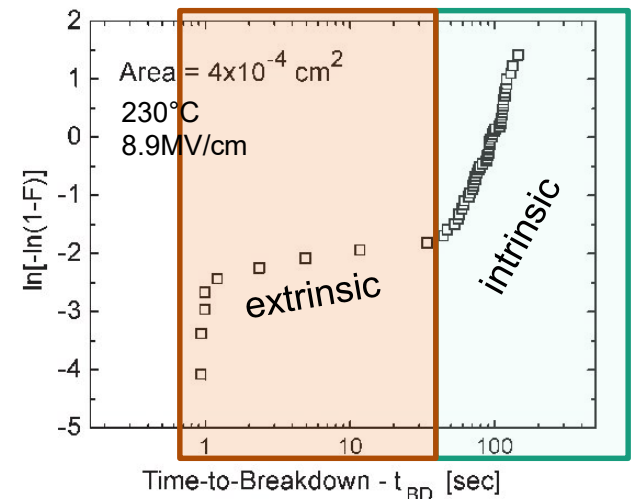
Thermal oxide w/ POA in NO



CVD oxide w/ POA in NO



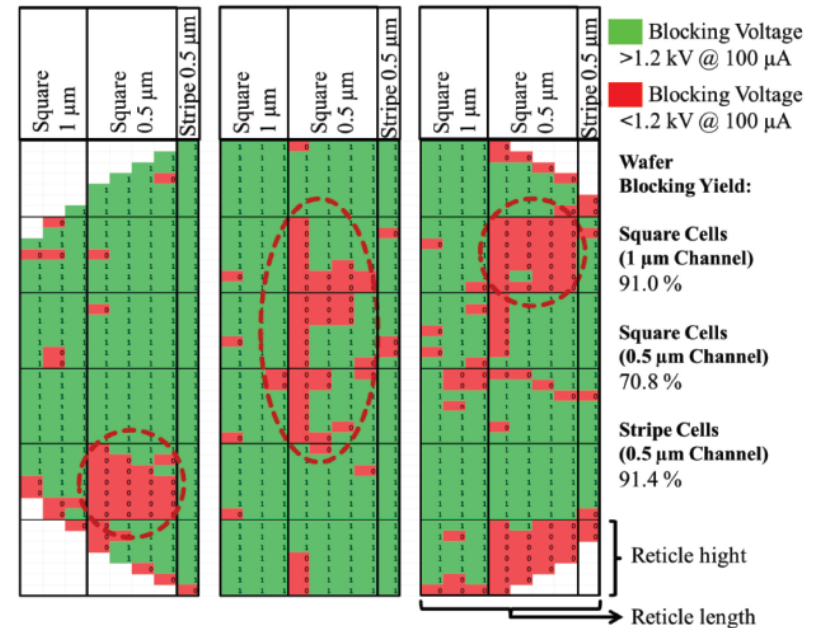
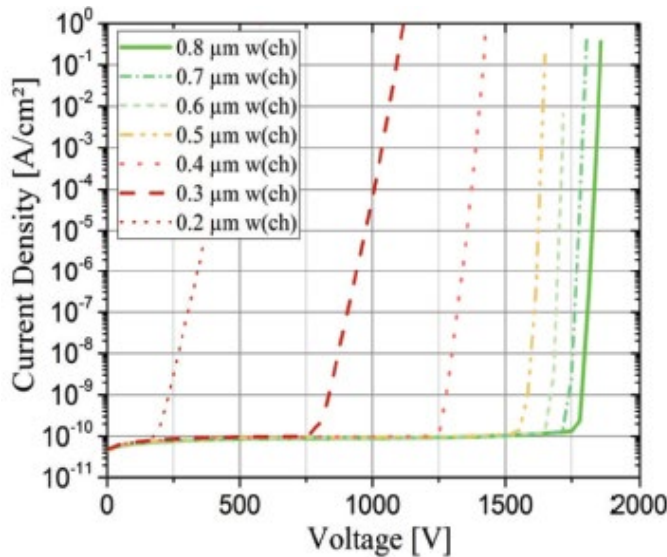
H. Schlichting et al., ECSCRM 2021



M. Gurfinkel et al., IEEE Trans Dev. Mat. Reliab. 8 (2009) 635

# Evolution of SiC Power MOS technology

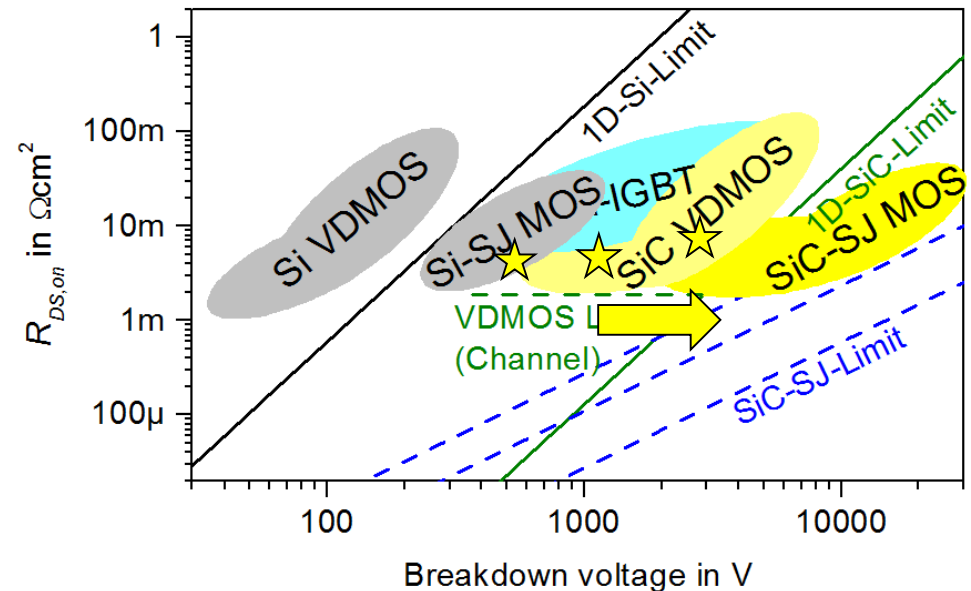
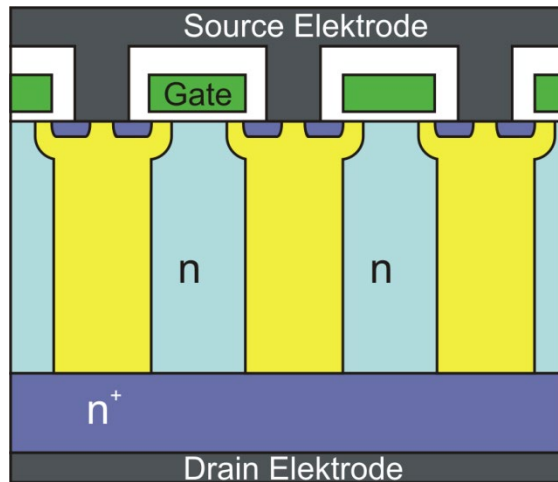
- Task 2: Design for Reliability, Manufacturability and Ruggedness
  - On-state resistance can be “traded off” to achieve application specific goals
  - Example: Integration density limited by overlay accuracy
    - Cell shrink minimizes on-state resistance → But lack of self-aligned gate process
    - Device variations and leakage currents emanate from overlay limitations
    - Self-aligned channel formation technique (additional processing effort)



H. Schlichting et al., Mat. Sci. Forum 963 (2018) 763-767

# Evolution of SiC Power MOS technology

- Challenges for further advancements
  - Unipolar high voltage devices
  - Superjunction device topology using vertical pillar structure (approx. 60 $\mu\text{m}$  @ 10kV)
  - Concepts (similar to Infineon / Toshiba solutions in Silicon):
    - Mid-energy ion implantation and epitaxial overgrowth (rinse & repeat)
    - High-energy ion implantation (e.g. filter implantation)
    - Deep trench etching and epitaxial refill





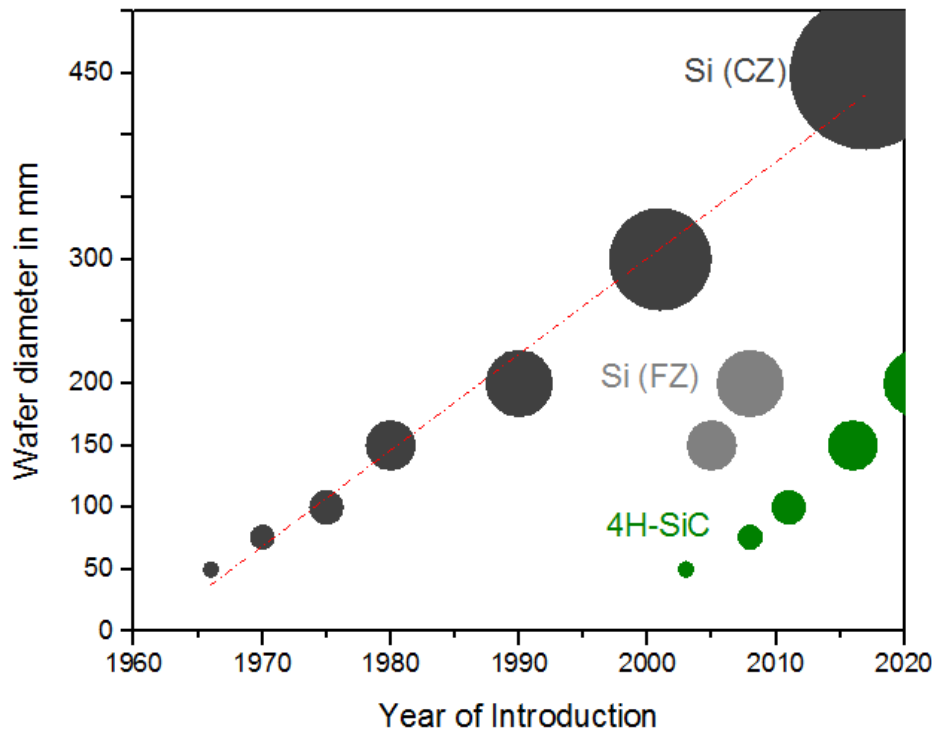
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# Possible goals for further tool optimization

- Challenges from device processing for fabrication tools
  - 200mm wafer diameter: SiC is on the go...
    - Significant cost in SiC is wafer substrate
    - Larger wafer size enables “double cost down” (per cm<sup>2</sup> wafer & processing)



- Main drivers:
- Cost down
  - Cost down
  - 200mm Si-Fabs available
    - Application pull

- Main challenges:
- High defect density
  - Growing larger diameters (Restart from scratch!)
  - Control of wafer bow/warp

# Possible goals for further tool optimization

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- Challenges from device processing for fabrication tools
  - High temperature oxidation
    - Reliability issues for gate oxide, by defects induced by epitaxy or process.
    - Need for high reliability gate oxide → optimization of defect density
    - Investigations on long-term reliability required
    - Tool assessment and optimization for HT processing have to be established
  - Implantation and high-temperature annealing
    - Al and N as “new” dopants
    - Silicon implanters are feasible, high-temperature implantation as an add-on?
    - High temperature annealing requires capping layer (typically carbon)
  - General requirements
    - Difficult handling of (200 mm) wafers due to warp/bow, need for high volume feasibility
    - Transparent wafers or “back to opaqueness” or both side-by-side?
    - Low manufacturing yield, especially for trench MOSFETs

# Possible goals for further tool optimization

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- Challenges from device processing for fabrication tools
  - Lithography requirements are very diverse, resolution is one, but not the only factor
    - Resolution, overlay and alignment accuracy
    - High exposure field size
    - High depth-of-focus
    - High energy dose for thick photoresist
    - Wafer warpage
    - Low costs / high throughput
  - Initial wafer thickness target is 500  $\mu\text{m}$  in order to reach acceptable bow/warp
    - Transition to “standard” 350  $\mu\text{m}$  (for 100/150mm) or even 200  $\mu\text{m}$  is anticipated
  - Backgrinding / Wafer thinning is available with laser annealing of ohmic contacts
    - Temporary wafer bonding
    - Concepts similar to silicon (90 $\mu\text{m}$  IGBTs) feasible, manufacturability (line yield)?

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# Opportunities and Conclusion

- Development of advanced SiC devices has just started
- Strong differentiation through performance, reliability, ruggedness trade-offs
  - System performance acts as guideline!

*Application specific solutions*

*or*

*Components-of-the-shelf?*

- Not all technological solutions are known
  - Roadmaps in power electronics (like ITRS) are not publicly available
    - But industry (from tools to fabs) would benefit from clear routes



INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

2021 UPDATE  
MORE THAN MOORE  
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Baseline-VDMOS			
Technology Node	2021	2022	2023
1200V	Green	Yellow	Red
1700V	Green	Yellow	Red
2400V	Green	Yellow	Red
3300V	Green	Yellow	Red
4500V	Green	Yellow	Red
6000V	Green	Yellow	Red
8000V	Green	Yellow	Red
10000V	Green	Yellow	Red
12000V	Green	Yellow	Red
15000V	Green	Yellow	Red
18000V	Green	Yellow	Red
22000V	Green	Yellow	Red
27000V	Green	Yellow	Red
33000V	Green	Yellow	Red
40000V	Green	Yellow	Red
48000V	Green	Yellow	Red
57000V	Green	Yellow	Red
67000V	Green	Yellow	Red
78000V	Green	Yellow	Red
90000V	Green	Yellow	Red
103000V	Green	Yellow	Red
117000V	Green	Yellow	Red
132000V	Green	Yellow	Red
148000V	Green	Yellow	Red
165000V	Green	Yellow	Red
183000V	Green	Yellow	Red
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259000V	Green	Yellow	Red
280000V	Green	Yellow	Red
302000V	Green	Yellow	Red
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349000V	Green	Yellow	Red
374000V	Green	Yellow	Red
400000V	Green	Yellow	Red
427000V	Green	Yellow	Red
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545000V	Green	Yellow	Red
577000V	Green	Yellow	Red
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715000V	Green	Yellow	Red
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869000V	Green	Yellow	Red
910000V	Green	Yellow	Red
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1039000V	Green	Yellow	Red
1084000V	Green	Yellow	Red
1130000V	Green	Yellow	Red
1177000V	Green	Yellow	Red
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2327000V	Green	Yellow	Red
2395000V	Green	Yellow	Red
2464000V	Green	Yellow	Red
2534000V	Green	Yellow	Red
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2750000V	Green	Yellow	Red
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8359000V	Green	Yellow	Red
8489000V	Green	Yellow	Red
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8885000V	Green	Yellow	Red
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9154000V	Green	Yellow	Red
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19157000V	Green	Yellow	Red
19340000V	Green	Yellow	Red
19523000V	Green	Yellow	Red
19707000V	Green	Yellow	Red
19891000V	Green	Yellow	Red
20076000V	Green	Yellow	Red
20261000V	Green	Yellow	Red
20447000V	Green	Yellow	Red
20633000V	Green	Yellow	Red
20820000V	Green	Yellow	Red
21007000V	Green	Yellow	Red
21195000V	Green	Yellow	Red
21383000V	Green	Yellow	Red
21572000V	Green	Yellow	Red
21761000V	Green	Yellow	Red
21951000V	Green	Yellow	Red
22141000V	Green	Yellow	Red
22332000V	Green	Yellow	Red
22523000V	Green	Yellow	Red
22714000V	Green	Yellow	Red
22906000V	Green	Yellow	Red
23098000V	Green	Yellow	Red
23290000V	Green	Yellow	Red
23483000V	Green	Yellow	Red
23676000V	Green	Yellow	Red
23870000V	Green	Yellow	Red
24064000V	Green	Yellow	Red
24258000V	Green	Yellow	Red
24453000V	Green	Yellow	Red
24648000V	Green	Yellow	Red
24843000V	Green	Yellow	Red
25039000V	Green	Yellow	Red
25235000V	Green	Yellow	Red
25431000V	Green	Yellow	Red
25628000V	Green	Yellow	Red
25825000V	Green	Yellow	Red
26022000V	Green	Yellow	Red
26220000V	Green	Yellow	Red
26418000V	Green	Yellow	Red
26616000V	Green	Yellow	Red
26815000V	Green	Yellow	Red
27014000V	Green	Yellow	Red
27213000V	Green	Yellow	Red
27413000V	Green	Yellow	Red
27613000V	Green	Yellow	Red
27813000V	Green	Yellow	Red
28013000V	Green	Yellow	Red
28213000V	Green	Yellow	Red
28413000V	Green	Yellow	Red
28613000V	Green	Yellow	Red
28813000V	Green	Yellow	Red
29013000V	Green	Yellow	Red
29213000V	Green	Yellow	Red
29413000V	Green	Yellow	Red
29613000V	Green	Yellow	Red
29813000V	Green	Yellow	Red
30013000V	Green	Yellow	Red

Spread the word: ***We want you for SiC!***

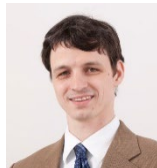


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# Thank you for Your attention!

Priv.-Doz. Dr. Tobias Erlbacher  
Fraunhofer IISB  
Schottkystrasse 10  
91058 Erlangen  
Germany



+49 (0) 9131 761-319

[tobias.erlbacher@iisb.fraunhofer.de](mailto:tobias.erlbacher@iisb.fraunhofer.de)