Wide Bandgap Power Devices for a Sustainable Future

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Agenda

1. **Introduction & Scope**
2. **More than Moore technologies**
3. **WBG Power Device Status**
    - **SiC-devices**
    - **GaN-devices**
    - **Diamond, AlN and Ga_2O_3 based devices**
4. **Potential new areas – High temperature applications**
5. **Summary & Conclusions**

Today’s Agenda

1. Introduction & Scope
2. More than Moore technologies
3. WBG Power Device Status
    - SiC-devices
    - GaN-devices
    - Diamond, AlN and Ga_2O_3 based devices
4. Potential new areas – High temperature applications
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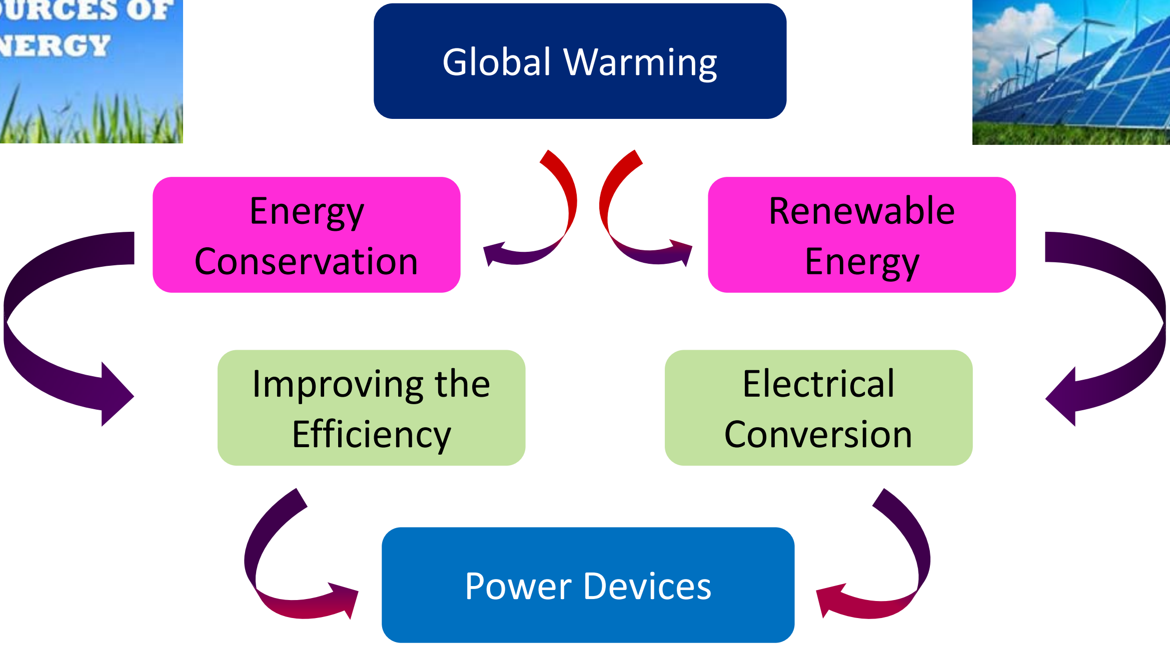
The Great Societal Challenge



Global Warming

Energy Conservation

Renewable Energy

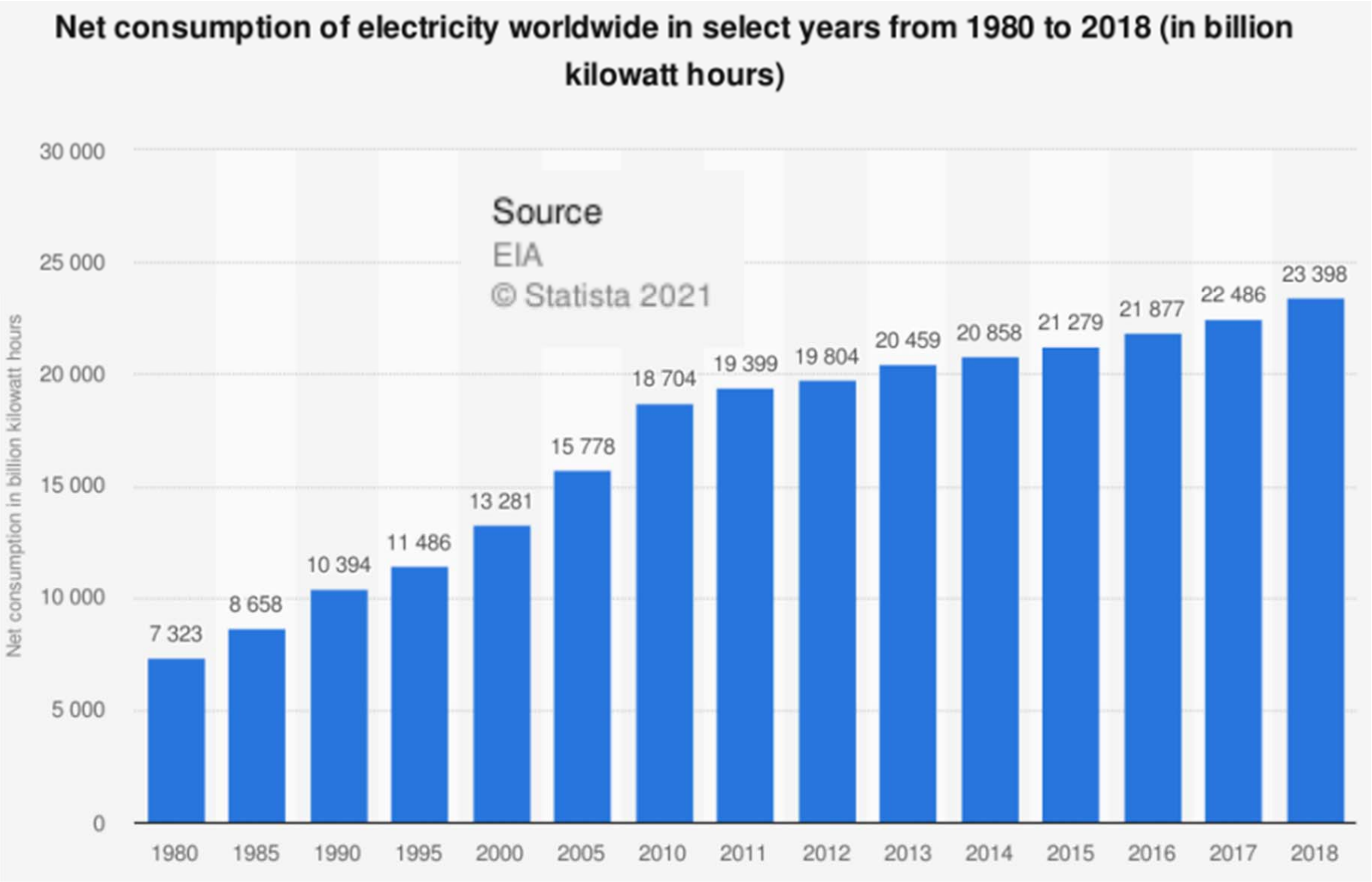
Improving the Efficiency

Electrical Conversion

Power Devices

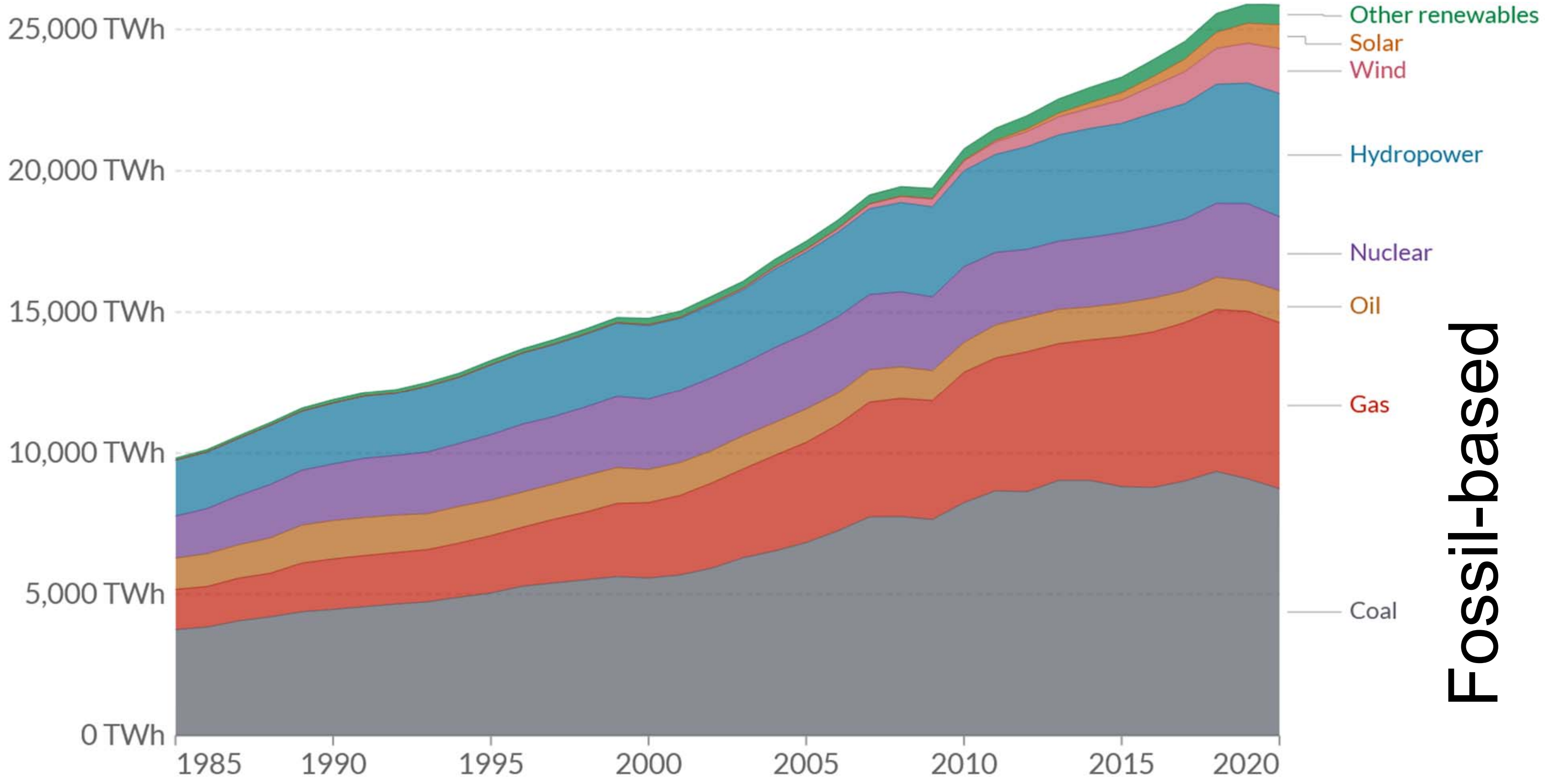
- At least 50 % of the electricity used in the world is controlled by Power Devices.

B.J. Baliga, Advanced High Voltage Power Device Concepts, Springer



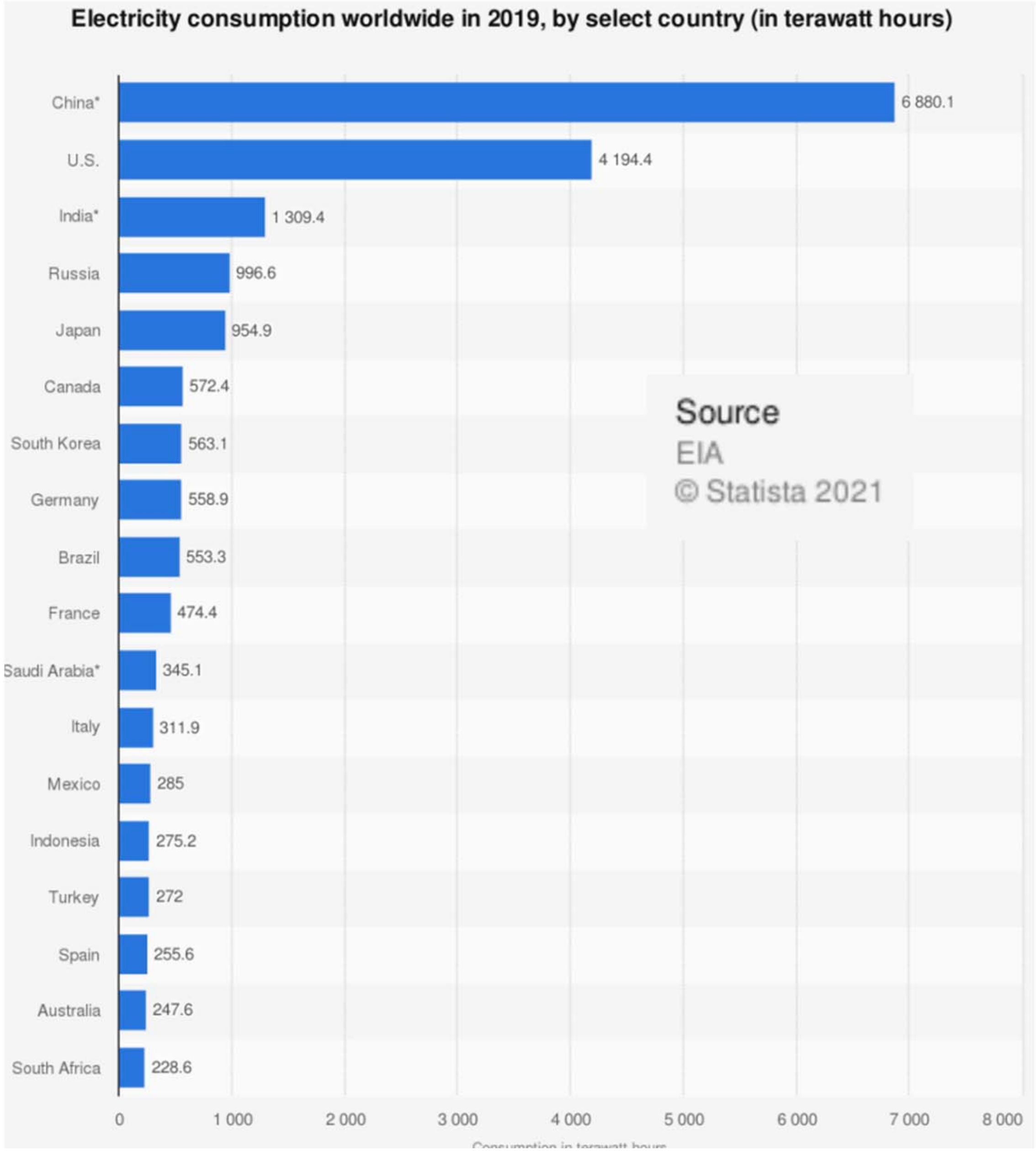
Today 26000 TWh
By 2050 50000 TWh

Global Electricity Production



Fossil-based

Source: Our World in Data based on BP Statistical Review of World Energy & Ember (2021)
Note: 'Other renewables' includes biomass and waste, geothermal, wave and tidal.


Electricity consumption worldwide in 2019, by select country (in terawatt hours)

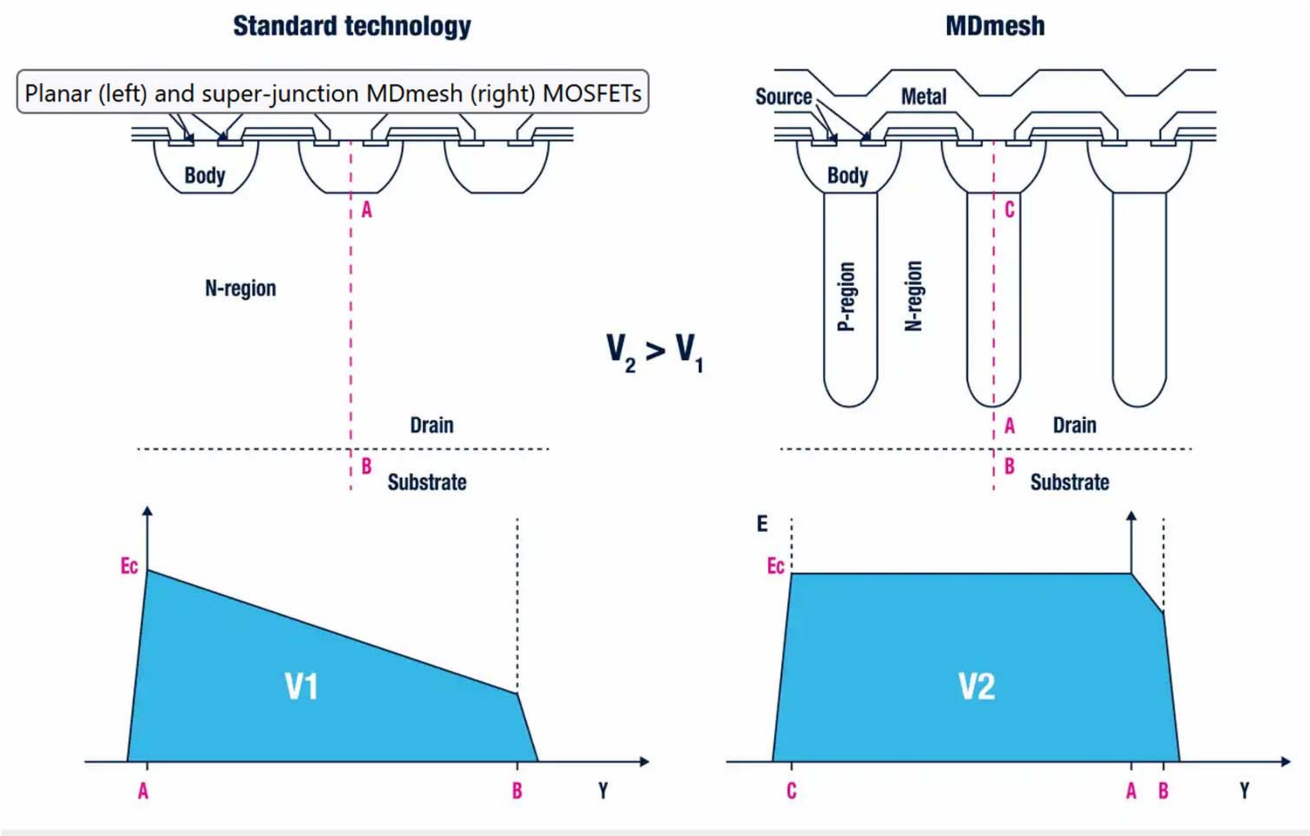
Source
EIA
© Statista 2021

How about efficiency – What can we expect?

- More than 63% of the generated electrical energy is produced by fossil based fuel
- Urgent to change the energy mix in a sustainable way
- At the same time we need to improve the efficiency in both the way we produce the electrical energy and how efficient we can distribute and consume the energy
- One important technology to improve power electronic efficiency is to introduce Wide Bandgap Semiconductors, such as SiC and GaN in our future technology

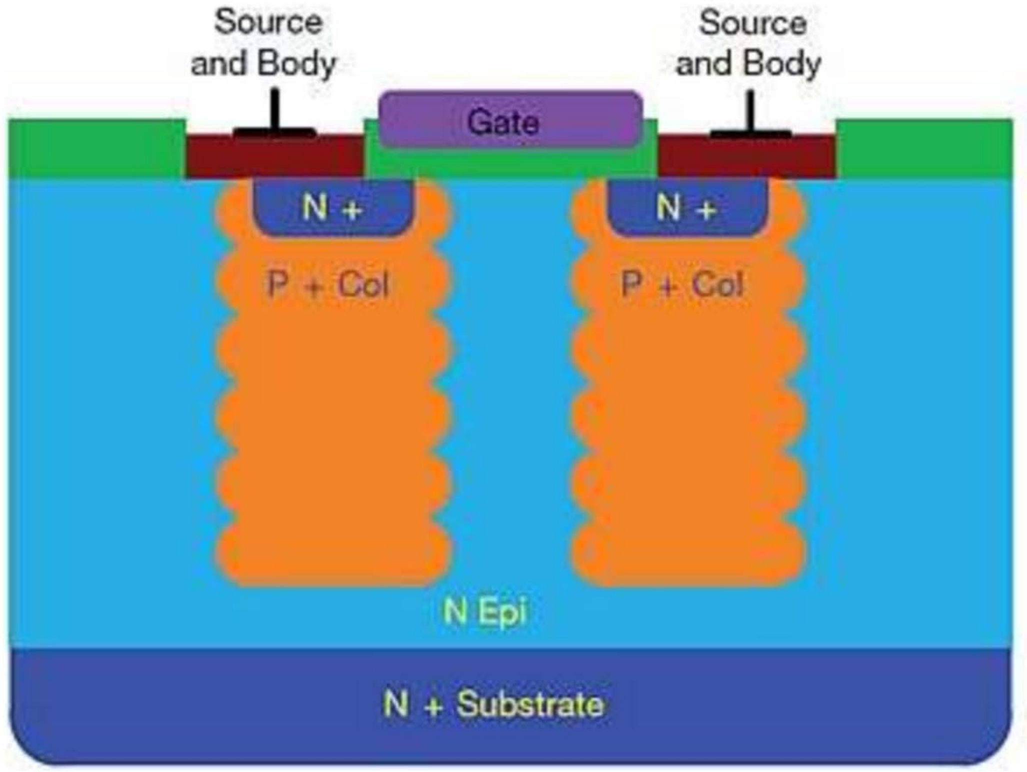
By improving today’s power electronics efficiency by only 1% will reduce the consumption → by 250 TWh – about 75 typical coal powered plants !

Superjunction MOSFET (ST Microelectronics)



Planar (left) and super-junction MDmesh (right) MOSFETs

Superjunction MOSFET in practise



The deep p+ col is made by Ion-implantation and epi overgrowth

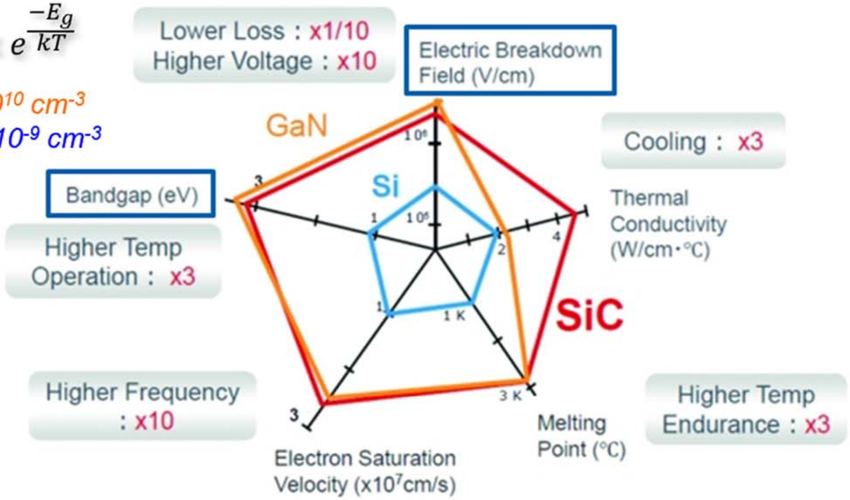
In this illustration there are 6 such implants

Fundamental WBG Characteristics

$n_i^2 \propto e^{\frac{-E_g}{kT}}$

Si: ~10^{10} cm^{-3}

SiC: ~10^{-9} cm^{-3}



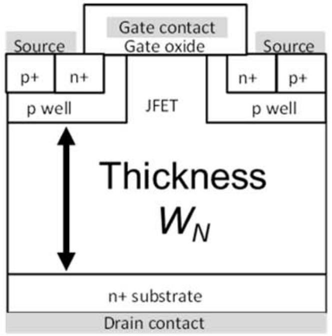
Courtesy: Rohm Semiconductor

Device Thickness

$$W_N = \left(\frac{3}{2}\right)\left(\frac{V_B}{E_C}\right)$$

Device Resistance

$$R_{ON,SP} = \left(\frac{3}{2}\right)^3 \frac{V_B^2}{\mu_N \varepsilon_S E_C^3}$$



Large Bandgap and Critical Electric Field allow for high voltage devices with thinner layers: lower resistance and associated conduction losses, low leakage, and robust high temperature operation

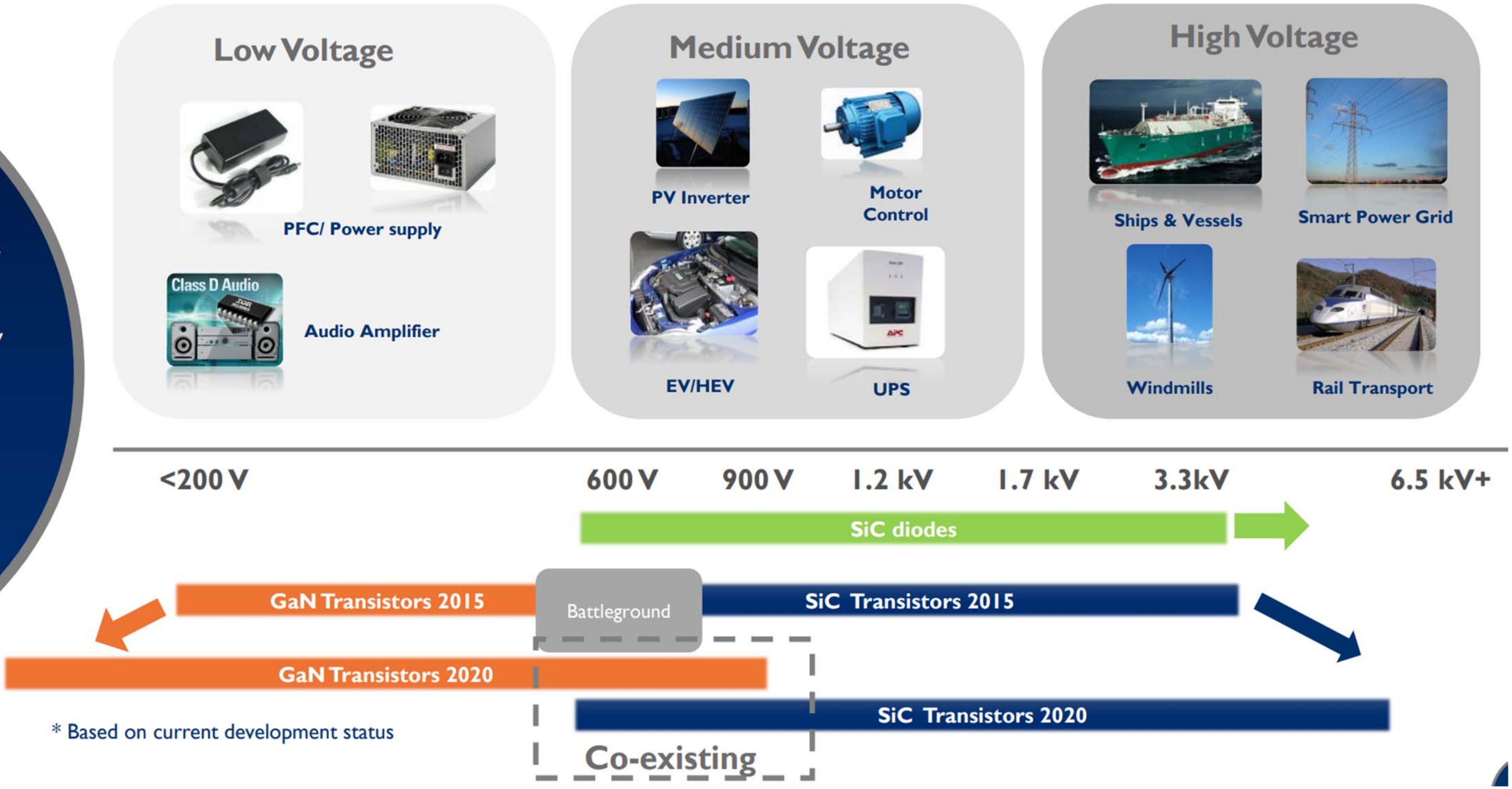
Thinner layers and lower specific on-resistances allow for smaller form factors that reduce capacitance: higher frequency operation, reduced size passives

Large Thermal Conductivity: high power operation with simplified thermal management

Modified slide from Victor Veliadis, Power America

The WBG Device Landscape

While SiC is used for high-voltage applications, GaN is mainly used for low voltage. The 600 - 900V range will be the battleground.



Low Voltage

PFC/ Power supply

Class D Audio

Audio Amplifier

Medium Voltage

PV Inverter

Motor Control

EV/HEV

UPS

High Voltage

Ships & Vessels

Smart Power Grid

Windmills

Rail Transport

<200 V

600 V

900 V

1.2 kV

1.7 kV

3.3kV

6.5 kV+

SiC diodes

GaN Transistors 2015

Battleground

SiC Transistors 2015

GaN Transistors 2020

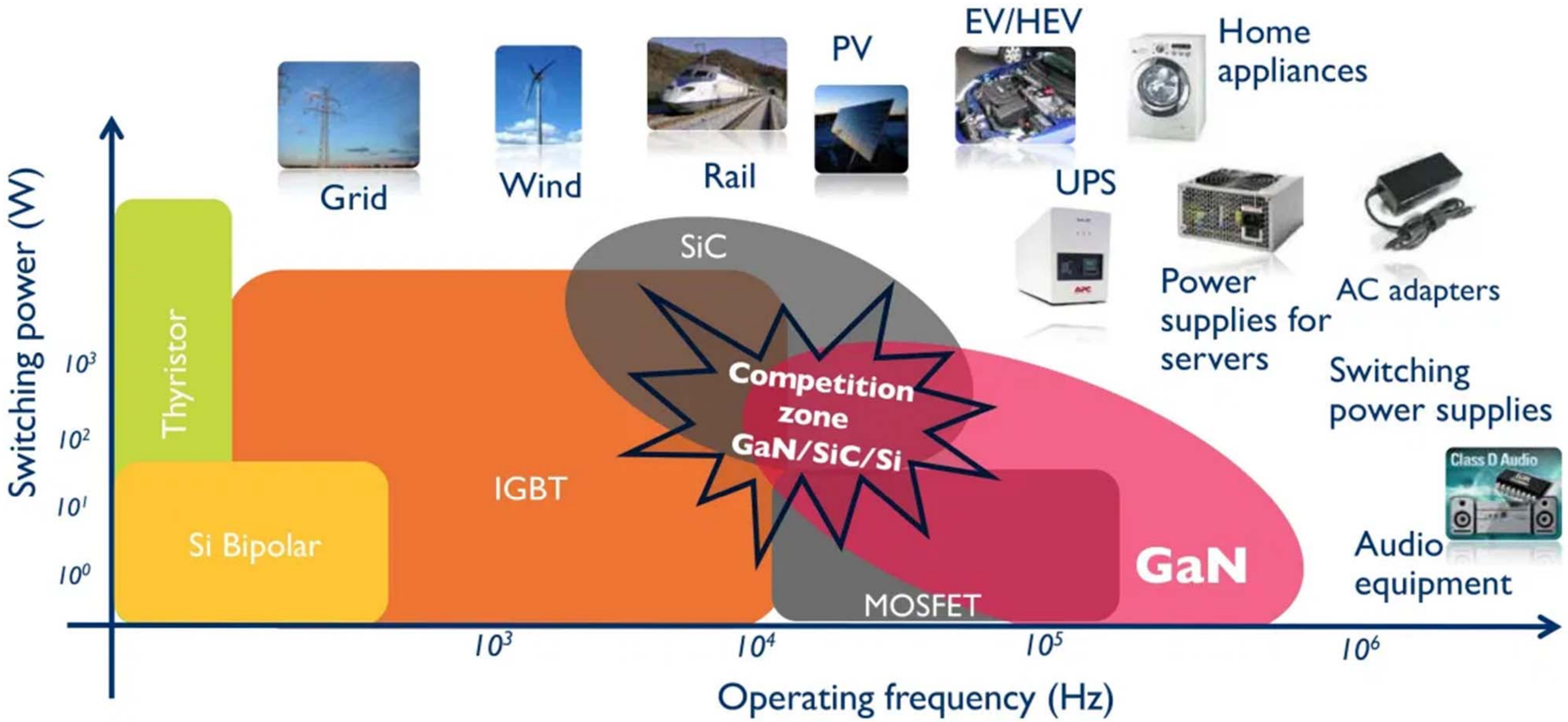
SiC Transistors 2020

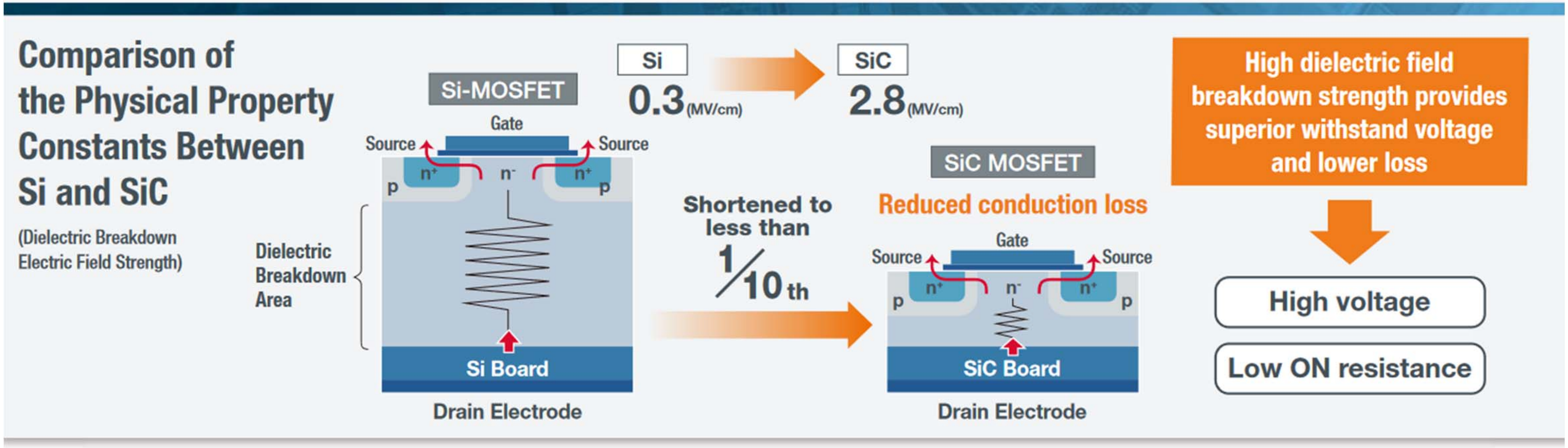
Co-existing

* Based on current development status

Power vs frequency on electronics: device technology positioning in 2020

(Source: Power GaN: Epitaxy, Devices; Applications, and Technology Trends report, Yole Développement, 2019)



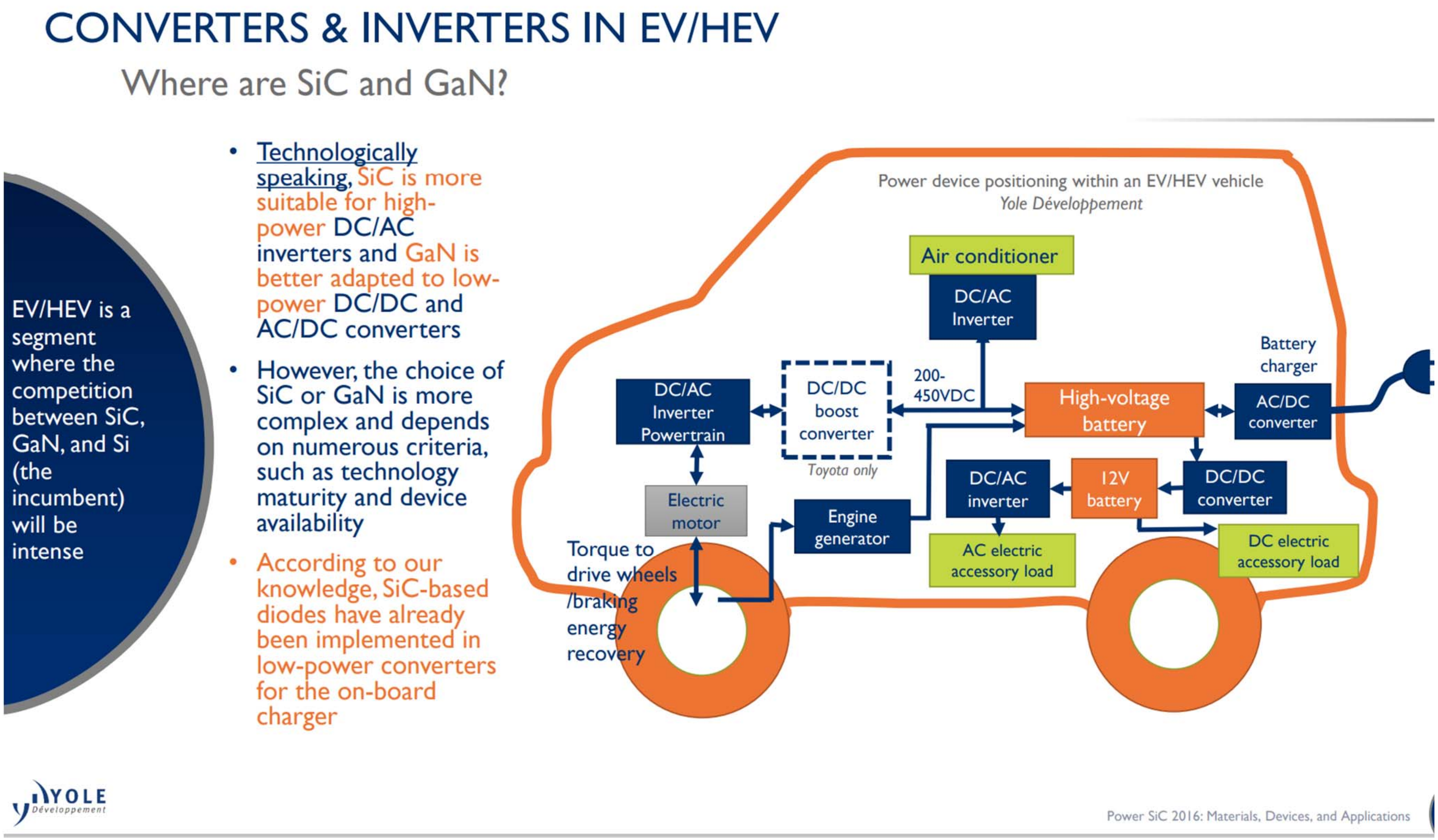


Comparison of the Physical Property Constants Between Si and SiC

(Dielectric Breakdown Electric Field Strength)

High dielectric field breakdown strength provides superior withstand voltage and lower loss

WBG in Automotive



CONVERTERS & INVERTERS IN EV/HEV

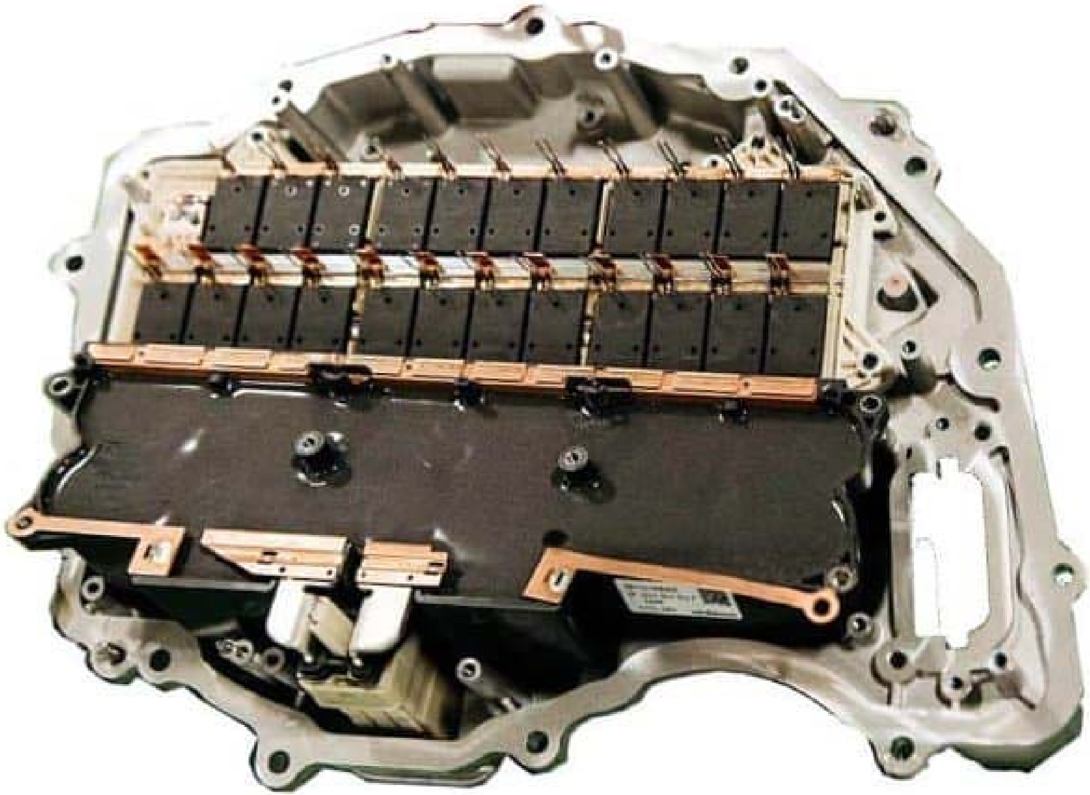
Where are SiC and GaN?

EV/HEV is a segment where the competition between SiC, GaN, and Si (the incumbent) will be intense

- Technologically speaking, SiC is more suitable for high-power DC/AC inverters and GaN is better adapted to low-power DC/DC and AC/DC converters
- However, the choice of SiC or GaN is more complex and depends on numerous criteria, such as technology maturity and device availability
- According to our knowledge, SiC-based diodes have already been implemented in low-power converters for the on-board charger

Power device positioning within an EV/HEV vehicle
Yole Développement

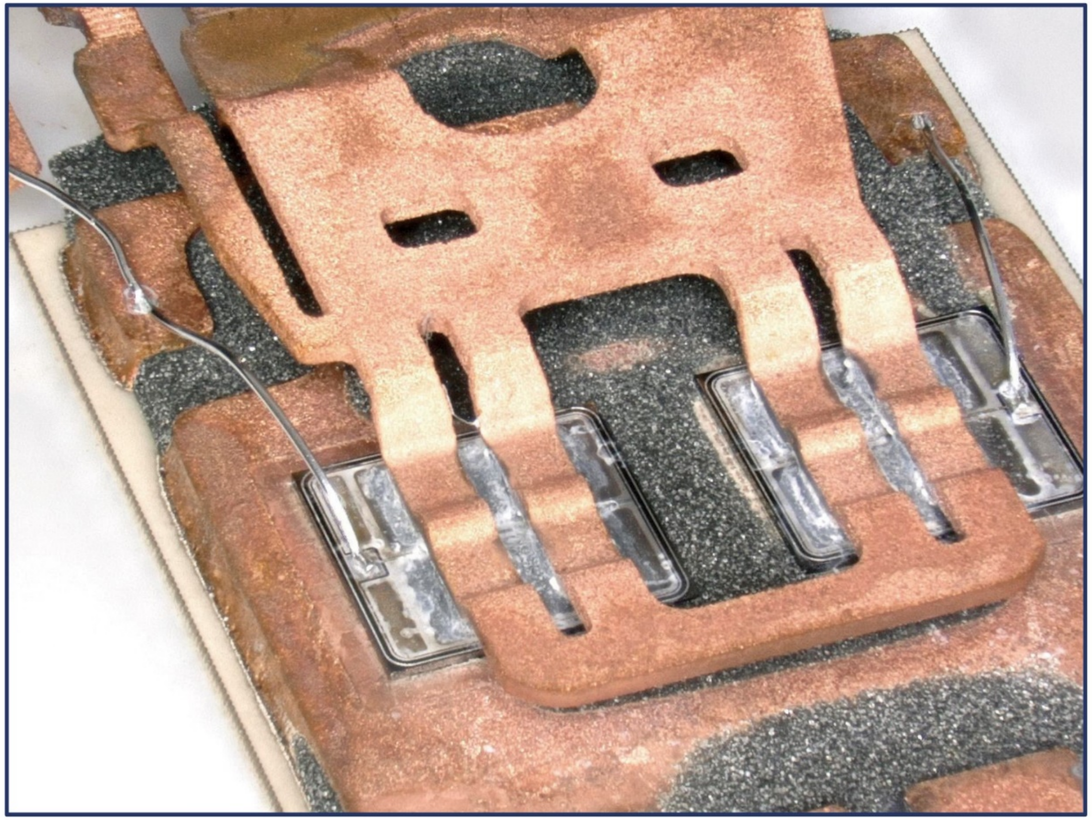
SiC MOSFETs in Tesla



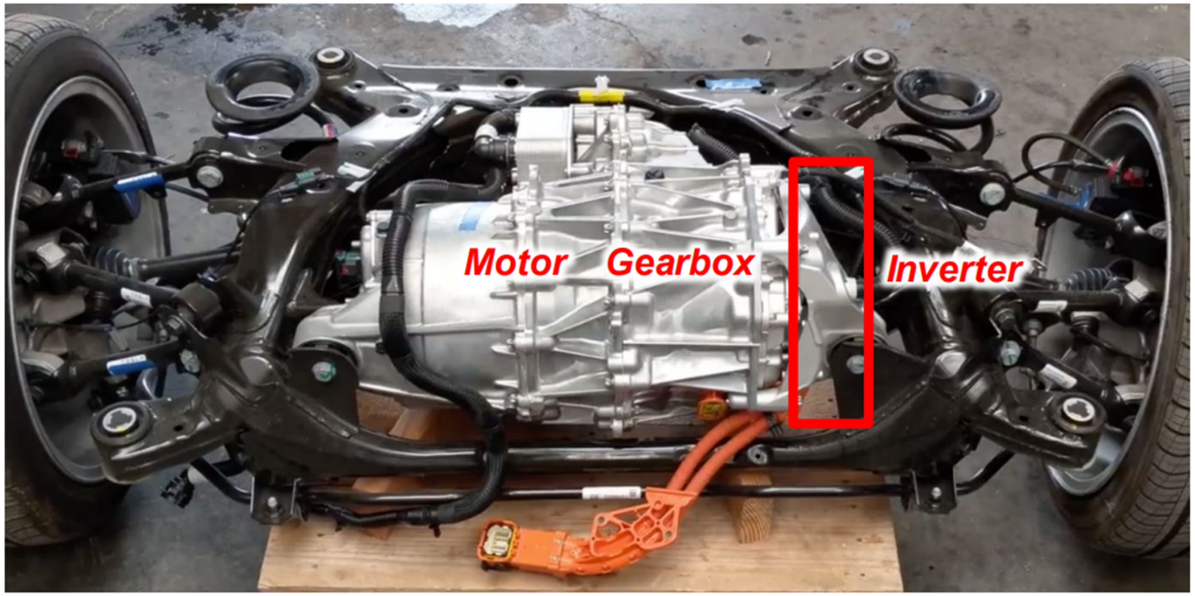
Model 3 power inverters are composed of 24 power modules, each of which are composed of two Silicon Carbide MOSFETs. Tesla is the first EV manufacturer that uses a full Silicon Carbide power module.

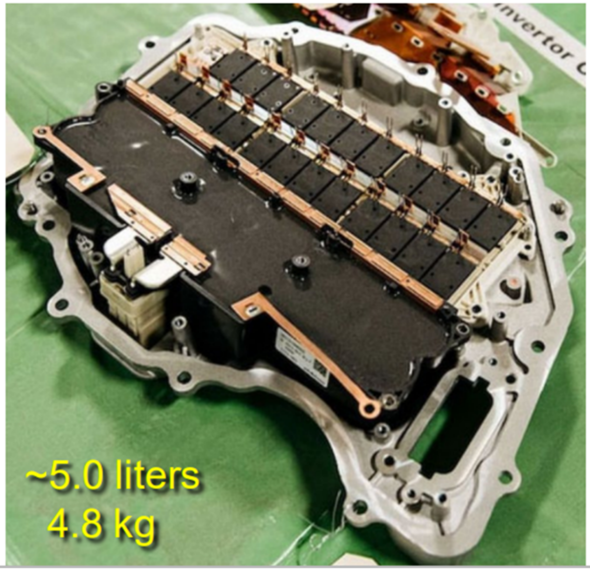
STMicroelectronics SiC Power Module in Tesla Model 3 Inverter

(Source: Tesla Model 3 Inverter with SiC Power Module from STMicroelectronics report, System Plus Consulting, 2018)



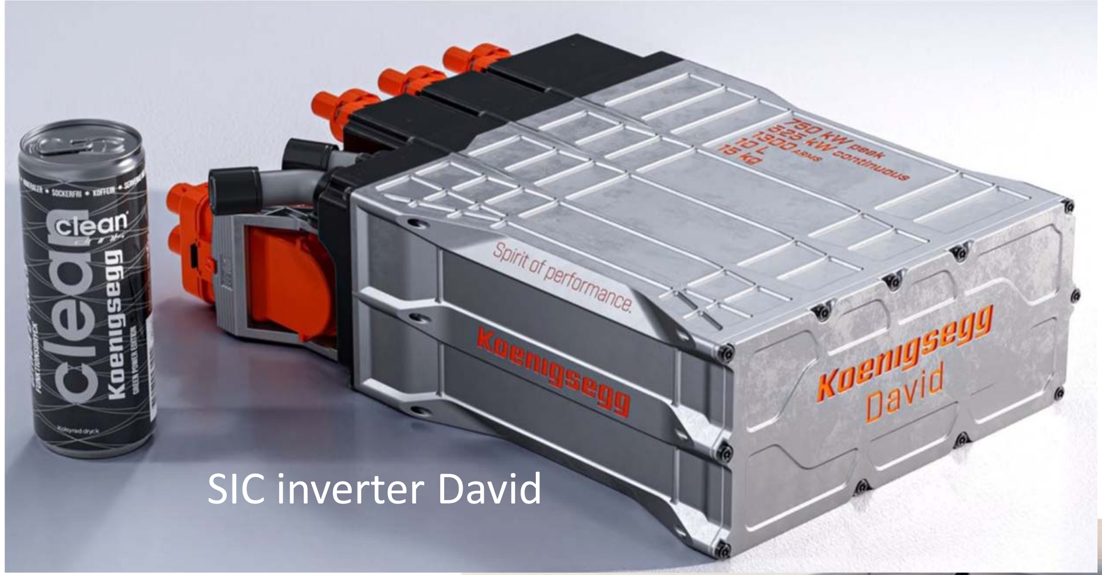
Tesla 3 Powertrain Shares Several Key Integration Features of Integrated Motor Drives (2018)





- First production battery EV to use SiC switches!
  - 221 kW (peak), ~42 kW(pk)/L, ~44 kW(pk)/kg
- Shares several key integration features of IMD

Super power density – Driving forces

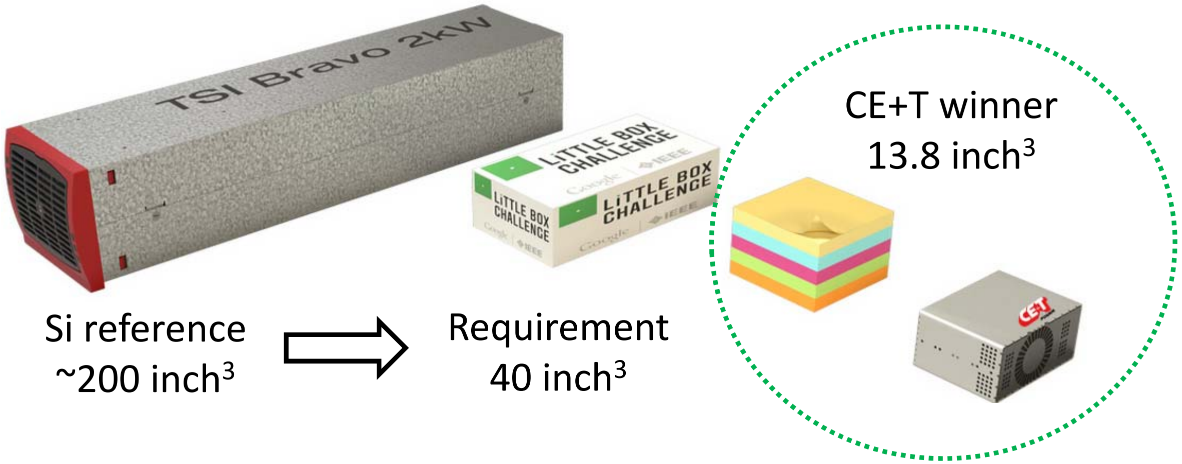


SIC inverter David

750 kW
10 liter
15 kg
6-phase
SiC MOSFETs

Google little box challenge

Task: minimize the volume of a 2kW inverter



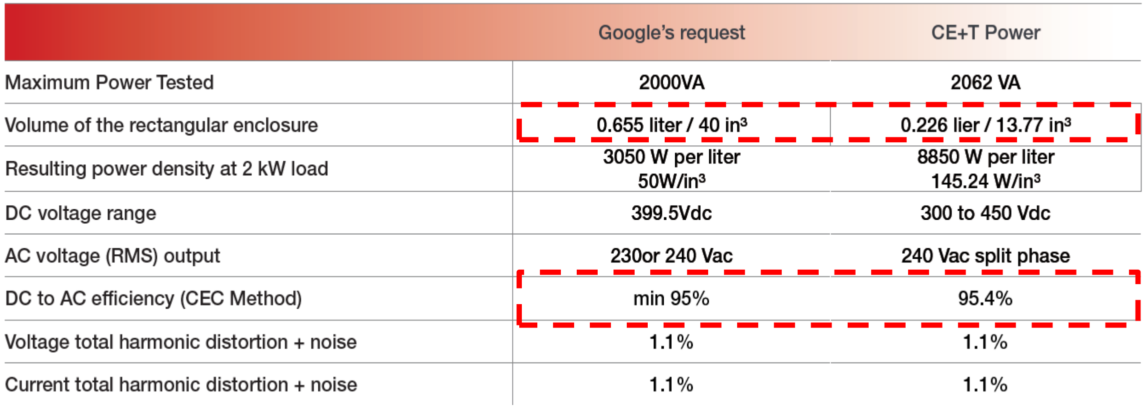
Si reference
~200 $inch^3$

Requirement
40 $inch^3$

CE+T winner
13.8 $inch^3$

Won by CE+T POWER

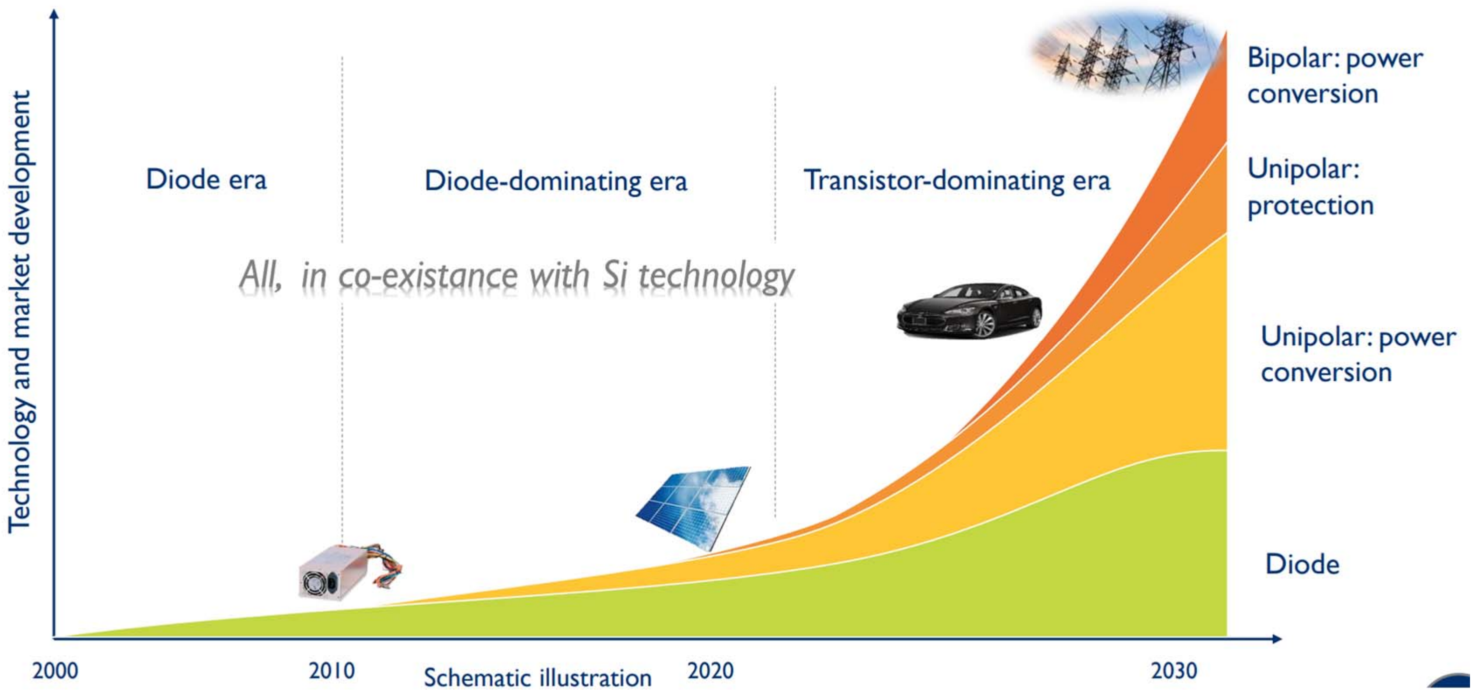
Powered by GaN!



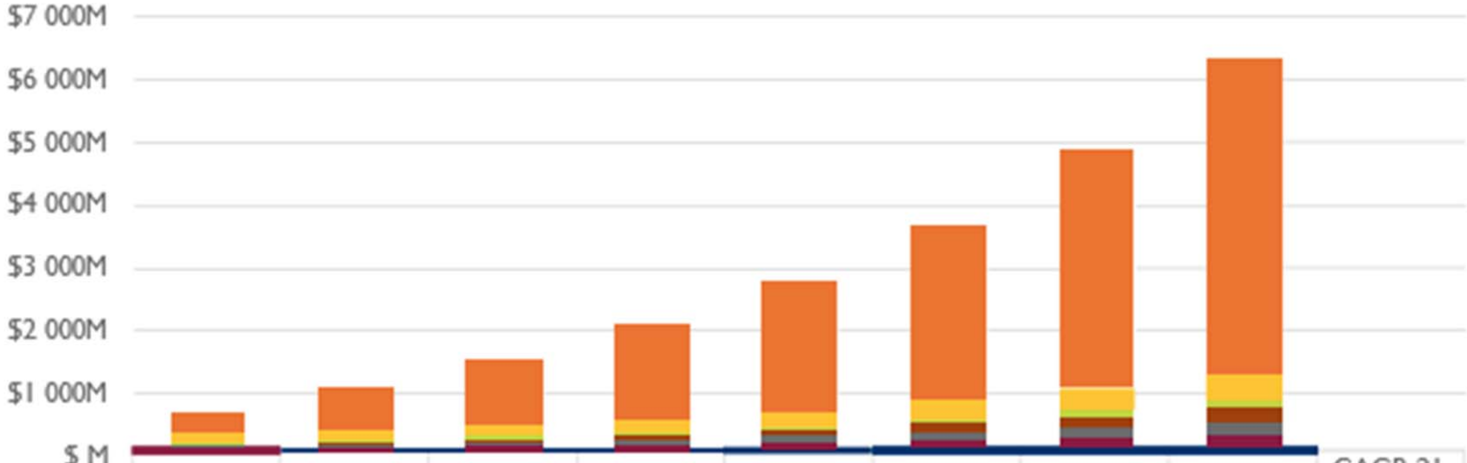
	Google's request	CE+T Power
Maximum Power Tested	2000VA	2062 VA
Volume of the rectangular enclosure	0.655 liter / 40 in^3	0.226 lier / 13.77 in^3
Resulting power density at 2 kW load	3050 W per liter 50W/in^3	8850 W per liter 145.24 W/in^3
DC voltage range	399.5Vdc	300 to 450 Vdc
AC voltage (RMS) output	230or 240 Vac	240 Vac split phase
DC to AC efficiency (CEC Method)	min 95%	95.4%
Voltage total harmonic distortion + noise	1.1%	1.1%
Current total harmonic distortion + noise	1.1%	1.1%

SiC market development

Understanding by Yole



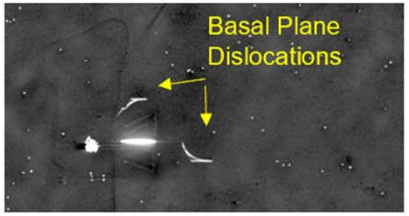
YOLE Développement

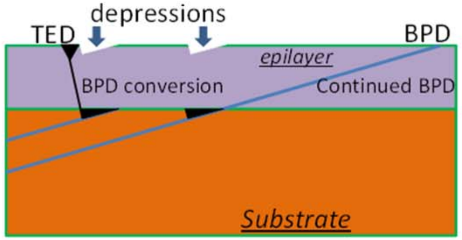

Power SiC device market ($M)
split by application

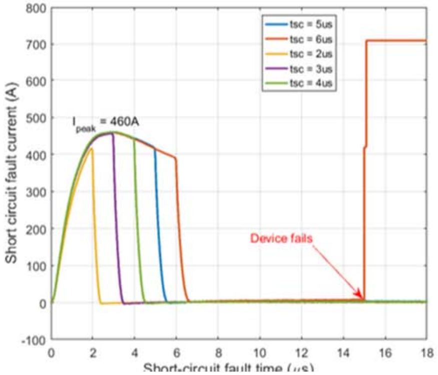
	2020	2021	2022	2023	2024	2025	2026	2027	CAGR 21-27
Total SiC device market	$696M	$1 090M	$1 534M	$2 091M	$2 769M	$3 658M	$4 896M	$6 297M	34%
■ xEV (Main inverter+OBC+DC-DC)	$334M	$685M	$1 055M	$1 522M	$2 067M	$2 775M	$3 810M	$4 986M	39%
■ PV+ESS	$143M	$154M	$179M	$209M	$238M	$304M	$363M	$423M	18%
■ xEV Charging Infrastructure	$39M	$37M	$45M	$55M	$68M	$85M	$107M	$135M	24%
■ Motor Drive (including air conditioning)	$17M	$26M	$37M	$54M	$93M	$138M	$182M	$224M	43%
■ PFC/Power Supply	$55M	$61M	$69M	$80M	$103M	$120M	$151M	$193M	21%
■ Rail (including auxiliary power)	$66M	$78M	$88M	$99M	$116M	$137M	$164M	$191M	16%
■ UPS	$30M	$36M	$46M	$54M	$64M	$74M	$83M	$92M	17%
■ Wind	$M	$M	$1M	$3M	$5M	$10M	$19M	$36M	163%
■ Others (Oil and Gas, Defense, R&D)	$13M	$13M	$14M	$14M	$15M	$16M	$16M	$17M	4%

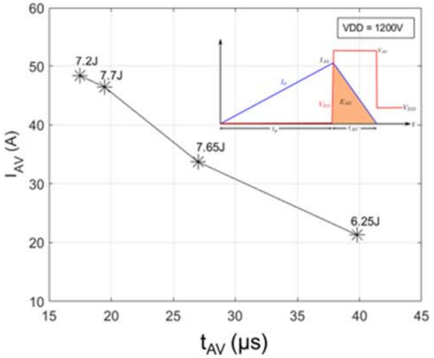
Initial problems with materials quality

- Material and Fabrication optimizations improve device yields and reliability
  - Minimize killer material defects (BPDs, micro-pipes, etc.)
  - Improve wafer planarity
  - Eliminate defect generation during processing (implantation)
  - Reduce Threshold-Voltage-Instability (high quality gate oxide)
- Design rugged SiC devices and fast gate drives for safe operating areas similar to Si
  - Short circuit withstand time similar to that of Si or use fast/intelligent gate drives
  - High Avalanche Energy tolerance









Understanding by Yole

SHORTAGE of SiC wafer or at other levels?

Why is the industry concerned about SiC wafer supply?

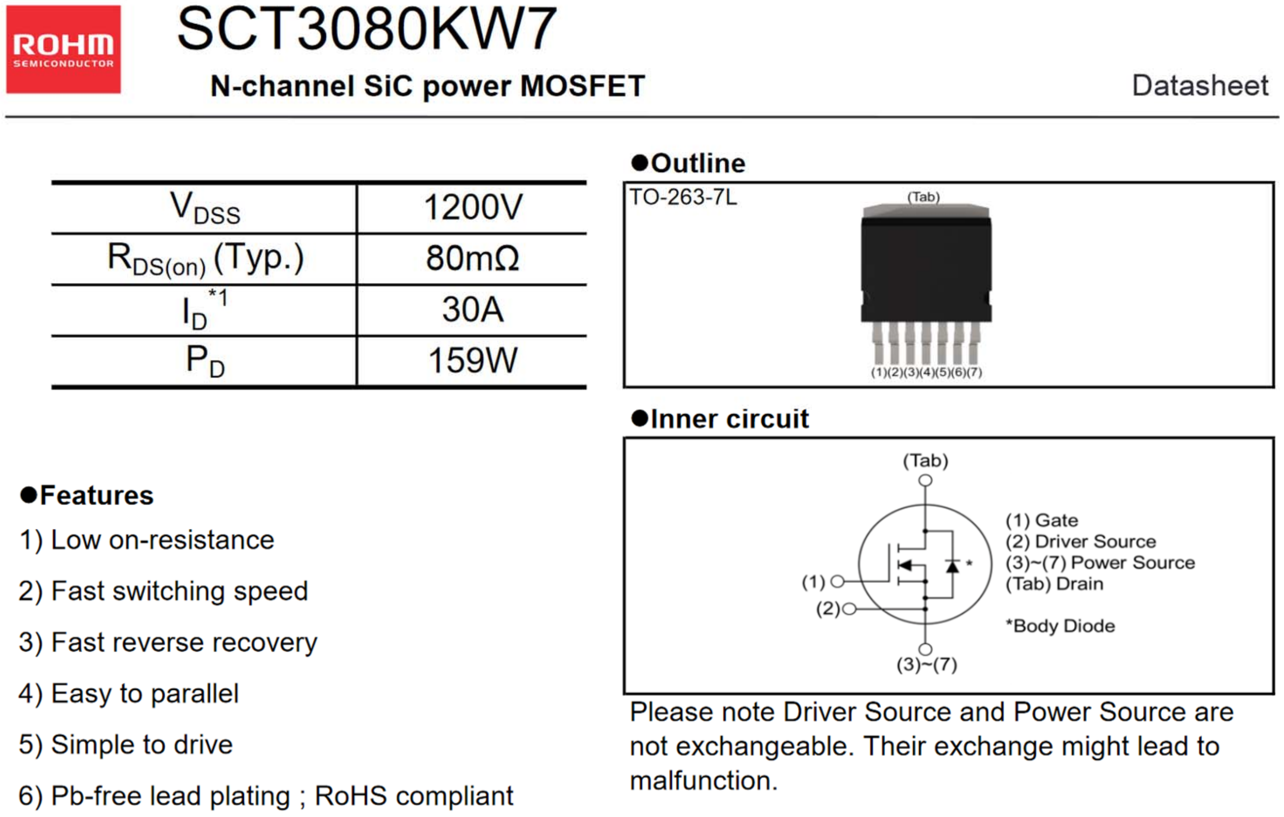
1. ***The wafer quality***: with more stringent demands on automotive and high-voltage applications, higher quality is required to improve yield and reliability. Therefore, the next discussion point is the volume of automotive-grade wafers, instead of just "good enough".

2. Since the pandemic outbreak, supply chain interruptions extended the ***lead-time*** for end-systems to receive devices. This further increased the market pull to secure the supply.

3. Following the global semiconductor shortage issues, ***OEMs and tier-1s are more cautious about supply chain issues***. Thus, they have become more intrusive in controlling the supply chain.

4. ***8" SiC wafer*** is considered as the key resource to minimize the costs. However, these wafers are not yet in mass production as of 2022 but only available for sampling. The capacity expansion plans of many wafer suppliers include 8". In our understanding, mass production is likely to happen starting from 2025. Then the crucial question is "how fast can the suppliers provide high-volume and high-quality 8" wafers?"

1200 V Commercial MOSFET



ROHM SEMICONDUCTOR

SCT3080KW7

N-channel SiC power MOSFET

Datasheet

V_{DSS}	1200V
$R_{DS(on)}$ (Typ.)	80mΩ
I_D *1	30A
P_D	159W

●Outline

TO-263-7L

●Inner circuit

(1) Gate
(2) Driver Source
(3)~(7) Power Source
(Tab) Drain

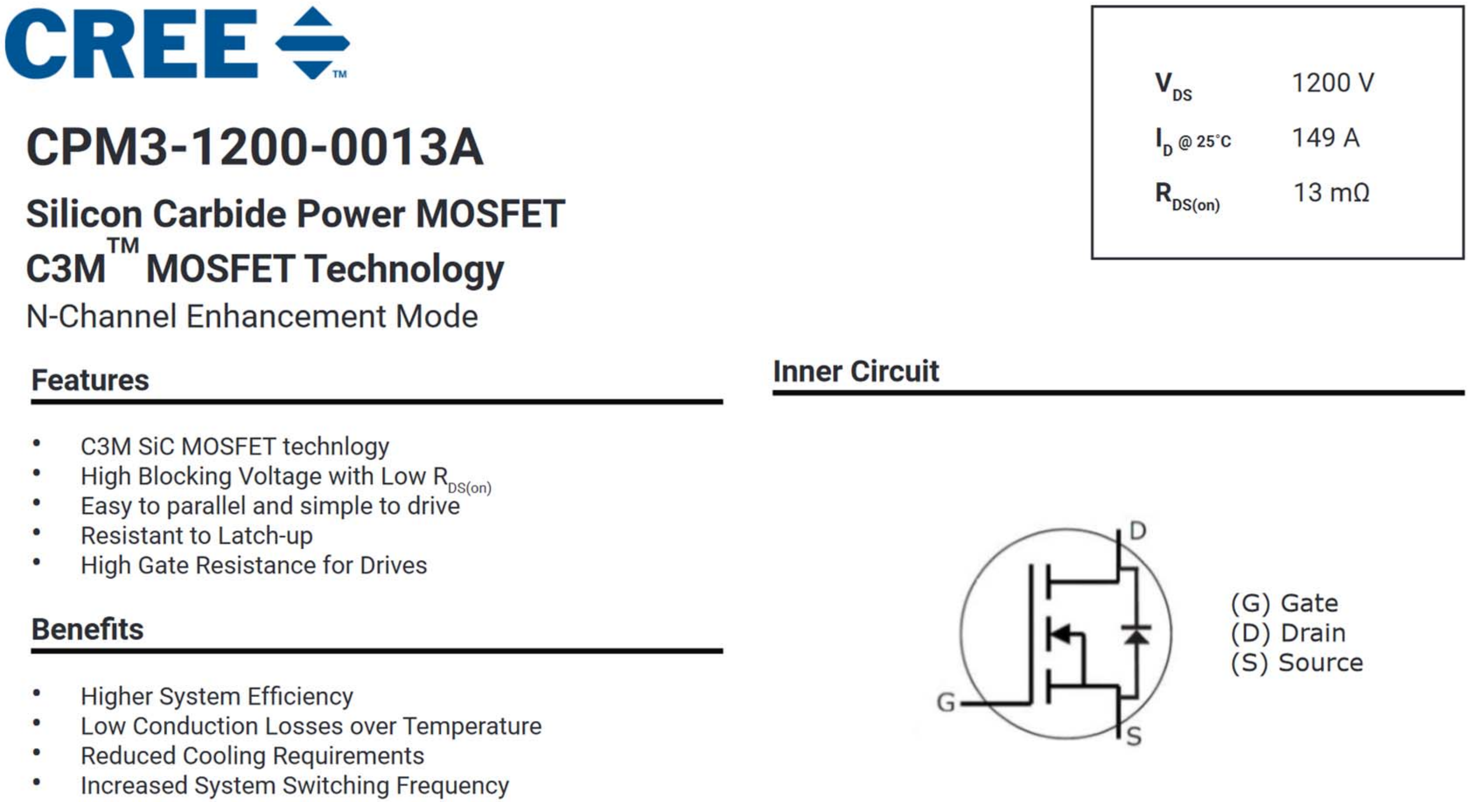
*Body Diode

Please note Driver Source and Power Source are not exchangeable. Their exchange might lead to malfunction.

●Features

1) Low on-resistance
2) Fast switching speed
3) Fast reverse recovery
4) Easy to parallel
5) Simple to drive
6) Pb-free lead plating ; RoHS compliant

SiC DMOS example



CREE

CPM3-1200-0013A

Silicon Carbide Power MOSFET
C3M^{TM} MOSFET Technology
N-Channel Enhancement Mode

V_{DS}	1200 V
$I_{D\ @\ 25^{\circ}C}$	149 A
$R_{DS(on)}$	13 mΩ

Features

- C3M SiC MOSFET technlogy
- High Blocking Voltage with Low $R_{DS(on)}$
- Easy to parallel and simple to drive
- Resistant to Latch-up
- High Gate Resistance for Drives

Benefits

- Higher System Efficiency
- Low Conduction Losses over Temperature
- Reduced Cooling Requirements
- Increased System Switching Frequency

Inner Circuit

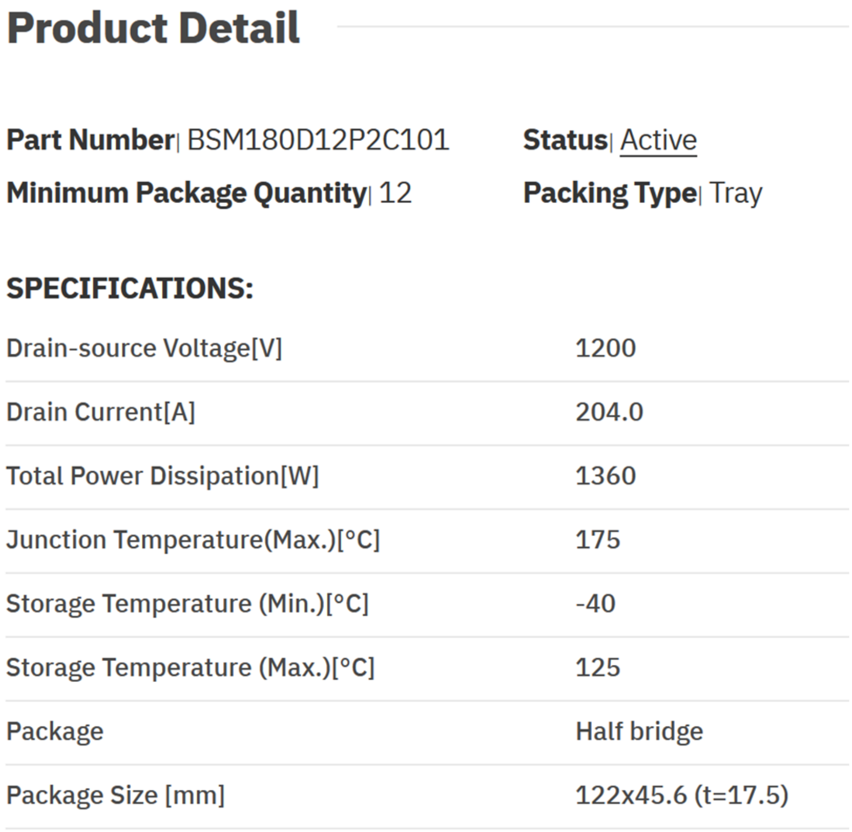
(G) Gate
(D) Drain
(S) Source

CREE Wolfspeed

BSM180D12P2C101
1200V, 204A, Half bridge, Silicon-carbide (SiC) Power Module

Half bridge module consisting of ROHM SiC-DMOSFETs.

ROHM
SEMICONDUCTOR



Product Detail

Part Number| BSM180D12P2C101 **Status**| Active

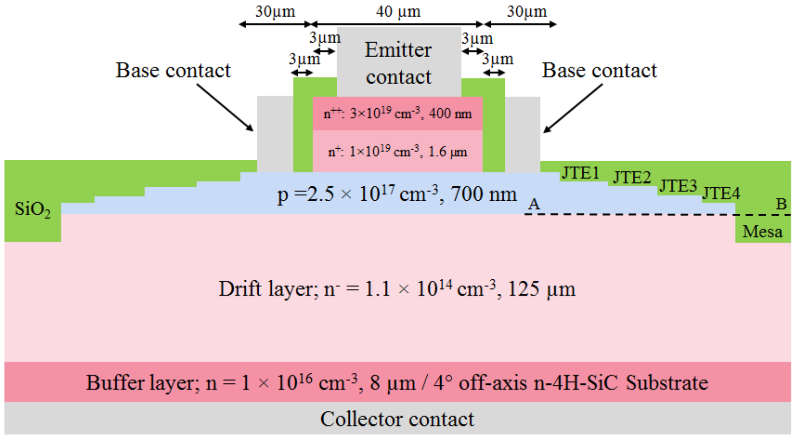
Minimum Package Quantity| 12 **Packing Type**| Tray

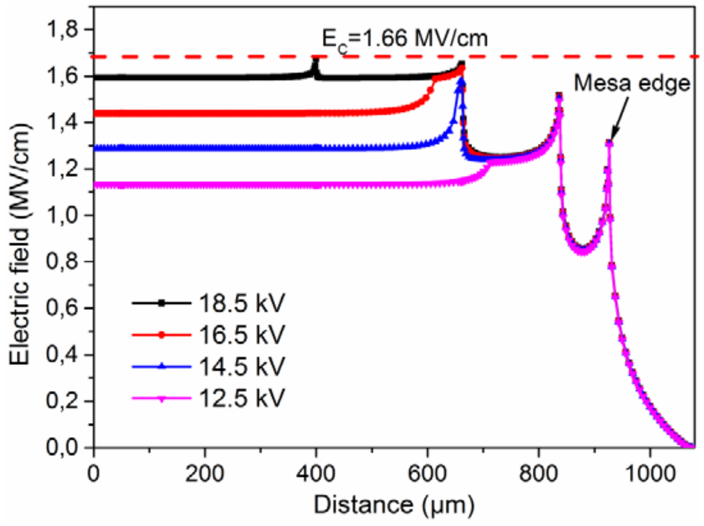
SPECIFICATIONS:

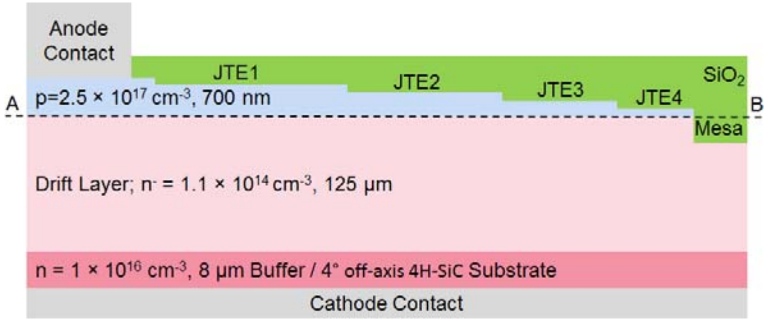
Drain-source Voltage[V]	1200
Drain Current[A]	204.0
Total Power Dissipation[W]	1360
Junction Temperature(Max.)[°C]	175
Storage Temperature (Min.)[°C]	-40
Storage Temperature (Max.)[°C]	125
Package	Half bridge
Package Size [mm]	122x45.6 (t=17.5)

KTH research on high voltage SiC

15 kV-Class BJTs and PiN Diodes



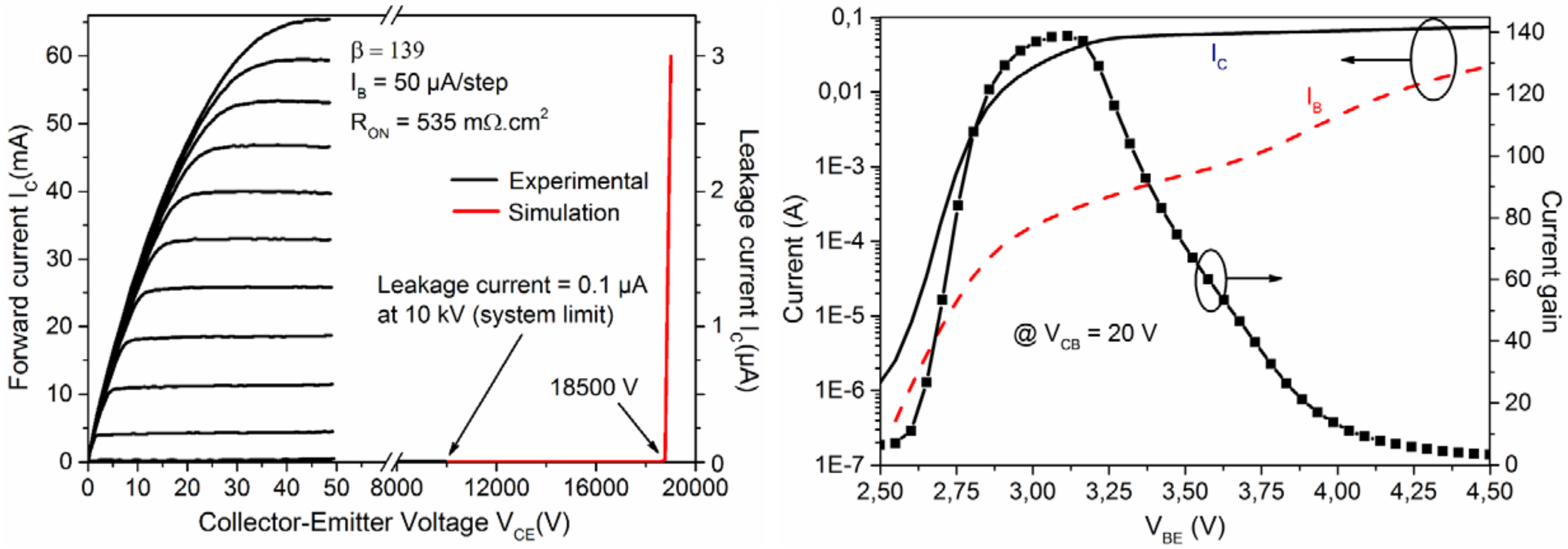




Zone	JTE1	JTE2	JTE3	JTE4	Mesa
Etching depth	260 nm	80 nm	80 nm	120 nm	1.5 µm
Lengh	350 µm	263 µm	175 µm	87 mm	80 µm
% of total length	33	25	17	8	7

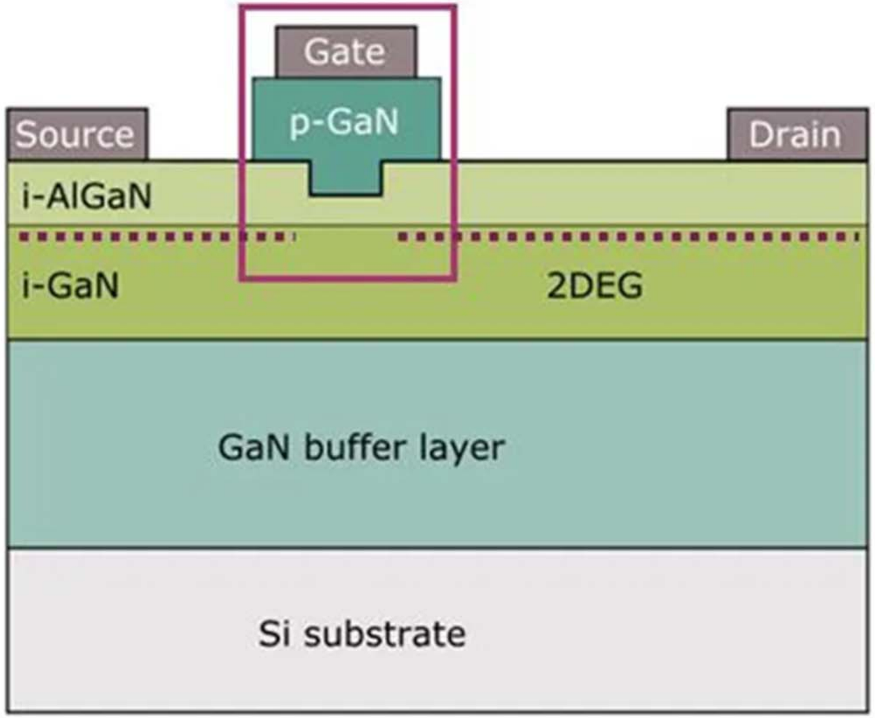
A. Salemi, H. Elahipanah, K. Jacobs, C. Zetterling and M. Östling, "15 kV-Class Implantation-Free 4H-SiC BJTs With Record High Current Gain," in *IEEE Electron Device Letters*, vol. 39, no. 1, pp. 63-66, Jan. 2018, doi: 10.1109/LED.2017.2774139.

I-V Characteristics of the BJTs

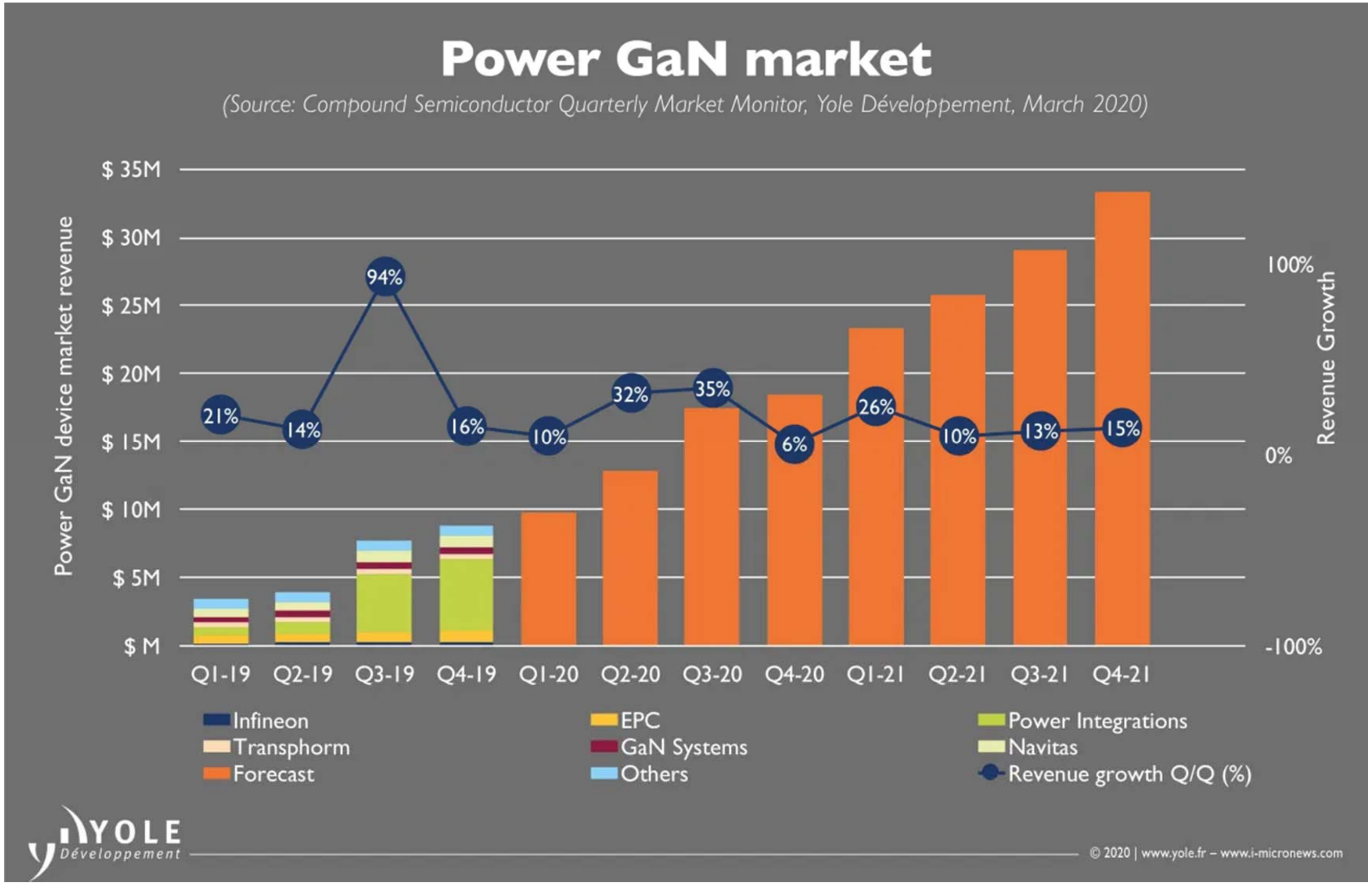


A current gain record of 139 for 15 kV-class BJTs

Typical lateral GaN HEMT transistor on Si or SiC



CoolGaN by Infineon

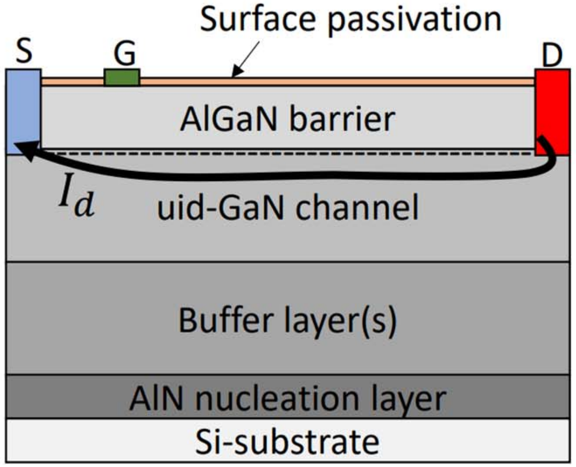


Power GaN market

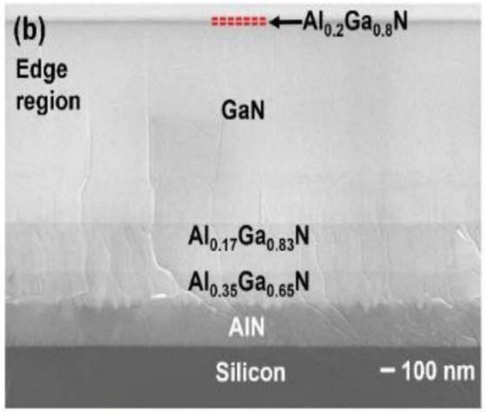
(Source: Compound Semiconductor Quarterly Market Monitor, Yole Développement, March 2020)

Vertical vs Lateral

Lateral GaN device

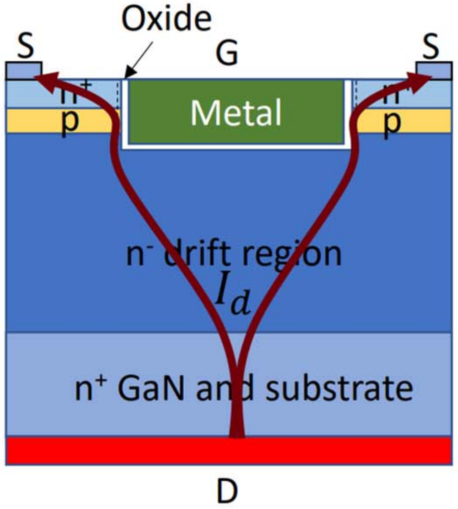


GaN-on-Si epi



http://dx.doi.org/10.3390/ma11101968

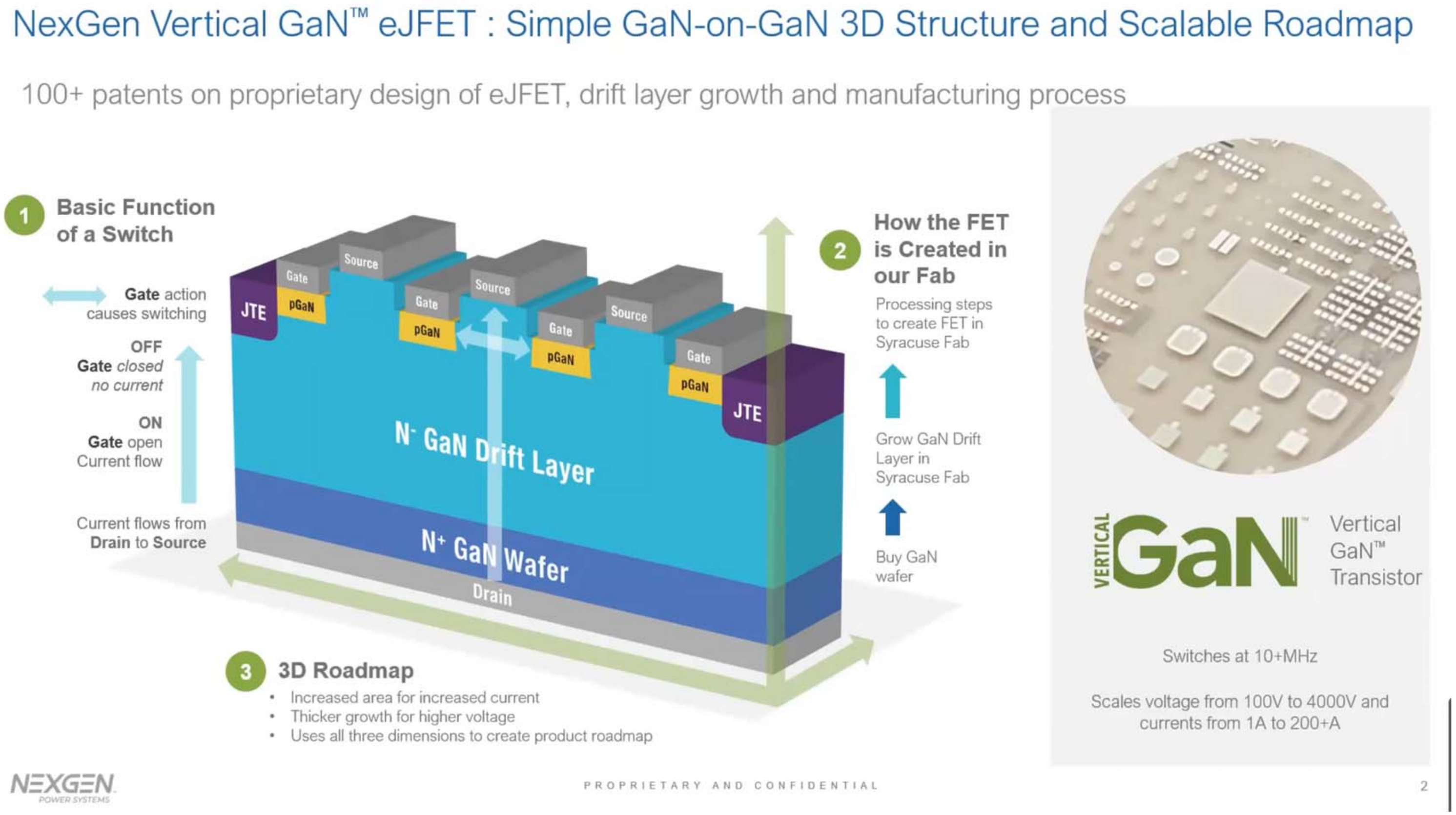
Vertical GaN device



Two main device architectures:

- **Lateral:** high speed, highest mobility, already on the market on silicon substrate
- **Vertical:** high breakdown voltage, high current capability, several concepts proposed

Vertical GaN



NexGen Vertical GaN™ eJFET : Simple GaN-on-GaN 3D Structure and Scalable Roadmap

100+ patents on proprietary design of eJFET, drift layer growth and manufacturing process

① **Basic Function of a Switch**

Gate action causes switching

OFF
Gate *closed*
no current

ON
Gate open
Current flow

Current flows from **Drain** to **Source**

② **How the FET is Created in our Fab**

Processing steps to create FET in Syracuse Fab

Grow GaN Drift Layer in Syracuse Fab

Buy GaN wafer

③ **3D Roadmap**

- Increased area for increased current
- Thicker growth for higher voltage
- Uses all three dimensions to create product roadmap

Vertical GaN™ Transistor

Switches at 10+MHz

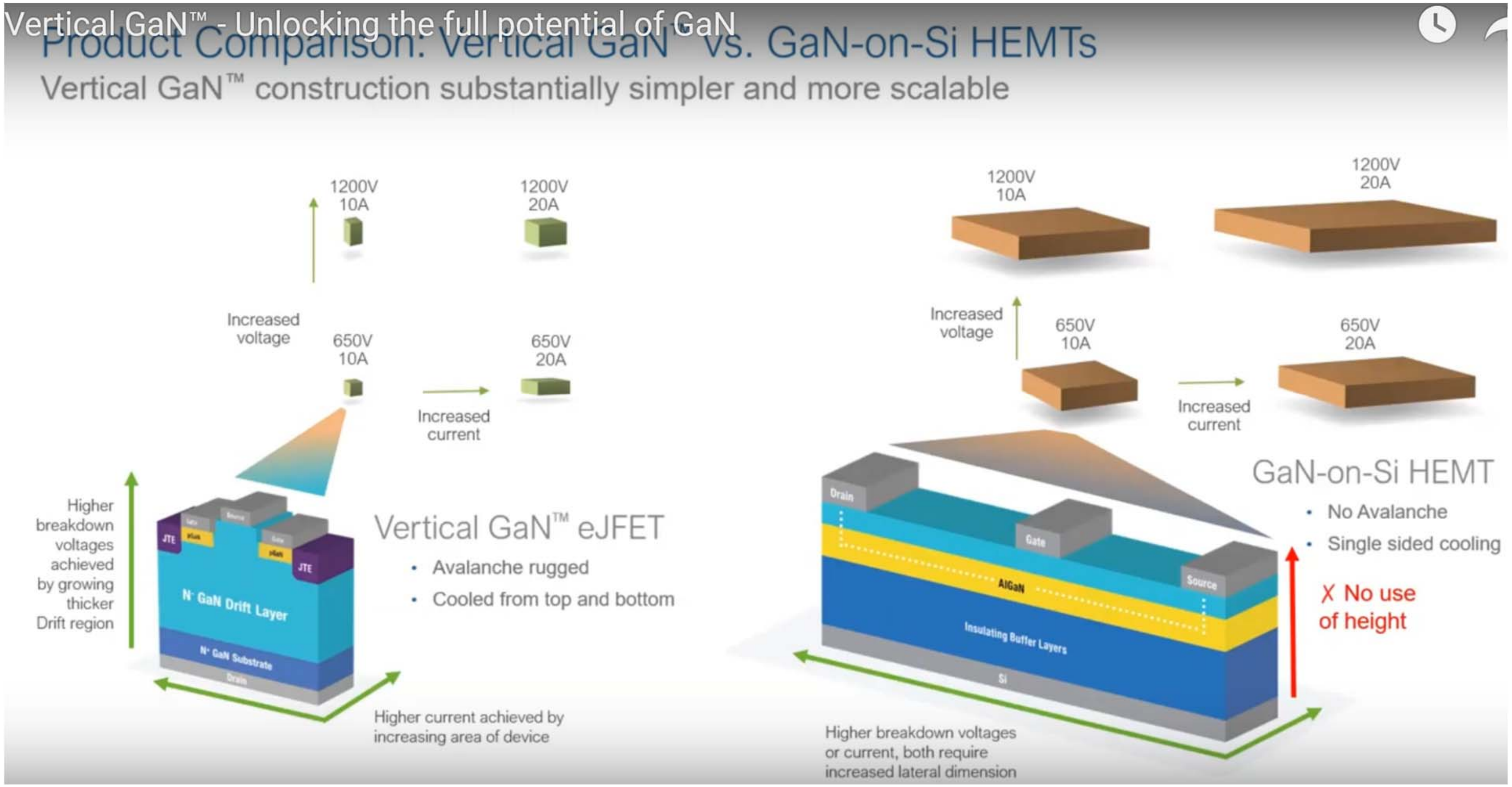
Scales voltage from 100V to 4000V and currents from 1A to 200+A

NEXGEN POWER SYSTEMS

PROPRIETARY AND CONFIDENTIAL

2

Vertical vs Lateral



Vertical GaN™ - Unlocking the full potential of GaN

Product Comparison: Vertical GaN™ vs. GaN-on-Si HEMTs

Vertical GaN™ construction substantially simpler and more scalable

Vertical GaN™ eJFET

- Avalanche rugged
- Cooled from top and bottom

Higher breakdown voltages achieved by growing thicker Drift region

Higher current achieved by increasing area of device

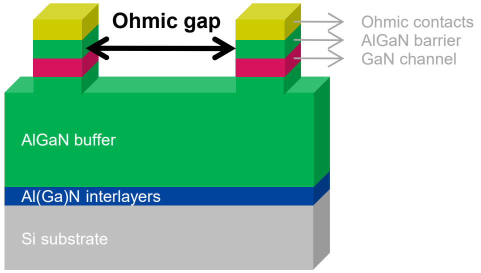
GaN-on-Si HEMT

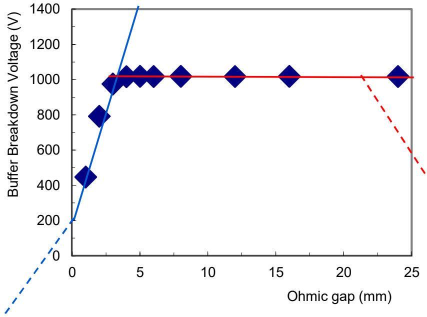
- No Avalanche
- Single sided cooling

✗ No use of height

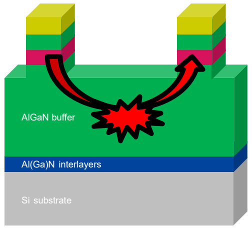
Higher breakdown voltages or current, both require increased lateral dimension

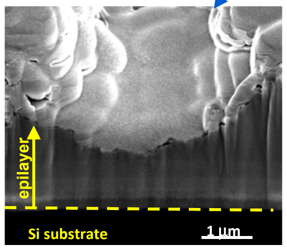
GaN on Si – substrate removal



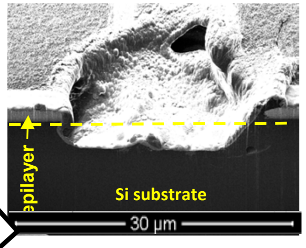


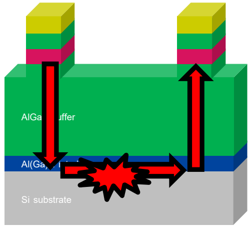
- Two breakdown regimes
- Occur at different location in stack
- Saturation level scales with thickness of the epitaxial layer stack





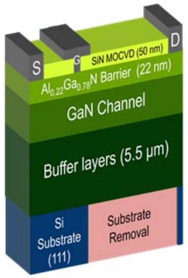
breakdown in *AlGaN buffer*

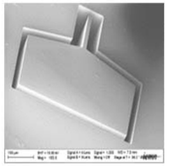




breakdown in *Si substrate*

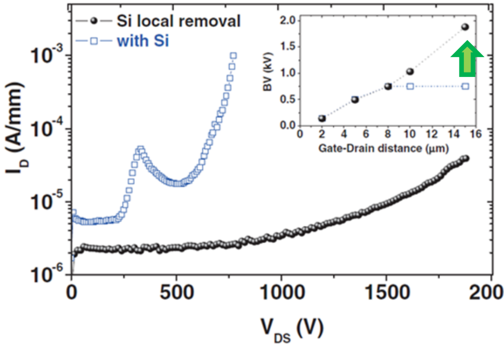
Mitigation





Concept: Eliminating parasitic conduction at the AlN/Si substrate interface thru local substrate removal

Breakdown 750V -> 2kV



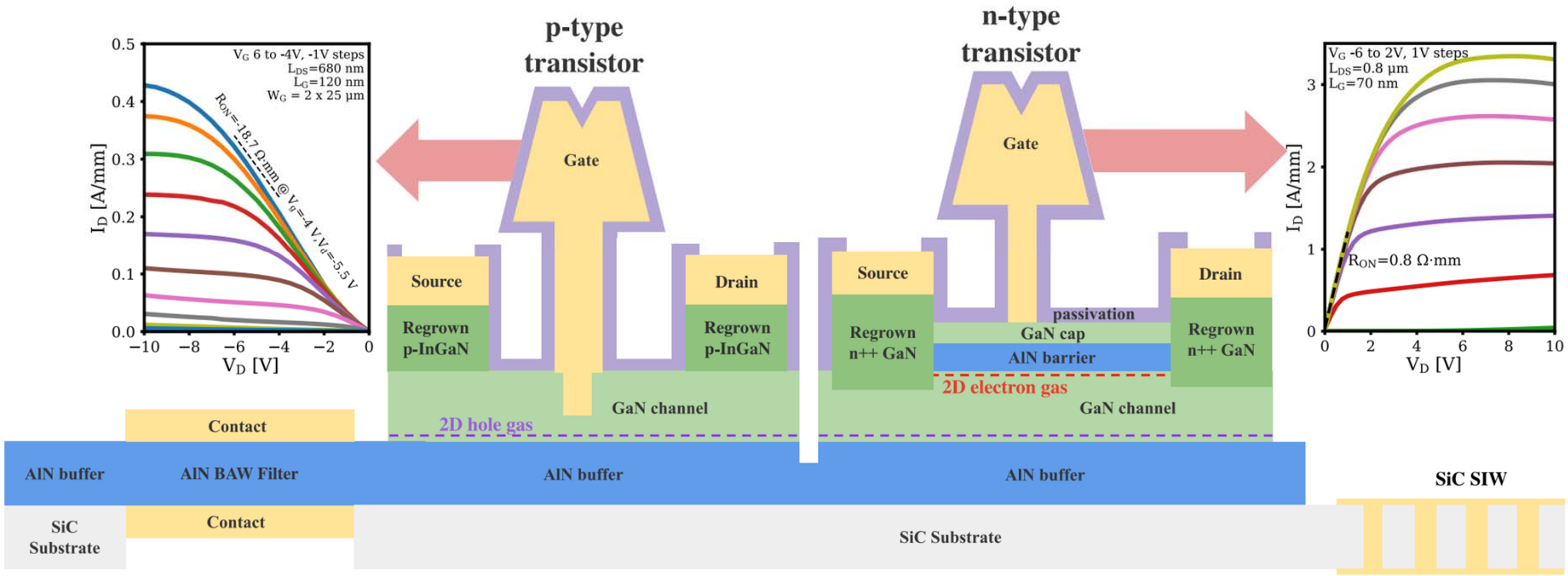
Courtesy of F. Medjdoub, IEMN

Emerging WBG materials

- AlN
- Diamond
- Gallium Oxide

Ultrawide-bandgap aluminum nitride platform

Semicond. Sci. Technol. **36** (2021) 044001 A L Hickman *et al*



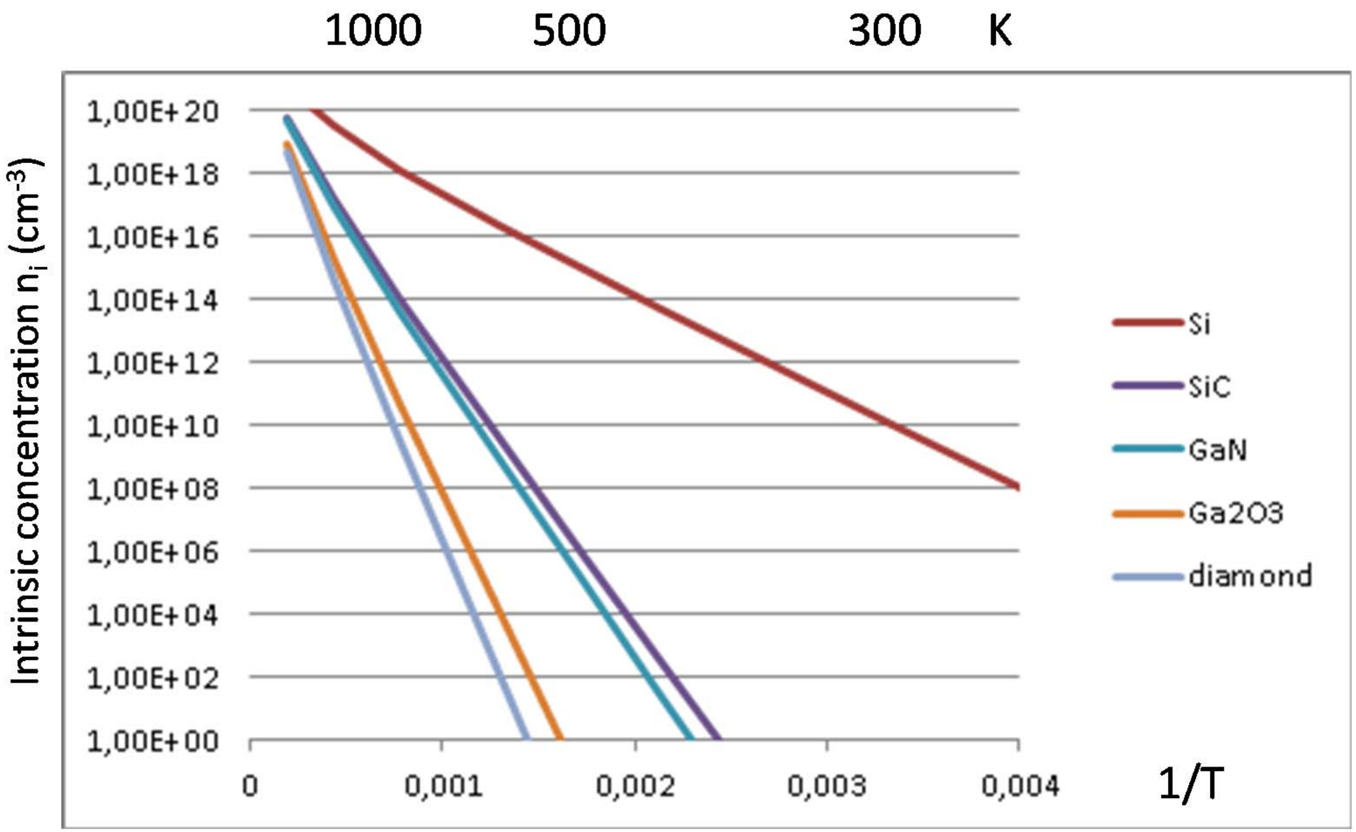
Other advantages of SiC:
High Temperature and Radiation Hard

Applications for harsh environments

Application	Type	Temperature	Radiation
Oil and gas drilling	P, S	600 °C	No
Industrial motor drives	P	300 °C	No
Automotive	P, S	300-600 °C	No
Aviation	P, S	300-600 °C	(Yes)
Space exploration	S	600 °C	Yes
Nuclear energy	(P) S	300-600 °C	Yes

P = Power switching applications
S = Sensor signal processing

Intrinsic Concentration vs Temperature



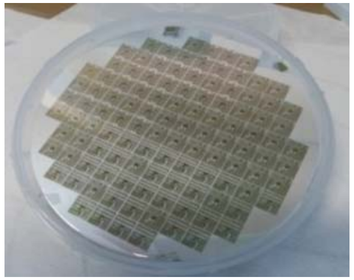
$n_i = (N_C N_V)^{0.5} \exp(-E_g / 2\,k\,T)$

Cleanroom for IC and Device Fabrication

- **Electrum Laboratory 1300 m^2**
- ISO 9001 certified / controlled processes and calibrated characterization tools
- 100 – 200 mm wafers

- **Silicon Technology**
- Silicon - IC
- Silicon - Microsystems

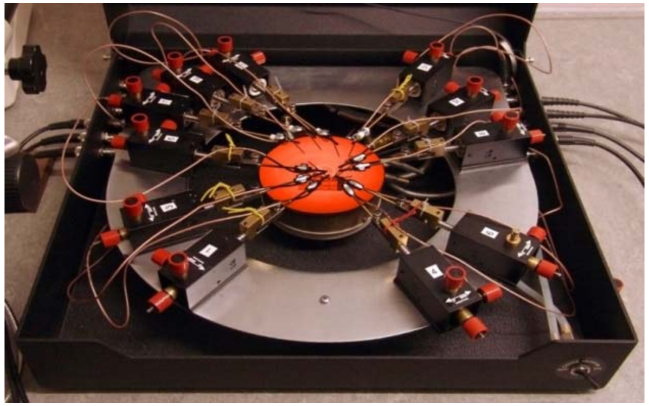
- **Compound Semiconductors**
- SiC – Electronics, 100 mm
- InP - Opto / electronics
- GaAs - Opto / electronics

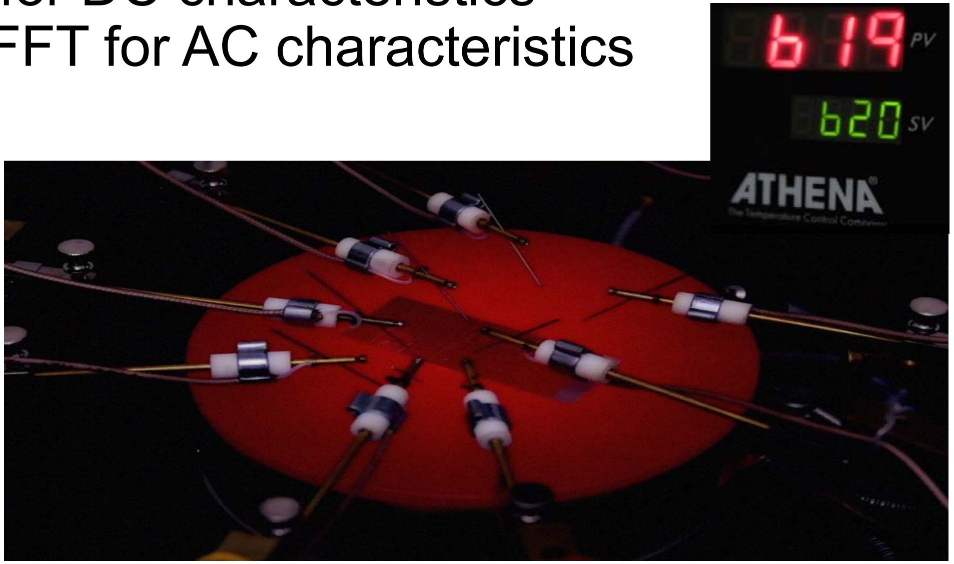


Testing facilities for electrical characterization

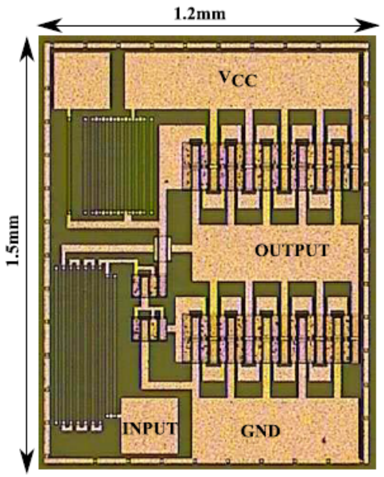
On wafer probing up to 620 °C

Parameter analyzer for DC characteristics
Digital oscilloscope/FFT for AC characteristics

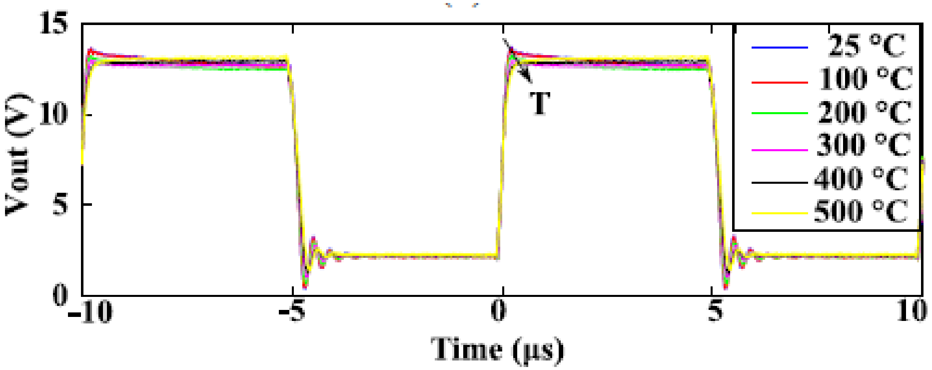


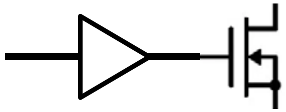


SiC Drive Circuits for High Voltage Switches



A monolithic SiC drive circuit for SiC power BJTs
S. Kargarrazi et al. ISPSD (2015) 285 - 288
DOI: 10.1109/ISPSD.2015.7123445





4 bit

11.4 mm X 13.2 mm = 151 mm^2

BJTs = 5911

Integrated Resistors = 3918

Vcc = 15 V, 1 A

2 metal layers

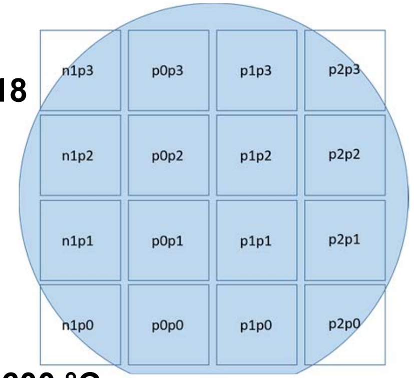
LVS and DRC

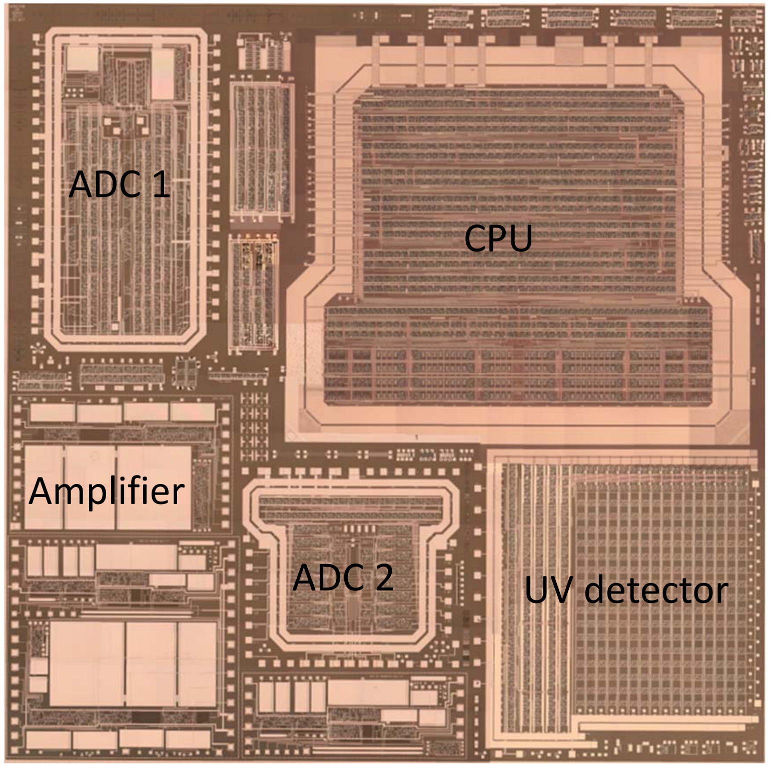
Simulated in Spice

Parts characterized up to 600 °C

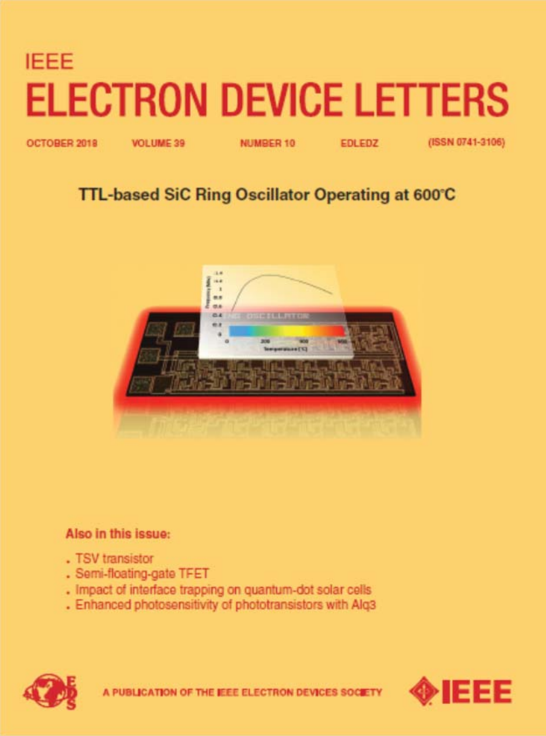
Test chip also contains ADCs,

Amplifiers and UV pixel detector





A 600 °C TTL-based 11-stage Ring Oscillator in Bipolar Silicon Carbide



IEEE
ELECTRON DEVICE LETTERS

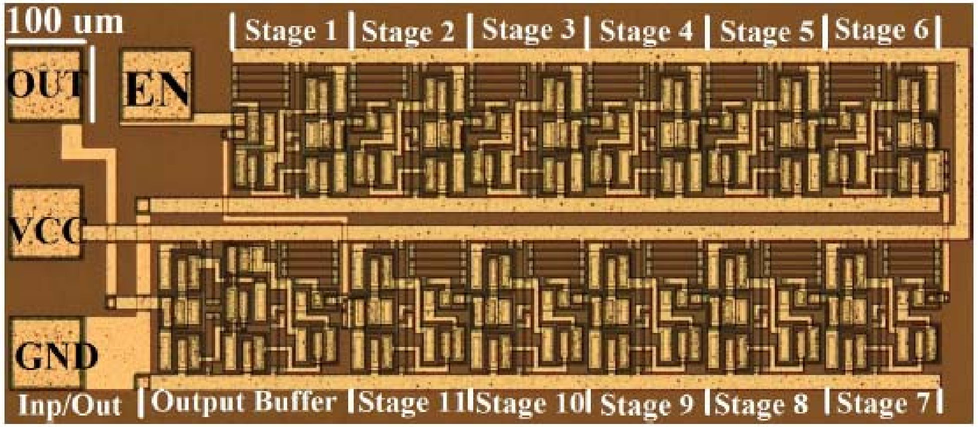
OCTOBER 2018 VOLUME 39 NUMBER 10 EDLEDZ (ISSN 0741-3106)

TTL-based SiC Ring Oscillator Operating at 600°C

Also in this issue:

- TSV transistor
- Semi-floating-gate TFET
- Impact of interface trapping on quantum-dot solar cells
- Enhanced photosensitivity of phototransistors with Alq3

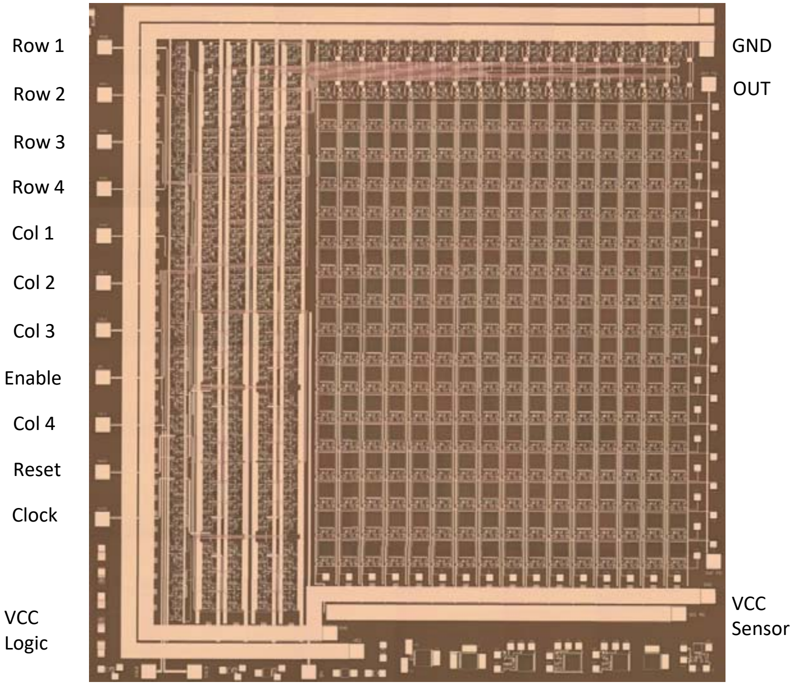
A PUBLICATION OF THE IEEE ELECTRON DEVICES SOCIETY



120 devices

M. Shakir et al, IEEE Electron Device Letters, vol 39, p 1540, 2018

Fabricated Image Sensor Operational at 400 C



- Schematic and Layout of the digital circuits are from collaborator contributed TTL PDK
- Two 4-to-16 decoders
- One 8-bit counter
- 16x16 pixels
- 1959 transistors
- 68.2 mm^2
- Dynamic mode - 7 I/Os
- Static mode – 13 I/Os

S. Hou, M. Shakir, P. Hellström, B. G. Malm, C. Zetterling and M. Östling, "A Silicon Carbide 256 Pixel UV Image Sensor Array Operating at 400 °C," in *IEEE Journal of the Electron Devices Society*, vol. 8, pp. 116-121, 2020, doi: 10.1109/JEDS.2020.2966680.

Conclusions for SiC

- SBD, JFET, MOSFETs and BJTs are commercially available from several major vendors
- Qualified long term stability and the bipolar degradation effect is minimized
- Very promising power modules are commercially available
- Cost is still the main issue. Volume production can yield switch devices at realistic prices of <5-10 cents/Amp for 1200 V rating
- There are other advantages of SiC yet to be fully investigated: the possibility of high temperature operating and radiation hard devices.
- When integrated circuits in SiC are also available, the system advantages can be considerable

Conclusions for GaN

- Many devices have been demonstrated – Several major vendors offer commerical power transistors up to 900 V
- Two alternative strategies – GaN on Si or GaN on SiC
  and also lateral or vertical design
- COST is always the defining parameter
- For Automotive (the upcoming major market) needs cost efficiency

THANK YOU

ICOS
International Cooperation On Semiconductors

Funded by the European Union

SiNANO Institute

IRDS
INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS

This project has received funding from the European Union's Horizon Europe research and innovation programme under GA Nº 101092562

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