Si Trench IGBTs and SiC MOSFETs: Automotive applications

Dr. Marina Antoniou, University of Warwick

5th July 2022

Background

- BA and MEng in Electrical and Information Engineering, University of Cambridge.
- PhD in Electrical Engineering, University of Cambridge.
- EPSRC and Commonwealth Trust Scholar

- Associate Professor, University of Warwick
- Royal Society Dorothy Hodgkin Fellow (2017-2024)
- Chair of the IEEE Electron Device Society, Power Devices & ICs Committee
- Consulting experience and collaborations with major industrial organisations in power technologies: ABB, XFAB, AMS.

Outline

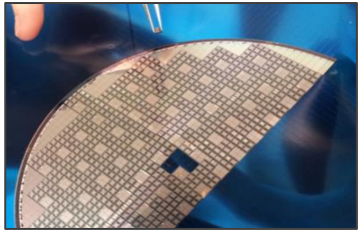
- Background
  - Requirements of Automotive Applications
  - Requirements of Power Device chips for Automotive applications
- Si Trench IGBT Technology
  - Narrow Mesa IGBTs
  - SJ IGBTs
  - RC IGBTs
- SiC MOSFETs
  - Main cell designs
  - Performance of SiC MOSFETs
  - Reliability
- Trends and Challenges

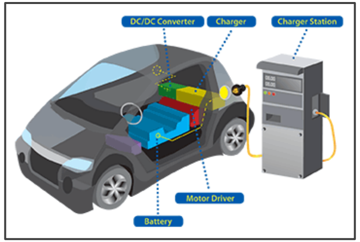
Background

Requirements to curb the global carbon emissions include:

- Improved electrical efficiency
- More green electricity in the energy mix

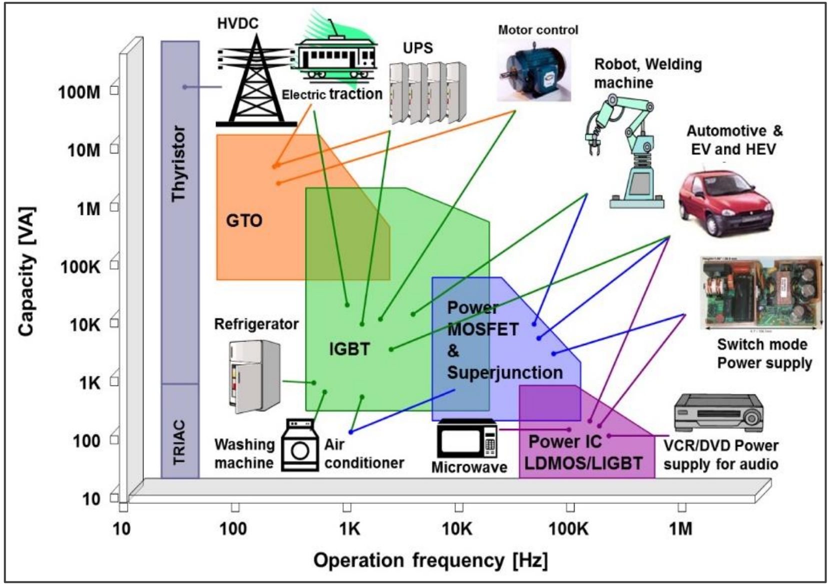
The objectives can only be achieved with the utilization of energy efficient power semiconductor devices - building blocks of any power electronics technology.



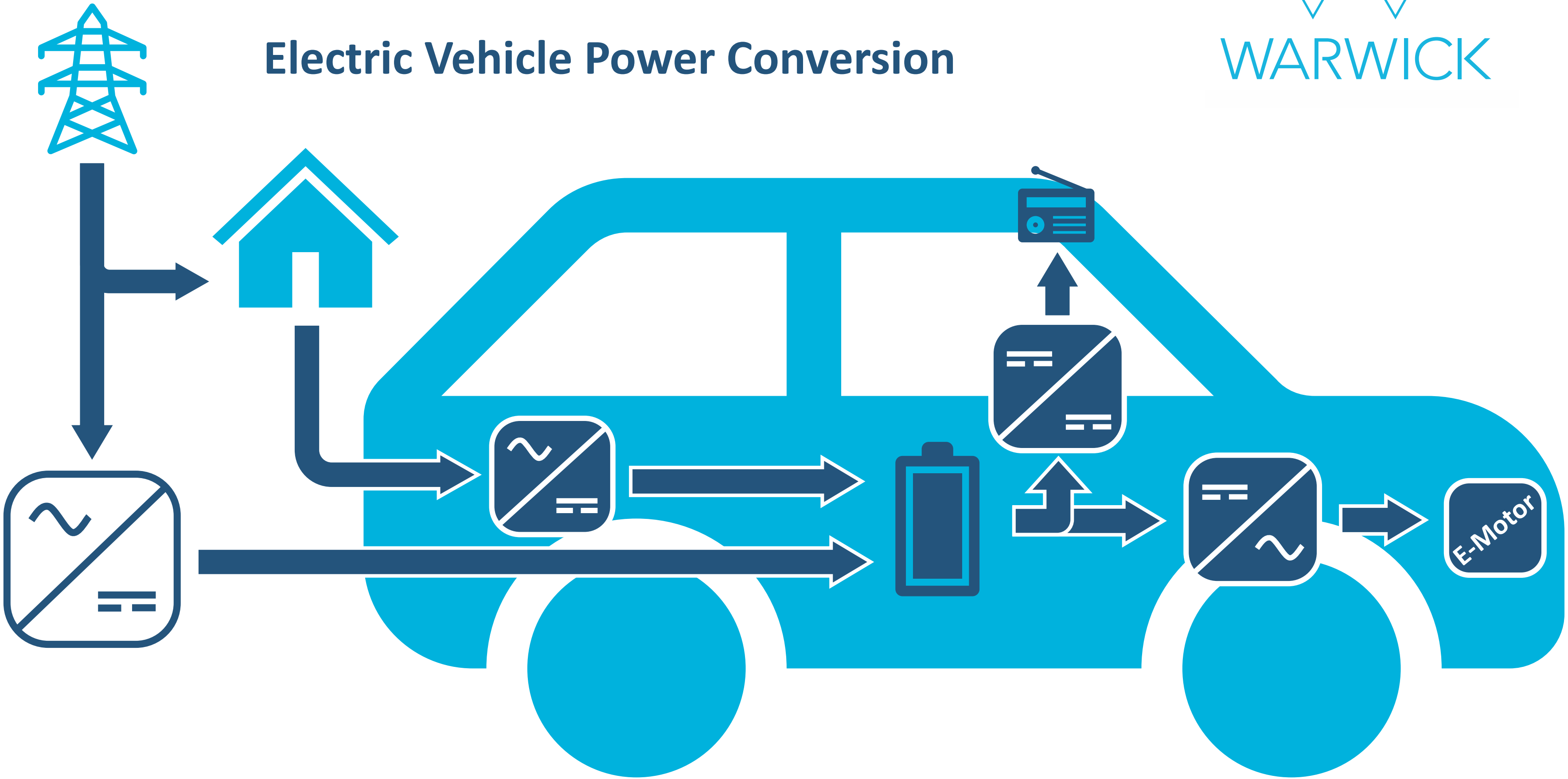


Background: Power Semiconductor Devices

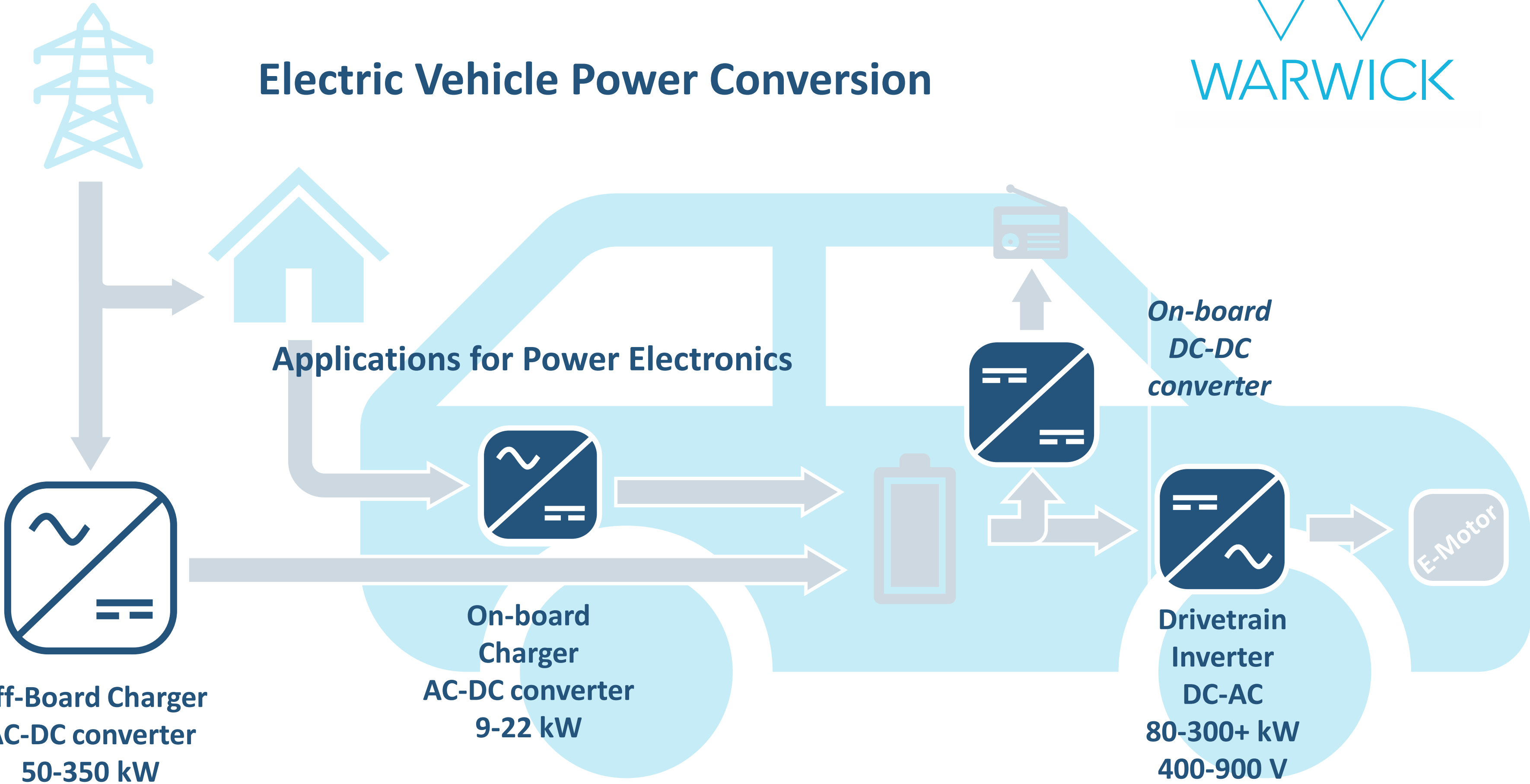
- They are key drivers and enablers in power electronics
- Used as a switches or rectifiers
- Achieve the supply of voltages and currents in a form that is optimally suited for each application with the smallest amount of energy loss.
- The global power semiconductor market is 40bn USD - every electronic device contains a power device.



Electric Vehicle Power Conversion



Electric Vehicle Power Conversion



Applications for Power Electronics

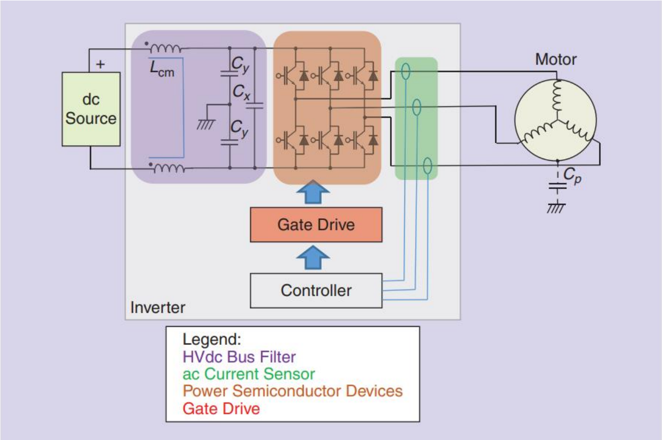
Off-Board Charger
AC-DC converter
50-350 kW

On-board
Charger
AC-DC converter
9-22 kW

On-board
DC-DC
converter

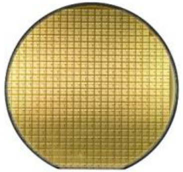
Drivetrain
Inverter
DC-AC
80-300+ kW
400-900 V

Automotive Applications Requirements

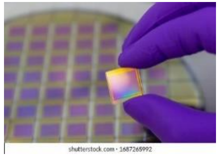


IEEE Electrification Magazine / March 2017

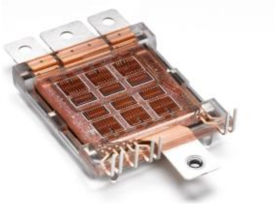
Monocrystaline ingot



Wafer



Chip die



Power module

Inverter

Automotive Applications Requirements

From the device perspective:

- High Power/ Efficiency
- Reliability (high vibrations, high humidity and ambient temperature variations)
- Cost
- Controllability and High Integration/Intelligence (integrated temperature and current sensors and shunt resistors, Drive-IC)

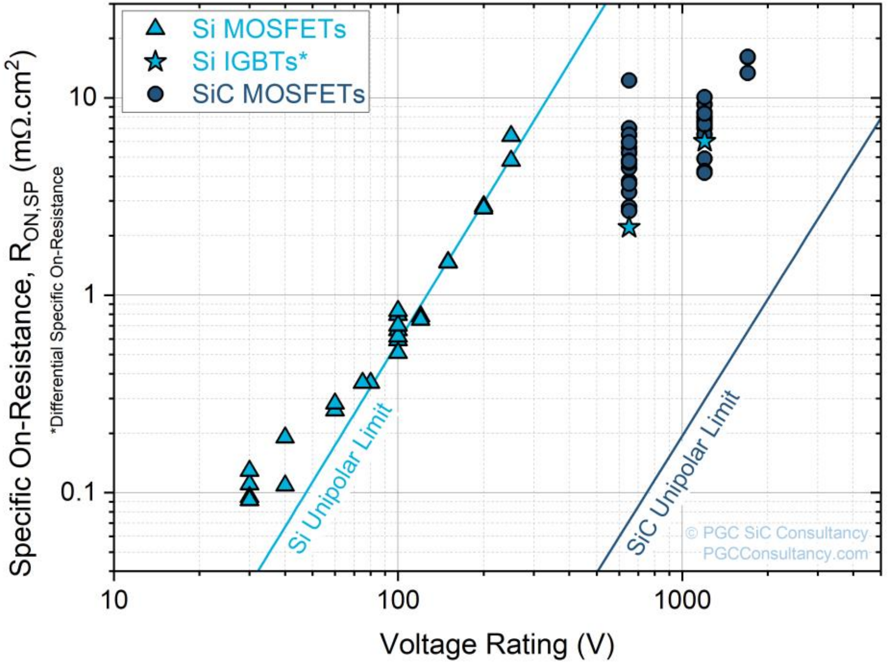
Enabling 800 V Architectures

- Automotive industry drive to move from 400V towards a battery DC link 800V.
  - ➢ With the same power, the lower the current through the **cables, the lower the power loss**
    - ➢ reduce the diameter of the power cables,
    - ➢ save installation space, reduce the cost of cables,
    - ➢ reduce the overall mass.
  - ➢ **Smaller, lighter motors** due to the reduction of copper windings, and thus the efficiency of the motor drive is improved.
  - ➢ When charging, the charging system needs to provide a voltage that matches the battery. When the battery voltage goes up, the **charging power will be increased and thus shortening the charging time**.

Therefore, to satisfy the high battery DC link voltage requirement, **1200V devices** need to be employed.

Automotive Applications Requirements

The main power devices in the inverter are currently Si IGBTs or SiC MOSFETs.

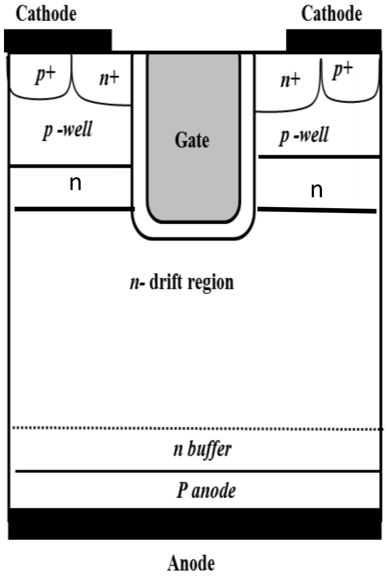


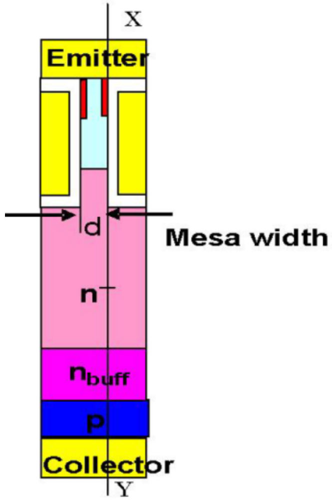
Si IGBT Developments

- Si IGBTs:
  - High Power Density
  - Highly reliable technology
  - Cost effective

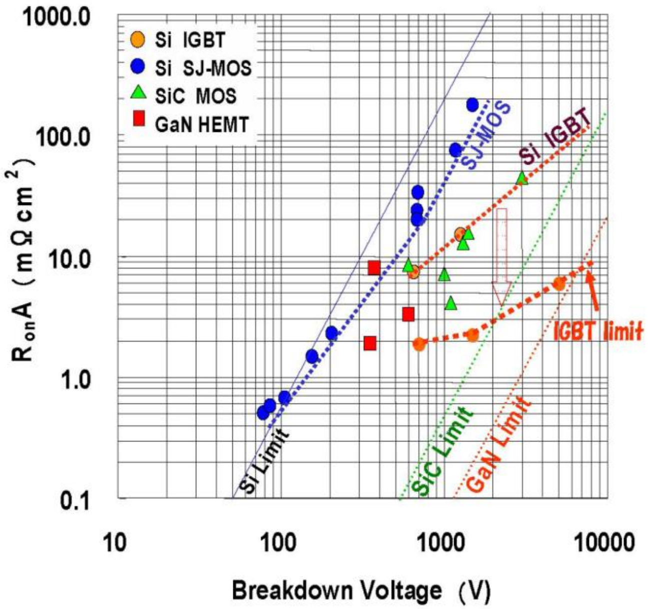
- Potential Improvements
  - Better material/wafer utilisation (wafer thinning and larger wafer sizes up to 12inch)
  - Controllability through structure optimisation
  - Reverse Conducting IGBT

The conventional Si Trench IGBT





Narrow mesa structures (<100nm)



- Very narrow mesa structure results to very high injection efficiency and lower switching losses
- Short circuit capability has to be considered.

A. Nakagawa, Toshiba, ISPSD 2006

The conventional IGBT – narrow mesa technology

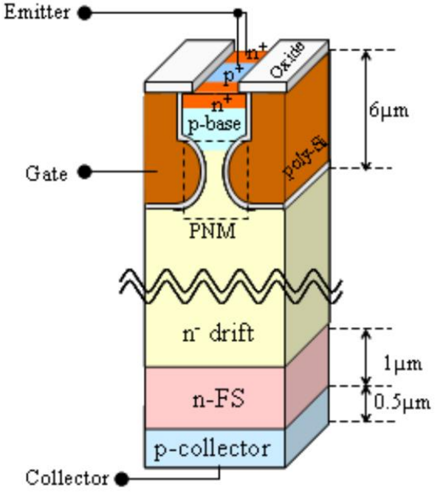
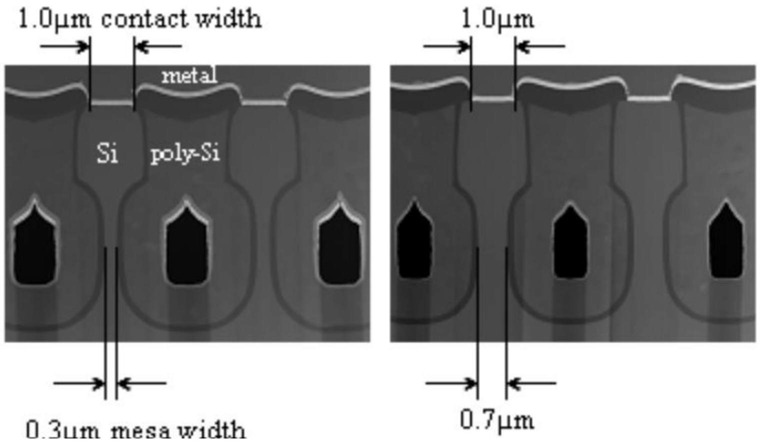
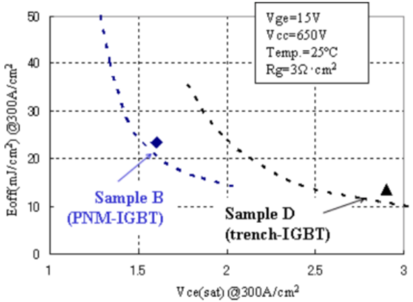


Fig.2 Schematic 3D view of a PNM-IGBT

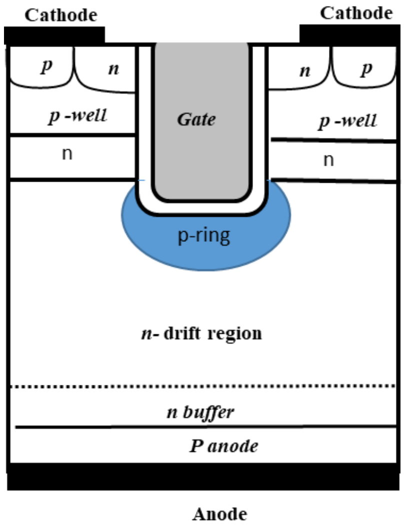


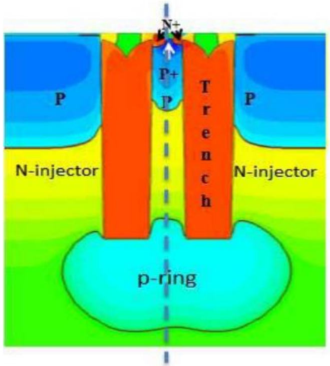


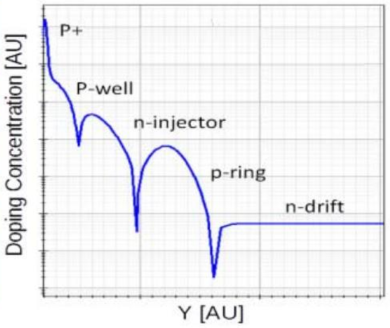
- Very narrow 30nm mesa opening offering point injection enhancement
- Contact area remains sufficient for fabrication purposes.

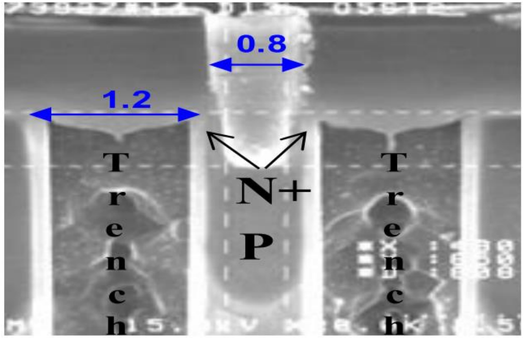
M.Sumitomo et al. Denso, ISPSD 2012

The p-ring IGBT





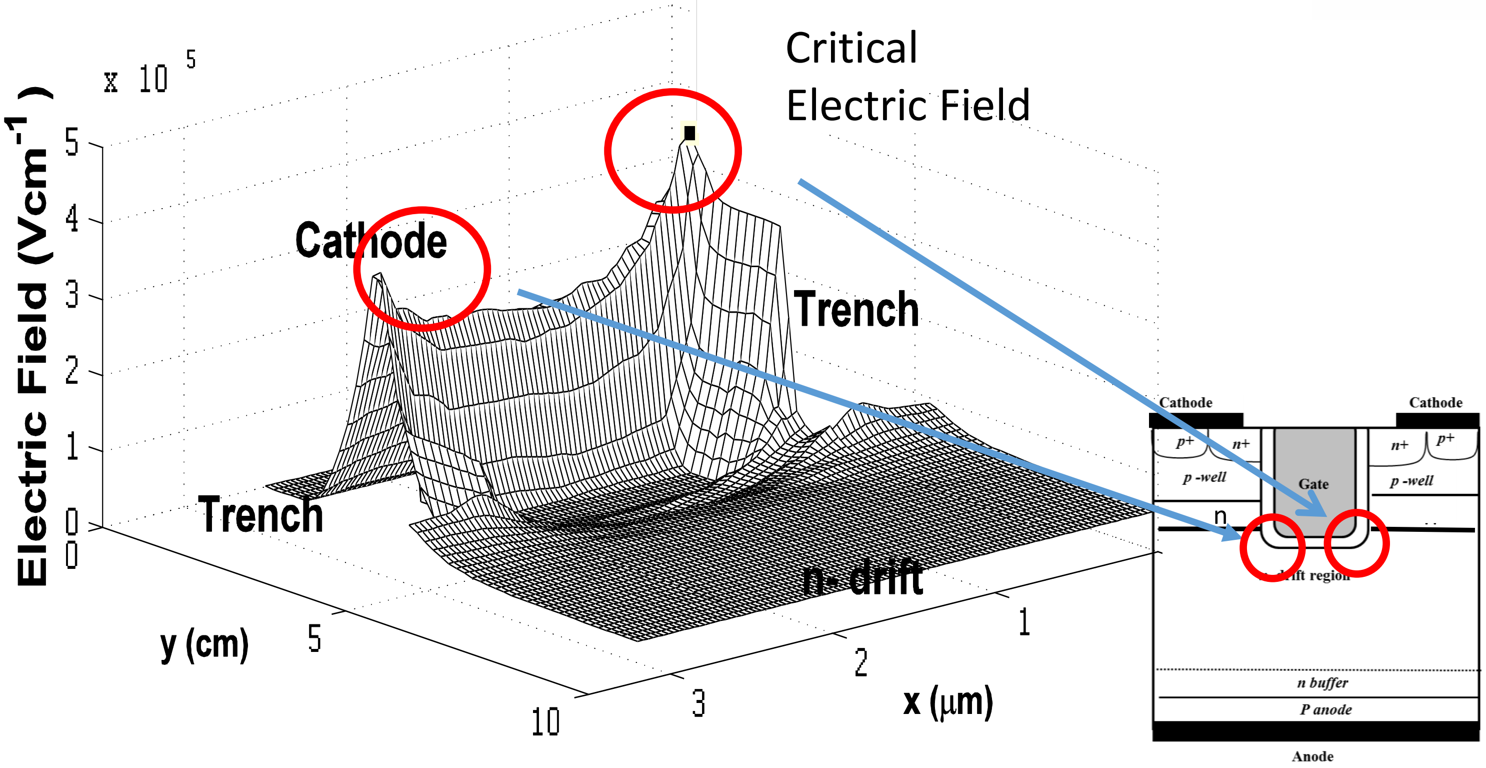




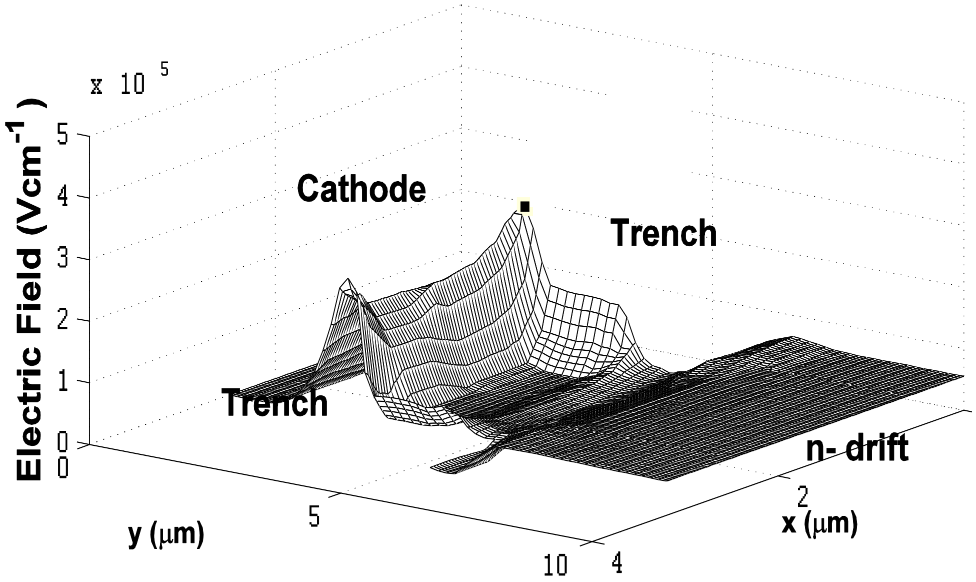
- p-ring achieved by implantation and diffusion and requires no additional masks
- The p-n regions help to distribute the field more uniformly across the cathode side
- 20% reduction in on-state losses without compromising the switching performance or the breakdown rating at both RT and 125 °C

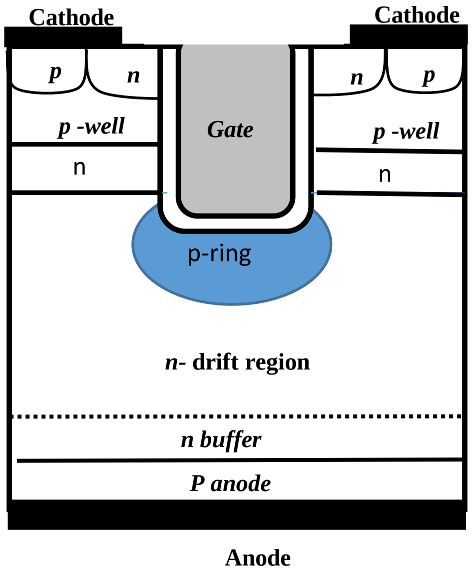
M. Antoniou, F.Udrea et al. IEEE EDL 2017

The IGBT Electric Field Distribution @Va=240V


Critical Electric Field

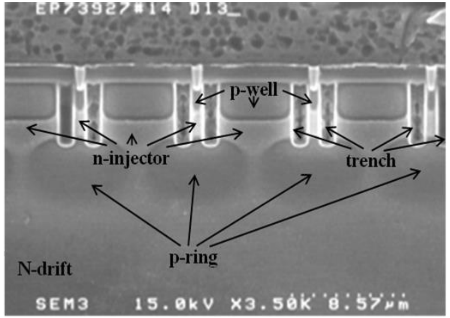
The p-ring IGBT Electric Field Distribution @1.2kV

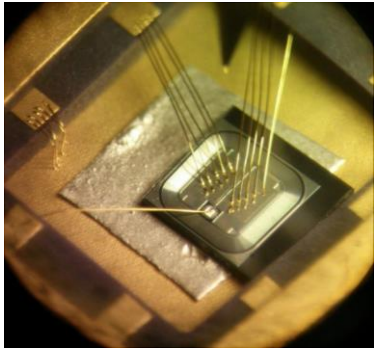


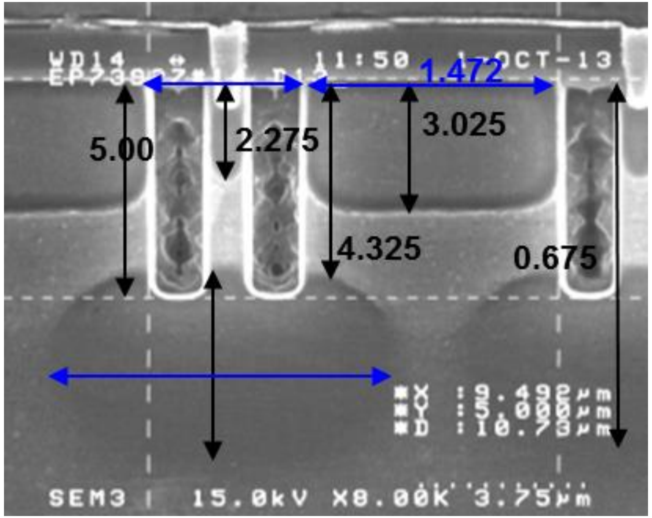


- Improvement in breakdown and the long term reliability: reducing the high electric fields peaks at the bottom or corner of the trenches oxide.

SEM Images of the p-ring IGBT

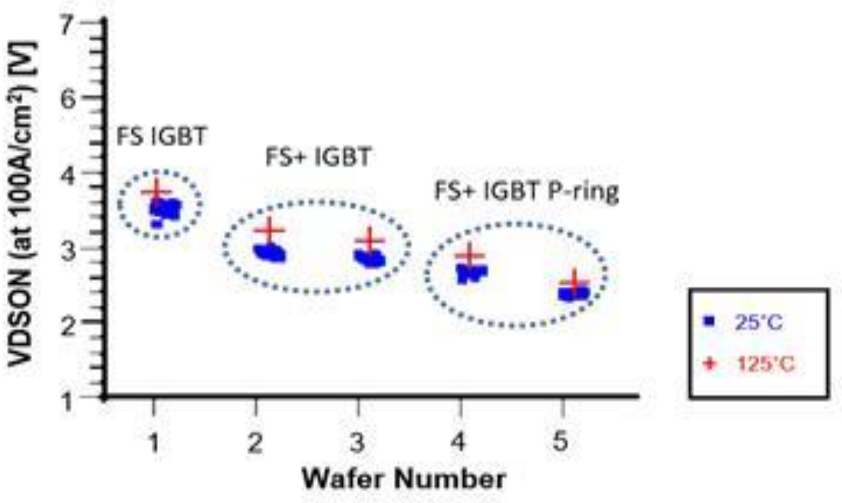






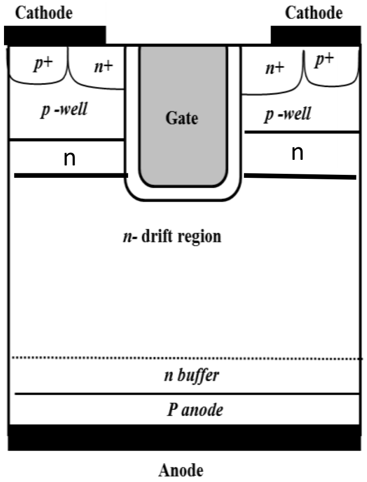
On state characteristics of the IGBT and the p-ring IGBT

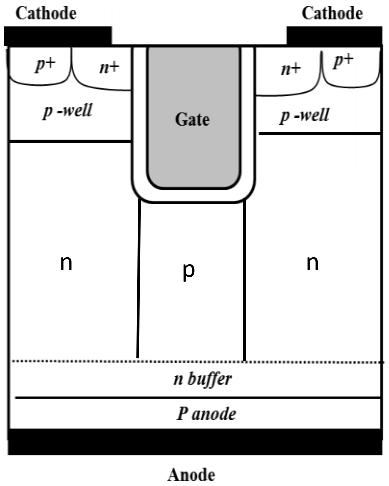
On state voltage drop @100A/cm^2



Up to 15% improvement in the on-state device performance

Si SuperJunction IGBT

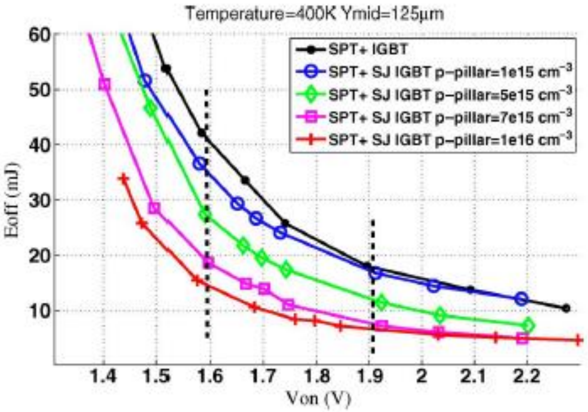


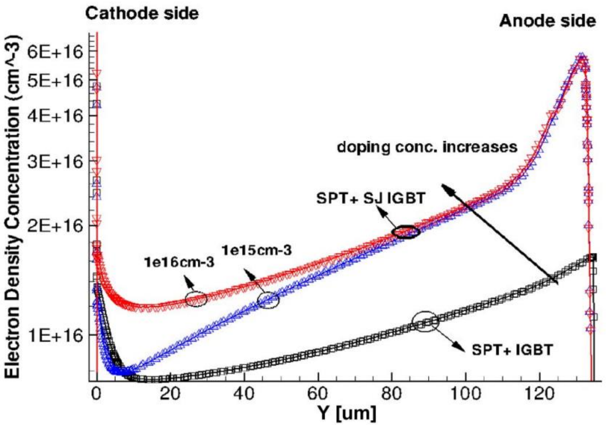


- The disconnected p column acts as deep collector of holes from the anode end of the drift region, thus increasing the turn-off speed.
- The SJ IGBT offers minimal drift length (for 1.2 kV this is just below 100 um) - 20% cut from the conventional structure.

M. Antoniou et al. IEEE Trans of Electron Devices 2010

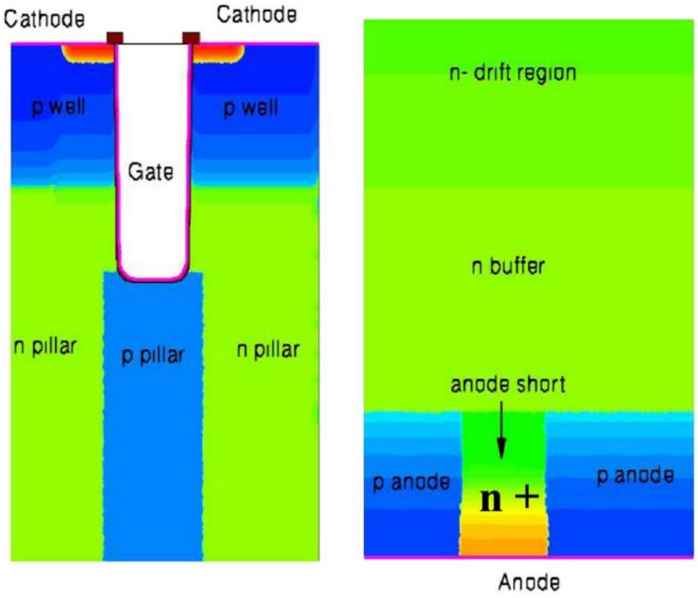
The technology curve: 1.2kV SuperJunction IGBT

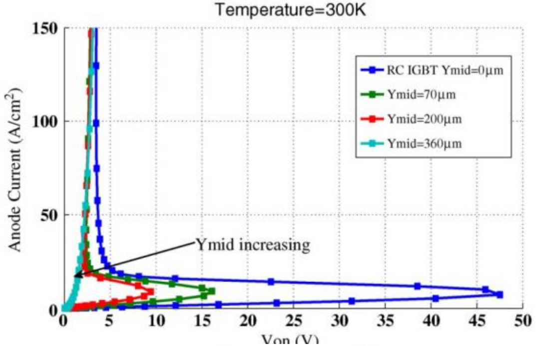


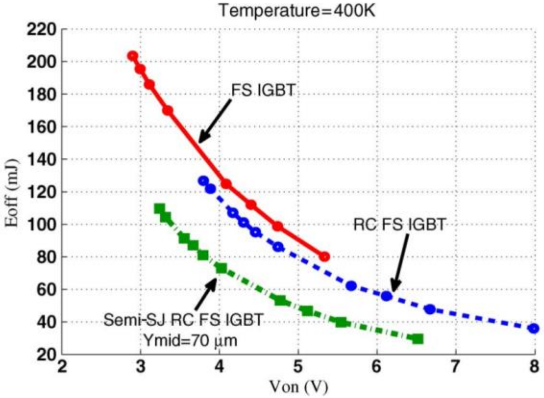


- The device can cut the on-state losses by 20% and the turn-off losses by almost 50% compared to a conventional structure.

Reverse Conducting IGBT

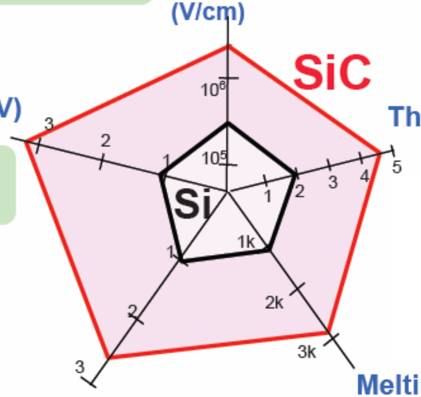






M. Antoniou, F.Udrea et al. IEEE Trans of Electron Devices 2010

Properties of SiC compared to Si



Low loss: x 100
High voltage: x 10

Radiation: x 3

Endurable for radioactivity: x 3

High temperature: x 3

High frequency: x 10

Why Silicon Carbide?

- 9x Higher Critical Electric Field can be used to:
  - Produce **high voltage** solutions
  - Drive up **switching speeds**, reducing **converter size**
  - Drive up converter **efficiency**
  - Or a combination of all three.

- 2.5x greater thermal conductivity and 3x wider bandgap
  - Improved **thermal performance**
  - High **maximum operating temperature** (packaging allowing)

- Like Silicon:
  - **Freestanding SiC substrates** can be produced.
  - It can be oxidised to form **SiO_2**

All figures compared to Si

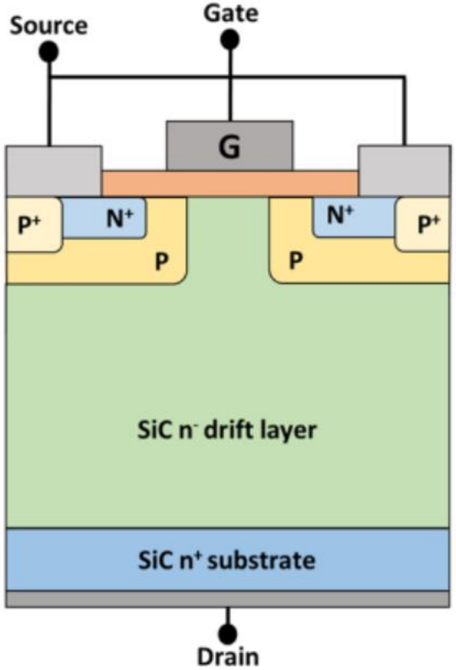
Performance of SiC MOSFETs

- For the 1.2kV rating, the channel resistance contributes 40% of the Rdson
- SiC MOSFET have strong positive temperature coefficient
- SiC MOSFET have a good body diode
- E_{rec} are very low and don't increase much with temperature.

- Challenges
  - Low channel mobility
  - No suitable HT package materials
  - Gate Oxide reliability issues
  - Short circuit Performance

Silicon Carbide MOSFET

- Commercial planar SiC Power MOSFET



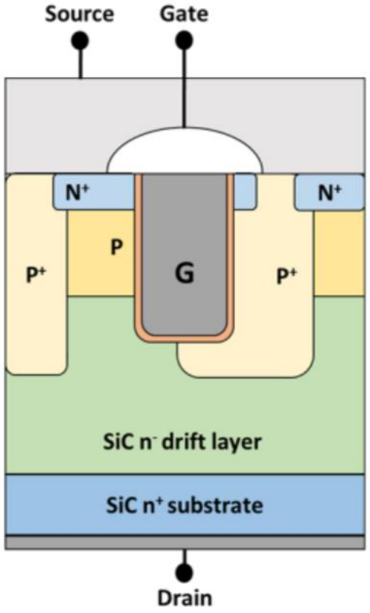
Many planar SiC MOSFETs are available today,
Such as the STMicroelectronics structure.

- The channel is horizontal and quite resistive
- Body diode operation
- JFET effect

Silicon Carbide MOSFET

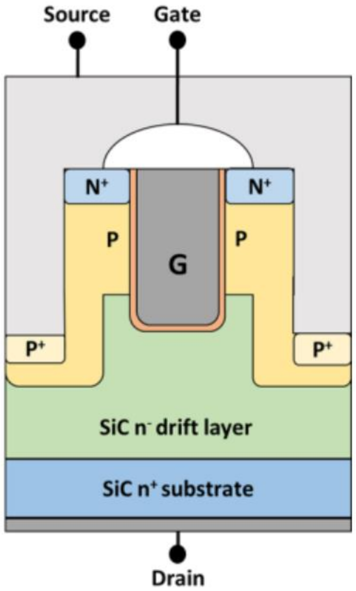
Infineon CoolSiC Trench MOSFET

- The channel is vertical with better mobility values.
- The trench MOSFET removes JFET region, however one side conduction channel along the trench wall.
- Deep P-regions on every trench to lower the electric field strength across the gate oxide.



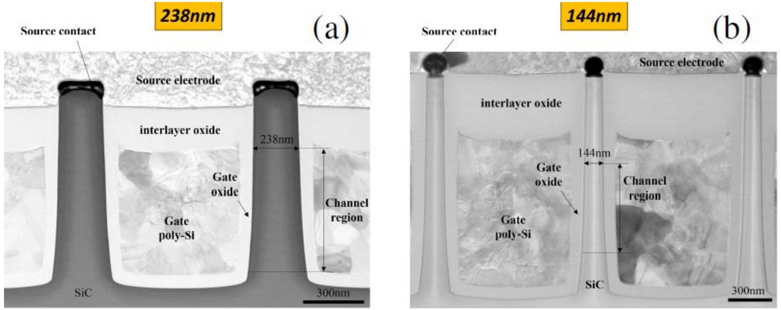
Silicon Carbide MOSFET

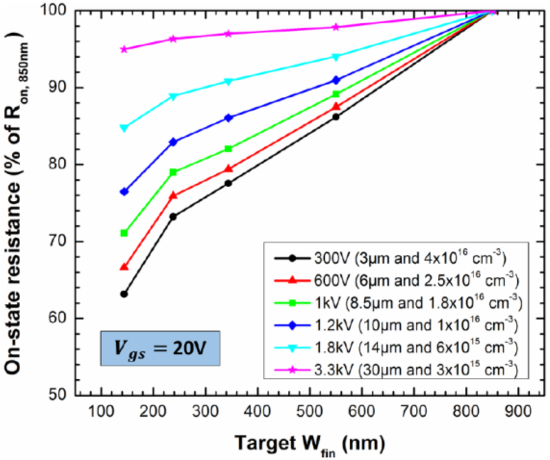
Rohms Double Trench MOSFET



- The trench MOSFET removes JFET region, and two side conduction channels along the trench wall.
- Deep p-layers to protect the gate oxide
- Source connected trench every other trench to enhance short-circuit ruggedness and to protect the gate oxide.
- On-state resistance improved by 50% and input capacitance down by 35%.

Silicon Carbide FIN MOSFET





- The FinFET effect can overcome the low channel mobility.
- The structure is limited by the need for ultranarrow bodies between ~ 150 and 30 nm.
- This effect is more prominent for voltage ratings below ~ 1 kV where the drift resistance is relatively low compared to Rch; its impact fades away above 1.8 kV.

F.Udrea et al. ISPSD 2022

SJ SiC MOSFET

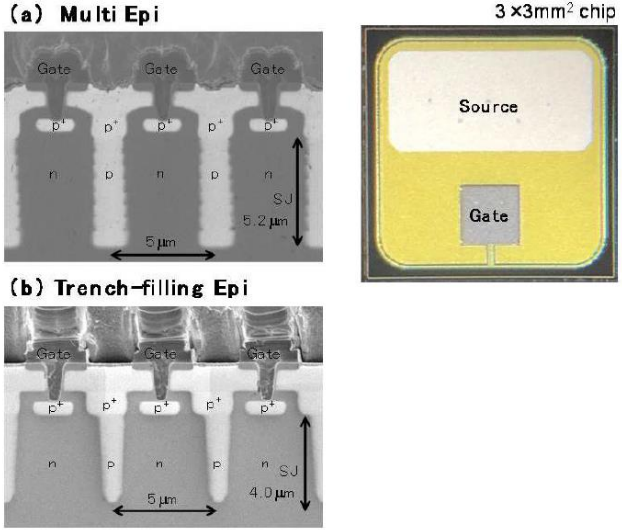
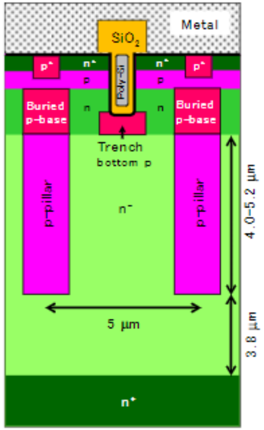


Fig. 3: Cross-sectional SEM micrograph and photograph of the fabricated semi-SJ devices.



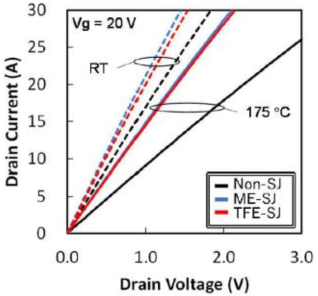
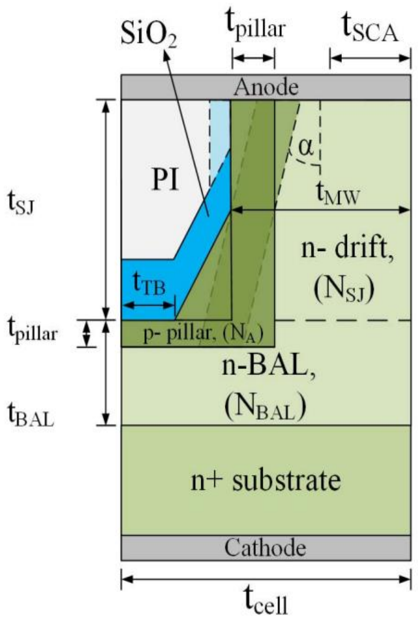


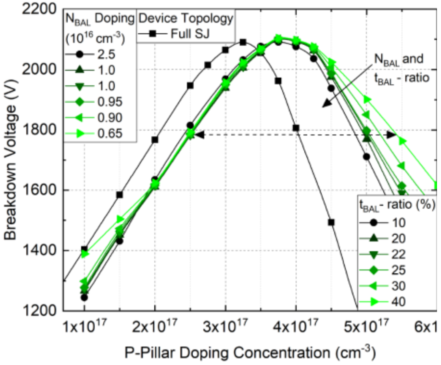
Fig. 4: I_d–V_d characteristic for $V_g = 20$V at RT and 175 °C.

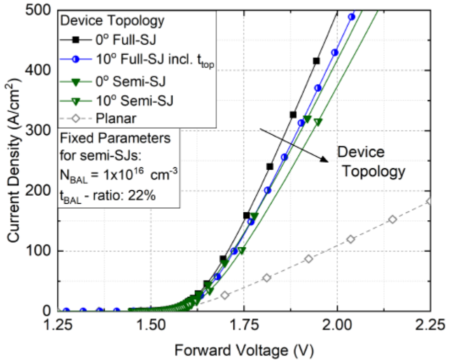
- SJ concept is applied in the drift of the SiC MOSFETs
- The RonA at HT is decreased by the SJ structure due to small drift resistance
- 1.2kV devices demonstrated.

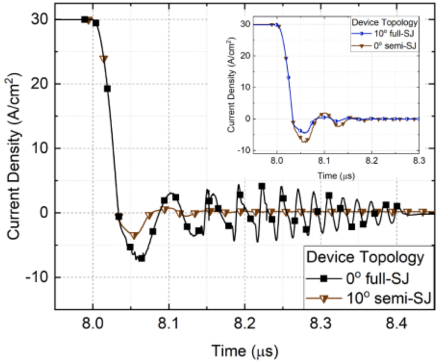
M. Sometani, AIST, Japan,ISPSD 2022

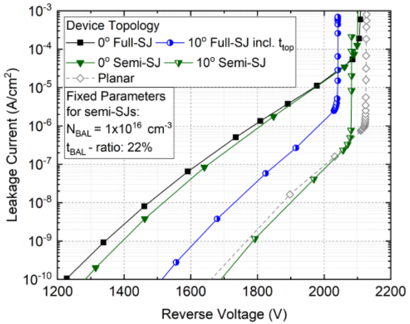
Semi-SJ SiC structures with angled side wall









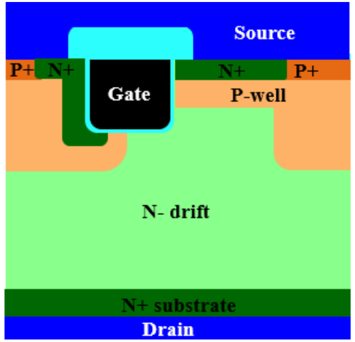


- P-pillars are created through implantation into both the trench sidewalls and trench bottom
- Improved Process robustness against breakdown and performance improvement.
- Widens the implantation window by 34%, while maintaining a VBD and a $R_{ON,SP}$ comparable to a vertical full-SJ.
- Reduces the peak I_{RR} by 50%

G. Baker et.al IEEE TED 2022

Hybrid-Channel SiC Trench MOSFET

- The trench IGBT removes JFET region, and two side conduction channels along the trench wall.
- Deep p-layers to protect the gate oxide from high electric fields
- On-state resistance improved by 30% for the same blocking capability.



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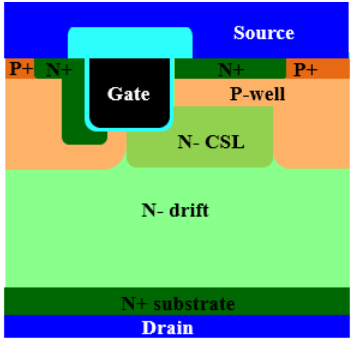

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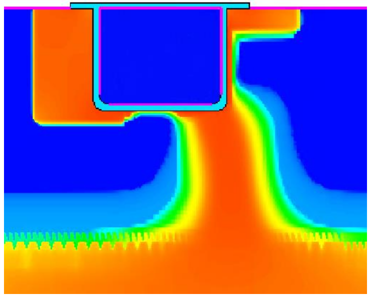

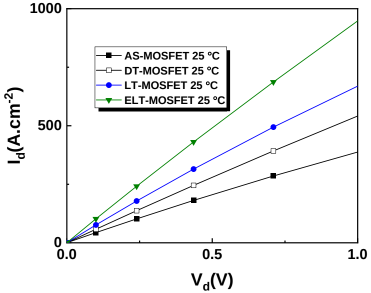

L.Zhang, ECPE 2022

The Power of Silicon Carbide

SiC MOSFETs run hotter, switch faster and waste less power than Si IGBTs.

All of which lead to **Smaller, lighter converters**

ROHM SEMICONDUCTOR

Source: Rohm

ROHM supplies Full SiC Power Modules to Formula E racing team Venturi

Driving down SiC costs

SiC costs remain high compared to Si technology

Four key factors will drive down costs in the coming decade:

- **Larger area substrates:** adopting 8” / 200 mm wafers.
- **Incremental device/process improvement:** driving die size reduction.
- **Incremental yield improvements:** reducing substrate defect densities; improving fabrication methods.

Conclusions

- The automotive industry is shifting towards the 800V battery DC link Voltage
- Si IGBTS and SiC MOSFETS and the current two competing technologies to deliver this power.
- IGBTs are continually improving despite the Si material limitations and absence of body diode
- SiC MOSFET is establishing its self as the device of choice. However the device reliability issues and cost still limit its full potential.

Thank you!