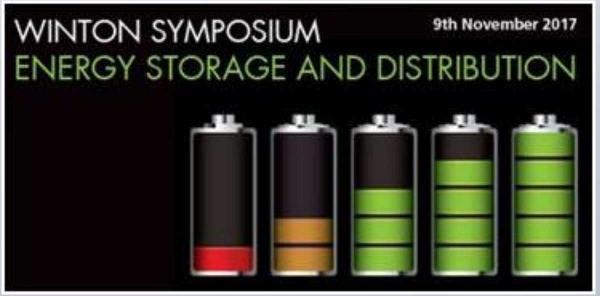
9.11.2017

Power semiconductors

for grid system power electronics applications

Munaf Rahimo, Corporate Executive Engineer

ABB Switzerland Ltd., Semiconductors, Grid Integration, Power Grids



Agenda

- ABB Grid Systems and HVDC
- Power Electronics and Power Semiconductors
- Silicon Power Semiconductor Devices
- Wide Band-gap Power Semiconductor Devices
- Conclusions

PART 1: ABB Grid Systems and HVDC

Grid Systems Market Trends

Towards renewables and distributed generation

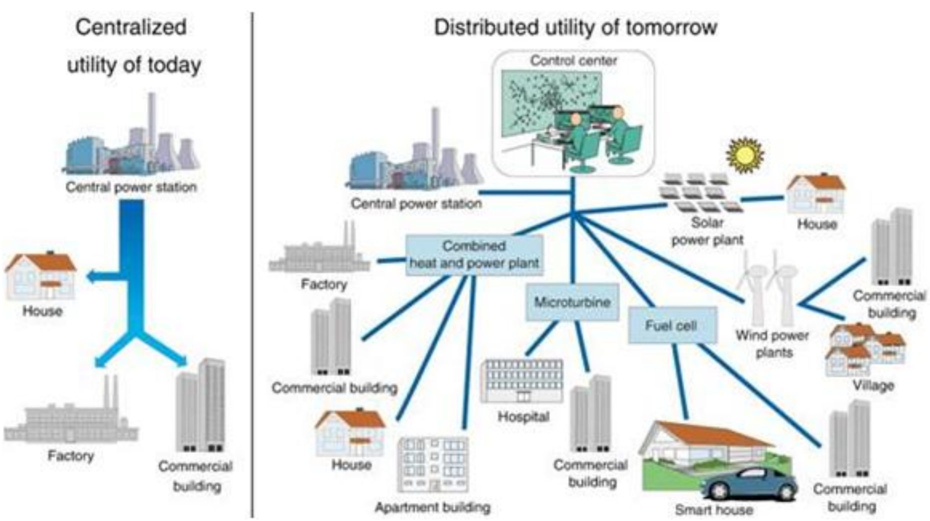
Social and Technology Trends

The market trends are driven by development in society and technology:

– **Increasing power consumption and demand worldwide**
  - Heavily populated and industrialised urban areas
  - Rural electrification in fast developing countries
  - Availability and competitive cost of electricity

– **Change of power generation and technology landscape**
  - Environmental concerns, lowering greenhouse gases
  - Integration of renewable energy sources
  - Energy storage (intermittent supply of renewables)
  - Energy efficient
  - Reliable and intelligent/smart systems (ABB Ability™)

- Renewables and distributed generation



A changing grid with increased requirements

ABB

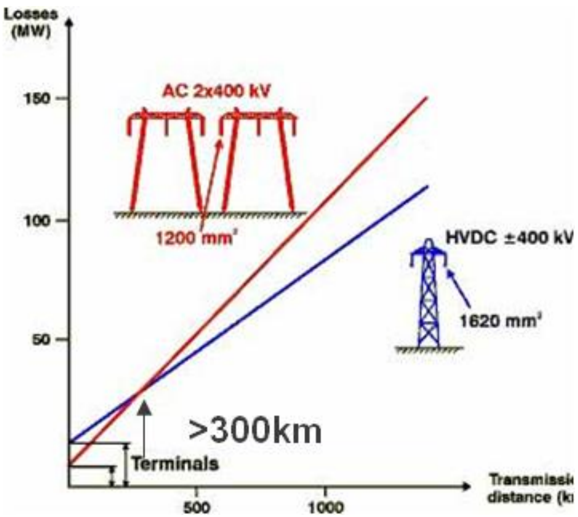
High Voltage Direct Current Transmission

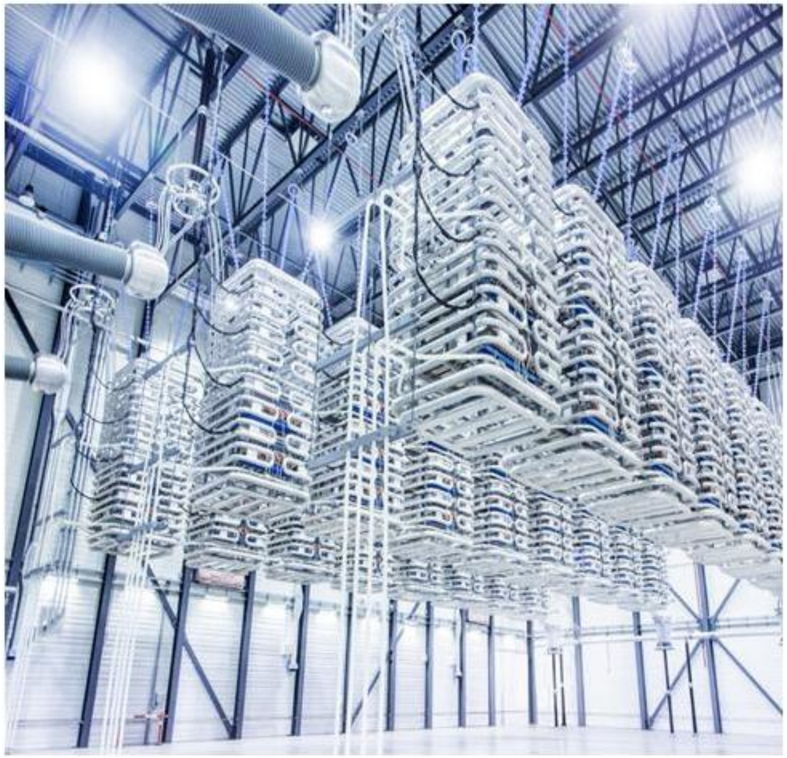
HVDC

Overview

HVDC (high-voltage direct current) is a highly efficient alternative for transmitting large amounts of electricity over long distances and for special purpose applications.

- Using HVDC to interconnect two points in a power grid is in many cases the best economic alternative.
- Furthermore it has excellent environmental benefits.

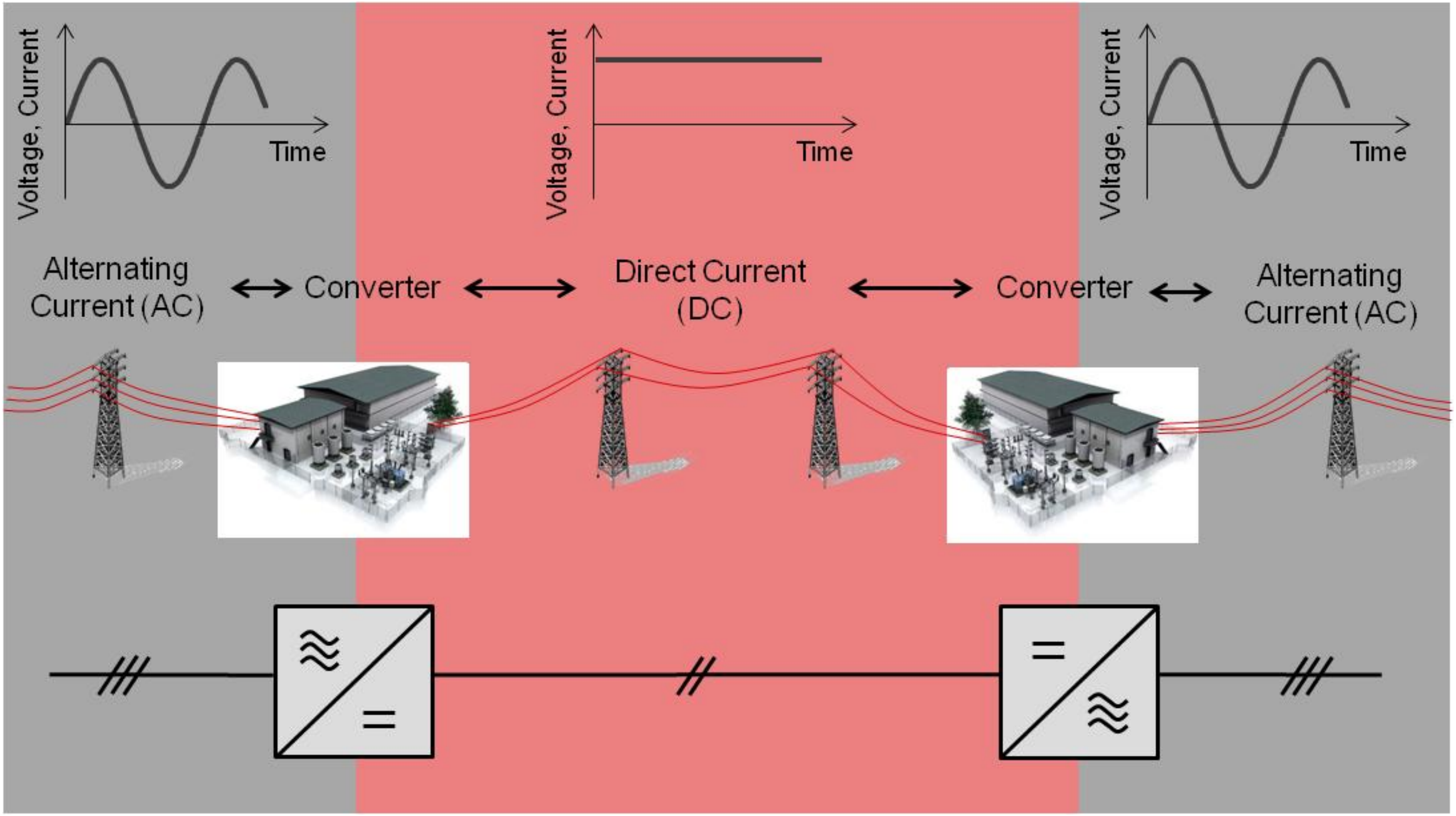




As a key enabler in future energy systems based on renewables, HVDC is shaping the grid of the future

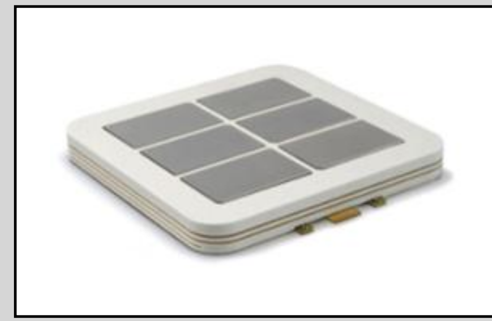
HVDC Working Principle

POWER CONVERSION



Power Semiconductors in Grid Applications

High Performance Power Semiconductors for HVDC Classic and HVDC Light

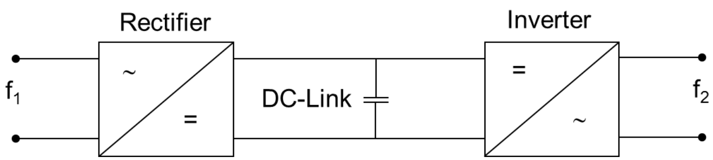
Criterion	Line Commutated HVDC (LCC HVDC)	Self Commutated HVDC (VSC HVDC)
Power Semiconductor Technology **<u>Heavy series and parallel operation</u>** • Lower losses, better efficiency, smaller systems and lower costs • Increased current handling capability through modularity • Higher voltage rating for reducing the number of components in a valve	Line Commutated Phase Controlled Thyristor PCT 	Self Commutated IGBT 
Power	10GW	1GW (3GW)
Voltage	+/- 800kV (+/- 1100kV)	+/- 320kV (+/- 500kV)
Supply of reactive power	No (needs a strong grid)	Yes
Topology	Current source converter	Voltage source converter
Typical applications	Bulk power transmission	Connecting off-shore windfarms

PART 2: Power Electronics and Power Semiconductors

Power Electronics

Power Electronics is in essence an electrical system ...

… that conditions the power of a supply to suit the needs of the load …



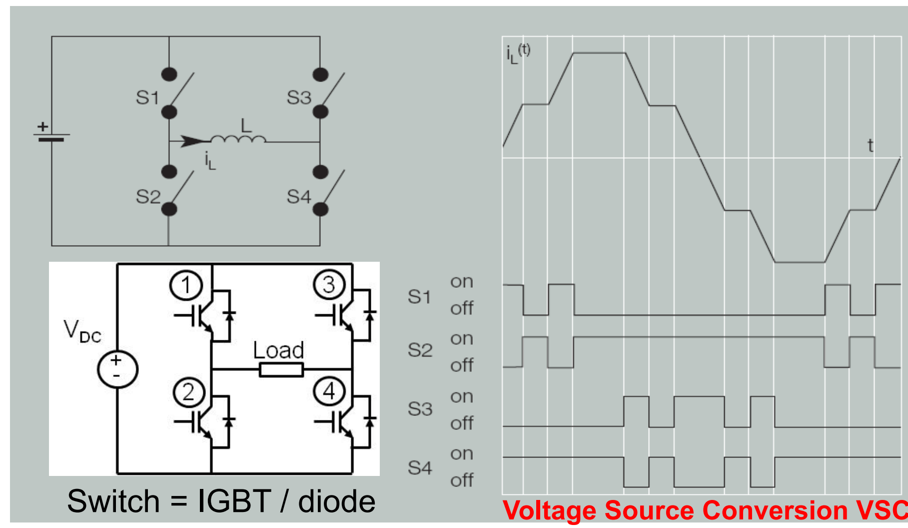
- DC → AC
- AC → DC
- $AC(V_1, \omega_1, \varphi_1) \rightarrow AC(V_2, \omega_2, \varphi_2)$
- $DC(V_1) \rightarrow DC(V_2)$

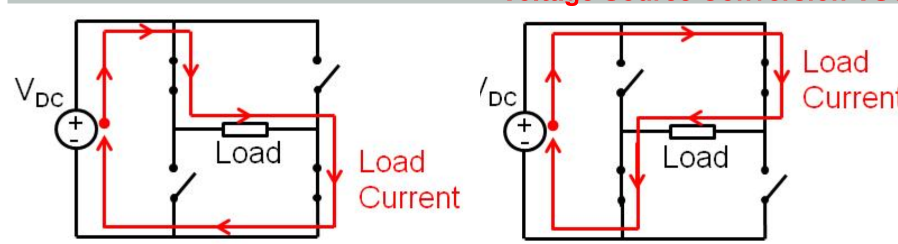
… by using fast and controllable solid-state switches referred to as

Power Semiconductor Devices

DC → AC

Four simple on/off switches and a DC battery are all that is needed to generate an approximately sinusoidal current (AC) in an inductor (Load)

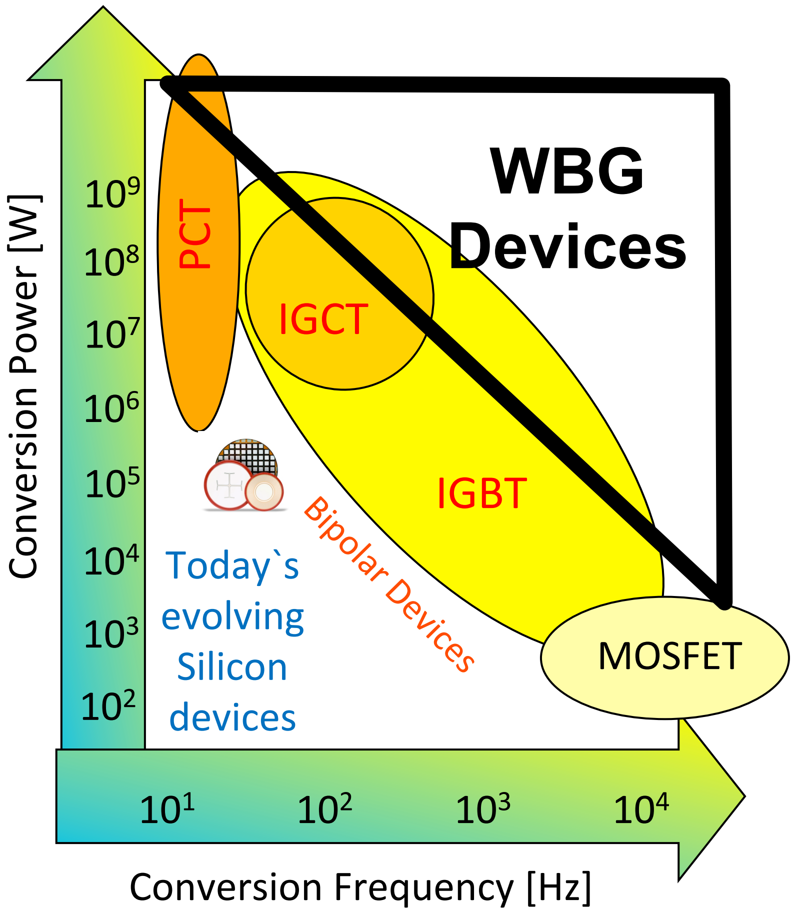


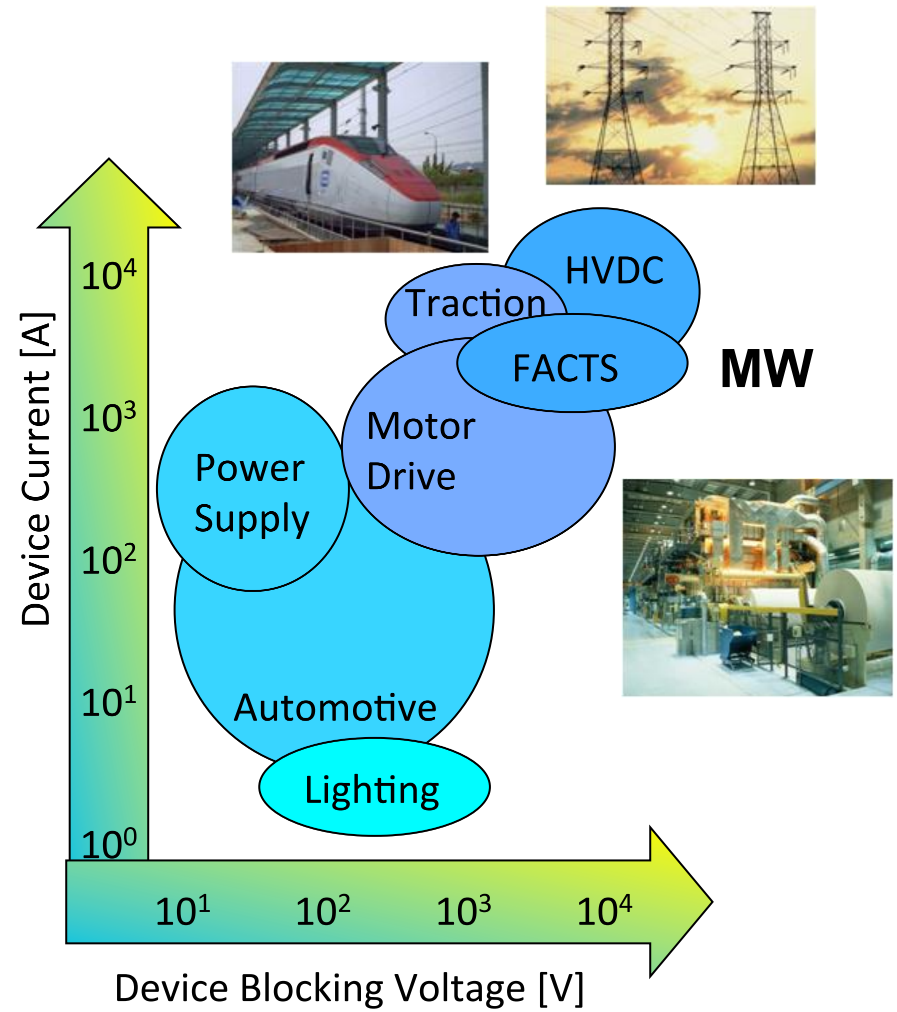


ABB

Power Semiconductors and Applications

Conversion power and device classification





Power Electronics Trends

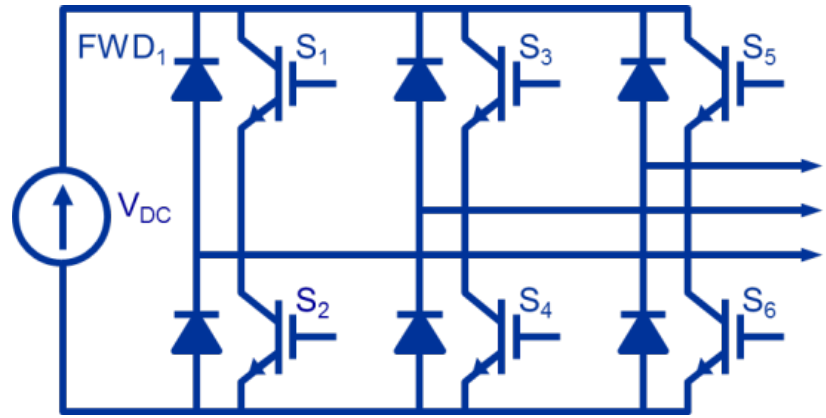
Application and Performance Trends

Application Trends

- Traditional: Grid, Traction and Industrial Applications
- Environmental: Renewables, Electric Mobility
- Solid State: Breakers "Event Switching", Transformers "HF"

Performance Trends

- Traditional: More Compact and Powerful Systems
- Efficient: Lower Losses
- Modern: Better Quality, Reliability and Health Monitoring



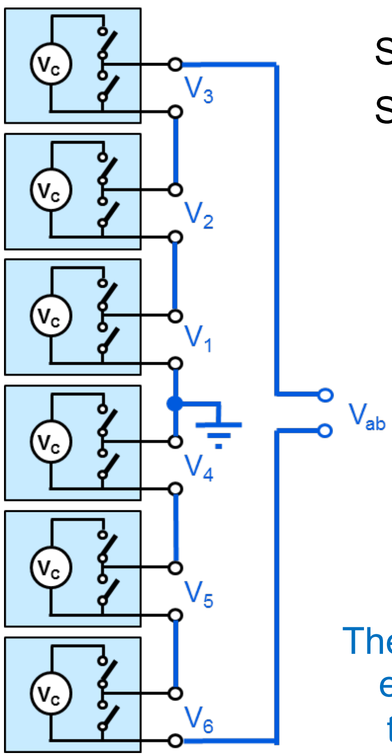



ABB

Power Electronics Developments for Grid Systems

VSC Multi Level Converter topologies Towards lower switching frequencies

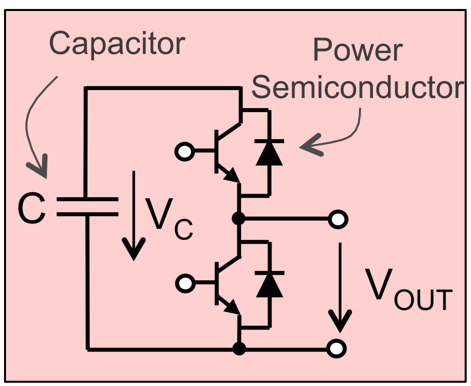
Conduction losses are key



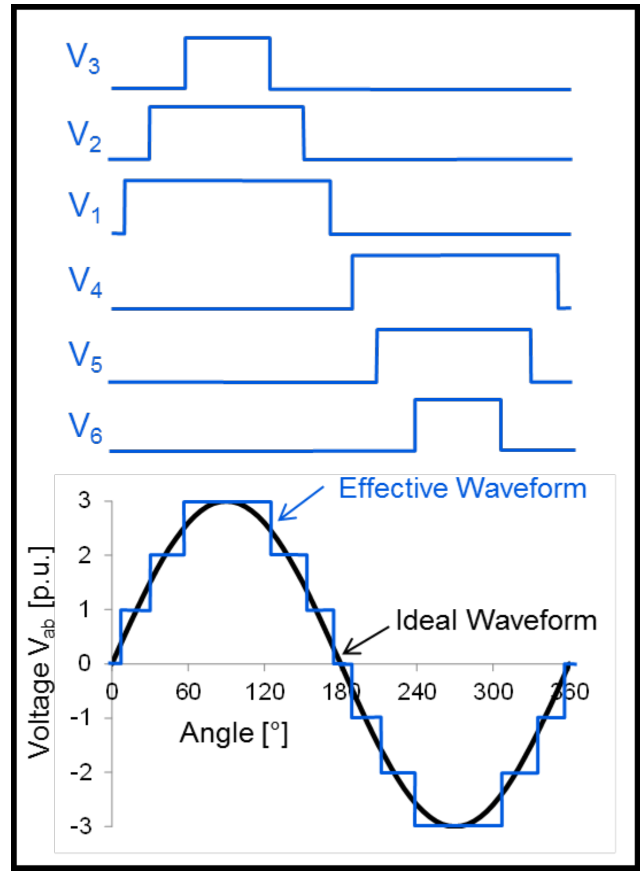
Series connected cells

Scalable (voltage & current)

Practical Realization



The power semiconductor technologies enables different power electronics topologies and operational modes

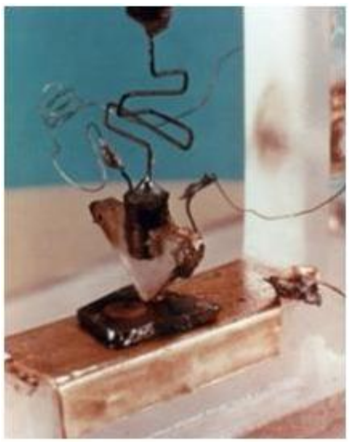


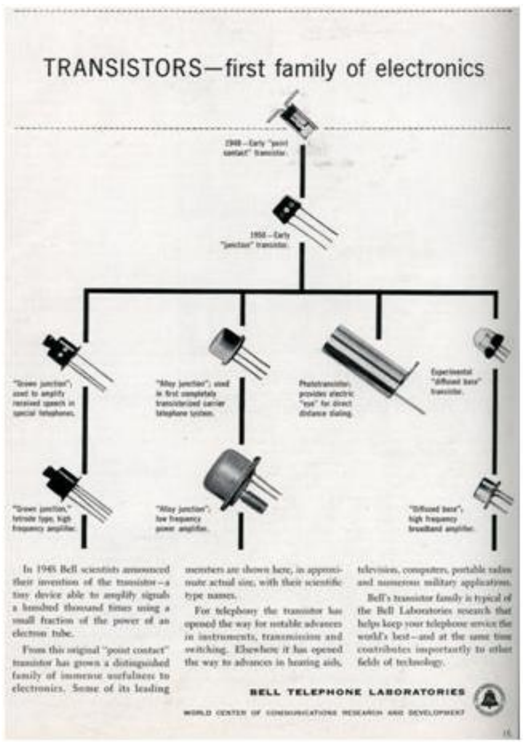
Low switching frequencies → **Conduction** losses are very important

The Power Semiconductors Silent Revolution

HVDC Example in Transmission

Then … and … Now





TRANSISTORS—first family of electronics

In 1948 Bell scientists announced their invention of the transistor—a tiny device able to amplify signals a hundred thousand times using a small fraction of the power of an electron tube.

From this original "point contact" transistor has grown a distinguished family of immense usefulness to electronics. Some of its leading members are shown here, in approximate actual size, with their scientific type names.

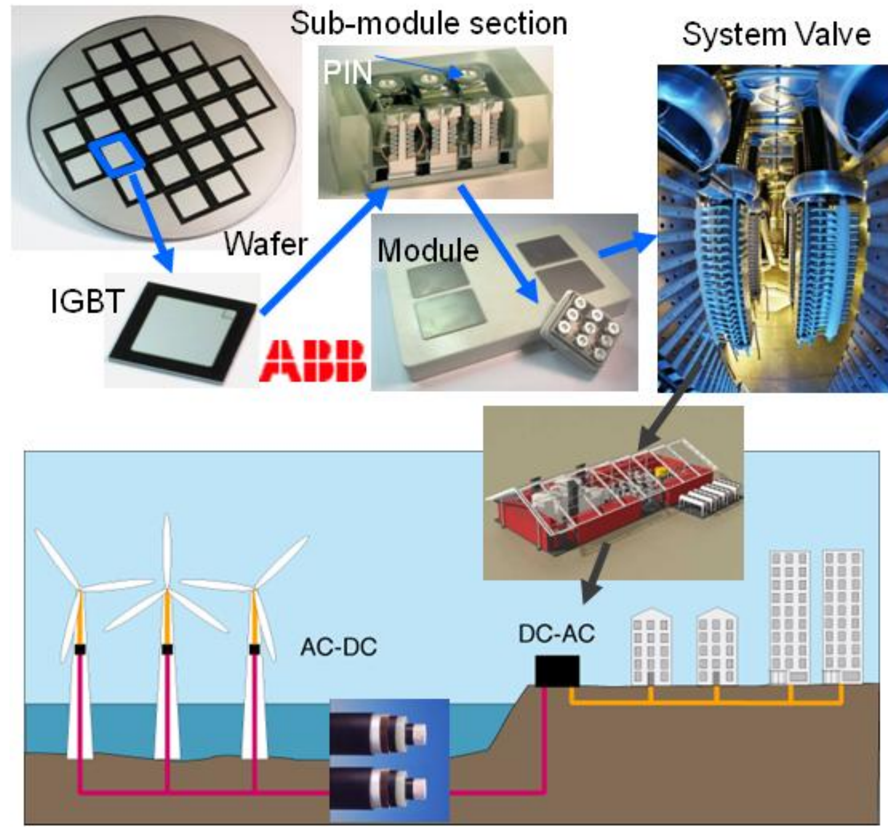
For telephony the transistor has opened the way for notable advances in instruments, transmission and switching. Elsewhere it has opened the way to advances in hearing aids, television, computers, portable radios and numerous military applications.

Bell's transistor family is typical of the Bell Laboratories research that helps keep your telephone service the world's best—and at the same time contributes importantly to other fields of technology.

BELL TELEPHONE LABORATORIES

WORLD CENTER OF COMMUNICATIONS RESEARCH AND DEVELOPMENT

1947: Bell`s Transistor



Today: GW IGBT based HVDC systems

PART 3: Silicon Power Semiconductor Devices

Semiconductors

Towards higher speed and power

A look back

- It took close to two decades after the invention of the solid-state bipolar transistor (1947) for semiconductors to hit mainstream applications

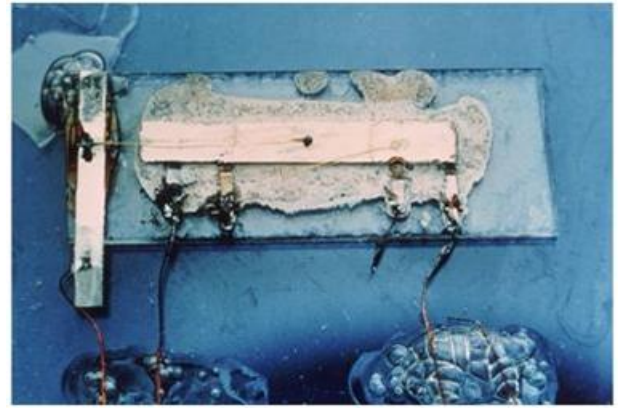
- The beginnings of power semiconductors came at a similar time with the integrated circuit in the fifties

- **Both lead to the modern era of advanced DATA and POWER processing**

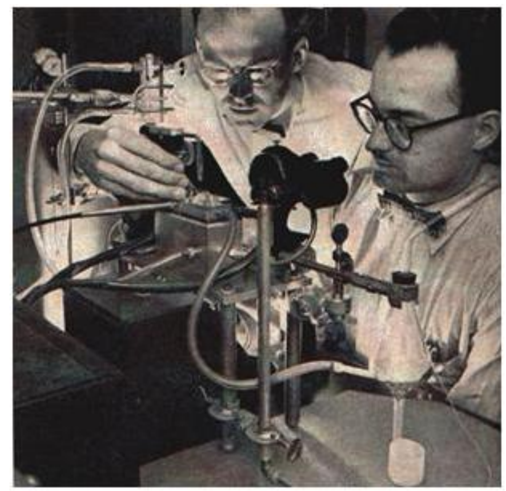
- While the main target for ICs is increasing the speed of data processing, for power devices it was the controlled power handling capability

- Since the 1970s, power semiconductors have benefited from advanced Silicon material and technologies/ processes developed for the much larger and well funded IC technologies and applications

- There are no disruptive technologies on the horizon



Kilby`s first IC in 1958



Robert N. Hall (left) at GE demonstrated the first 200V/35A Ge power diode in 1952

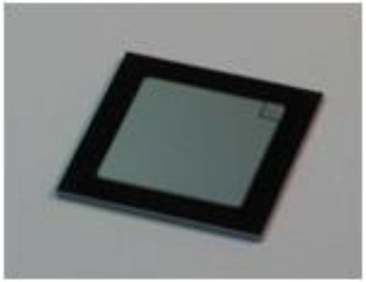
Silicon Semiconductor Processes

The power device challenge

Power Devices

- It takes basically the same technologies to manufacture power semiconductors like modern logic devices like microprocessors
- But the challenges are different in terms of Device Physics and Application
- Doping and thickness of the silicon must be tightly controlled (both in % range)
- Because silicon is a resistor, device thickness must be kept at absolute minimum
- Virtually no defects or contamination with foreign atoms are permitted
- Very high voltages (100s-1000s of volts) are supported across very narrow dimensions in the bulk and termination regions (< 1 mm)

Device	Critical Dimension	Min. doping concentration	Max. Process Temperature*
Logic Devices	<0.1 µm	10^{15} cm^{-3}	1050 - 1100°C (minutes)
MOSFET, IGBT	~ 1 µm	10^{13} - 10^{14} cm^{-3}	1250°C (hours)
Thyristor, GTO, IGCT	>10 µm	< 10^{13} cm^{-3}	1280-1300°C(days) melts at 1360°C



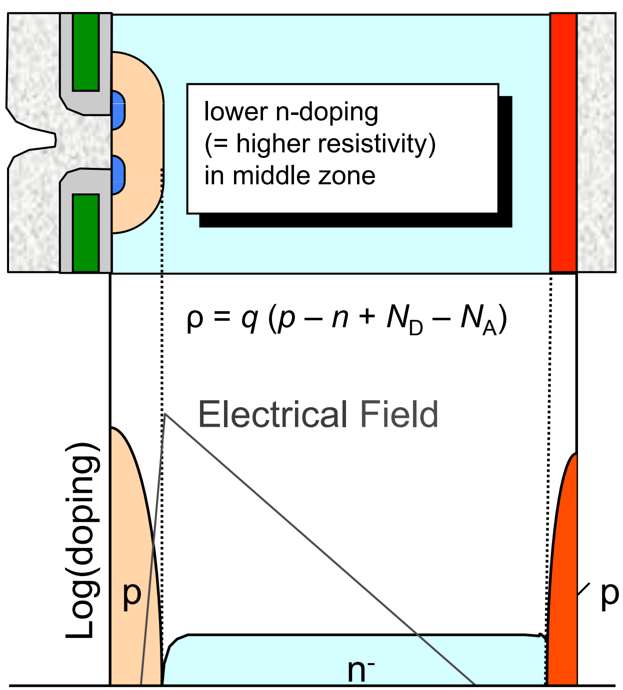
Power Semiconductor Structure and Function

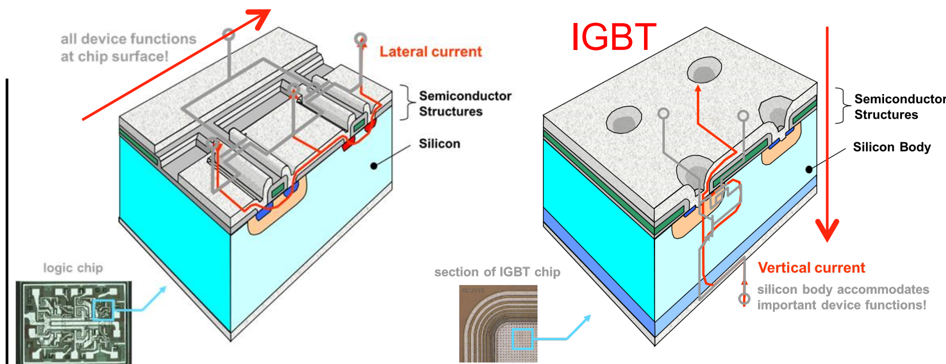
The fast high power switch

The main structural feature

• The low doped drift (base) region is the main differentiator for power devices (normally n-type)

IGBT





Lateral Logic Device

Vertical Power Device (Lateral device exist for lower power)

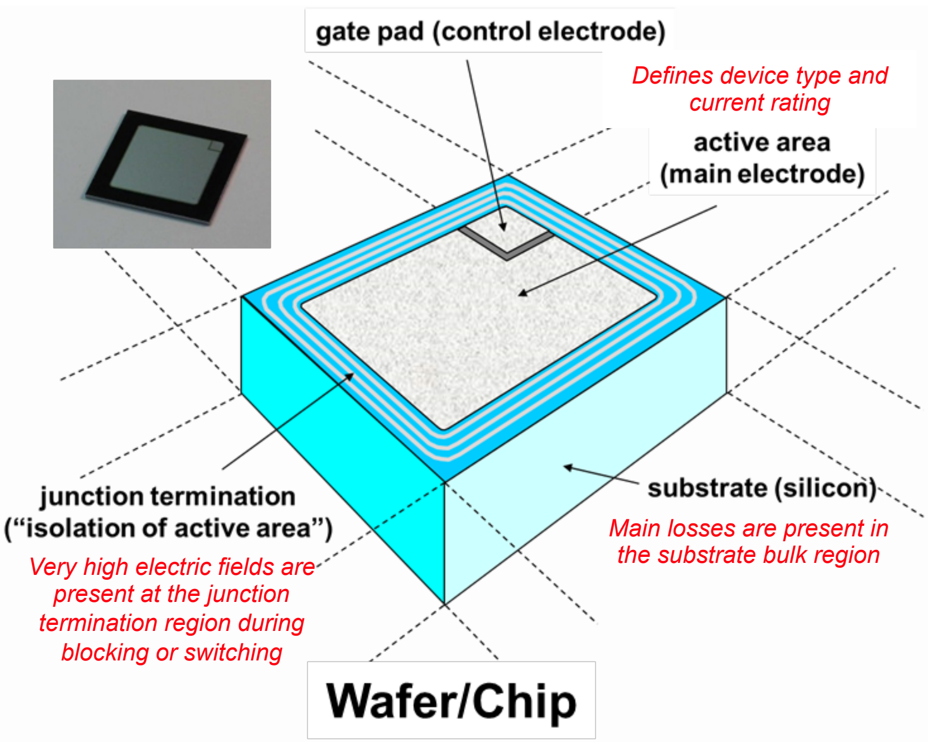
Main Functions of the power device:

- Support the off-voltage (100s-1000s of Volts)
- Conduct currents when switch is on (100s-1000s of Amps)
- Switch between the two above states

Switch

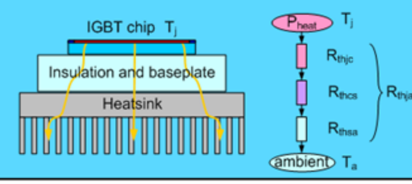
Power Semiconductor and Package

Device and Package pillars



Main Problem: Cool away the semiconductor losses
6MW converter with 1% semiconductor losses = 60kW losses

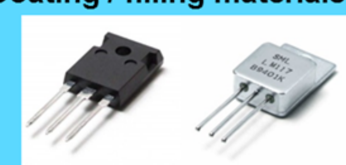
Heat dissipation
- Interconnections
- Advanced cooling concepts



Electrical distribution
- Interconnections
- Power / Signal terminals
- Low electrical parasitics

High Voltage Insulation
- Partial Discharges
- HV insulating
- Creepage distances

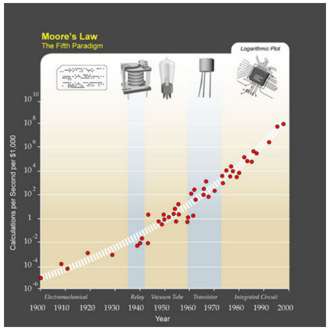
Encapsulation/ protection
- Hermetic / non-hermetic
- Coating / filling materials



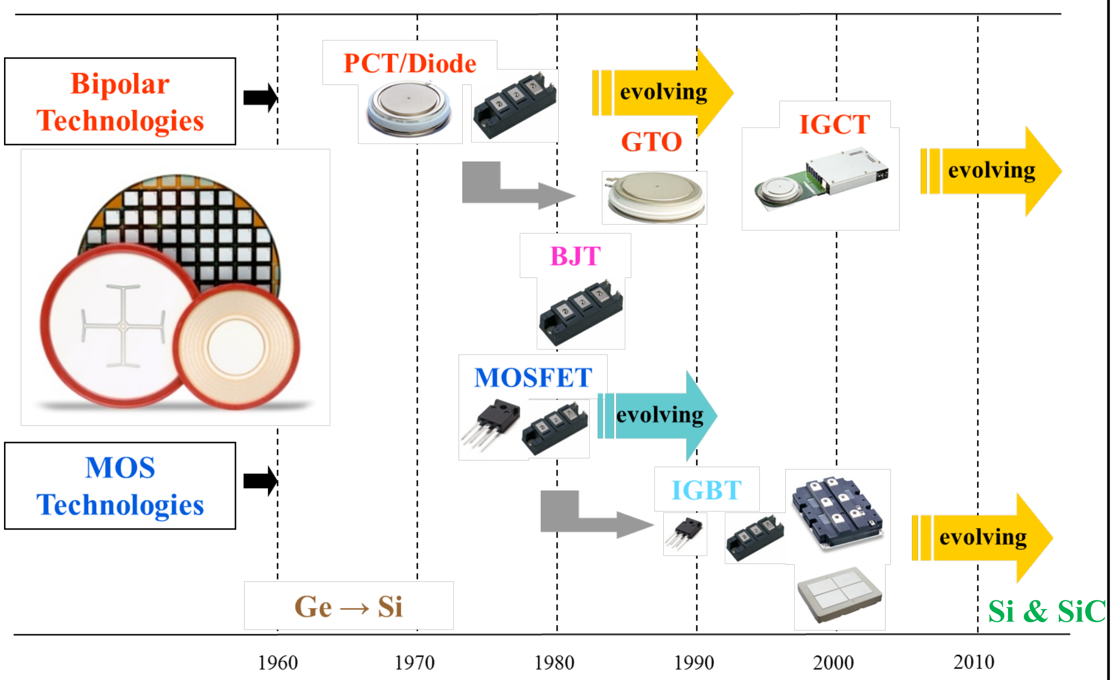
Package

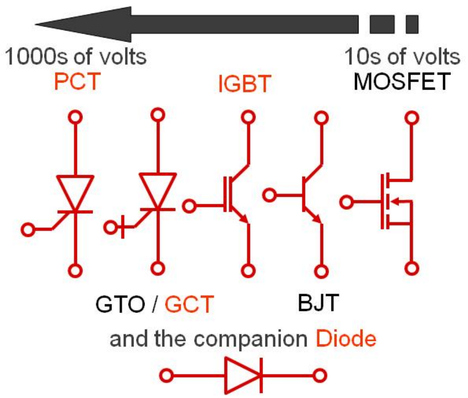
Power Semiconductors Evolution

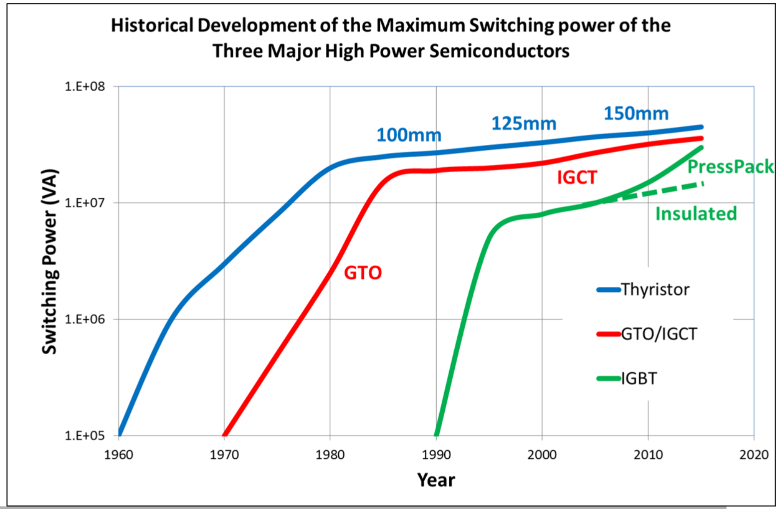
From rectifiers to IGBTs



Timeline



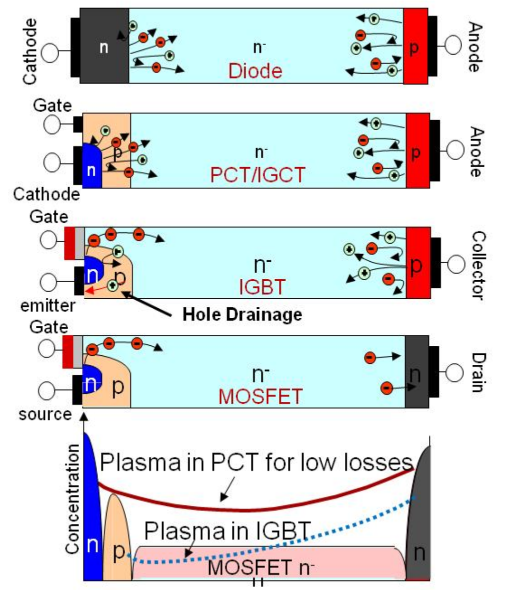




Power Semiconductor Requirements

Overview

- **Power Density Handling Capability:**
  - Low on-state and switching losses (traditional trend: improved technology curves)
  - Low thermal resistance (device active area selection and chip joining technology)
  - High operating temperatures (low leakage current and robustness)
- **Controllable and Soft Switching Characteristics:**
  - Soft and controllable turn-off (low overshoot voltages and EMI levels)
  - Turn-on controllability (gate control/response for optimum transients and losses)
- **Ruggedness, Fault-Handling and Reliability:**
  - SOA: Turn-off current capability (wide Safe-Operating-Area)
  - Fault-Handling: Short circuit capability for IGBTs (fault protection of Switch)
  - Fault-Handling: Surge current capability (fault protection for diodes)
  - Reliability: Current/voltage sharing for paralleled/series devices (low miss-match)
  - Reliability: Stable conduction/switching (stable device parameters)
  - Reliability: Stable blocking (stable device parameters, low cosmic ray FIT)
- **Packaging:**
  - Compact (chip packing density, low parasitic elements, optimum electrical layout)
  - Powerful (high current, high voltage, high temperature)
  - Reliable (temperature and power cycling, chip protection)



The device concepts could have many configurations depending on device process and design such as

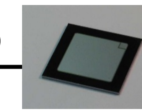
- Asymmetric
- Symmetric: Reverse Blocking
- Reverse Conducting
- Bidirectional

Power Semiconductor Boundaries

Overcoming the power device limitations

The Power

$$Power_{DC} = V_{on} . I_c = \frac{V^2_{on}}{R_{on}} = \frac{T_{j,max} - T_{j,amb}}{R_{th}}$$



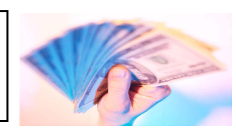
The Margins

$P_{max} = V_{max} . I_{max}$, Controllability, Reliability

The Application

Topology, Frequency, Control, Cooling

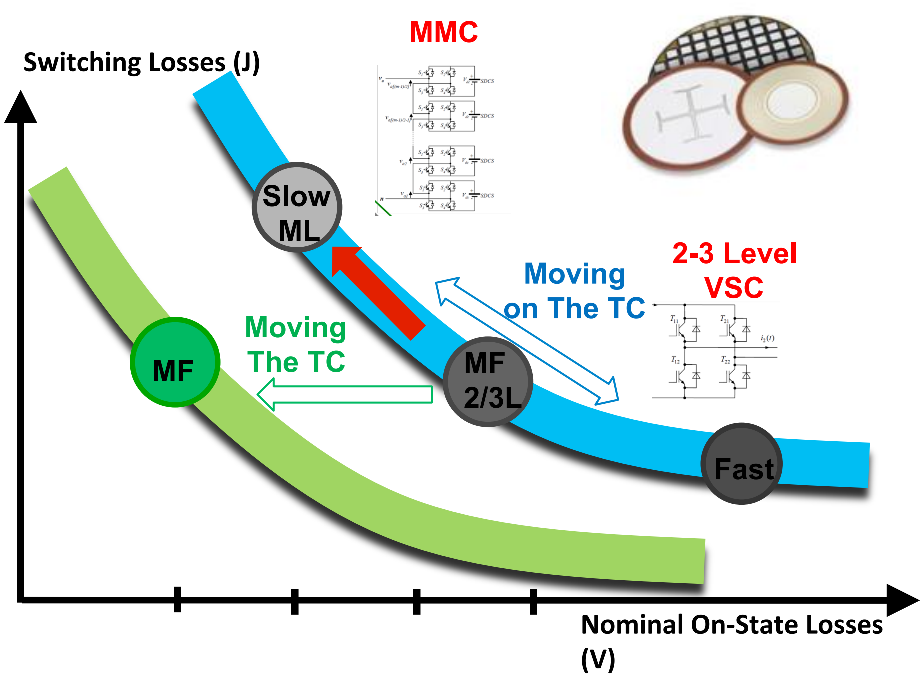
The Cost of Performance

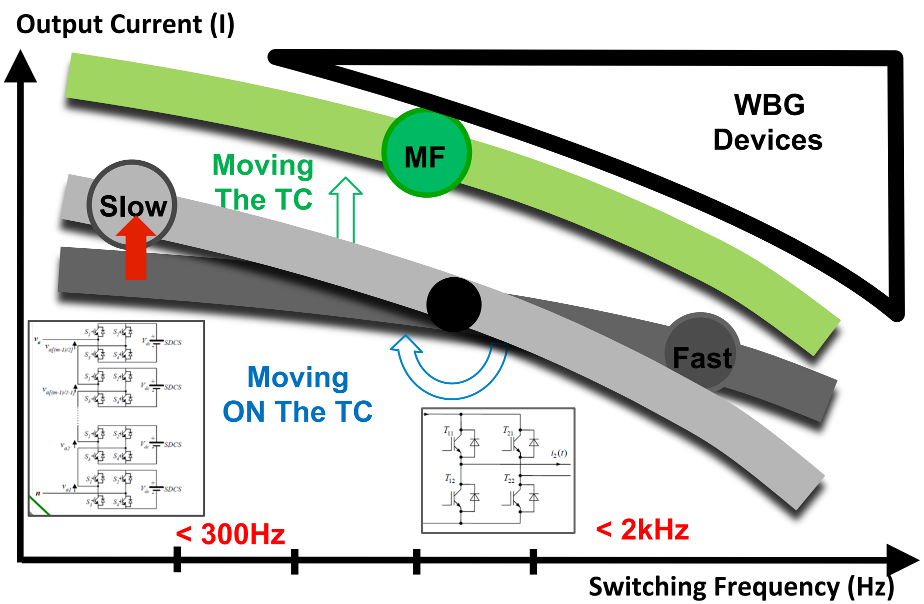


Power Semiconductor Optimization and Improvement

Bipolar power semiconductor Technology Curves (TC)

Technology Curves (Conduction vs. Switching)

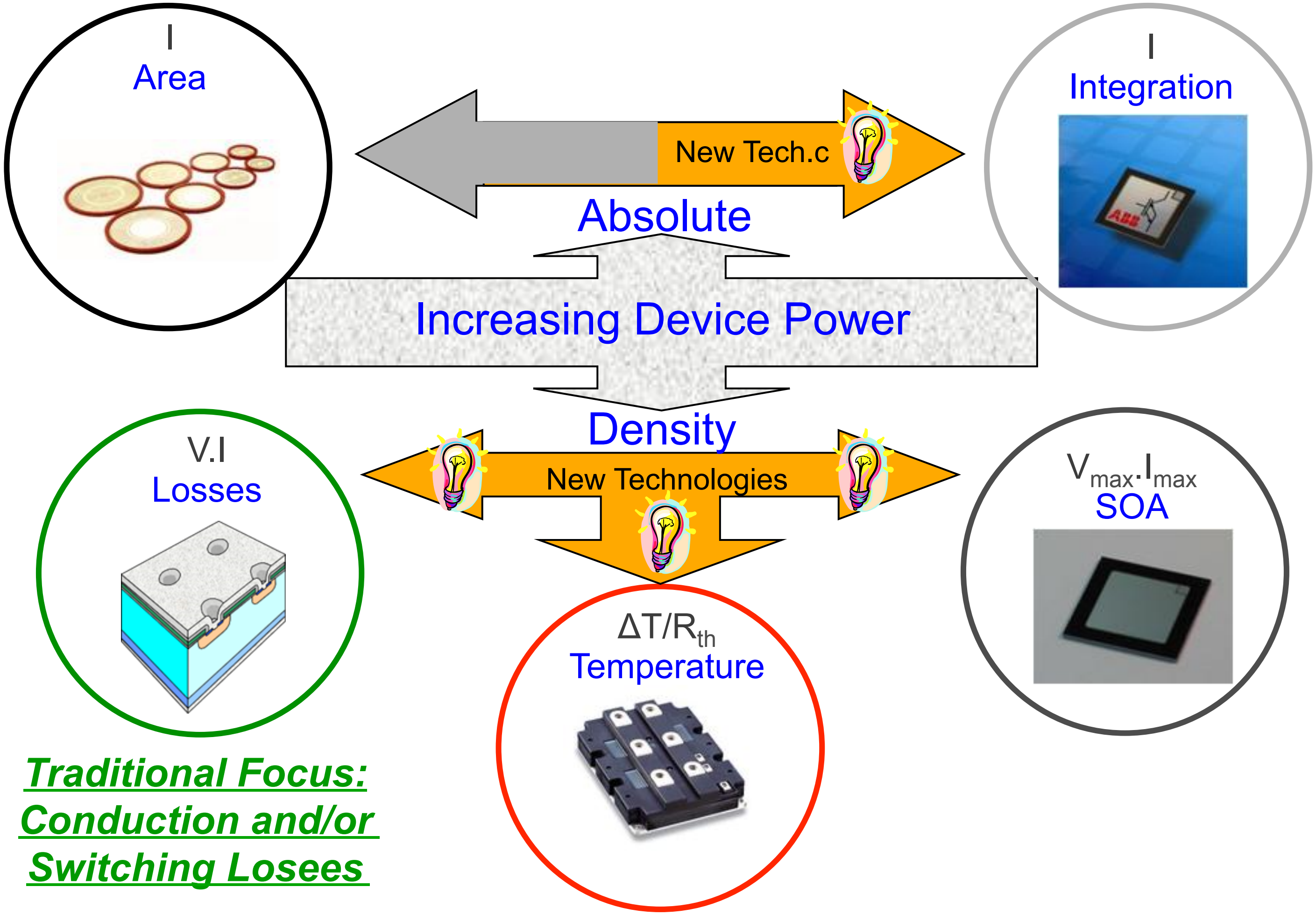




Higher voltage devices can present a stronger challenge

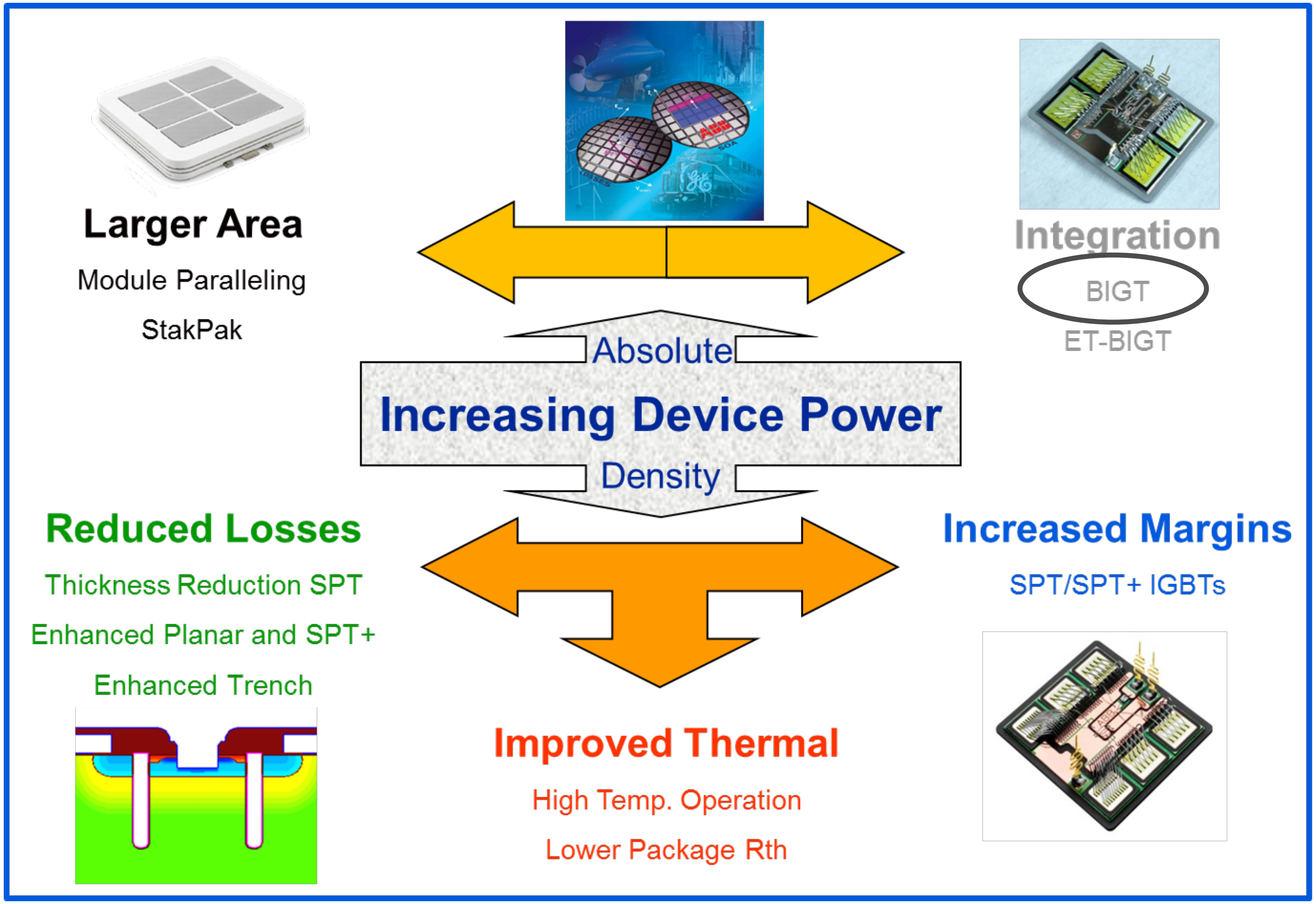
Power Semiconductor Technology Trends

Technology Drivers for higher power



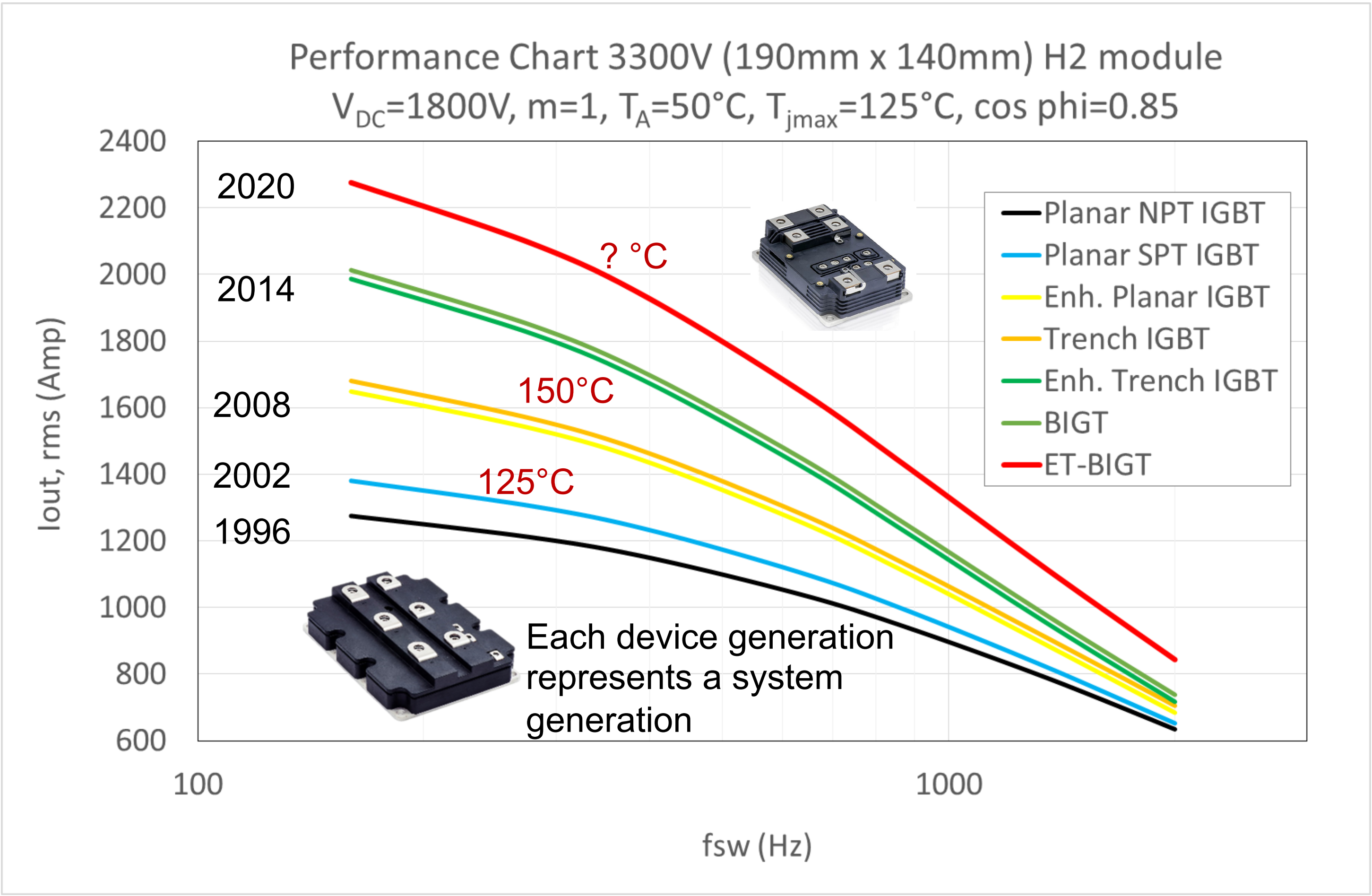
Power Semiconductor Technology Trends

IGBT Technology Drivers for higher power



Power Semiconductor Technology Trends

IGBT technology is on the move on all fronts



Arnost Kopta et al. “Next Generation IGBT and Package Technologies for High Voltage Applications”, IEEE Trans. on Electron Devices, Vol. 64, No. 3, March, 2017

Innovation Examples for Grid System Applications

Bimode Insulated Gate Transistor (BiGT)

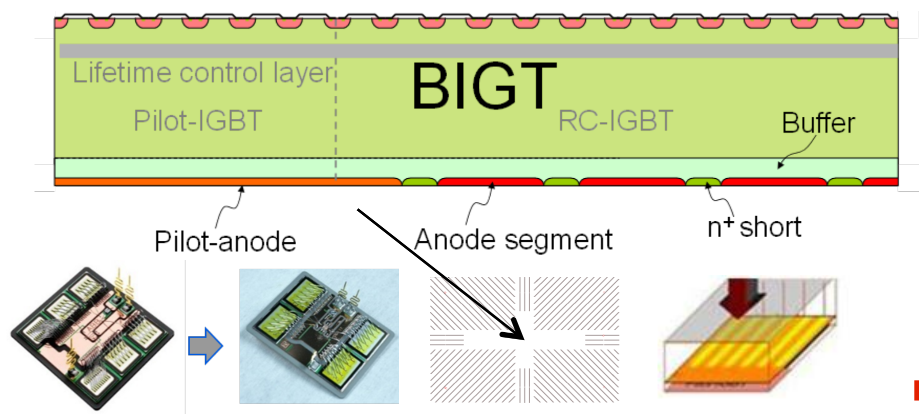
Device Concept

Conventional Solution Un-equal IGBT / diode loading

- Bad silicon utilization and lower area per module

BiGT solution = integrating the diode into the IGBT

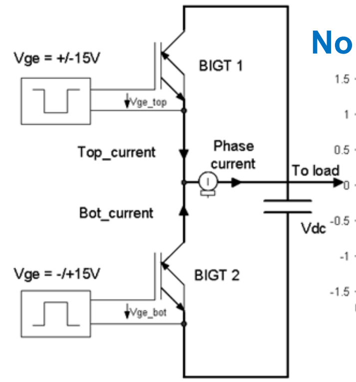
- No inactive periods for improved silicon utilization
- More area for each operational mode (IGBT/Diode)
- Higher total power density possible



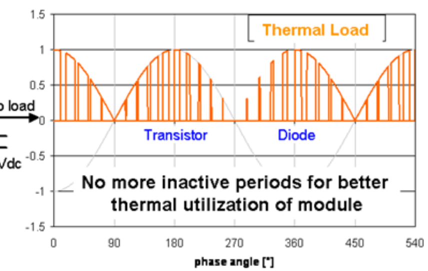
IGBT/Diode

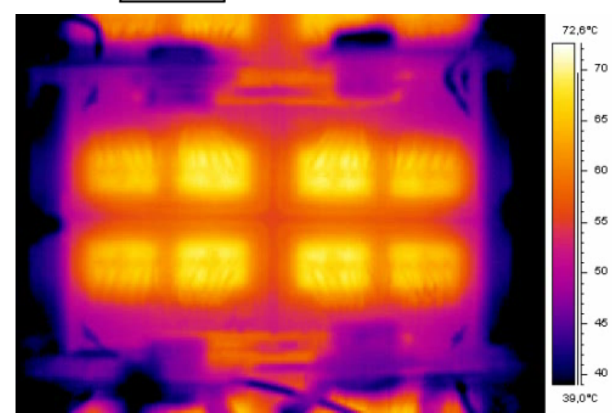
BIGT

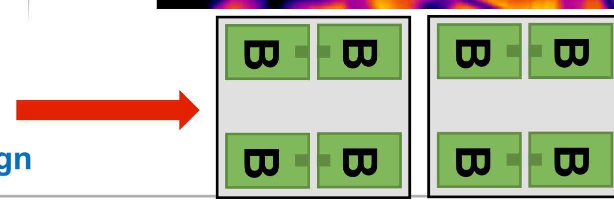
BIGT Chip Radial Shorting Design



No inactive periods for BIGT







Munaf Rahimo et al. "The Bi-mode Insulated Gate Transistor (BIGT) A Potential Technology for Higher Power Applications", ISPSD 2009, Barcelona, Spain

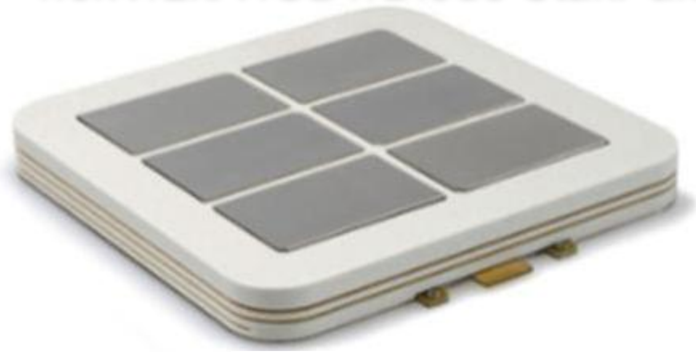
ABB

Next Generation Stakpak BIGT

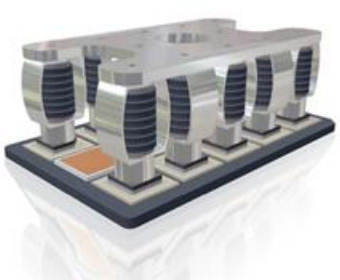
Enabling Higher Power Systems

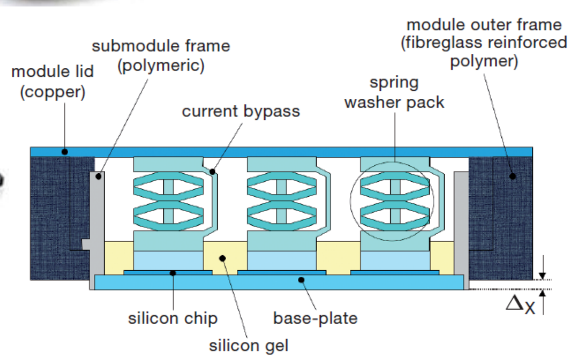
The Stakpak

4.5kV/2kA IGBT/Diode StakPak



Similar Footprint

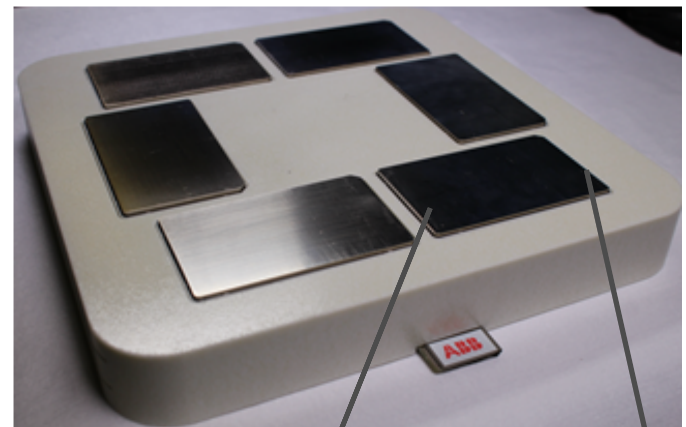




- Press Pack for Series connection and press assemblies
- Modular Concept and pressure tolerant

The most powerful IGBT module today

4.5kV/3kA BIGT StakPak



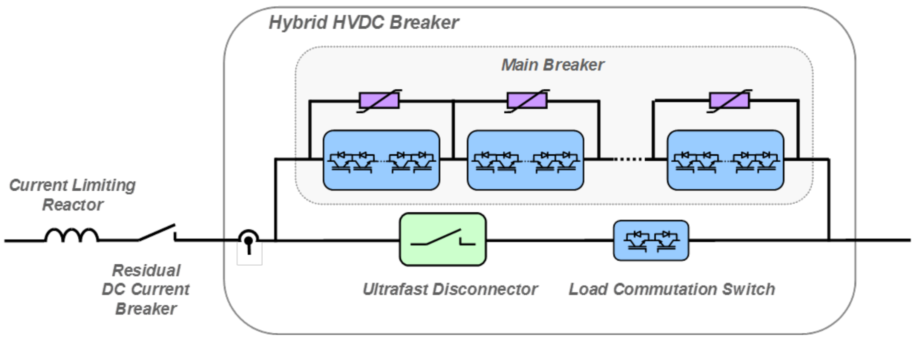
Submodule unit

Franc Dugal et al., "The Next Generation 4500V / 3000A BIGT Stakpak Modules" PCIM 2017, Nuremberg, Germany

Next Generation Stakpak BIGT

Enabling higher breaking current levels for HVDC Breaker

The ABB HVDC Breaker Breakthrough

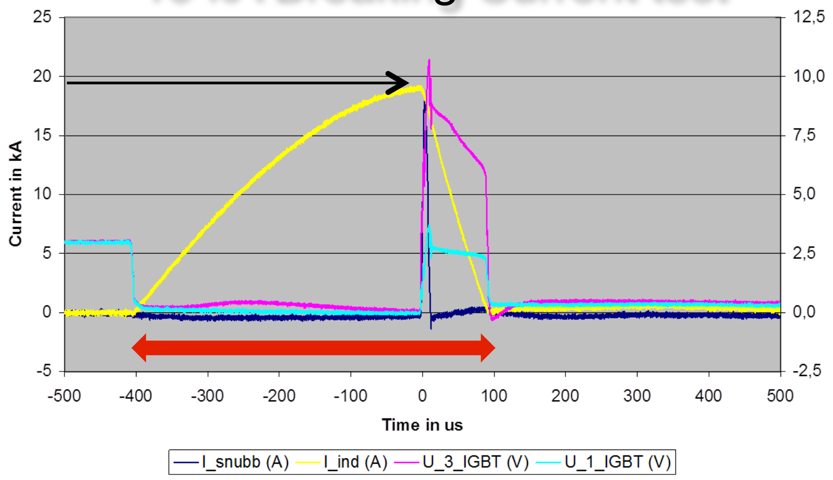


- The hybrid HVDC circuit breaker is capable of blocking and breaking DC currents at thousands of amperes and several hundred thousands of volts

- ABB's new Hybrid HVDC breaker, in simple terms will enable the transmission system to maintain power flow even if there is a fault on one of the lines

The BIGT StakPak breaking current is more than double that achieved with the equivalent IGBT module

19 kA Breaking Current test



Munaf Rahimo et al., "The Bimode Insulated Gate Transistor (BIGT), an ideal power semiconductor for power electronics based DC Breaker applications" CIGRE 2104, Paris, France

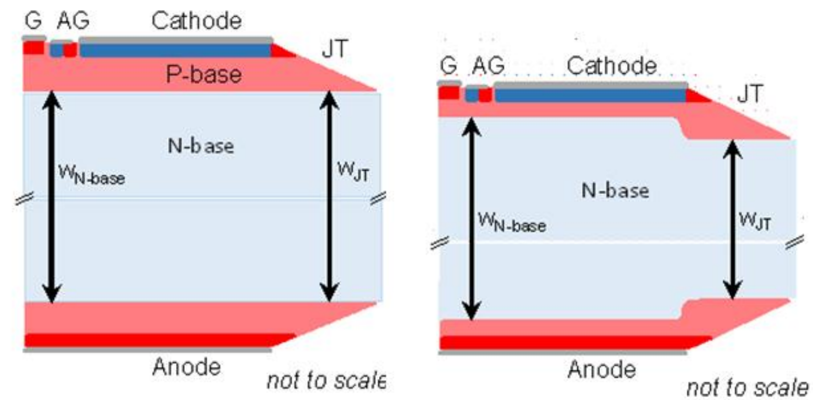
Innovation Examples for Grid System Applications

Phase Controlled Thyristor (PCT)

Higher Power and Lower Losses

150mm RB PCT:
8500 V/4200 A
50 kA surge

New level UHVDC transmission
“Xiangjiaba and Shanghai in China”
(7GW, ±800 kV, 4200A)



Conventional New

The latest low loss PCT technology offers lower conduction losses due to device thickness reduction and optimization

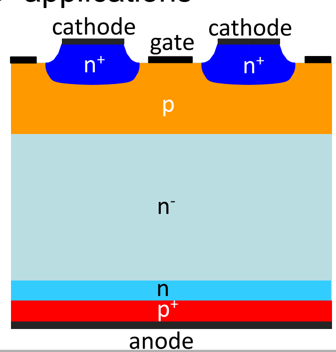
Jan Vobecky et al. “New Low Loss Thyristor for HVDC Transmission”, PCIM 2015, Nuremberg, Germany

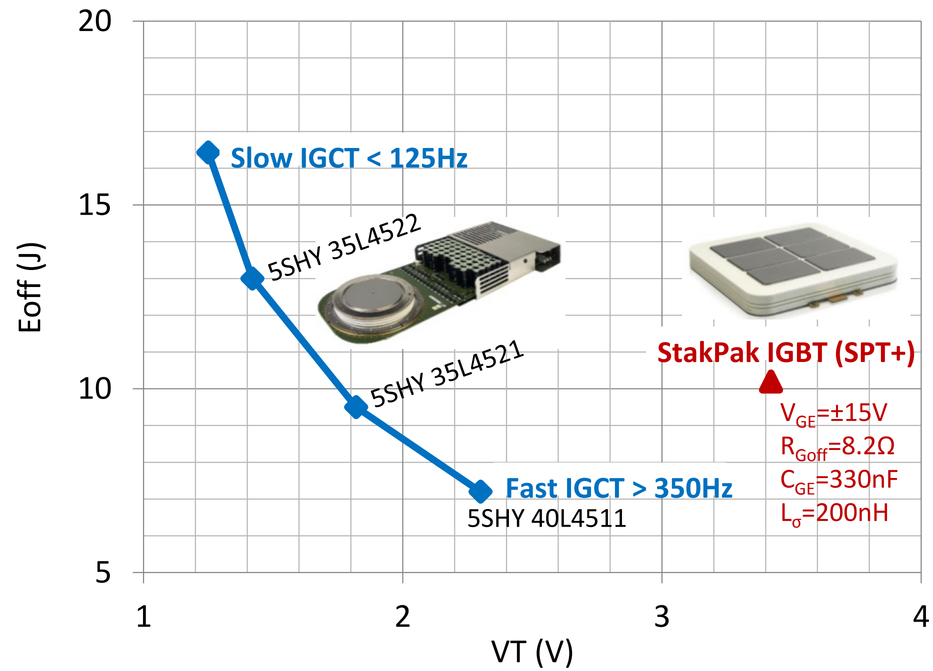
Innovation Examples for Grid System Applications

Integrated Gate Commutated Thyristor (IGCT)

Higher Power and Lower Losses

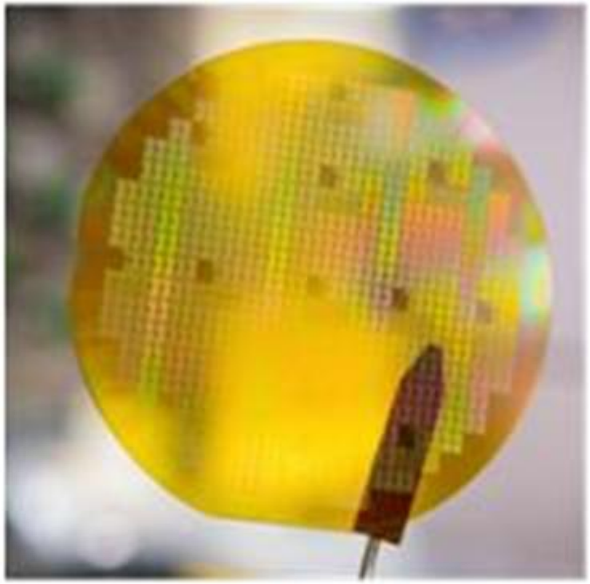
- IGCTs offers low conduction losses and hard turn-off switching
- High Power Technology HPT Improves the SOA capability due to corrugated base junction profile. HPT Technology is enabler for
  - Larger wafer diameters: ~ 150mm
  - Higher voltages: ~ 10kV
  - Higher op. temperatures: ~140°C
  - Integration: RB & RC IGCT, BGCT
  - Losses optimisation for MMC applications





Umamaheswara Vemulapati et al. “Recent Advancements in IGCT Technologies for High Power Electronics Applications”, EPE 2015, Geneva, Switzerland

PART 4: Wide Bandgap Power Semiconductors



Wide Bandgap Semiconductors

A potential leap in performance

Main Features and Drawbacks

Thinner Base Region

= Lower Conduction and Switching Losses = Higher power densities / efficiency at a wider frequency range

= Higher Blocking Capability per single device = Lower losses and lower component count in series

Lower Leakage Current

= Higher Operating Temperatures for higher power densities and optimum cooling

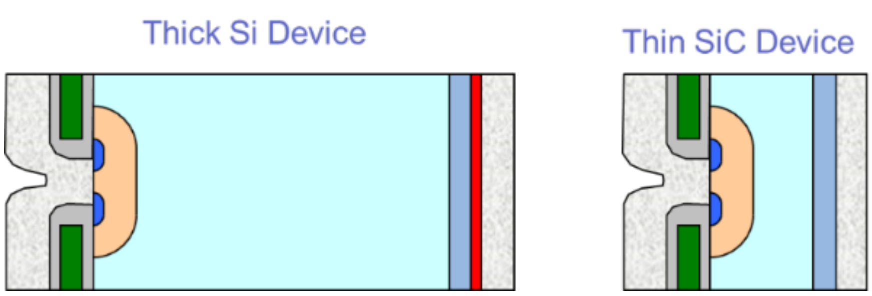
Higher junction built-in Voltage

= Higher conduction losses for bipolar devices such as PIN diode, IGBTs, Thyristors

Today, SiC is utilised for vertical power devices while GaN on substrate is utilised for lateral device concepts with lower power ratings

Parameter		Silicon	4H-SiC	GaN	Diamond
Band-gap E_g	eV	1.12	3.26	3.39	5.47
Critical Field E_{crit}	MV/cm	0.23	2.2	3.3	5.6
Permitivity ε_r	–	11.8	9.7	9.0	5.7
Electron Mobility μ_n	$cm^2/V\cdot s$	1400	950	800/1700*	1800
BFoM: $\varepsilon_r \cdot \mu_n \cdot E_{crit}^3$	rel. to Si	1	500	1300/2700*	9000
Intrinsic Conc. n_i	cm^{-3}	$1.4\cdot10^{10}$	$8.2\cdot10^{-9}$	$1.9\cdot10^{-10}$	$1\cdot10^{-22}$
Thermal Cond. λ	W/cm·K	1.5	3.8	1.3/3**	20

* significant difference between bulk and 2DEG   ** difference between epi and bulk



Silicon Carbide and Gallium Nitride

From low power towards high power applications

Challenges

Material cost and quality will decide the success of WBG devices:

• SiC: material is improving (6” in production) with respect to quality but still very expensive compared to Silicon

• GaN: for GaN on substrate, there is a trade-off between substrate cost and material quality

SiC and GaN devices

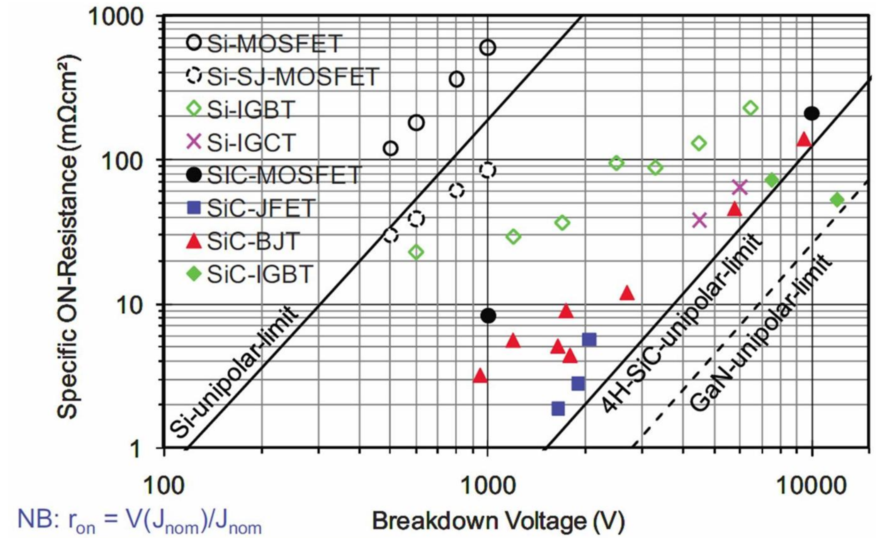
• SiC: For high voltage and high current applications, a vertical power semiconductor is needed. Silicon Carbide provides good options with respect to unipolar devices such as

- Schottky-diodes (well established up to 1700V)
- MOSFETs (well established up to 1700V)
- Higher voltages are possible up to 10 kV but bipolar SiC devices (IGBTs and diodes) needed for higher ratings

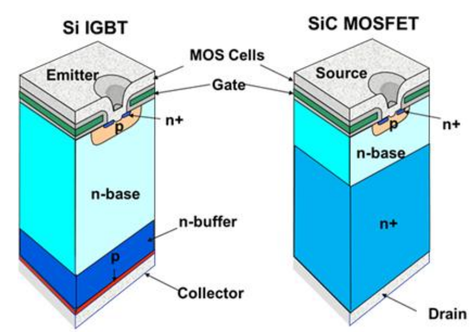
• GaN: Current working device is a HEMT GaN which is a lateral device

- Voltage rating up to 1kV and current ratings few 10s of Amps
- No avalanche capability and de-rating is required
- Higher voltages and vertical device concepts are needed for MW applications

Packaging has to be improved to fully exploit WGB advantages for high switching speeds and high temperature



NB: $r_{on} = V(J_{nom})/J_{nom}$

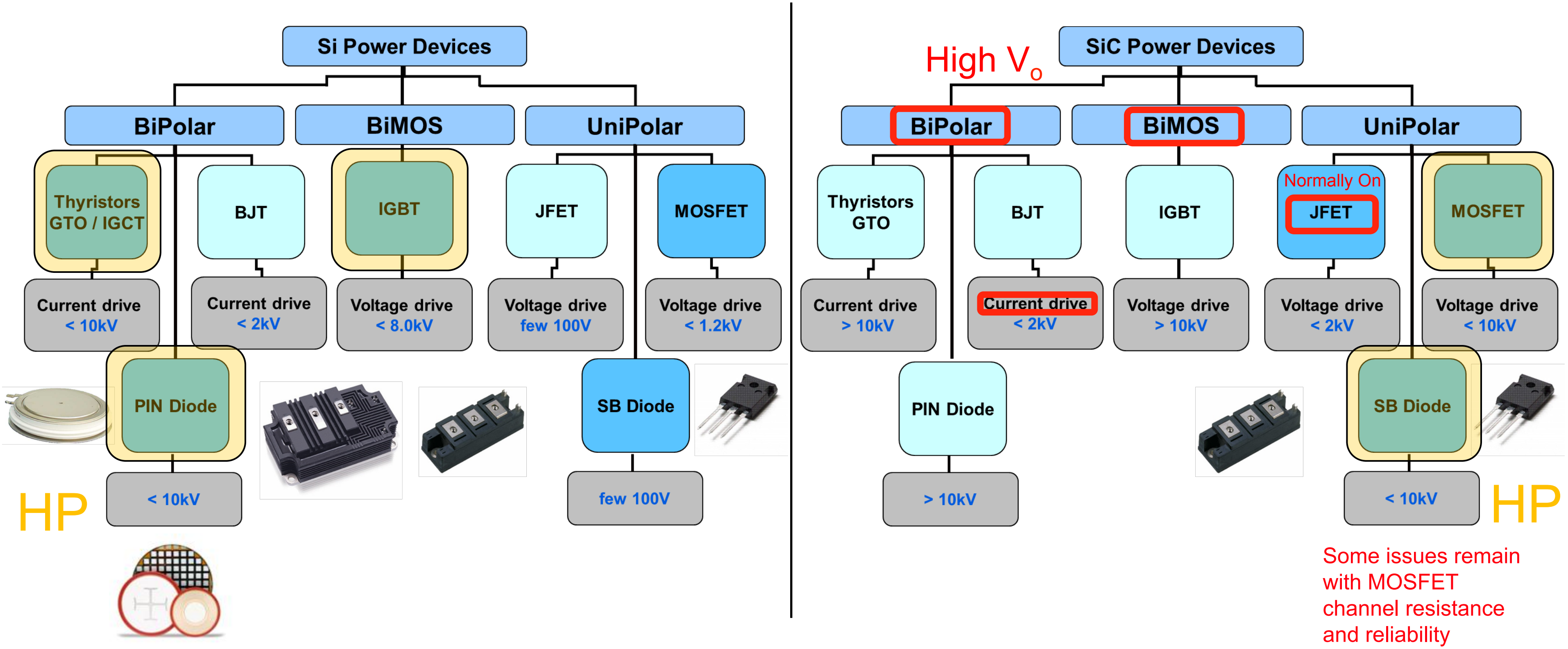


Nando Kaminski et al. “SiC and GaN Devices - Competition or Coexistence?” 7th International Conference on Integrated Power Electronics Systems (CIPS), 2012, Germany

Wide Bandgap Semiconductors

Silicon Carbide device classification compared to Silicon

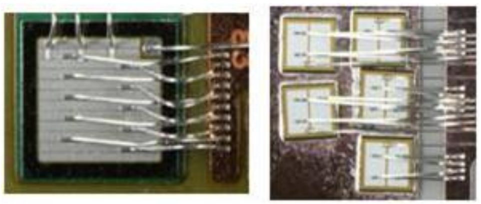
High Power Applications



SiC MOSFETs, close to ideal power device

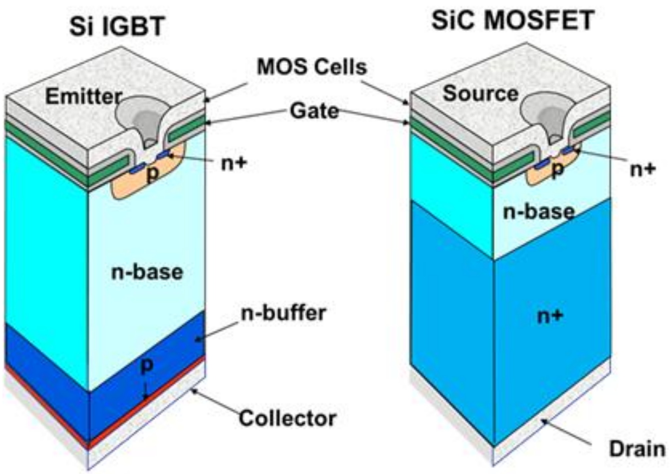
Higher Power Densities / Efficiency at HV

ABB Si IGBT vs. Rohm SiC MOSFET

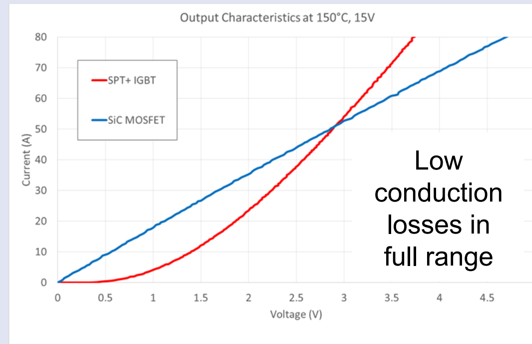


1 x Si IGBT(ABB) 5x SiC MOSFET (Rohm)

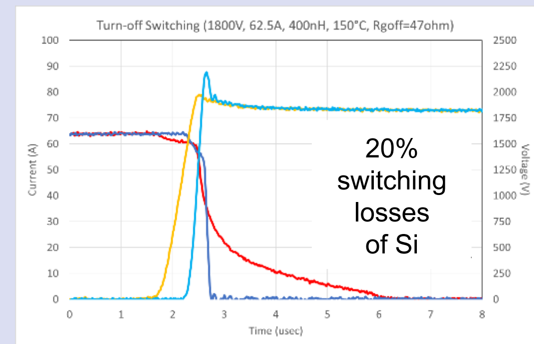
1cm^2 3300V



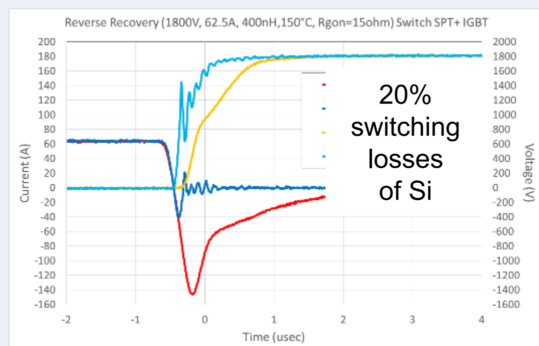
On / Conduct



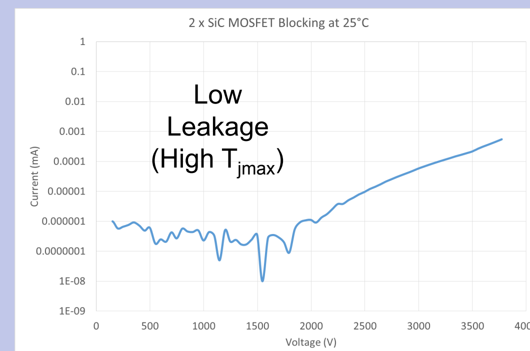
Turn - off



Turn - on, diode recovery



Off / Block

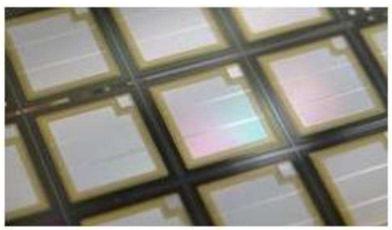


Munaf Rahimo, “Performance evaluation and expected challenges of Silicon Carbide power MOSFETs for high voltage applications”, Materials Science Forum, May, 2017

SiC Developments at ABB

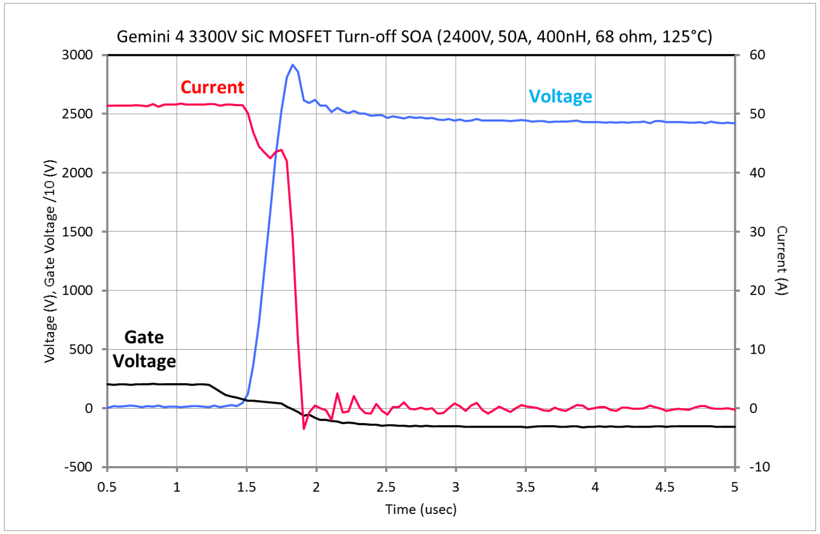
Optimised Devices and Low Inductance Packages

3300V SiC MOSFETs and LinPak



SiC MOSFETs from ABB

Next Generation Low Inductance Module (LinPak)



3.3kV MOSFET Turn-off waveforms

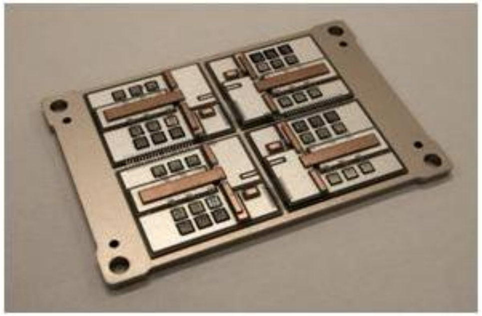


ABB Full SiC Module (Internal View)

Research and Development carried out at ABB Corporate Research Centre, Switzerland

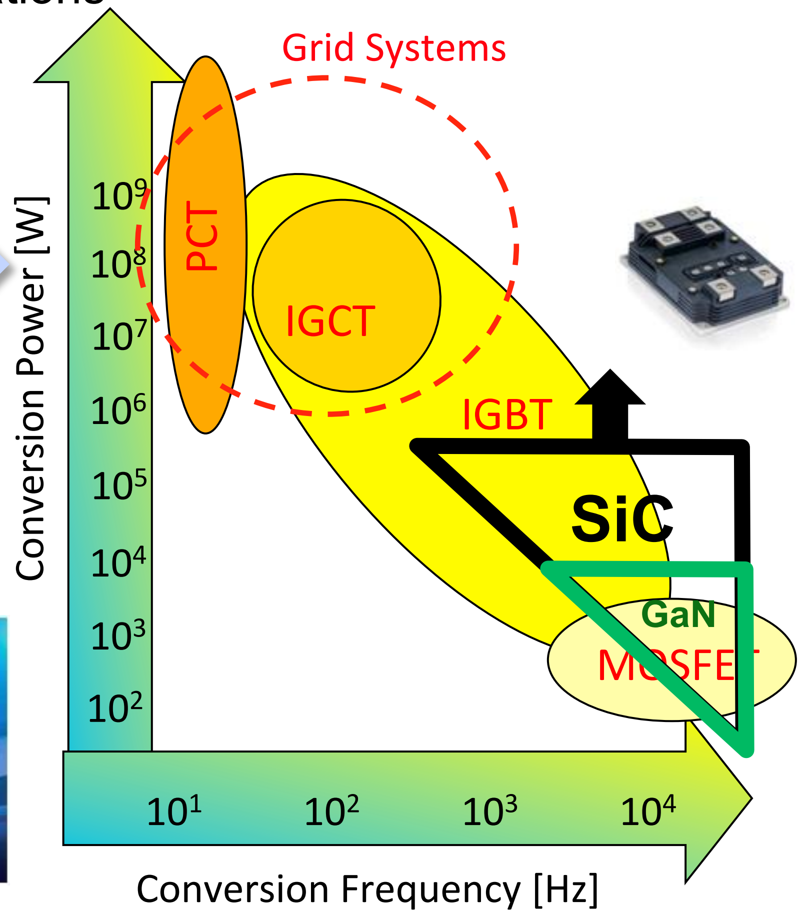
Lars Knoll et al., "Robust 3.3kV Silicon Carbide MOSFETs with Surge and Short Circuit Capability", ISPSD2017, Sapporo, Japan

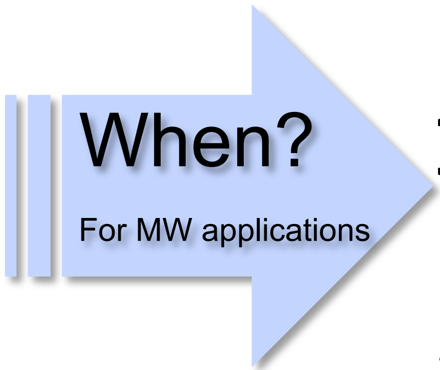
WBG Devices for High Power Applications

High voltage and high current applications

When?

For MW applications





Conclusions

Power semiconductors ...

- ... are a key enabler for modern and future power electronics applications including grid systems.
- Distributed and renewable power are the main features in future grid systems.
- High power semiconductors devices and new system topologies are continuously improving for achieving higher power, improved efficiency and reliability and better controllability.
- The IGBT is the main power device concept for achieving future grid system targets with the potential for improved performance through further losses reductions, higher operating temperatures and integration solutions.
- Wide band-gap based power devices with the potential for high blocking, high temperature and low losses could enable further improvements on the longer term.

ABB