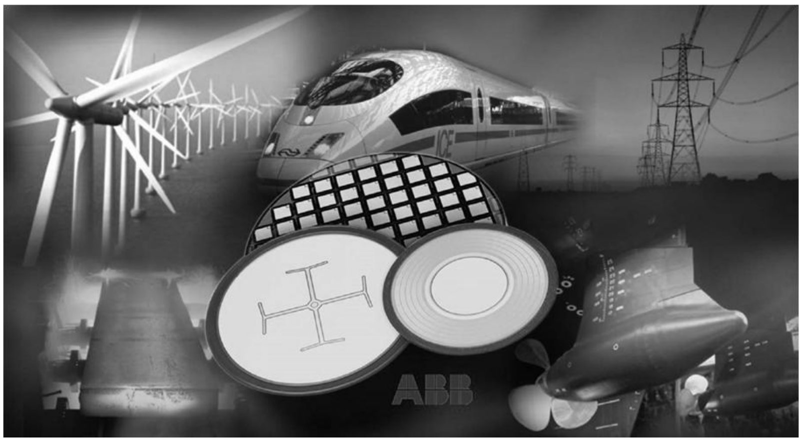

Power Semiconductors for Power Electronics Applications

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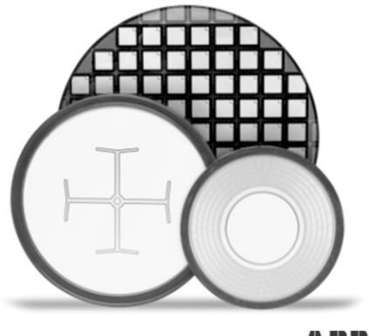
Grid Systems R&D, Power Systems
ABB Switzerland Ltd, Semiconductors

CAS-PSI Special course
Power Converters, Baden
Switzerland, 8th May 2014

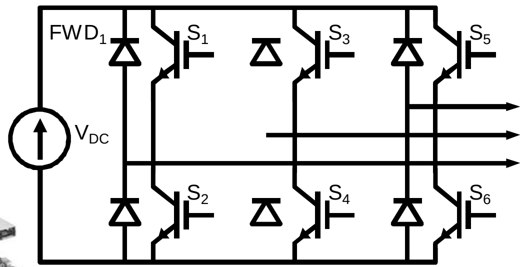
Contents

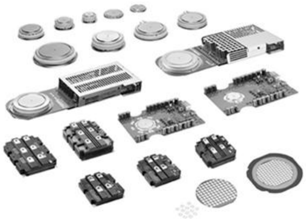
- **Power Electronics and Power Semiconductors**
- **Understanding the Basics**
- **Technologies and Performance**
- **Packaging Concepts**
- **Technology Drivers and Trends**
- **Wide Band gap Technologies**
- **Conclusions**



Power Electronics and

Power Semiconductors





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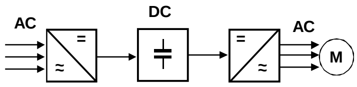
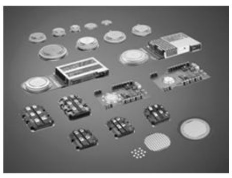
Power Electronics Applications are ….

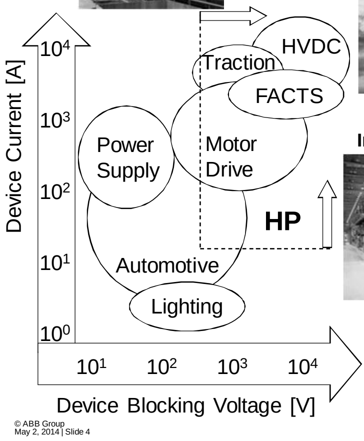
.. an established technology that bridges the power industry with its needs for flexible and fast controllers

Transportation

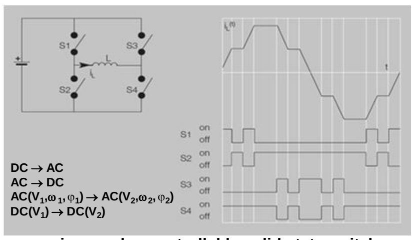


Grid Systems





Industrial Drives



PE conversion employ controllable solid-state switches referred to as "Power Semiconductors"

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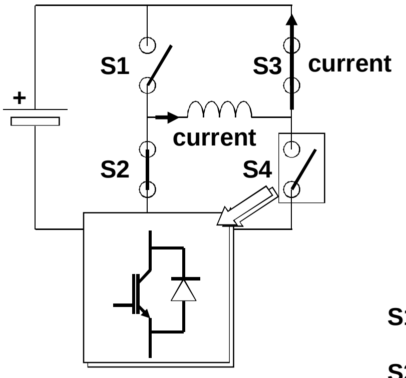
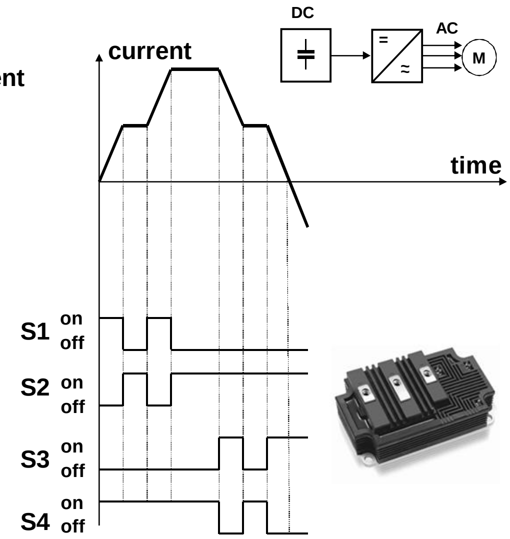
Power Conversion Example (DC/AC)

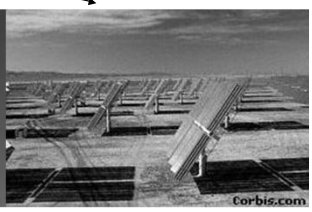




Four simple on/ off switches and a battery are all that is needed to generate an approximately sinusoidal current in an inductor (Load/Motor)

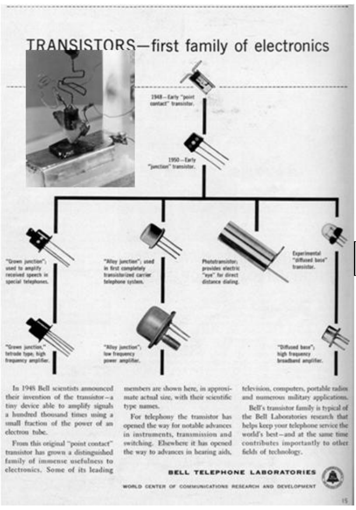
Power Electronics Application Trends

- Traditional: More Compact and Powerful Systems
- Modern: Better Quality and Reliability
- Efficient: Lower Losses
- Custom: Niche and Special Applications
- Solid State: DC Breakers, Transformers
- Environmental: Renewable Energy Sources, Electric/Hybrid Cars

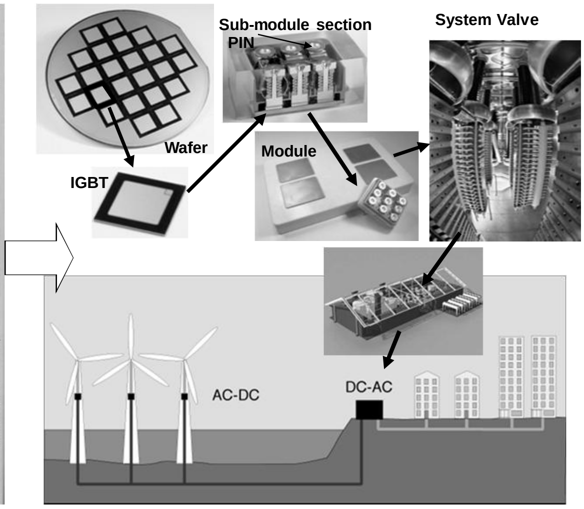


Economic | Environmental | Social

The Semiconductor Revolution



1947: Bell`s Transistor



Today: GW IGBT based HVDC systems

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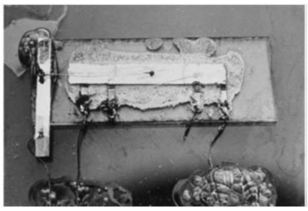
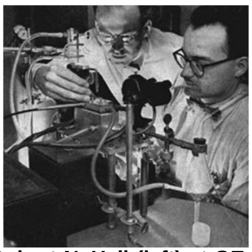
Semiconductors, Towards Higher Speeds & Power

- 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 applications and markets



Kilby`s first IC in 1958



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

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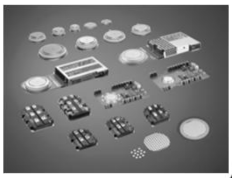
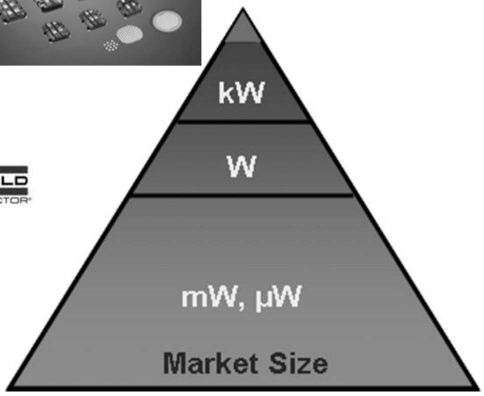
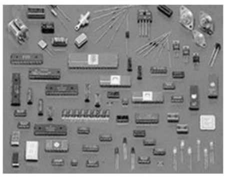
The Global Semiconductor Market and Producers

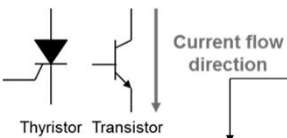


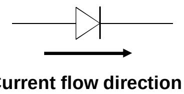




Power Semiconductors; the Principle

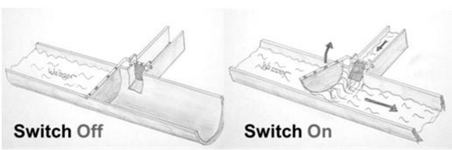
Power Semiconductor

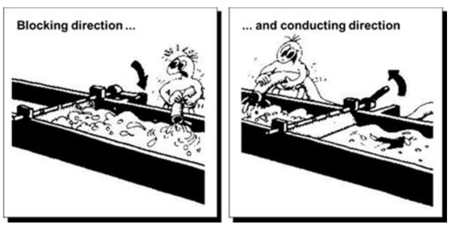




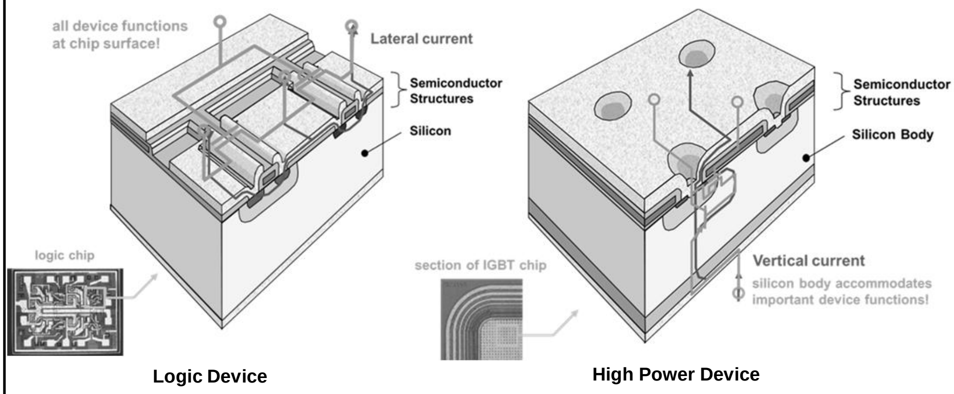
Switches
(MOSFET, IGBT, Thyistor)

Rectifiers
(Diodes)





Power Semiconductor Device Main Functions



- **Main Functions of the power device:**
  - **Support the off-voltage (Thousands of Volts)**
  - **Conduct currents when switch is on (Hundreds of Amps per cm²)**

Switch

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Silicon Switch/Diode Classification

Si Power Devices

- **BiPolar**
  - **Thyristors GTO/IGCT Triac**
    - ▪ Current drive
    - ▪ up to 10kV
  - **BJT**
    - ▪ Current drive
    - ▪ up to 2kV
  - **PIN Diode**
    - ▪ up to 13kV
- **BiMOS**
  - **IGBT (Lat. & Ver.)**
    - ▪ Voltage drive
    - ▪ up to 6.5kV
- **UniPolar**
  - **JFET**
    - ▪ Voltage drive
    - ▪ few 100V
  - **MOSFET (Lat. & Ver.)**
    - ▪ Voltage drive
    - ▪ up to 1.2kV
  - **SB Diode**
    - ▪ few 100V

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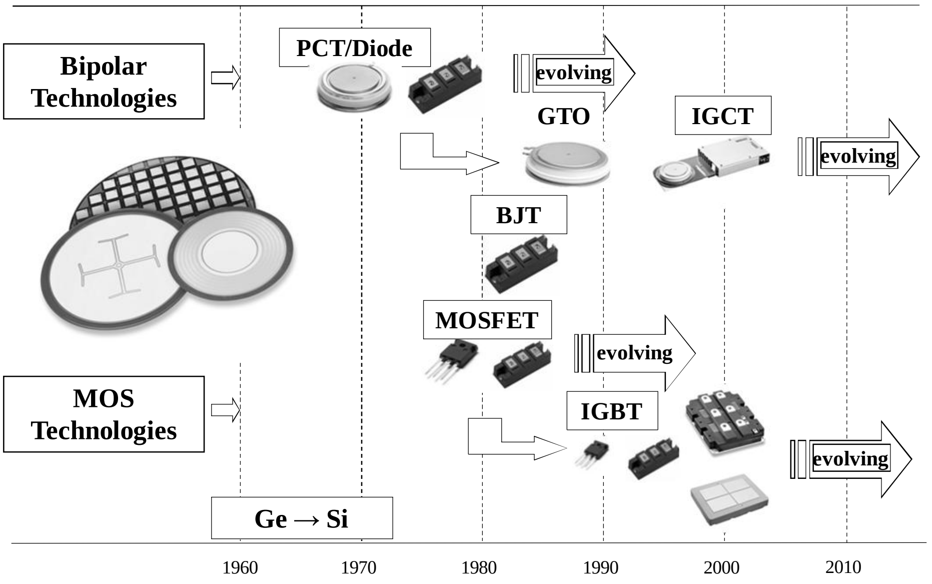
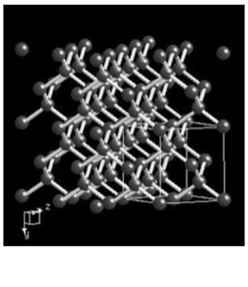
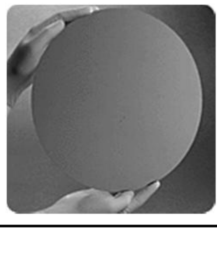
Evolution of Silicon Based Power Devices

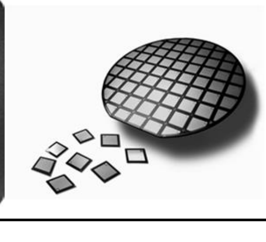


Silicon, the main power semiconductor material



- Silicon is the second most common chemical element in the crust of the earth (27.7% vs. 46.6% of Oxygen)
- Stones and sand are mostly consisting of Silicon and Oxygen (SiO_2)
- For Semiconductors, we need an almost perfect Silicon crystal
- Silicon crystals for semiconductor applications are probably the best organized structures on earth
- Before the fabrication of chips, the semiconductor wafer is doped with minute amounts of foreign atoms (p “B, Al” or n “P, As” type doping)





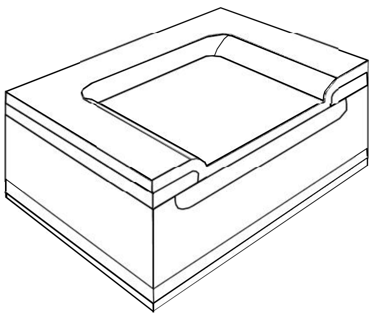
Power Semiconductor Processes

- 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

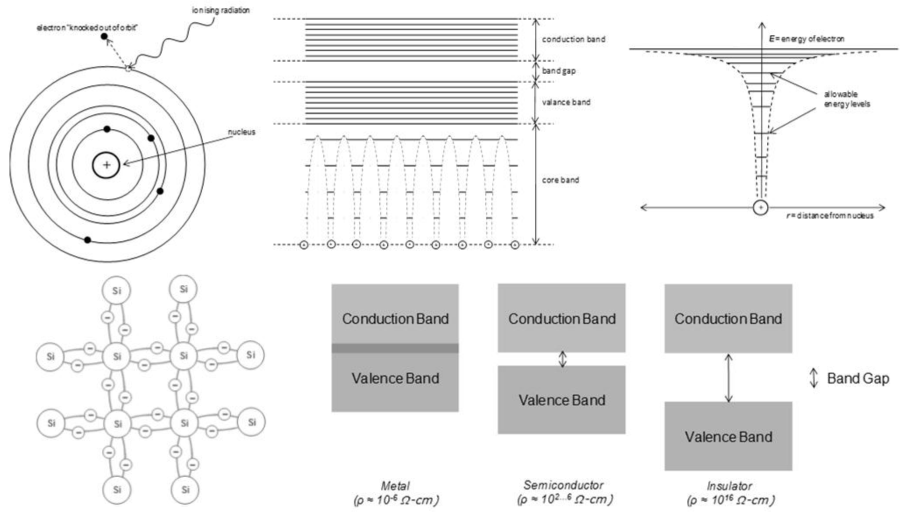
Device	Critical Dimension	Min. doping concentration	Max. Process Temperature*
Logic Devices	0.1 - 0.2 μm	10^{15} cm^{-3}	1050 - 1100°C (minutes)
MOSFET, IGBT	1 - 2 μm	10^{13} - 10^{14} cm^{-3}	1250°C (hours)
Thyristor, GTO, IGCT	10 -20 μm	< 10^{13} cm^{-3}	1280-1300°C(days) melts at 1360°C

- 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

Power Semiconductors
Understanding The Basics



… without diving into semiconductor physics …

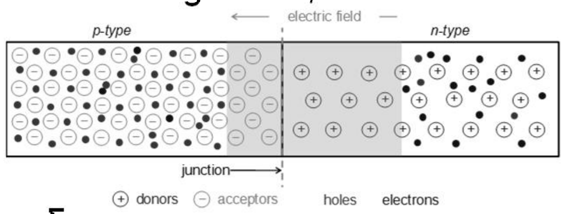


***Power Semiconductors*, S. Linder, EPFL Press**

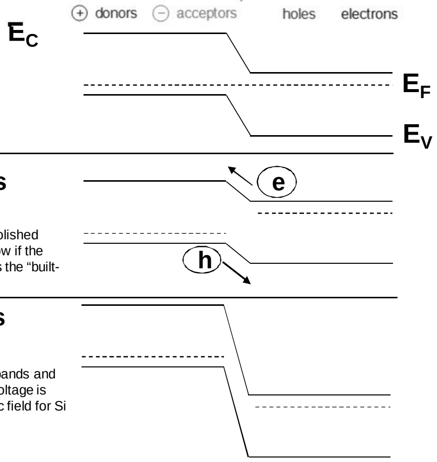
ISBN 2-940222-09-6

The Basic Building Block; The PN Junction

Anode



Cathode



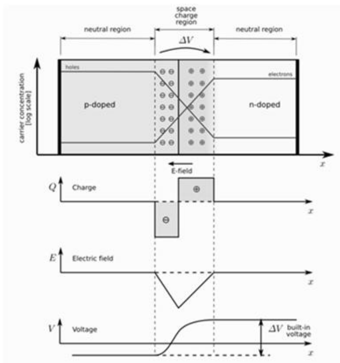
No Bias

Forward Bias P(+)N(-)

Space-charge region abolished and a current starts to flow if the external voltage exceeds the "built-in" voltage ~ 0.7 V

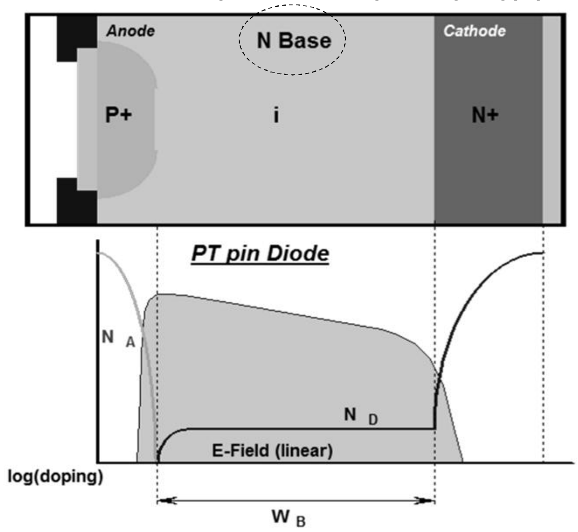
Reverse Bias P(-)N(+)

Space-charge region expands and avalanche break-down voltage is reached at critical electric field for Si ($2x10^5$V/cm)



The PIN Bipolar Power Diode

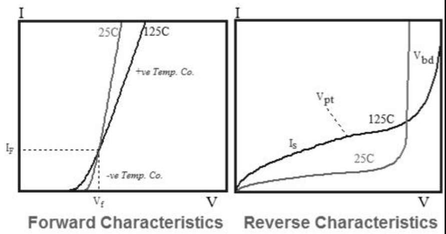
The low doped drift (base) region is the main differentiator for power devices (normally n-type)

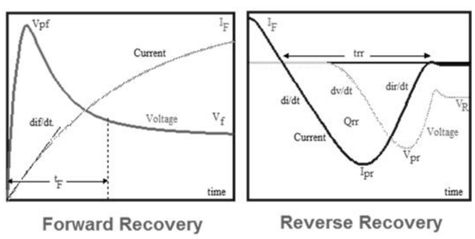


Power Diode Structure and Doping Profile

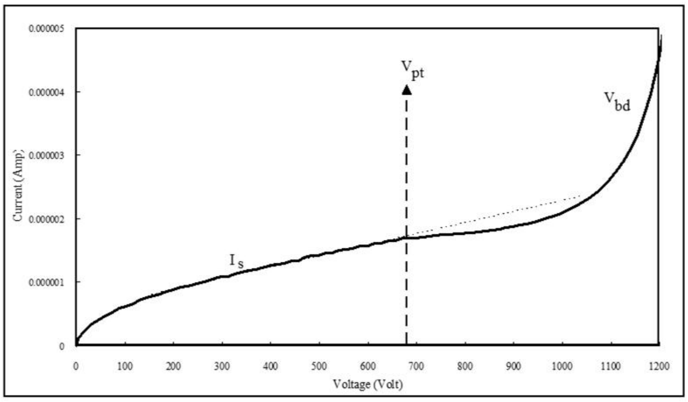
Power Diode Operational Modes

- Reverse Blocking State
  - Stable reverse blocking
  - Low leakage current
- Forward Conducting State
  - Low on-state losses
  - Positive temperature coefficient
- Turn-On (forward recovery)
  - Low turn-on losses
  - Short turn-on time
  - Good controllability
- Turn-Off (reverse recovery)
  - Low turn-off losses
  - Short turn-off time
  - Soft characteristics
  - Dynamic ruggedness





The Power Diode in Reverse Blocking Mode

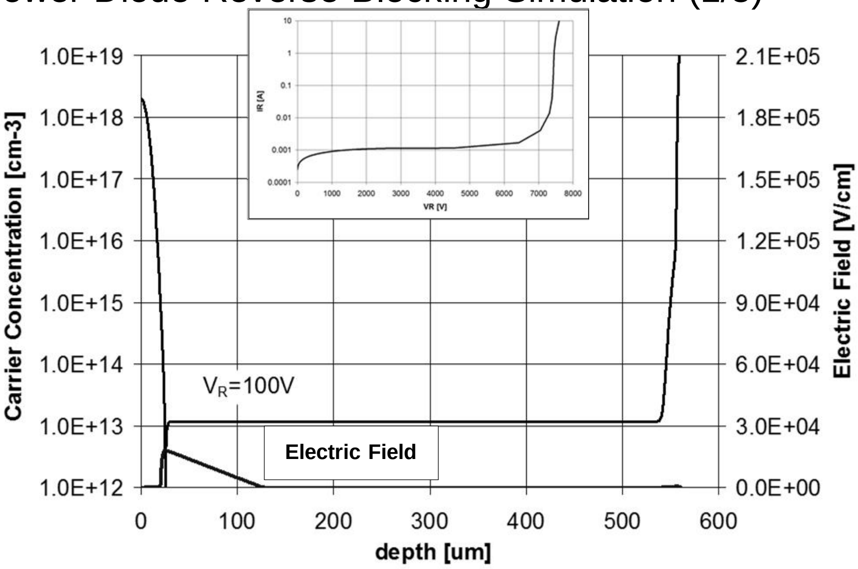


$V_{bd} = 5.34 \times 10^{13} N_D^{-3/4}$ **Non - Punch Through Breakdown Voltage**

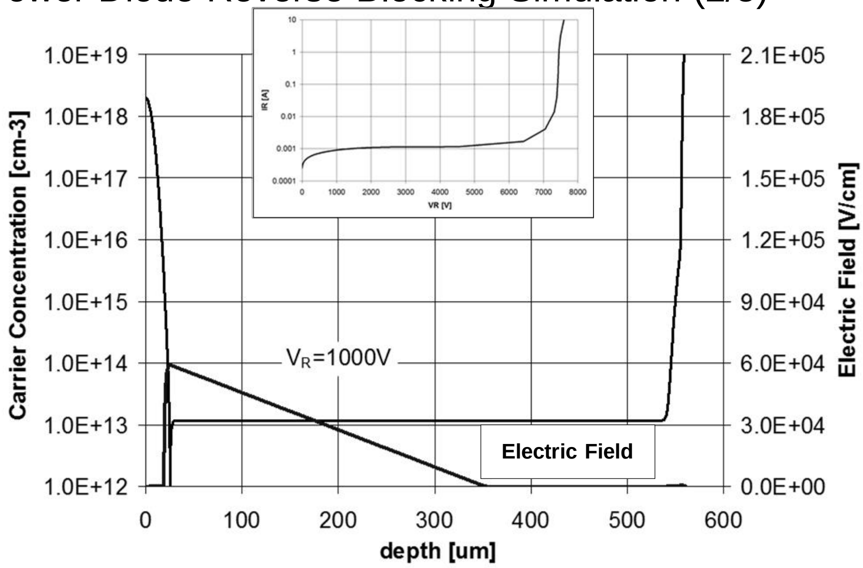
$V_{pt} = 7.67 \times 10^{-12} N_D W_B$ **Punch Through Voltage**

- **All the constants on the right hand side of the above equations have units which will result in a final unit in (Volts).**

Power Diode Reverse Blocking Simulation (1/5)

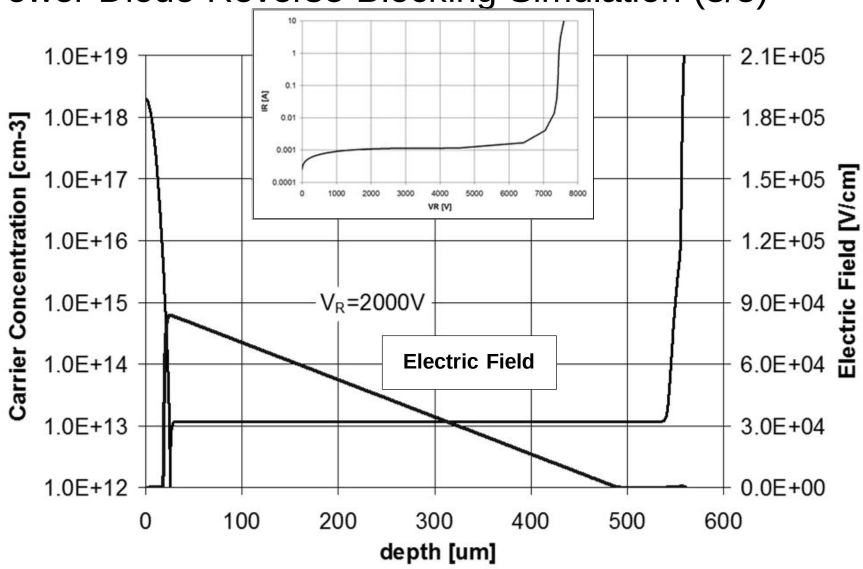


Power Diode Reverse Blocking Simulation (2/5)



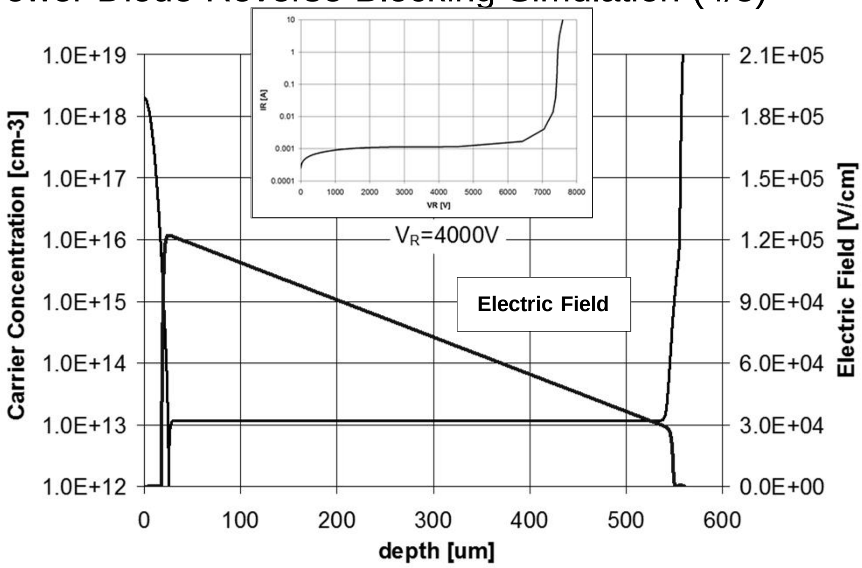
May 2, 2014 | Slide 23

Power Diode Reverse Blocking Simulation (3/5)

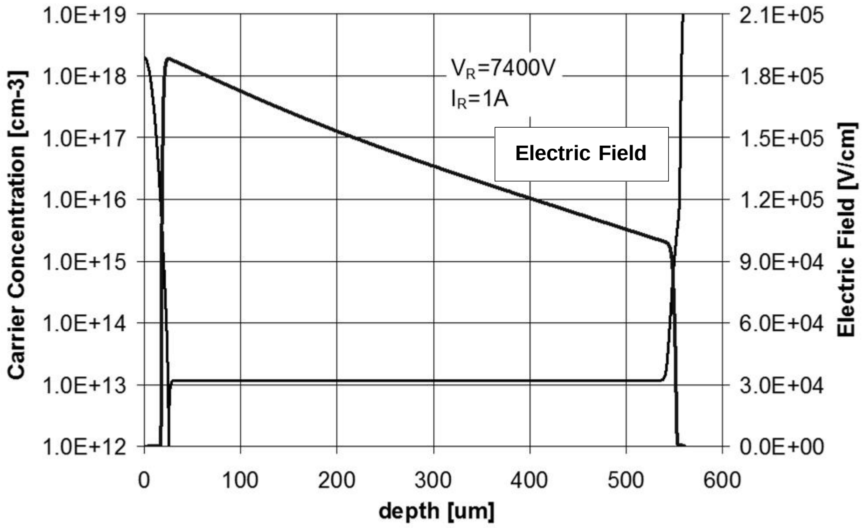


May 2, 2014 | Slide 24

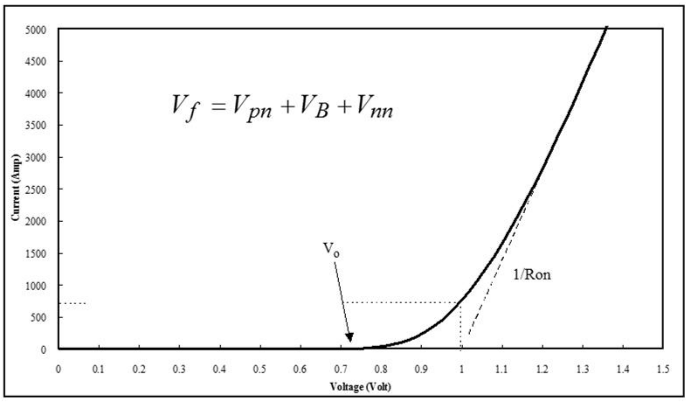
Power Diode Reverse Blocking Simulation (4/5)



Power Diode Reverse Blocking Simulation (5/5)

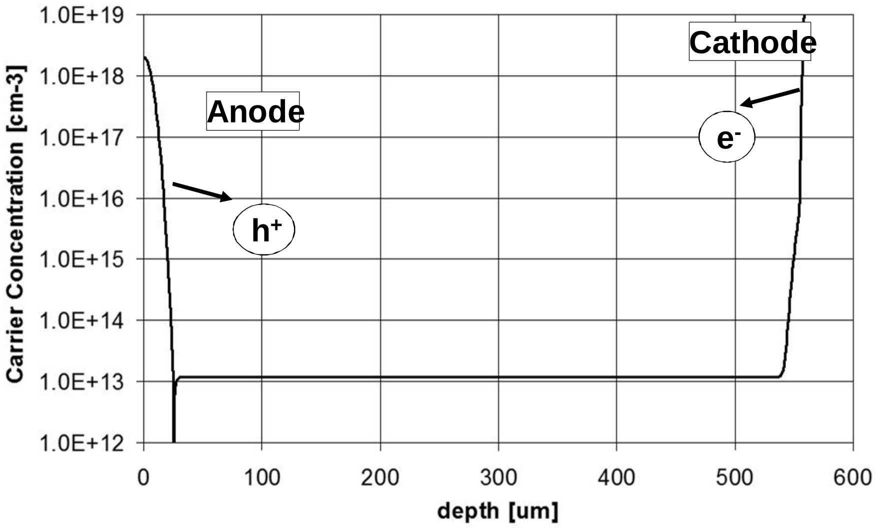


Power Diode in Forward Conduction Mode

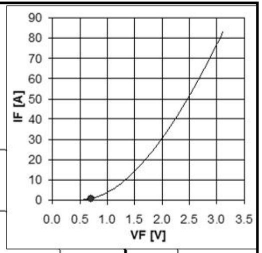


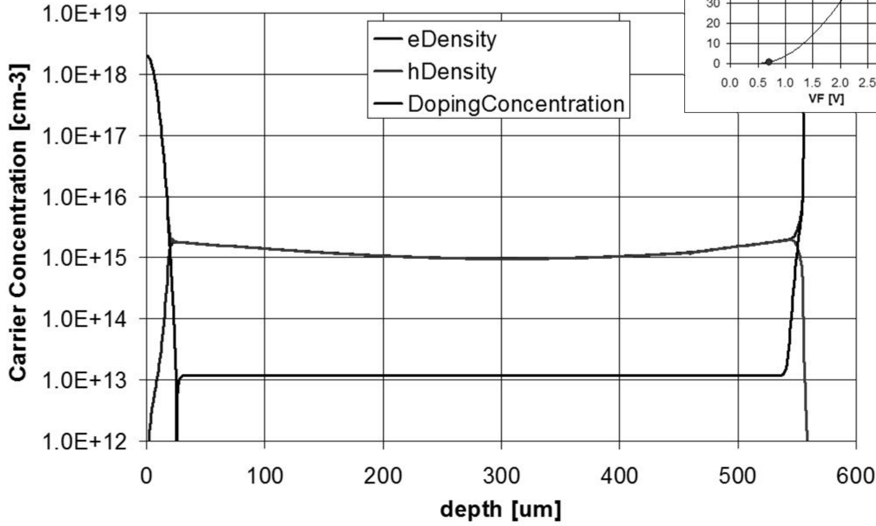
$$V_B = \frac{2kT}{q}\left(\frac{W_B}{2L_a}\right)^2$$ **Base (Drift) Region Voltage Drop**

Power Diode Forward Conduction Simulation (1/5)



Forward Conduction Simulation (2/5)





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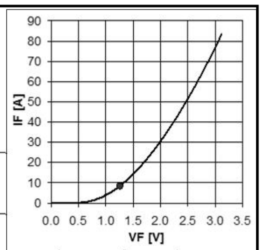
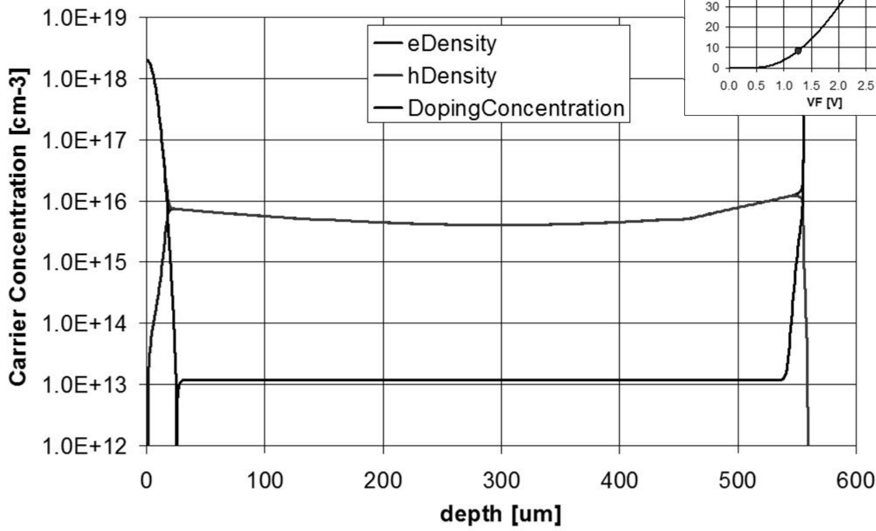
Forward Conduction Simulation (3/5)





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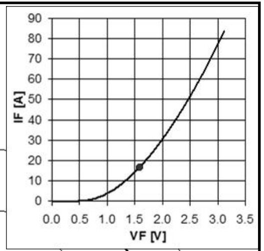
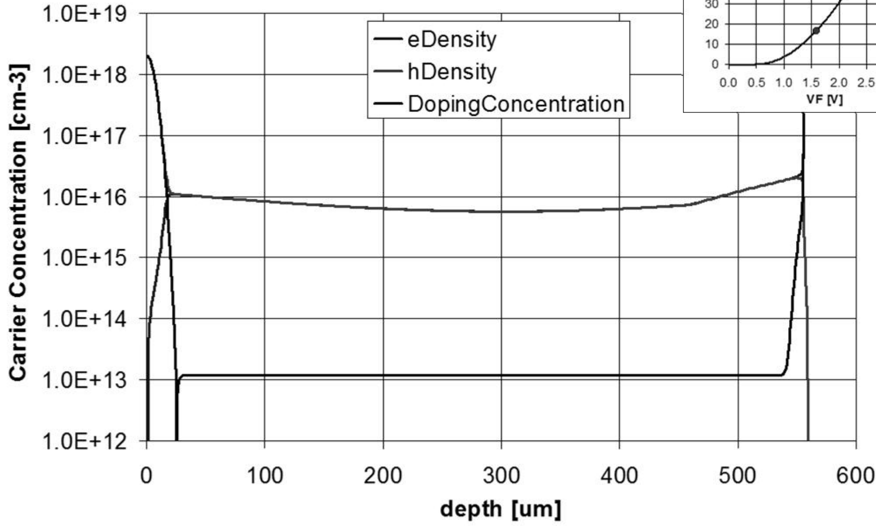
Forward Conduction Simulation (4/5)





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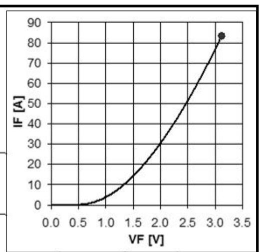
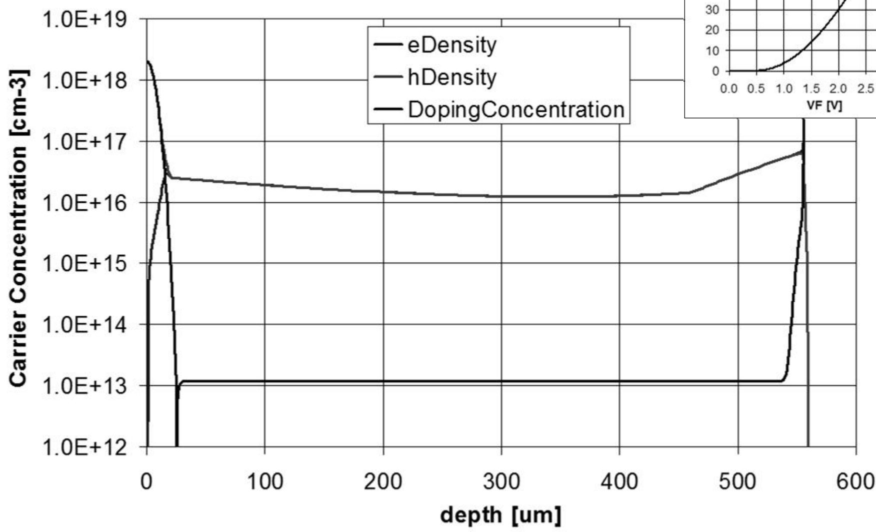
Forward Conduction Simulation (5/5)





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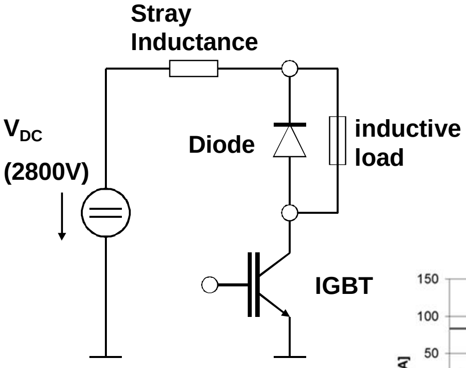
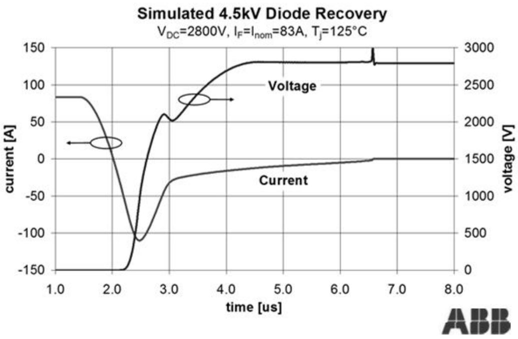
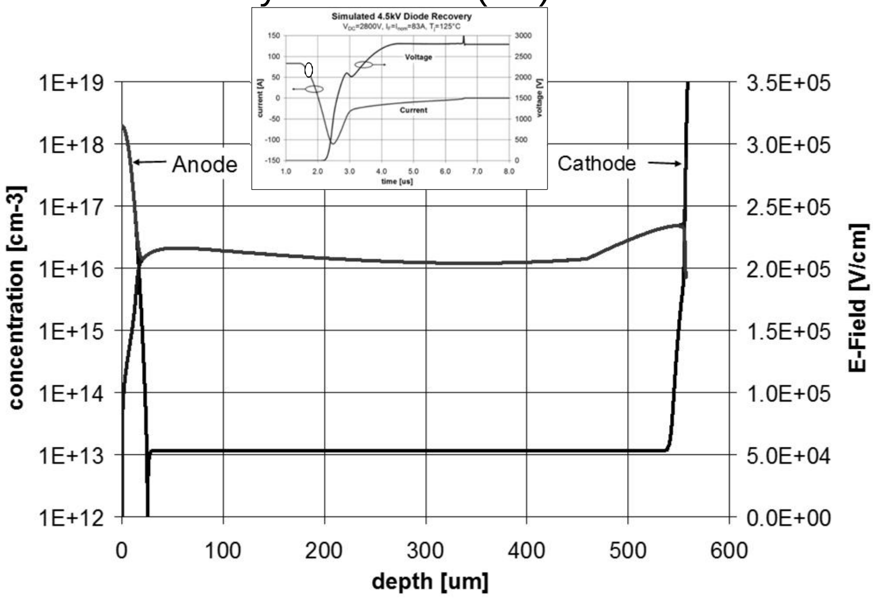
Power Diode Reverse Recovery

- Reverse Recovery: Transition from the conducting to the blocking state

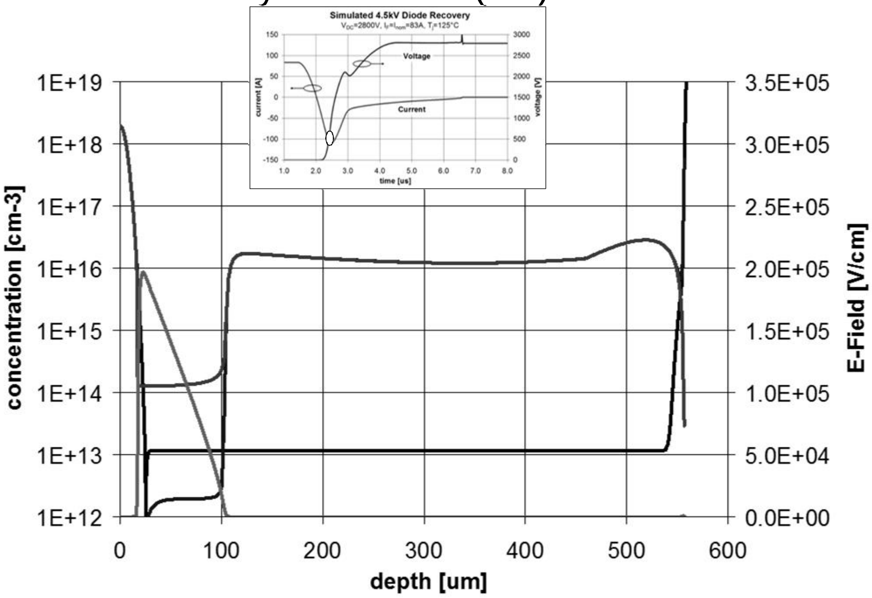




Reverse Recovery Simulation (1/5)



Reverse Recovery Simulation (2/5)



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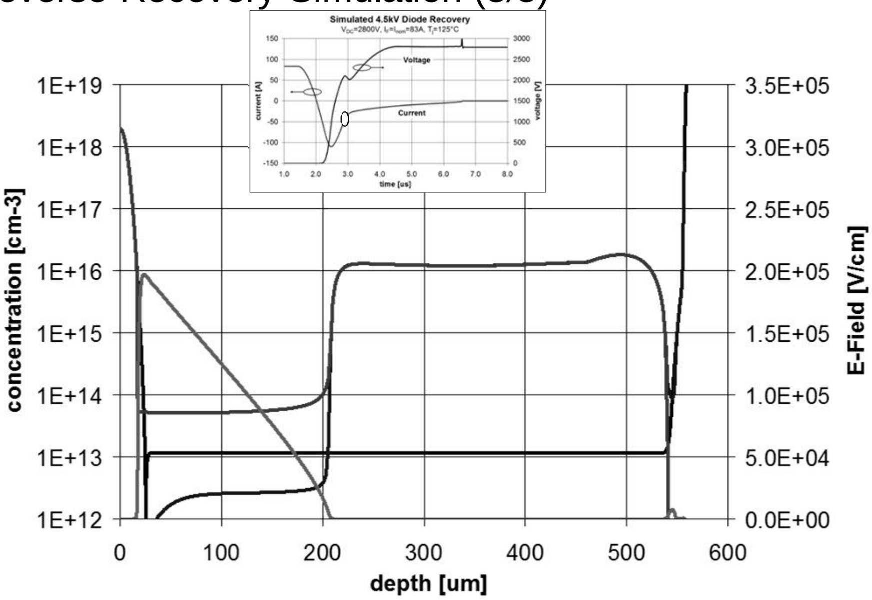
Reverse Recovery Simulation (3/5)



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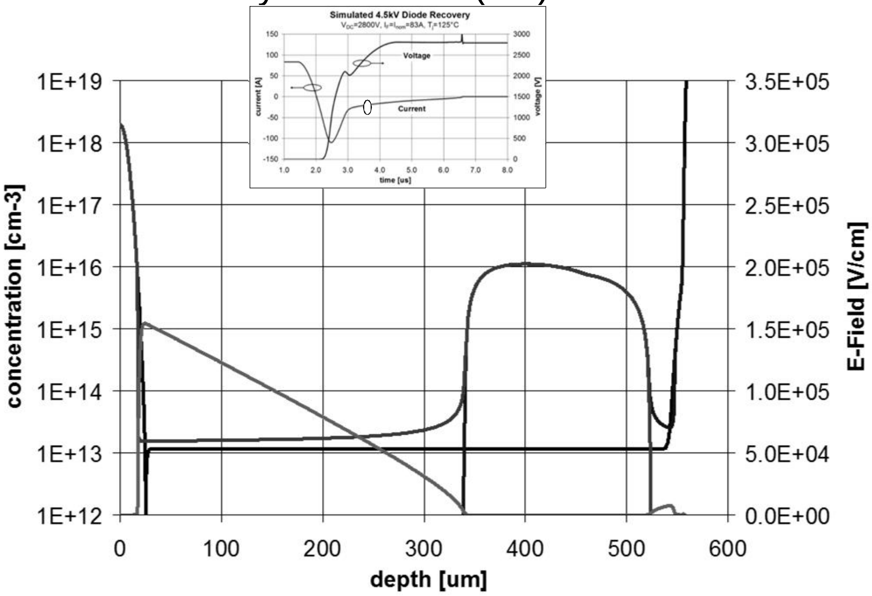
Reverse Recovery Simulation (4/5)



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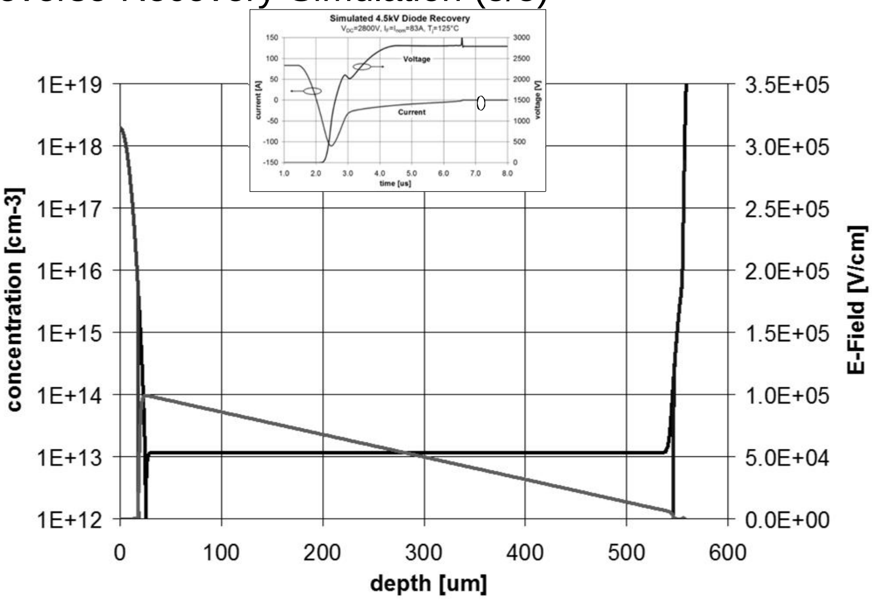
Reverse Recovery Simulation (5/5)



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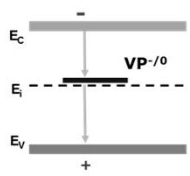
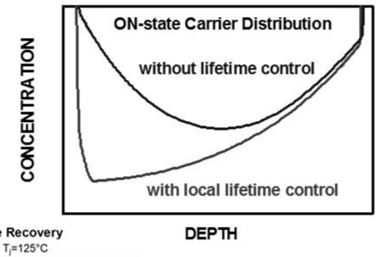
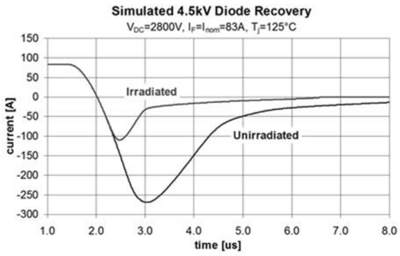
Lifetime Engineering of Power Diodes

- Recombination Lifetime: Average value of time (ns - us) after which free carriers recombine (= disappear).
- Lifetime Control: Controlled introduction of lattice defects ➔ enhanced carrier recombination ➔ shaping of the carrier distribution

Example of carrier recombination in Silicon:

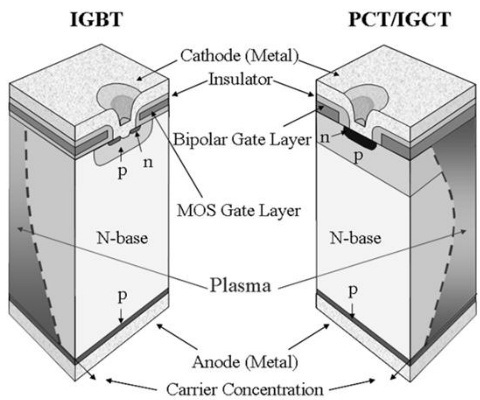






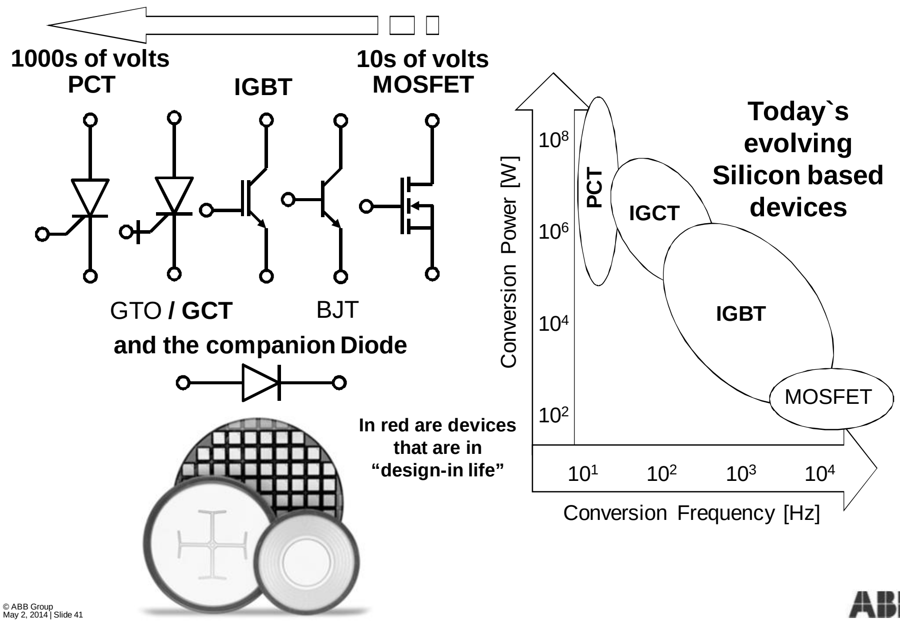
ABB

Power Semiconductors
Technologies and Performance



ABB

Silicon Power Semiconductor Device Concepts



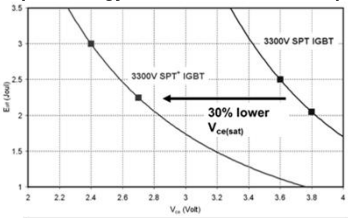
Silicon Power Semiconductor Switches

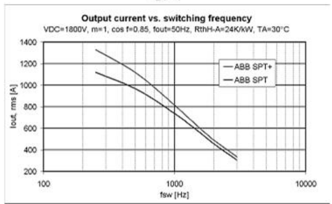
Technology	Device Character	Control Type
Bipolar (Thyristor) Thyristor, GTO, GCT	Low on-state losses High Turn-off losses	Current Controlled ("High" control power)
Bipolar (Transistor) BJT, Darlington	Medium on-state losses Medium Turn-off losses	Current Controlled ("High" control power)
BiMOS (Transistor) IGBT	Medium on-state losses Medium Turn-off losses	Voltage Controlled (Low control power)
Unipolar (Transistor) MOSFET, JFET	High on-state losses Low Turn-off losses	Voltage Controlled (Low control power)

Performance Requirements for Power Devices

- **Power Density Handling Capability:**
  - Low on-state and switching losses
  - High operating temperatures
  - Low thermal resistance
- **Controllable and Soft Switching:**
  - Good turn-on controllability
  - Soft and controllable turn-off and low EMI
- **Ruggedness and Reliability:**
  - High turn-off current capability
  - Robust short circuit mode for IGBTs
  - Good surge current capability
  - Good current / voltage sharing for paralleled / series devices
  - Stable blocking behaviour and low leakage current
  - Low “Failure In Time” FIT rates
  - Compact, powerful and reliable packaging

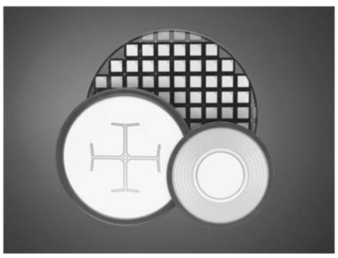
(technology curve: traditional focus)

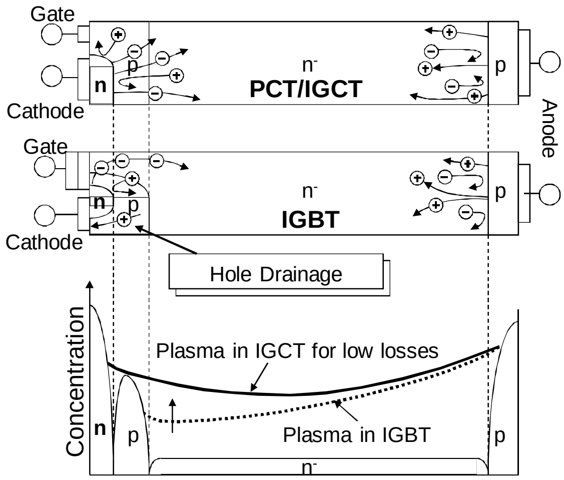




ABB

The main High Power MW Devices: LOW LOSSES

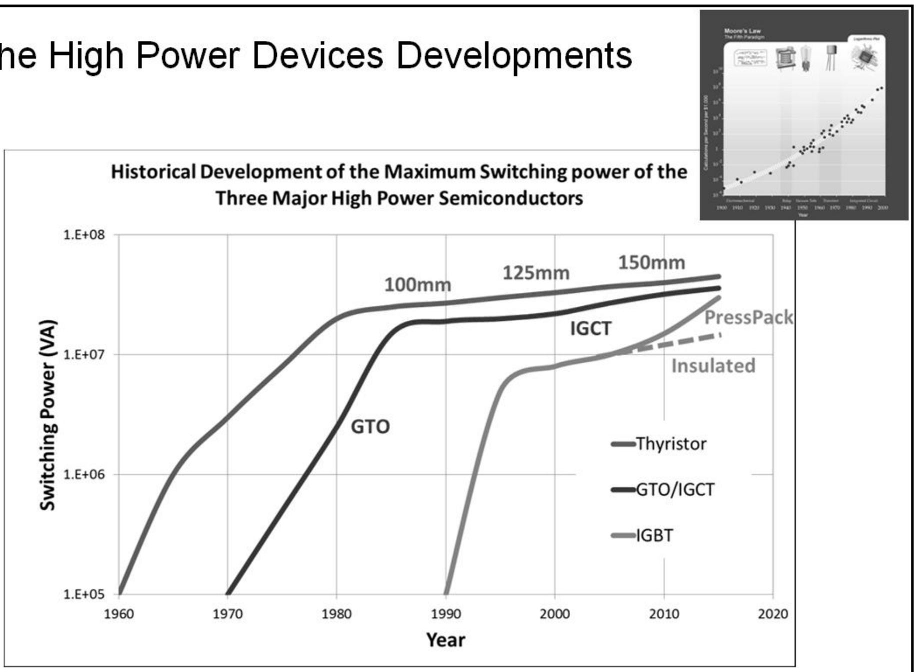




- **PCTs & IGCTs**: optimum carrier distribution for lowest losses
- **IGBTs:** continue to improve the carrier distribution for low losses

ABB

The High Power Devices Developments



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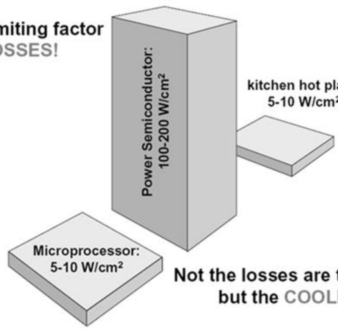
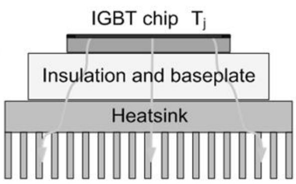
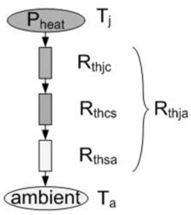
Power Semiconductor Power Ratings

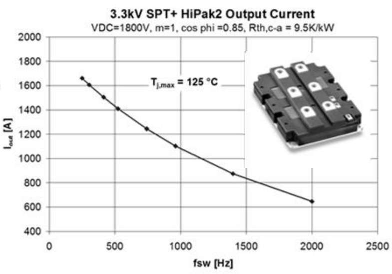
The limiting factor are LOSSES!







Not the losses are the problem, but the COOLING!



Example: Cont. Conduction 3.3kV/1.5kA IGBT Package

$V_{CE,on} = 3.0V$ @ $I_C = 1500A \rightarrow P_{heating} = 4.5kW$

$R_{th,\,j\text{-}a} = 18K / kW$

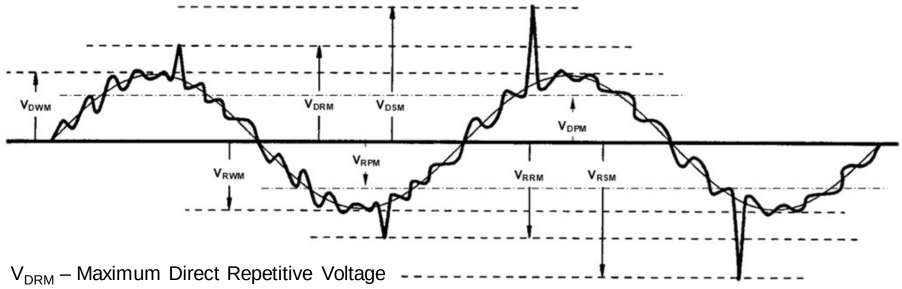
$P_{Cooling} = \frac{T_j - T_{amb}}{R_{th,\,j\text{-}a}}$ $T_{amb} = 40\ °C$

$P_{heating} = P_{cooling} \rightarrow T_j = R_{th,\,j\text{-}a} \cdot P_{heating} + T_{amb} =$
$4.5 \cdot 18 + 40 = 121\ °C$

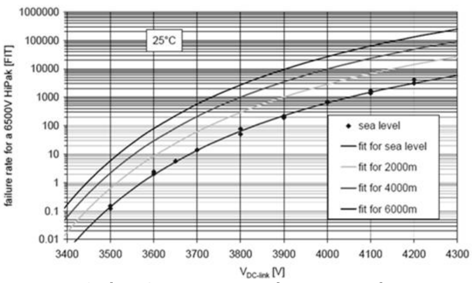
Total IGBT Losses : $P_{tot} = P_{cond} + P_{turn\text{-}off} + P_{turn\text{-}on}$

ABB

Power Semiconductor Voltage Ratings



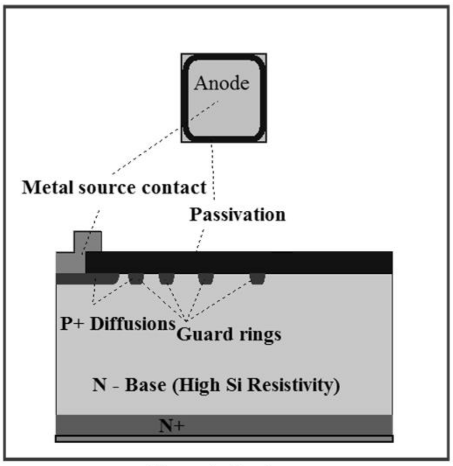
- V_{DRM} – Maximum Direct Repetitive Voltage
- V_{RRM} – Maximum Reverse Repetitive Voltage
- V_{DPM} – Maximum Direct Permanent Voltage
- V_{RPM} – Maximum Reverse Permanent Voltage
- V_{DSM} – Maximum Direct Surge Voltage
- V_{RSM} – Maximum Reverse Surge Voltage
- V_{DWM} – Maximum Direct Working Voltage



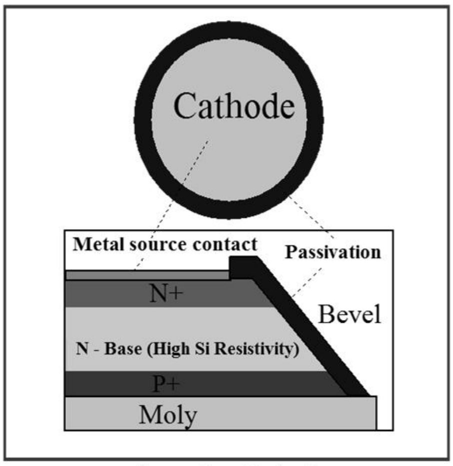
6.5kV IGBT FIT rates due to cosmic rays

ABB

Power Semiconductor Junction Termination



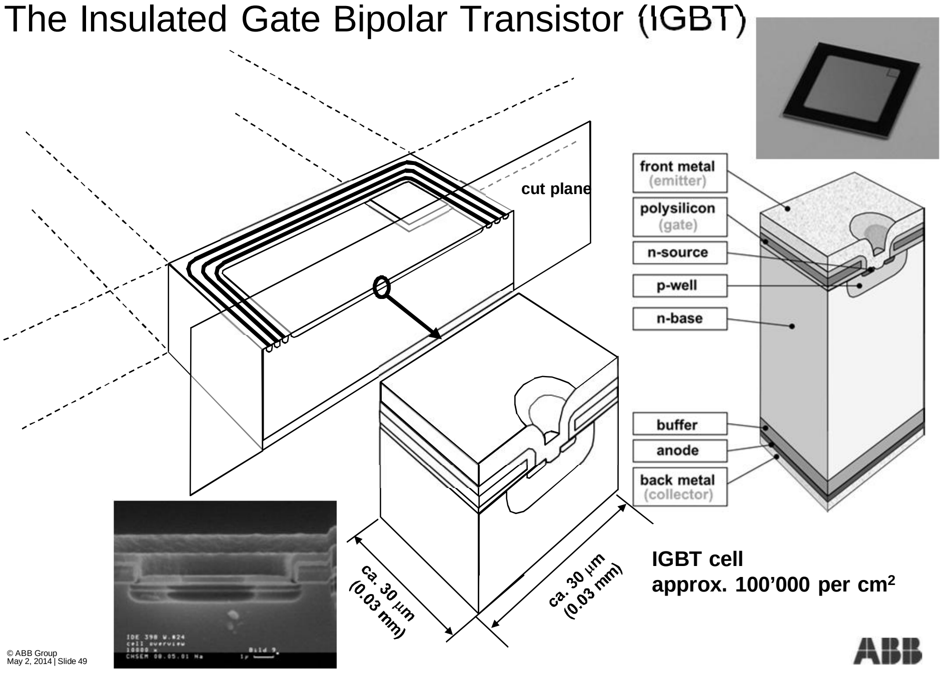
Planar technology



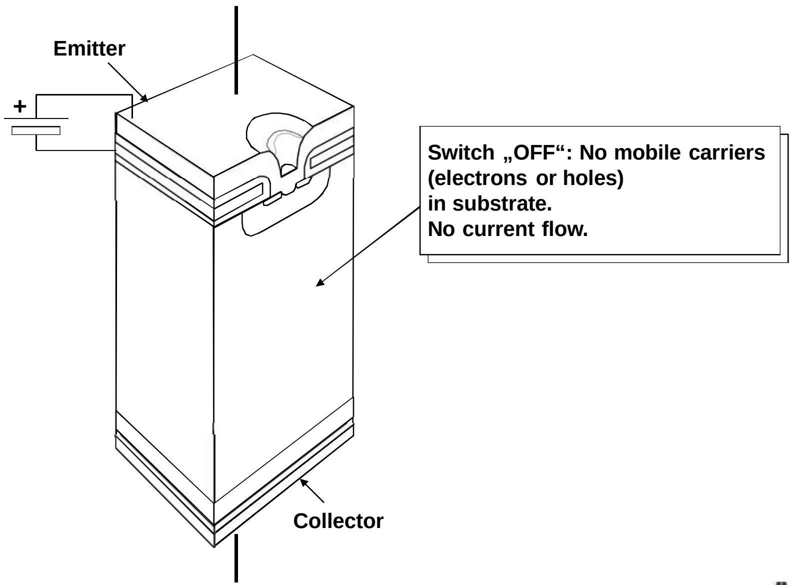
Conventional technology

ABB

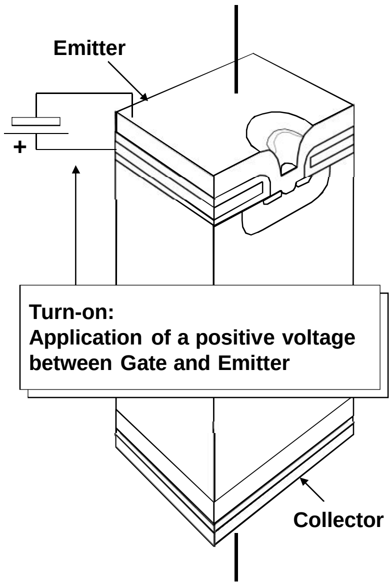
The Insulated Gate Bipolar Transistor (IGBT)

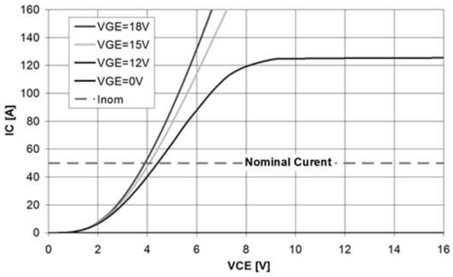


How an IGBT Conducts (1/5)



How an IGBT Conducts (2/5)

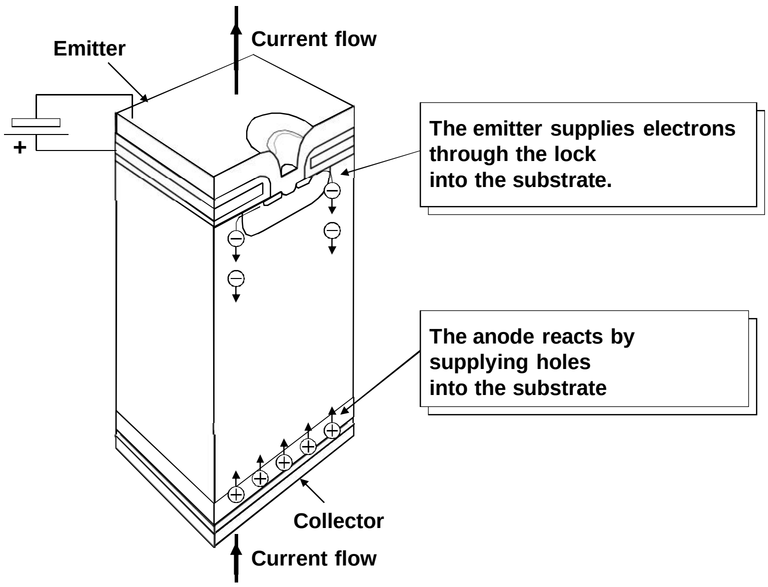




3.3kV IGBT output IV curves

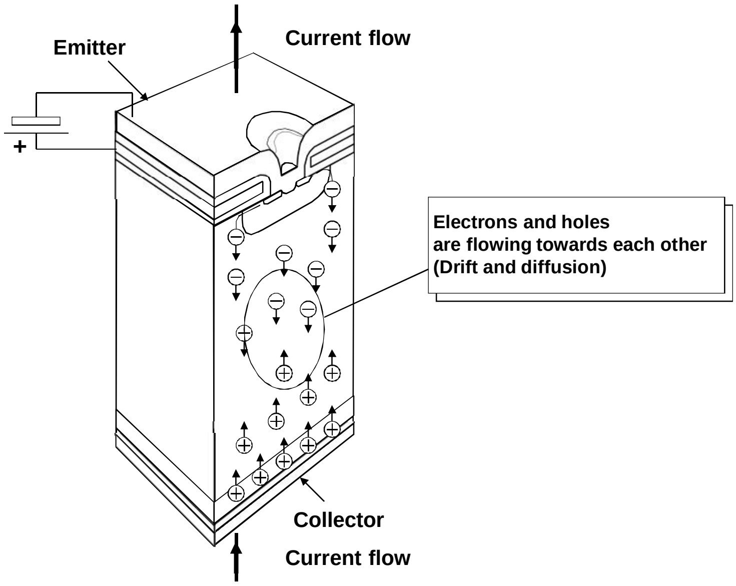
ABB

How an IGBT Conducts (3/5)



ABB

How an IGBT Conducts (4/5)



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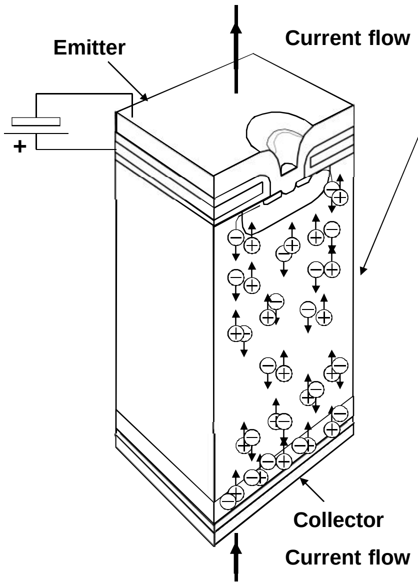
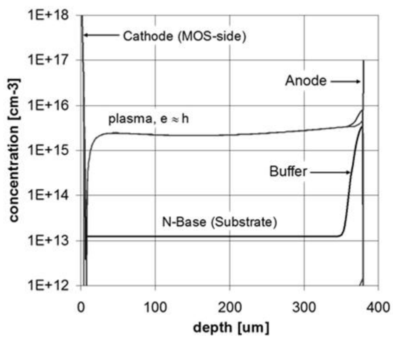
How an IGBT Conducts (5/5)

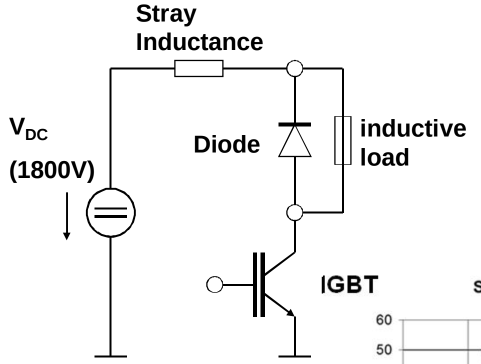


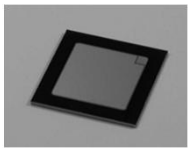


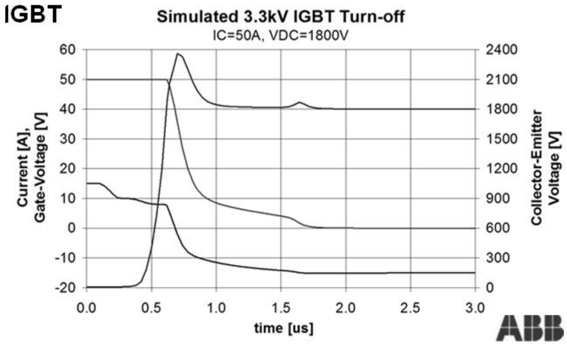
3.3kV IGBT doping/plasma

ABB

3.3kV IGBT Switching Performance: Test Circuit







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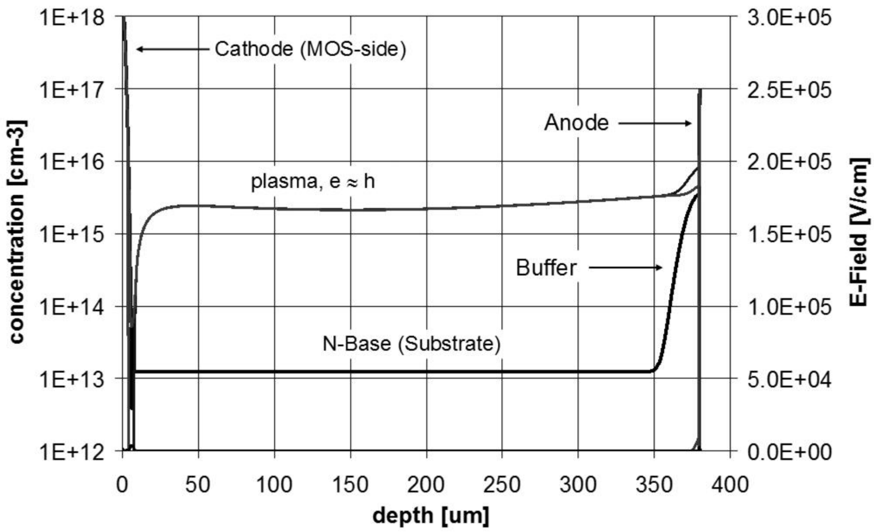
Plasma extraction during turn-off (1/5)



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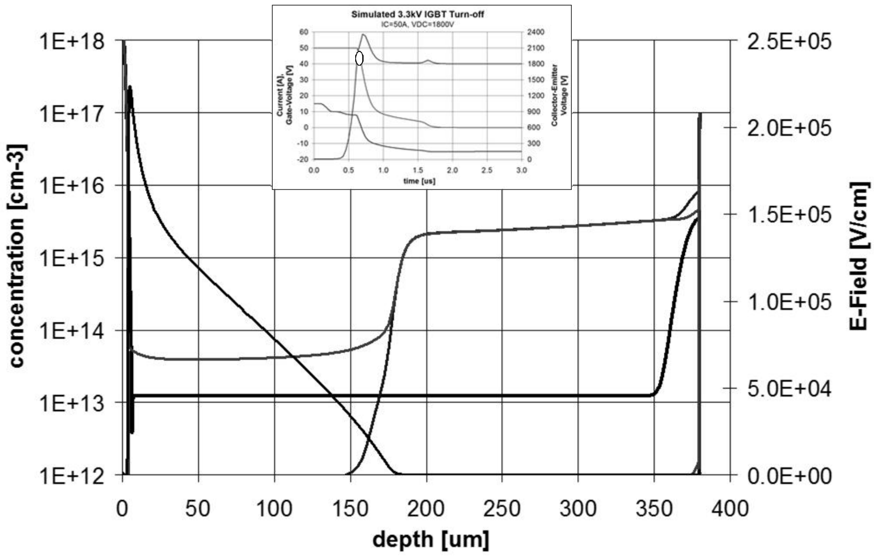
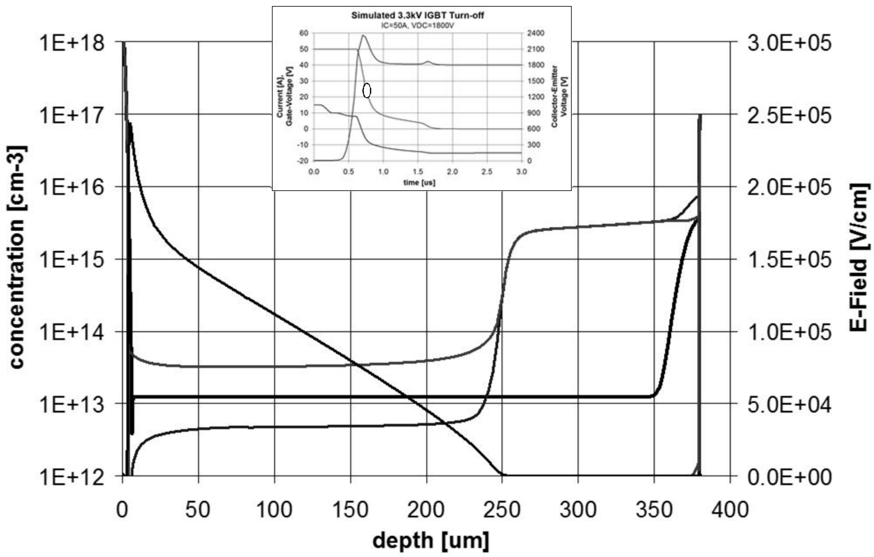
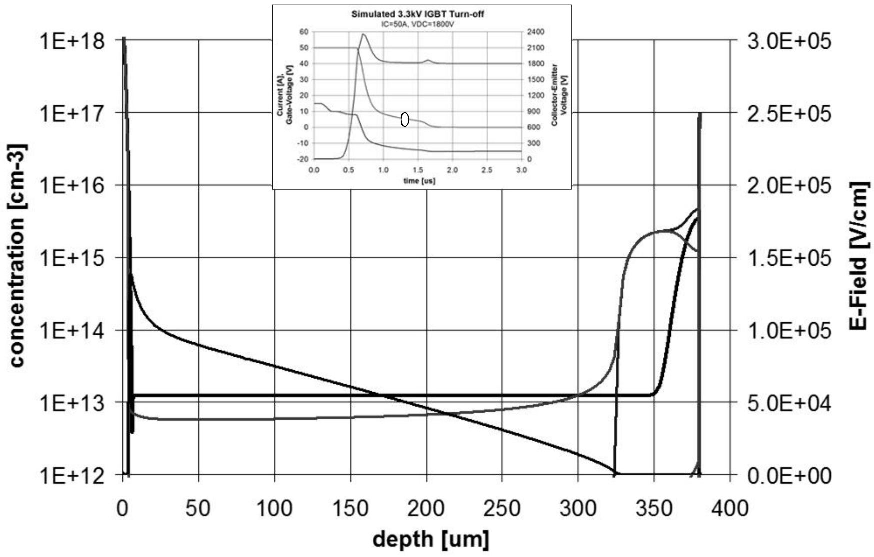
Plasma extraction during turn-off (2/5)



Plasma extraction during turn-off (3/5)

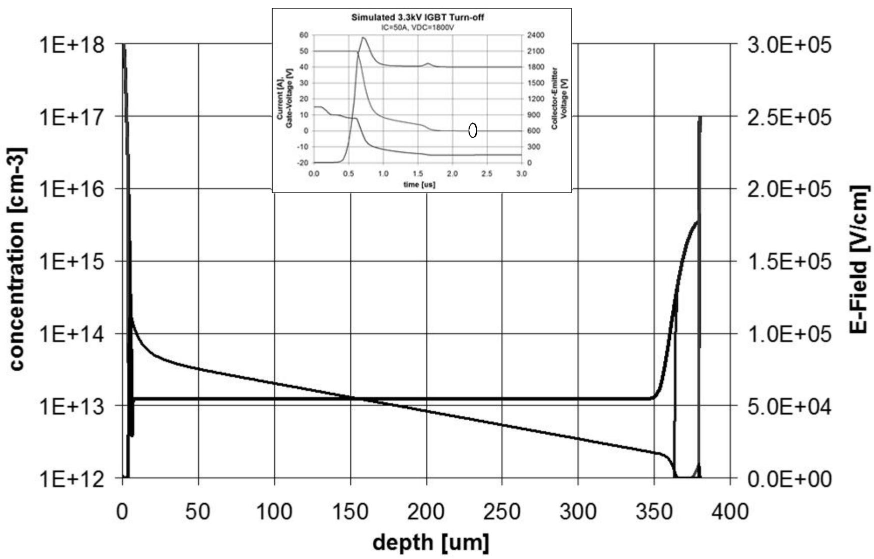


Plasma extraction during turn-off (4/5)



ABB

Plasma extraction during turn-off (5/5)



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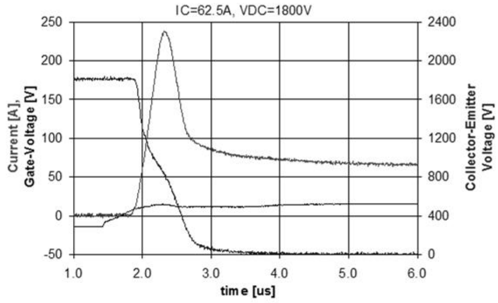
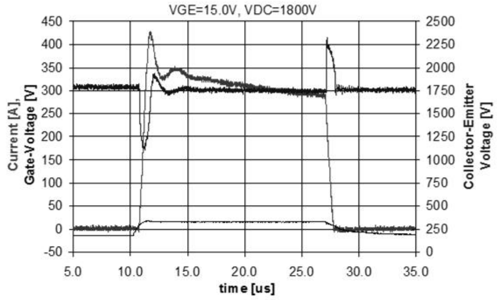
3.3kV IGBT Turn-on and Short Circuit Waveforms

Turn-on waveforms

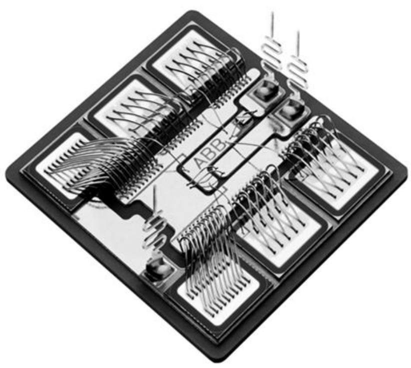


Short Circuit



ABB

Power Semiconductors
Packaging Concepts



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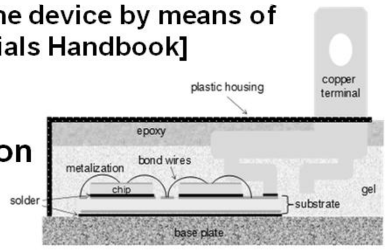
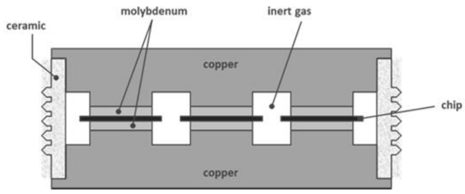
Power Semiconductor Device Packaging

- **What is Packaging ?**
- **A package is an enclosure for a single element, an integrated circuit or a hybrid circuit. It provides hermetic or non-hermetic protection, determines the form factor, and serves as the *__first level interconnection externally__* for the device by means of package terminals. [Electronic Materials Handbook]**
- **Package functions in PE**
  - **Power and Signal distribution**
  - **Heat dissipation**
  - **HV insulation**
  - **Protection**





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Power Semiconductor Device Packaging Concepts

	"Insulated" Devices	**Press-Pack Devices**
		
Mounting	**heat sink galvanically insulated from power terminals** ■ **all devices of a system can be mounted on same heat sink**	**heat sinks under high voltage** ■ **every device needs its own heat sink**
Failure Mode	**open circuit after failure**	**fails into low impedance state**
Markets	**Industry** **Transportation** **T&D**	**Industry** **Transportation** **T&D**
Power range	**typically 100 kW - low MW**	**MW**

transportation components have higher reliability demands

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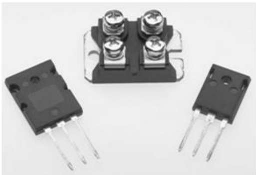
Insulated Package for 10s to 100s of KW

Low to Medium Power Semiconductor Packages

Discrete Devices

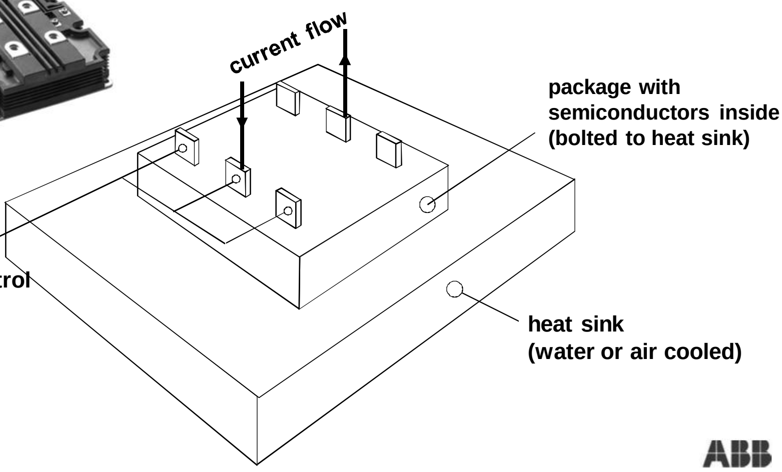


Standard Modules

ABB

Insulated Modules

- **Used for industrial and transportation applications (typ. 100 kW - 3 MW)**
- **Insulated packages are suited for Multi Chip packaging IGBTs**



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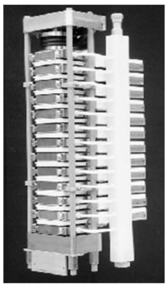
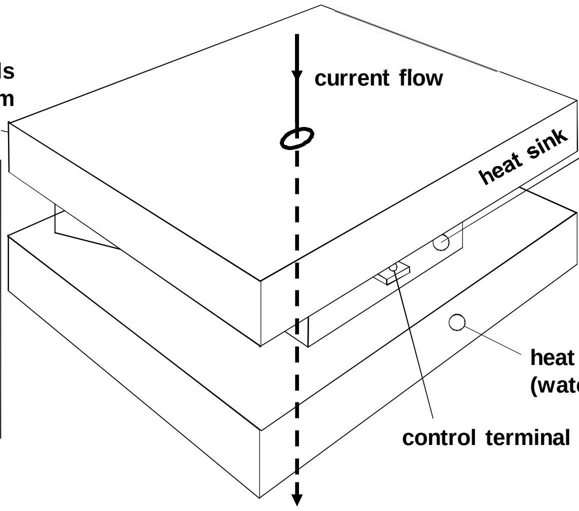
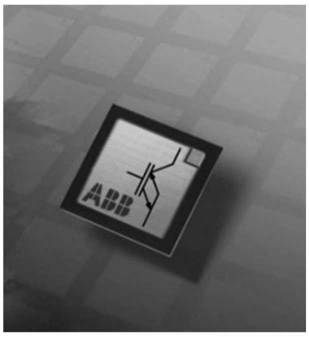
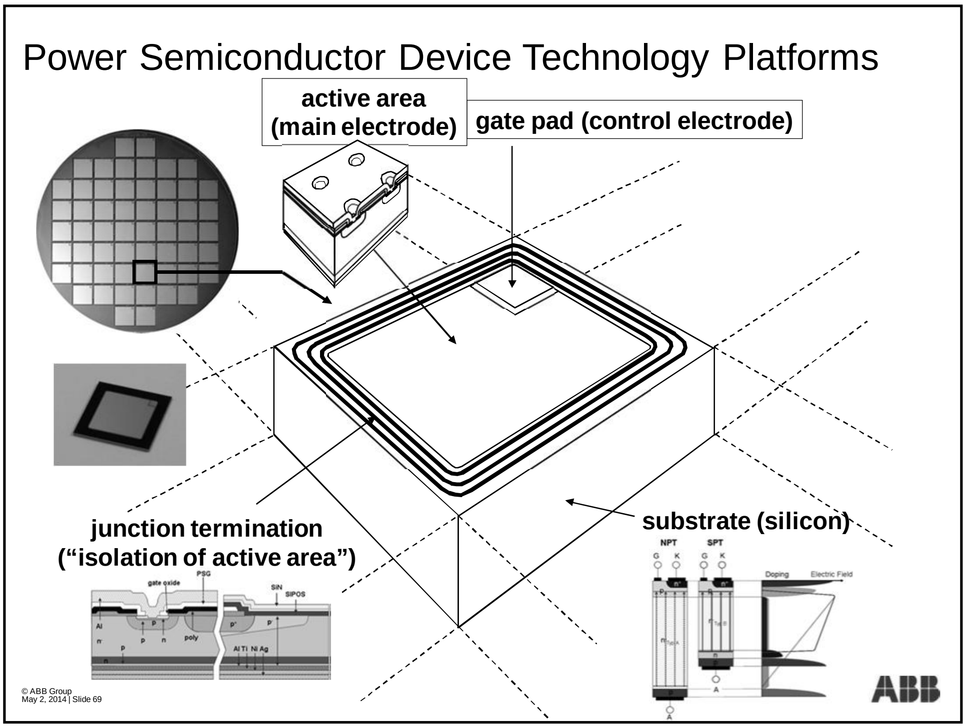
Press-Pack Modules





Power Semiconductors
Technology Drivers and Trends




Power Semiconductor Device Technology Platforms
active area
(main electrode)
gate pad (control electrode)
junction termination
("isolation of active area")
substrate (silicon)
NPT
SPT
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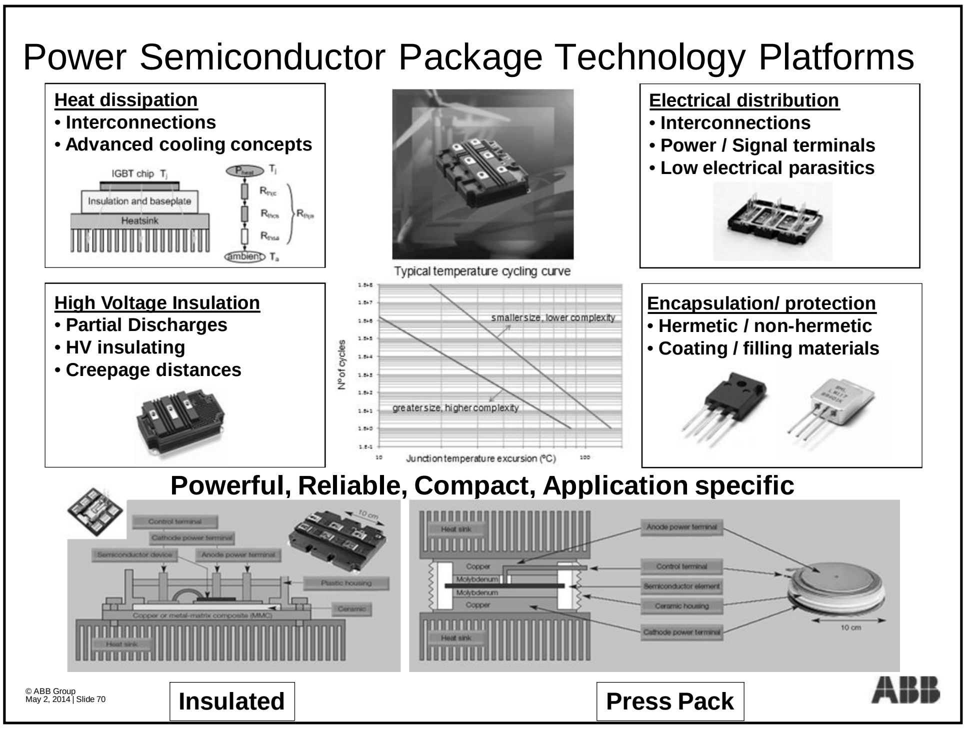
Power Semiconductor Package Technology Platforms
Heat dissipation
• Interconnections
• Advanced cooling concepts
IGBT chip
Insulation and baseplate
Heatsink
ambient
Electrical distribution
• Interconnections
• Power / Signal terminals
• Low electrical parasitics
Typical temperature cycling curve
smaller size, lower complexity
greater size, higher complexity
N° of cycles
Junction temperature excursion (°C)
High Voltage Insulation
• Partial Discharges
• HV insulating
• Creepage distances
Encapsulation/ protection
• Hermetic / non-hermetic
• Coating / filling materials
Powerful, Reliable, Compact, Application specific
Control terminal
Cathode power terminal
Semiconductor device
Anode power terminal
Plastic housing
Ceramic
Copper or metal-matrix composite (MMC)
Heat sink
Anode power terminal
Copper
Molybdenum
Control terminal
Semiconductor element
Ceramic housing
Cathode power terminal
10 cm
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Insulated
Press Pack
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Overcoming the **Limitations** (the boundaries)

The Power

$$\text{Power} = V_{on}\left[I_c \text{ or } \frac{V_{on}}{R_{on}}\right] = \frac{T_{j,max} - T_{j,amb}}{R_{th}}$$

The Margins

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

The Application

Topology, Frequency, Control, Cooling

The Cost of Performance

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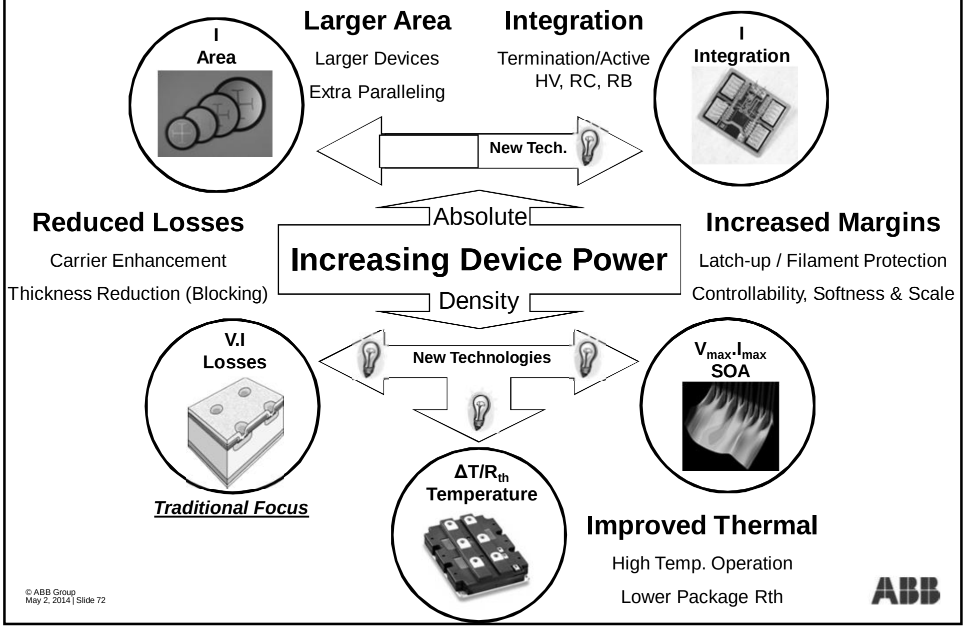
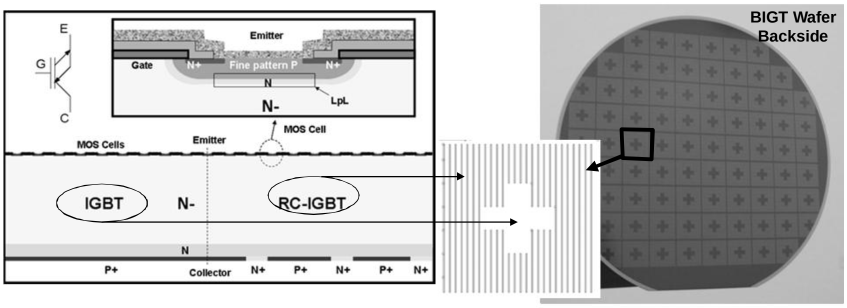
Technology Drivers for Higher Power (the boundaries)

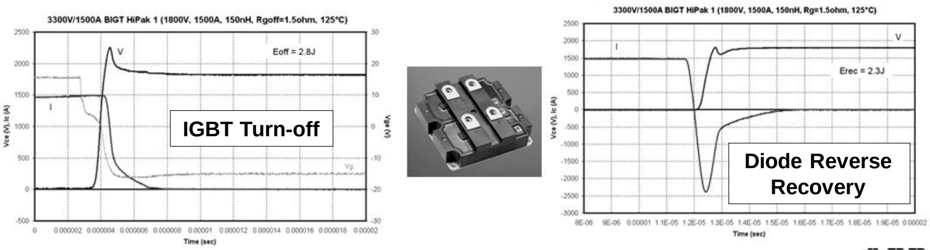


ABB

The Bimode Insulated Gate Transistor (BIGT)

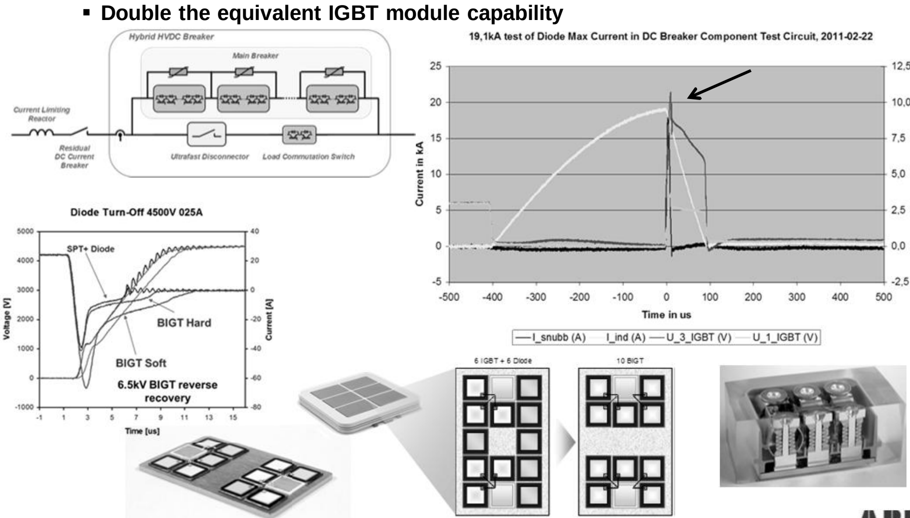
integrates an IGBT & RC-IGBT in one structure to eliminate snap-back effect





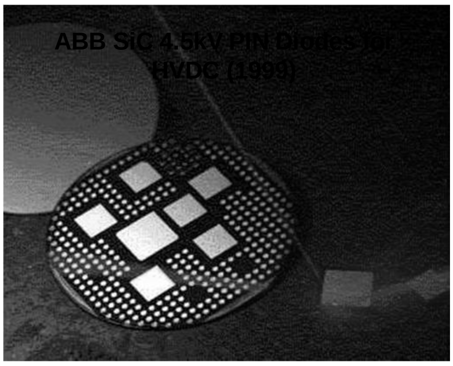
The BIGT StakPak for the Hybrid HVDC Breaker

- **BIGT StakPak Breaking Current increase demonstration:**
  - **BIGT Soft version for EVENT SWITCHING Applications**
  - **Breaking current capability of 19.1kA verified for 6-sub StakPak.**
  - **Double the equivalent IGBT module capability**



BIGT Submodule **V_{CES} = 4500V, I_{rated} = 3000 A**

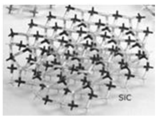
Wide Bandgap Technologies

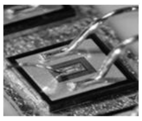


Wind Bandgap Semiconductors: Long Term Potentials

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}	$1.4 \cdot 10^{10}$	$\mathbf{8.2 \cdot 10^{-9}}$	$\mathbf{1.9 \cdot 10^{-10}}$	$1 \cdot 10^{-22}$
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

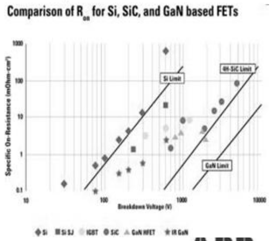




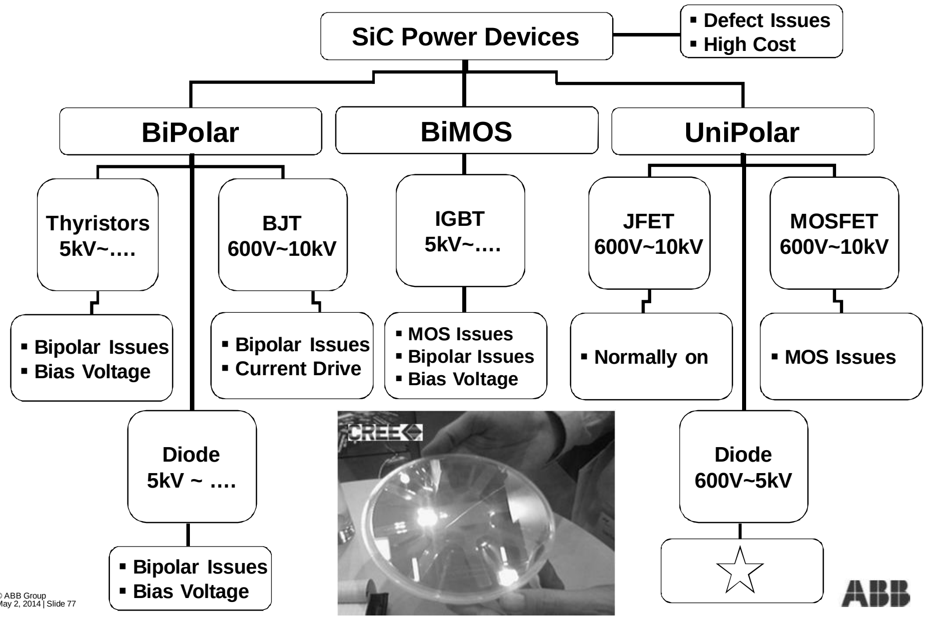
- **Higher Blocking**
- **Lower Losses**
- **Lower Leakage**
- **But higher built-in voltage**

⇨

- **Higher Power**
- **Wider Frequency Range**
- **Very High Voltages**
- **Higher Temperature**



SiC Switch/Diode Classification and Issues



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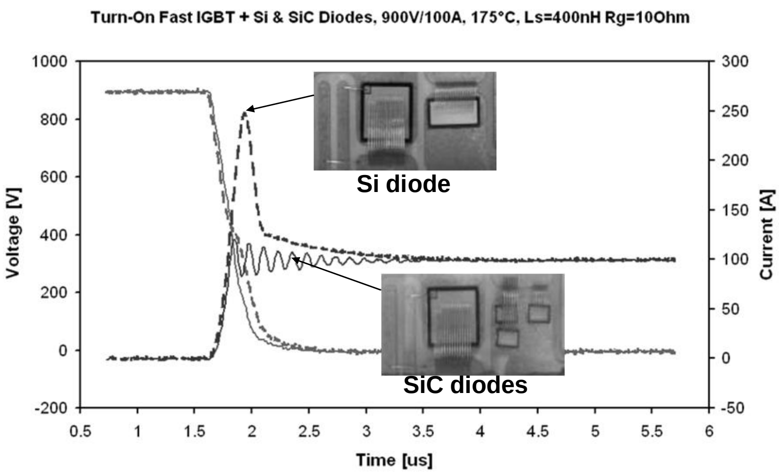
SiC Unipolar Diodes vs. Si Bipolar Diode

1700V Fast IGBTs with SiC Diodes during turn-on



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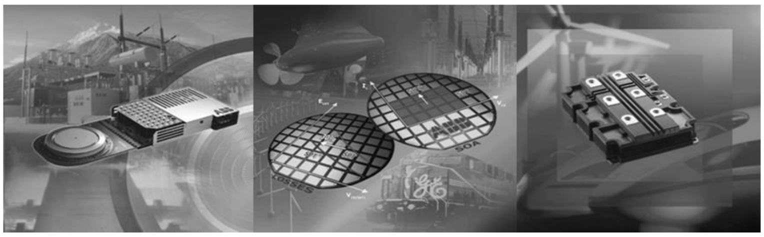
Conclusions

- **Si Based Power semiconductors are a key enabler for modern and future power electronics systems including 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 Diode, PCT, IGCT, IGBT and MOSFET continue to evolve for achieving future system targets with the potential for improved power/performance through further losses reductions, higher operating temperatures and integration solutions**
- **Wide Band Gap Based Power Devices offer many performance advantages with strong potential for very high voltage applications**



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