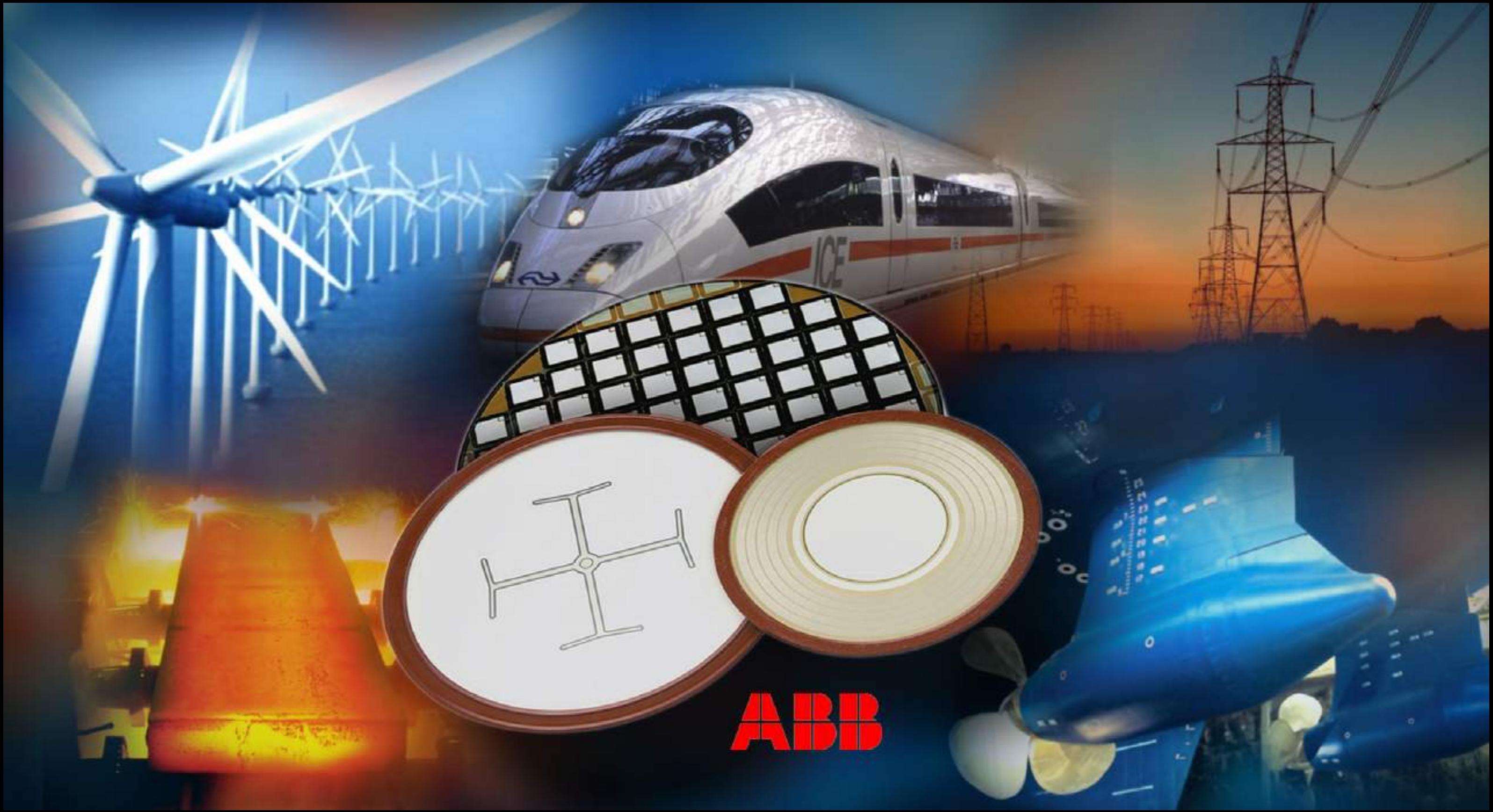


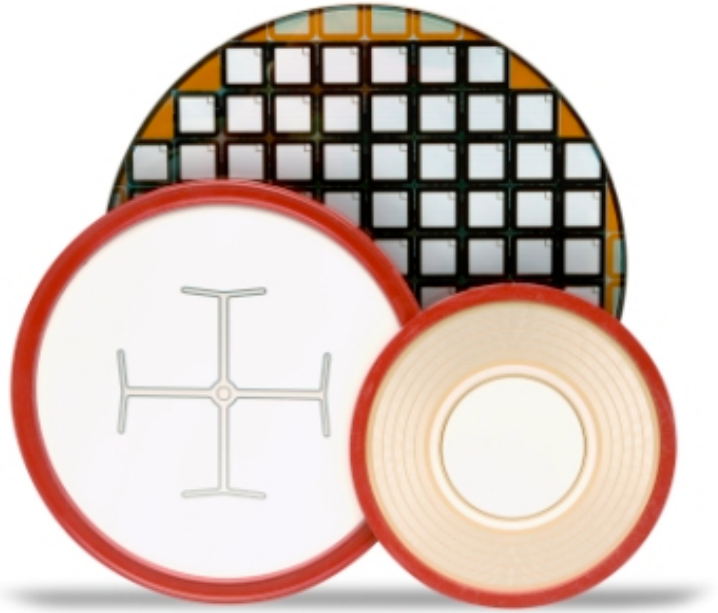
Power Semiconductors for Power Electronics Applications

Munaf Rahimo, Corporate Executive Engineer
Grid Systems R&D, Power Systems
ABB Switzerland Ltd, Semiconductors

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

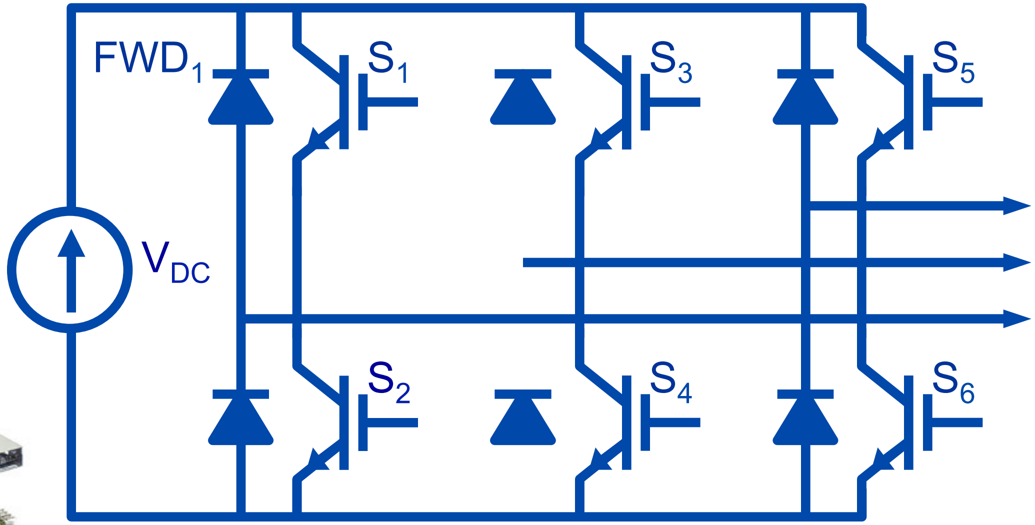
Contents

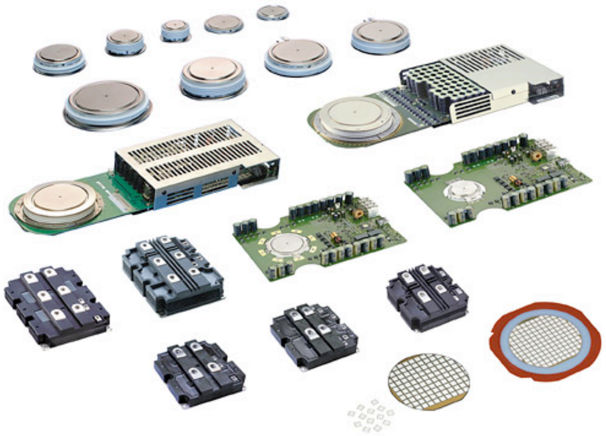
- **Power Electronics and Power Semiconductors**
- **Understanding the Basics**
- **Technologies and Performance**
- **Packaging Concepts**
- **Technology Drivers and Trends**
- **Wide Band gap Technologies**
- **Conclusions**



Power Electronics and

Power Semiconductors

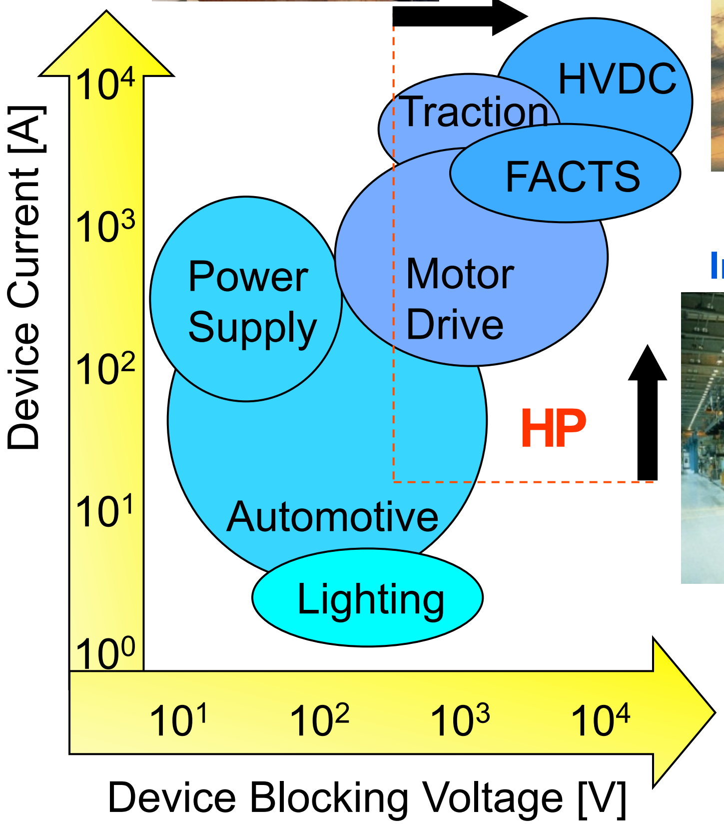


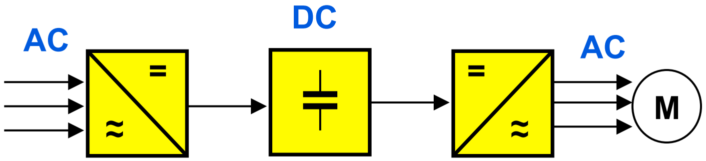


Power Electronics Applications are ….

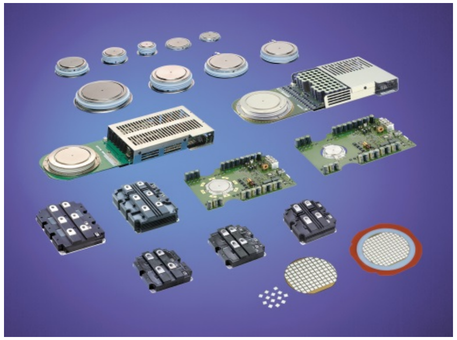
.. an established technology that bridges the power industry with its needs for flexible and fast controllers

Transportation

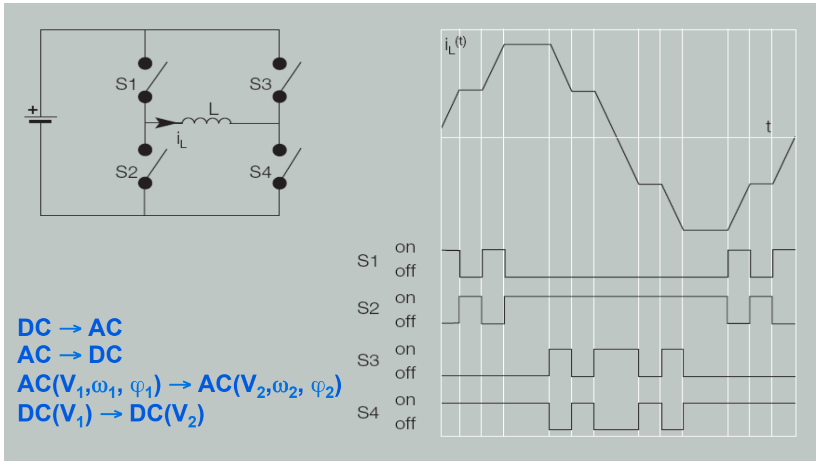




Grid Systems



Industrial Drives



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

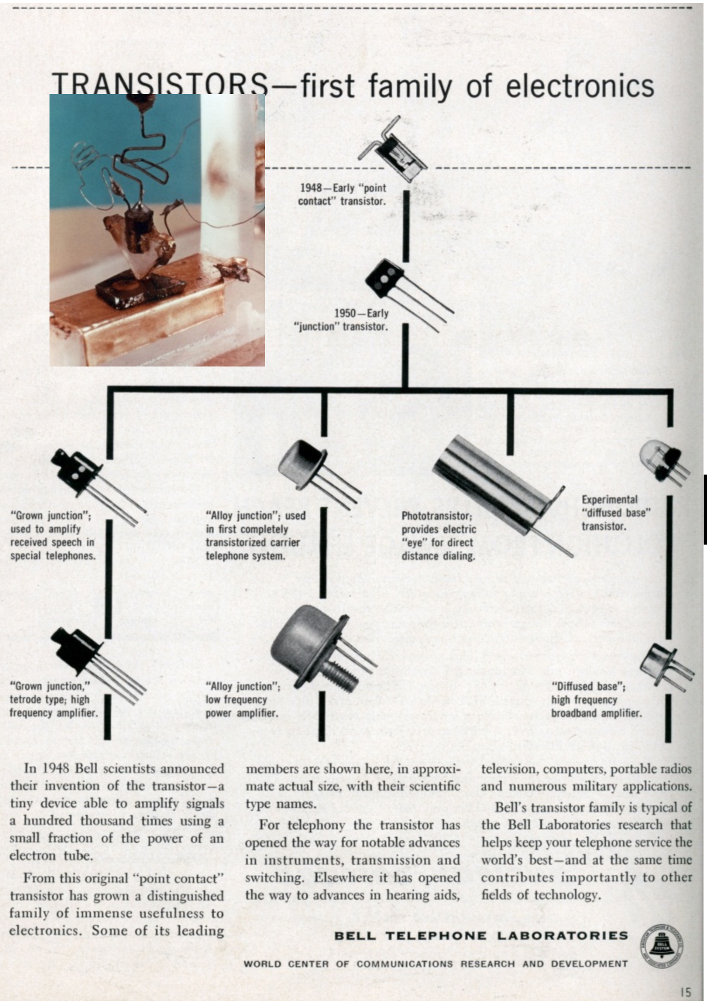
PE conversion employ controllable solid-state switches referred to as Power Semiconductors

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



TRANSISTORS—first family of electronics

1948—Early "point contact" transistor.

1950—Early "junction" transistor.

"Grown junction"; used to amplify received speech in special telephones.

"Alloy junction"; used in first completely transistorized carrier telephone system.

Phototransistor; provides electric "eye" for direct distance dialing.

Experimental "diffused base" transistor.

"Grown junction," tetrode type; high frequency amplifier.

"Alloy junction"; low frequency power amplifier.

"Diffused base"; high frequency broadband amplifier.

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.

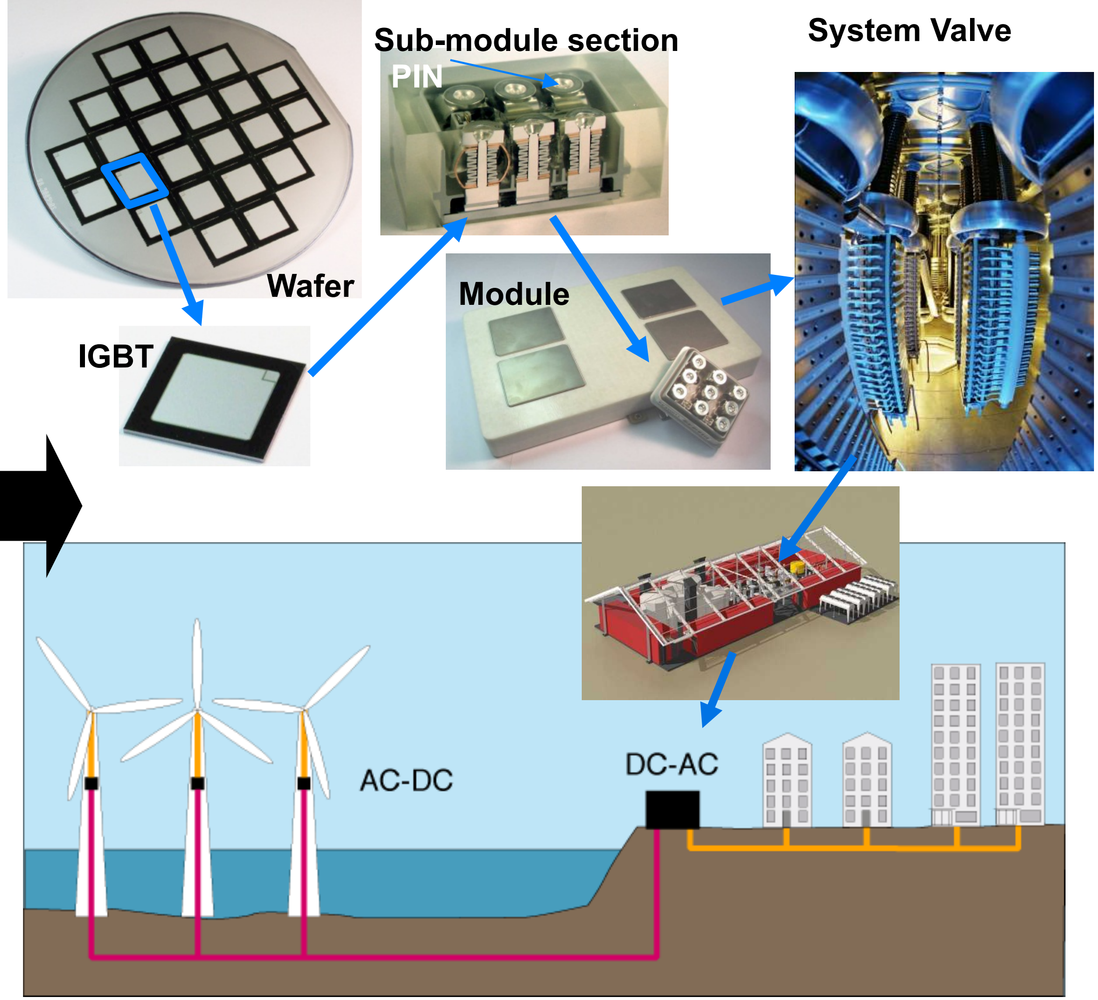
Bell's transistor family is typical of the Bell Laboratories research that helps keep your telephone service the world's best—and at the same time contributes importantly to other fields of technology.

BELL TELEPHONE LABORATORIES

WORLD CENTER OF COMMUNICATIONS RESEARCH AND DEVELOPMENT

15

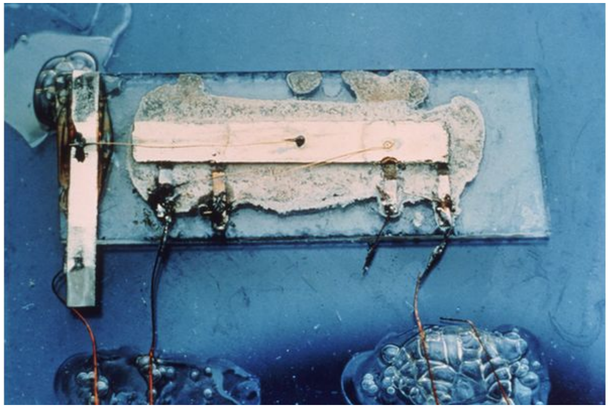
1947: Bell`s Transistor



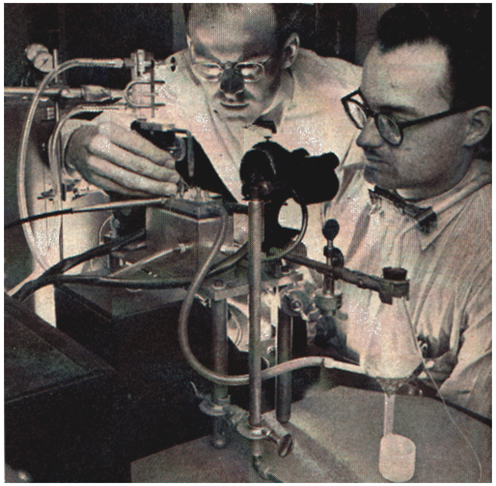
Today: GW IGBT based HVDC systems

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

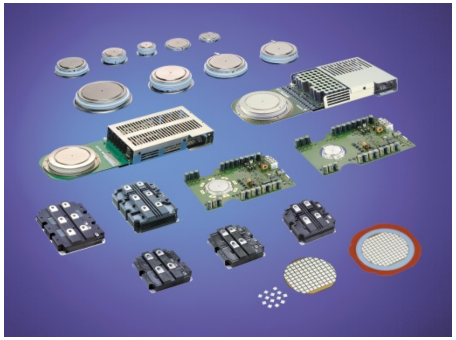


Kilby`s first IC in 1958

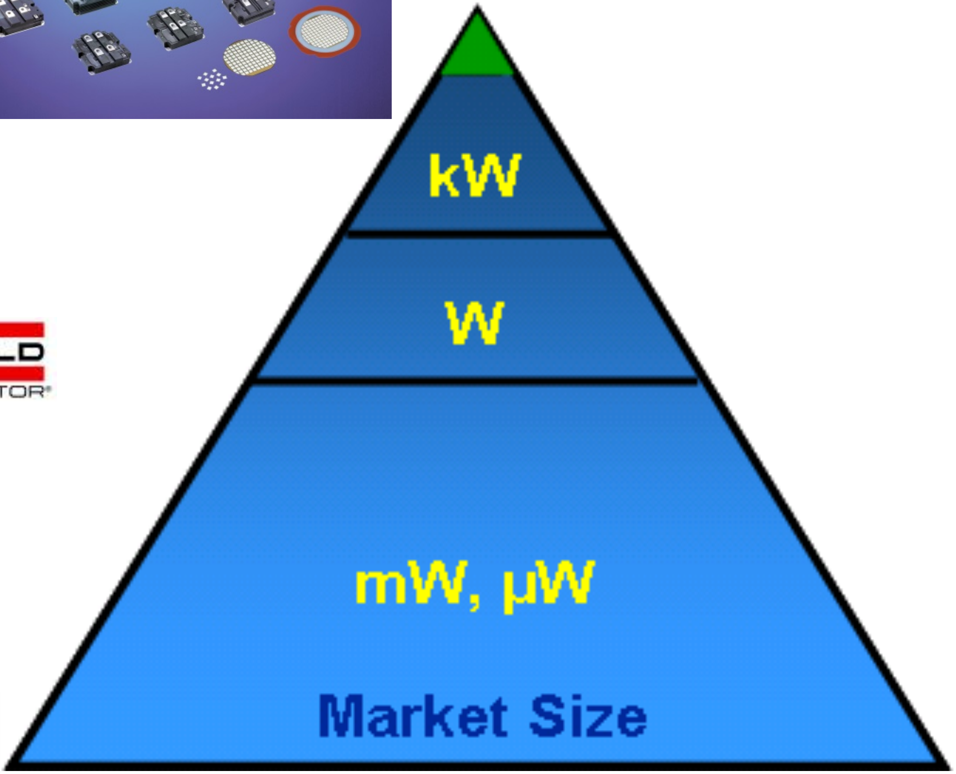


Robert N. Hall (left) at GE demonstrated the first 200V/35A Ge power diode in 1952

The Global Semiconductor Market and Producers



MITSUBISHI ELECTRIC
Changes for the Better
infineon
Never stop thinking
HITACHI
Inspire the Next
ABB
Fuji Electric Group
IXYS
IOR International Rectifier
VISHAY
ON
ON Semiconductor
ST
FAIRCHILD
SEMICONDUCTOR
TEXAS INSTRUMENTS
tsmc
freescale
semiconductor
NXP
founded by Philips
Agilent Technologies
AMD
The future is fusion
intel

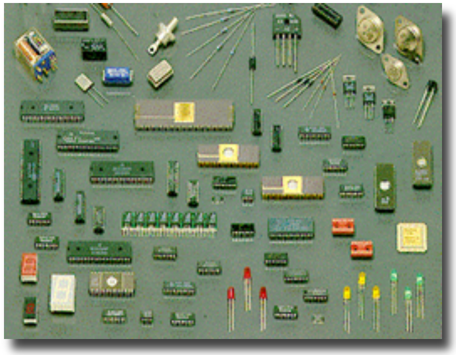


kW

W

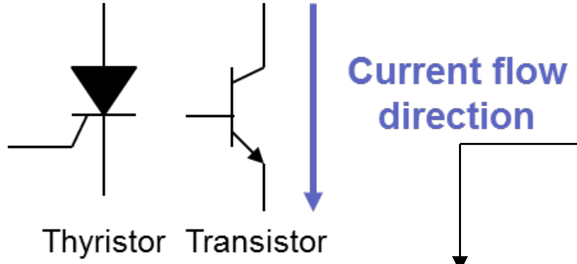
mW, µW

Market Size



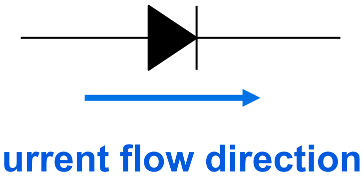
Power Semiconductors; the Principle

Power Semiconductor



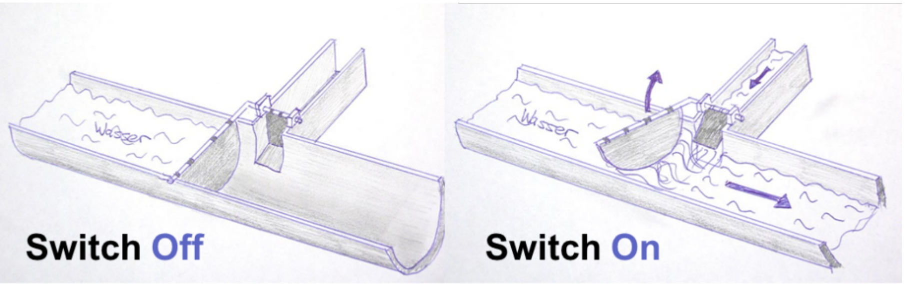
Switches

(MOSFET, IGBT, Thyistor)



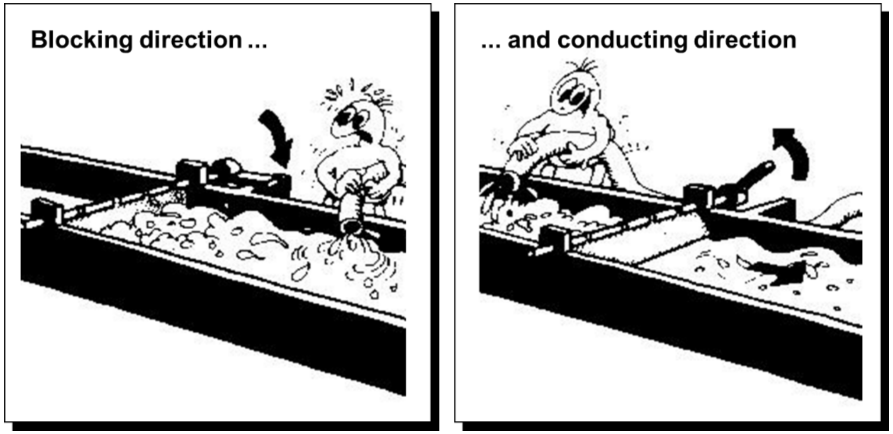
Rectifiers

(Diodes)



Switch Off

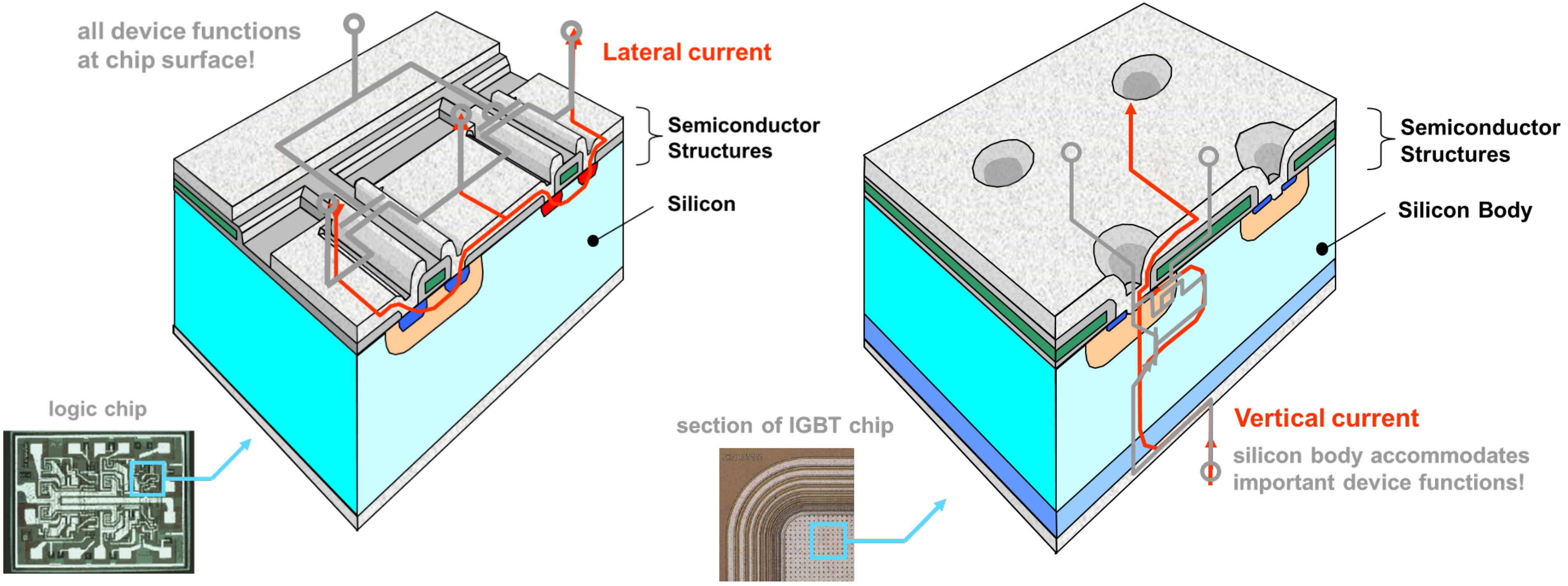
Switch On



Blocking direction ...

... and conducting direction

Power Semiconductor Device Main Functions



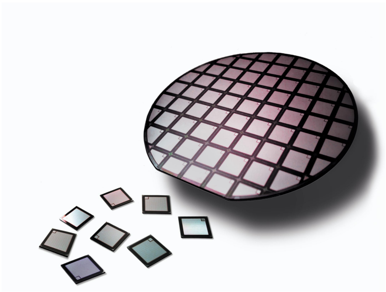
Logic Device

High Power Device

- **Main Functions of the power device:**
  - **Support the off-voltage (Thousands of Volts)**
  - **Conduct currents when switch is on (Hundreds of Amps per cm^2)**

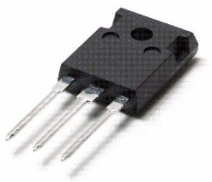
Switch

Silicon Switch/Diode Classification

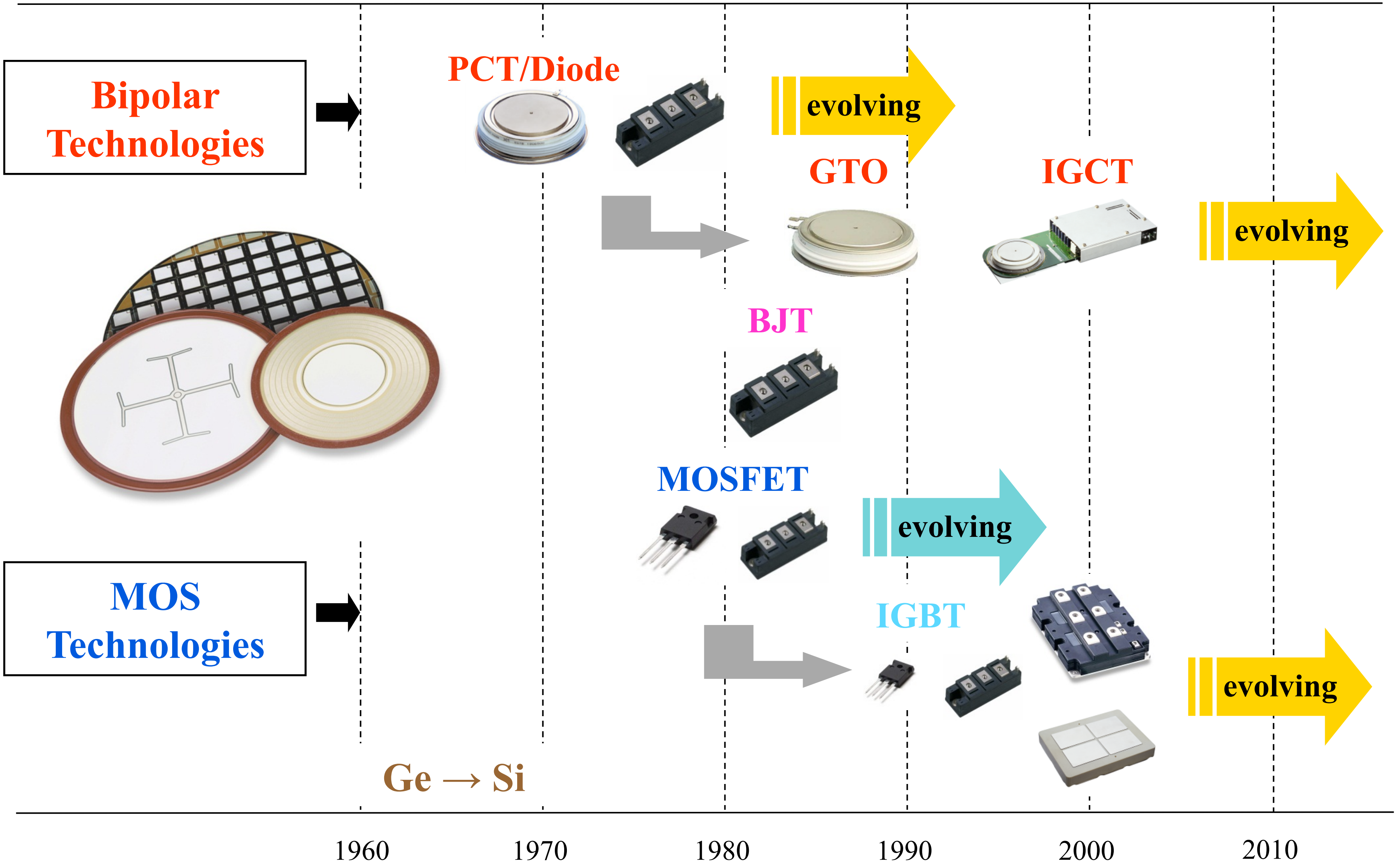


Si Power Devices

- **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



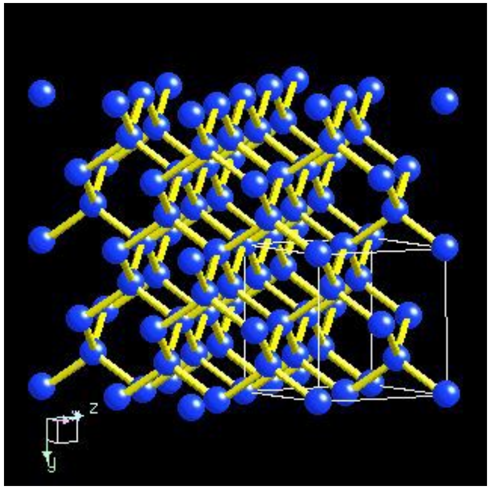
Evolution of Silicon Based Power Devices



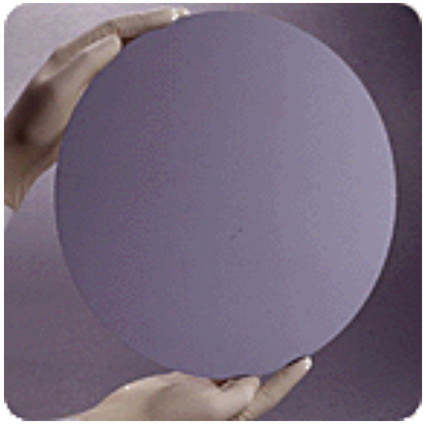
Bipolar Technologies

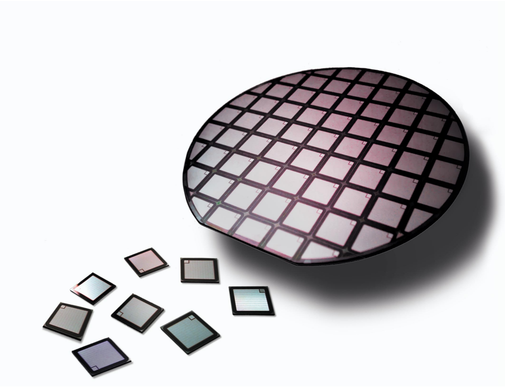
MOS Technologies

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

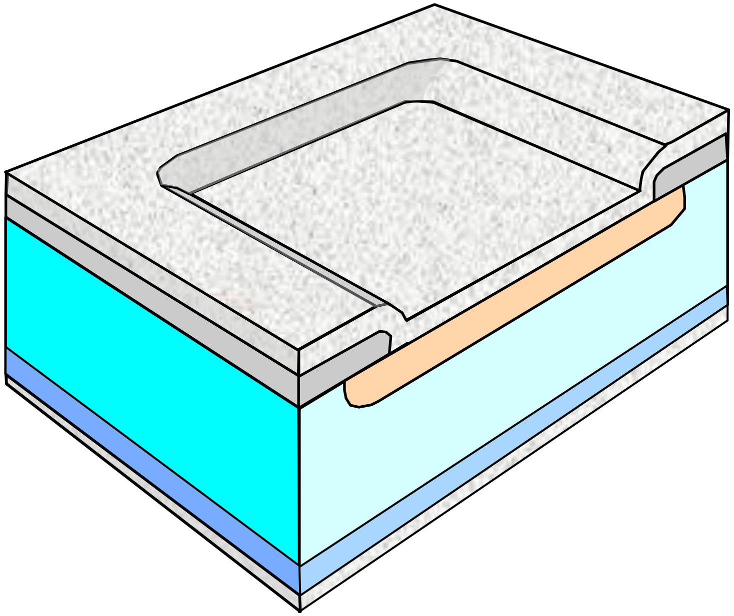
- **It takes basically the same technologies to manufacture power semiconductors like modern logic devices like microprocessors**
- **But the challenges are different in terms of Device Physics and Application**

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

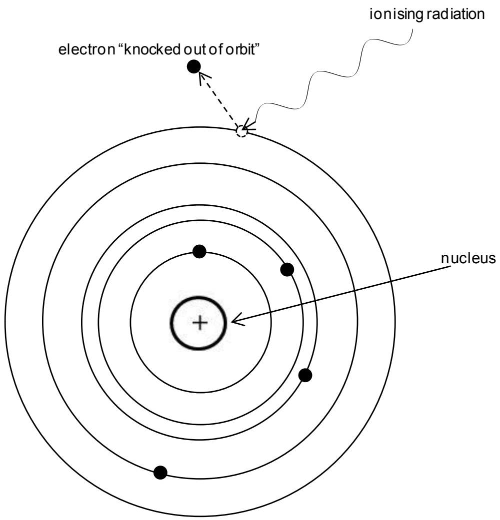
- **Doping and thickness of the silicon must be tightly controlled (both in % range)**
- **Because silicon is a resistor, device thickness must be kept at absolute minimum**
- **Virtually no defects or contamination with foreign atoms are permitted**

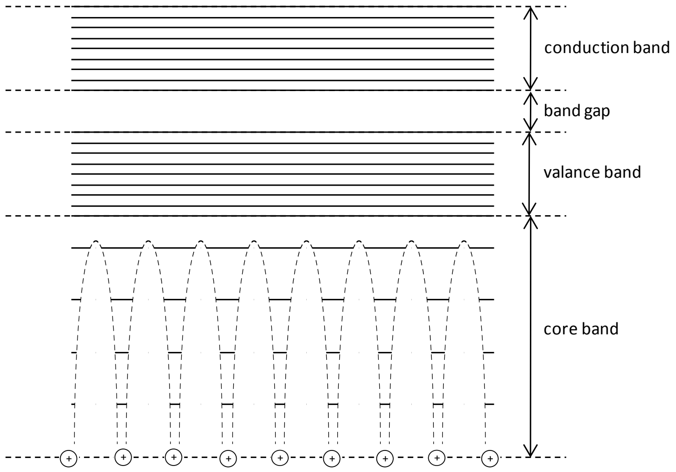
Power Semiconductors

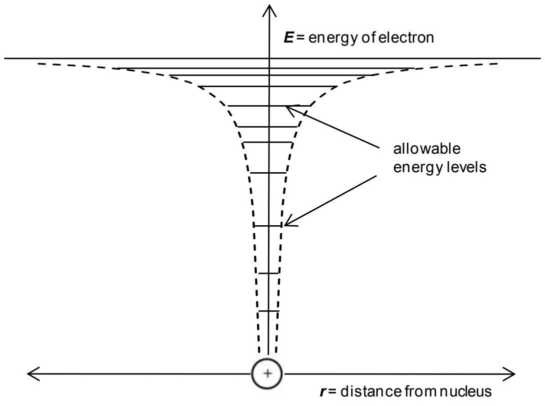
Understanding The Basics

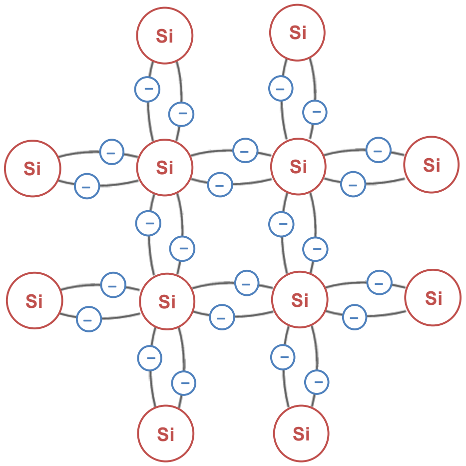


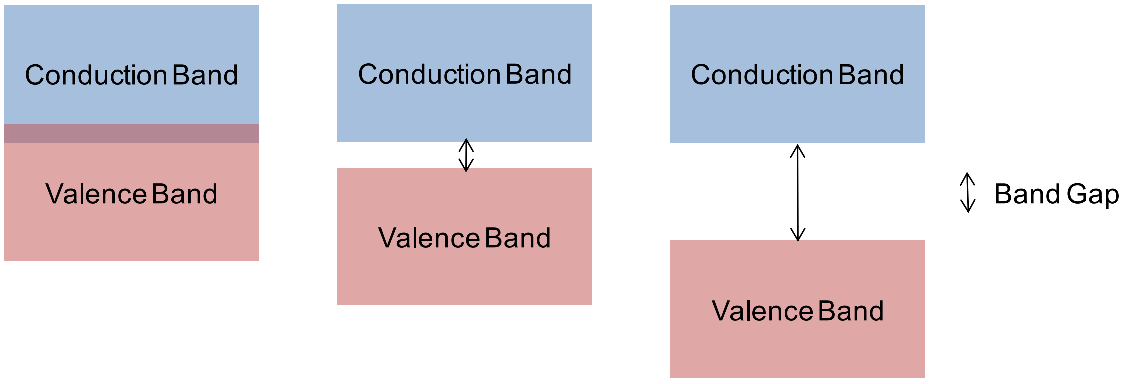
… without diving into semiconductor physics …











Metal
($\rho \approx 10^{-6}\ \Omega$-cm)

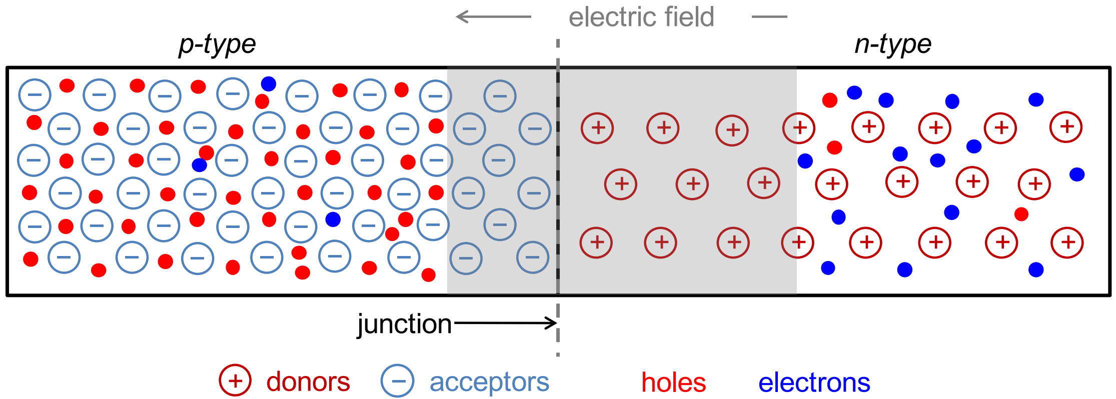
Semiconductor
($\rho \approx 10^{2 \ldots 6}\ \Omega$-cm)

Insulator
($\rho \approx 10^{16}\ \Omega$-cm)

***Power Semiconductors*, S. Linder, EPFL Press**
ISBN 2-940222-09-6

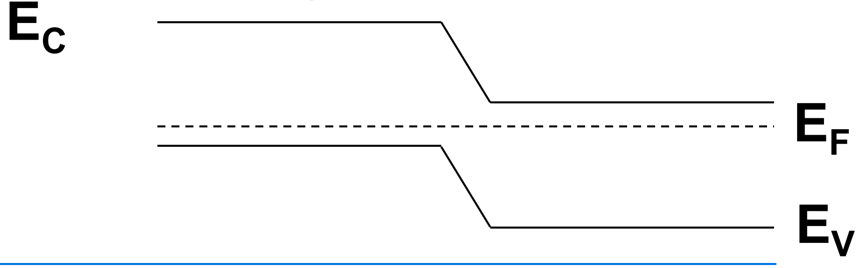
The Basic Building Block; The PN Junction

Anode



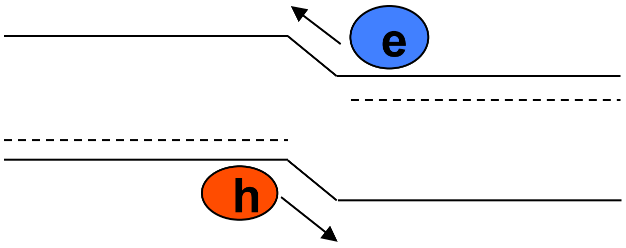
Cathode

No Bias



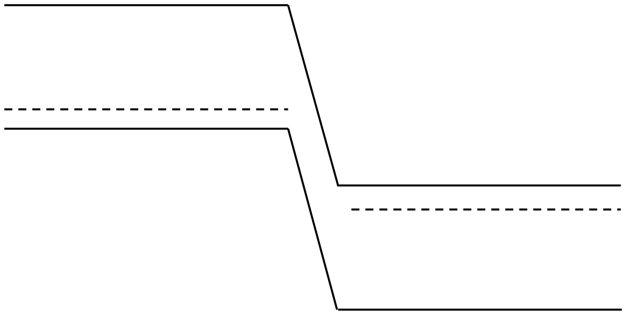
Forward Bias
P(+)N(-)

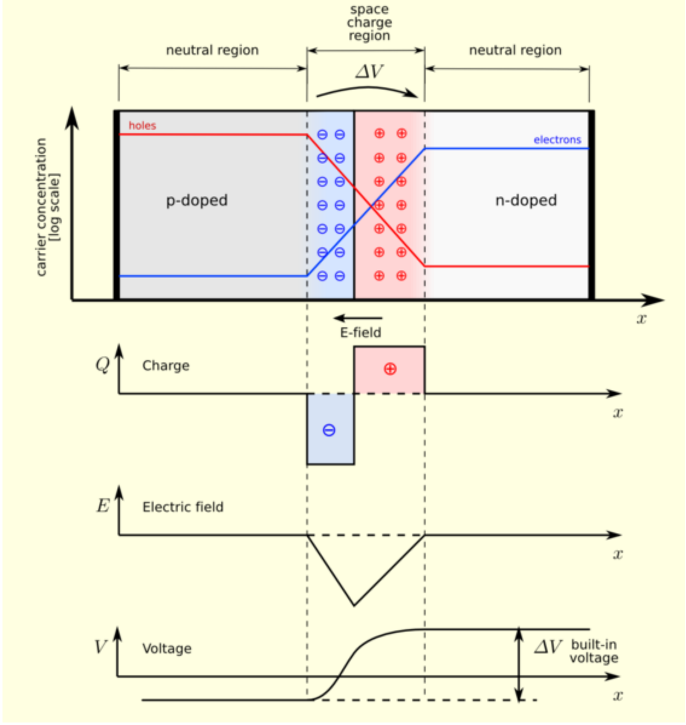
Space-charge region abolished and a current starts to flow if the external voltage exceeds the “built-in” voltage ~ 0.7 V



Reverse Bias
P(-)N(+)

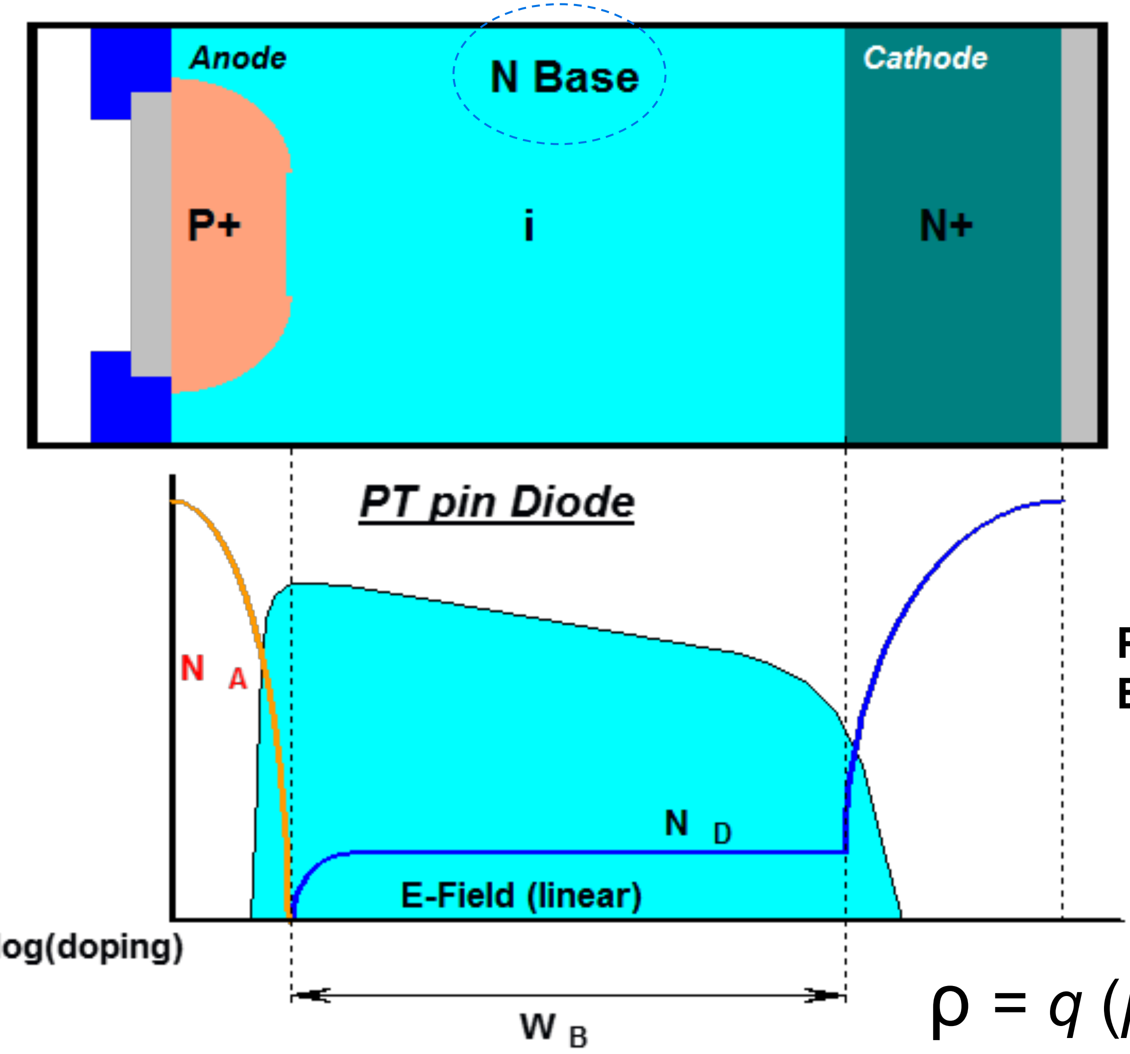
Space-charge region expands and avalanche break-down voltage is reached at critical electric field for Si (2x10^5V/cm)





The PIN Bipolar Power Diode

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



Poisson's Equation for Electric Field

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon_s}$$

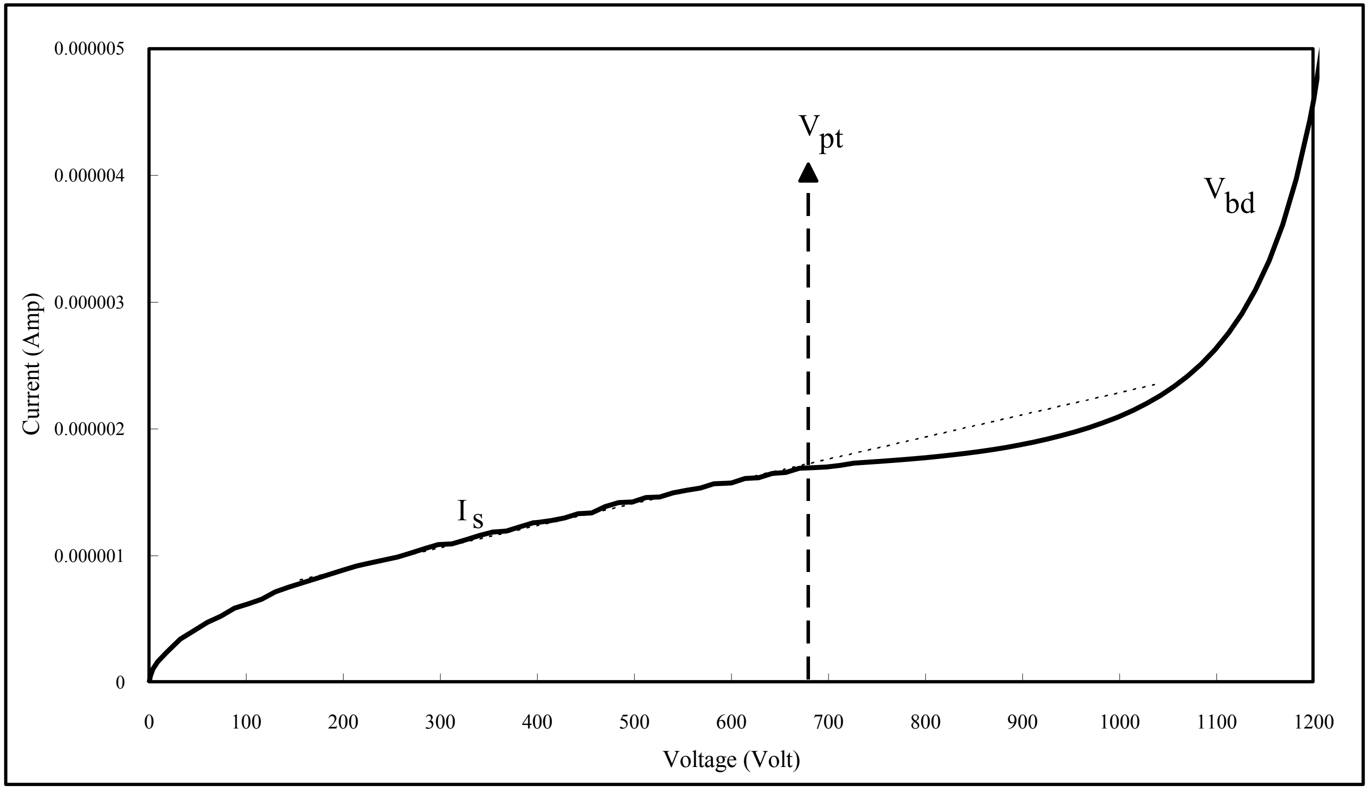
Charge Density

Permittivity

$$\rho = q\,(p - n + N_D - N_A)$$

Power Diode Structure and Doping Profile

The Power Diode in Reverse Blocking Mode

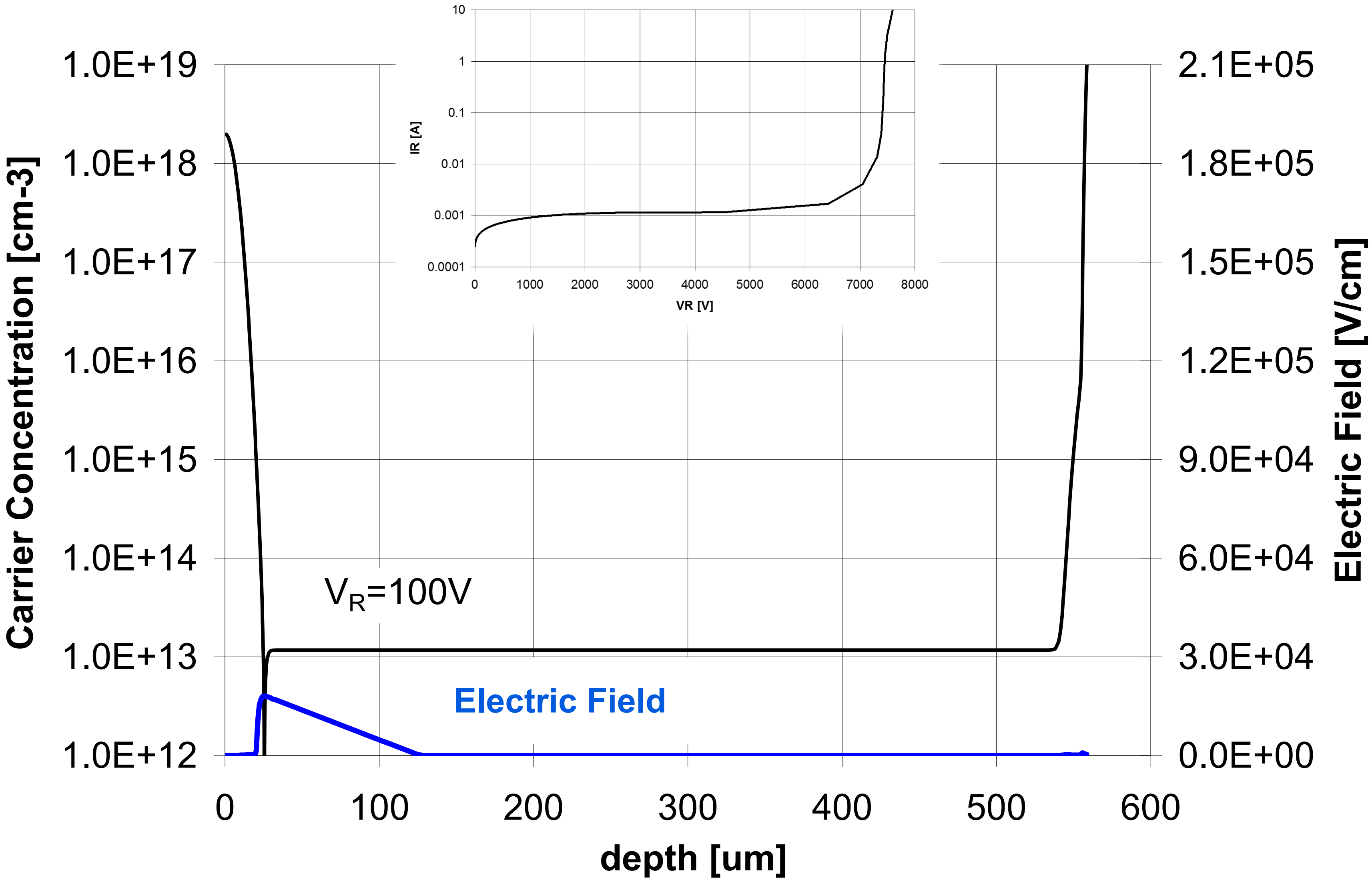


$$V_{bd} = 5.34 \times 10^{13} N_D^{-3/4}$$ **Non - Punch Through Breakdown Voltage**

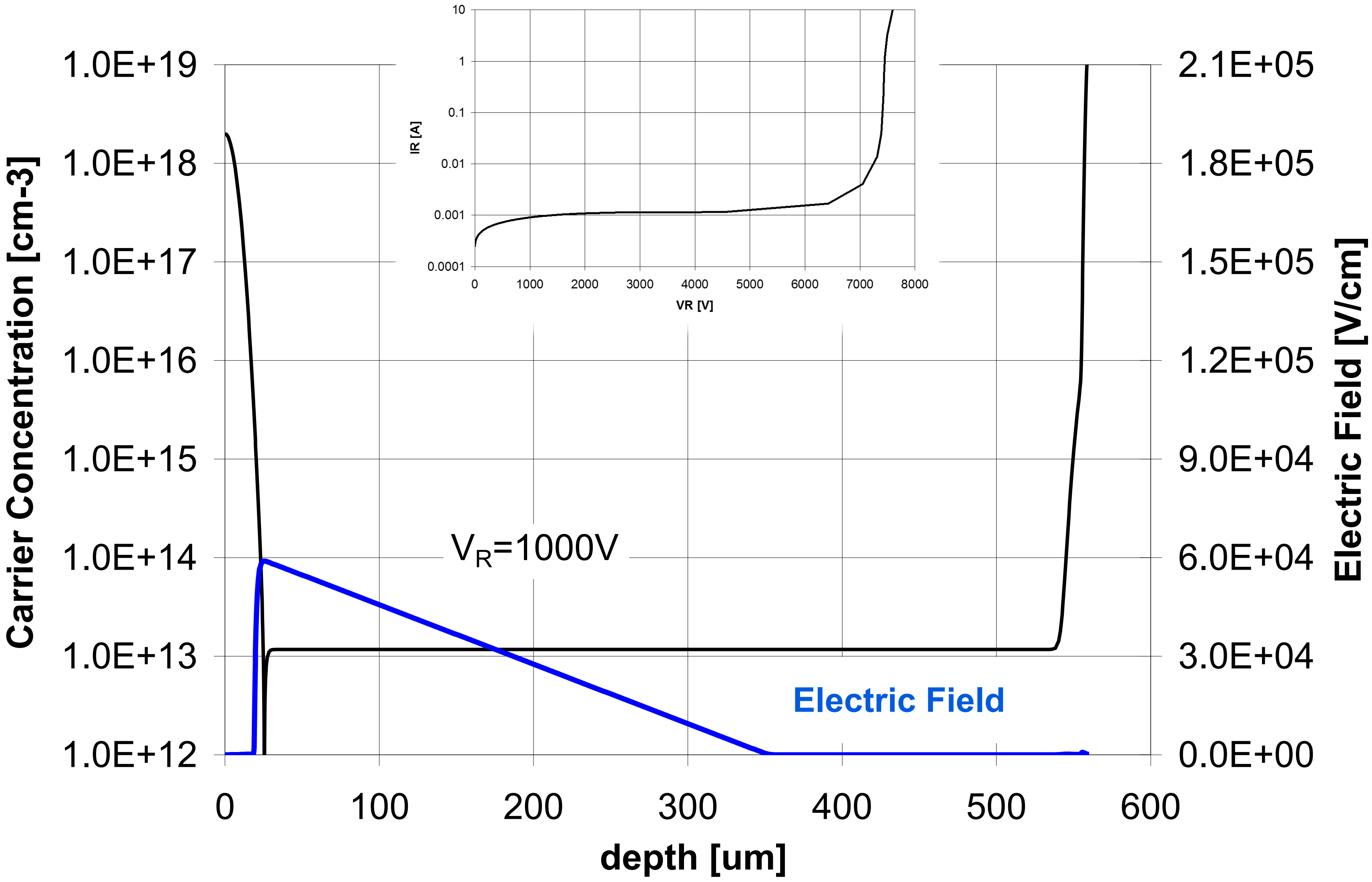
$$V_{pt} = 7.67 \times 10^{-12} N_D W_B$$ **Punch Through Voltage**

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

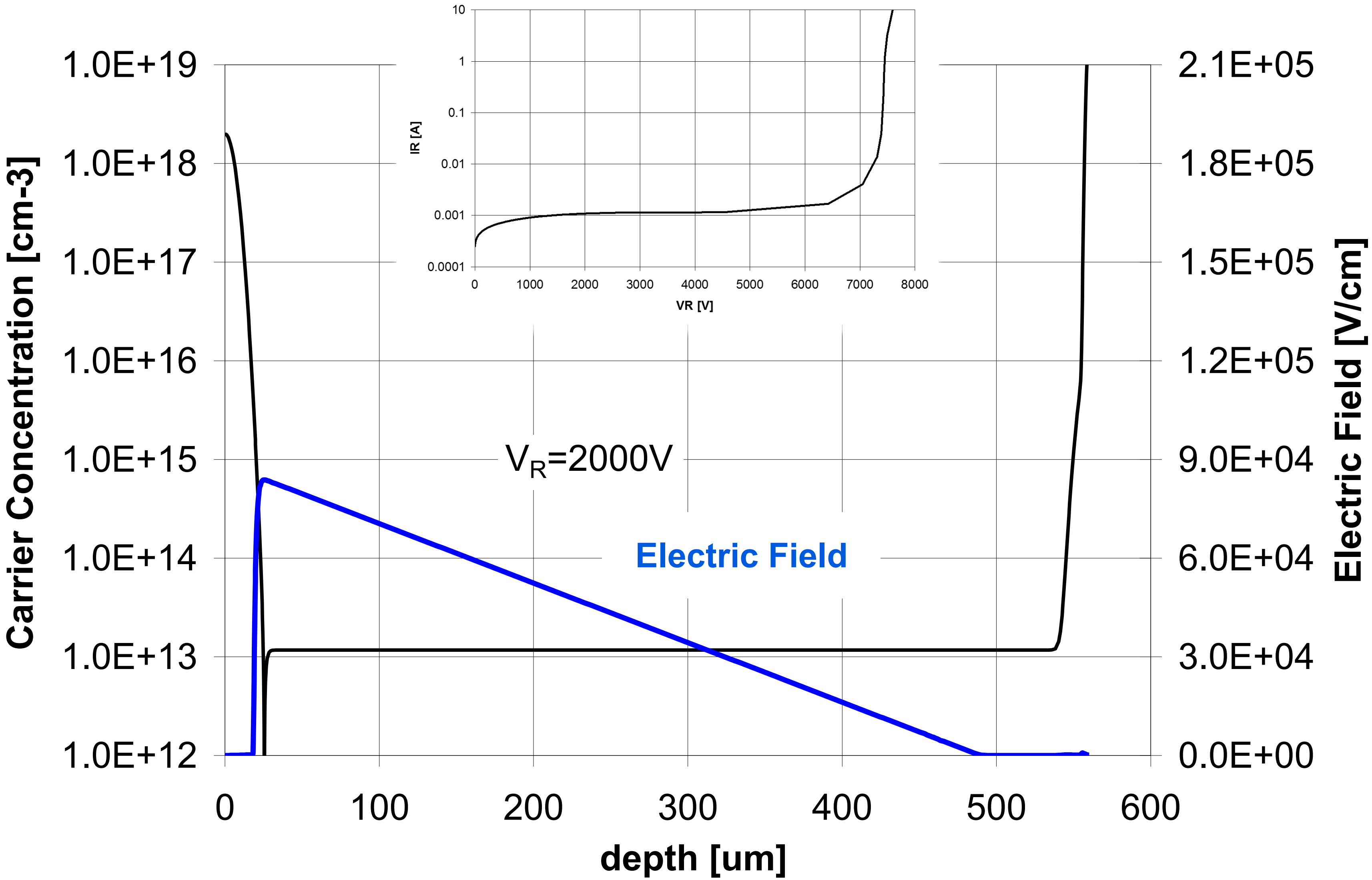
Power Diode Reverse Blocking Simulation (1/5)



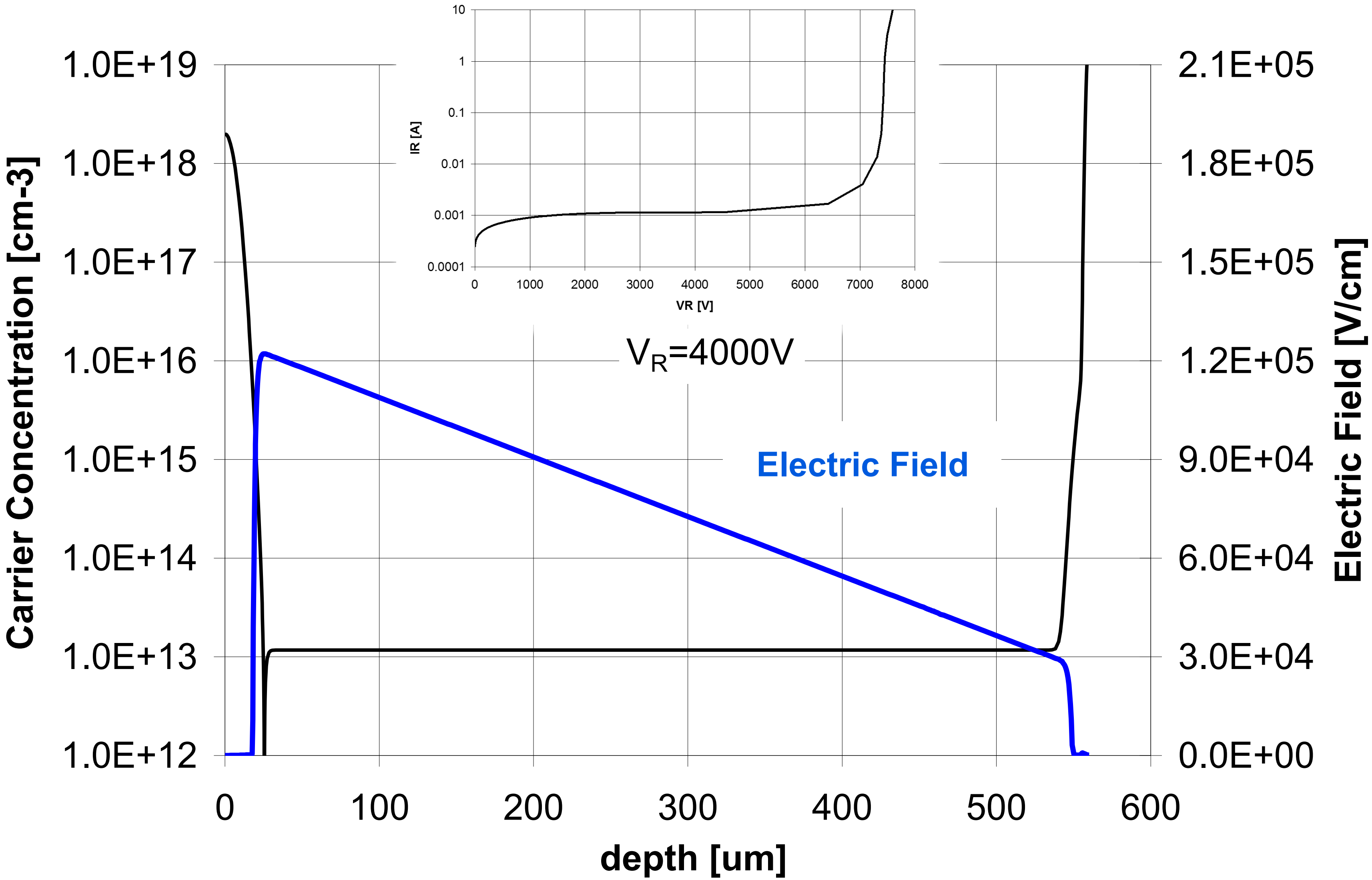
Power Diode Reverse Blocking Simulation (2/5)



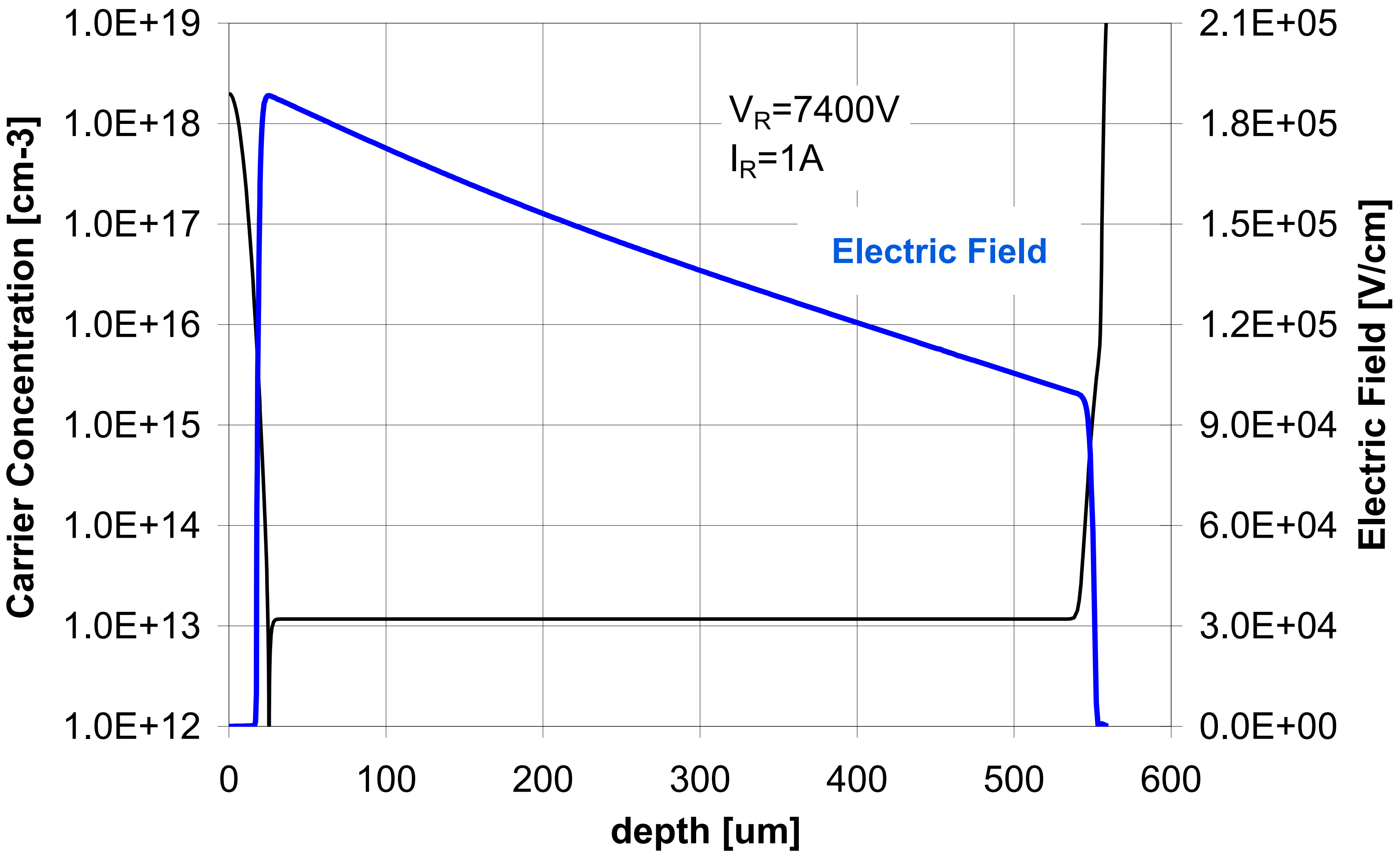
Power Diode Reverse Blocking Simulation (3/5)



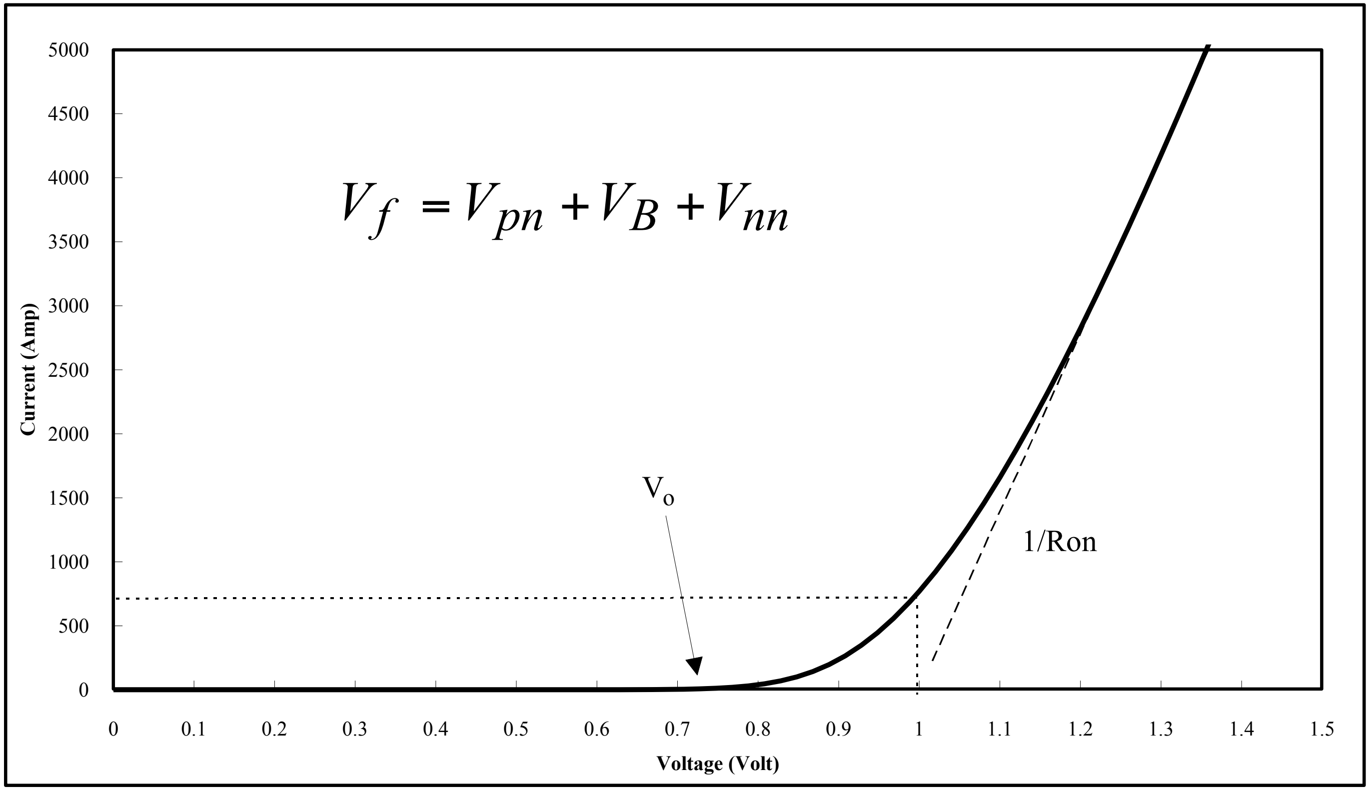
Power Diode Reverse Blocking Simulation (4/5)



Power Diode Reverse Blocking Simulation (5/5)



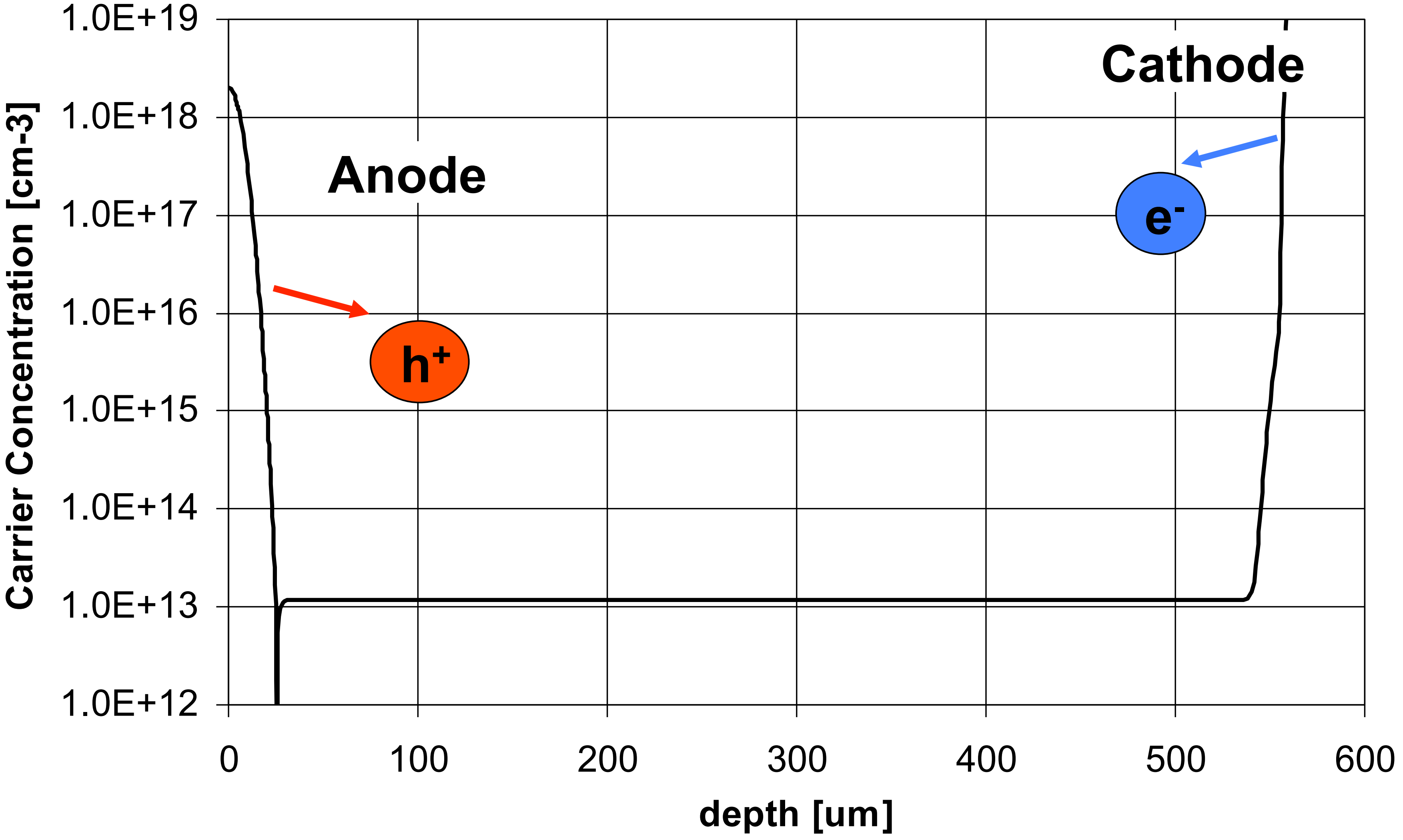
Power Diode in Forward Conduction Mode



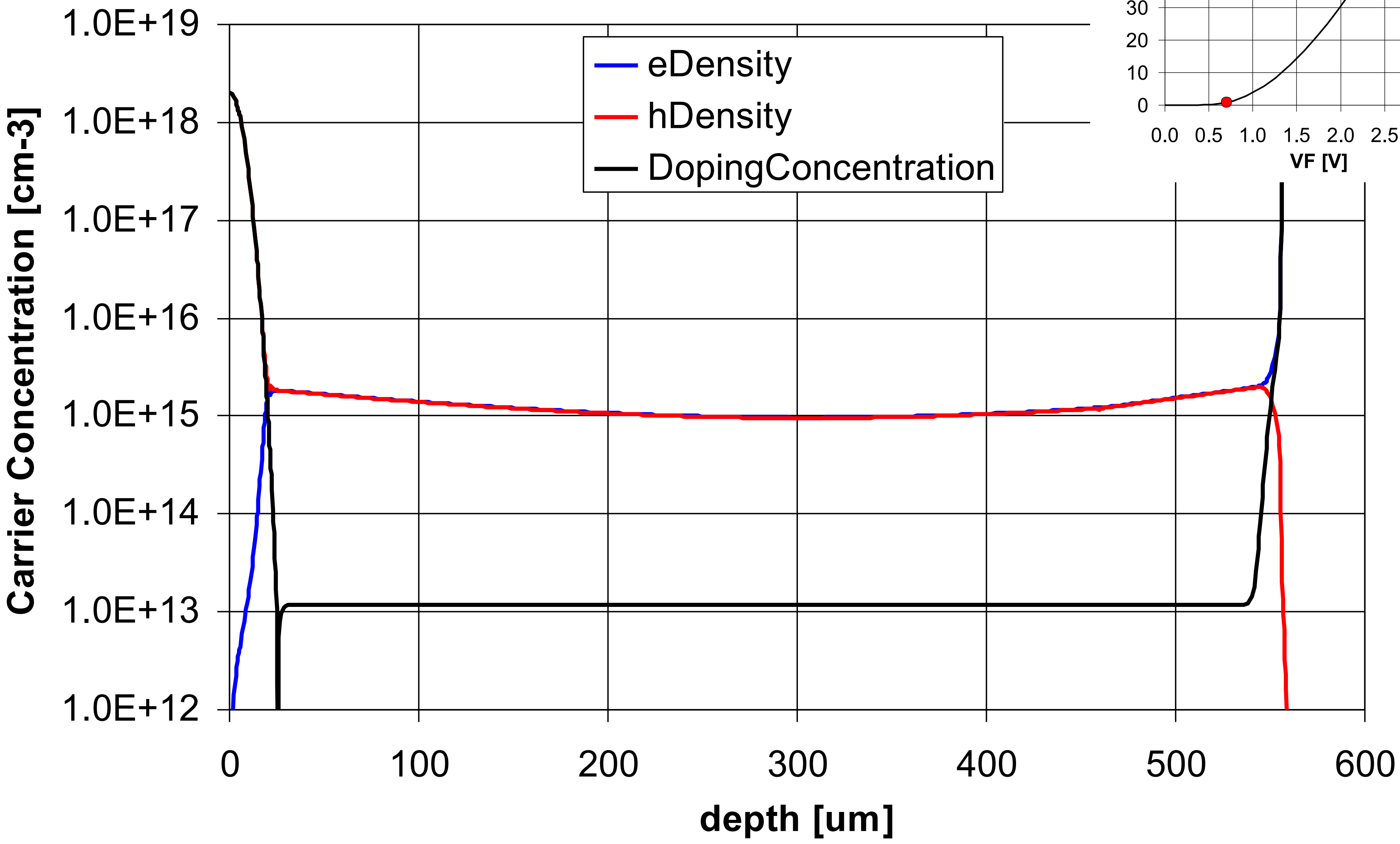
$$V_B = \frac{2kT}{q}\left(\frac{W_B}{2L_a}\right)^2$$

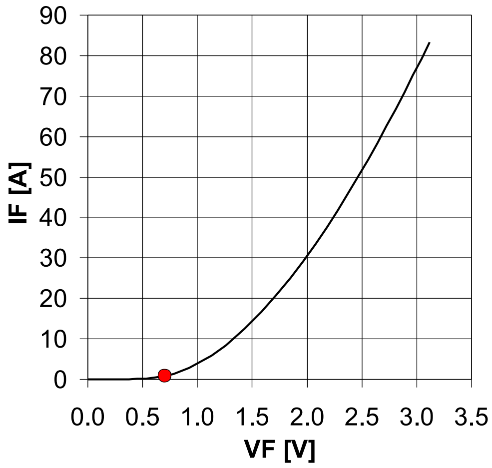
Base (Drift) Region Voltage Drop

Power Diode Forward Conduction Simulation (1/5)

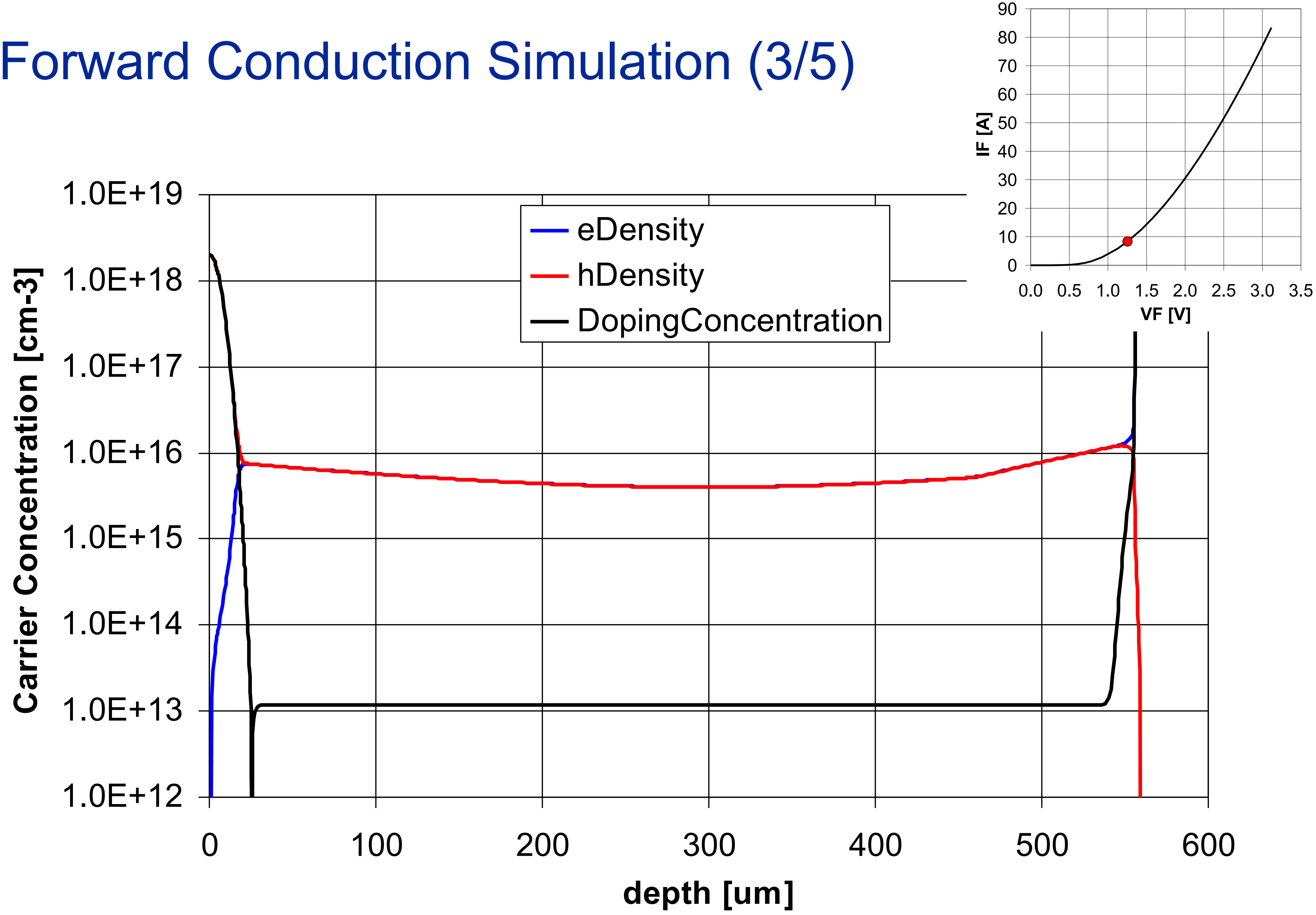


Forward Conduction Simulation (2/5)

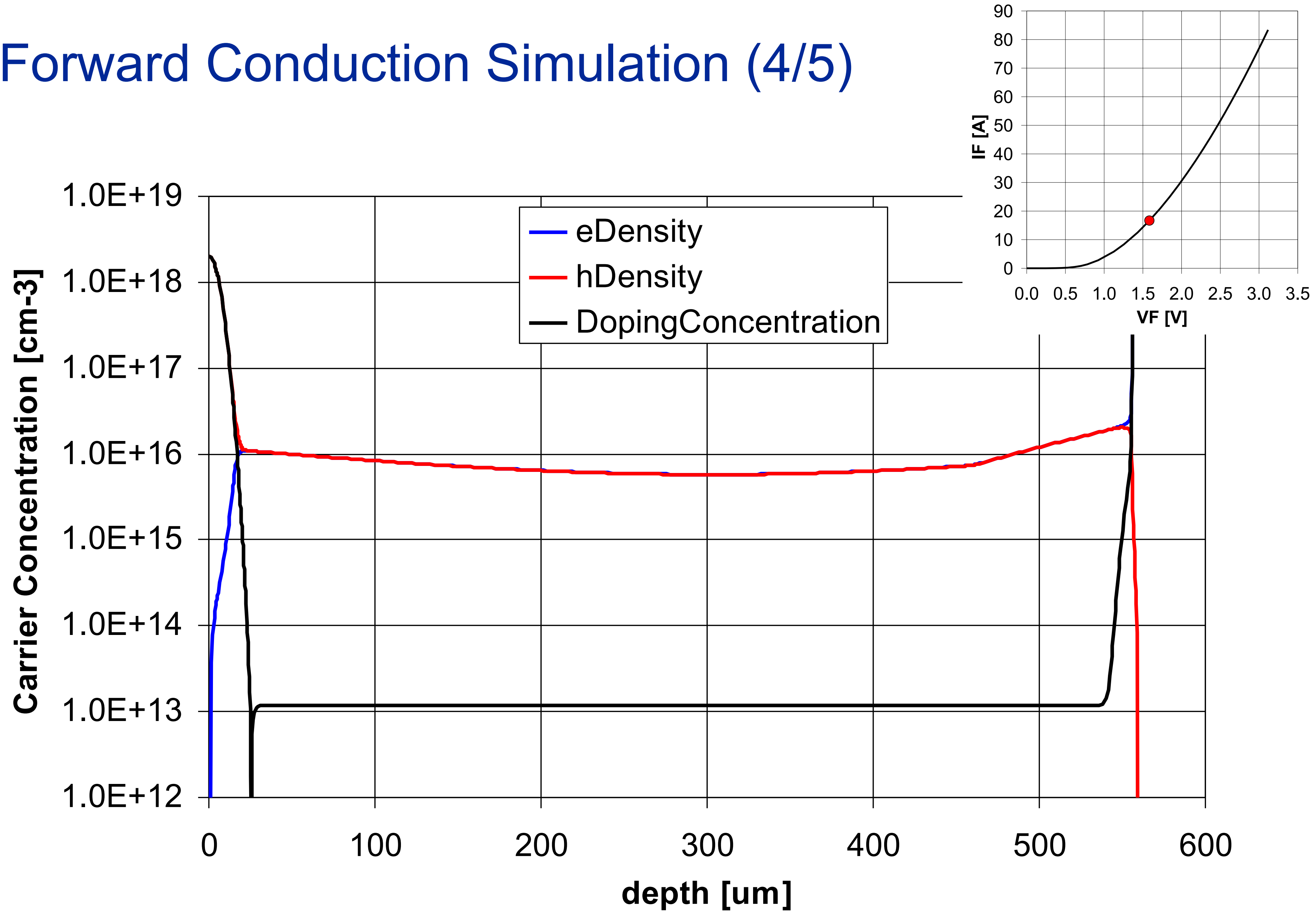




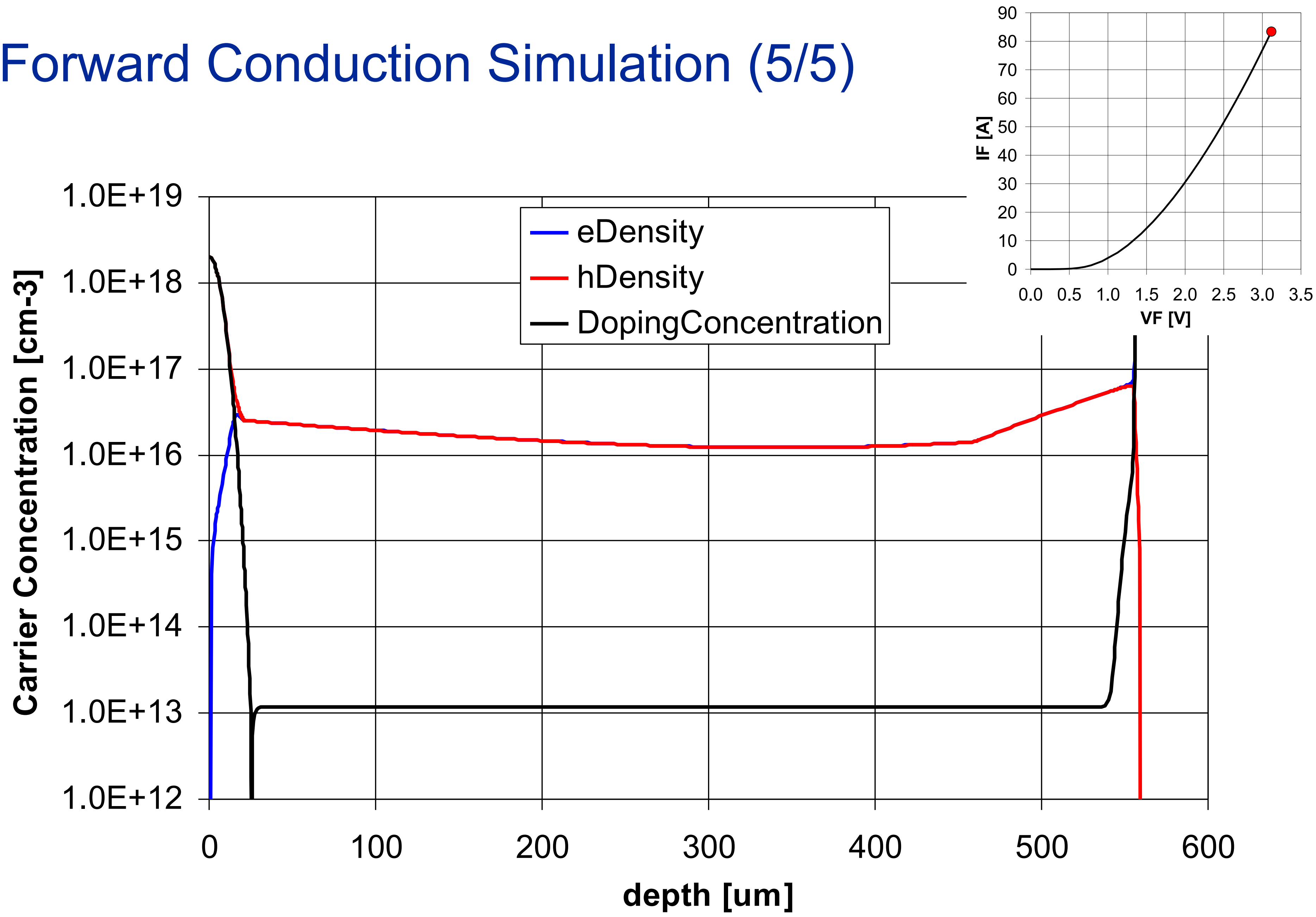
Forward Conduction Simulation (3/5)



Forward Conduction Simulation (4/5)

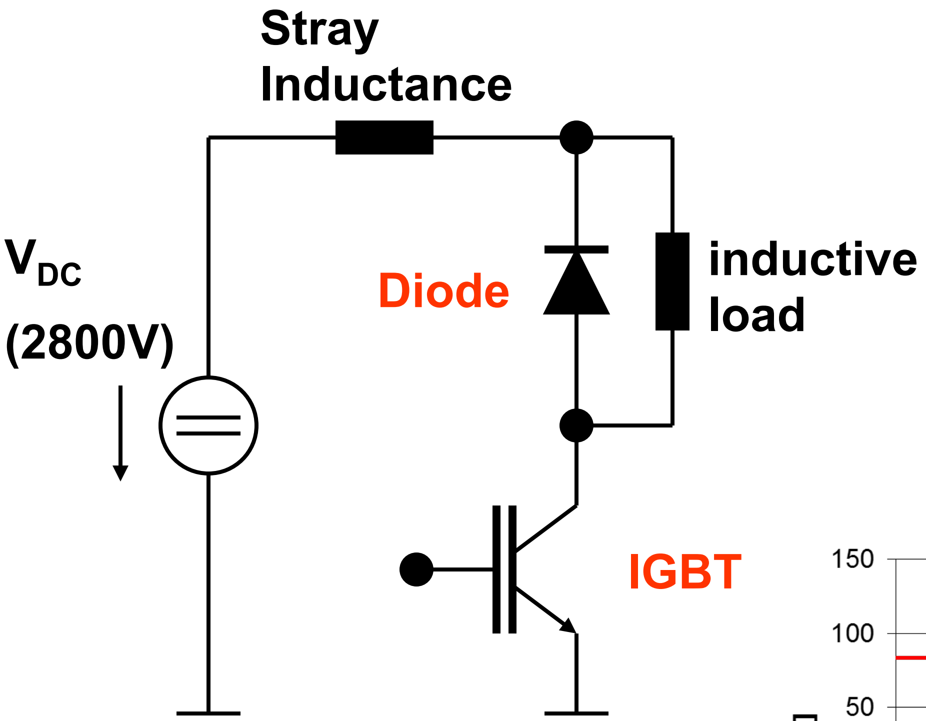


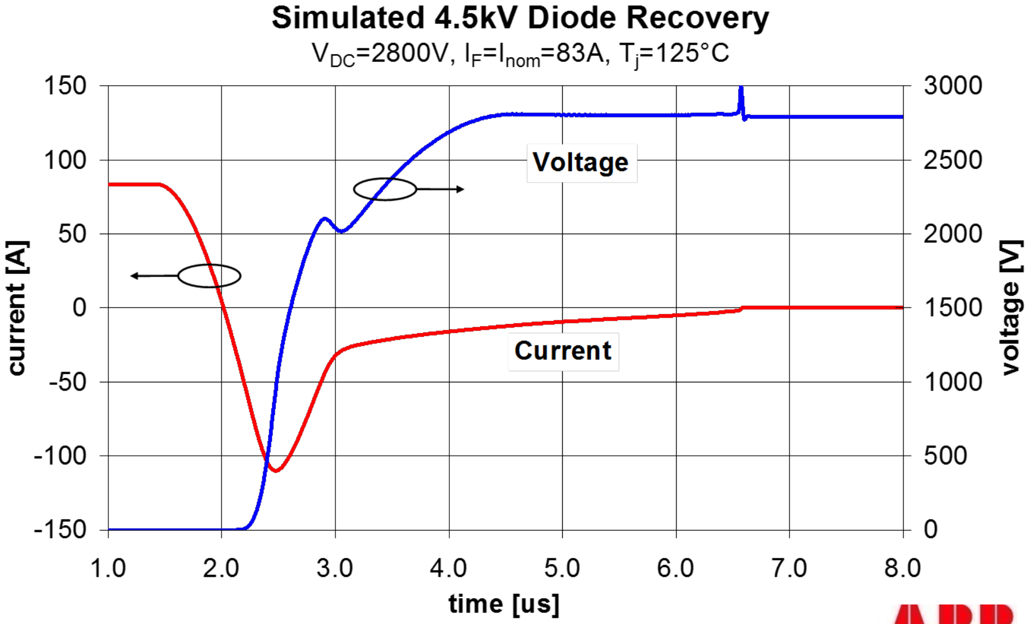
Forward Conduction Simulation (5/5)



Power Diode Reverse Recovery

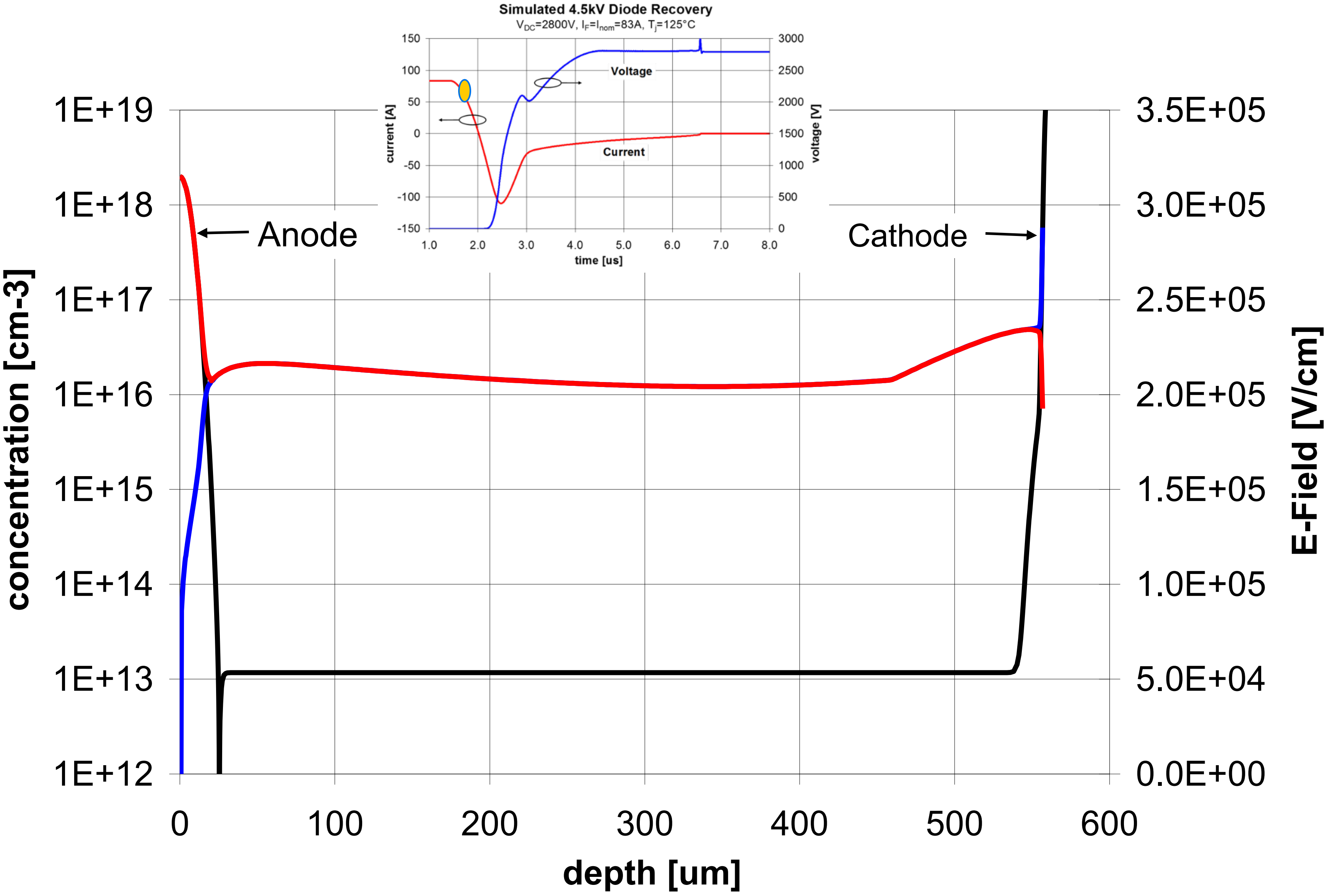
- Reverse Recovery: Transition from the conducting to the blocking state



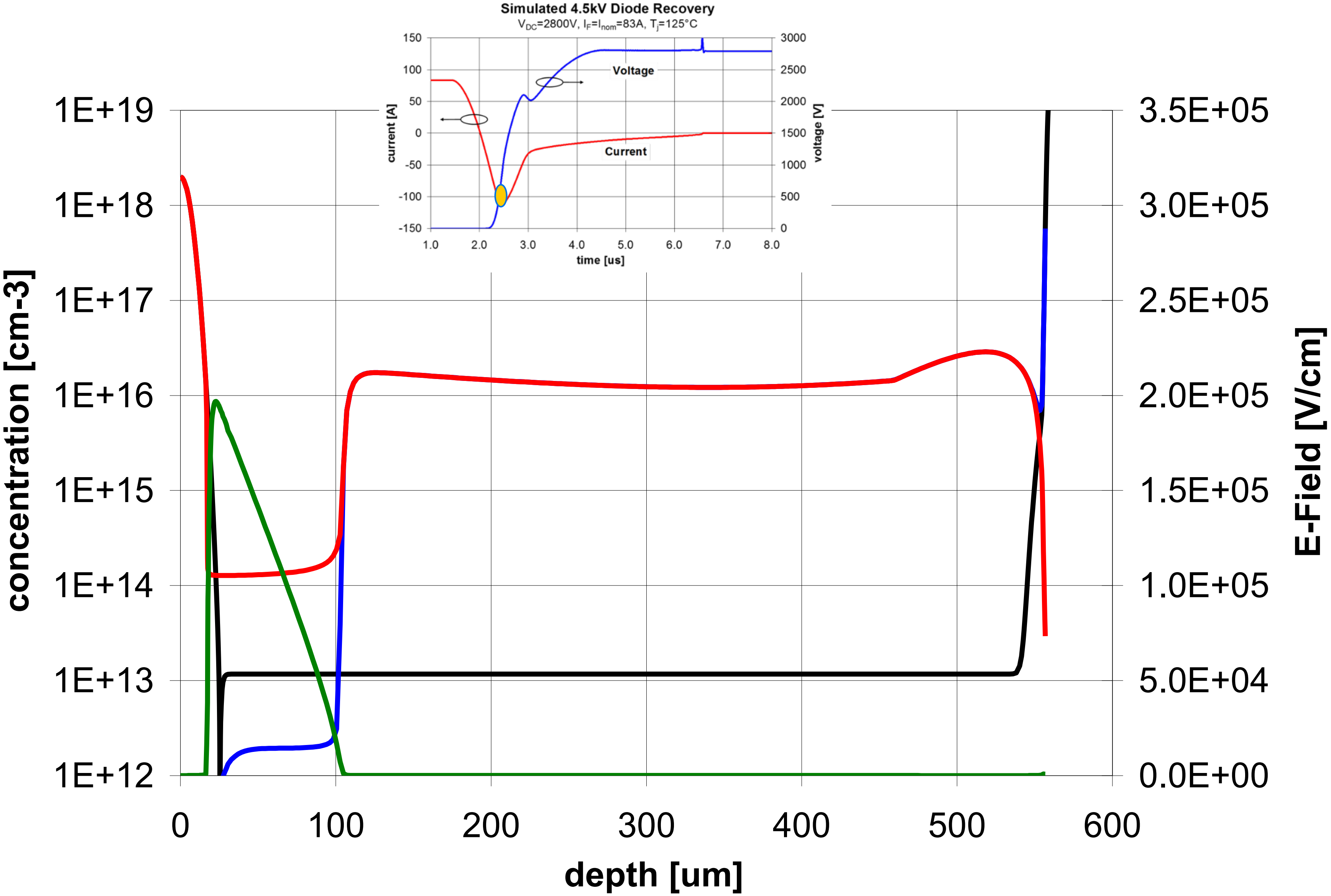

Simulated 4.5kV Diode Recovery

V_{DC}=2800V, I_F=I_{nom}=83A, T_j=125°C

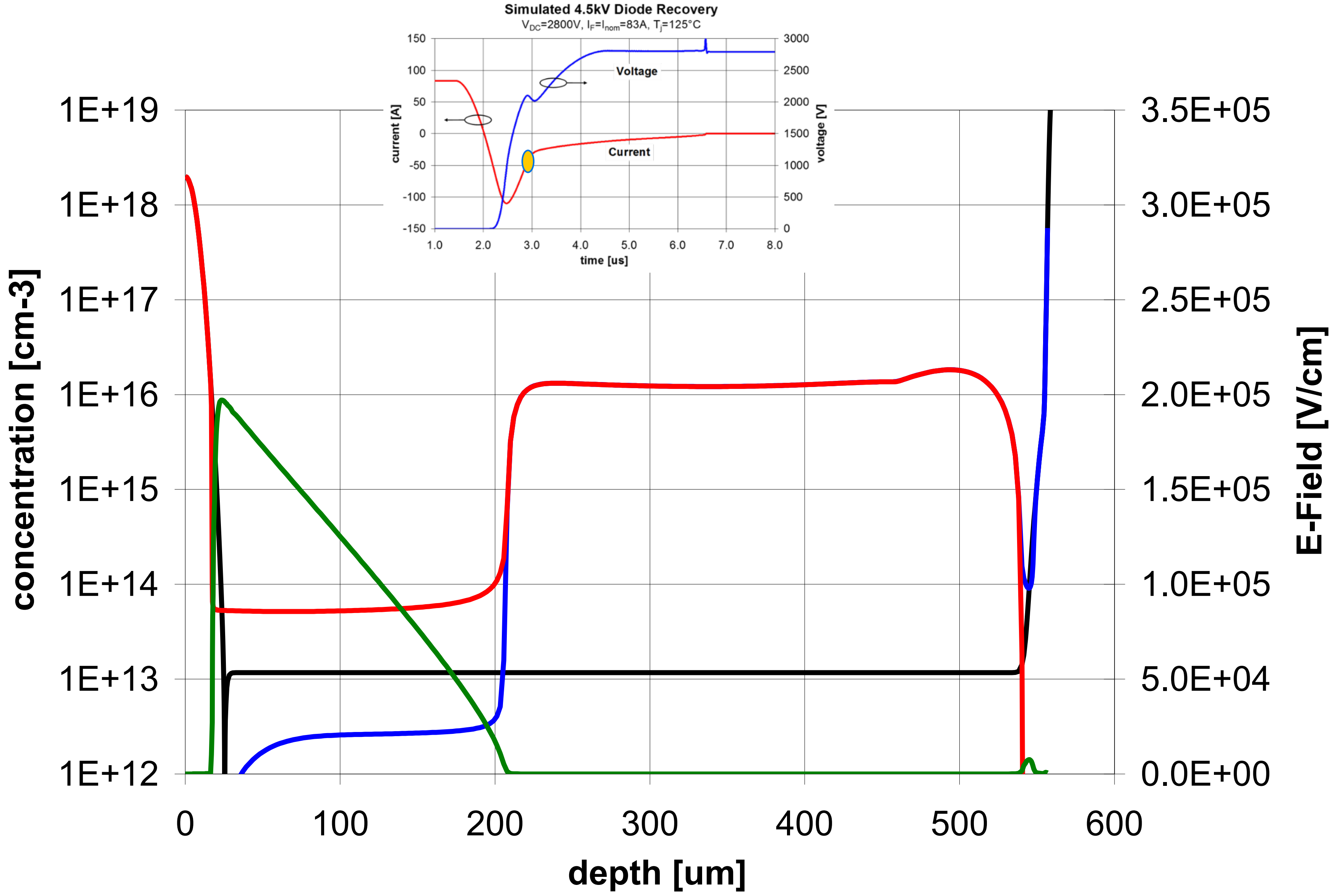
Reverse Recovery Simulation (1/5)



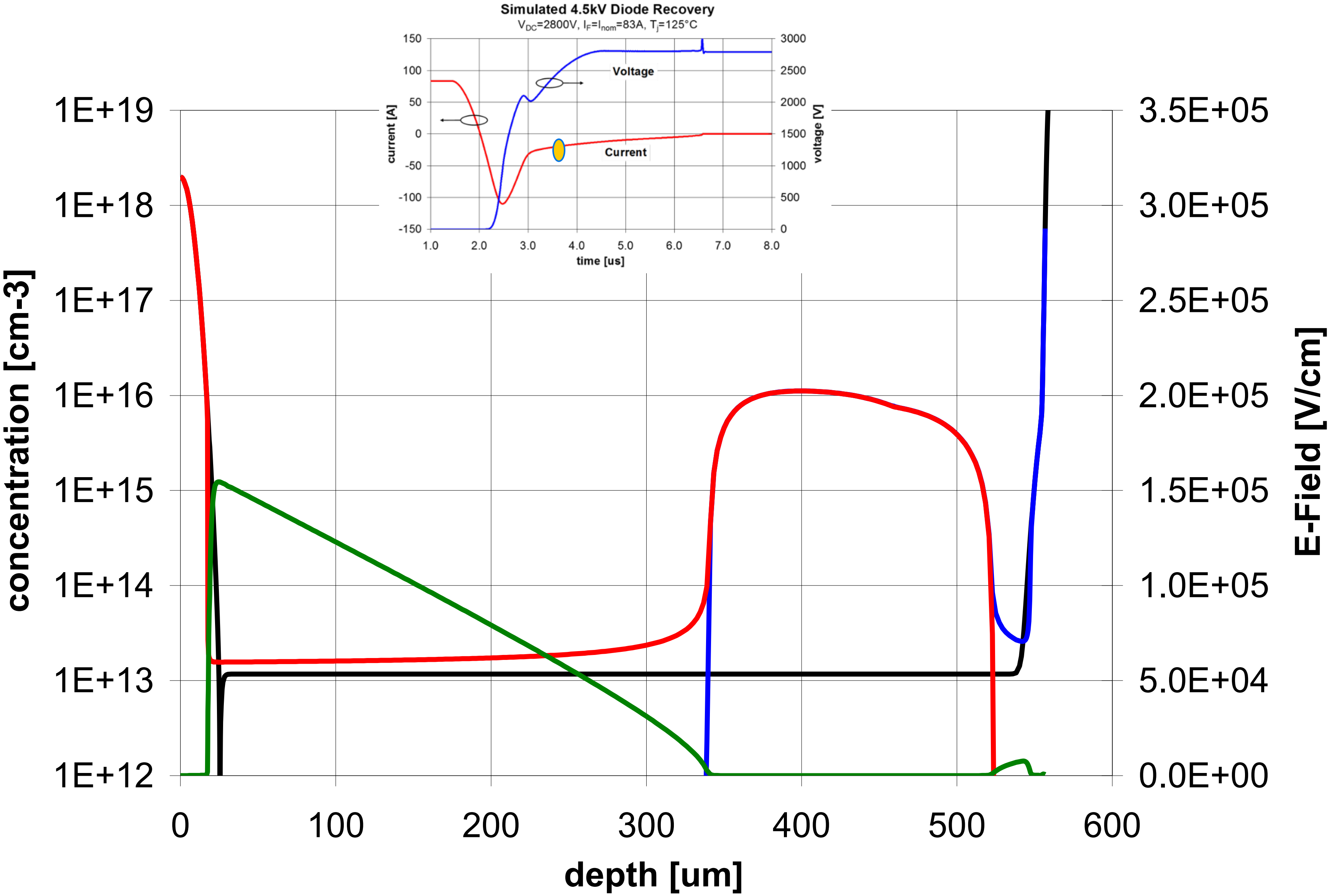
Reverse Recovery Simulation (2/5)



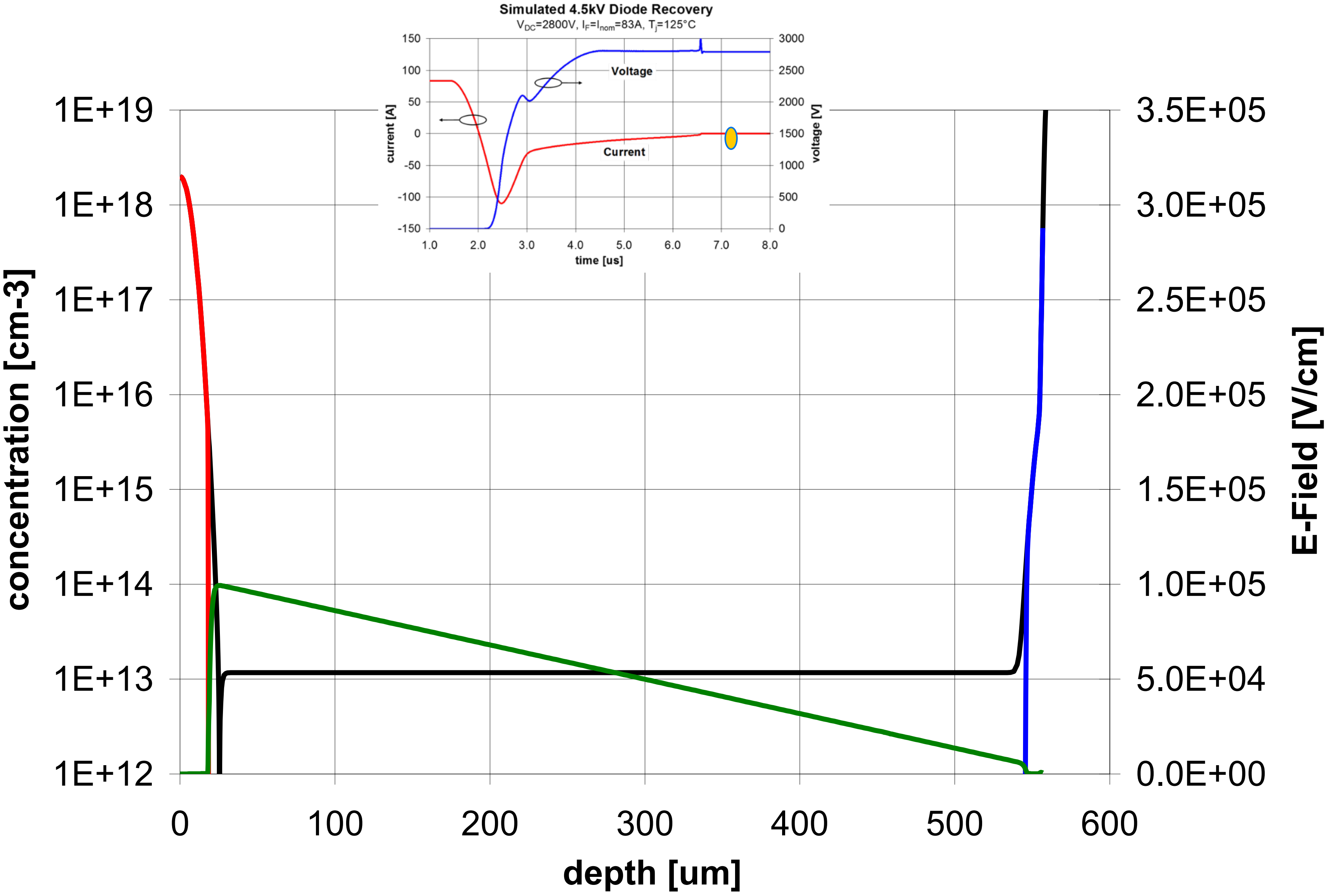
Reverse Recovery Simulation (3/5)



Reverse Recovery Simulation (4/5)



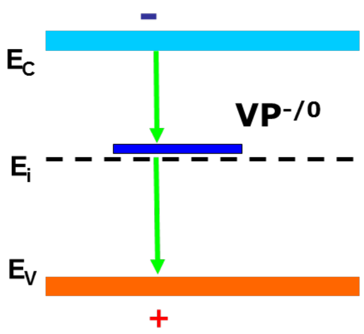
Reverse Recovery Simulation (5/5)

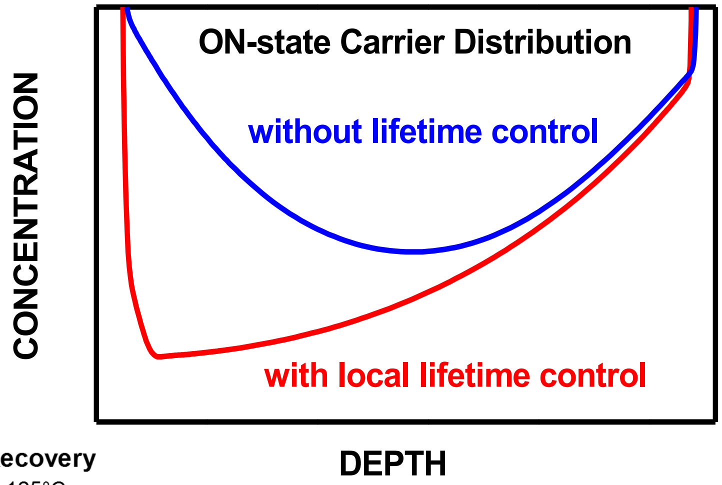


Lifetime Engineering of Power Diodes

- 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

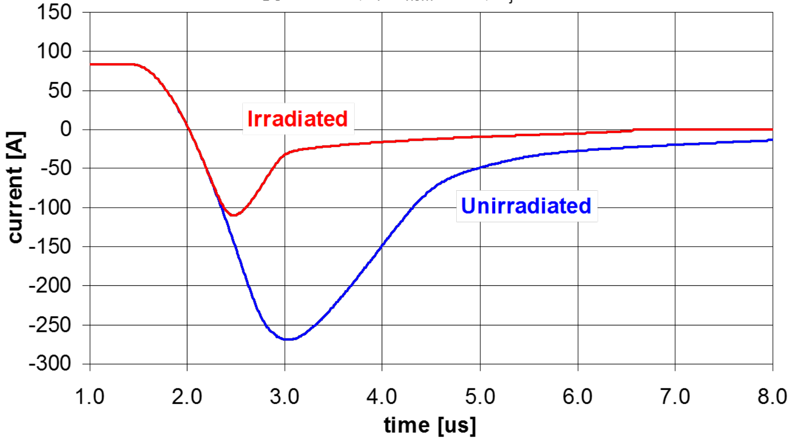
Example of carrier recombination in Silicon:





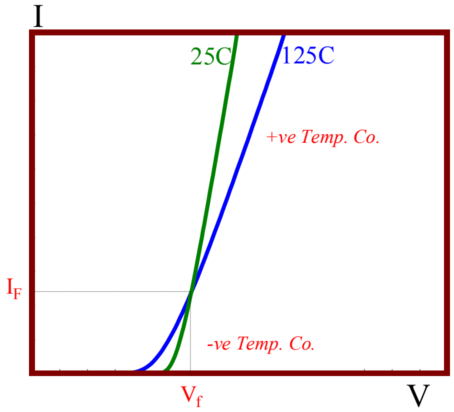
Simulated 4.5kV Diode Recovery

V_{DC}=2800V, I_F=I_{nom}=83A, T_j=125°C

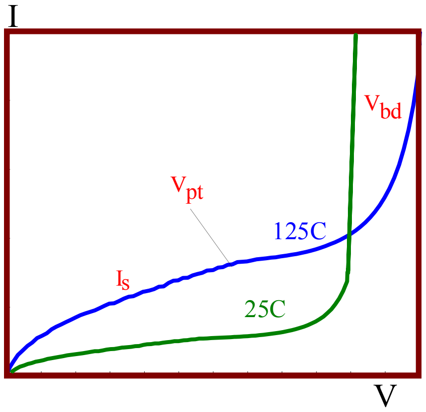


Power Diode Operational Modes

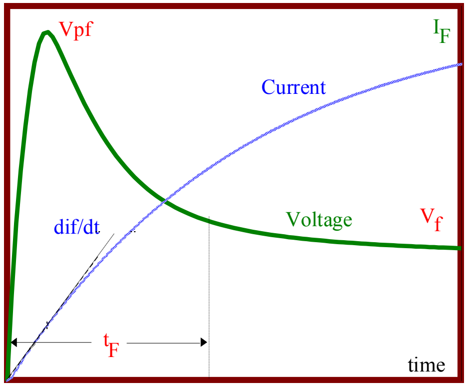
- Reverse Blocking State
  - Stable reverse blocking
  - Low leakage current
- Forward Conducting State
  - Low on-state losses
  - Positive temperature coefficient
- Turn-On (forward recovery)
  - Low turn-on losses
  - Short turn-on time
  - Good controllability
- Turn-Off (reverse recovery)
  - Low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



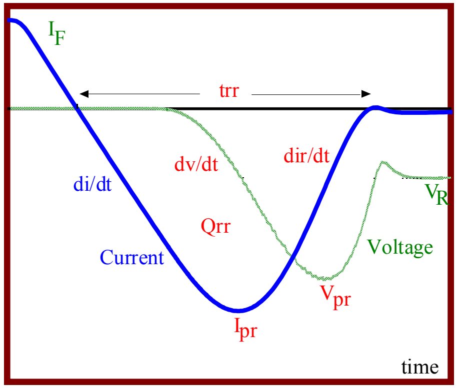
Forward Characteristics



Reverse Characteristics



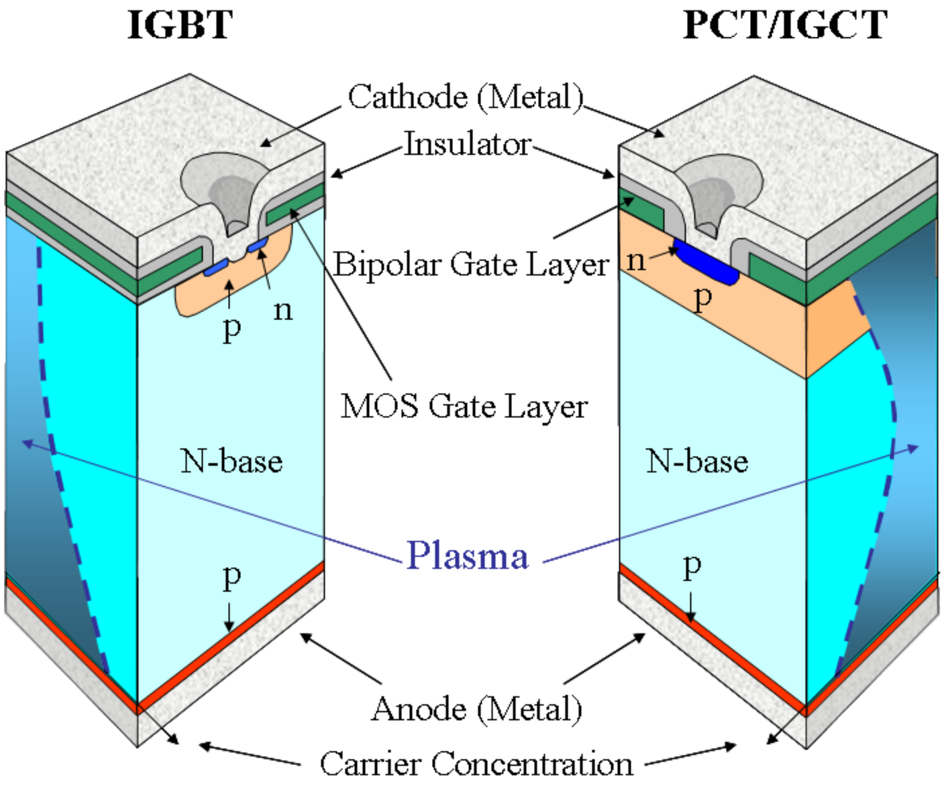
Forward Recovery



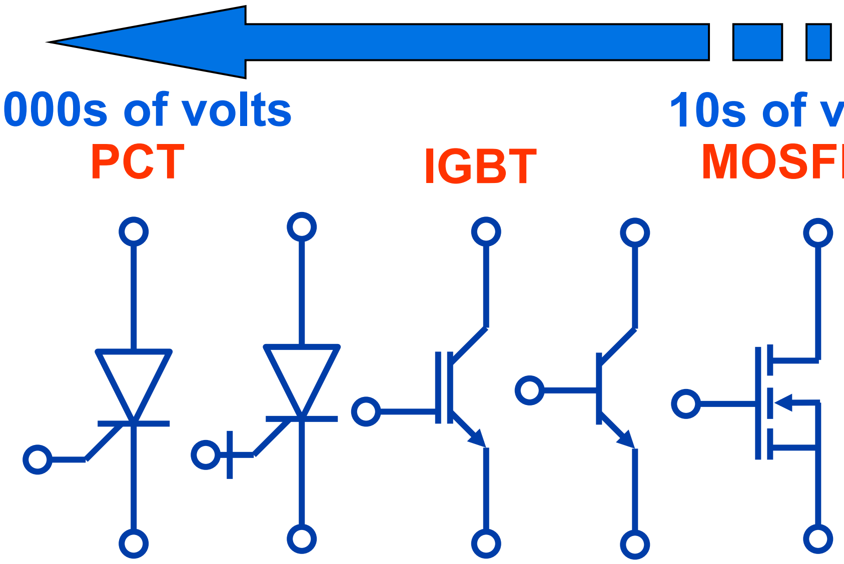
Reverse Recovery

Power Semiconductors

Technologies and Performance



Silicon Power Semiconductor Device Concepts

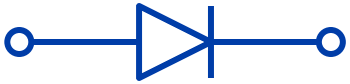


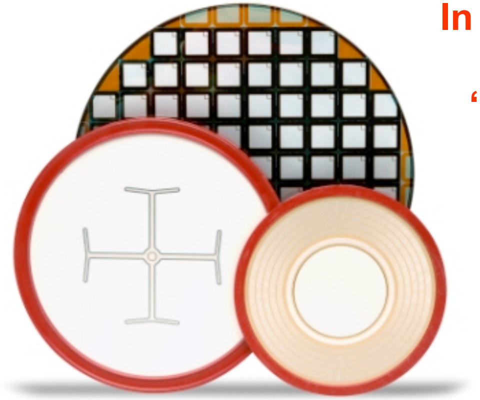
1000s of volts **10s of volts**

PCT **IGBT** **MOSFET**

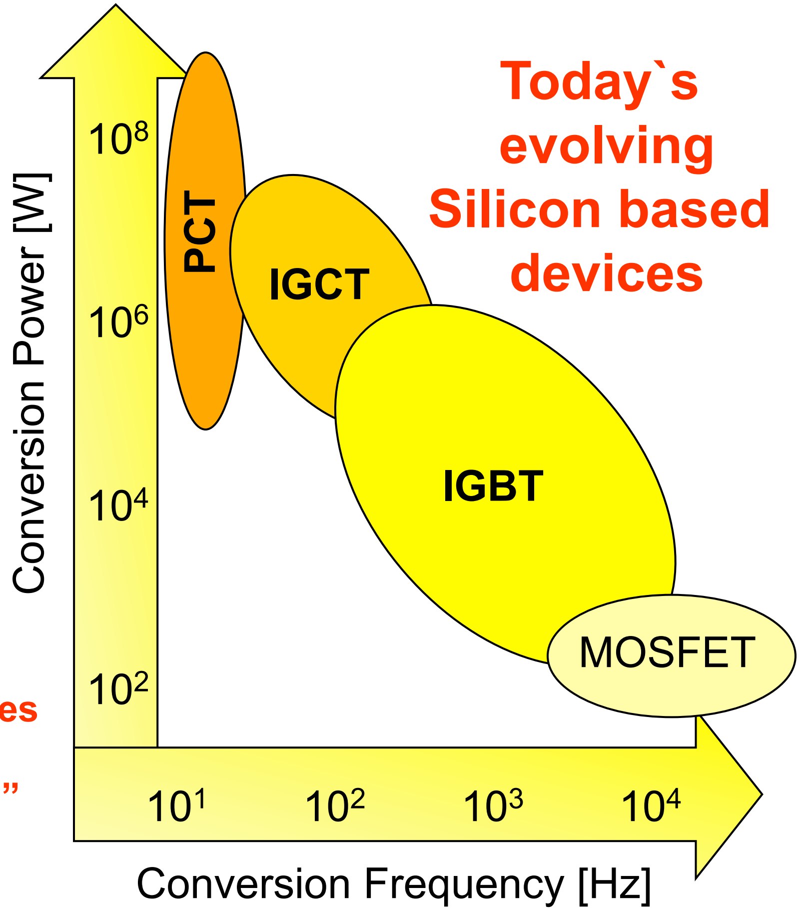
GTO / **GCT** BJT

and the companion Diode





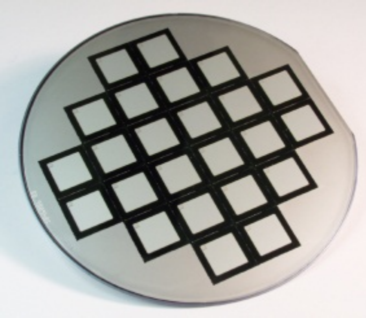
In red are devices that are in "design-in life"



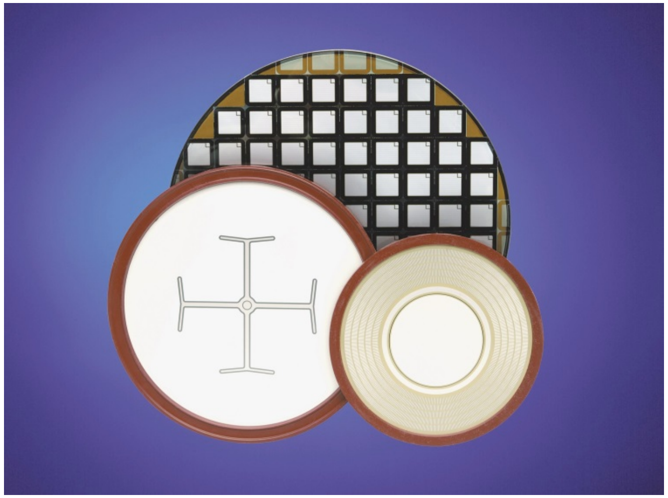
Today`s evolving Silicon based devices

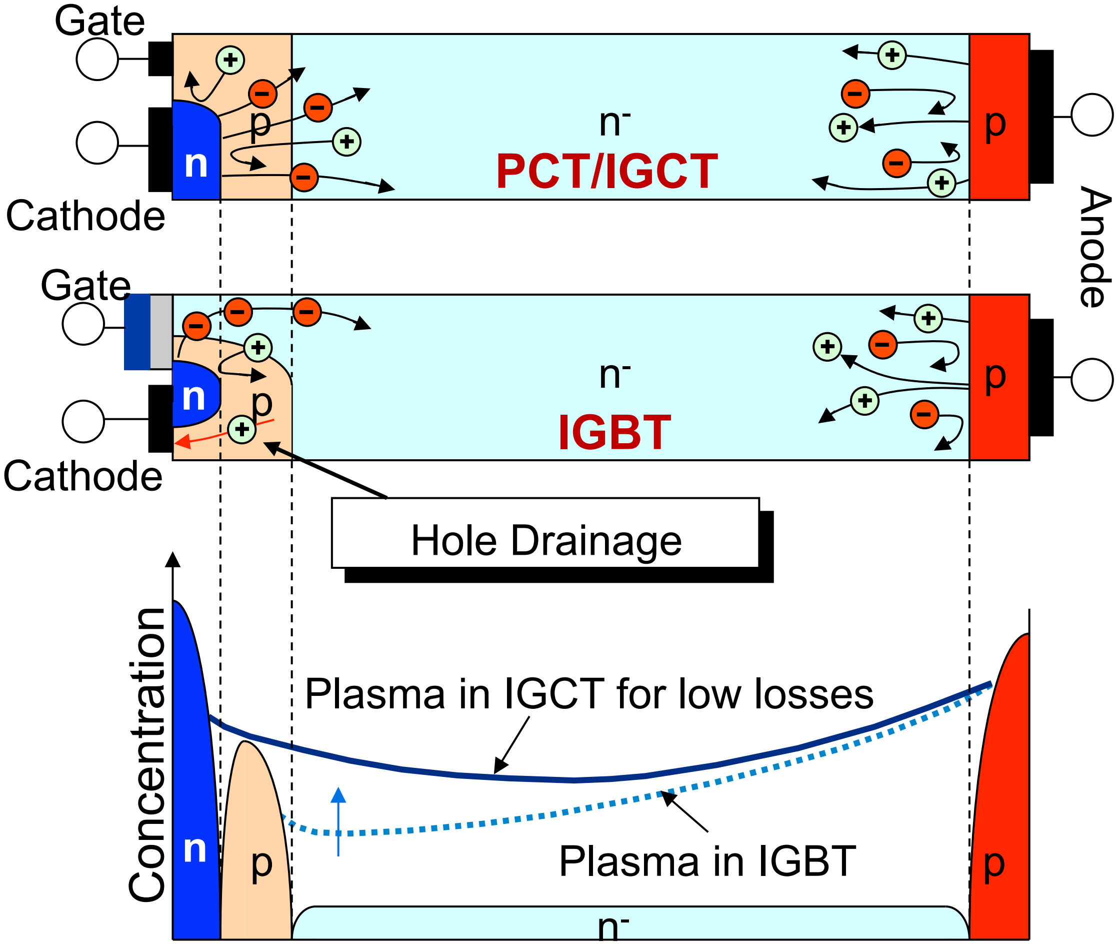
Silicon Power Semiconductor Switches

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)



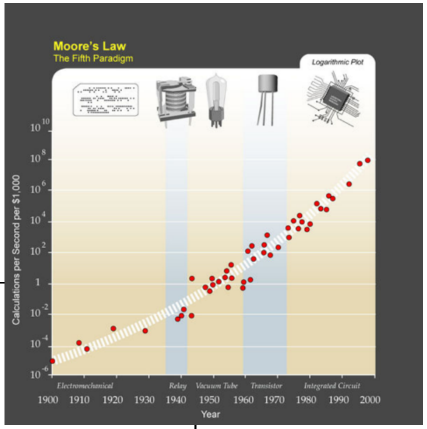
The main High Power MW Devices: LOW LOSSES



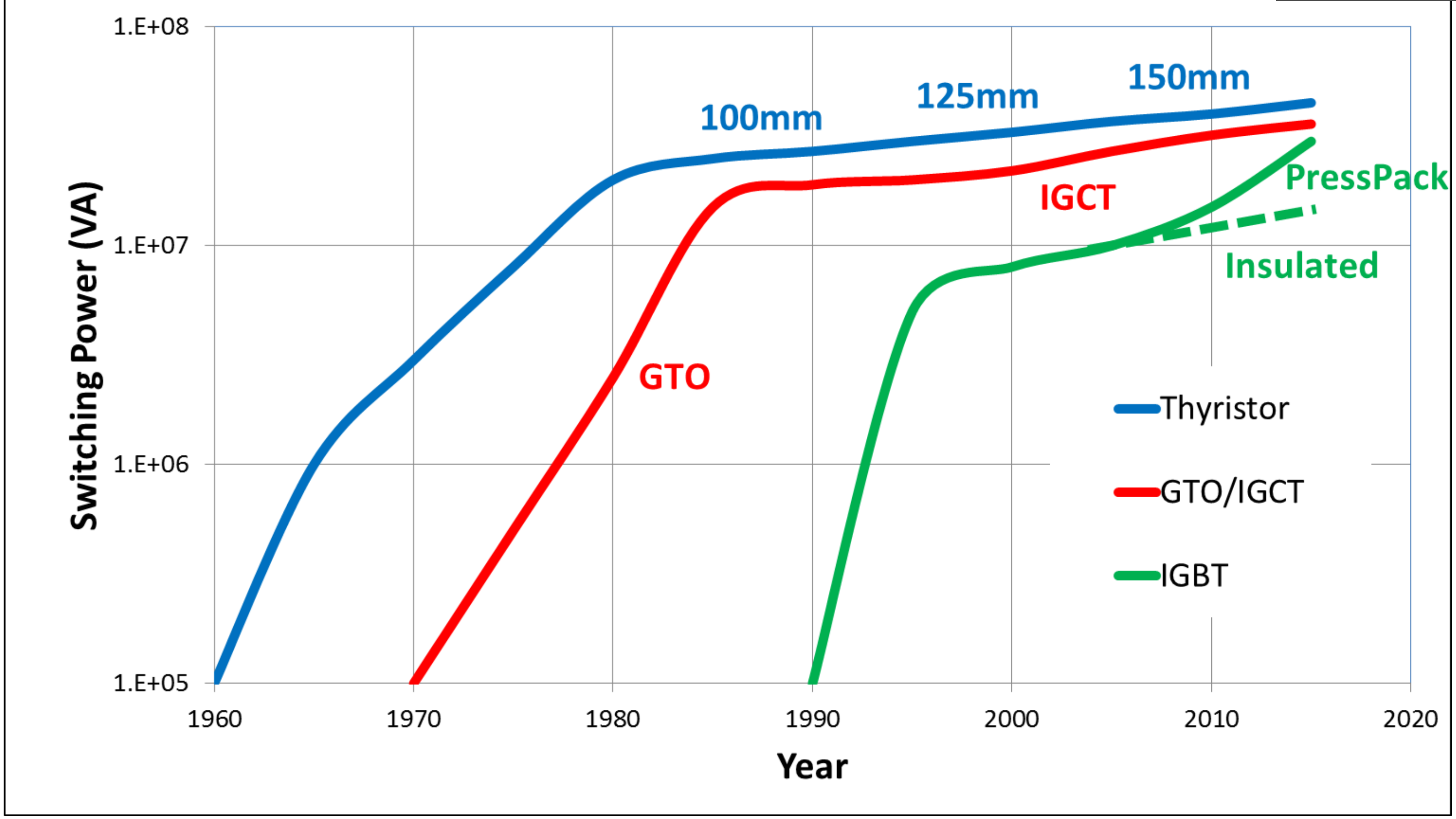


- **PCTs & IGCTs**: optimum carrier distribution for lowest losses
- **IGBTs:** continue to improve the carrier distribution for low losses

The High Power Devices Developments

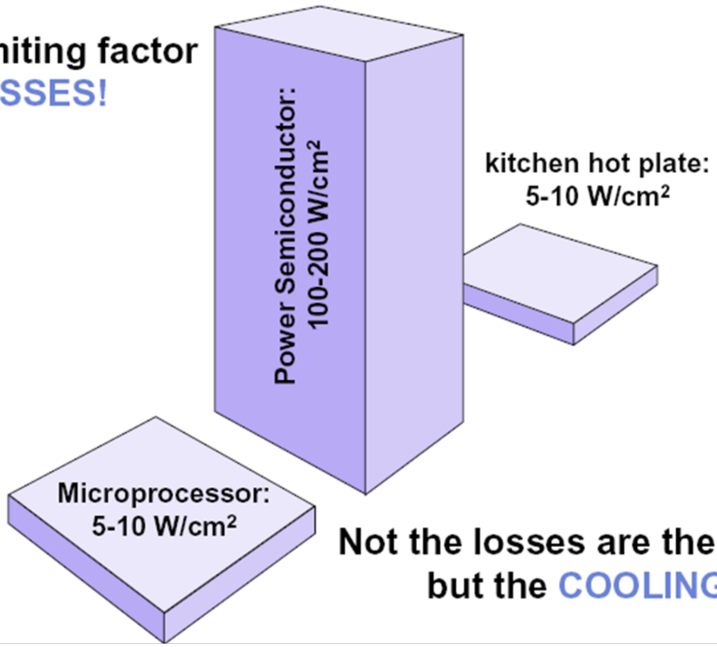


Historical Development of the Maximum Switching power of the Three Major High Power Semiconductors

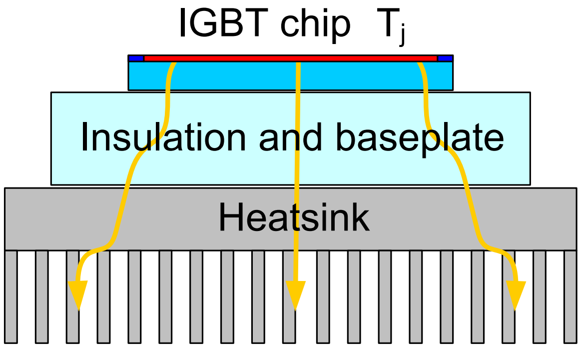


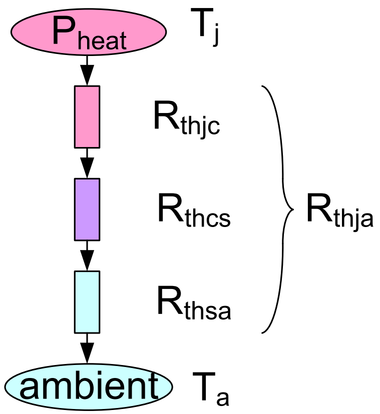
Power Semiconductor Power Ratings

The limiting factor are LOSSES!



Not the losses are the problem, but the COOLING!





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

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

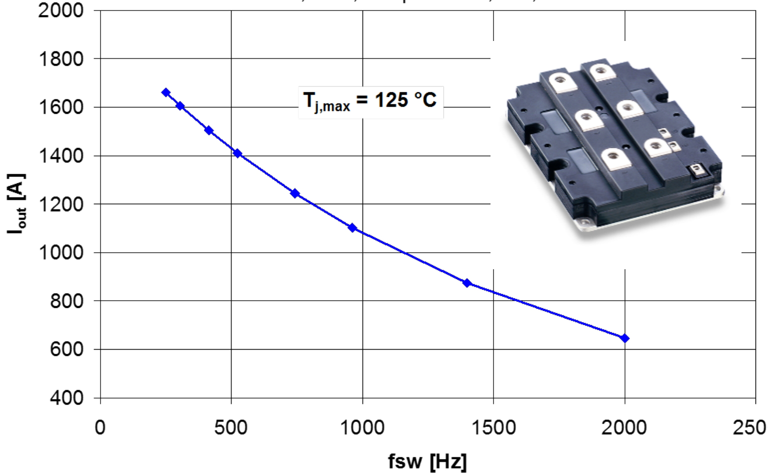
$R_{th,\ j\text{-}a} = 18K / kW$

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

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

3.3kV SPT+ HiPak2 Output Current

VDC=1800V, m=1, cos phi =0.85, Rth,c-a = 9.5K/kW

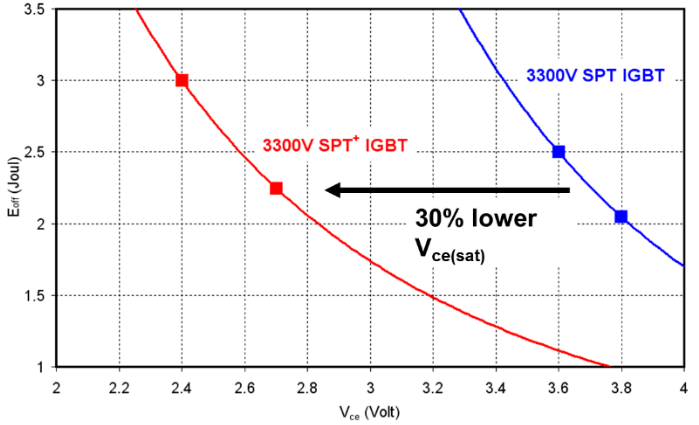


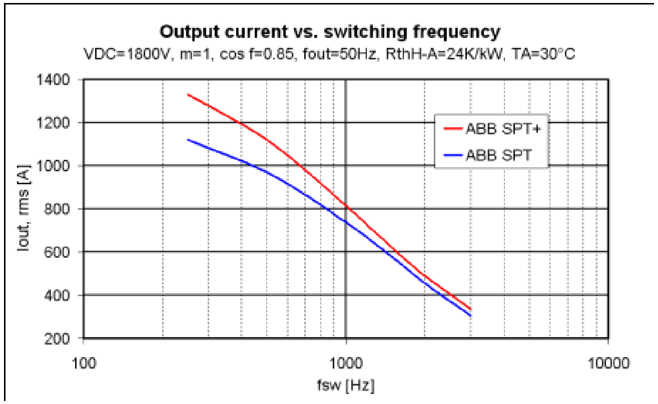
Total IGBT Losses : $P_{tot} = P_{cond} + P_{turn\text{-}off} + P_{turn\text{-}on}$

Performance Requirements for Power Devices

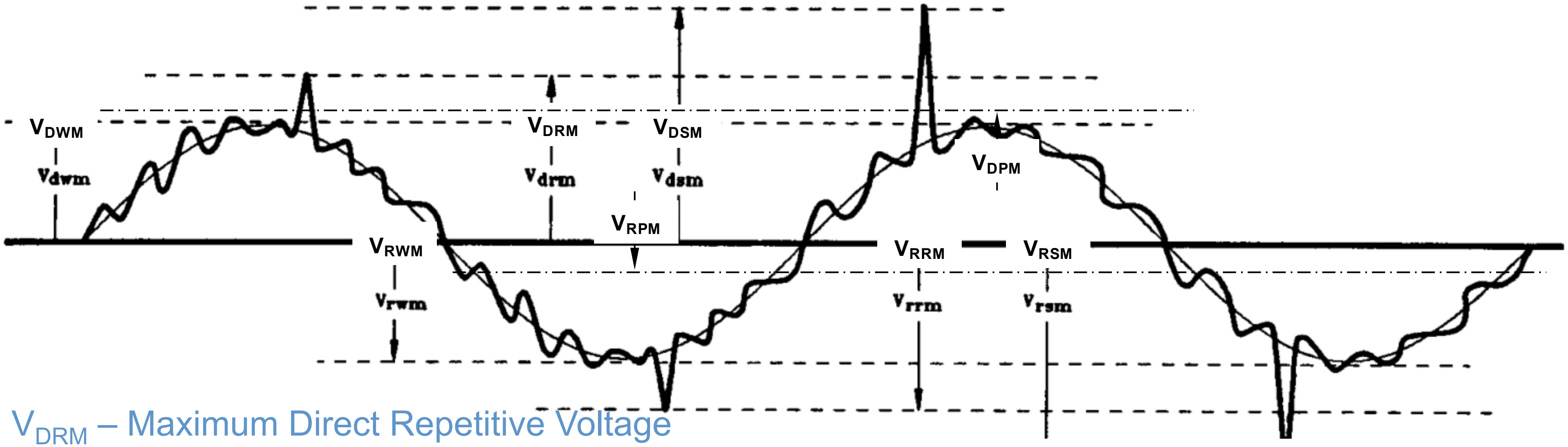
- **Power Density Handling Capability:**
  - Low on-state and switching losses
  - High operating temperatures
  - Low thermal resistance
- **Controllable and Soft Switching:**
  - Good turn-on controllability
  - Soft and controllable turn-off and low EMI
- **Ruggedness and Reliability:**
  - High turn-off 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)

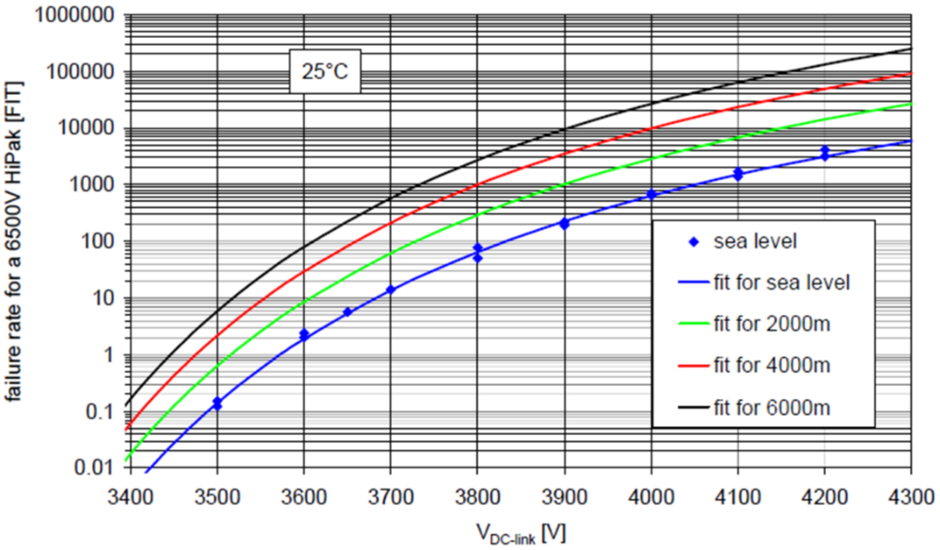




Power Semiconductor Voltage Ratings



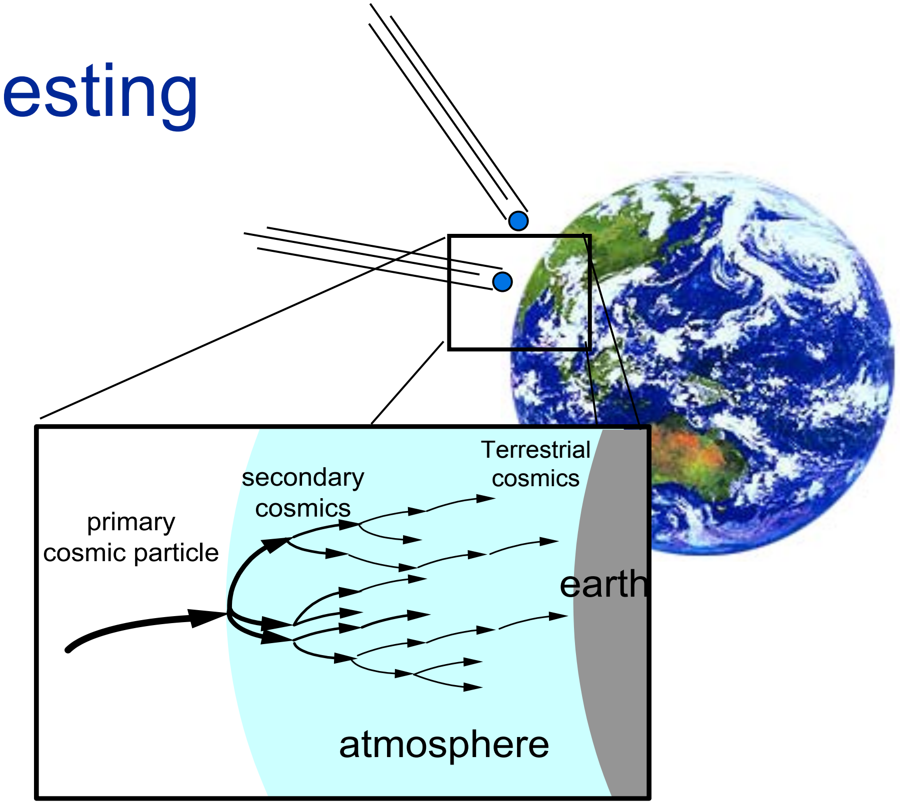
- V_{DRM} – Maximum Direct Repetitive Voltage
- V_{RRM} – Maximum Reverse Repetitive Voltage
- V_{DPM} – Maximum Direct Permanent Voltage
- V_{RPM} – Maximum Reverse Permanent Voltage
- V_{DSM} – Maximum Direct Surge Voltage
- V_{RSM} – Maximum Reverse Surge Voltage
- V_{DWM} – Maximum Direct Working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

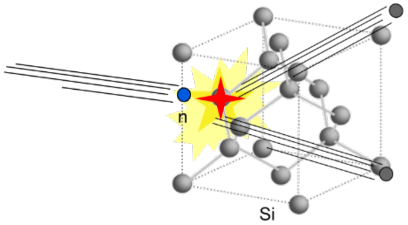


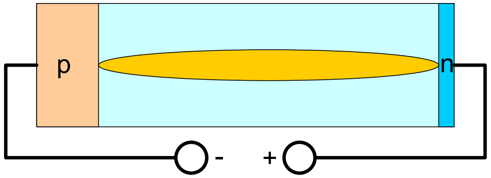
6.5kV IGBT FIT rates due to cosmic rays

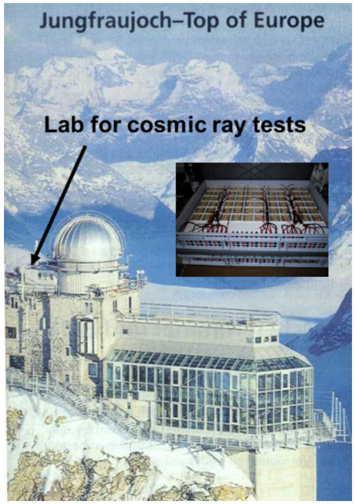
Cosmic Ray Failures and Testing

- Interaction of primary cosmics with magnetic field of earth “Cosmics are more focused to the magnetic poles”
- Interaction with earth atmosphere:
  - Cascade of secondary, tertiary … particles in the upper atmosphere
  - Increase of particle density
  - Cosmic flux dependence of altitude
- Terrestrial cosmic particle species:
  - muons, neutrons, protons, electrons, pions
- Typical terrestrial cosmic flux at sea level: 20 neutrons per cm^2 and h

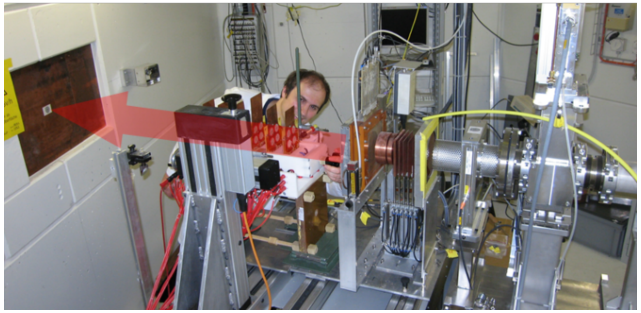






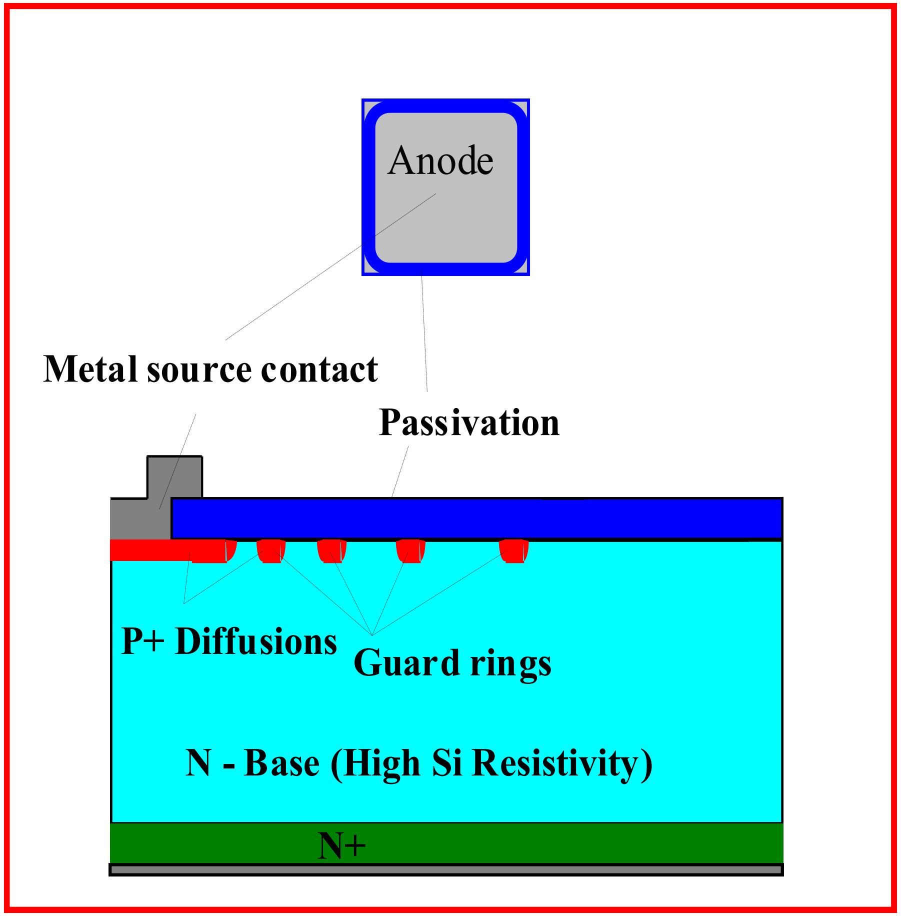


Proton beam at Paul Scherrer Institute, Switzerland

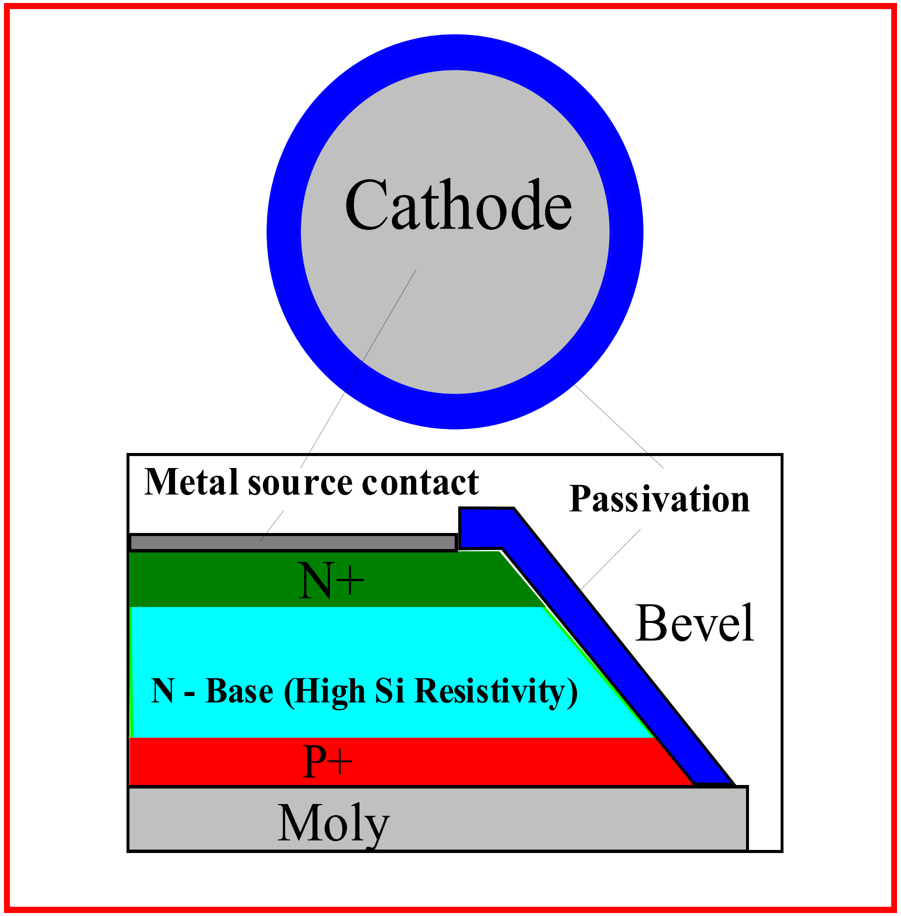


- **Failures due to cosmic under blocking condition without precursor**
- **Statistical process and Sudden single event burnout**

Power Semiconductor Junction Termination

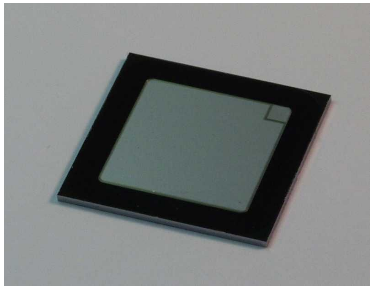


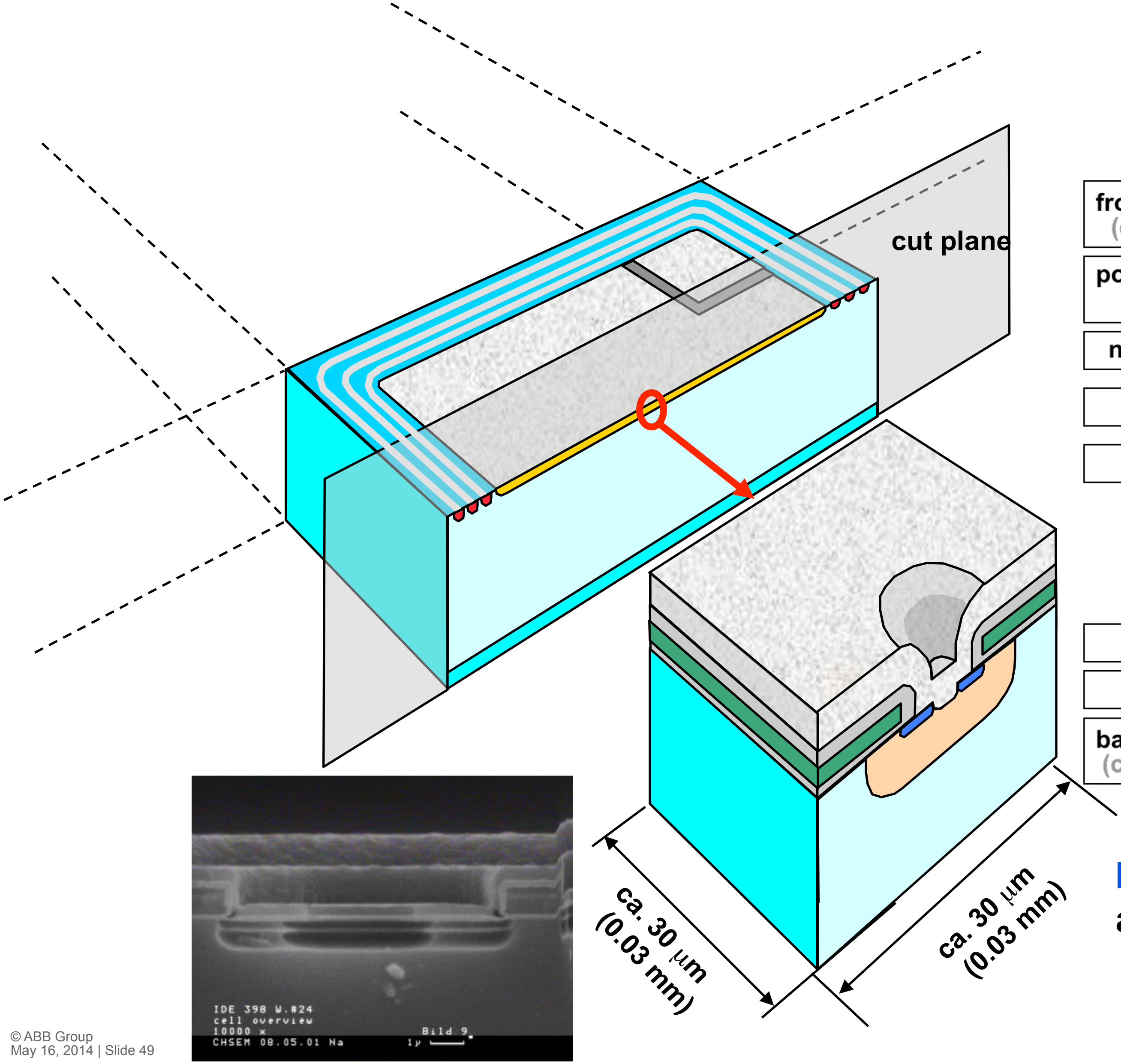
Planar technology

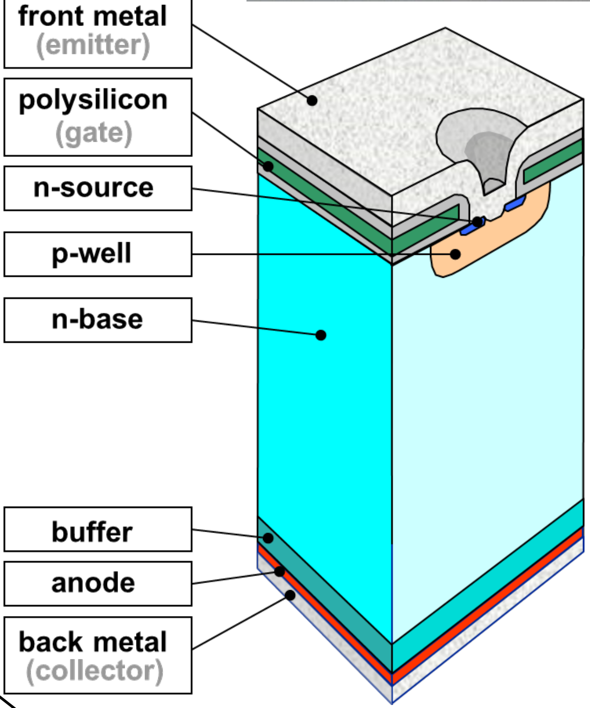


Conventional technology

The Insulated Gate Bipolar Transistor (IGBT)



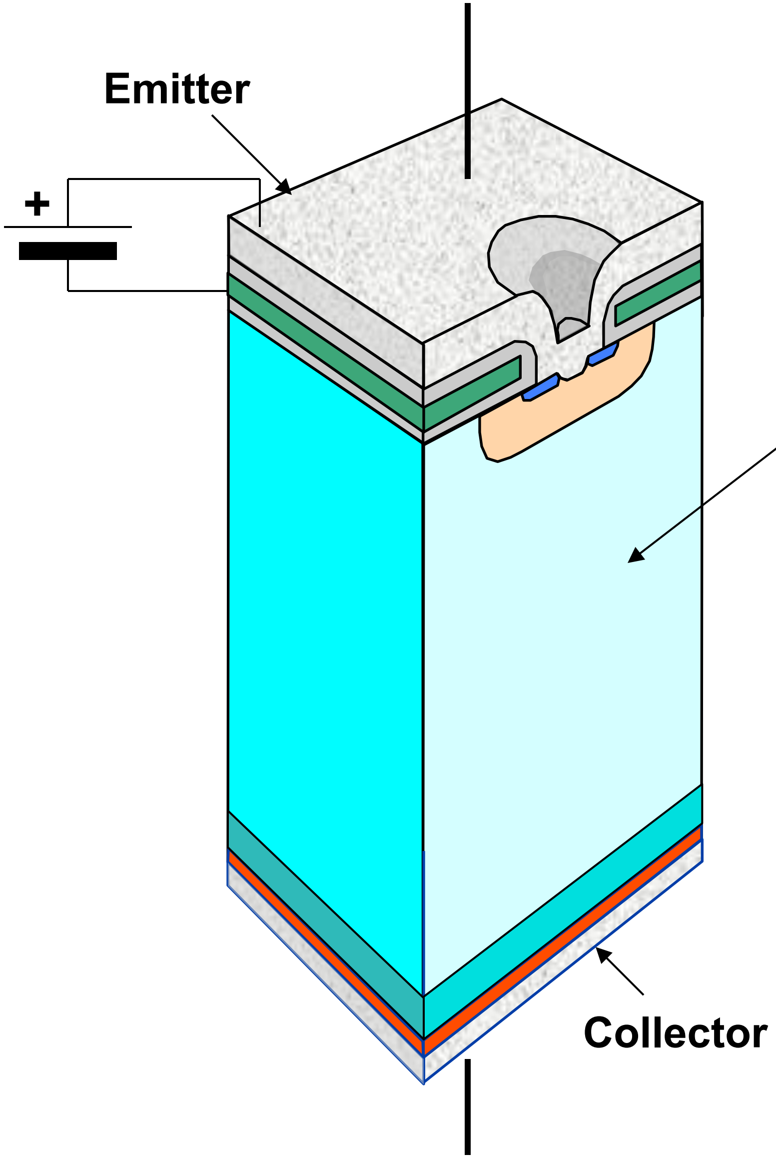




IGBT cell

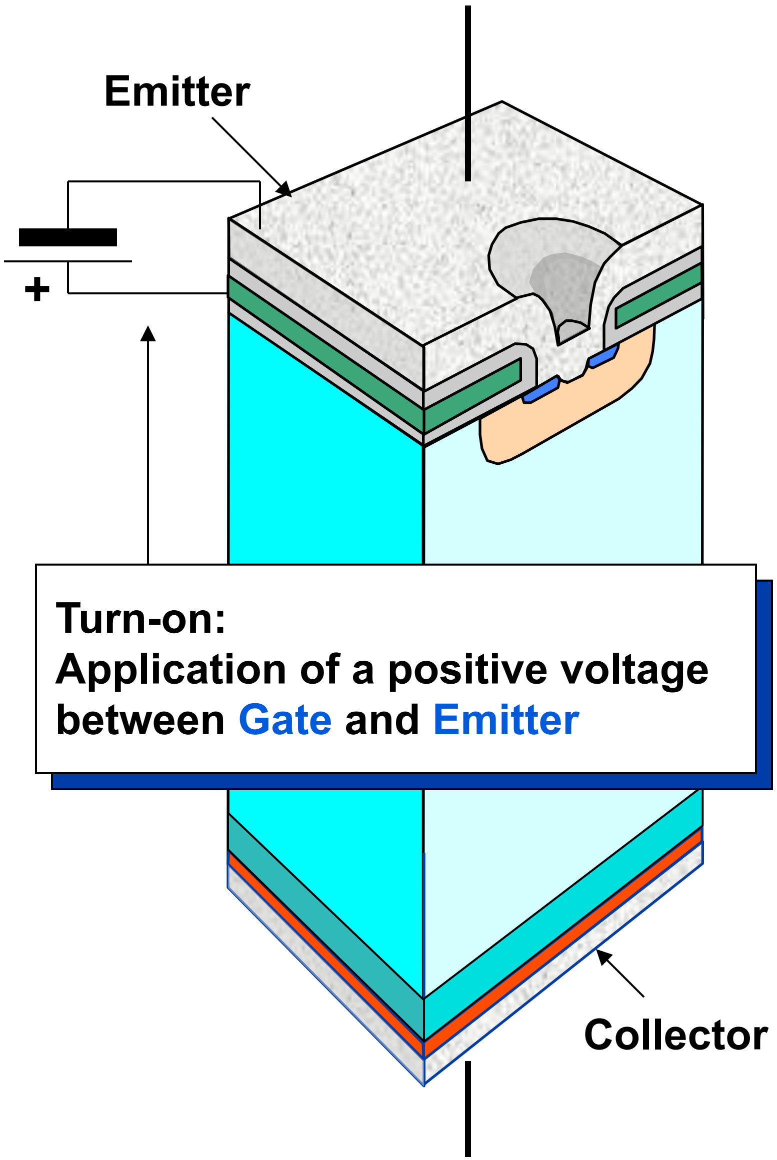
approx. 100’000 per cm^2

How an IGBT Conducts (1/5)

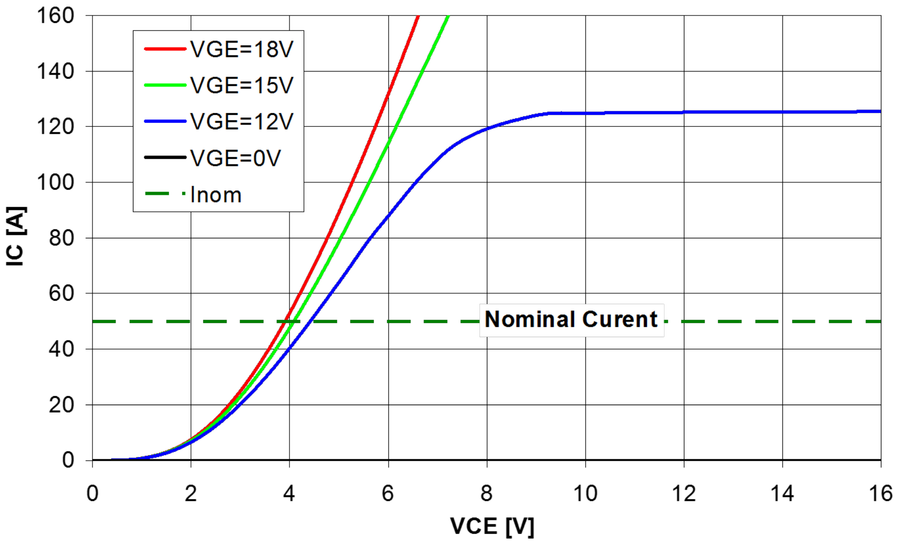


**Switch „OFF“: No mobile carriers (electrons or holes)
in substrate.
No current flow.**

How an IGBT Conducts (2/5)

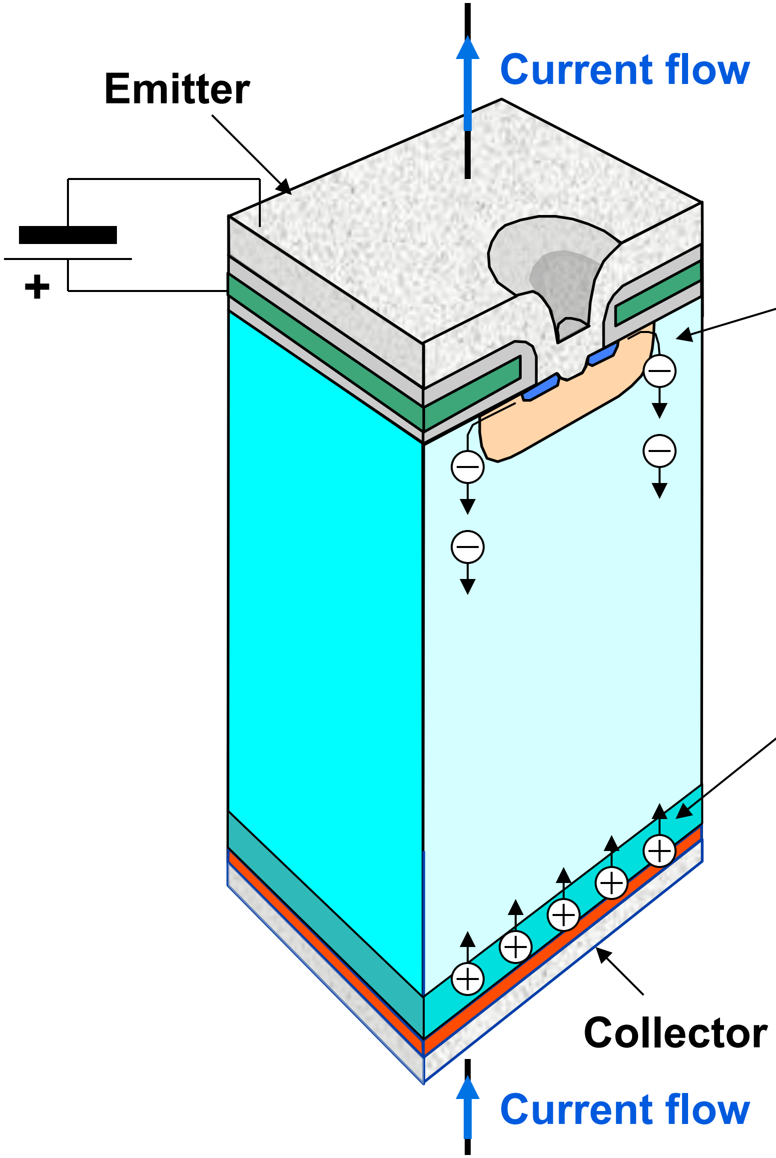


Turn-on:
Application of a positive voltage between Gate and Emitter



3.3kV IGBT output IV curves

How an IGBT Conducts (3/5)

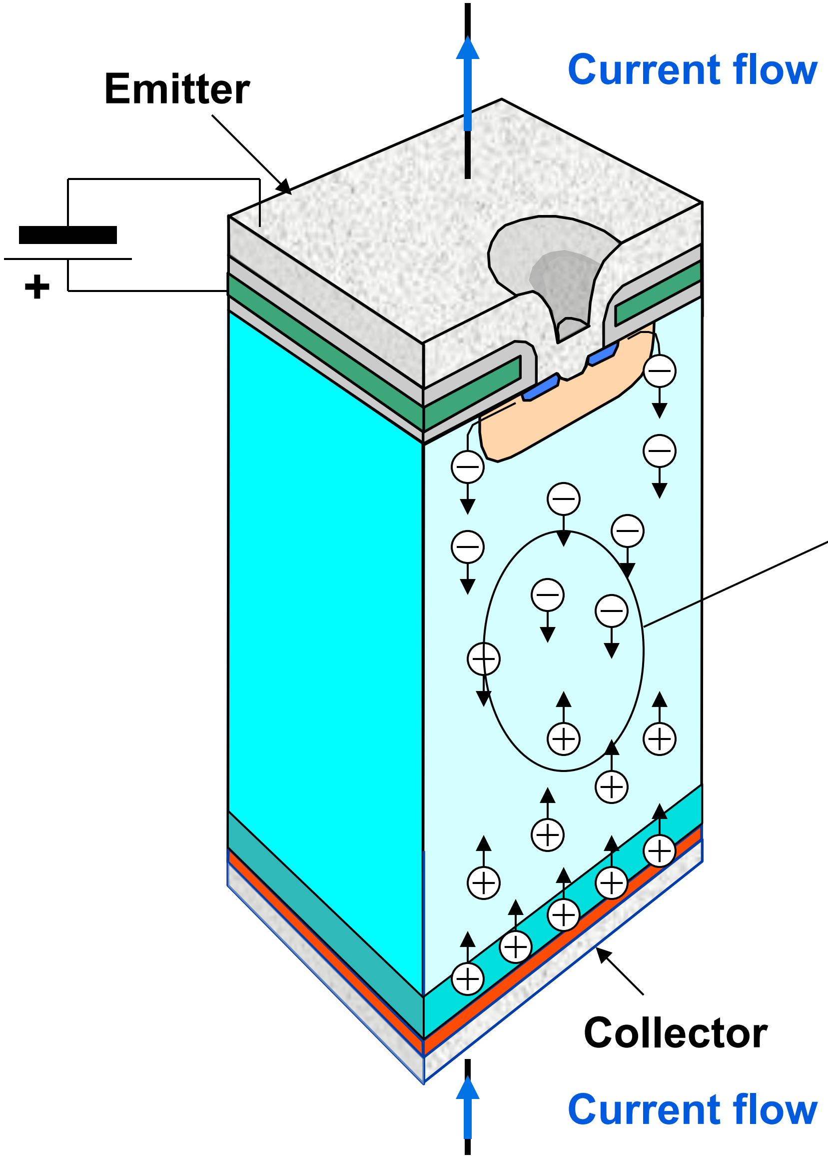


The emitter supplies electrons through the lock into the substrate.

The anode reacts by supplying holes into the substrate

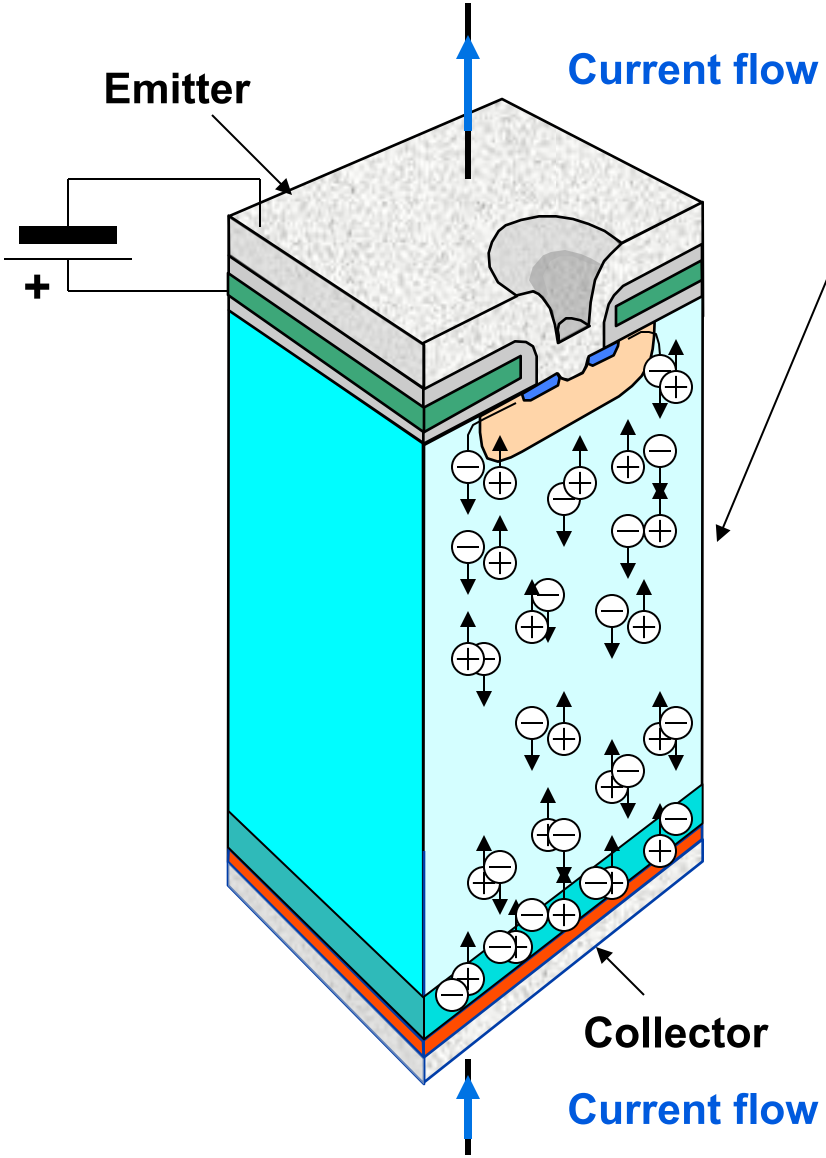
A MOSFET has only N+ region, so no holes are supplied and the device operates in Unipolar mode

How an IGBT Conducts (4/5)

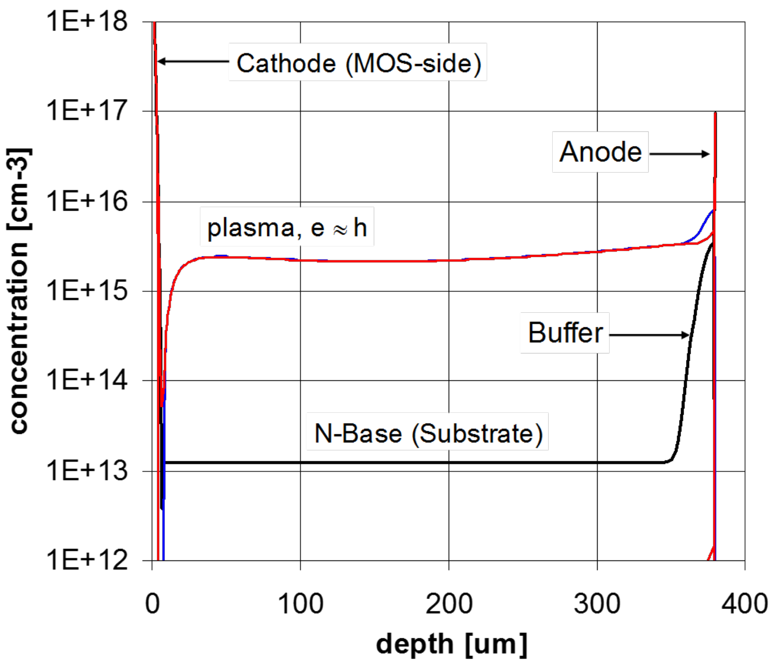


Electrons and holes
are flowing towards each other
(Drift and diffusion)

How an IGBT Conducts (5/5)

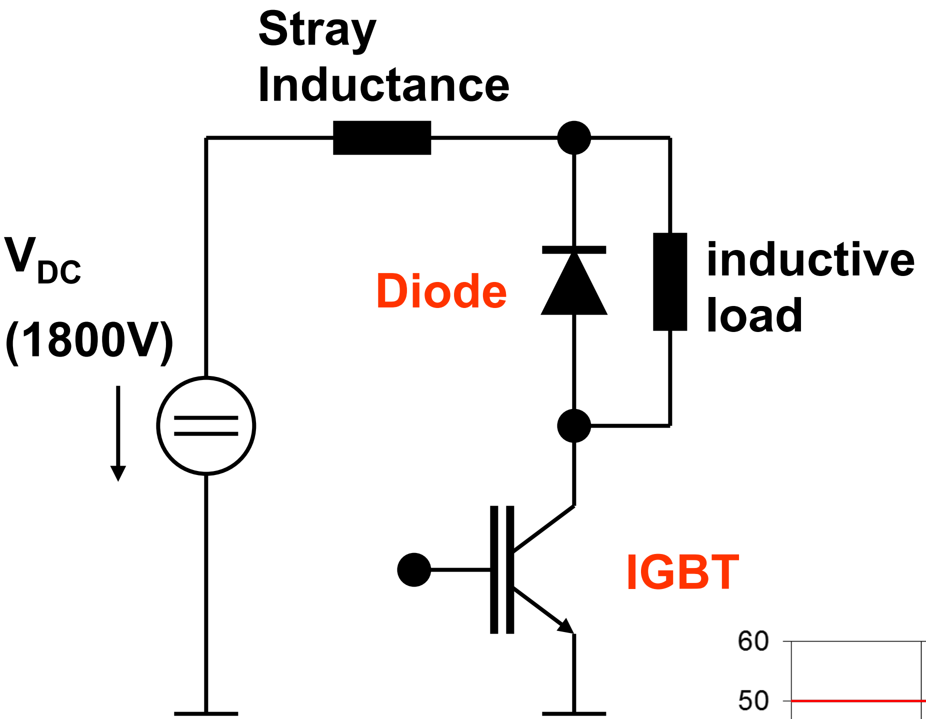


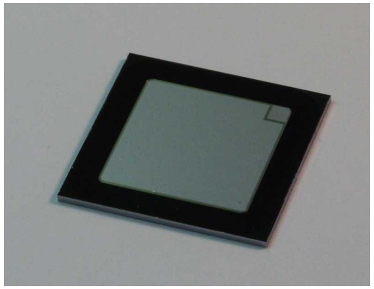
Electrons and holes are mixing to constitute a quasi-neutral plasma. With plenty of mobile carriers, current can flow freely and the device is conducting (switch on)



3.3kV IGBT doping/plasma

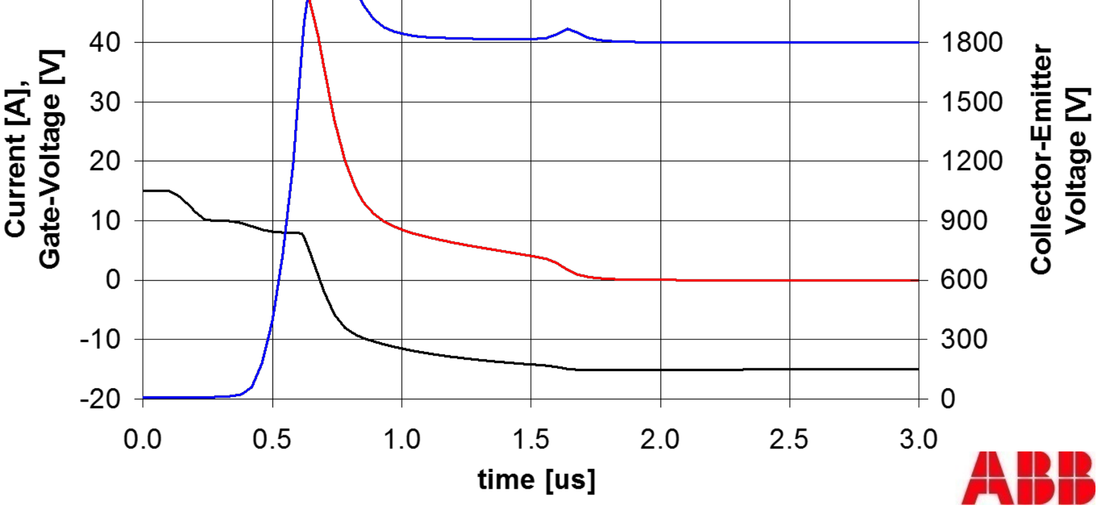
3.3kV IGBT Switching Performance: Test Circuit



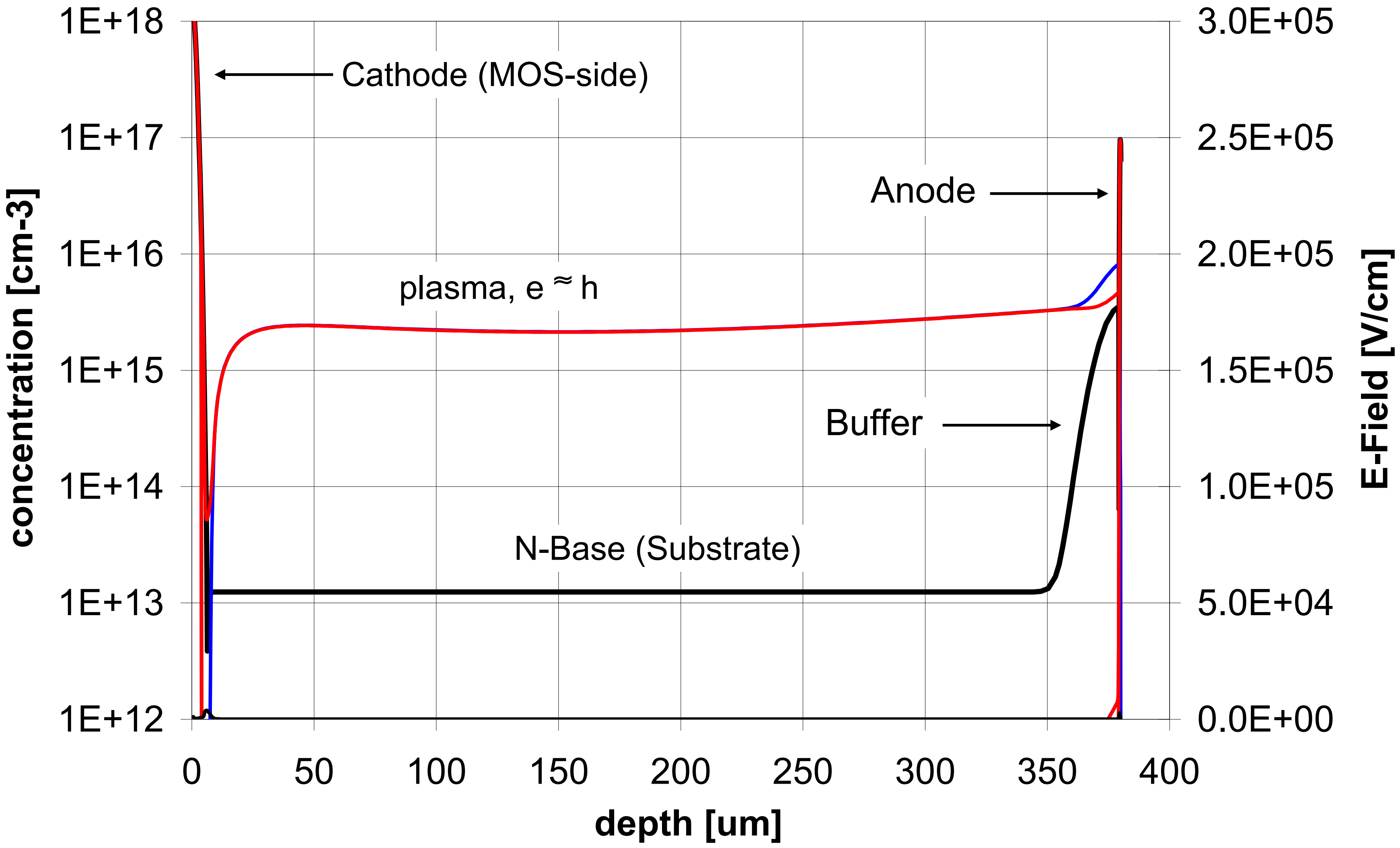


Simulated 3.3kV IGBT Turn-off

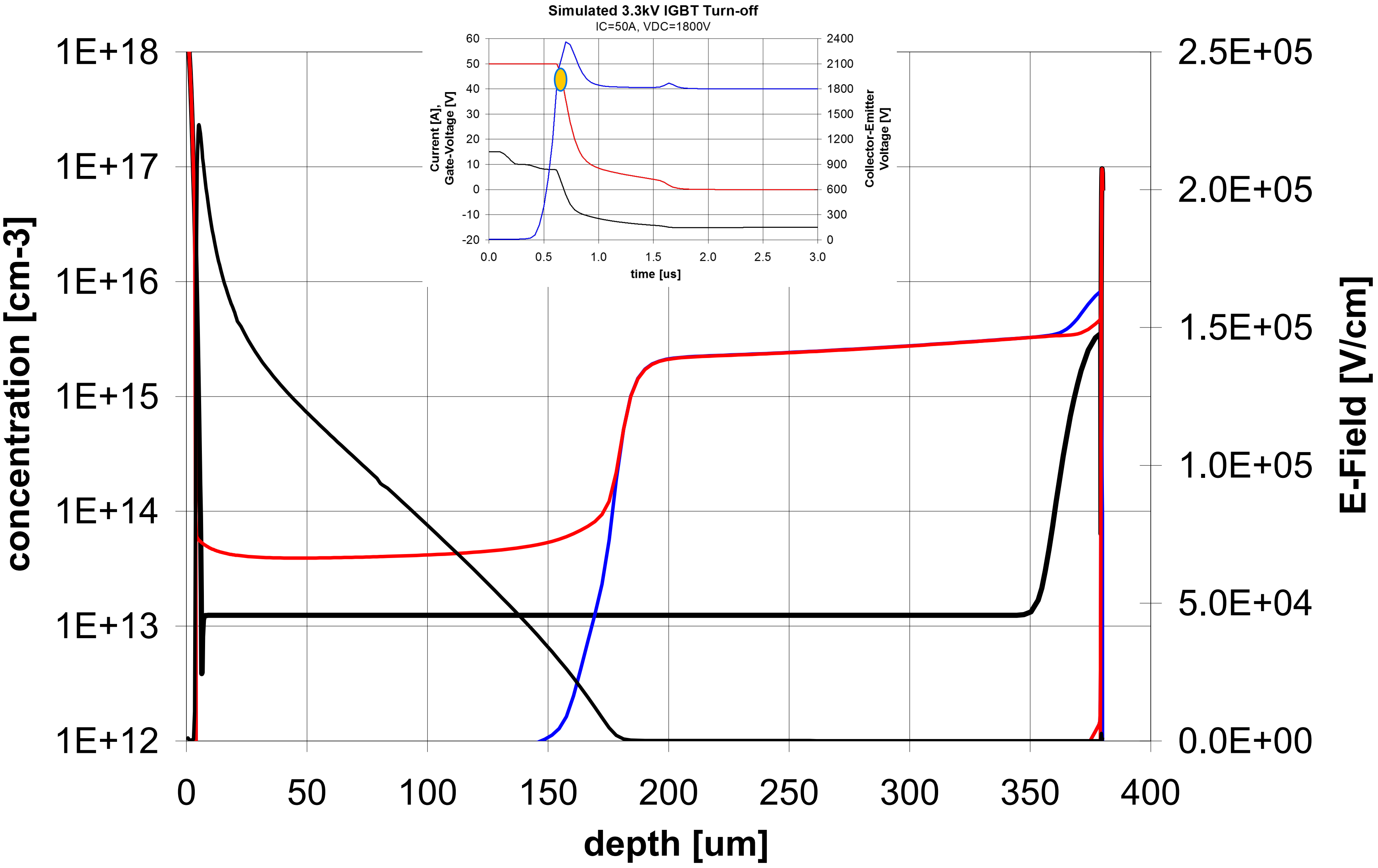
IC=50A, VDC=1800V



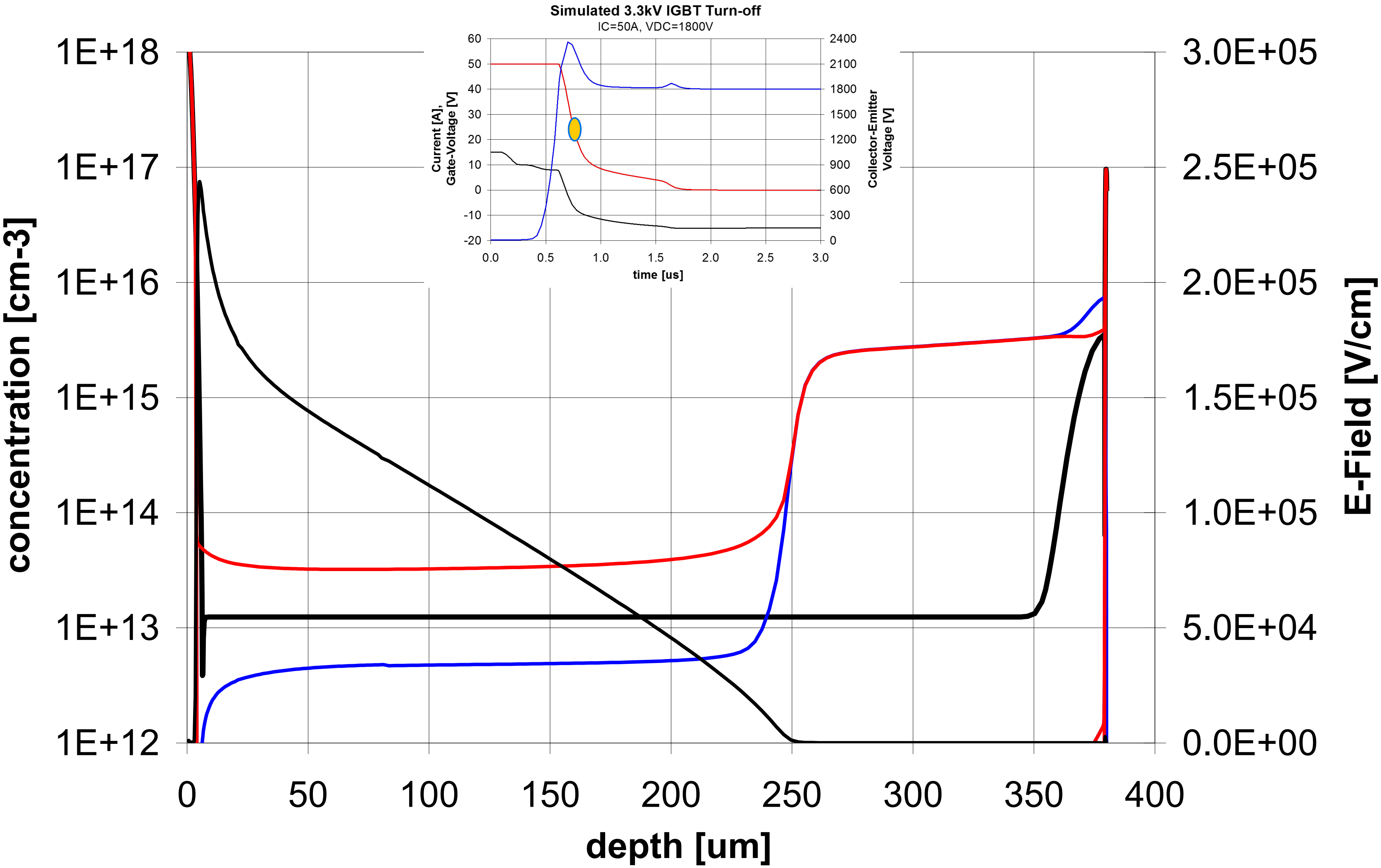
Plasma extraction during turn-off (1/5)



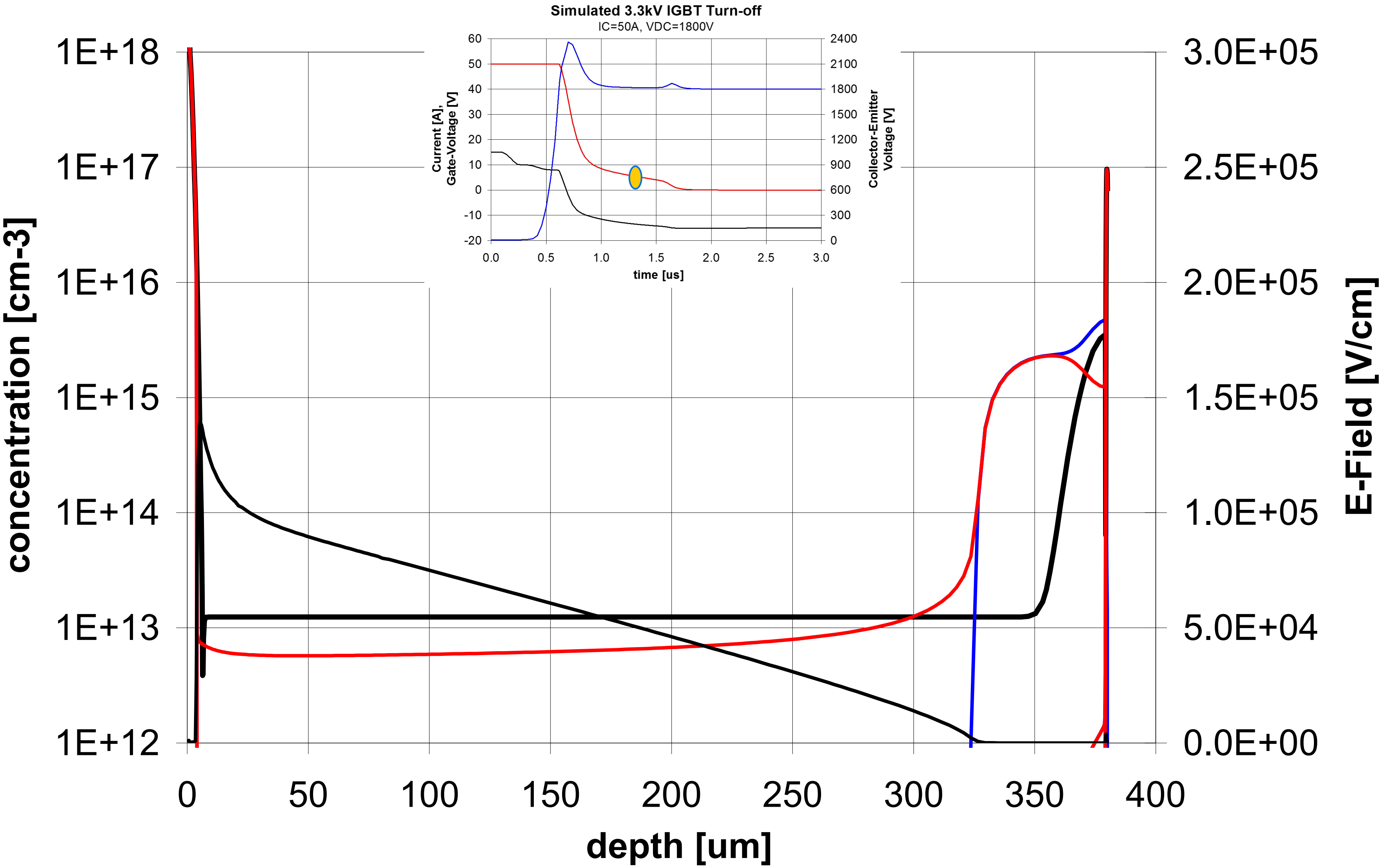
Plasma extraction during turn-off (2/5)



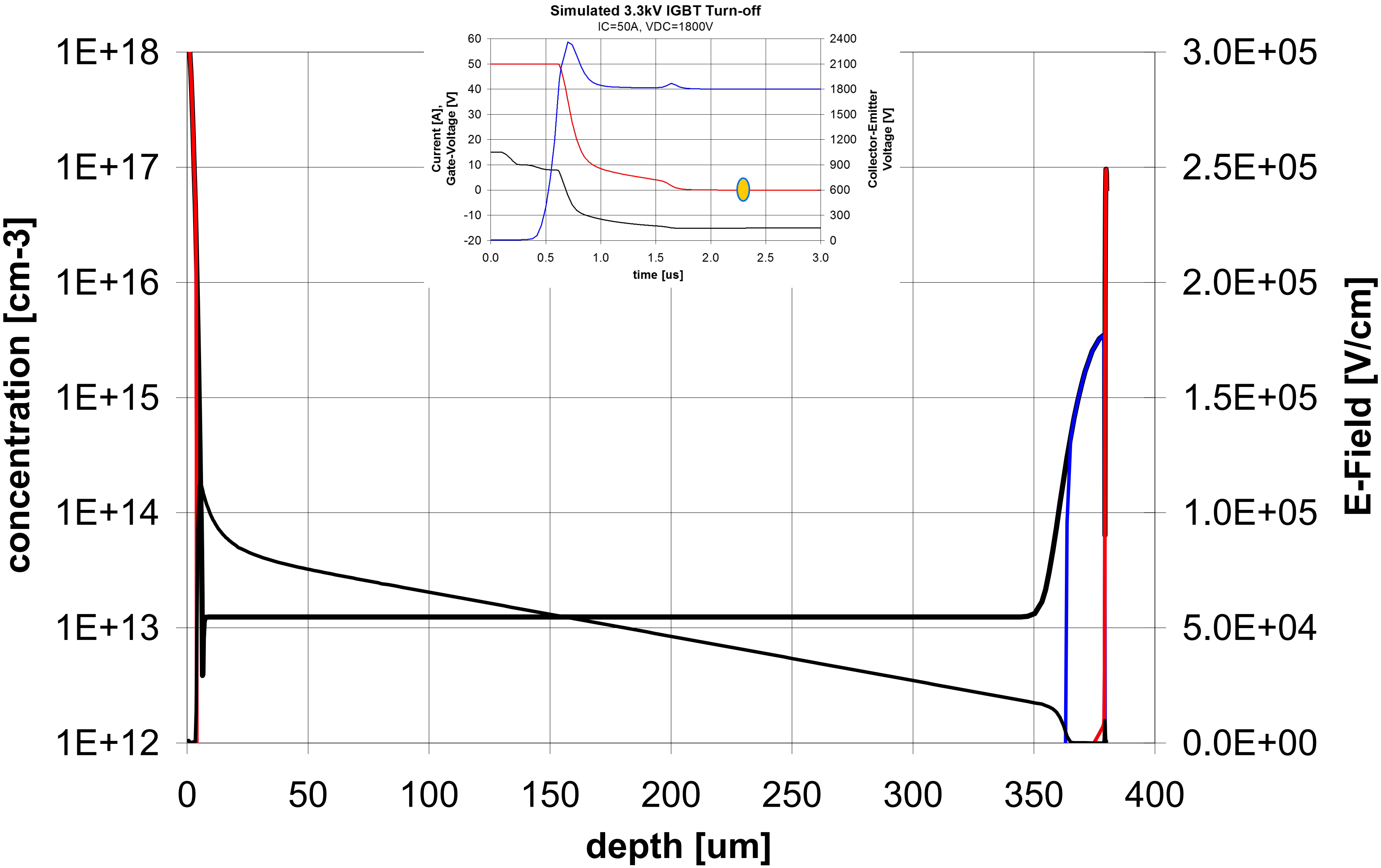
Plasma extraction during turn-off (3/5)



Plasma extraction during turn-off (4/5)



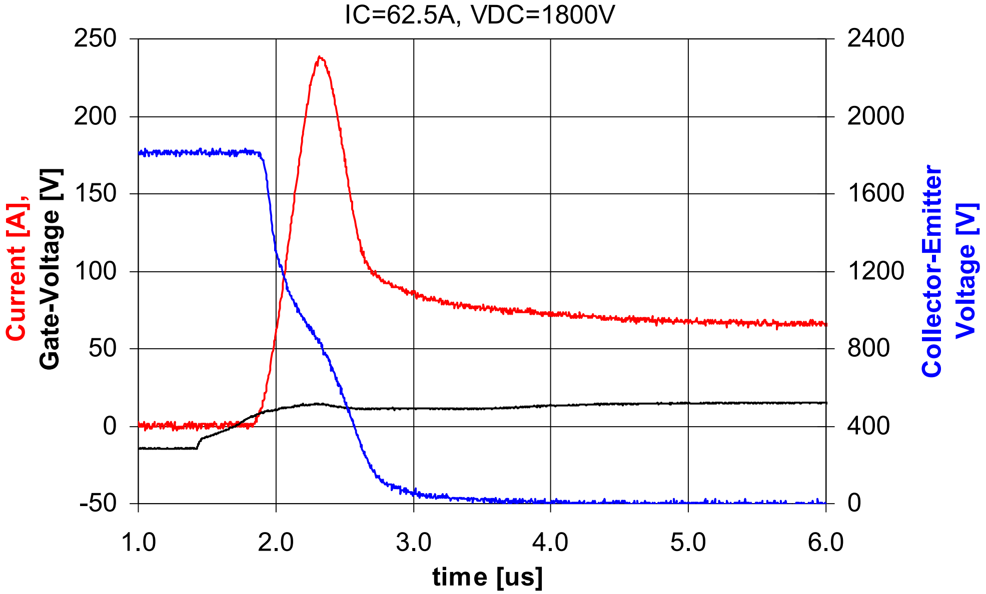
Plasma extraction during turn-off (5/5)



3.3kV IGBT Turn-on and Short Circuit Waveforms

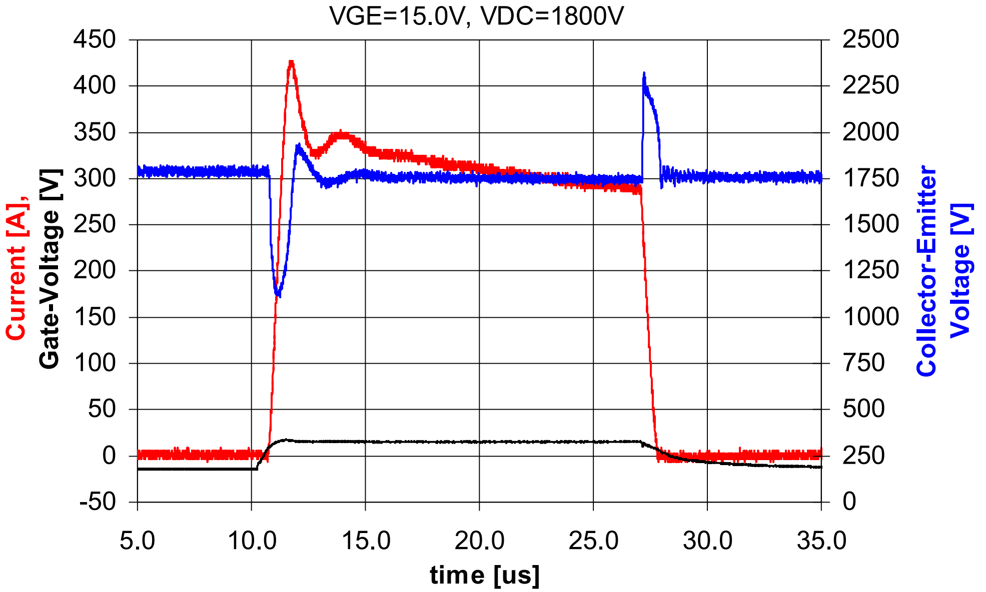
Turn-on

waveforms



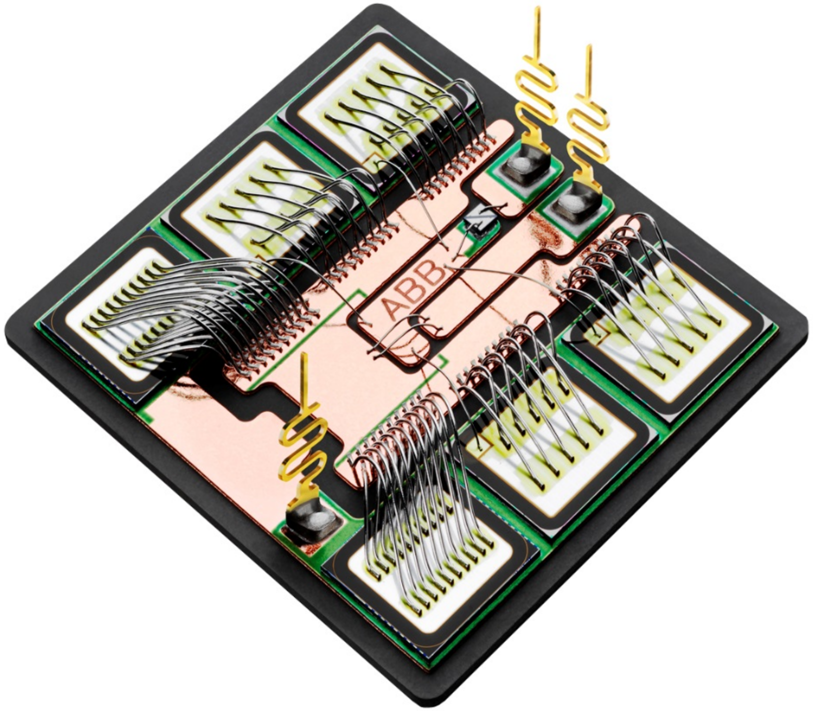
Short

Circuit



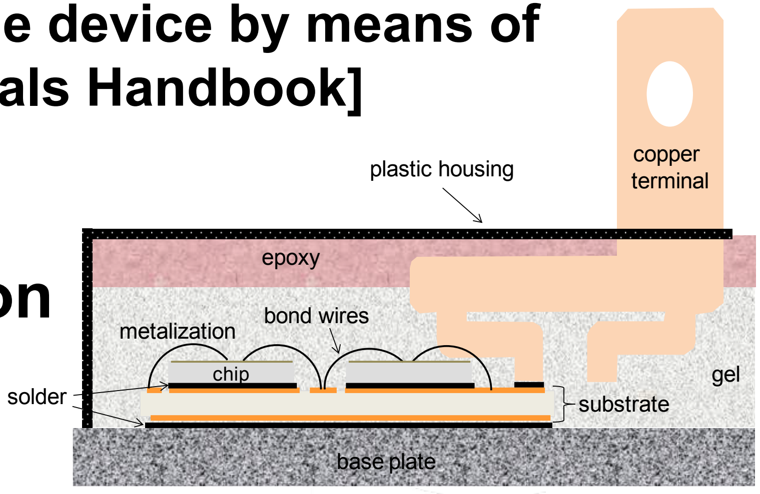
Power Semiconductors

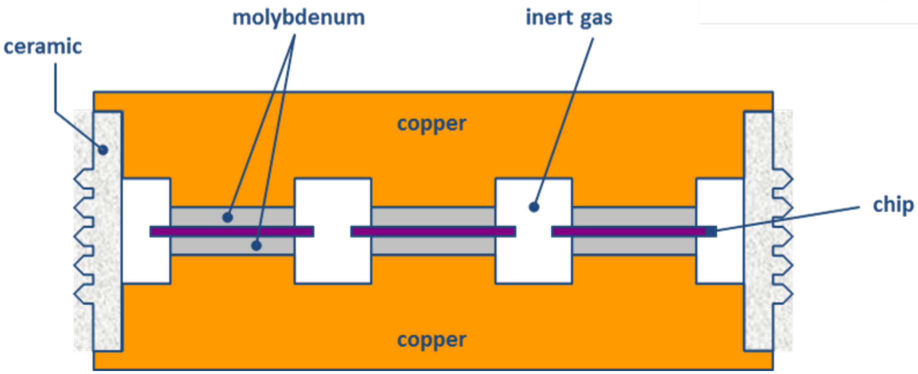
Packaging Concepts



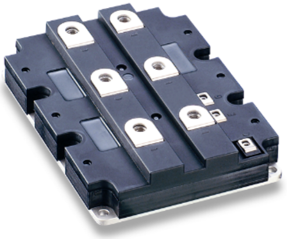
Power Semiconductor Device Packaging

- **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**





Power Semiconductor Device Packaging Concepts

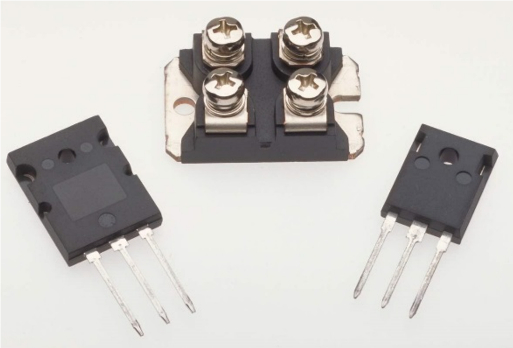
	"Insulated" Devices 	**Press-Pack Devices** 
Mounting	heat sink galvanically insulated from power terminals ■ all devices of a system can be mounted on same heat sink	heat sinks under high voltage ■ every device needs its own heat sink
Failure Mode	open circuit after failure	fails into low impedance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

transportation components have higher reliability demands

Insulated Package for 10s to 100s of KW

Low to Medium Power Semiconductor Packages

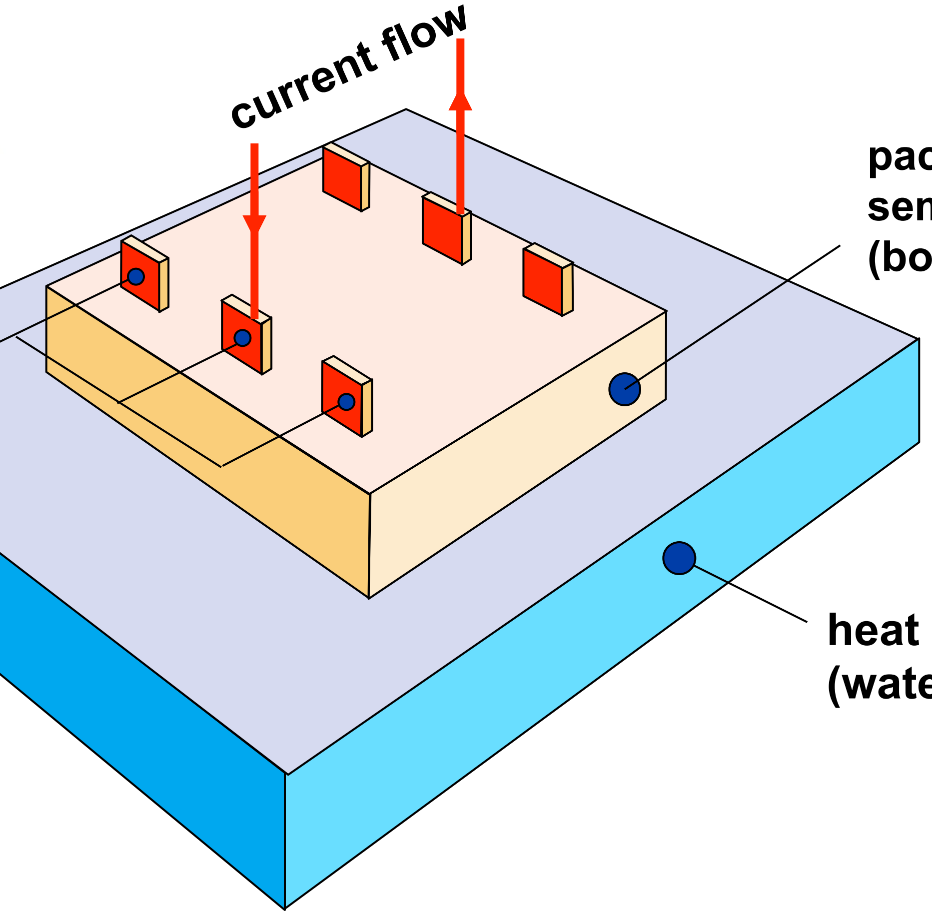
Discrete Devices



Standard Modules

Insulated Modules

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



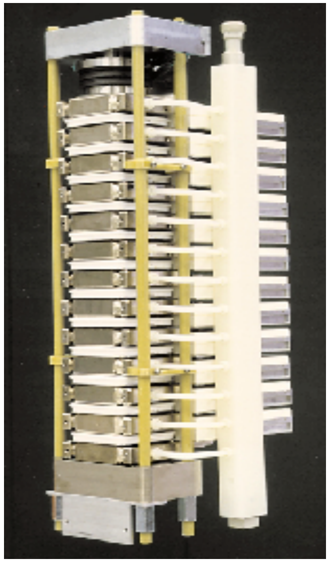
current flow

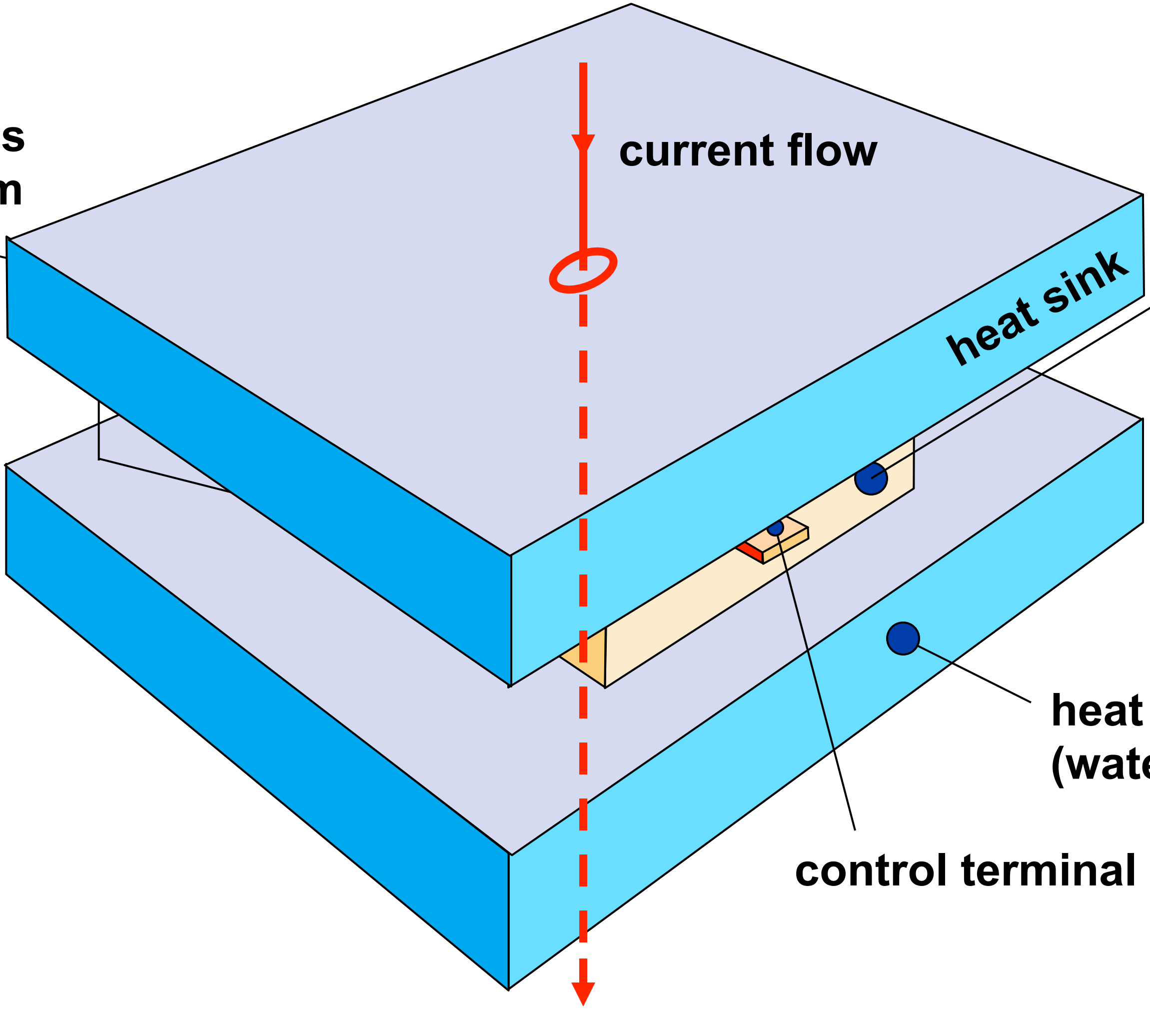
package with
semiconductors inside
(bolted to heat sink)

power & control
terminals

heat sink
(water or air cooled)

Press-Pack Modules





current flow

power terminals
(top and bottom
of module)

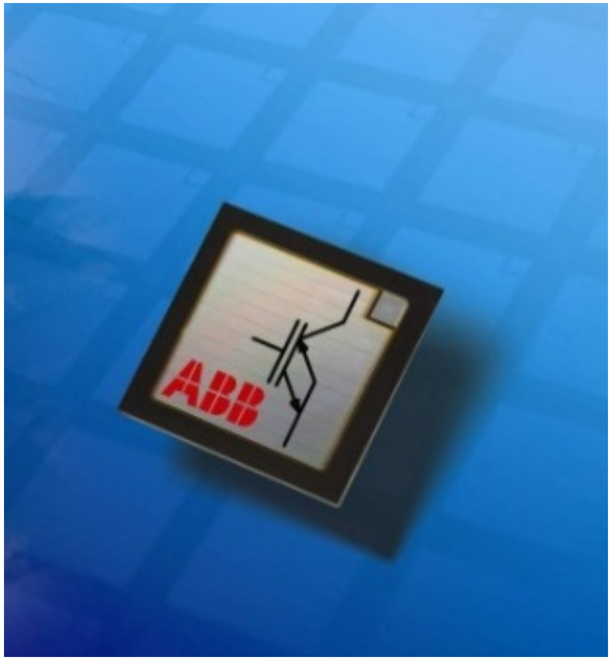
package with
semiconductors
inside

heat sink
(water or air cooled)

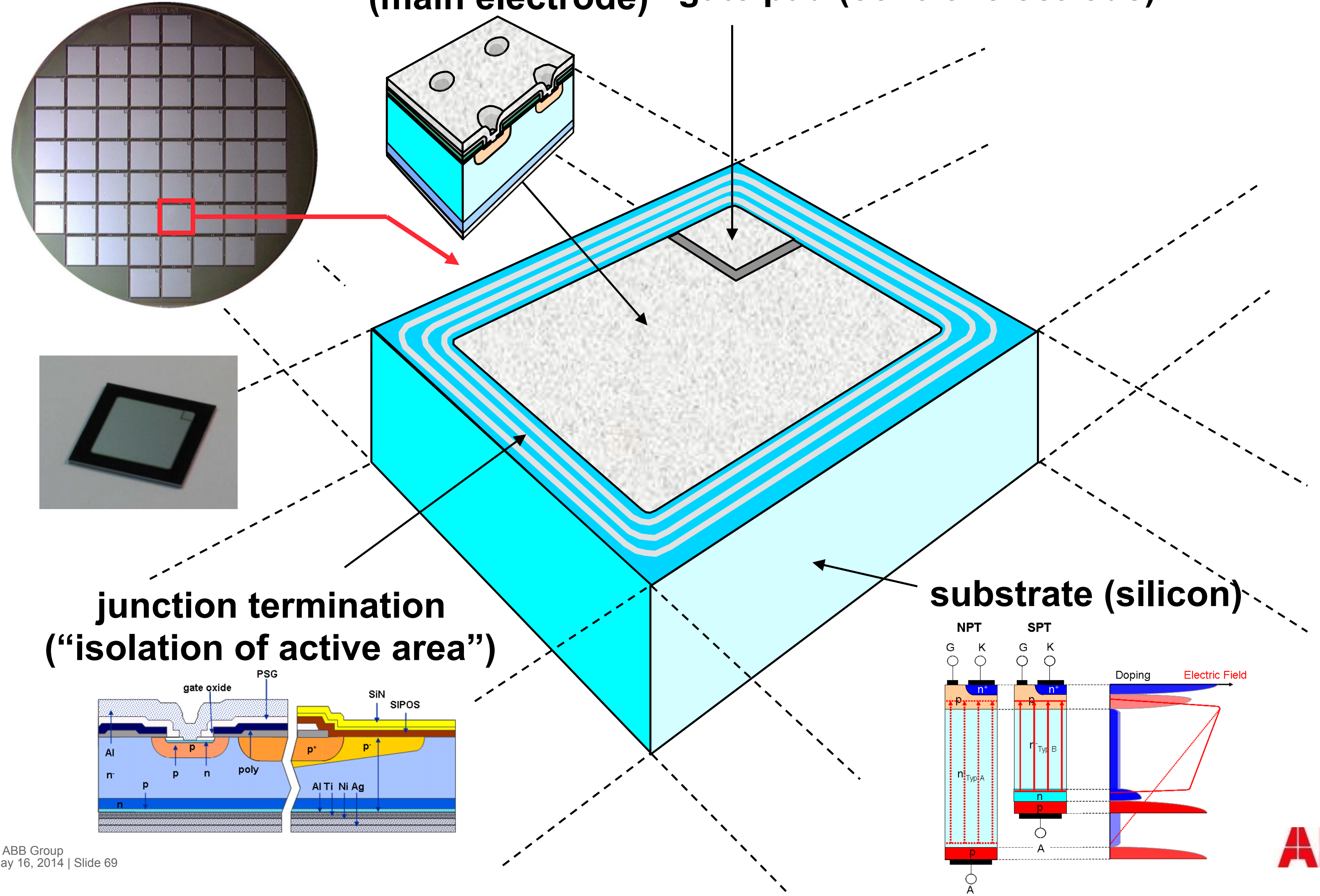
control terminal

Power Semiconductors

Technology Drivers and Trends



Power Semiconductor Device Technology Platforms



active area (main electrode)

gate pad (control electrode)

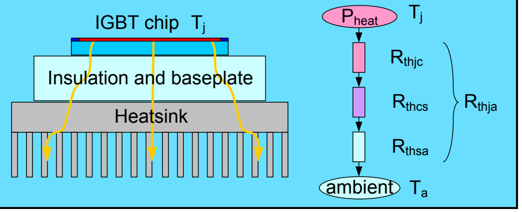
junction termination (“isolation of active area”)

substrate (silicon)

Power Semiconductor Package Technology Platforms

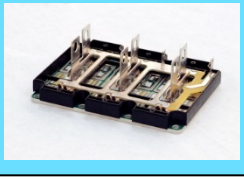
Heat dissipation

- Interconnections
- Advanced cooling concepts



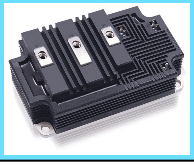
Electrical distribution

- Interconnections
- Power / Signal terminals
- Low electrical parasitics

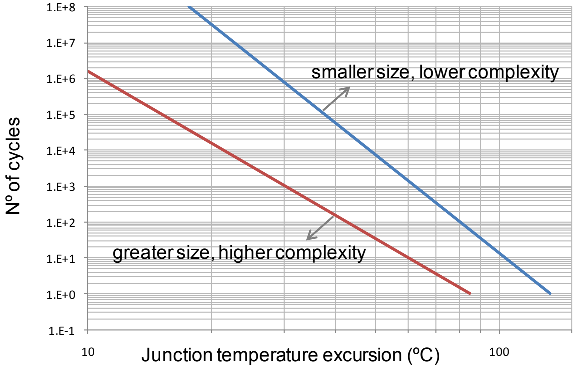


High Voltage Insulation

- Partial Discharges
- HV insulating
- Creepage distances

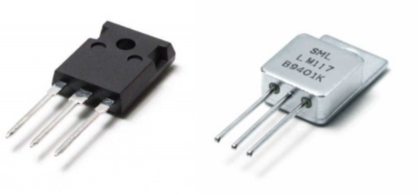


Typical temperature cycling curve

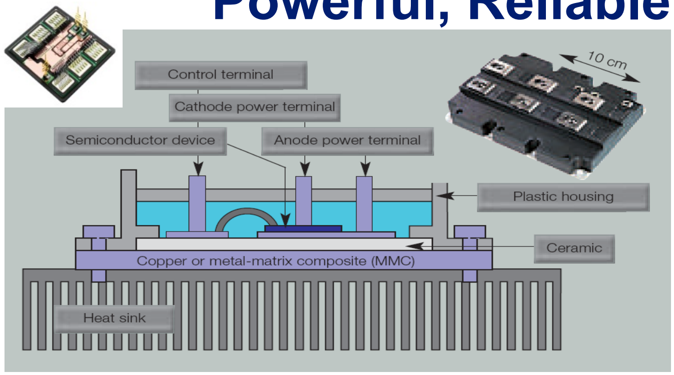


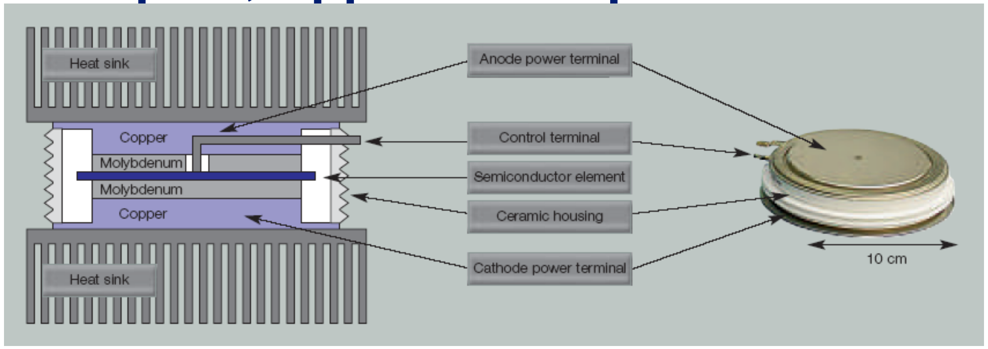
Encapsulation/ protection

- Hermetic / non-hermetic
- Coating / filling materials



Powerful, Reliable, Compact, Application specific

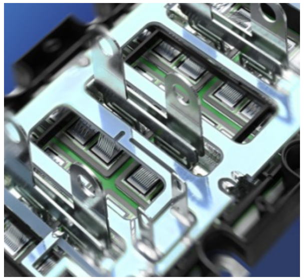




Insulated

Press Pack

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

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

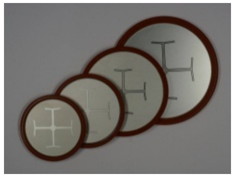
The Application

Topology, Frequency, Control, Cooling

The Cost of Performance

Technology Drivers for Higher Power (the boundaries)

I
Area



Larger Area

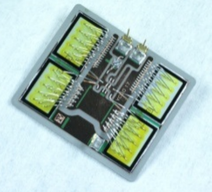
Larger Devices

Extra Paralleling

Integration

Termination/Active
HV, RC, RB

I
Integration



New Tech.

Reduced Losses

Carrier Enhancement

Thickness Reduction (Blocking)

Absolute

Increasing Device Power

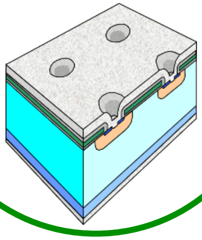
Density

Increased Margins

Latch-up / Filament Protection

Controllability, Softness & Scale

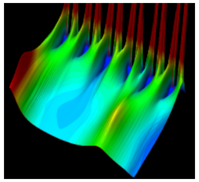
V.I
Losses



Traditional Focus

New Technologies

$V_{max}.I_{max}$
SOA



$\Delta T/R_{th}$
Temperature

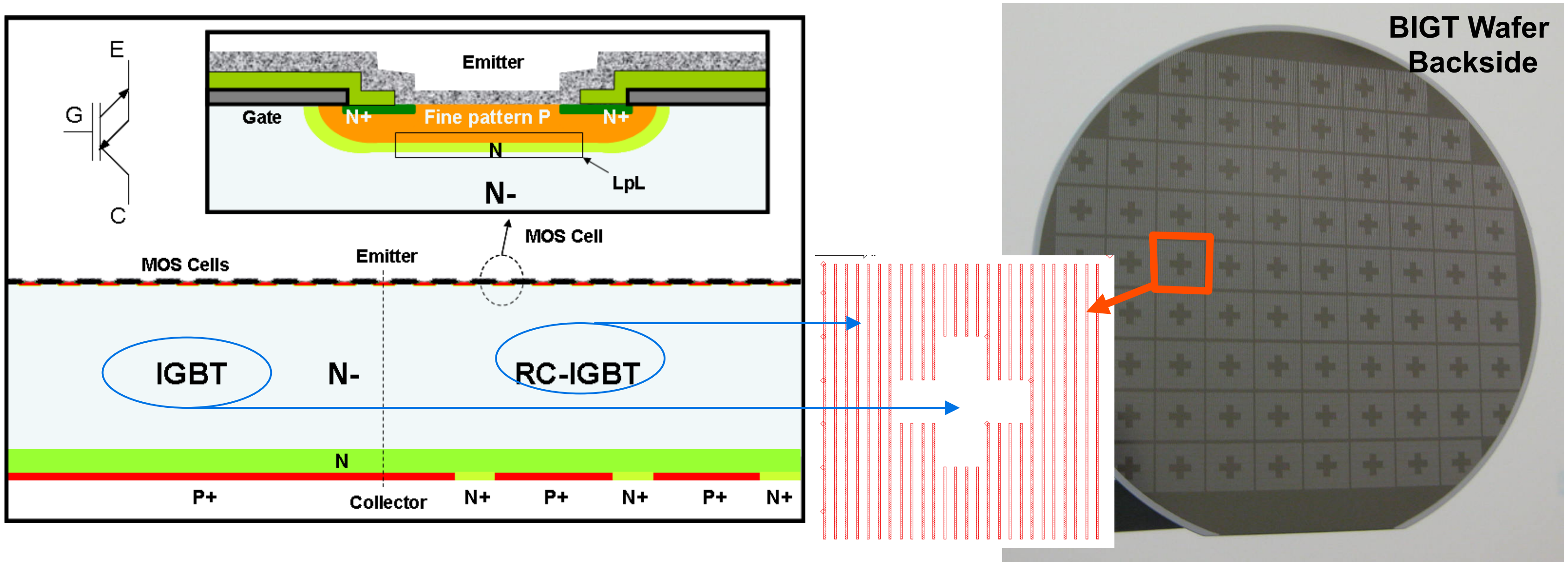
Improved Thermal

High Temp. Operation

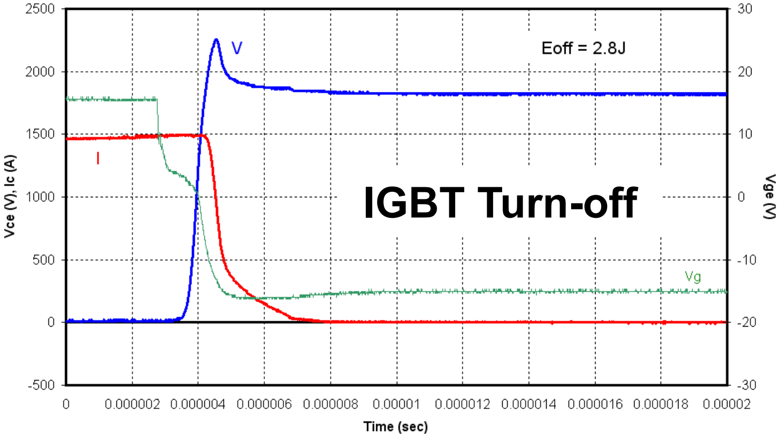
Lower Package Rth

The Bimode Insulated Gate Transistor (BIGT)

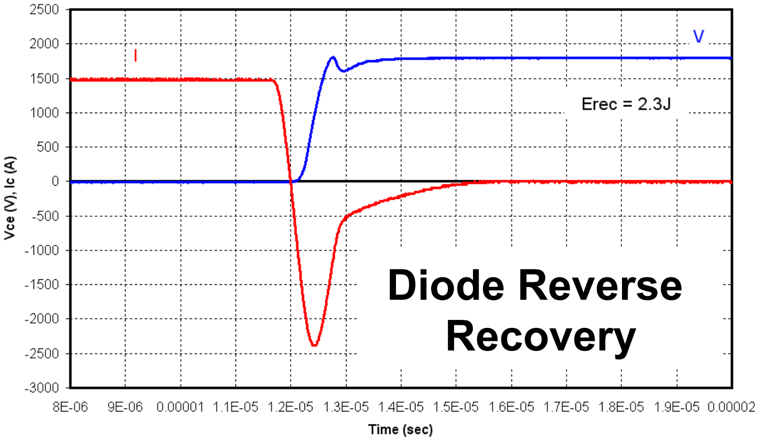
integrates an IGBT & RC-IGBT in one structure to eliminate snap-back effect



3300V/1500A BIGT HiPak 1 (1800V, 1500A, 150nH, Rgoff=1.5ohm, 125°C)



3300V/1500A BIGT HiPak 1 (1800V, 1500A, 150nH, Rg=1.5ohm, 125°C)



Wide Bandgap Technologies

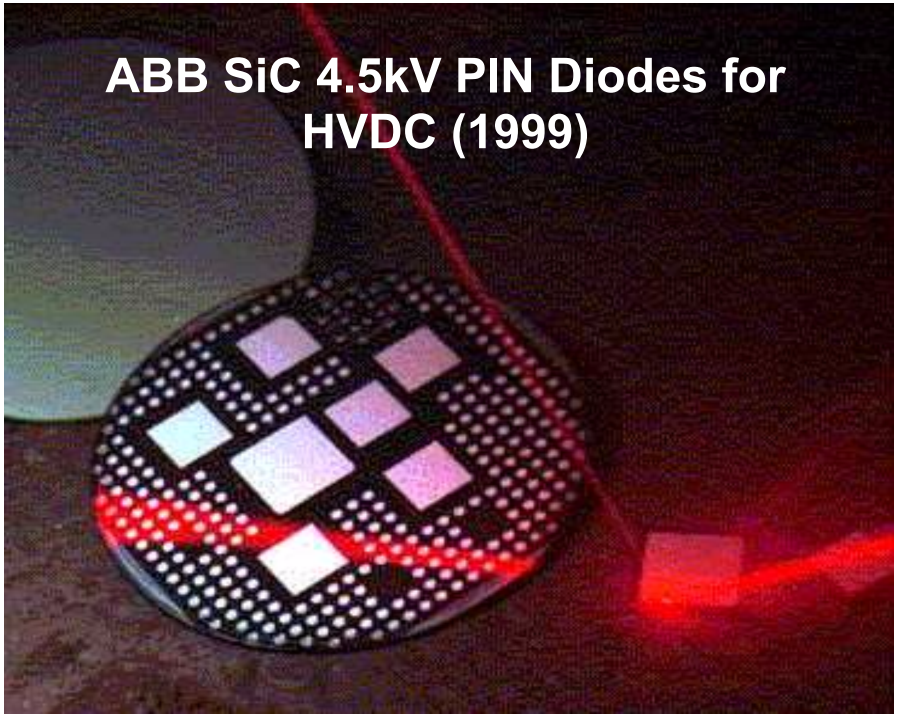


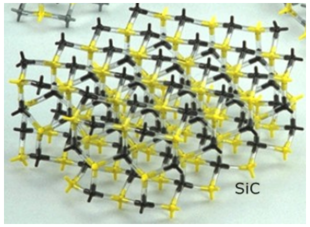
ABB SiC 4.5kV PIN Diodes for HVDC (1999)

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}	$1.4\cdot10^{10}$	$8.2\cdot10^{-9}$	$1.9\cdot10^{-10}$	$1\cdot10^{-22}$
Thermal Cond. λ	W/cm·K	1.5	**3.8**	**1.3/3****	20

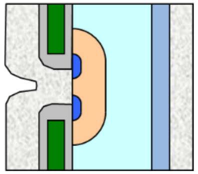
* significant difference between bulk and 2DEG

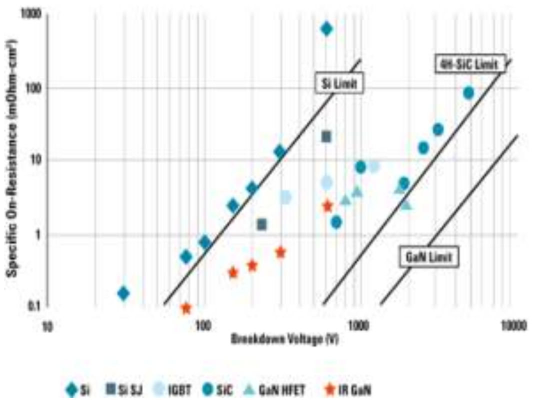
** difference between epi and bulk



Thick Si Device

Thin SiC Device





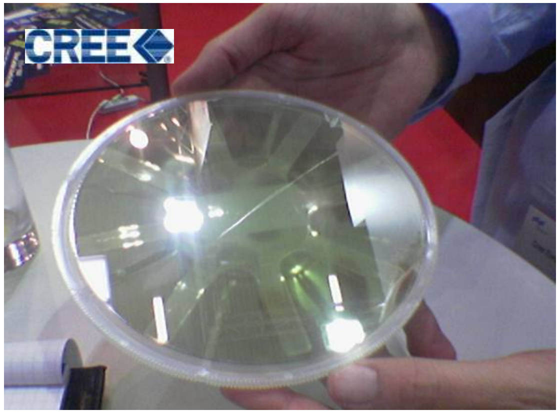
Comparison of R_{on} for Si, SiC, and GaN based FETs

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

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

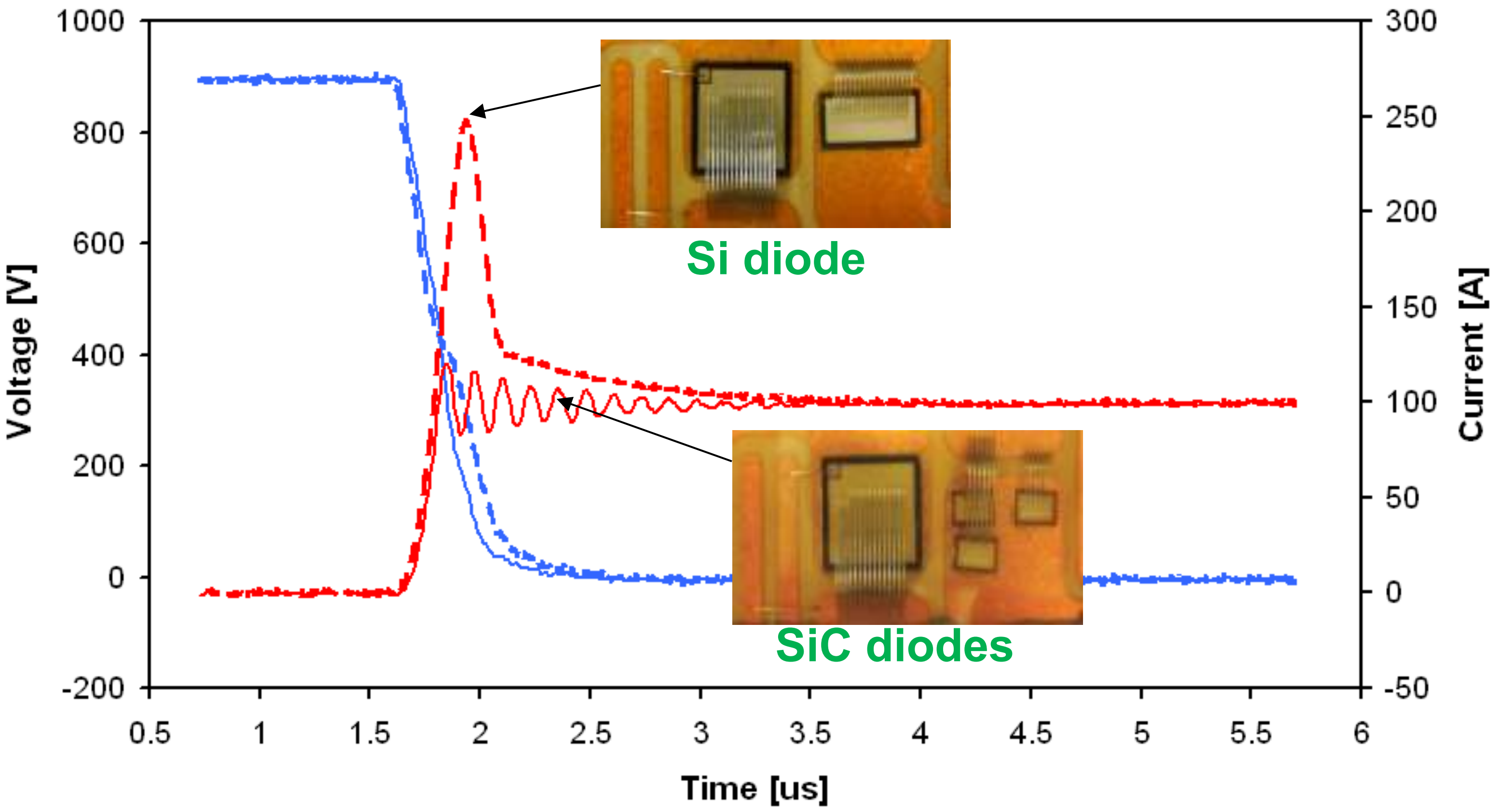
SiC Switch/Diode Classification and Issues

- **SiC Power Devices**
  - Defect Issues
  - High Cost
  - **BiPolar**
    - **Thyristors 5kV~….**
      - Bipolar Issues
      - Bias Voltage
    - **BJT 600V~10kV**
      - Bipolar Issues
      - Current Drive
    - **Diode 5kV ~ ….**
      - Bipolar Issues
      - Bias Voltage
  - **BiMOS**
    - **IGBT 5kV~….**
      - MOS Issues
      - Bipolar Issues
      - Bias Voltage
  - **UniPolar**
    - **JFET 600V~10kV**
      - Normally on
    - **MOSFET 600V~10kV**
      - MOS Issues
    - **Diode 600V~5kV**
      - ★



SiC Unipolar Diodes vs. Si Bipolar Diode

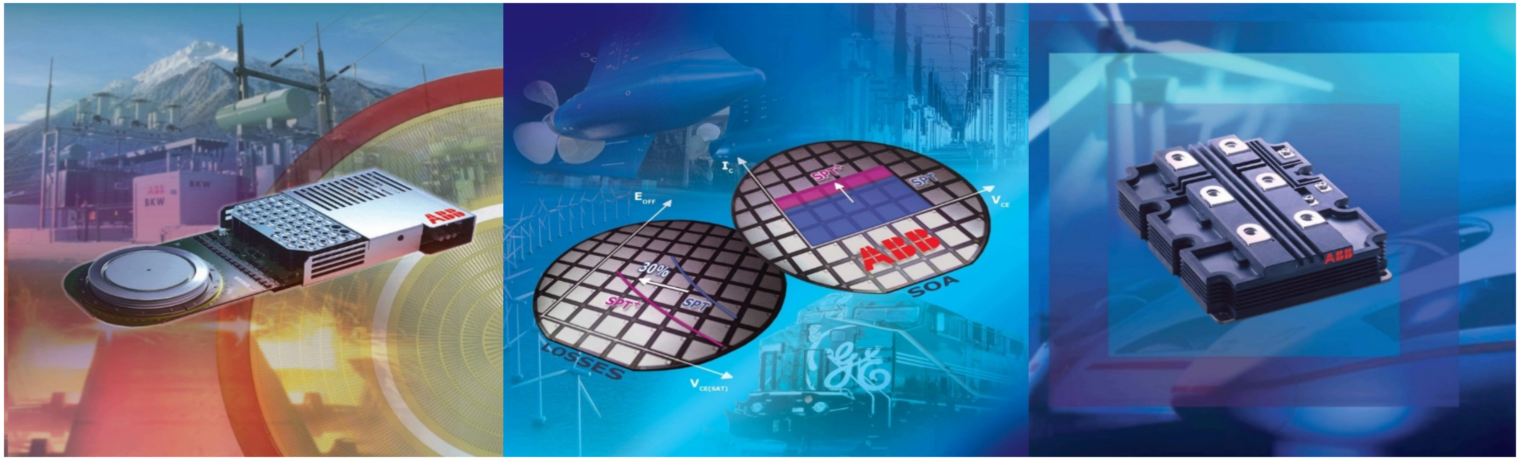
1700V Fast IGBTs with SiC Diodes during turn-on



Turn-On Fast IGBT + Si & SiC Diodes, 900V/100A, 175°C, Ls=400nH Rg=10Ohm

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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