Power Management in the New Millennium

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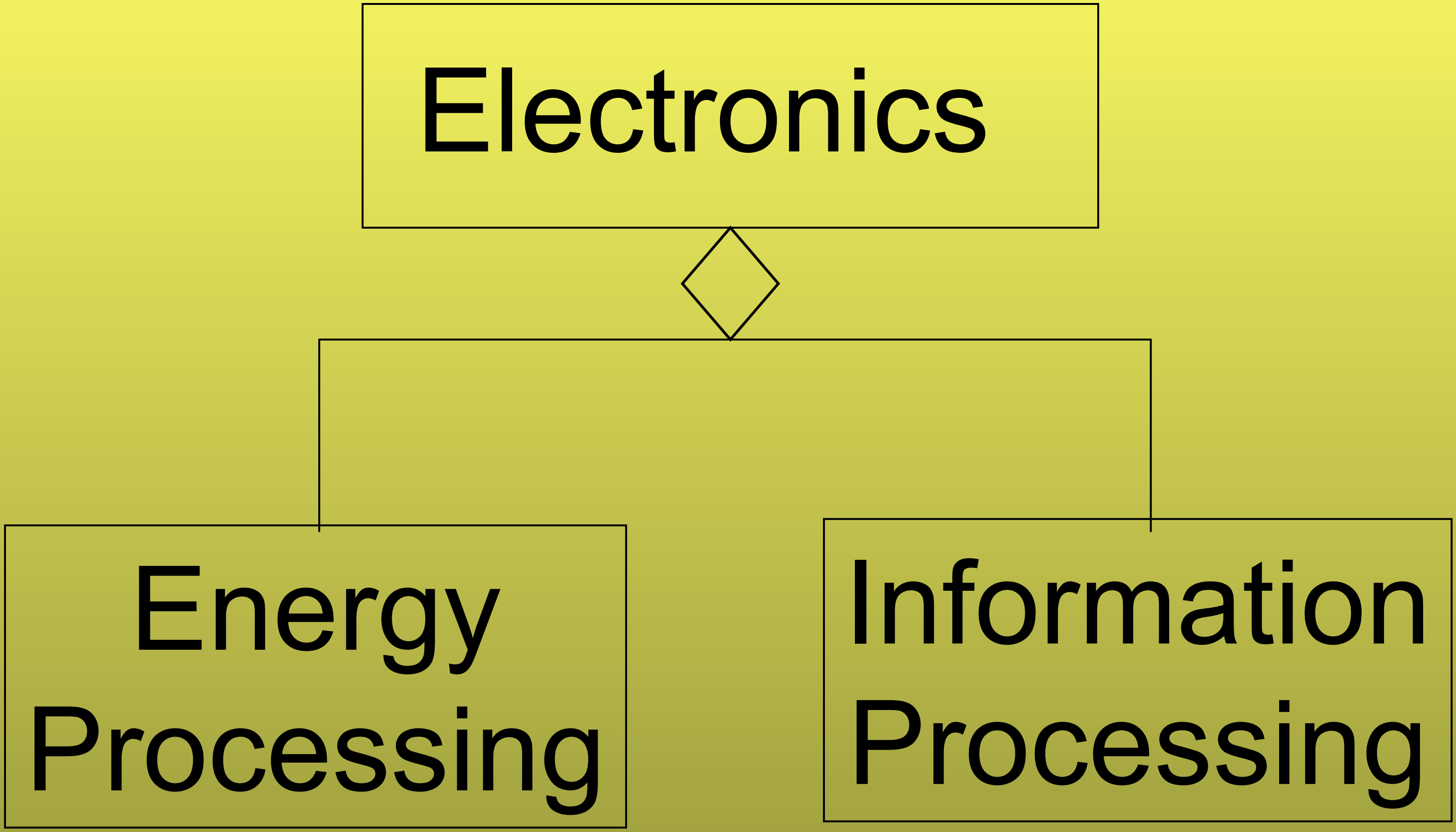
University of Wales Swansea

Talk Overview

- Introduction
- Silicon Power Devices
- Packaging
- Application Areas
- New Materials – SiC & Diamond
- Conclusion



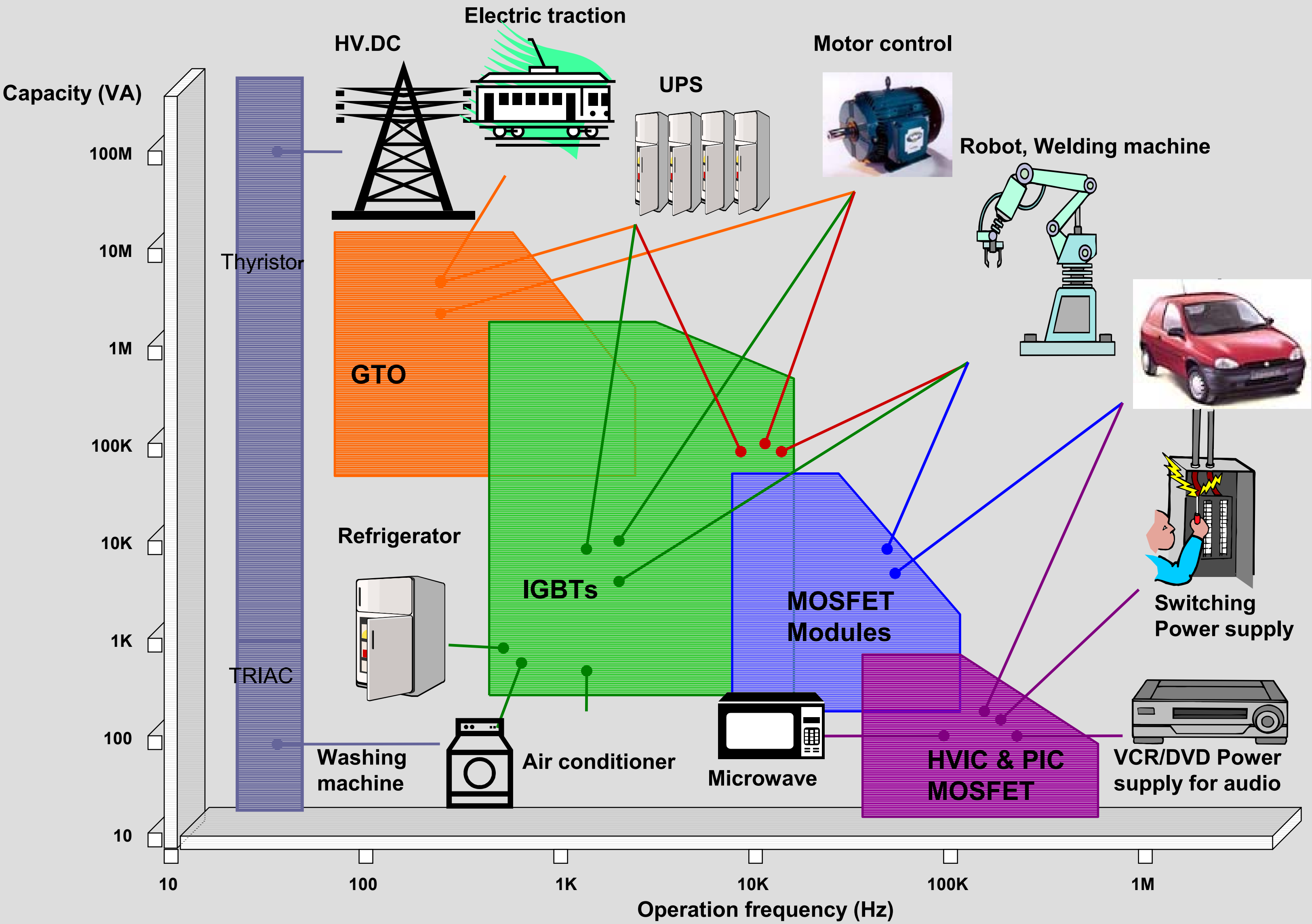
Electronics

Energy Processing

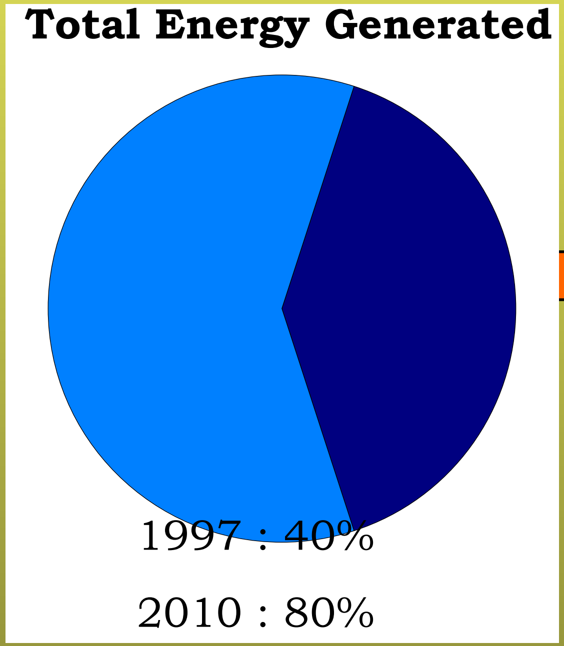
Information Processing

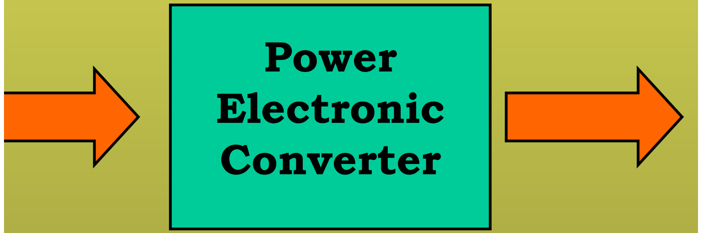
Power Electronics is

“Efficient processing of electrical energy through means of electronic switching devices ”

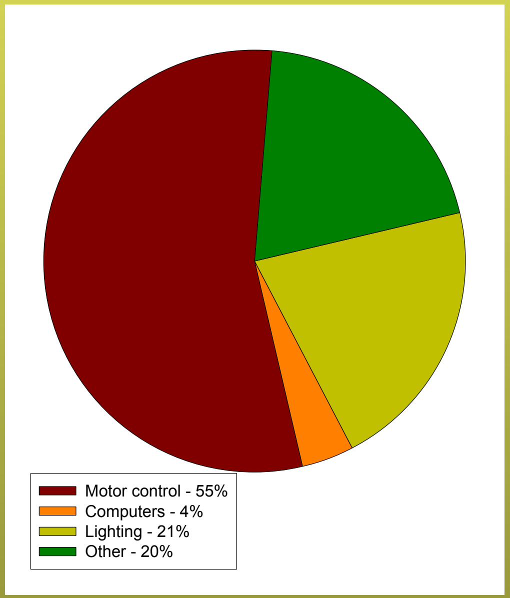

Capacity (VA)
100M
10M
1M
100K
10K
1K
100
10
Thyristor
TRIAC
HV.DC
Electric traction
UPS
Motor control
Robot, Welding machine
GTO
Refrigerator
IGBTs
MOSFET Modules
Switching Power supply
Washing machine
Air conditioner
Microwave
HVIC & PIC MOSFET
VCR/DVD Power supply for audio
10
100
1K
10K
100K
1M
Operation frequency (Hz)

Increasing Importance of Power Electronics in Energy Management





Power Electronic Converter

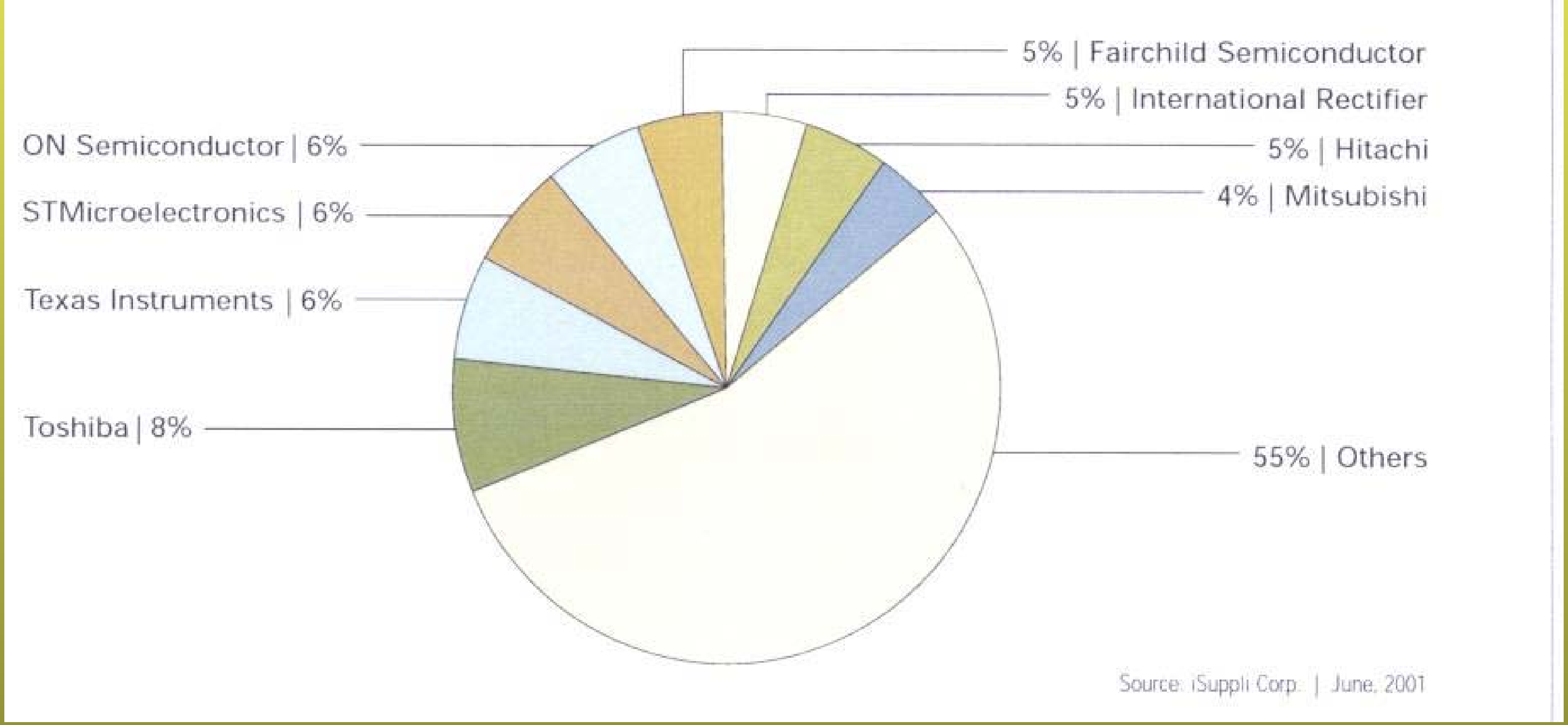


Converter Technology is Driven by Devices

Power Management Market

- Total semiconductor market in 2000 - $204b
  - 5% Power discretes - $10b; CAGR 28%
    - Thyristors – 8%; $0.8b
    - Diodes – 23%; $2.3b
    - Power Transistors – 69%; $6.9b
  - 3% Power Management ICs - $6b; CAGR 61%; 20% of total analogue IC market

Market Share



Source: iSuppli Corp. | June, 2001

Application areas

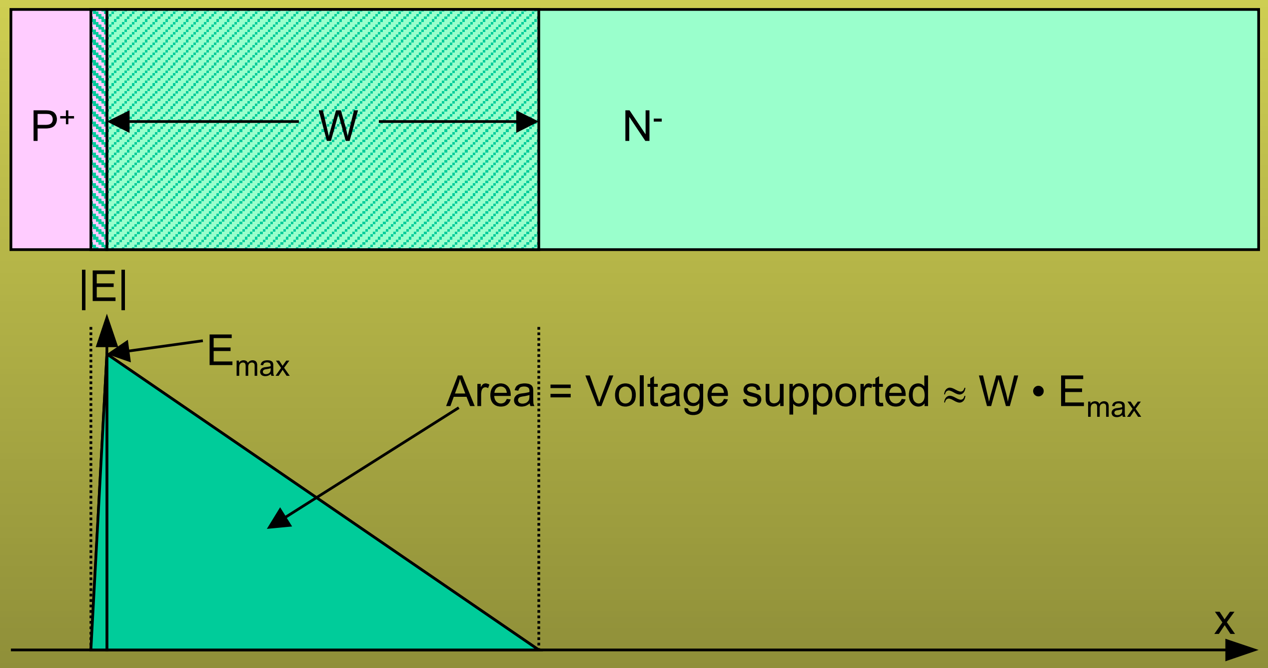
- Two Main Areas of Growth
  - IT, communications, computers – DC/DC
  - Motion control - DC/AC
- Both are driven by improvements in devices and device technology

2. Basics of Power Devices

The ideal power device:

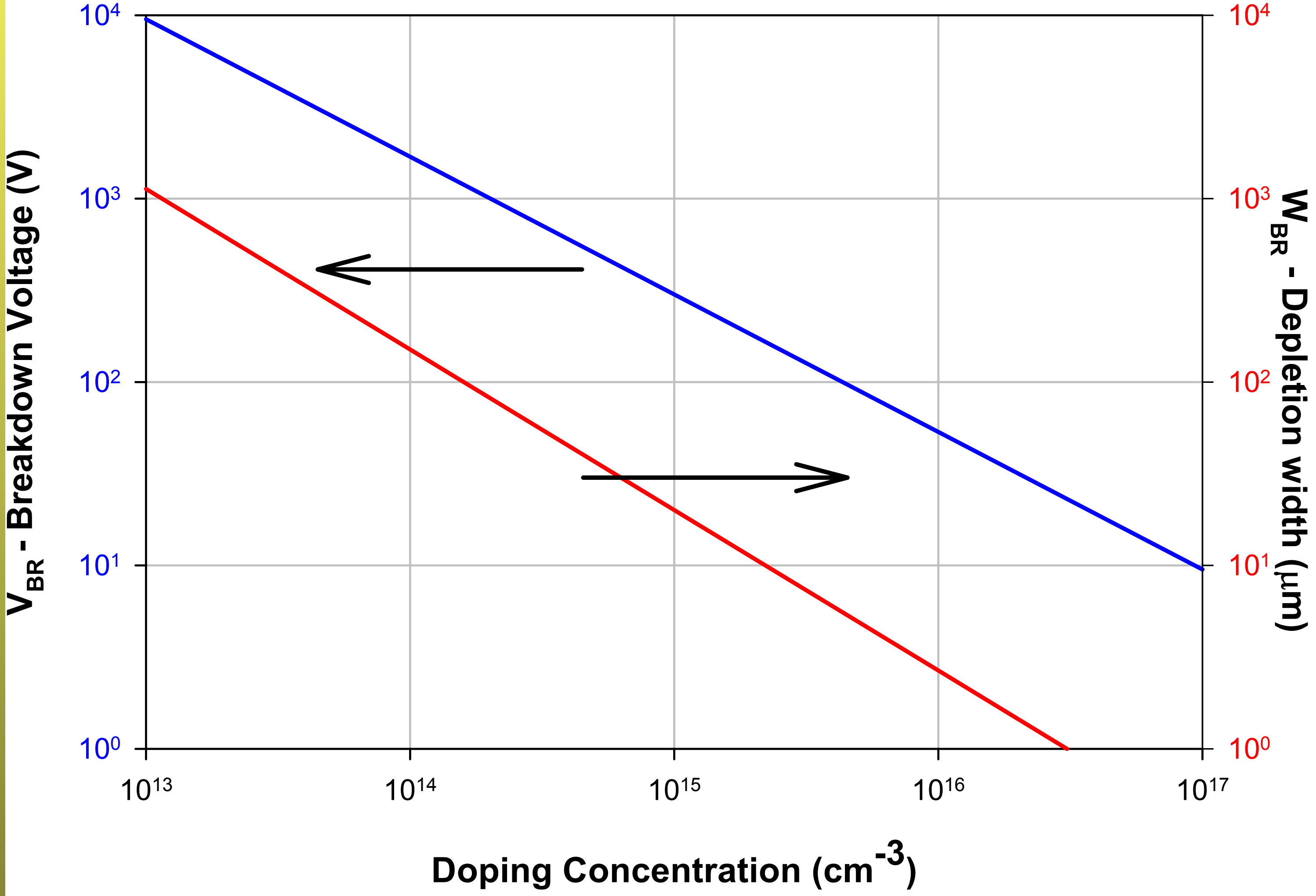
1. When on – zero resistance
2. When off – support infinite voltage
3. Switch between on and off (and *vice-versa)* in zero time
4. Zero Power dissipation
5. Small, light and cheap!

Blocking capability



Area = Voltage supported ≈ W • E_{max}

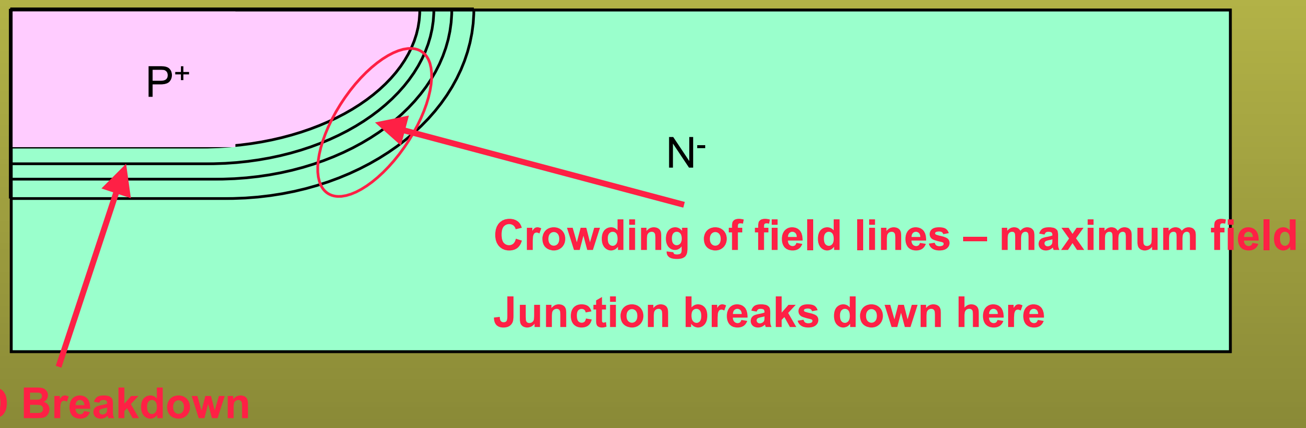
Avalanche Breakdown Voltage and Depletion Region Thickness



NOTE: Maximum VBR for silicon is approximately 10kV

Junction Termination

- In real structures the *pn*- junction will need terminate at some point
  - Thyristor/GTO - Edge of Wafer
  - MOSFET/IGBT - Edge of Chip or device



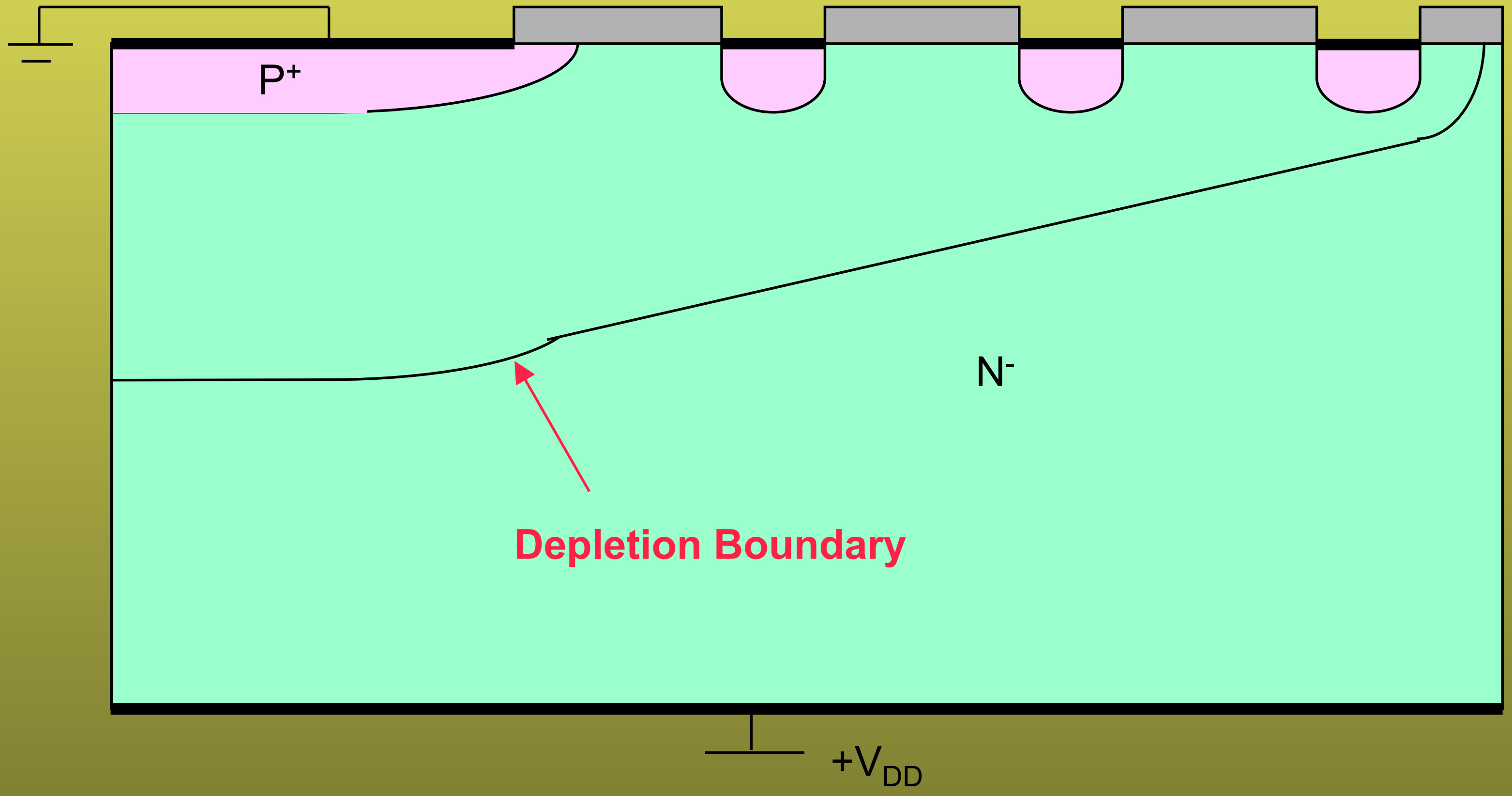
Crowding of field lines – maximum field

Junction breaks down here

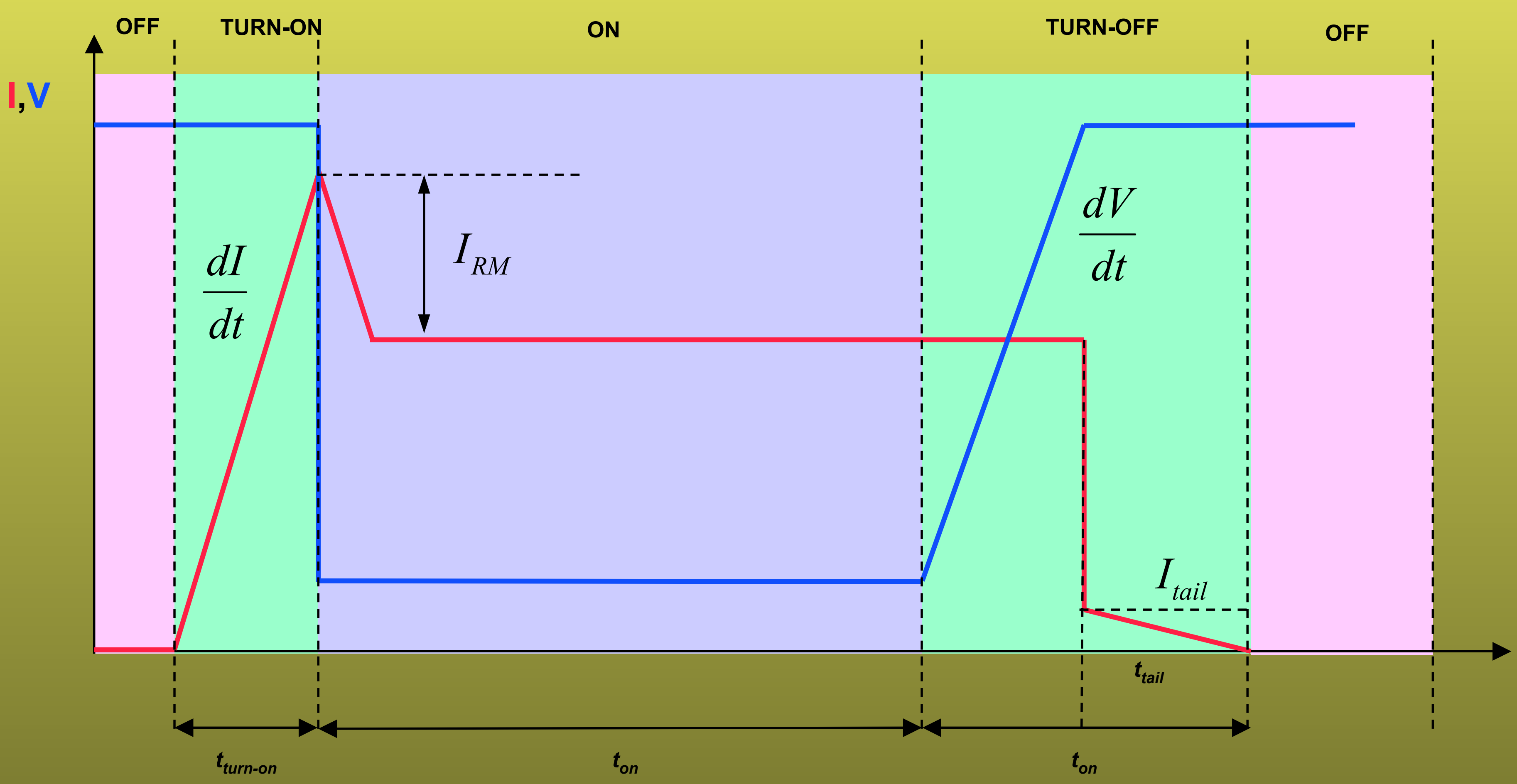
Ideal 1-D Breakdown

- Tight radius of curvature gives largest fields
- Without proper termination may get < 50% of abrupt junction breakdown voltage
- Termination is used to add extra charge on the surface to spread out the field lines
- Usual techniques
    - Floating rings
    - Field Plates
    - Junction Termination Extension (JTE)
    - SIPOS, DLC – Very high voltage devices

Floating Rings



On-state and Switching losses



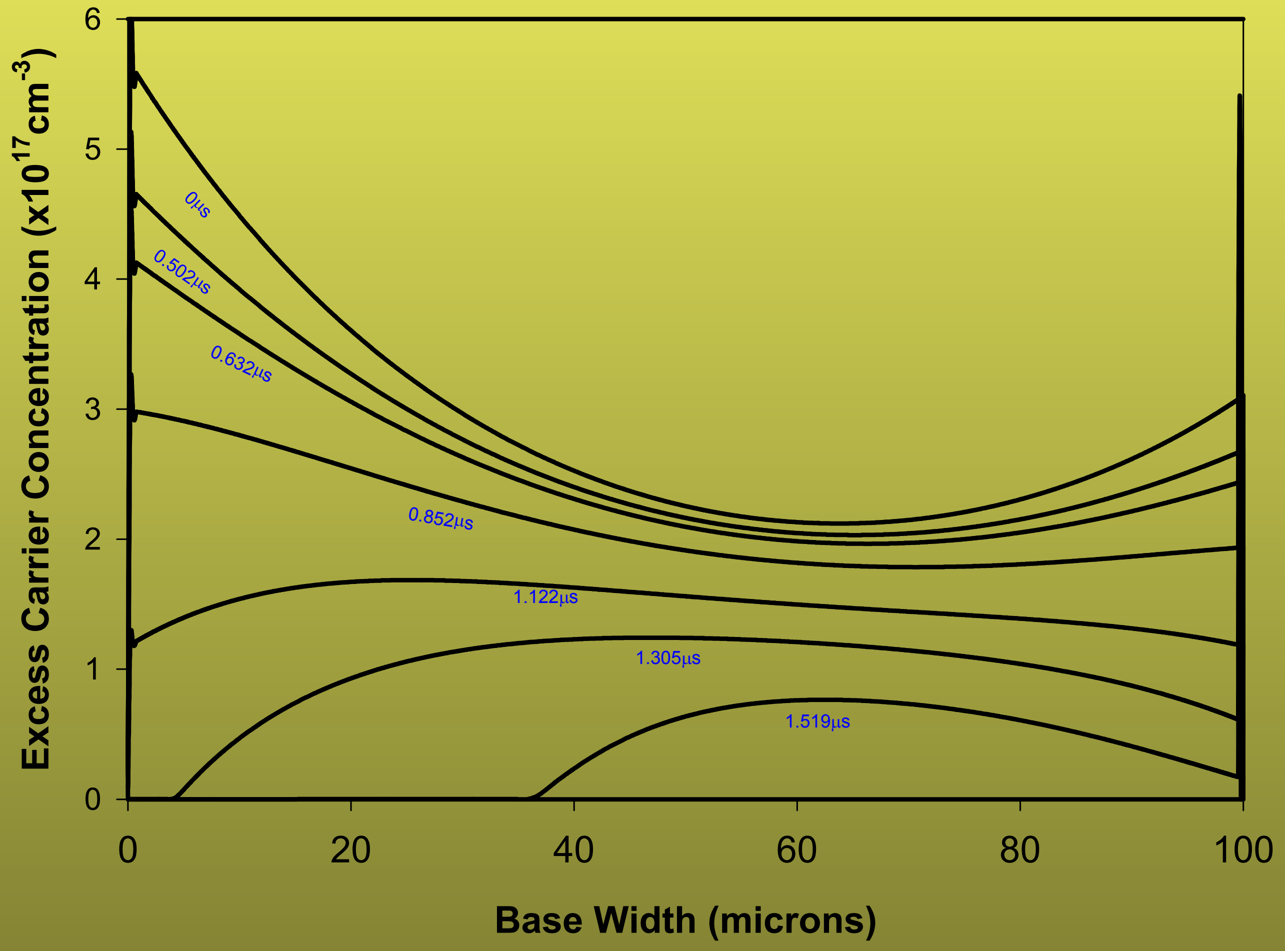
Bipolar Devices

- A bipolar device is defined as one in which both electrons and holes take part in the current conduction process.

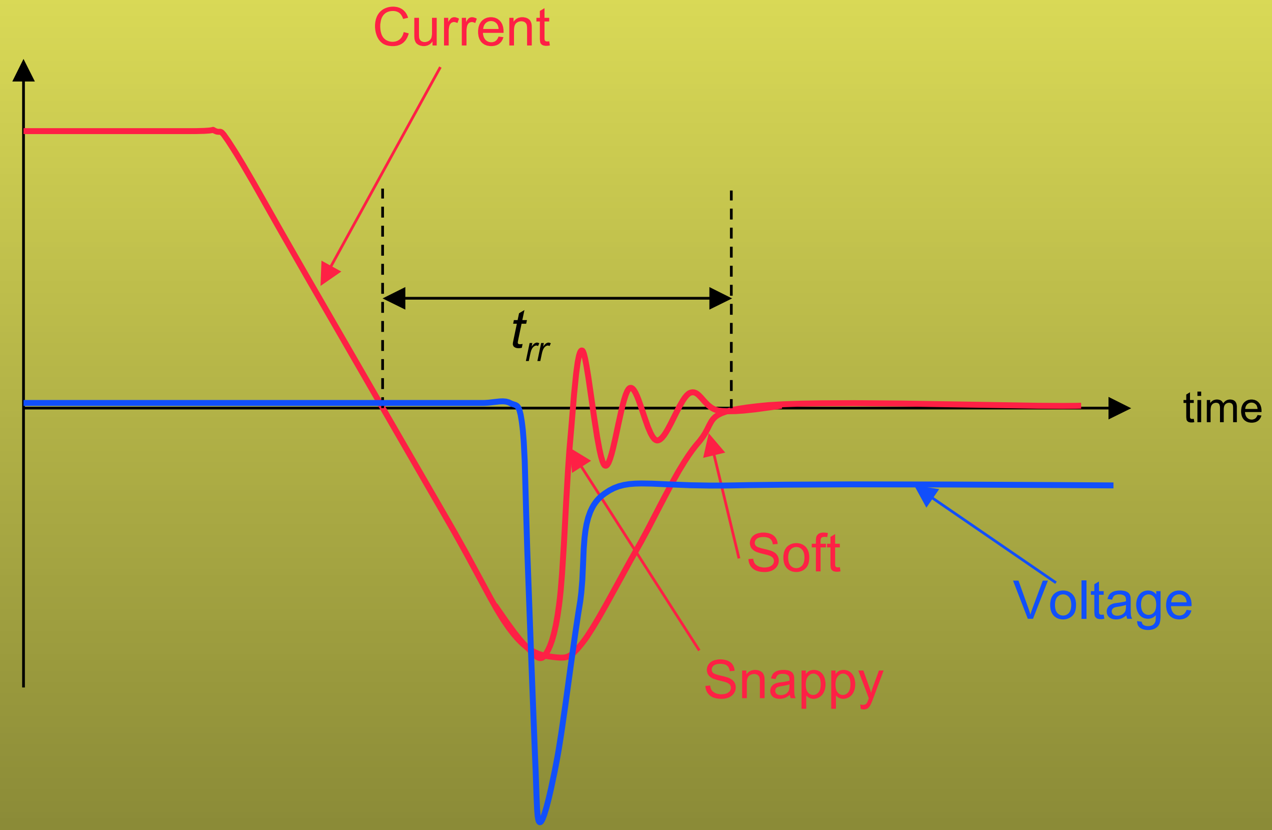
- Bipolar operation is essential in all high voltage devices (>800V)

- Bipolar operation is much slower than Unipolar, hence devices based on this tend to be used at lower frequencies.

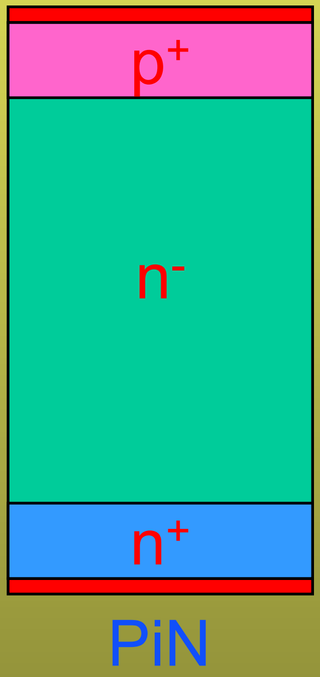
Bipolar switching Devices

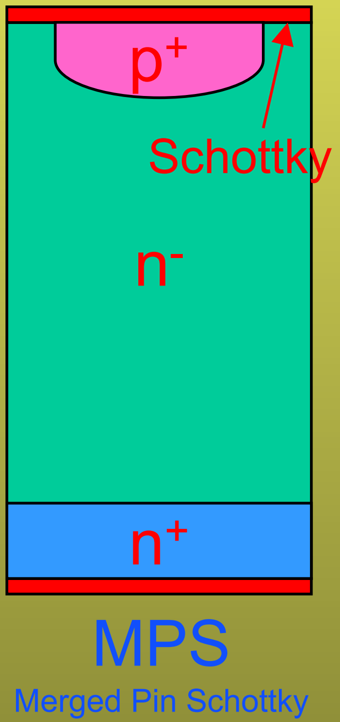


Recovery Definitions

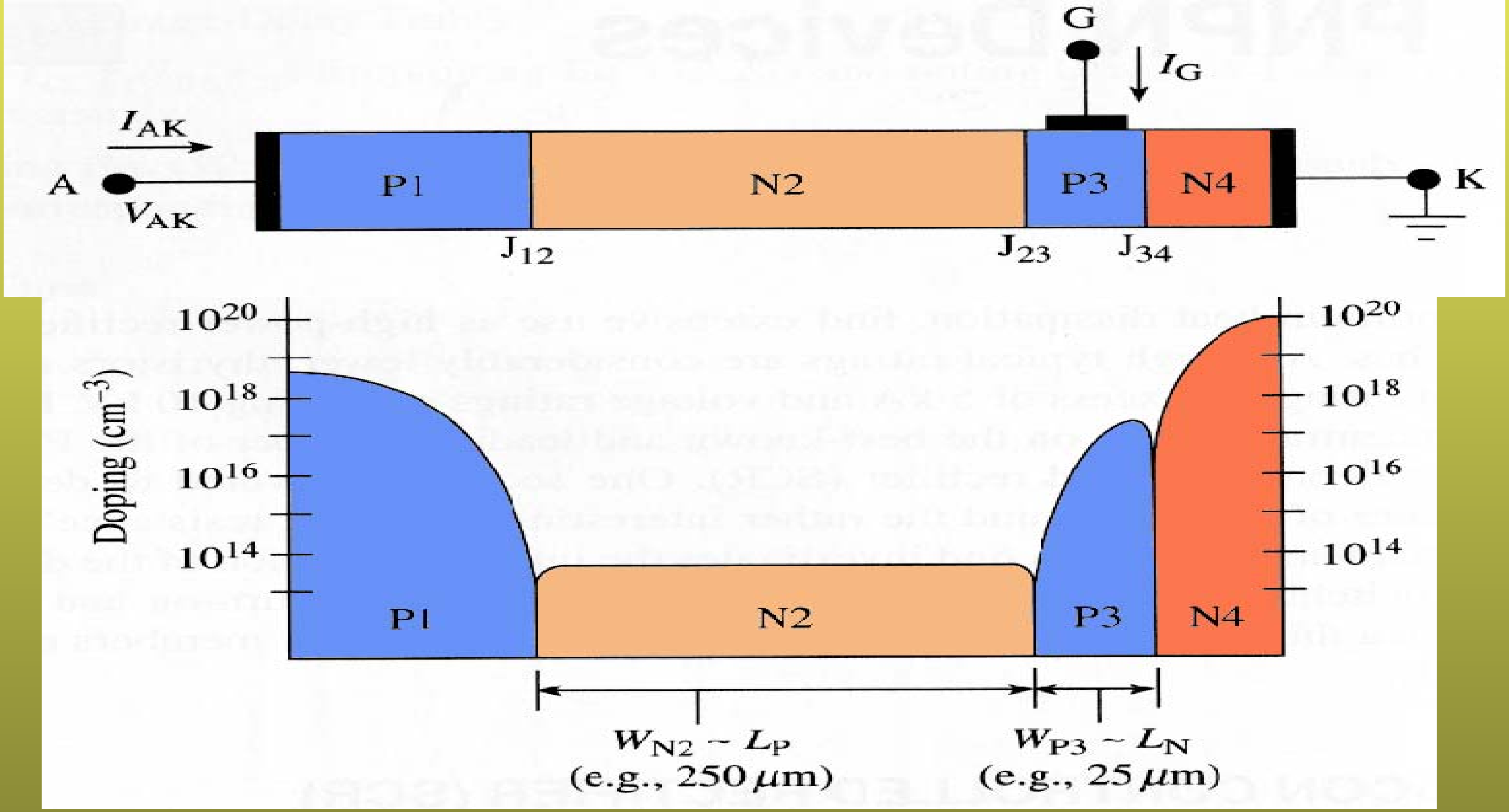


Diode Structures

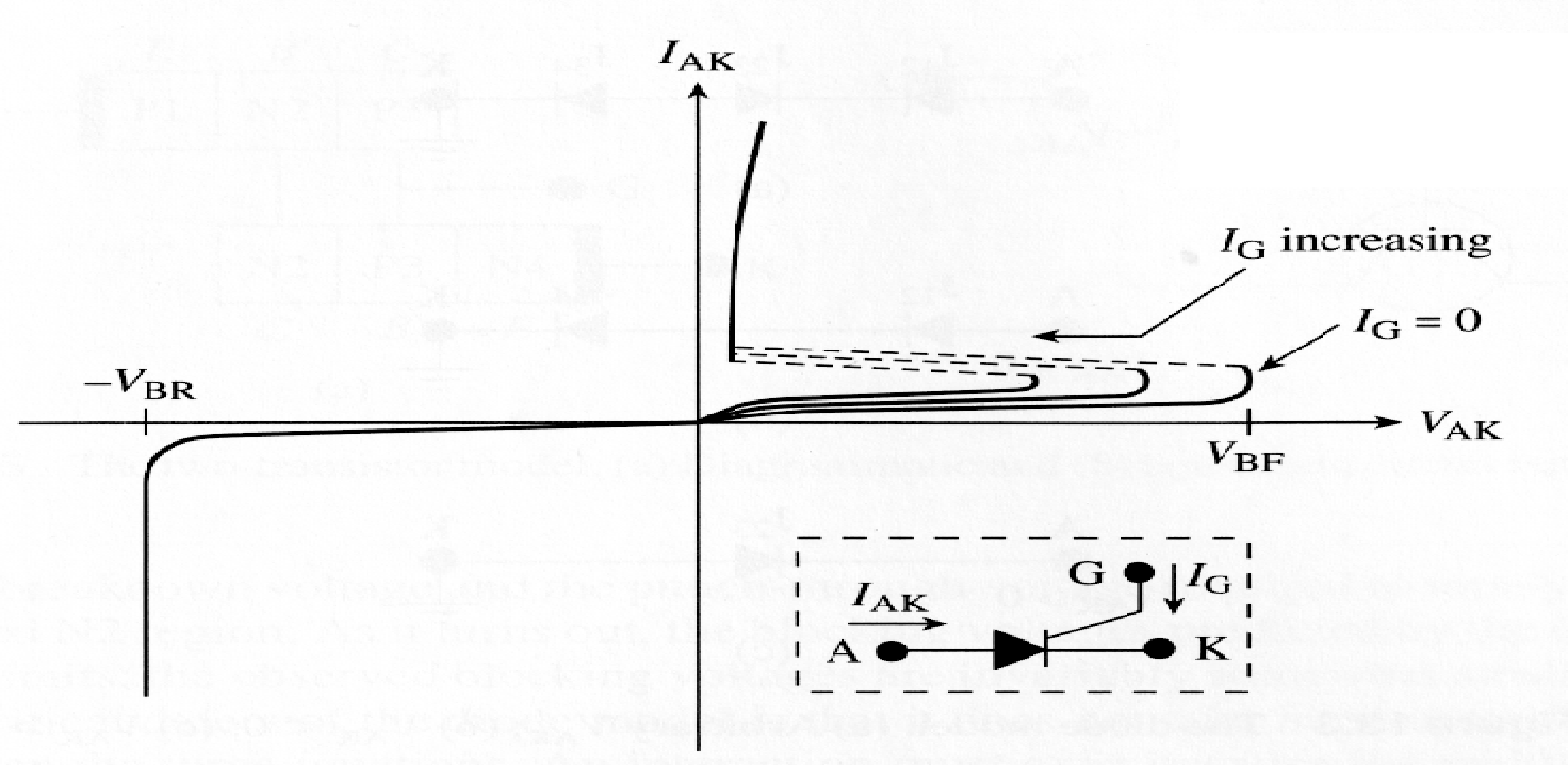




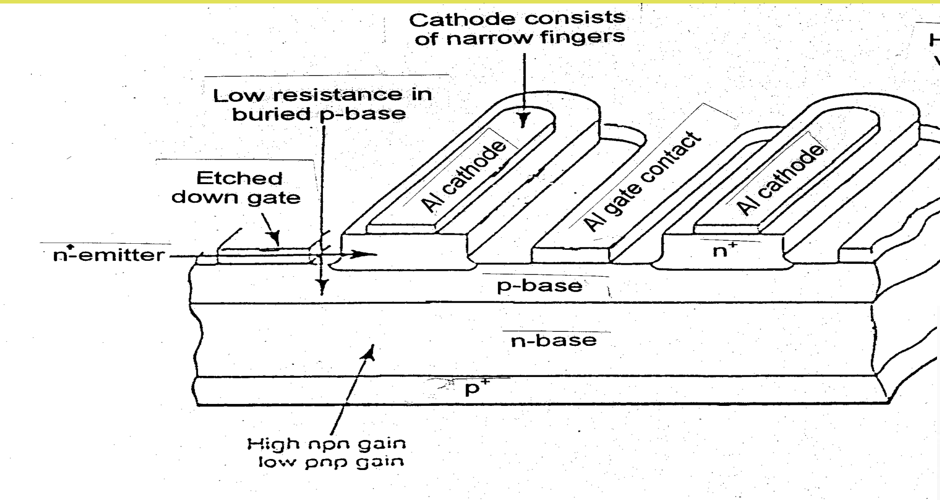
Thyristor Structures

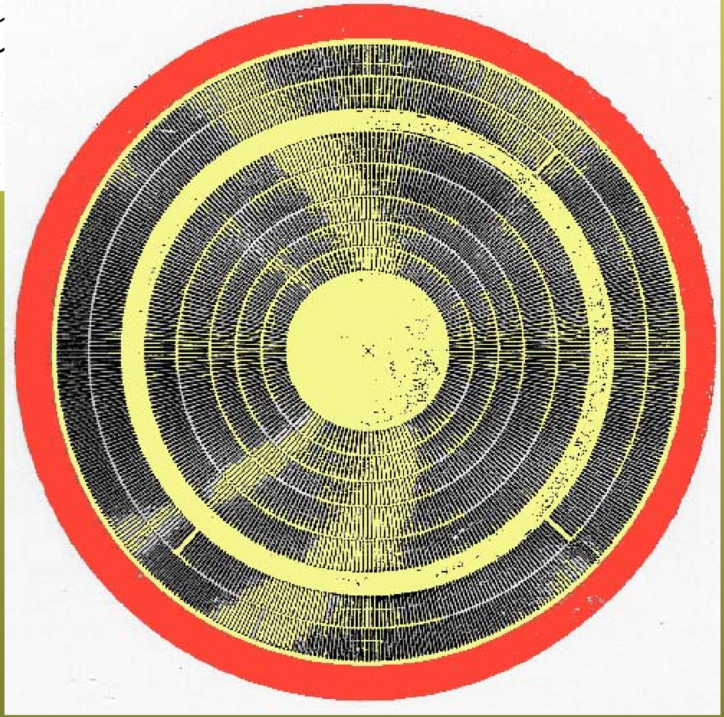


Terminal Characteristics

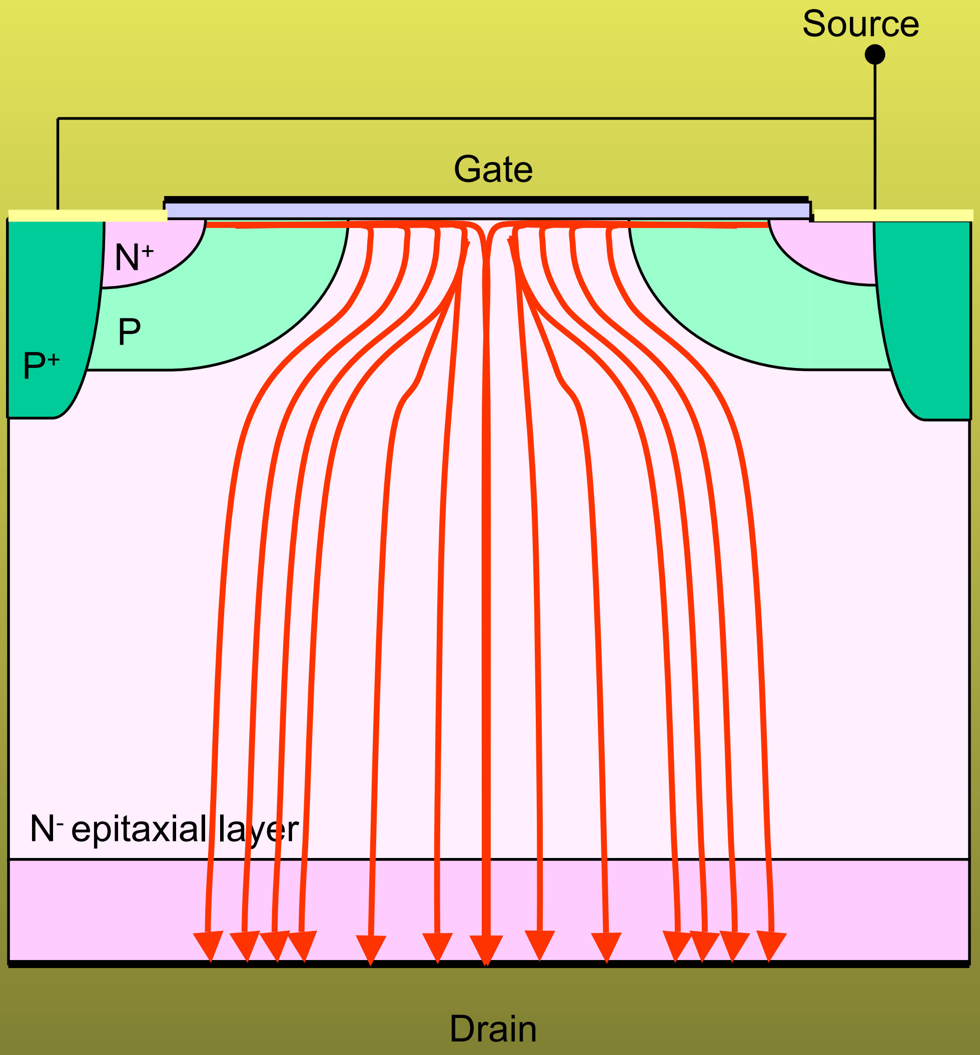


Gate Turn-off Thyristors (GTO)

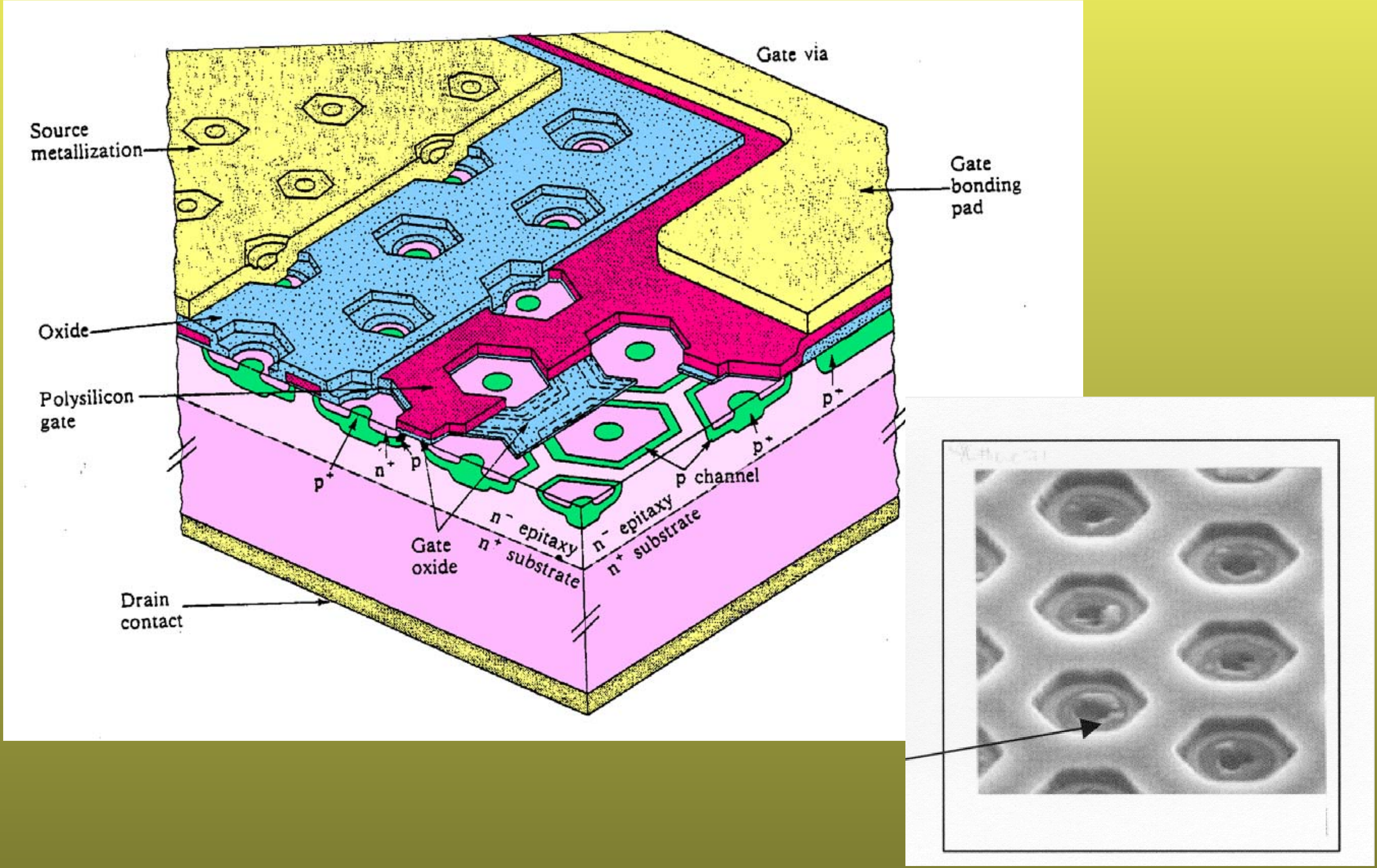




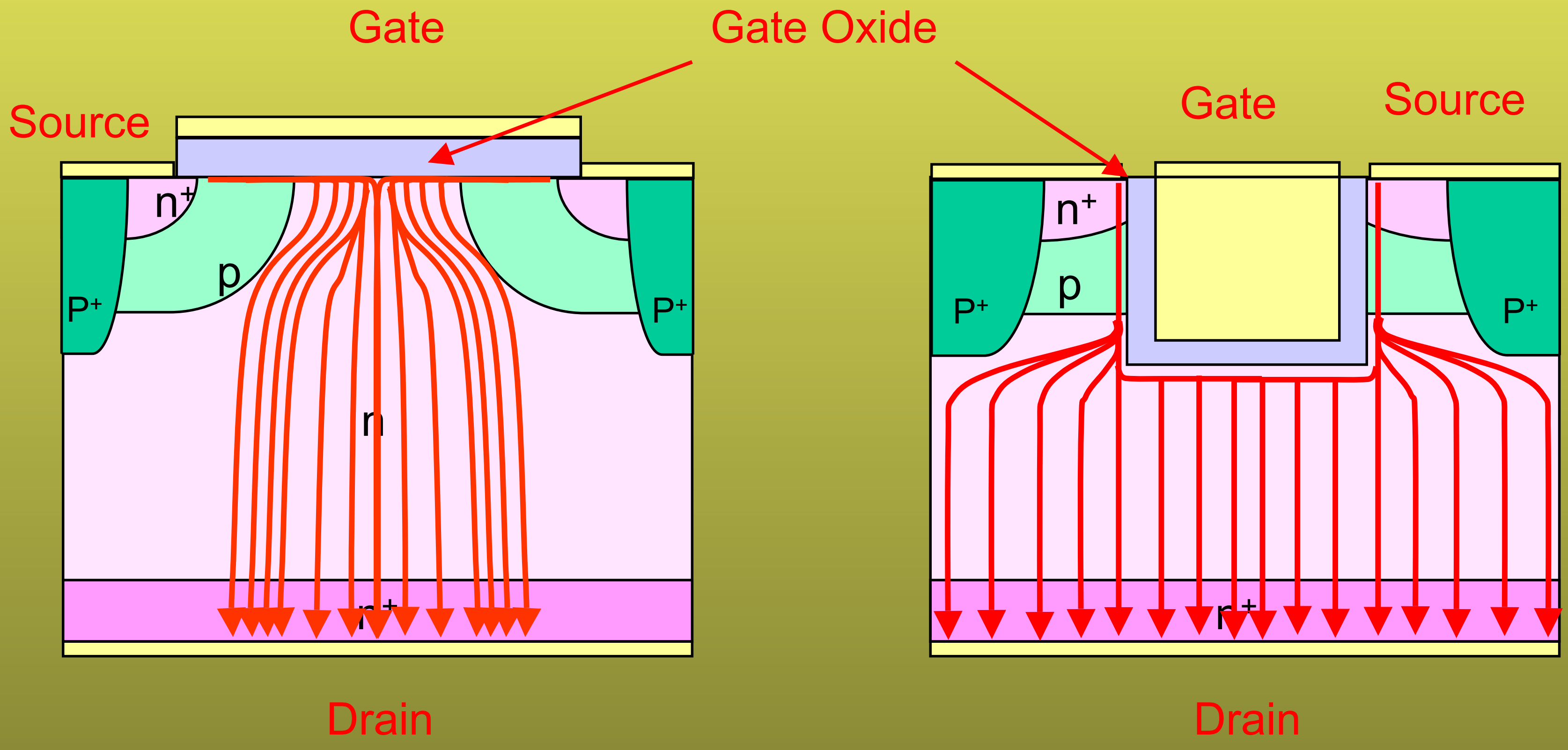
DMOS



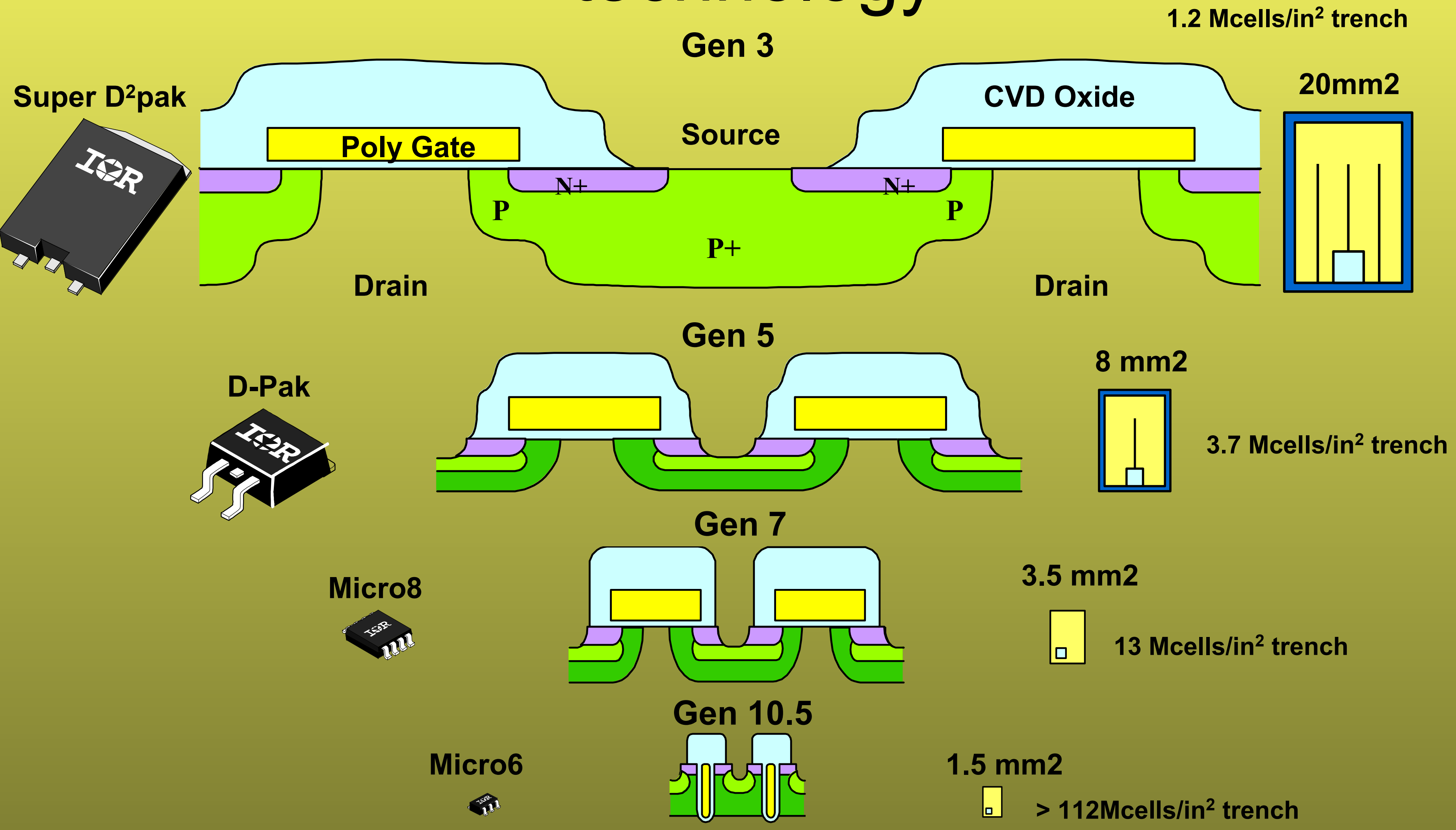
Cross sectional view of HEXFET



Comparison of Structures



Trend in low voltage MOSFET technology



Gen 3

Super D^{2}pak

1.2 Mcells/in^2 trench

20mm2

Gen 5

D-Pak

8 mm2

3.7 Mcells/in^2 trench

Gen 7

Micro8

3.5 mm2

13 Mcells/in^2 trench

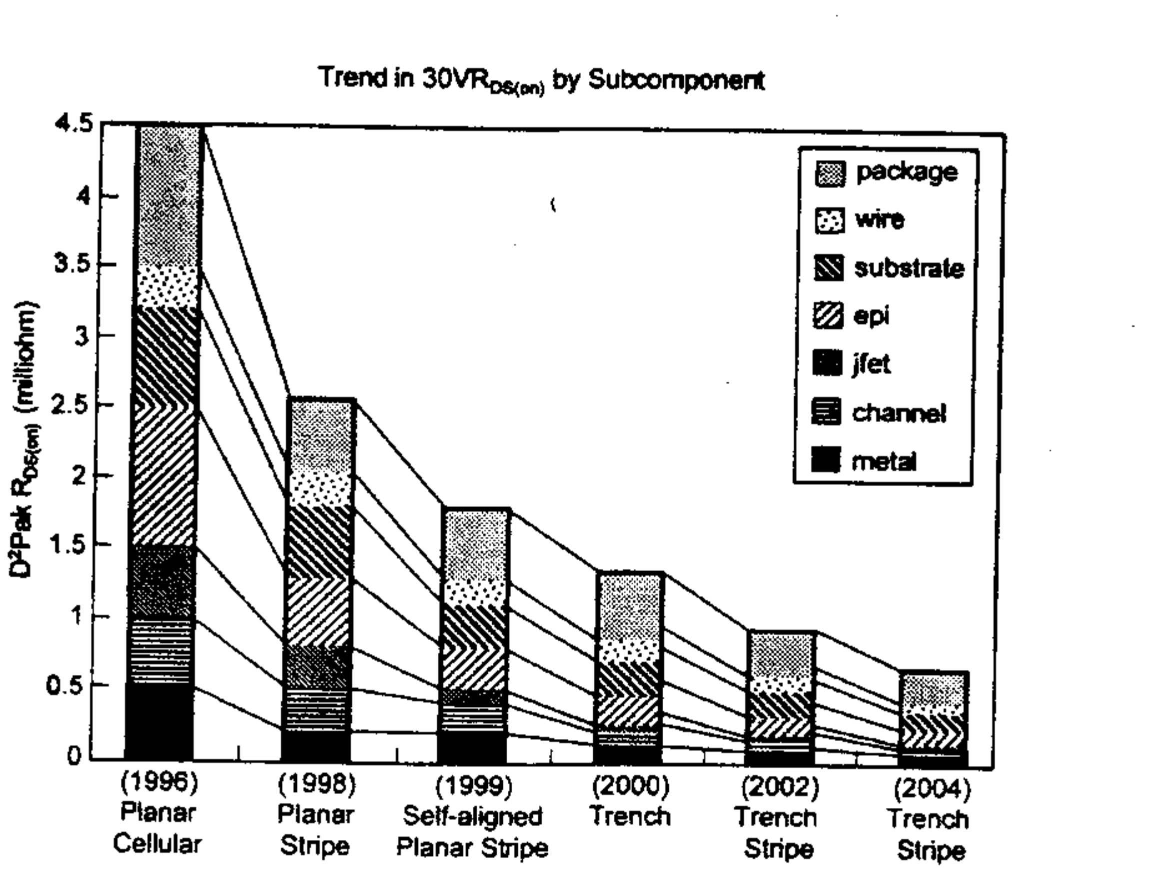
Gen 10.5

Micro6

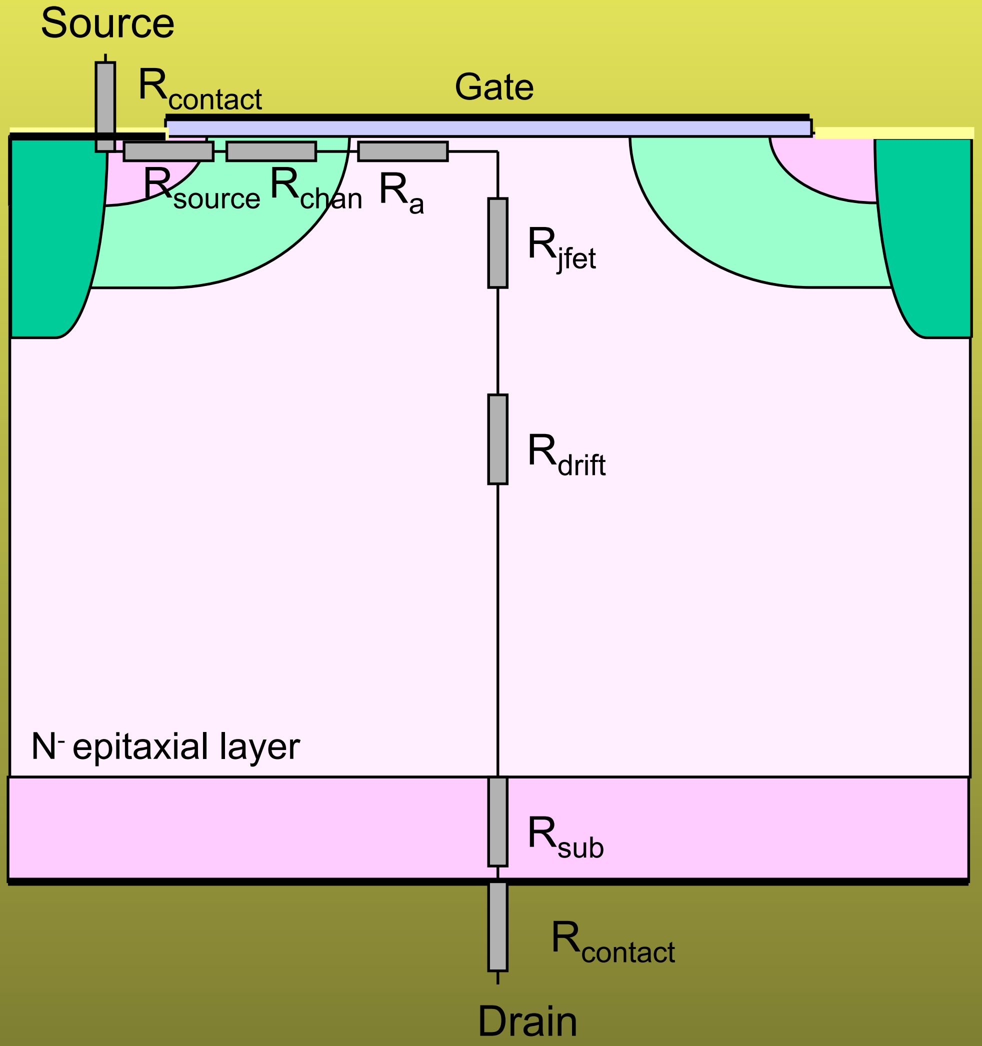
1.5 mm2

> 112Mcells/in^2 trench

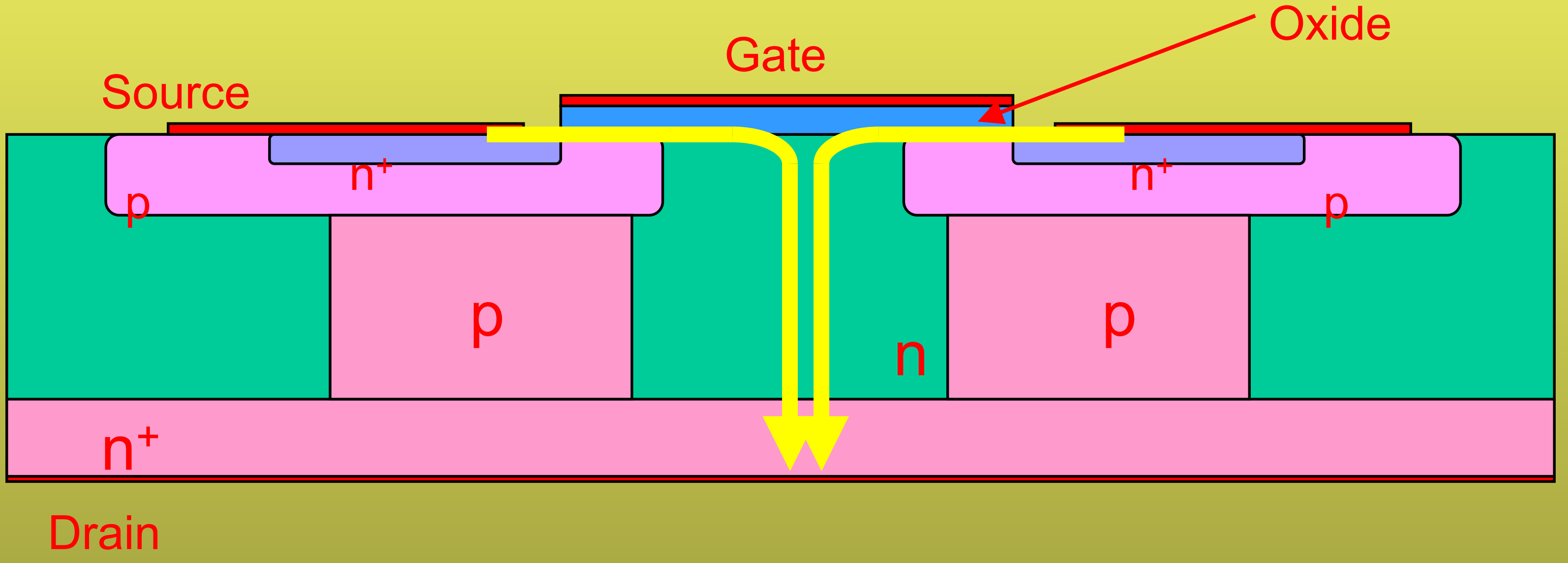
Trench Road-map (30V)



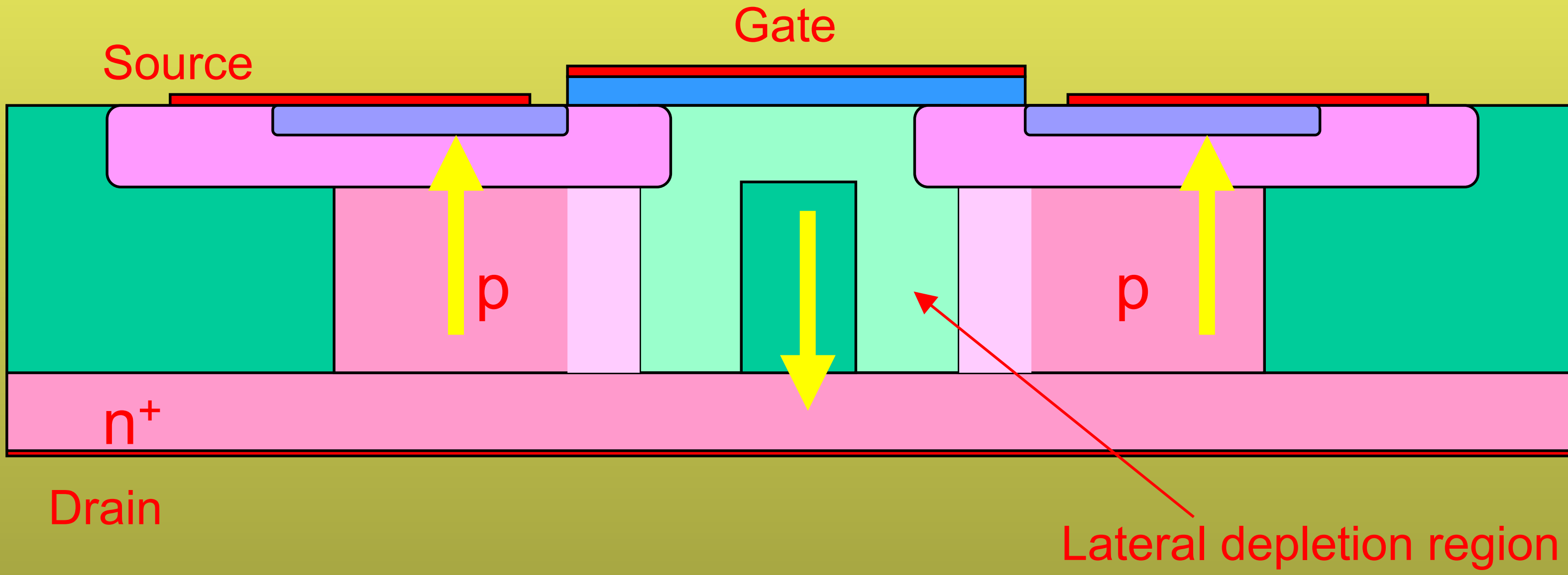
On-State Resistance



Charge Compensation (COOLMOS)



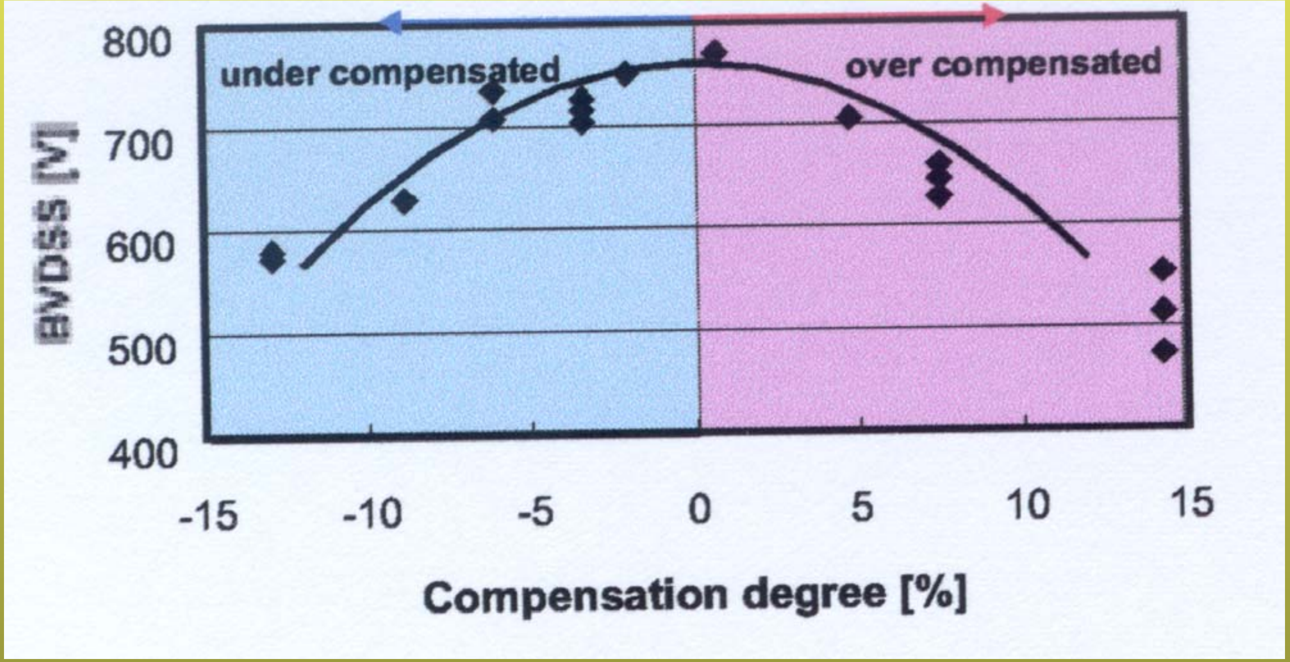
Charge Compensation (COOLMOS)



600V, 40A/cm^2

Reduce R_{epi} to 20%

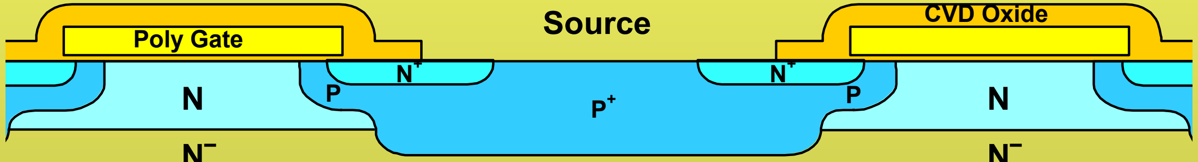
Compensation balancing act



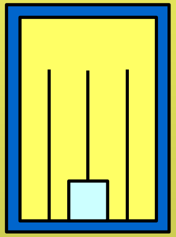
Trend in 400 – 600V FET technology

TO-247

Gen 3

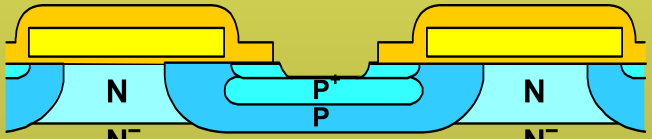


40mm²

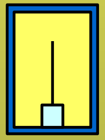


TO-220

Gen 6



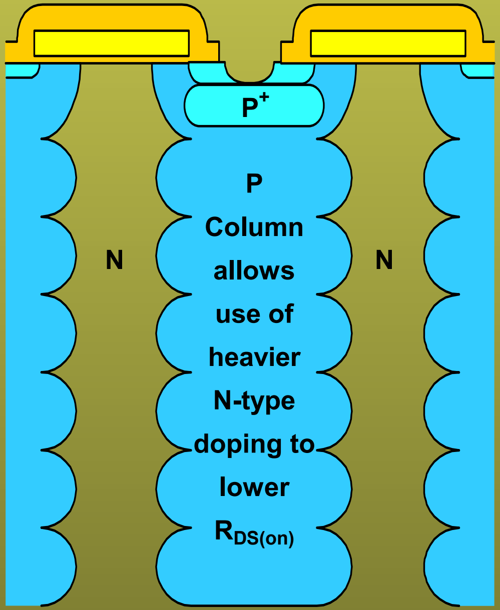
25 mm²



High density planar process

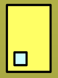
Gen 9

D-Pak



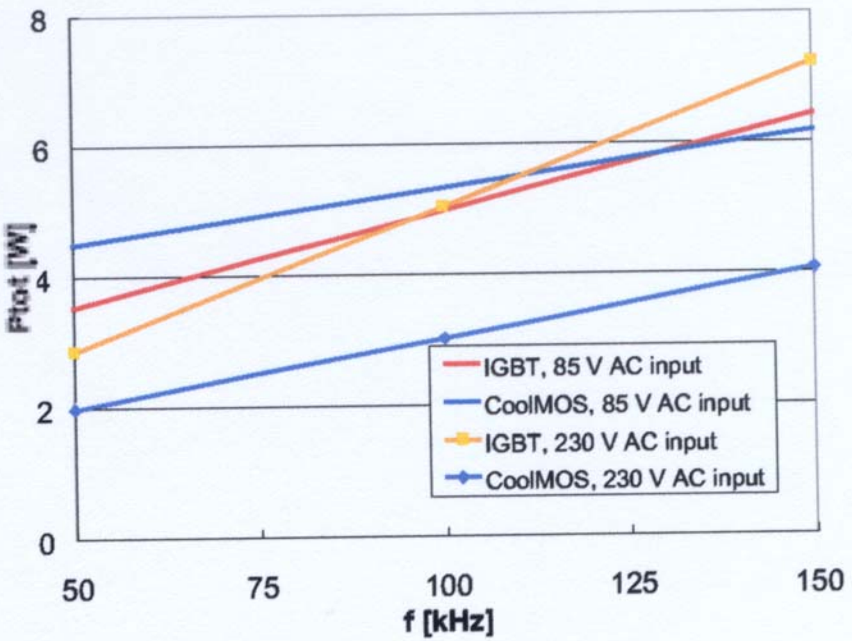
P Column allows use of heavier N-type doping to lower $R_{DS(on)}$

10 mm²



3x $R_{DS(on)}$ reduction
High conductivity drift region

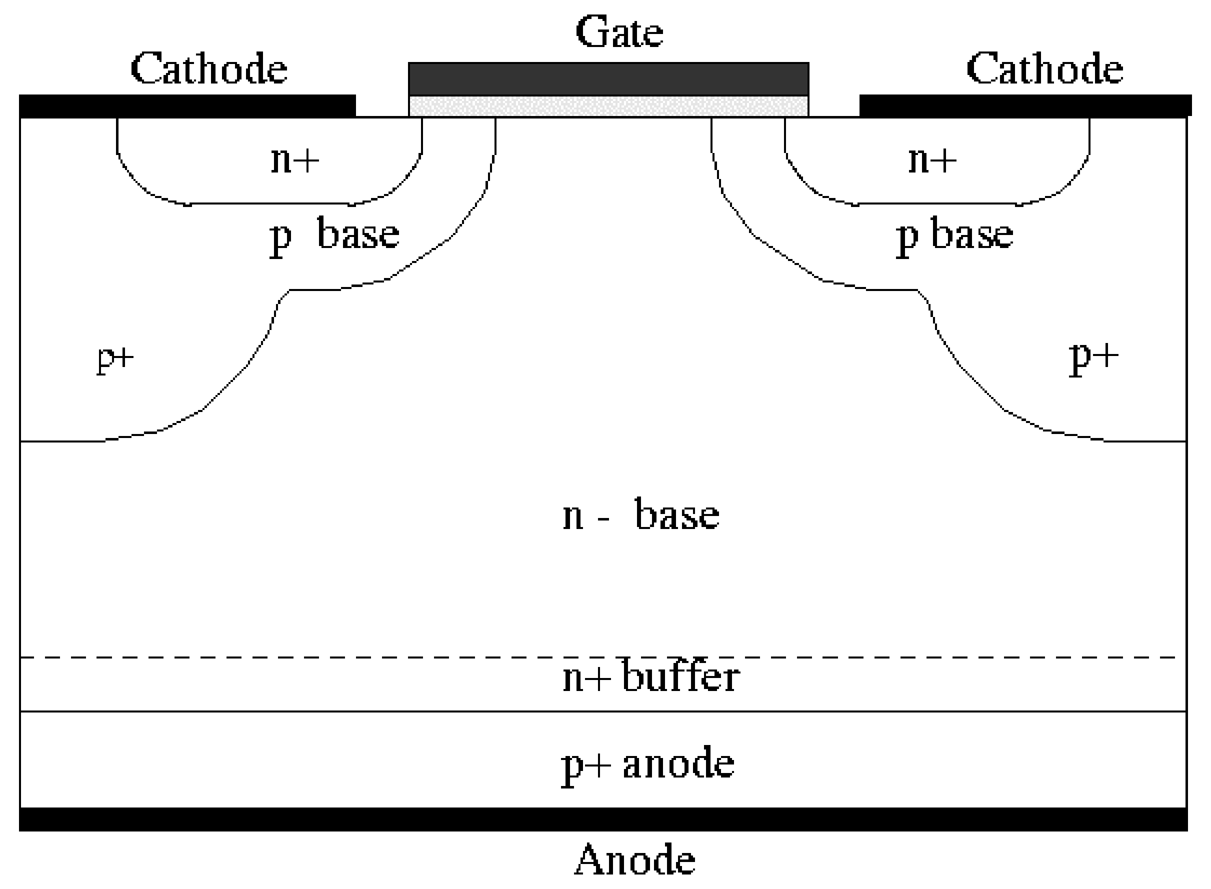
CoolMOS performance



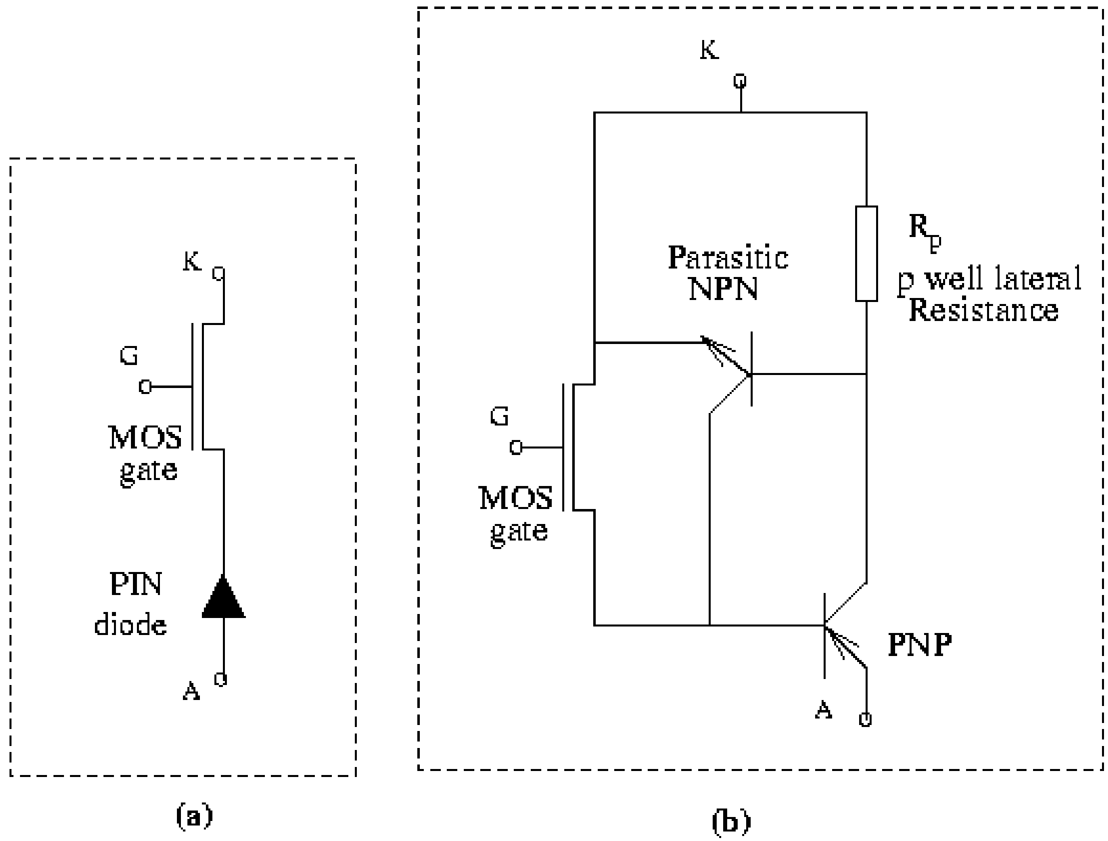
Comparison of the power losses of a 600 V high speed IGBT versus CoolMOS™ in a 70 W flyback converter.

Note: Patent filed by Professor XB Chen!

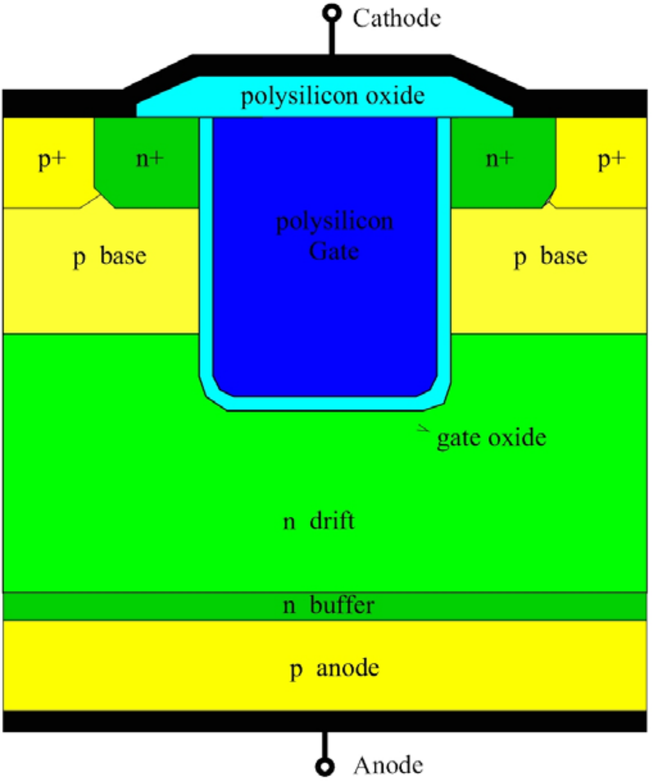
IGBT


Gate
Cathode
Cathode
n+
n+
p base
p base
p+
p+
n - base
n+ buffer
p+ anode
Anode

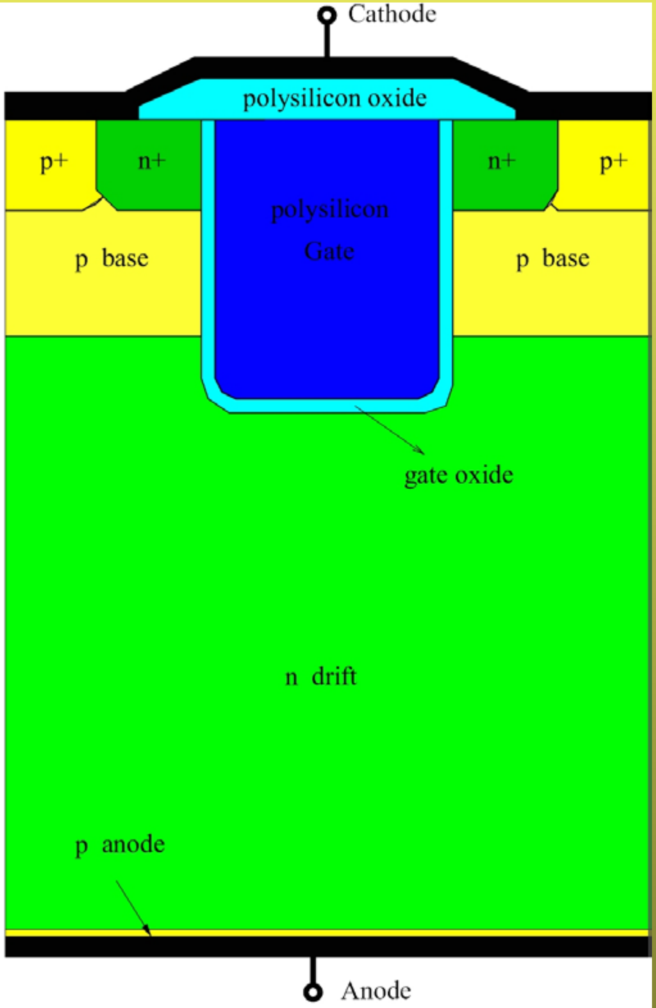
The IGBT equivalent circuit



PT & NPT IGBT structures

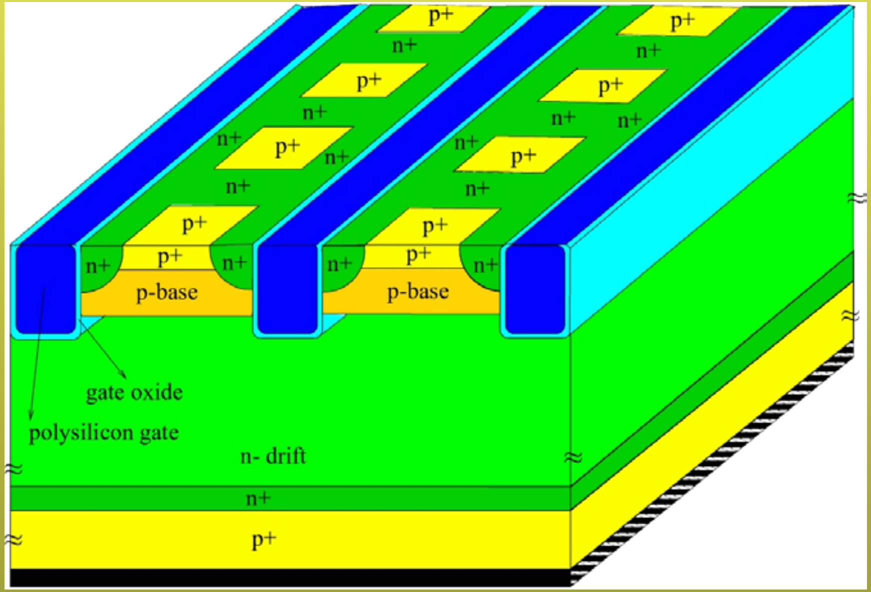


b) Punch Through (PT) TIGBT



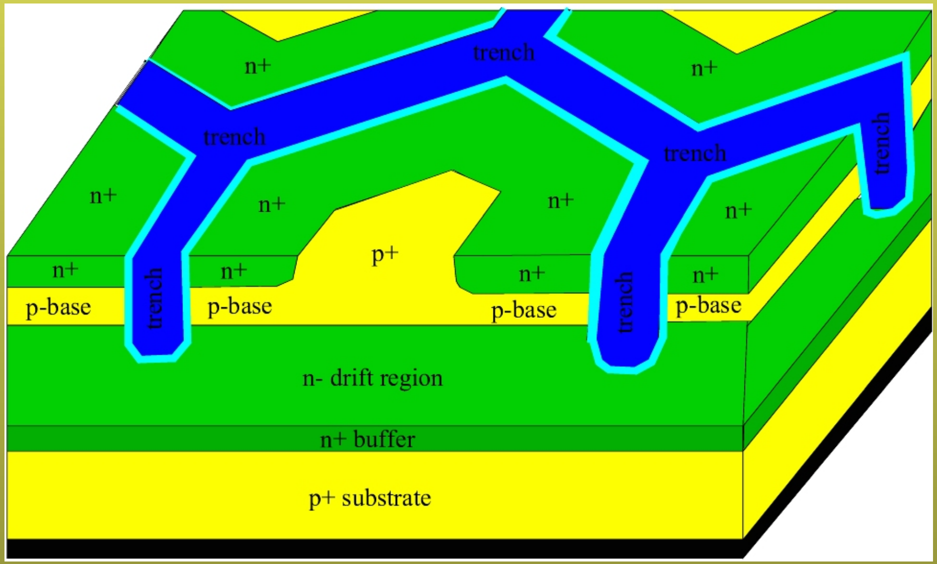
b) Non Punch Through (NPT) TIGBT

Trench IGBT Layout- Stripe or Hex ?

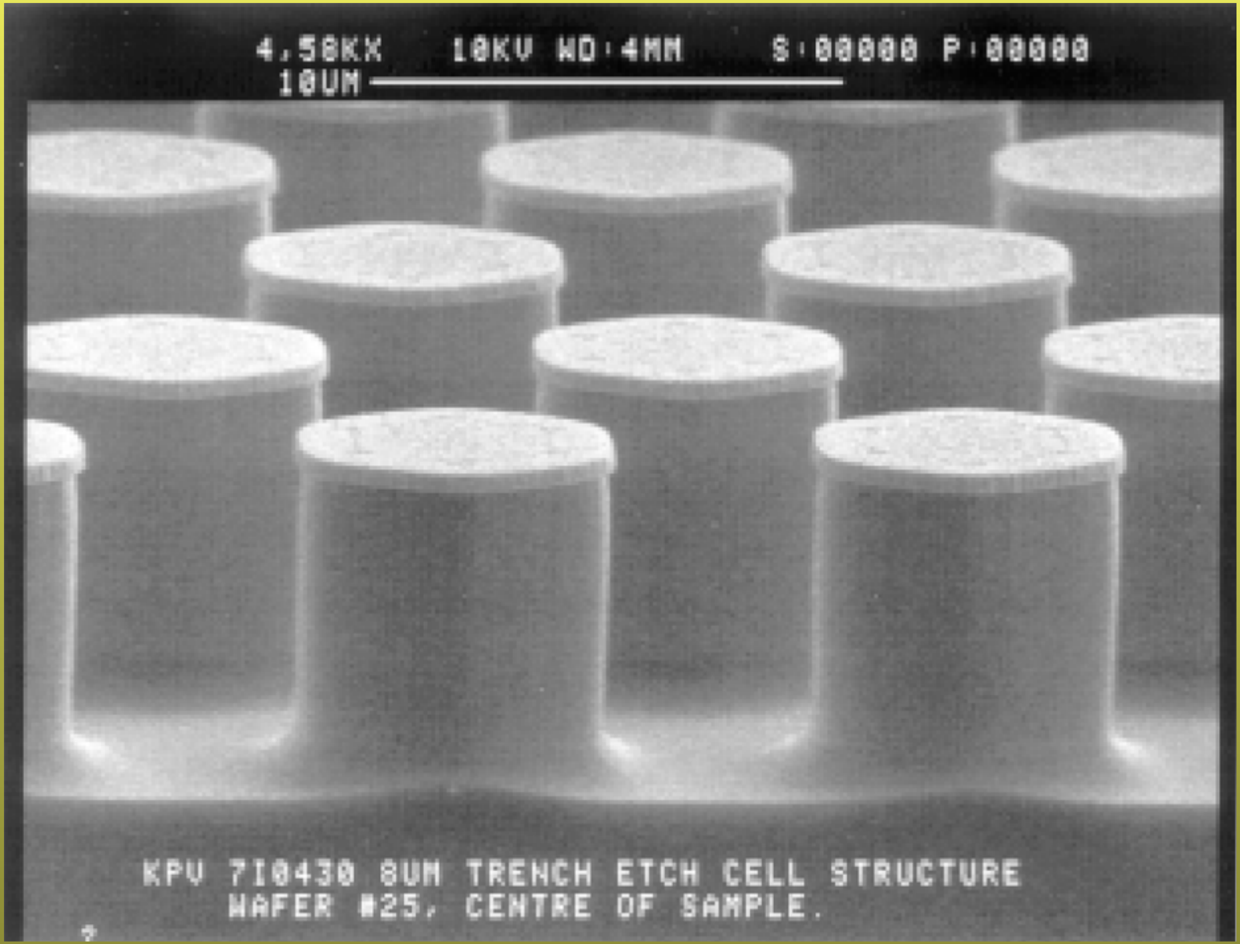


Stripe IGBT

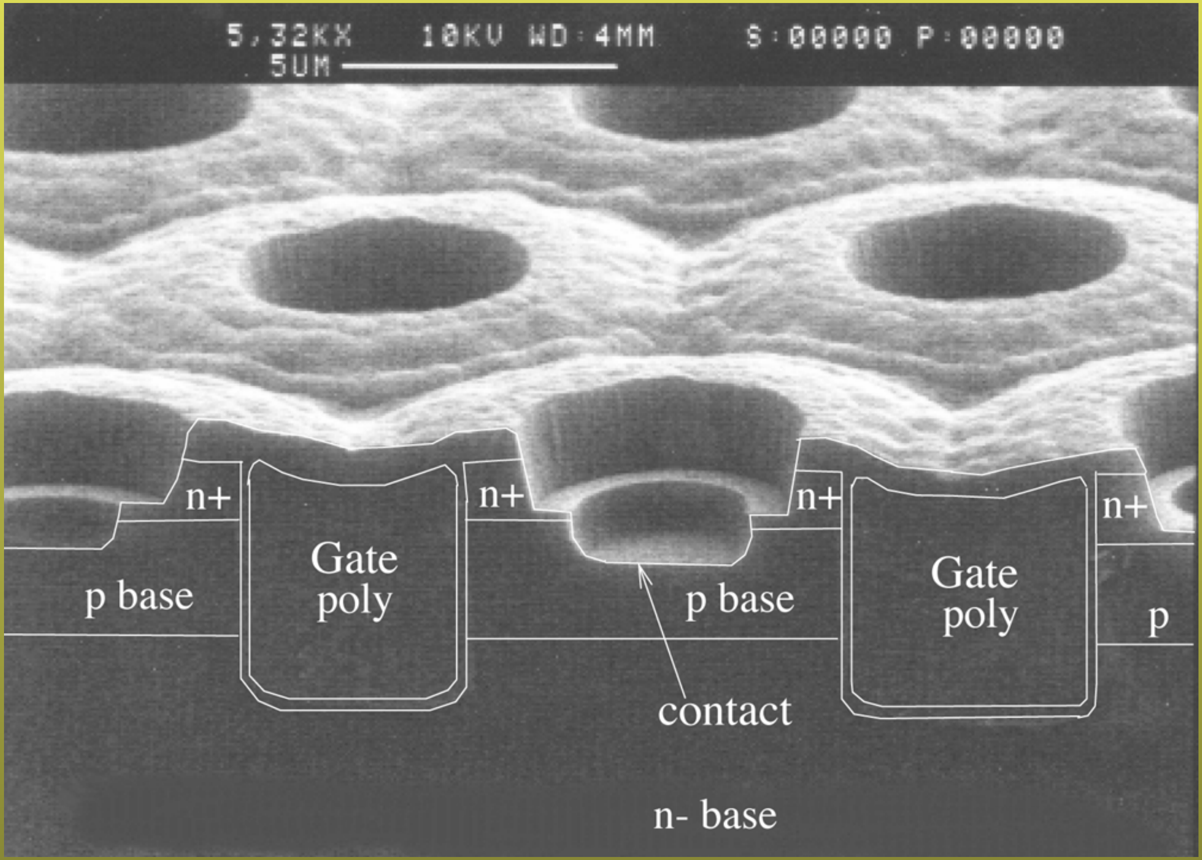
Hexagonal IGBT



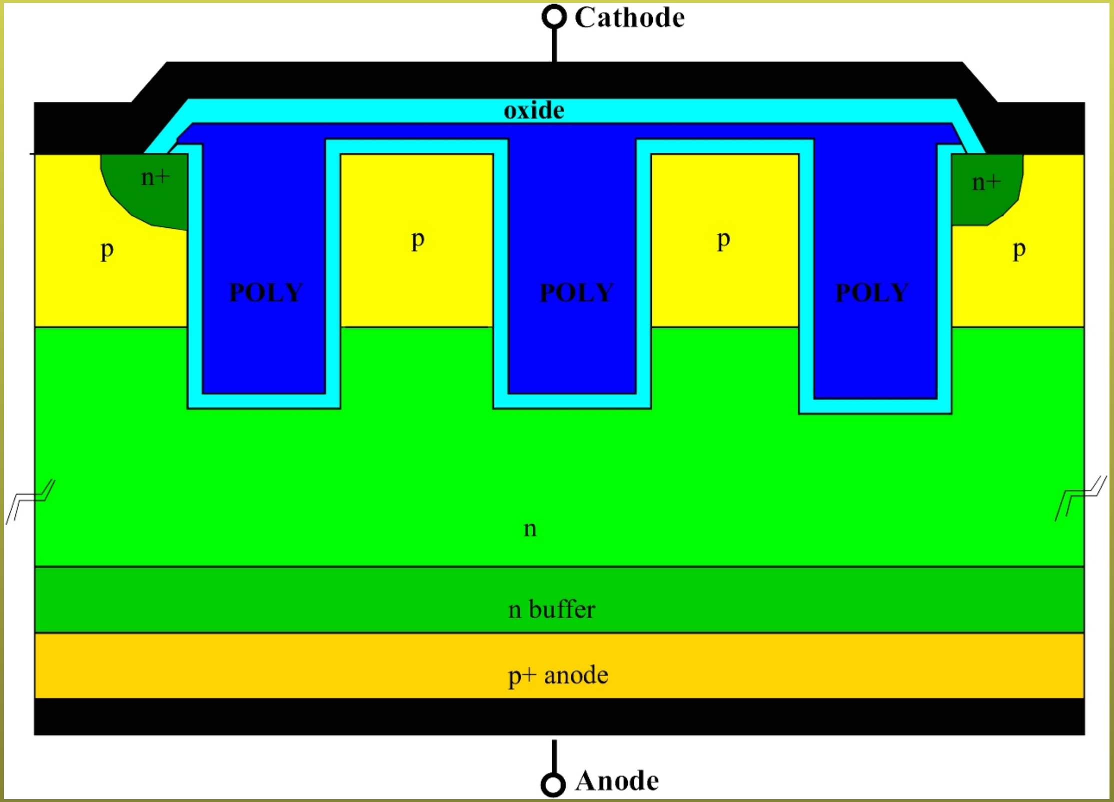
The Hexagonal Trench



Trench IGBT Showing Active Trench

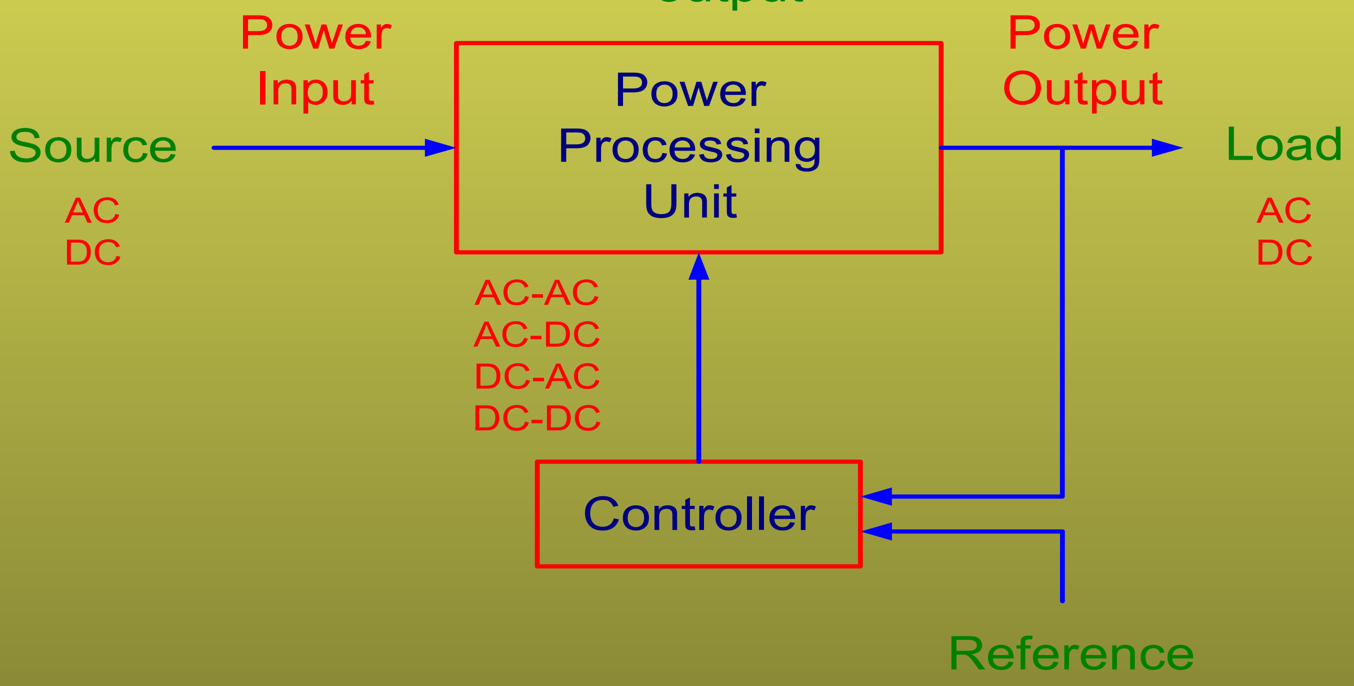


The Injection Enhanced Gate Transistor (IEGT)



Power Electronics Systems

Changes any electrical power source to any desired form voltage, current, and frequency output



Power Input

Source

AC
DC

Power Processing Unit

Power Output

Load

AC
DC

AC-AC
AC-DC
DC-AC
DC-DC

Controller

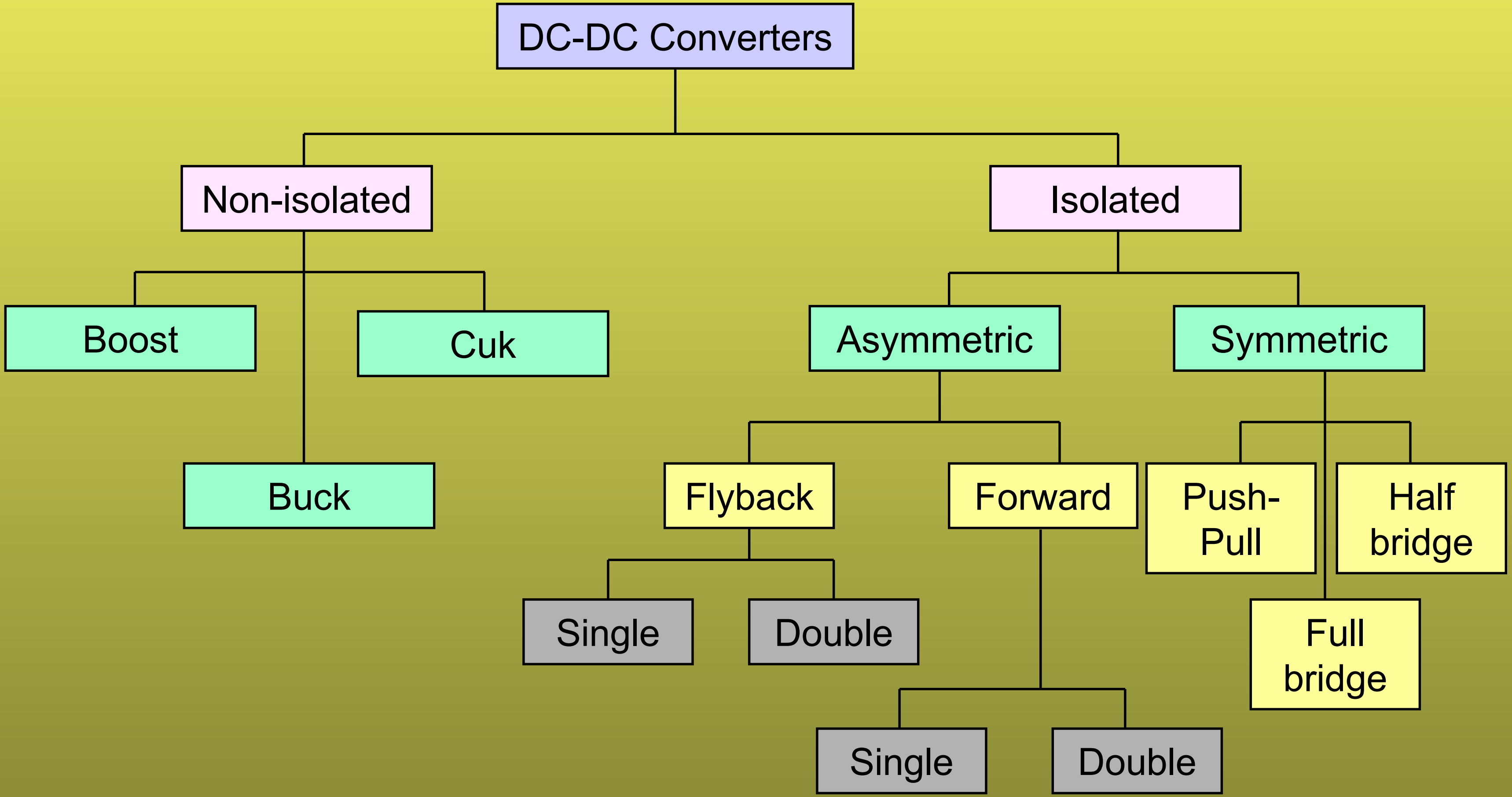
Reference

Power Electronic Circuits

The power electronic circuits can be classified into the following types:

- AC-DC converters (controlled and uncontrolled rectifiers)
- DC-DC converters (dc choppers)
- DC-AC converters (inverters)
- AC-AC converters (ac voltage regulators)

DC-DC Converter Topologies


DC-DC Converters

Non-isolated

Boost

Cuk

Buck

Isolated

Asymmetric

Flyback

Single

Double

Forward

Single

Double

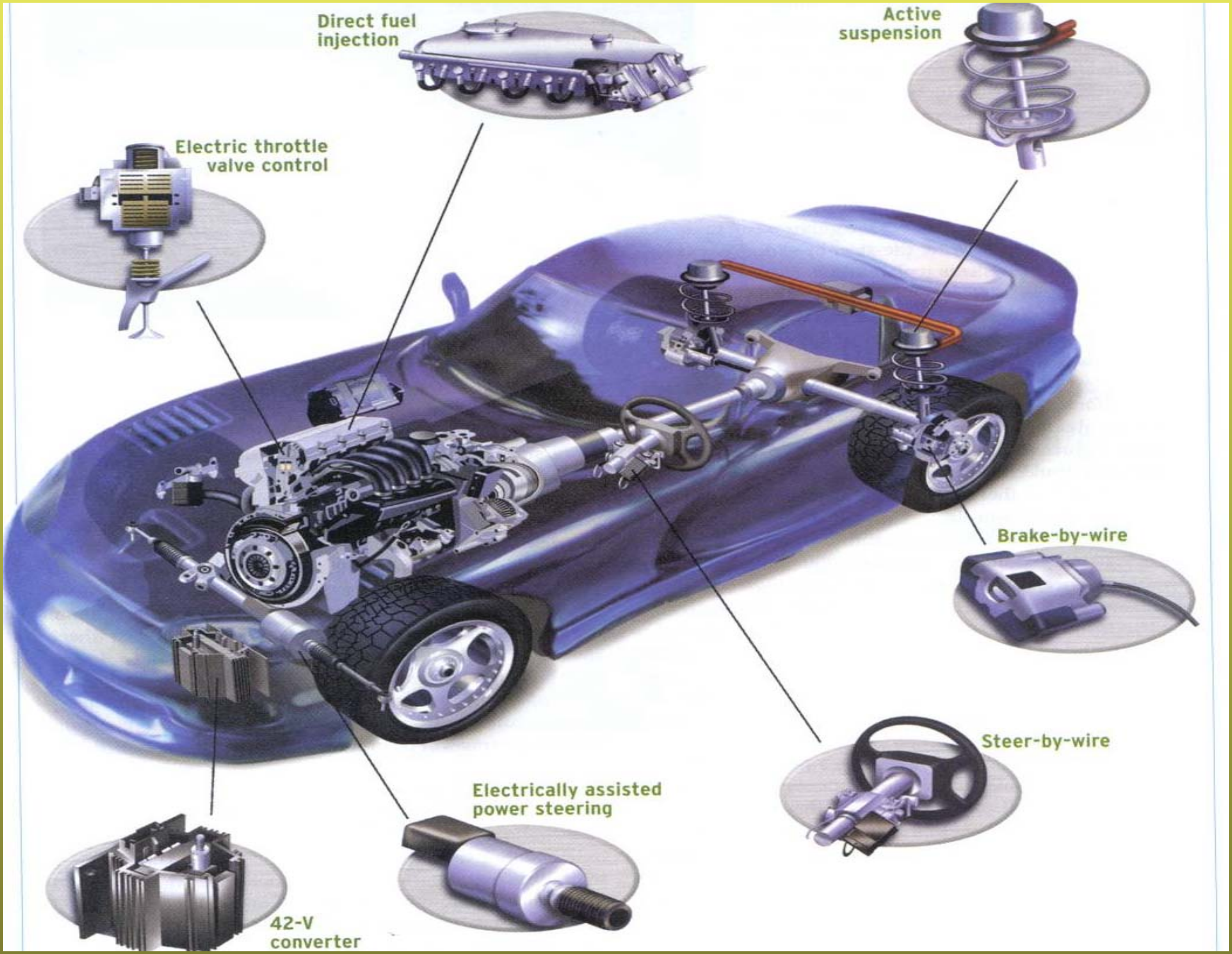
Symmetric

Push-Pull

Half bridge

Full bridge

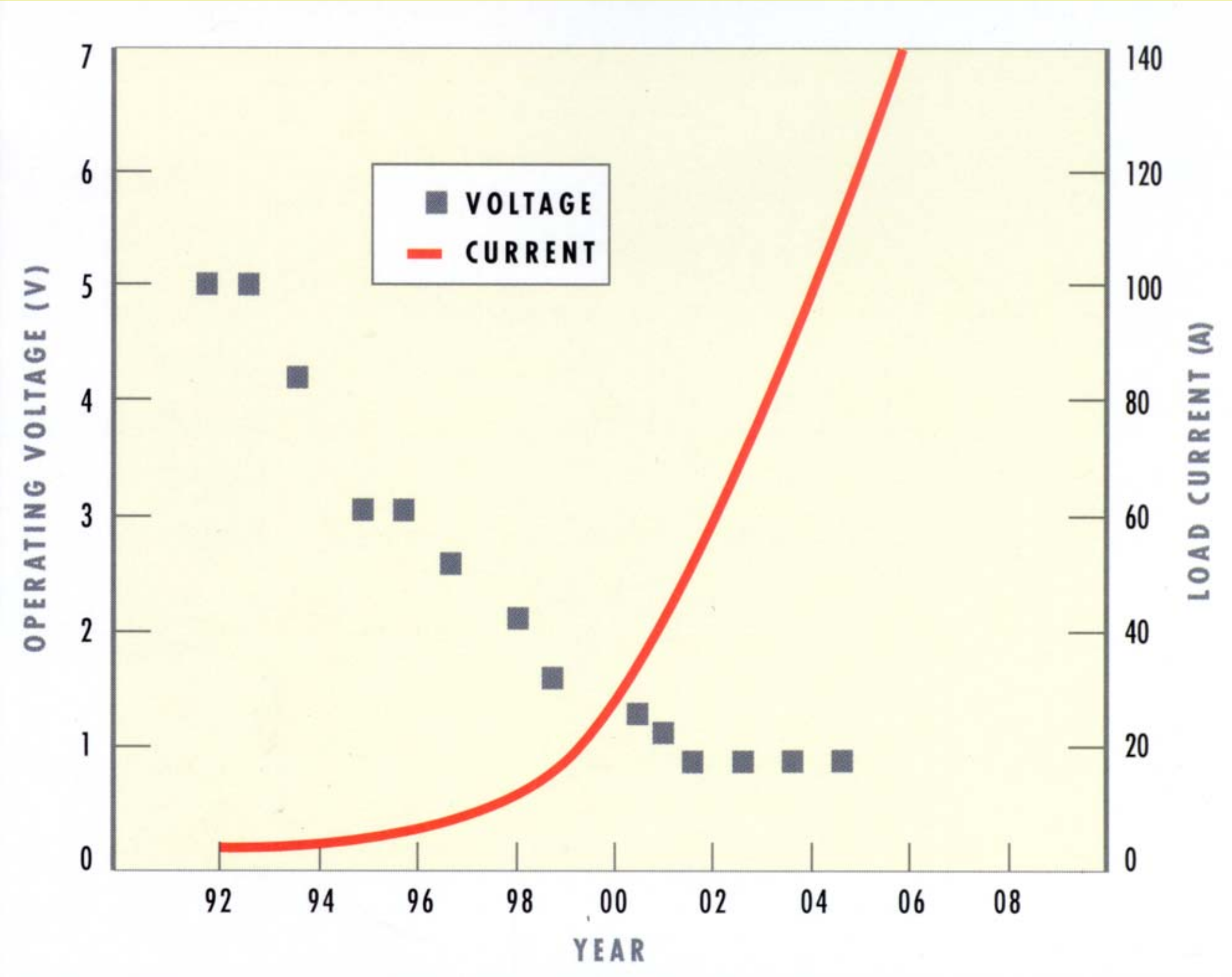
Automotive


Direct fuel injection
Active suspension
Electric throttle valve control
Brake-by-wire
Steer-by-wire
Electrically assisted power steering
42-V converter

Advanced SynQor Quarter-Brick

- •Ultra high efficiency, up to 91% at 3.3Vout
- •High current output, up to 40 amps
- •Industry standard size (1.45 x 2.3) and pin out
- •Low profile, only 0.4" (10.2mm) high
- •Low weight, 1.2 oz. (34g)
- •No heatsink, baseplate or potting materials required
- •Available in 48Vin and 24Vin

Synchronous Rectification



CPU Supply Specs

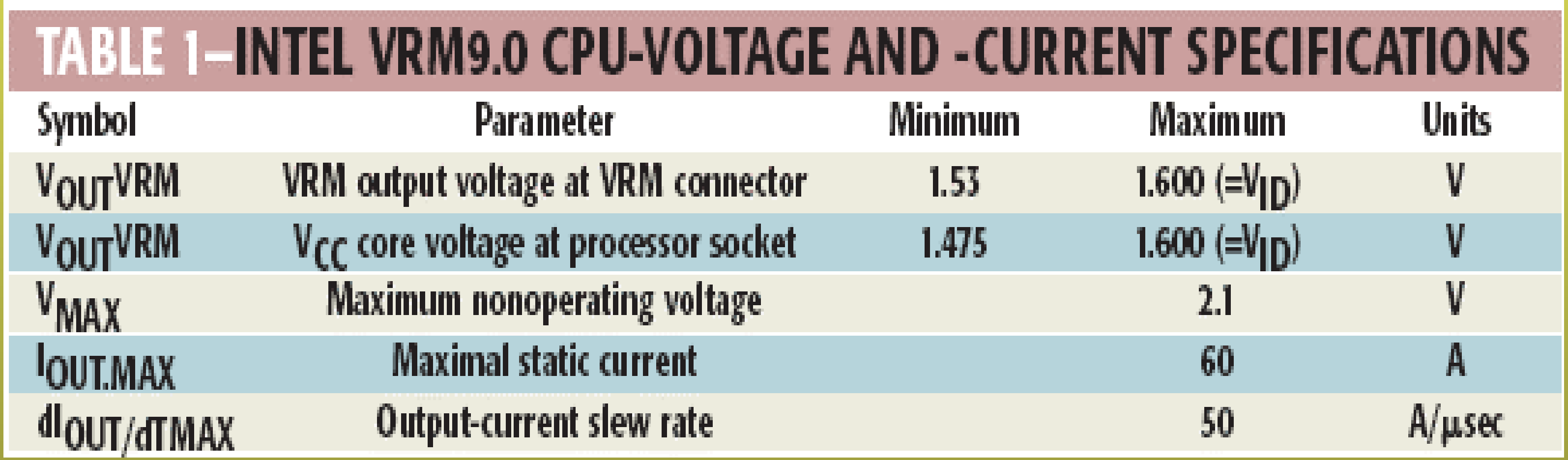
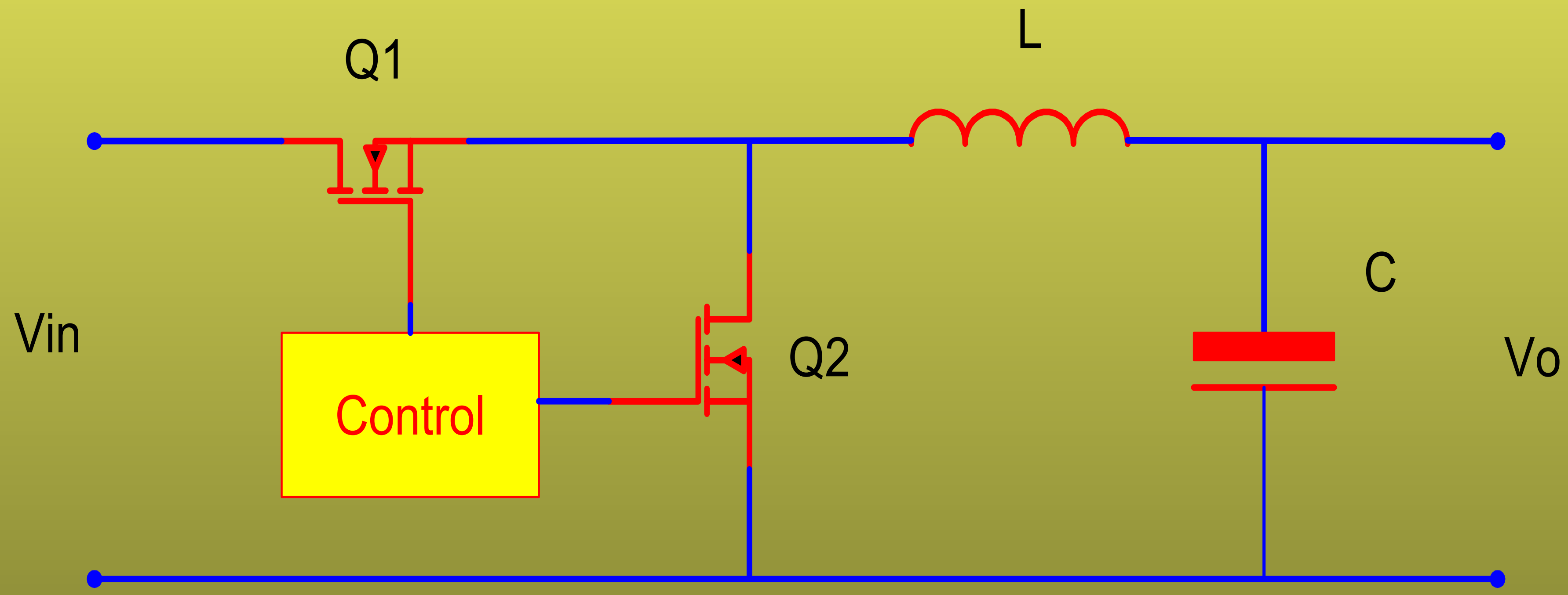


TABLE 1–INTEL VRM9.0 CPU-VOLTAGE AND -CURRENT SPECIFICATIONS

Symbol	Parameter	Minimum	Maximum	Units
V_{OUT}VRM	VRM output voltage at VRM connector	1.53	1.600 (=V_{ID})	V
V_{OUT}VRM	V_{CC} core voltage at processor socket	1.475	1.600 (=V_{ID})	V
V_{MAX}	Maximum nonoperating voltage		2.1	V
$I_{OUT.MAX}$	Maximal static current		60	A
$dI_{OUT/dTMAX}$	Output-current slew rate		50	A/µsec

Synchronous Buck Circuit

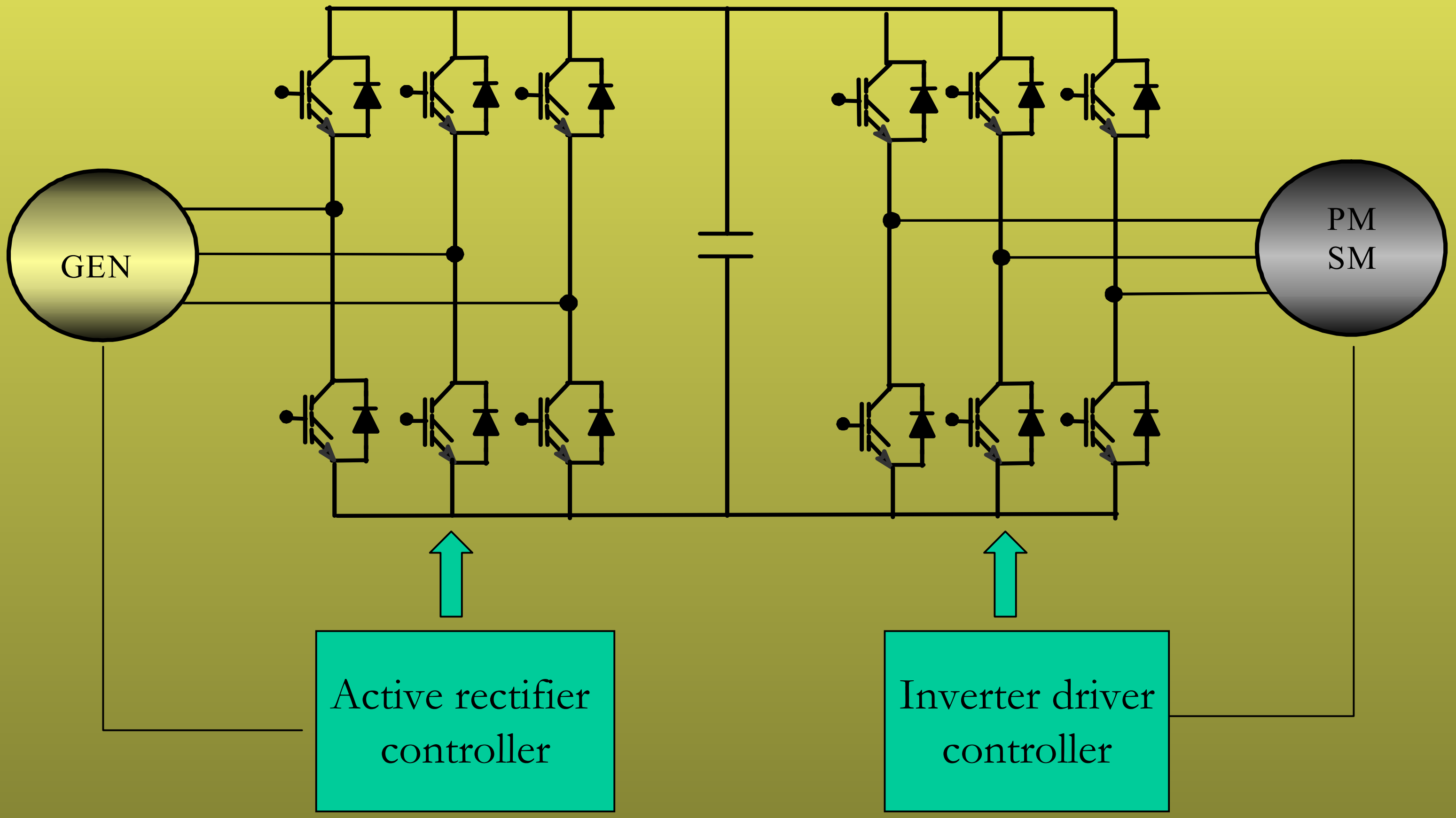


DC-AC Conversion (Inversion)

LTT Application in HVDC System

- Over 50% of electricity is consumed by motors
  - Domestic (Washing machine, Refrigerators, air conditioning..) < 2kW
  - Factory Automation – 100kw – MW
- Simple on/off wastes up to 50%

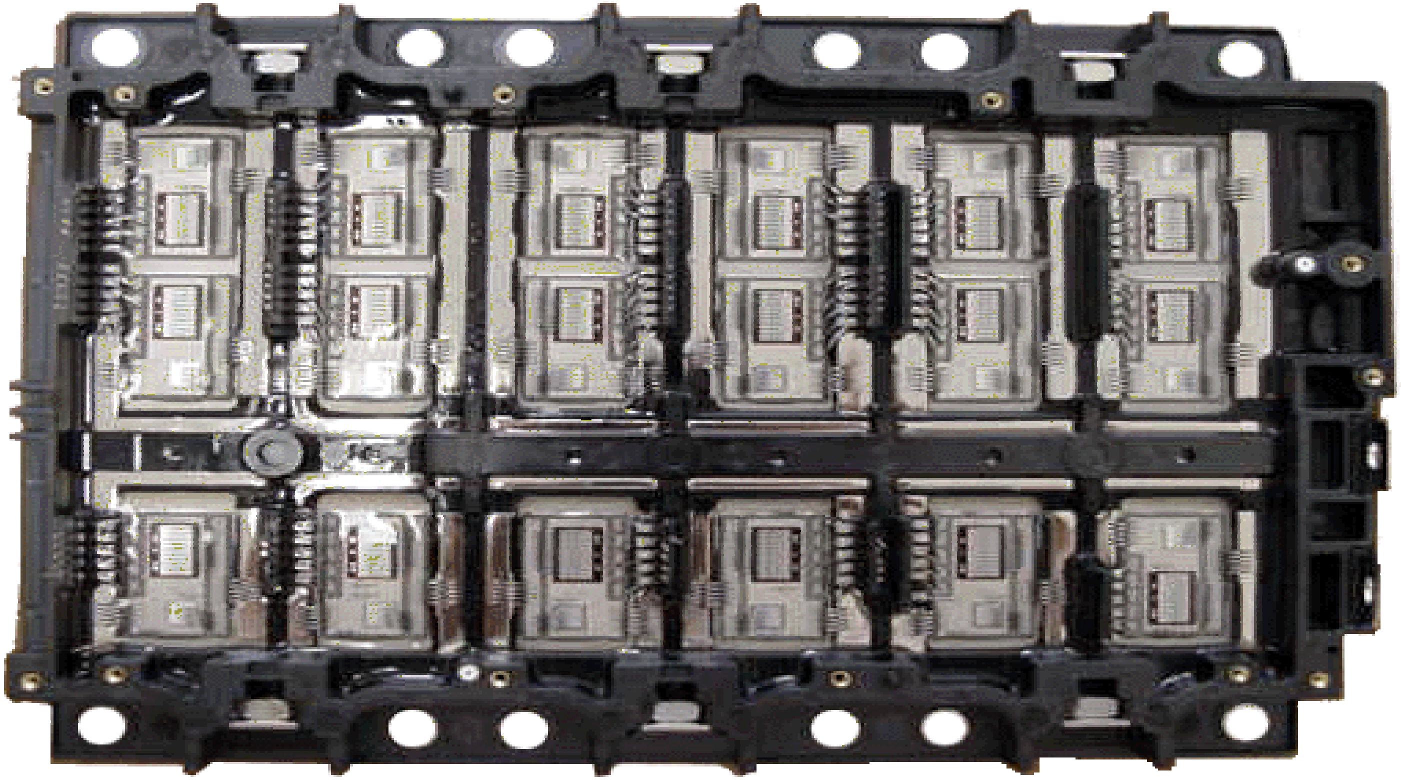
Application	**Units/yr**	**Ave power consumption**	**% Savings**	**Power Savings**
Fridge/Freezer	77.8M	700kWHr	60%	32.7B kWHr
Air Conditioning	31.5M	750kWHr	60%	14.2B kWHr
Washing Machine	55.6M	930kWHr	64%	33.1B kWHr



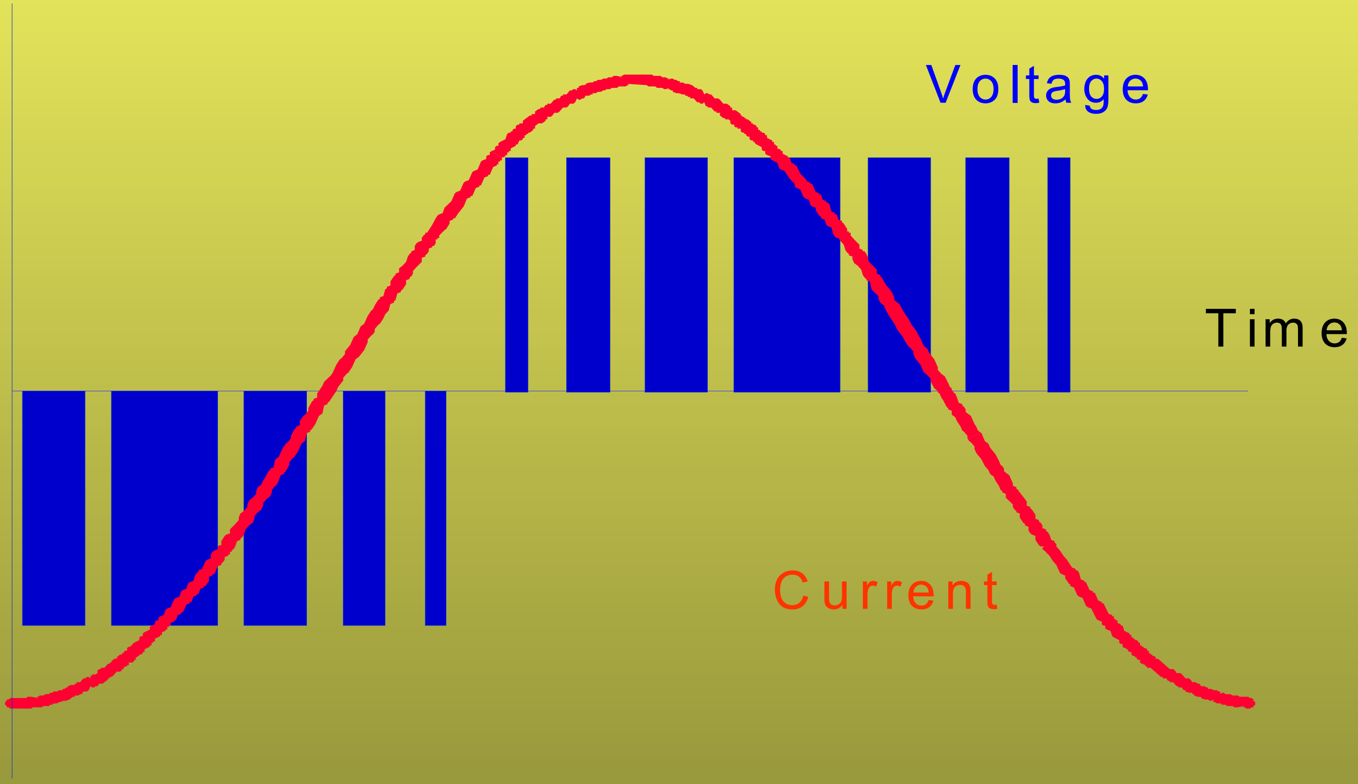
Active rectifier controller

Inverter driver controller

IPM

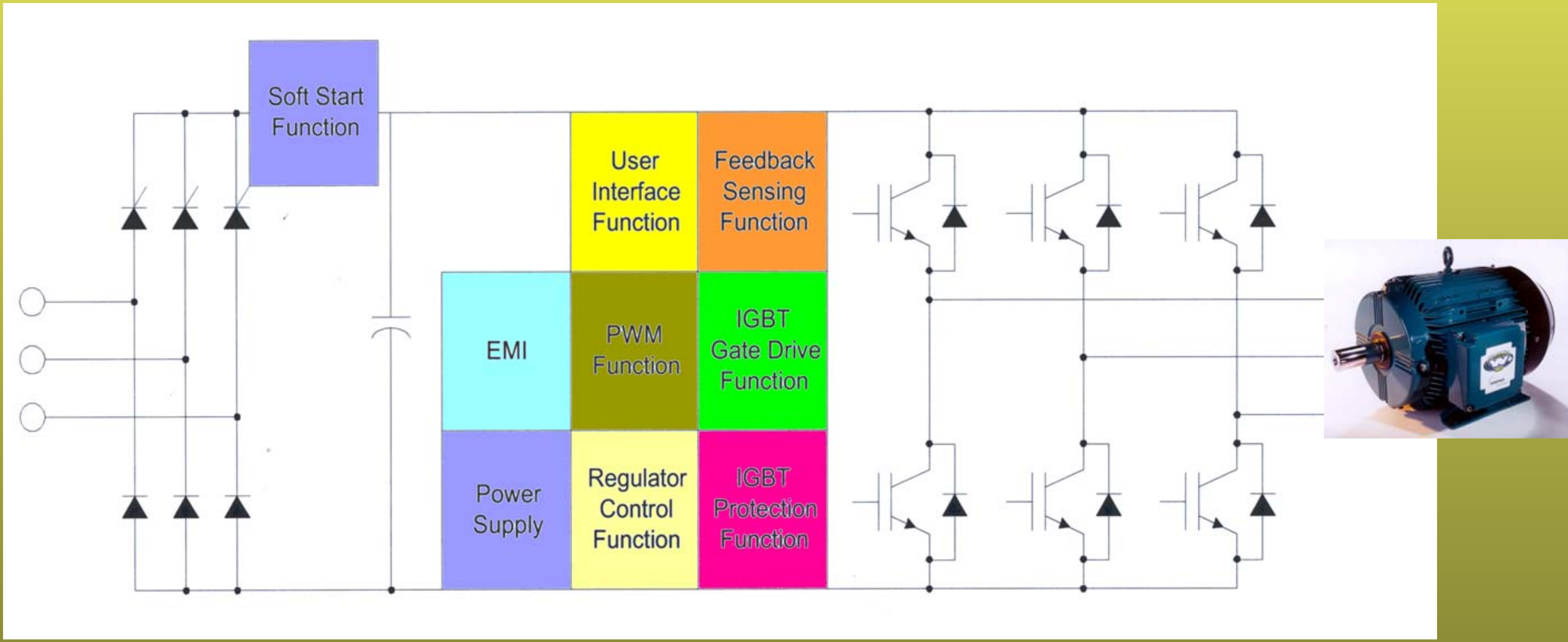


PWM VSI

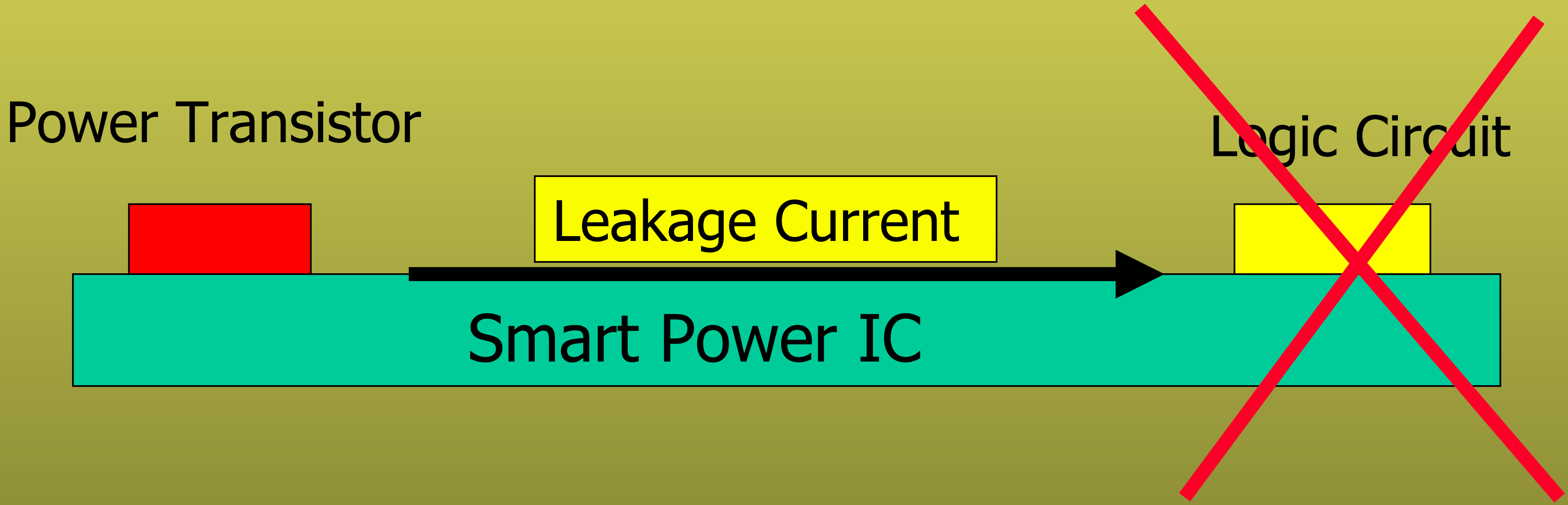


Simplified diagram showing the pulse width modulated output from an inverter drive.

Functional blocks in inverter

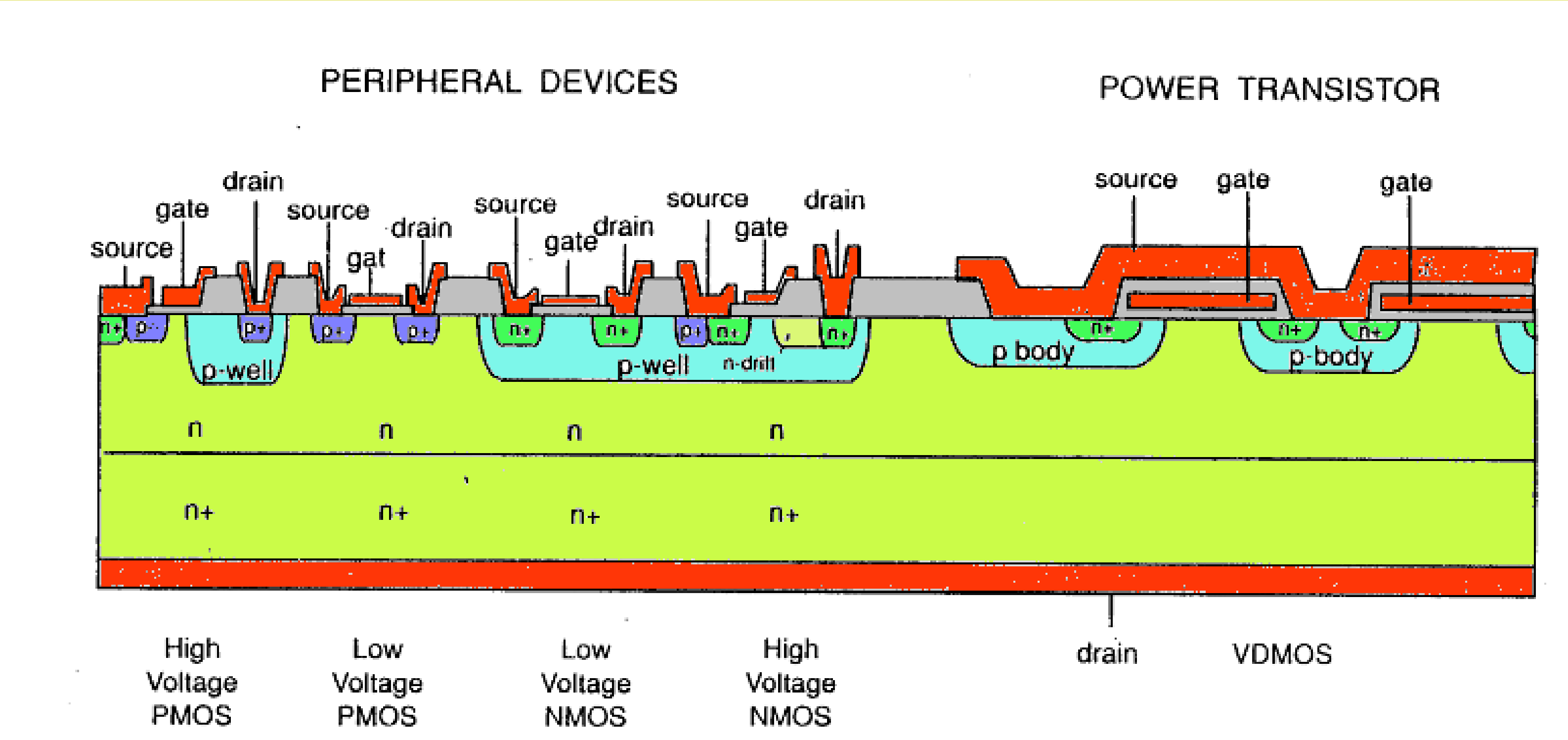


Devices and Isolations for PICs

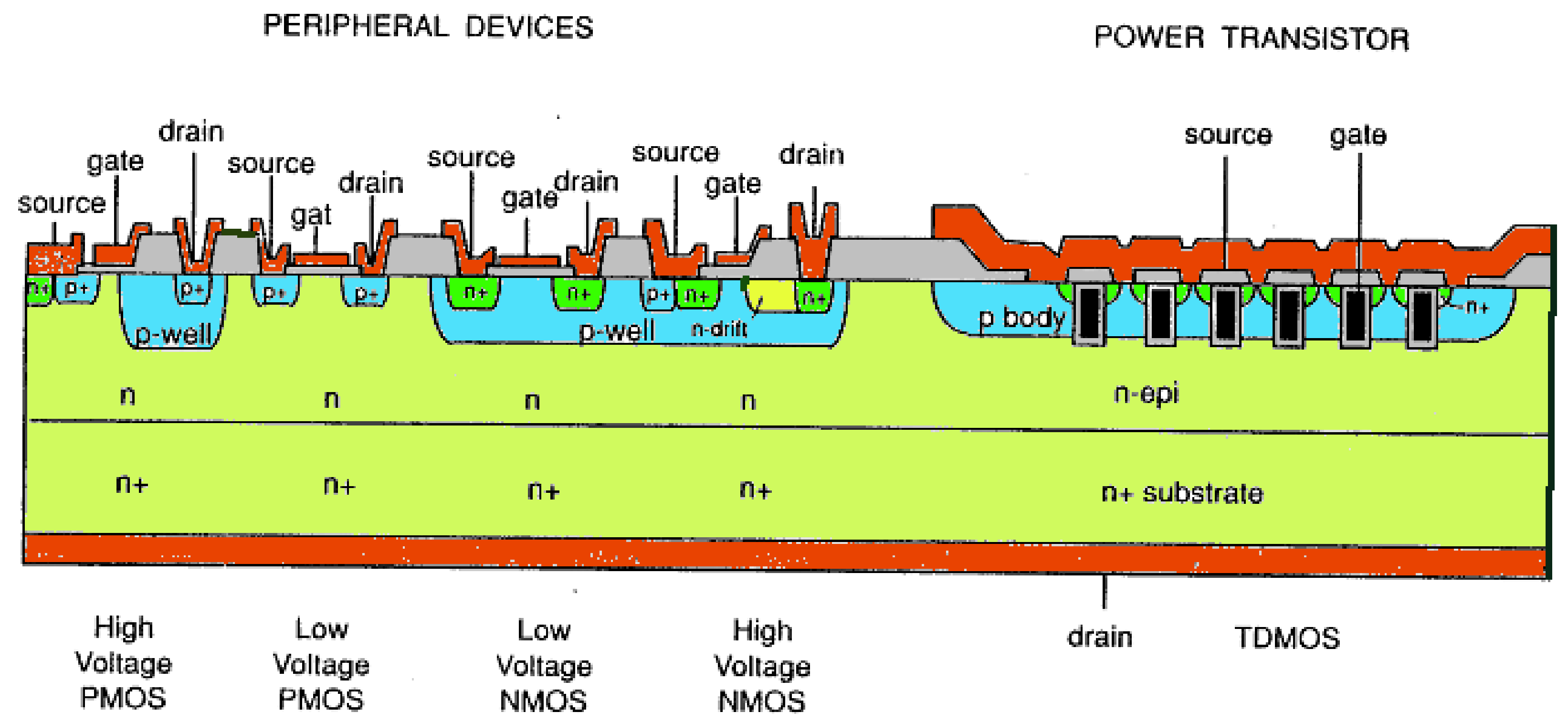


Devices and Isolations for PICs

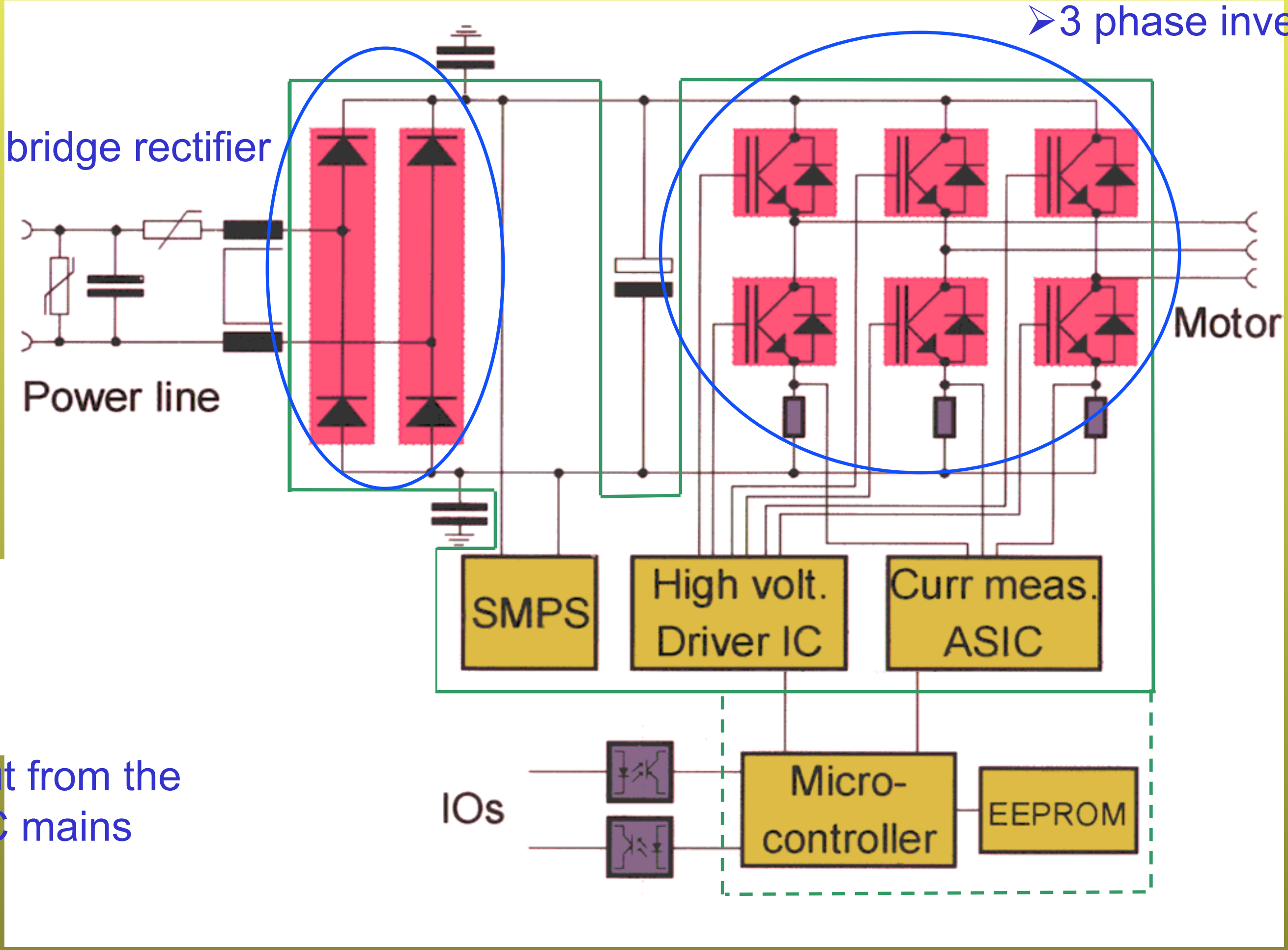
A High Current PIC Process with Dense CMOS and Power Switch



Cross-Section of a High Current PIC Process Incorporating Trench DMOS as the Power Switch

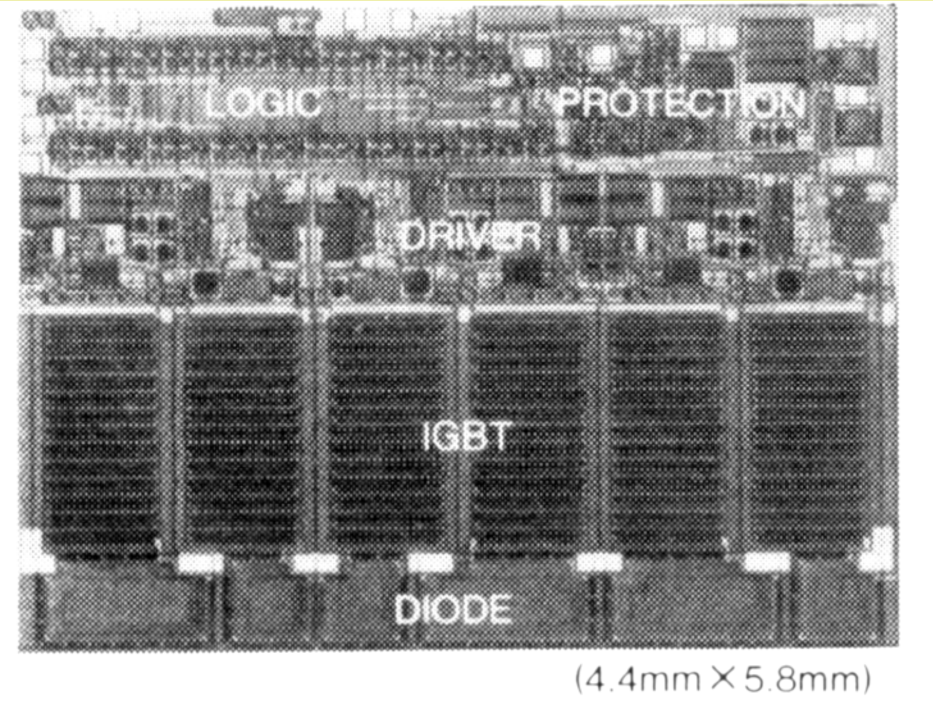


A Variable Frequency Electronic Drive for a 250 - 1kW Rated Electric Motor



- ➢Full bridge rectifier
- ➢3 phase inverter
- ➢3 phase output from the single phase AC mains

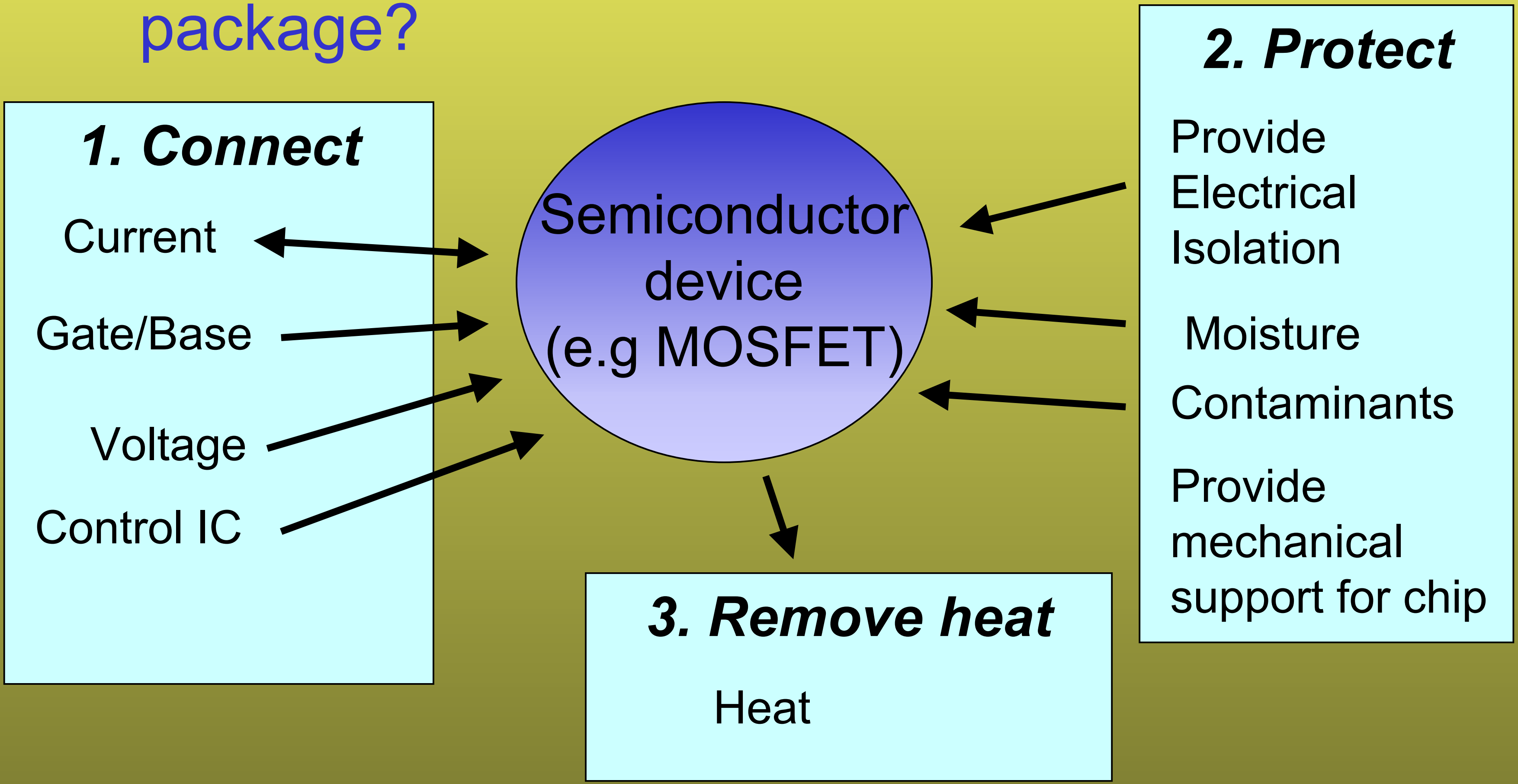
Power Integrated Circuit for Motor Control Marketed by Hitachi (only Available in Japan)



Features: 250V, 1A

Packaging

- What are the key functions of an electronic package?



1. Connect

Current

Gate/Base

Voltage

Control IC

Semiconductor device (e.g MOSFET)

2. Protect

Provide Electrical Isolation

Moisture

Contaminants

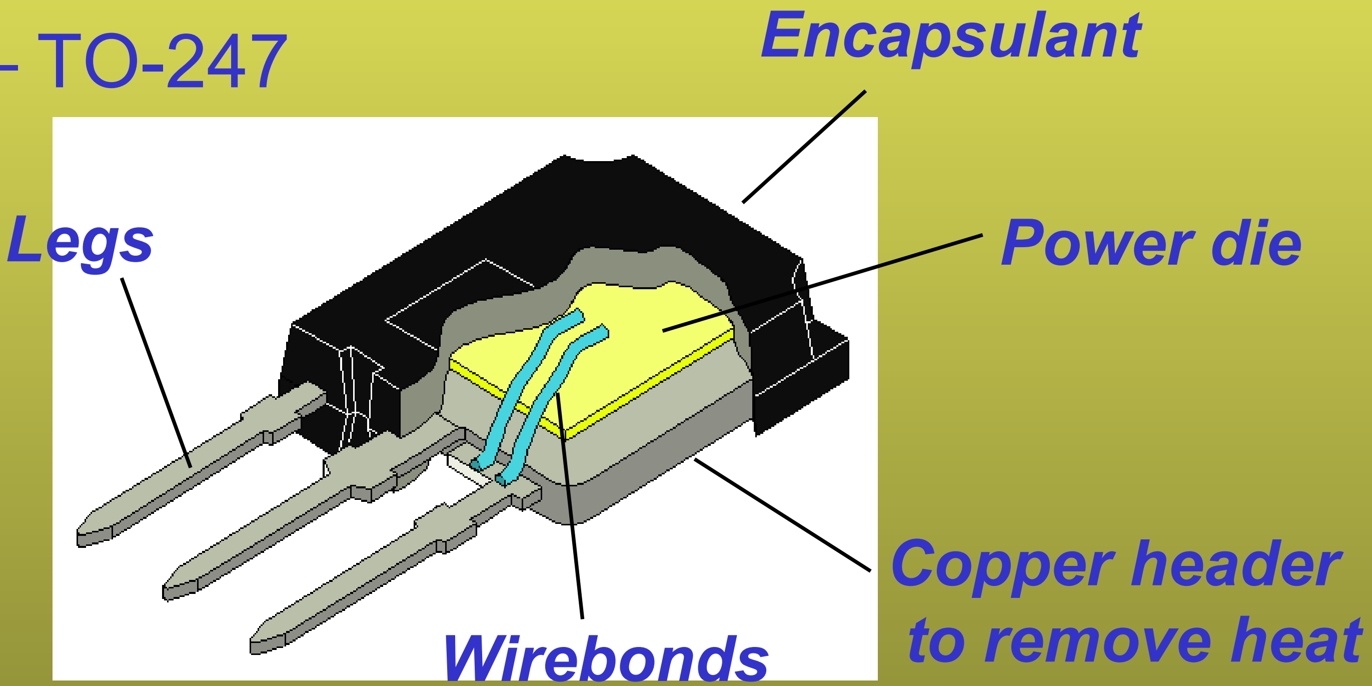
Provide mechanical support for chip

3. Remove heat

Heat

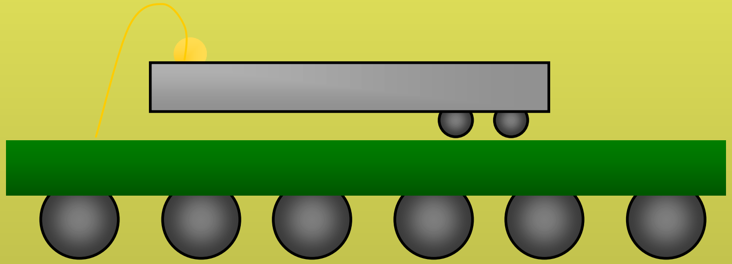
power electronic package

- Plastic encapsulated package
  - TO-247

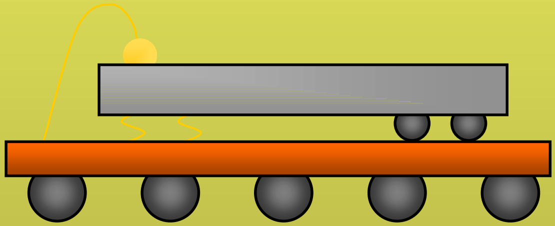


Packages defined

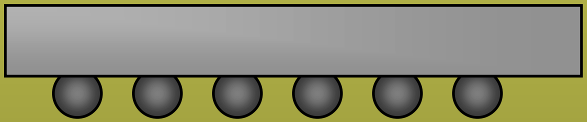
Examples of IC packaging technology



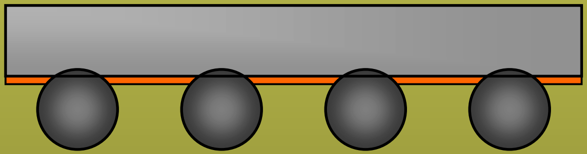
BGA:- Ball grid array



CSP- Chip Scale Package



Flip Chip

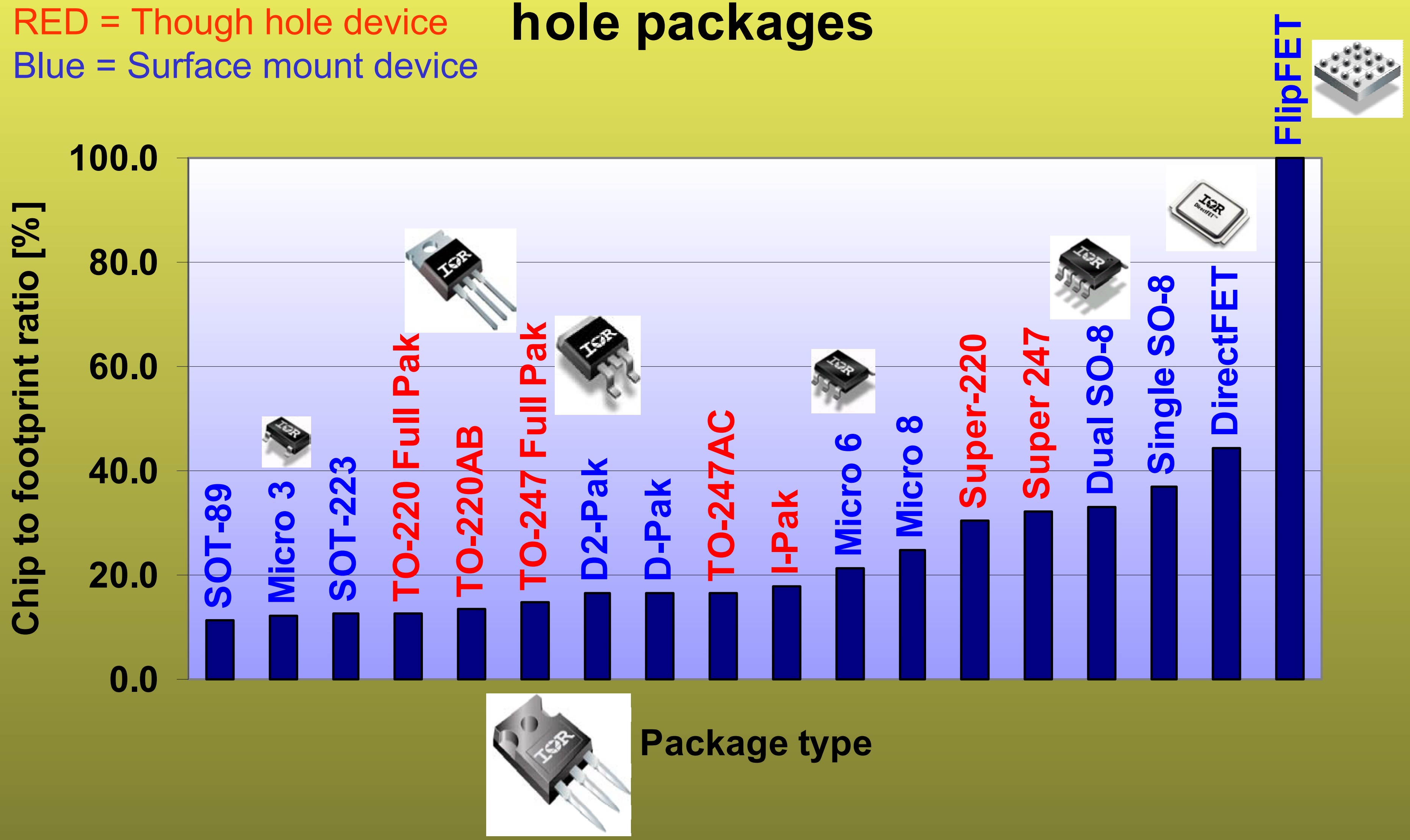


WLP-Wafer level package

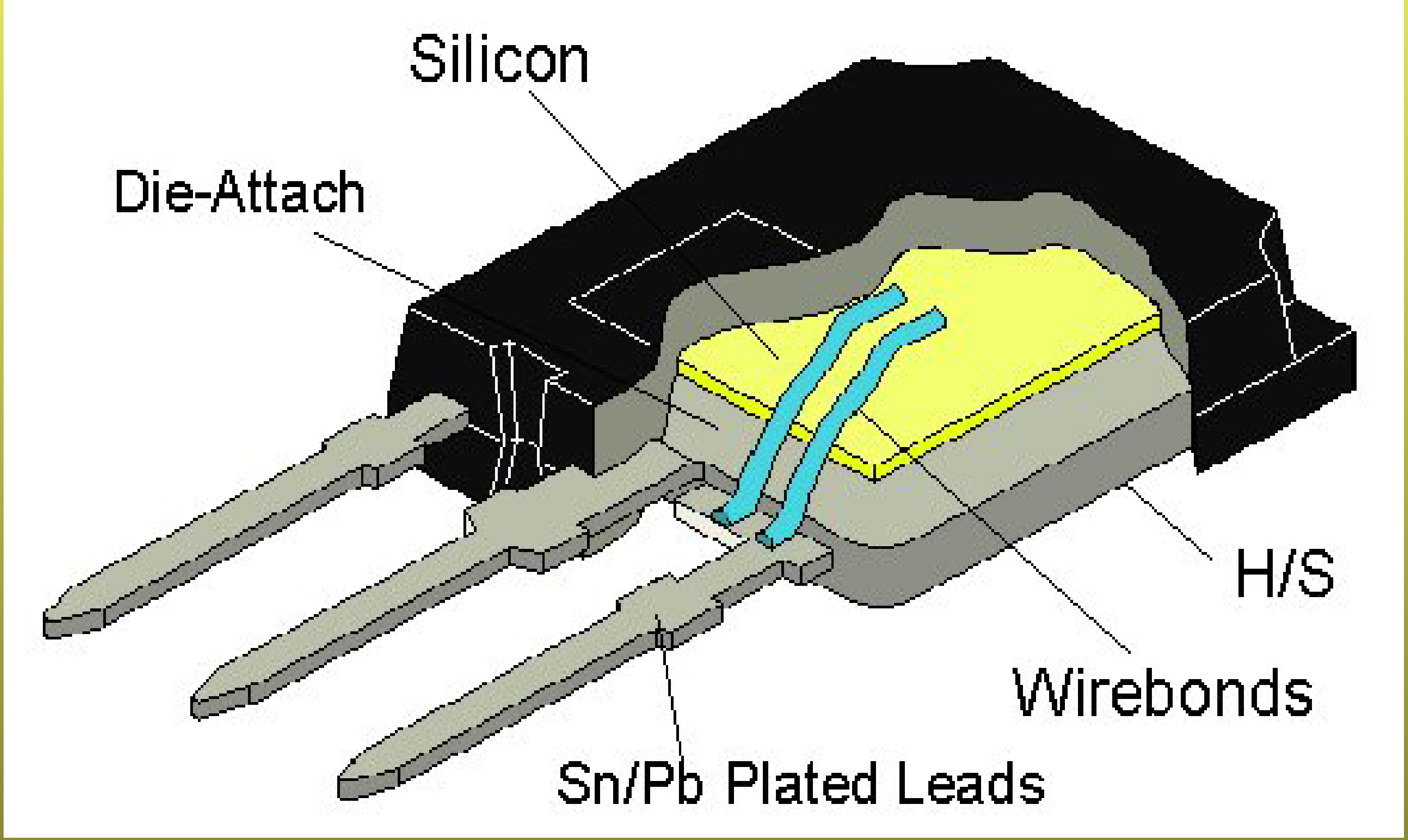
Strong focus on high I/O count, space saving and low inductance packaging

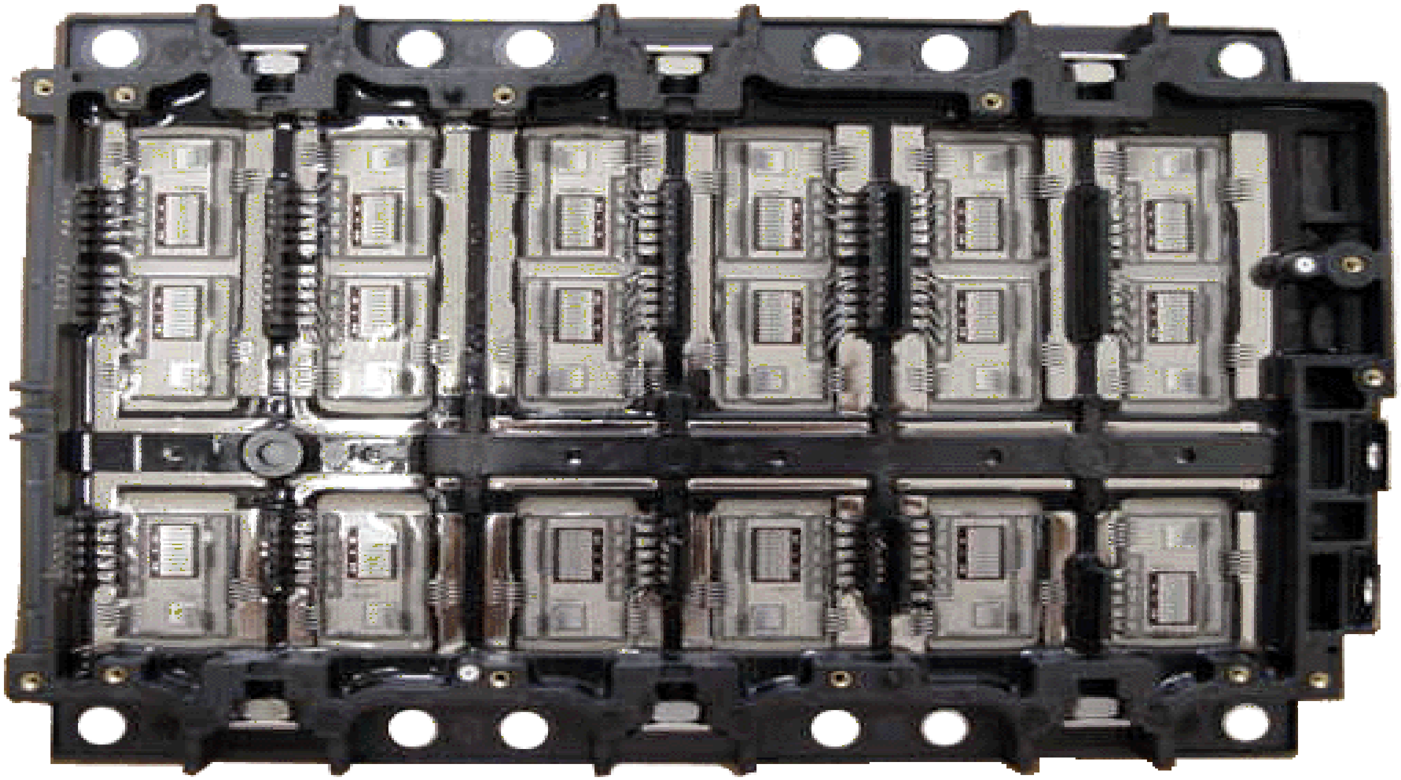
Chip to Footprint ratio for SMD and through hole packages

RED = Though hole device
Blue = Surface mount device



12. Construction of Power Semiconductors

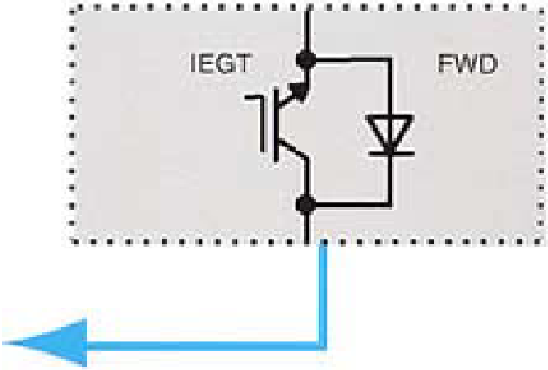




- Low losses with smaller snubber circuit
- Low gate power based on voltage driven MOS (Metal Oxide Semiconductor) gate
- Fast switching speed

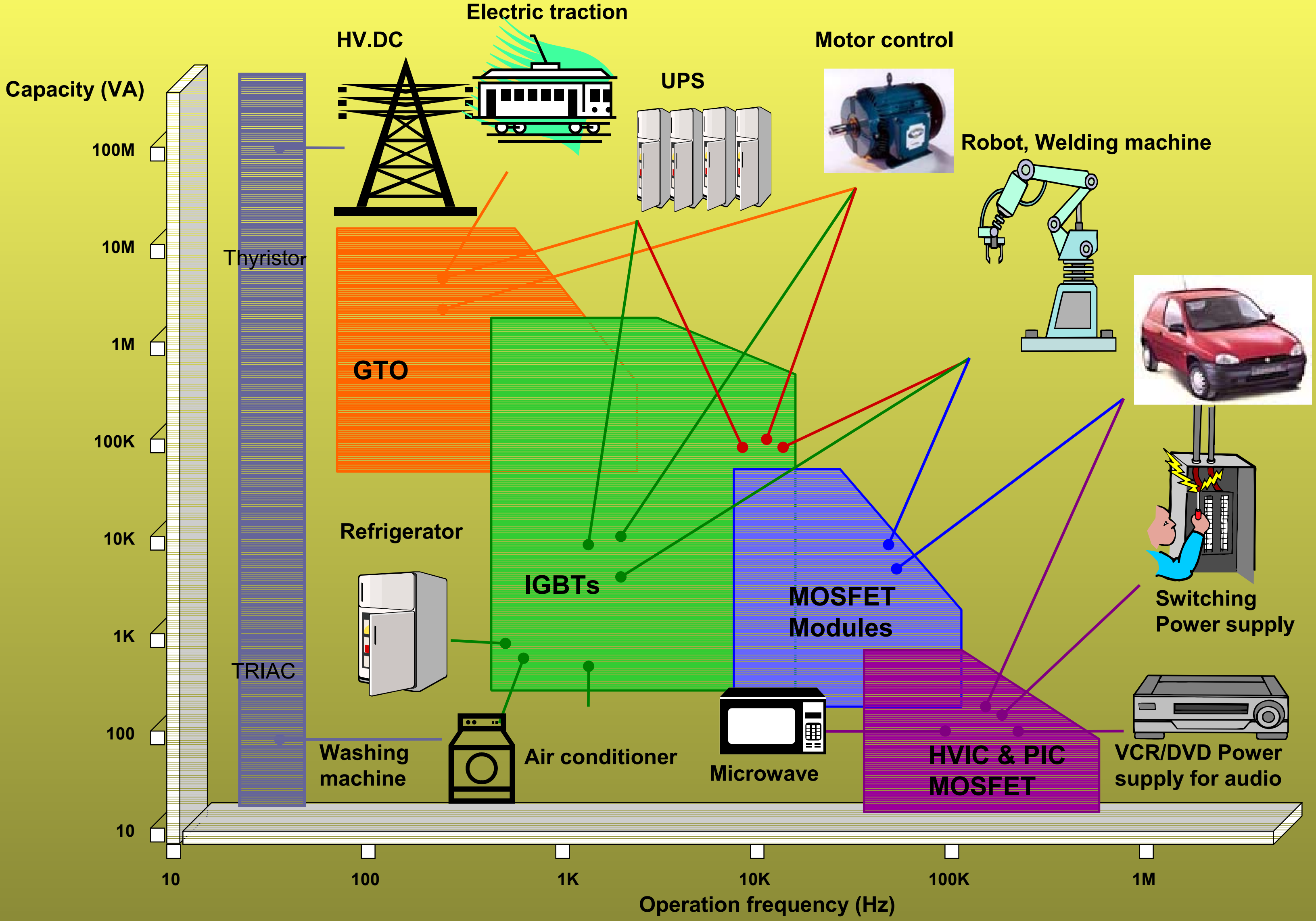
Outside View of IEGT

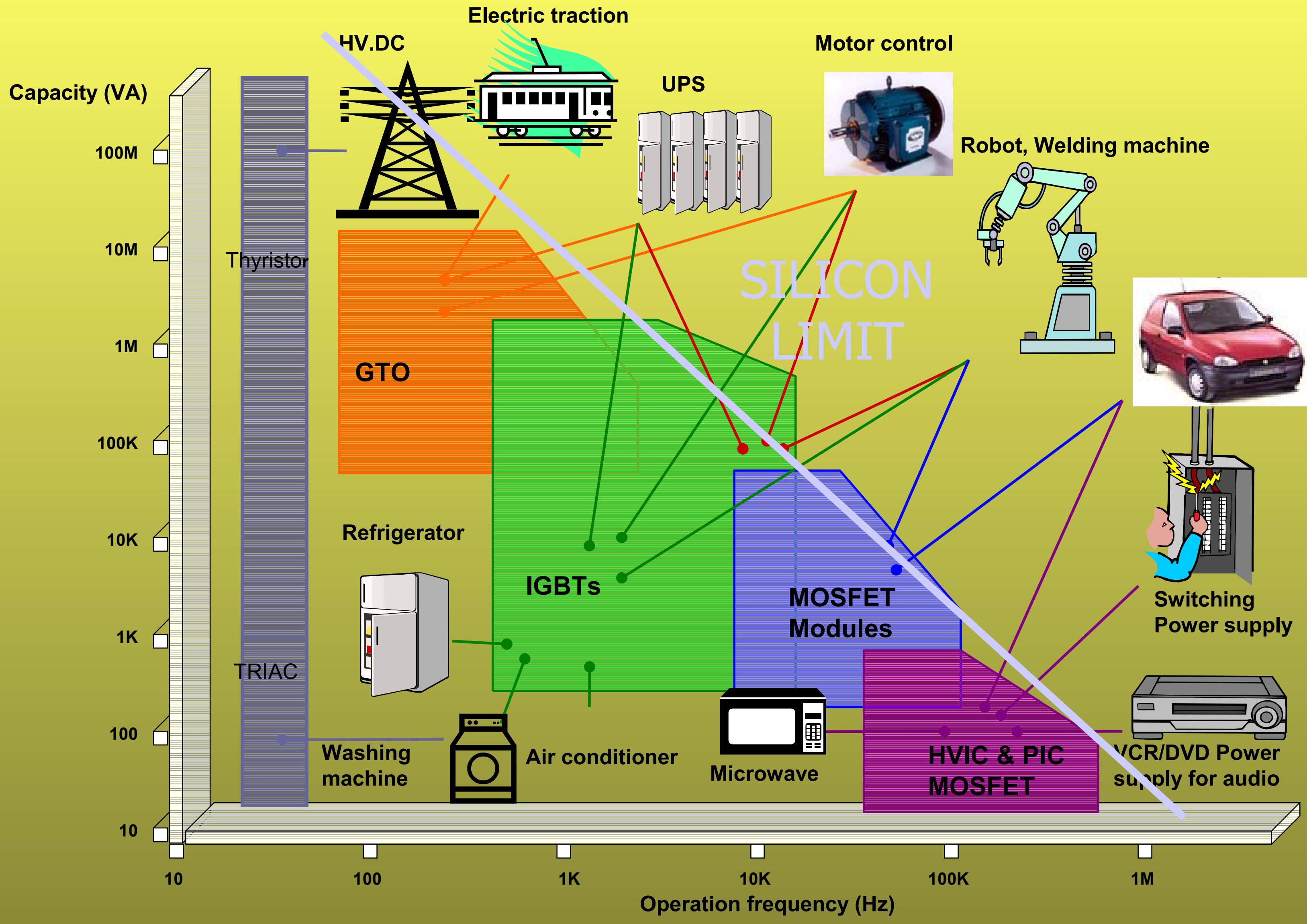
FWD chips are included in the IEGT shell.

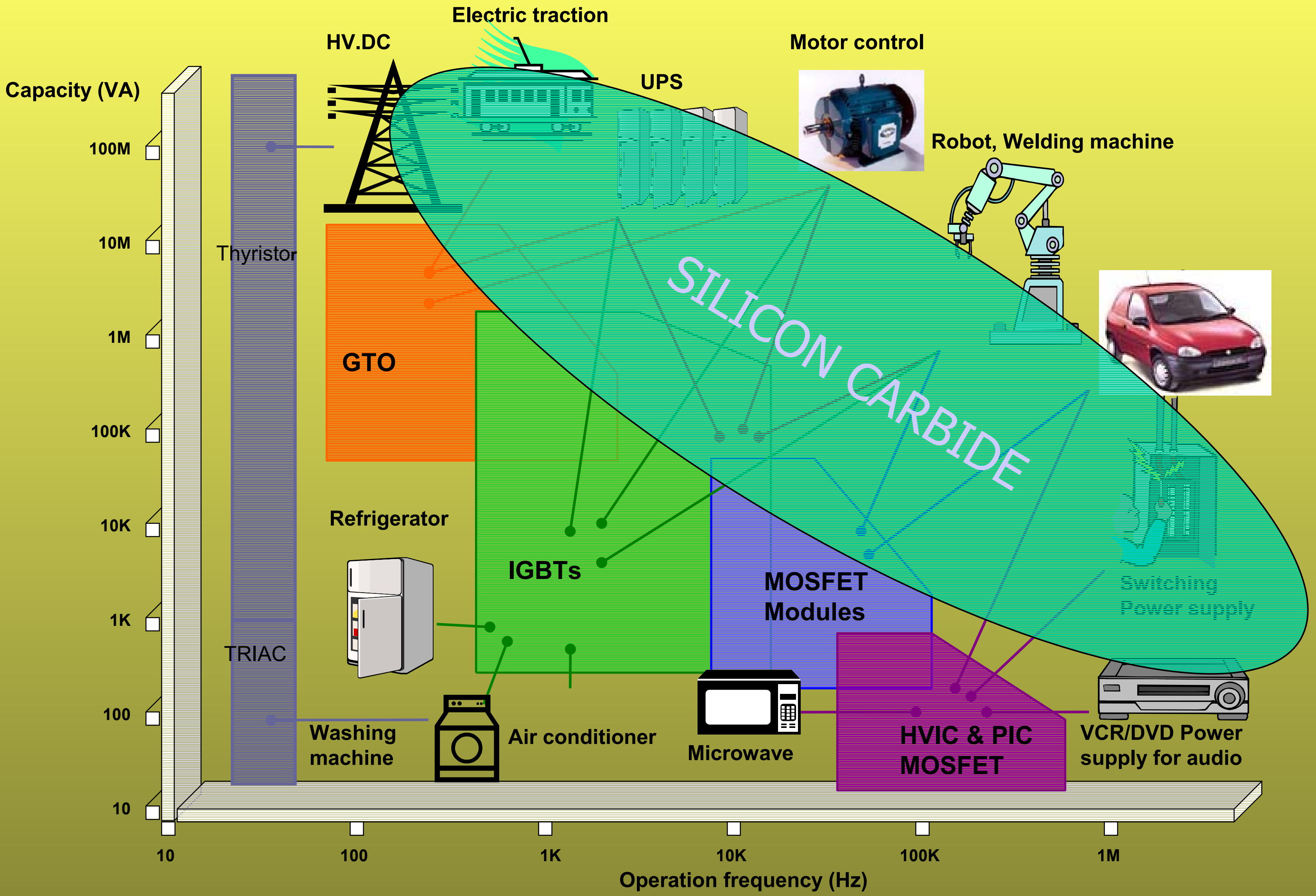


FWD : Free Wheeling Diode

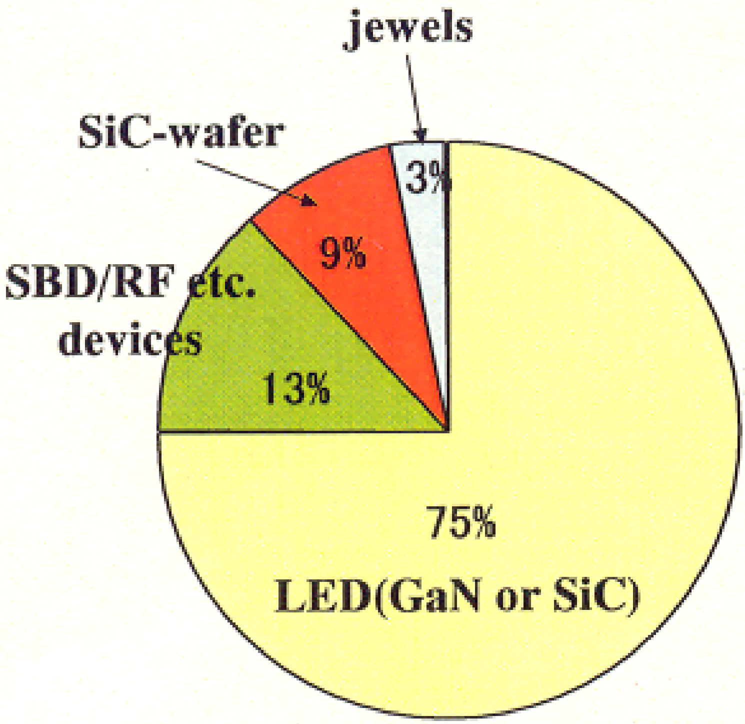
Silicon Carbide Power Devices

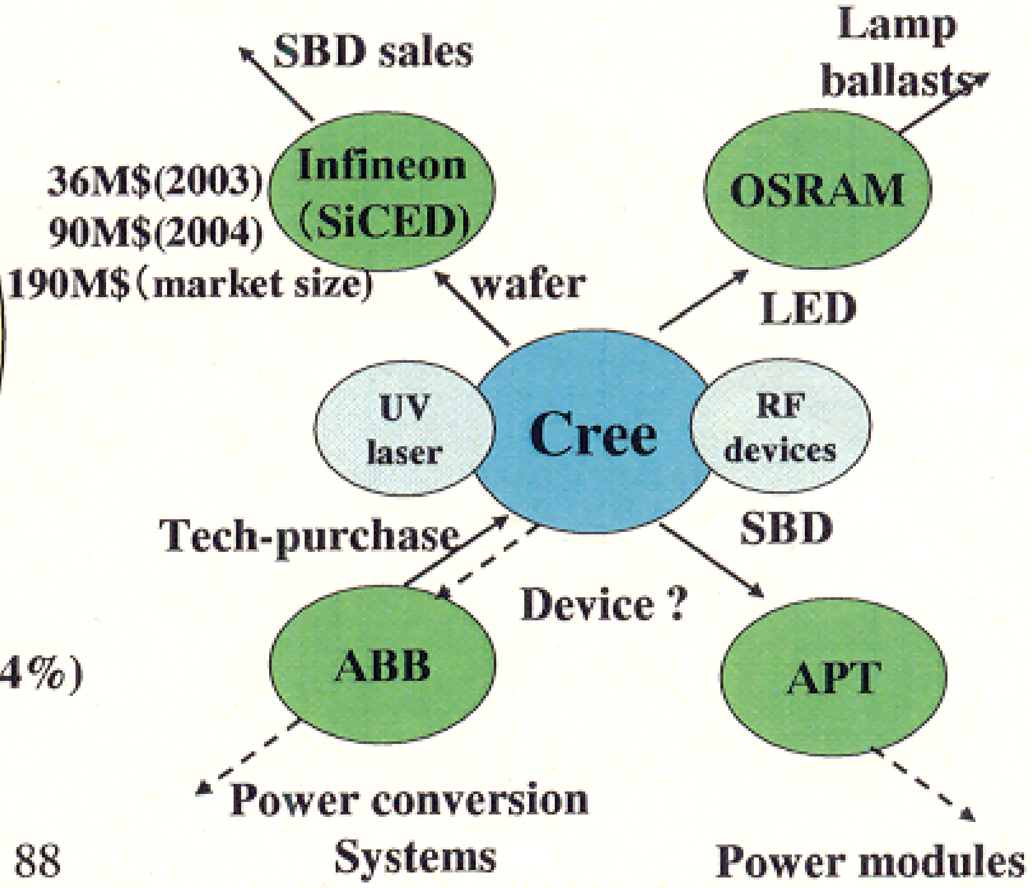

Capacity (VA)
100M
10M
1M
100K
10K
1K
100
10
HV.DC
Electric traction
UPS
Motor control
Robot, Welding machine
Thyristor
GTO
Refrigerator
IGBTs
MOSFET
Modules
Switching
Power supply
TRIAC
Washing
machine
Air conditioner
Microwave
HVIC & PIC
MOSFET
VCR/DVD Power
supply for audio
10
100
1K
10K
100K
1M
Operation frequency (Hz)


Capacity (VA)
100M
10M
1M
100K
10K
1K
100
10
Thyristor
TRIAC
HV.DC
Electric traction
UPS
Motor control
Robot, Welding machine
SILICON LIMIT
GTO
IGBTs
MOSFET Modules
HVIC & PIC MOSFET
Refrigerator
Washing machine
Air conditioner
Microwave
Switching Power supply
VCR/DVD Power supply for audio
10
100
1K
10K
100K
1M
Operation frequency (Hz)


Capacity (VA)
100M
10M
1M
100K
10K
1K
100
10
Thyristor
TRIAC
HV.DC
Electric traction
UPS
Motor control
Robot, Welding machine
GTO
SILICON CARBIDE
Refrigerator
IGBTs
MOSFET Modules
Switching Power supply
Washing machine
Air conditioner
Microwave
HVIC & PIC MOSFET
VCR/DVD Power supply for audio
10
100
1K
10K
100K
1M
Operation frequency (Hz)

Trends of CREE Co. (2003) http://www.cree.com





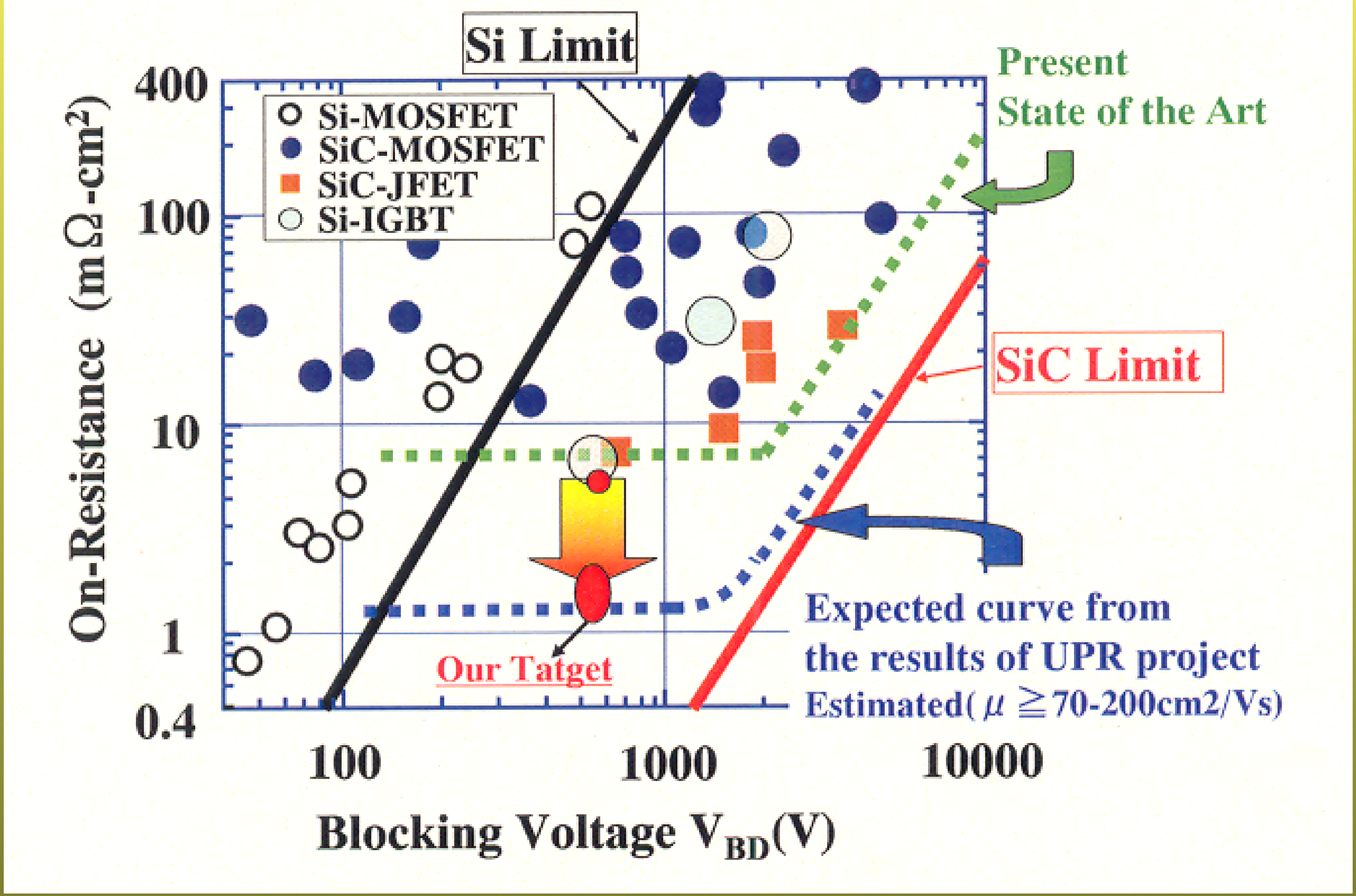
Sales ; 218M$ (profit-rate >14%)

Employee ; 1221 peaple
products; 865
research; 168
business/manage; 88

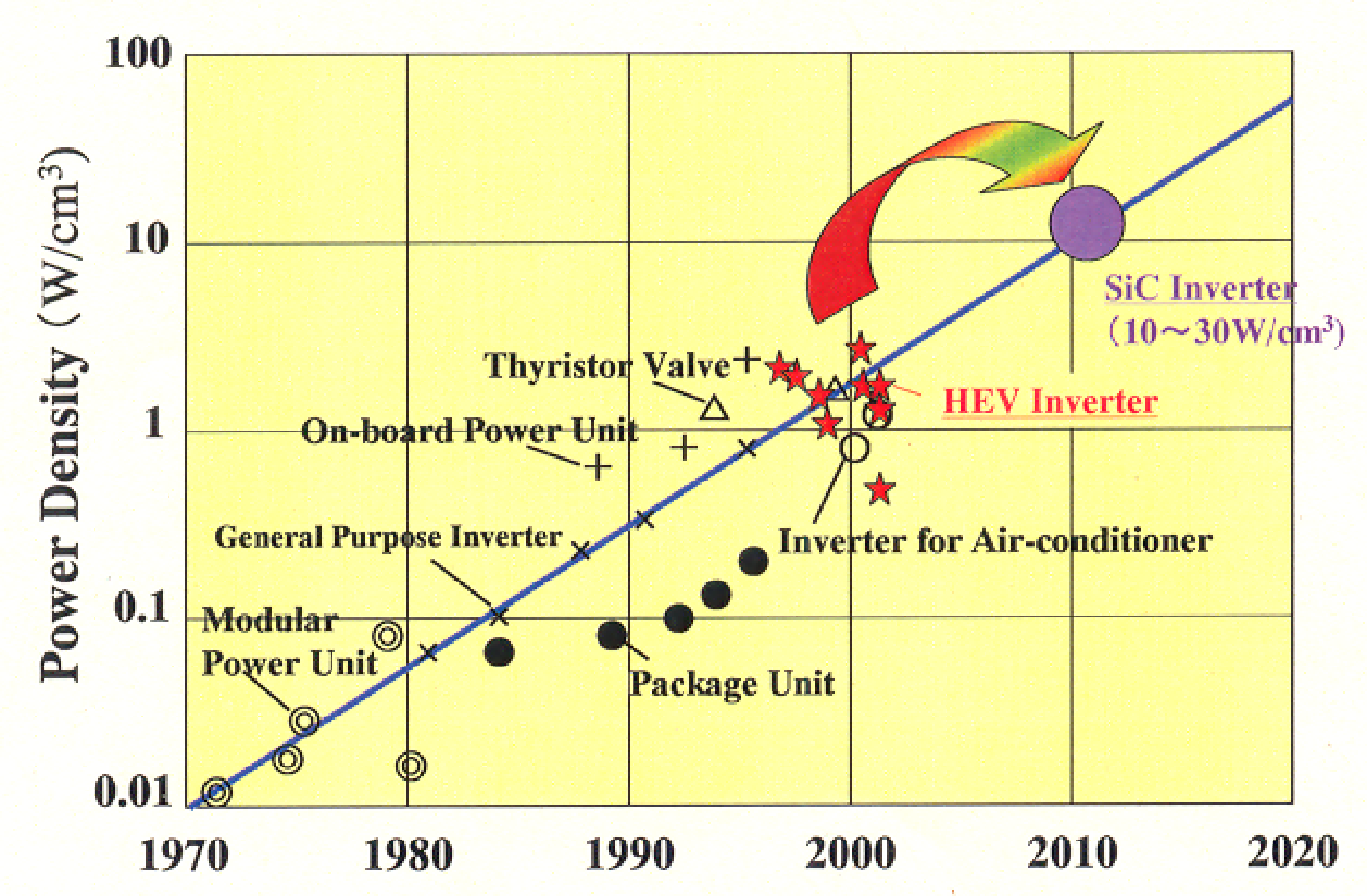
Patents ; 207(USP), 98(Wo)

SiC Applications

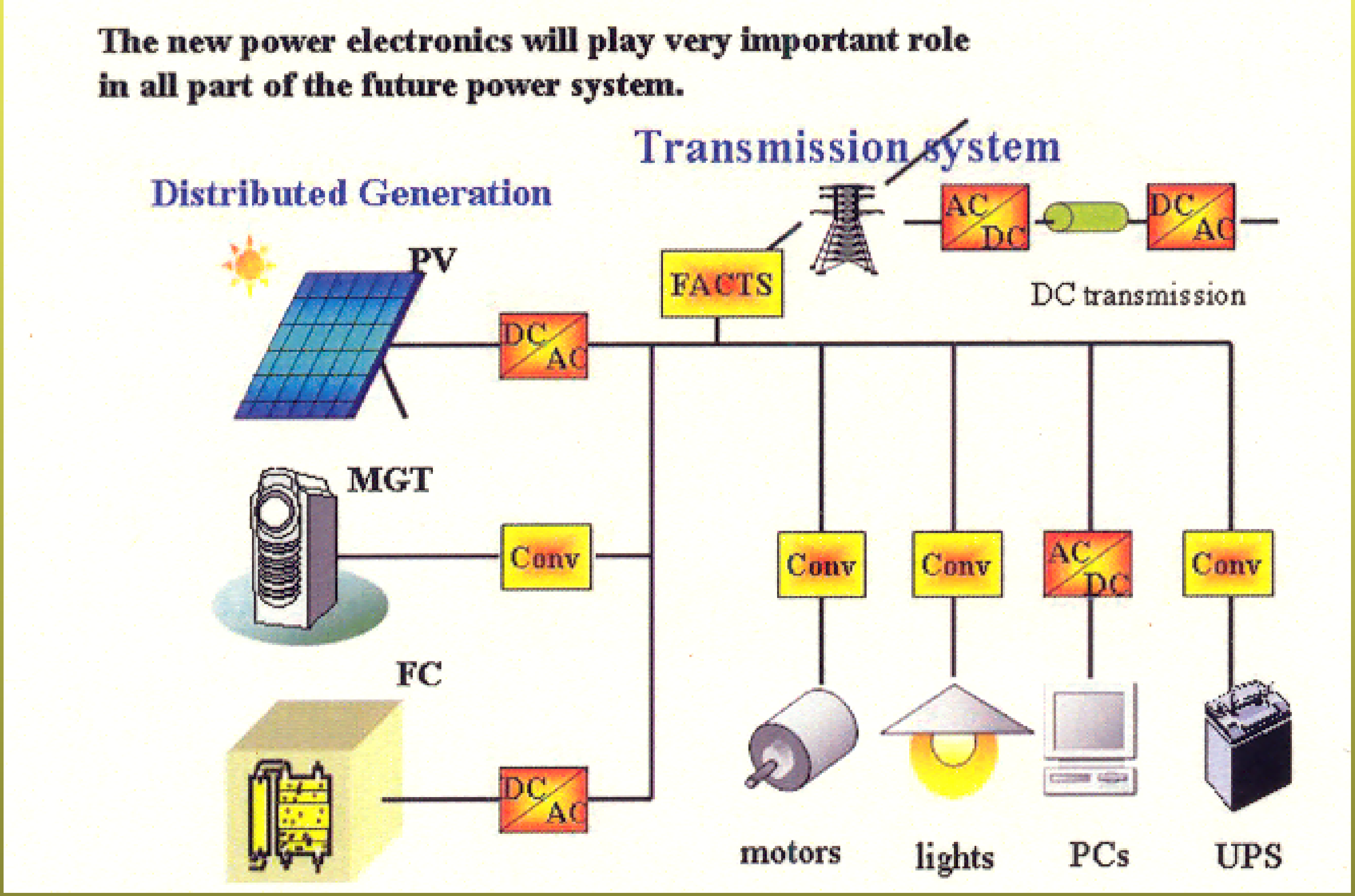
On-state limit for Switching Devices



Trend for power density in power converters



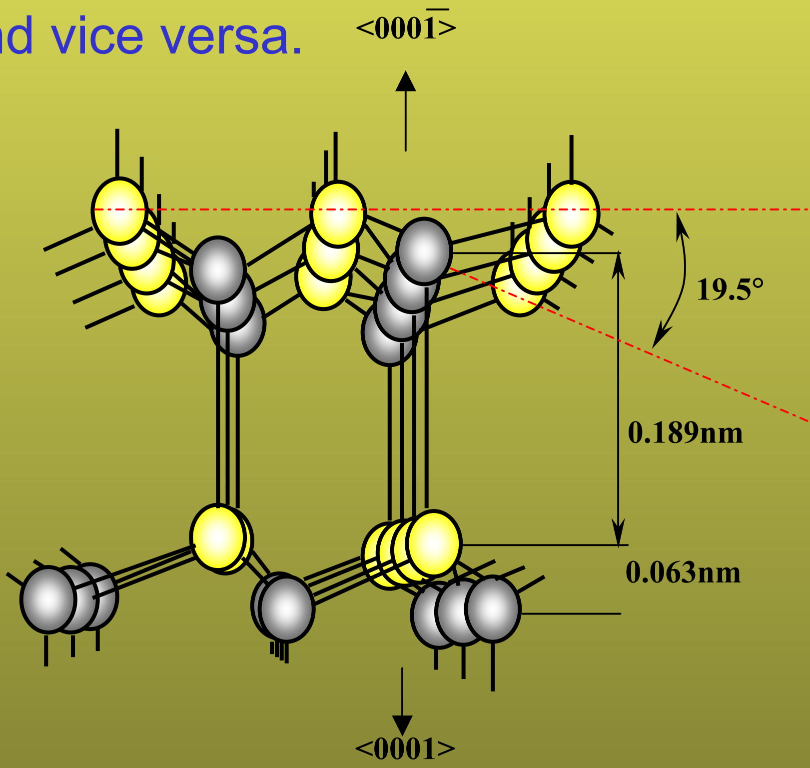
Power Systems in the Future

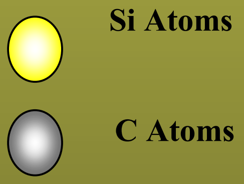


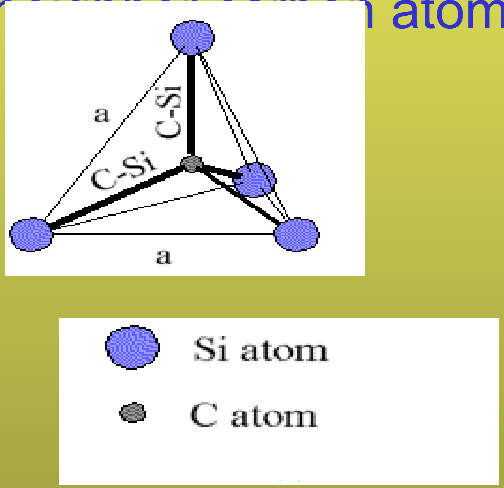
The new power electronics will play very important role in all part of the future power system.

What is Silicon Carbide ?

- Silicon Carbide (SiC) exists in several hundred forms known as polytypes.
- Each silicon atom bonds to four nearest-n n atoms, and vice versa.







SiC Polytypes

- Crystal structure dictates the polytype or form of SiC.
- Difference between polytypes is the stacking order between double layers of carbon and silicon atoms.

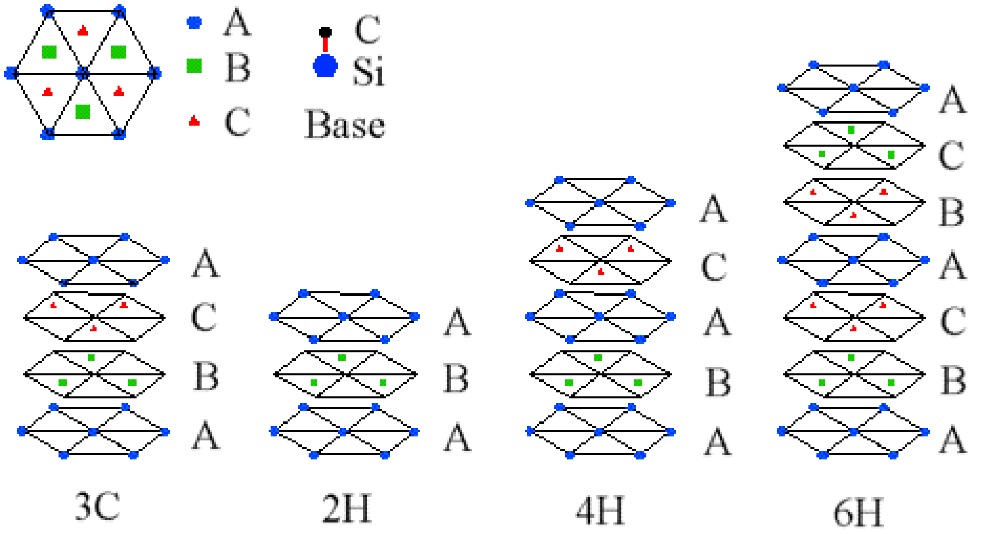


Fig. 5. The stacking sequence of double layers of the three most common SiC polytypes.

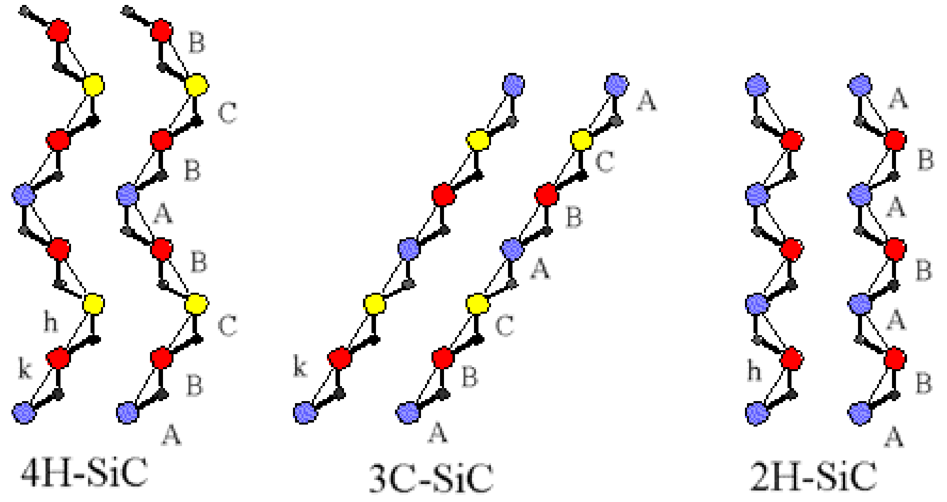


Fig. 7. The [11$\bar{2}$0] plane of the 4H-, 3C-, and 2H-SiC polytypes.

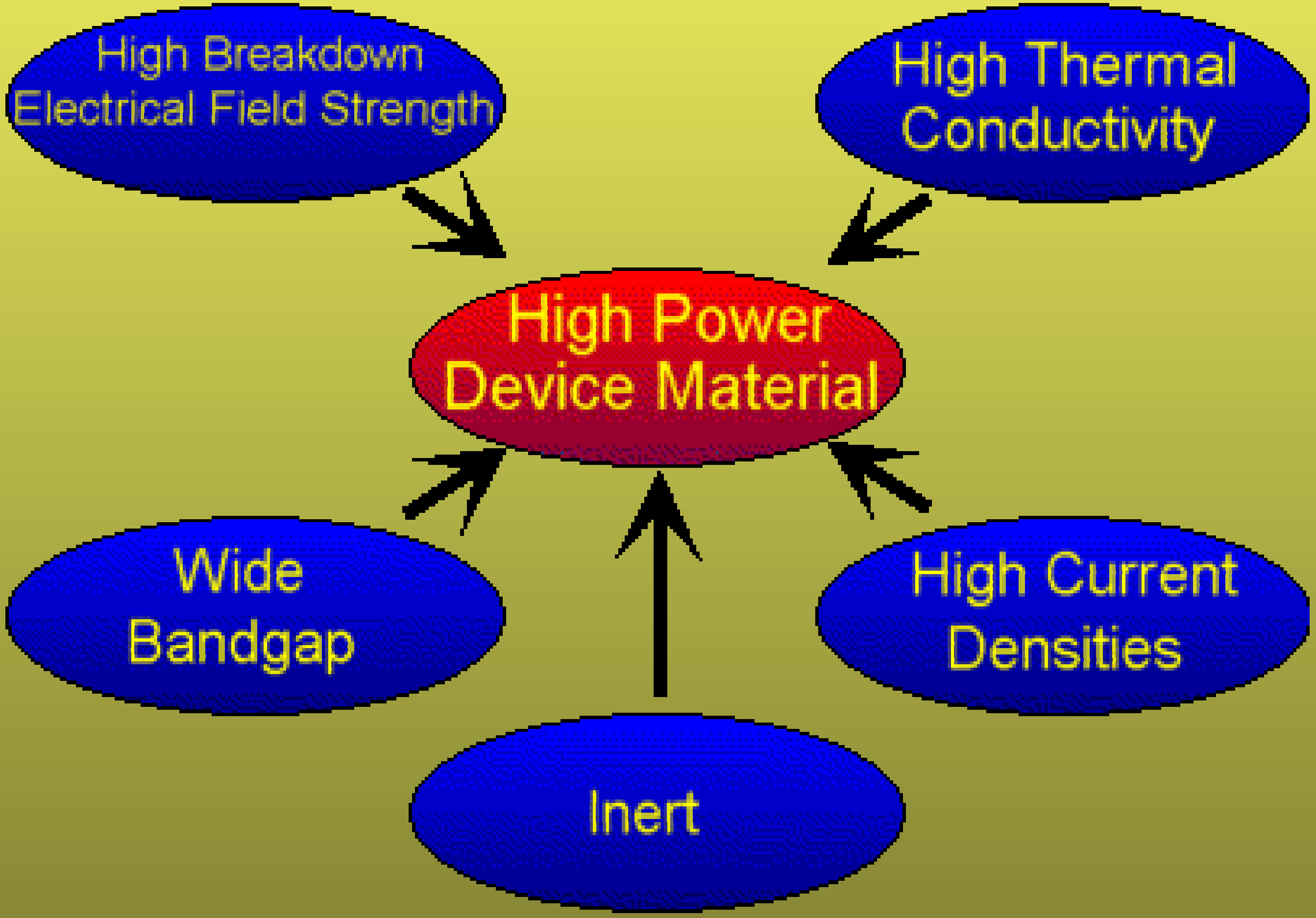
Alternatives to Silicon Technology

- Wide Band Gap Semiconductors
    - Stronger Atomic Bonds
    - Larger Breakdown voltage
    - Lower intrinsic carrier concentration

- GaN - poor thermal conductivity, no native oxide, high frequency?
- C (diamond) - No established technology at present
    - Other WBG materials like Diamond and III/V nitrides suffer from the lack of suitable substrates for epitaxial growth.

- SiC - Relatively mature technology, native oxide, blue light

Properties of SiC



High Breakdown Electrical Field Strength

High Thermal Conductivity

High Power Device Material

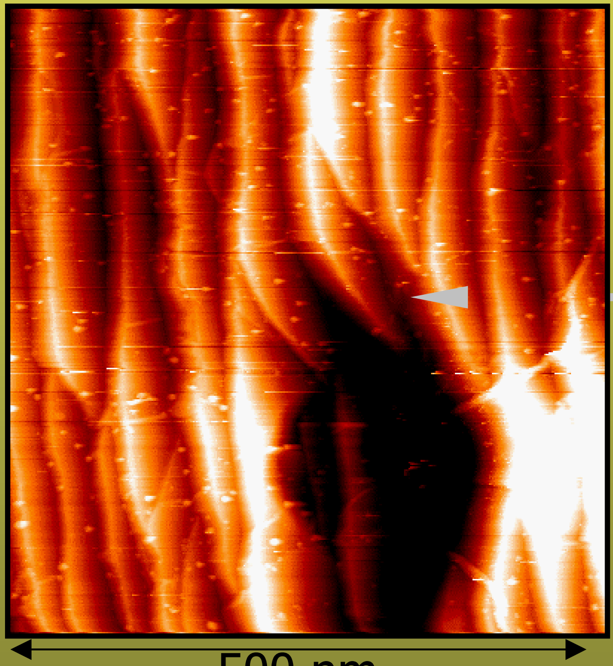
Wide Bandgap

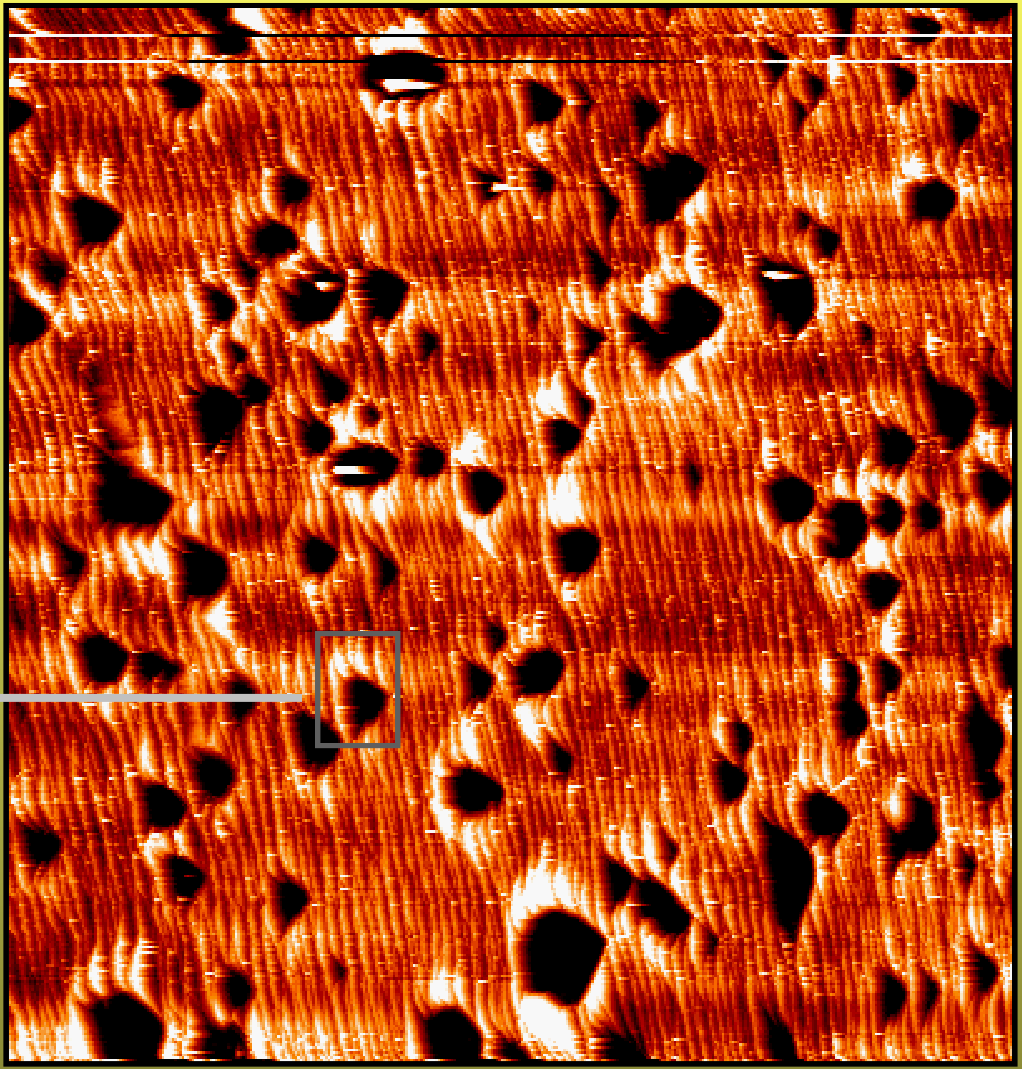
High Current Densities

Inert

STM images

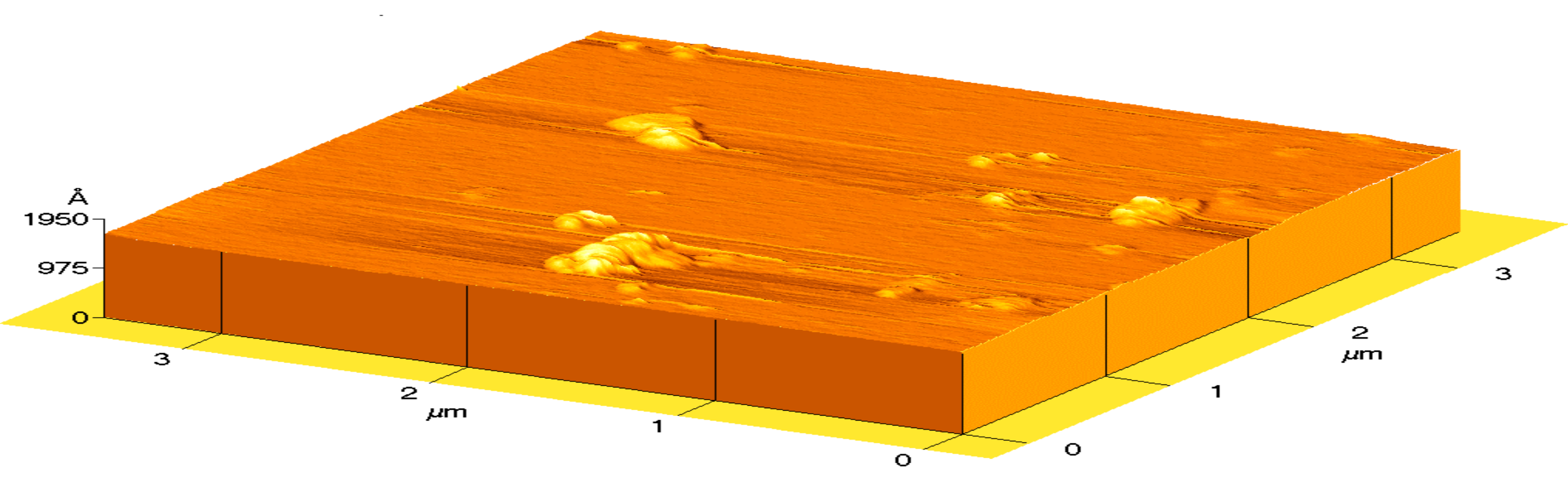
- STM studies on treated surfaces





5µm x 5µm UHV cleaned SiC surface that had been WOS

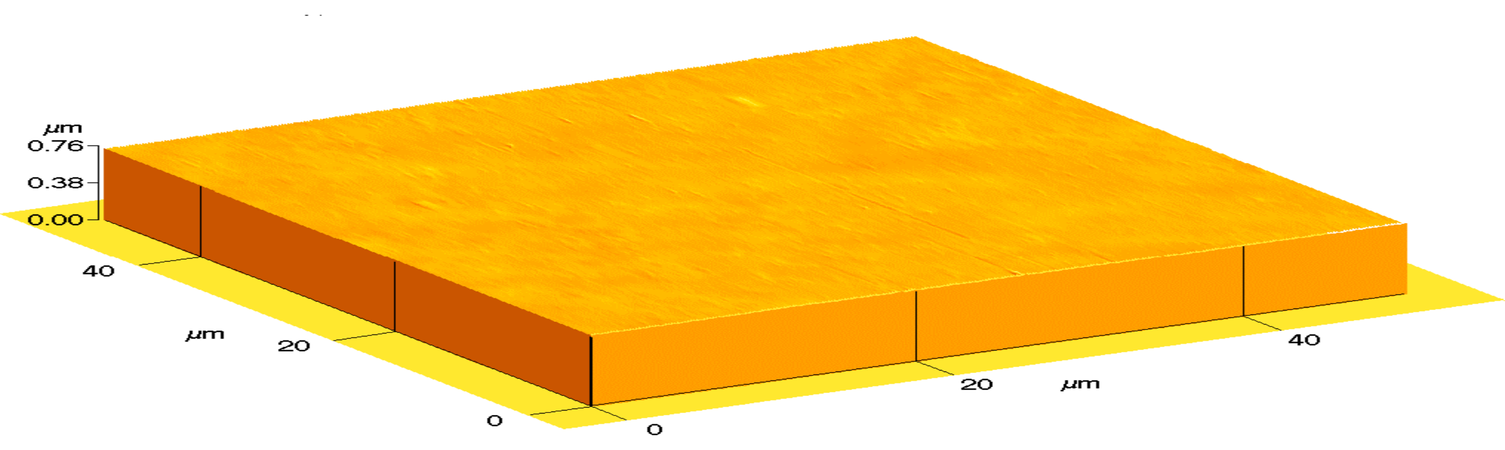
Surface Studies - AFM



SiC Surface After Removal of Wet Thermal SiO_2

RMS Surface Roughness
23.4Å

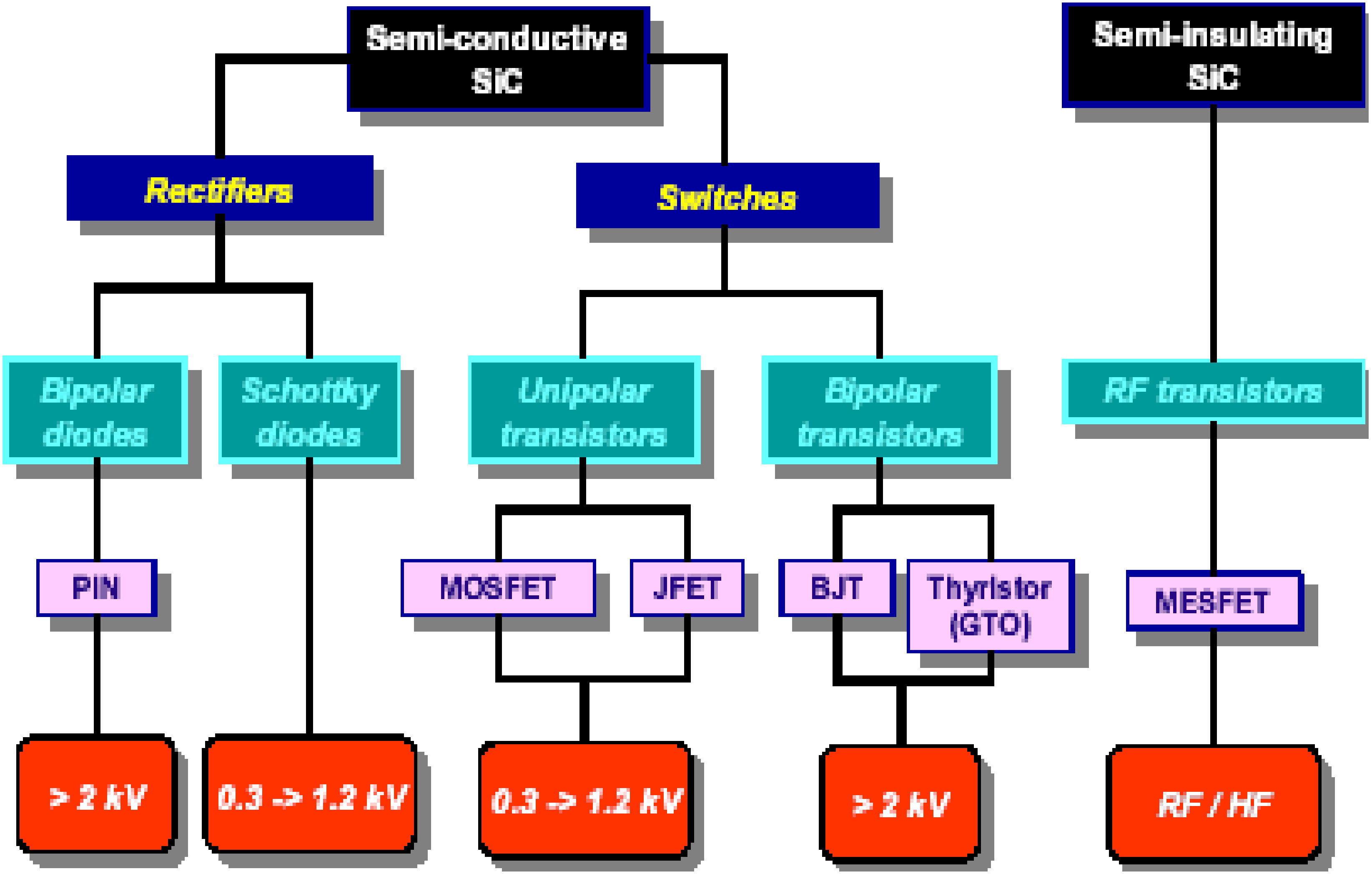
Surface Studies - AFM



SiC Surface After Removal of SSO Thermal SiO_2

RMS Surface Roughness
11.1Å

SiC Applications – Devices



Semi-conductive SiC

Semi-insulating SiC

Rectifiers

Switches

Bipolar diodes

Schottky diodes

Unipolar transistors

Bipolar transistors

RF transistors

PIN

MOSFET

JFET

BJT

Thyristor (GTO)

MESFET

> 2 kV

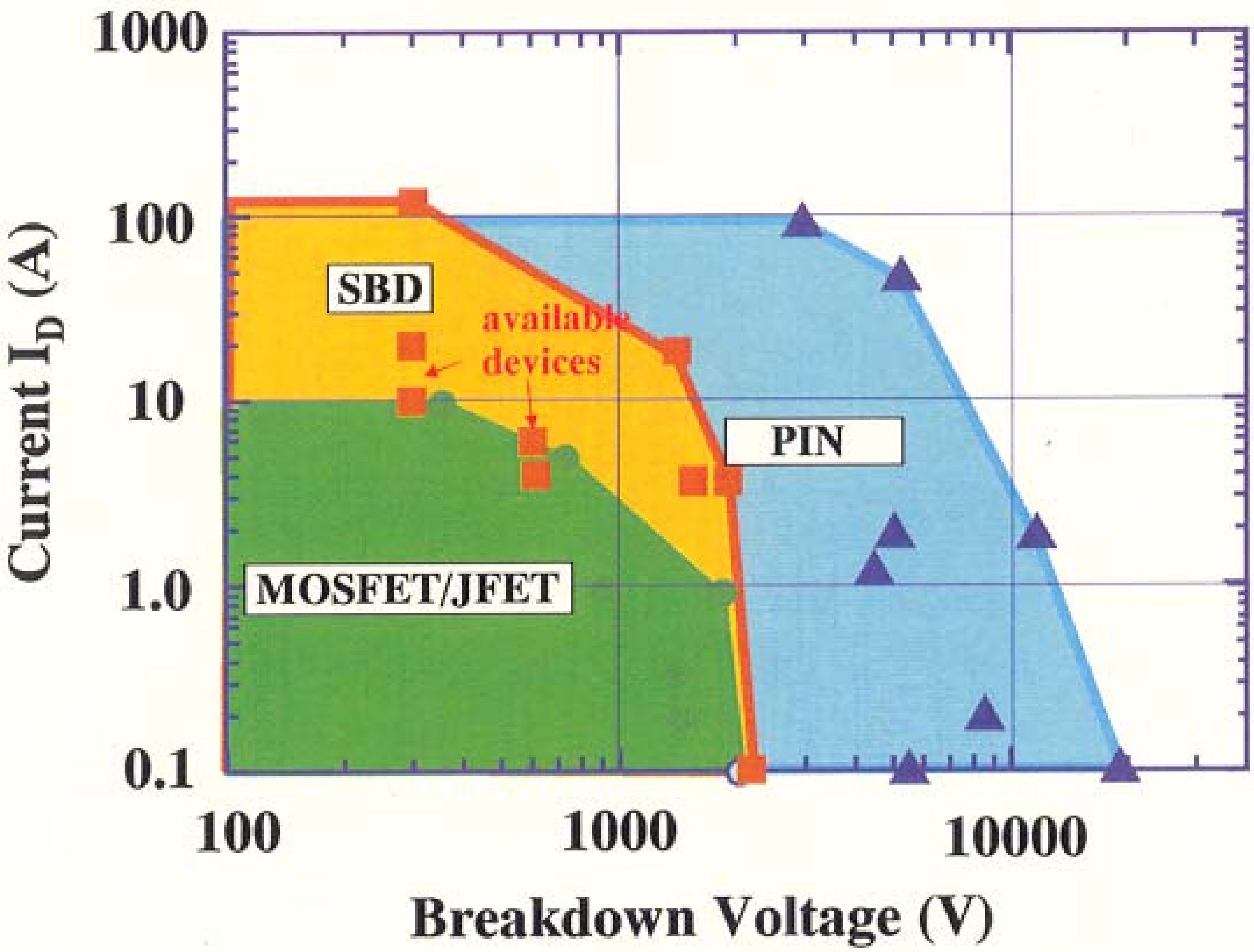
0.3 -> 1.2 kV

0.3 -> 1.2 kV

> 2 kV

RF / HF

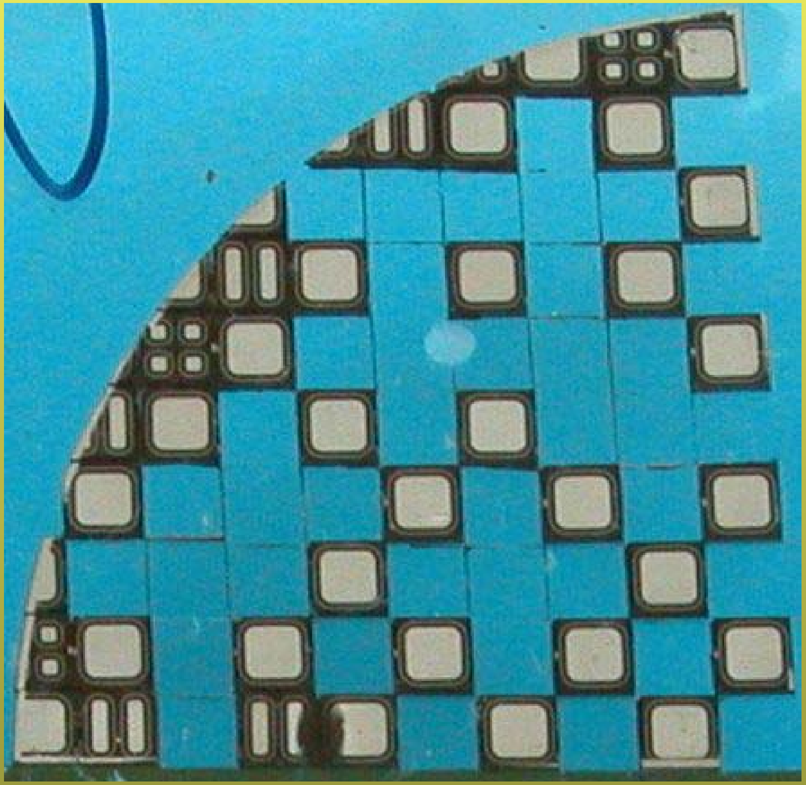
Current -Voltage Capacity of trial fabricated SiC-power devices



from homepage of Purdue Univ.

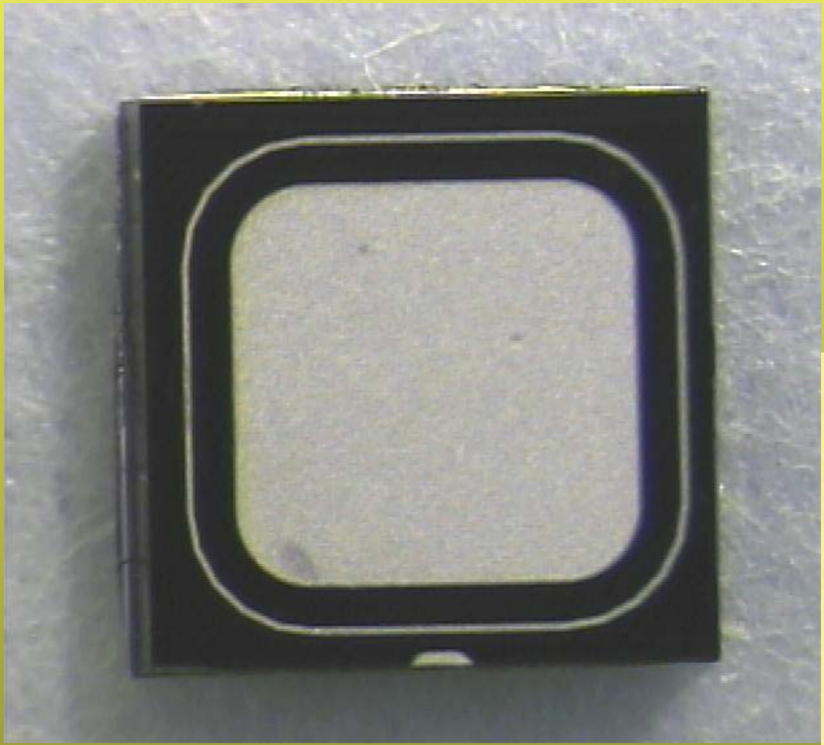
ESCAPEE Diodes

- 3 Different sized diodes
- 2x2mm largest
- 12%, 74% and 86% yield
- 1.2kV rated
- Diced ready for mounting

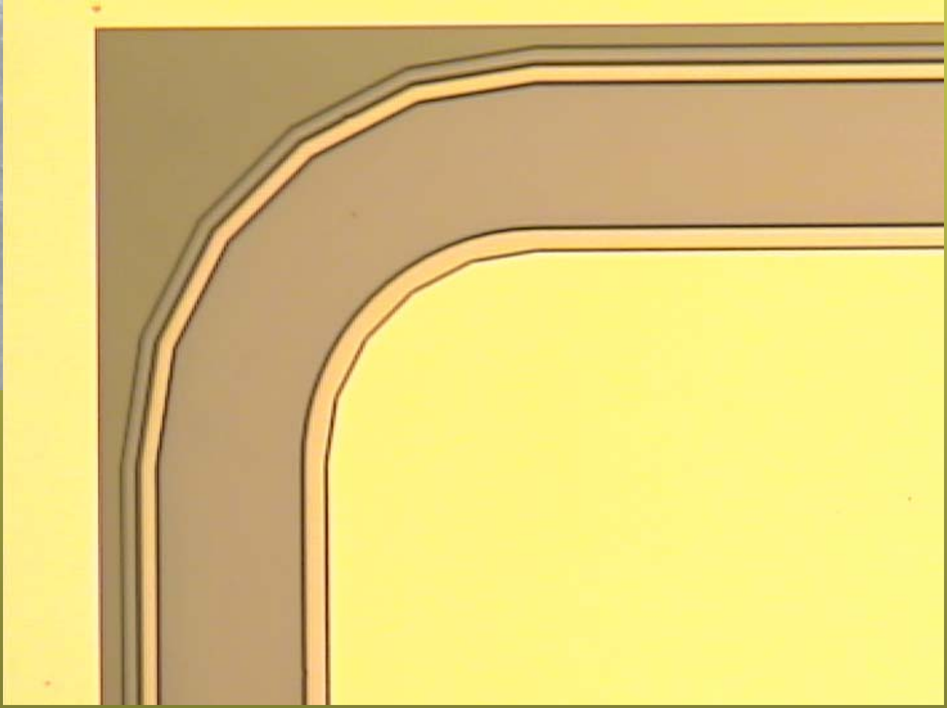


ESCAPEE Diode Die on Foil

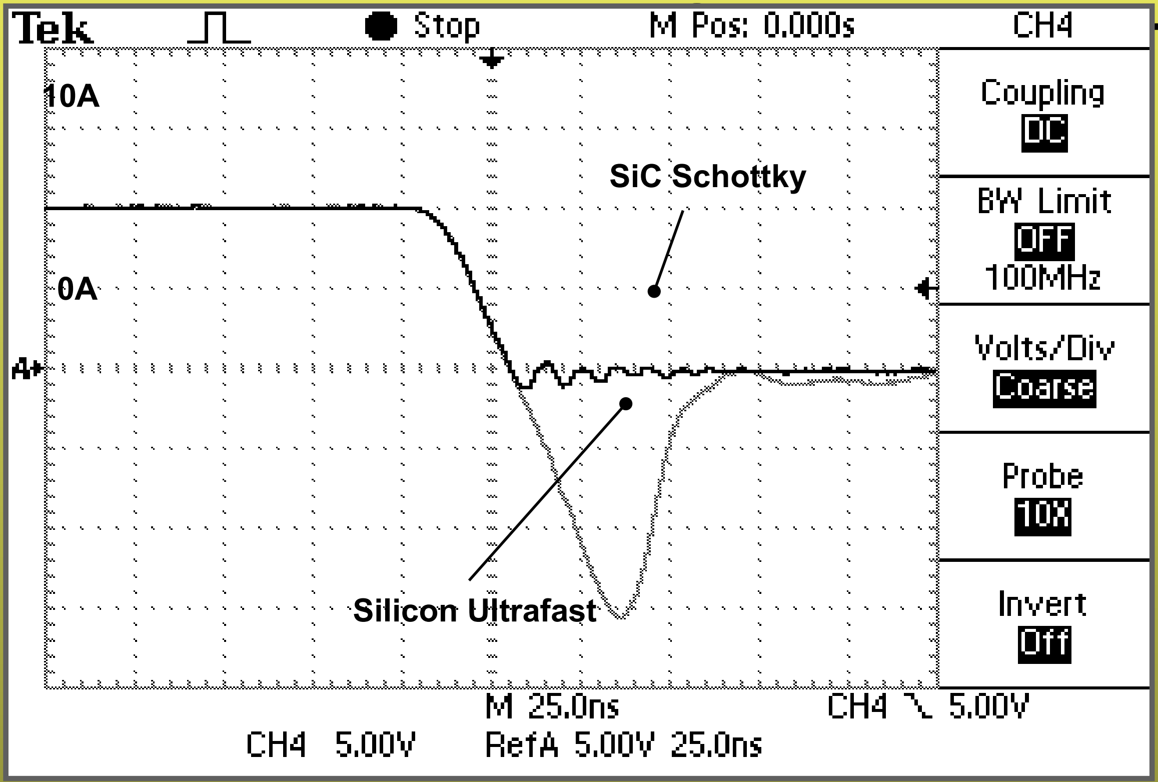
ESCAPEE Diodes - fabricated



Large area 1.6x1.6 mm2



State of the art SiC Devices Schottky Diode Switching tics



Coupling DC

BW Limit OFF 100MHz

Volts/Div Coarse

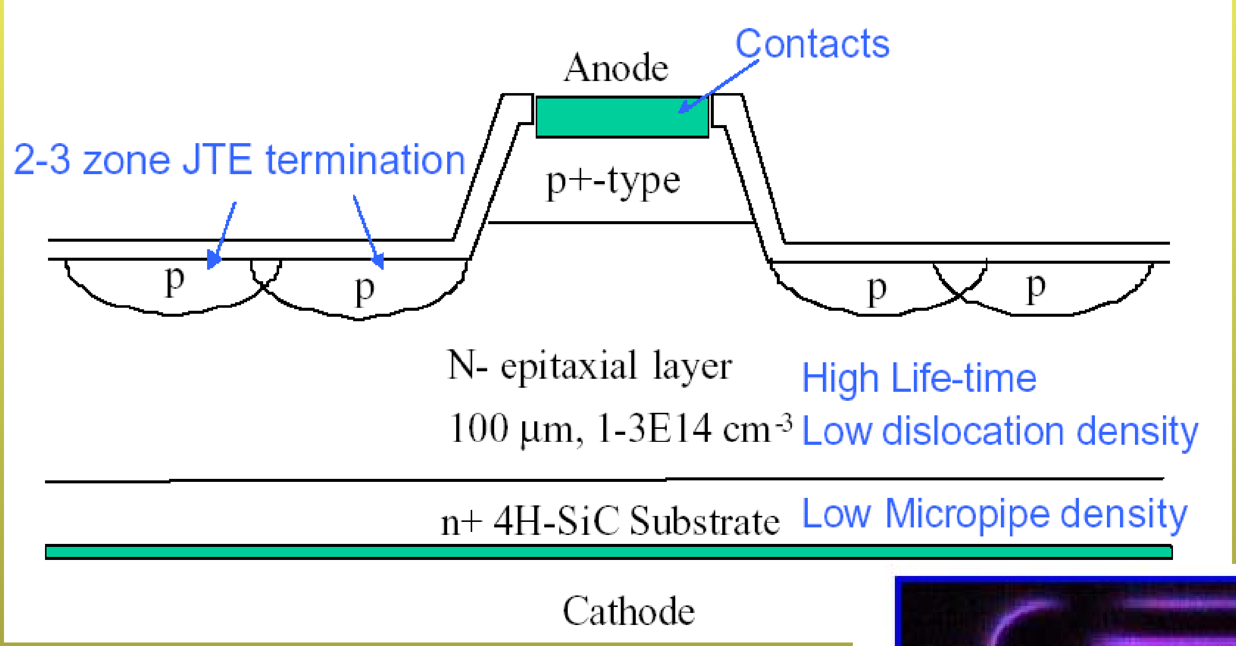
Probe 10X

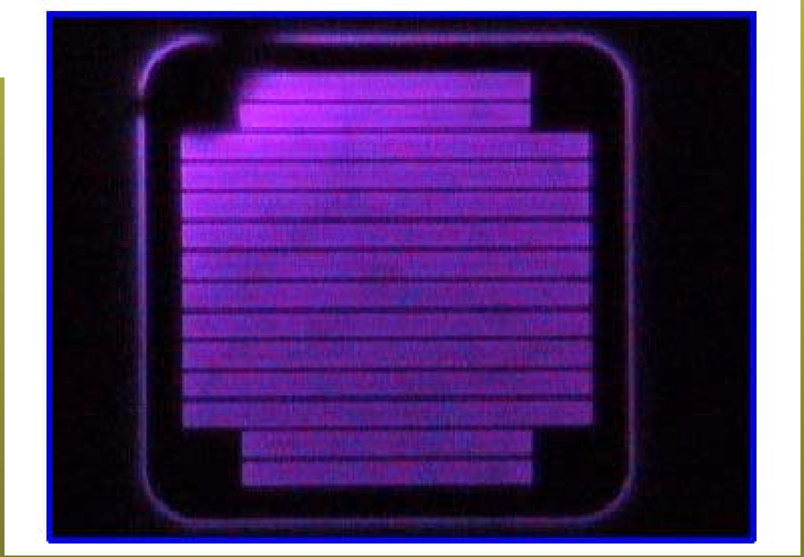
Invert Off

- Lack of reverse recovery.
- Minimized switching losses make high pulse frequencies possible
- Higher efficiency, smaller equipment size

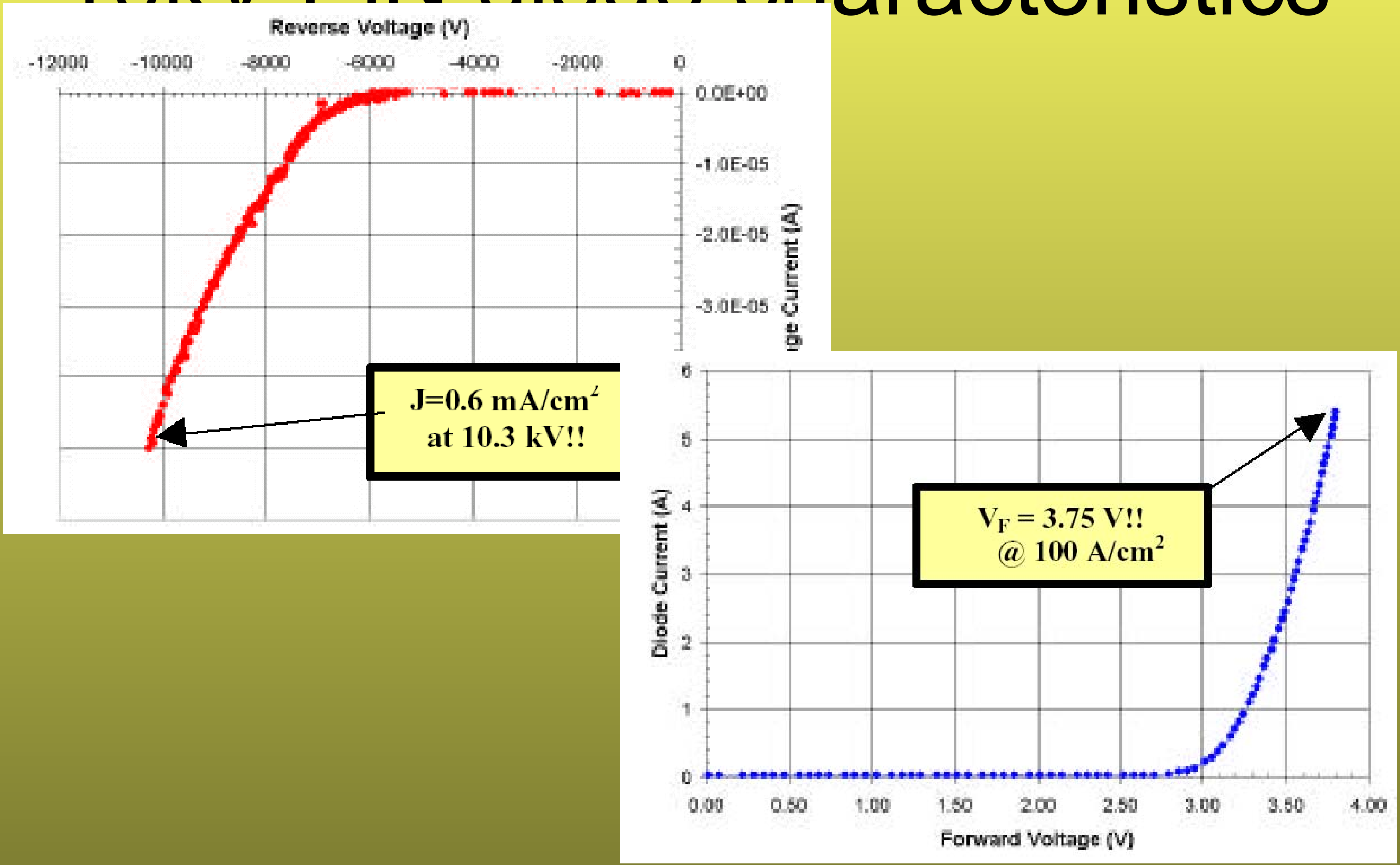
- 1200V 2mmx2mm SiC Schottky diode switching characteristics.
- 1200V 8A Silicon ultrafast diode waveform shown for reference.

10kV PiN Diode with low stacking Fault density – Cree EPE2003





10kV PiN diode characteristics

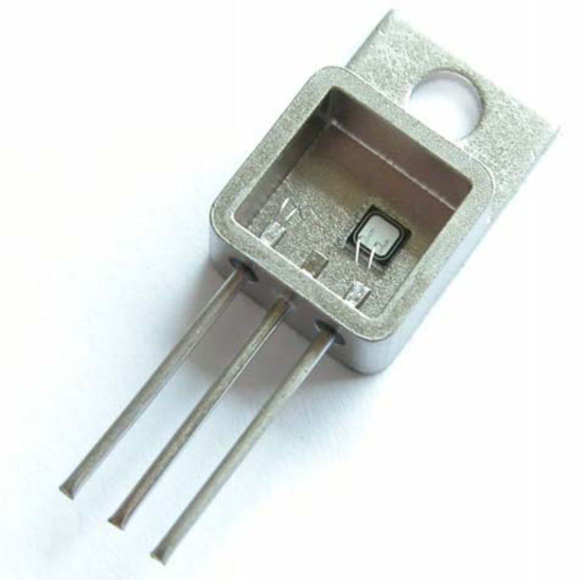


J=0.6 mA/cm^2 at 10.3 kV!!

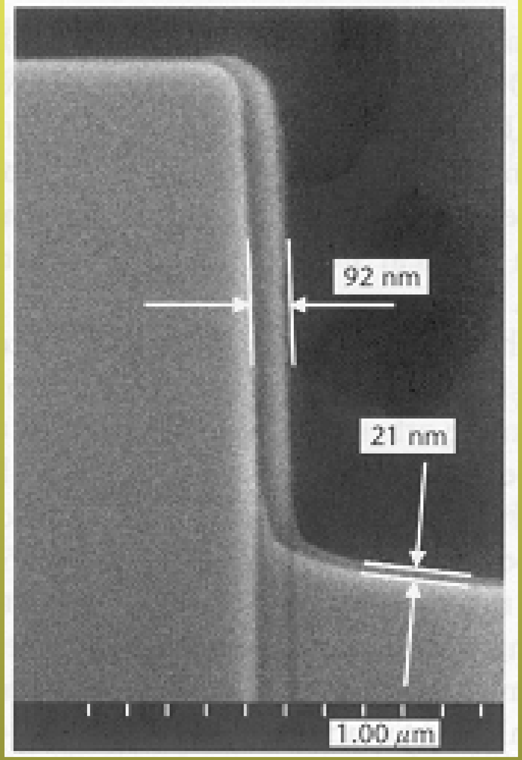
V_F = 3.75 V!! @ 100 A/cm^2

State of the Art SiC Devices
Schottky Barrier Diodes

- **Commercial diodes**
- 600V and 20A , 1.2kV and 10A ratings
- SiCED has realized blocking voltages up to 1700 V. Expected to extend this to 3300 V
- Expected to dominate market for blocking voltages below 3000V
- Capable of replacing Si junction rectifiers in medium power motor drive electronics modules



Trench MOSFET



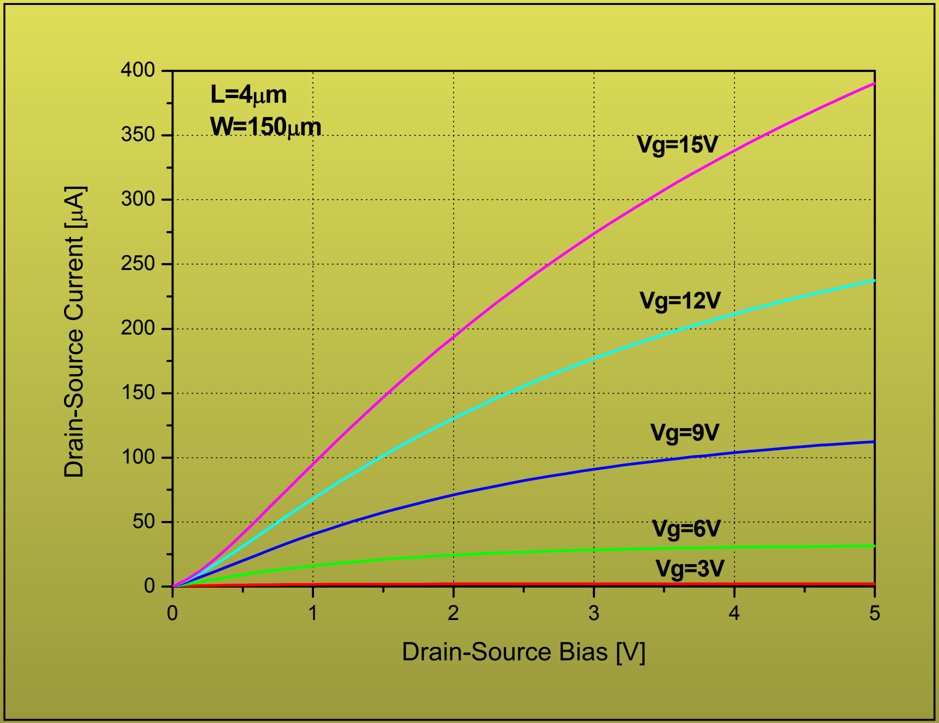
Oxide growth rate slower on trench bottom

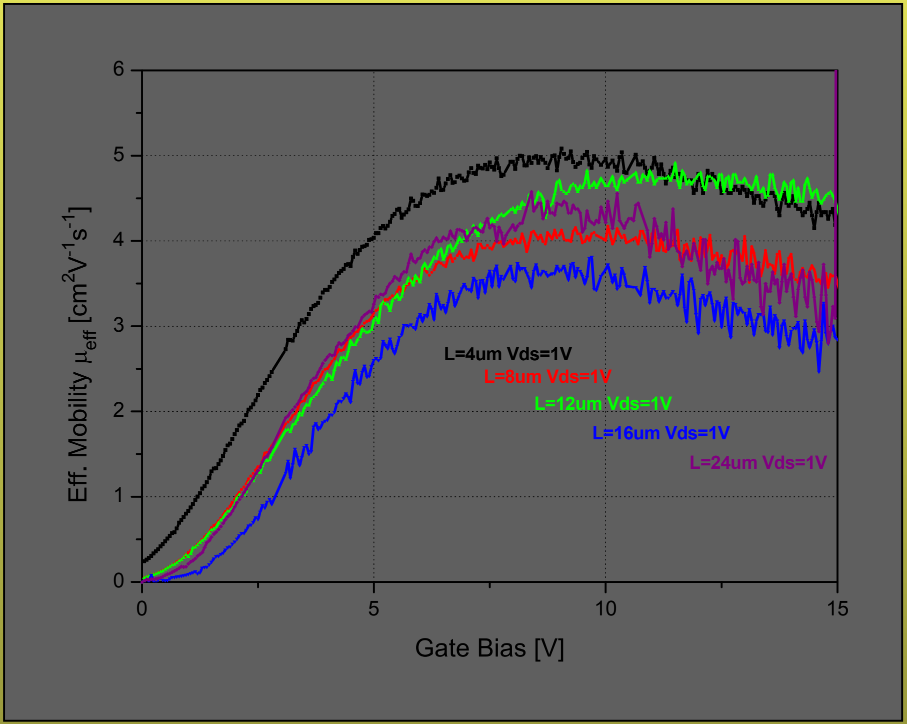
Maximum Oxide field 2MV/cm limits field in SiC to 0.8MV/cm ie 0.2 of critical value

Can implant P+ layer at bottom of trench to reduce field

MOSFET test structure

N-MOSFET on 4H-SiC



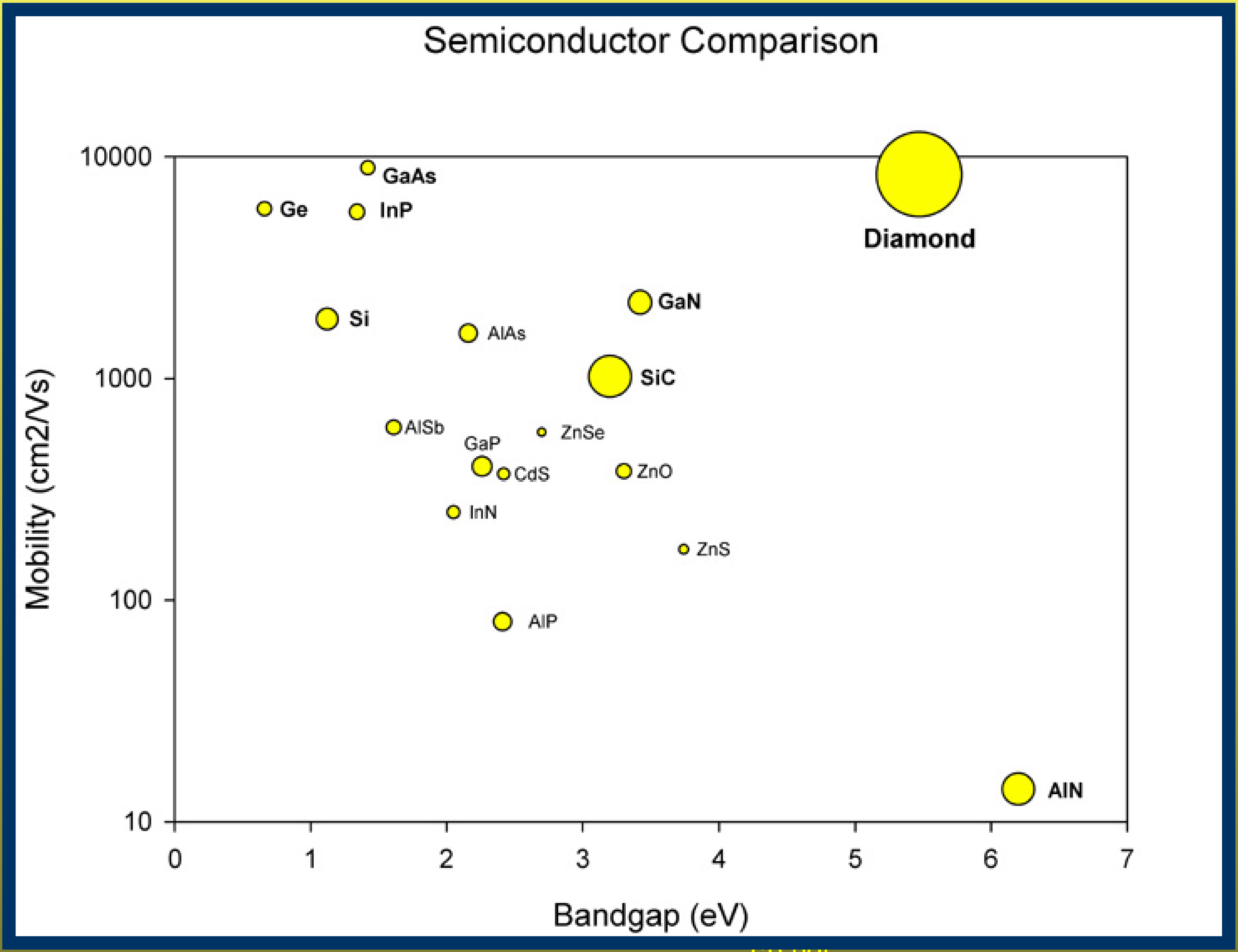


Gate oxide thickness: 38 nm
Effective channel mobility 2 cm2/Vs
Not rectifying contact
Reference device.

Science 297 (6 Sept. 2002) p1670

Not only polycrystalline diamond was possible but E6 had developed technology for producing free-standing single crystal CVD diamond with material properties which far exceeded even the most optimistic expectations.

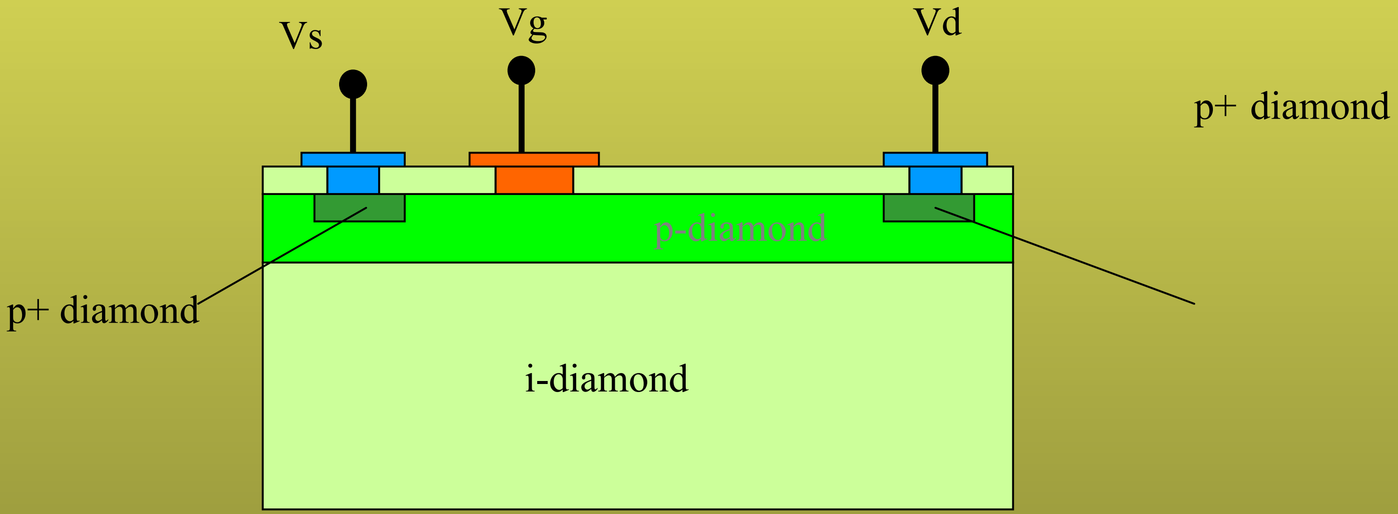
Diamond - the only wide bandgap high mobility material



Diamond Properties

	Si	**SiC-4H**	**GaN**	**Diamond**
Band gap (eV)	1.1	3.2	3.44	**5.5**
Breakdown field (MV/cm)	0.3	3	5	**10**
Electron mobility (cm^2/Vs)	1450	900	440	**4500**
Hole mobility (cm^2/Vs)	480	120	200	**3800**
Thermal conductivity (W/cmk)	1.5	5	1.3	**24**
Johnson's Figure of Merit	1	410	280	**8200**
Keyes' Figure of Merit	1	5.1	1.8	**32**
Baligas Figure of Merit	1	290	910	**17200**

CVD Diamond MESFETs for Power applications



Conclusions

- Power Device Performance is doubling every 18 months
- Power Electronics is Critical for Efficient energy usage
- New Devices and Materials are needed to maintain this rapid change

Many Thanks to

- Dr Petar Igic, Dr Owen Guy, Dr Li Chen, Dr. Zhonfu Zhou, Dr. Salah Khanniche plus all other members of the Power Electronics Research Centre