Power Semiconductor Devices

(Why WBG Devices for PE?)

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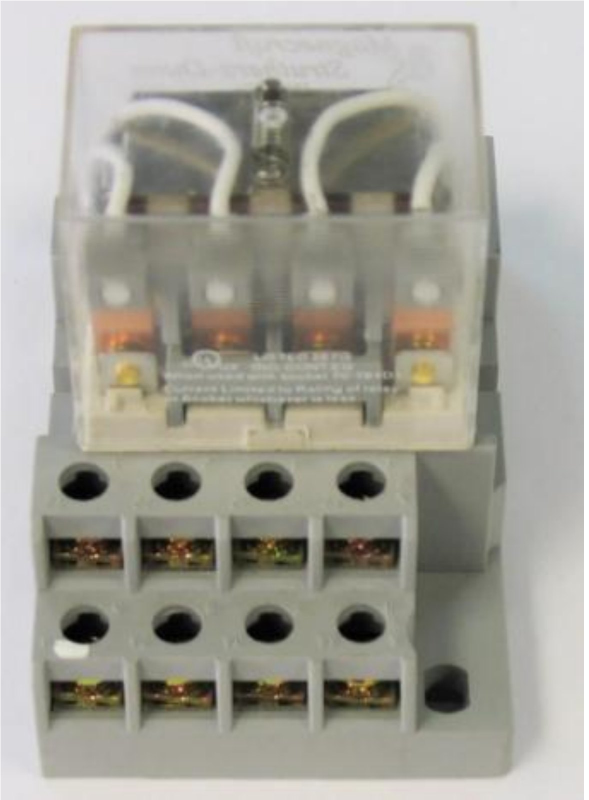
Comparison of Relay



VS

mechanical relay

(ex : 20mm × 10mm × 10mm)

semiconductor relay

(ex : 5mm × 5mm × 3mm)

Power Semiconductor Devices (PSD)

Power Semiconductor Devices

Deals with power

- Power
  = current × voltage
- Electrical circuit

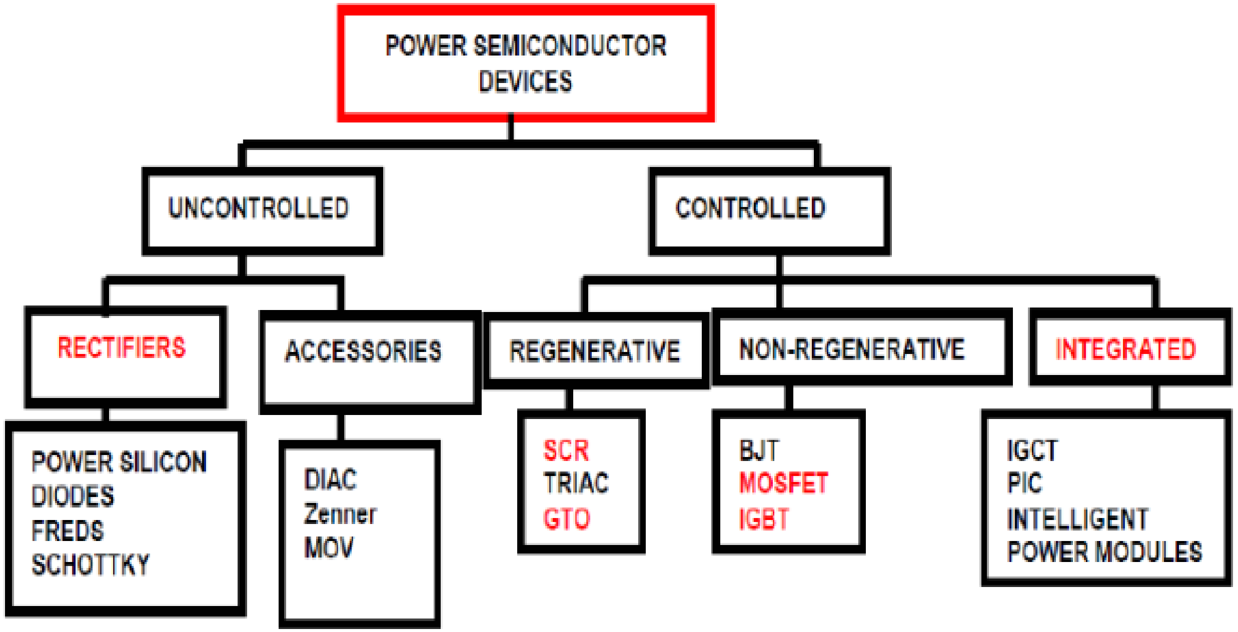
Made of semiconductor

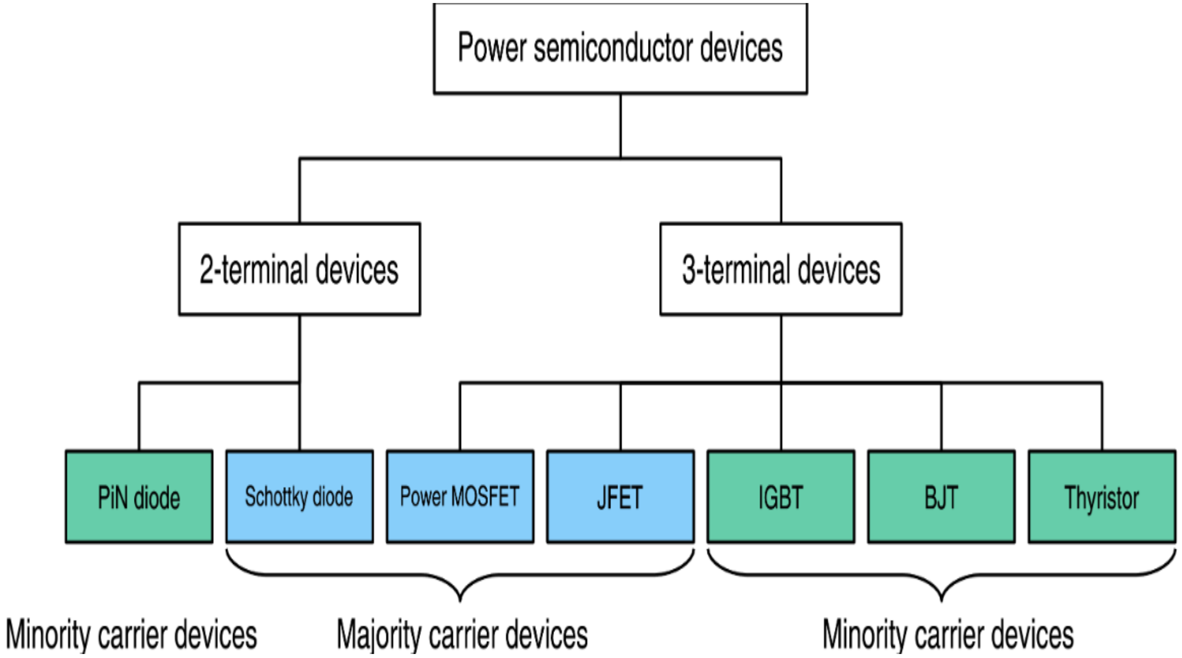
- Why semiconductor'?
- Which one?

Has particular functionality

- What?
- Where?
- How?

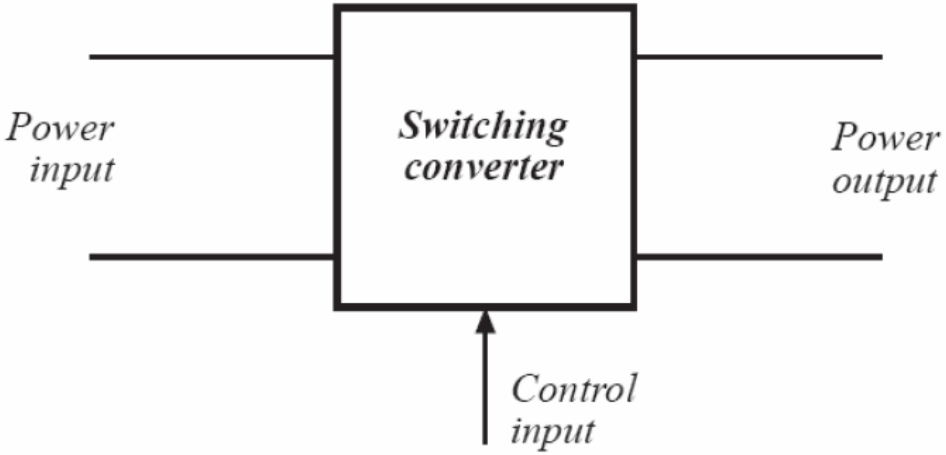
Category of PSD





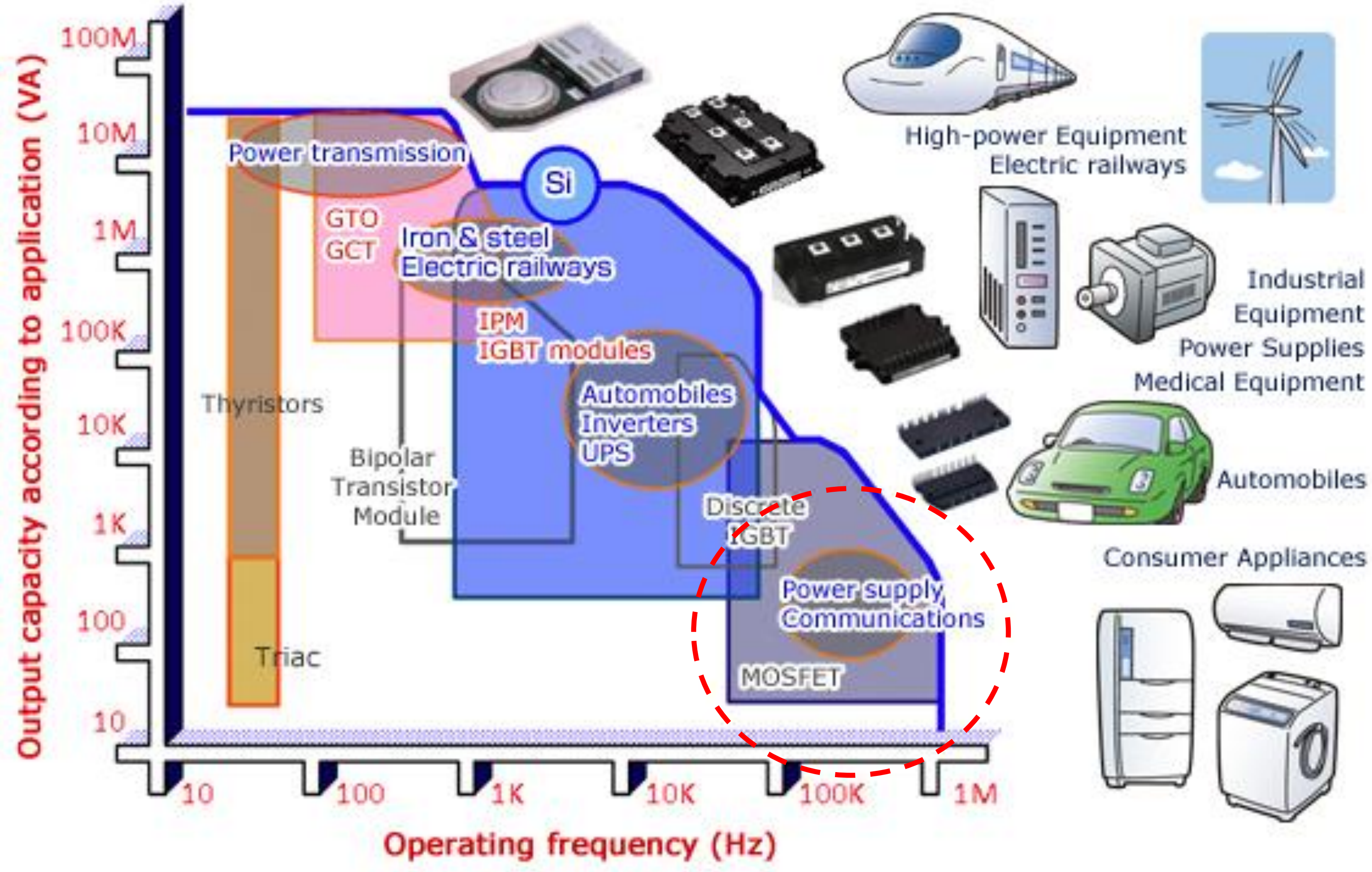
Role of PSD

Switching converter is a ***power processor***

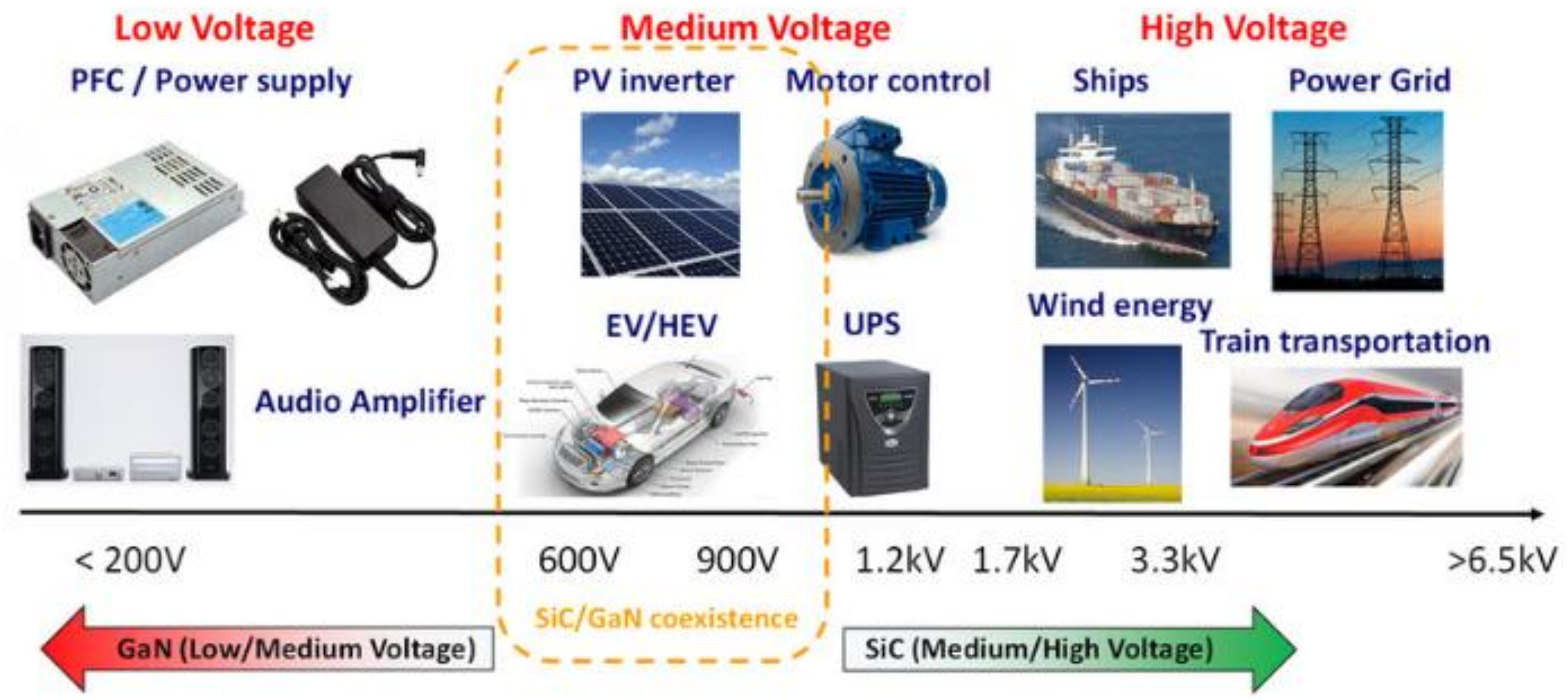


Dc-dc conversion:	Change and control voltage magnitude
Ac-dc rectification:	Possibly control dc voltage, ac current
Dc-ac inversion:	Produce sinusoid of controllable magnitude and frequency
Ac-ac cycloconversion:	Change and control voltage magnitude and frequency

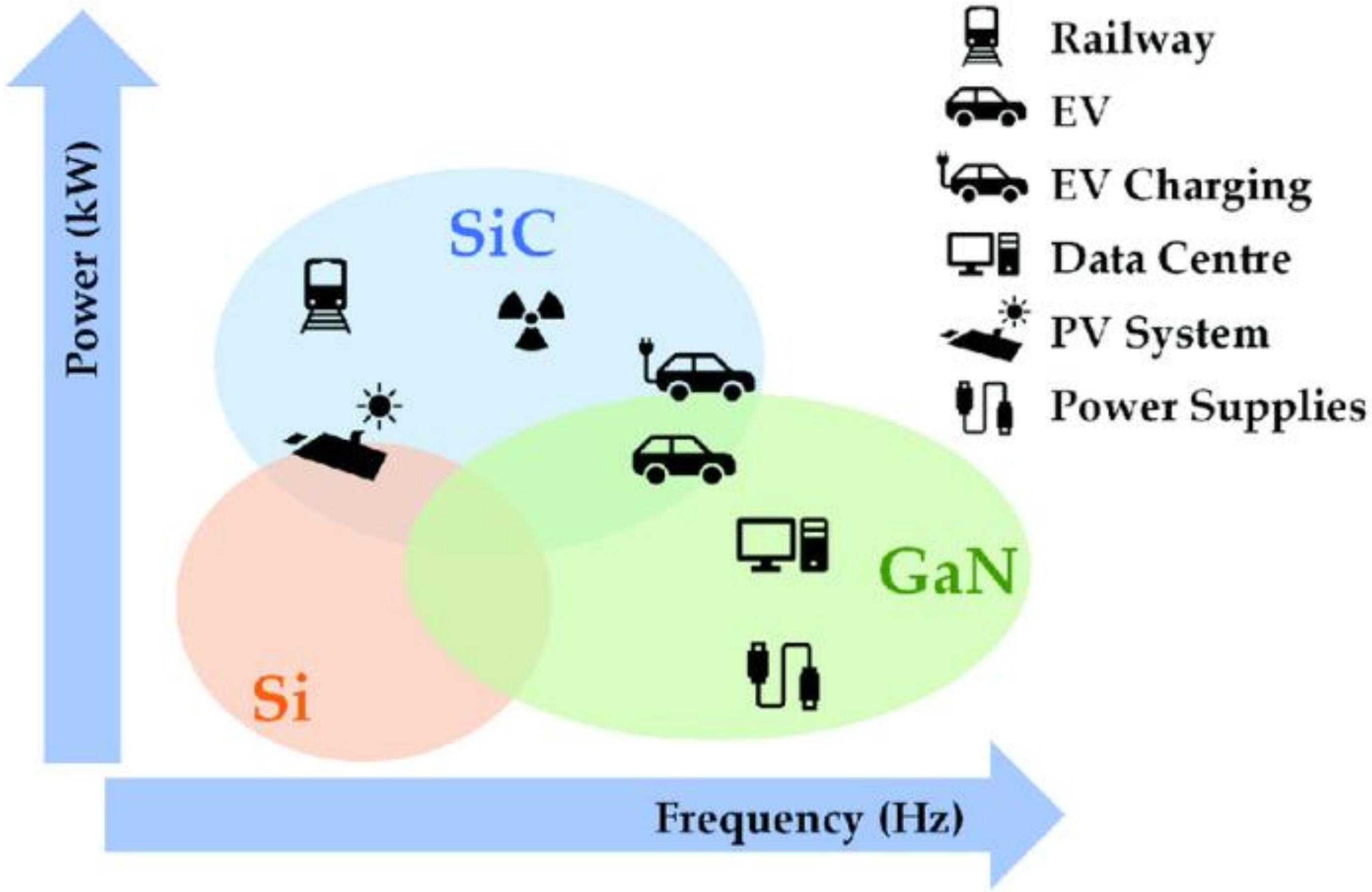
Applications of Silicon PSD



Applications of WBG PSD



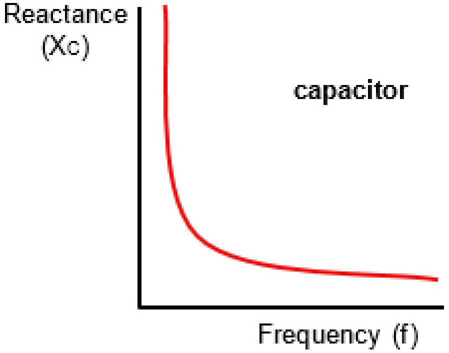
Applications of WBG PSD



WBG semiconductor devices in transportation applications.

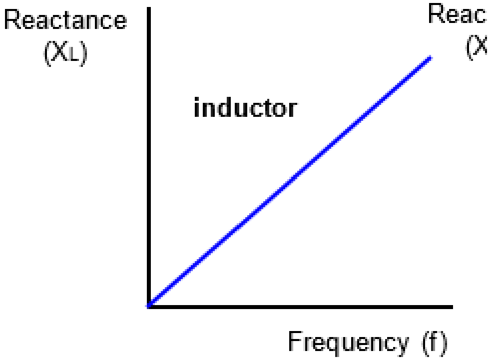
Power System Performance vs Frequency

Capacitor



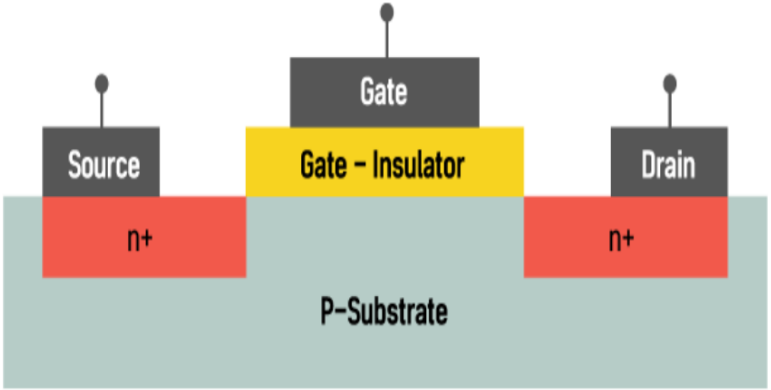
- $Z_C = \dfrac{V}{I} = \dfrac{1}{jwC}$
- **magnitude of impedance** = $|Z_C| = \dfrac{1}{wC}$

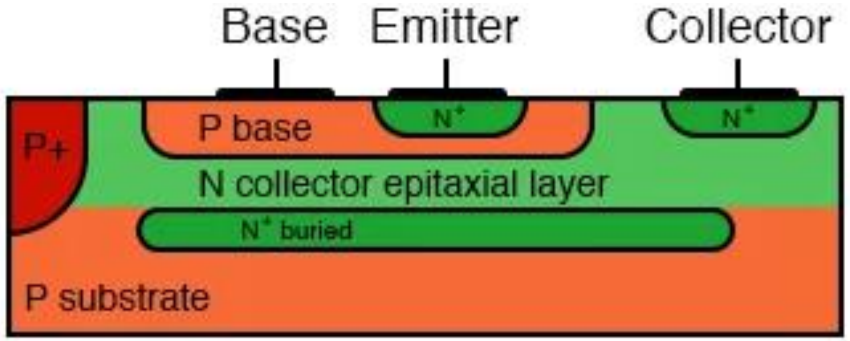
Inductor



- **impedance** $\boxed{Z_L = \dfrac{V}{I} = jwL}$

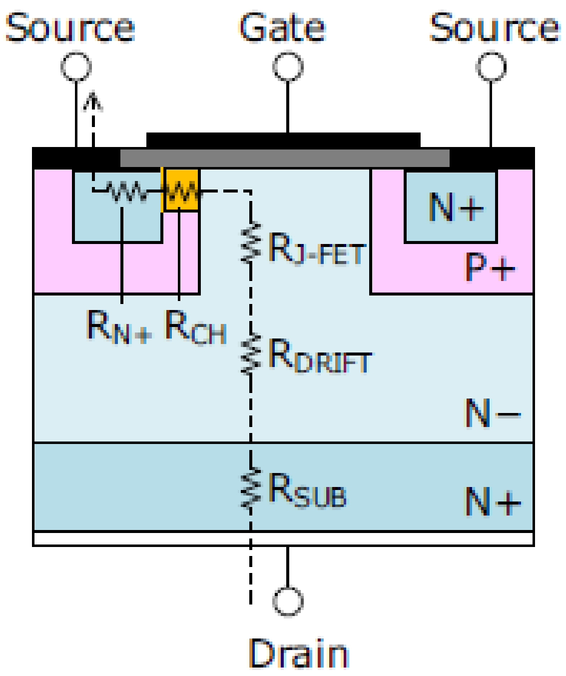
MOSFET vs Bipolar Tr

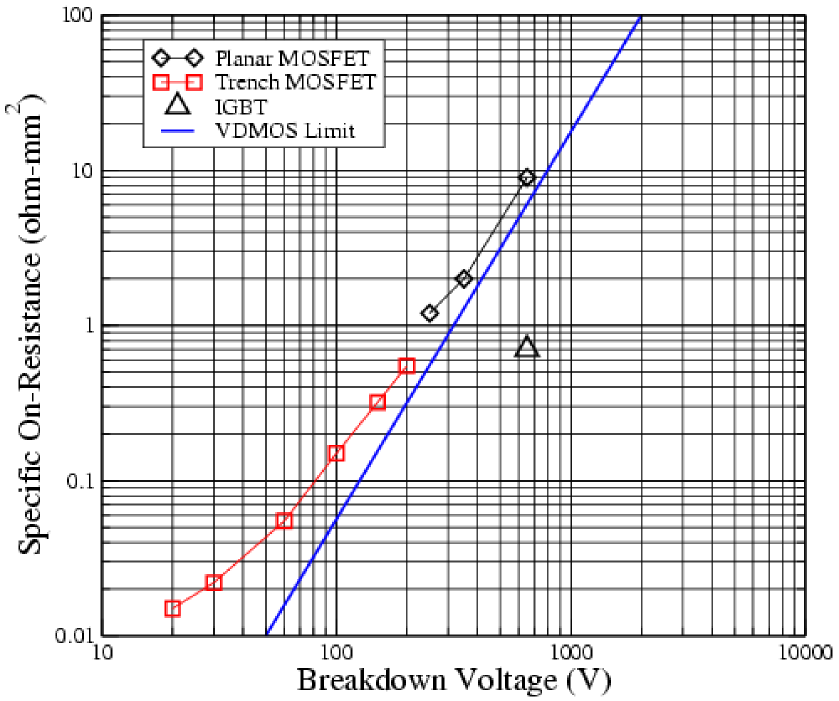


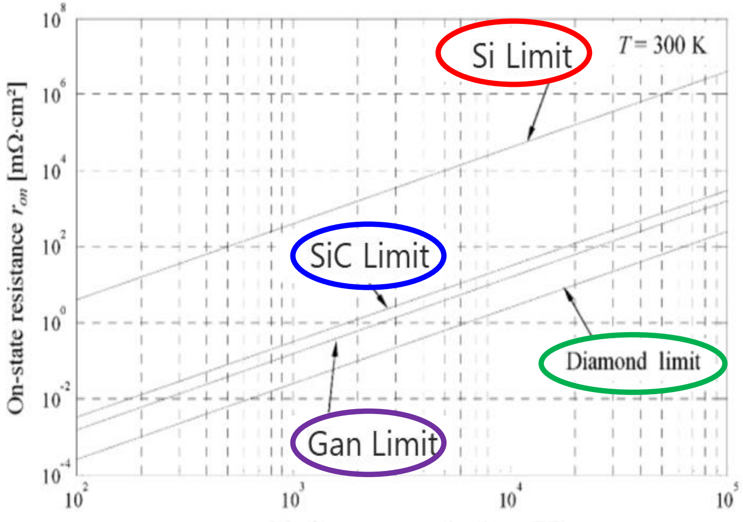


Feature	MOSFET	BJT
Control Type	Voltage-controlled	Current-controlled
Input Impedance	High (MΩ-GΩ)	Low (kΩ)
Output Impedance	High	Low
Switching Speed	**Fast (suitable for high frequency)**	Slow
Power Dissipation	Low	High (due to base current)
Thermal Stability	Good (prevents thermal runaway)	Poor (prone to thermal runaway)
Common Applications	Switching, RF circuits, digital circuits	Analog amplification, low-frequency power amplification
Carrier Movement	Majority	Minority

Silicon Power MOSFET Limit







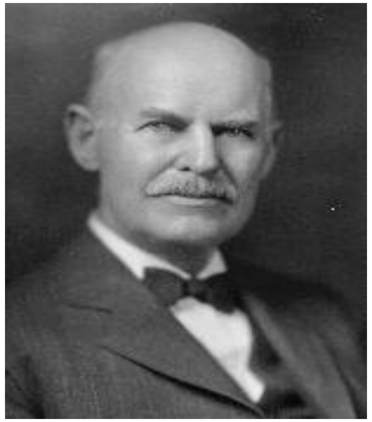
Breakdown Voltage (V)

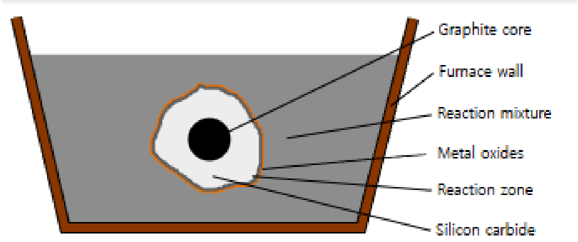
$R_{DS(ON)} = R_{SUB} + R_{DRIFT} + R_{J\text{-}FET} + R_{CH} + R_{N+}$

R_{sp} vs BV

R_{sp} vs BV

Discovery of SiC



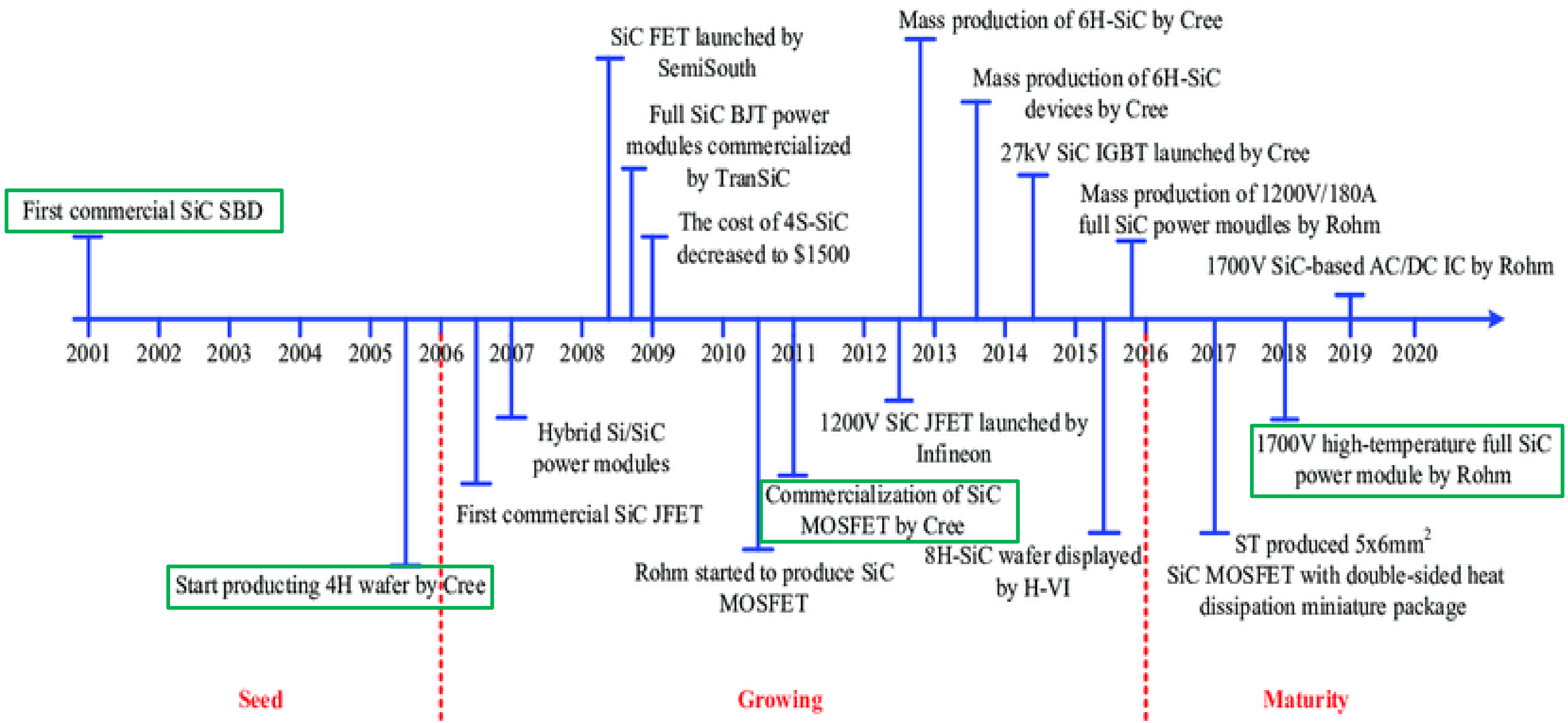


In 1891 Edward G Acheson (USA) produced a small amount of Silicon Carbide while conducting experiments with the aim of obtaining a hard material from the reaction of clay and carbon.

He passed a strong electric current from a carbon electrode through a mixture of clay and coke contained in an iron bowl, which served as the second electrode.

Acheson recognized the abrasive value of the crystals obtained, had them analysed, found the formula to be SiC, incorporated The Carborundum Company in September 1891, and filed application for a patent on May 10, 1892.

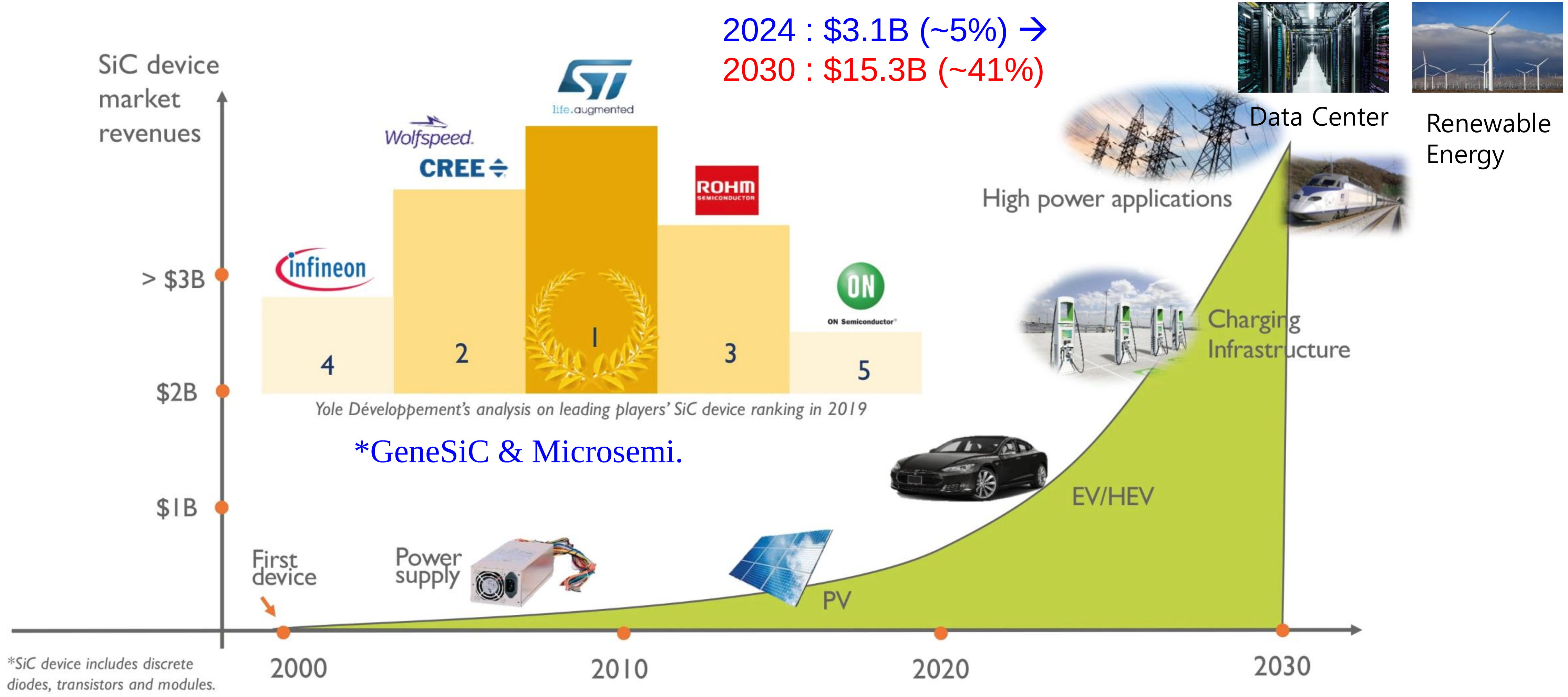
The milestones of the development process of SiC power electronic devices.



Wafer Diameter Evolution by Material

Power SiC Market Forecast

2024 : $3.1B (~5%) →
2030 : $15.3B (~41%)



OUTLINE

1. **WHY** is SiC better than silicon?

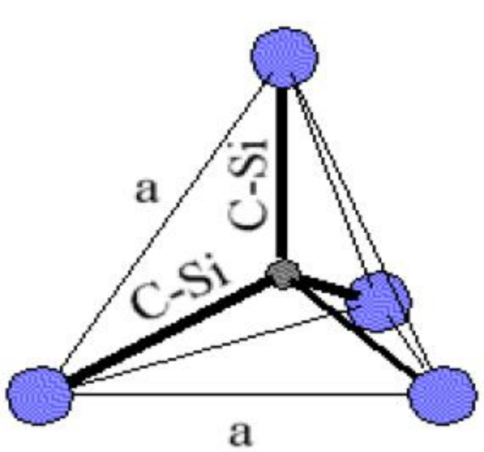
2. **HOW** do we make SiC devices?

3. **WHICH** SiC devices have been made?

1. Why is SiC better than silicon?

- What is SiC?
- Properties of SiC
- What is advantageous for devices?

What is SiC?



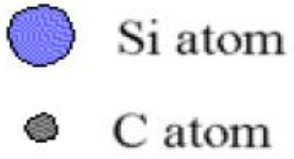


Fig. 4. The tetragonal bonding of a carbon atom with the four nearest silicon neighbours. The distances a and C-Si are approximately 3.08Å and 1.89Å respectively.

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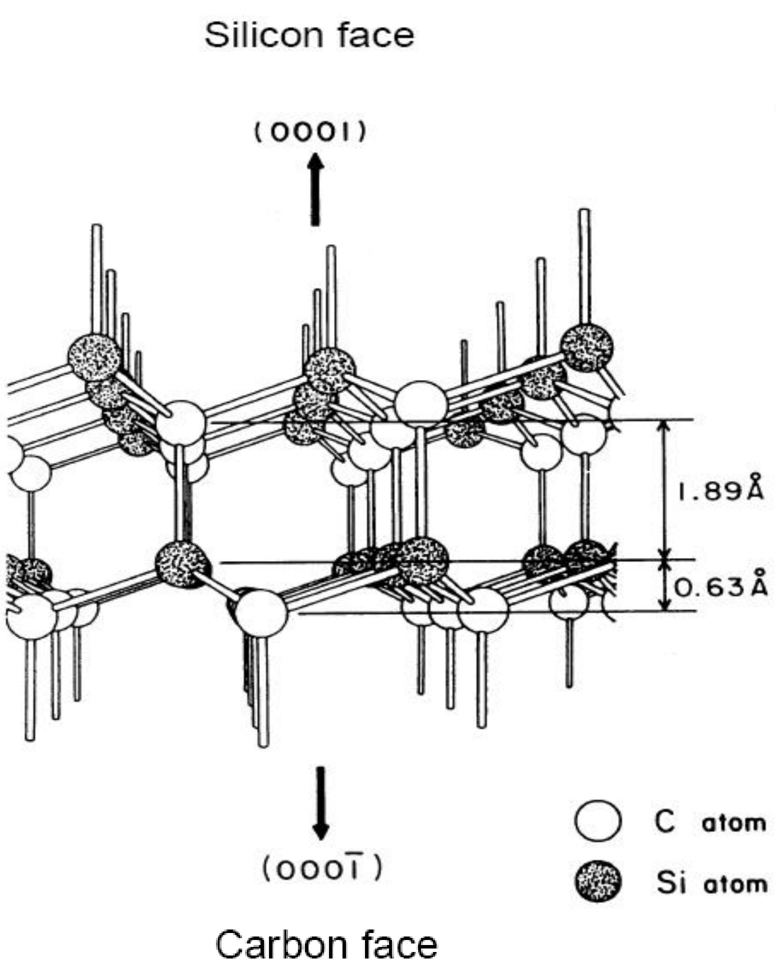
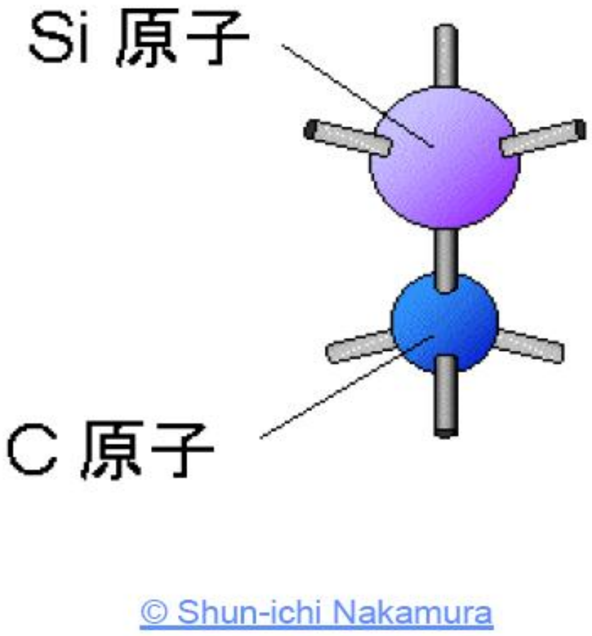
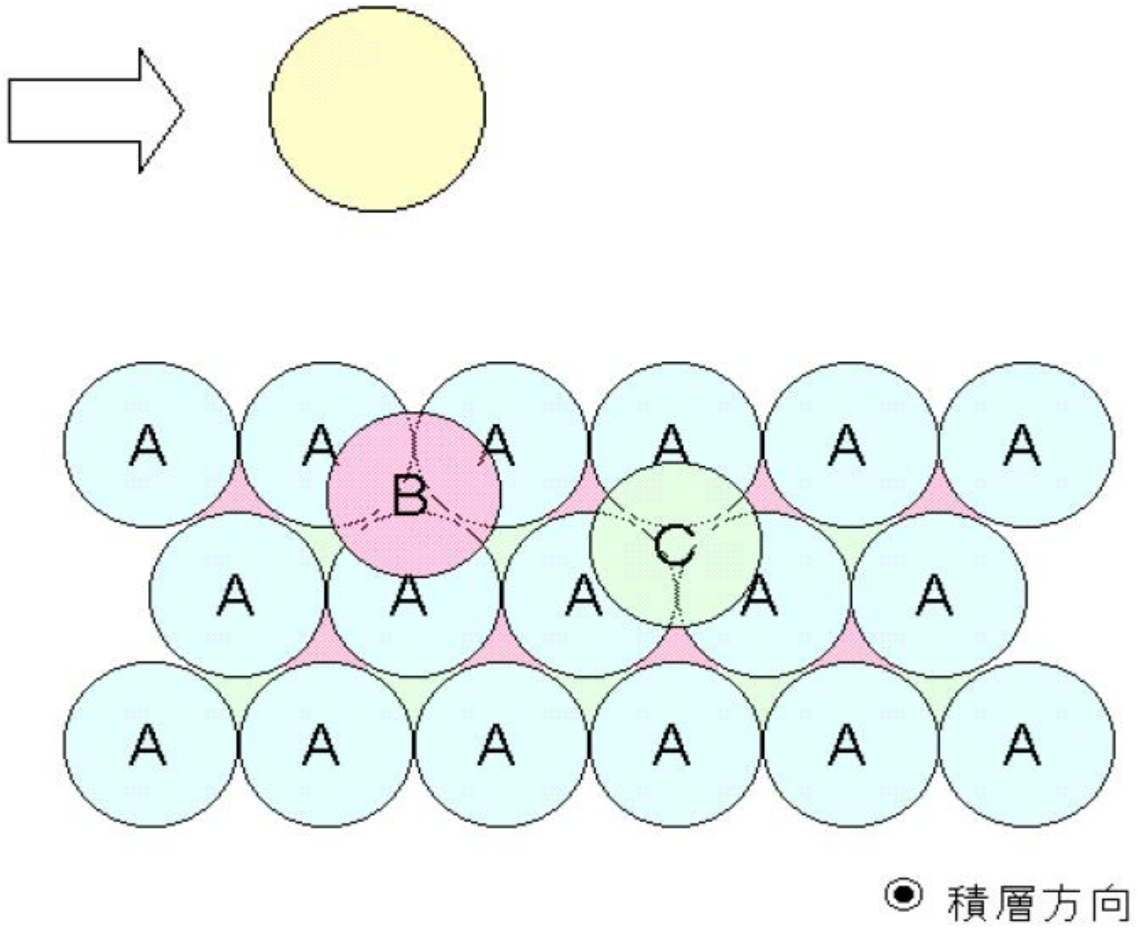
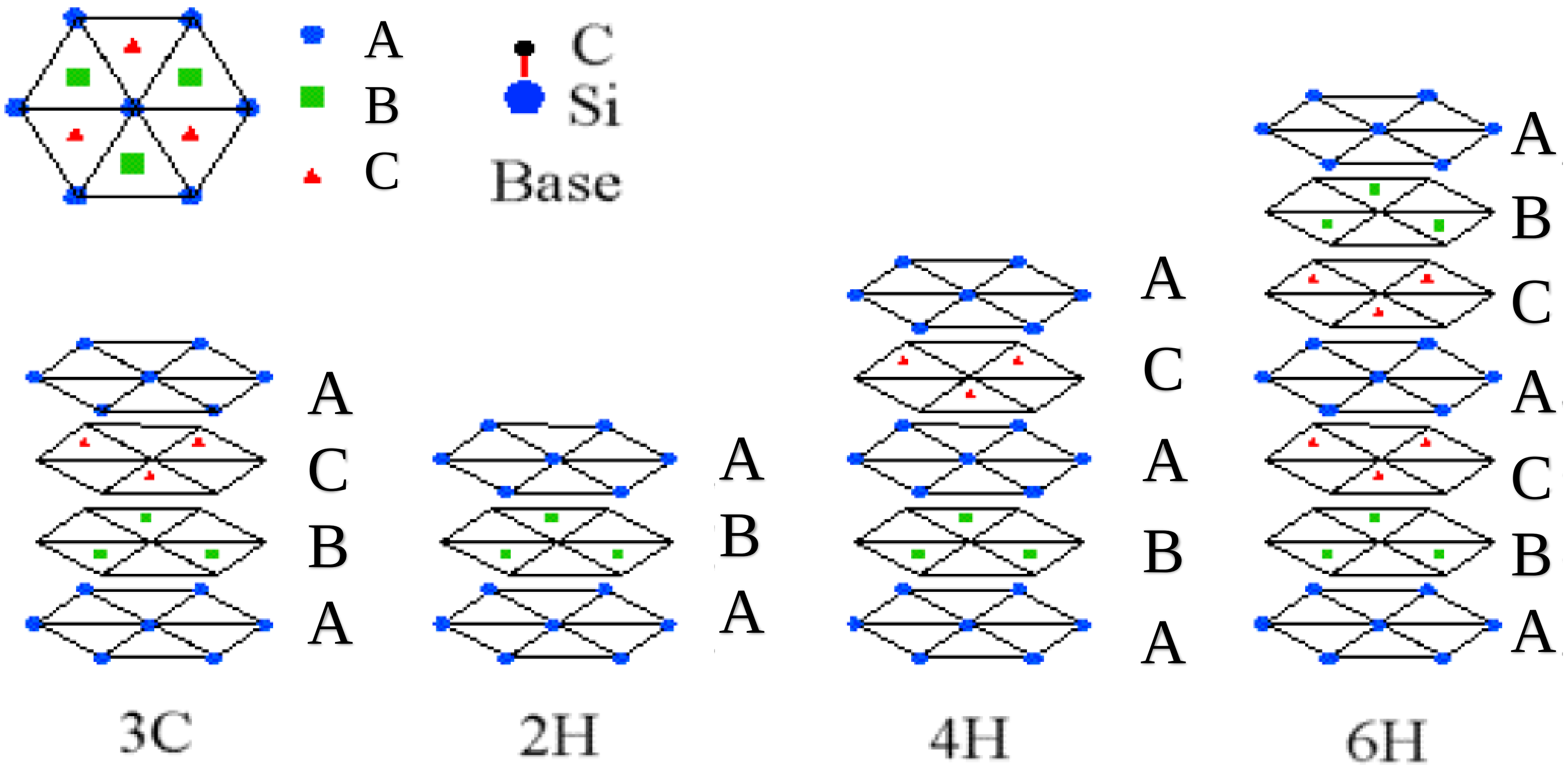


Crystals of SiC





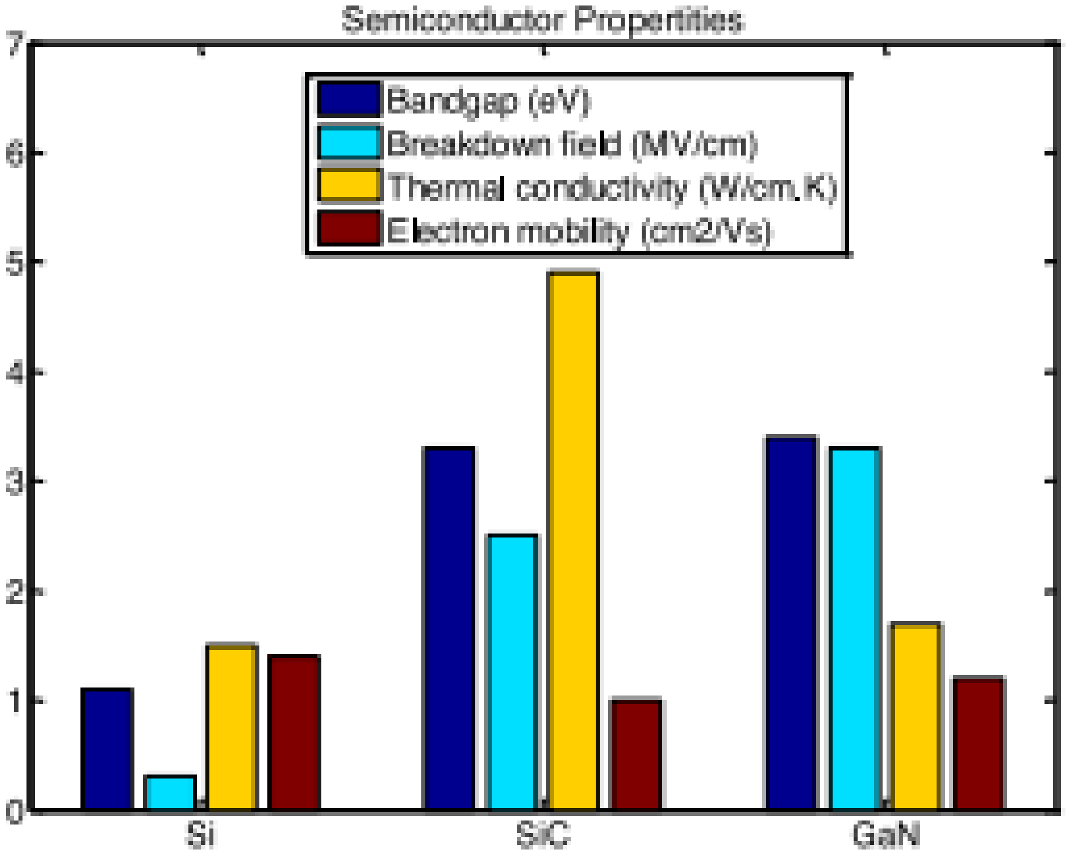
What are polytypes?



Properties of SiC

Property	*Si*	*GaAs*	*3C-SiC*	*6H-SiC*	*4H-SiC*	*GaN*	*Diamond*
Melting point [C]	1420	1238	2830	2830	2830	1123	4000
Thermal conductivity [W/cmK]	1.3	0.54	5	4.9	4.9	1.3	20
Bandgap [eV]	1.12	1.42	2.23	3.02	3.26	3.39	5.45
Intrinsic carrier concentration (cm^{-3})	10^{10}	1.8×10^{6}	~10	$\sim10^{-5}$	$\sim10^{-7}$	$\sim10^{-10}$	$\sim10^{-27}$
Electron mobility [cm^2/Vs]	1500	8500	1000	370	1000	1500	2200
Hole mobility [cm^2/Vs]	600	400	50	90	50	150	1600
Saturation electron drift velocity [$\times10^7 cm/s$]	1	1	2.5	2	2	3.0	2.7
Breakdown field [$\times10^5$ V/cm]	3	6	20	25	30	50	100
Dielectric constant	11.9	13.1	9.7	9.66	9.7	9.5	5.5

Properties of Si, SiC, and GaN



Properties of SiC

- Figures of merit

  - ✓ **KFM** – Key's Figure of Merit (Switching Speeds)

  - ✓ **KFJ** – Johnson's Figure of Merit (High Power Applications)

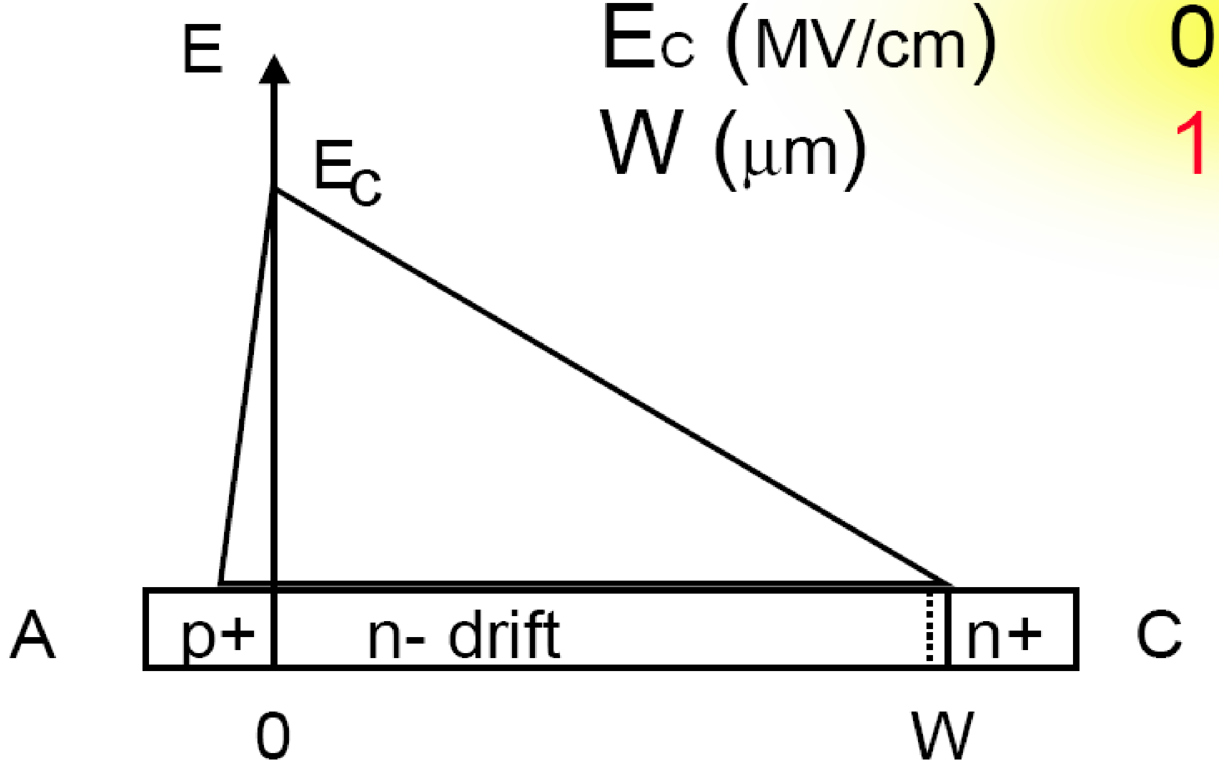
	KFM $\kappa \cdot \sqrt{\frac{c \cdot v_s}{4\pi\varepsilon_s}}$	KFJ $\frac{E_B^2 \cdot v_s^2}{4\pi^2}$
Si	1	1
SiC	6.5	281

Device basics

Non punch-through

design for 1 kV:

	Si	SiC
E_C (MV/cm)	0.25	2.5
W (μm)	100	10



$$V_B = \frac{W\,E_C}{2}$$

On resistance

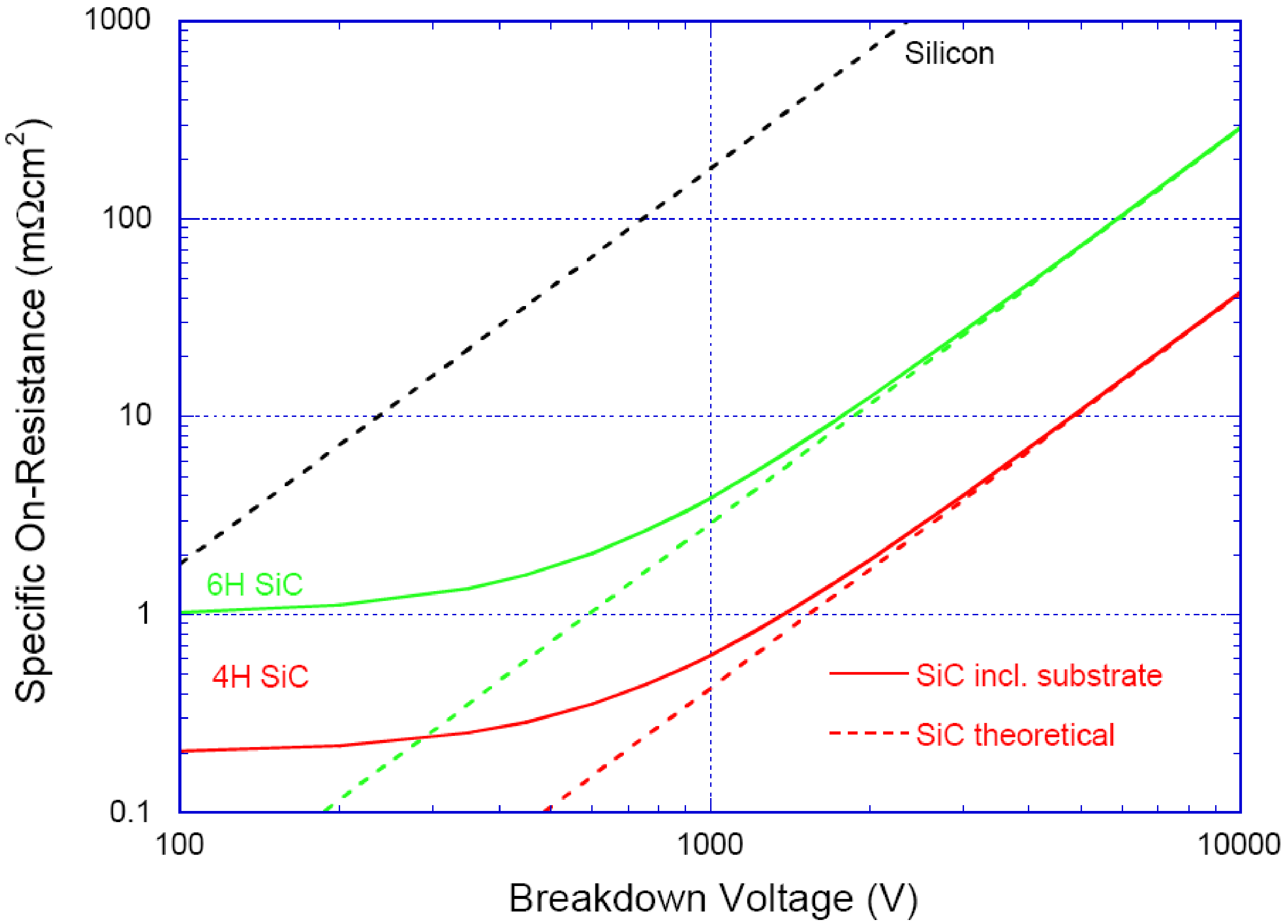
$$W \approx \sqrt{\frac{2\varepsilon V_B}{q N_D}} \qquad N_D = \frac{2\varepsilon V_B}{q W^2} = \frac{\varepsilon E_C^2}{2 q V_B}$$

For 1 kV:	Si	SiC
W (μm)	100	10
N_D (cm^{-3})	10^{14}	10^{16}

$$R_{on,sp} = \frac{W}{q \mu_n N_D} = \frac{4 V_B^2}{\varepsilon \mu_n E_C^3}$$

$$\frac{V_B^2}{R_{on,sp}} = \frac{\varepsilon \mu_n E_C^3}{4}$$

High voltage devices



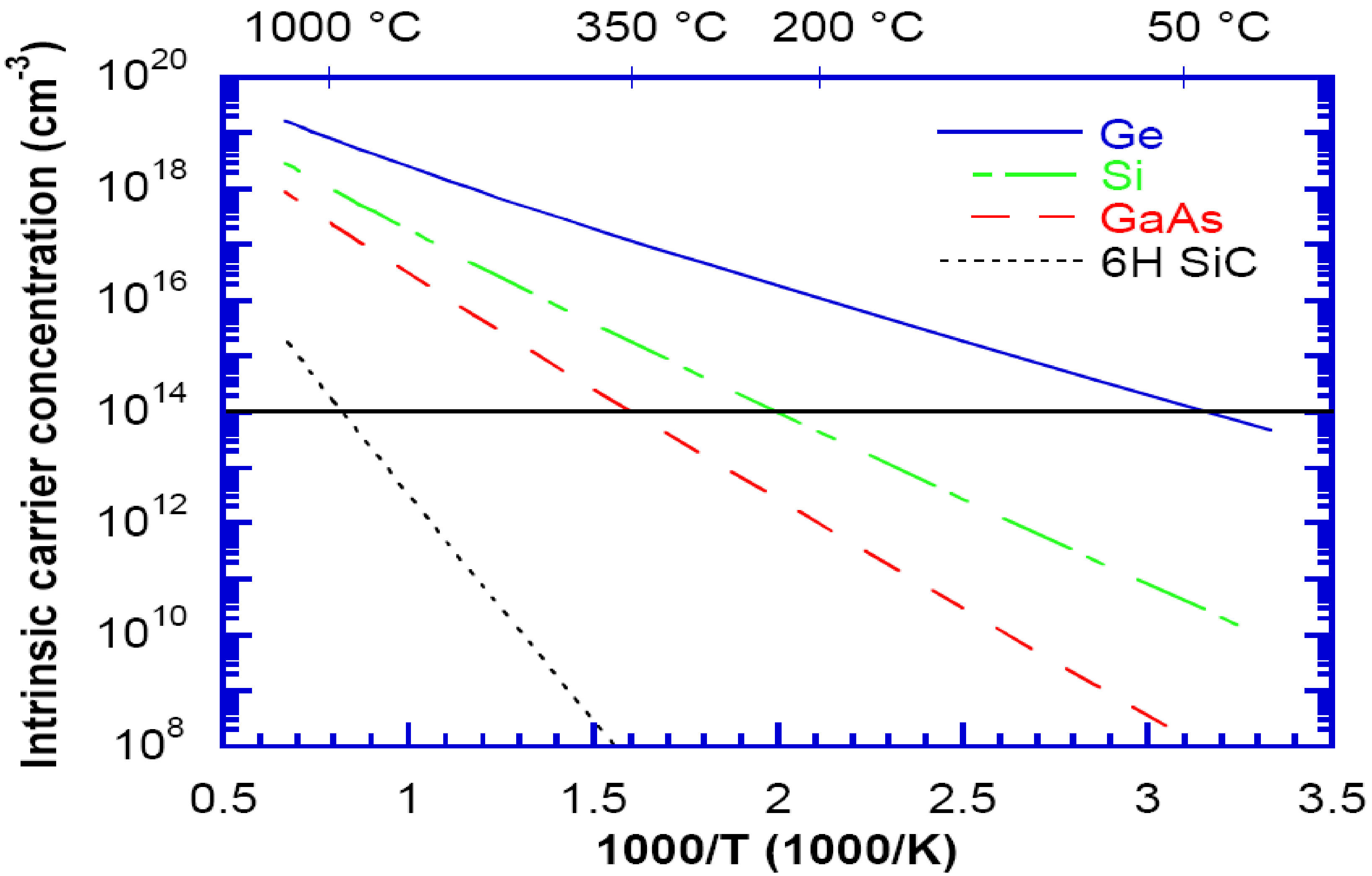
High frequency devices

$$\tau = \frac{W}{2v_{sat}}$$

$$C \propto \varepsilon_r$$

at 300 K	Si	GaAs	4H/6H-SiC	GaN
Ec (MV/cm)	0.25	0.3	2.2-2.5	3
ε_r	11.9	13	10	9.5
Vsat (cm/s)	$1x10^7$	$1x10^7$	$2x10^7$	$3x10^7$

High temperature devices



High power devices

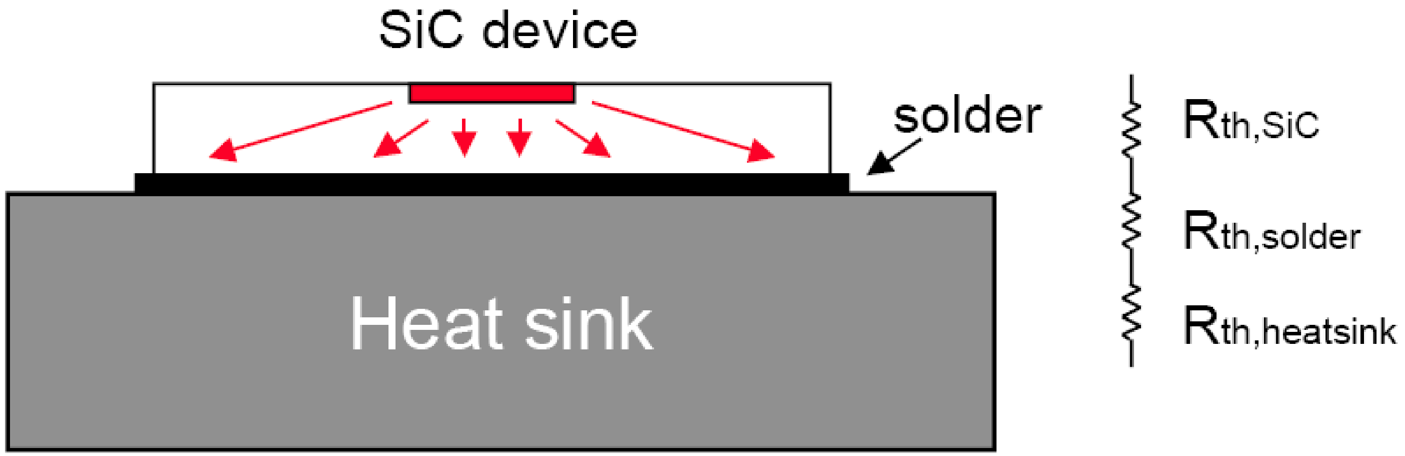
$$\Delta T = R_{TH}\,P = \frac{l}{\lambda\,A}P$$

λ : thermal conductivity

$$P_{SiC} \approx 10 \times P_{Si}$$

$$\lambda_{SiC} \approx 2-3 \times \lambda_{Si}$$

$$\Delta T_{SiC} \approx 5 \times \Delta T_{Si}$$



High integration devices ?

- Needs good material, few defects
- Not for SiC!

SiC VLSI ?

Summary Why SiC ?

- High critical field
  => low on-resistance (high frequency)
- Low permittivity and high v_{sat}
  => high frequency
- Wide bandgap
  => high temperature
- High thermal conductivity
  => high power and high temperature

2. How do we make SiC devices?

- SiC wafers
- SiC epitaxy
- Heteroepitaxy
- SiC doping
- SiC etching
- SiC isolation
- SiC contacts

SiC wafers

- SiC Growth Methods

  ✓Acheson process (Acheson 1892)

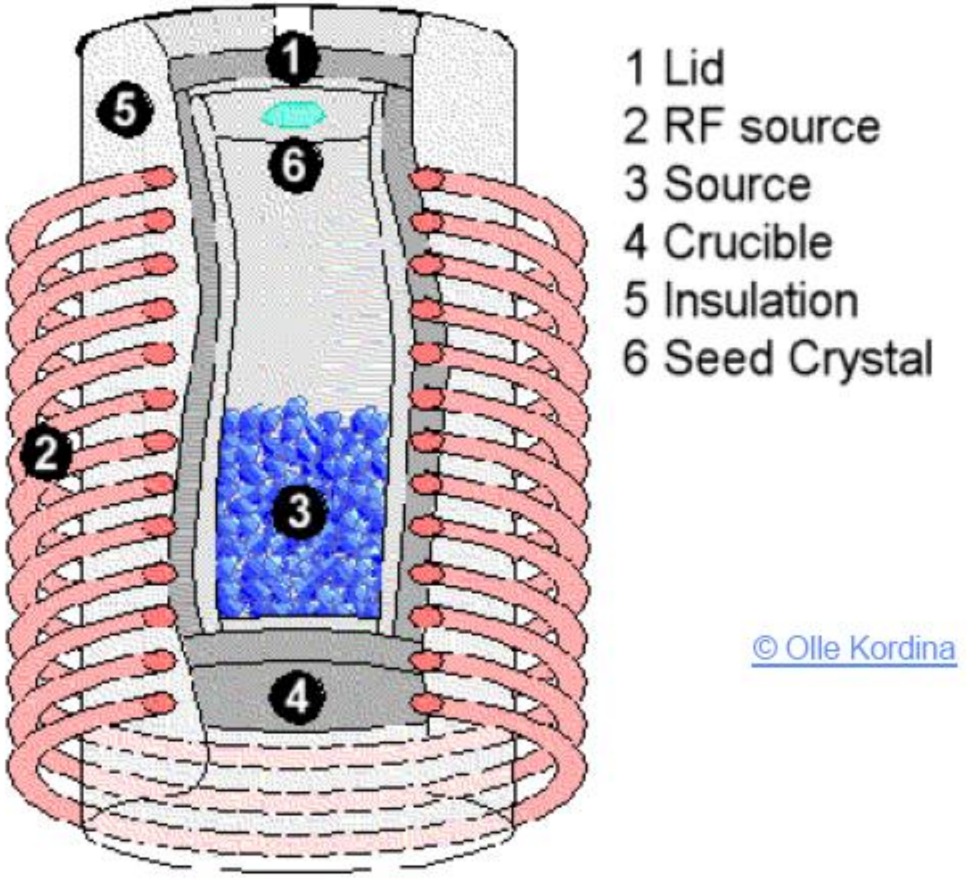
  ✓Lely process (Lely 1954)

  ✓ Modified Lely process (Tairov and Tsvetkov 1978; Tairov and Tsvetkov 1981)

SiC wafers

2300 °C

1 mm/h



Schematic drawing of a modified Lely setup

SiC wafers

- **The crystal growth quality**

In 2013

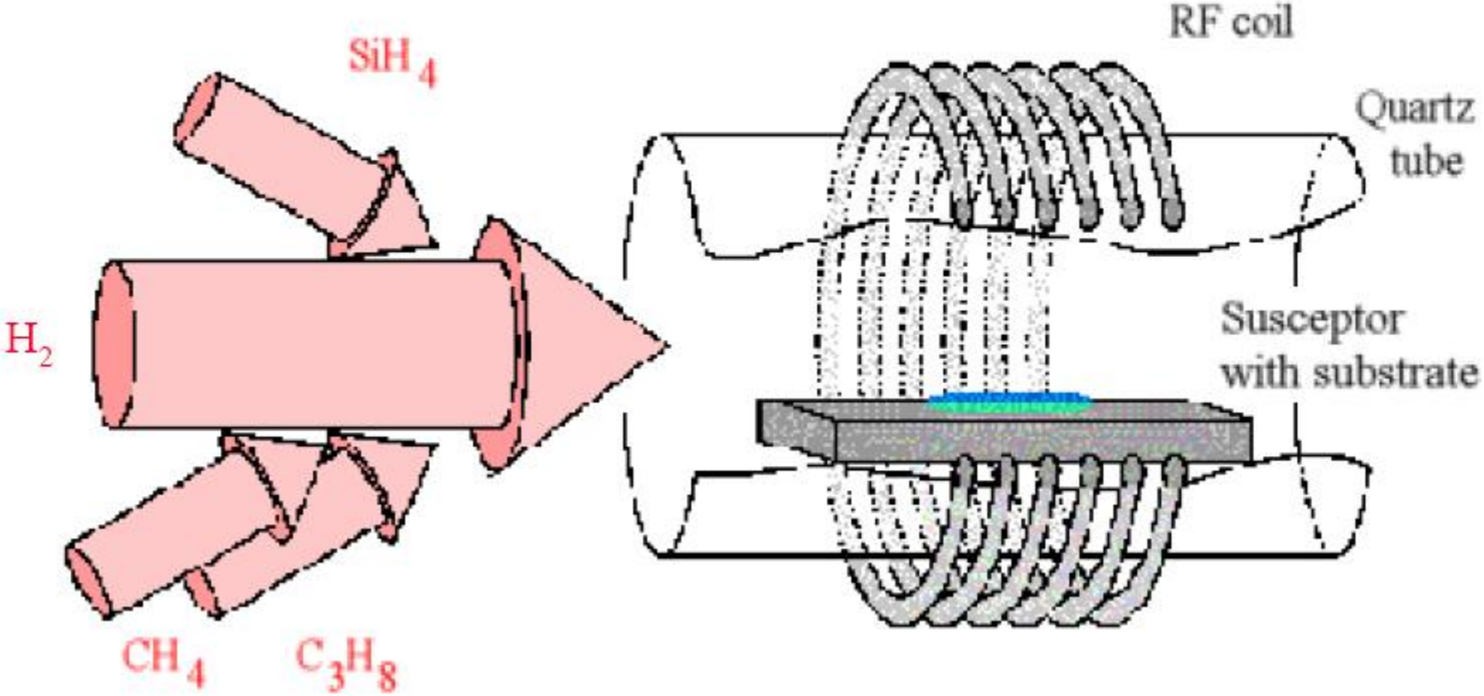
✓ 6” wafers available

✓ with 0.2 micropipes/cm^2

✓ less than 30 dislocations/cm^2

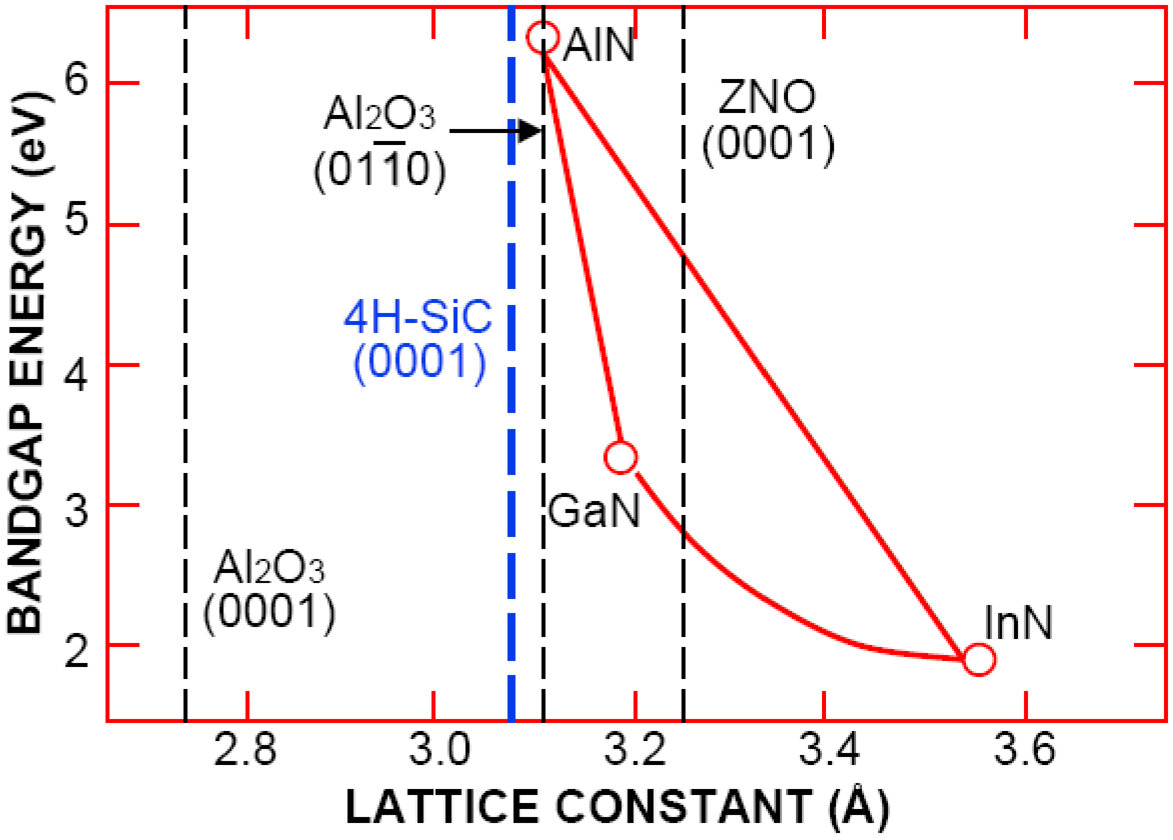
SiC epitaxy

1400-1600 °C   3 μm/h



The Principle of SiC CVD. The precursors are transported by the hydrogen to a zone where the reactions takes place

Heteroepitaxy

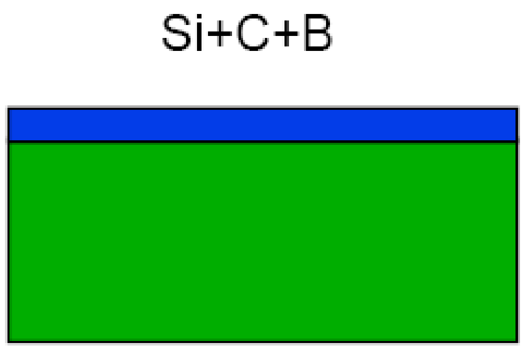


CVD:
900-1200 °C
MBE:
700-800 °C

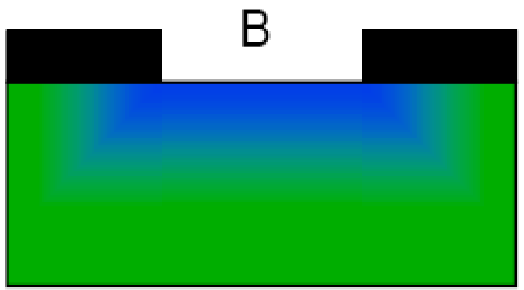
SiC doping

Dopants in SiC:
n-type and p-type

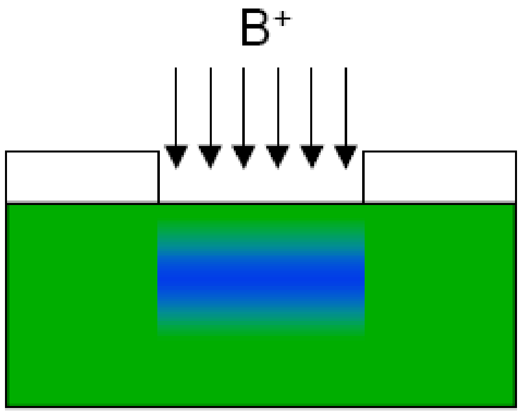
III	IV	V
B 5	C 6	N 7
Al 13	Si 14	P 15



Epitaxy 1400-1600 °C



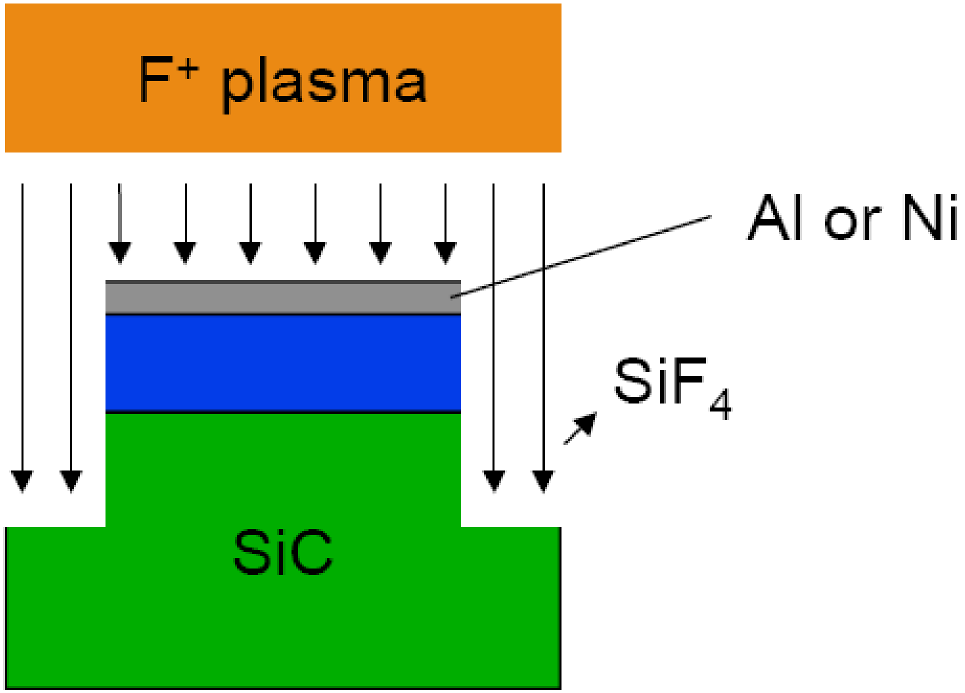
Diffusion > 1800 °C



Implant 700 °C
Anneal 1200-1700 °C

SiC etching

- Wet etching using KOH (500°C) ?
- Dry etching using CF_4, SF_6 etc



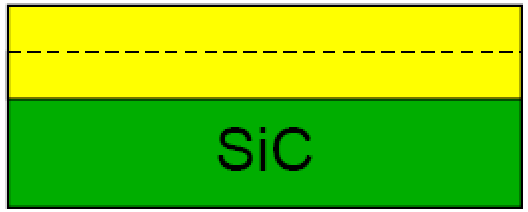
SiC isolation

Thermal oxidation of SiC (>1,100 ^oC):

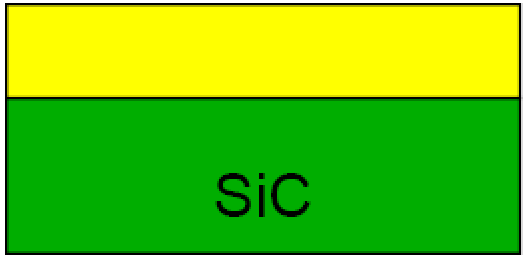
$$2\,SiC + 3O_2 \Rightarrow 2\,SiO_2 + 2\,CO$$

Thermal oxidation of silicon:

$$2\,Si + 2\,O_2 \Rightarrow 2\,SiO_2$$

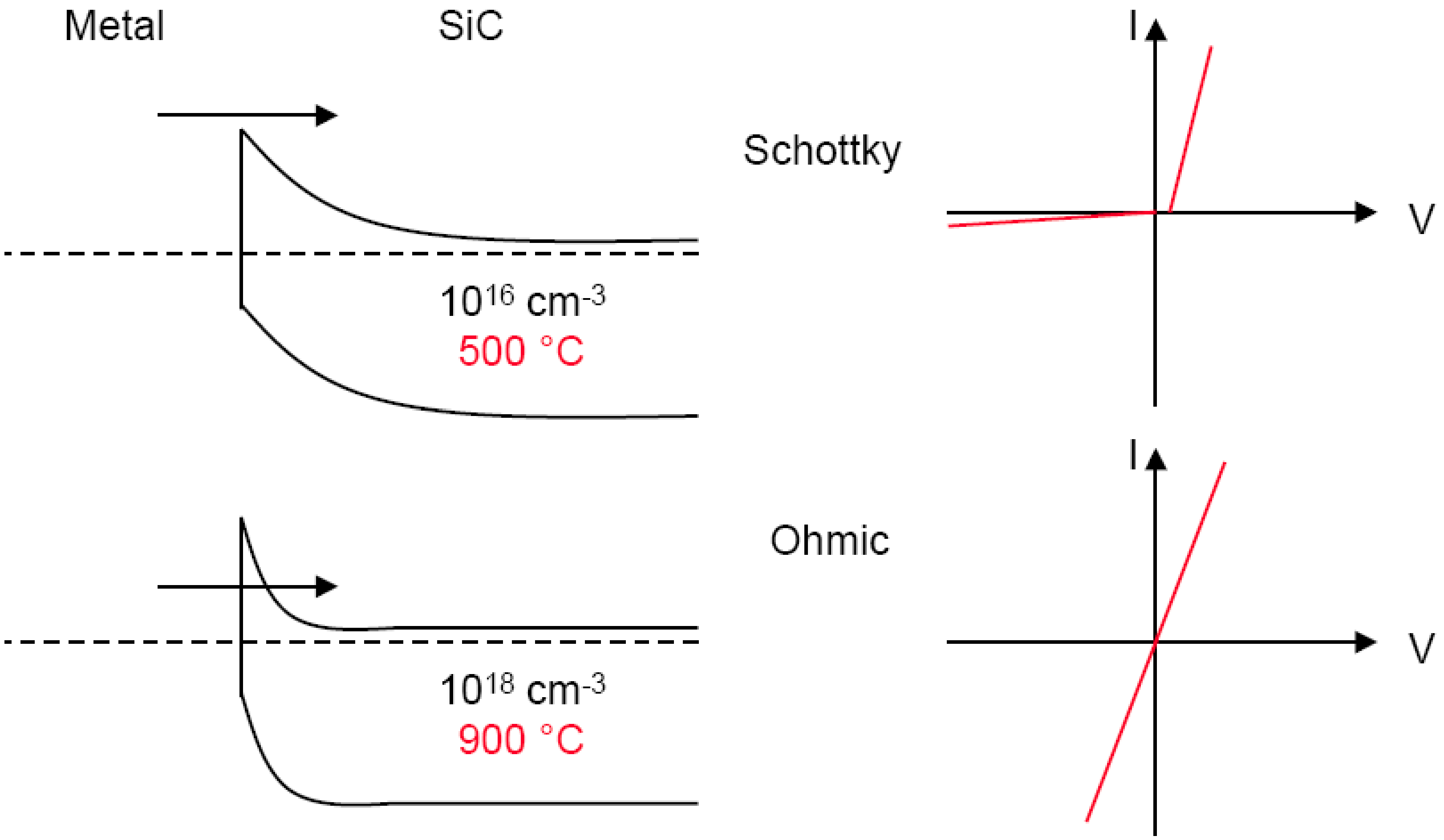


Thermal oxide 1100 °C



Deposited oxide 700 °C

SiC contacts



Summary How SiC ?

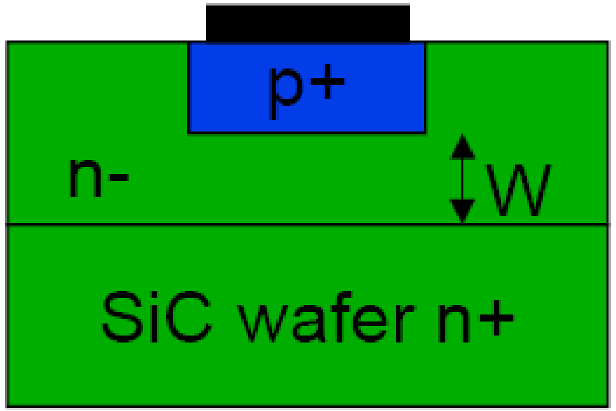
- Similar to silicon
- Much higher temperatures
- Nothing is impossible
- Material quality largest obstacle

3. Which SiC devices ...?

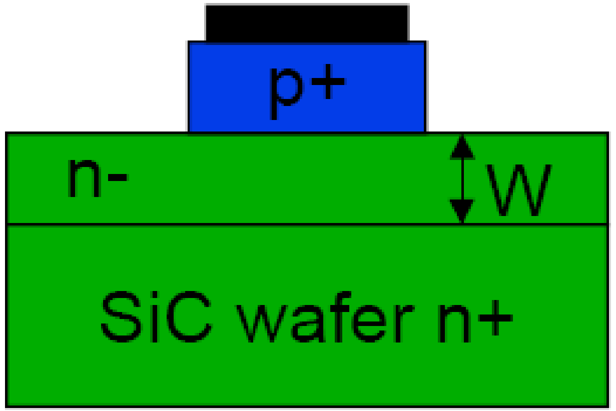
- Diodes
- Transistors
- Thyristors

pn Diodes

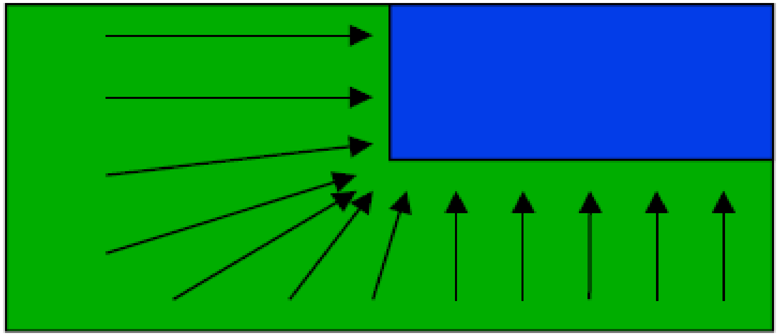
Ion implanted



Mesa etched

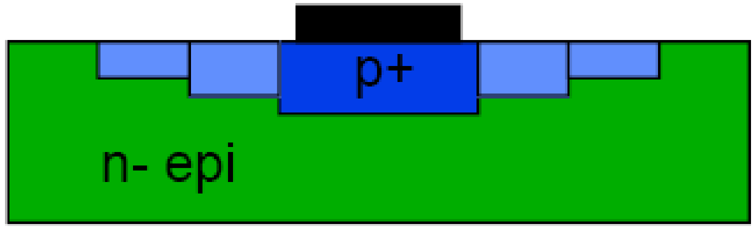


Field crowding causes premature breakdown

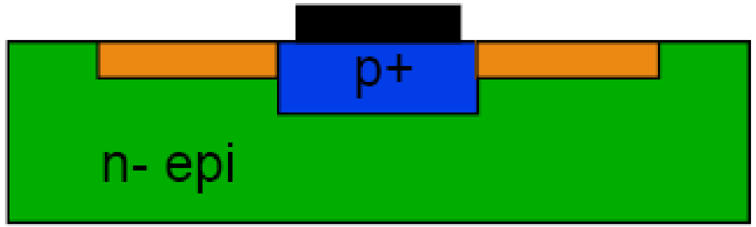


Junction Terminations

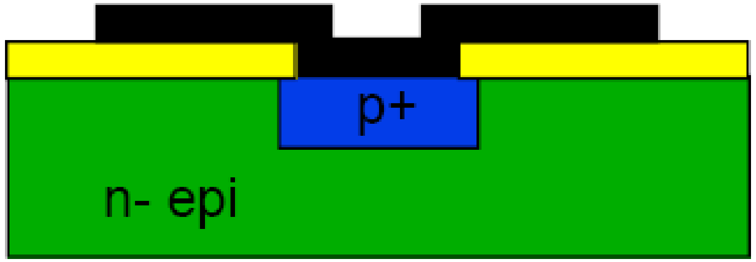
Junction Termination Extension



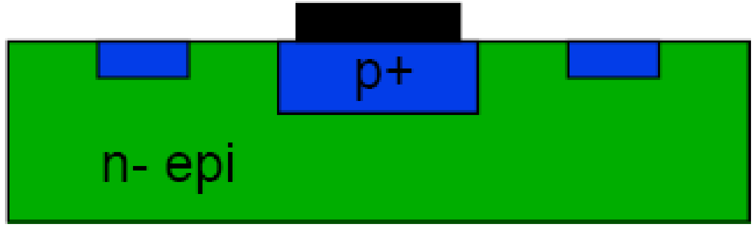
Ar Implant (damaged area)



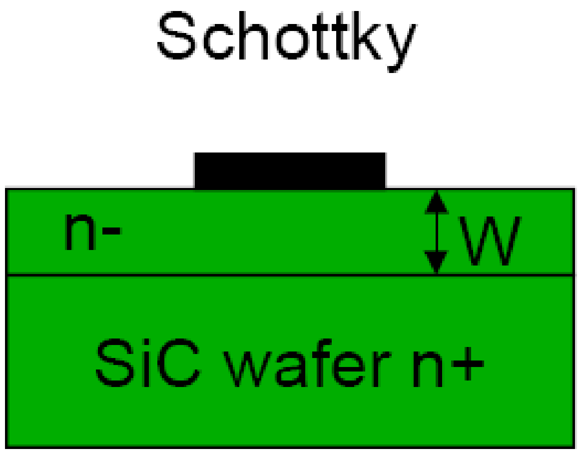
Field Plate on SiO_2



Field Ring(s) (circular)



Schottky Diodes

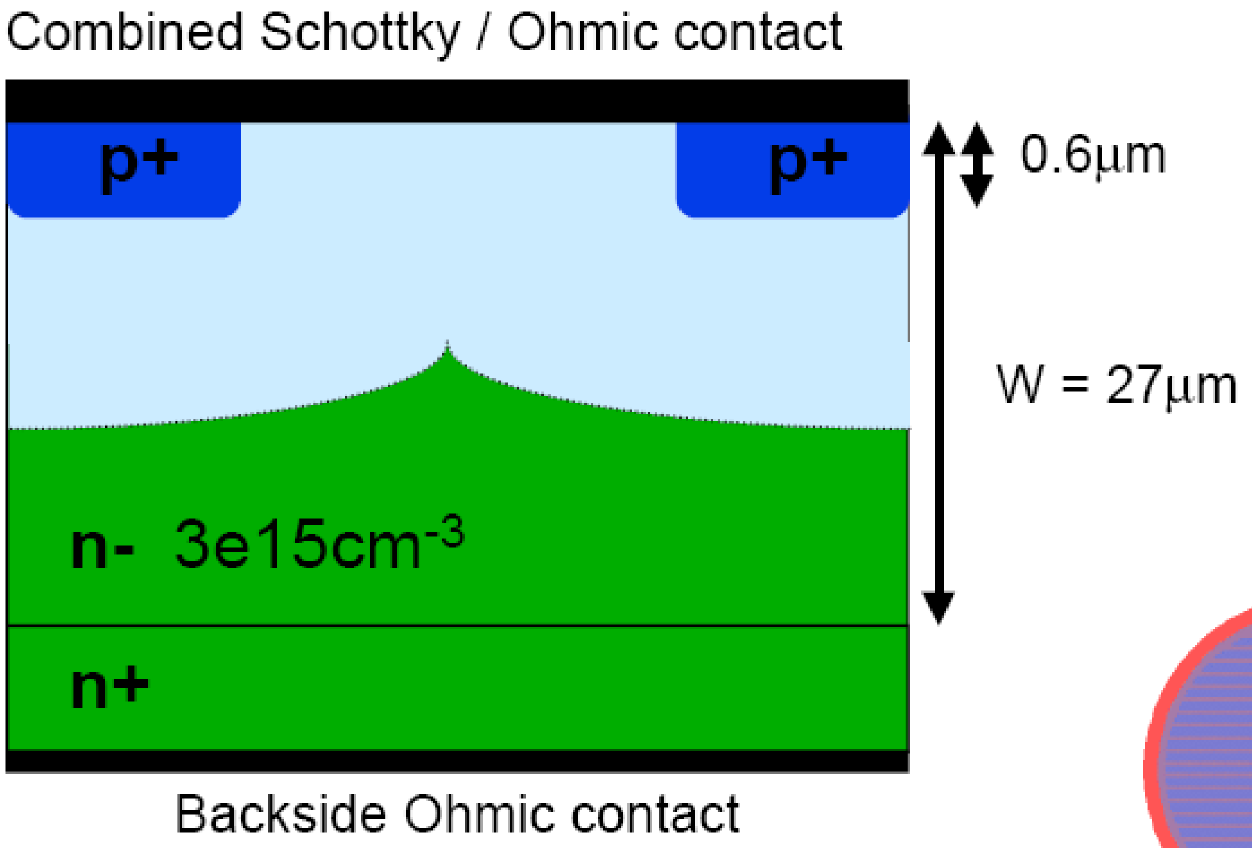


$$V_{F,Schottky} = R_{ON} J_F + \Phi_B$$

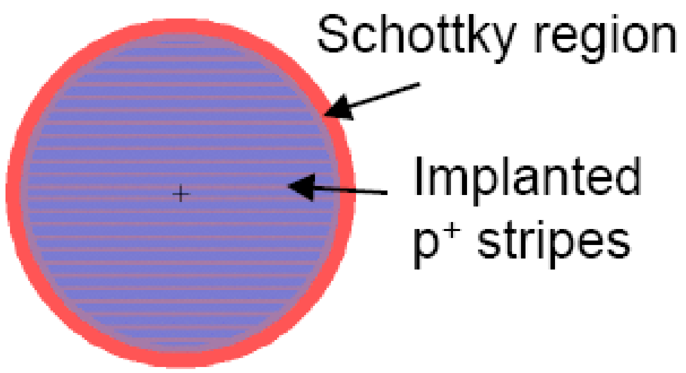
$$V_{F,pn} = R_{ON} J_F + V_{bi}$$

- Application: protection for silicon IGBTs
- No reverse recovery from majority carriers
- Forward voltage drop lower than pn diode

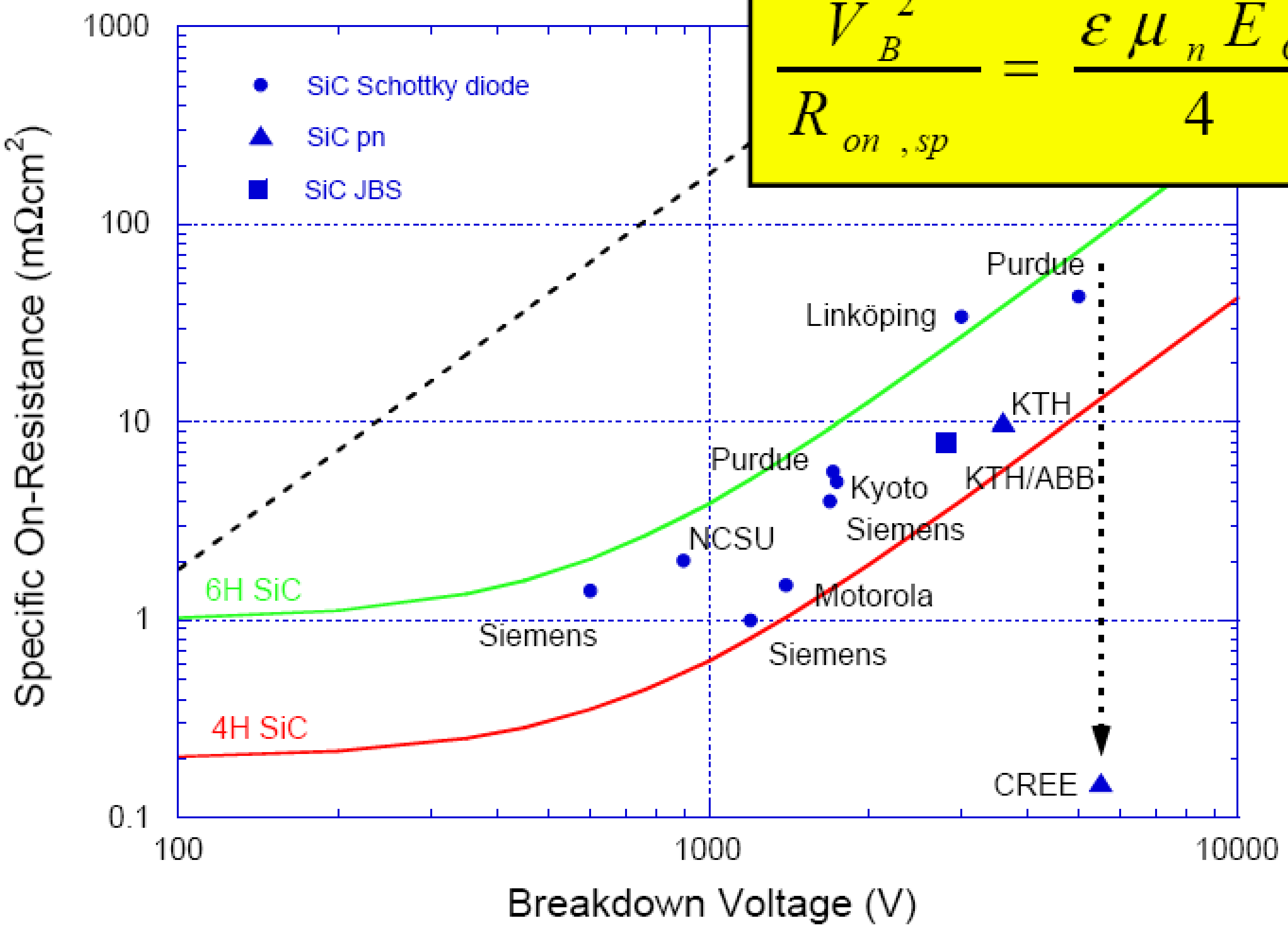
JBS Diodes



- Combination of Schottky and pn diode



2 terminal devices



$$\frac{V_B^2}{R_{on,sp}} = \frac{\varepsilon \mu_n E_C^3}{4}$$

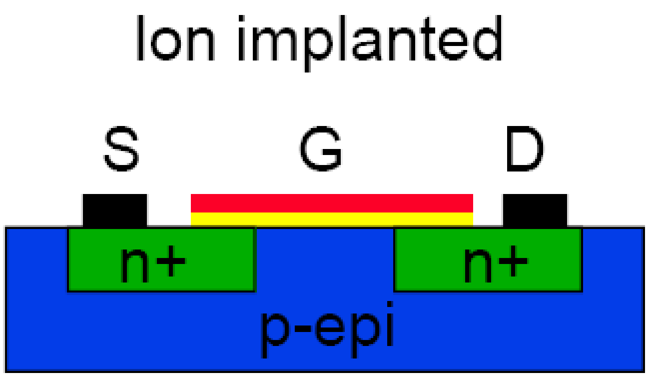
- Schottky and now JBS diodes are commercially available up to 1.2 kV: CREE, Infineon basically.
- PiN diodes will be only relevant for BV over 3 kV.
  - Need to overcome its reliability problem (forward voltage drift) before commercialization

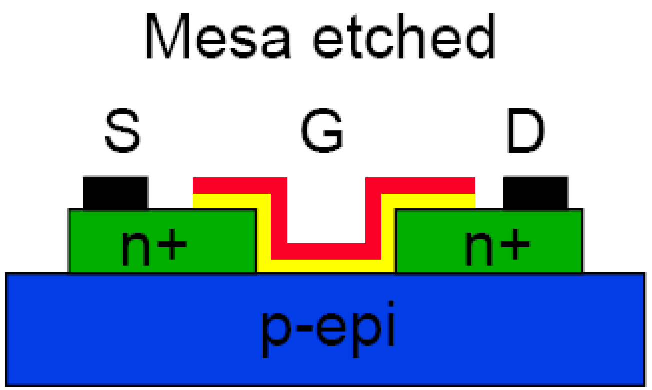
MOSFETs

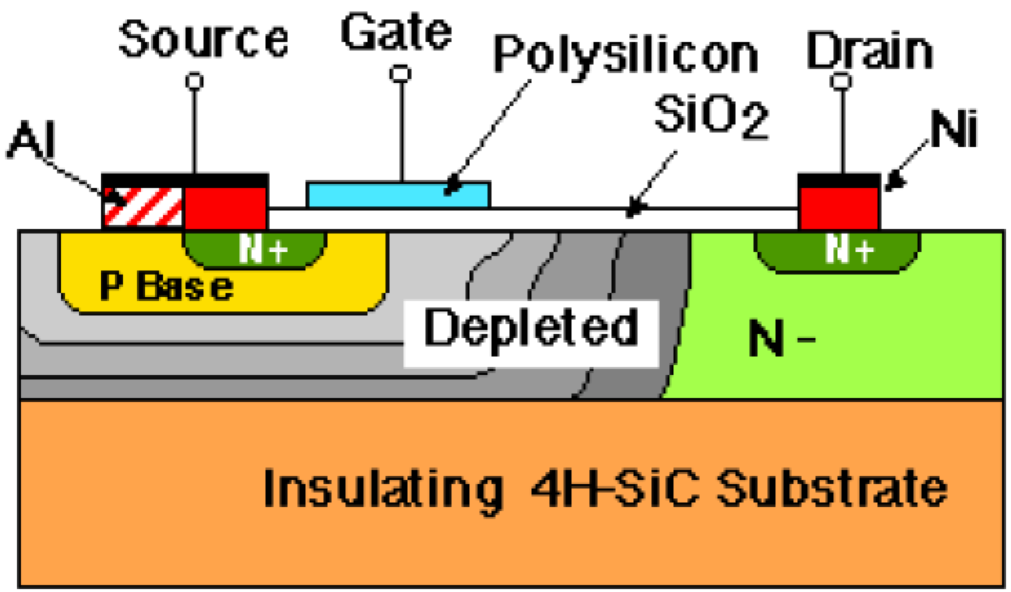
- **MOSFET Advantages**
  - Simple planar structure
  - Voltage gate control
  - Extensively used in Si technology
  - Normally-off

- **MOSFET main problems**
  - Low channel mobility in SiC
  - High temperature operation ?
  - Gate reliability ?

Lateral MOSFETs

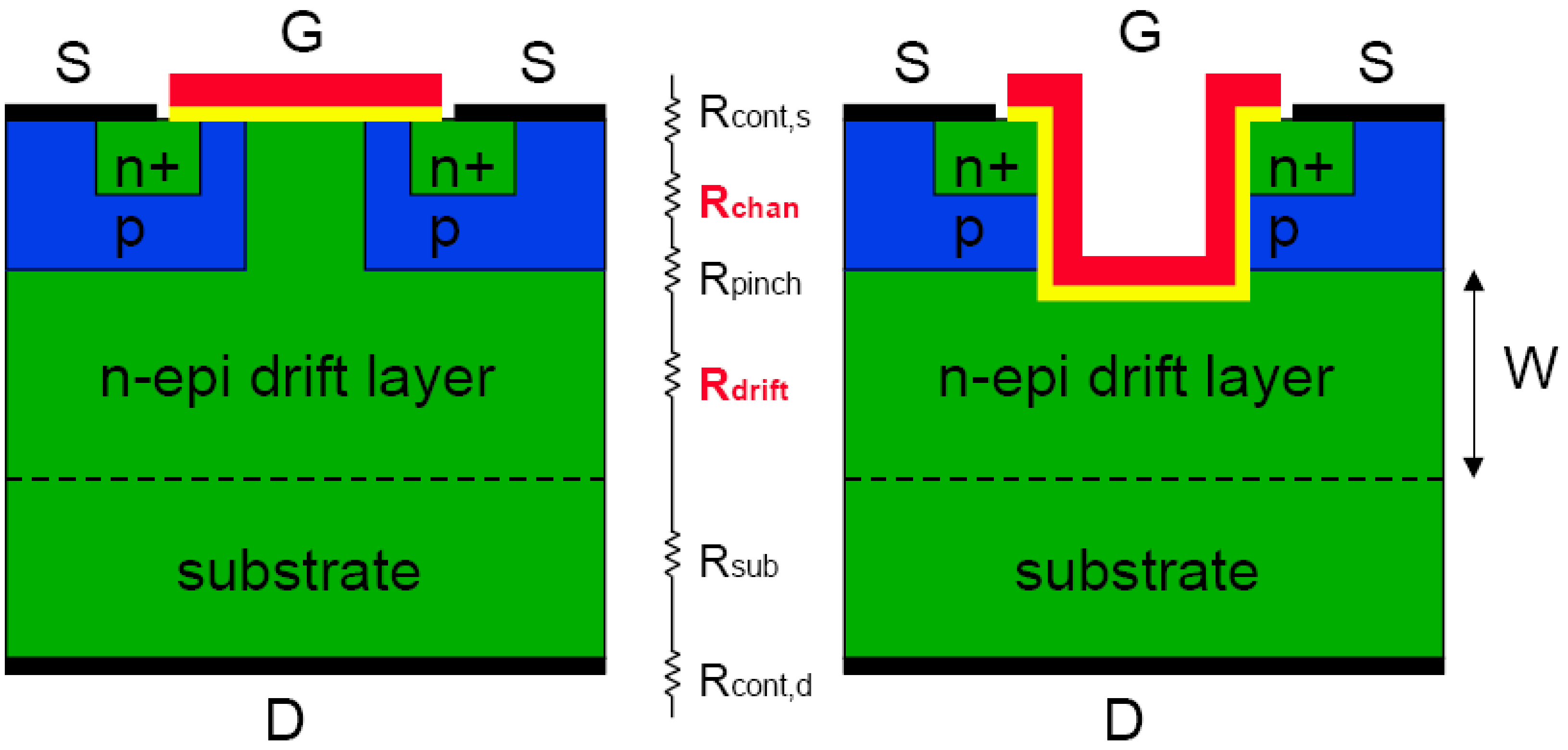






Vertical MOSFETs

DMOSFET versus UMOSFET



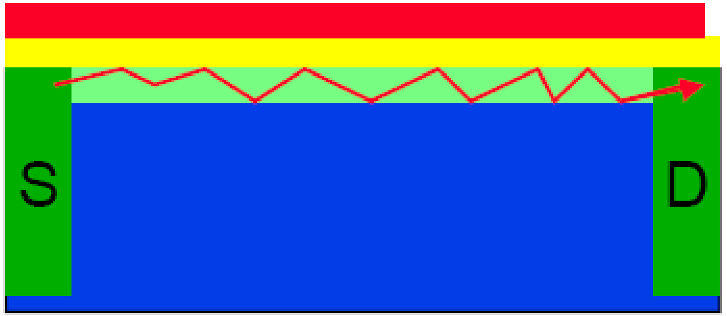
MOSFET Channel Mobility

$$g_D \equiv \frac{\partial I_D}{\partial V_D} = \frac{Z}{L}\mu_{eff} C_{ox}(V_G - V_T) = \left(\frac{A}{R_{on,sp}}\right)$$

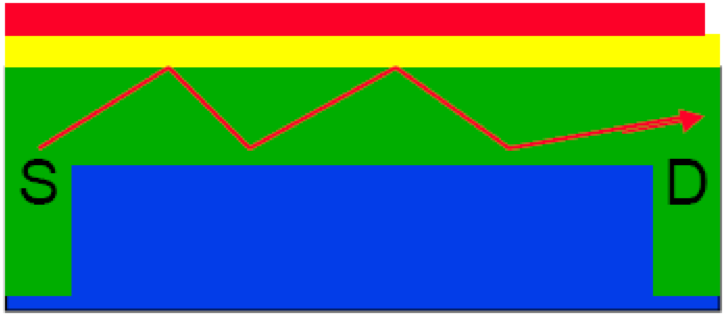
Inversion channel:

$$\mu_{eff} = {}^{1}\!/_{2}\, \mu_{n,bulk}(Si)$$

$$\mu_{eff} = {}^{1}\!/_{10}\, \mu_{n,bulk}(SiC)$$



Accumulation channel:



MOSFET Reliability

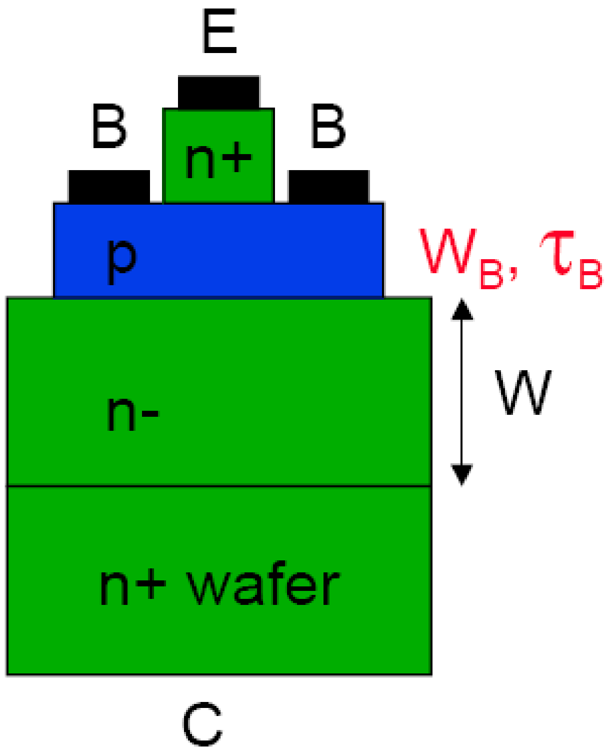
$$E_{oxide,ON} = \frac{V_G}{t_{oxide}}$$

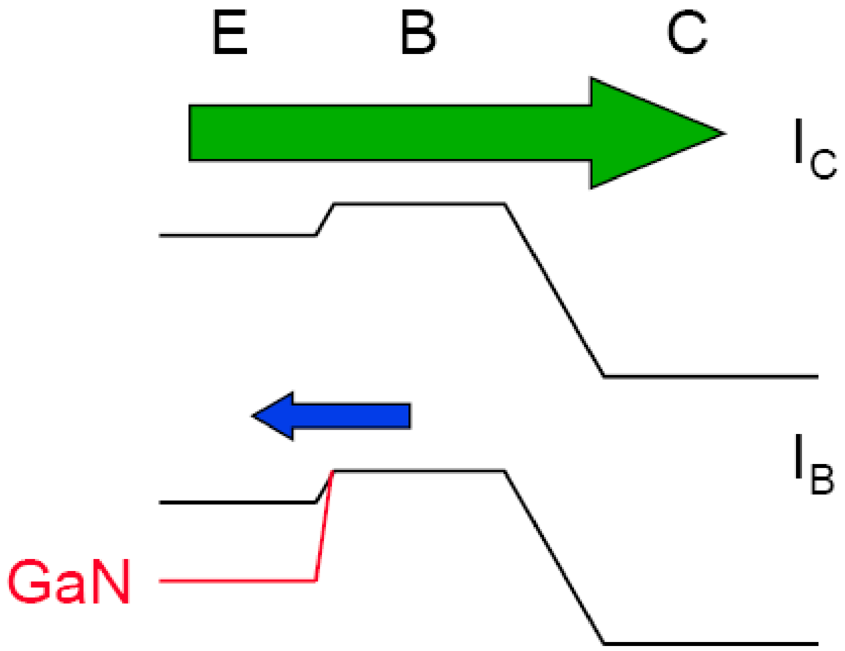
$$E_{oxide,OFF} = E_{SiC}\frac{\varepsilon_{SiC}}{\varepsilon_{oxide}}$$

- $E_{C,SiC}$ = 2.5 MV/cm
- $E_{C,oxide}$ = 10 MV/cm
- For long term reliability:
- E_{oxide} < 3 MV/cm

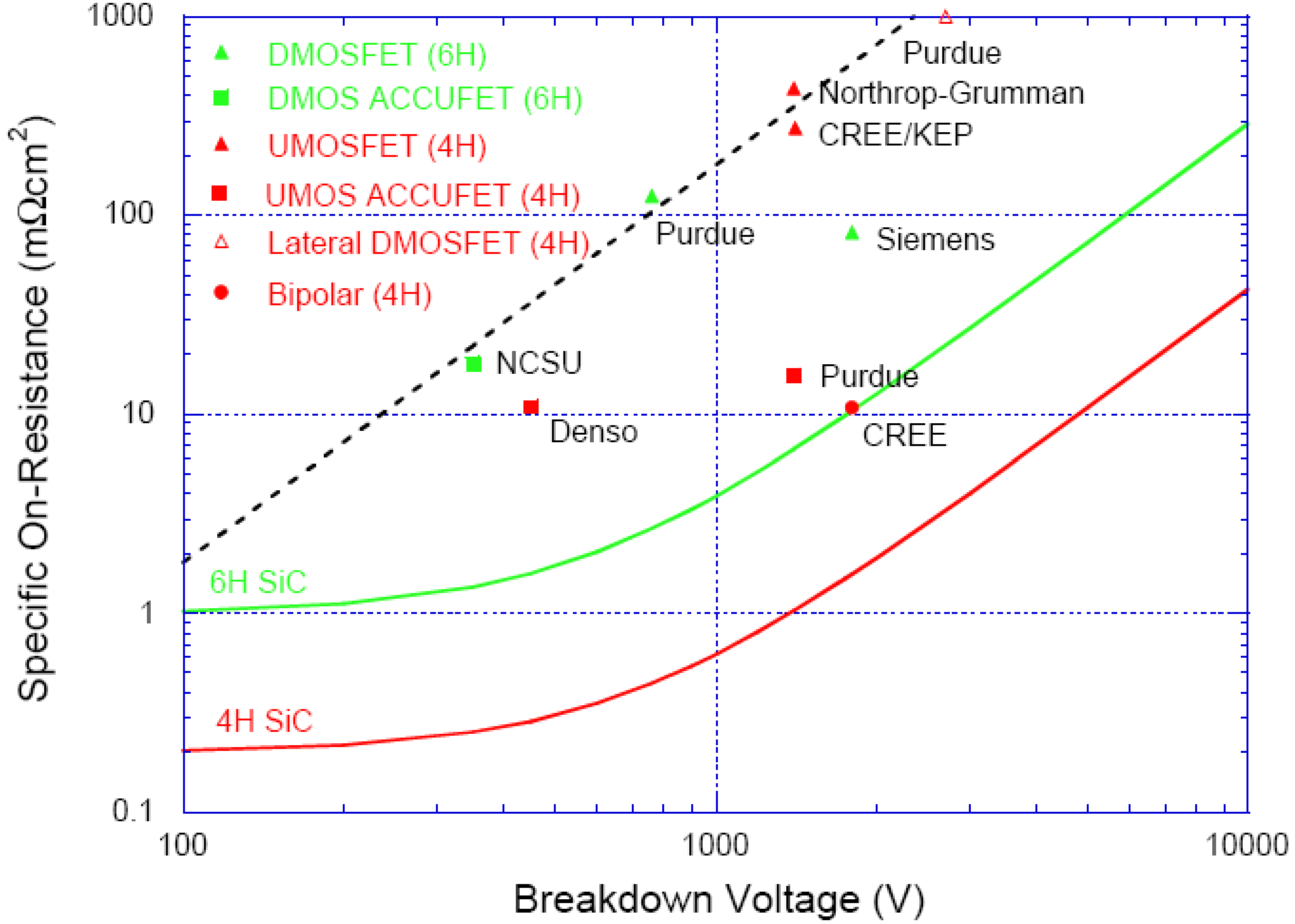
Bipolar Transistors

- High voltage or High frequency
- Hetrojunction od Homojunction



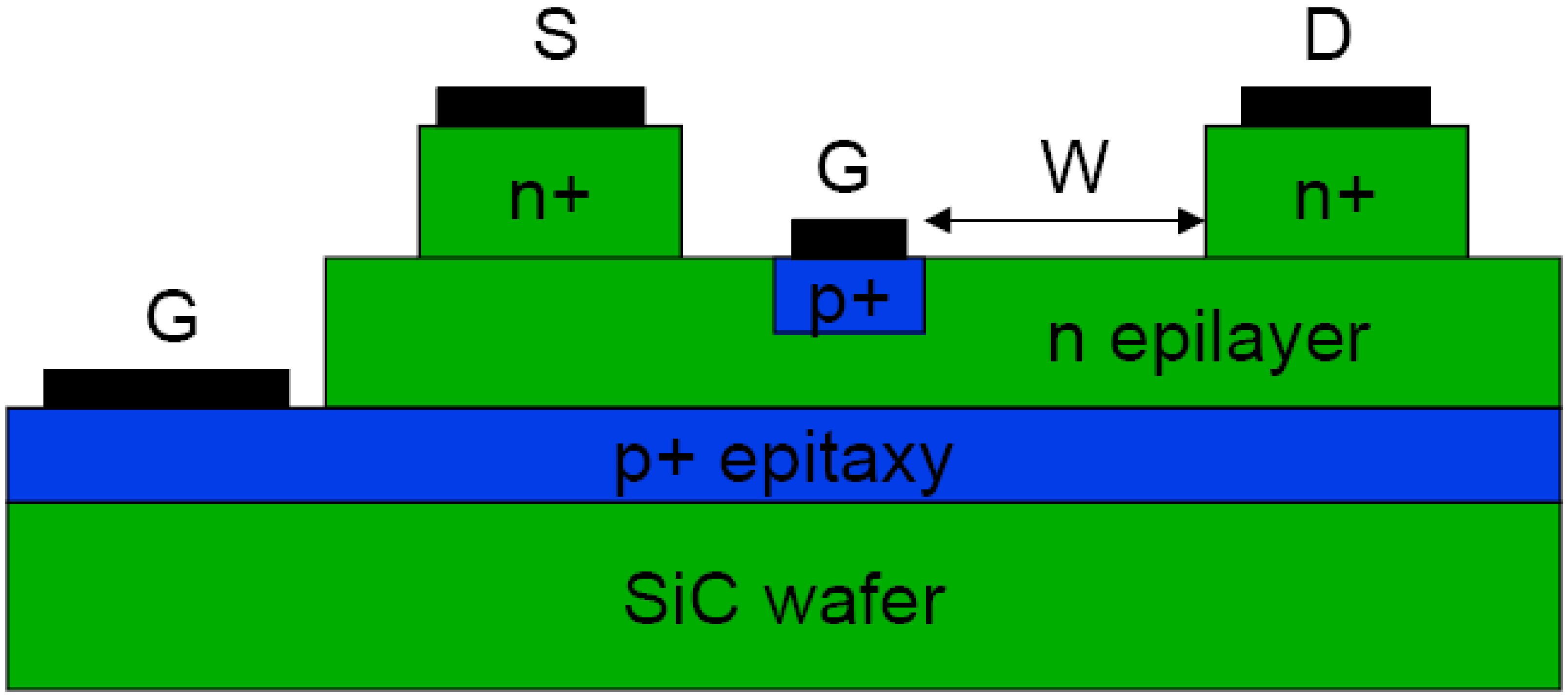


3 Terminal Devices: high V_B



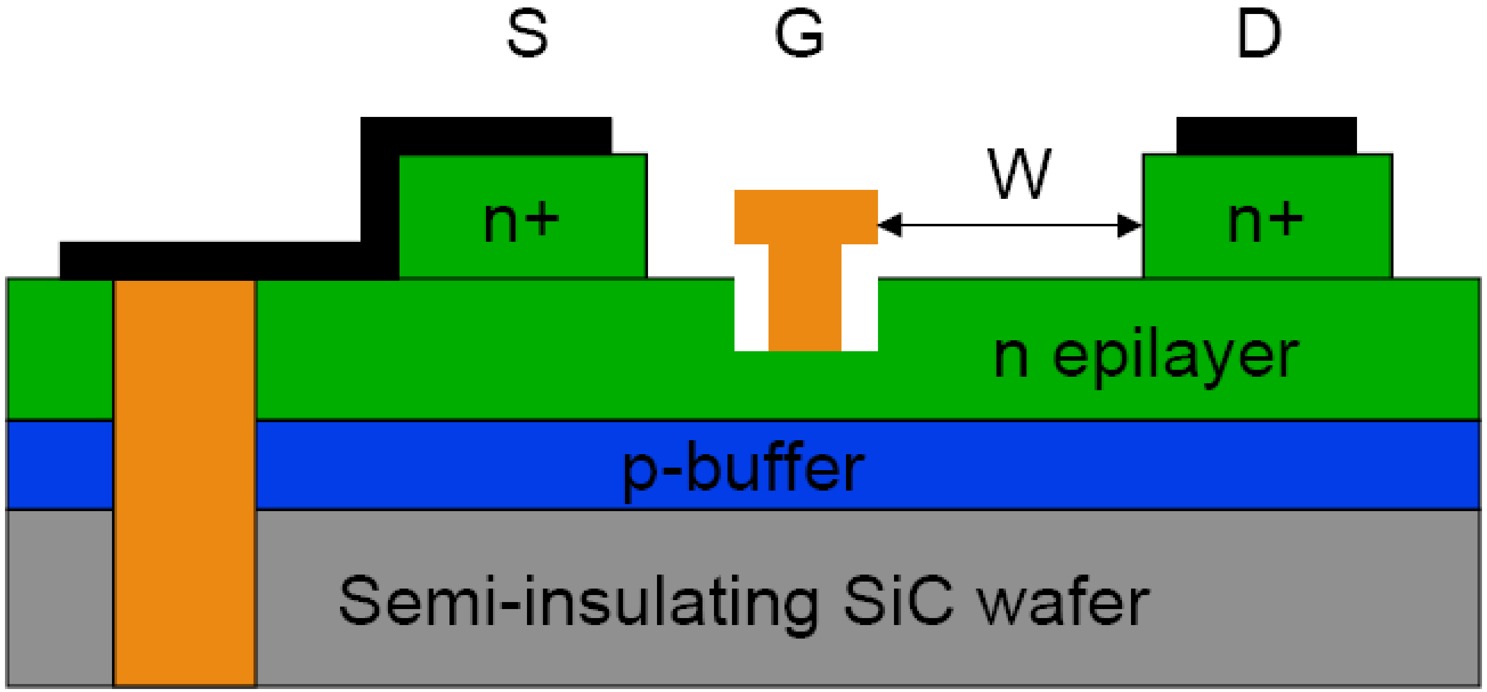
JFETs

- Junction gate difficult to reduce in length
- Semi-insulating wafer ?



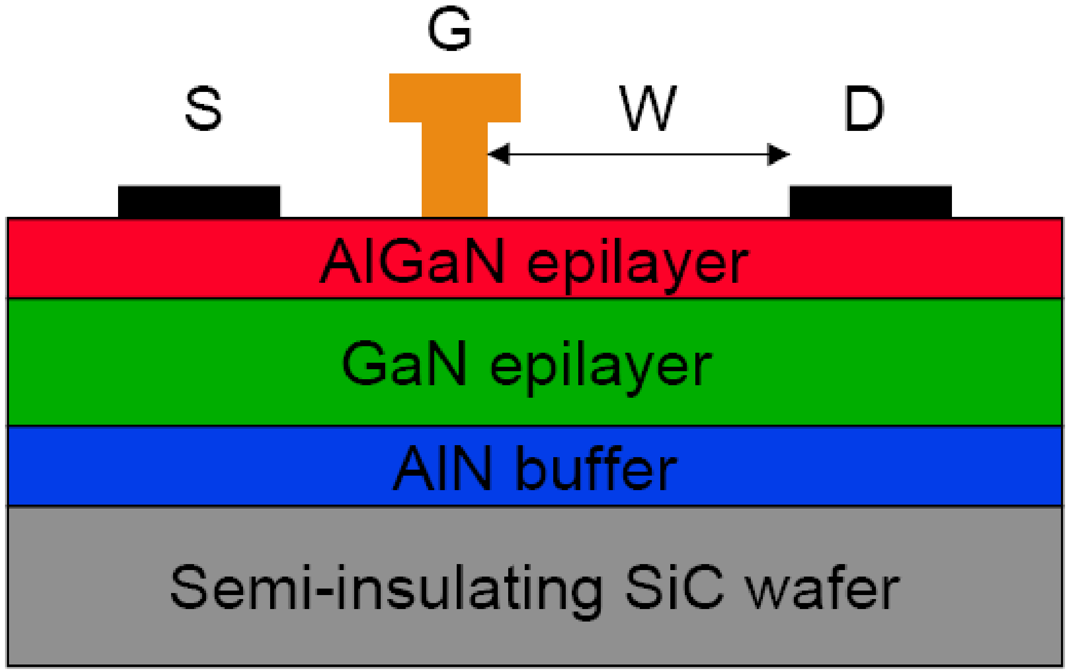
MESFETs

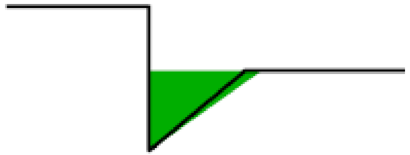
- Semi-insulating wafer to reduce capacitance
- Source via-hole to reduce inductance
- Schottky gate



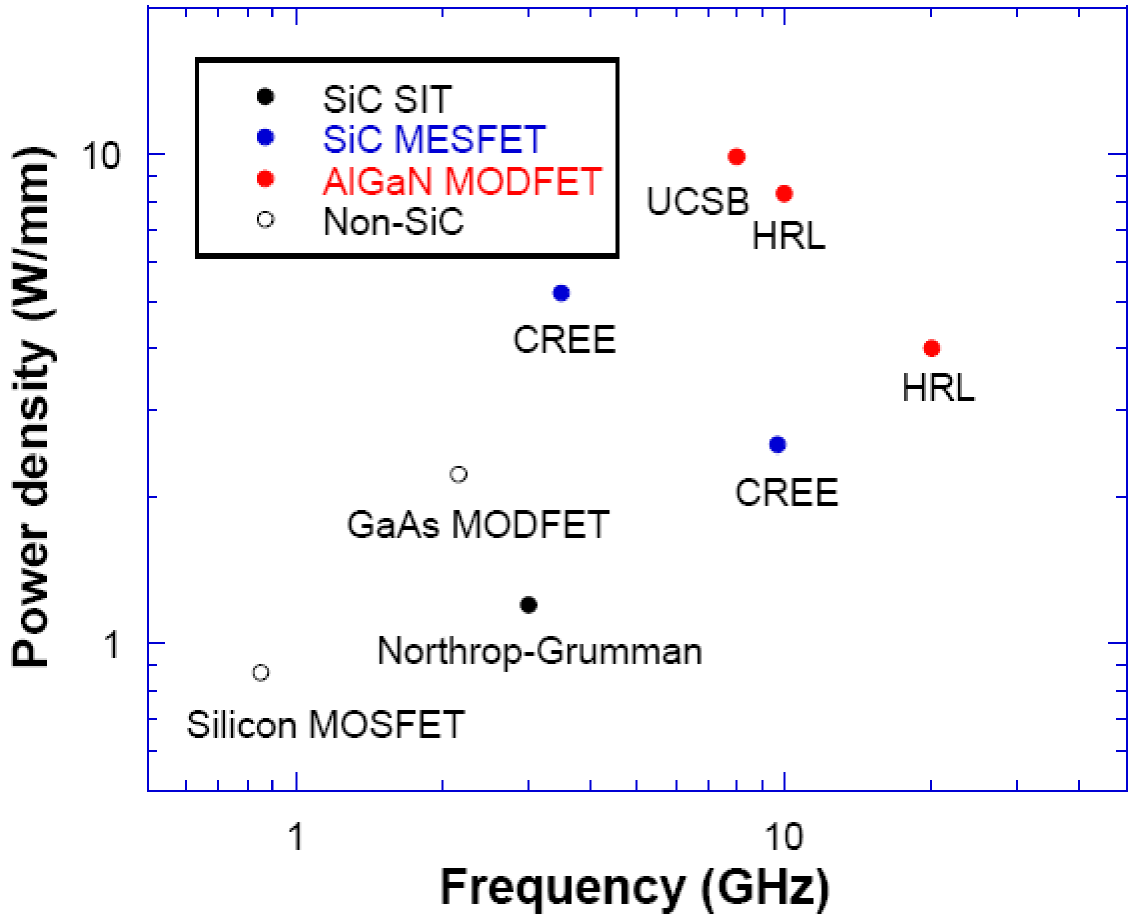
HFETs

- Semi-insulating wafer to reduce capacitance
- Low doped GaN channel layer (piezo)
- Schottky gate

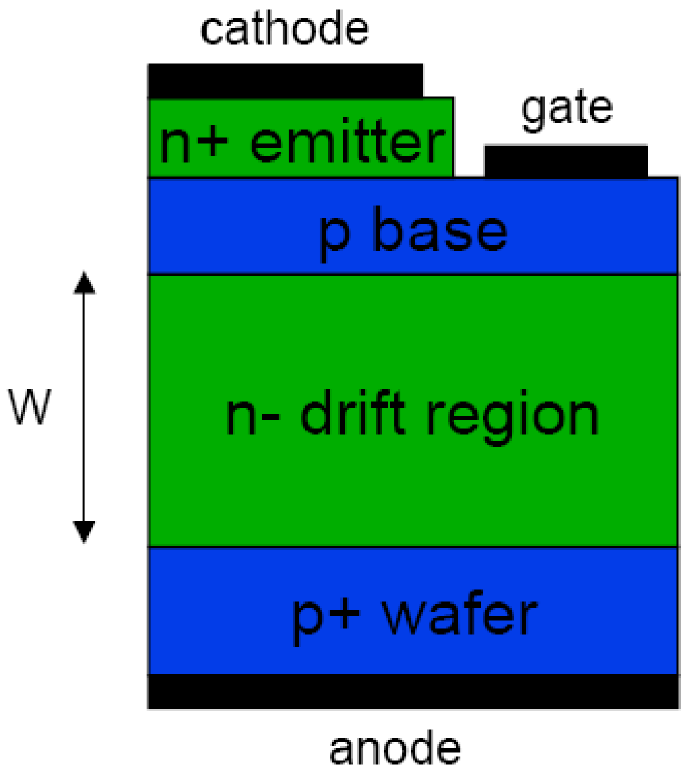


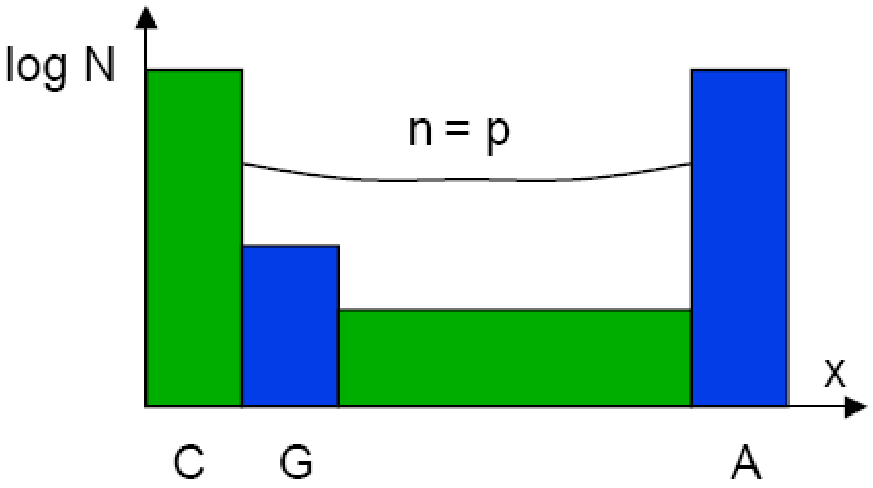


3 Terminal Devices: High Frequency



Thyristors





- Needs long minority carrier lifetime
- Needs large area

Summary Which SiC ?

- Many devices demonstrated
- Vertical (power) vs lateral (high frequency)
- Breakdown voltages close to theoretical
- MOSFET mobility obstacle
- Production economy - yield - chip size

CONCLUSIONS

WHY SiC?

Excellent Properties!

HOW SiC?

Higher T than Silicon!

WHICH SiC?

Small Area for Economy!