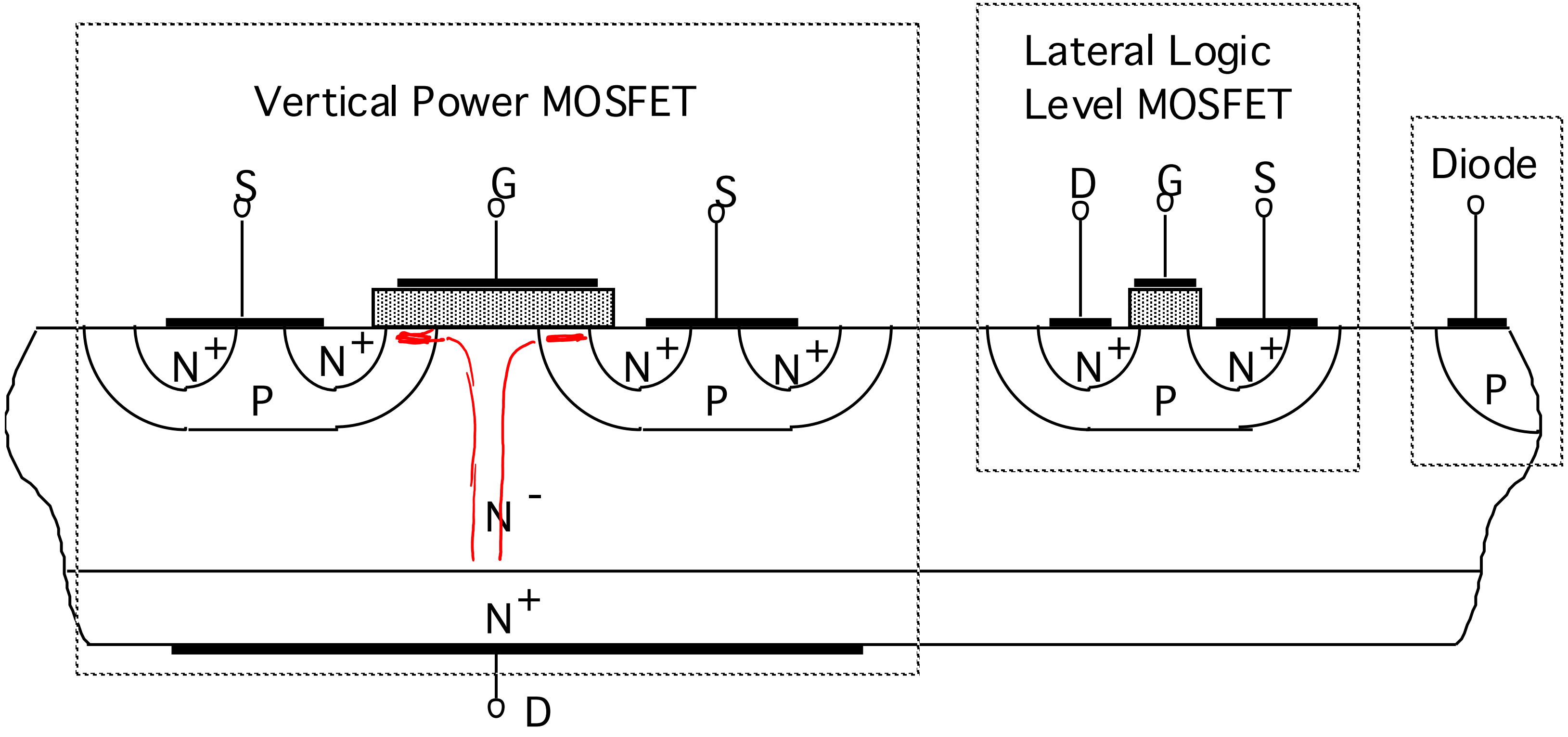
Power Integrated Circuits

Type	Ratings	Process (example)
Discrete modules	V up to ~KV, I up to ~KA	
Smart Power/Smart Switches	I < 50-100 A V < 1 KV	Vertical + Lateral Devices
High-Voltage ICs	I < 50-100 A, V< 1 KV	High Voltage BCD
High-density **PMICs**	V<100 V	High Density BCD

Smart Power / Smart Switches (I < 50-100 A, V < 1KV):

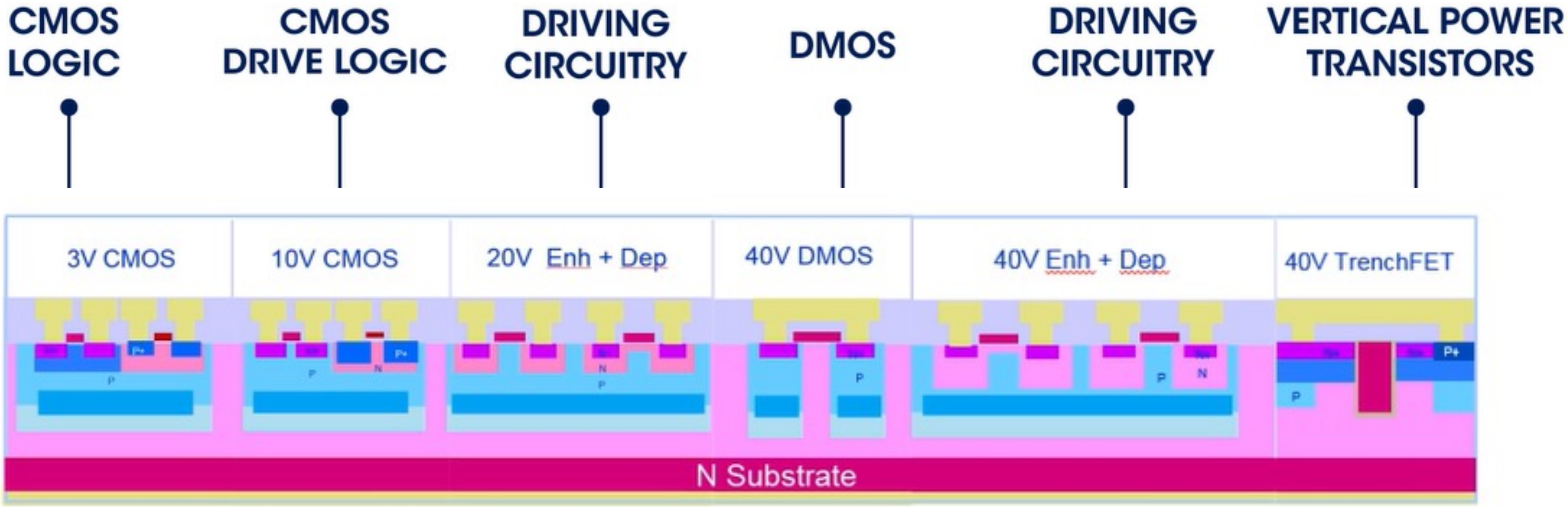
Vertical Power devices + Lateral Devices for (some) logic



If Drain of Power MOSFET at positive voltage → devices are insulated by the reversed biased p-body - n-drift region junction

Smart Power / Smart Switches (I < 50-100 A, V < 1KV):

Vertical Power devices + Lateral Devices for (some) logic



If Drain of Power MOSFET at positive voltage → devices are insulated by the reversed biased p-body - n-drift region junction

STM BCD Process

Three process technologies on a single chip

- **B**ipolar for precise analog circuits (e.g. bandgap)
- **C**MOS for digital design
- **D**MOS for power and high voltage

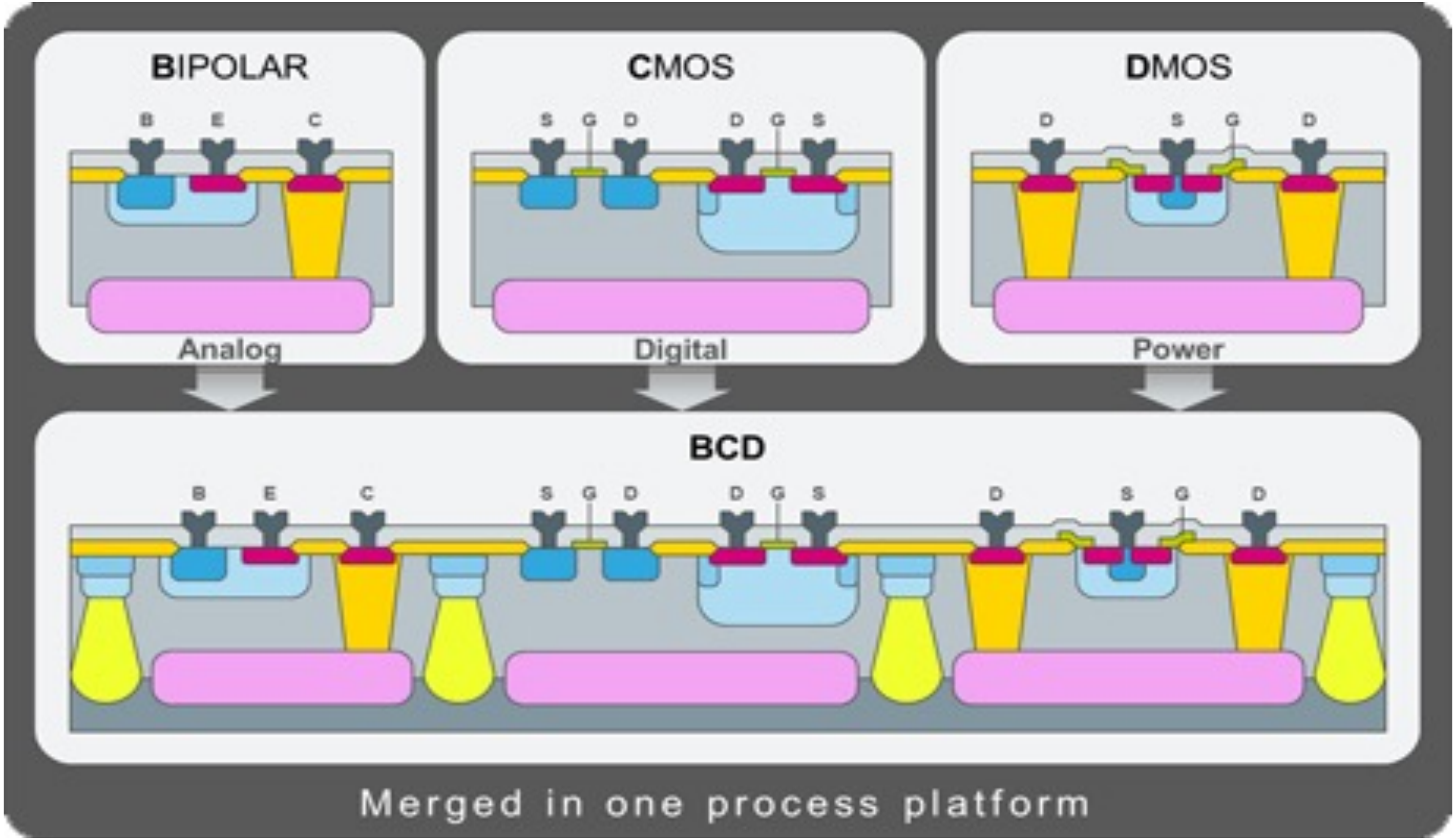
Pros:

- Improved reliability (no bonding, no complex packaging)
- Reduced EMI
- Smaller chip area (improved integration)

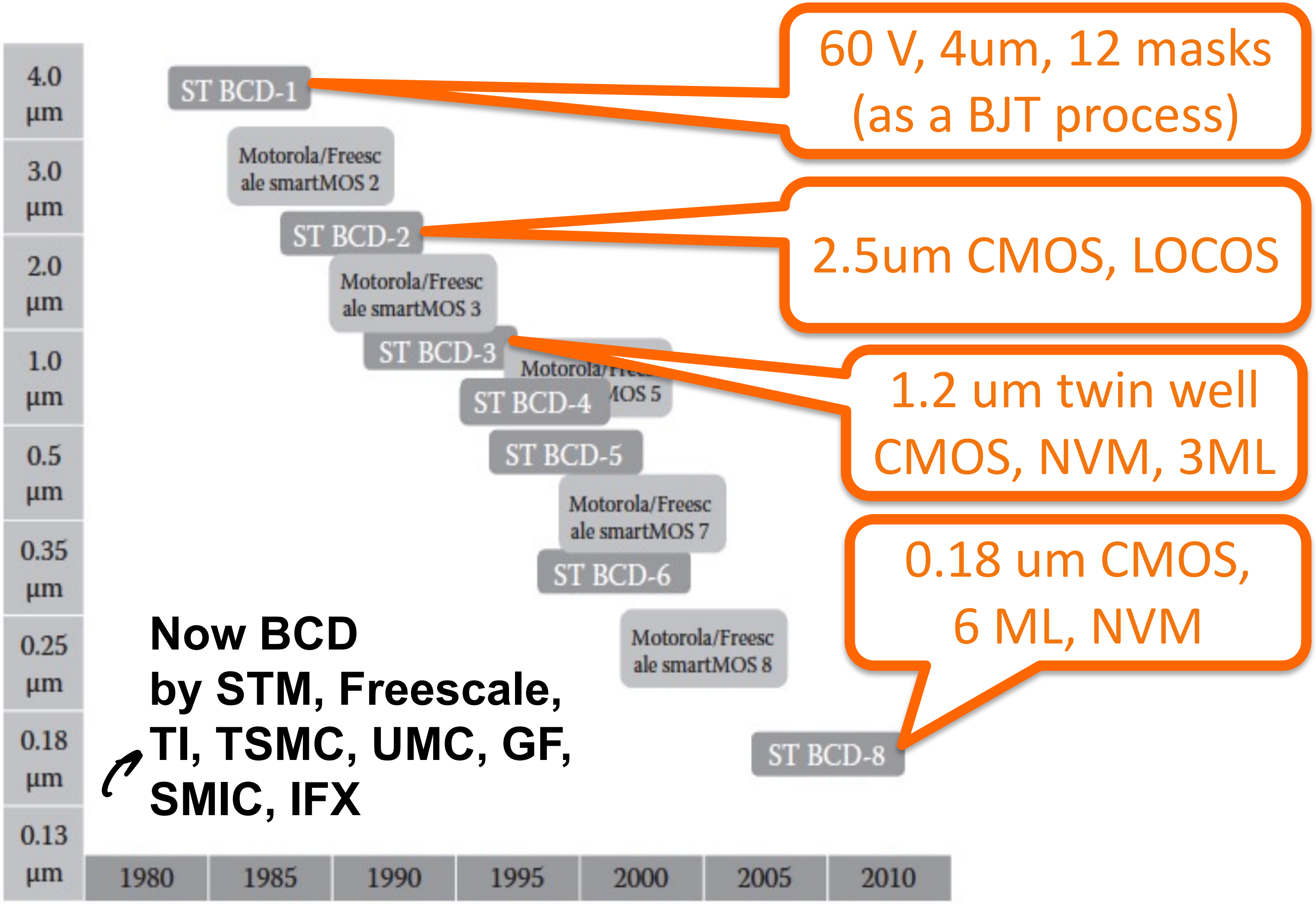
Cons

- No component is optimized (e.g. digital is not optimized (long channel lengths and thick oxides))

STM BCD Process



Chronology of BCD Processes



60 V, 4um, 12 masks
(as a BJT process)

2.5um CMOS, LOCOS

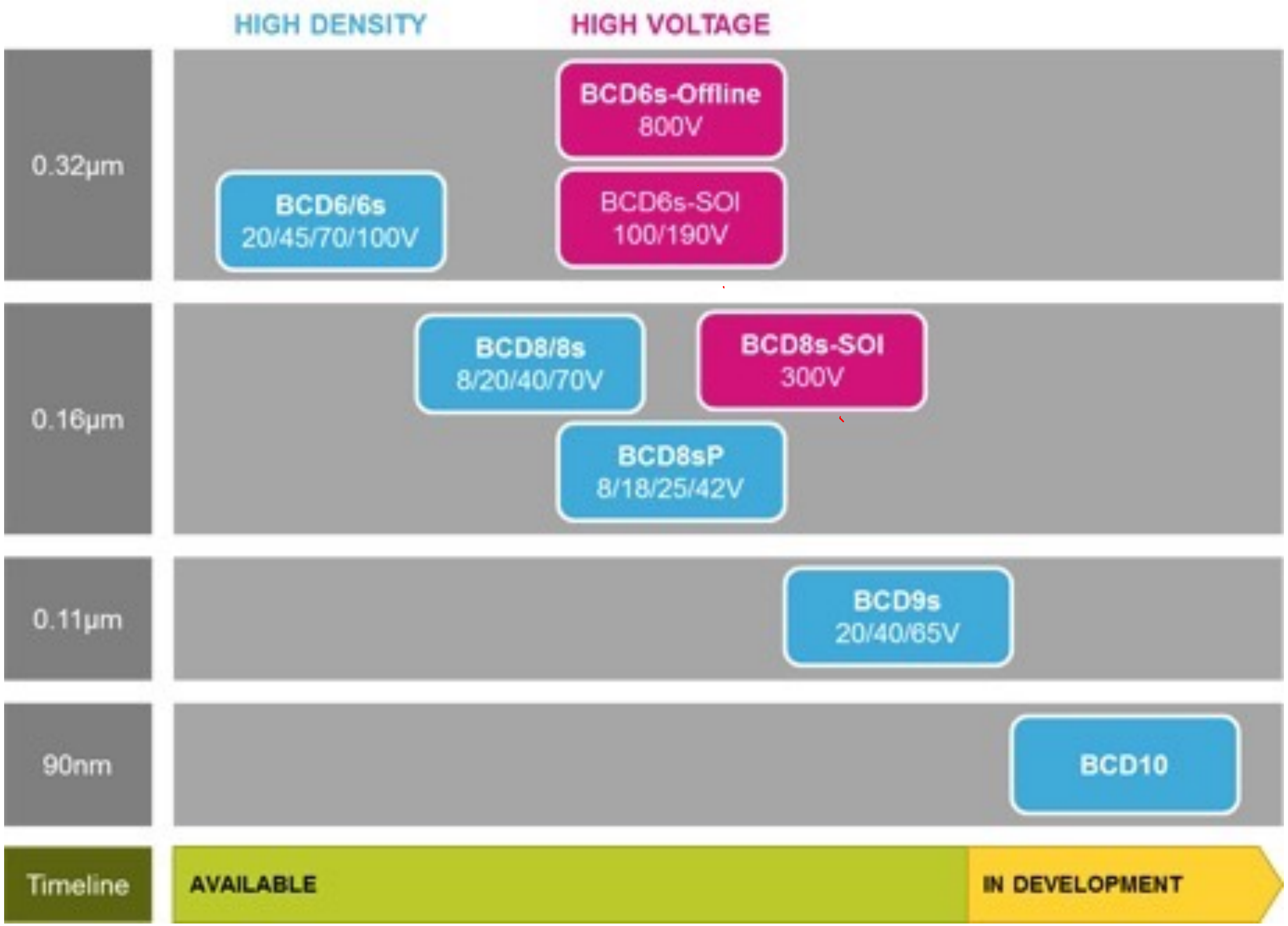
1.2 um twin well
CMOS, NVM, 3ML

0.18 um CMOS,
6 ML, NVM

Now BCD
by STM, Freescale,
TI, TSMC, UMC, GF,
SMIC, IFX

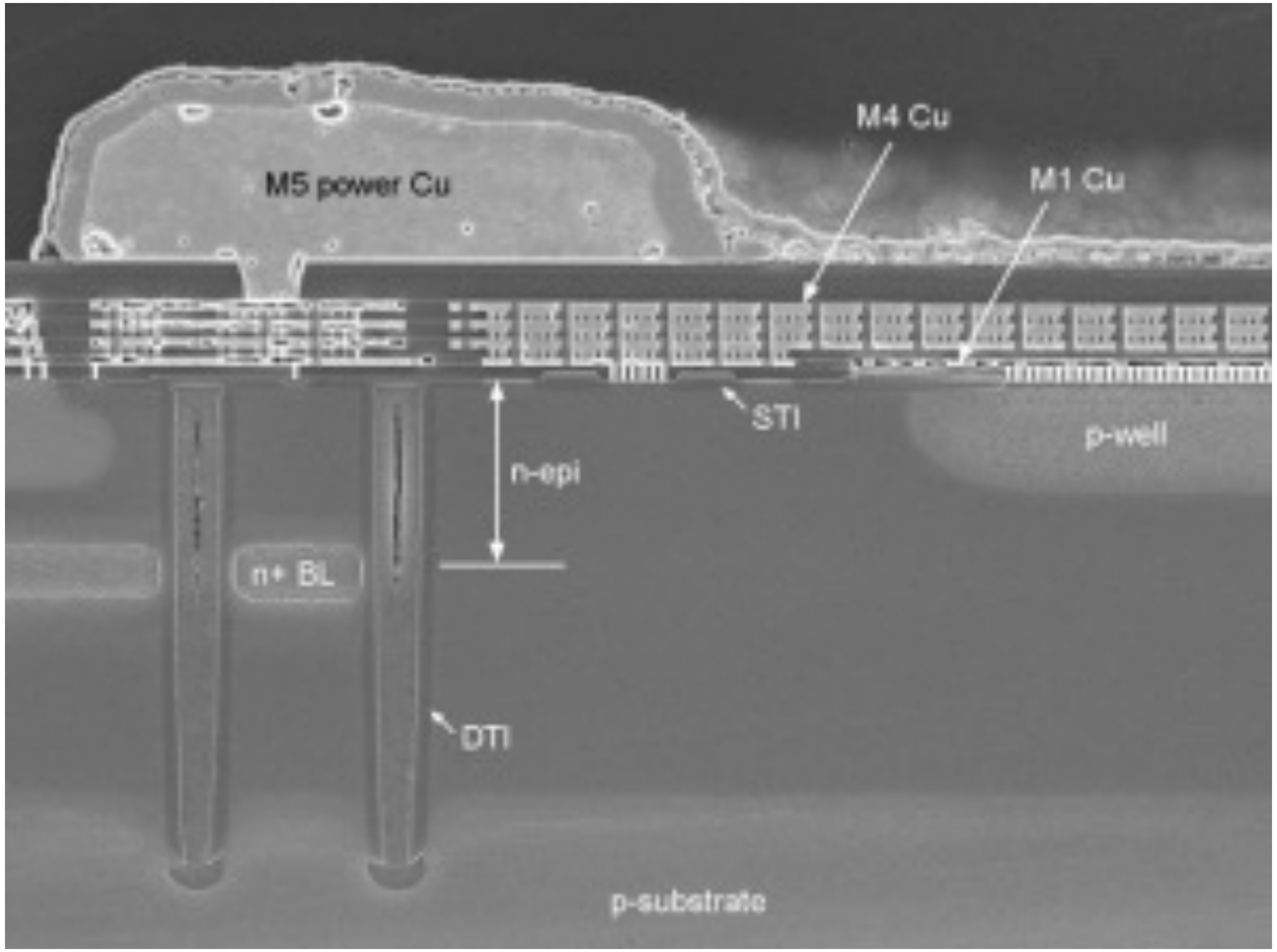
taken from Fig. 4.4 of Y. Fu et al. CRC Press, 2014

STM BCD process family



	HIGH DENSITY	HIGH VOLTAGE
0.32µm	**BCD6/6s** 20/45/70/100V	**BCD6s-Offline** 800V BCD6s-SOI 100/190V
0.16µm	**BCD8/8s** 8/20/40/70V **BCD8sP** 8/18/25/42V	**BCD8s-SOI** 300V
0.11µm	**BCD9s** 20/40/65V	
90nm	**BCD10**	
Timeline	**AVAILABLE**	**IN DEVELOPMENT**

Infineon 130 nm BCD



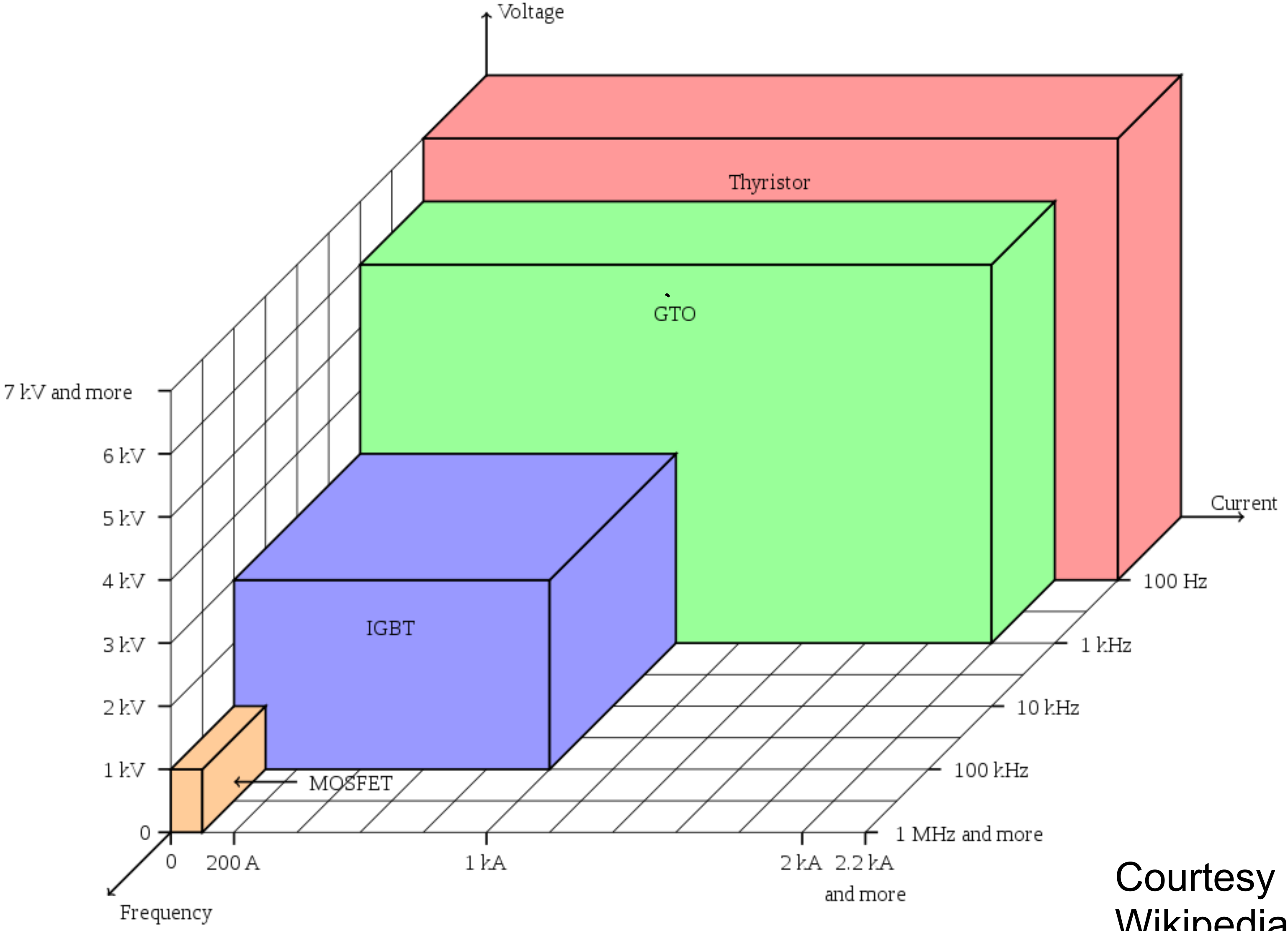
5 metal layer

STI

Buried layer

DTI

Capabilities of power devices

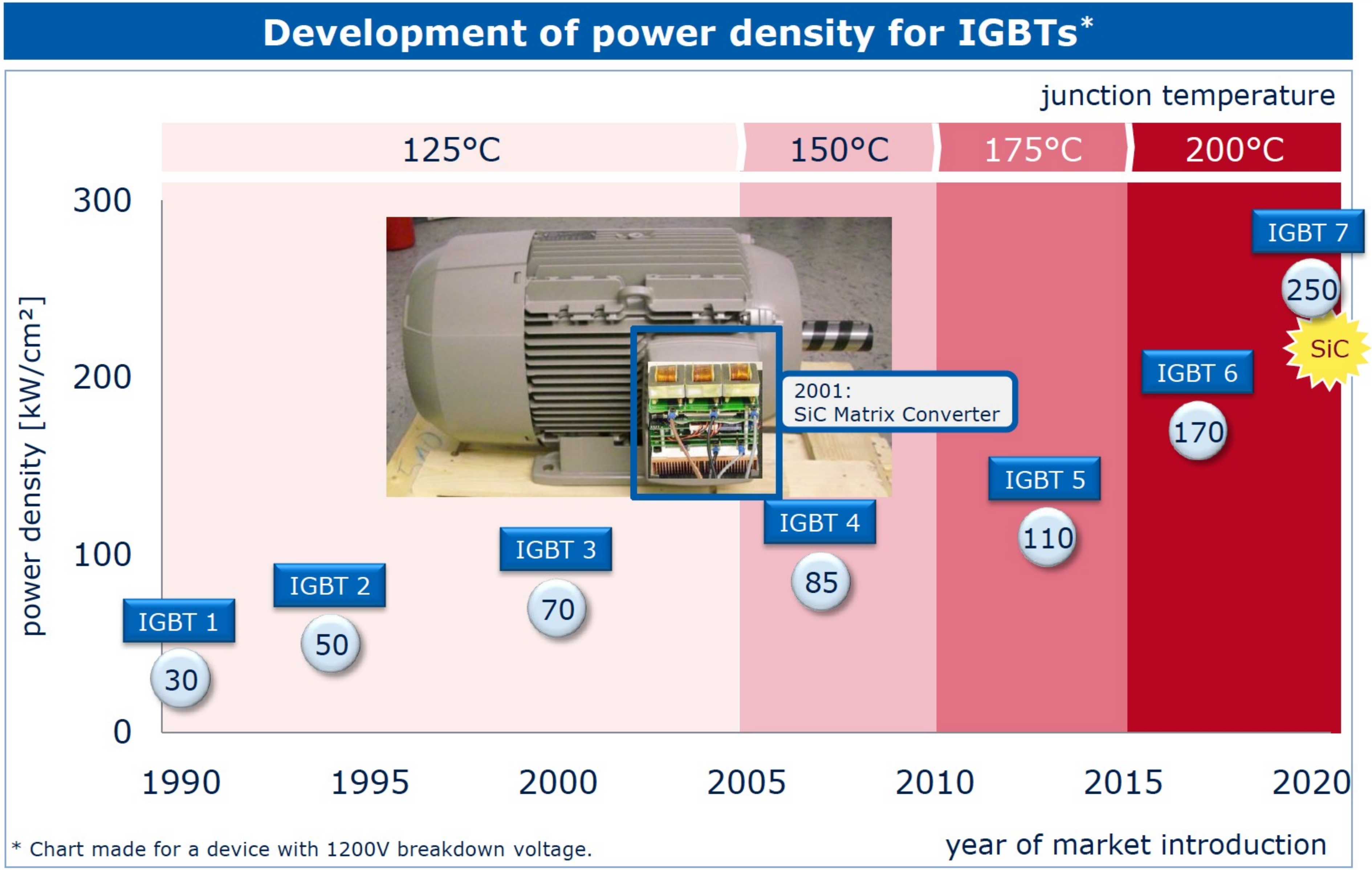


Courtesy of Wikipedia (Cyril

The domain of MOSFETs and IGBTs is increasing

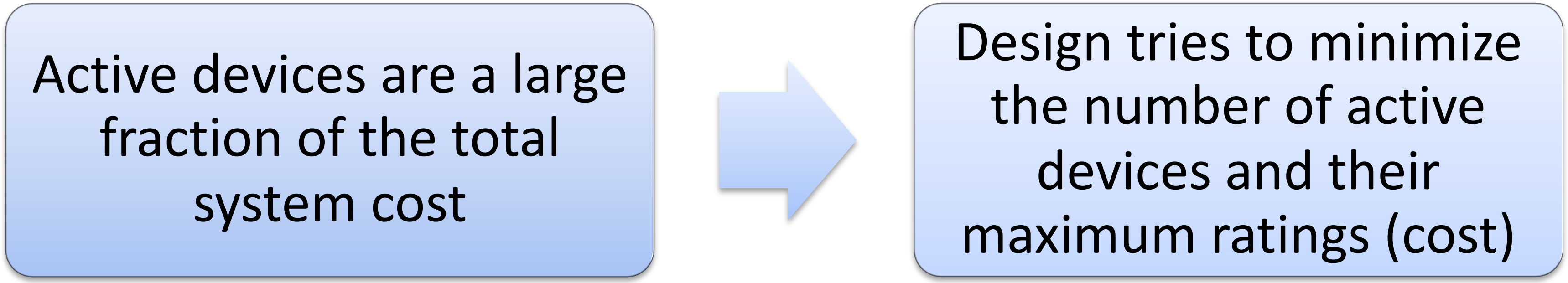
Progress in IGBTs

Courtesy of
Infineon 2011



* Chart made for a device with 1200V breakdown voltage.

Evolution of power devices



Active devices are a large fraction of the total system cost

Design tries to minimize the number of active devices and their maximum ratings (cost)

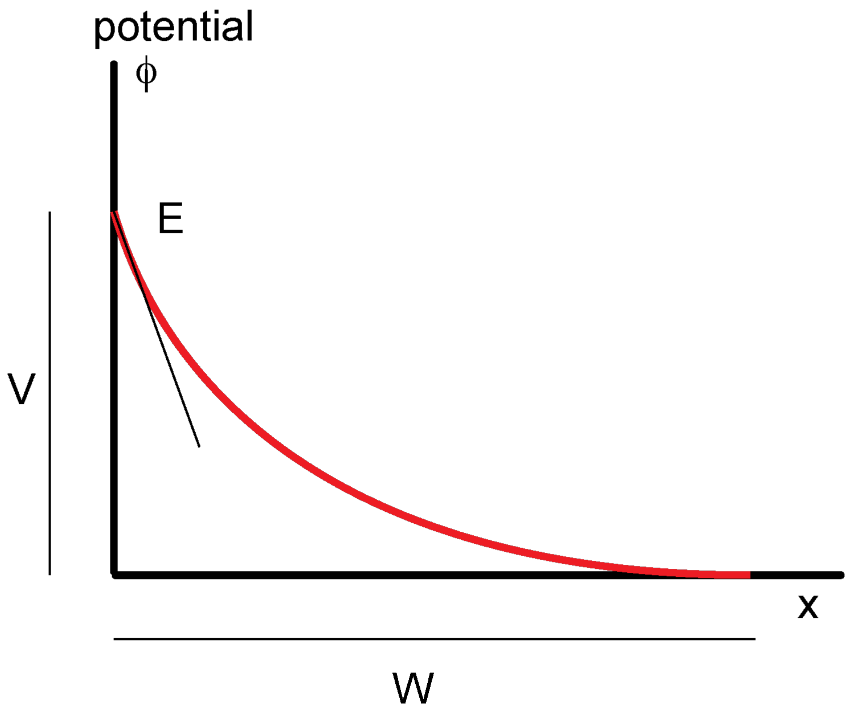
Progress in Power devices DRIVES

changes in circuit choices and market adoption.

Power MOSFETs	switched-mode power supplies
IGBTs	Energy efficient motor drives with inverters
New materials: SiC, GaN	Class D audio amplifier, Inverter for motion control – AC-DC and DC-DC power supply

Comparison between different materials for power FETs

Let us consider a PN junction with NO punchthrough:



- W is the width of the depletion region (contained in the drift region)
- Electric field at the junction: $E = \dfrac{qN_D}{\varepsilon} W$
- Voltage drop V in W: $V = \dfrac{1}{2}\dfrac{q\,N_D}{\varepsilon} W^2 = \dfrac{WE}{2}$
- We also have $2V\dfrac{qN_D}{\epsilon} = E^2$

Resistance in the ON state R_{ON}

if we put the breakdown field E_{BD} in the place of E, and the breakdown voltage V_{BD} in the place of V:

- $2V_{BD} = WE_{BD} \rightarrow W = \frac{2V_{BD}}{E_{BD}}$
- $2V_{BD}\frac{qN_D}{\epsilon} = E_{BD}^2 \rightarrow qN_D = \frac{\epsilon E_{BD}^2}{2V_{BD}}$

R_{ON} is due to transport in the drift region. We consider the case of no conductivity modulation $n=N_D$ (MOSFETs and Schottky diodes):

$$R_{ON} = \frac{W}{A}\frac{1}{\mu q n} = \frac{W}{A}\frac{1}{\mu q N_D}$$

$$R_{ON}A = \boxed{\frac{2V_{BD}}{E_{BD}}}\frac{1}{\mu}\boxed{\frac{2V_{BD}}{\epsilon E_{BD}^2}} = \frac{4}{\mu\varepsilon}\frac{V_{BD}^2}{E_{BD}^3}$$

FOM of alternative materials (to Si)

$$R_{ON}A = \frac{4}{\mu\varepsilon}\frac{V_{BD}^2}{E_{BD}^3}$$

The breakdown voltage is a system specification

→ For the same V_{BD}, different materials give different R_{ON}

Baliga proposed a Figure of Merit for materials normalized to Si:

$$FOM = \mu\varepsilon E_{BD}^3$$

	Si	GaAs	SiC	GaN
Breakdown Electric Field (MV/cm)	0.3	0.4	2.4	3.0
Electron mobility (cm^2/Vs) at 300K	1350	8500	370	900
Relative dielectric constant	11.8	13.1	10	9.5
BFOM = $1/(\mu\varepsilon E_{BD})$ normalized to Si	1	17	119	537

Thermal properties of alternative semiconductors

	Si	GaAs	SiC	GaN
Bandgap at Room T (eV)	1.12	1.43	2.2-3	3.4
Thermal conductivity (W/(cm K))	1.5	0.5	5	1.3
Max Operating Temp. (C)	150	300	600-1000	400
Saturation velocity (cm/s)	1e7	2e7	2.5e7	2.5e7

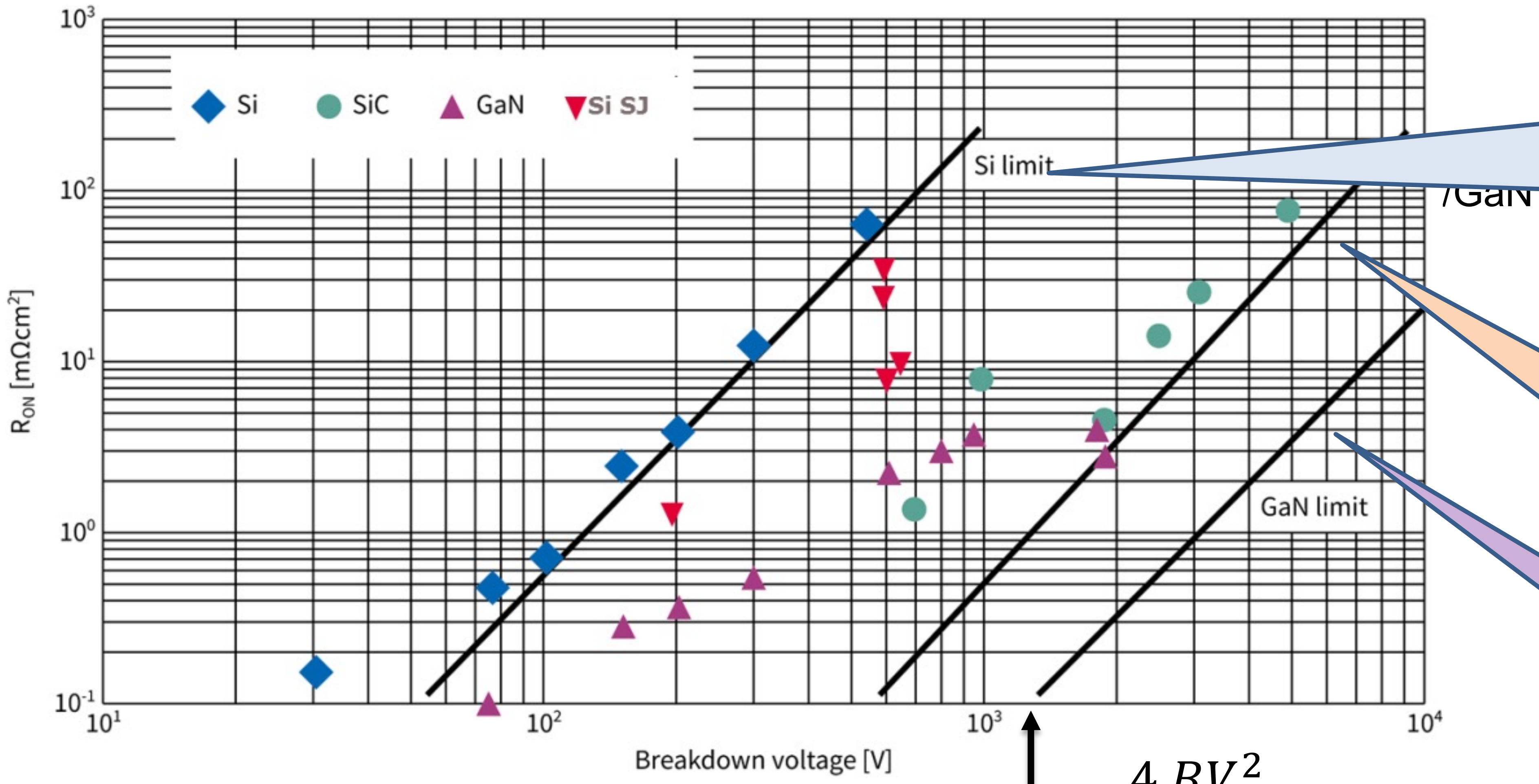
Higher bandgap → Harder impact ionization → Higher E_{BD}

Higher bandgap → Lower intrinsic carrier density n_i at a given T

→ Lower leakage currents at given T

→ Higher Max operating Temp

Ideal limits of SiC and GaN have not been reached yet



Superjunction MOSFETs let Si surpass “theoretical” limits

SIC still has room for improvement

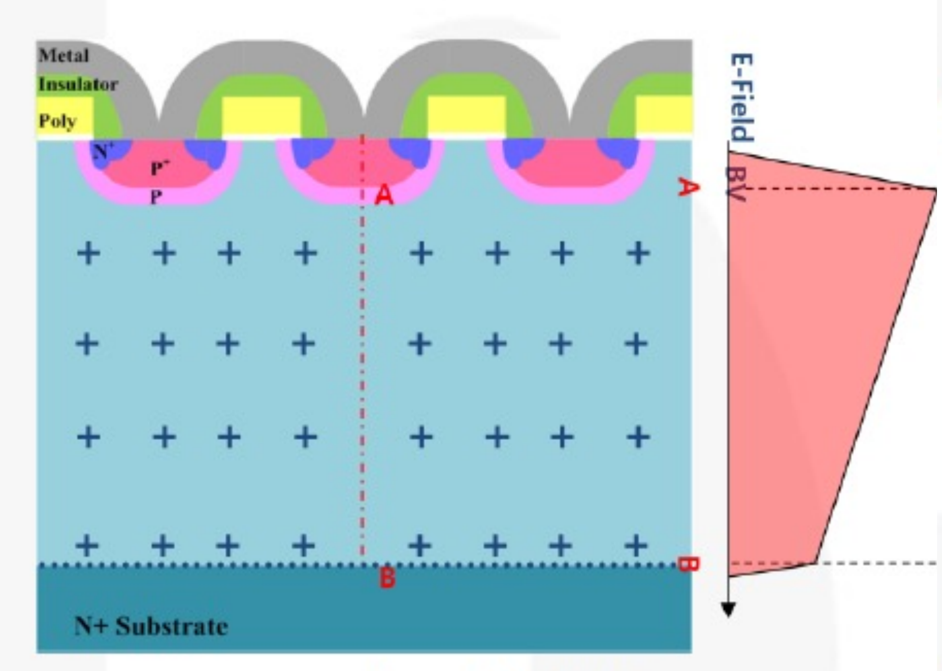
GaN is far from limit

$$R_{ON} = \frac{4\,BV^2}{\varepsilon \mu E_{BV}^3}$$

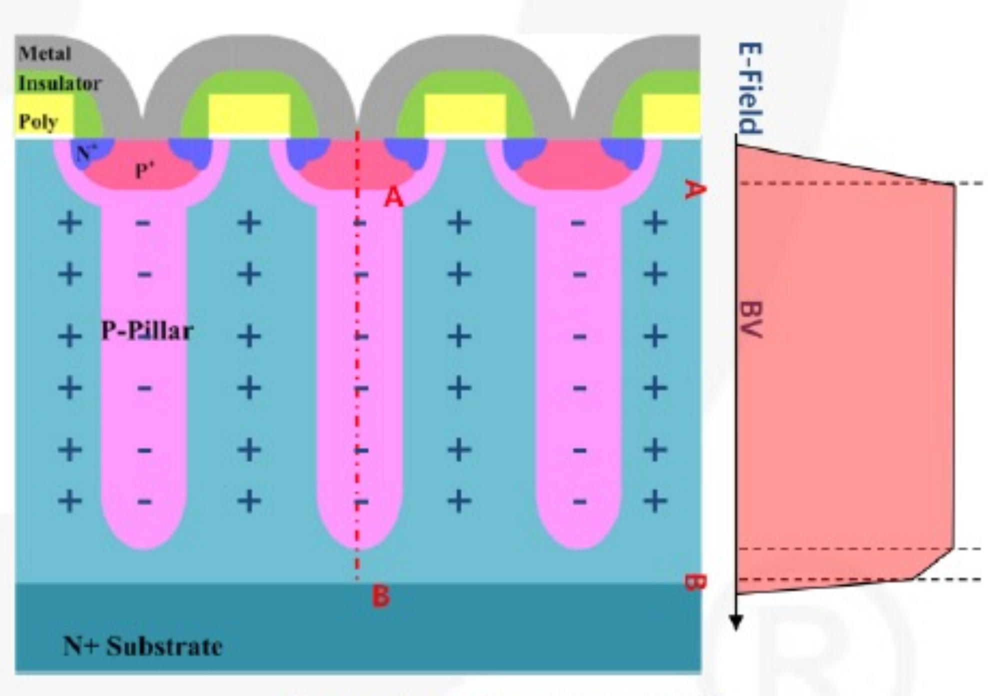
Image: courtesy of Infineon

Superjunction MOSFET

Siemens 1999,
STM 2000



Planar MOSFET



Super-Junction MOSFET

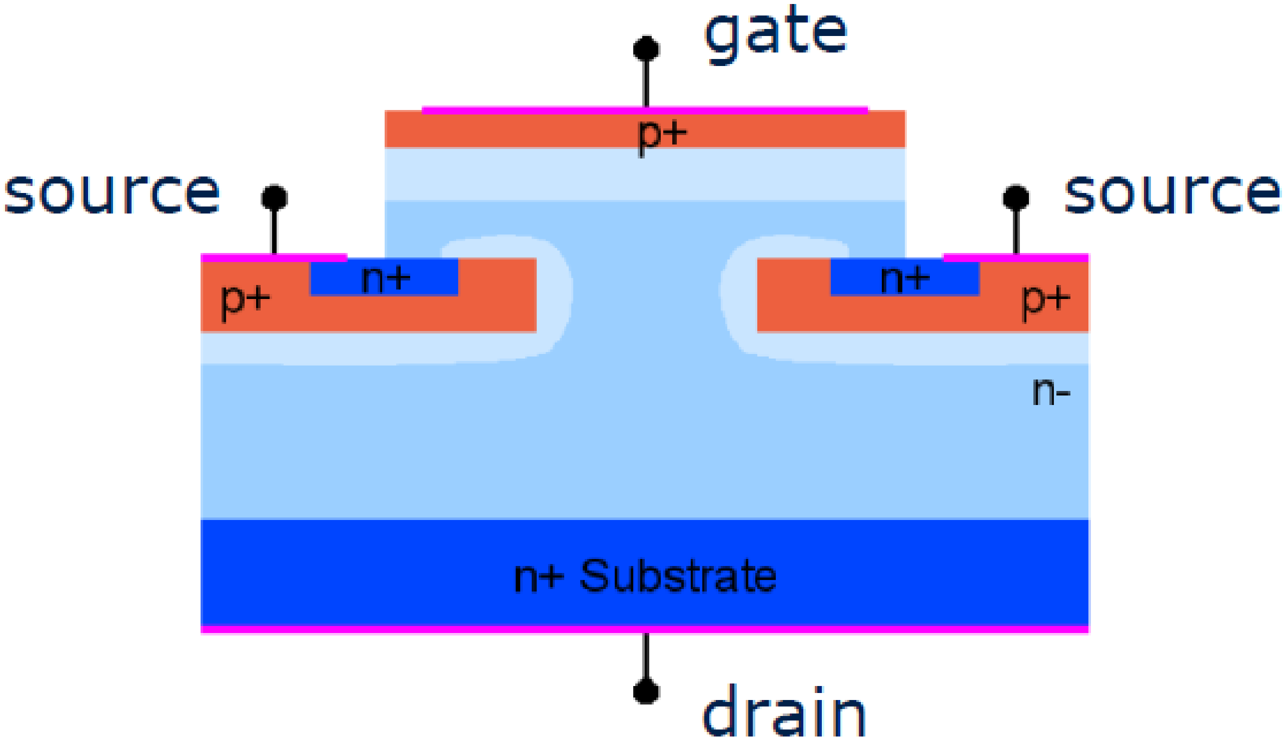
P-pillar introduces a charge sharing mechanism that enables to increase drift region doping (10x) for the same V_{BD} and drift region thickness

For V_{BD} = 600 V → 5x reduction in R_{ON} wrt MOSFET

Source:
Fairchild AN5232

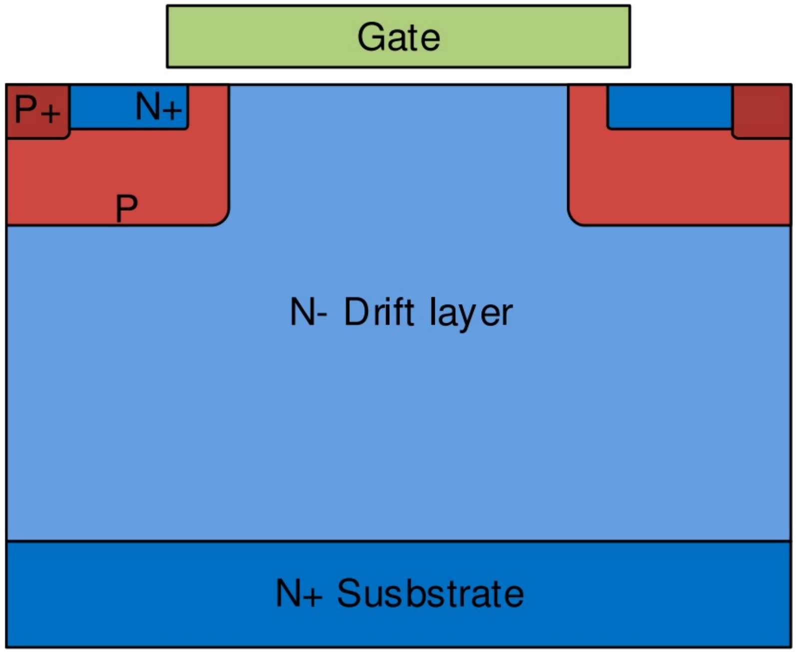
SiC devices

- SiC diodes, SiC JFETs, SiC MOSFETs
- **SiC JFET (Infineon)**

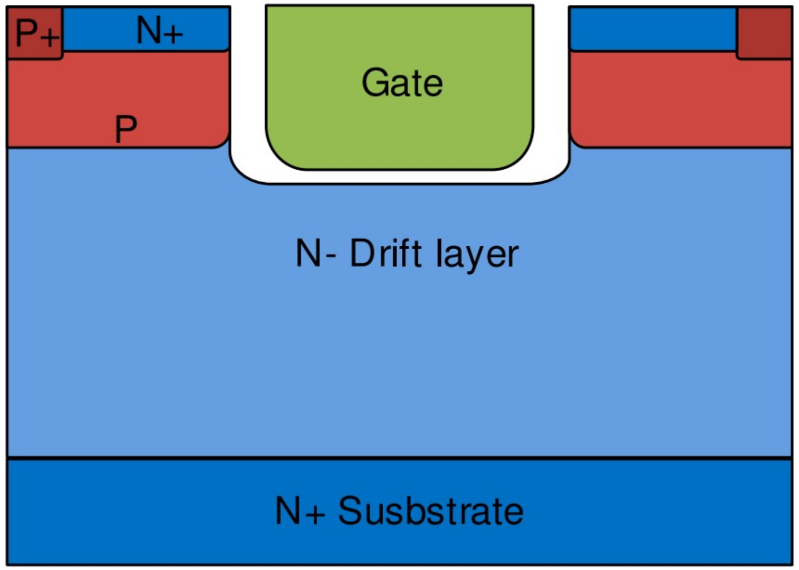


SiC MOSFET

Planar MOSFET



Trench MOSFET



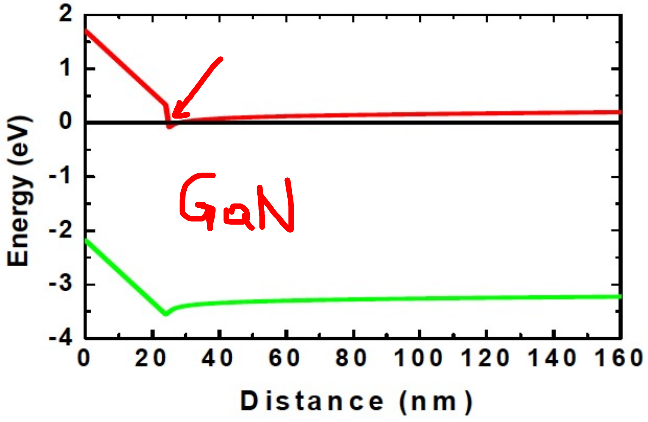
Channel resistance higher than in Si (low mobility)

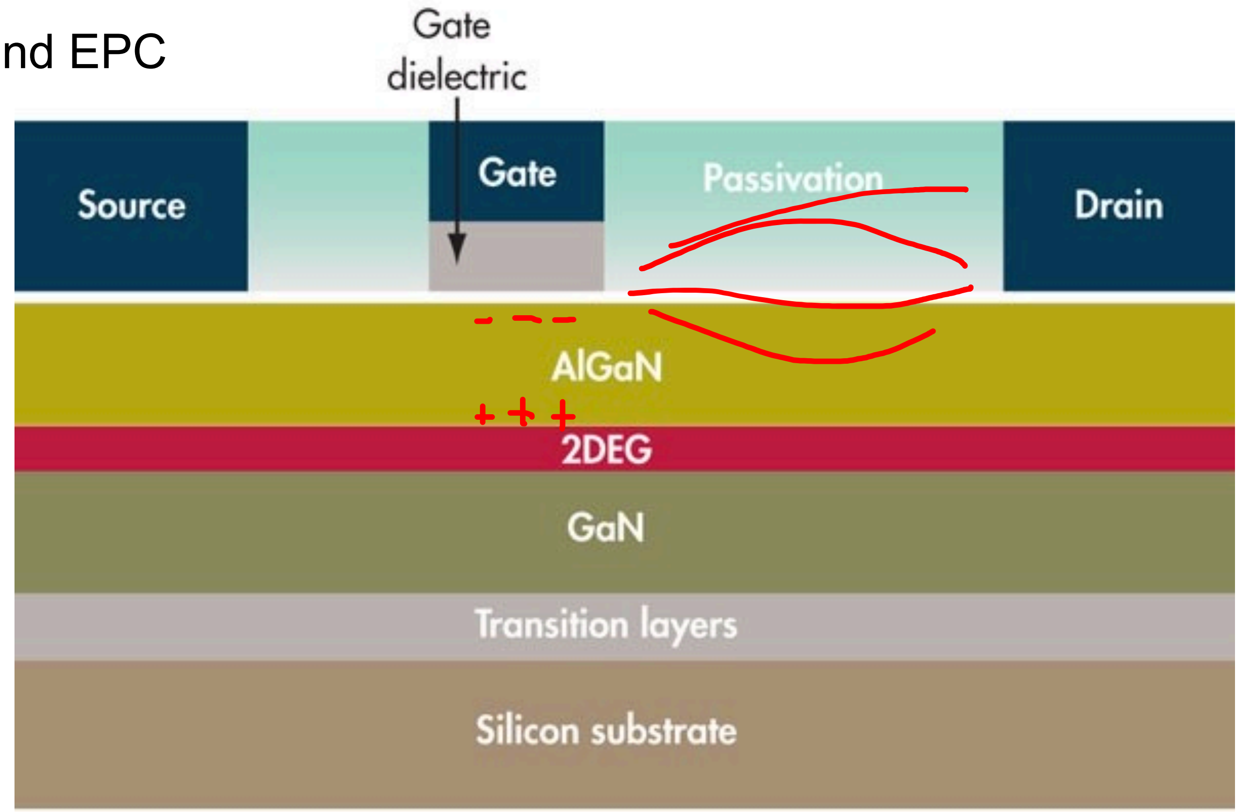
1.2-6.5 KV highly reliable can replace Si MOSFET

Max BV 15 KV (but R_{ON} is too high) → SiC IGBT required

GaN-AlGaN HEMT

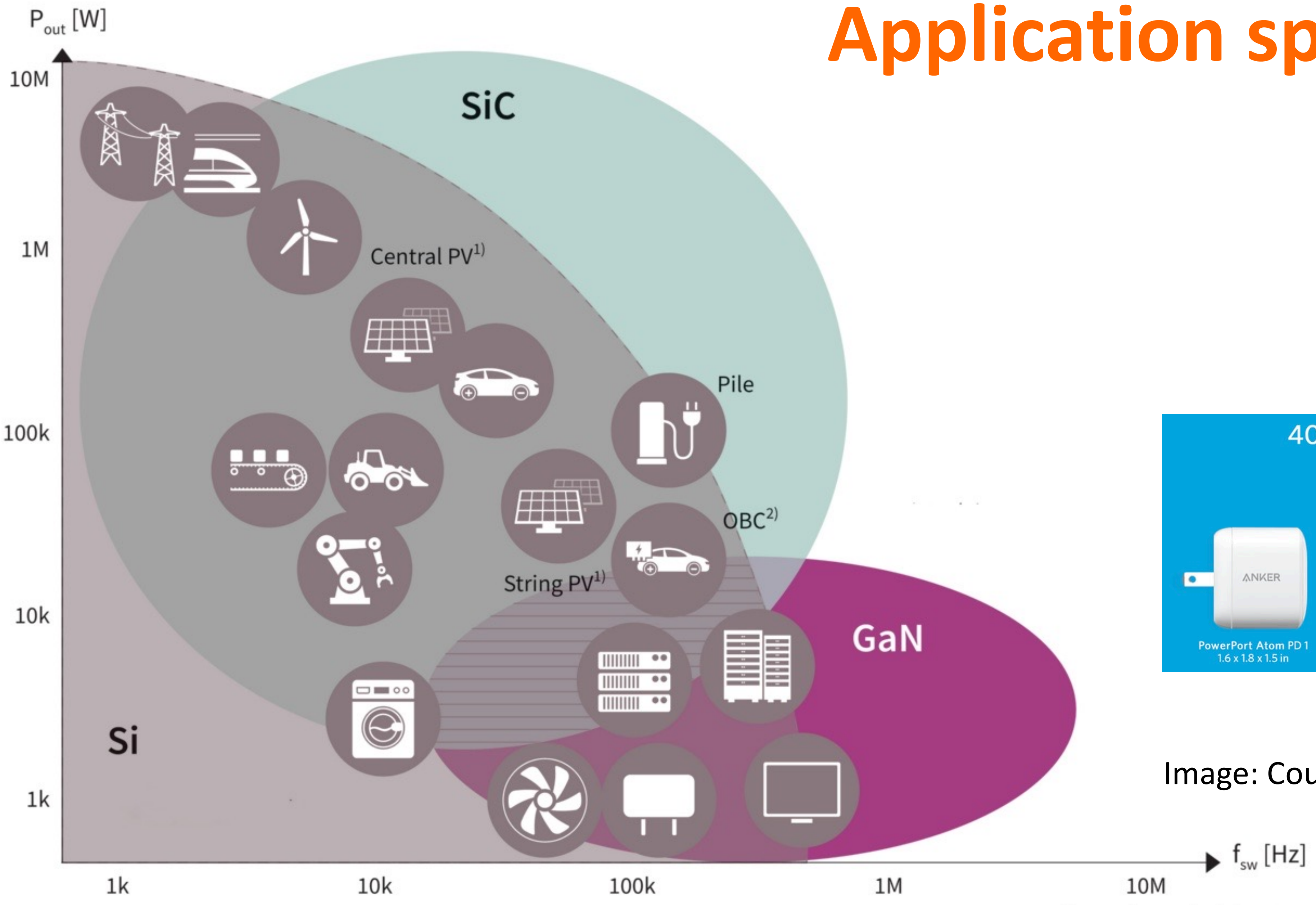
Only 2 producers now: IRF and EPC





- AlGaN is piezoelectric (no doping -> high mobility)
- Lateral device (reduced C, high field in the upper layers)
- Normally ON

Application spectrum

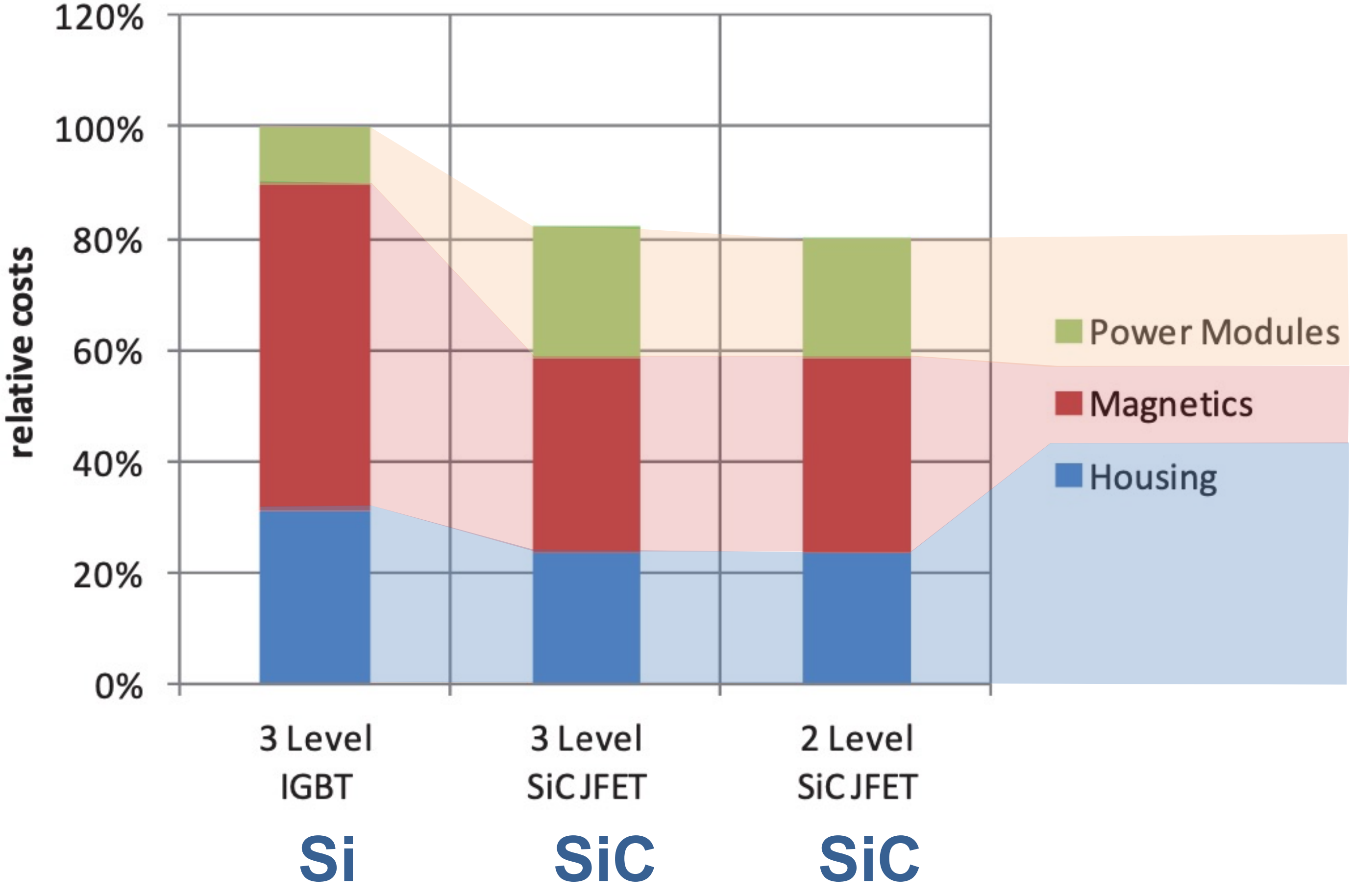


1) PV = photovoltaic inverter
2) OBC = on-board charger

Image: Courtesy of Infineon

Reduced system cost even with higher device cost

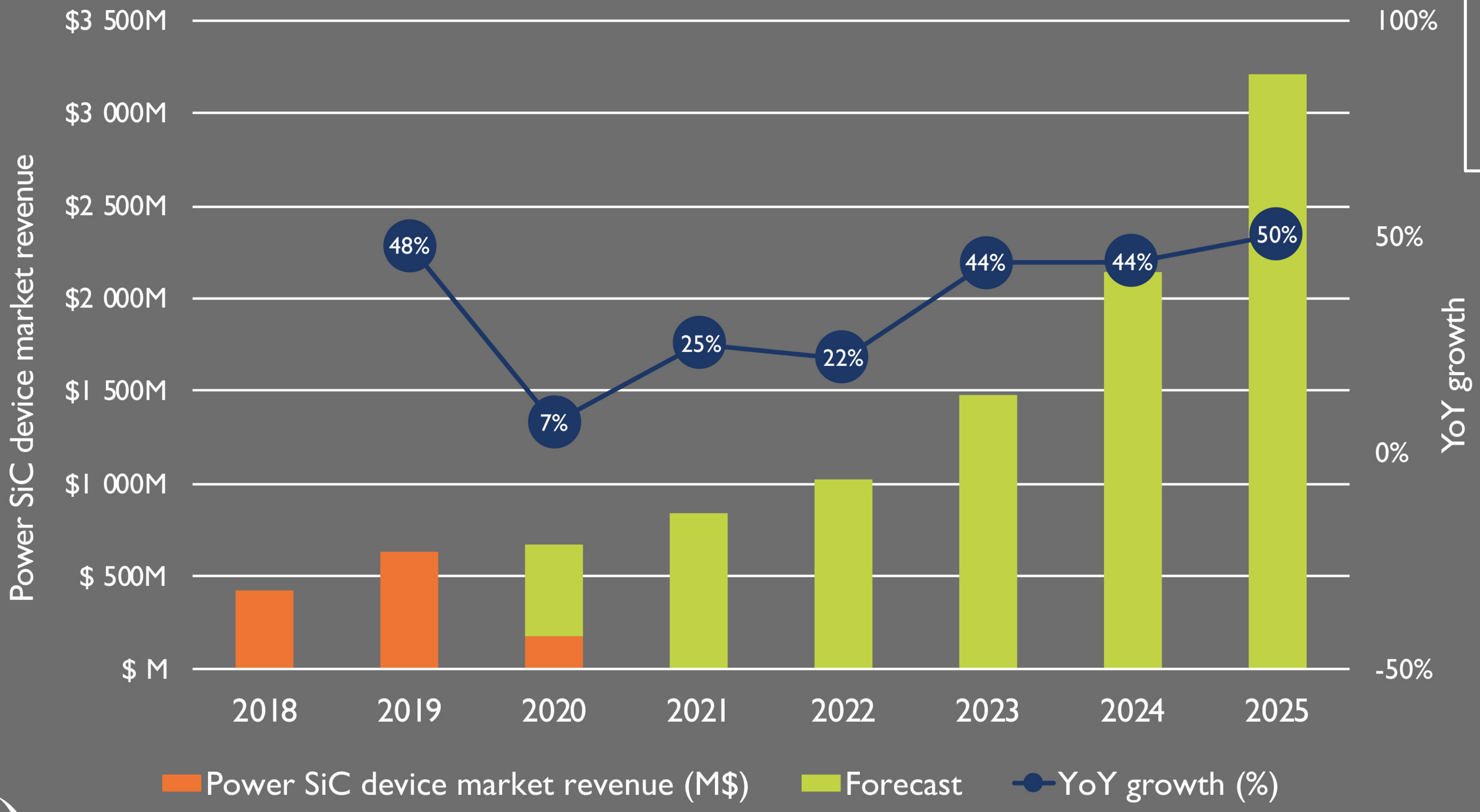
<table>
<tr><th colspan="3">Inverter of PV system</th></tr>
<tr><td colspan="3">Input DC 600 V – Output 400 V (triphase)</td></tr>
<tr><td colspan="3">Output power 17 KW</td></tr>
<tr><td colspan="3">Output current 25 A</td></tr>
<tr><td colspan="3">Max ripple 10%</td></tr>
<tr><td colspan="3">Min conversion efficiency 98%</td></tr>
<tr><th>Si IGBT</th><th>3L - SiC JFET</th><th>2L - SiC JFET</th></tr>
<tr><td>f_s = 16 KHz</td><td>f_s = 48 KHz</td><td>f_s = 96 KHz</td></tr>
<tr><td>L_{AC} = 2.5 mH</td><td>L_{AC} = 0.83 mH</td><td>L_{AC} = 0.415 mH</td></tr>
<tr><td>P_{LOSS} = 732 W</td><td>P_{LOSS} = 514 W</td><td>P_{LOSS} = 381 W</td></tr>
<tr><td>System cost 100%</td><td>System cost 82%</td><td>System cost 80%</td></tr>
</table>



U. Schwarzer et al. *PCIM Europe Conf. Proc. May 2014*, 787–794.

Power SiC device market revenue

(Source: Compound Semiconductor Quarterly Market Monitor, Yole Développement, June 2020)

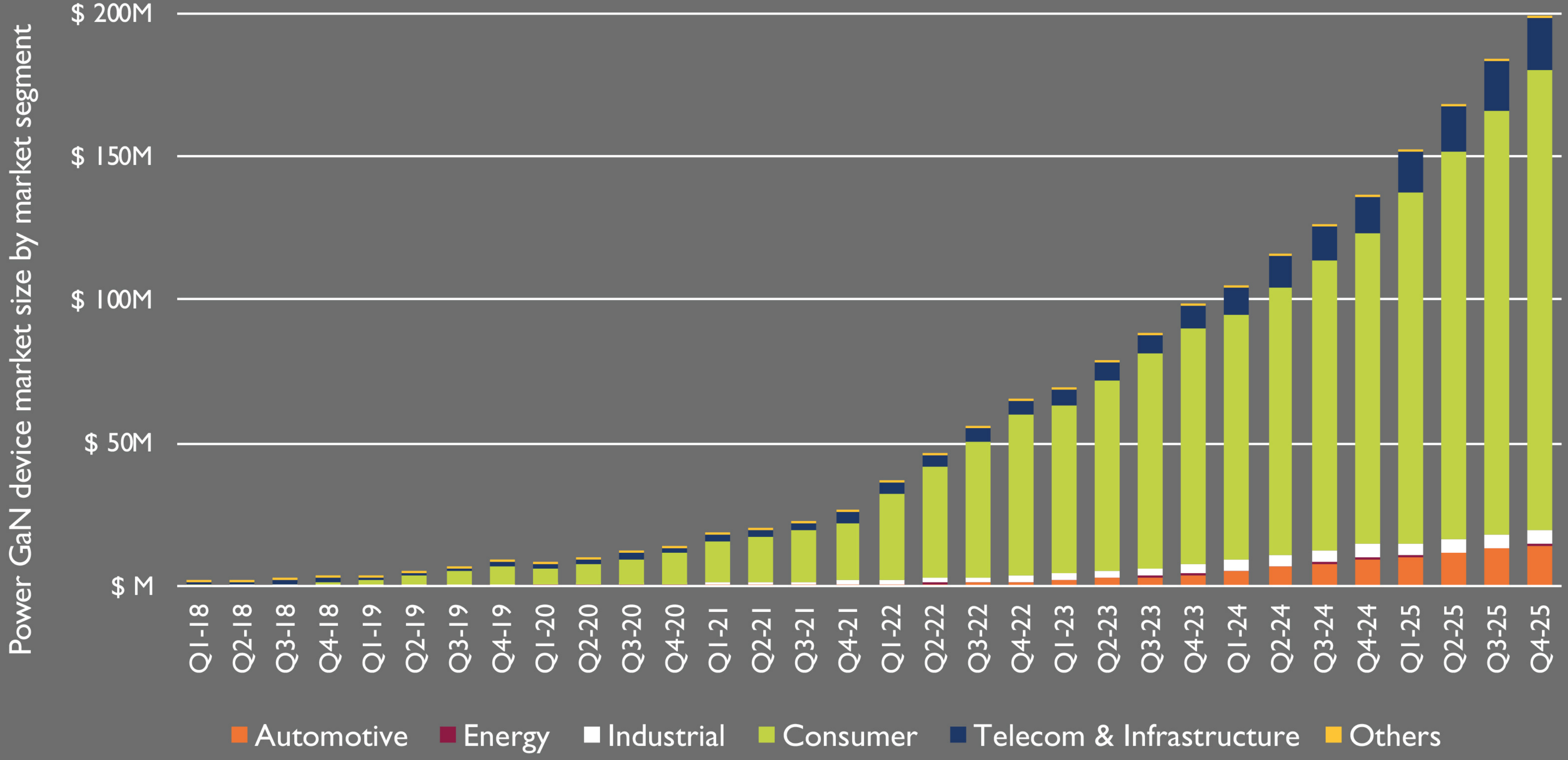


Diode
JFETs
MOS
IGBTs
GTOs

YOLE
Développement

Power GaN device market forecast by segment

(Source: Compound Semiconductor Quarterly Market Monitor, Yole Développement, June 2020)



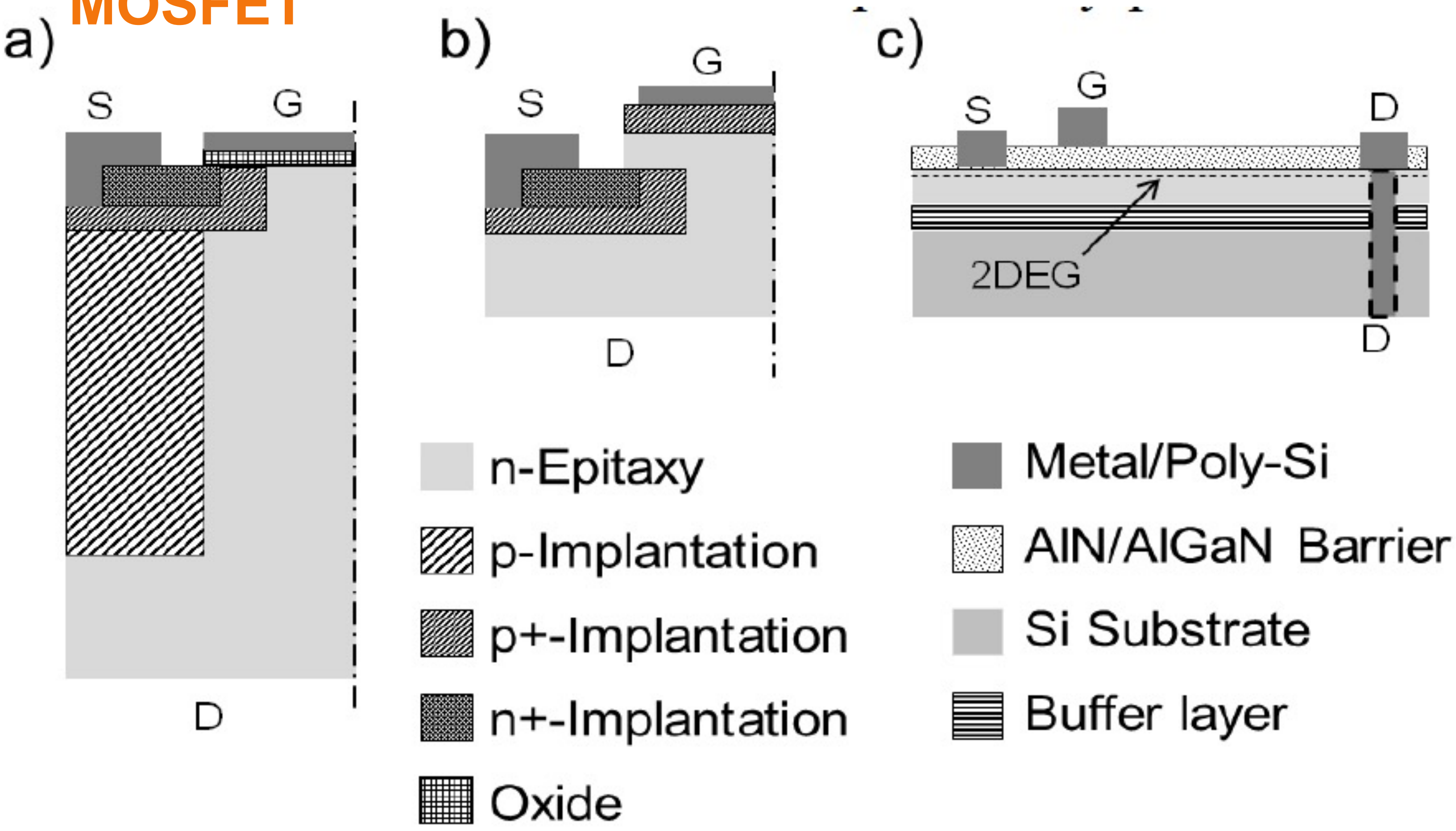
Challenges of alternative materials

- Silicon has enormous accumulated past investments. Money spent on other materials is small in comparison
- GaAs
  - Small wafer size (→ higher cost)
  - Unwanted impurities → reduce EBD and carrier lifetime
  - No oxide (is it really a problem?)
- SiC
  - Even smaller wafer size and more impurities (SiC on Si)
  - SiC-SiO_2 interface not perfect
- GaN (GaN on Si)
  - Reliability issues (impurities)

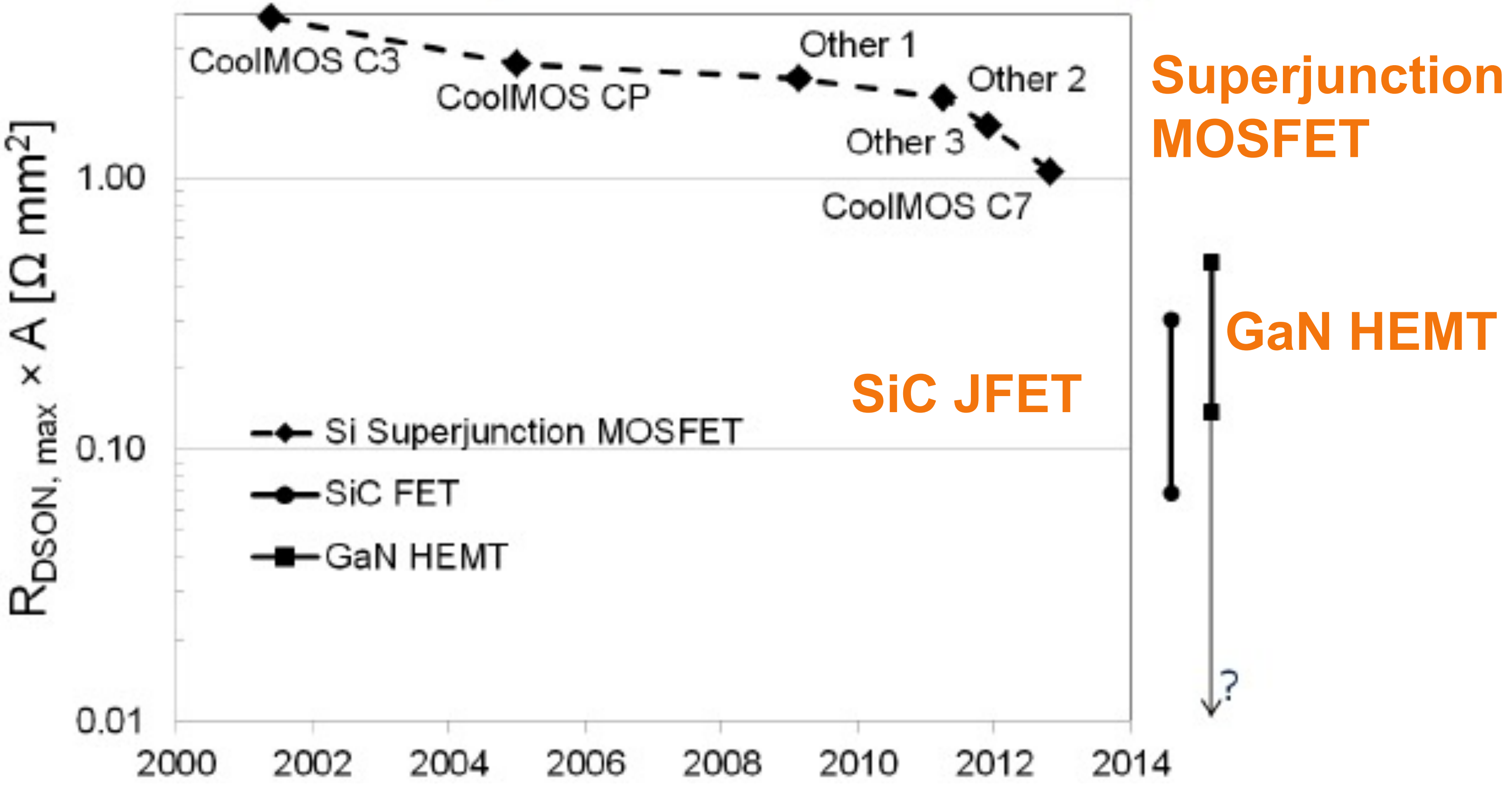
Backup slides

Comparison between different technologies

Superjunction MOSFET **SiC JFET** **GaN HEMT**



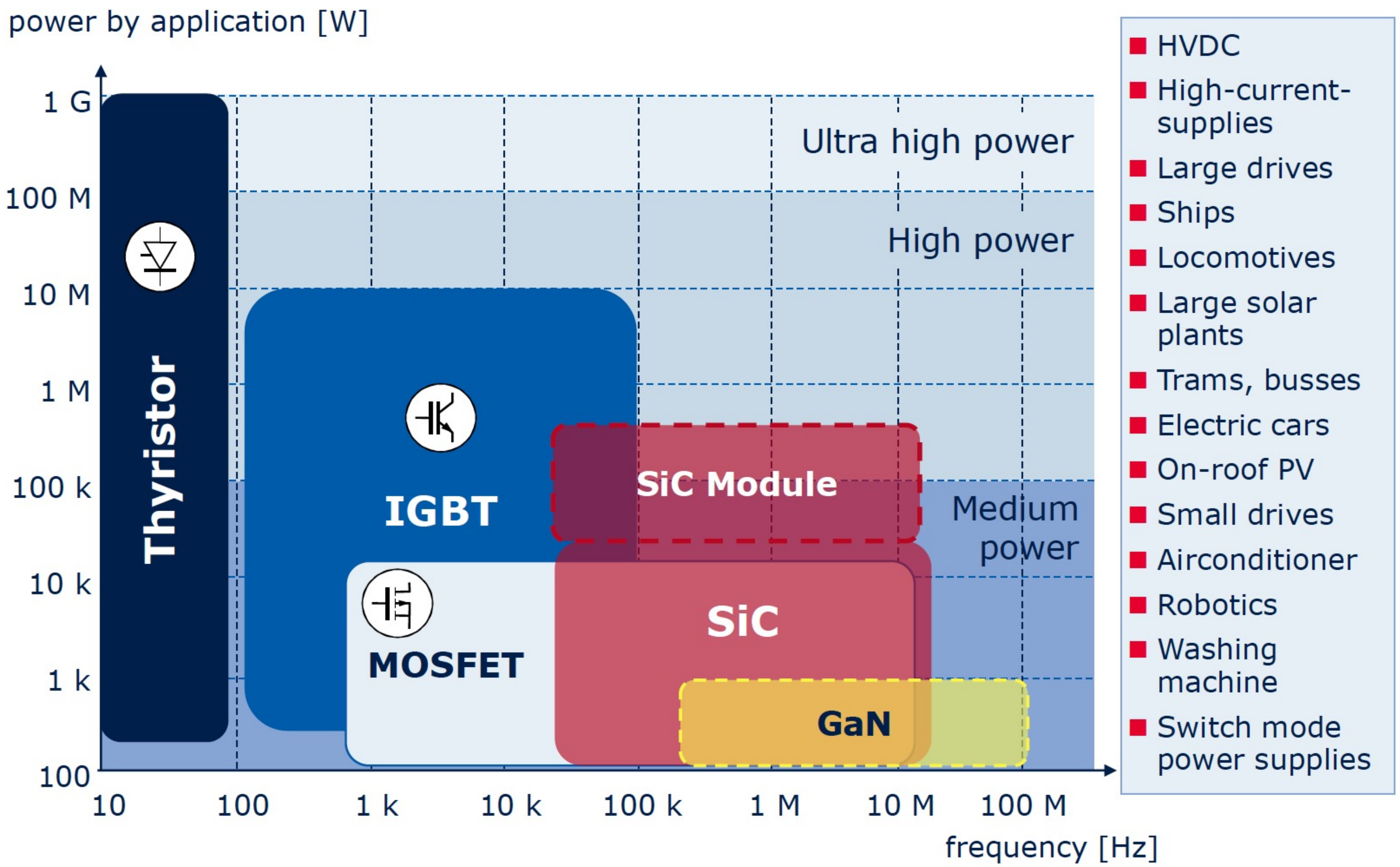
Evolution of R_{ON} for 600 V V_{BD}



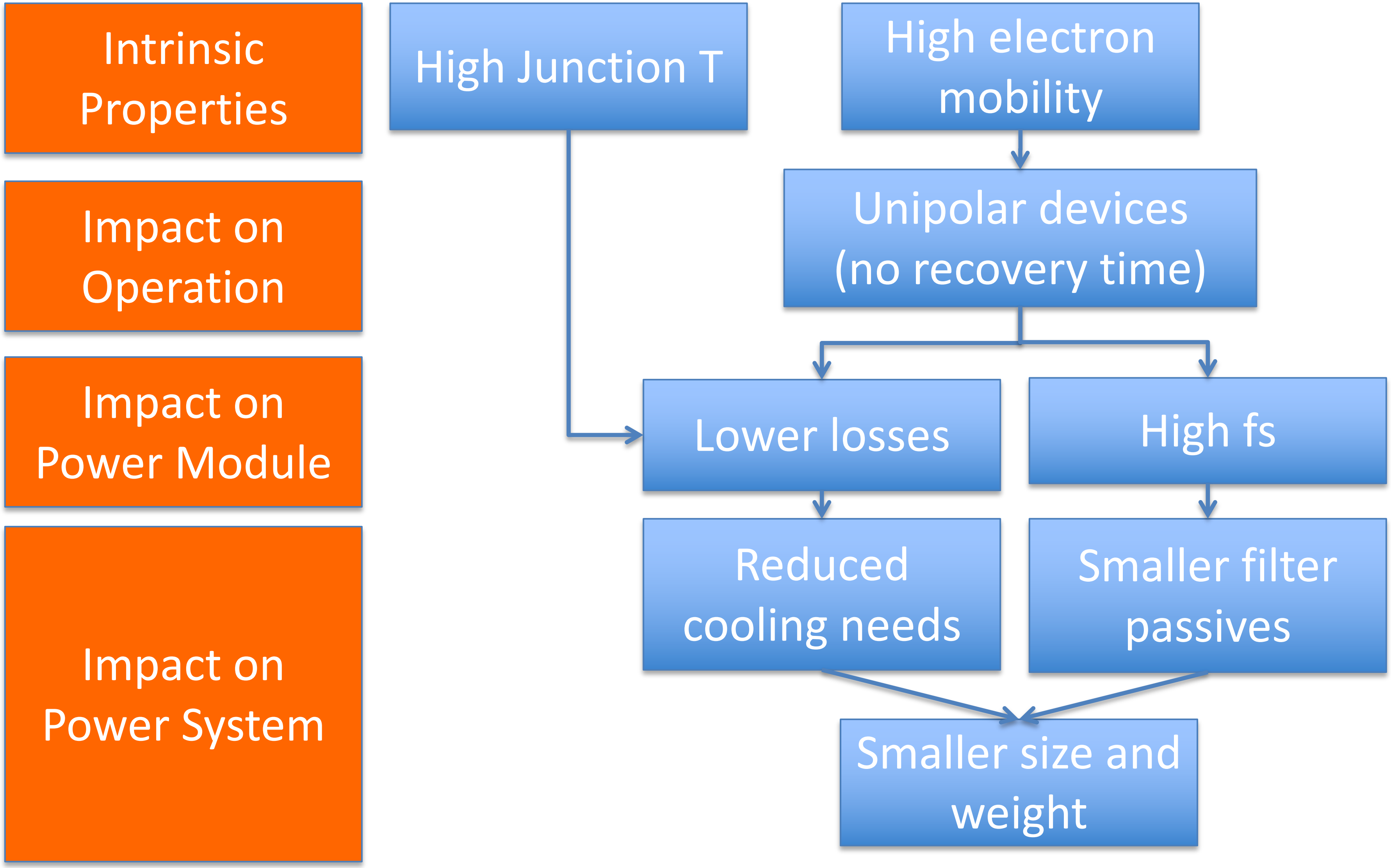
GaN also has lower output switching charge, enabling higher frequency

Power versus frequency

Courtesy of
Infineon 2011



Added value of SiC and GaN



Intrinsic Properties

Impact on Operation

Impact on Power Module

Impact on Power System

High Junction T

High electron mobility

Unipolar devices (no recovery time)

Lower losses

High fs

Reduced cooling needs

Smaller filter passives

Smaller size and weight