État de l’art et tendances des dispositifs semiconducteurs de puissance pour une gestion optimisée de l’énergie

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State of the art and trends in power semiconductor devices for optimized power management

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Outline

- Introduction
- Unipolar power devices: MOSFETs
  - Conventional devices and their « silicon limits »
  - Novel concepts : Superjunction and floating islands
  - Limits of performance with these novel concepts
- Bipolar power devices: IGBTs
  - « Low losses » IGBT
  - Bidirectional IGBT
  - Integration of an IGBT transistor and a diode
  - Limits of performance of IGBTs
- Wide band-gap power semiconductor devices
  - Properties of wide band-gap semiconductors
  - Comparison of limits of performance
  - SiC, GaN, Diamond : future trends
- Conclusion

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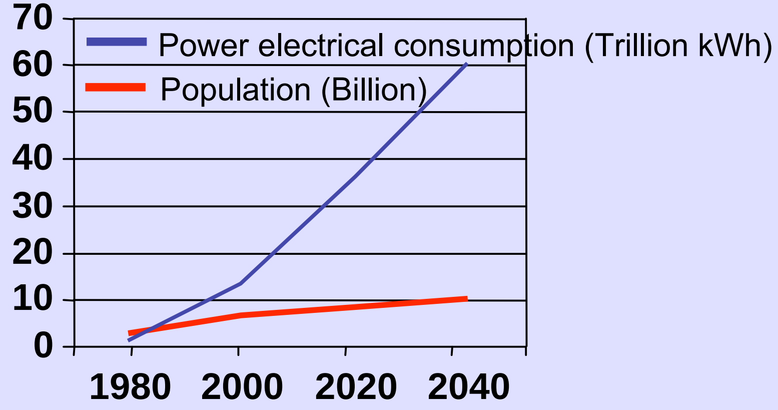
Context

- Despite many efforts to save energy, demand for electricity is expected to grow much faster than other energy sources over the next three decades.
- Today 40% of all energy consumption is in electrical energy, but this will grow to 60% by 2040.



- Power electronics is the key technology to control the flow of electrical energy from the source to the load: it is responsible for the reliability and stability of the whole power supply infrastructure in the world from the sources, the energy transmission and distribution up to the huge variety of applications in industry, transportation systems and the home & office appliances.
- Semiconductors in power management are estimated to exceed 50 billion dollars by 2010.

➡ **High power (high voltage and/or high current), high frequency, high temperature and low losses power switches are needed for an optimized power management**

The power switch

OFF

Breakdown voltage (BV_{dss})

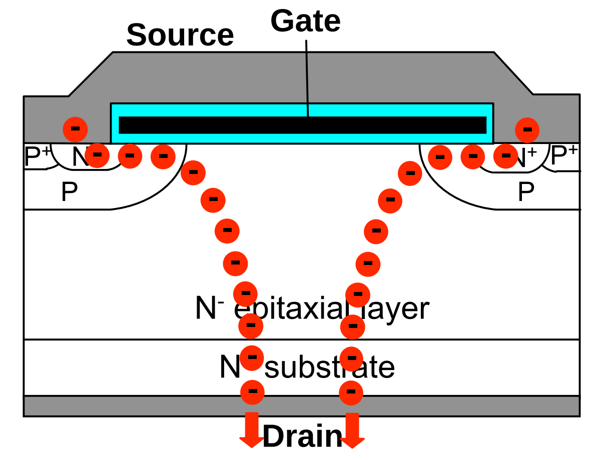
ON

Specific ON-resistance ($R_{ON}.S$)

- **Performances improvement:**
  - BV_{dss}: static OFF-state performance
  - $R_{ON}.S$ (or V_{ON}): static ON-state performance
  - Operating frequency: switching losses
  - Operating temperature
- **Functionalities increase:**
  - Voltage bidirectionality
  - Current bidirectionality

Comparison of unipolar and bipolar power devices

Unipolar devices
(MOSFET, Schottky diode,…)



VDMOSFET

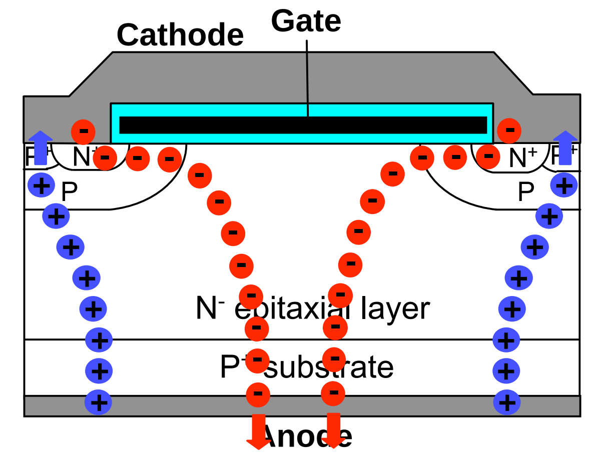
- low switching losses

➡ high frequency operation

- increasing on-resistance with breakdown voltage

➡ increasing conduction losses with breakdown voltage

Bipolar devices
(PN diode, bipolar transistor, IGBT,…)



IGBT

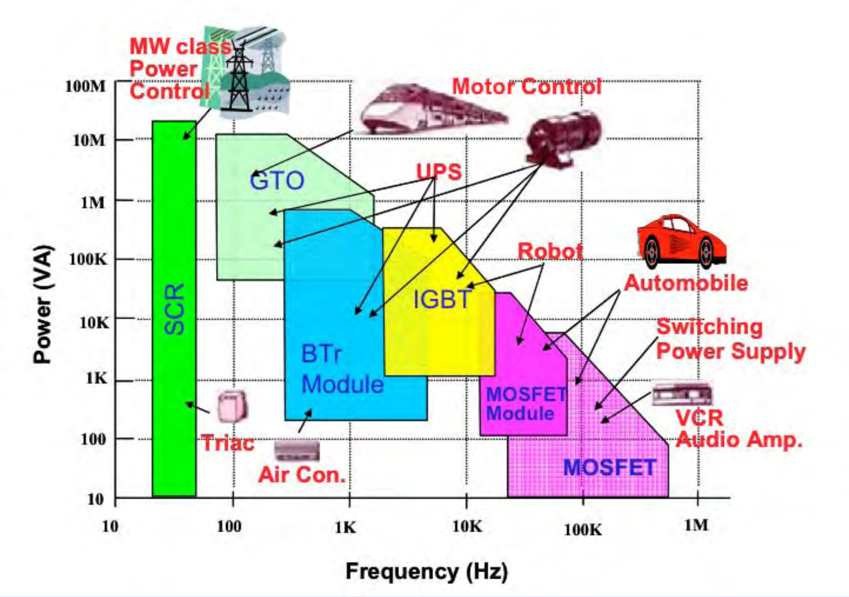
- high switching losses

➡ low frequency operation

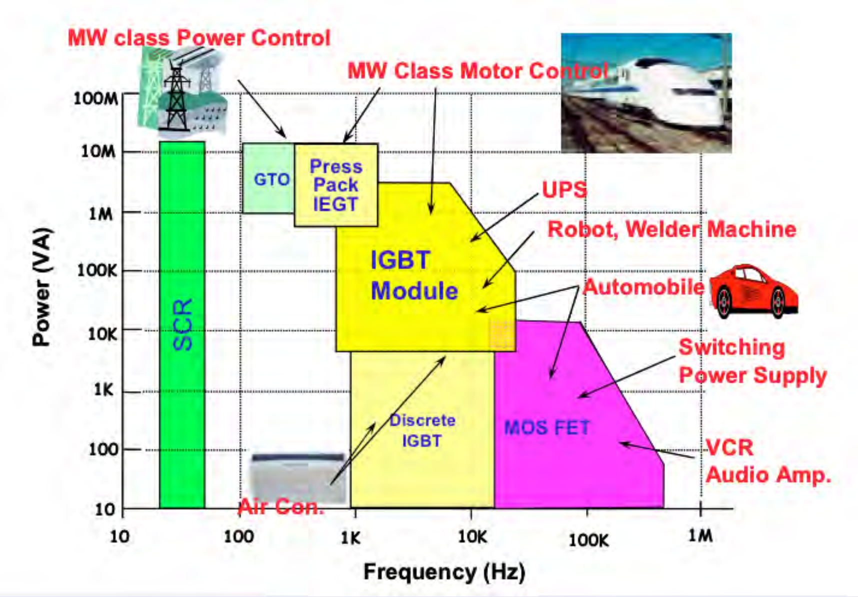
- on-resistance not depending on breakdown voltage

➡ low conduction losses

Application fields of power devices



Application fields of power devices in 1997



Application fields of power devices in 2005

→ MOS gate devices are predominantly used in most of the application fields:

- LDMOSFETs in power ICs,
- MOSFETs for low voltage and medium voltage applications,
- IGBTs for high power applications

from ***Silicon Limit Electrical Characteristics of Power Devices and Ics***, A. Nakagawa, Y. Kawaguchi, K. Nakamura, ISPS'08, Invited paper

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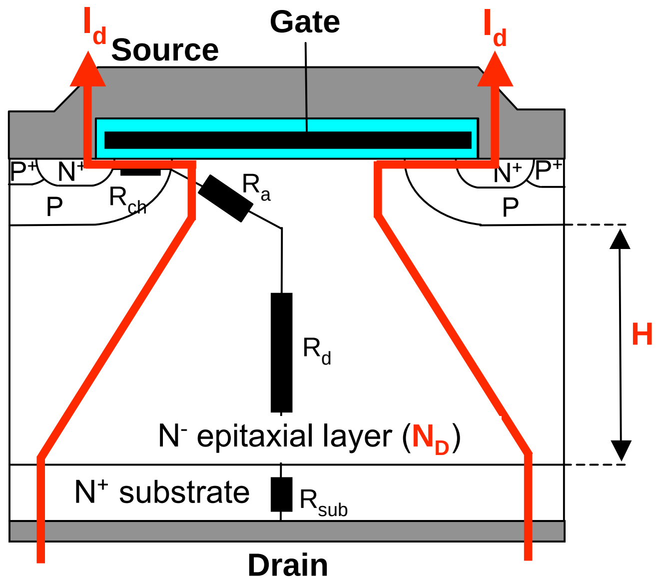
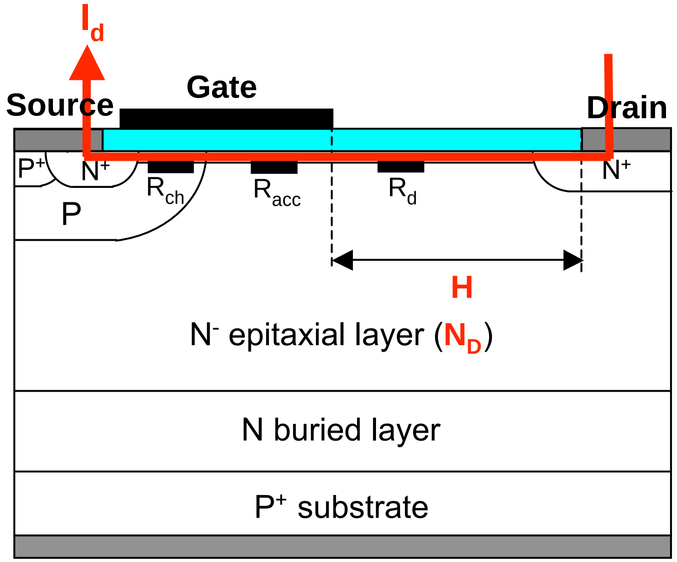
Unipolar power devices : MOSFETs

Conventional power MOSFETs

VDMOSFET



LDMOSFET



- **OFF-state**: the breakdown voltage (BV_{dss}) depends on N_D and H
- **ON-state**: the specific on-resistance ($R_{on}.S$) also depends on N_D and H

→ “$R_{on}.S$ / BV_{DSS}” trade-off < “silicon limit”

Silicon limits of conventional unipolar devices

What is the "silicon limit" ?

Silicon limit = optimal specific on-resistance for a given breakdown voltage

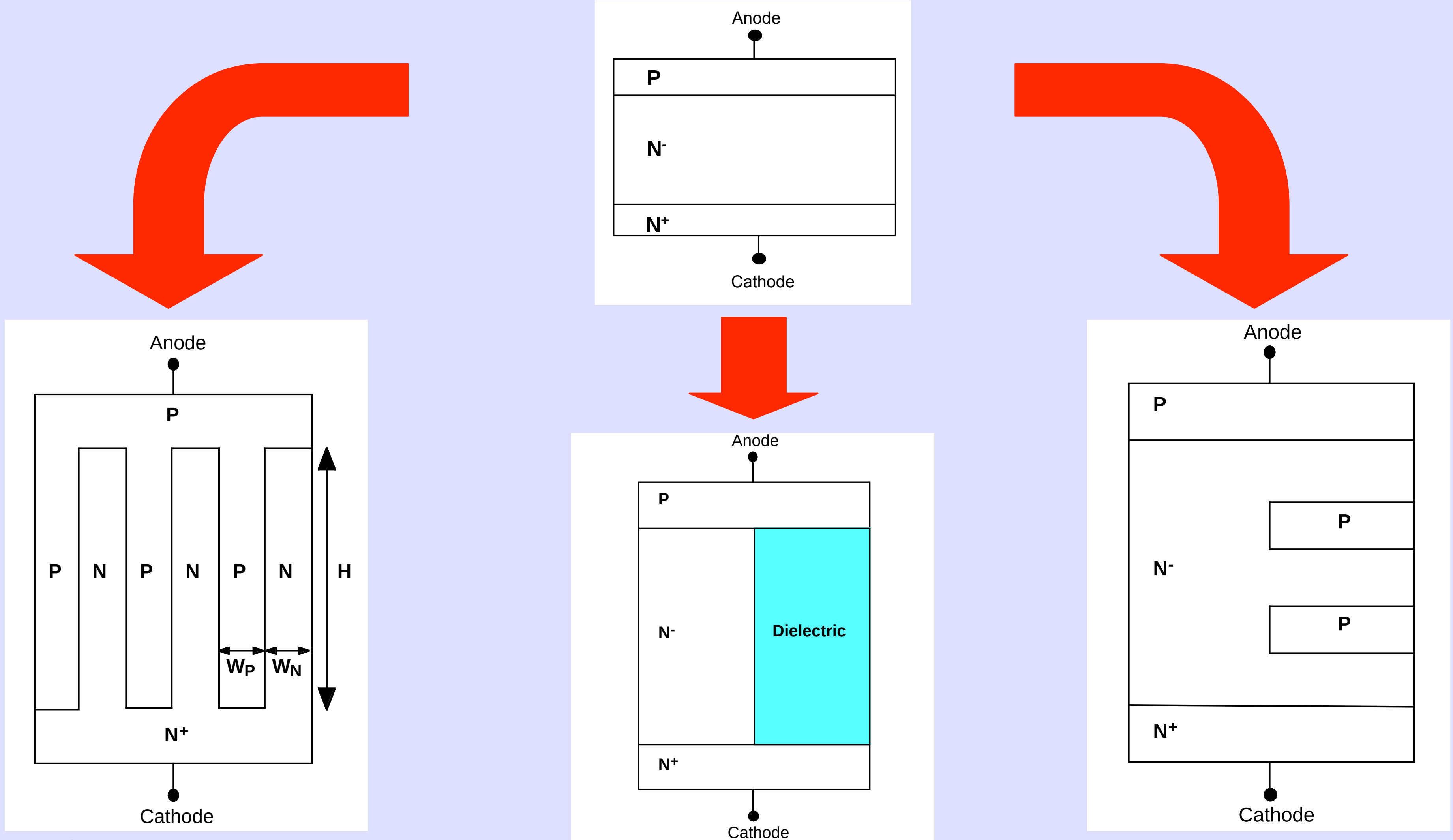
$$R_{ON}.S = \frac{H}{q \cdot \mu_n \cdot N_D}$$ (simple calculation with: $R = \rho.\frac{l}{S}$)

Vertical MOSFETs: $R_{ON}.S\left(\Omega.cm^2\right) = 8.9 \times 10^{-9} \times BV_{dss}{}^{2.4}$

Lateral MOSFETs: $R_{ON}.S\left(\Omega.cm^2\right) = 1.66 \times 10^{-14} \times h^{-1} \times BV_{dss}{}^{3.56}$

RESURF LDMOSFETs: $R_{ON}.S\left(\Omega.cm^2\right) = 1.02 \times 10^{-8} \times BV_{dss}{}^{2.33}$

Novel concepts are mandatory



Superjunction

U-diode

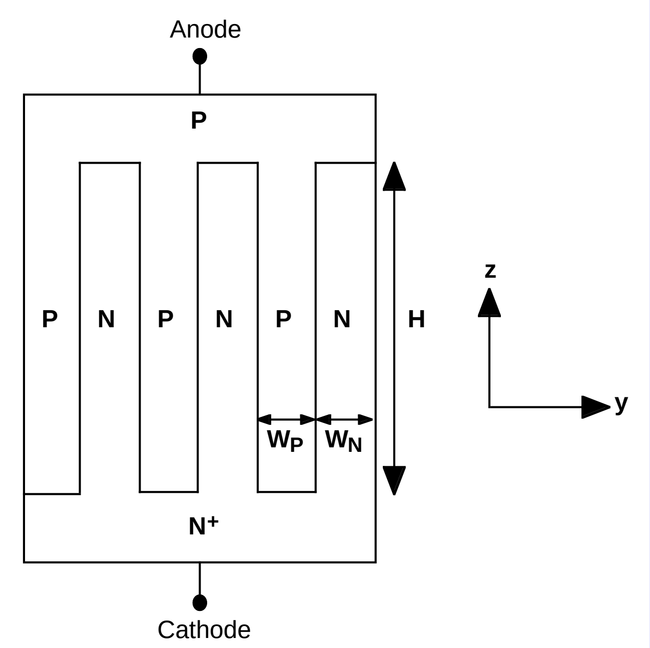
FLI-diode

The « Superjunction » concept

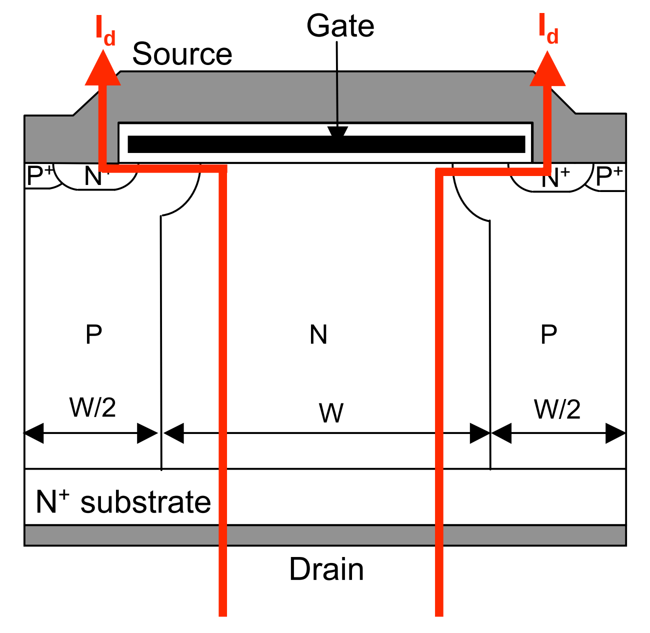
PRINCIPLE : **perfect charge balance between P and N-regions** ($N_A.W_P = N_D.W_N$)
(for example : $\mathbf{N_A = N_D}$ **et** $\mathbf{W_N = W_P = W << H}$)

- lateral depletion with: $E_{yMAX} < E_C$
- after lateral depletion: $V_{ds} = E_z .H$

→ $\mathbf{BV_{dss} = E_C.H}$



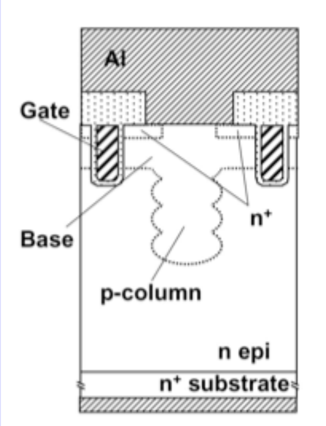
First application:
the COOLMOS™ from Infineon

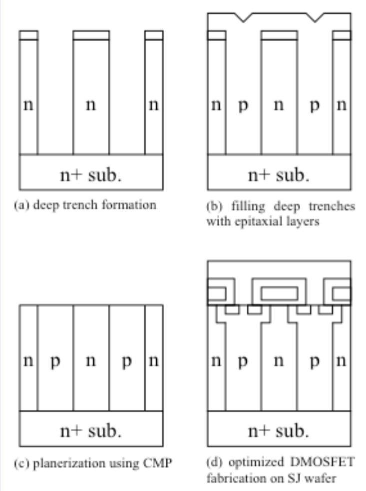


Vertical Superjunction MOSFETs

New limits for vertical power MOSFETs:

$$R_{ON}\,.\,S\left(\Omega.cm^{2}\right)=1.98\times10^{-1}\times W^{\frac{5}{4}}\times BV_{dss}$$



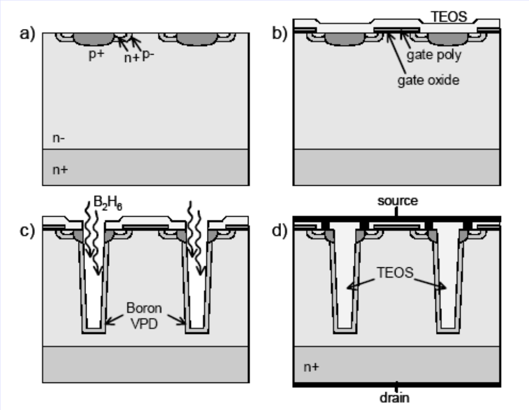


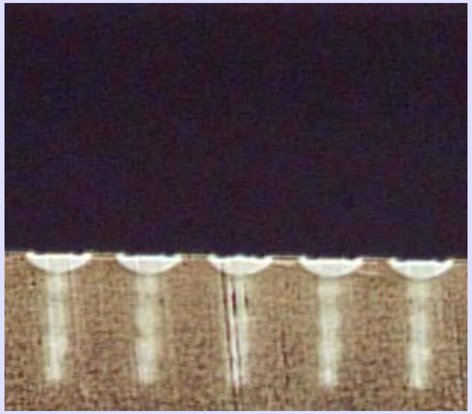
(a) deep trench formation

(b) filling deep trenches with epitaxial layers

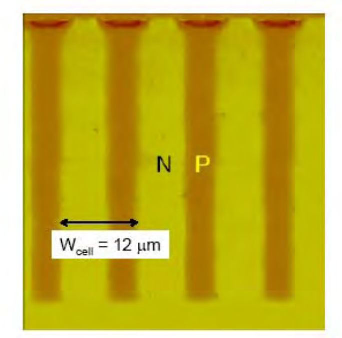
(c) planerization using CMP

(d) optimized DMOSFET fabrication on SJ wafer

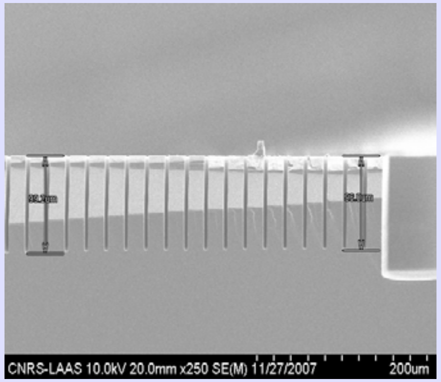




Multiple epitaxies
(Infineon, STMicroelectronics)

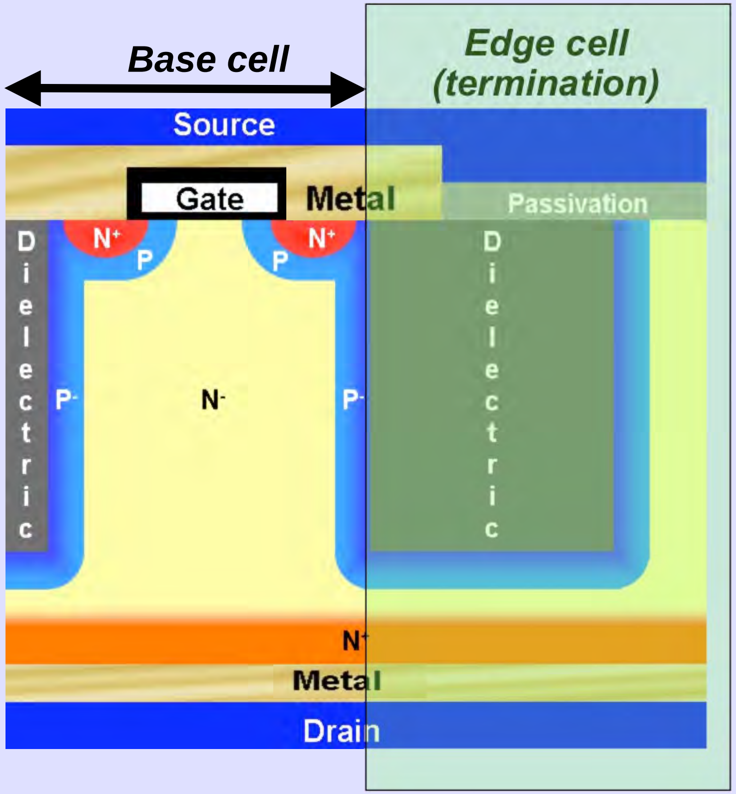


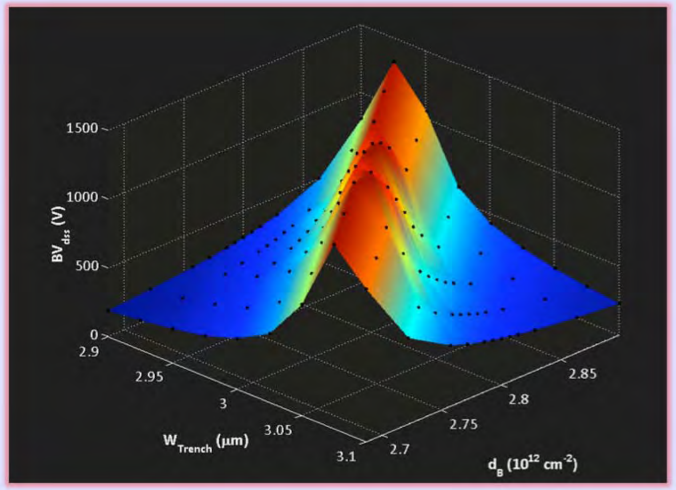
Deep trench etching and filling with epitaxial layers (Fuji Electric)



Deep trench etching, implantation / diffusion then filling with a dielectric (NXP, LAAS)

The Deep Trench Superjunction MOSFET



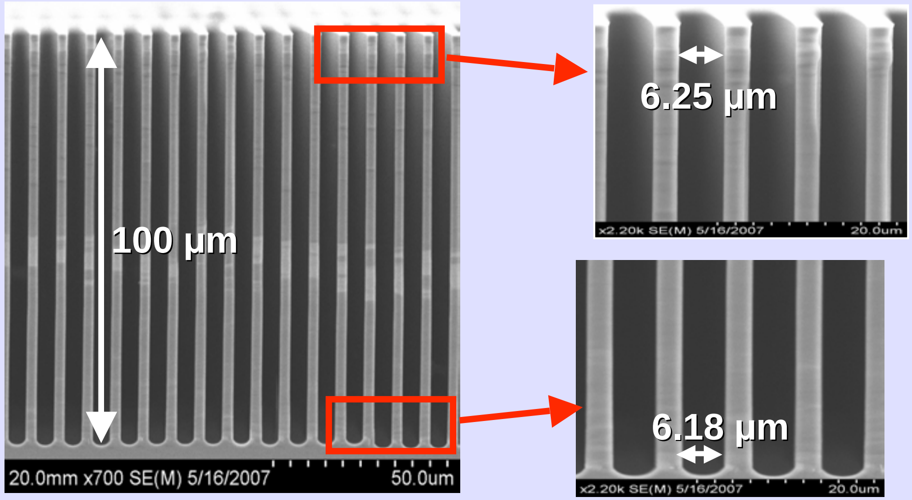


	Conventional VDMOSFET	DT-SJMOSFET
R_{ON}.S (mΩ.cm^2)	507	51

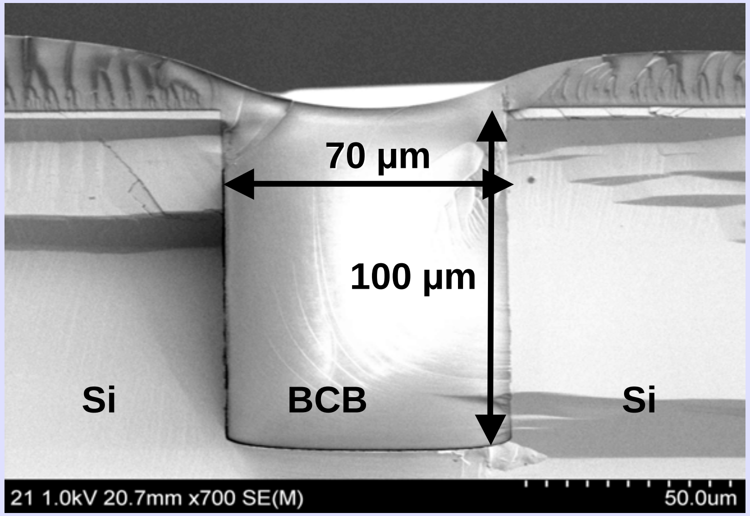
Critical technological steps:

- Deep Trench Reactive Ion Etching (DRIE)
- Boron diffusion through an oxide
- Trench filling with BCB (BenzoCycloButene)
- Chemical Mechanical Polishing (CMP) of the surface

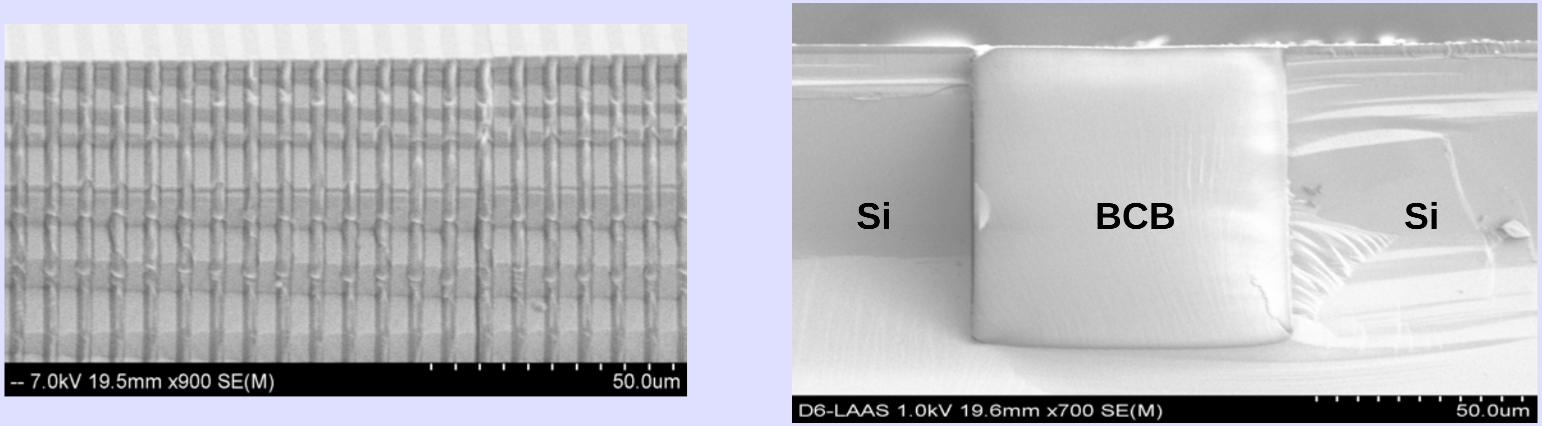
The Deep Trench Superjunction MOSFET



1. DRIE with a quasi-perfect verticality of the trenches

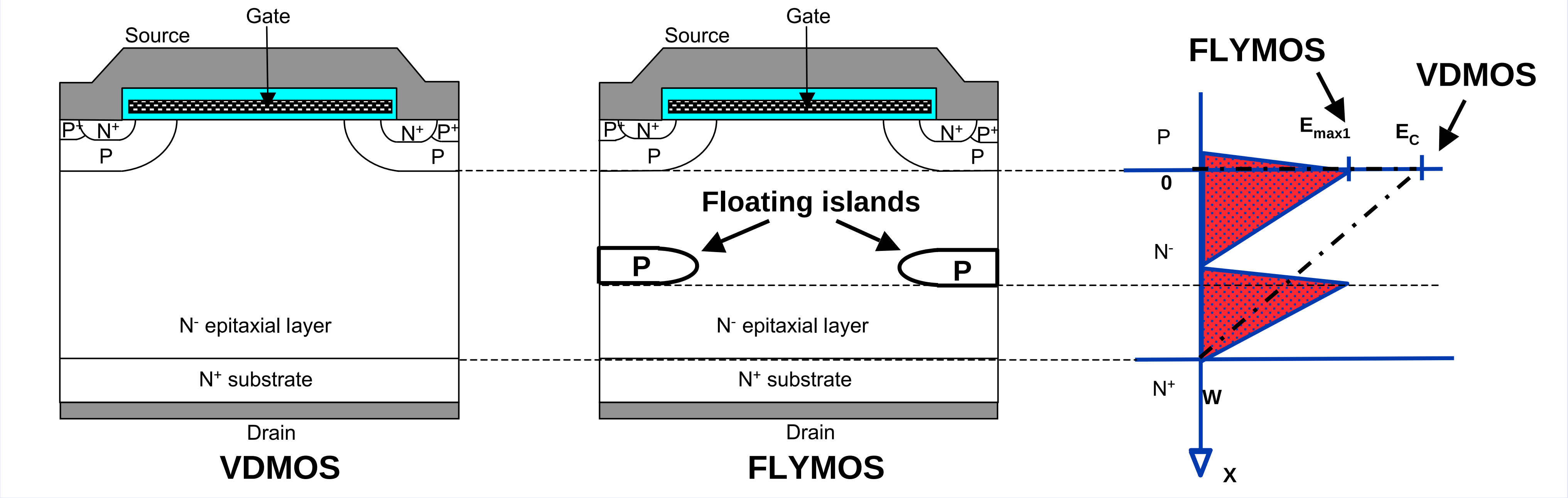


2. Trench filling with BCB (BenzoCycloButene)



3. Central trenches and trench termination after CMP of the BCB at the surface

The "Floating Islands" concept



➢ Breakdown voltage (BV_{dss}) improvement:

N_{epi} (VDMOS) = N_{epi} (FLYMOS) → R_{ON} (VDMOS) ≈ R_{ON} (FLYMOS)

→ BV_{dss} (VDMOS) < BV_{dss} (FLYMOS)

OR

➢ ON-resistance (R_{ON}) reduction:

BV_{dss} VDMOS = BV_{dss} FLYMOS → N_{epi} (VDMOS) < N_{epi} (FLYMOS)

→ R_{ON} (VDMOS) > R_{ON} (FLYMOS)

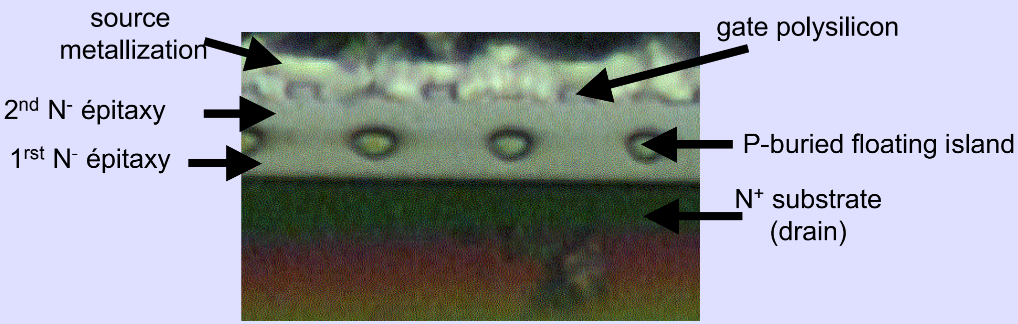
The "Floating Islands" MOSFETs

New limits for vertical power MOSFETs:

$$R_{ON}\,.\,S\left(\Omega.cm^{2}\right)=1.78\times10^{-8}\times\left(BV_{dss}\right)^{2.4}\times\left(n+1\right)^{-1.4}$$

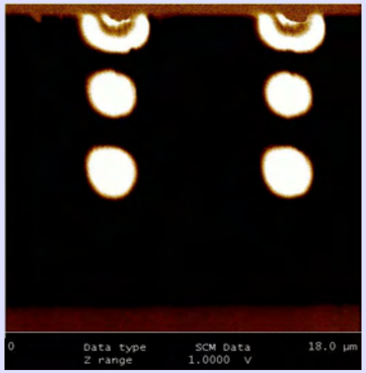
(n = number of floating islands between drain et source)

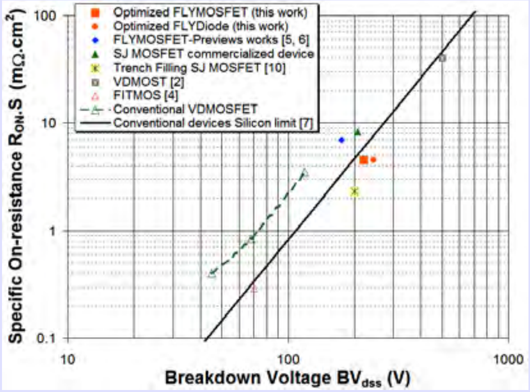
First technological realization of FLYMOSFETs (BV_{dss} = 80 V)



→ 33% R_{ON}.S improvement compared to a conventional 80 V VDMOSFET

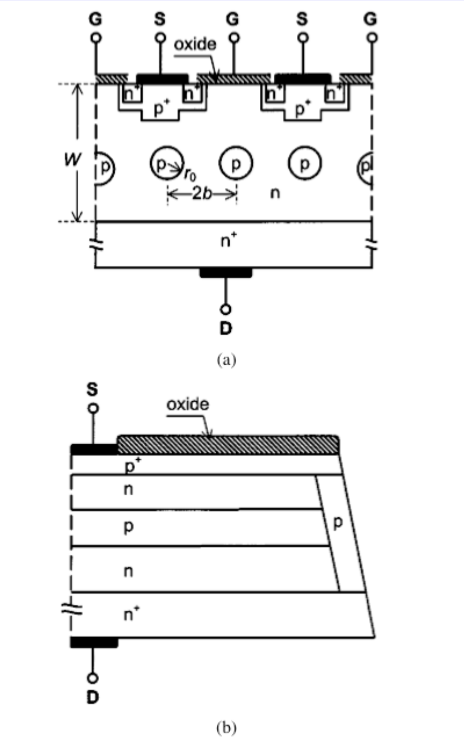
200 V FLYMOSFETs with 2 levels of floating islands between drain and source
(for the first time in the world)



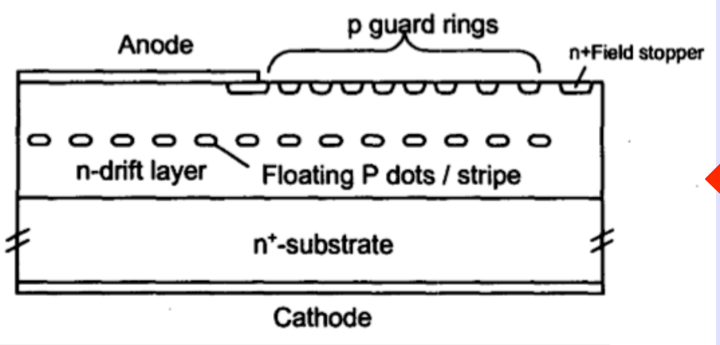


→ Best performance (in terms of $R_{ON}.Q_{gd}$) at BV_{dss} = 200 V

Other « Floating Islands » devices

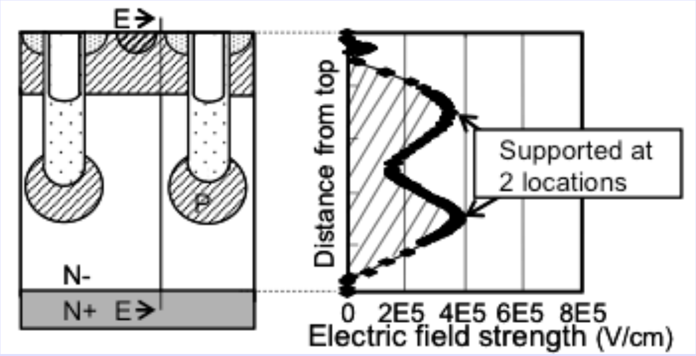


500 V Floating Islands MOSFET and its termination (University of Chengdu, China)

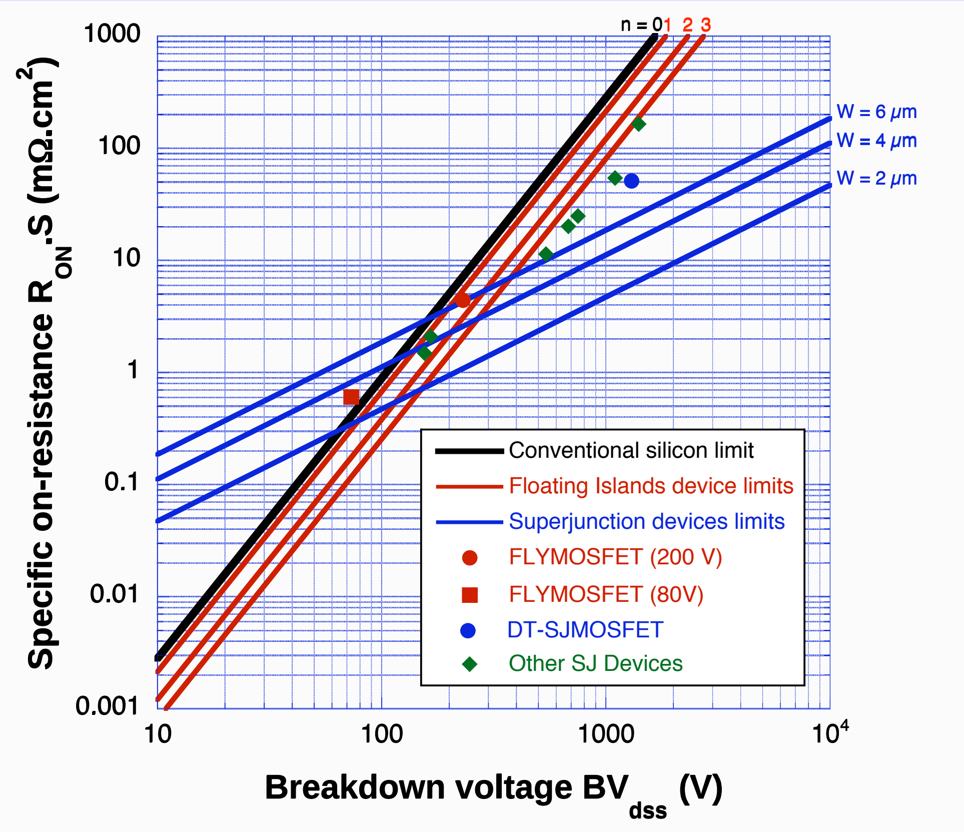


300 V Floating Islands Schottky diode and its termination (Toshiba)

80 V Floating Islands Trench MOSFET - FITMOS - (Toyota)



Limits of static performance with these new concepts on silicon



Conventional silicon limit :

$$R_{ON}.S = 8.9\times10^{-9}x(BV_{dss})^{2.4} \quad (\Omega.cm^2)$$

Superjunction devices :

$$R_{ON}.S = 1.98\times10^{-1}xW^{5/4}x(BV_{dss}) \quad (\Omega.cm^2)$$

Floating Islands devices :

$$R_{ON}.S = 1.78x10^{-8}x(BV_{dss})^{2.4}x(n+1)^{-1.4} \quad (\Omega.cm^2)$$

W = P and N layers width of Superjonction MOSFETs
n = number of floating islands of FLYMOSFETs

- superiority of Superjunction MOSFET at high voltage range (> 600 V)
- competition “FLYMOSFET/Superjunction MOSFET” at medium voltage range (200 to 600 V)
- superiority of FLYMOSFET at low voltage range (< 200 V)

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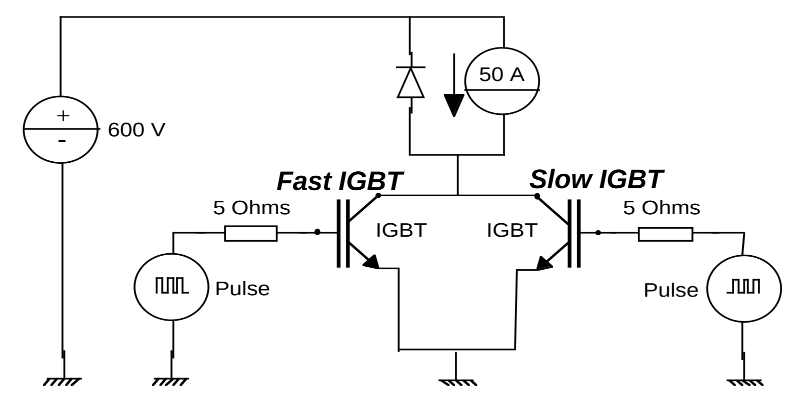
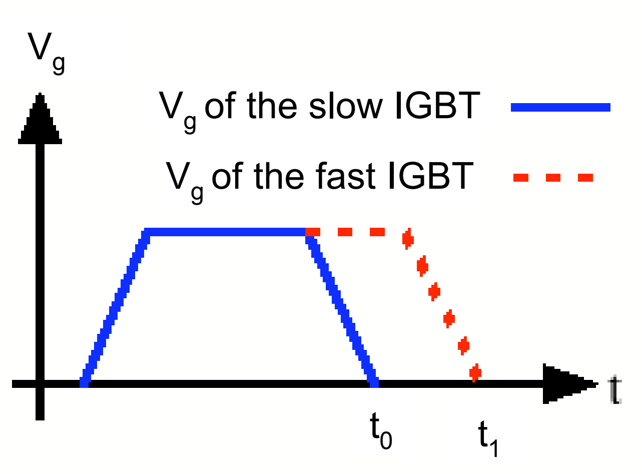
The « Low losses » IGBT

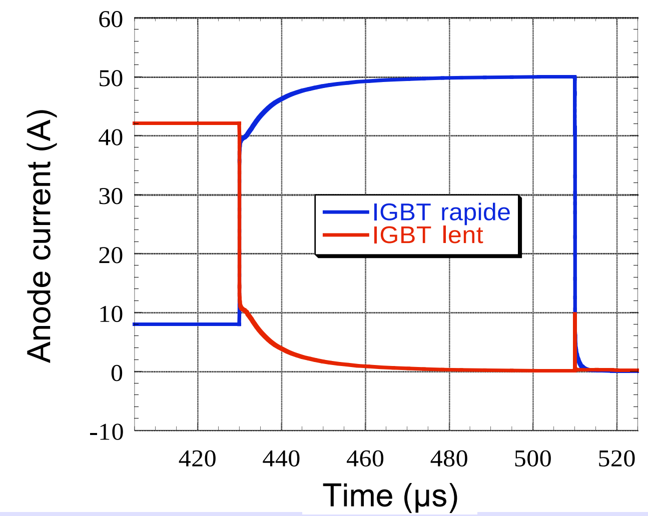
Objective: optimize the « conduction losses / switching losses » trade-off with a parallel association of 2 IGBTs :

- Fast IGBT: high V_{ON} and low switching losses
- Slow IGBT: low V_{ON} and high switching losses



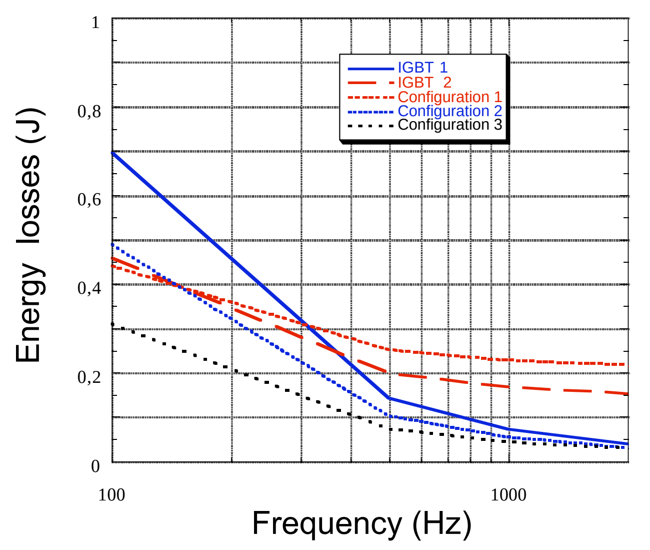


Driving cycle



Anode current repartition

The « Low losses » IGBT



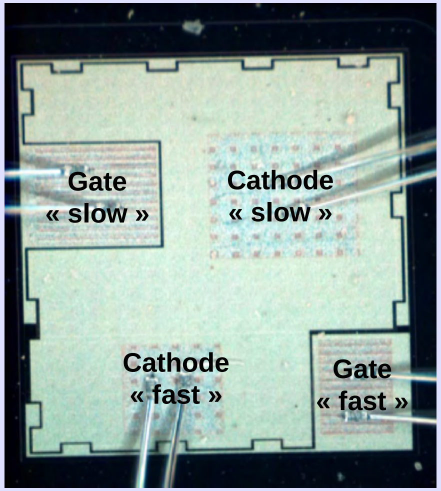
IGBT 1: Fast

IGBT 2: Slow

Configuration 1: slow IGBT // slow IGBT

Configuration 2: fast IGBT // fast IGBT

Configuration 3: slow IGBT // fast IGBT

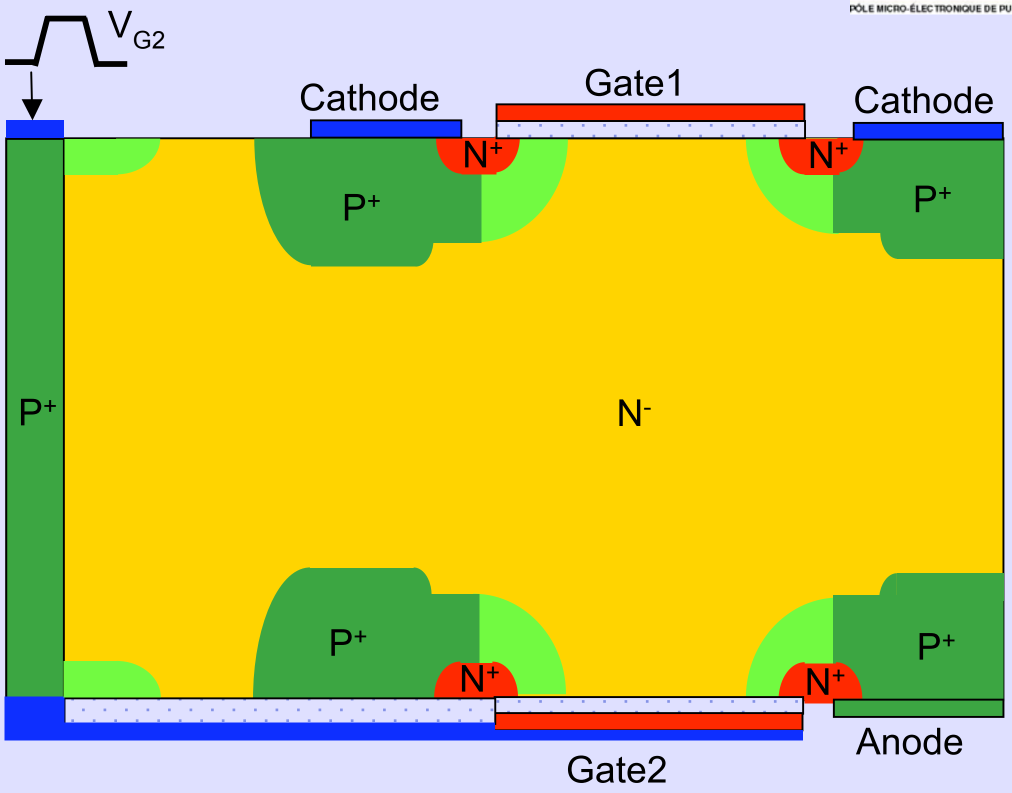


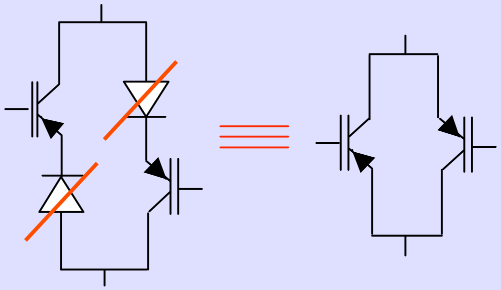
Slow IGBT:
P^+ Anode
(C_S = 3.10^{19} cm^{-3} ; X_j = 7 µm)

Fast IGBT:
Semi-transparent anode
(C_S = 10^{17} cm^{-3} ; X_j = 0,3 µm)

The bidirectional IGBT

ANR MOBIDIC

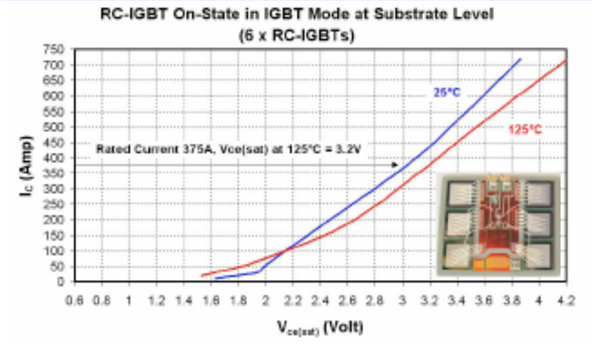




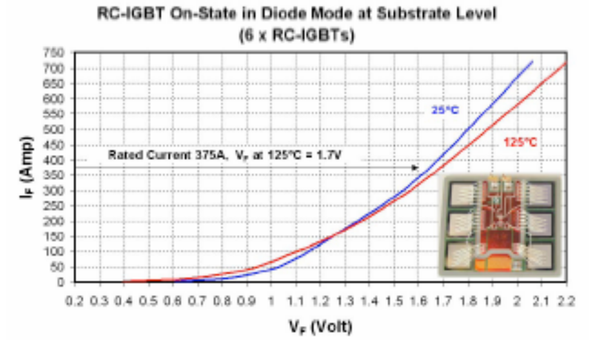
Monolithical integration

Use of wafer bonding technique or double face lithography

Integration of an IGBT and its freewheeling diode

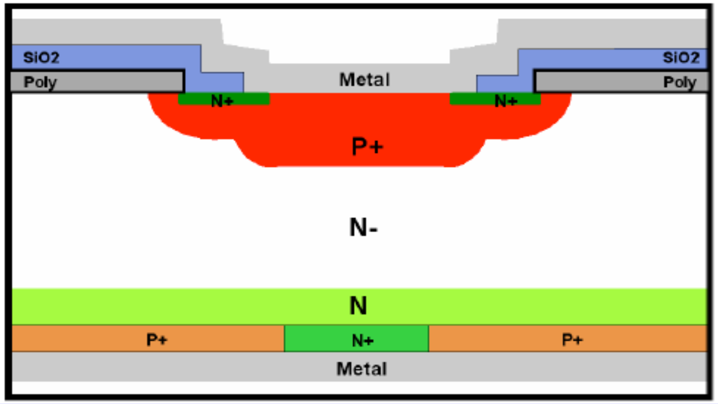


(a) RC-IGBT in IGBT mode.



(b) RC-IGBT in Diode mode

ON-state characteristics of the RC-IGBT



The Reverse Conducting IGBT (RC-IGBT)

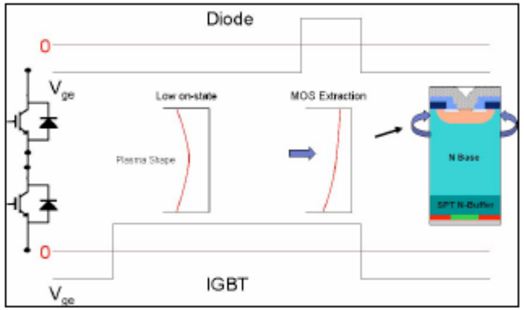


Fig. 5: RC-IGBT gate control charge extraction at reverse recovery.

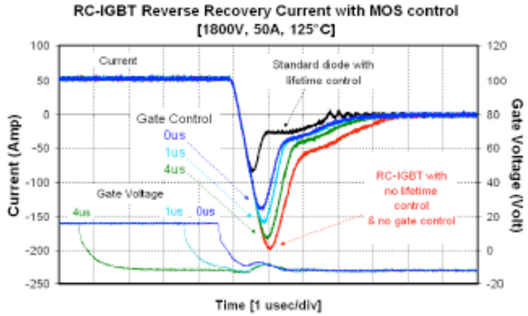
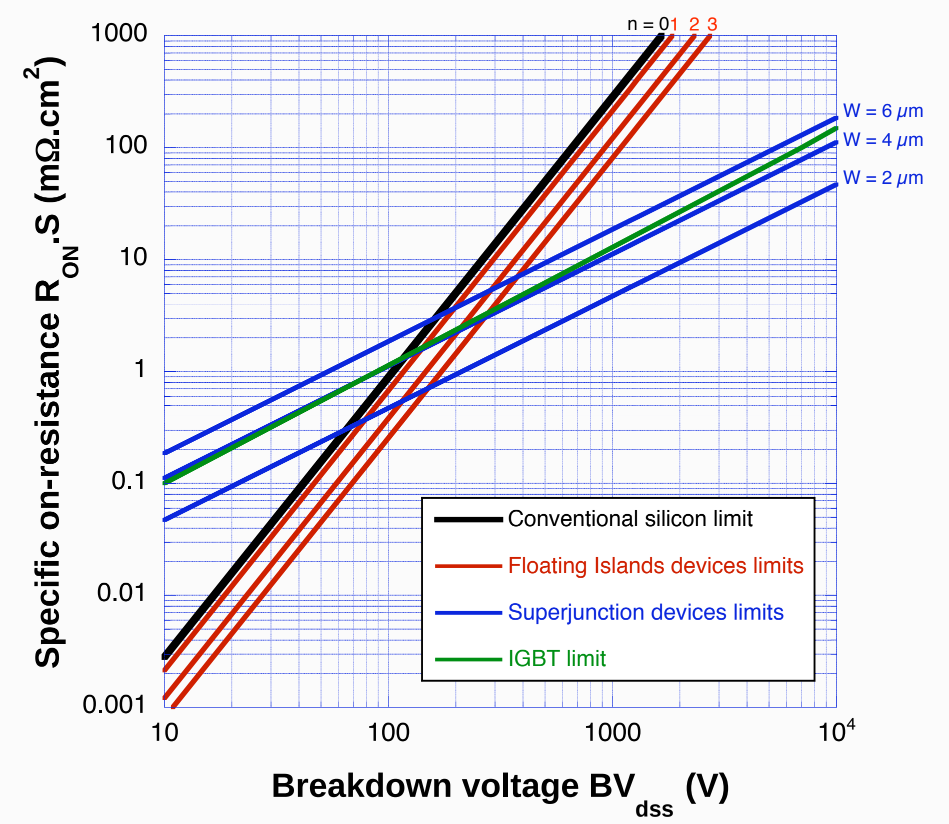


Fig. 6: RC-IGBT reverse recovery current and gate control waveforms for charge extraction.

RC-IGBT reverse recovery current and gate control waveforms for charge extraction

from ***A High Current 3300V Module Employing Reverse Conducting IGBTs Setting a New Benchmark in Output Power Capability***,
M. Rahimo *et al*, ABB Switzerland Ltd Semiconductors ISPSD'08, pp. 68-71.

Limits of static performance of IGBTs



High voltage (> 1 kV): IGBT is the best device. IGBT and SJMOSFET exhibit the same static performance but IGBT technology is cheaper.

Medium voltage (around 600 V): same performance for MOSFETs (FLYMOSFET, SJMOSFET) and IGBT. The choice will depend on the operating frequency.

Low voltage (< 400 Volts): MOSFETs (FLYMOSFET or SJMOSFET) are the best devices

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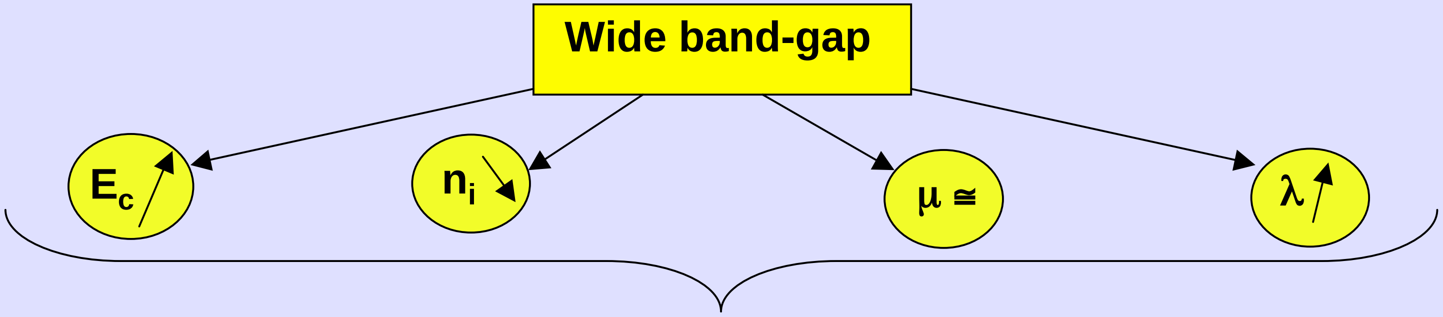
Properties of wide band-gap semiconductors

	« Conventional » semiconductors		Wide band-gap semiconductors				
	Si	GaAs	3C – SiC	6H – SiC	4H – SiC	GaN	Diamond
Band-gap E_g (eV)	1.12	1.4	2.3	2.9	3.2	3.39	5.6
Electron mobility μ_n ($cm^2.V^{-1}.s^{-1}$)	1 450	8 500	1000	415	950	1000	4000
Hole mobility μ_p ($cm^2.V^{-1}.s^{-1}$)	450	400	45	90	115	35	3800
Critical electric field E_C ($V.cm^{-1}$)	3×10^5	4×10^5	2×10^6	2.5×10^6	3×10^6	5×10^6	10^7
Intrinsic concentration n_i (cm^{-2})	1.5×10^{10}	2.1×10^6	6.9	2.3×10^{-6}	8.2×10^{-9}	1.6×10^{-10}	1.6×10^{-27}
Saturation velocity v_{sat} ($cm.s^{-1}$)	10^7	2.10^7	2.5×10^7	2×10^7	2×10^7	2×10^7	3×10^7
Thermal conductivity λ ($W.cm^{-1}.K^{-1}$)	1.3	0.54	5	5	5	1.3	20
Maximal operation temperature T_{max} (°C)	125	150	500	500	500	650	700
Dielectric constant	11.7	12.9	9.6	9.7	10	8.9	5.7



Wide band-gap

$E_c \nearrow$

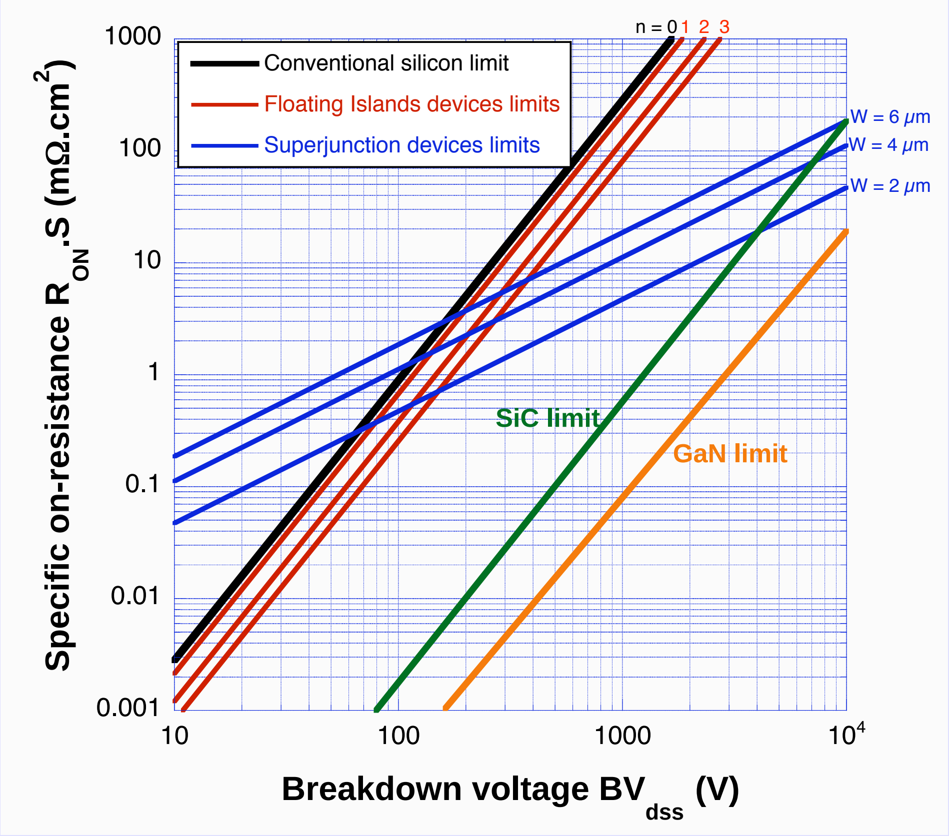
$n_i \searrow$

$\mu \cong$

$\lambda \nearrow$

High voltage, high temperature, high frequency and low losses devices

Si, SiC, GaN: comparison of limits of static performance



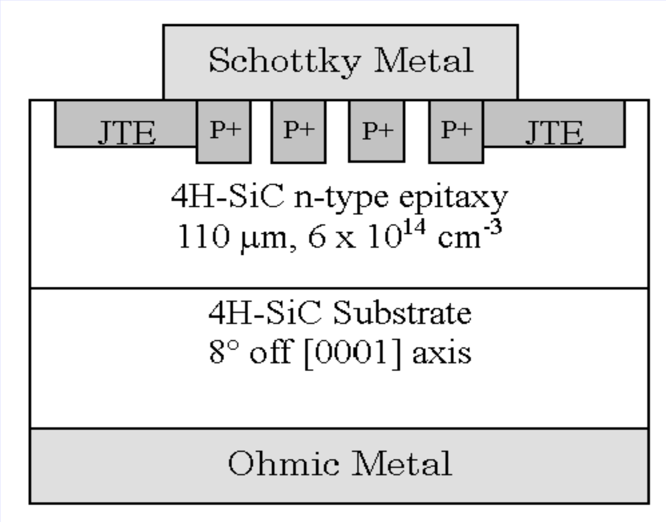
Compared to the conventional silicon limit, the improvement factor of the static performance is very important:

- R_{ON}. S: 3 decades for SiC and 4 decades for GaN!
- BV_{dss}: more than 1 decade!

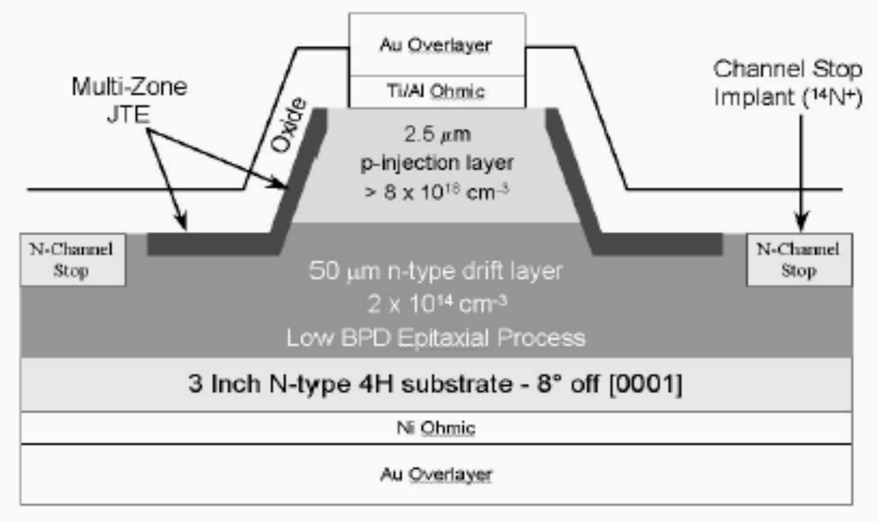
Compared to Superjunction devices limits:

Superjunction devices are theoretically performant at BV_{dss} = 10 kV but its technology would be too expensive (or impossible) in this voltage range.

SiC power diodes

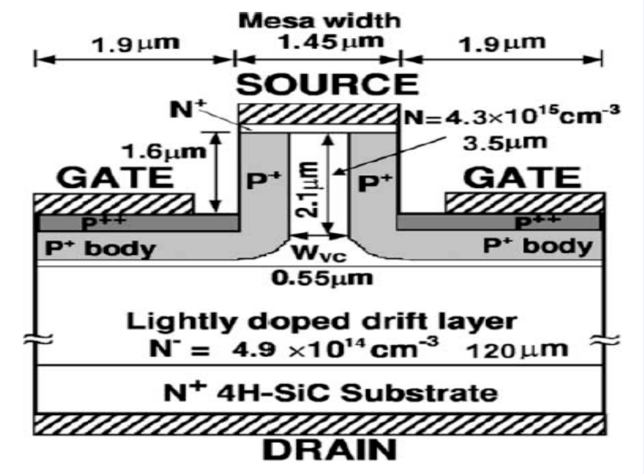


Diode Schottky 300 V, 130 A,
R. Singh et al, IEEE Transaction on Electron Devices, 2002

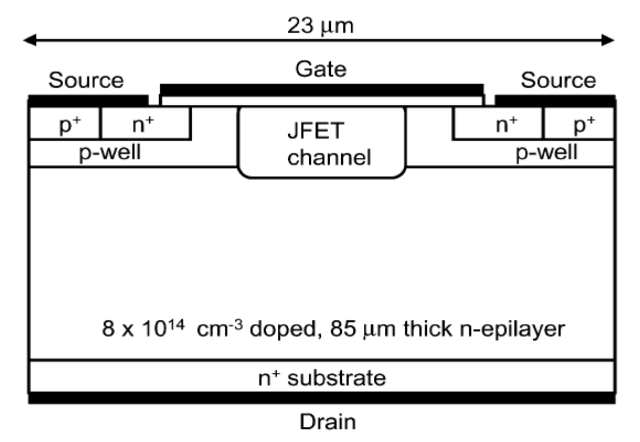


Bipolar diode 4.5 kV, 150 A
Brett A. Hull et al, ISPSD'06

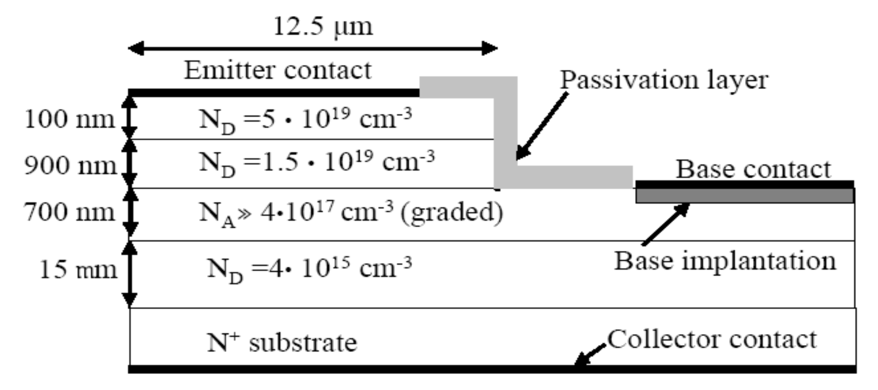
SiC power transistors



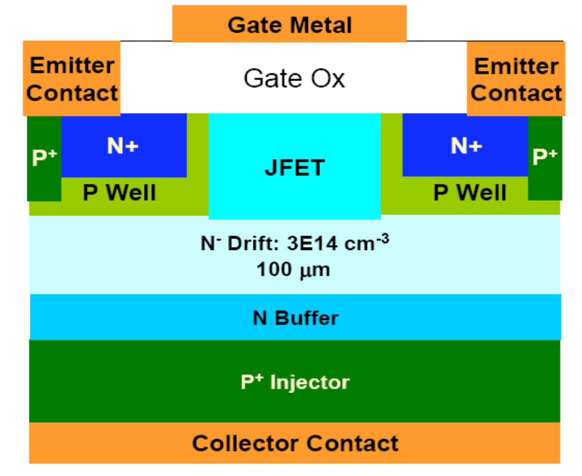
JFET (BV_{dss} = 11 kV, R_{ON}.S = 130 mΩ.cm^2)
J.H. Zhao et al, IEEE Electron Device Letters, 2004



MOSFET (BV_{dss} = 10 kV, R_{ON}.S = 123 mΩ.cm^2)
S.H. Ryu et al, IEEE Electron Device Letters, 2004

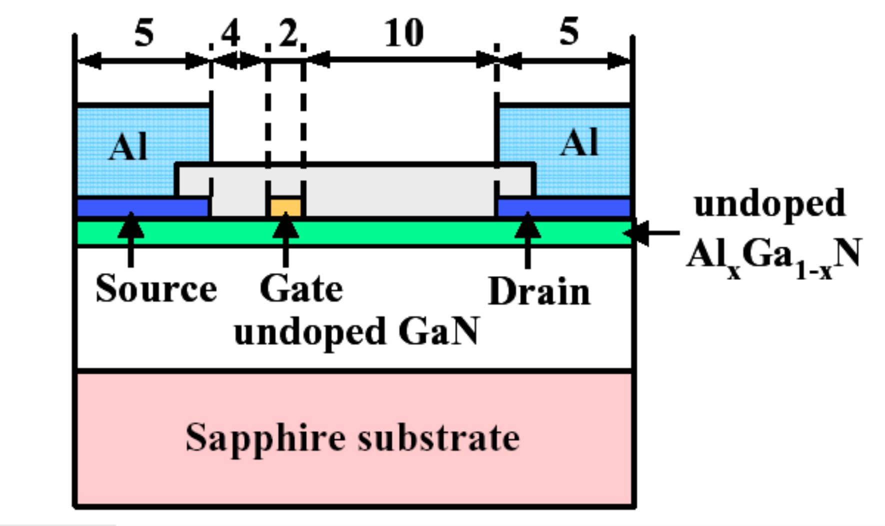


Bipolar transistor 1200 V / 15 A (@V_{CE}=2V)
H.S. Lee et al, ICSCRM'07

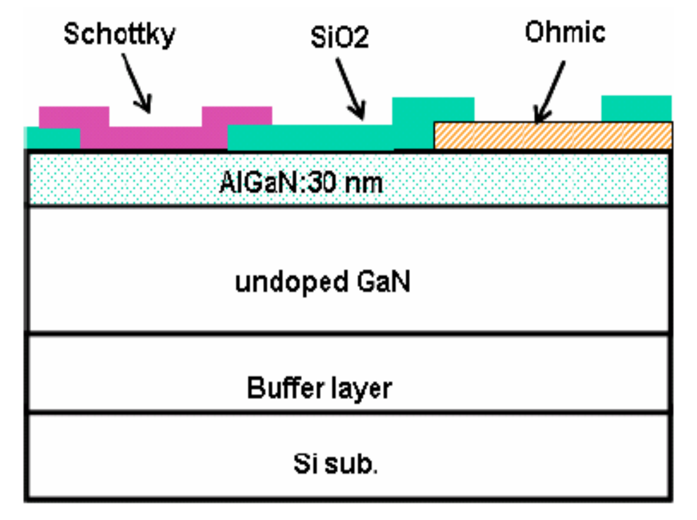


N-type IGBT 13 kV / 4 A (@V_F<5 V)
M.K. Das et al, ICSCRM'07

GaN power devices

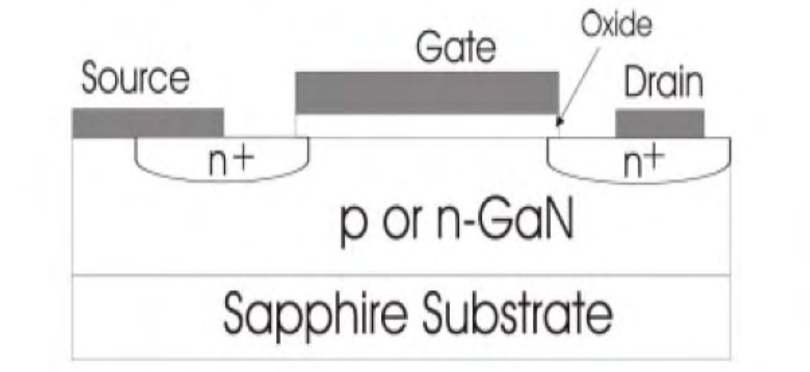


AlGaN/GaN HEMT (BV_{dss} = 1050 V, R_{ON}.S = 6 mΩ.cm^2)
[Ueda et al, ISPSD'2005]

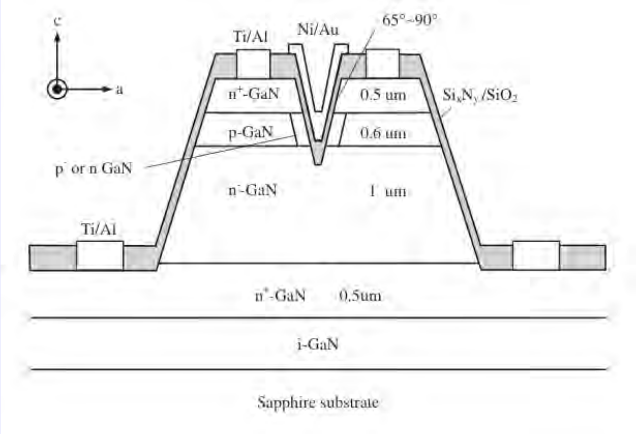


Schottky Diode (BV_{dss} = 1050 V, R_{ON}.S = 6 mΩ.cm^2)
[Yoshida et al, ISPSD'2006]

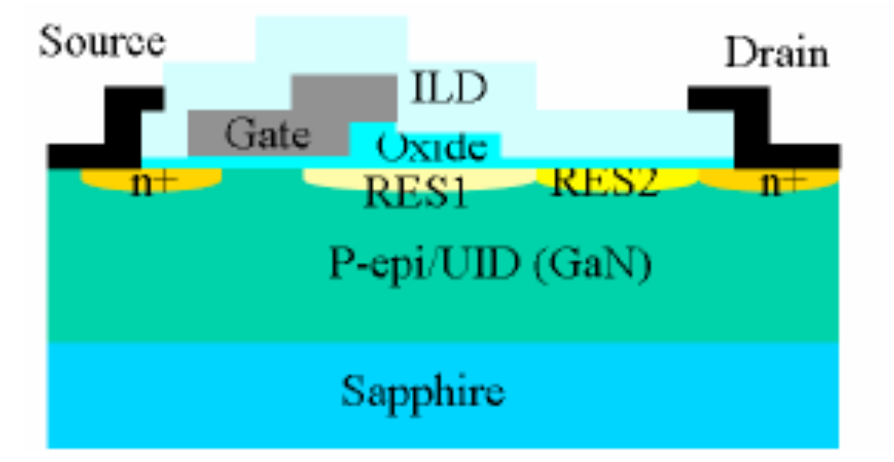
GaN power MOSFETs



Lateral MOSFET (BV_{dss} = 940 V)
[Huang et al, ISPSD'2006]



Trench Gate MOSFET
[Otake et al. JJAP 2007]



RESURF LDMOSFET (BV_{dss} = 1570 V , R_{ON}.S = 30 mΩ.cm^2)
[Huang et al, ISPSD'2008]

Trends in wide band-gap semiconductors

	Si	SiC	GaN	Diamond
Material	+ + +	—	— —	— —
Substrate cost	+ + +	—	+ (depends on the substrate)	— — —
Technology	+ + +	+	+ + (silicon compatible)	— —
Type of devices	All	All (MOS gated devices only at very high voltage)	Essentially unipolar, lateral and normally-on devices	Unipolar (Schottky, JFET)
Voltage range	Low and medium voltage	Medium and high voltage	Medium voltage	Very high voltage

SiC: Schottky and JBS diodes are commercially available up to 1.2 kV. PiN diodes will be soon available. Regarding power switches, a normally-off switch is always expected.

GaN is already commercialised in photonics area. However, its application in power devices requires further work in material, processing and device design.

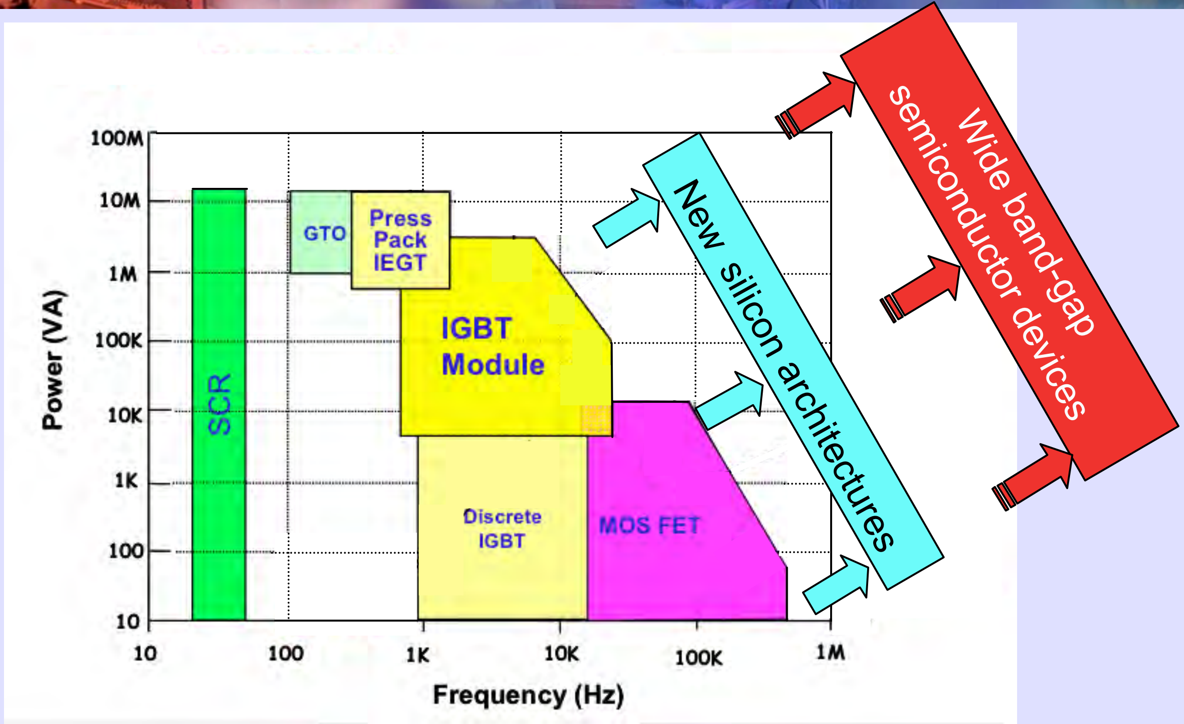
→ Can GaN power devices overtake or displace SiC power devices ?

Diamond: material, processing and device design are at a very early stage.

Outline

- Introduction
- Unipolar power devices: MOSFETs
  - Conventional devices and their « silicon limits »
  - Novel concepts : Superjunction and floating islands
  - Limits of performance with these novel concepts
- Bipolar power devices: IGBTs
  - Low losses IGBT
  - Integration of an IGBT and a diode
  - Limits of performance of IGBTs
- Wide band-gap power semiconductor devices
  - Properties of wide band-gap semiconductors
  - Comparison of llimits of performance
  - SiC, GaN, Diamond : future trends
- Conclusion

Application fields of power devices: future trends

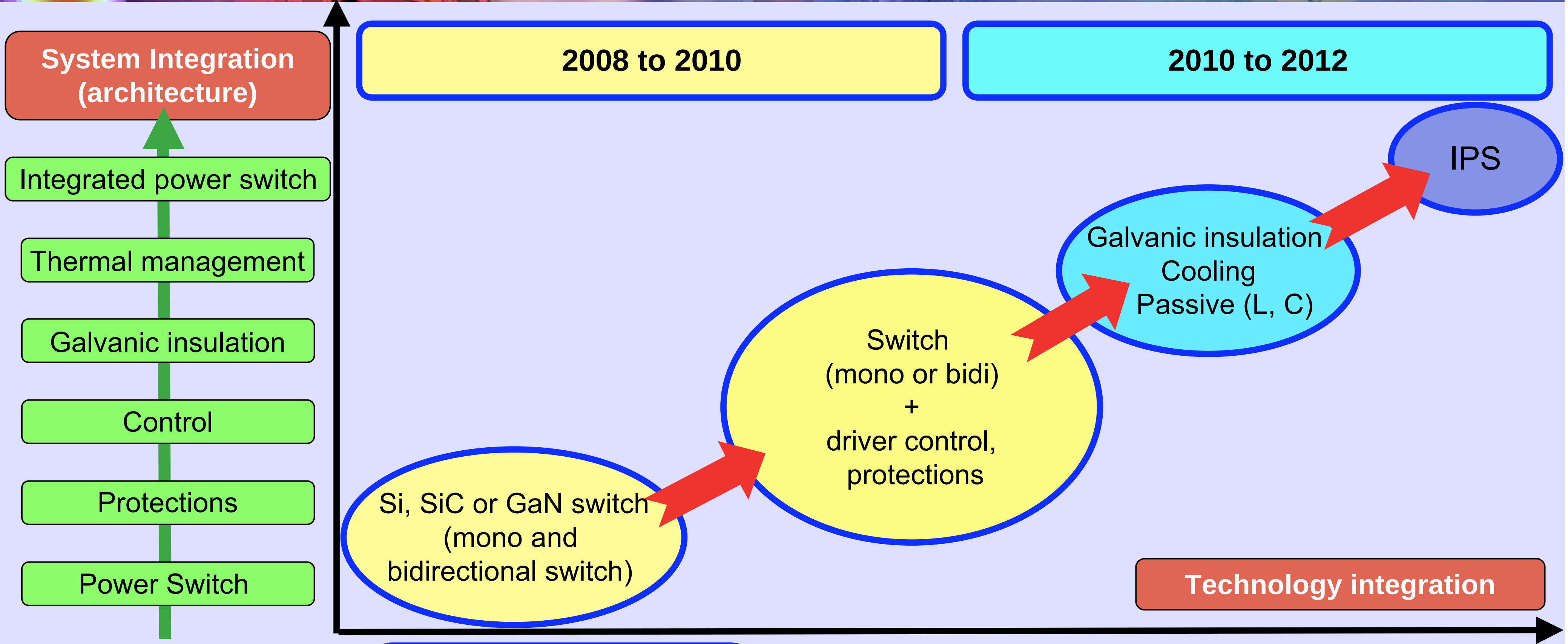


MOS gate devices (MOSFETs, IGBTs): new silicon architectures are available and performant up to 3.3 kV.

Schottky and JBS diodes: wide band-gap devices are displacing silicon devices even at breakdown voltages from 300 to 600 Volts.

Silicon still has a future in the « power devices » field, but rapid progress has been made in the development of wide band-gap power devices!

Integrated Power Switch Roadmap



System Integration (architecture)

Integrated power switch

Thermal management

Galvanic insulation

Control

Protections

Power Switch

2008 to 2010

2010 to 2012

Si, SiC or GaN switch (mono and bidirectional switch)

Switch (mono or bidi) + driver control, protections

Galvanic insulation
Cooling
Passive (L, C)

IPS

Technology integration

Flexible process:
- Dry deep silicon etching
- Trench MOS
- Thin wafer techno
- Wafer bonding
- Vias
- Backside lithography

Materials:
- Magnetic
- High K
- Low K
- Piezo

3D integration:
- Planarisation process
- Interconnect metallization
- Stacking (3D integration)
- Diamant, CNT

LAAS-CNRS: about 40 years of research in the « power devices » field