ON Semiconductor®

General Overview of GaN Power Devices

Peter Moens

Why are you here today ?

- Power semiconductors are a hot topic
- Power devices=solid state physics
  - 1D limit for a vertical transistor
  - Resurf effect (2D)
- Non-polar and polar materials
  - Concept of polarization charge
  - Simple band structure
- HEMT "High Electron Mobility Transistor"
  - Sheet resistance
  - HEMT versus vertical power device
- Cost versus performance

$$Ron = \frac{4.V_{bd}^2}{E_C^3.\varepsilon.\mu_N}$$

Break

$$Ron = \frac{2.V_{bd}}{E_C^2.\varepsilon.\mu_N}$$

$$Ron = \frac{1}{q.n_s.\mu_N}.\frac{V_{bd}^2}{E_c^2}$$

Test

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Power Semiconductor Market Forecast

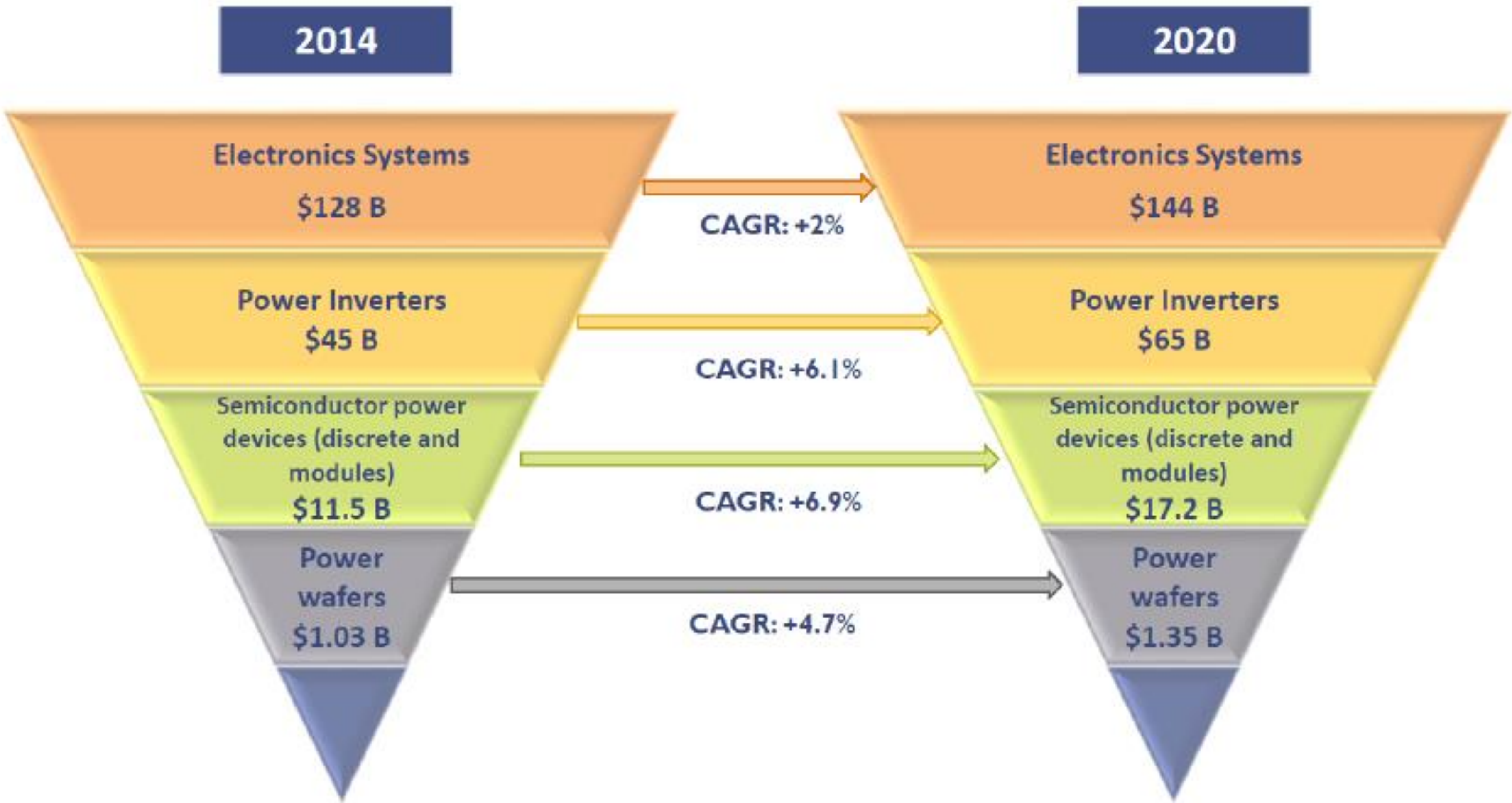


Figure 1 Power electronics CAGR along the typical value chain[3]

What drives the market ?

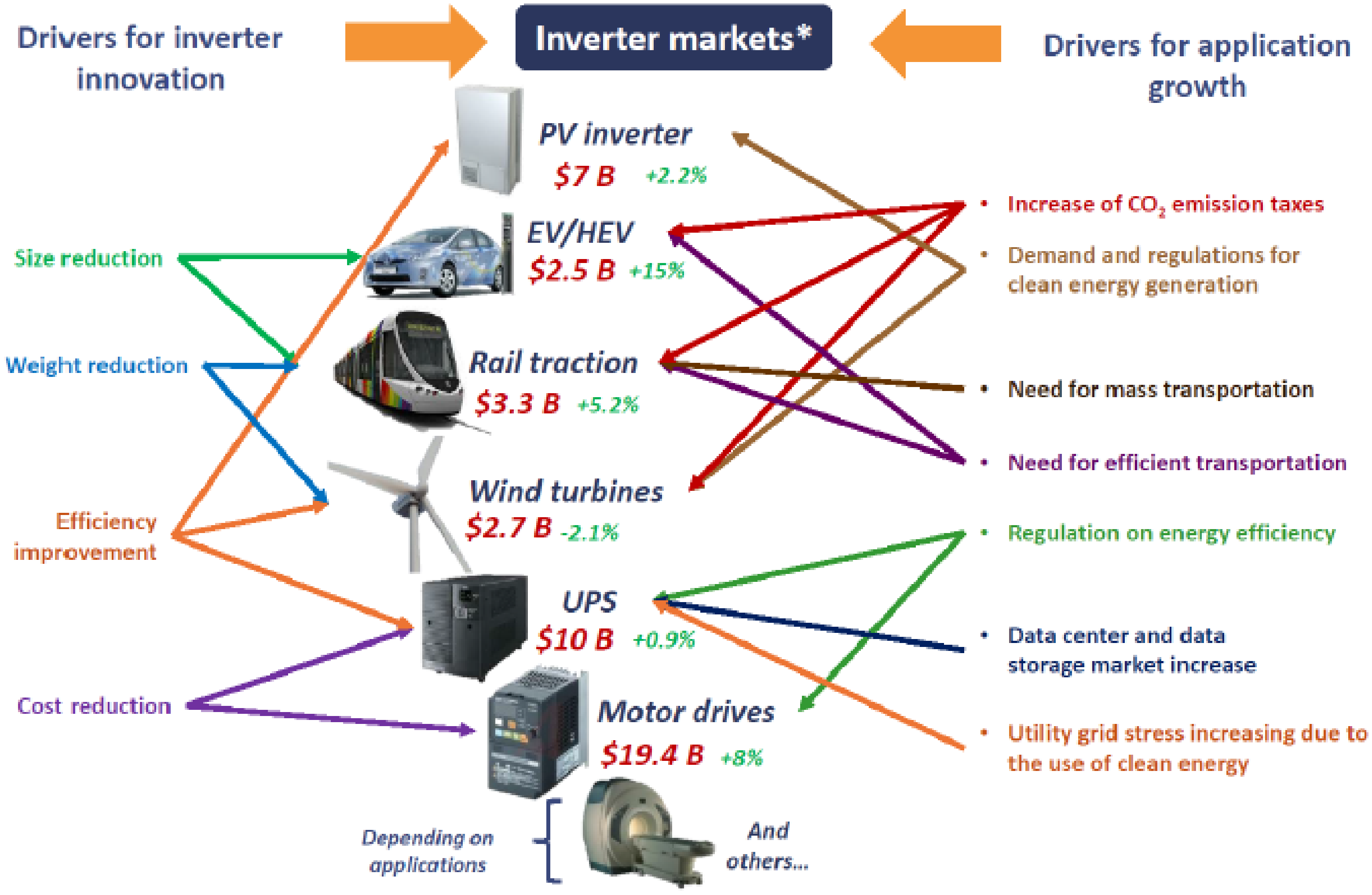
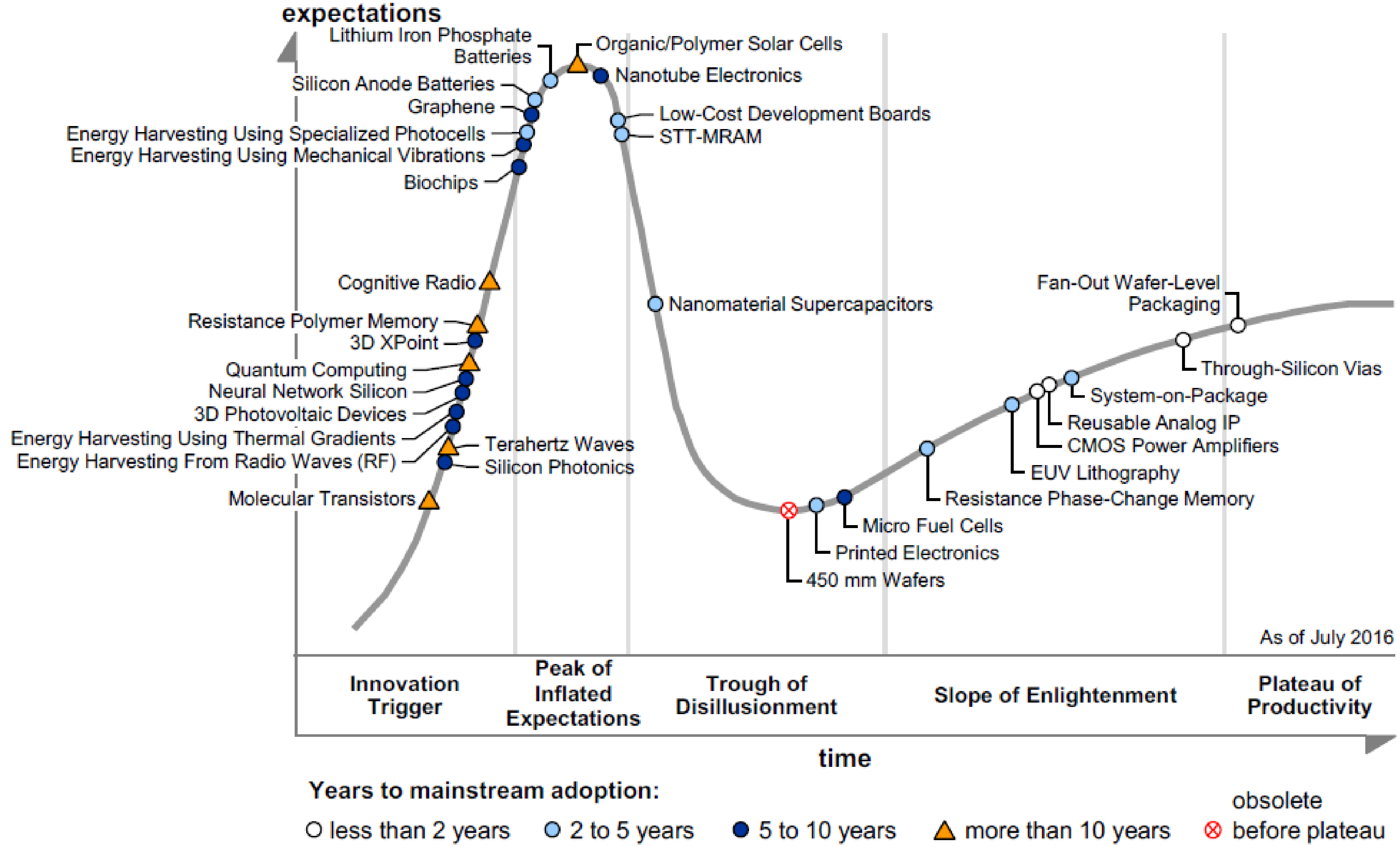


Figure 2 Growth chances and market drivers for inverters[4]

The Hype Cycle for Electronic Technologies

Figure 1. Hype Cycle for Semiconductors and Electronics Technologies, 2016



Source: Gartner (July 2016)

2015—?? Power Technology

WBG Market Segmentation by 2020

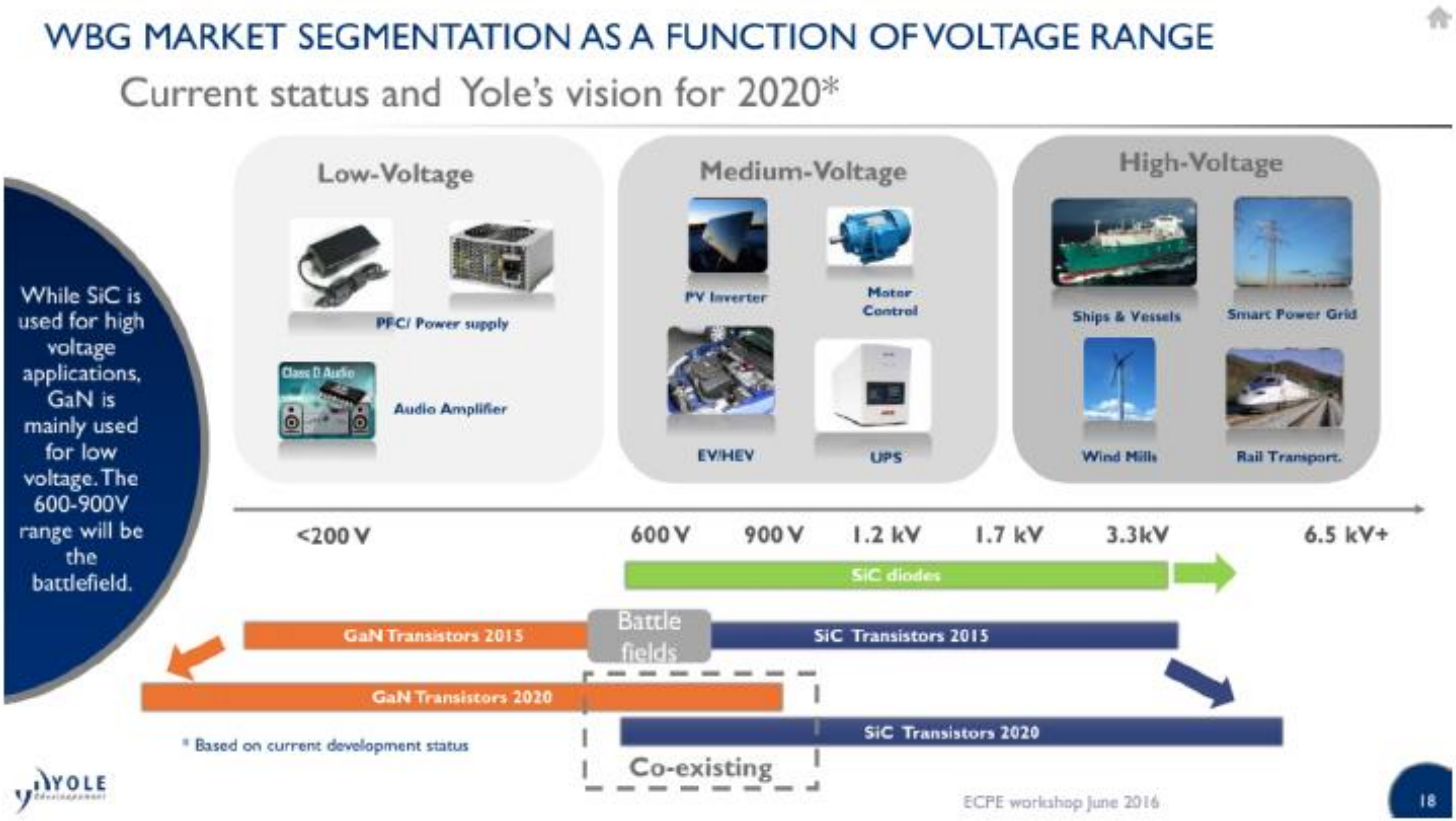


Figure 11 Yole's vision of WBG-applications for 2020 (Source: Yole)

WBG Segmentation by Power Rating

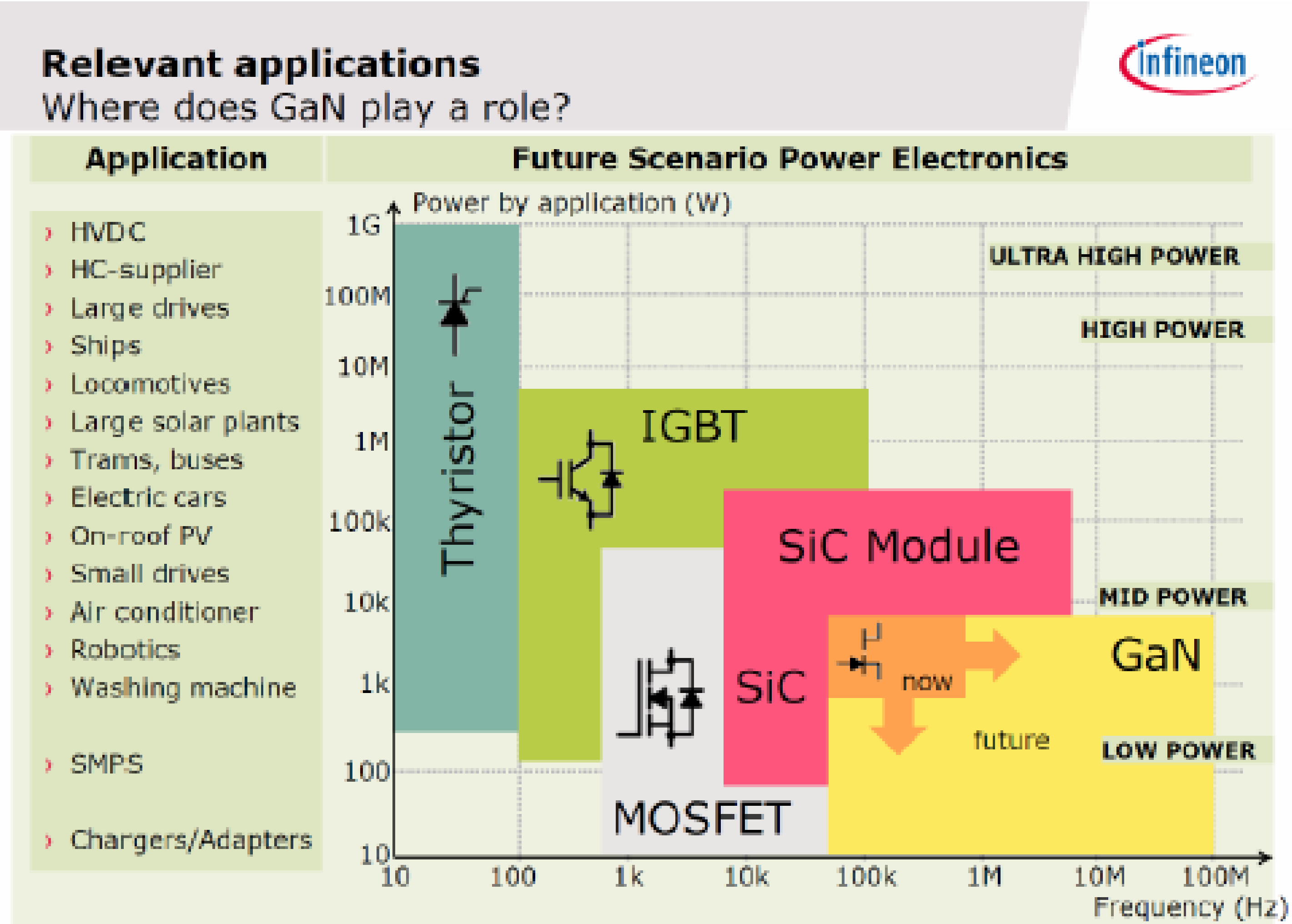


Figure 15 Relevant applications (Source: Infineon)

WBG: High Potential for Market Disruption

High Power Motor Drive System

Si Solution

SiC Solution

Appliance Motor Drive System

Si Solution

GaN Solution

Stronger
Greener
Faster

Laptop Power Supply

Si Solution

SiC Solution

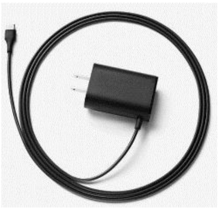
Smaller
Lighter
Cheaper
Cooler

Solar Inverter

*Illustrative representation

What does it mean to me...

10-15W/cm³

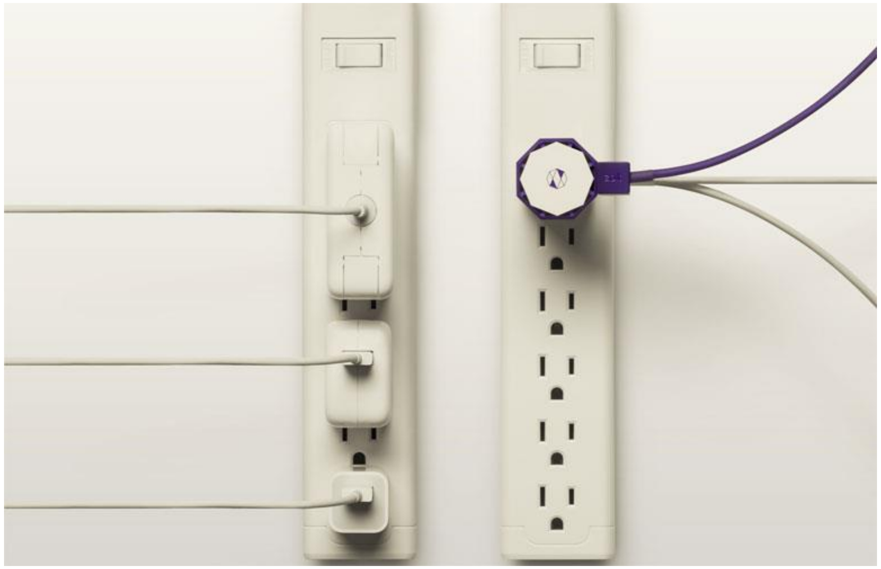


>40W/cm³

- Smaller / Power density
- Lighter / Power density

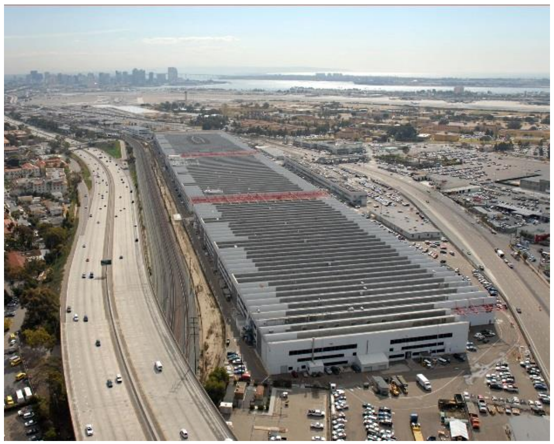
Zolt Charger

- https://www.gozolt.com/



What does it mean to me…

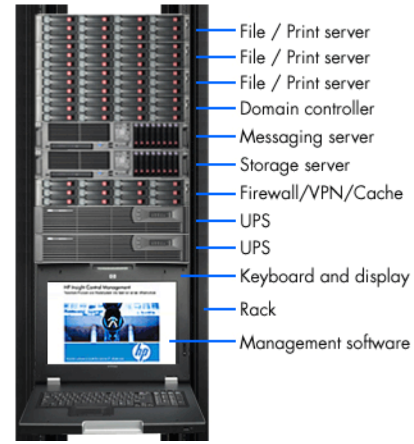
- 300M photos uploaded each day
- 300 hours uploaded every minute
- 10B hours watched per month



360,000 servers!

Annual maintenance cost ~200$/ft

150MW power usage/datacenter



- Lower electricity bill / Higher efficiency
- Fit it into the same space / Power density

Google Little Box Challenge → GaN

- https://www.littleboxchallenge.com/
- Downscale a 2kW inverter down to the size of a tablet.

And the winner of the $1 Million Little Box Challenge is…CE+T Power's Red Electrical Devils

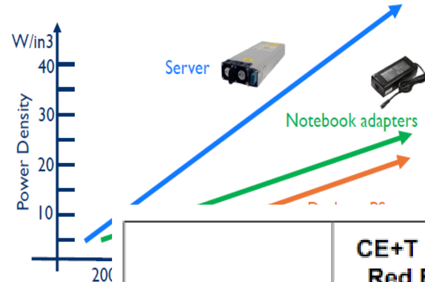
Monday, February 29, 2016

Posted by Ross Koningstein, Engineering Director Emeritus, Google Research

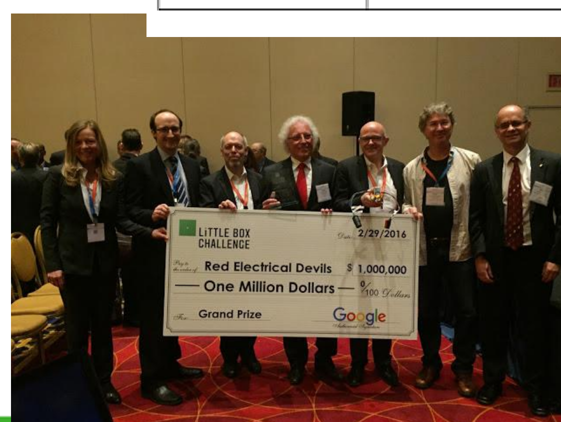
In July 2014, Google and the IEEE launched the $1 Million Little Box Challenge, an open competition to design and build a small kW-scale inverter with a power density greater than 50 Watts per cubic inch while meeting a number of other specifications related to efficiency, electrical noise and thermal performance. Over 2,000 teams from across the world registered for the competition and more than 80 proposals qualified for review by IEEE Power Electronics Society and Google. In October 2015, 18 finalists were selected to bring their inverters to the National Renewable Energy Laboratory (NREL) for testing.

LITTLE BOX CHALLENGE

Google | IEEE



	CE+T Power's Red Electric Devils	Schneider Electric	Virginia Tech's Future Energy Electronics Center	Little Box Challenge requirements
Power Density (W/in^3)	142.9	96.2	68.7	>50
Volume (in^3)	14.0	20.8	29.1	<40



Winner : $P=143W/in^3$

CE+T POWER
WWW.CET-POWER.COM

Google's Little Box Challenge

- https://littleboxchallenge.com/

2kW inverter

CET POWER
WWW.CET-POWER.COM

- http://googleresearch.blogspot.be/2016/02/and-winner-of-1-million-little-box.html?m=1
- https://www.youtube.com/watch?v=bSrHXpK338k

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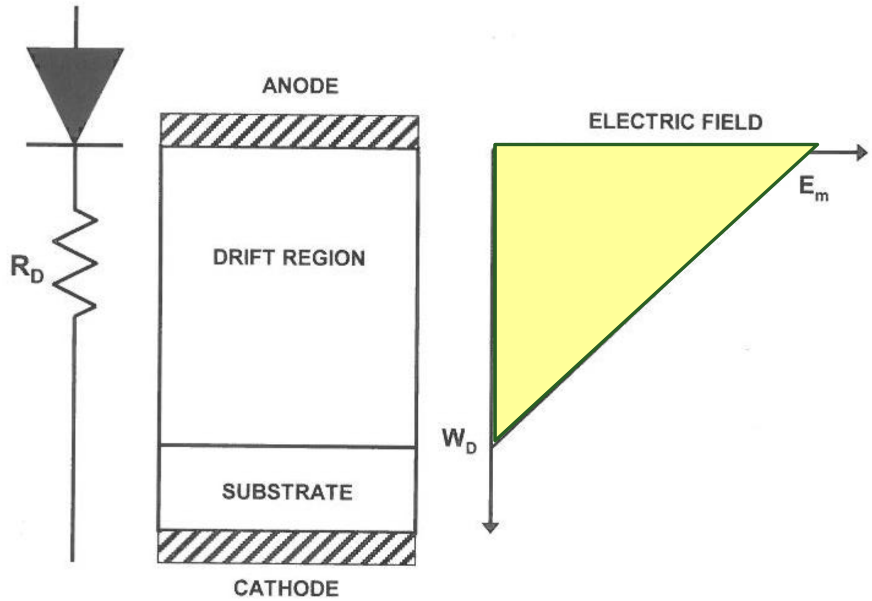
The ideal power semiconductor switch

- Off-state
  - Should block a high voltage, with no leakage current
- On-state
  - Should have no resistance (ideal conductor)
- During switching from off to on (and vice versa)
  - Should happen immediately
  - No hysteresis
  - No charge storage
- Enabled by new material properties and novel device concepts which enable new system solutions

Basic Equation for Power Semiconductors

- Assume an abrupt junction, parallel plane



$$\frac{\partial^2 V}{\partial x^2} = -\frac{\partial E}{\partial x} = \frac{-q.N_D}{\varepsilon}$$

$$E(x) = \frac{-q.N_D}{\varepsilon}.(W_D - x)$$

$$V(x) = \frac{q.N_D}{\varepsilon}.(W_D.x - \frac{x^2}{2})$$

$$V(W_D) = V_{bd} \qquad V_{bd} = \frac{E_C.W_D}{2}$$

$$Ron = \frac{W_D}{q.N_D.\mu_N}$$

Drift width

Resistivity

$$W_D = \sqrt{\frac{2.\varepsilon.V_{bd}}{q.N_D}}$$

Figure-of-merit : Ron versus Vbd

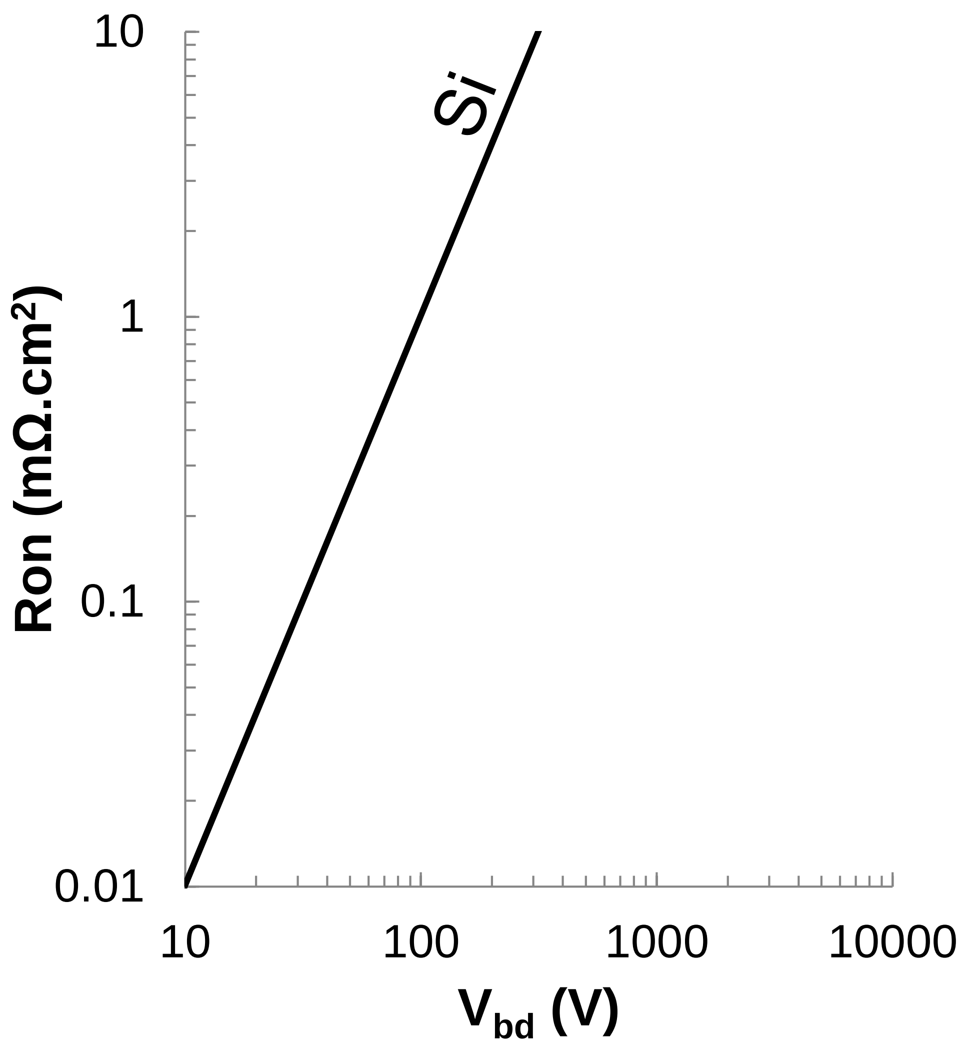
$$Ron = \frac{W_D}{q.N_D.\mu_N} \quad [\Omega.m^2]$$

$$W_D = \sqrt{\frac{2.\varepsilon.V_{bd}}{q.N_D}}$$

$$V_{bd} = \frac{E_C.W_D}{2}$$

$$N_D = \frac{\varepsilon.E_C{}^2}{2.q.V_{bd}}$$

$$Ron = \frac{4.V_{bd}{}^2}{E_C{}^3.\varepsilon.\mu_N}$$



The Baliga Figure of Merit—1D

$$Ron\ [\Omega.cm^2] = \frac{4.V_{bd}^{\ 2}}{\varepsilon.\mu.E_c^{\ 3}}$$

- E_c : critical electric field : the field one has to apply to free electrons from bonds
- ε : (relative) permittivity or “dielectric constant “ ; a measure for how fast the electric field changes between charges
- μ : carrier mobility ; a measure for how fast charges move along

Material Properties

- Baliga Figure-of-Merit is a metric for how good a material is for uni-polar power device technology. It contains the drift electron mobility and the critical electric field.
- [note : mobility reduction due to doping is not taken into account !]

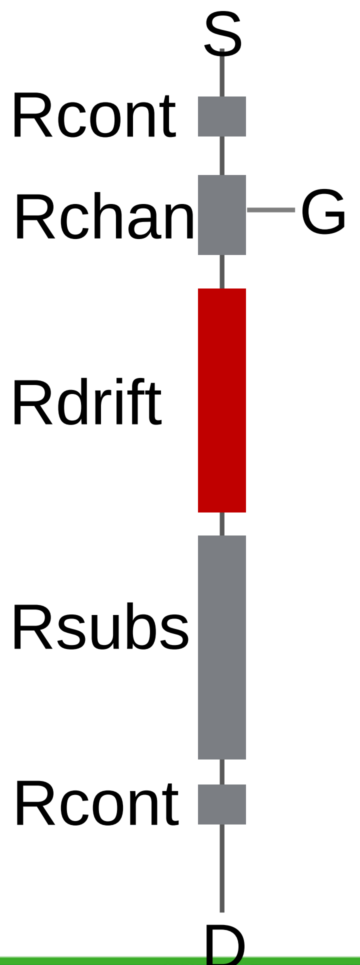
$$Ron\ [\Omega.cm^2] = \frac{4.V_{bd}^{\ 2}}{\varepsilon.\mu.E_c^{\ 3}}$$

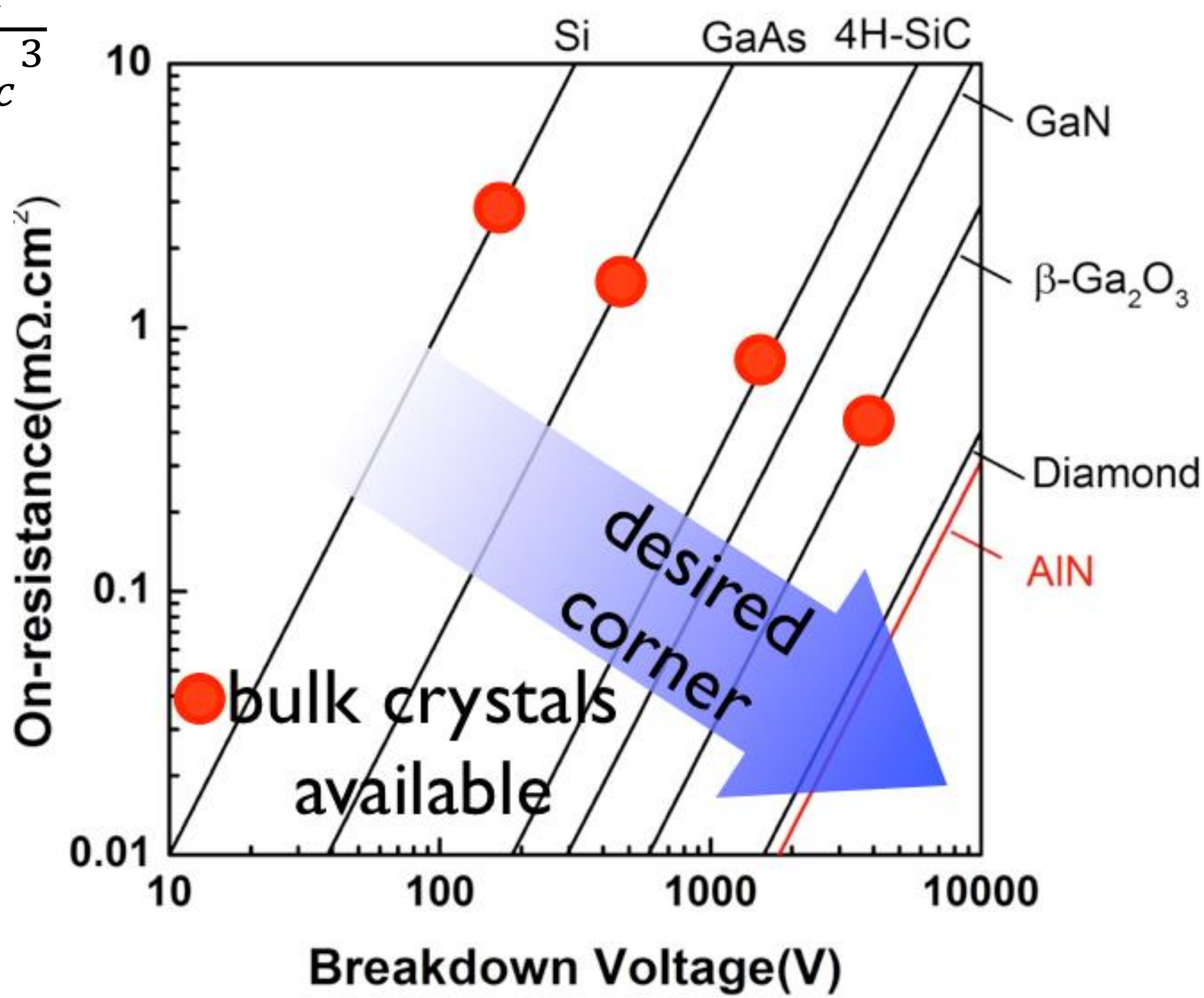
	Si	GaAs	4H-SiC	GaN	Diamond	β-Ga_2O_3	AlN
Bandgap Eg (eV)	1.1	1.4	3.3	3.4	5.5	4.8-4.9	6
Electron mobility μ (cm^2/Vs)	1400	8000	1000	1200	2000	300	500
Breakdown field E_b (MV/cm)	0.3	0.4	2.5	3.3	10	8	15
Relative dielectric constant ε	11.8	12.9	9.7	9.0	5.5	10	8.5
Baliga's FOM $\varepsilon\mu E_b^3$	1	15	340	870	24664	3444	32158

WBG (4H-SiC, GaN) U-WBG (Diamond, β-Ga_2O_3, AlN)

Baliga FOM—only for drift region (1D)

$$Ron\ [\Omega.cm^2] = \frac{4.V_{bd}^{\ 2}}{\varepsilon.\mu.E_c^{\ 3}}$$





How to go beyond the Baliga FOM ?

- Can we do better than the 1D approximation ?

1. RESURF is a way of **shaping the electrical fields** in a device in such a way that the breakdown voltage is increased in comparison with the 1D planar junction
2. RESURF is a way of increasing the drift doping in a device (lowering the Ron) without the BVds going down, **by shaping the electrical field**

Junction Resurf Diode

The RESURF diode

A good way to explain why the 1D theory does not apply is to consider that the the effecting doping charge in the n- epi layer is reduced by the presence of the electric field set by the epi-substrate junction.

HIGH VOLTAGE THIN LAYER DEVICES (RESURF DEVICES)

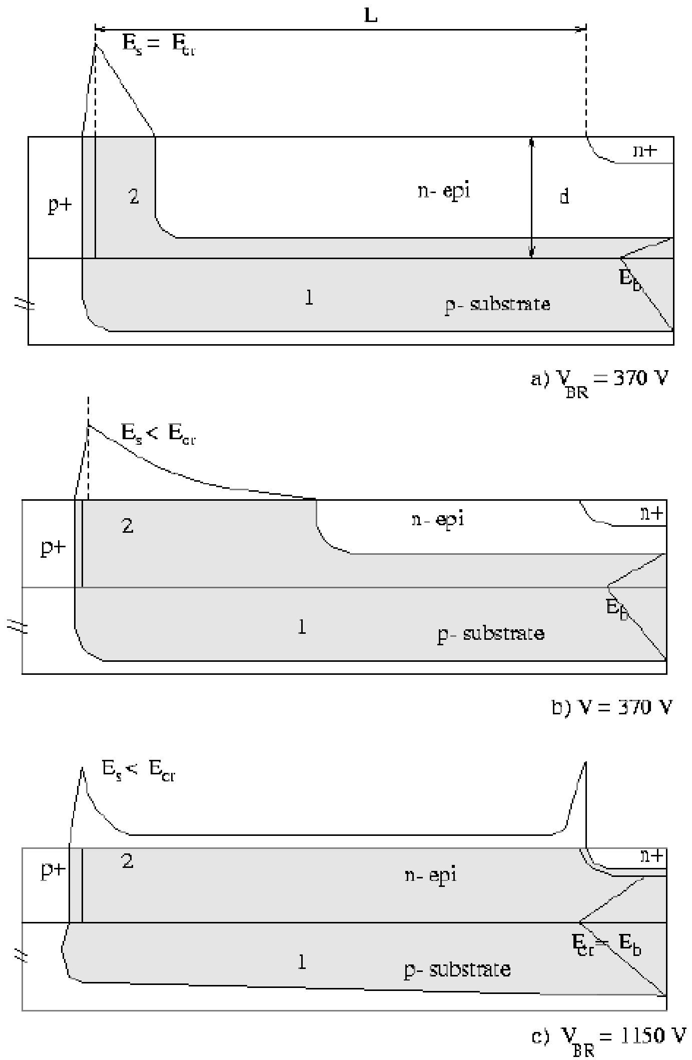
J.A. Appels and H.M.J. Vaes

Philips Research Laboratories
Eindhoven - The Netherlands

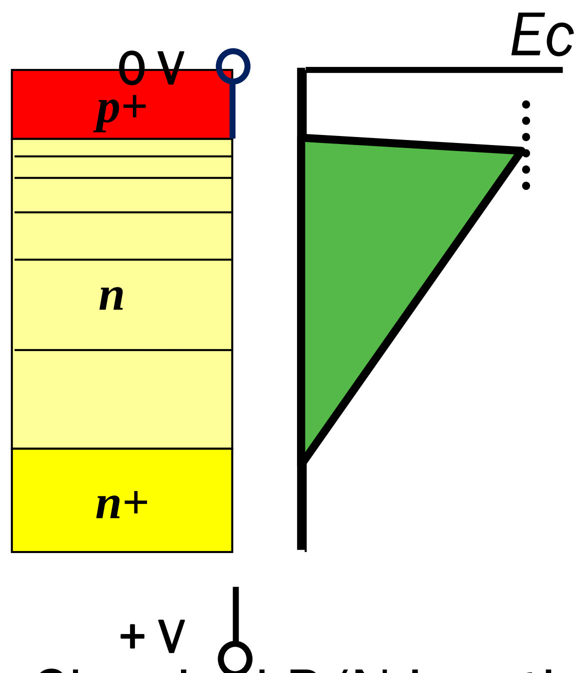
CONCLUSION

The use of high-ohmic substrates with relatively thin epitaxial layers on them, which meet the requirements mentioned in this paper (i.e. $N_{epi} \times d_{epi} \cong 10^{12}$ at/cm^2) opens the possibility of making high-voltage devices whose structure and operation, in particular the electric field distribution, differ essentially from those of conventional devices.

Ref.
1) Late News Paper, ESSDERC '79 München.

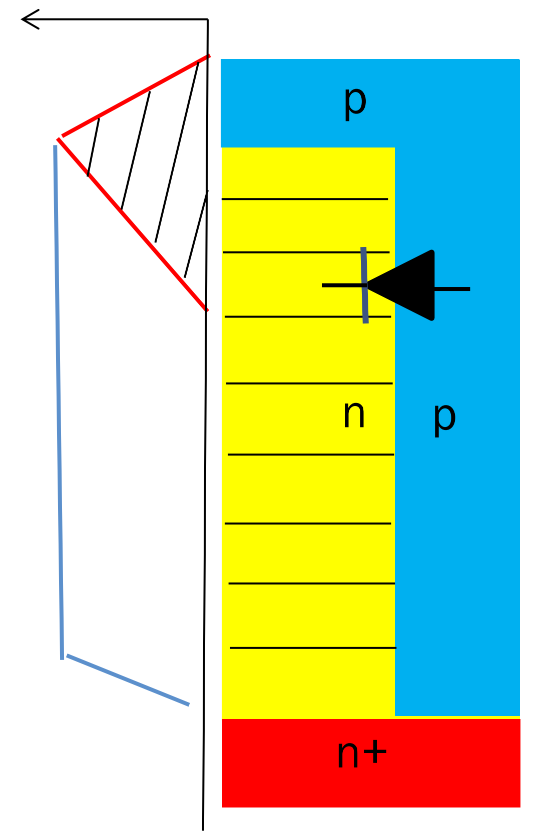


Field plate Resurf concept



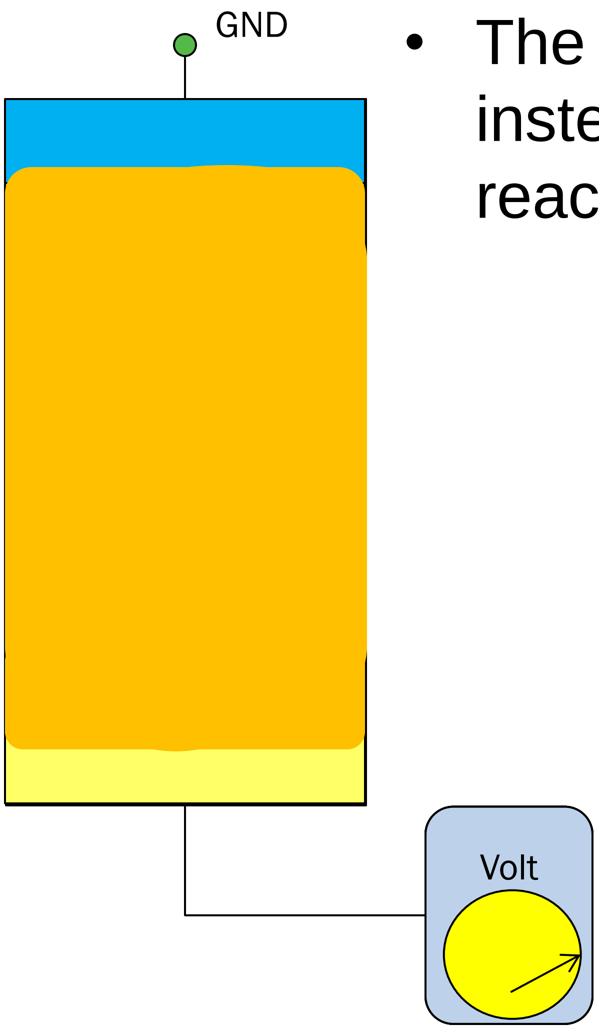
Classical P/N junction

E-field

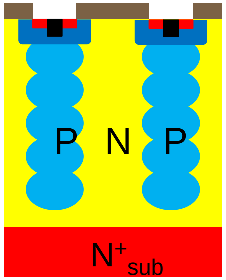


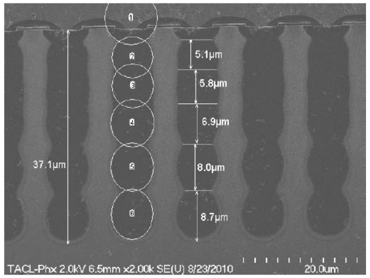
'pretending' being n−
(n+p~0)

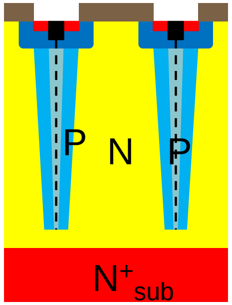
Super Junction Basics

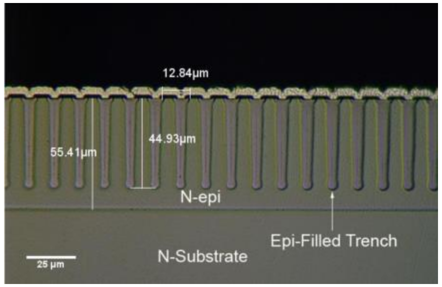


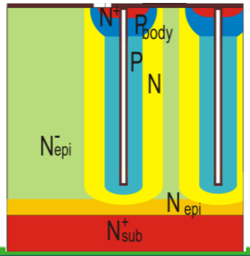
- The drift region is depleted from the side instead from top-down. Full depletion reached @ Vds~20-60V

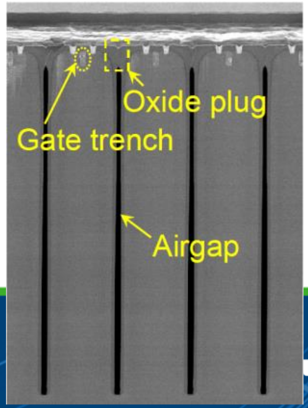




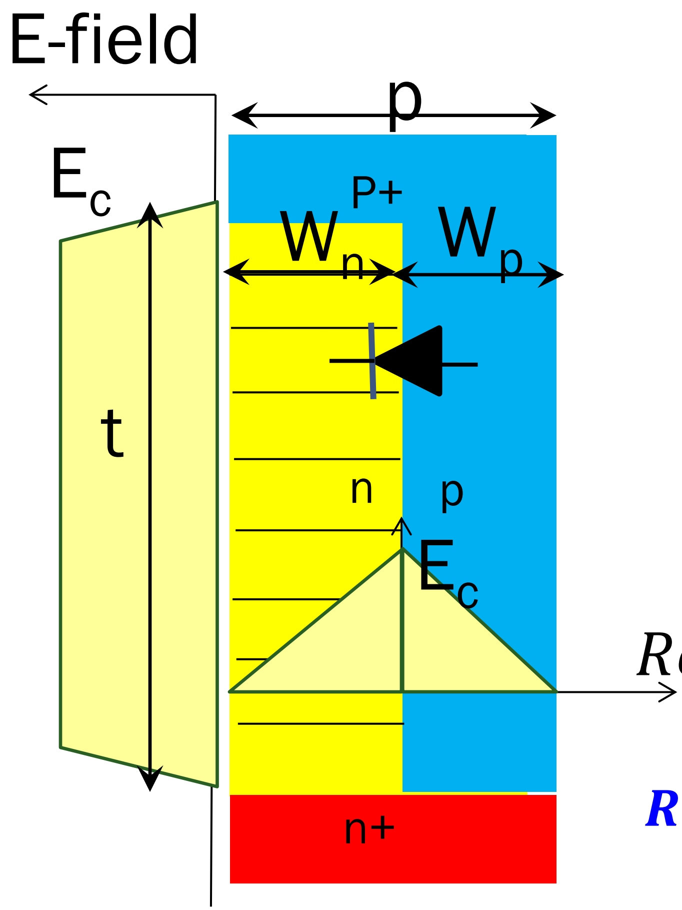








Resurf Limit (2D)—Optimal Charge



$$\frac{\partial^2 V}{\partial x^2} = -\frac{\partial E}{\partial x} = \frac{-q.N_D}{\varepsilon}$$

$$E_C = \frac{q.N_n.W_n}{\varepsilon_s} + \frac{q.N_p.W_p}{\varepsilon_s}$$

$$N_n = N_p ; W_n = W_p$$

$$E_C = 2.\frac{q.N_n.W_n}{\varepsilon_s}$$

Ec=[V]/[cm]
Eps=[F]/[cm]
[F]=[C]/[V]

$$E_C.\varepsilon_s = 2.q.N_n.W_n$$

$$E_C.\varepsilon_s = 2.q.N_n.W_n = Q_{opt}[\frac{C}{cm^2}]$$

	Q_{opt} (cm^{-2})
Si	$1.96\ 10^{12}$
GaN	$1.34\ 10^{13}$
SiC	$1.64\ 10^{13}$
AlN	$5.82\ 10^{13}$
Ga_2O_3	$4.42\ 10^{13}$

$$Ron = \frac{1}{q.N_n.\mu_N}.\frac{p}{W_n}.t$$

$$Ron = \frac{2.p.t}{Q_{opt}.\mu_N}$$

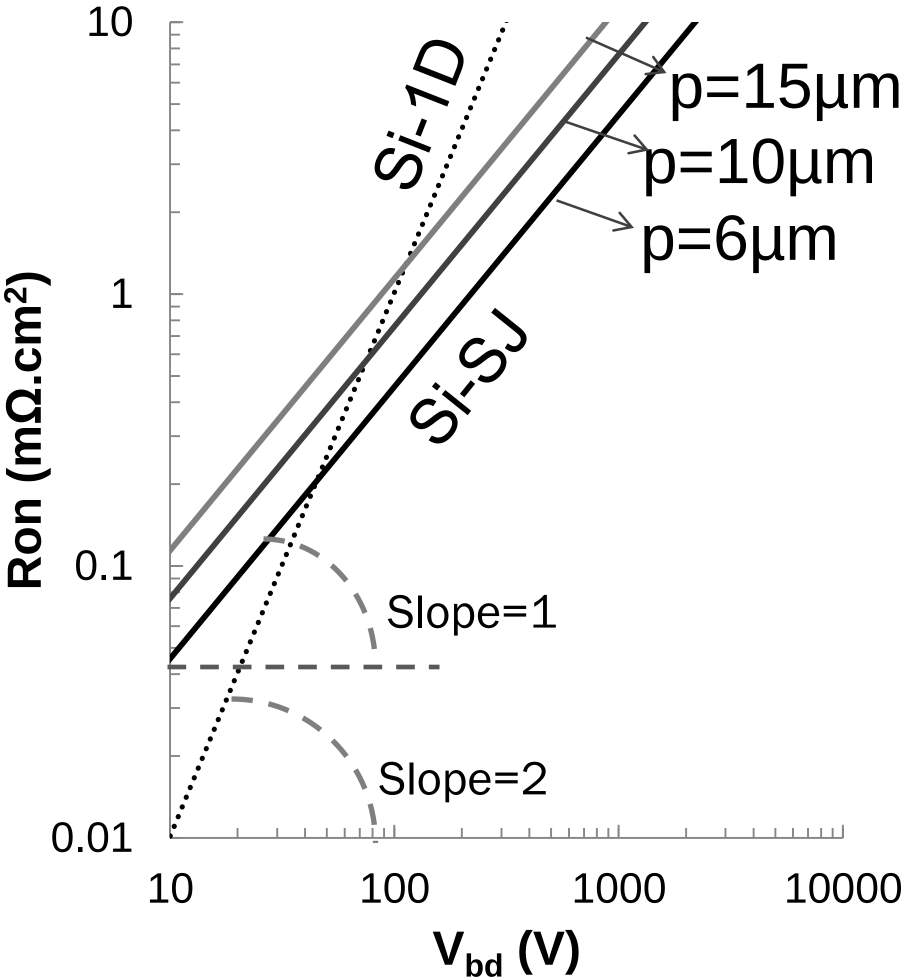
$$V_{bd} = E_c.t$$

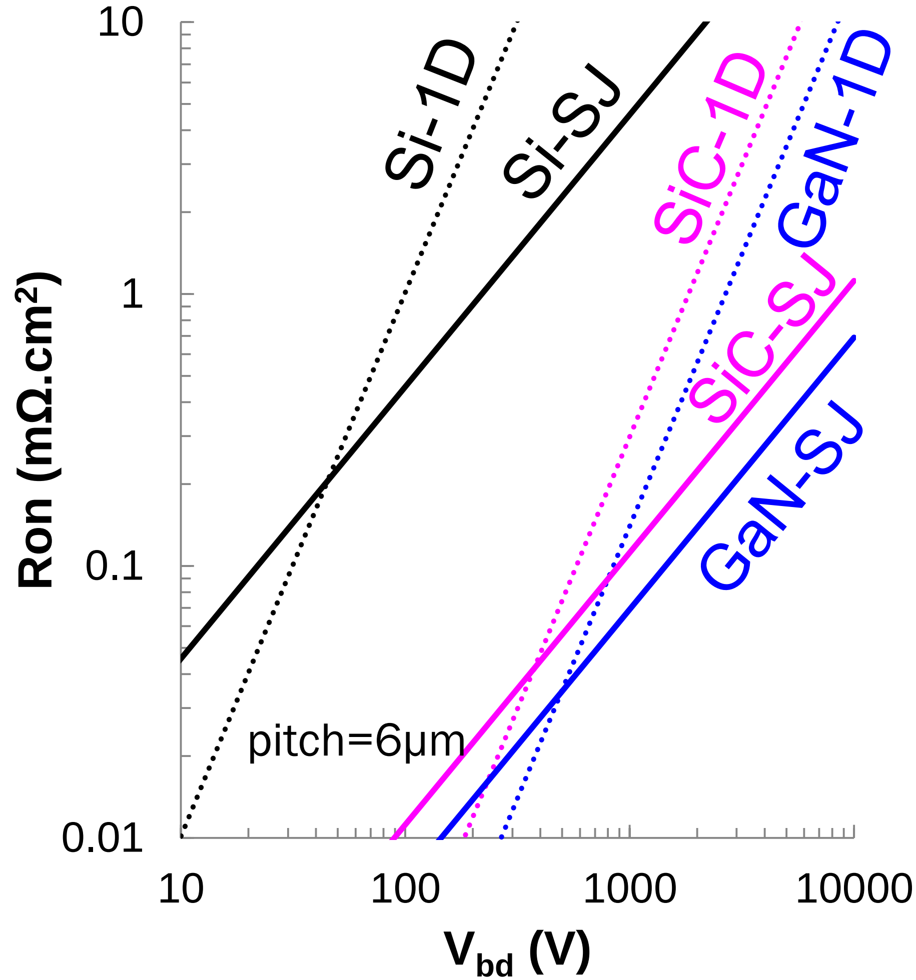
$$Ron = \frac{2.p.V_{bd}}{E_c.Q_{opt}.\mu_N}$$

$$Ron = \frac{2.p.V_{bd}}{\mu_N.\varepsilon_s.E_c{}^2}$$

Resurf limit--2D

- Depends on device pitch (p) : process capability





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Periodic Table & Electro Negativity

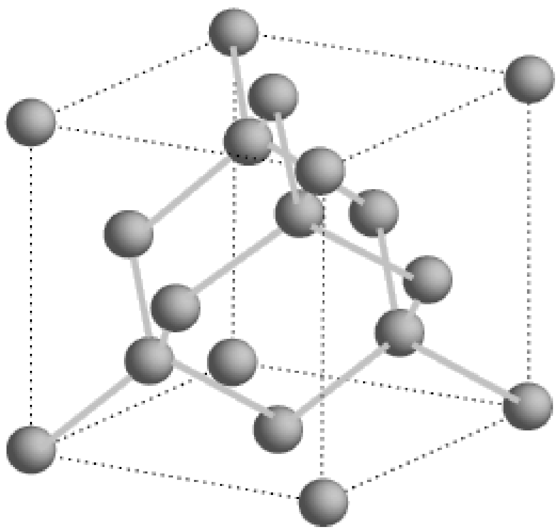
III IV V

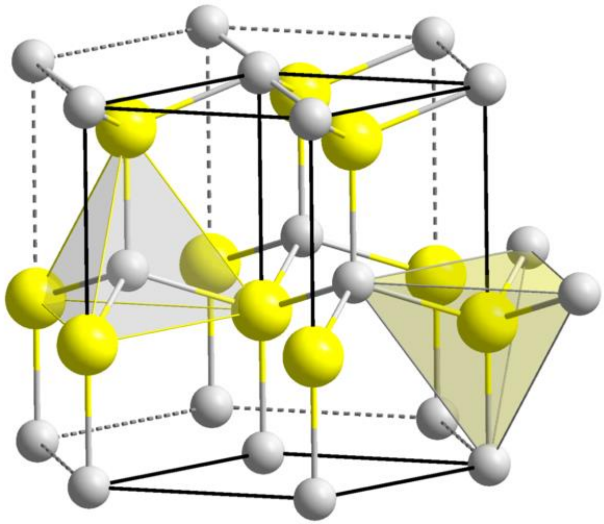
H 2.1																	He
Li 1.0	Be 1.5											B 2.0	C 2.5	N 3.0	O 3.5	F 4.0	Ne
Na 0.9	Mg 1.2											Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0	Ar
K 0.8	Ca 1.0	Sc 1.3	Ti 1.5	V 1.6	Cr 1.6	Mn 1.5	Fe 1.8	Co 1.8	Ni 1.8	Cu 1.9	Zn 1.6	Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8	Kr 3.0
Rb 0.8	Sr 1.0	Y 1.2	Zr 1.4	Nb 1.6	Mo 1.8	Tc 1.9	Ru 2.2	Rh 2.2	Pd 2.2	Ag 1.9	Cd 1.7	In 1.7	Sn 1.8	Sb 1.9	Te 2.1	I 2.5	Xe 2.6
Cs 0.7	Ba 0.9	La 1.1	Hf 1.3	Ta 1.5	W 1.7	Re 1.9	Os 2.2	Ir 2.2	Pt 2.2	Au 2.4	Hg 1.9	Ti 1.8	Pb 1.8	Bi 1.9	Po 2.0	At 2.2	Rn 2.4
Fr 0.7	Ra 0.7	Ac 1.1	Unq	Unp	Unh	Uns	Uno	Une									

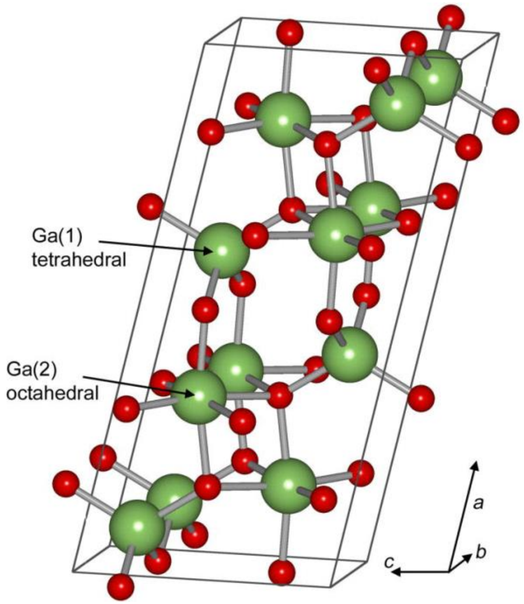
Ce 1.1	Pr 1.1	Nd 1.1	Pm 1.1	Sm 1.1	Eu 1.1	Gd 1.1	Tb 1.1	Dy 1.1	Ho 1.1	Er 1.1	Tm 1.1	Yb 1.1	Lu 1.2
Th 1.3	Pa 1.5	U 1.7	Np 1.3	Pu 1.3	Am 1.3	Cm 1.3	Bk 1.3	Cf 1.3	Es 1.3	Fm 1.3	Md 1.3	No 1.3	Lr

Crystal Structures

Cubic	Wurtzite	Monoclinic
Si, SiC, Diamond	GaN, AlN	Ga_2O_3, In_2O_3





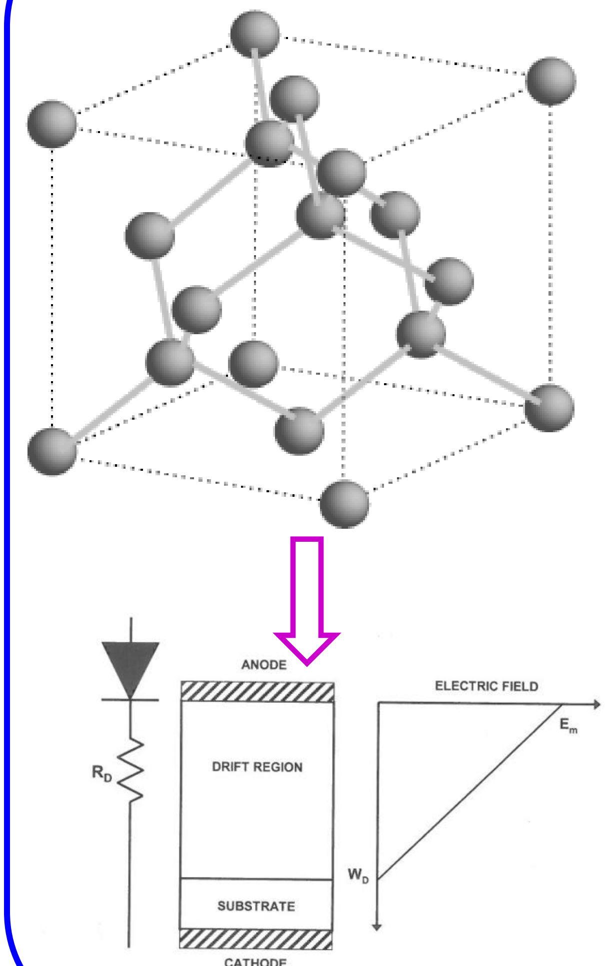


Cubic	Wurtzite	Monoclinic
Covalent bond Non-polar	Ionic bond polar	Ionic bond polar

Note : the number of atoms per unit cell, the symmetry of the cell and the mass of the elements determines the thermal conductivity of the material.

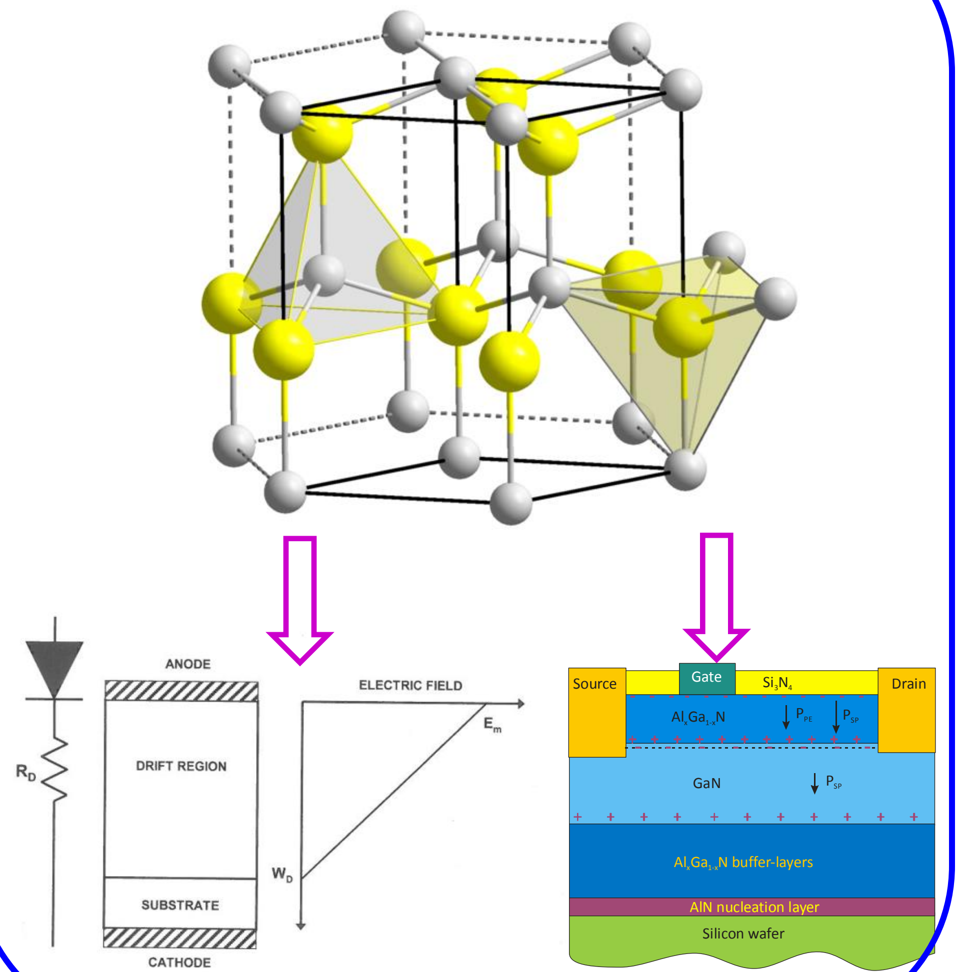
Polar versus Non-Polar Materials

Non-polar



Junction transistor

polar

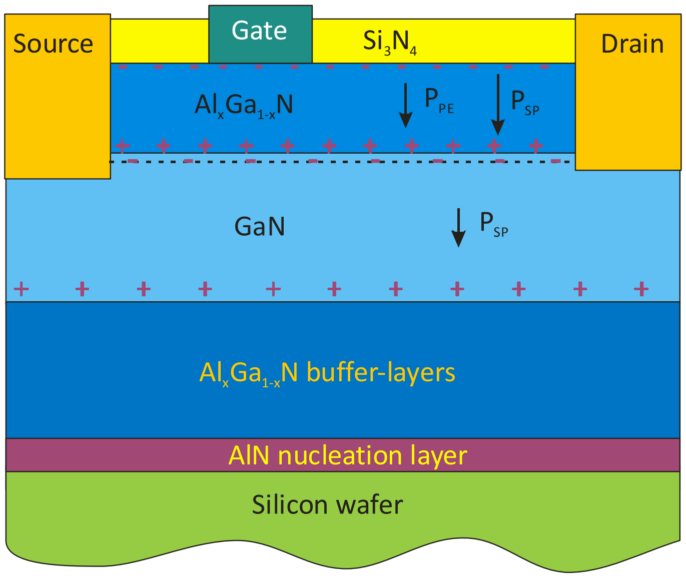


Junction transistor

HEMT

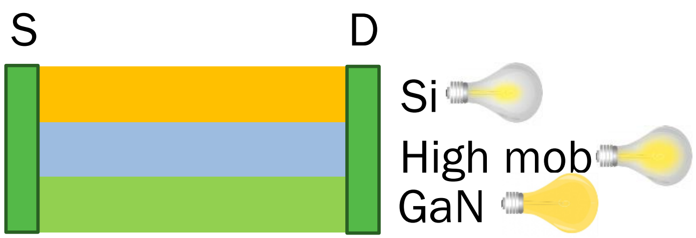
AlGaN/GaN Lateral HEMT Devices

- AlGaN/GaN High Electron Mobility Transistors feature :
  - **Low Ron** due to high **2DEG density** with n_s~$9x10^{12}$ cm^{-2} and **high mobility** (~2000 cm^2/V.s)
  - **High breakdown** because of **high bandgap** (3.4 eV)
  - **Low capacitance** : no junctions to deplete (**un-doped**)



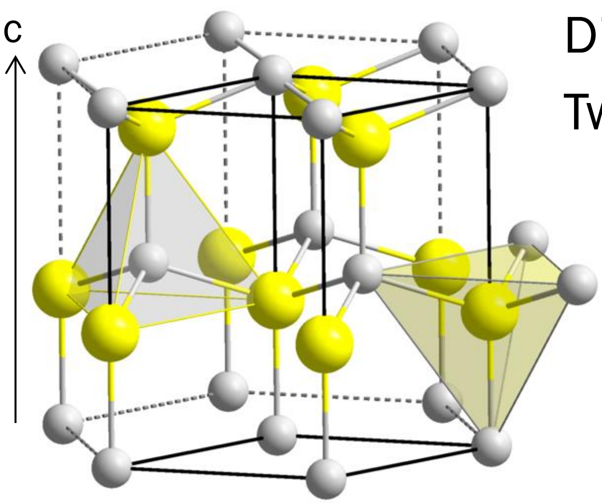
Device Property

Material Property



GaN Crystal Structure—Wurtzite

- GaN has a **Wurtzite** structure, thermodynamically stable.
- Growth is along the c-axis, can be **Ga-face** or N-face. Two interpenetrating hexagonal close-packed sublattices.

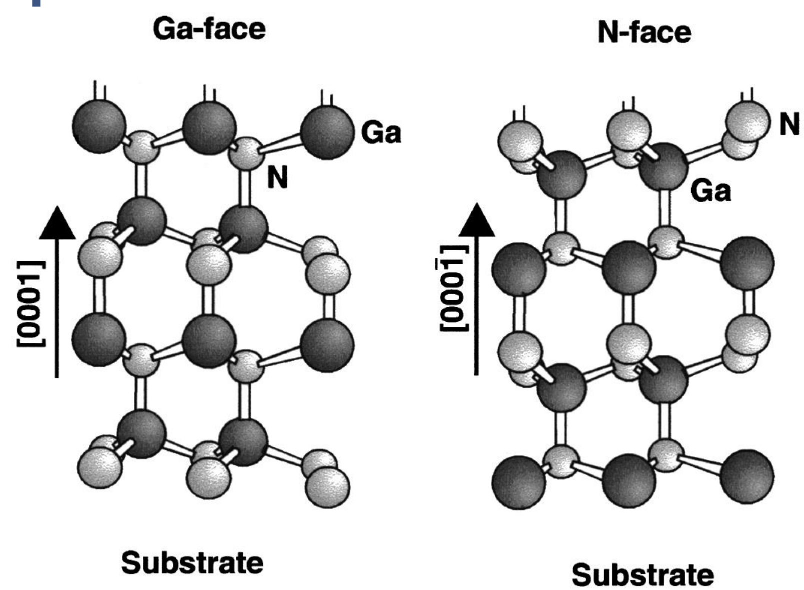


Direct bandgap

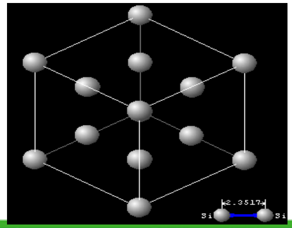
Two lattice constants

a = 3.189 Å

c = 5.186 Å



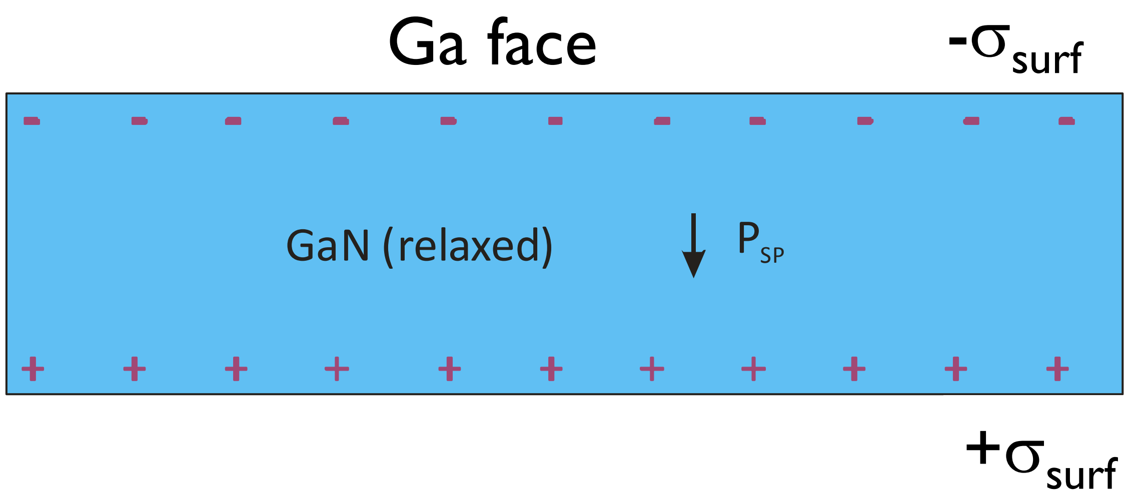
View in <111> direction

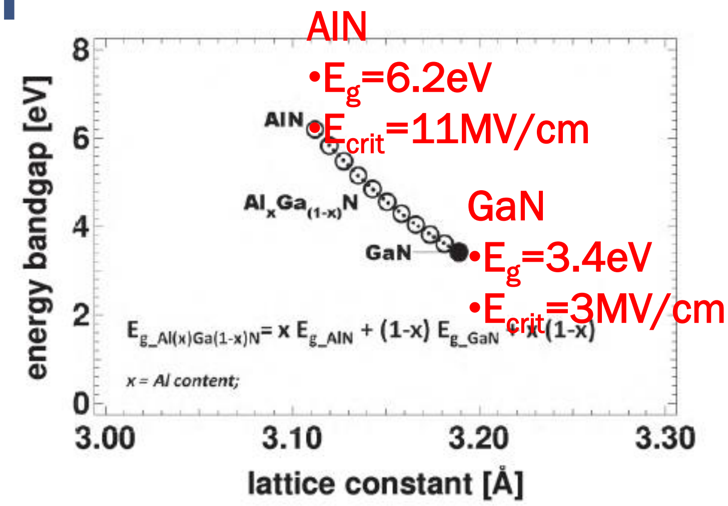


- Can be grown on (111) Si (hexagonal)

Spontaneous polarization

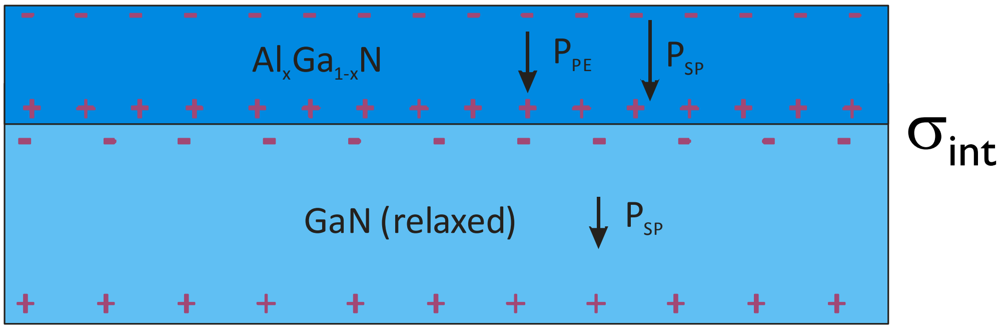
- Spontaneous Polarization due to electro-negativity difference between N-atoms and Ga-atoms (binary crystal).
  - Pauling's electronegativity : N=3.4, Ga=1.8, Al=1.6
- Poisson's equation yields σ_{surf}
- Results in a polarization field P

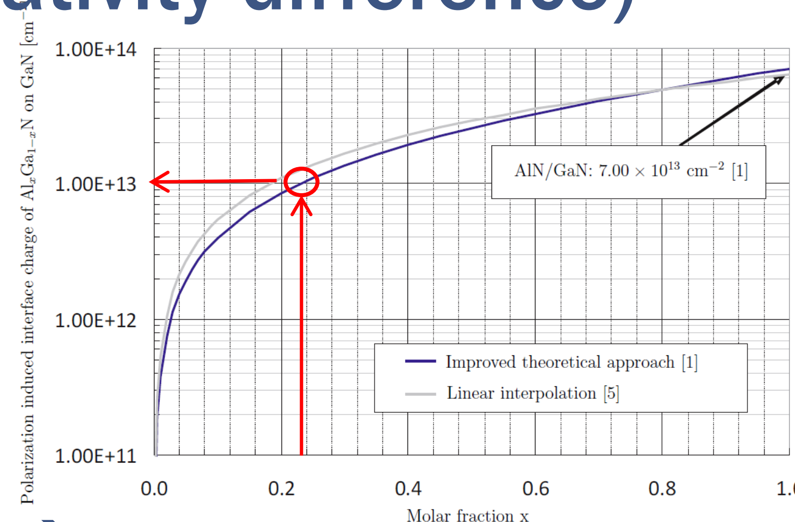




Spontaneous and piezo-electric polarization

- Al(Ga)N has larger polarization field than GaN (due to larger Electro-negativity difference)

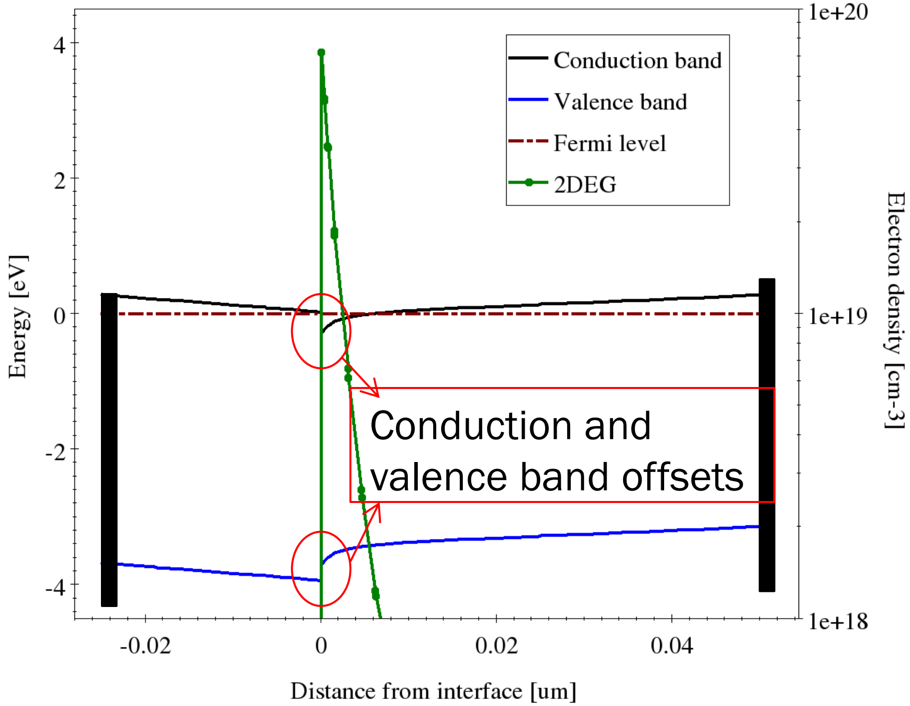


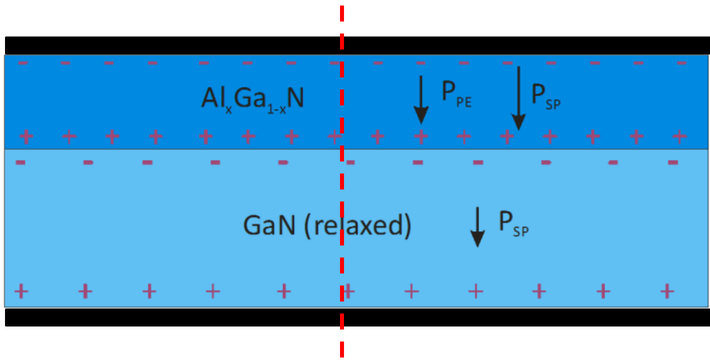


- Thin AlGaN layer strained → piezo-electric pol.
- Induced net positive charge at the AlGaN/GaN interface (but inside the AlGaN !) is very large !
  - HEMT ns~ 10^{13} cm^{-2} ↔ Typical MOSFET ns ~10^{12} cm^{-2}

Solving the Poisson equation—1D

- Ohmic contacts at bottom and top of the structure
- Charge neutrality : Electrons compensate the net positive polarization charge, i.e. creation of a 2DEG
- Leads to the creation of a quantum well at the AlGaN/GaN interface (but in the GaN layer !)

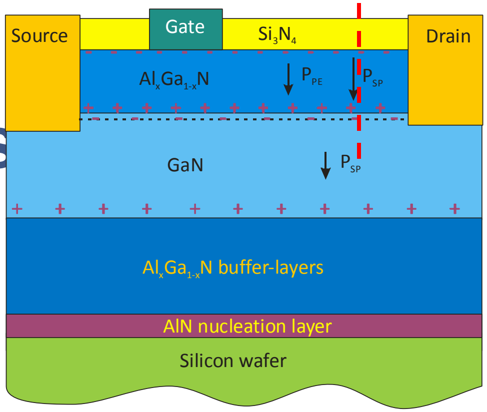


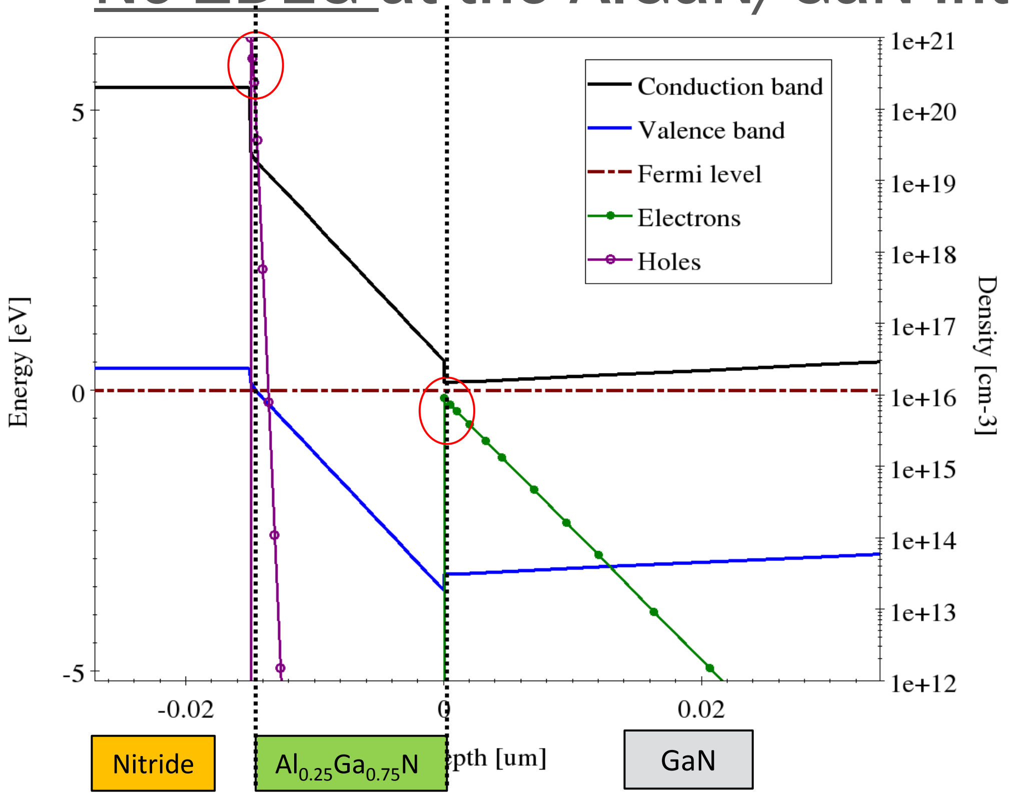


$$\sigma_{2DEG} = -\sigma_{int}$$

Passivation of the surface

- Ideal case = no surface traps
- Solving the Poisson equation (2D) leads
  - 2DHG at the SiN/AlGaN interface
  - No 2DEG at the AlGaN/GaN interface



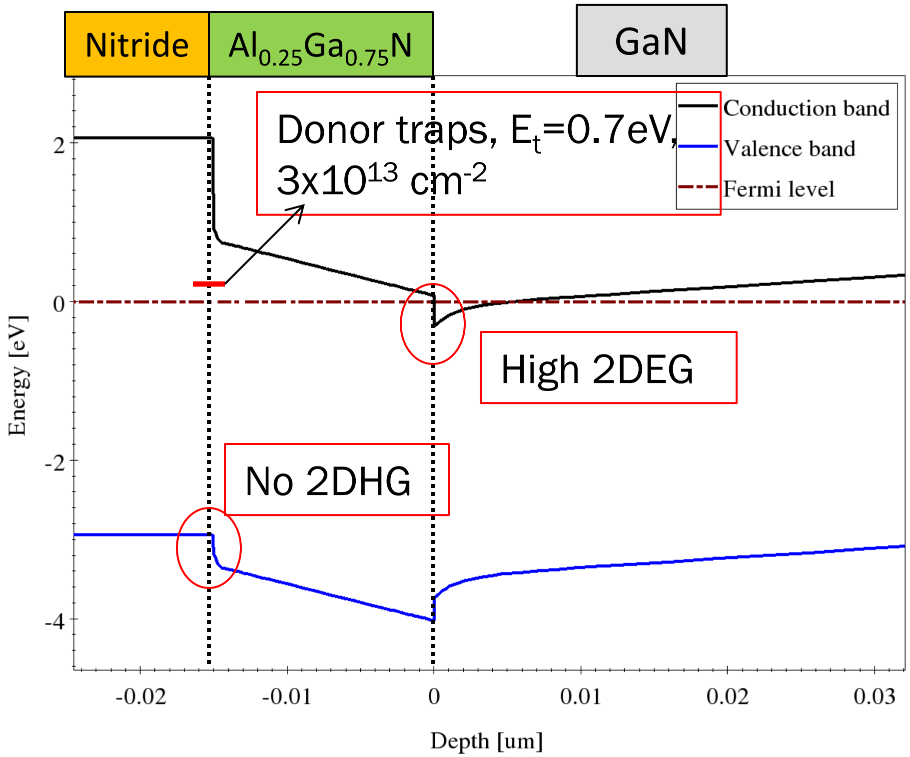


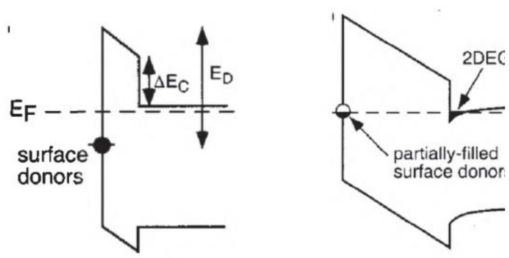
This is not reality !!

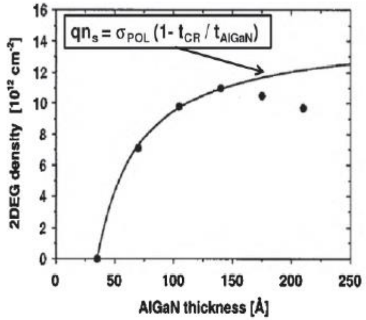
Need surface traps to explain !!

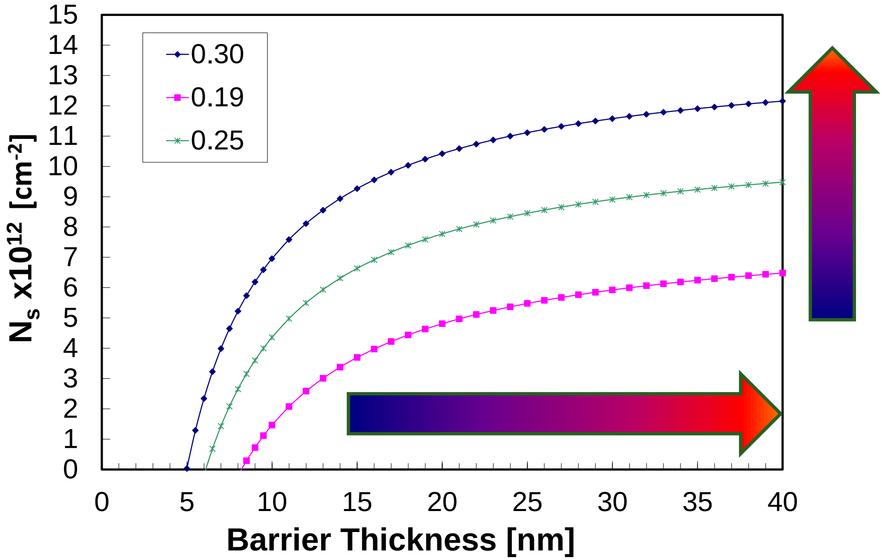
Surface : The Donor State Model

- Only **model** that can explain the observed features.
- It is only a “model”. Direct experimental evidence is rather weak

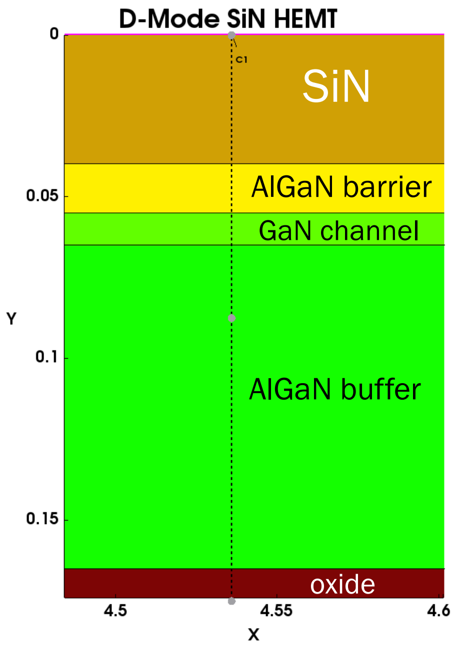


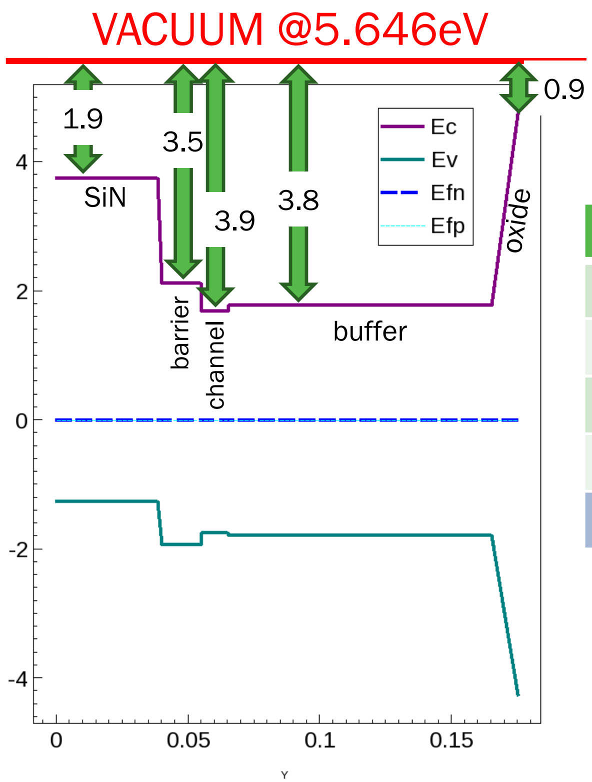






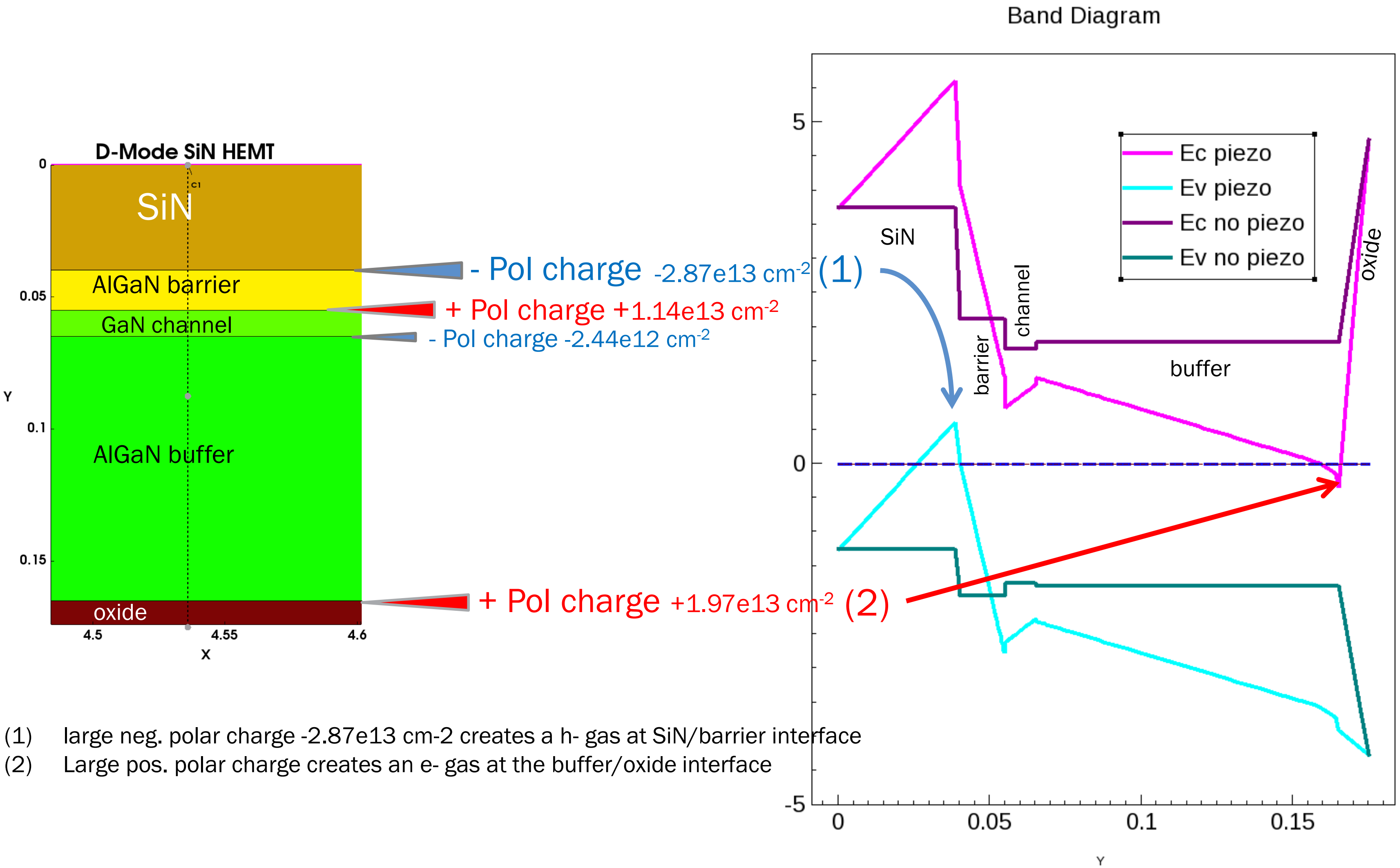
D-Mode: without Piezo charges without traps





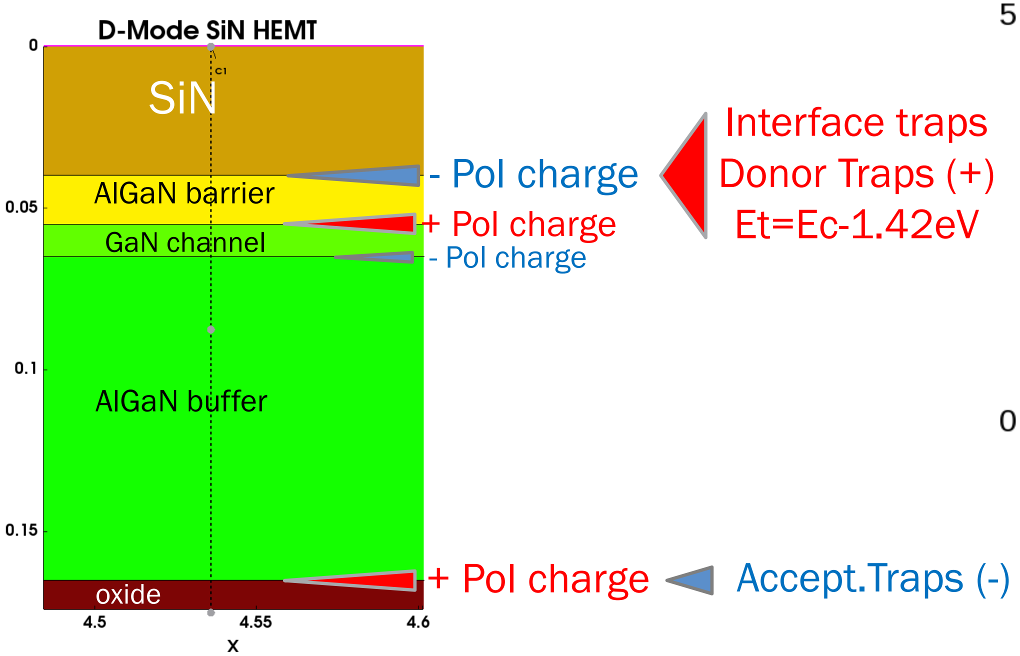
	SiN	Barrier	GaN	Buffer	Ox
E_c	3.746	2.129	1.689	1.784	4.736
E_v	-1.254	-1.928	-1.747	-1.786	-4.264
E_{bg}	5	4.057	3.436	3.57	9
e_{aff} χ	1.9	3.518	3.958	3.862	0.910
$\chi+E_c$	5.646	5.647	5.647	5.646	5.646

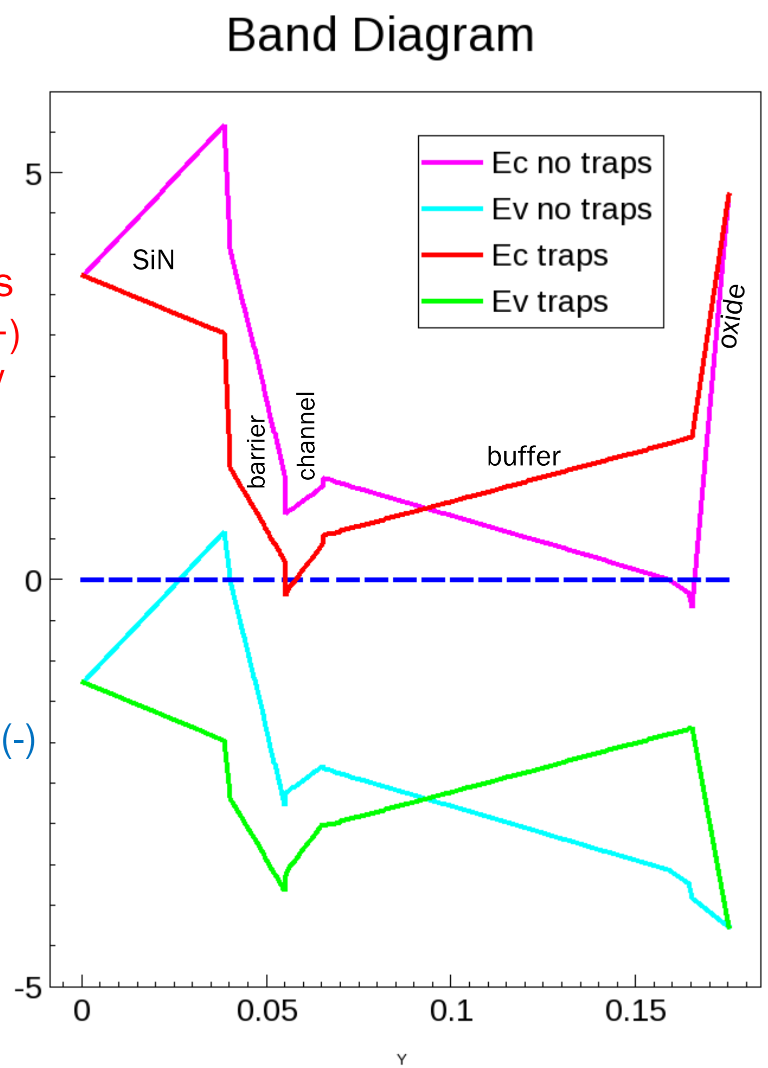
D-Mode: with/without Piezo charges without traps



(1) large neg. polar charge -2.87e13 cm-2 creates a h- gas at SiN/barrier interface
(2) Large pos. polar charge creates an e- gas at the buffer/oxide interface

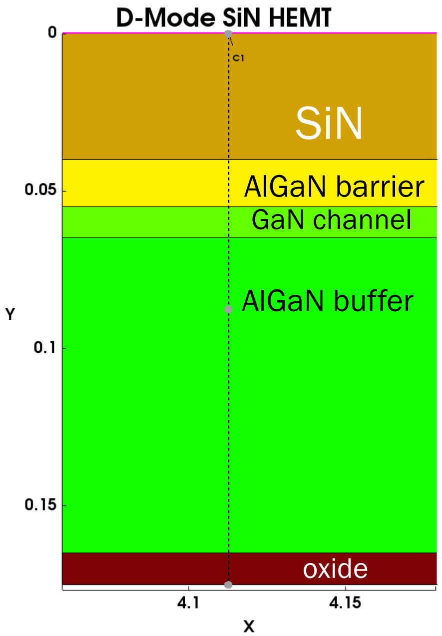
D-Mode: with Piezo charges with/without traps

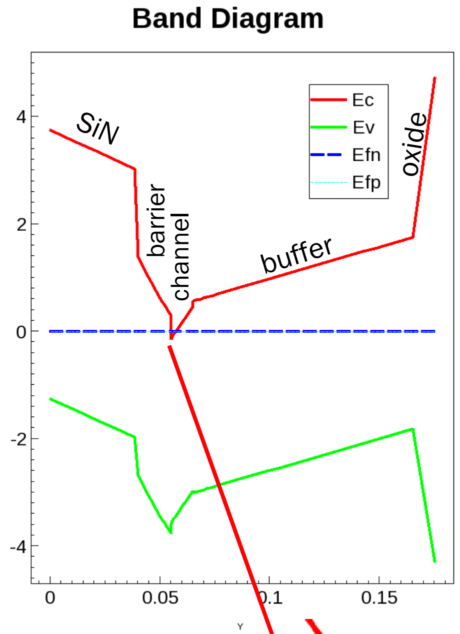


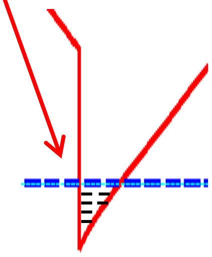


Only after adding the interface traps we get the final result with 2DEG

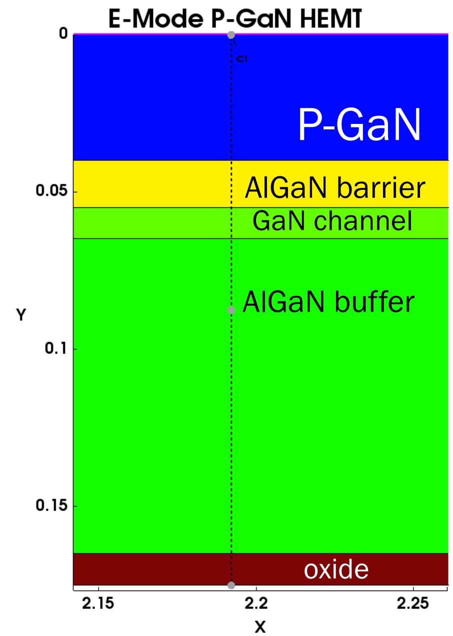
D-Mode vs E-Mode : pGaN

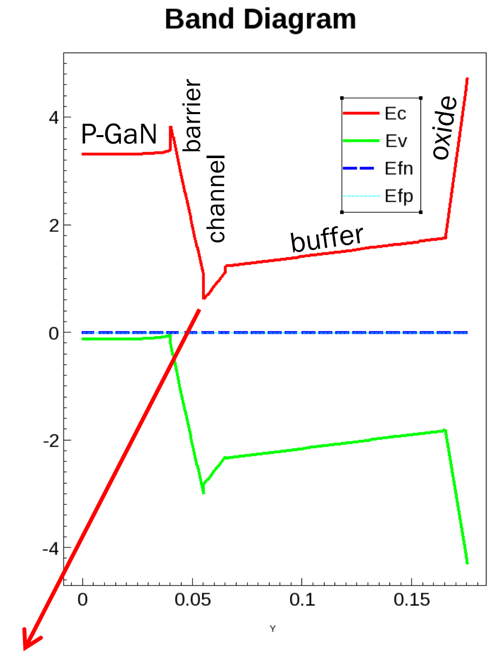




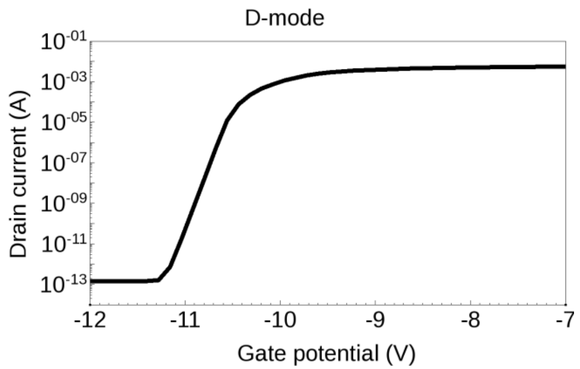


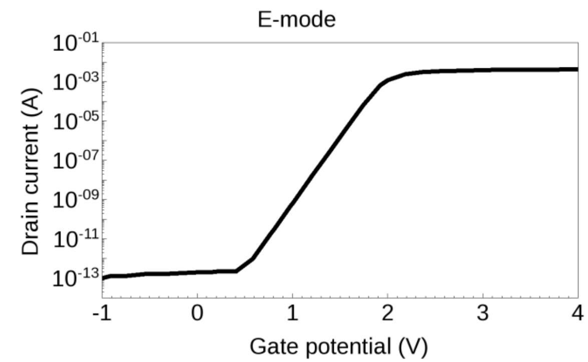
2DEG under SiN





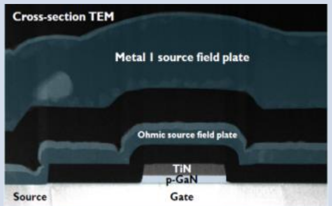
No 2DEG under P-GaN





GaN-on-Si Lateral Technologies for E-mode

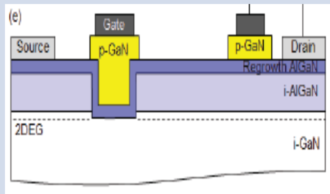
Blanket pGaN



Blanket pGaN with etch back except under gate
Need tight control etch back (nm res)
[Mg] diffusion in access region
Surface passivation
High Vth↔low Ron

EPC, TSMC
(GaNSys, Navitas,..)
IMEC, FerdBraun B.

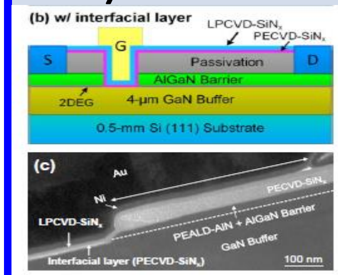
Barrier Regrowth



Thick AlGaN (>50 nm)
Etch back AlGaN in gate region
Barrier regrowth + blanket pGaN
No [Mg] in access
Surface passivation
Vth decoupled from Ron

Panasonic/IFX

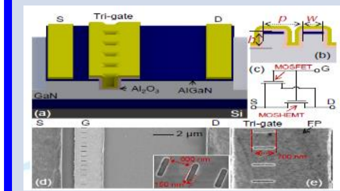
MOS/MIS HEMT



Full/partial barrier ALE recess under gate
Gate dielectric eng. for low Dit and Hysteresis.
Also F implant
IEDM2016 : full barrier recess with SiN gate
Vth >2.3V ; μ_{chan}=160 cm^2/V.s ; Vth stable during NBTI and PBTI ; no hysteresis.

U Hong Kong, ST, IMEC, many other R&D

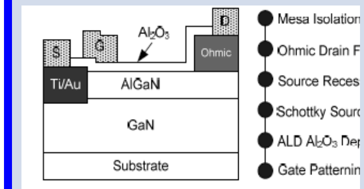
TriGate/GAA



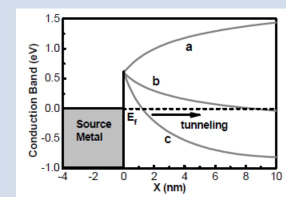
Deplete 2DEG from top and sidewall
Fins need to be <80nm
Atomic Layer Etch
Gate dielectric(ALD)
Vth ~ 2V
Good channel mob due to HEMT

MIT, EPFL

Tunnel FET



Modulation of Schottky barrier at Source by Gate
Low Ron
Vth low (1.35V)
Process control (alignment)

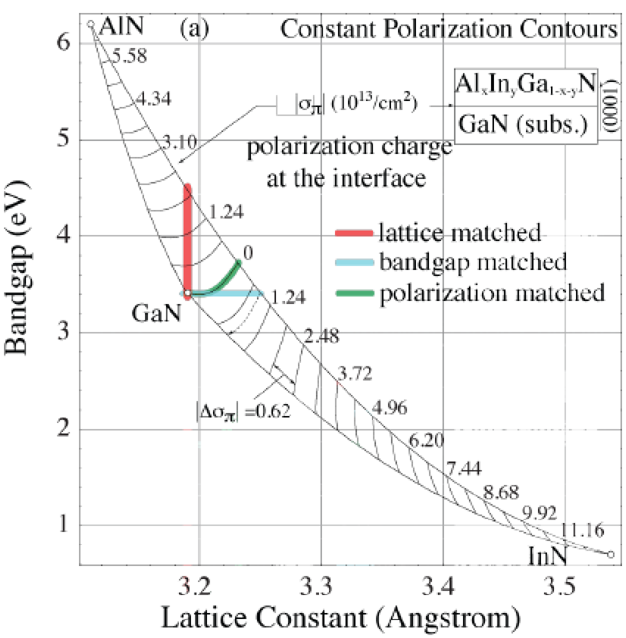


U Hong Kong (ISPSD2011)

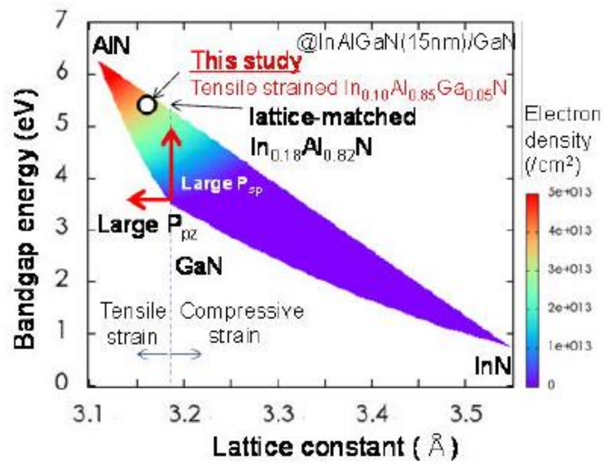
Production → **R&D**

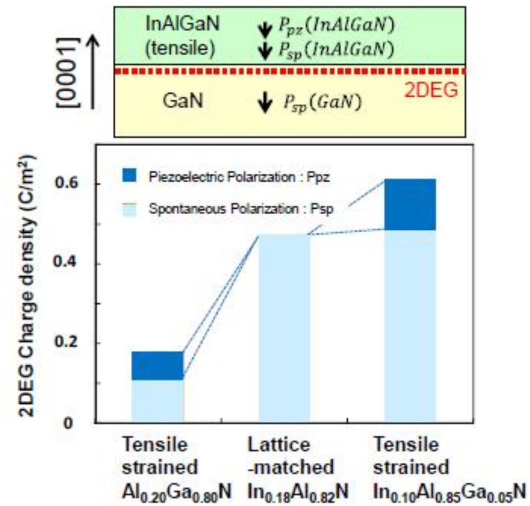
Polarization Engineering : Quarternary alloys

- $Al_xIn_yGa_{1-x-y}N$ quarternary alloys coherently grown on GaN
  - Lattice matched (reliability?), Polarization matching (E-mode)
  - Higher sheet density (lower Ron) & larger bandgap



DJ Jena et al, 2010





Polarization Engineering

Polarization Engineering : Quarternary alloys

Polarization-Engineering in III-V Nitride Heterostructures:
New Opportunities For Device Design

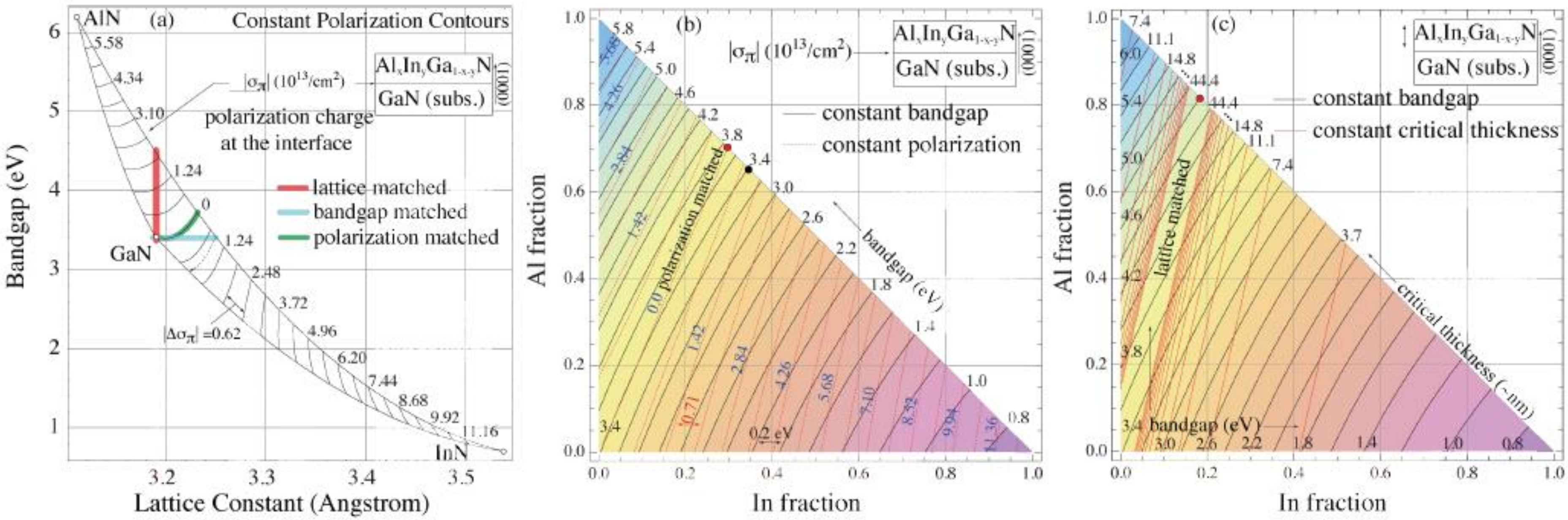


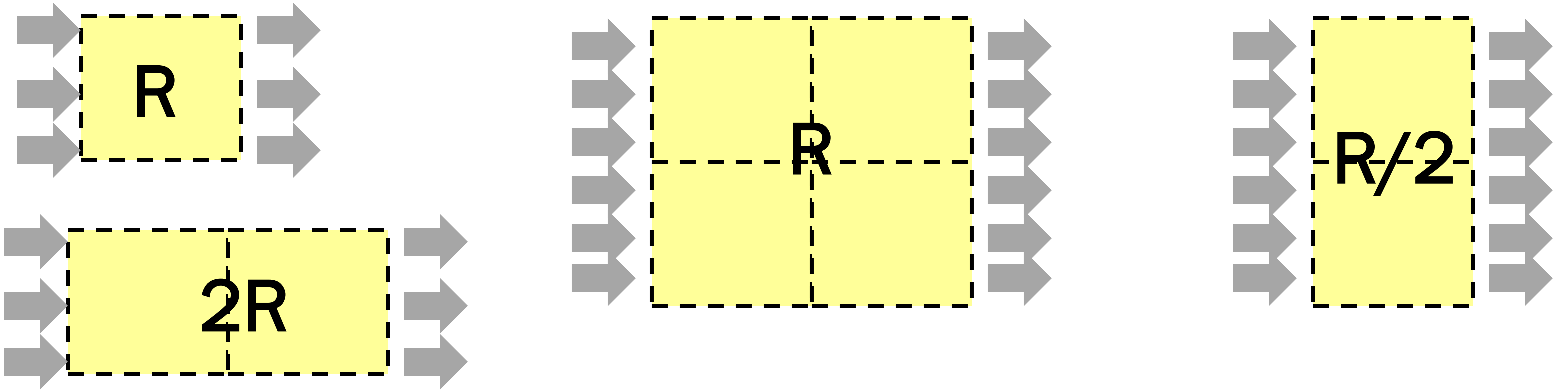
FIG. 1: (a) Constant polarization (spontaneous + piezoelectric) contours on the energy bandgap-lattice constant plot for nitrides grown lattice matched to GaN along the (0001) orientation. The lattice-matched, bandgap-matched, and polarization-matched compositions are highlighted. (b) Contours of constant polarization (red dashed lines) and constant bandgap (black solid lines) as a function of the In and Al mole fractions in AlInGaN layers grown strained on (0001) oriented GaN. (c) Contours of constant critical thickness (red solid lines) and constant bandgap (black solid lines) as a function of the In and Al mole fractions in AlInGaN layers grown strained on (0001) oriented GaN.

DJ Jena et al, 2010

Sheet Resistance

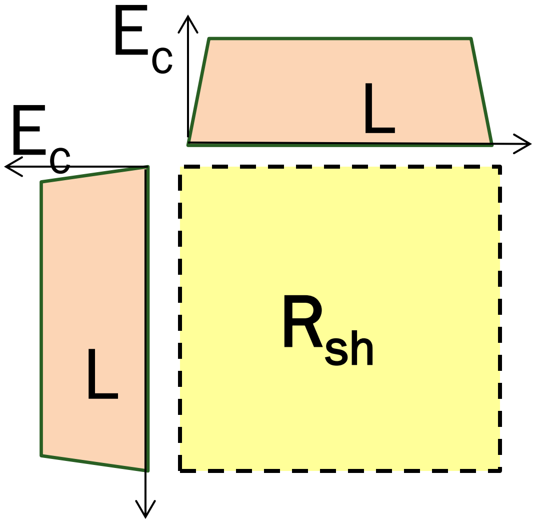
- The resistance of a thin sheet with uniform doping (e.g. 2DEG). Conveniently expressed in Ω/square, or Ω/□
  - Just count #squares parallel to the current flow
  - Depends on carrier density (n_s) and mobility

$$Rsheet = \frac{1}{q.n_S.\mu_N}\ [\Omega/\square]$$



Ron/Vbd of a HEMT (drift region only !)

- Semiconductor is un-doped i.e. behaves like a dielectric→Electric field is rectangular



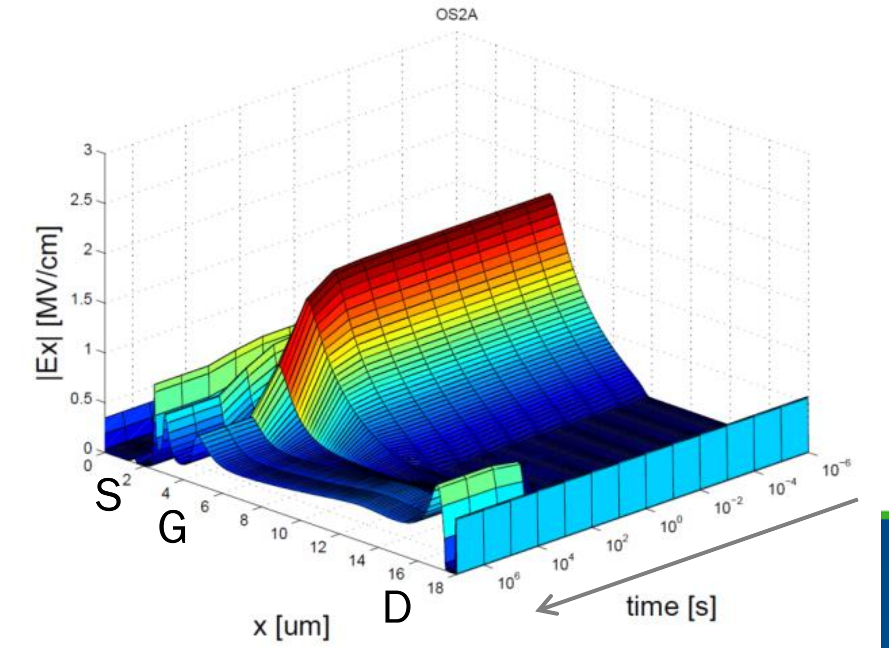
$$Ron = Rsheet.Area$$

$$Ron = \frac{1}{q.n_S.\mu_N}.L^2$$

$$\mathbf{Ron = \frac{1}{q.n_S.\mu_N}.\frac{V_{bd}^2}{E_c^2}}$$

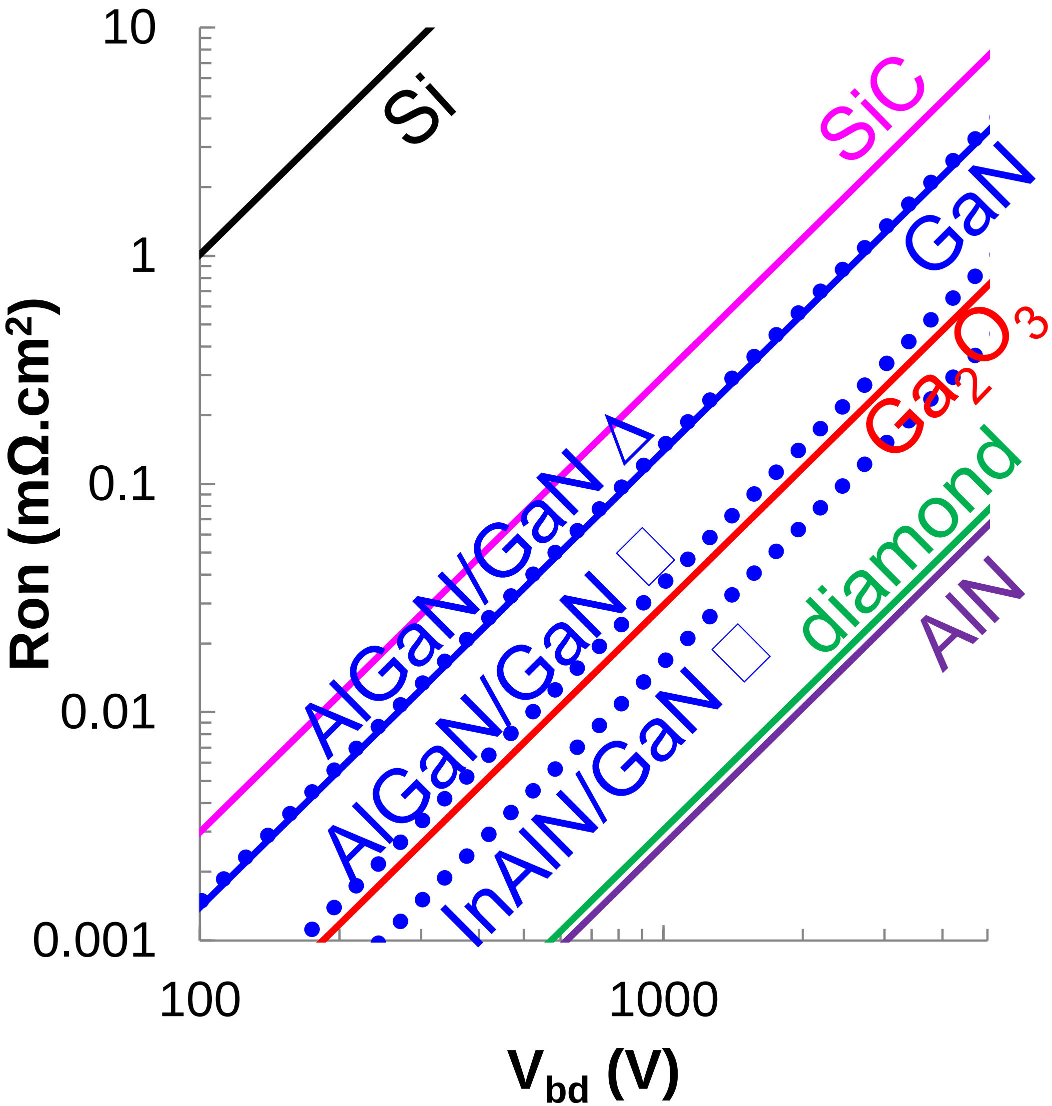
- Surface field shaping and dynamic effects might result in more triangular electric field

$$\mathbf{Ron = \frac{4}{q.n_S.\mu_N}.\frac{V_{bd}^2}{E_c^2}}$$



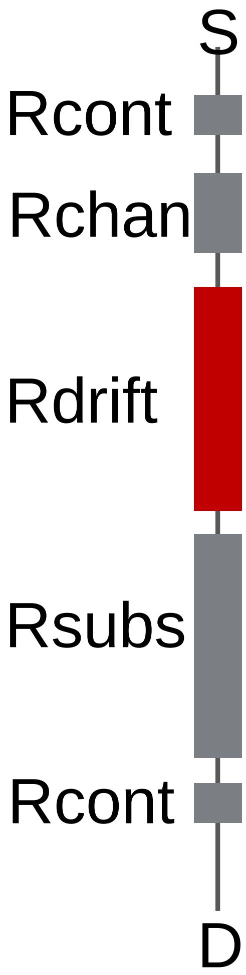
Ron/Vbd of a HEMT (drift region only !)

- AlGaN/GaN HEMT with rectangular field will go beyond the 1D GaN limit.
- By introducing polarization engineering (InAlN), even the Ga_2O_3 1D limit is broken.



The Baliga FOM revisited

- Baliga FOM (and its derivatives) only refer to the drift region.
  - Drift region blocks the voltage (V_{bd})
  - Ron also includes other contributions
- A transistor has
  - Contacts to the outside world
  - A channel to switch the transistor on and off
  - A substrate



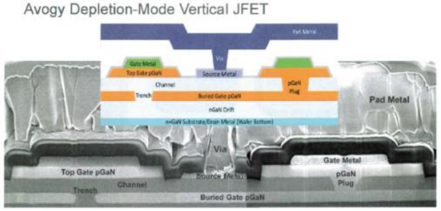
GaN-on-GaN : vertical transistors

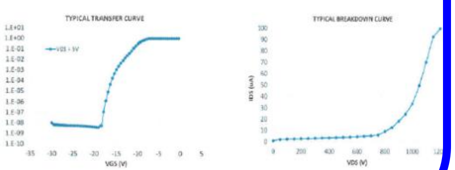
- Homo-epitaxy yields low DD ($<10^6$ cm^{-2})

Avogy

GaN bulk substrates from Furukawa, Mitshubishi, Sumitomo : \$700 (**2"**), transitioning to 4" at \$1500 in 2017 (?). Add ~\$250 for epi.
Schottky and PIN diodes with V_{bd}~900-2000V in 2013. UIS~900 mJ.
JFET (Dmode) : 3x through HVPE/MOCVD ?

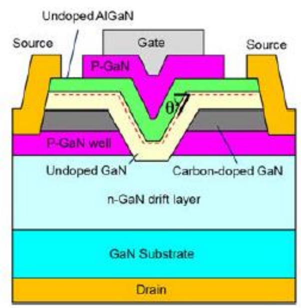
Avogy Depletion-Mode Vertical JFET

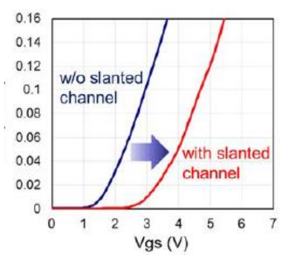




Panasonic

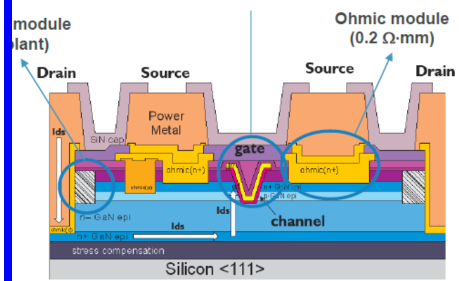
Normally-off JFET on bulk GaN substrates .
Regrowth of [C]-GaN, AlGaN and pGaN on semi-polar surface. Pitch=20µm.
V_{th}>2.5V, Ron=1mΩ.cm², V_{bd}~1.7kV (IEDM2016)



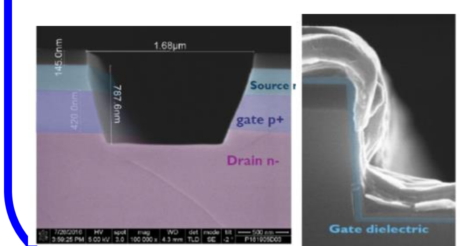


imec

Process module dvlpmt.
No regrowth in MOCVD.
Ohmic contact to n+ & p-body
Trench gate/V-gate, ALD Al_2O_3
First lot running in Pline

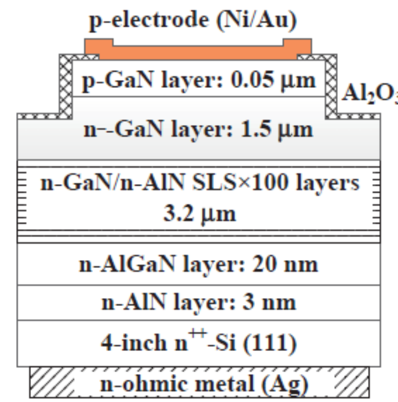


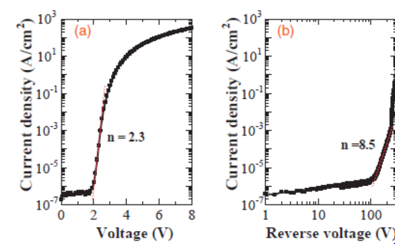
- Module development in PLINE
- First PLINE lot running



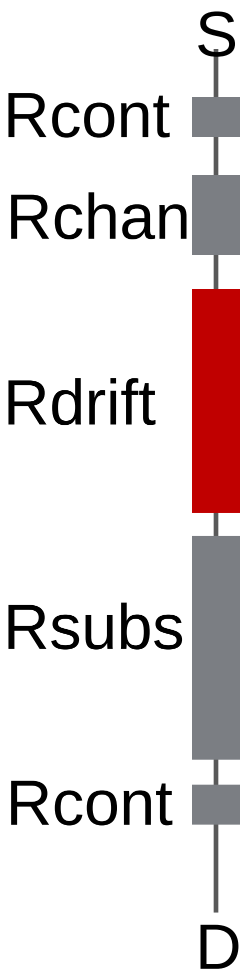
Nagoya (Egawa)

GaN-on-Si vertical transistors (APL 2016).
N++ Si substrate.
No regrowth in MOCVD.
Ron high, V_{bd} still low
First attempt.

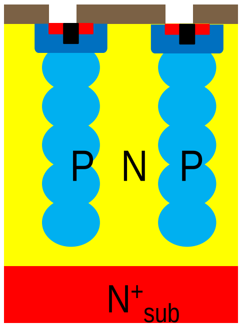


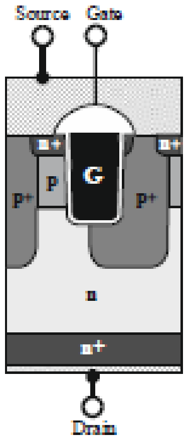


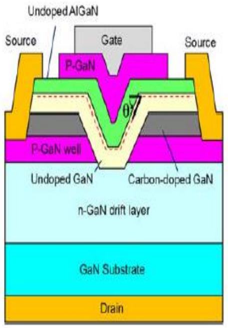
The Baliga FOM revisited

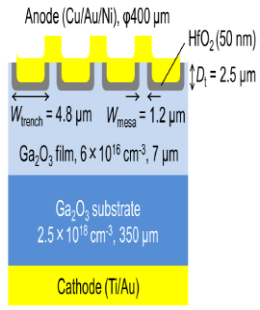


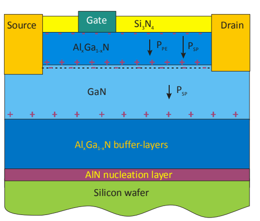
	Si SJ	SiC TrenchMOS	GaN V-MOS	Ga_2O_3	HEMT
Rcont	Very low	low	<5%	<5%	~10%
Rsubs	<3mΩ.cm	20mΩ.cm	10mΩ.cm	6mΩ.cm	NA
Rdrift	$Ron = \frac{2.V_{bd}}{E_C{}^2.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}{}^2}{E_C{}^3.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}{}^2}{E_C{}^3.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}{}^2}{E_C{}^3.\varepsilon.\mu_N}$	$Ron = \frac{1}{q.n_S.\mu_N}.\frac{V_{bd}{}^2}{E_C{}^2}$
Rchan	low	high	Medium	?	Very low









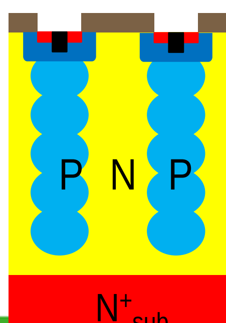


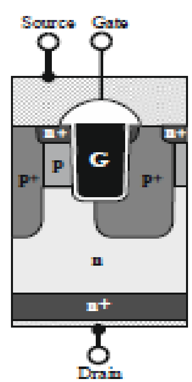
Why are you here today ?

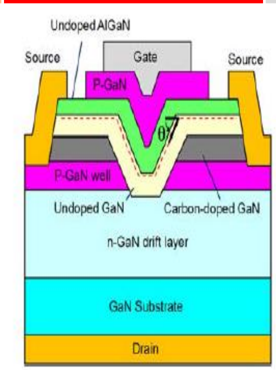
- Power semiconductors are a hot topic
- Power devices=solid state physics
  - 1D limit for a vertical transistor
  - Resurf effect (2D)
- Non-polar and polar materials
  - Concept of polarization charge
  - Simple band structure
- HEMT “High Electron Mobility Transistor”
  - Sheet resistance
  - HEMT versus vertical power device
- Cost versus performance

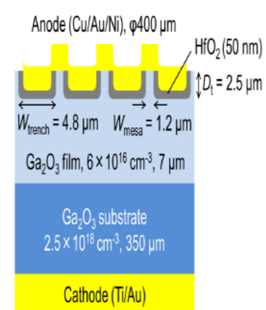
The Baliga FOM revisited

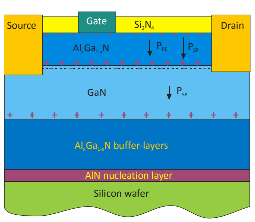
	Si SJ	SiC TrenchMOS	GaN V-MOS	Ga_2O_3	HEMT
Rcont	Very low	low	<5%	<5%	~10%
Rsubs	<3mΩ.cm	20mΩ.cm	10mΩ.cm	6mΩ.cm	NA
Rdrift	$Ron = \frac{2.V_{bd}}{E_C^2.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}^2}{E_C^3.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}^2}{E_C^3.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}^2}{E_C^3.\varepsilon.\mu_N}$	$Ron = \frac{1}{q.n_S.\mu_N} . \frac{V_{bd}^2}{E_C^2}$
Rchannel	low	high	Medium	?	Very low
Wafer (mm)	200-300	100-150	75-100	50-100	150-200
Cost/wfr ($)	low	high	Very high	medium	low





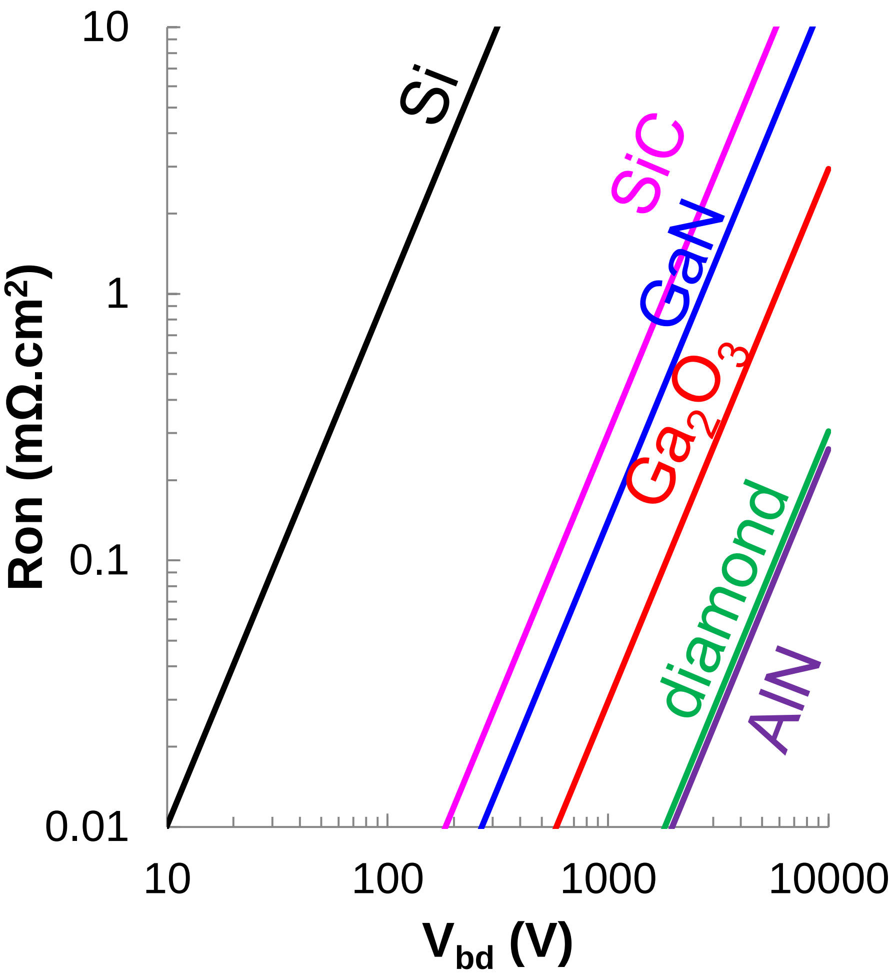


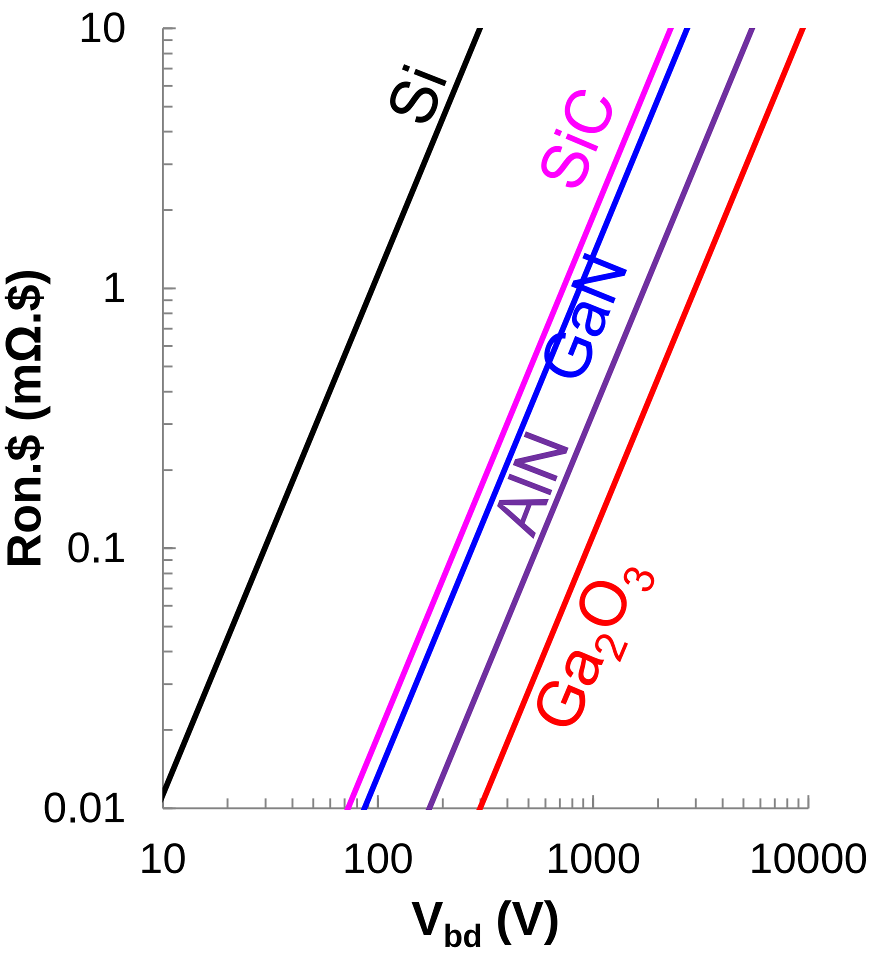




The Baliga FOM revisited—Cost

- Multiply Ron (mΩ.cm²) by cost/cm²

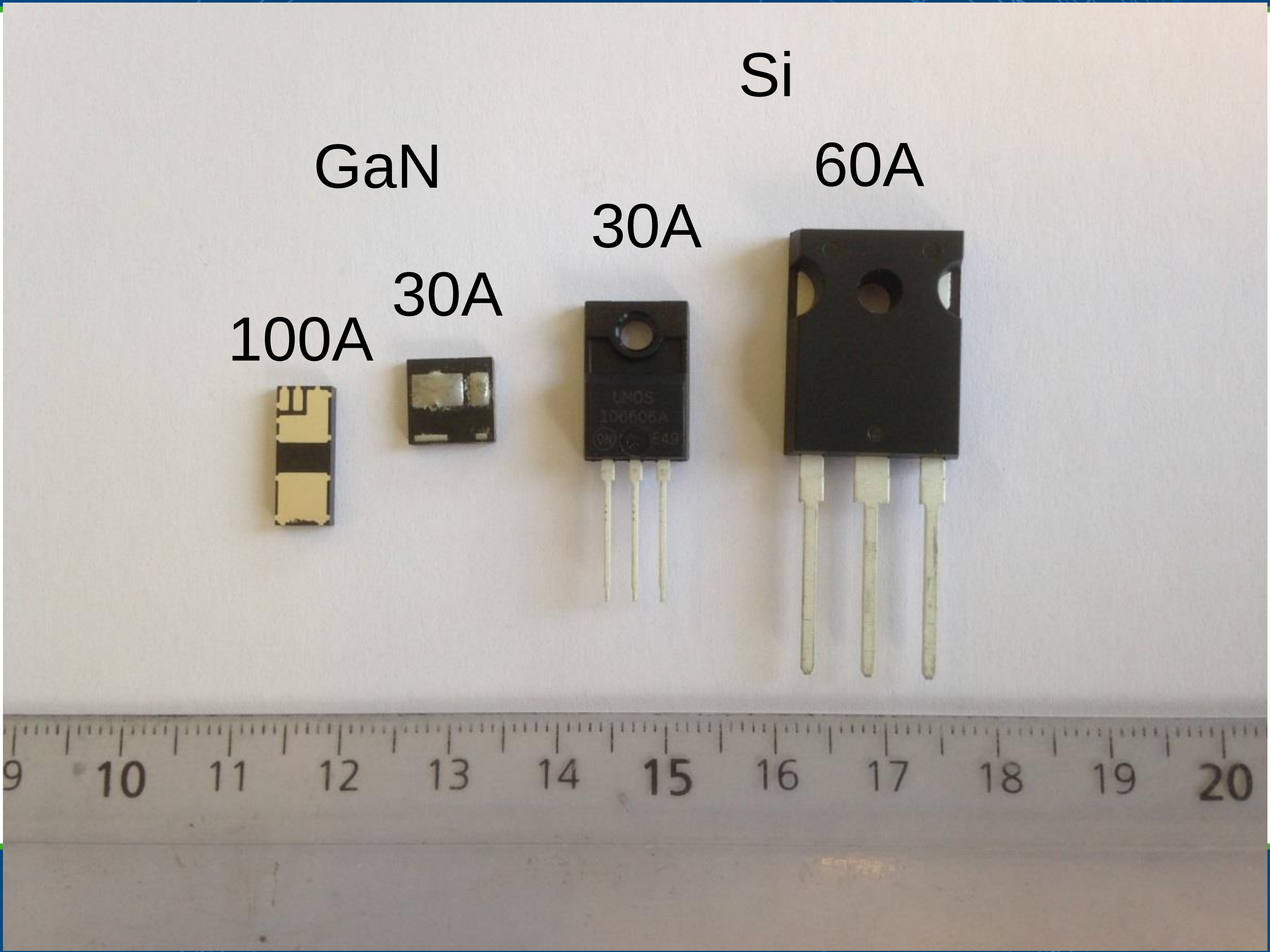




Main Take-Aways

- Novel device concepts allow to go beyond the simple 1D FOM (resurf, superjunction)
- III-V materials are Polar (vs Si, which is non-polar).
- Most important (popular) III-V materials are :
  - GaN, AlN, Ga_2O_3, In_2O_3
- Polar materials allow both junction transistors as well as High Electron Mobility Transistors.
- HEMTs have lower Ron and lower Capacitance than standard junction transistors in the same material.
- Don't forget about cost ! Efficiency is key, but cost is king !

650V GaN products

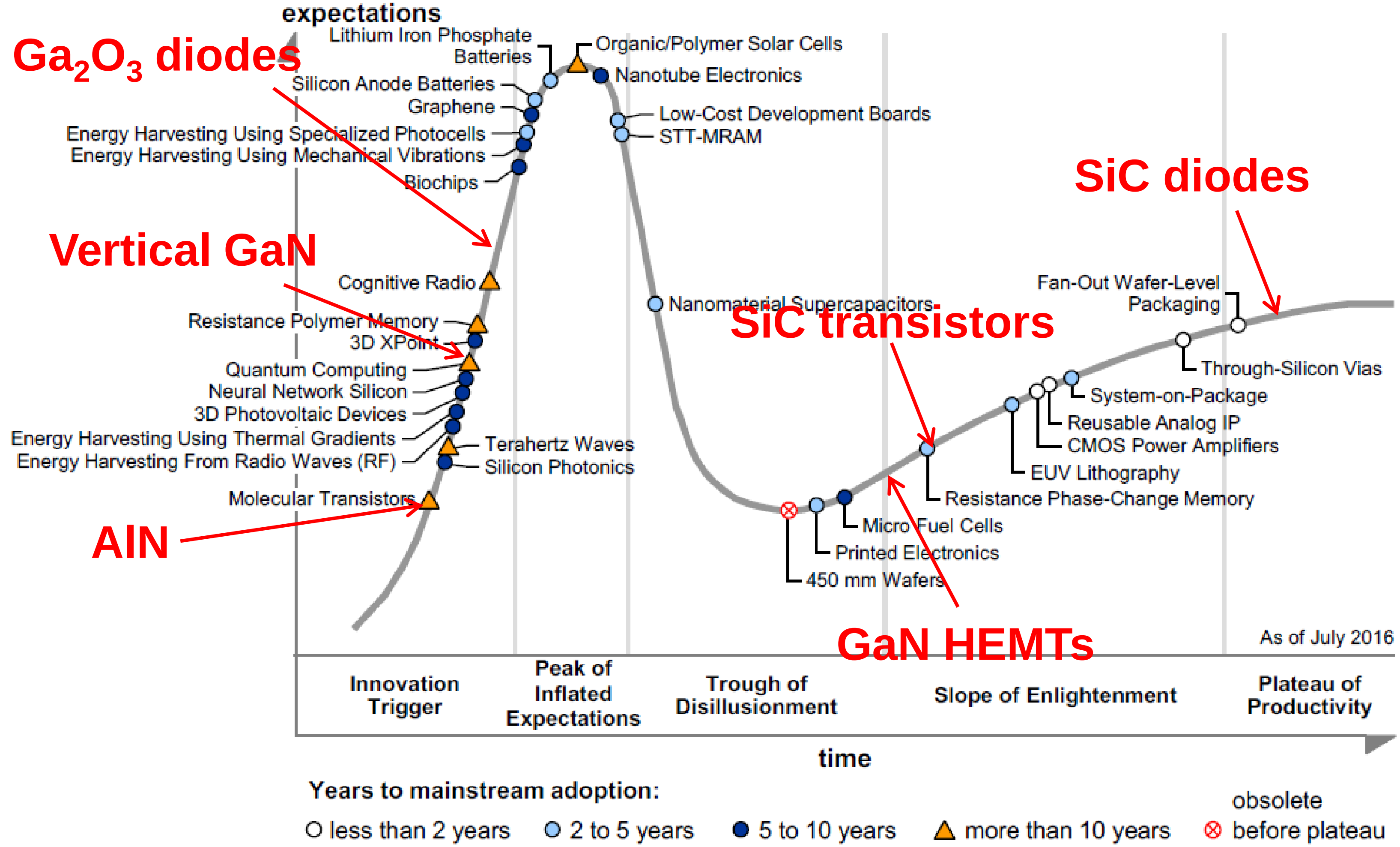


The end of the road for Silicon….

Is the start of the journey for WBG

The Hype Cycle for Electronic Technologies

Figure 1. Hype Cycle for Semiconductors and Electronics Technologies, 2016



Source: Gartner (July 2016)