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Semiconductor Power Devices :

Part 1 : From Junction to Material Engineering
Part 2 : Reliability Basics

Peter Moens

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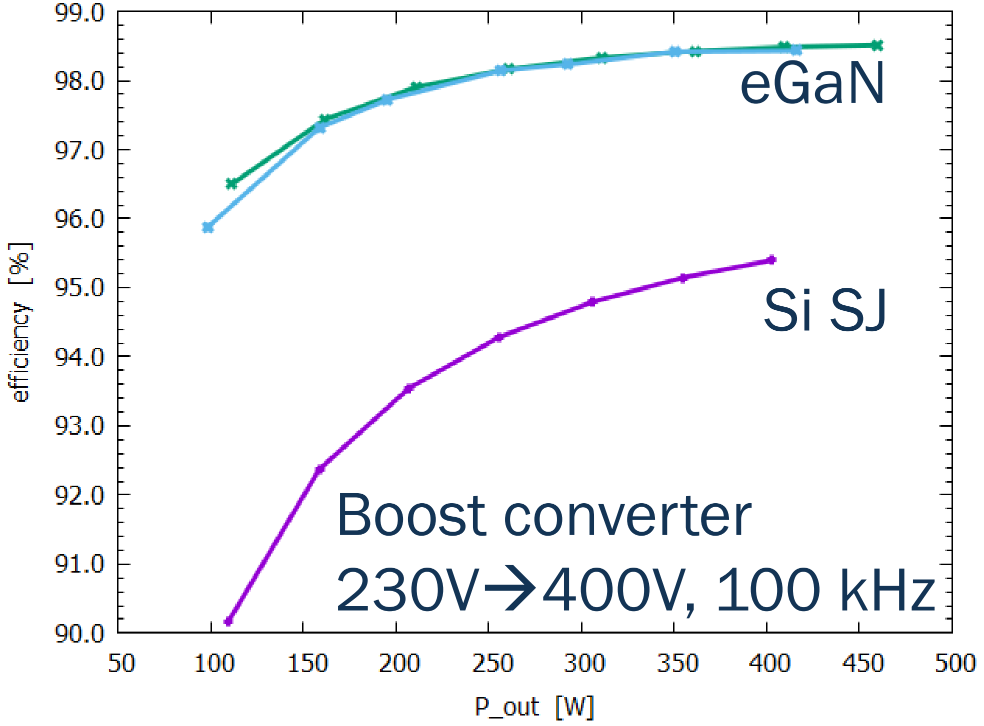
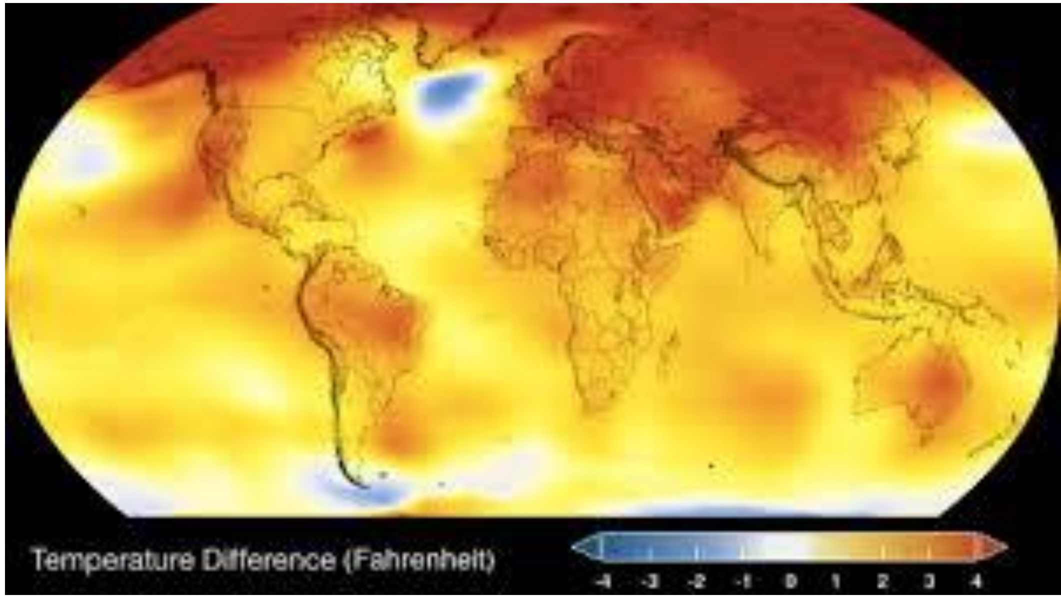
Semiconductor Power Devices : Part 1 : From Junction to Material Engineering

Peter Moens

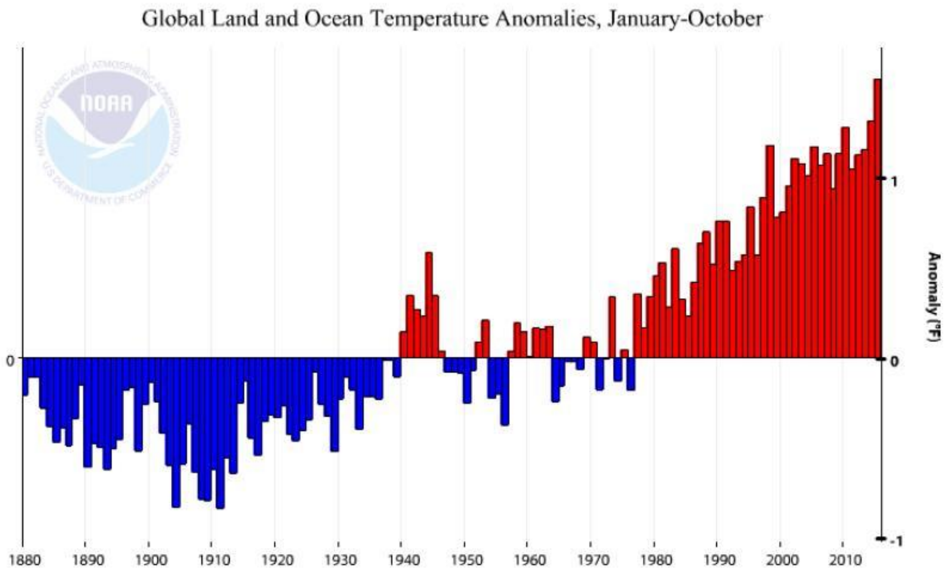
Global Challenges : Global Warming

- 50% of all energy in the world is electrical (~8 TW.yr out of ~18 TW.yr)
- 40-60% of all produced electricity is lost, mainly due to the many transmission and conversion steps (HV to LV, AC to DC etc.)→~**4TW.yr is lost !**
- E.g 4 conversion steps :
  - Si : 95% of each step : total eff. ~81%
  - GaN : 98% of each step : total eff. ~92%

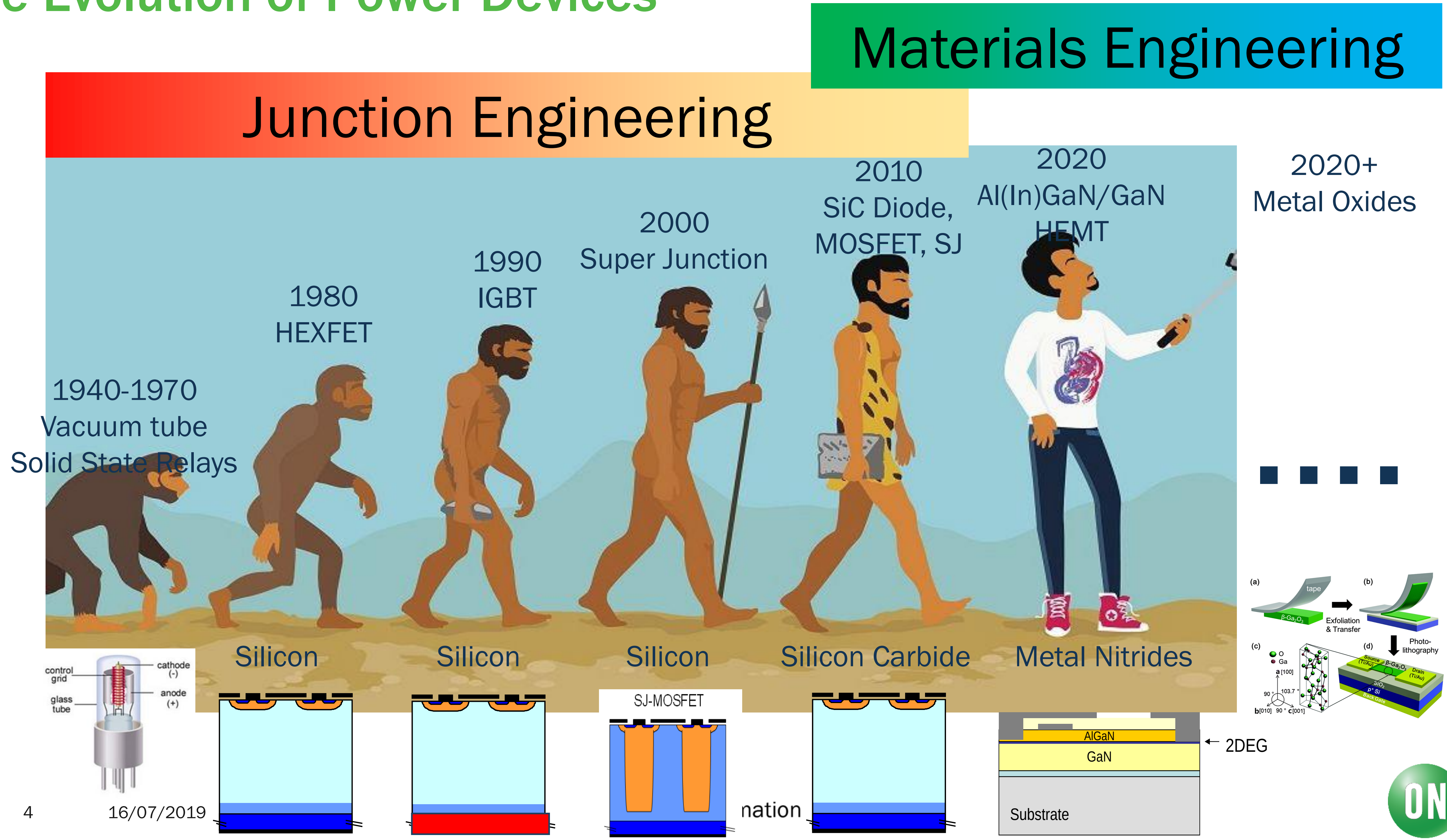




Global Land and Ocean Temperature Departure from 20th Century Average, January-October



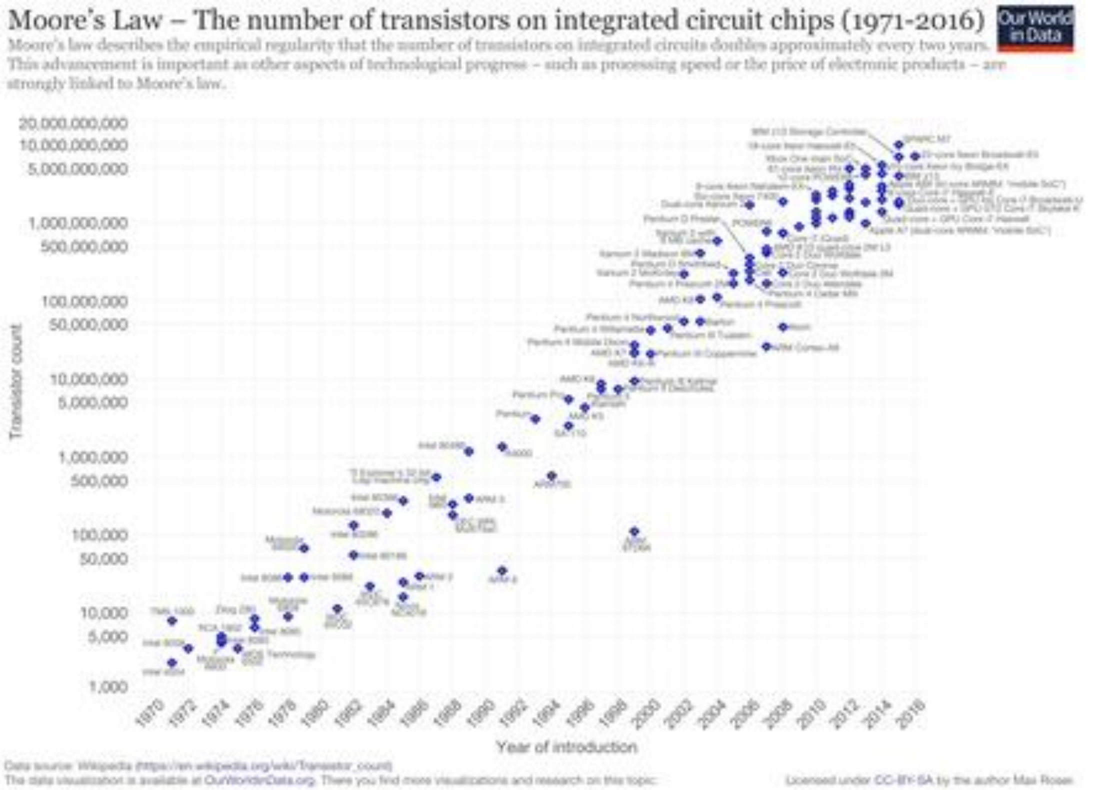
The Evolution of Power Devices

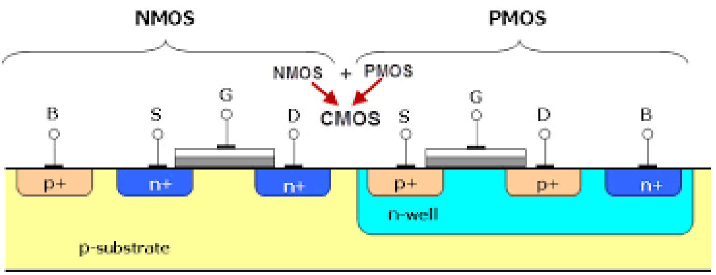


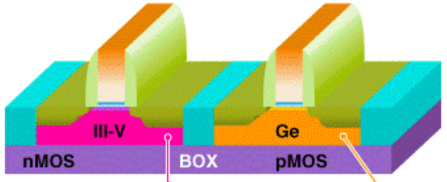
The Evolution of Logic Devices

Moore's law driven by scaling.

- Up to 10nm node "<u>junction engineering</u>"
  - Si nMOS and pMOS
  - High k gate dielectric and metal gates
- Below 10nm node "<u>material engineering</u>"
  - Ge-based for pMOS
  - III-V based for nMOS

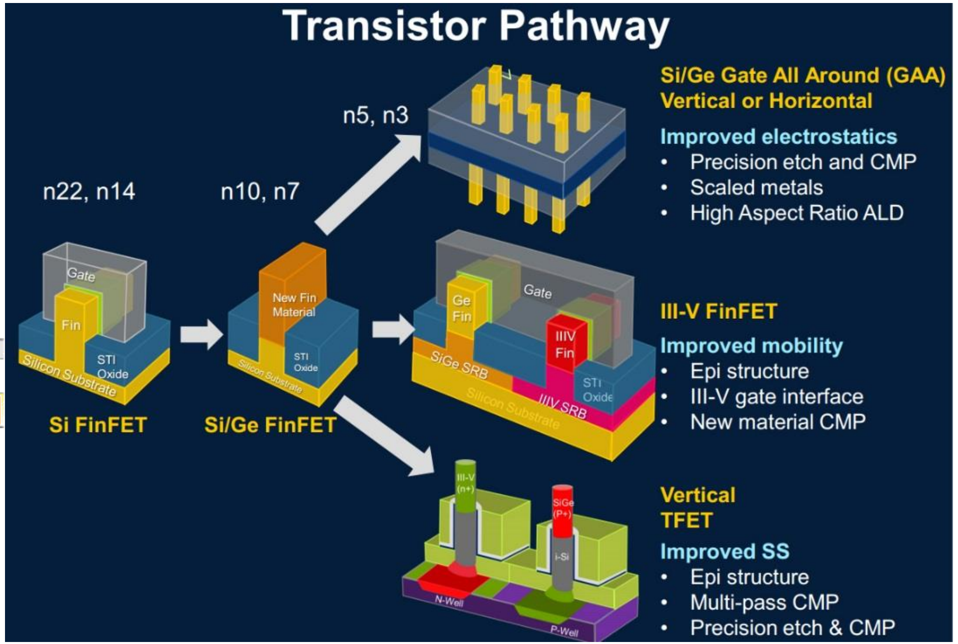






Material	Si	InAs	Ge
Electron mobility (㎠/Vs)	1,600	40,000	3,900
Hole mobility (㎠/Vs)	430	500	1,900

Existing channel material



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

Outline

- Power devices=material properties
  - 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”
  - HEMT versus vertical power device
- Ron and Capacitance versus Voltage
- Cost and performance

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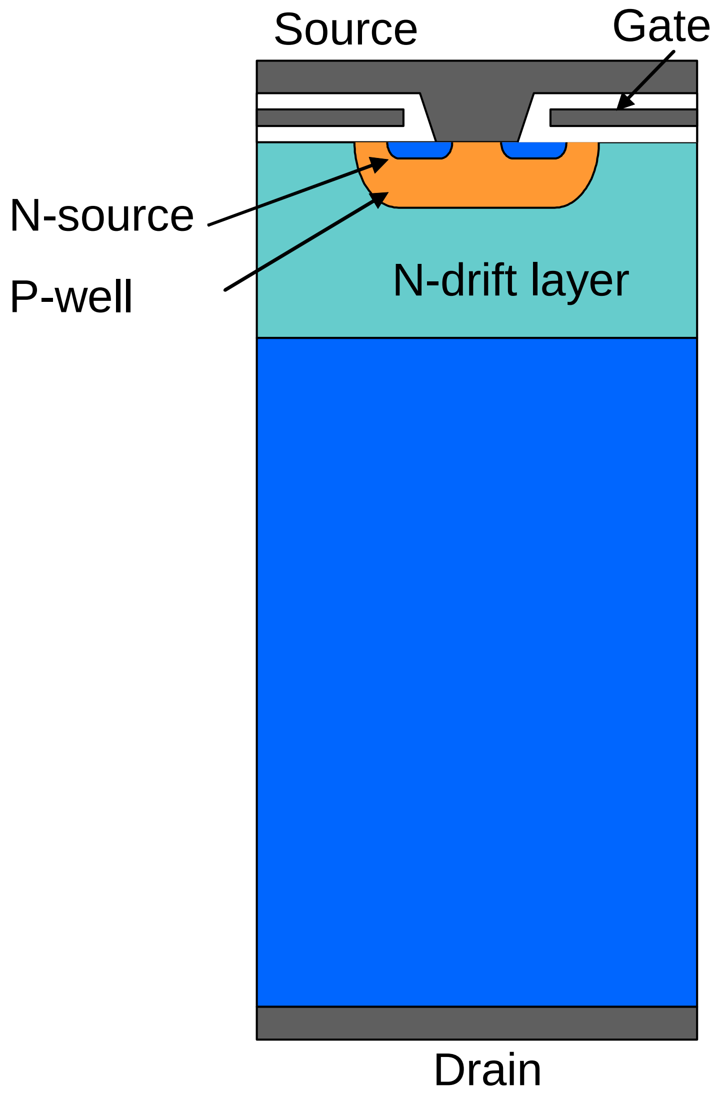
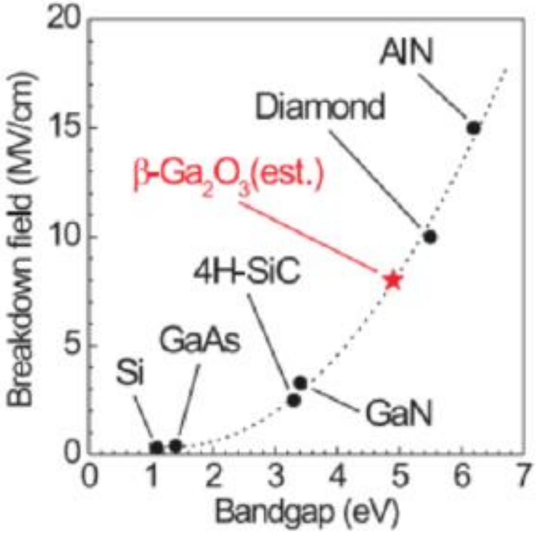


The Baliga Figure of Merit—1D

Baliga Figure-of-Merit is a metric for how good a material is for uni-polar power device technology.

- [note : Ec and mobility are assumed constant (independent of doping) !]

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

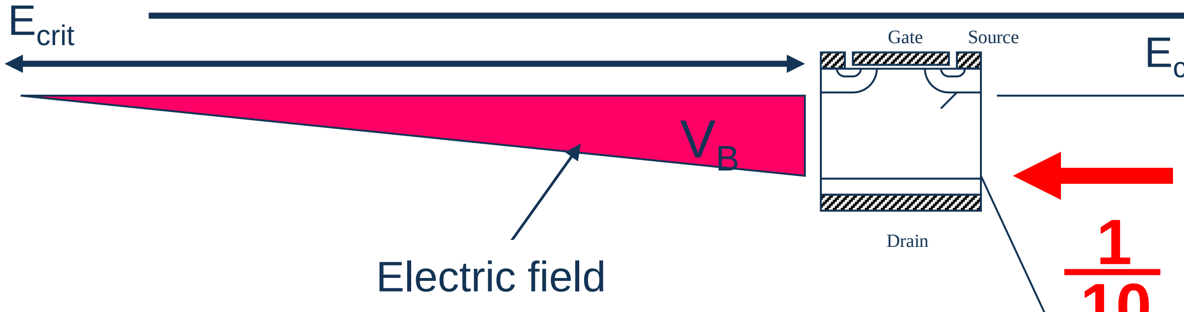


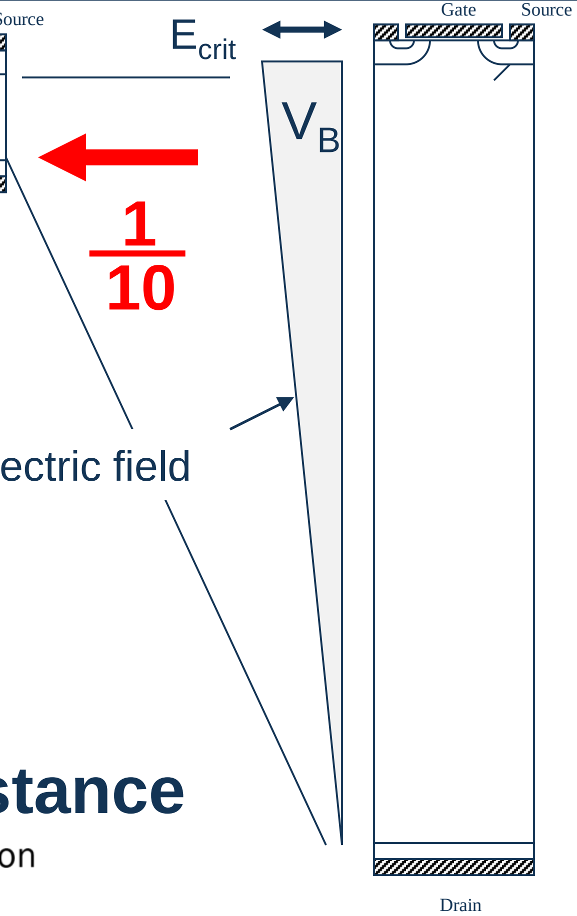
	Si	GaAs	4H-SiC	GaN	Diamond	β-Ga_2O_3	AlN
Bandgap Eg (eV)	1.1	1.4	3.3	3.4	5.5	4.8-4.9	6
Electron mobility μ (cm^2/Vs)	1400	8000	1000	1200	2000	300	500
Breakdown field E_b (MV/cm)	0.3	0.4	2.5	3.3	10	8	15
Relative dielectric constant ε	11.8	12.9	9.7	9.0	5.5	10	8.5
Baliga's FOM $\varepsilon\mu E_b^3$	1	15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

WBG U-WBG

Wide Band Gap Semiconductor Advantage

	WBG	Si
Max. Elec. Field (E_{crit})	**2×10^6 V/cm**	**2×10^5 V/cm**
Band Gap	3V	1.1V



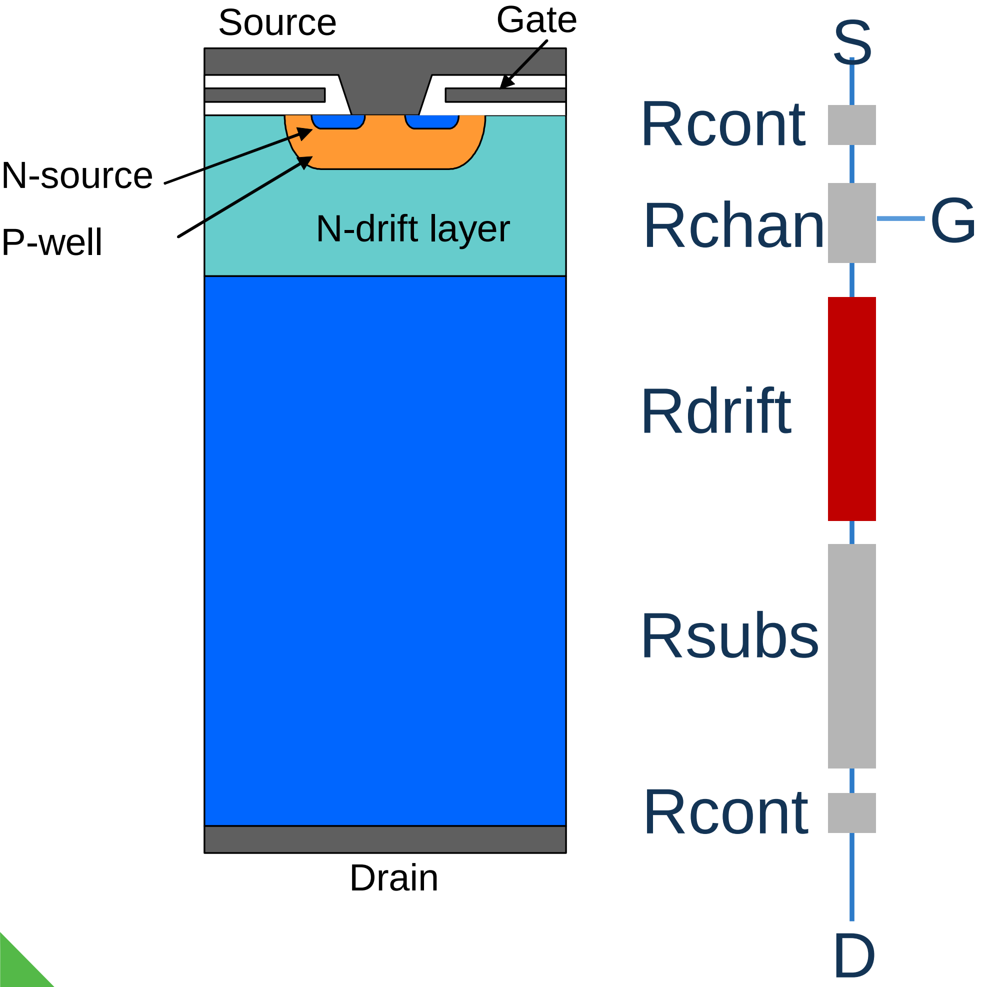


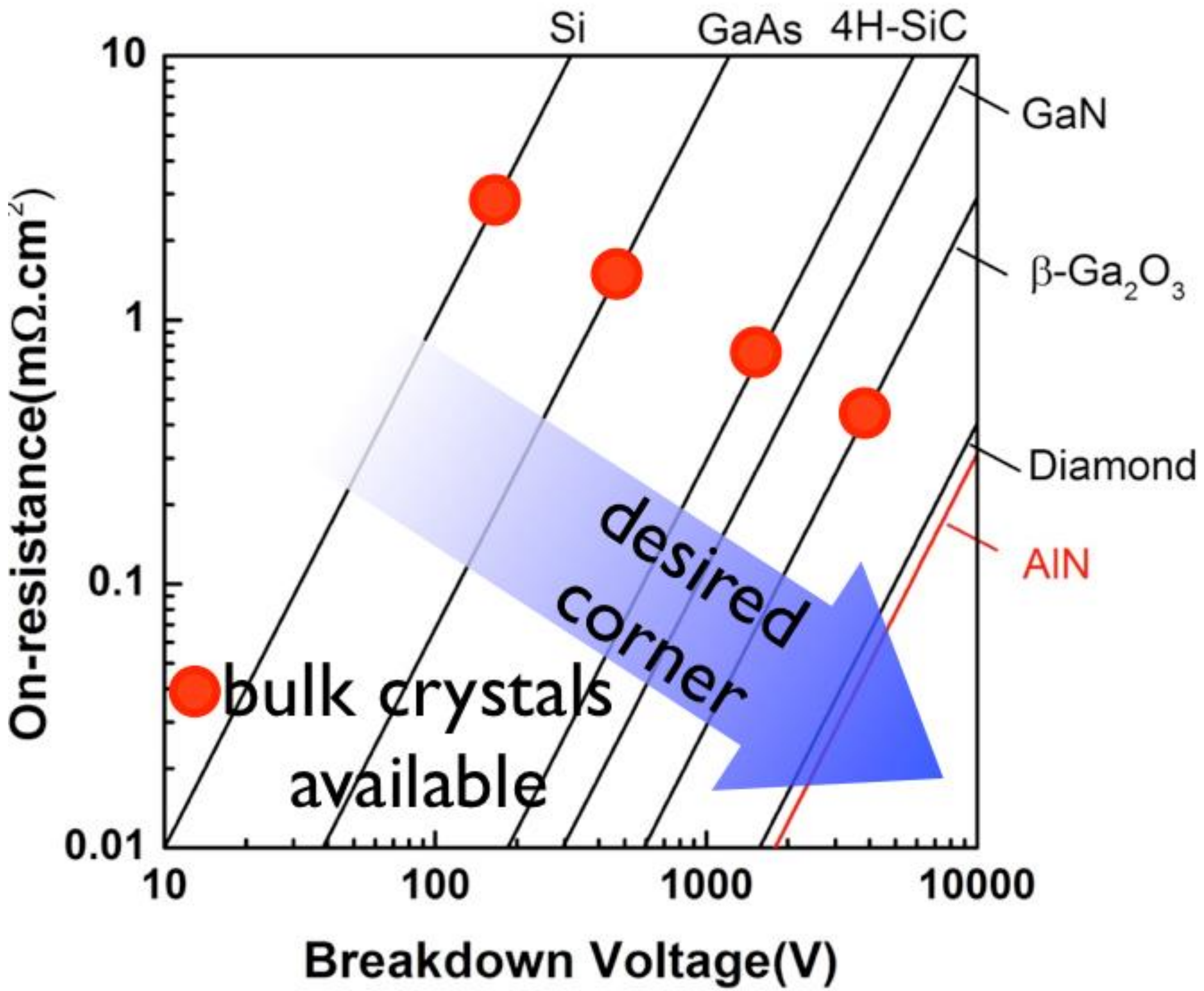
$$R_{on} = \frac{4V_B^2}{\mu_n \varepsilon E_{crit}^3}$$

Significantly Low On-resistance

Baliga FOM—only for drift region (1D)

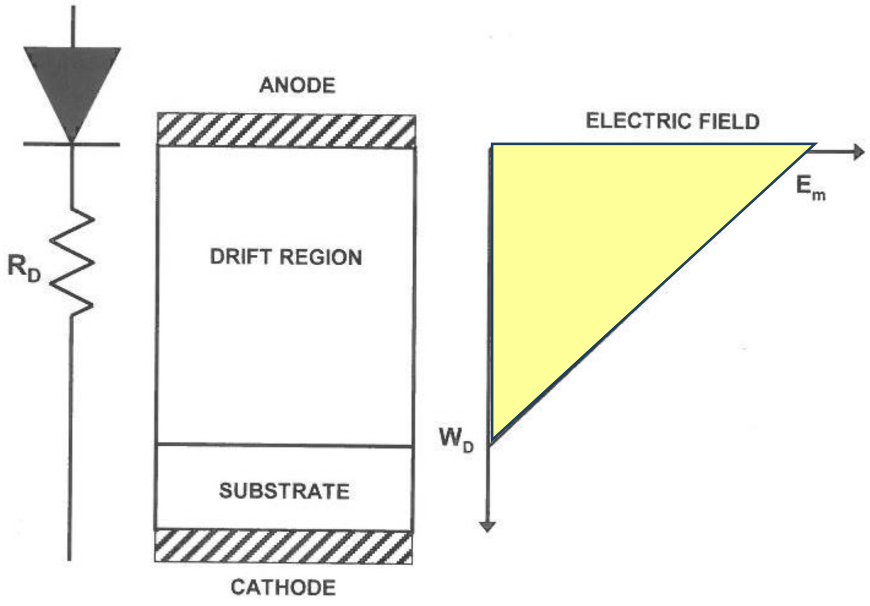
$$Ron\ [\Omega.cm^2] = \frac{4.V_{bd}^{\ 2}}{\varepsilon.\mu.E_c^{\ 3}}$$





Basic Equation for Power Semiconductors

Assume an abrupt junction, parallel plane



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

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

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

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

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

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

Drift width

Resistivity

Figure-of-merit : Ron versus Vbd

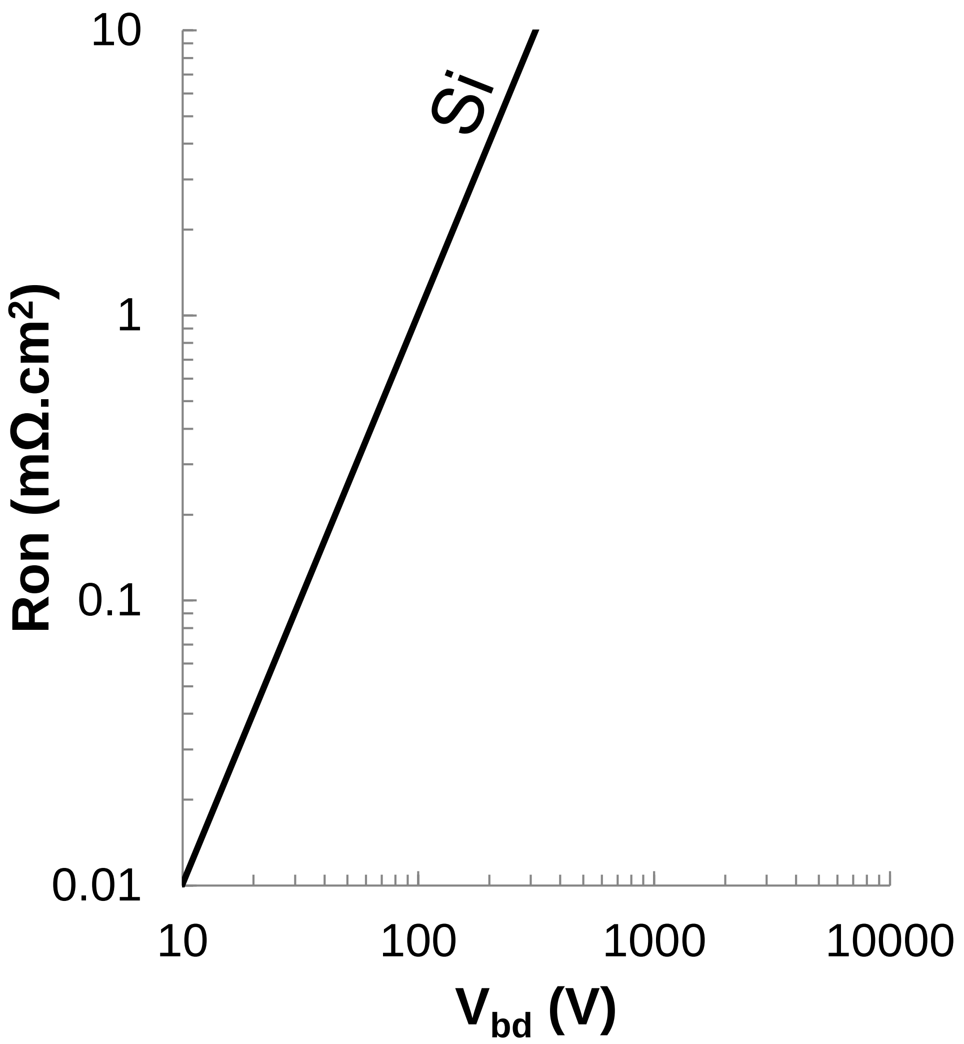
$$Ron = \frac{W_D}{q.N_D.\mu_N} \quad [\Omega.m^2]$$

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

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

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

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



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Super Junction :
An Example of Junction Engineering

Public Information

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)

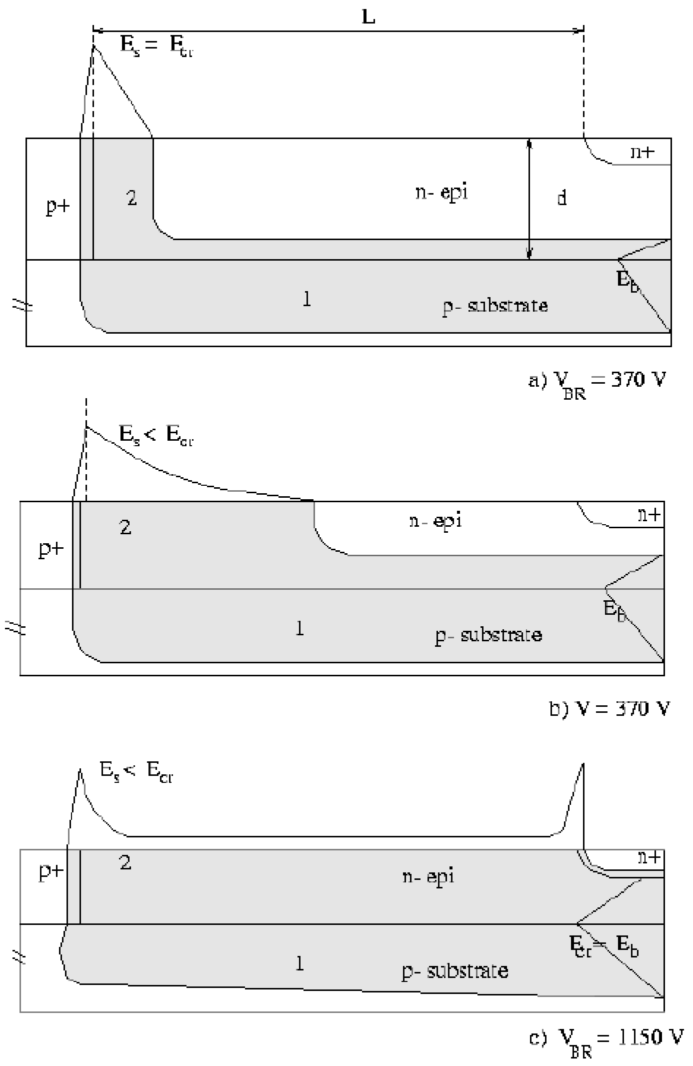
J.A. Appels and H.M.J. Vaes

Philips Research Laboratories
Eindhoven - The Netherlands

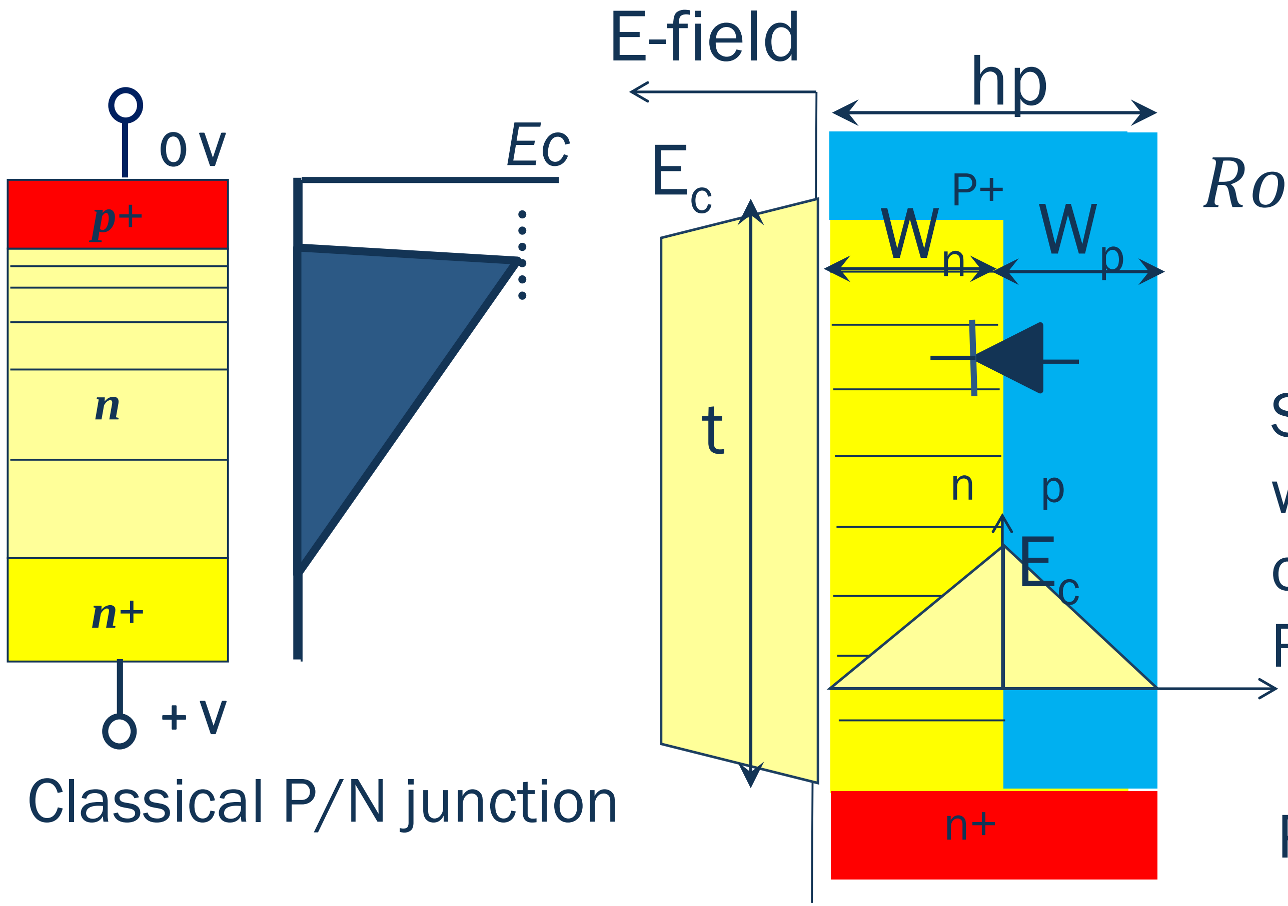
CONCLUSION

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.



Junction Resurf Diode



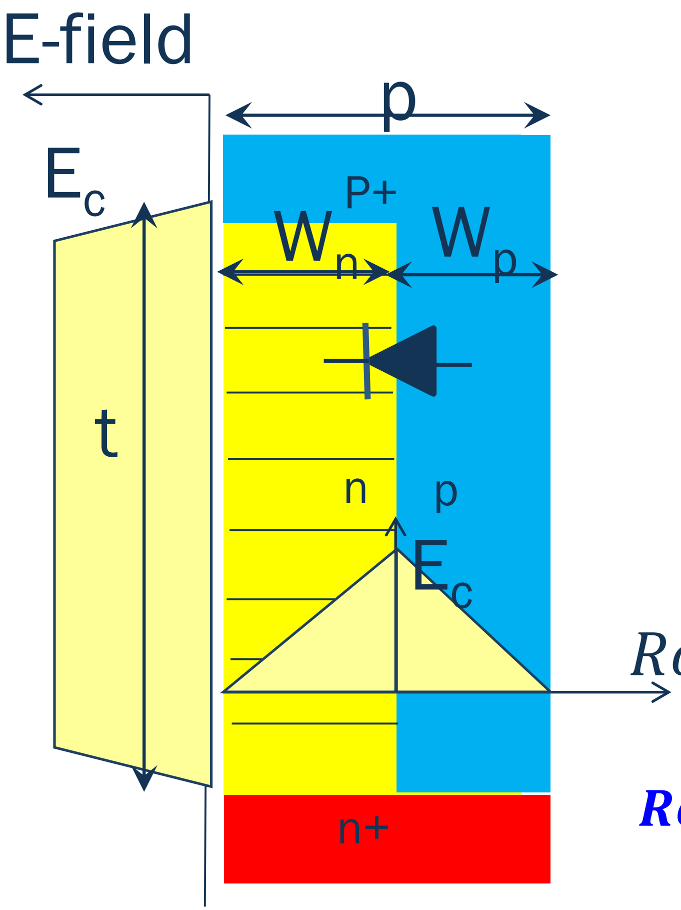
Classical P/N junction

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

SJ devices have a weaker dependency on V_{bd} and E_c.
Ron depends on hp

Pitch (p) =2.hp

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	$4.42\ 10^{13}$

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

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

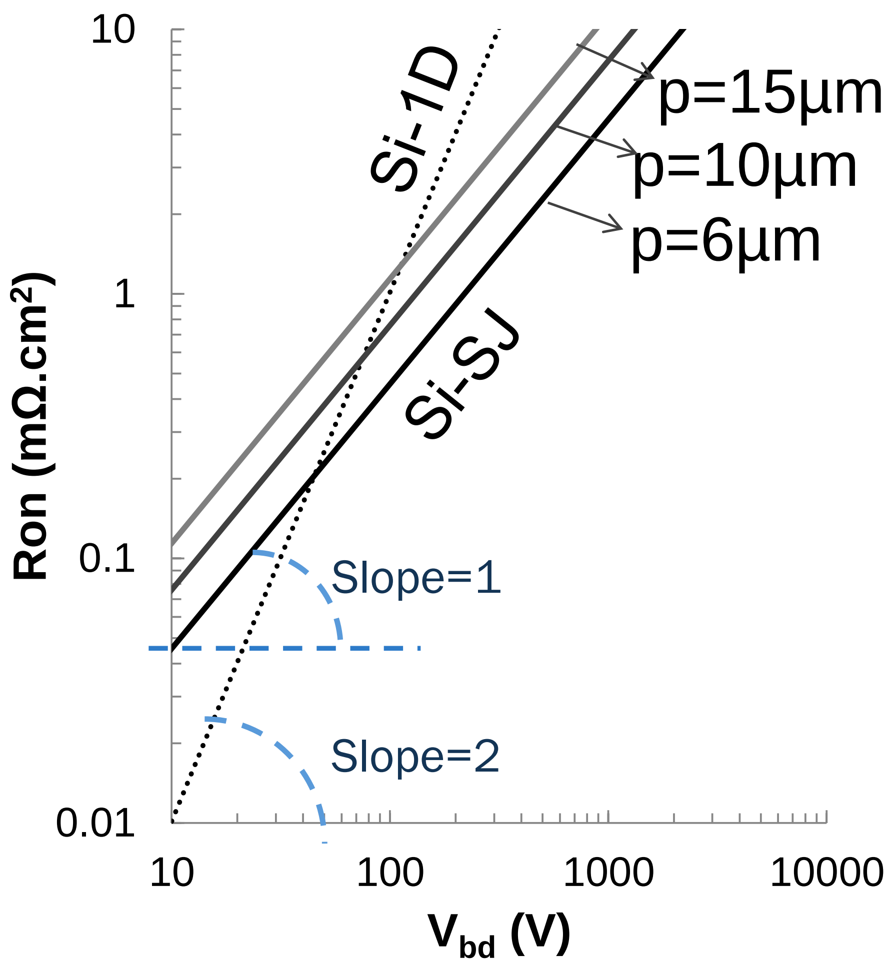
$$V_{bd} = E_c.t$$

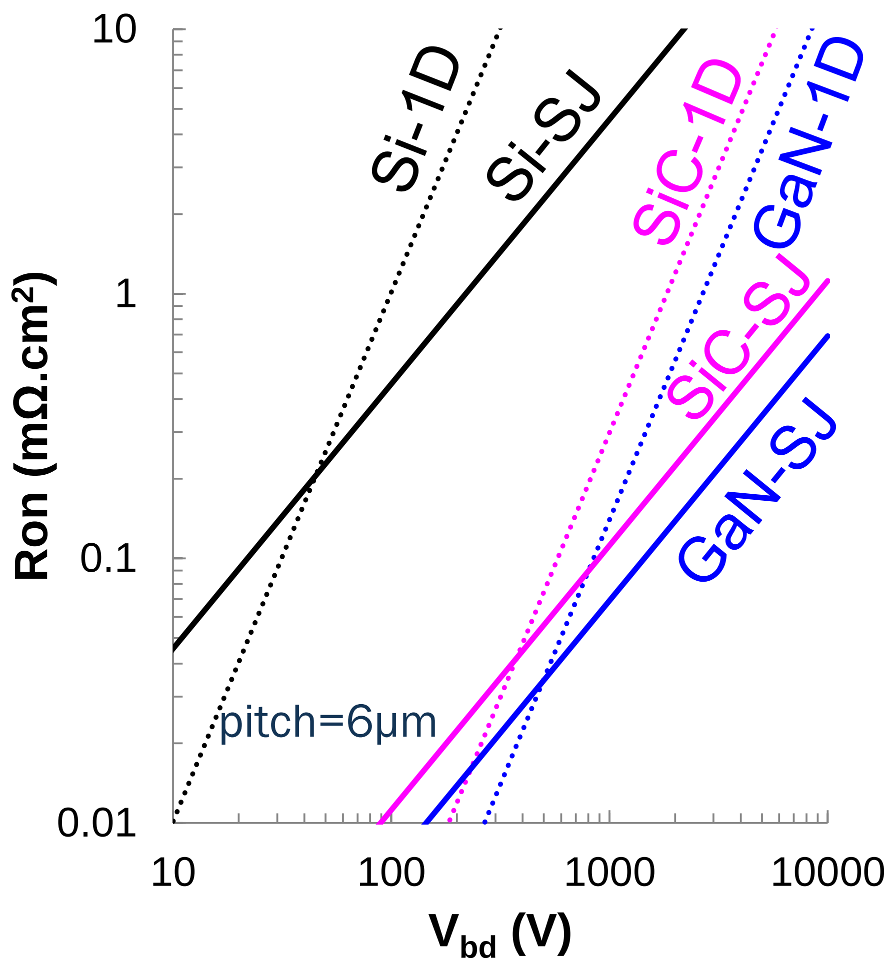
$$Ron = \frac{2.p.V_{bd}}{E_c.Q_{opt}.\mu_N}$$

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

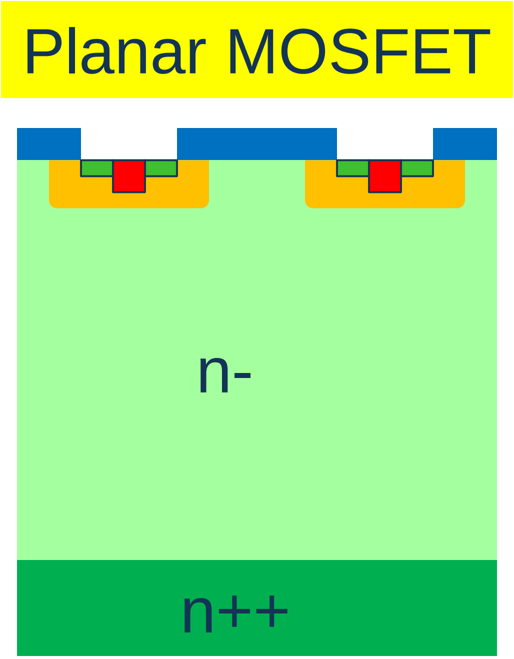
Resurf limit–2D

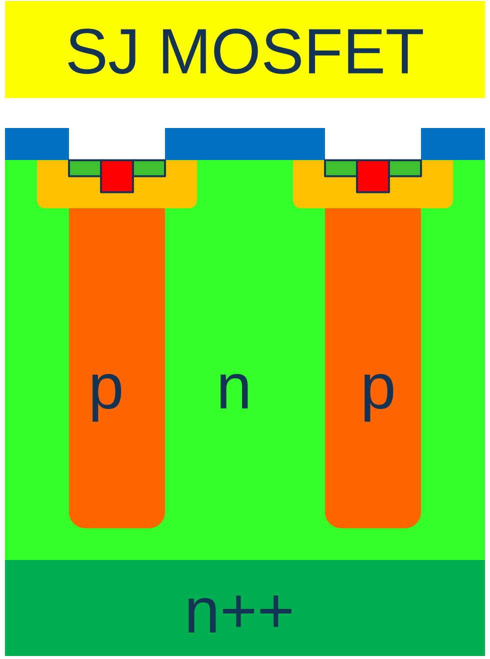
Depends on device pitch (p) : process capability

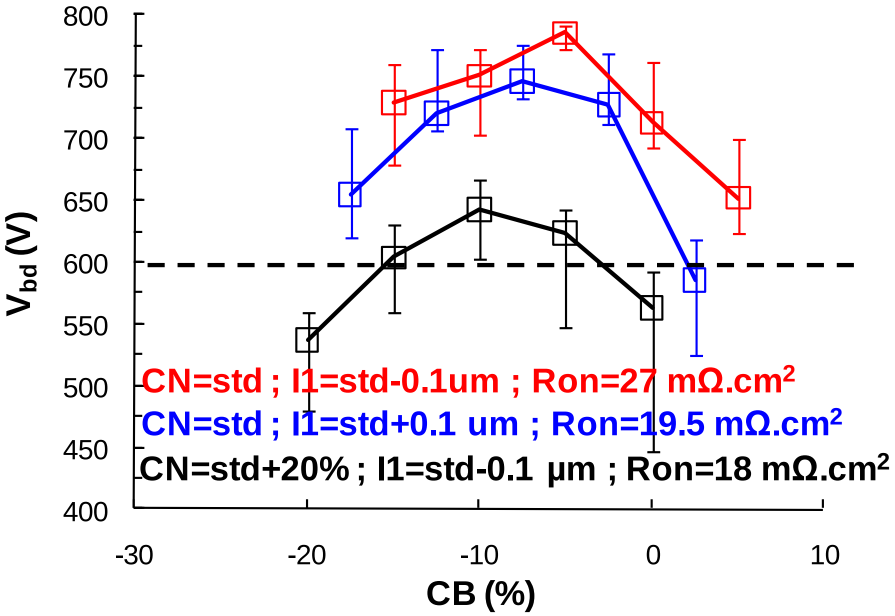




Super Junction Transistors (Based on Resurf)





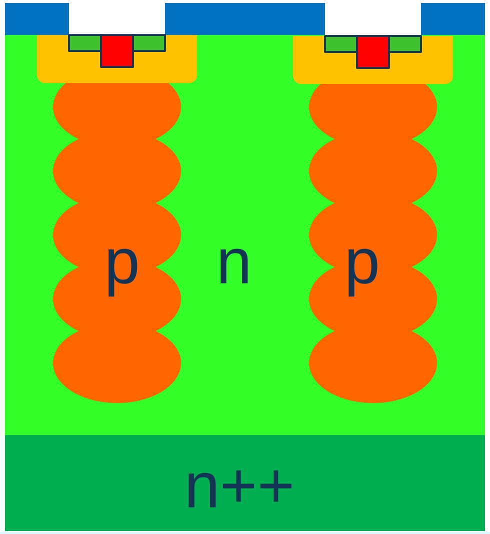


To achieve Resurf Action, the total charge in the n and p columns must be balanced across the total structure !

Tight Process control is key !

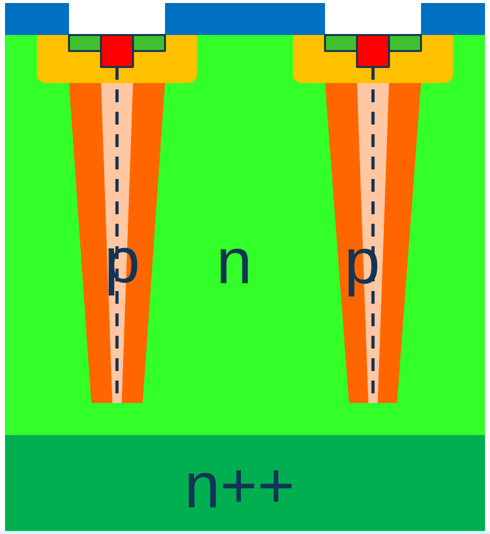
Ways to achieve a vertical SJ structure

Multi-epi multi-implant



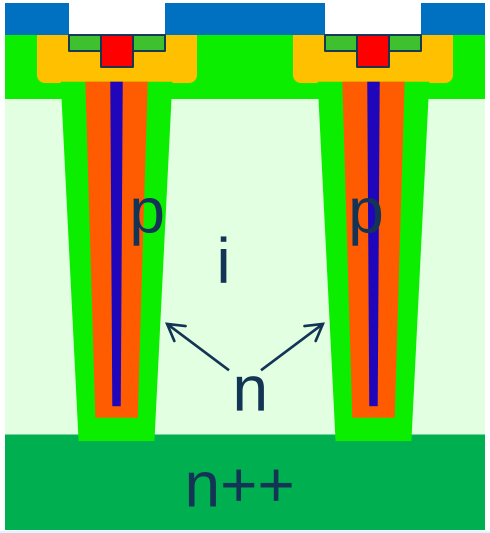
- n-epi control ~2-3%
- p-type control <1%
- Shrinking limited by litho and diffusion, need more epi/implant steps

Deep trench etch single epi refill



- Shrinking potential
- n-epi control ~2-3%
- p-type control ~ 2-3%
- Deep trench etch taper angle for seamless epi fill

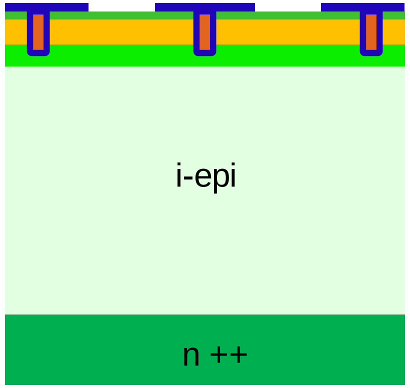
Deep trench etch, dual epi, oxide fill



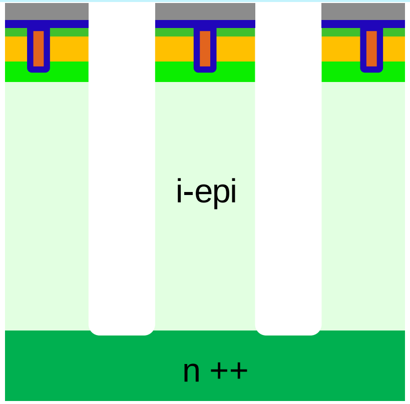
- Large shrinking potential
- n-epi/p-epi control ~2-3%, grown during same run !
- Dielectric fill

Trench based Super Junction Device cross-section

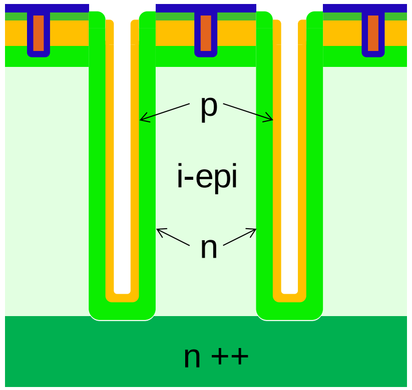
- Pring termination
- Gate trench



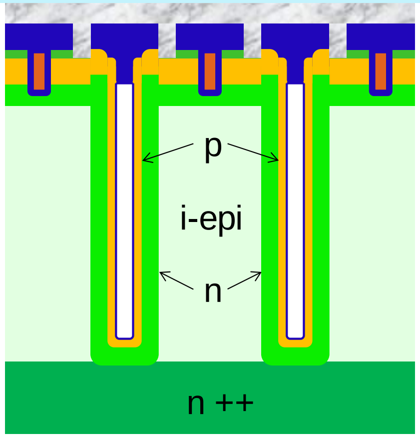
- Hard Mask
- Deep Trench etch

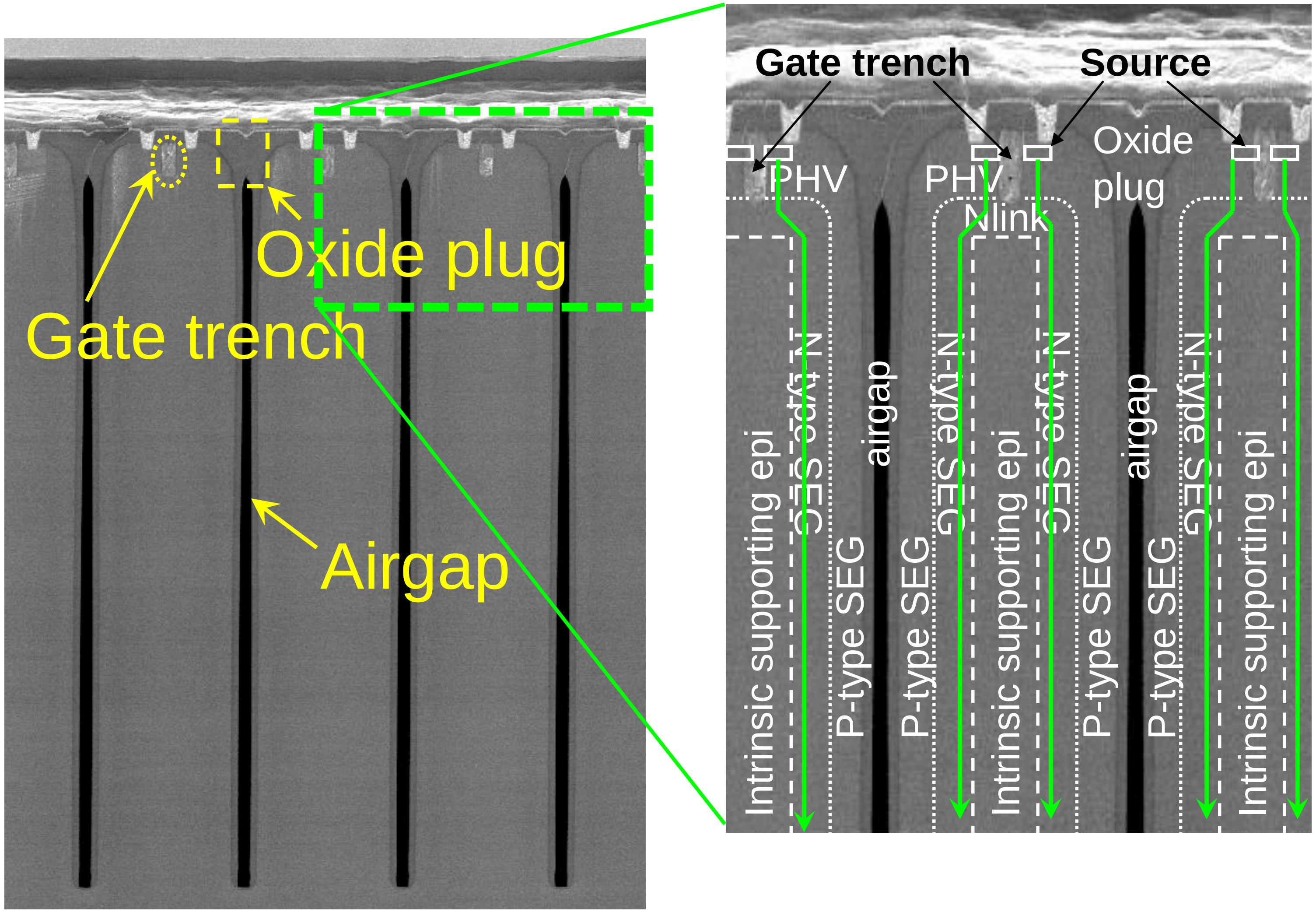


- Selective epi, n- and p-type



- Oxide seal
- Contact, metal





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- Non-polar and polar materials
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Periodic Table & Electro Negativity

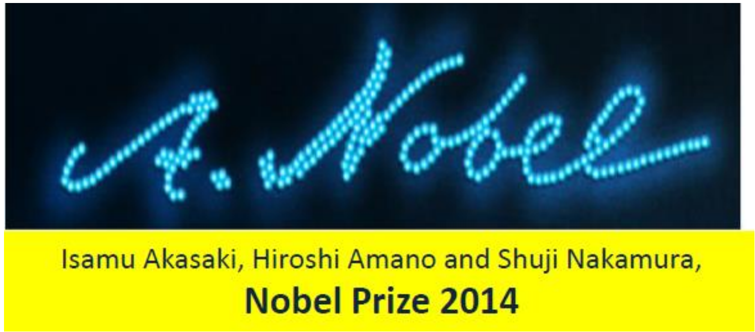
III IV V

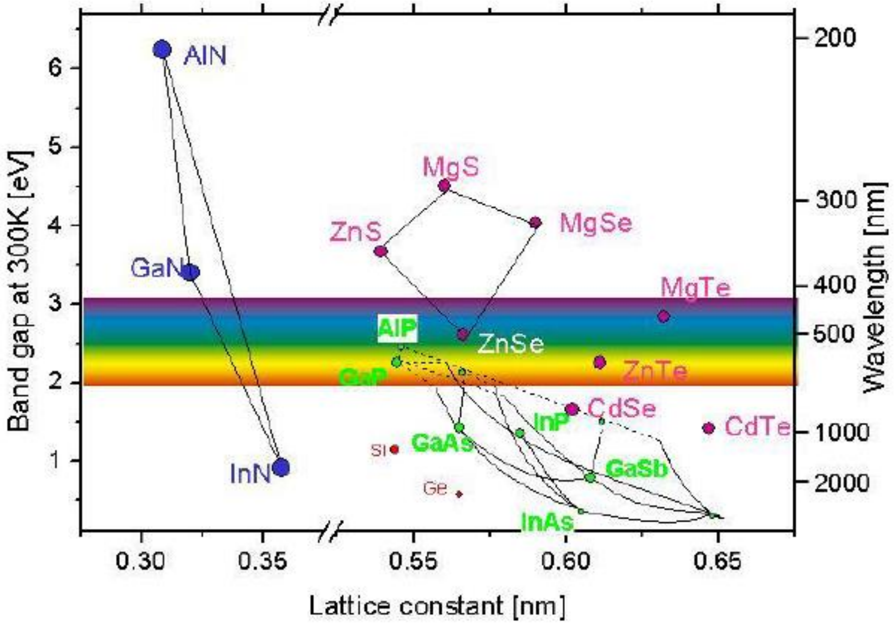
H 2.1																	He
Li 1.0	Be 1.5											B 2.0	C 2.5	N 3.0	O 3.5	F 4.0	Ne
Na 0.9	Mg 1.2											Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0	Ar
K 0.8	Ca 1.0	Sc 1.3	Ti 1.5	V 1.6	Cr 1.6	Mn 1.5	Fe 1.8	Co 1.8	Ni 1.8	Cu 1.9	Zn 1.6	Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8	Kr 3.0
Rb 0.8	Sr 1.0	Y 1.2	Zr 1.4	Nb 1.6	Mo 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

GaN/AlGaN/InAlGaN (III-V)

- Al/Ga/In Nitride system ("III-V") stems from LEDs
  - By tuning the In %, the full visible spectrum can be covered (photon emission), Direct bandgap
  - Bandgap engineering by tuning Al % for power devices
- 2 Nobel prizes in Physics
  - Alferov et al., 2000
  - Akasaki et al., 2014

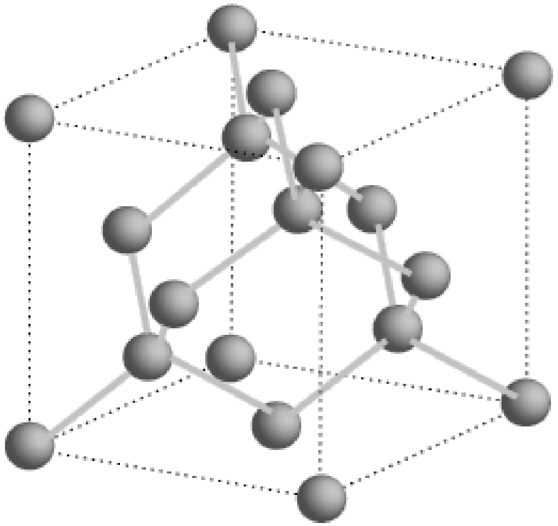




Crystal Structures. Polar vs non-polar

Cubic

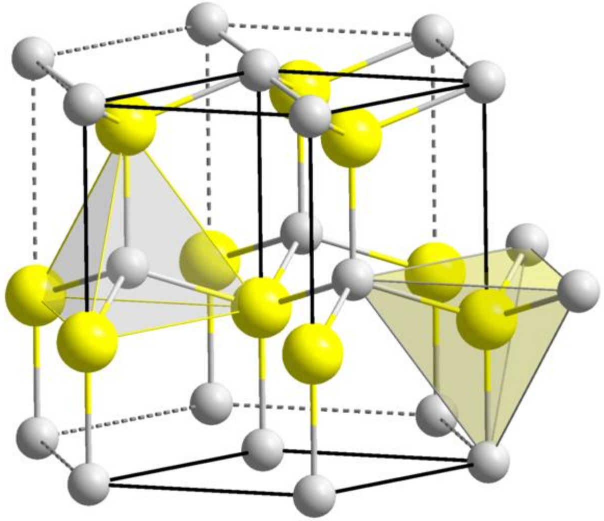
Si, SiC, Diamond



Covalent bond
Non-polar

Wurtzite

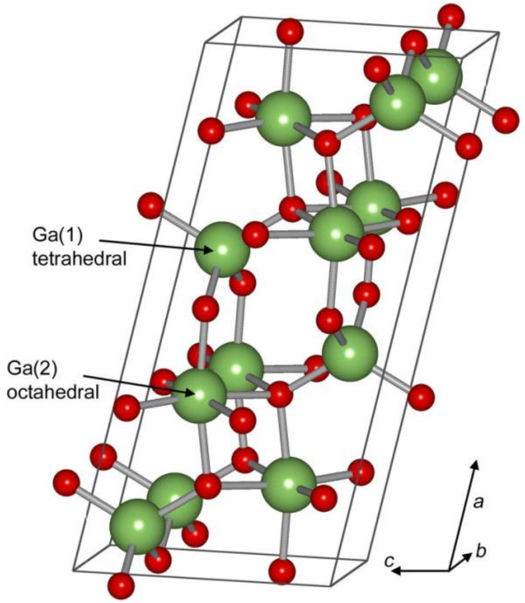
GaN, AlN



Ionic bond
polar

Monoclinic

Ga_2O_3, In_2O_3



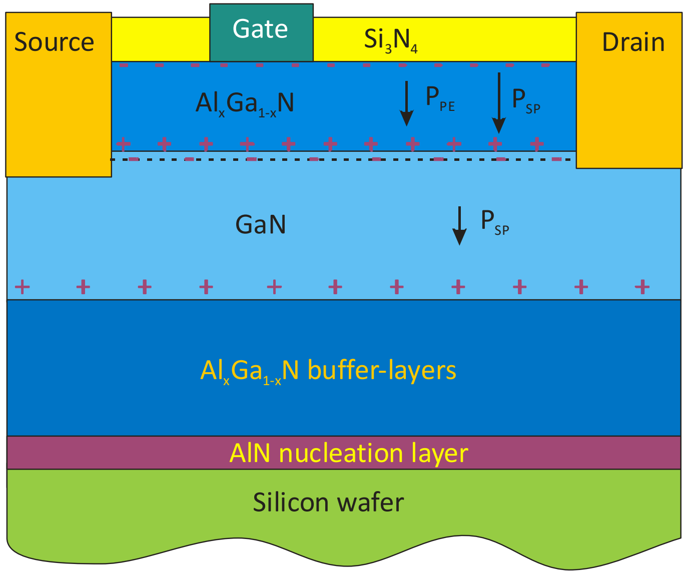
Ionic bond
polar

<u>Note</u> : 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.

AlGaN/GaN Lateral HEMT Devices

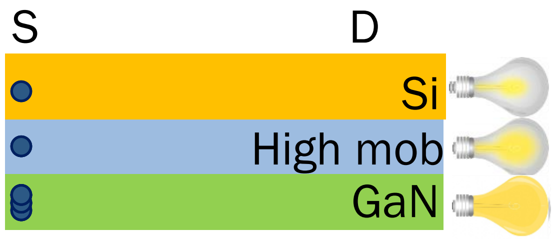
AlGaN/GaN High Electron Mobility Transistors feature :

- Low Ron due to high 2DEG density with $n_s \sim 9 \times 10^{12}$ 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)



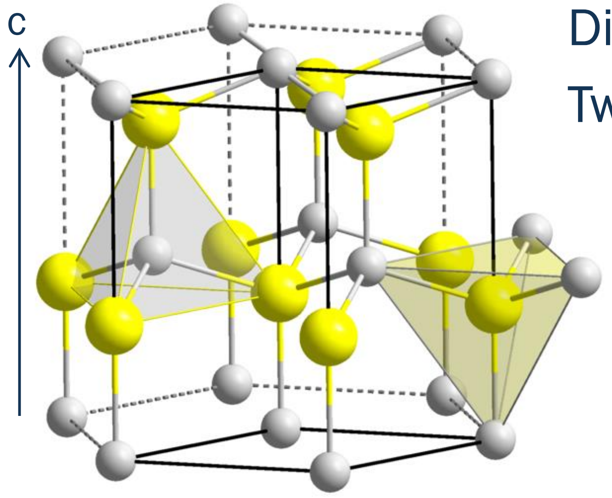
Device Property

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.

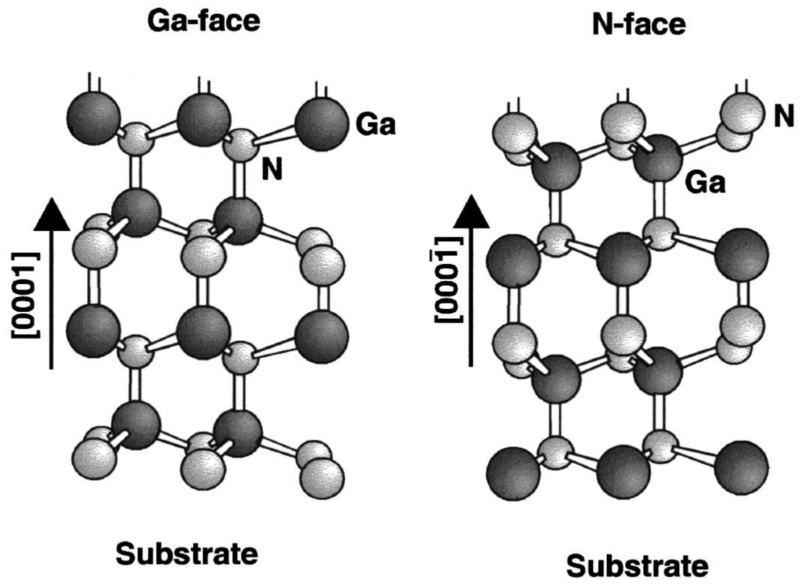


Direct bandgap

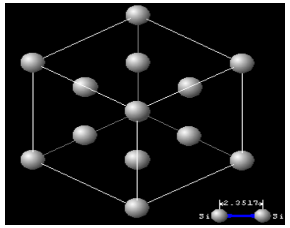
Two lattice constants

a = 3.189 Å

c = 5.186 Å



View in <111> direction



Can be grown on (111) Si (hexagonal)

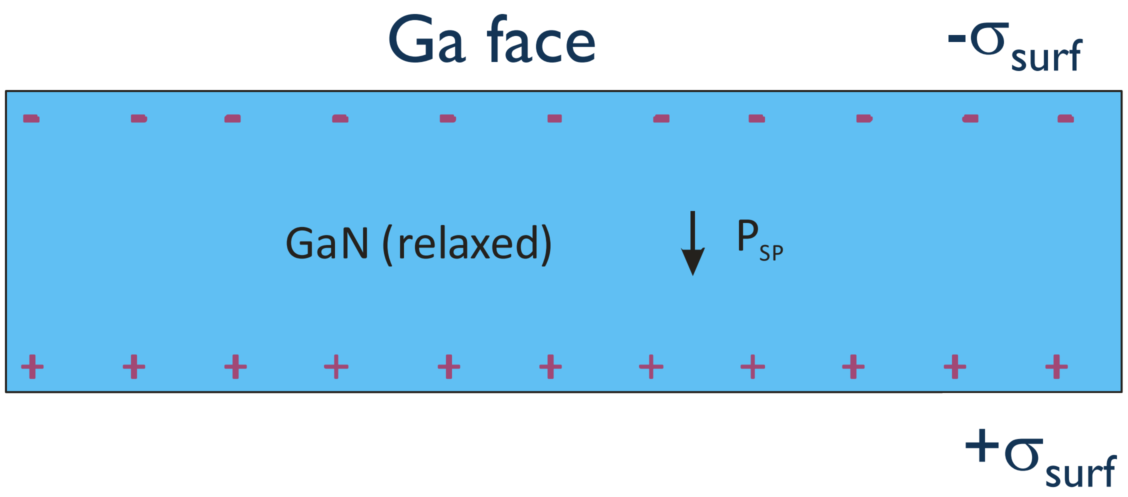
Spontaneous polarization

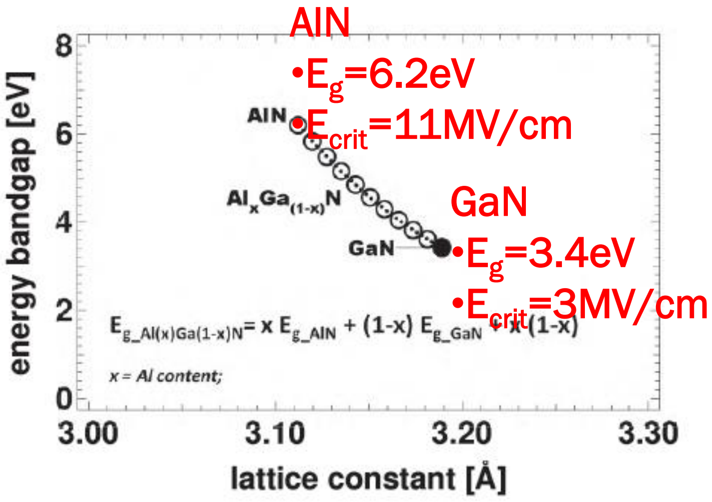
<u>Spontaneous Polarization</u> due to electro-negativity difference between N-atoms and Ga-atoms (binary crystal).

- Pauling's electronegativity : N=3.4, Ga=1.8, Al=1.6

Poisson's equation yields σ_{surf}

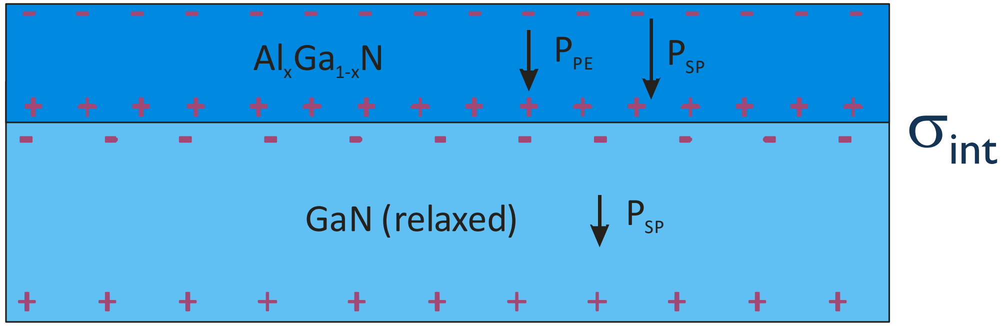
Results in a polarization field P

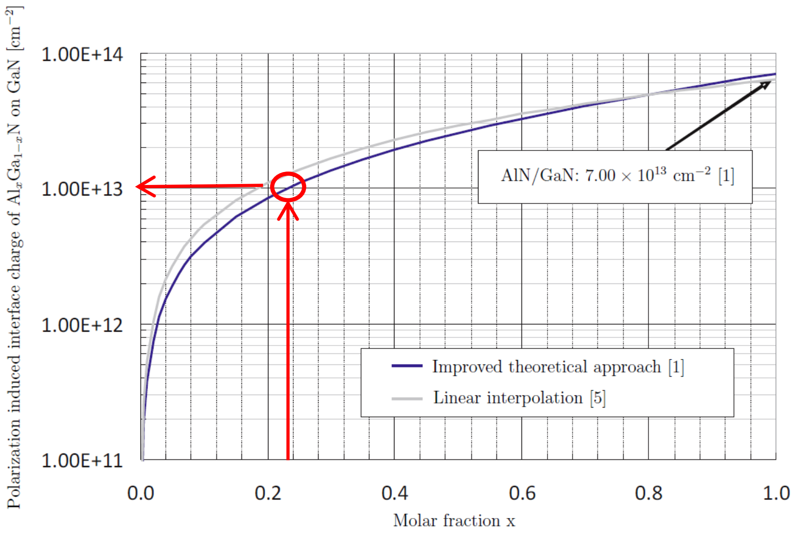




Spontaneous and piezo-electric polarization

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

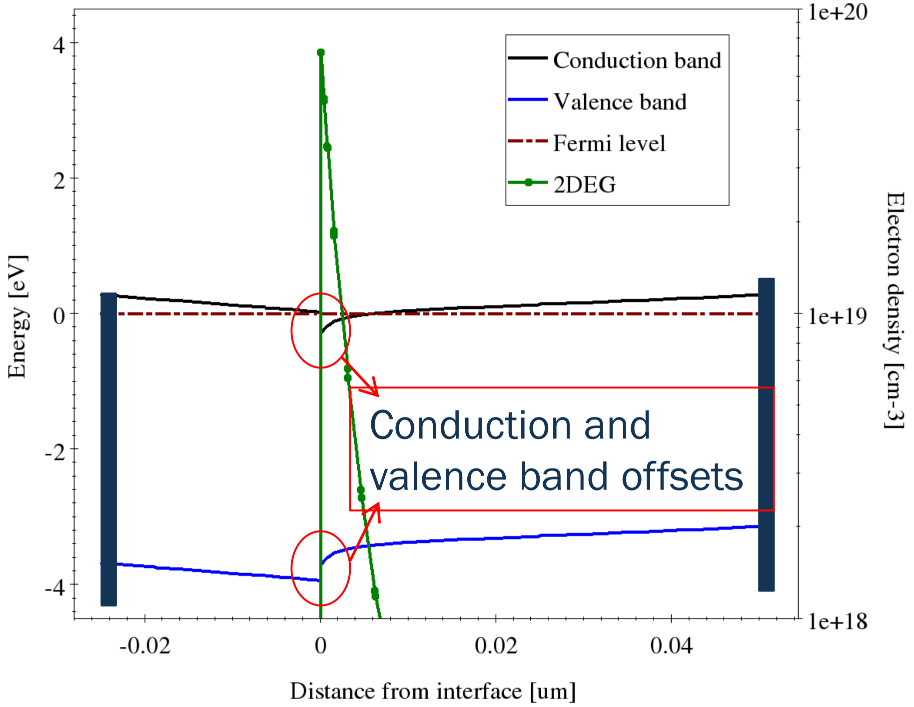


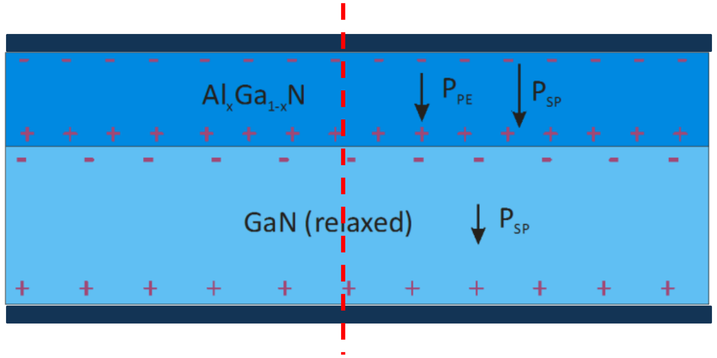


- Thin AlGaN layer strained → piezo-electric pol.
- Induced net positive charge at the AlGaN/GaN interface (but inside the AlGaN !) is very large !
  - HEMT $n_s \sim 10^{13}$ cm^{-2} ↔ Typical MOSFET $n_s \sim 10^{12}$ cm^{-2}

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 <u>2DEG</u>
- Leads to the creation of a quantum well at the AlGaN/GaN interface (but in the GaN layer !)





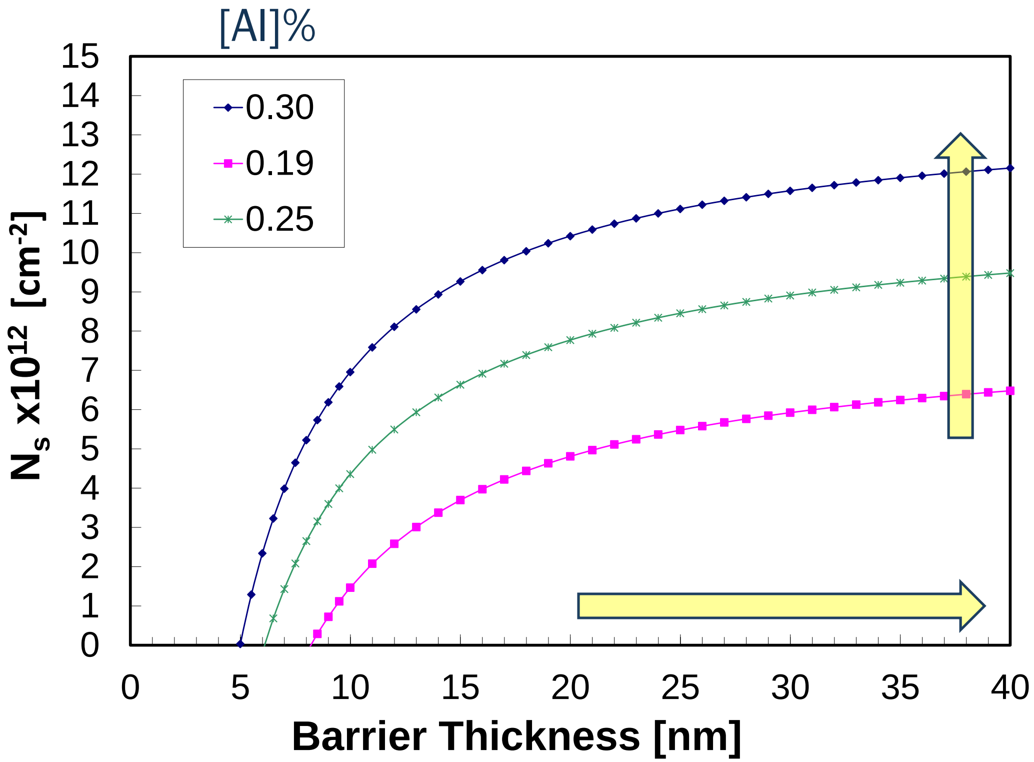
$$\sigma_{2DEG} = -\sigma_{int}$$

Device Engineering (AlGaN/GaN)

2DEG is a sheet of electrons

- Density n_s (set by barrier design)
- Mobility μ_N

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



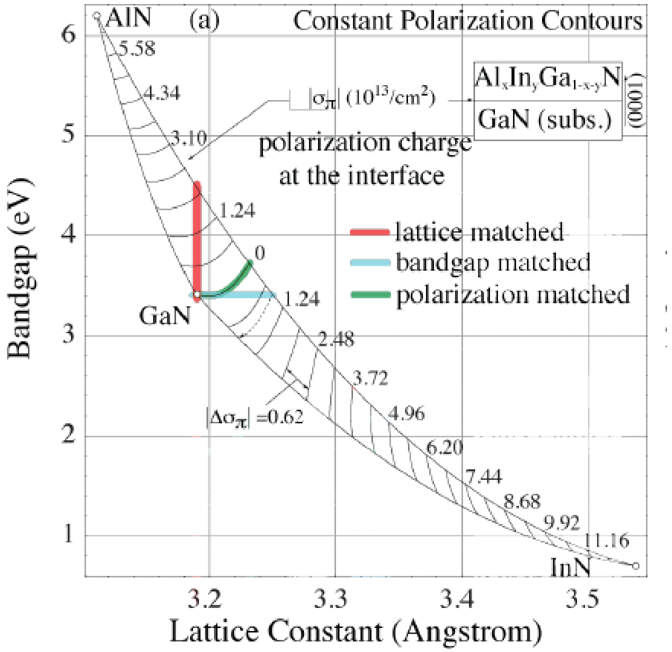
Limitations :

- If the (strained) AlGaN barrier is too thick, it will crack.
- The higher the [Al]%, the lower the critical thickness

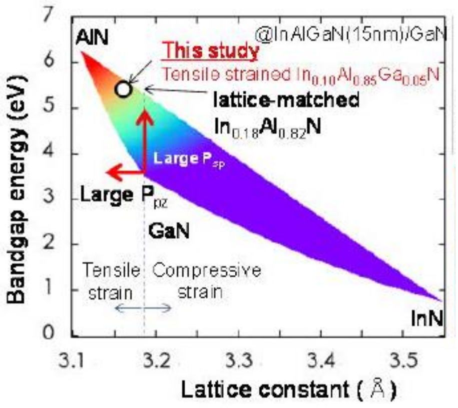
Polarization Engineering : Quarternary alloys

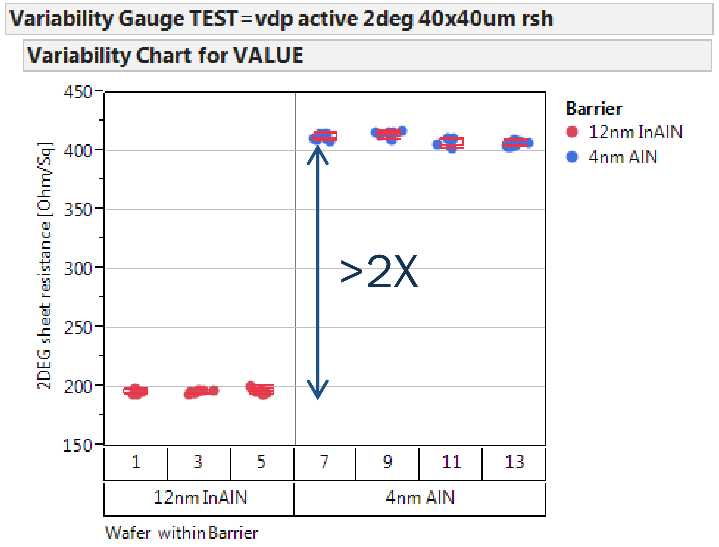
$Al_xIn_yGa_{1-x-y}N$ quarternary alloys coherently grown on GaN

- Lattice matched (reliability?), Polarization matching (E-mode)
- Higher sheet density (lower Ron) & larger bandgap



DJ Jena et al, 2010



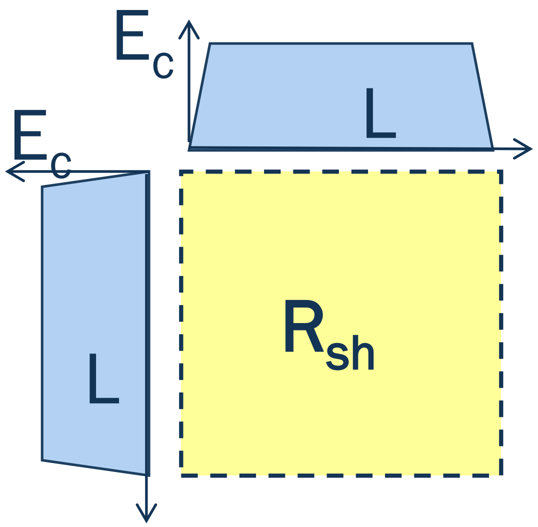


Polarization Engineering

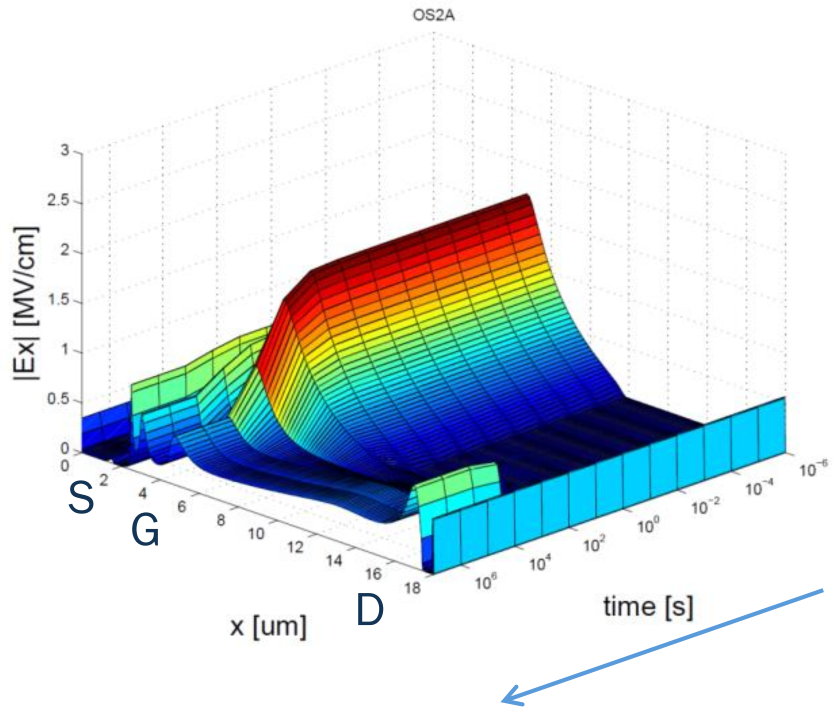
Reduces Ron by 2-3X

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

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



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



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

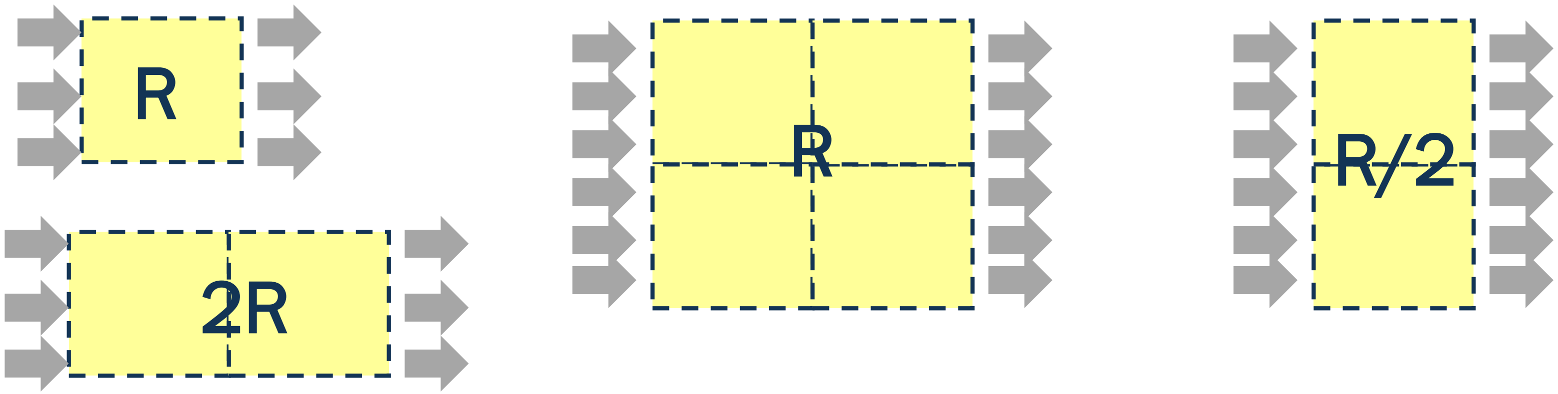
$$Ron = \frac{4}{q.n_s.\mu_N} . \frac{{V_{bd}}^2}{{E_c}^2}$$

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

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



Outline

- Power devices=material properties
  - 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"
  - HEMT versus vertical power device
- Ron and Capacitance versus Voltage
- Cost and performance

Summary : Ron versus Vbd for different device concepts

1D unipolar device :

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

2D unipolar Super Junction device :

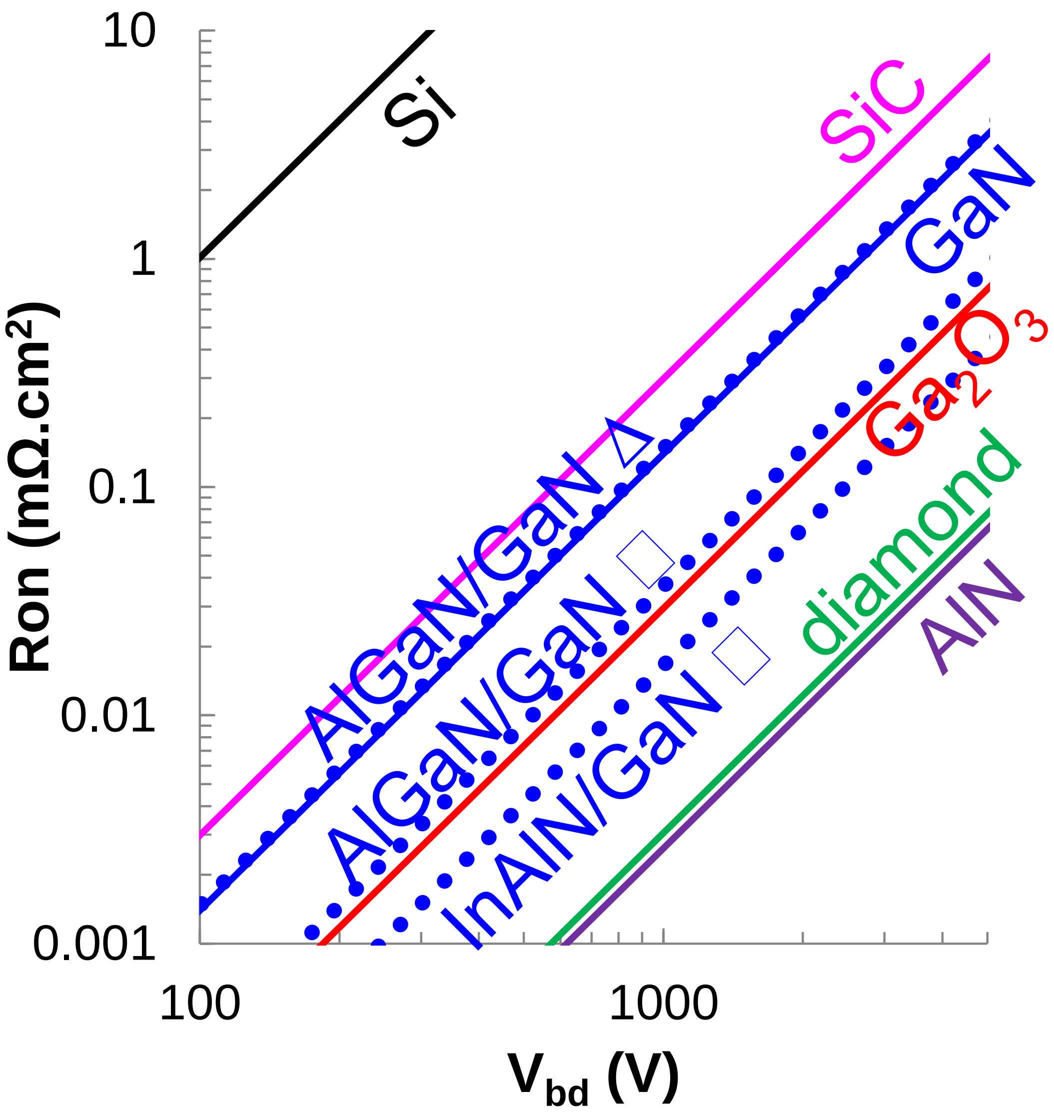
$$Ron = \frac{2.V_{bd}}{E_{C}^{2}.\varepsilon.\mu_N}$$

Lateral hetero-structure HEMT :

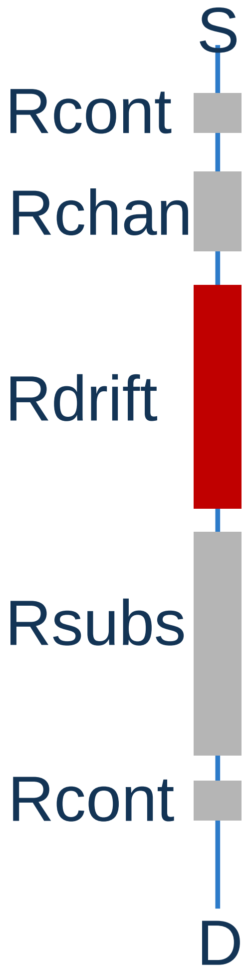
$$Ron = \frac{1}{q.n_s.\mu_N}.\frac{V_{bd}^{2}}{E_c^{2}}$$

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

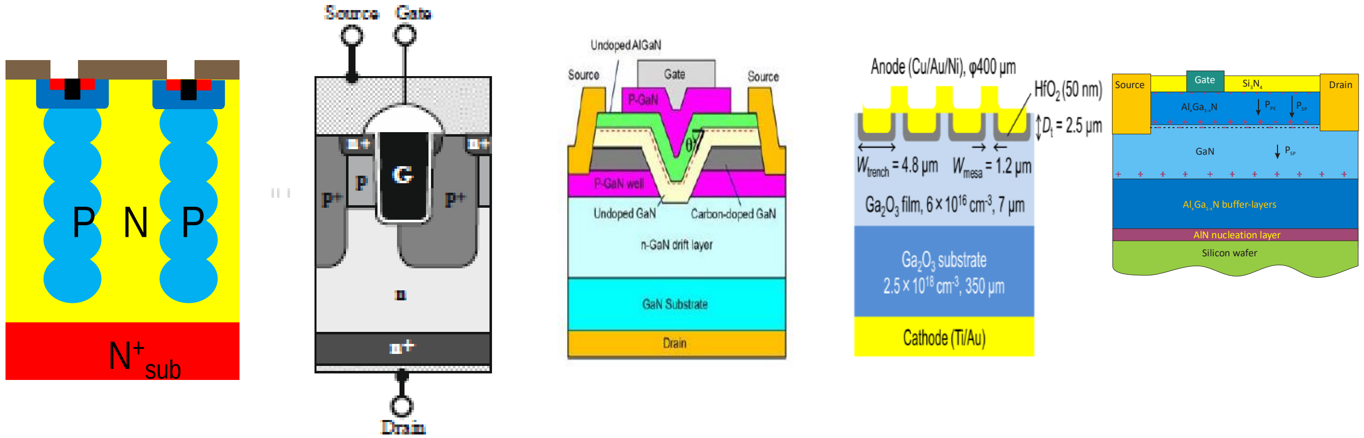
- AlGaN/GaN HEMT with rectangular field will go beyond the 1D GaN limit.
- By introducing polarization engineering (InAlN), even the Ga_2O_3 1D limit is broken.



The Baliga FOM revisited



	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	$Ron = \frac{2.V_{bd}}{E_C{}^2.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}{}^2}{E_C{}^3.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}{}^2}{E_C{}^3.\varepsilon.\mu_N}$	$Ron = \frac{4.V_{bd}{}^2}{E_C{}^3.\varepsilon.\mu_N}$	$Ron = \frac{1}{q.n_s.\mu_N} \cdot \frac{V_{bd}{}^2}{E_c{}^2}$
Rchan	low	high	Medium	?	Very low



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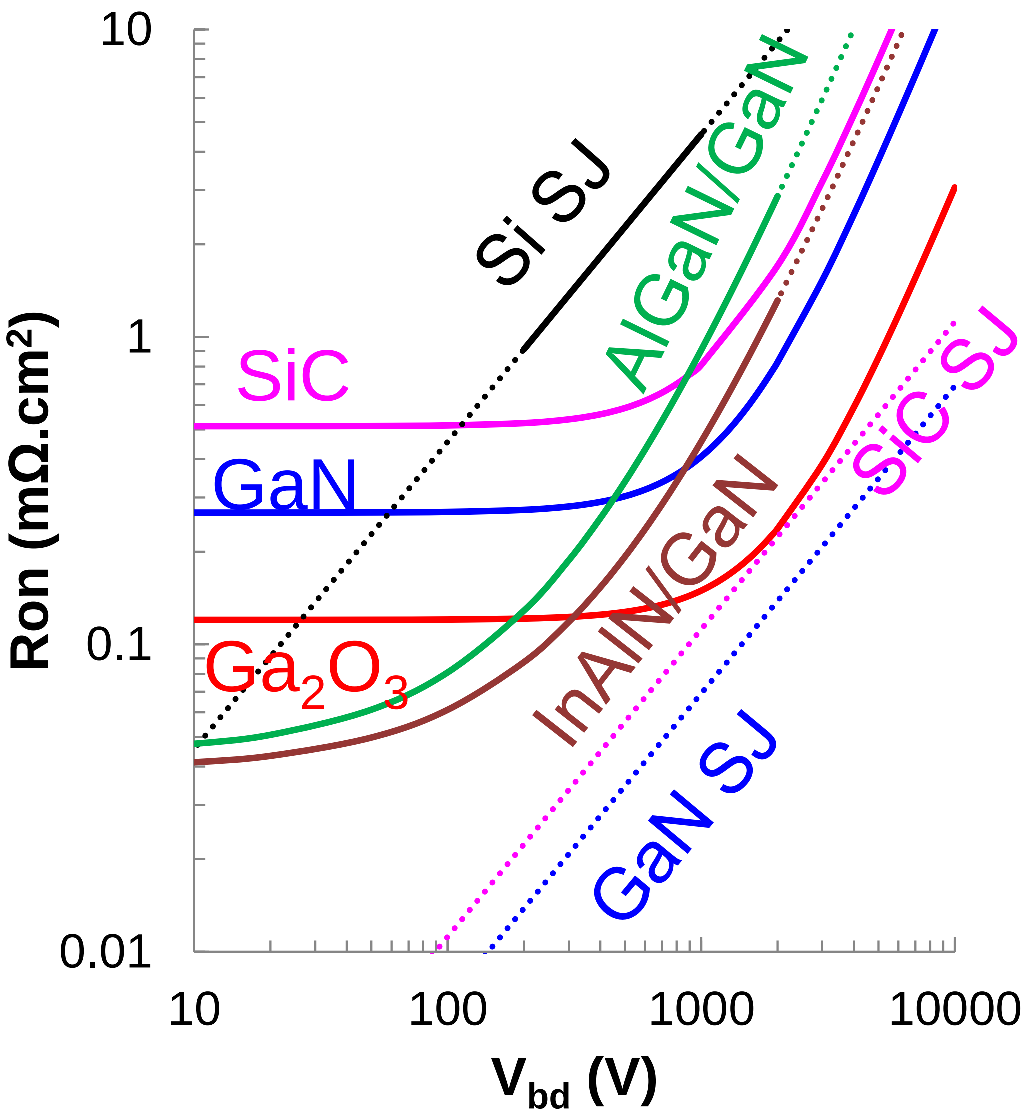


Si SJ

- p=6µm

HEMTs

- E_c=2MV/cm (triang field)
- E-mode (R_{ch}=2XR_{access})

SiC

- TrenchMOS
- Subs=100µm, 20mΩ.cm
- p=5µm, μ_{ch}=100cm^2/V.s

GaN

- V-MOS
- Subs=100µm, 10mΩ.cm
- p=10µm, μ_{ch}=1500cm^2/V.s

Ga_2O_3

- Schottky diode
- Subs=200µm, 6mΩ.cm
- μ_{bulk}=300cm^2/V.s

Capacitances : jct transistor vs HEMT

1D-Jct transistor, C_{depl} is dependent on voltage

$$C_{depl} = \frac{\epsilon}{W_D} ; W_D = \sqrt{\frac{2.\epsilon.(V_{applied}+V_{bi})}{q.N_D}}$$

$$N_D = \sqrt{\frac{\epsilon.{E_C}^2}{2.q.V_{BD}}}$$

$$Q_{OSS}\Big|_V = \sqrt{2.\epsilon.q.N_D}.V^{1/2}$$

$$E_{OSS}\Big|_V = \frac{1}{3}\sqrt{2.\epsilon.q.N_D}.V^{3/2}$$

$$Q_{OSS} = \epsilon.E_C$$

$$E_{OSS} = \frac{1}{3}\epsilon.E_C.V$$

Super-junction device

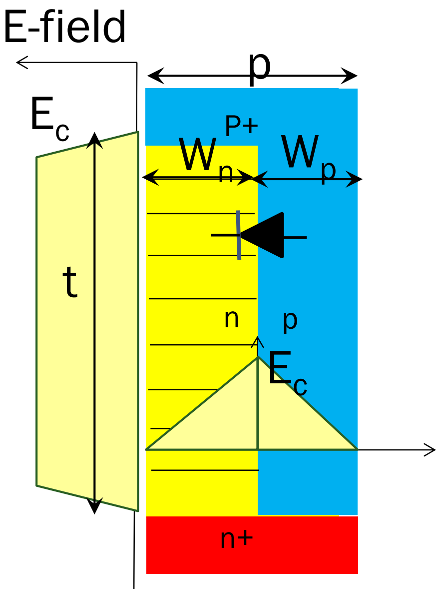
Depletion of Q_{opt} (Q_{opt}=313nC/cm^2)

Large junction area, will deplete at ~25V

Once depleted, capacitance is very low

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

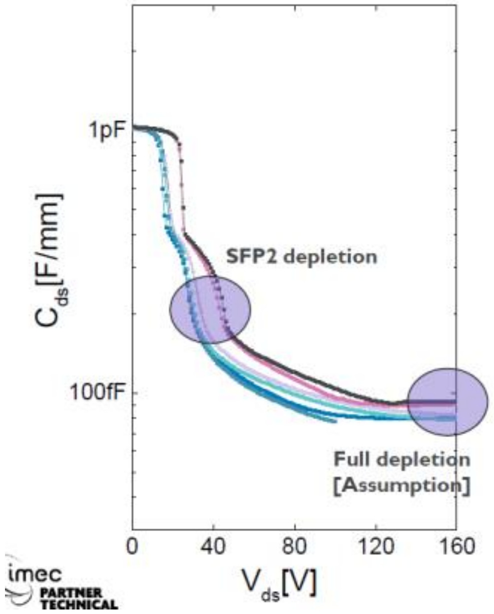
$$Q_{OSS}\Big|_V = 313.hp.\frac{V}{E_C}$$

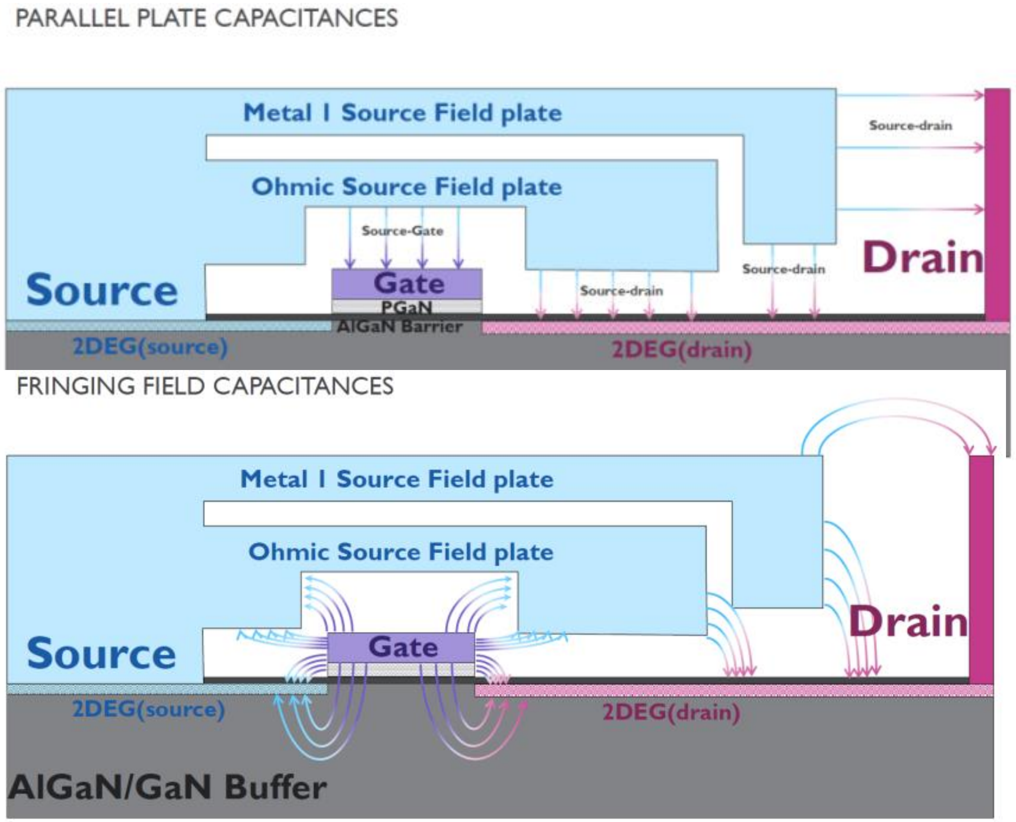


Capacitances : jct transistor vs HEMT

<u>HEMT</u> : capacitance is a sum of dielectric capacitances, each independent of voltage

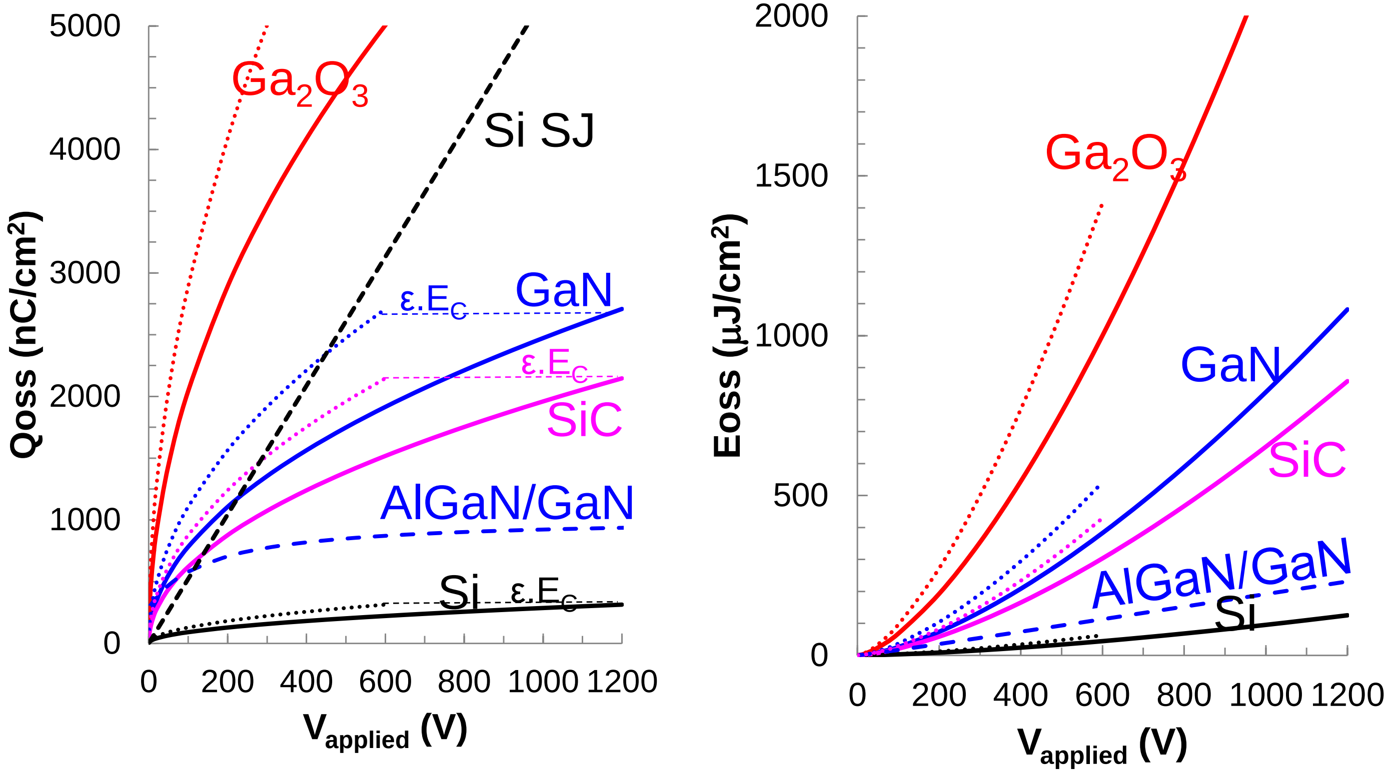
- Field plate capacitors that deplete the 2DEG
- Substrate capacitance
- Fringe capacitances





Capacitances

- Q_{oss} and E_{oss} are ~ to ε.E_c [in cm^{-2}, per unit area]
  - 1S--Si is better than GaN and SiC and Ga_2O_3
  - AlGaN/GaN HEMT behaves differently
  - Si SJ has high Q_{oss} due to large effective junction area



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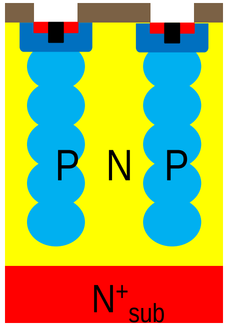
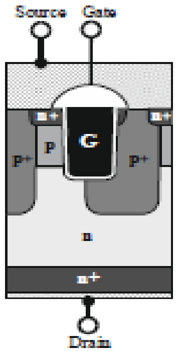
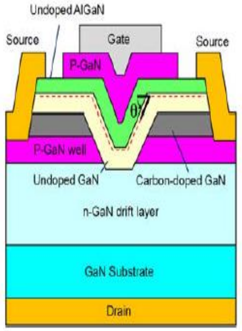
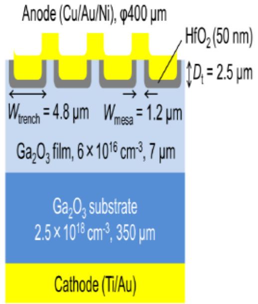
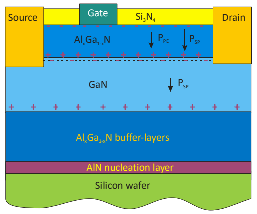
Rchannel	low	high	Medium	?	Very low
Capacitance	low	medium	medium	high	low
Wafer (mm)	200-300	100-150	75-100	50-100	150-200
Cost/wfr ($)	lowest	high	Very high	medium	low
Robustness	High	High	Some	?	None

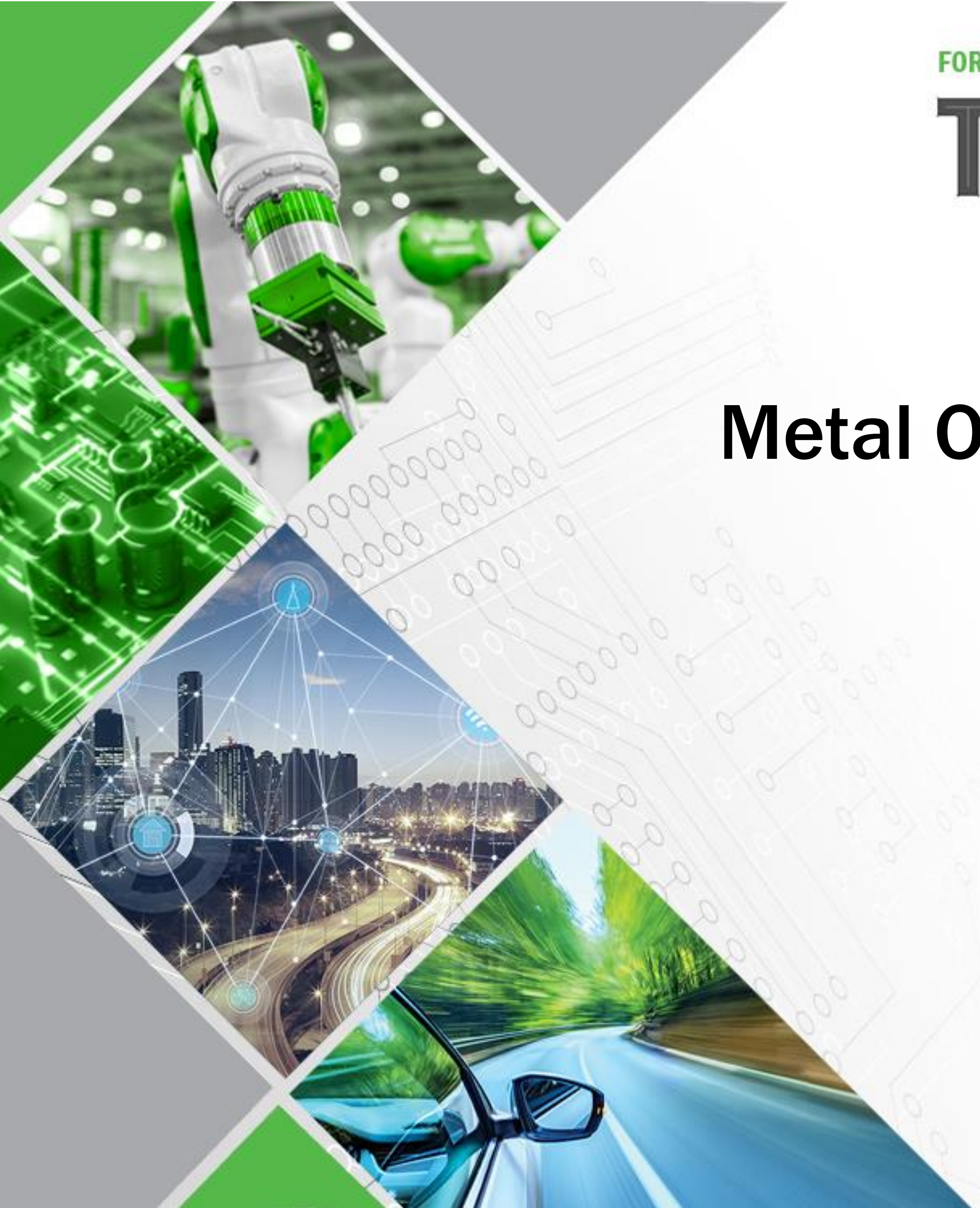








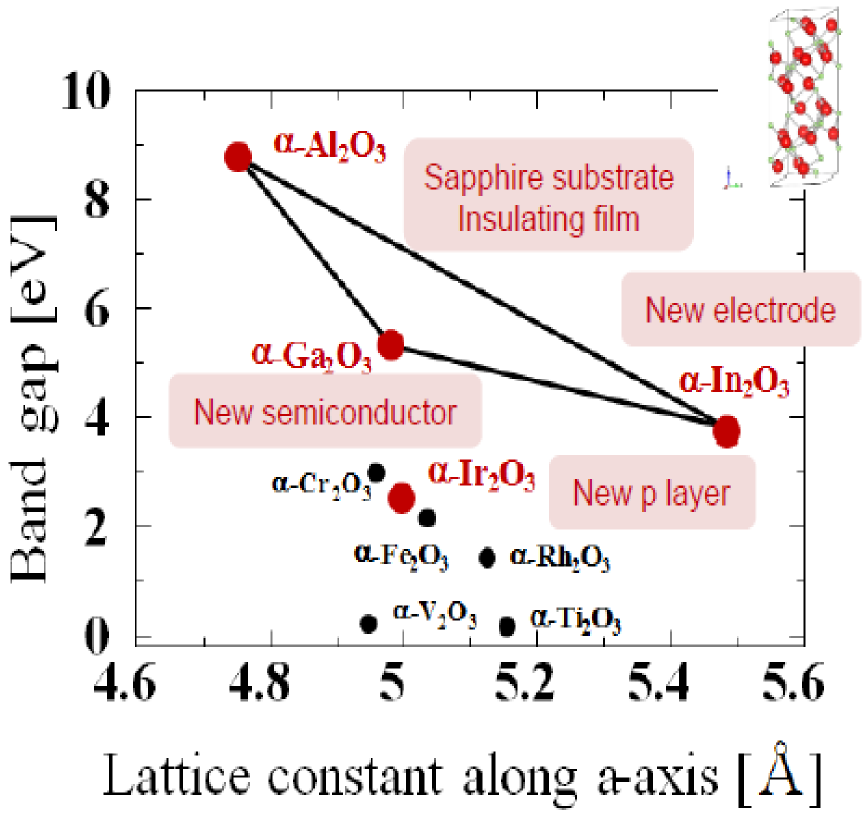


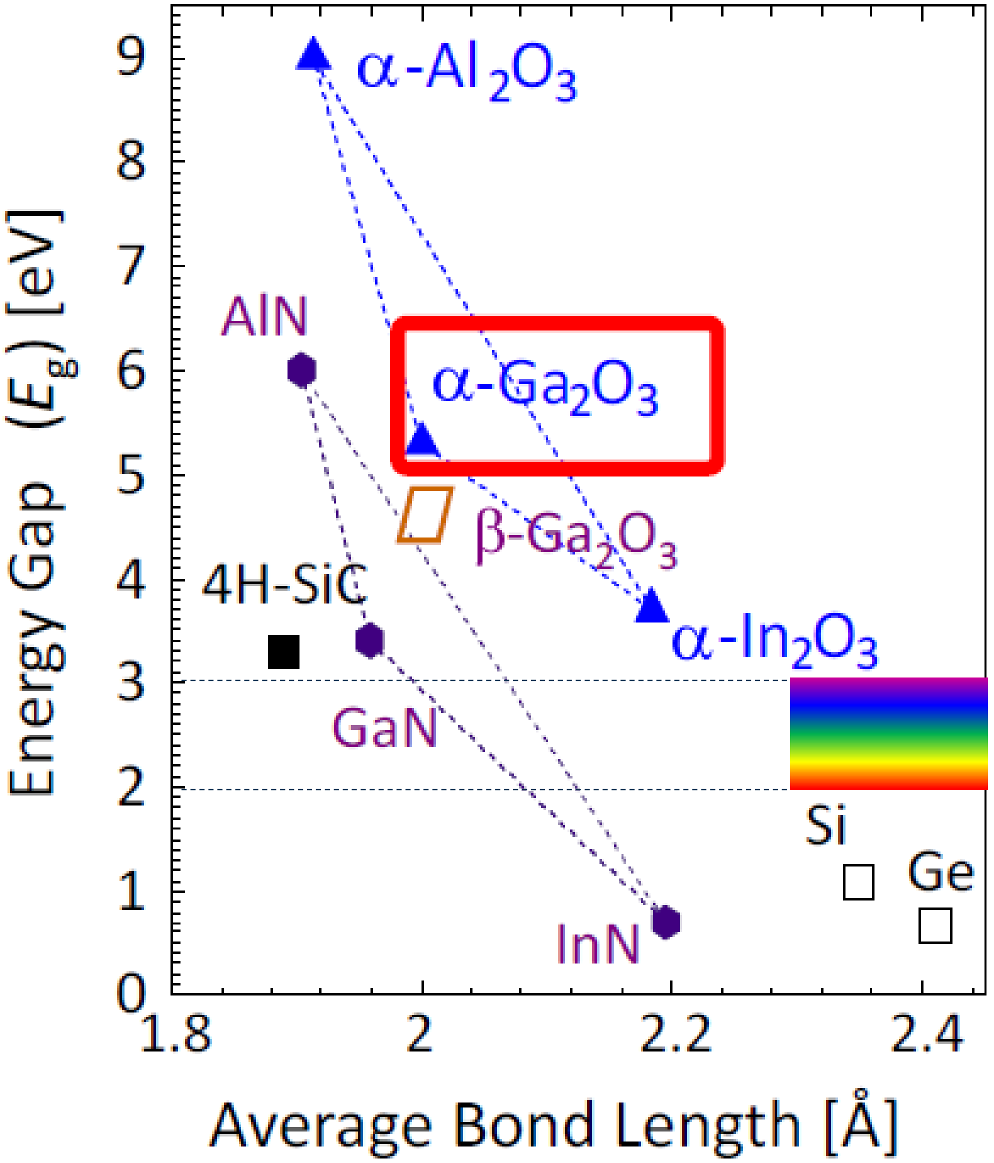


Metal Oxides : The Case of Ga_2O_3

α-Ga/Al/In/$_2O_3$ (III-VI)

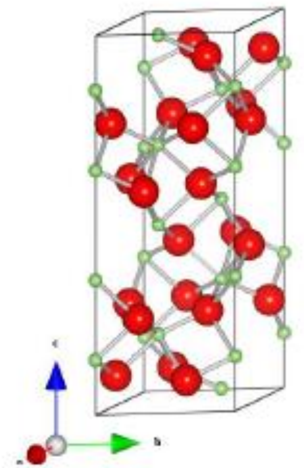
- α-Ga_2O_3, α-Al_2O_3 and α-In_2O_3 have same crystal structure
  - Alloys & Hetero-structures
  - P-type !





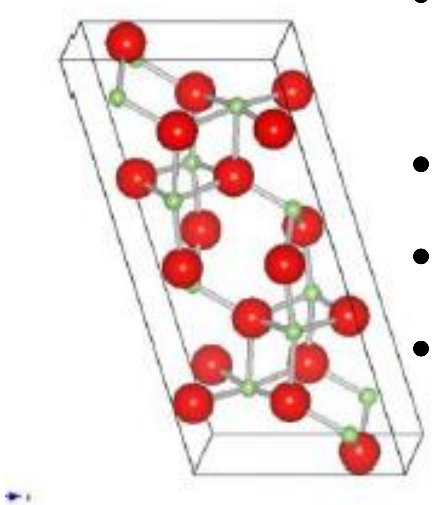
Ga_2O_3 has many poly-types

α-Ga_2O_3



- Rhombohedral ; stable till ~800ºC
- Eg=5.6eV
- Ec=10MV/cm
- Alloys / heterostructures with Al/Ir/Rh/In_2O_3
- N-type doping by Sn, Si, ...
- P-type ! Ir/Rh/$_2O_3$
- Grown on Sapphire + liftoff

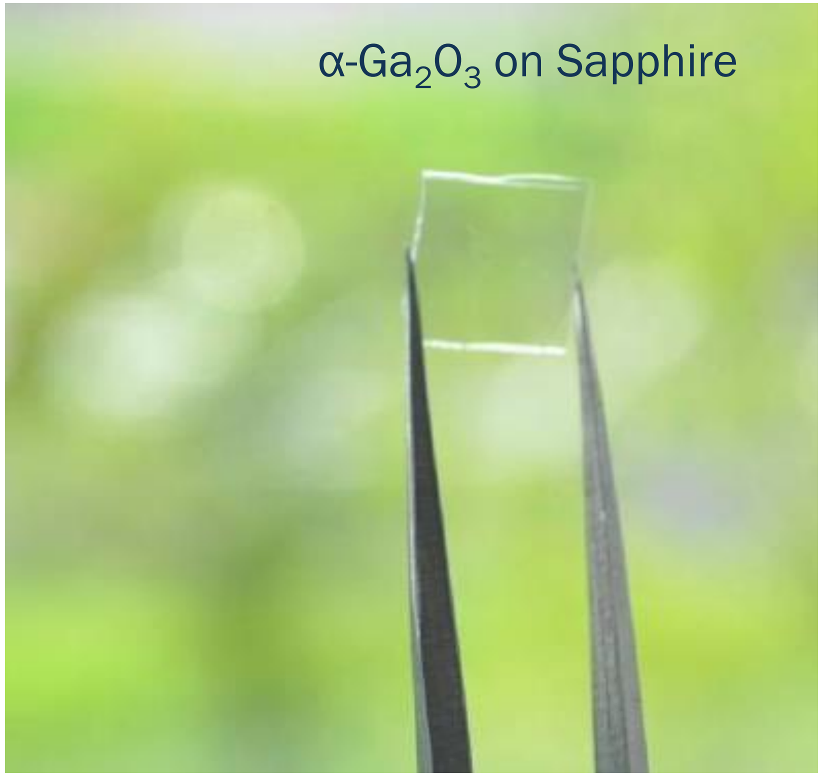
β-Ga_2O_3

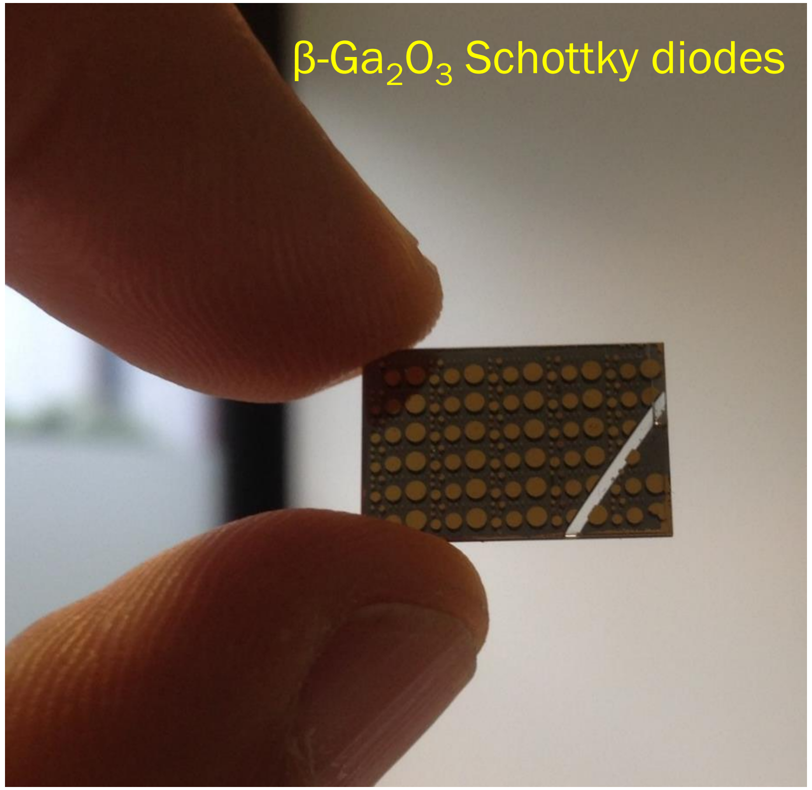


- Monoclinic, stable till melting point (~1700ºC)
- Eg=4.8eV
- Ec=8MV/cm
- No alloys or heterostructures
- N-type doping by Sn, Si, ..
- No P-type ! (Mg, deep acc)
- Grown from the melt (CZ)

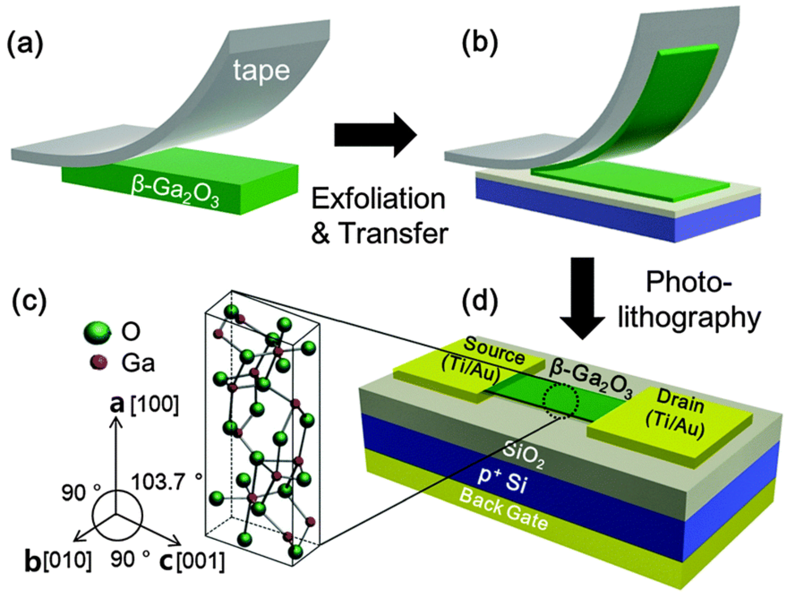
How Cool is That !

- Metal Oxides are transparent to the visible light
- They have a direct bandgap→opto-electronic devices
- Exfoliation of 20μm films→flexible electronics



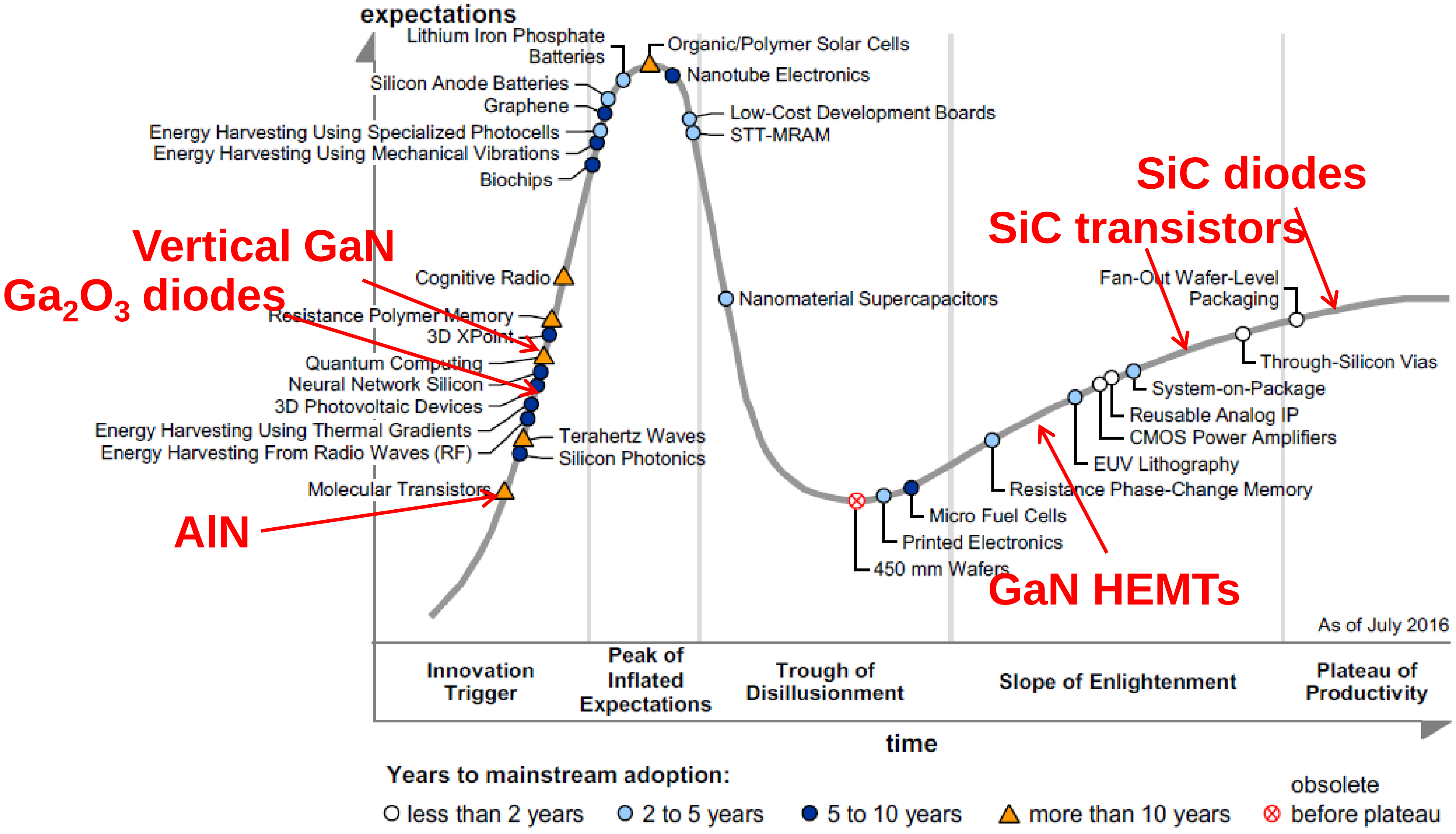


Exfoliation



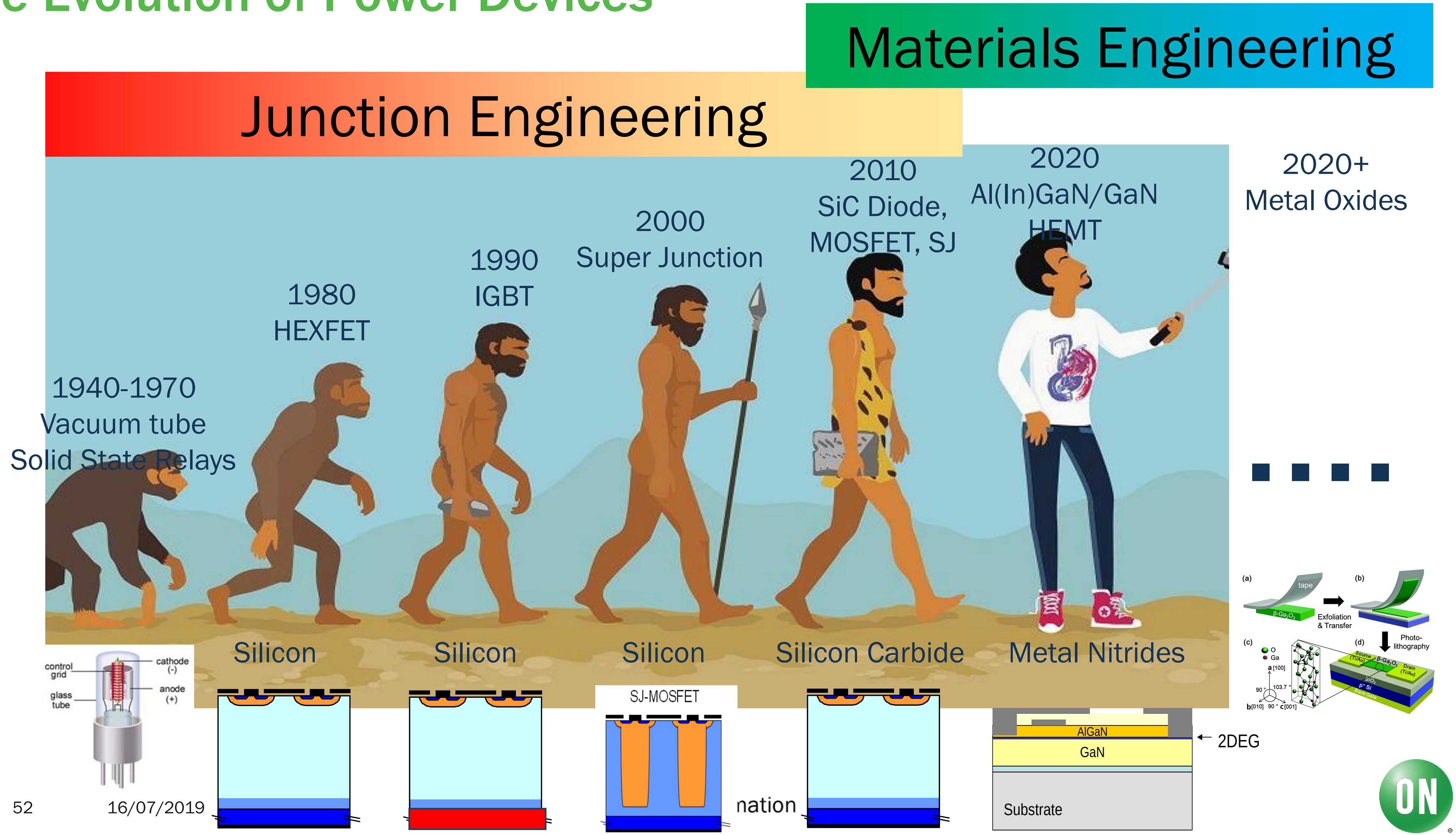
The Hype Cycle for Electronic Technologies

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



Source: Gartner (July 2016)

The Evolution of Power Devices



FOR ENERGY EFFICIENT INNOVATIONS

THINK ON.

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Semiconductor Power Devices : Part 2 : Reliability Basics

Peter Moens

Outline

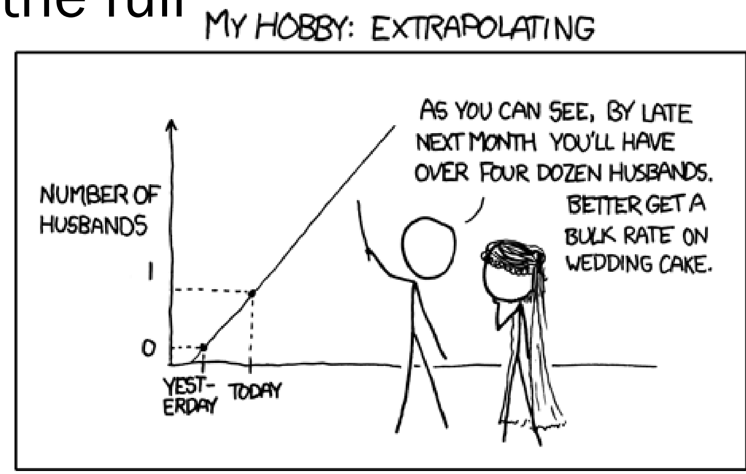
- Reliability Basics
  - What is Reliability ?
  - Reliability Distribution Functions & Failure rates
    - Lognormal and Weibull Statistics
  - Acceleration testing and Lifetime Prediction


reliability
business
quality
support
satisfaction
confidence
success
reliable
trust
improve
building
connection
achievement
dependable
management
communications
togetherness
community
marketing
reputation
protection
commitment
occupation
cooperation
relationship
strategy
service
progress
corporate
care
partnership
effect
job
competence
professional
teamwork
education
assurance
trustworthy
businessman
client
unity
efficiency
together
warranty
human
agreement
communication
consumerism
customer
loyalty
people
power
advice
technology
assistance
safety
company
performance
security
responsibility
finance
global
promise
excellence

Reliability : What ?

re·li·a·bil·i·ty rəˌlīəˈbilədē/ the quality of being trustworthy or of performing consistently well

- Reliability = predict and guarantee a certain function over the full lifetime of the product
  - What is the desired “performance” ?
  - What is the desired “lifetime” ?
  - How to predict ?
- Reliability = Quality over time
- Reliability = physics, mathematics, statistics, economics and psychology
- Reliability = engineering in its most practical form



No reliability

=

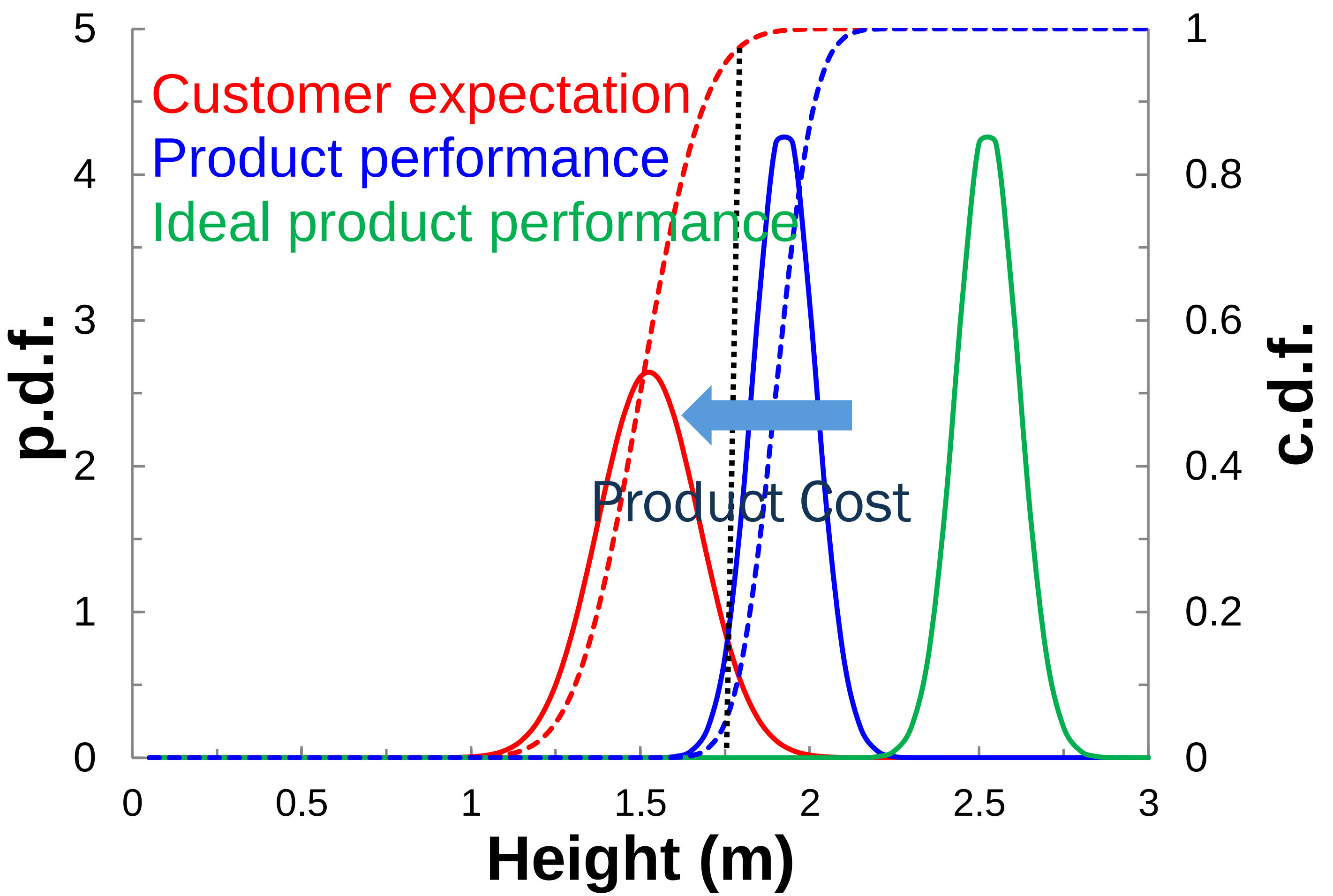
No Product

=

No Money

Product Reliability : the economical approach

- Example : product return due to dropping of a smartphone from a certain height.



Electronic Product Reliability Grades

- Consumer
- Industrial
- Automotive/Medical
- Military
- Space

Stress Test	Market: Commercial/ Consumer (g, h) ~2-3 year life	Market: Industrial (g) > 3 year life	Market: Automotive/ Medical (b,c,f)	Market: Military (d, e)
HTOL[a] IC	77 Units/Lot 504 Hours Tj=125°C	77 Units/Lot 1008 Hours Tj=125°C	77 Units/Lot Grade 1: 1000 Hr @ Ta=125°C, See Q100 for other grades	45 Units/Lot 1000 Hr @ Ta=125°C or 184 Hr @ Ta=150°C
HTRB Discrete	77 Units/Lot 504 Hours Tj=150°C or specified TJ(max)	77 Units/Lot 1008 Hours Tj=150°C or specified TJ(max)	77 Units/Lot 1008 Hours Tj=150°C or specified TJ(max)	NA to Discrete Military.
HTGB[a] Discrete	77 Units/Lot 504 Hours Tj=150°C or specified TJ(max)	77 Units/Lot 1008 Hours Tj=150°C or specified TJ(max)	77 Units/Lot 1008 Hours Tj=150°C or specified TJ(max)	NA to Discrete Military.
HTBB[a] VHVIC only	77 Units/Lot 504 Hours Tj=125°C	77 Units/Lot 1008 Hours Tj=125°C	77 Units/Lot 1008 Hours Tj=125°C	NR
HVTHB[a] VHVIC only	77 Units/Lot 168 Hours Tj=85°C/60%RH	77 Units/Lot 168 Hours Tj=85°C/60%RH	77 Units/Lot 168 Hours Tj=85°C/60%RH	NR
ELFR IC	NR	800 Units/Lot 48 Hours @ Tj=125C 24 hrs @ Tj=150C (Optional, FIO)	800 Units/Lot Grade 1: 48 Hours @ Ta=125C or 24 hrs @ Ta=150C. See AEC Q100-008 for other grades	NA
ELFR Discrete(not mandatory, not gating)	NR	NR	800 Units/Lot 48 Hours @ Tj=150C or specified TJ(max)	NA
HTSL[a] IC	25 Units/Lot 504 Hours $Ta=T_{storage\ max}$	25 Units/Lot 1008 Hours $Ta=T_{storage\ max}$	77 Units/Lot Grade 1: +150°C Ta for 1000 hours or +175°C Ta for 500 hours, see AEC Q100 for other grades	45 Units/Lot 1008 hrs $Ta=T_{storage\ max}$
HTSL[a] Discrete	25 Units/Lot 504 Hours $Ta=T_{storage\ max}$	25 Units/Lot 1008 Hours $Ta=T_{storage\ max}$	77 Units/Lot 1008 Hours $Ta=T_{storage\ max}$	45 Units/Lot 1008 hrs $Ta=T_{storage\ max}$
NVM Data Retention IC as required by technology	25 Units/Lot 504 Hours $Ta=T_{storage\ max}$	25 Units/Lot 1008 Hours $Ta=T_{storage\ max}$	77 Units/Lot Grade 1: +150°C Ta for 1000 hours or +175°C Ta for 500 hours, see AEC Q100 for other grades	45 Units/Lot 1008 hrs $Ta=T_{storage\ max}$
PC surface mount only	SECTION 4	SECTION 4	SECTION 4	SECTION 4
TC[a] IC	25 Units/Lot 500 cyc -55 to 150 °C	25 Units/Lot 500 cycles -65 to 150 °C	77 Units/Lot Grade 1: 1000 cyc -55 to 150 °C or equiv, see AEC Q100 for other grades	45 Units/Lot 1000x @ -65 to 150 °C
TC[a] Discrete	25 Units/Lot 500 cyc -55 to 150 °C	25 Units/Lot 1000 cycles -55 to 150 °C	77 Units/Lot 1000 cycles -55 to 150 °C	NA to Discrete Military.
IOL Discrete	25 Units/Lot Per per Table 6 Mid Read Point	25 Units/Lot Per Table 6 Final Read Point	77 Units/Lot Per Per Table 6 Final Read Point	NA to Discrete Military.
AC or UHAST[a]	25 Units/Lot 48hrs	25 Units/Lot 96 hrs	77 Units/Lot 96 hrs	45 Units/Lot 96 hrs
HAST[a]	25 Units/Lot 48hrs	25 Units/Lot 96 hrs/Cu wire 192 hrs	77 Units/Lot 96 hrs	45 Units/Lot 96 hrs
THB in lieu of HAST[a] IC	25 Units/Lot 504 hrs	25 Units/Lot 1008 hrs/Cu Wire 2016 hrs	77 Units/Lot 1008 hrs	45 Units/Lot 1008 hrs
H^3TRB in lieu of HAST[a] Discrete	25 Units/Lot 504 hrs	25 Units/Lot 1008 Hours/Cu wire 2016 hrs	77 Units/Lot 1008 Hours	na

Sample sizes may be adjusted by the rel engineer based on historical knowledge or product need.

Sample size ? How many parts to test ?

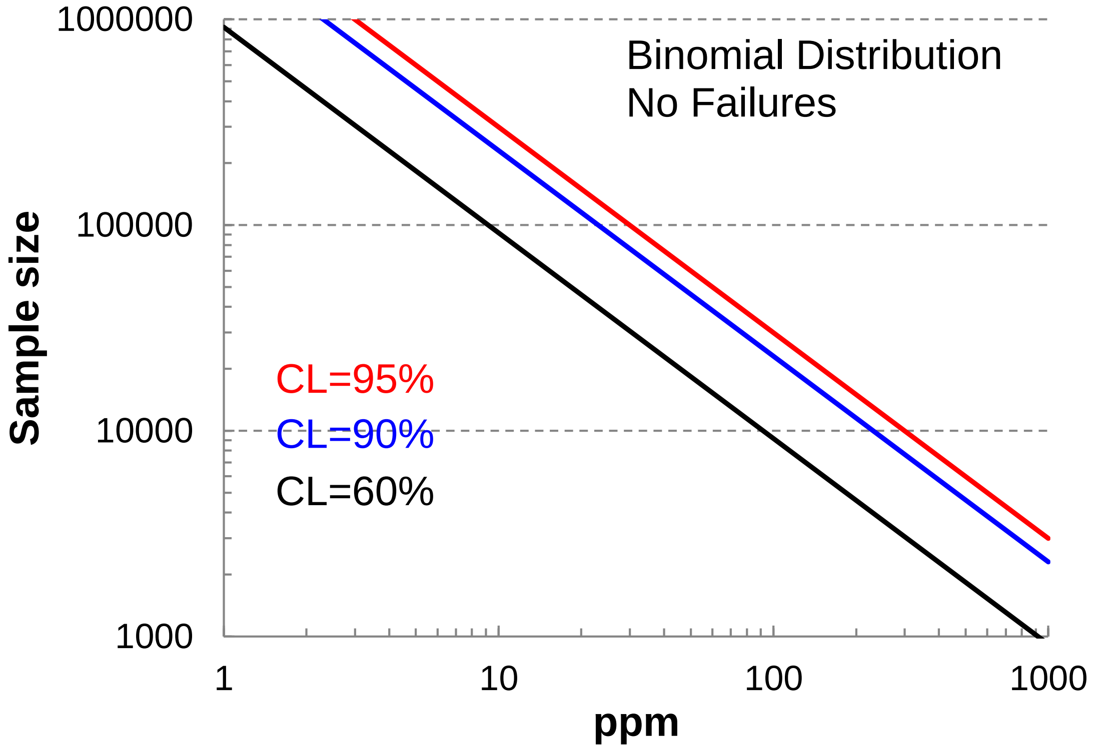
- Samples shipped to the customer should obey the Poisson distribution function
  - Probability that an event (failure) occurs in a fixed interval of time, is constant, and independent of the time since the last event
  - For large sample size, the Poisson distribution is a good approximation of the Binomial distribution (“Poisson limiting theorem”)
  - $P(x) = \frac{n!}{x! * (n-x)!} p^x * (1-p)^n$

P(x) : probability of having x failures
n : sample size
p : probability of having a single fail
x : number of failures

Sample size from Binomial distribution

$$P(x) = \frac{n!}{x! * (n-x)!} p^x * (1-p)^n$$

E.g. : Failure rate of a product is 100ppm. How many samples should be tested at CL=90% to prove you have 0 fails during qual ?



P(x) : probability of having x failures : 0.1

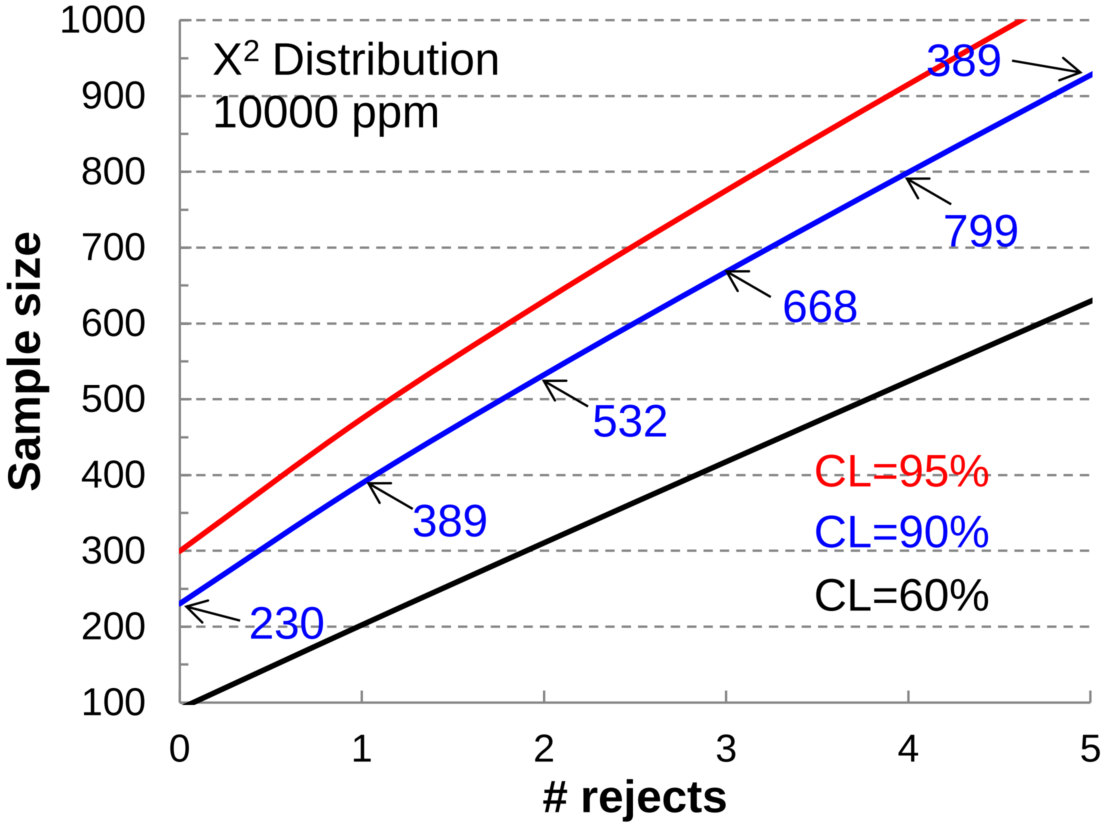
n : sample size : ?

p : probability of having a single fail : 1e-4

x : number of failures : 0

Sampling Statistics

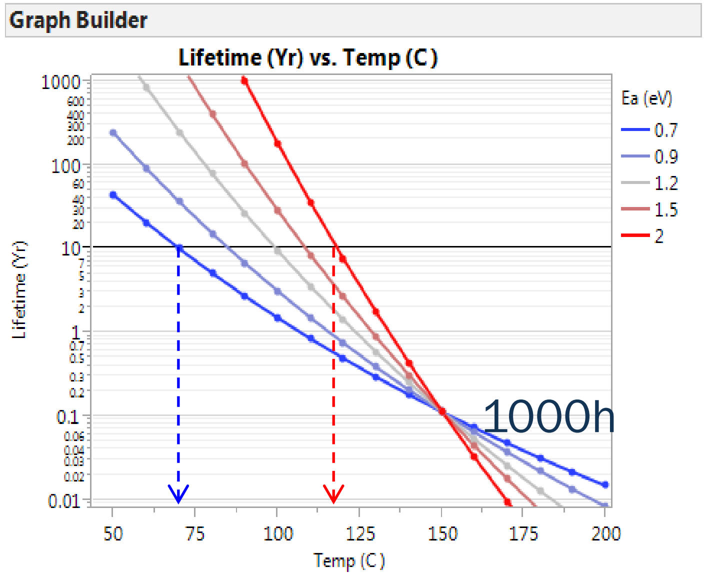
- Sampling statistics allow you to draw conclusion on an unknown distribution based on sampling
- χ^2 distribution is the most widely used
  - For Hypothesis testing, Confidence Intervals, ML etc,
  - Distribution of the sum of squares of normally distributed variables
  - $\chi 2$ test is part of t-test or F-test

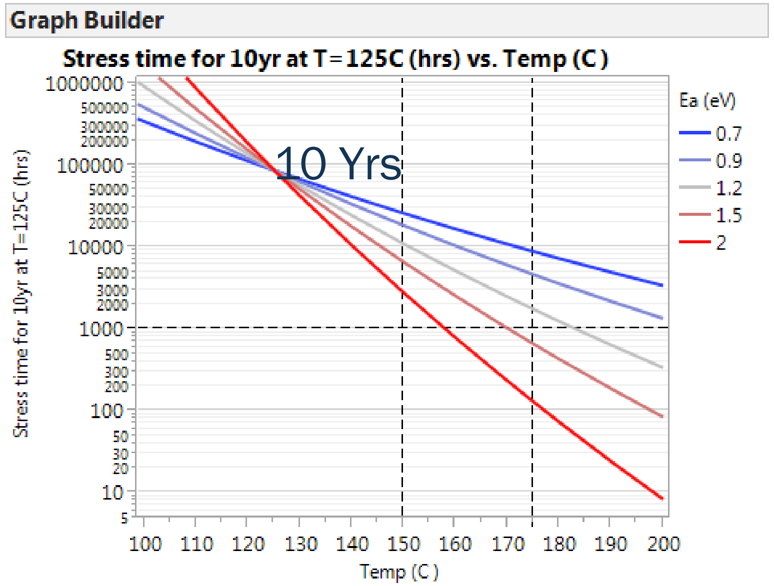


  - $N \geq ½.\chi 2\ (2c+2;1\text{-}CL).(1/ppm-0.5)$

Accelerated testing : JEDEC Testing—designed for Si !

- JESD47 : (for Si) use an apparent E_a=0.7eV
  - T_{use}=55ºC, T_{stress}=125ºC →1000h at T=125ºC equals 9 yrs at T=55ºC
  - T_{use}=70ºC, T_{stress}=150ºC →1000h at T=150ºC equals 10 yrs at T=70ºC
- E_a for GaN ? Little data available. E_a=2.1 eV ? [Whitman, MR 2014]
  - Larger E_a yields stronger impact of temperature on lifetime





FIT rates (Failure in time)

$$\text{FIT} = -\frac{\ln(1-F(t))}{t} \times 10^9$$

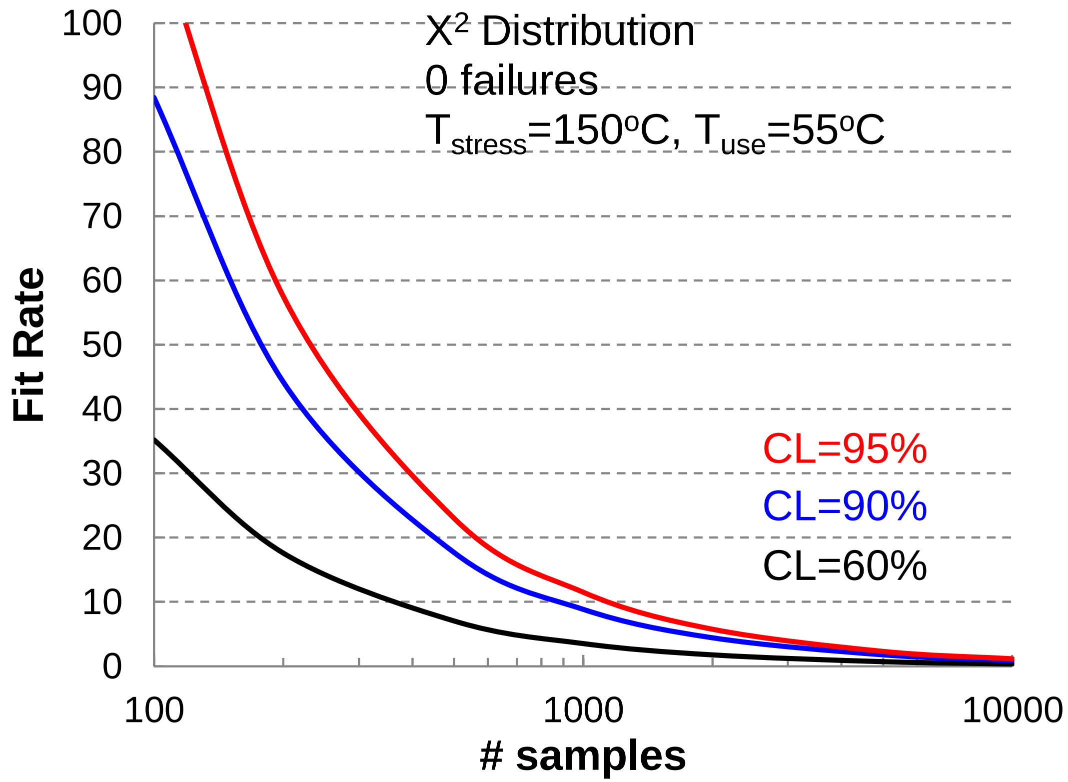
- 1FIT=1 failure per 10^9 device.hours
- Acceleration factors for temperature and field
  - Stress at highest Voltage : $AF_V=1$
  - Use Arhenius for AF_T with E_a=0.7 eV (Si), $T_{stress}=150^oC$
    - T_{use} = 55°C for consumer
    - T_{use} = 70°C for commercial
    - T_{use} = 85°C for industrial
  - Tstress=1008 hrs

$$\lambda = \frac{\chi^{2(X,\nu)}.10^9}{2*N*AF*tstress}$$

- λ = FIT rate
- X = 1-CL (confidence level)
- ν = 2r -2
- r = amount of rejects
- N = total sample size

(X, ν, r and N: To be looked up in chi-square table)

- $AF = AF_V * AF_T$
- $AF_V = e^{\gamma*(V_{stress}-V_{use})}$
- $AF_T = e^{\frac{E_a}{k}*(\frac{1}{T_{use}}-\frac{1}{T_{stress}})}$
- t_{stress} = total stress time



JEDEC Testing

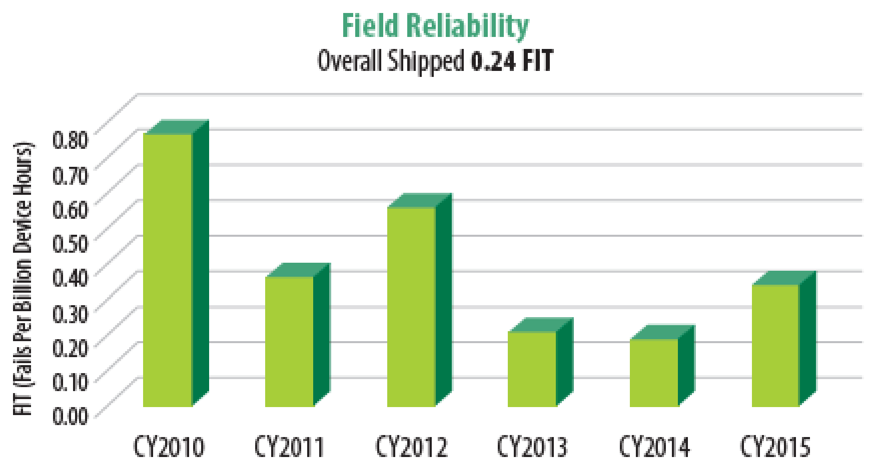
What comes to mind when you hear "JEDEC Qualification": a typical qualification table

Part Type	Test	Conditions	Duration	Parameter measurements @	Quantity
Part no "X"	TC	-55°C/150°C	1000 cy	0/168/500/1000	3 x 77
	H^3TRB	85°C/85%RH/100V	1000 hrs	0/168/500/1000	3 x 77
	HTRB	150°C/960V	1000 hrs	0/168/500/1000	3 x 77
	HTGB	150°C/20V	1000 hrs	0/168/500/1000	3 x 77
	IOL	delta Tj = 100°C	5,000 cy	0/2500/5000	3 x 77
	AC	121°C/15psig	96 hrs		

When you pass the JEDEC test, you have proven that (with :
For a binomial distribution (Poisson distribution)→Constan

- FIT rate<18 for CL=60% (χ^2 estimate)
- FIT rate<38 for CL=90% (χ^2 estimate)

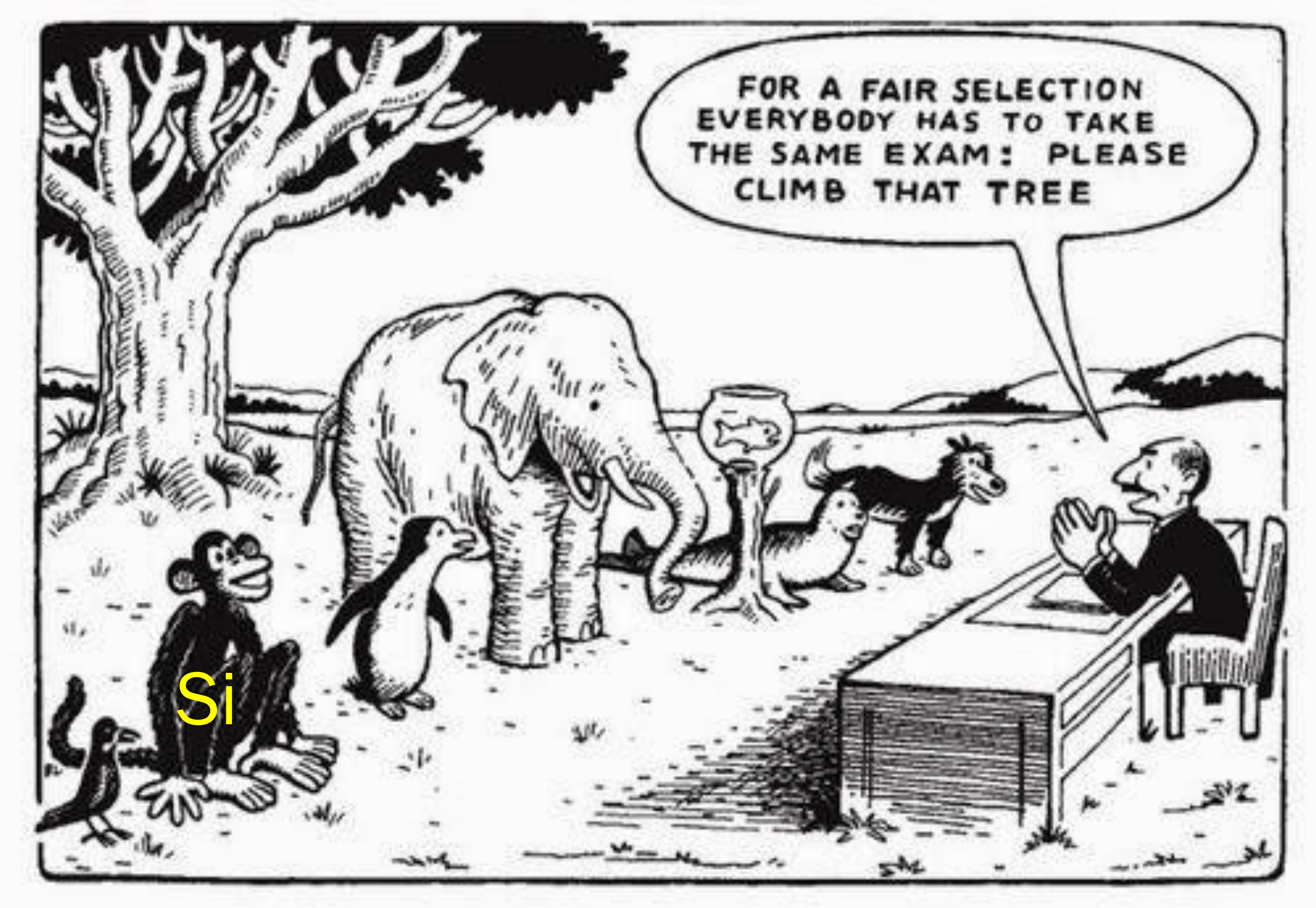
- For FIT<10, one would need to test >1000 samples for : failures.



Actual FIT rates, EPC Reliability Report #7

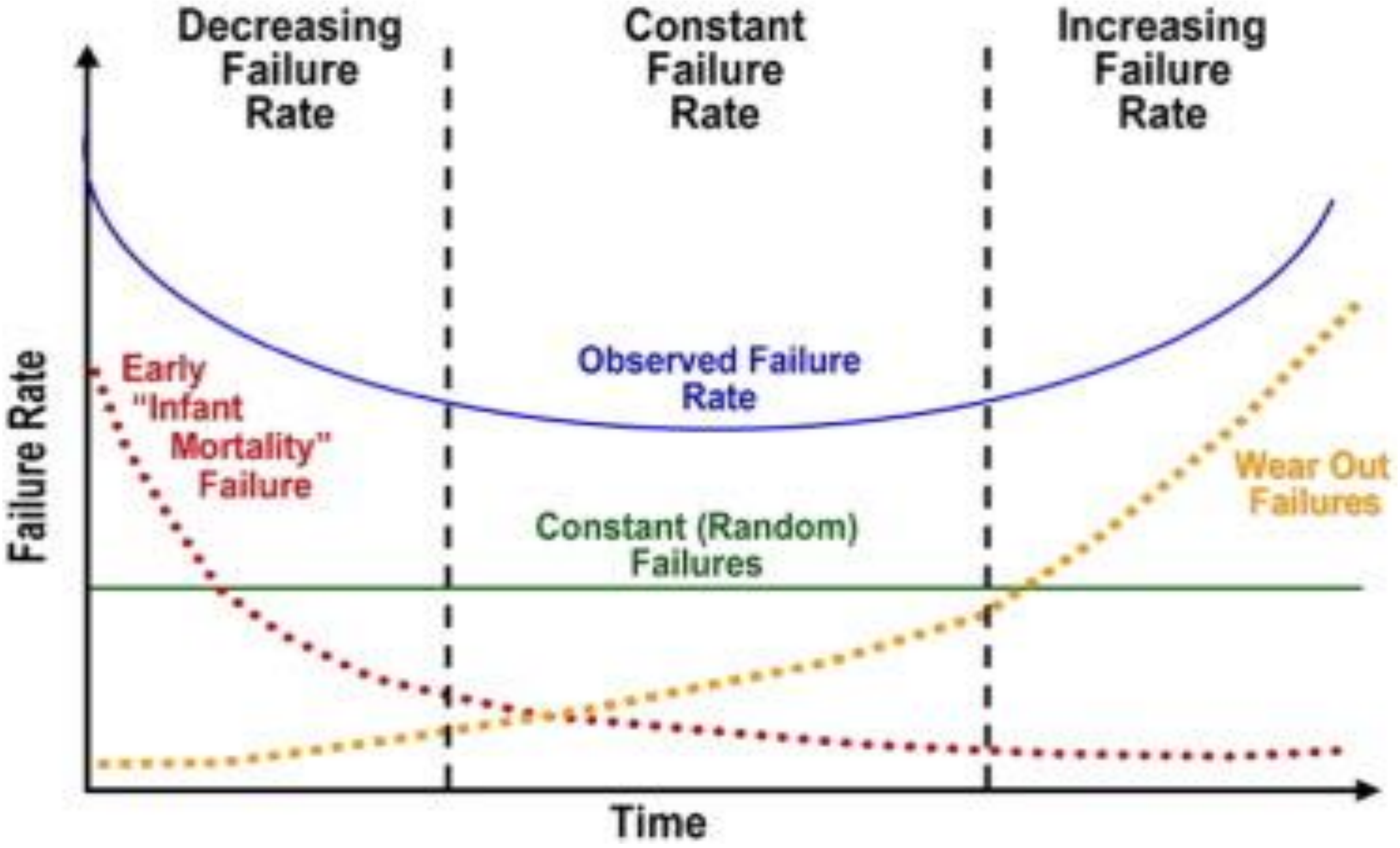
Figure 6: Field reliability trend chart for all deployed eGaN products over the past 6 years. Values represent 60% confidence upper bound on the FIT rate.

JEDEC testing for WBG—makes sense ?



The Bath-tub Curve

- Failure (Hazard) rate λ as a function of time



Quality failures
Mfc defects

Stress related failures
Latent defects

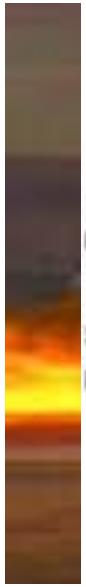
Wear out failures
Accumulated damage

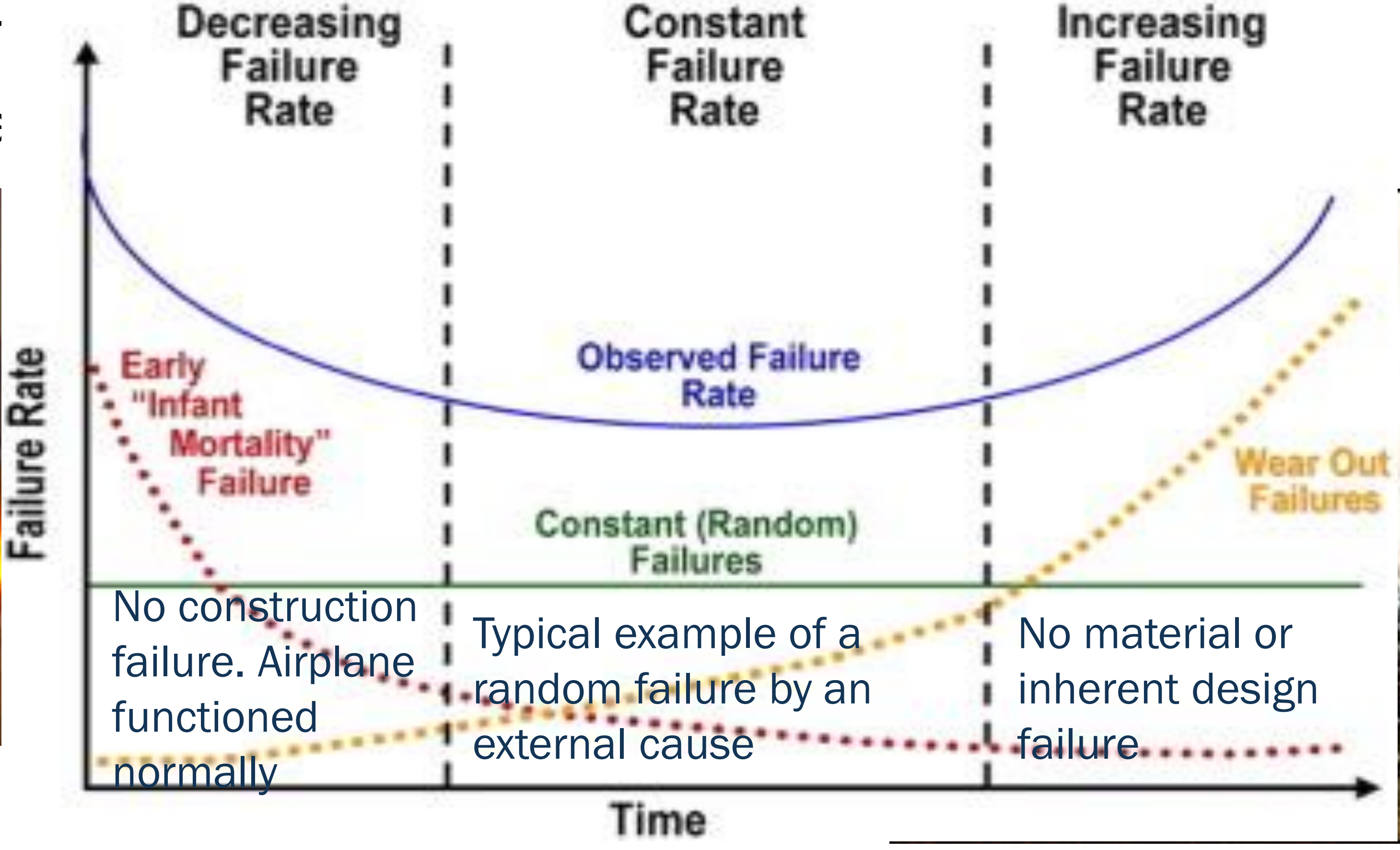
Crash of the Concorde (Mach 2)

First commercial flight on 12 Jan 1976

Cr

La





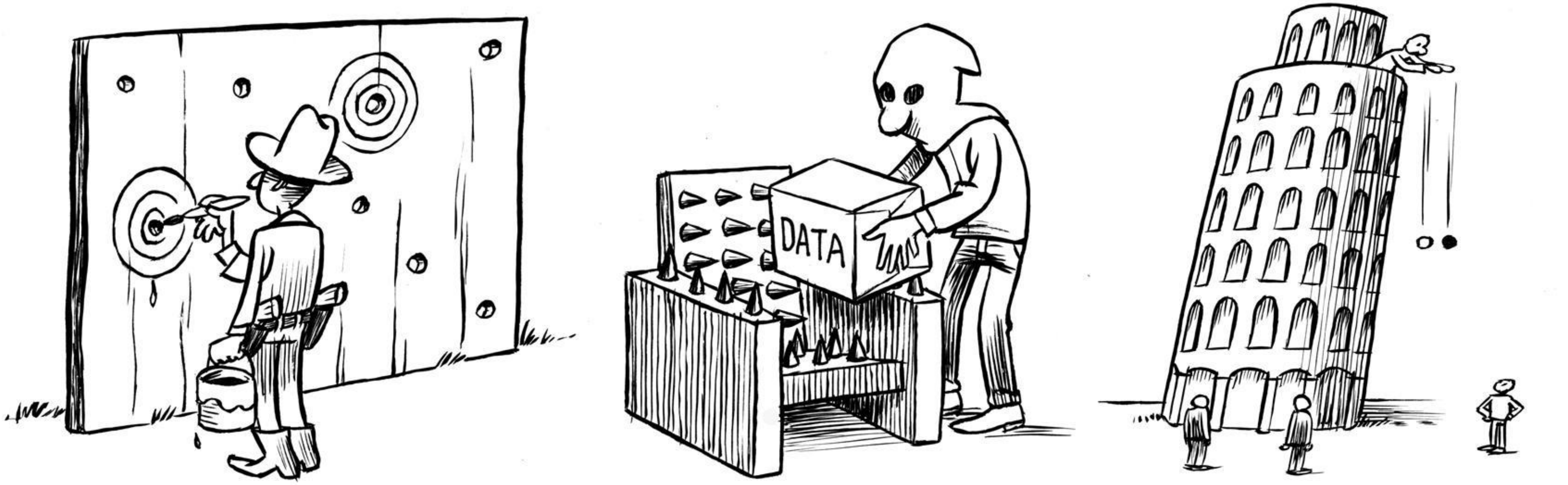
No construction failure. Airplane functioned normally

Typical example of a random failure by an external cause

No material or inherent design failure

- **Was the Concorde less reliable after the crash ?**

No Statistics=No Reliability



Exploratory Research ⟷ Confirmatory Research

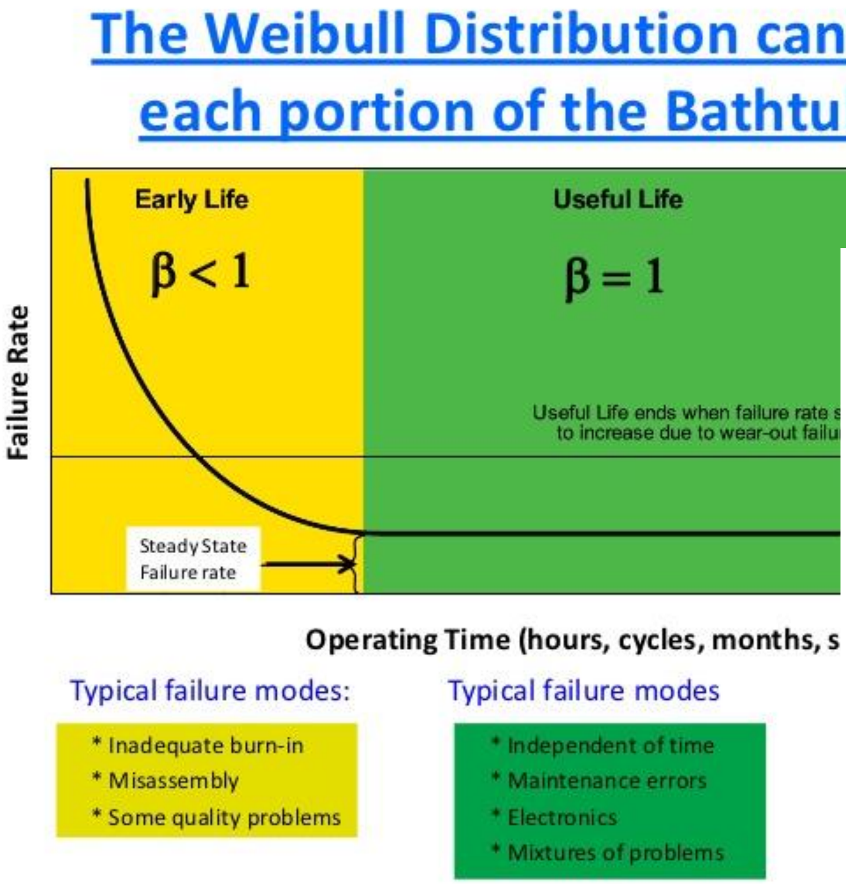
Wonky Stats ⟷ Sound Stats

Exciting

Boring

The Bath-tub Curve and Failure Functions

- Failure (Hazard) rate λ as a function of time

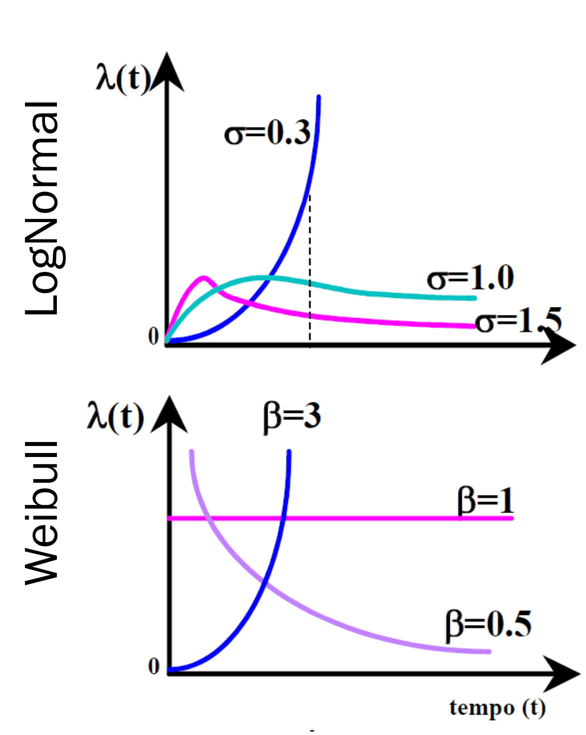


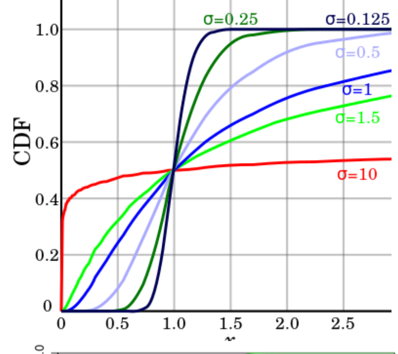
Poisson distribution

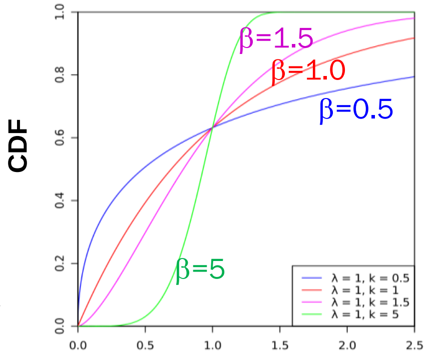
– Constant λ

Normal distribution

– Increasing λ







Weibull—Percolation

Weibull distribution is used for modeling "percolation" events. Has been widely used to model degradation of dielectrics.

Weibull distributed parameter is Charge-to-Breakdown ("Q_{bd}")

- To assess Q_{bd}, constant current stress has to be applied (Q=I.t)
- Not practical, since lifetime acceleration/prediction requires voltage
- Constant voltage stress is used instead (but is actually not correct).

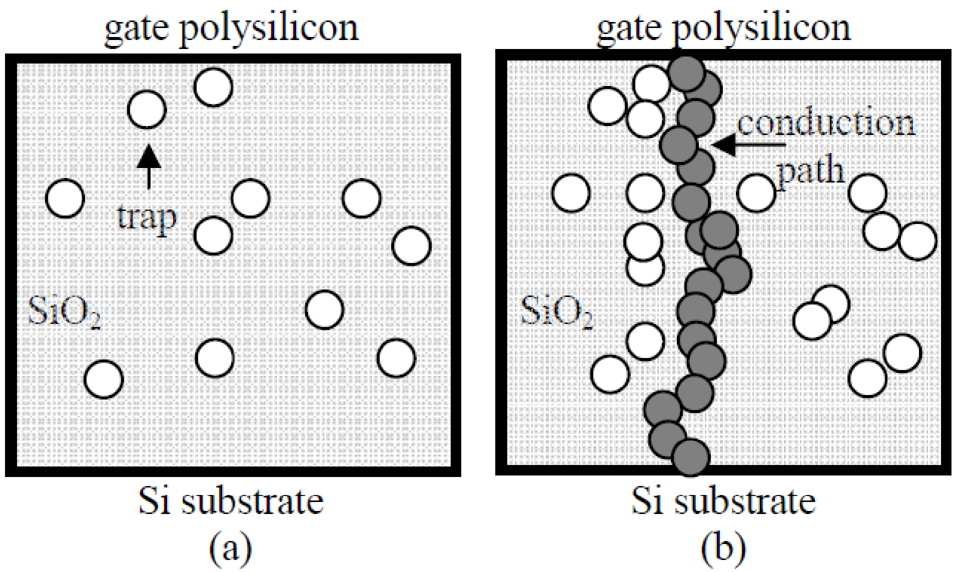
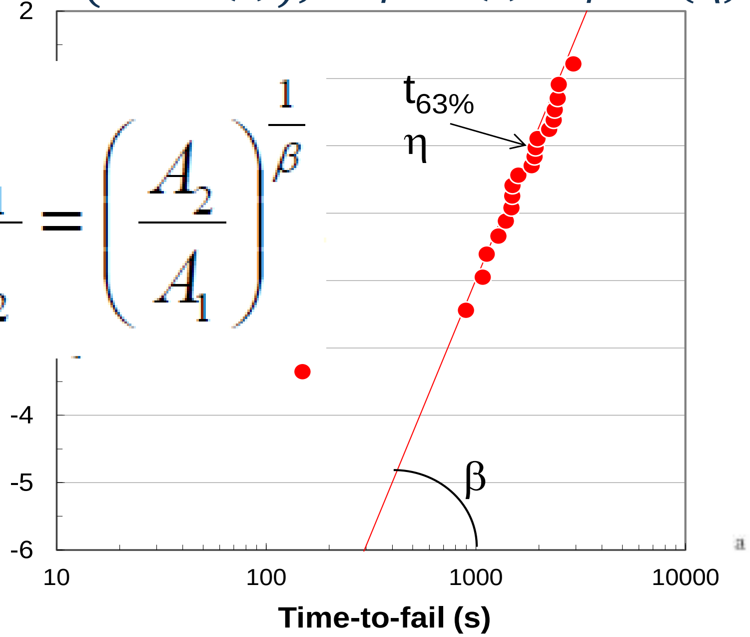


Figure 1: Graphical representation of the percolation model: (a) creation of traps and (b) formation of conduction path.

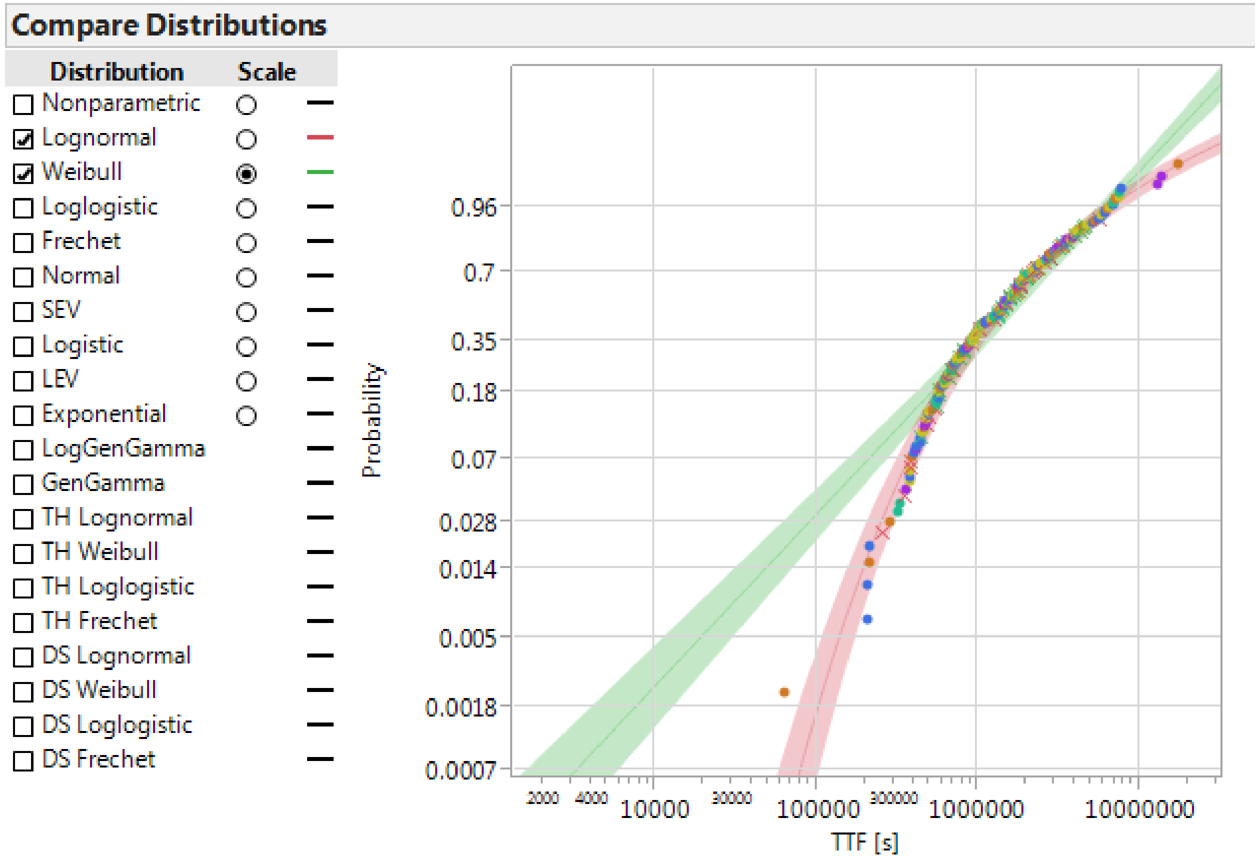
$$\ln(-\ln(1-F(t))) = \beta.\ln(t) - \beta.\ln(\eta)$$

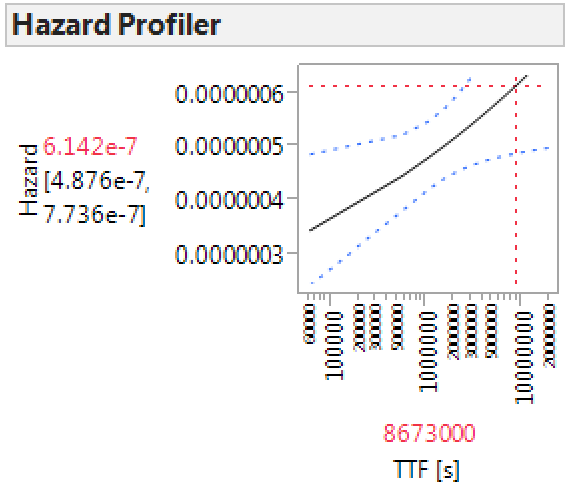
$$\frac{\eta_1}{\eta_2} = \left(\frac{A_2}{A_1}\right)^{\frac{1}{\beta}}$$

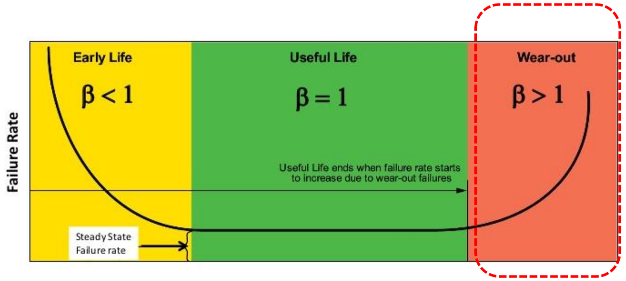


Weibull versus LogNormal distribution (eGaN gate reliability)

- Weibull and LogNormal differ in low percentiles
- LogNormal more optimistic
- All data for 100mΩ devices, at T=150^{o}C







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