GaN electronic devices

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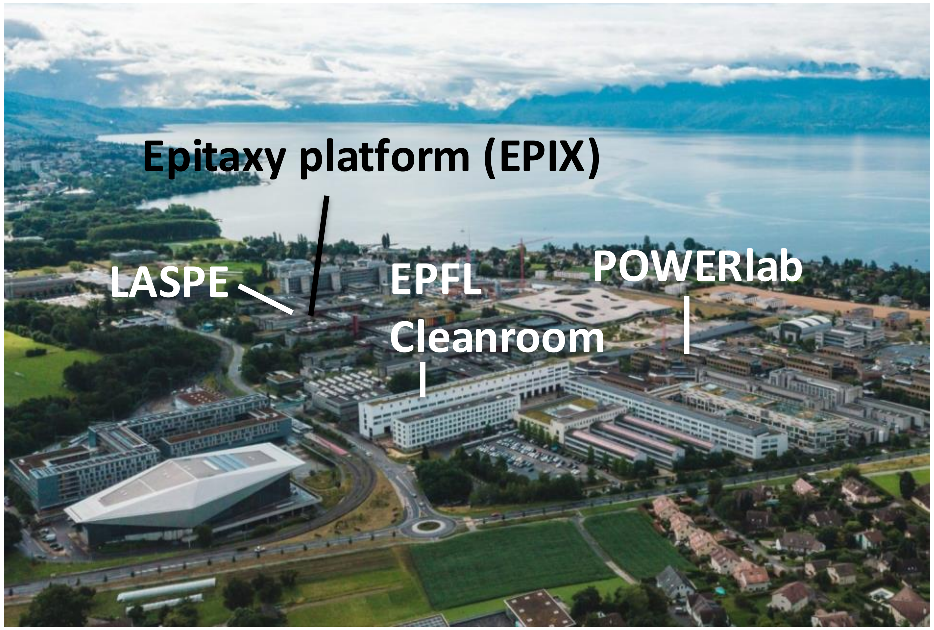
Nitrides environment at EPFL



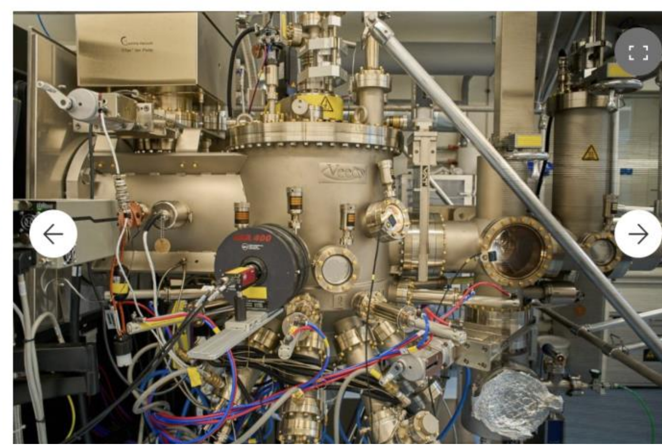
Center for MicroNanoTechnology (CMi) at EPFL

Epitaxy Platform (EPiX) at EPFL

GaN vertical chamber CCS MOVPE reactor

GaN horizontal chamber MOVPE reactor

III-V dual chamber MOVPE reactor



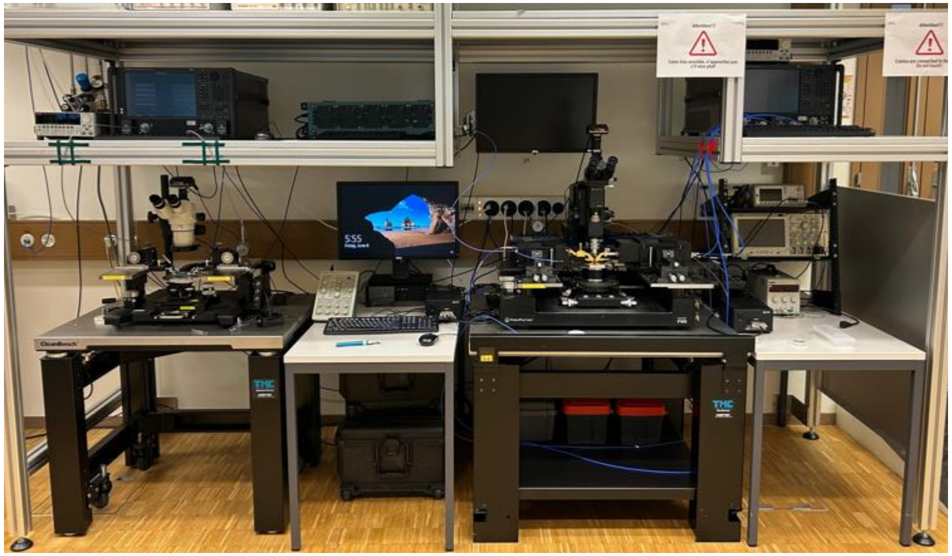
MBEs – III-V and Nitrides

https://www.epfl.ch/research/facilities/epix/

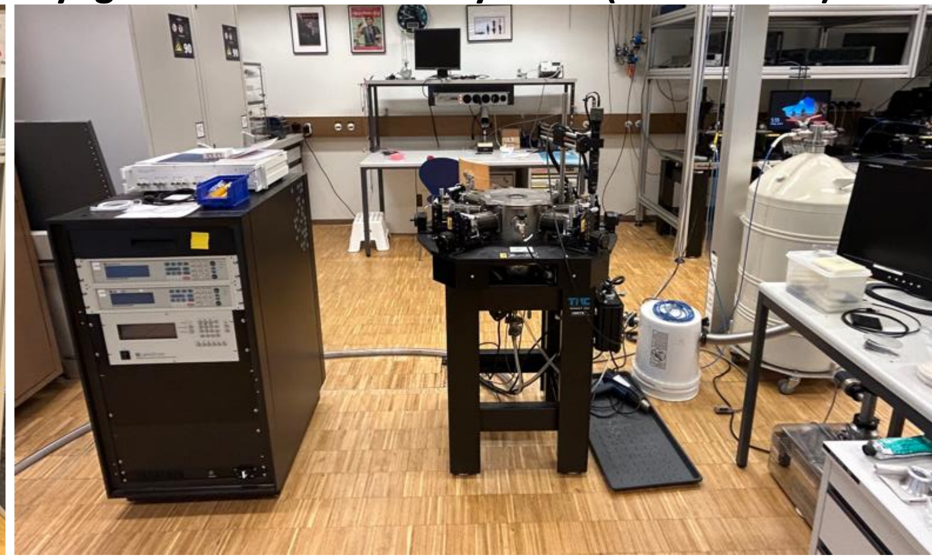
Introduction to our lab - POWERlab at EPFL

EPFL

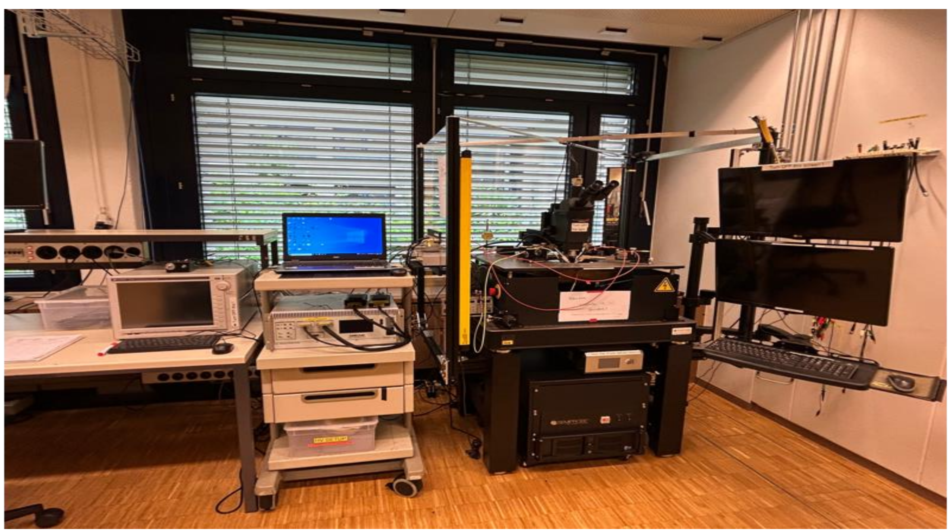
RF and THz measurement systems



Cryogenic measurement systems (down to 4K)



Power measurement systems (10kV, DC and pulsed)



Thermal and Microfluidic measurement systems

Introduction to POWERlab at EPFL

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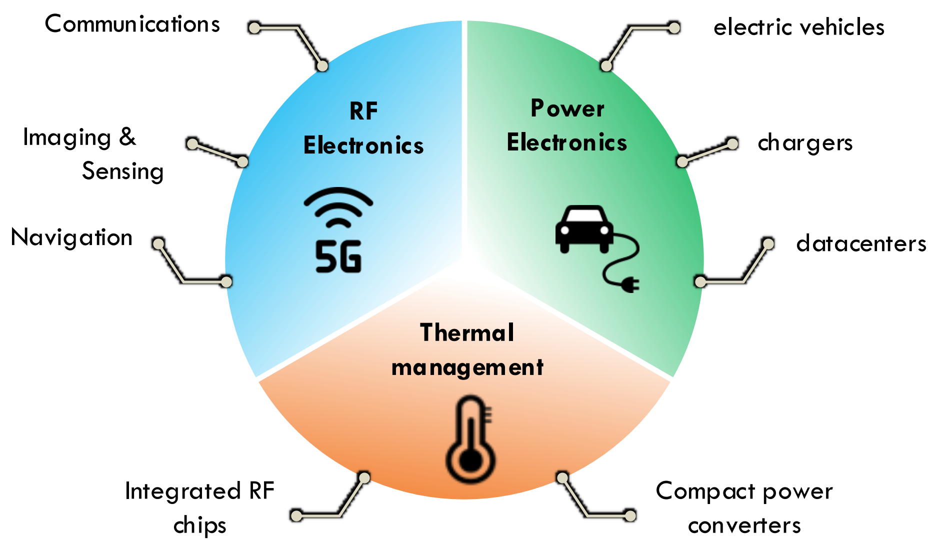
Challenges for more efficient electronic devices

RF Electronics

Lower losses (lower resistances)
Larger Breakdown voltage
Increase cut-off frequency
Higher Pxf^2

Power Electronics

Lower losses (lower resistances)
Larger breakdown voltage
Efficient dynamic performance



Thermal management

Efficient thermal management
Extract heat closer to the junction

Introduction to POWERlab at EPFL

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Challenges for more efficient electronic devices

RF Electronics

Lower losses (lower resistances)
Larger Breakdown voltage
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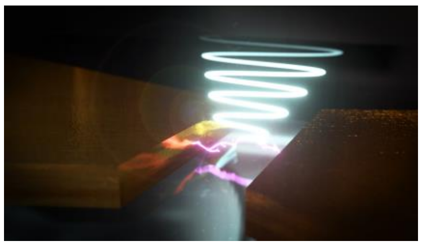
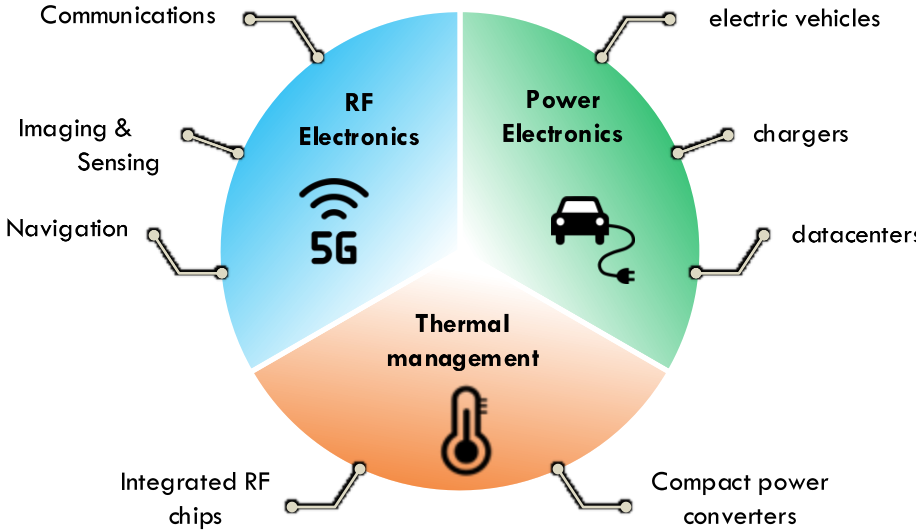


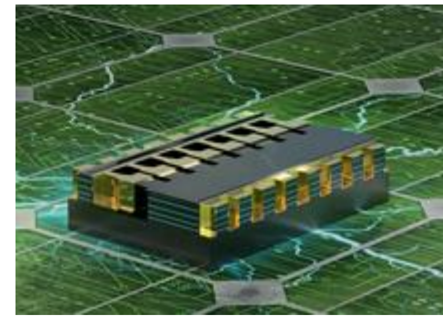
New RF and THz devices

Nanoplasma devices: **Nature,** 579 (7800), 534-539, (2020)
Electronic metadevices: **Nature** 614 (7948), 451-455 (2023)



Power Electronics

Lower losses (lower resistances)
Larger breakdown voltage
Efficient dynamic performance

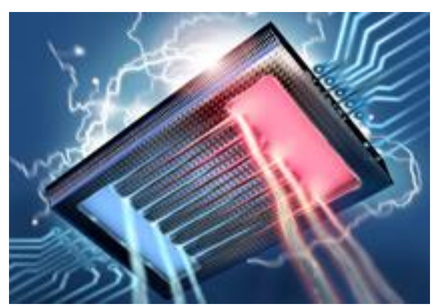


Lateral and vertical devices
Semiconductors:
GaN, diamond

Multichannel devices: **Nature Electronics** 2021
Diamond transistor on GaN: **IEEE Electron Device Letters,** 2020

Thermal management

Efficient thermal management
Extract heat closer to the junction



Effective microfluidic cooling

Microfluidic cooling: **Nature** 585 (7824), 211-216 (2020)

Outline of the electronic module

EPFL

Lecture I: Electronic devices

- Introduction
- Heterostructures
- Lateral devices: HEMTs

Lecture II: RF devices

- Equivalent circuit and FOM: important aspects
- Technologies to improve RF performance

Lecture III: Lateral Power devices

- E- and D-mode devices
- Reaching low resistance and high voltage
- current commercial technology
- Losses in GaN power devices

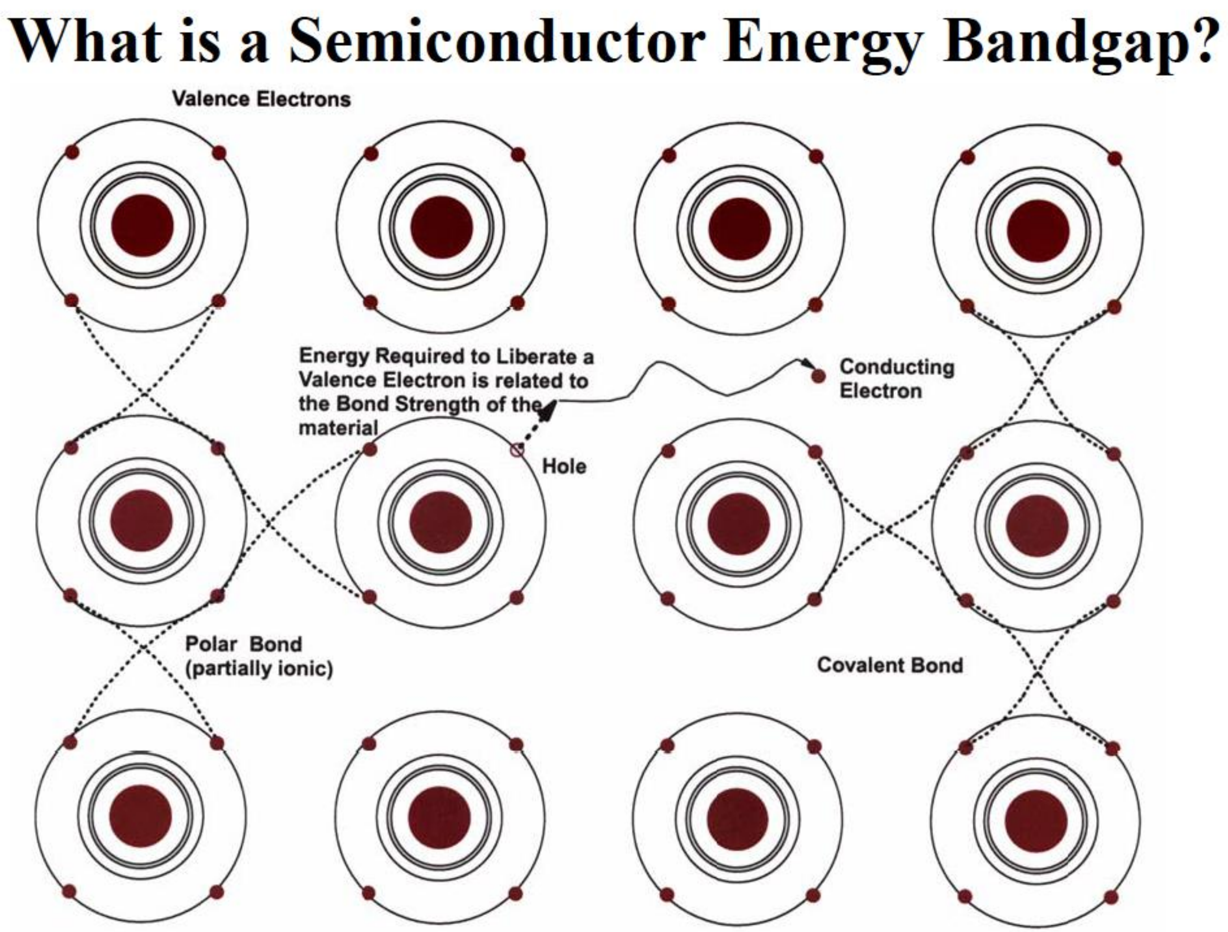
Lecture IV: Vertical Power devices

- Introduction
- Vertical devices: GaN PN diodes and MOSFETs
- Novel concepts in vertical power electronics

Bonus: Novel trends

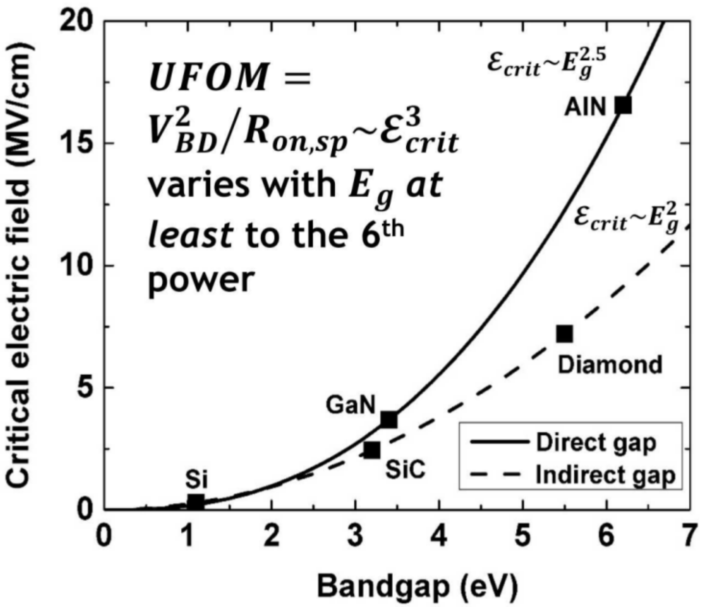
GaN materials for electronics

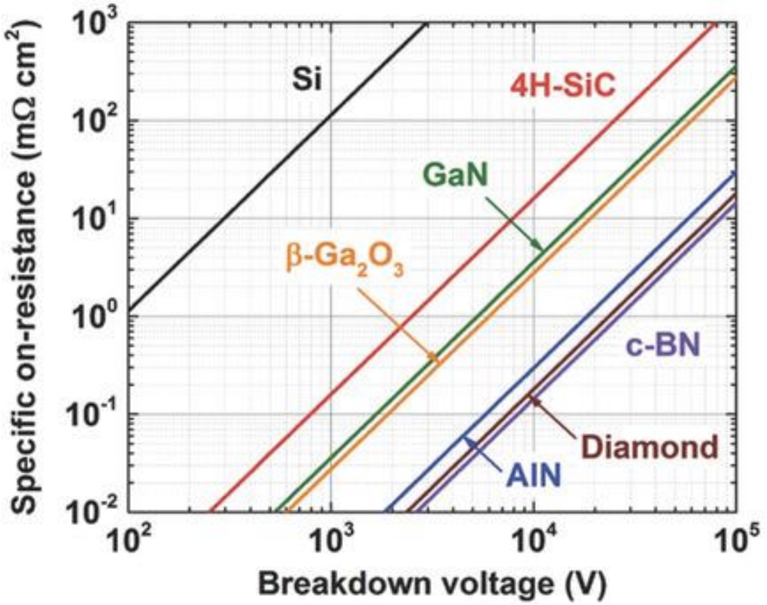
Energy band-gap



Wide-band-gap semiconductors

Interest of wide-band-gap materials for power electronics





Hudgins et al., IEEE Trans. on Pow. Elec. 18, 3 (2003),
Tsao et al., Advanced Elec. Mat. 4, 1600501 (2018)

Ideal Specific On-Resistance ($R_{ON,SP}$):

$$R_{ON,SP} = \frac{4BV^2}{\varepsilon_S \mu_n E_C^3}$$

$R_{on,sp}$ is related to material properties

Much larger voltage blocking with a smaller resistance and size

What is truly unique of III-Nitrides?

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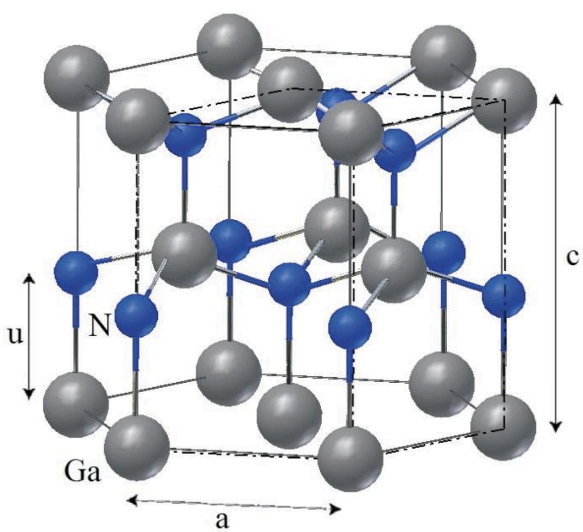
What is truly unique of III-Nitrides?

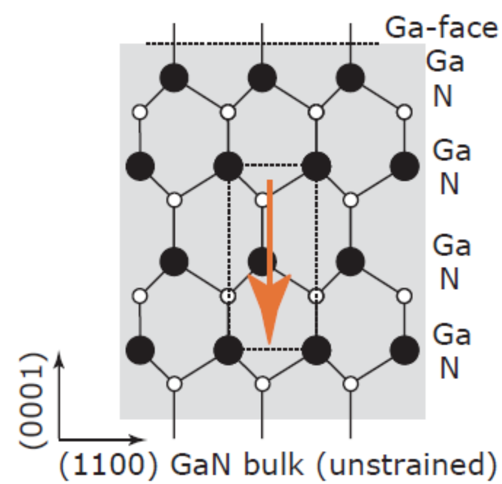
Spontaneous polarization and piezoelectric constants of III-V nitrides

Fabio Bernardini and Vincenzo Fiorentini
INFM – Dipartimento di Scienze Fisiche, Università di Cagliari, I-09124 Cagliari, Italy

David Vanderbilt
Department of Physics and Astronomy, Rutgers University, Piscataway, NJ, U.S.A.

Wurtzite structure





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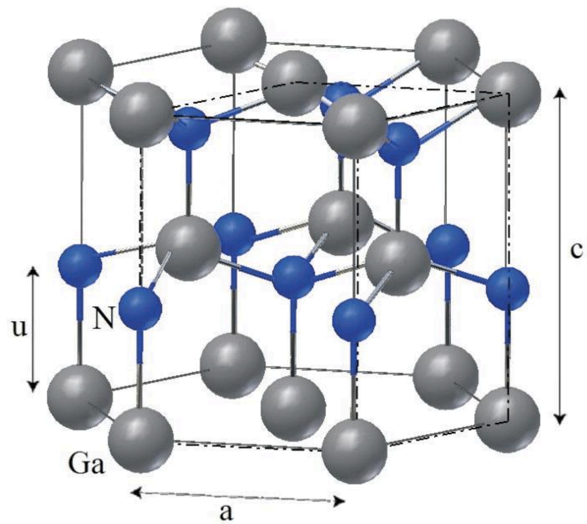
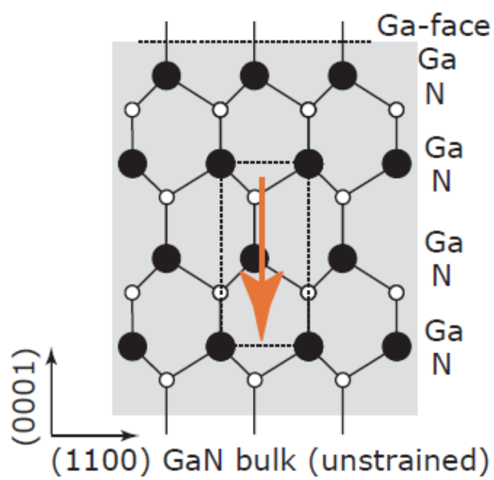
Wurtzite structure





PHYSICAL REVIEW X **6,** 021038 (2016)

Correct Implementation of Polarization Constants in Wurtzite Materials and Impact on III-Nitrides

Cyrus E. Dreyer,[1,2] Anderson Janotti,[1,*] Chris G. Van de Walle,[1] and David Vanderbilt[2]
[1]*Materials Department, University of California, Santa Barbara, California 93106-5050, USA*
[2]*Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08845-0849, USA*
(Received 22 December 2015; published 20 June 2016)

1. Spontaneous polarization

	$P_{\text{eff}}^{(\text{H ref})}$	$P_{\text{eff}}^{(\text{ZB ref})}$	$P_{\text{eff}}^{(\text{ZB ref})}$, previously reported[a]
GaN	1.312	−0.035	−0.034
AlN	1.351	−0.090	−0.090
InN	1.026	−0.053	−0.042

2. Piezoelectric polarization

		Proper	Improper	Previously reported[a]
GaN	e_{31}	−0.551	−1.863	−0.22 to −0.55
	e_{33}	1.020	1.020	0.43 to 1.12
AlN	e_{31}	−0.676	−2.027	−0.38 to −0.81
	e_{33}	1.569	1.569	1.29 to 1.94
InN	e_{31}	−0.604	−1.63	−0.23 to −0.59
	e_{33}	1.238	1.238	0.39 to 1.09

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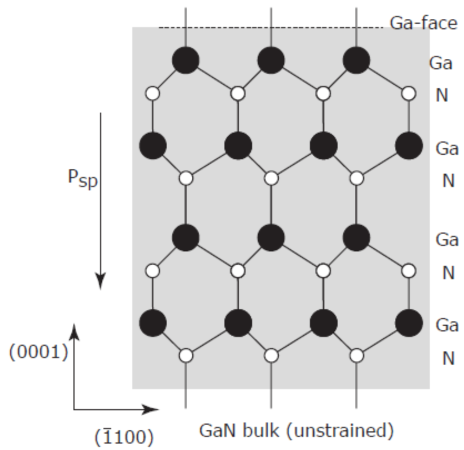
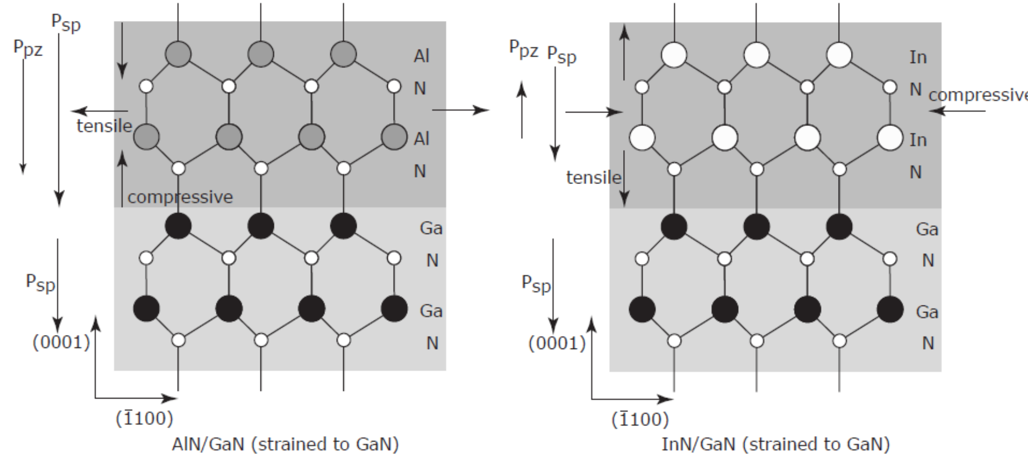
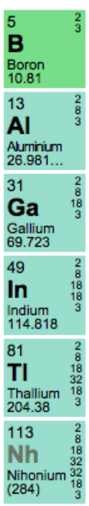
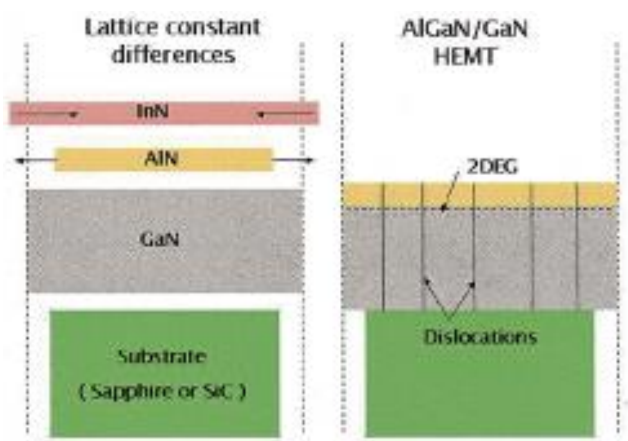
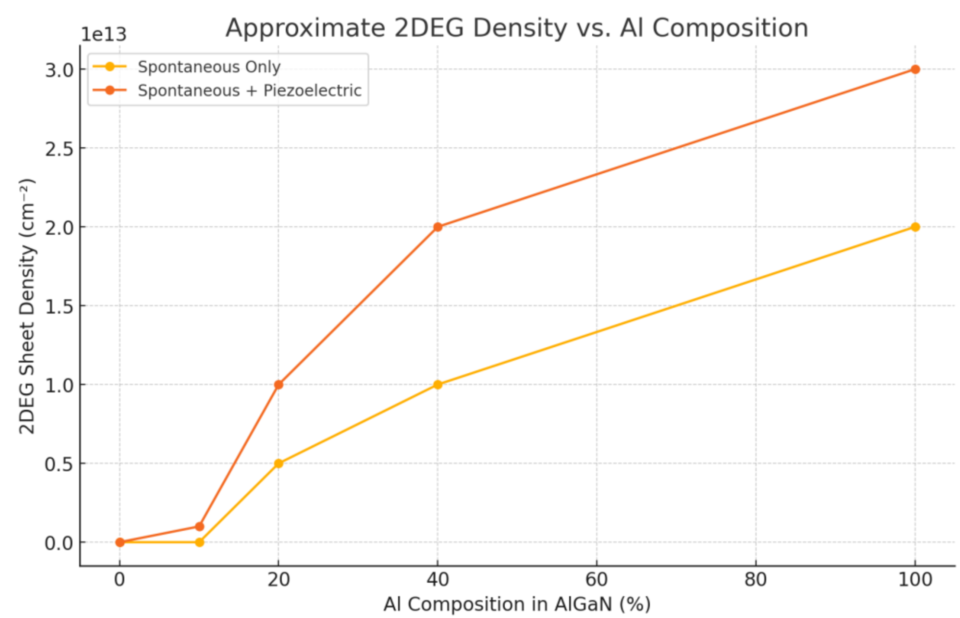
Effect of Piezoelectric Polarization







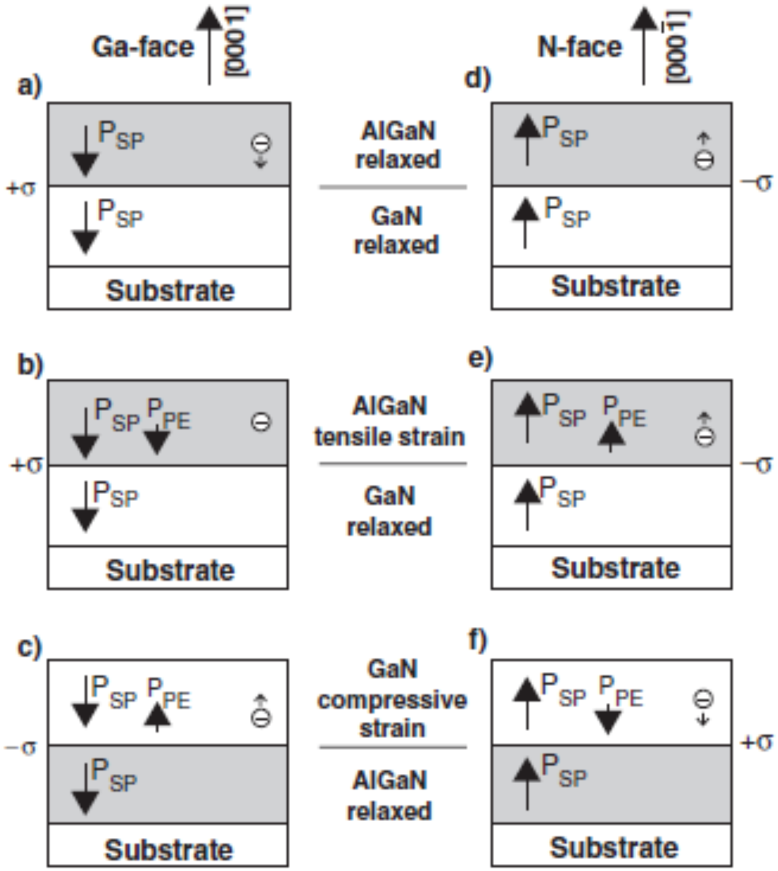




Ambacher et al., J. Appl. Phys., Vol. 85, No. 6, 15 March 1999
UMESH K. MISHRA, POCEEDINGS OF THE IEEE, VOL. 90, NO. 6, JUNE 2002

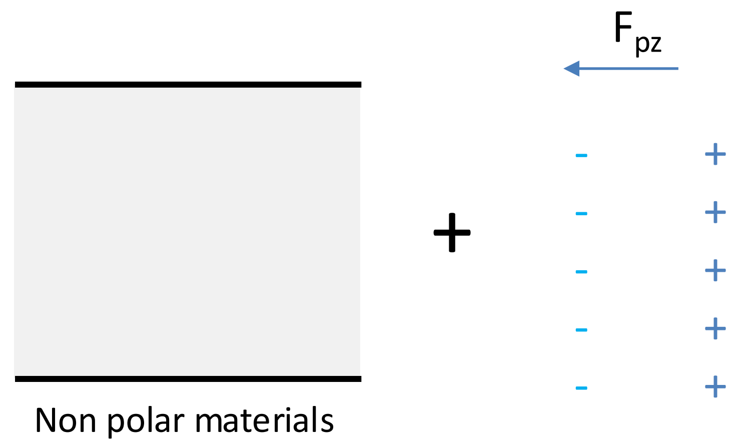
Case for GaN: Basics of III-Nitrides

Spontaneous and piezo contributions



C. Wood et al. "Polarization effects in Semiconductors"

What does it do to the band structures?



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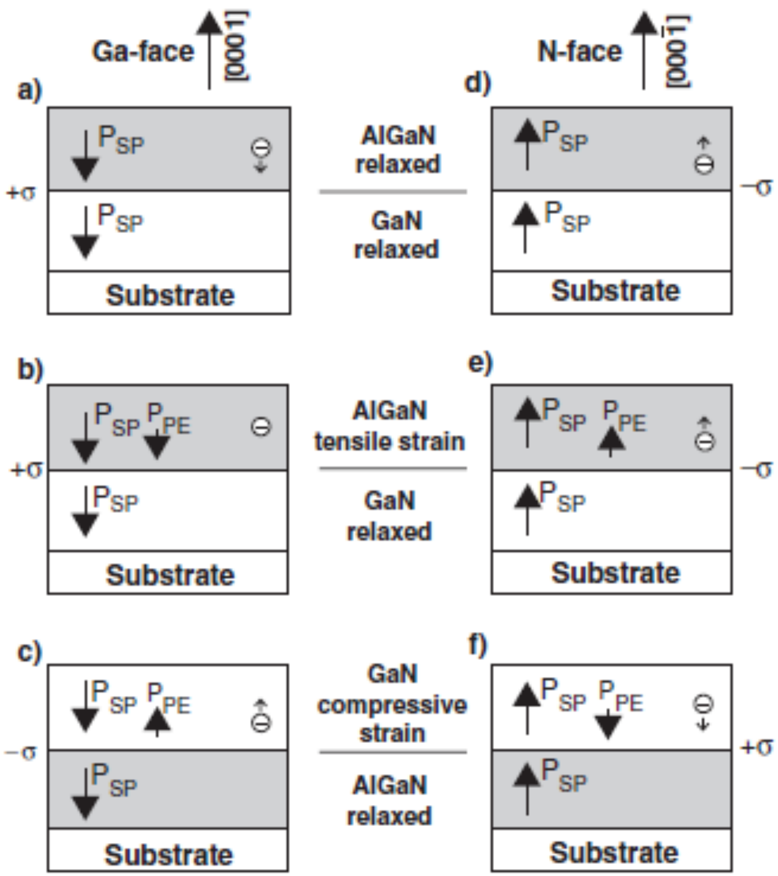

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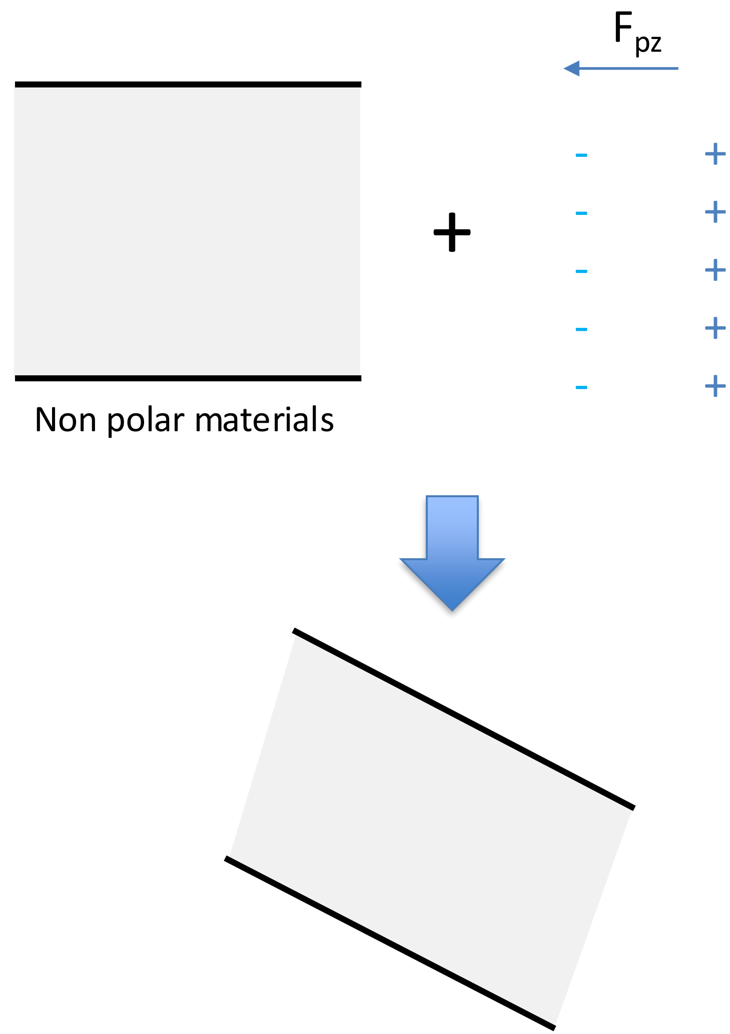


Polarization fields create slopes in the bands!

How to make useful devices

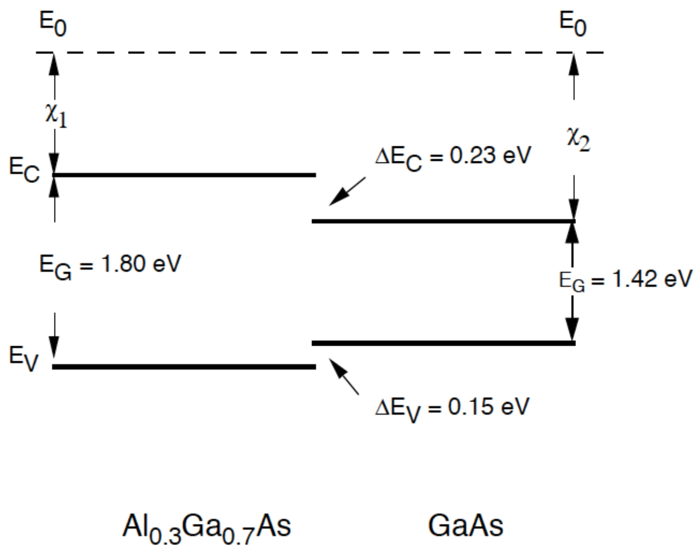
Uniqueness of III-Nitrides

Very unique property of Nitrides:

1. Spontaneous and piezoelectric polarization fields
2. Several compounds can be used to form heterostructures

GaN, AlN, AlGaN, InGaN, InAlN, InAlGaN, ScAlN, etc…

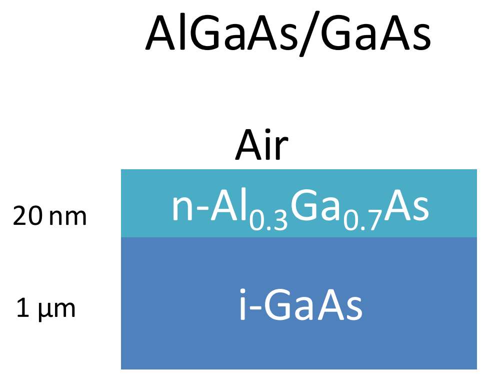
AlGaAs/GaAs



AlGaN/GaN

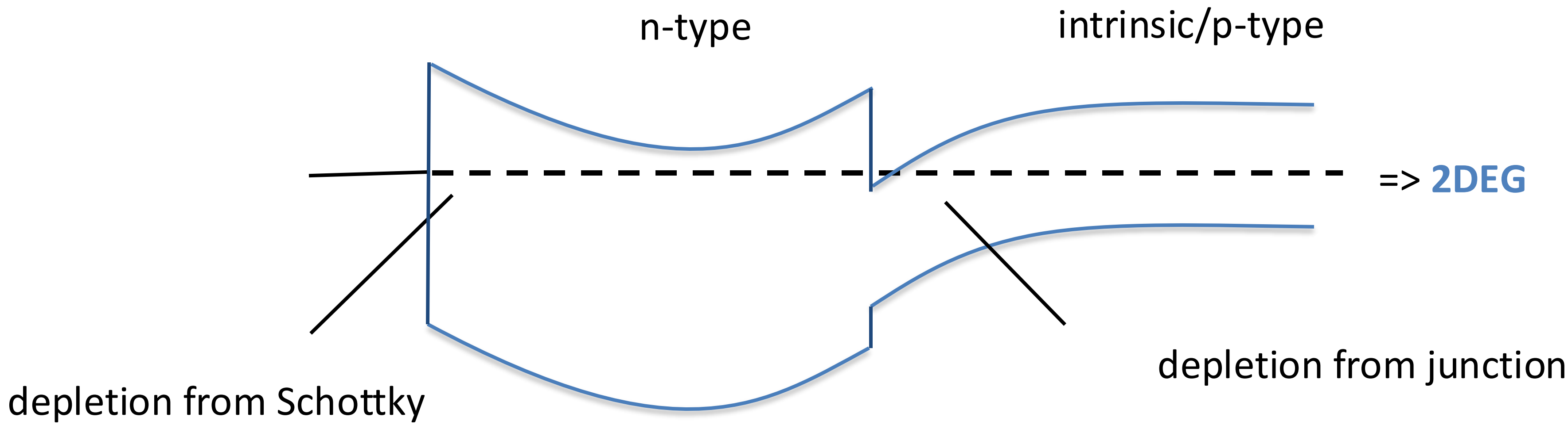
?

Simple case: AlGaAs/GaAs

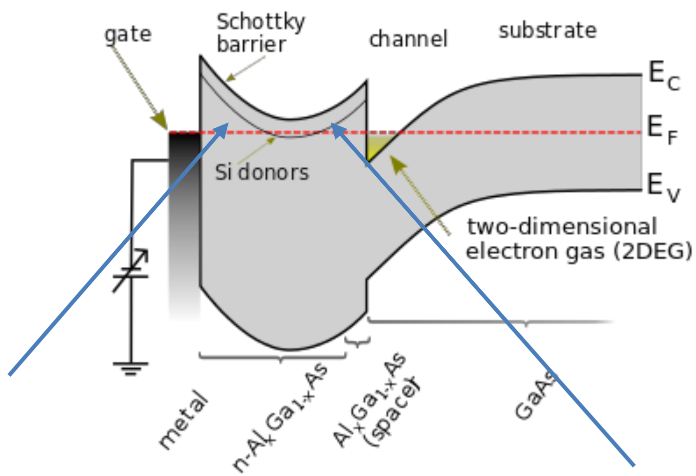


Simple case: AlGaAs/GaAs

+ Schottky gate => **HEMT**



HEMT

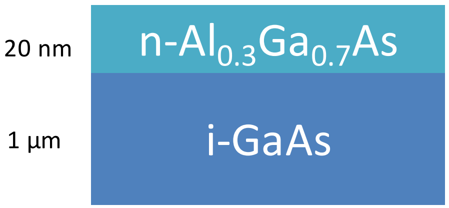


Well designed HEMT: barrier fully depleted (needed for gate control)

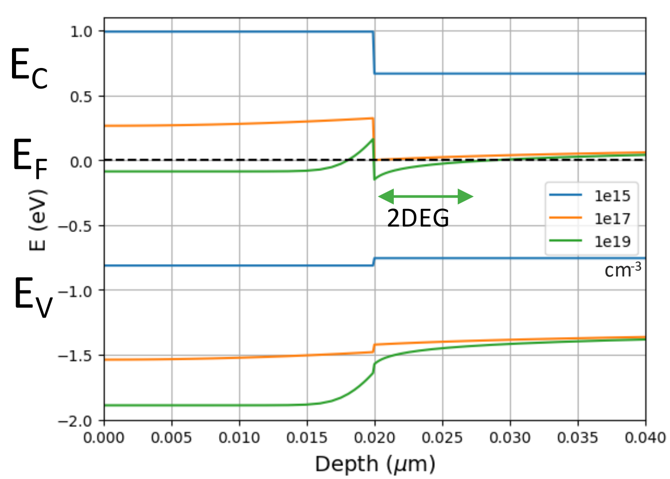
Simple case: AlGaAs/GaAs

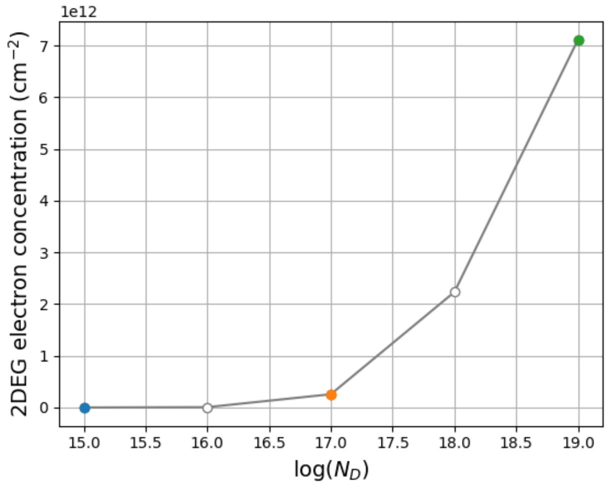
AlGaAs/GaAs

Vary donor concentration



Model details
- Uniform doping profile
- No surface states

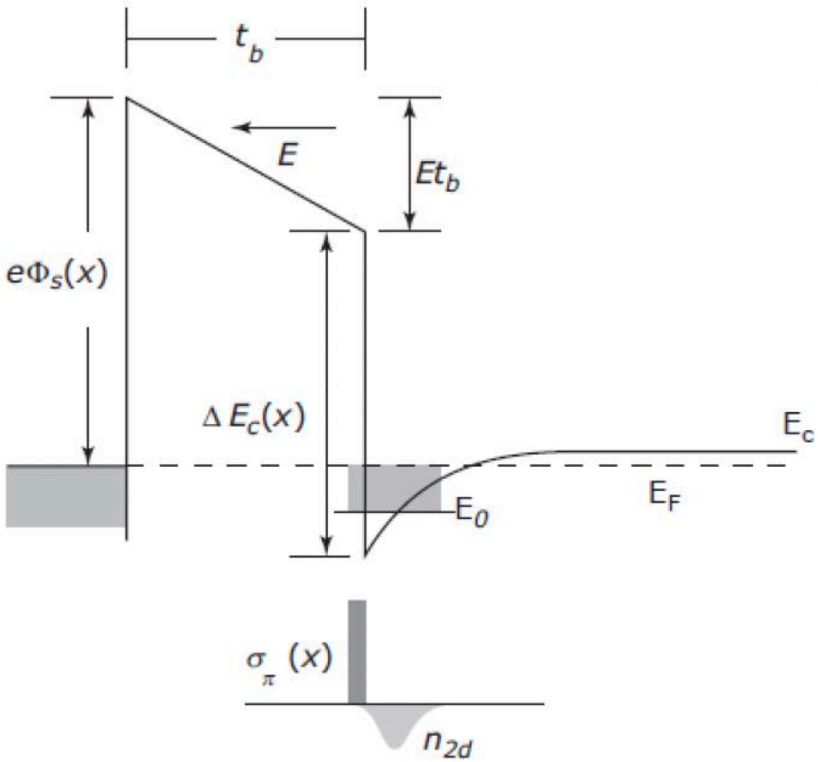




2DEG is formed by n-doping the AlGaAs barrier

Expressions for Ns in GaN

Simplified analytical description of GaN HEMT: charge control



$$e\Phi_s - E \times t_b - \Delta E_c + E_0 + (E_F - E_0) = 0$$

From Gauss' law:

$$E = e(\sigma_\pi(x) - n_{2d})/\epsilon(x)$$

Using 2D density of states and assuming a triangular well:

$$E_F - E_0 = \frac{\pi\hbar^2}{m^*} n_{2d}$$

$$E_0 \approx \left(\frac{9\pi\hbar e^2 n_{2d}}{8\epsilon(x)\sqrt{8m^*}} \right)^{2/3}$$

Express n_{2D} analytically and neglect E_F dependence on n_{2D}

$$n_{2d} = \sigma_\pi - \frac{\epsilon(x)}{t_b} \frac{e\Phi_s - \Delta E_c + E_F}{e^2}$$

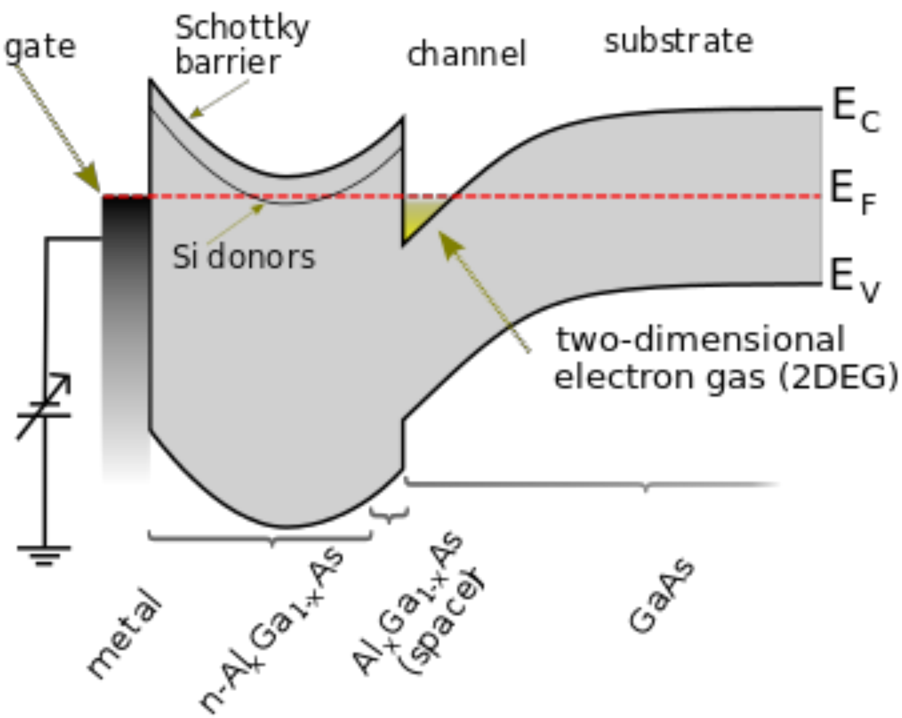
$\sigma_\pi(x)$ total polarization charge (piezo and spontaneous)

$\epsilon(x)$ absolute electric permittivity

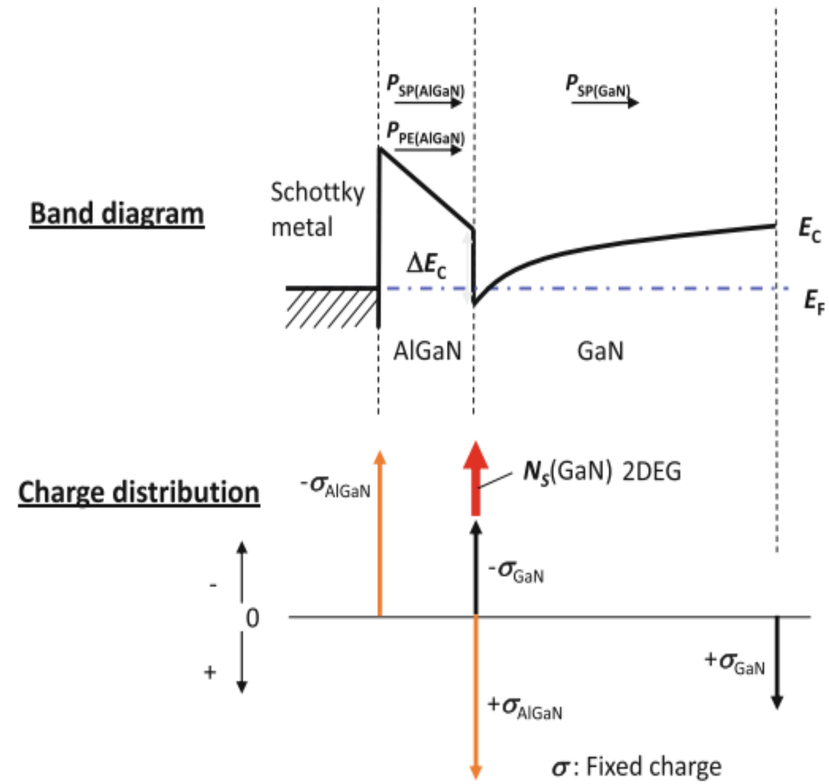
D. J. C. Wood, Polarization Effects in Semiconductors, 1st ed. Springer US, 2008, ISBN: 978-0-387-68319-5.

Summary: difference between Arsenides and Nitrides

AlGaAs/GaAs



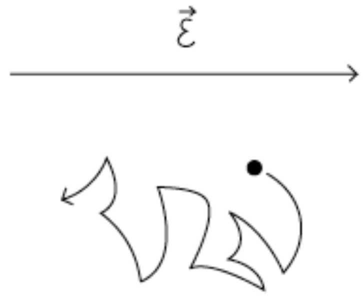
AlGaN/GaN

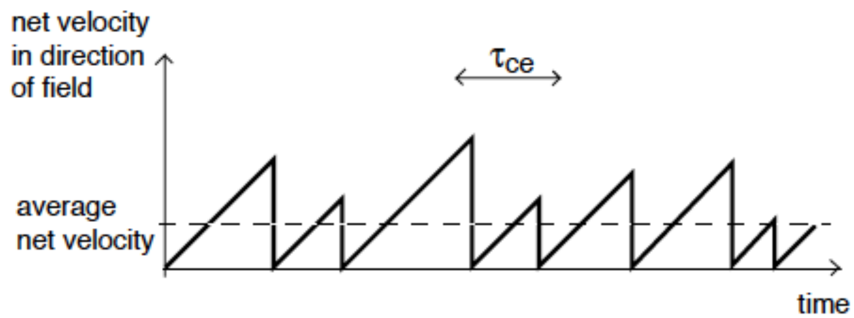


Why are these structures important?

Electron mobility

In the presence of an electric field, electrons drift:





Drift velocity

$$v_e^{drift} = -\frac{q\mathcal{E}\tau_{ce}}{m_{ce}^*}$$

$$v_e^{drift} = -\mu_e \mathcal{E}$$

$$\mu_e \equiv \text{electron mobility } [cm^2/V \cdot s]$$

Electron mobility: Corresponds to the **ease of carrier motion** in response to *E*.
It depends on the **strength of the scattering mechanisms**.

Electron mobility

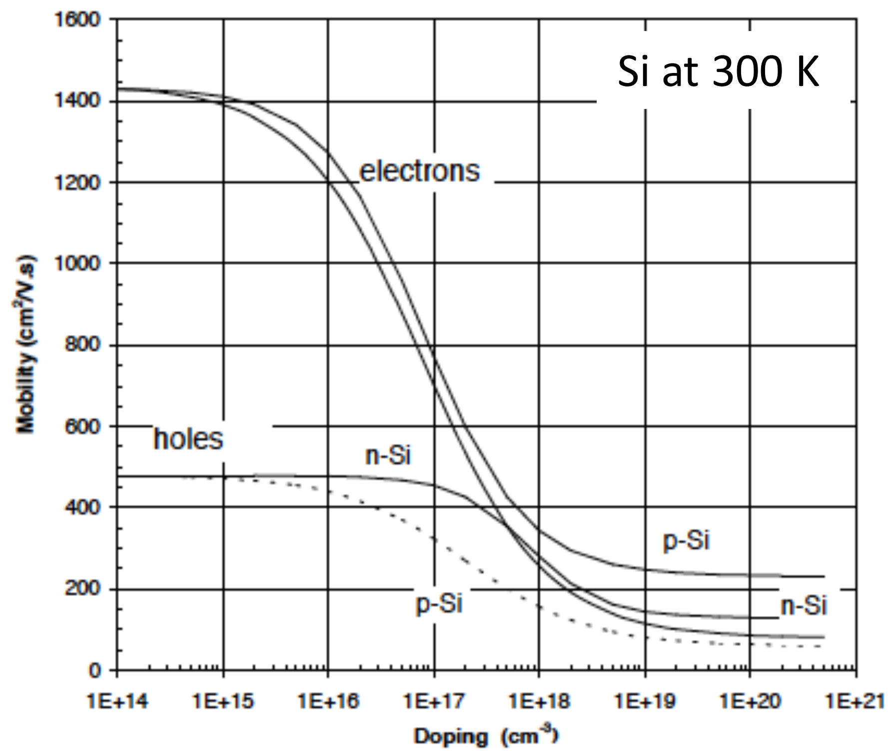
In the presence of an electric field, electrons drift:

$$v_e^{drift} = -\mu_e \mathcal{E}$$

$$v_h^{drift} = \mu_h \mathcal{E}$$

Mobility depends on:

- **doping level**
- whether carrier is **majority** or **minority-type**.



at low *n*:

- Mobility is limited by phonon scattering
- thus independent of doping.

at high *n*:

- Mobility is limited by ionized impurity scattering;
- It is not a strong function of the type of dopant, but only on its concentration.

Electron mobility

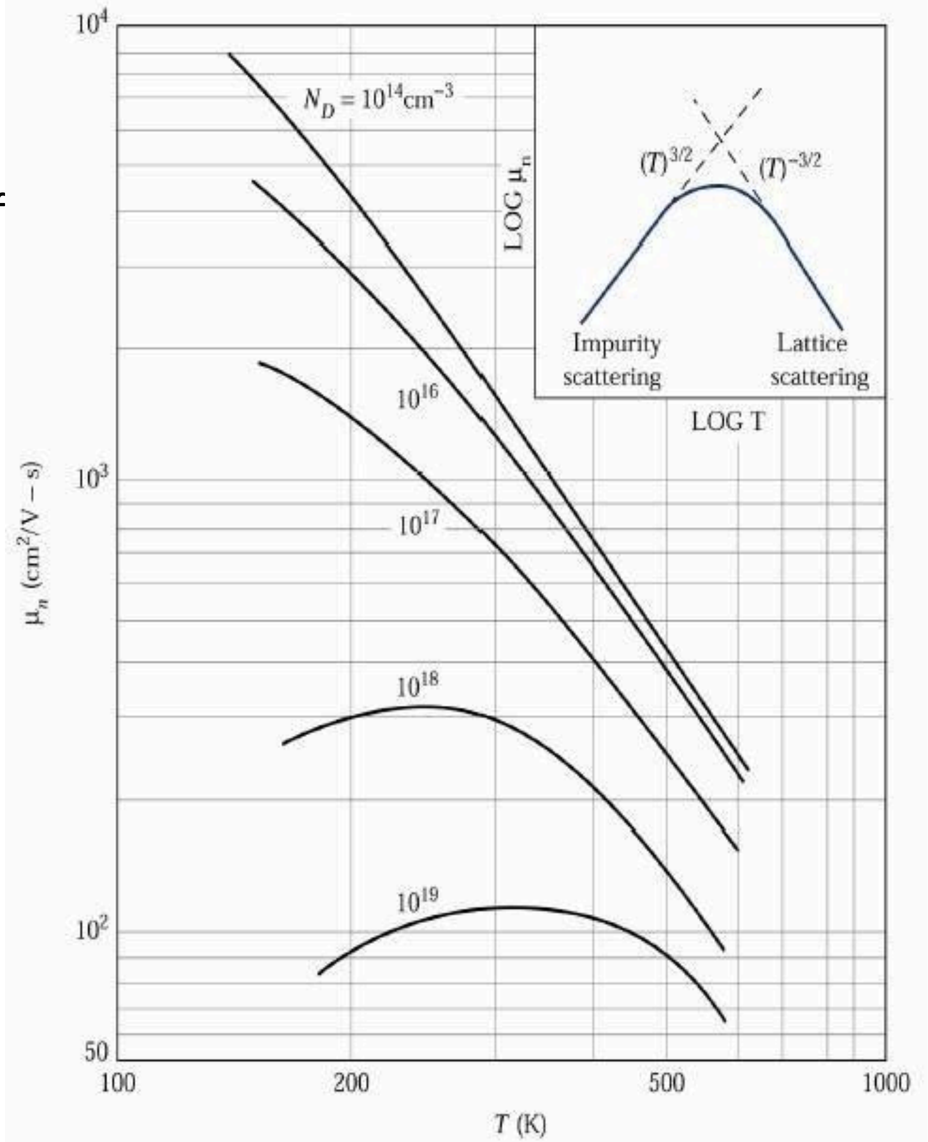
Increasing temperature and increasing doping results in reduction of mobility.

Increasing temperature: increases the number of phonons, which increases the probability that an electron will be scattered by a phonon.

Increasing doping: each dopant atom can scatter electrons.

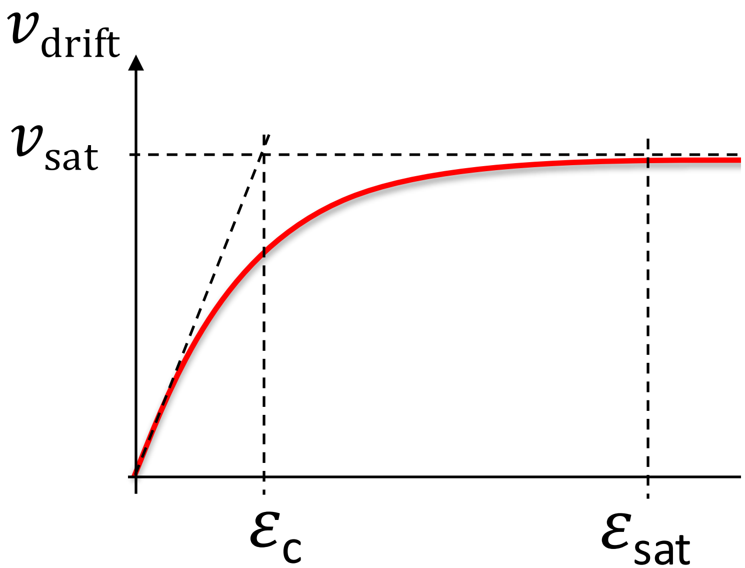
Thus:

higher doping level -> lower mobility
higher temperature -> lower mobility

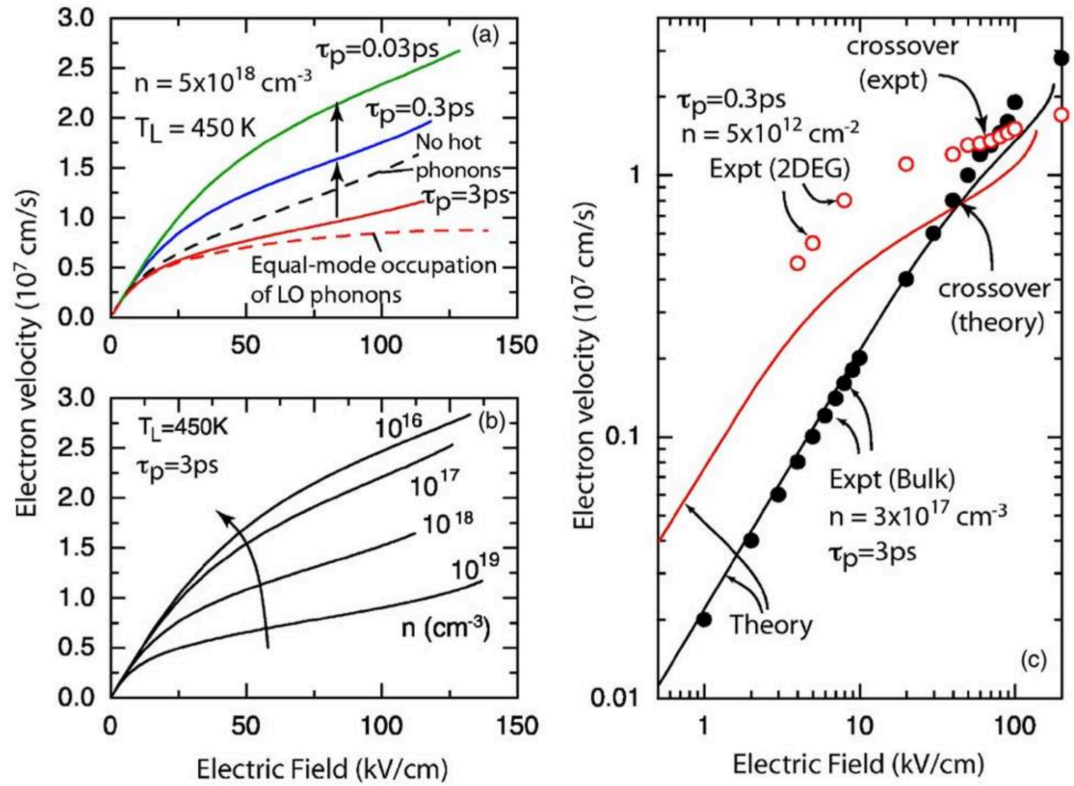


Velocity saturation

The **linear relationship** between drift velocity and electric field **is no longer valid at high fields**



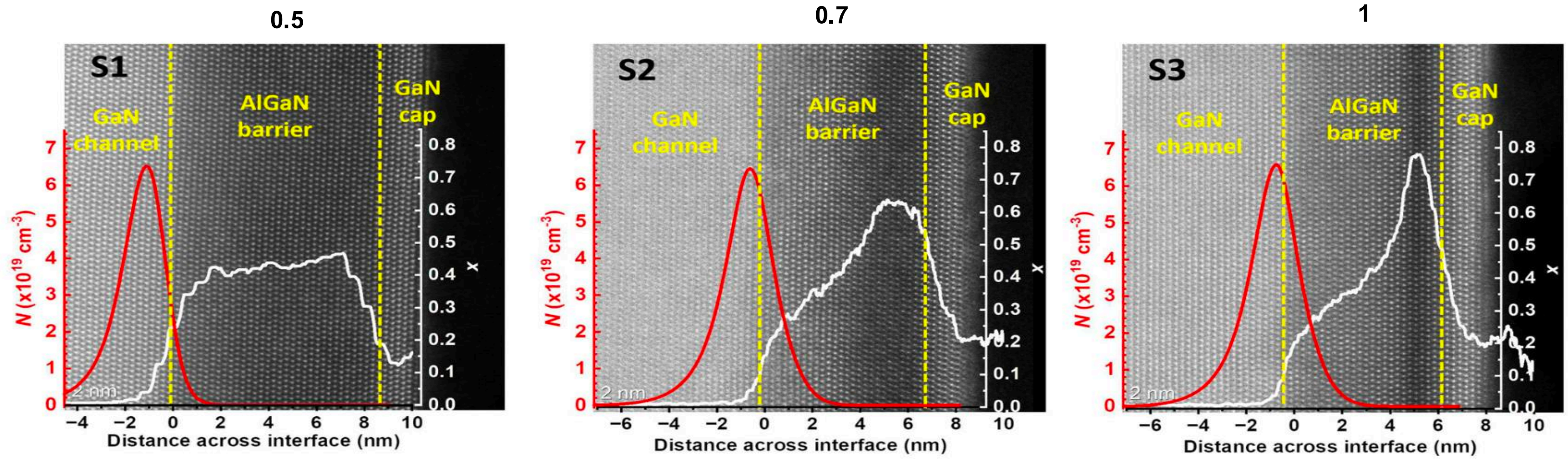
$$v^{drift} = \mp \frac{\mu \mathcal{E}}{1 + \left|\frac{\mu \mathcal{E}}{v_{sat}}\right|}$$



Jacob Khurgin, Yujie J. Ding, Debdeep Jena; Hot phonon effect on electron velocity saturation in GaN: A second look. *Appl. Phys. Lett.* 17 December 2007; 91 (25): 252104.

Velocity saturation in GaN devices: 1.5-2x10^7 cm/s

Alloy scattering



Papamichail, Alexis, et al. "Impact of Al profile in high-Al content AlGaN/GaN HEMTs on the 2DEG properties." Applied Physics Letters 125.12 (2024).

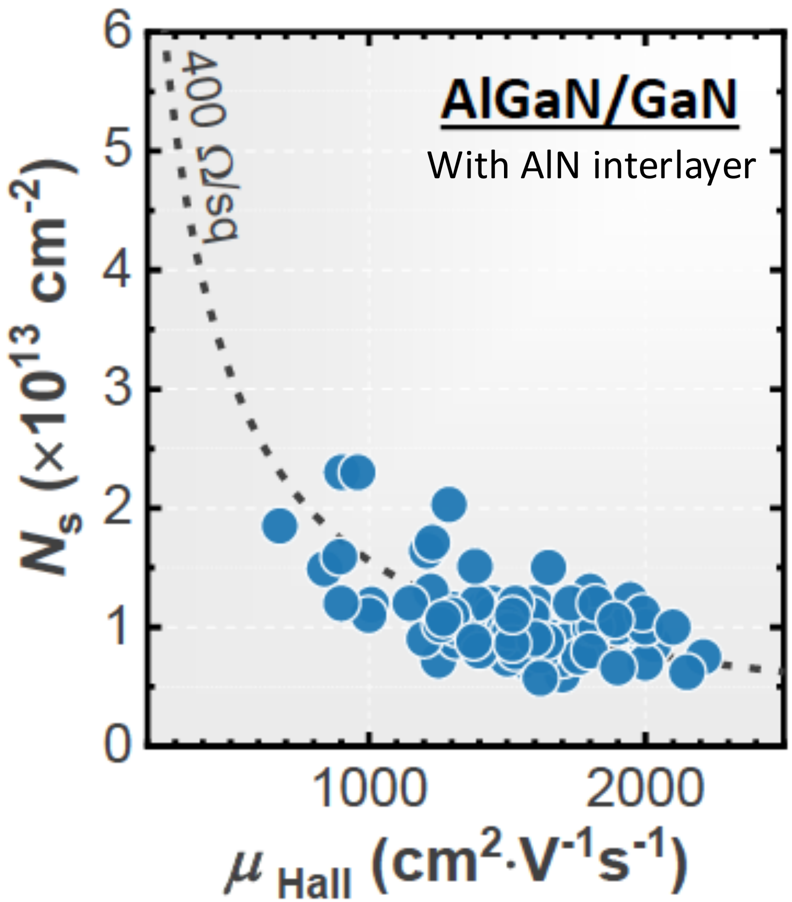
Sample	S_1	S_2	S_3
Nominal barrier thickness, t_b^n (nm)	8.0	5.0	4.5
Measured barrier thickness, t_b (nm)	8.2	7.1	6.1
Nominal Al content	0.50	0.70	1.00
Measured peak Al content	0.46	0.64	0.78
R_S (Ω/sq) (vendor)	335	431	542
R_S (Ω/sq) (Eddy current)	290	370	570
R_S (Ω/sq) (Hall)	298	350	415
N_S ($\times 10^{13}$ cm^{-2}) (Lehighton)	1.24	1.23	0.88
N_S ($\times 10^{13}$ cm^{-2}) (Hall)	1.10	1.42	1.51
N_S ($\times 10^{13}$ cm^{-2}) (simulated)	1.55	1.75	1.67
μ (cm^2/Vs) (Lehighton)	1730	1390	1270
μ (cm^2/Vs) (Hall)	1775	1270	1045

Alloy scattering in $Al_xGa_{1-x}N$: local potential fluctuations due to the randomly distributed atoms scatter electrons

Strong grading in the Al profile leads to increased wavefuntion overlap with the barrier
→ Increased alloy scattering → reduced mobility

Trade-off between carrier density and mobility in a 2DEG

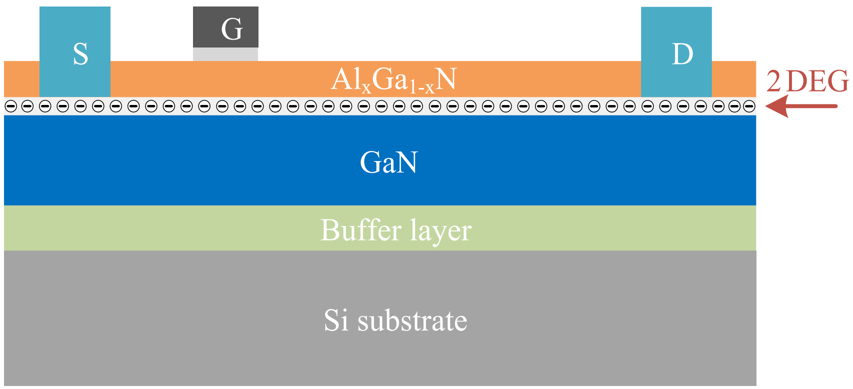
Intrinsic trade-off: in a 2DEG increasing n_s deteriorates μ

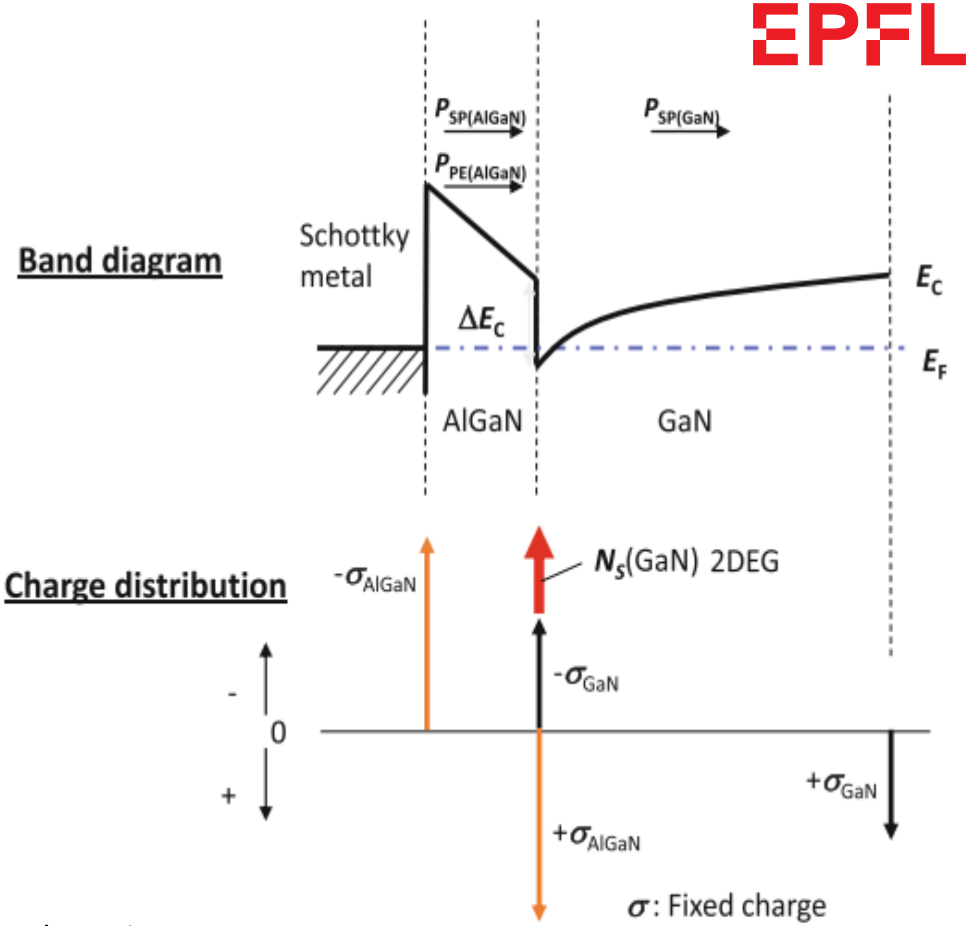


Low sheet resistance (R_{sh}) requires both high n_s and high μ

Lateral devices

HEMTs or MOSHEMTs



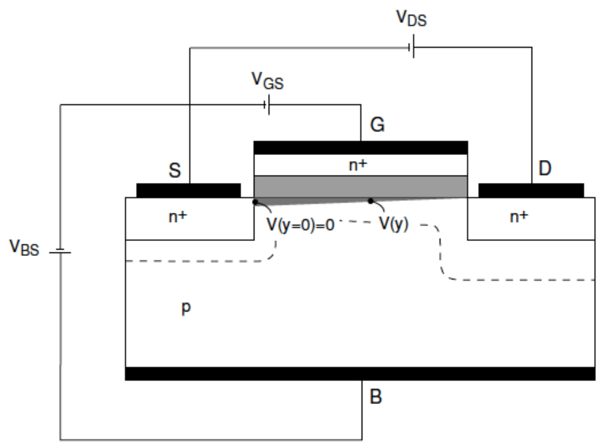


- GaN system: no need for doping (Contrary to AlGaAs/GaAs)
- Mobilities over 2200 $cm^2/V \cdot s$
- Large carrier density, over $10^{13} cm^{-2}$
- Carriers are induced by donor-like surface states at the AlGaN surface facilitated by spontaneous and piezoelectric polarization electric field inside the AlGaN layer

High Electron Mobility Transistors (HEMTs)

Comparison between MOSFETs and HEMTs

MOSFET

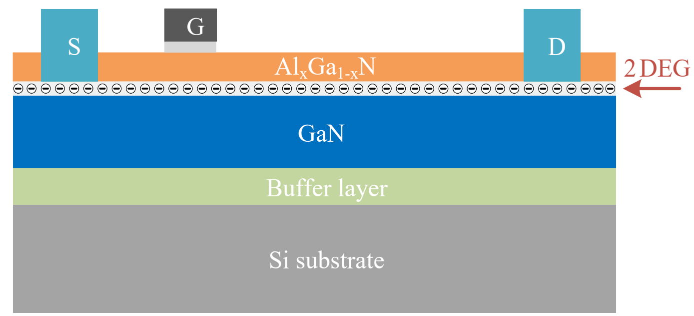


Mobility of the inverter channel is low
- Electrons propagate in a doped medium

Enhancement-mode device:

normally-off operation

HEMT



Due to the 2DEG:
- Superior mobility
- Higher frequency
- Lower noise figure
- If GaN: higher power density

Depletion-mode device:

normally-on operation