GaN electronic devices

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Outline of the electronic part

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Lecture I: Electronic devices

- Introduction
- Heterostructures
- Lateral devices: HEMTs

Lecture II: Lateral Power devices

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

Lecture III: Vertical Power devices

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

Lecture III: RF devices

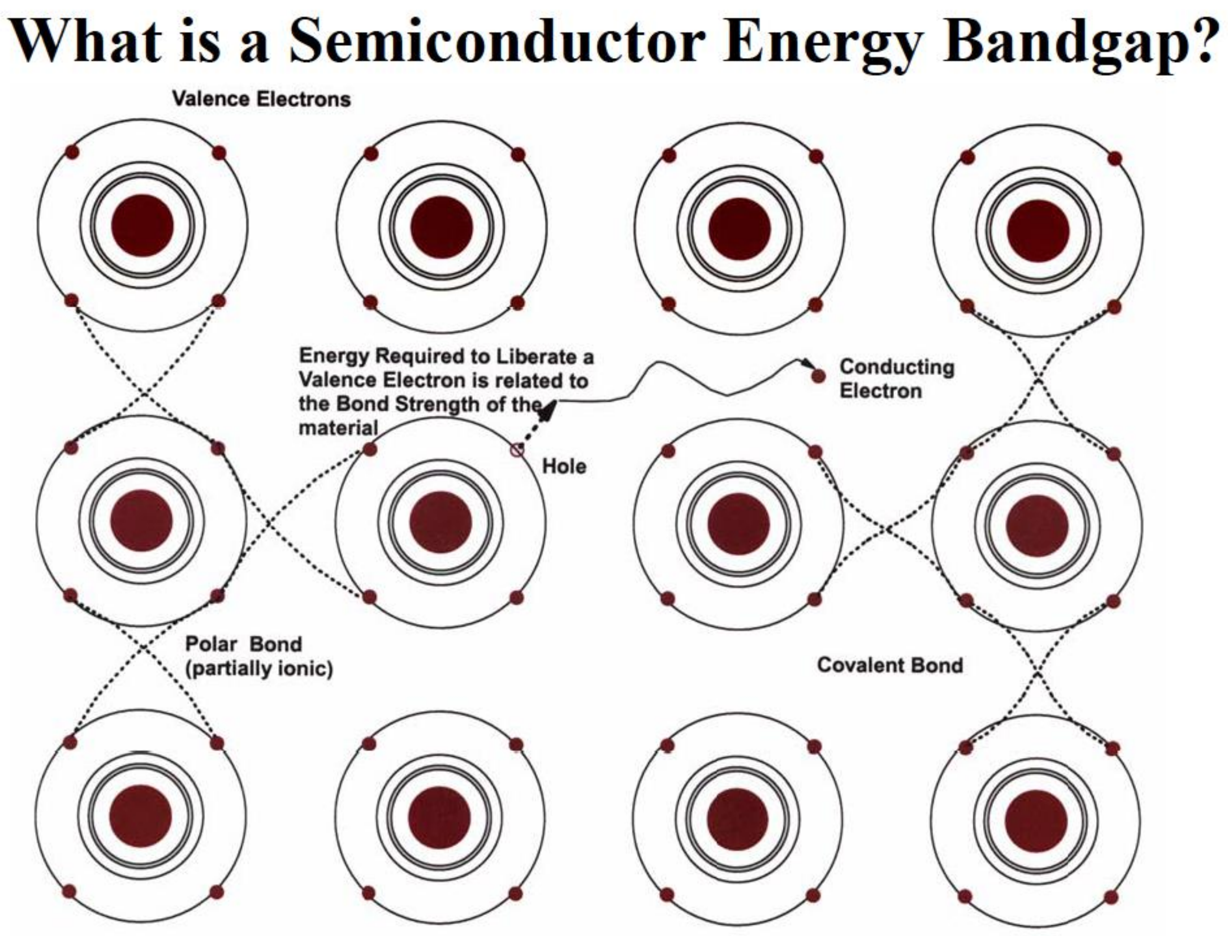
- Equivalent circuit and FOM: important aspects
- Technologies to improve RF performance

Lecture IV: Current trends – state of the art

- recent advances in the literature in GaN electronics
- superjunctions

GaN materials for electronics

Energy band-gap



Wide-band-gap semiconductors

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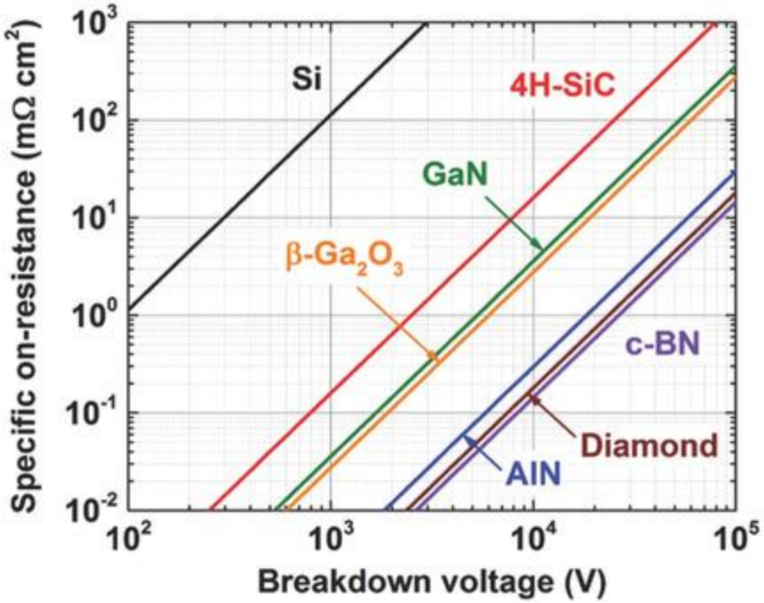
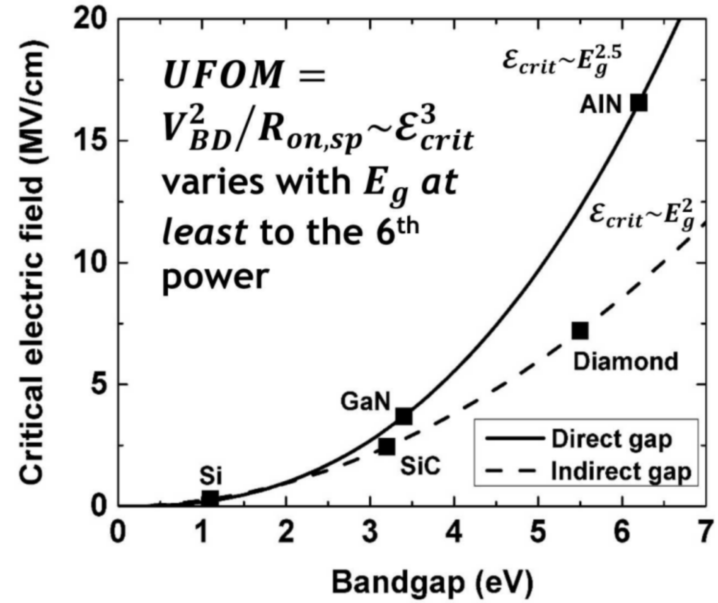
Interest of wide-band-gap materials for power electronics





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?

Case for GaN: Basics of III-Nitrides

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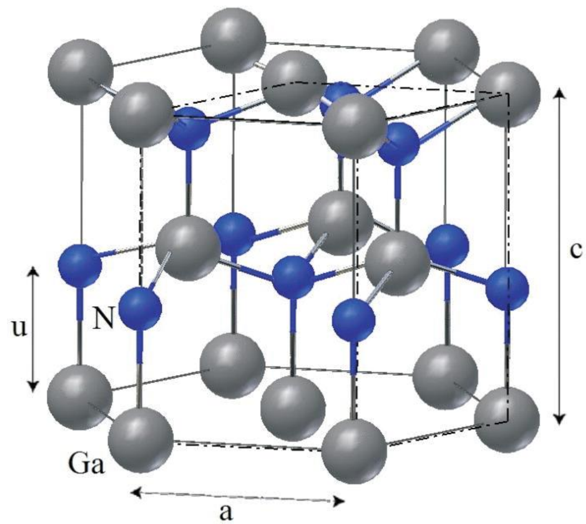
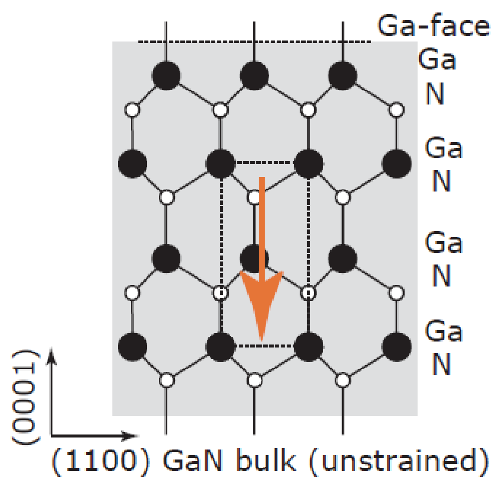
What is truly unique of III-Nitrides?

Wurtzite structure





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.

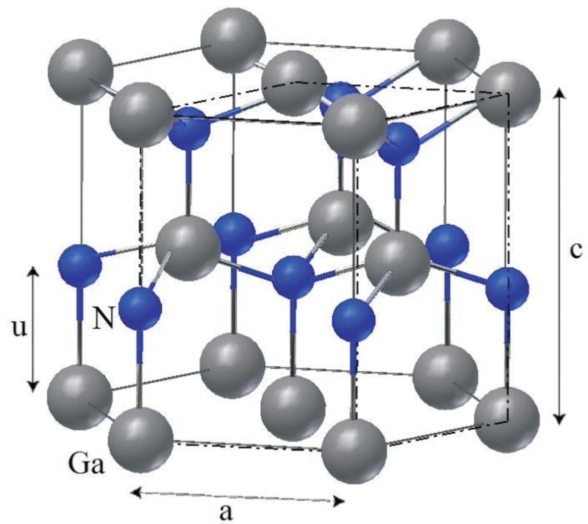
$$\mathbf{P}_e(\lambda) = -\frac{2e}{(2\pi)^3} \int_{BZ} d\,\mathbf{k} \frac{\partial}{\partial \mathbf{k}'} \phi^{(\lambda)}(\mathbf{k}, \mathbf{k}') \Big|_{\mathbf{k}'=\mathbf{k}}$$

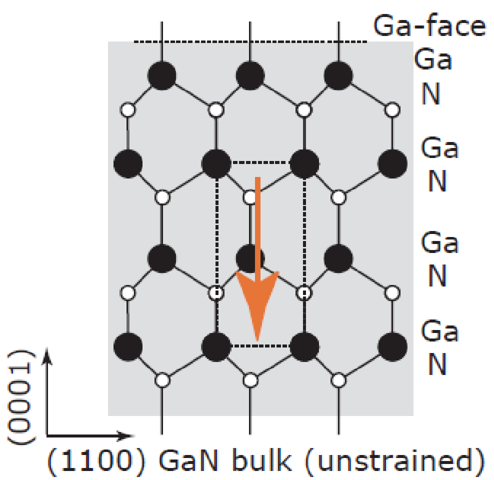
	P^{eq}	Z^*	$du/d\epsilon_3$	e_{33}	e_{31}	$e_{33}^{(0)}$	$e_{31}^{(0)}$
AlN	–0.081	–2.70	–0.18	1.46	–0.60	–0.47	0.36
GaN	–0.029	–2.72	–0.16	0.73	–0.49	–0.84	0.45
InN	–0.032	–3.02	–0.20	0.97	–0.57	–0.88	0.45

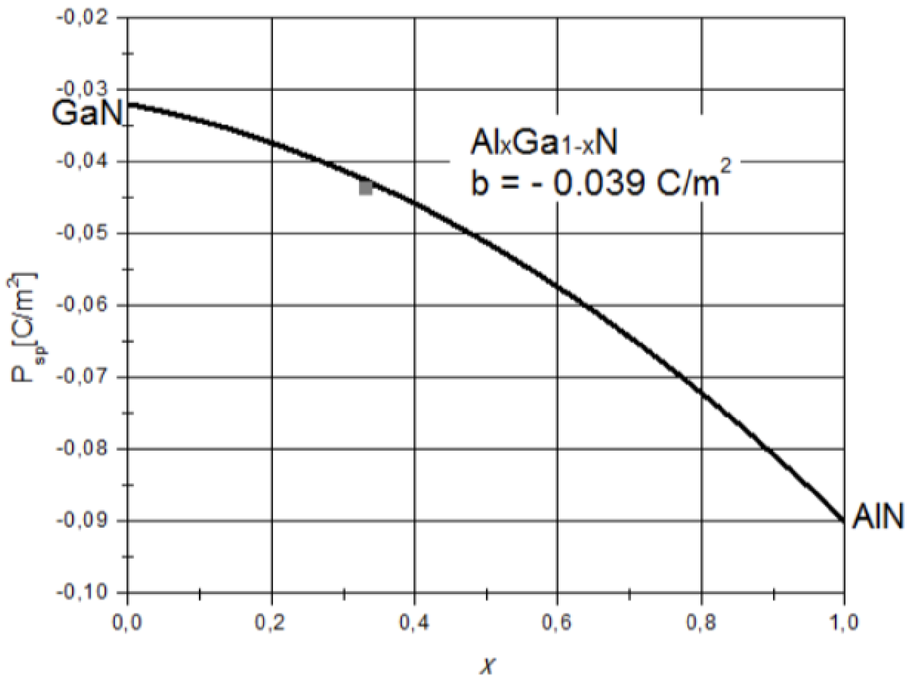
Case for GaN: Basics of III-Nitrides

1. Spontaneous Polarization

Wurtzite structure







Supryadkina et al. Phys. Status Solidi C, 1– 5 (2014)

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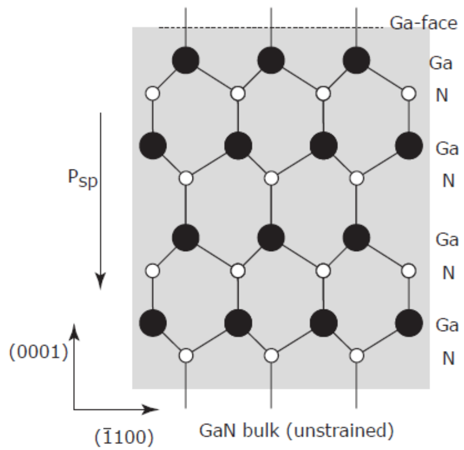
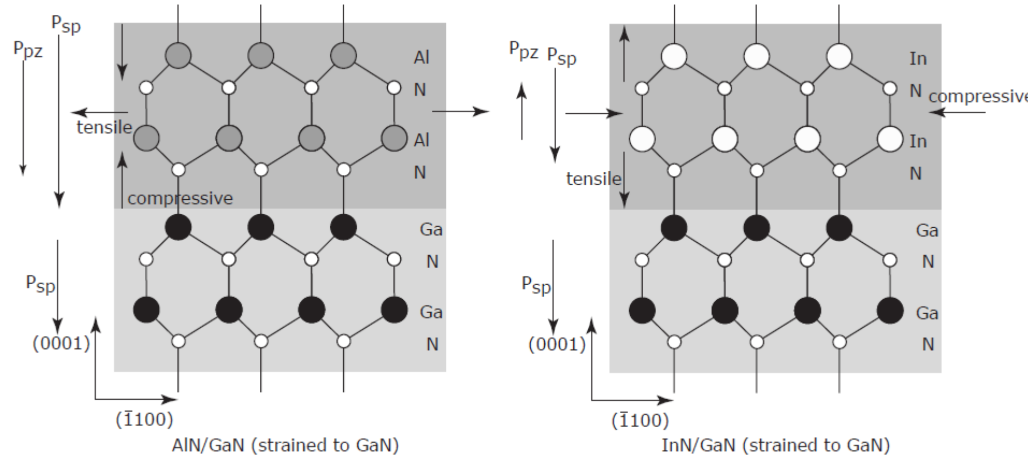
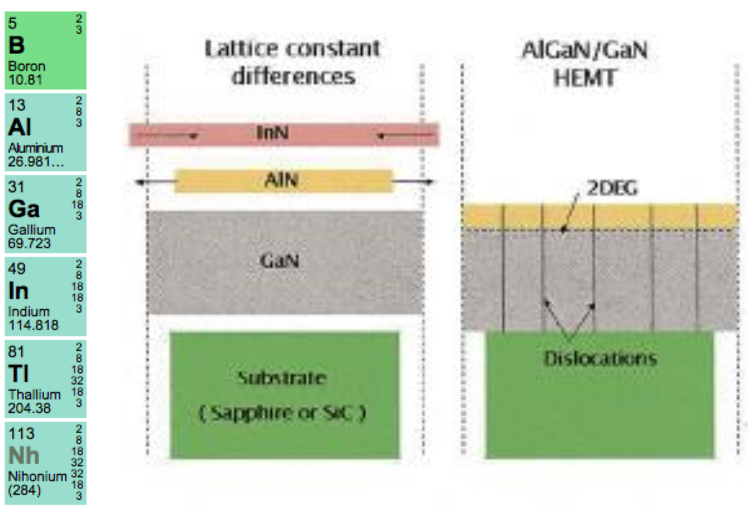
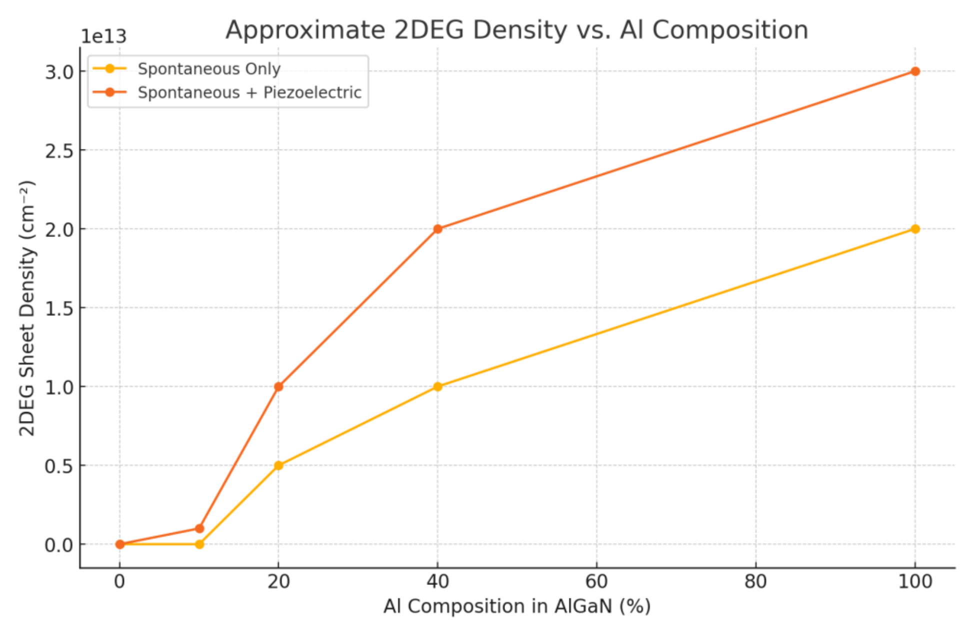
2. Piezoelectric Polarization



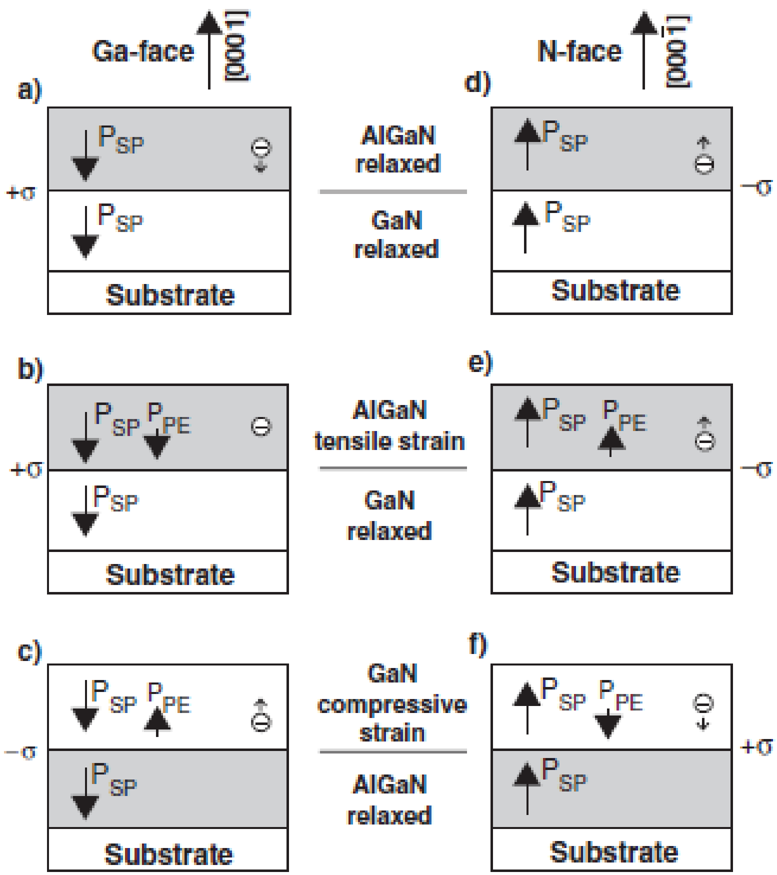






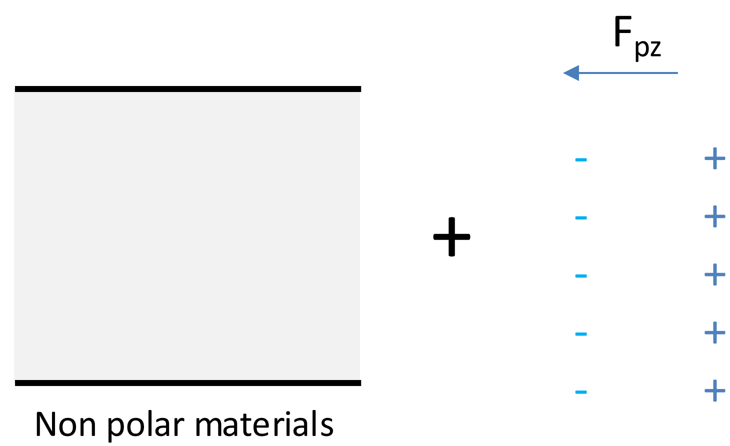
Ambacher et al., J. Appl. Phys., Vol. 85, No. 6, 15 March 1999
UMESH K. MISHRA, POCEEDINGS OF THE IEEE, VOL. 90, NO. 6, JUNE 2002

Spontaneous and piezo contributions

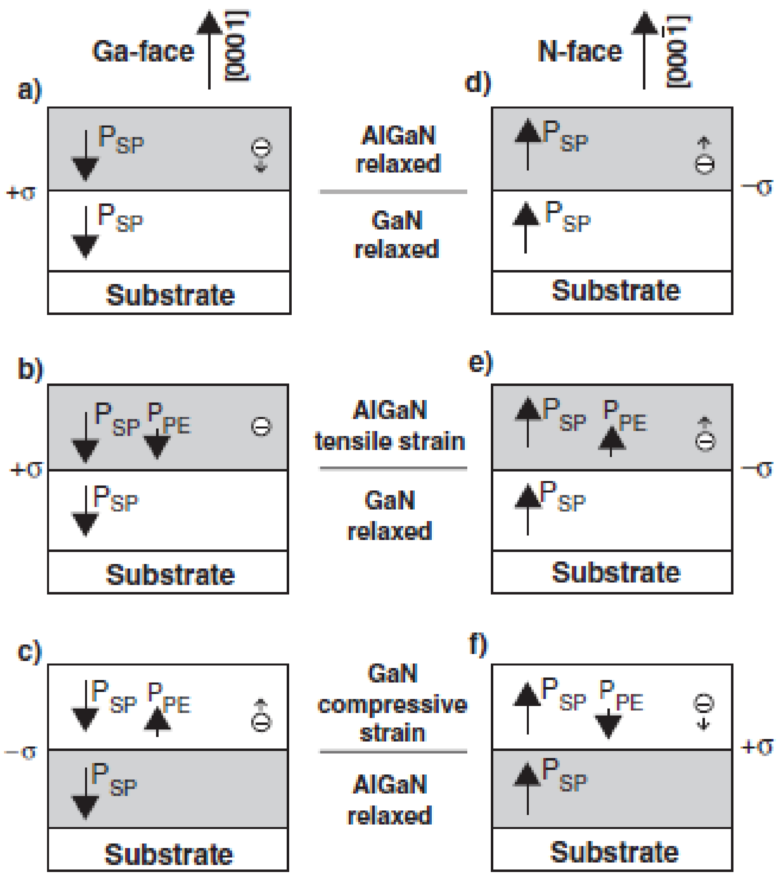


C. Wood et al. "Polarization effects in Semiconductors"

What does it do to the band structures?



Spontaneous and piezo contributions



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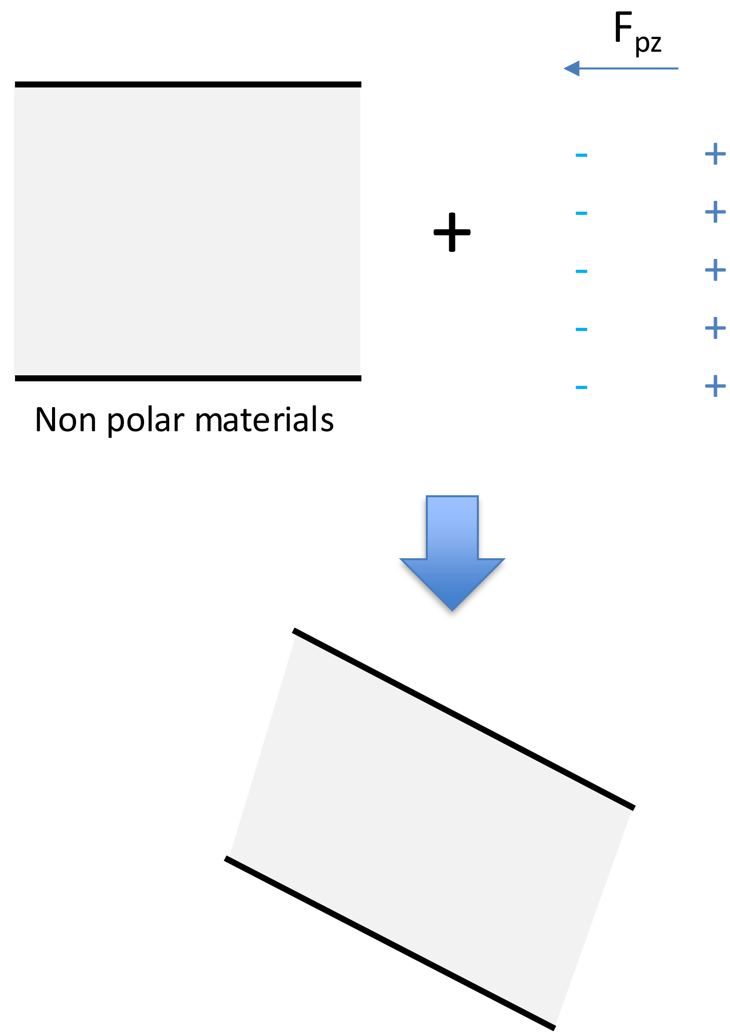

Polarization fields create slopes in the bands!

How to make useful devices

Uniqueness of III-Nitrides

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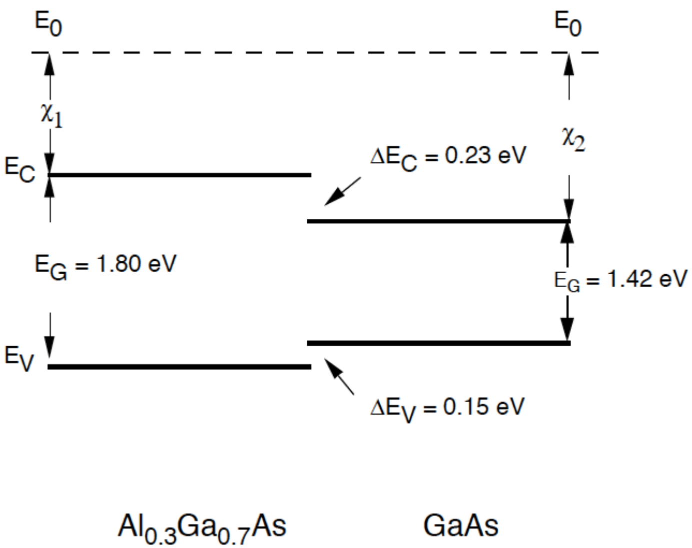
Very unique property of Nitrides:

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

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

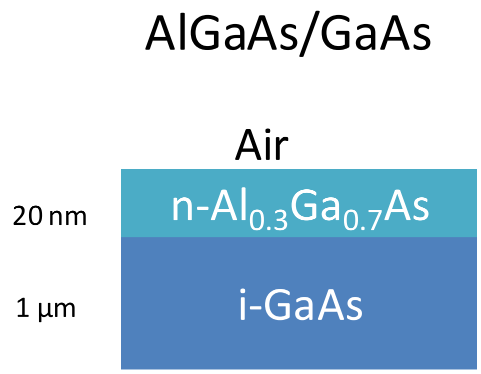
AlGaAs/GaAs



AlGaN/GaN

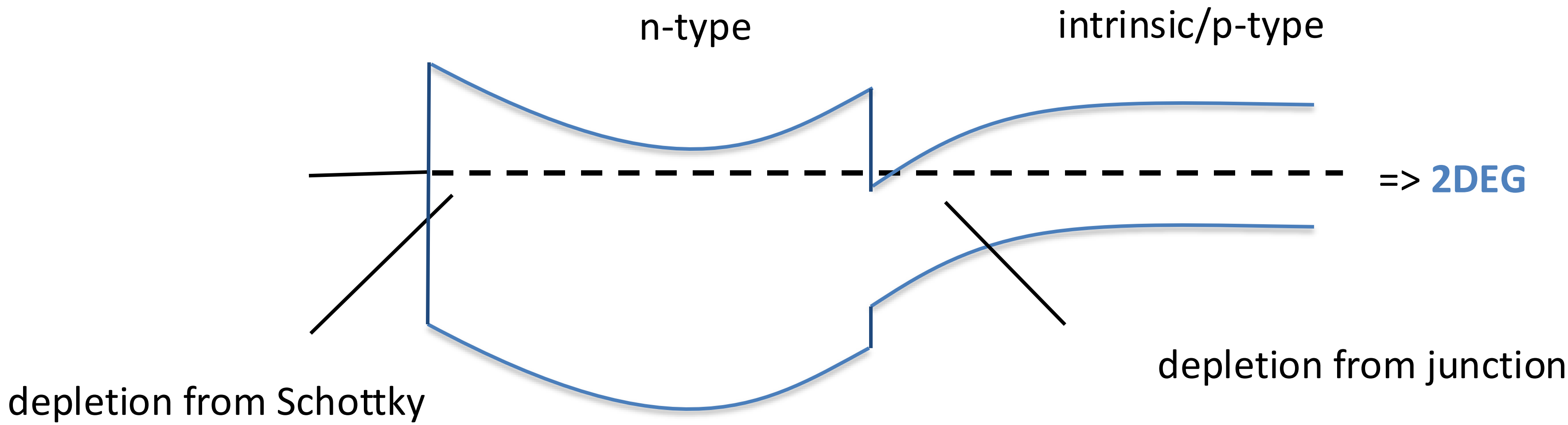
?

Simple case: AlGaAs/GaAs

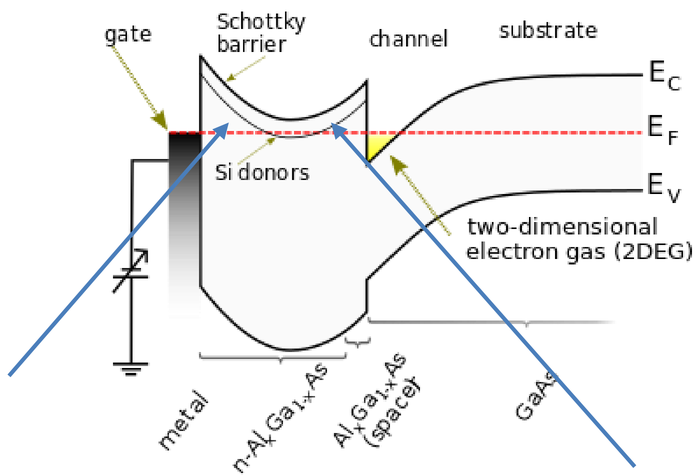


Simple case: AlGaAs/GaAs

+ Schottky gate => **HEMT**



HEMT

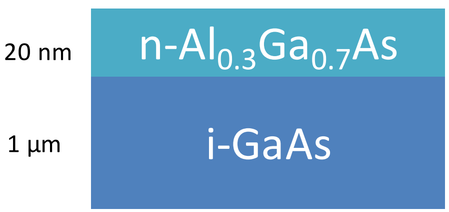


Well designed HEMT: barrier fully depleted (needed for gate control)

Simple case: AlGaAs/GaAs

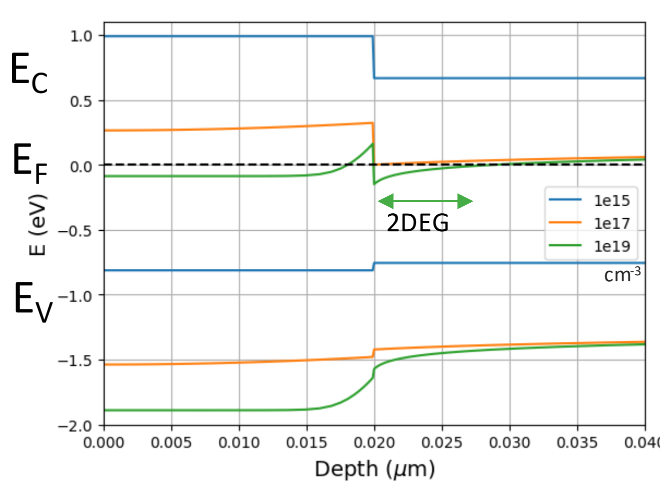
AlGaAs/GaAs

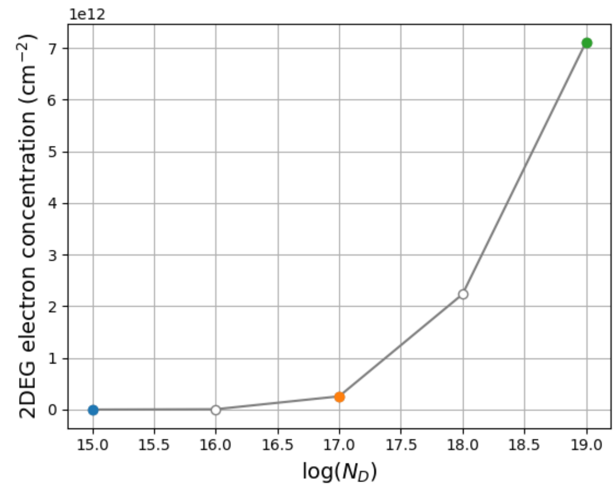
Vary donor concentration



Model details

- Uniform doping profile
- No surface states

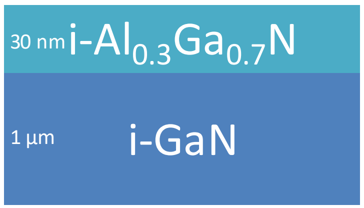




2DEG is formed by n-doping the AlGaAs barrier

GaN polarization: First "naïve" picture

Effect of polarization on creating the 2DEG: "First picture"



GaN polarization: First "naïve" picture

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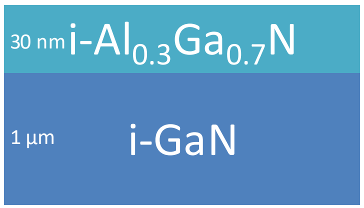
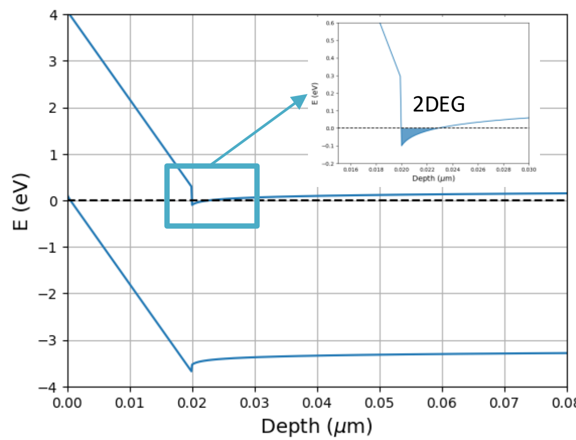
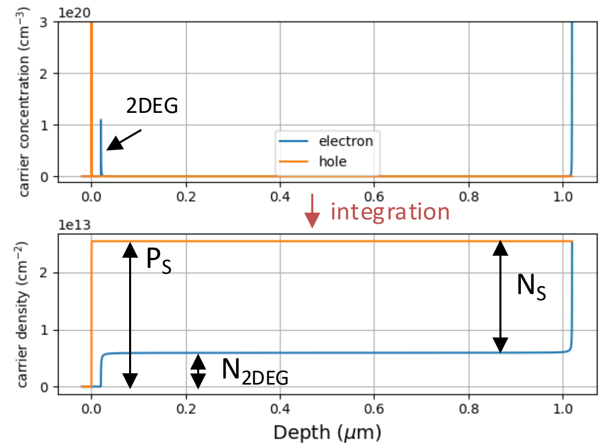
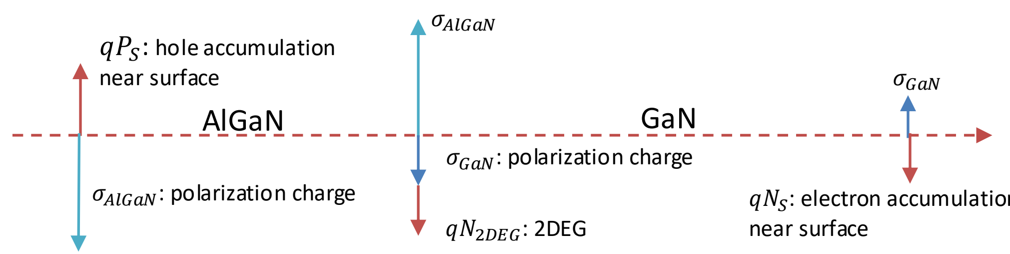






Charge balance: $N_{2DEG} = P_S - N_S$



Is this picture correct?

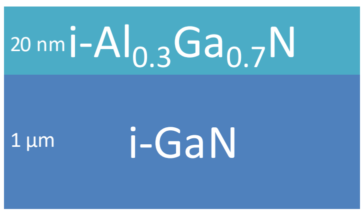
GaN polarization: surface states

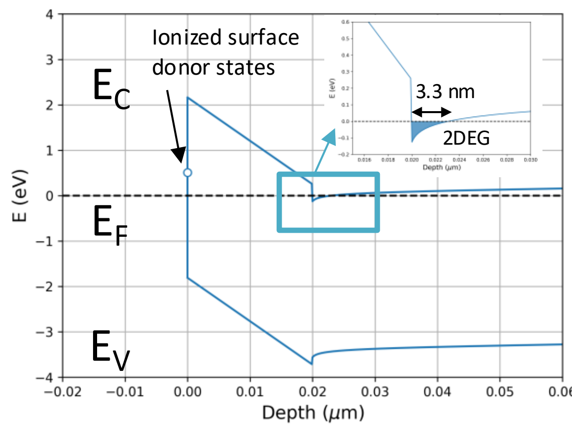
No! electrons come from surface and buffer states, which populate the 2DEG channels*

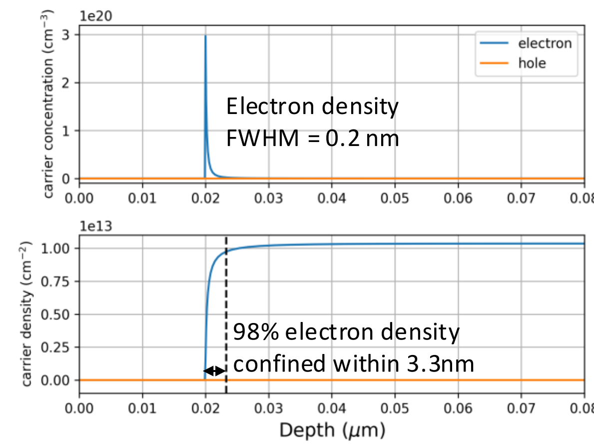
*J. P. Ibbetson; P. T. Fini; K. D. Ness; S. P. DenBaars; J. S. Speck; U. K. Mishra, **Appl. Phys. Lett.** 77, 250–252 (2000)

AlGaN/GaN with surface traps

P_S = 0, 2DHG comes from ionized surface donor states (P_D)







Model details

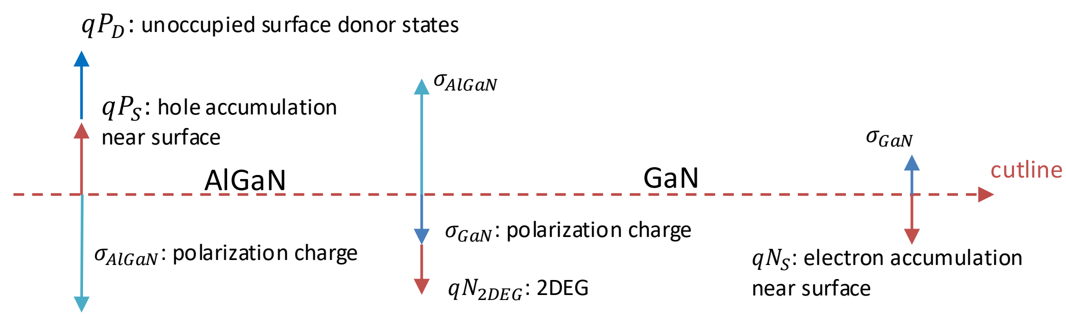
Traps on AlGaN surface

- E_C-E_t = 1.65 eV
- N_t = 3e13 cm^{-2}

Traps on i-GaN bottom

- E_t-E_V = 2.53 eV
- N_t = 3e13 cm^{-2}

Charge balance: $N_{2DEG} = P_D + P_S - N_S$



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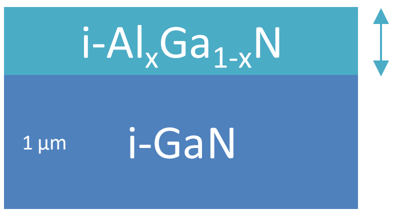
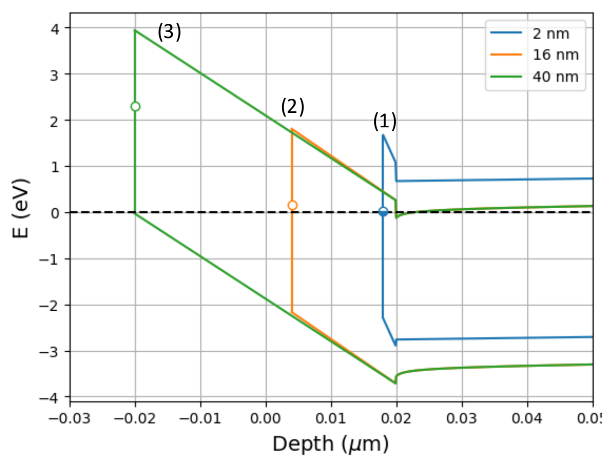
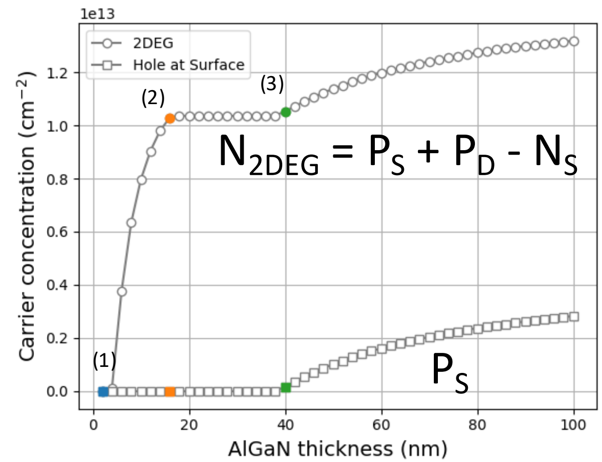
AlGaN/GaN with surface traps

Varying AlGaN thickness







(1) surface donors partially ionized, P_D increase, $P_S = 0$

- At 2nm, $P_D - N_S = 0$, no 2DEG is formed

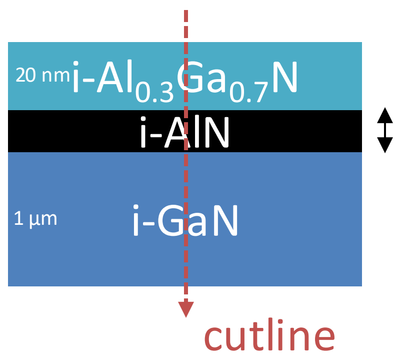
(2) surface donors are fully ionized, $P_S = 0$

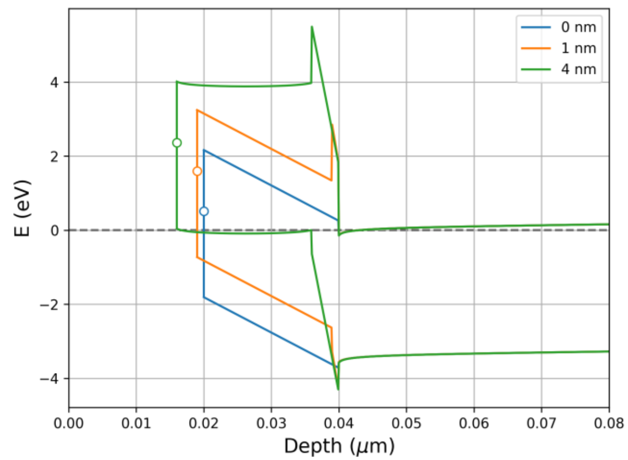
(1) hole start accumulating at surface, P_S increase

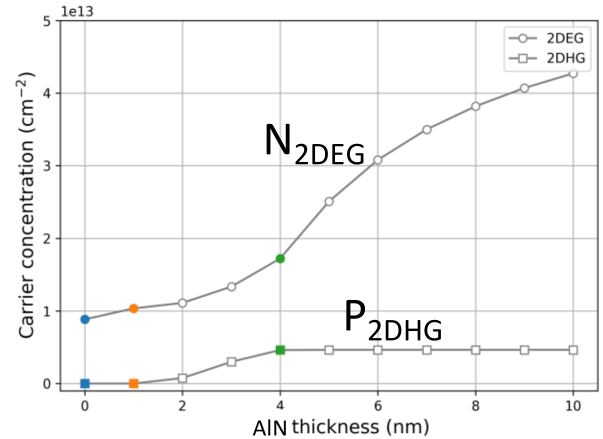
GaN polarization: surface states

AlGaN/GaN with AlN interlayer

Vary AlN thickness:





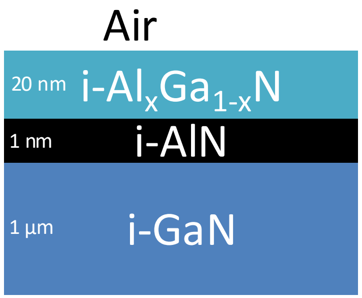


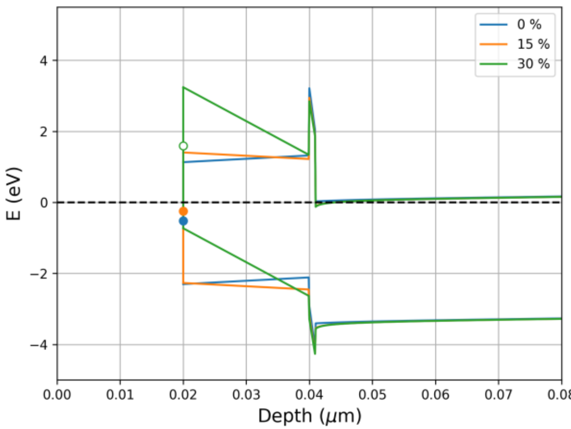
- 1 nm interlayer does not boost the 2DEG concentration, but improves mobility by reducing alloy scattering
- 2DHG forms at AlGaN/AlN interface when AlN is thick

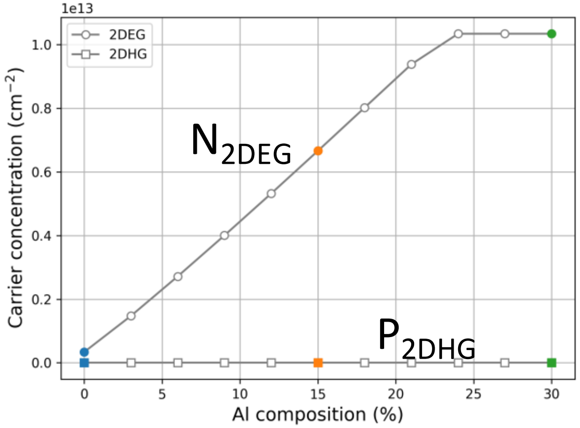
GaN polarization: surface states

Varying Al composition of the barrier:

Vary barrier composition:



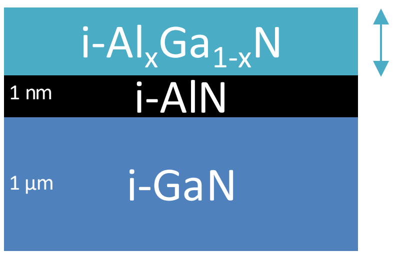


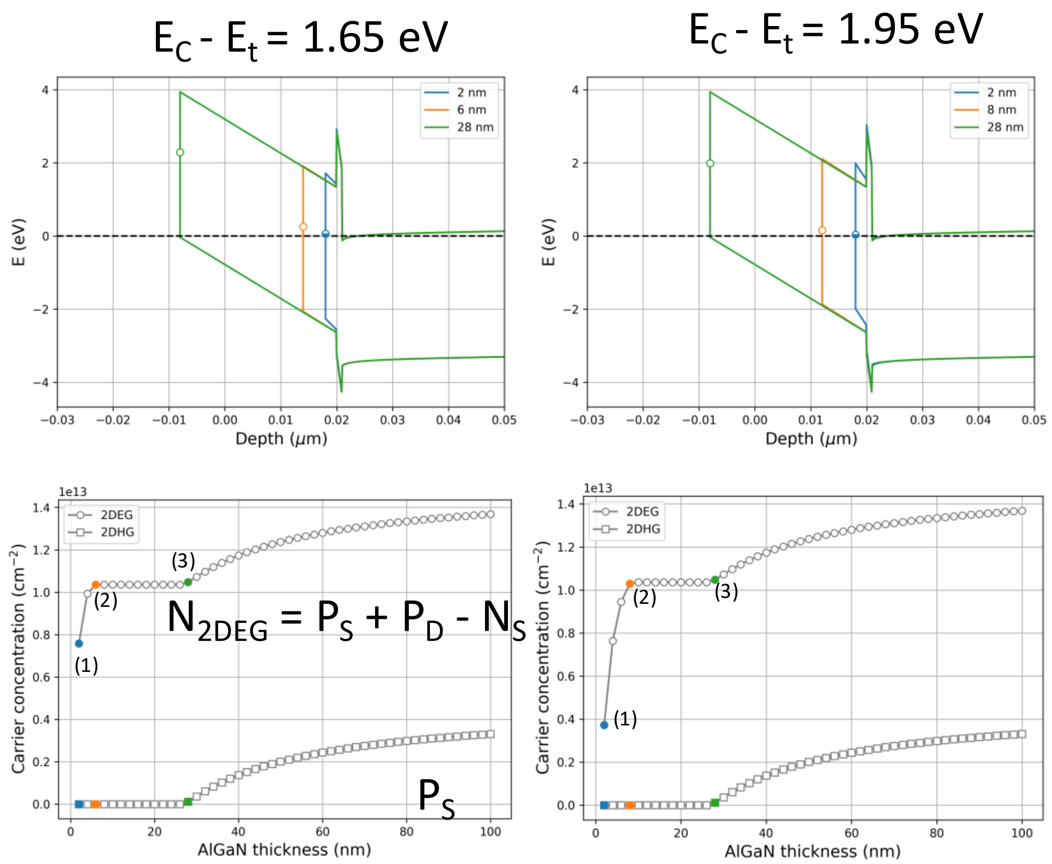


2DEG density increases with Al composition and saturates as the surface states are fully ionized

GaN polarization: surface states

Vary AlGaN thickness and surface trap level





- Deeper trap takes larger AlGaN thickness to fully ionize
- But the maximum contribution of discharged surface state is the same, limited by donor state density

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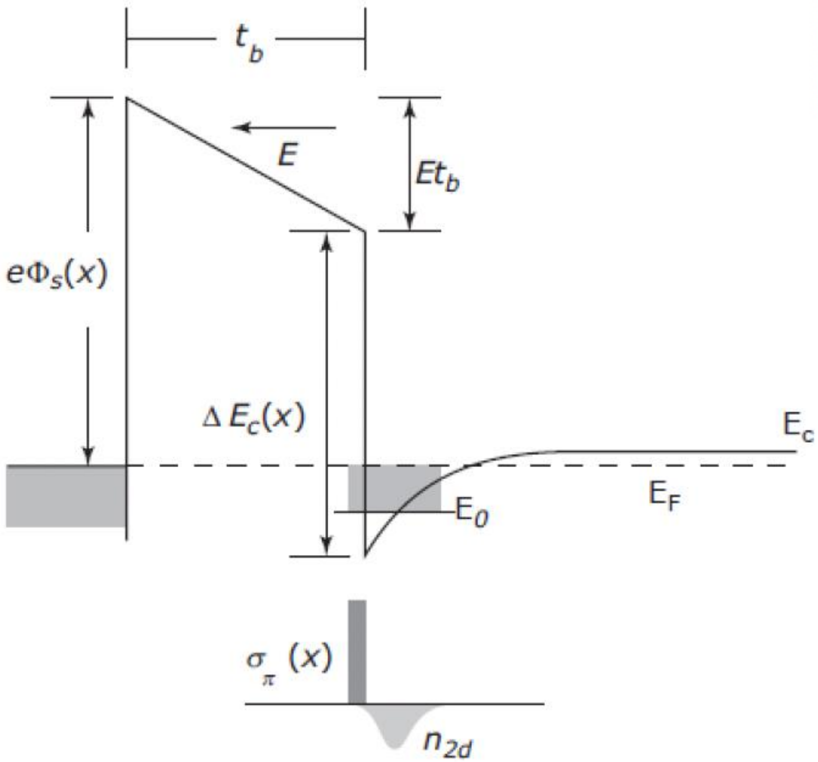
Simplified analytical description of GaN HEMT: charge control



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

From Gauss' law:

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

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

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

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

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

$\epsilon(x)$ absolute electric permittivity

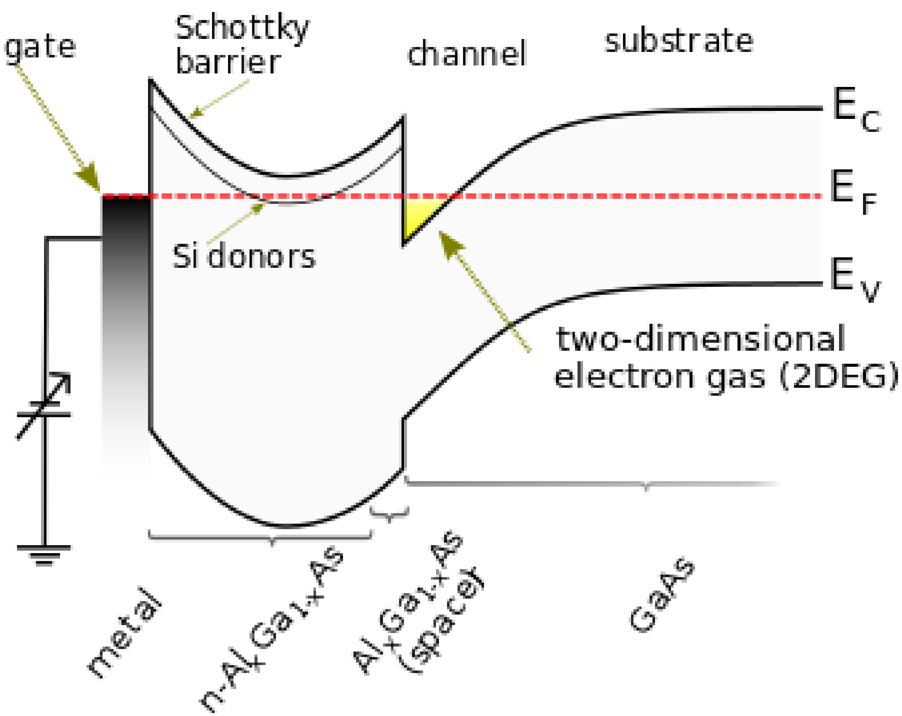
Express n_{2D} analytically and neglect E_F dependence on n_{2D}

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

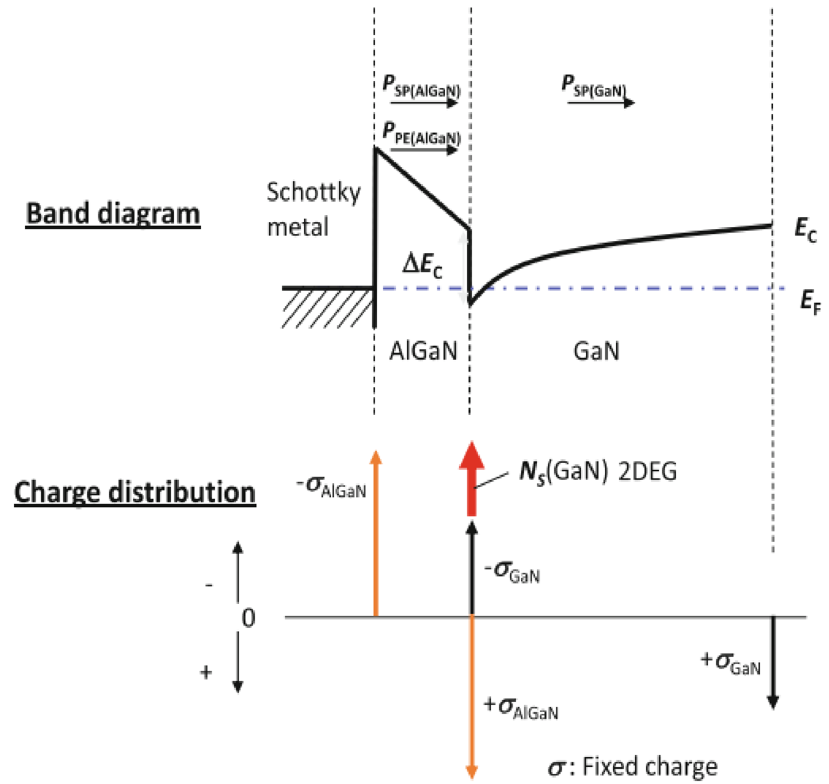
D. J. C. Wood, Polarization Effects in Semiconductors, 1st ed. Springer US, 2008, ISBN: 978-0-387-68319-5.

Summary: difference between Arsenides and Nitrides

AlGaAs/GaAs



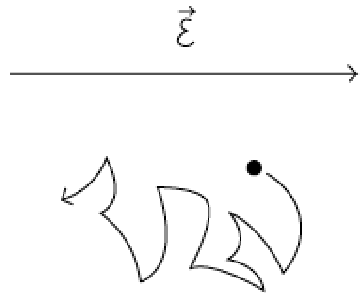
AlGaN/GaN

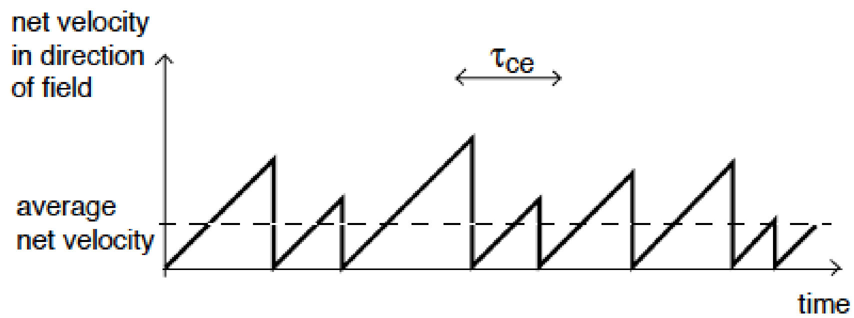


Why are these structures important?

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

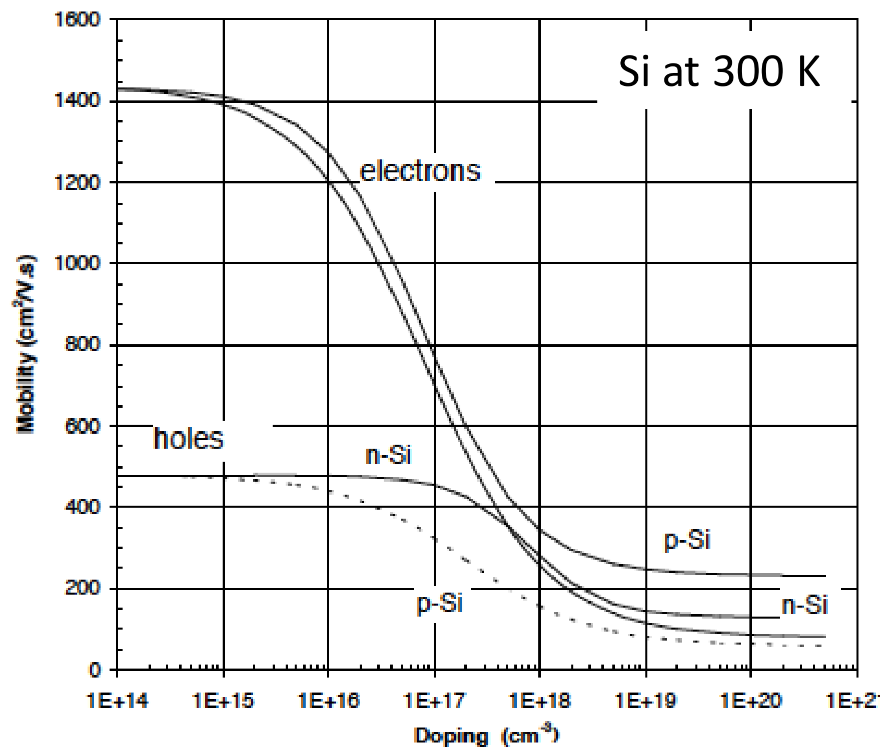
In the presence of an electric field, electrons drift:

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

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

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

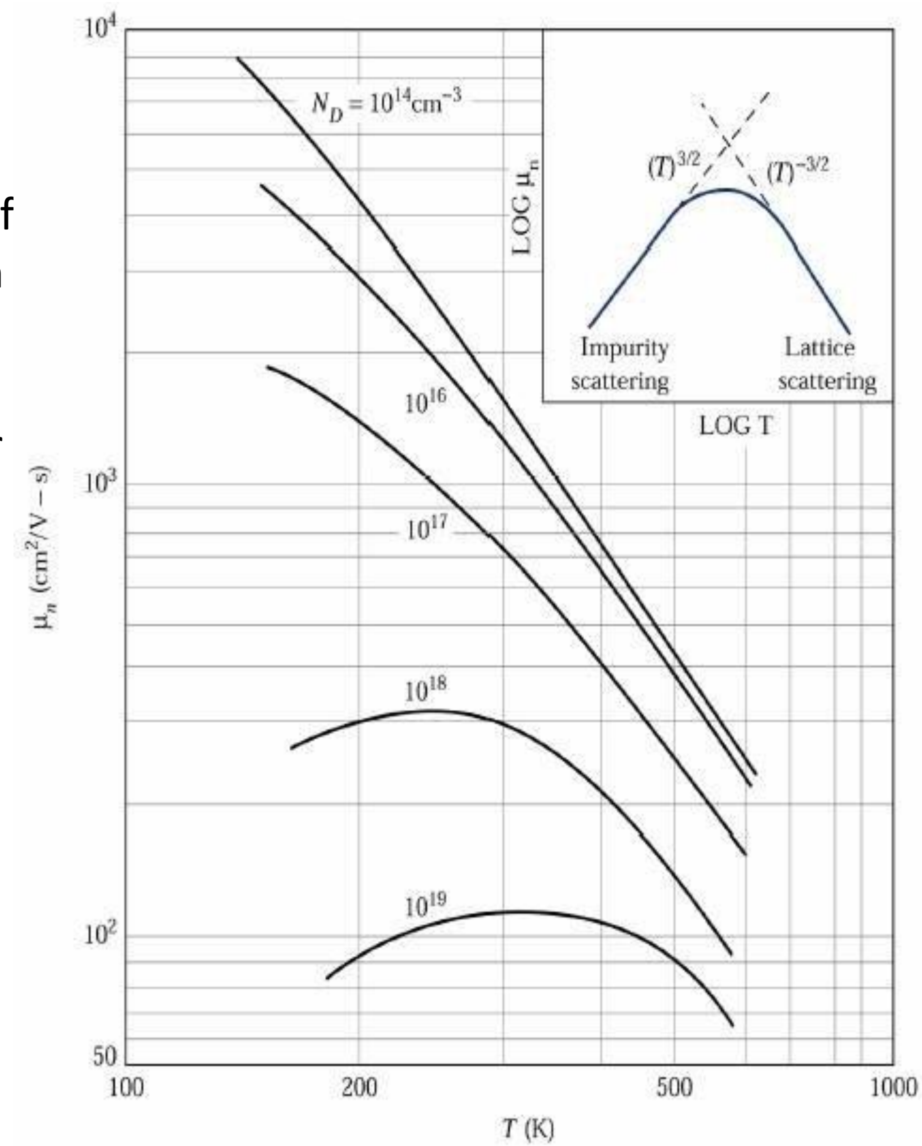
Increasing temperature and increasing doping results in reduction of mobility.

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.

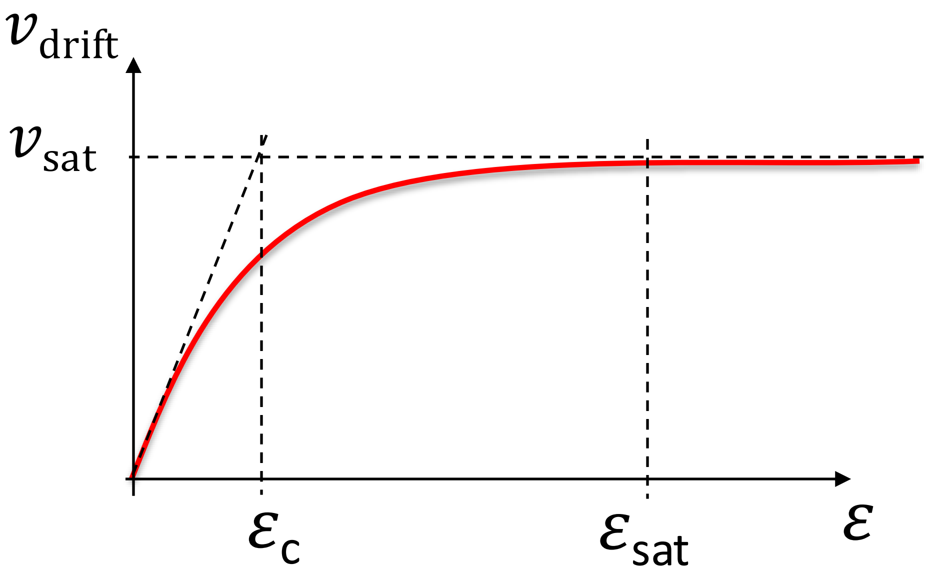
Thus:

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**



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

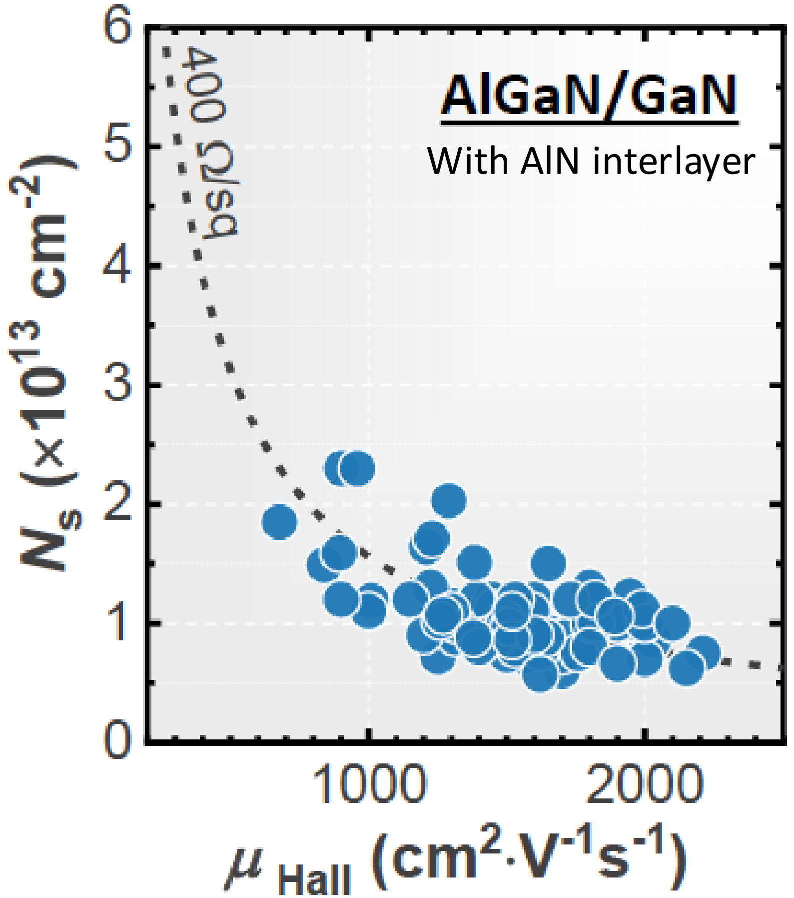
$$v_{\text{sat}} = \frac{\omega_{\text{op}}}{4\sqrt{2\pi n_s}}$$

ω_{op}: optical phonons

Velocity saturation in GaN devices: 2.5-3x10^7 cm/s

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

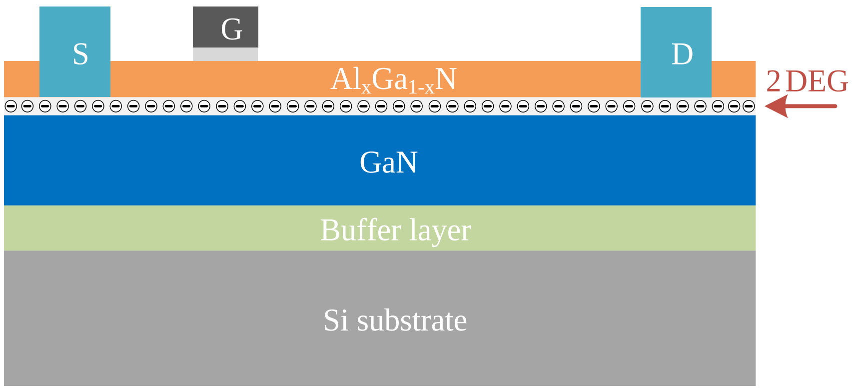
Intrinsic trade-off: in a 2DEG increasing n_s deteriorates μ

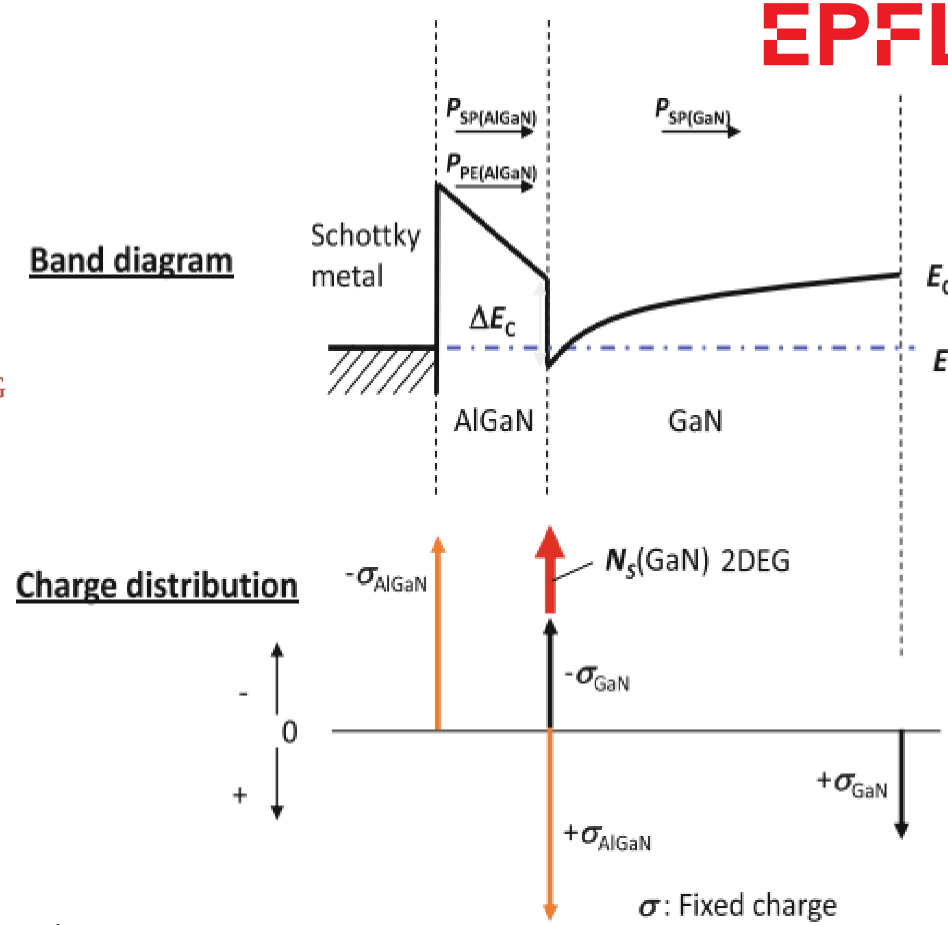


Low sheet resistance (R_{sh}) requires both high n_s and high μ

Lateral devices

HEMTs or MOSHEMTs



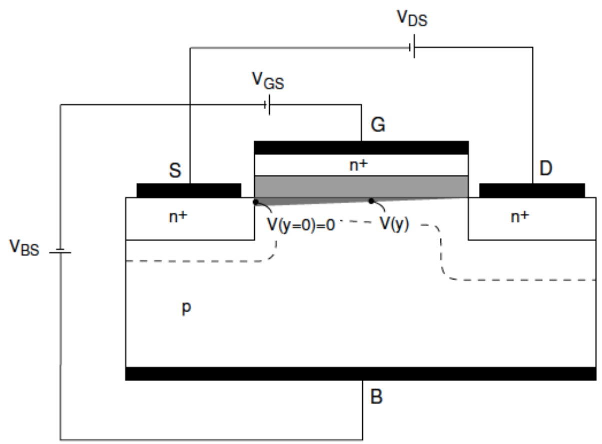


- GaN system: no need for doping (Contrary to AlGaAs/GaAs)
- Mobilities over 2200 $cm^2/V{\cdot}s$
- Large carrier density, over $10^{13} cm^{-2}$
- Carriers are induced by donor-like surface states at the AlGaN surface facilitated by spontaneous and piezoelectric polarization electric field inside the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

High Electron Mobility Transistors (HEMTs)

Comparison between MOSFETs and HEMTs

MOSFET



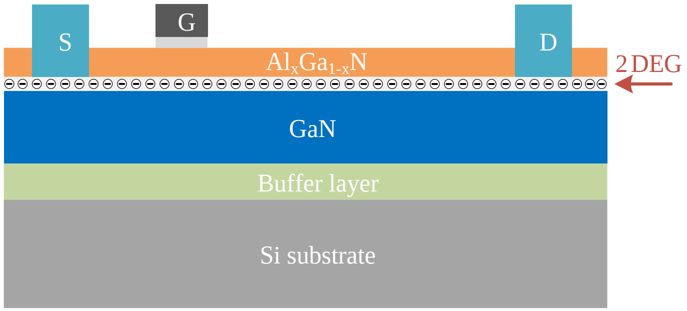
Mobility of the inverter channel is low

- Electrons propagate in a doped medium

Enhancement-mode device:

normally-off operation

HEMT



Due to the 2DEG:

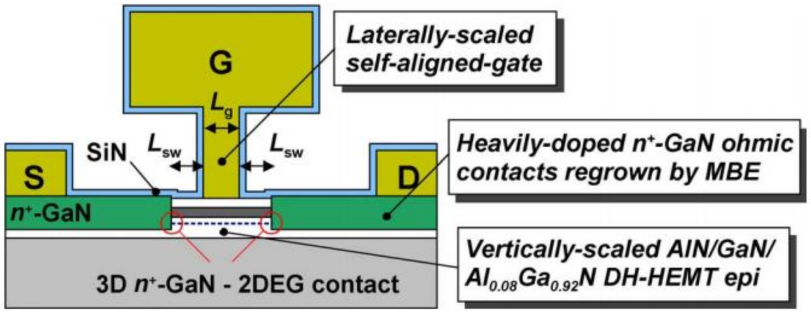
- Superior mobility
- Higher frequency
- Lower noise figure
- If GaN: higher power density

Depletion-mode device:

normally-on operation

What can we make with HEMTs

RF devices: high frequency and high output power



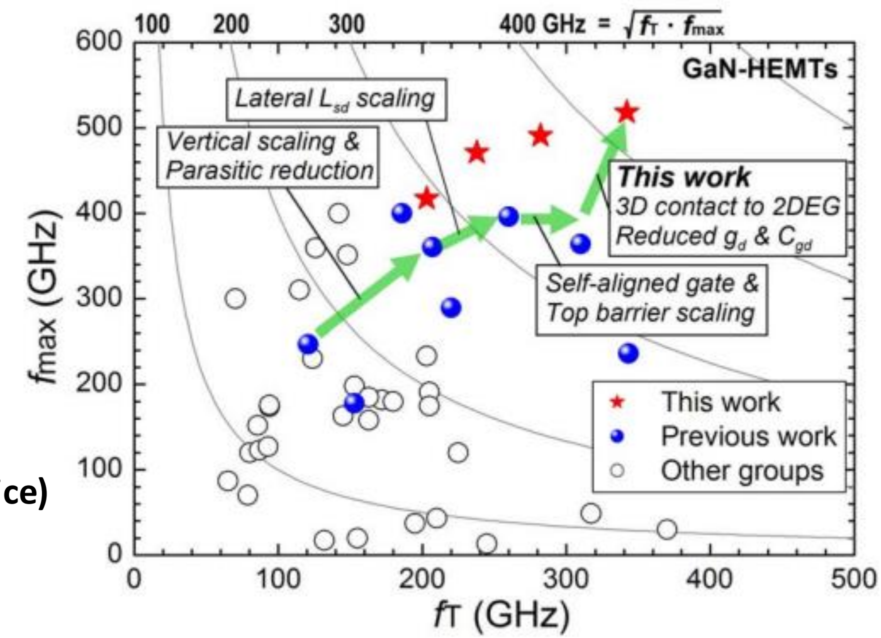
IEEE ELECTRON DEVICE LETTERS, VOL. 36, NO. 6, JUNE 2015

Ultrahigh-Speed GaN High-Electron-Mobility Transistors With f_T/f_{max} of 454/444 GHz

Yan Tang, Keisuke Shinohara, *Senior Member, IEEE*, Dean Regan, Andrea Corrion, *Member, IEEE*, David Brown, *Member, IEEE*, Joel Wong, Adele Schmitz, Helen Fung, Samuel Kim, and Miroslav Micovic, *Member, IEEE*

- Barrier thickness: 3.5 nm
- ns = 1.5×10^{13} cm^{-2}
- **mobility (μ) of 1100 cm^2 /V·s**
- Si-doped n^+-GaN ohmic (7×10^{19} cm^{-3}):

  to laterally contact to 2DEG in the GaN channel
- ultra-short gate length of 20nm
- gate-source and gate-drain separation of 70nm
- **fT / fmax as high up to 454/518GHz (not on the same device)**
- **However, Vbr = 10V**



HRL laboratories:

Shinohara et al., IEDM 2011

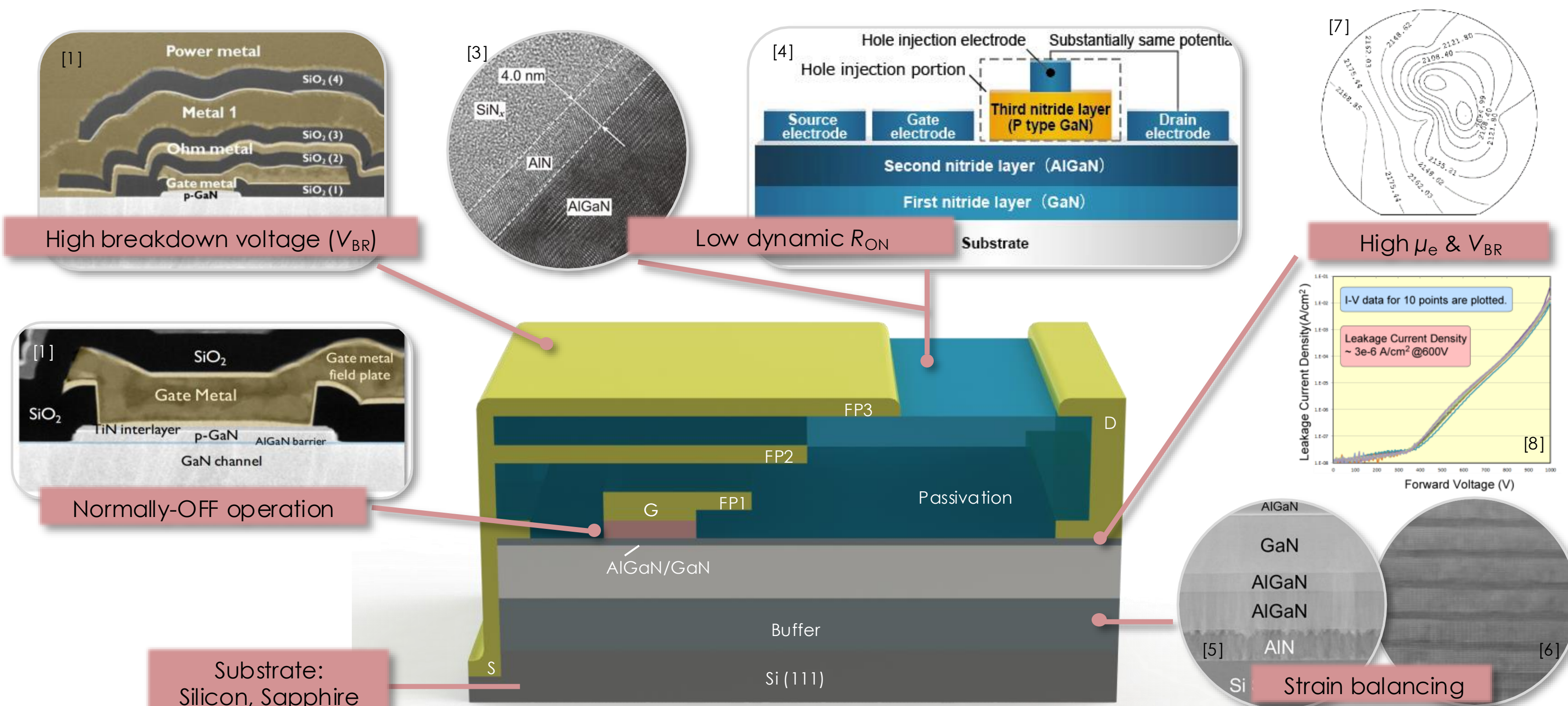
Shinohara et al., IEEE IEDM, Dec. 2012

Tang et al., IEEE ELECTRON DEVICE LETTERS, VOL. 36, NO. 6, JUNE 2015

What can we make with HEMTs

Lateral power devices: high voltage and output power, at high switching frequency

Technologies involved in making a high performance power devices



[1] IMEC, "Perspectives for disruptive 200 mm/8-inch GaN power device and GaN-IC technology," SEMICON Europa 2018. [[3] Y. Lu, Q. Jiang, Z. Tang, S. Yang, C. Liu and K. J. Chen, Appl. Phys. Express 8, 064101 (2015). [4] https://industrial.panasonic.com/kr/products/semiconductors/powerics/ganpower
[5] https://compoundsemiconductor.net/article/99114-heat-sinking-gan-on-silicon-the-substrate-removal-challenge.html [7] http://en.enkris.com/cp/html/?31.html
[6] https://www.researchgate.net/post/Determination_of_the_lattice_parameter_of_the_GaN_AlN_layers_of_a_superlattice_from_TEM_images [8] http://www.ntt-at.com/product/epitaxial/