Génie Electrique et Electronique
Master Program
Prof. Elison Matioli

EE-557
Semiconductor devices I

Power semiconductor devices

Outline of the lecture

Semiconductor heterostructures

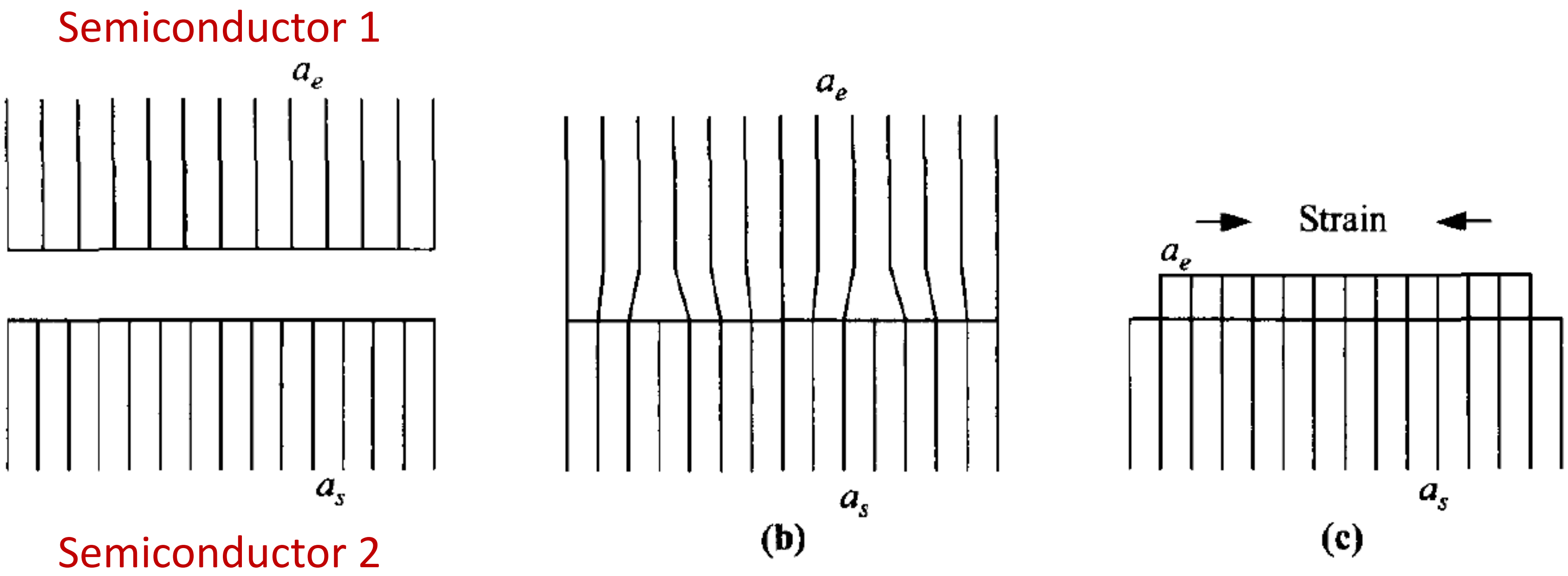
- Effect of different lattices: strain, dislocations…
- Band alignments
- HEMTs
- Advanced device concepts

Key questions

- What happens when 2 different semiconductors are connected together?
- How to make fast devices with such structure?

Epitaxial growth of heterojunctions

The successful applications of heterojunctions in various devices is due to the capability of epitaxy technology to grow semiconductor materials on top of one another with virtually no interface traps.



If the lattice constants are not severely mismatched, good-quality heteroepitaxy can still be grown, provided that the epitaxial layer is thin enough. The amount of lattice mismatch and the maximum allowed epitaxial layer are directly related.

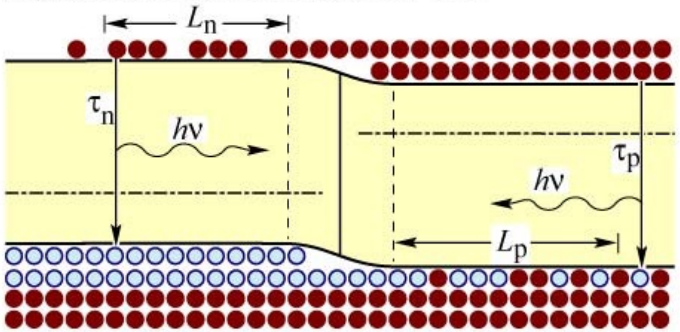
lattice mismatch is defined as

$$\Delta \equiv \frac{|a_e - a_s|}{a_e}$$

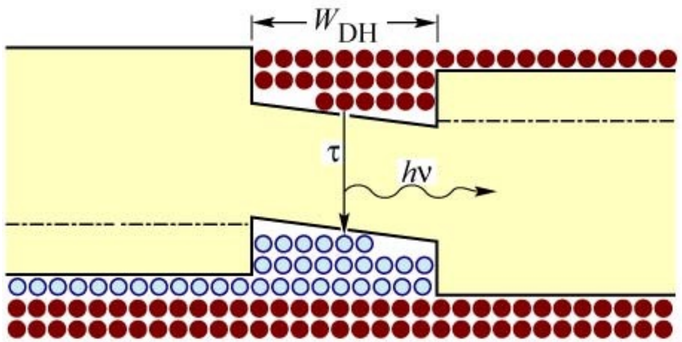
Heterojunctions – quantum wells for light emitting devices

Quantum wells (QW)

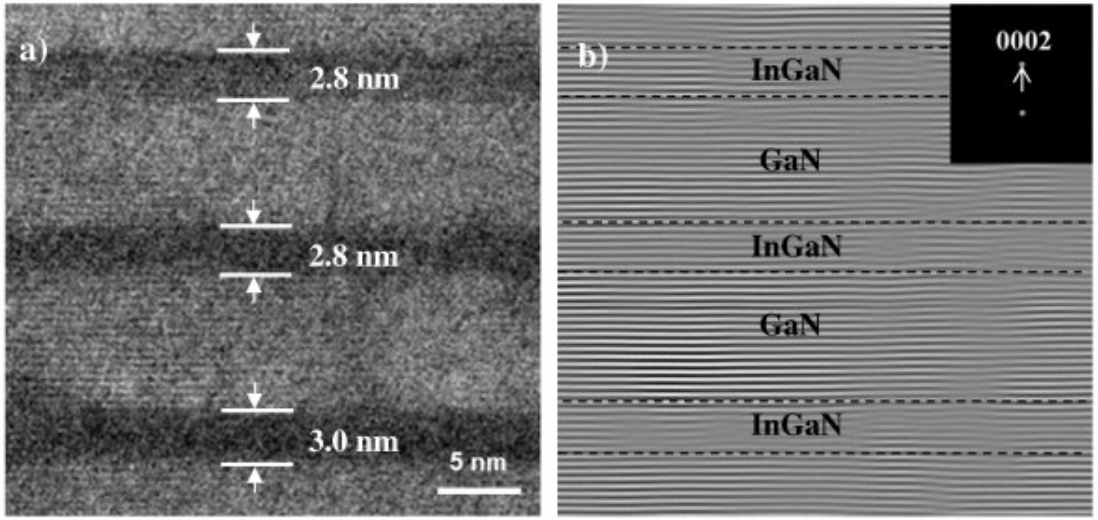
(b) Homojunction under forward bias



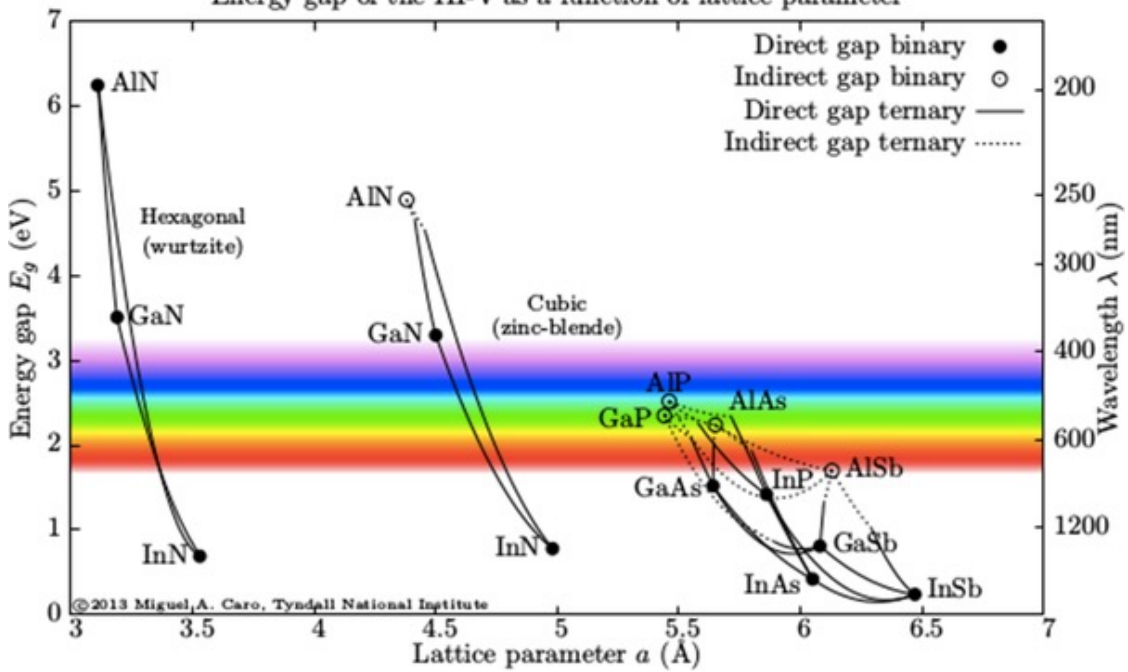
(c) Heterojunction under forward bias



e.g Blue LEDs – InGaN/GaN QWs



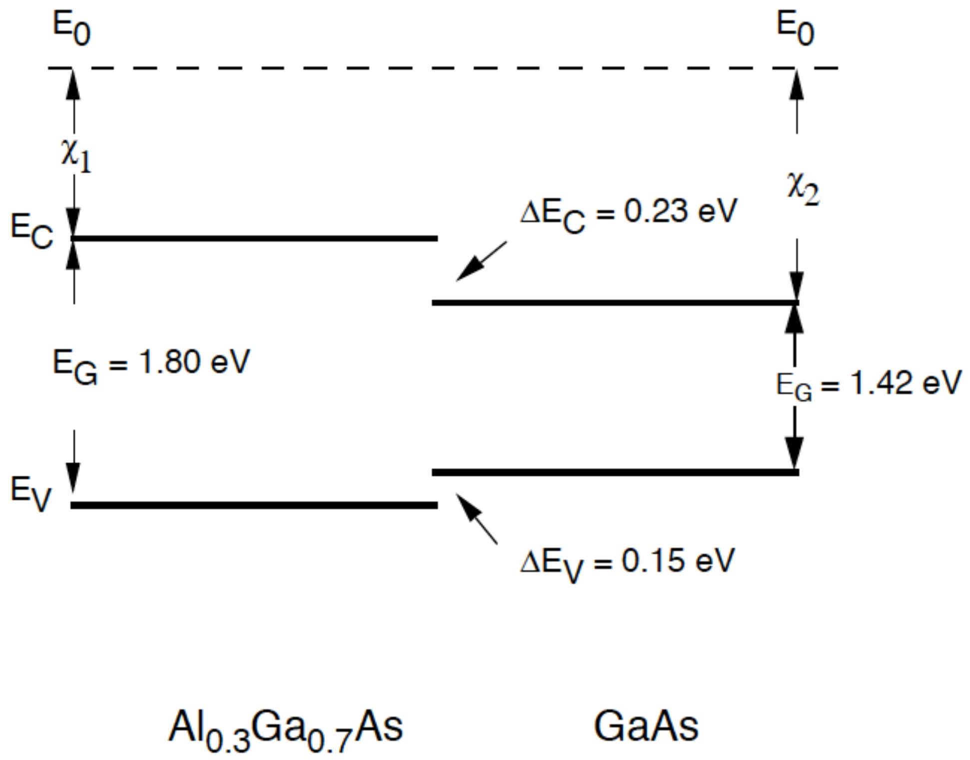
Energy gap of the III-V as a function of lattice parameter



Energy Bands in Abrupt Heterojunctions

Drawing energy band diagrams for abrupt heterojunctions, it is essential to know more about the device operation. We must also know how the bands line up at compositional junctions

Type I heterojunctions: $Al_{0.3}Ga_{0.7}As/GaAs$



For $Al_xGa_{1-x}As$, the offset in valence bands is observed to be about 40% of the difference in band gaps.

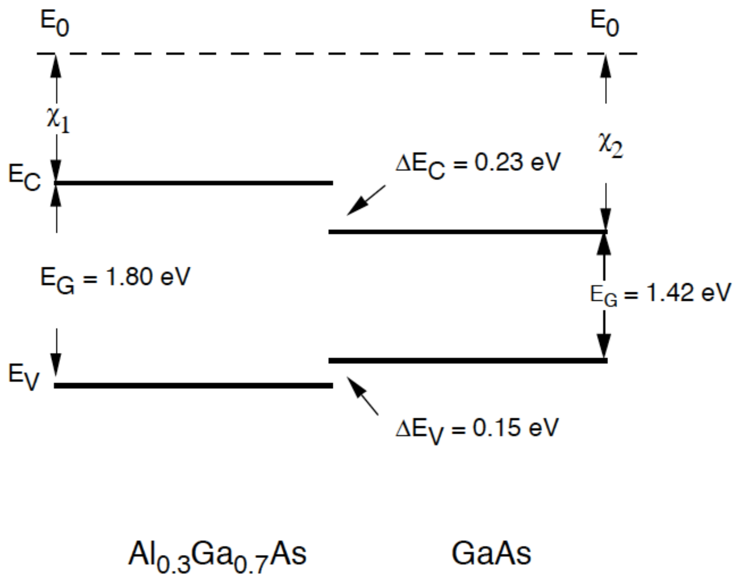
For this material pair, the conduction and valence bands of the smaller bandgap semiconductor lie completely within the bandgap of the wider bandgap semiconductor: **type I heterojunctions**

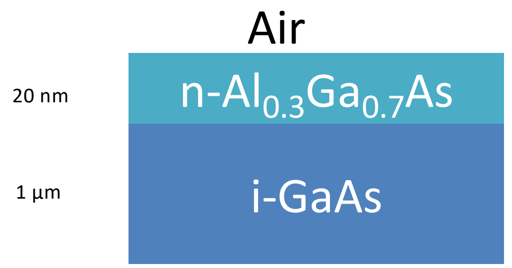
How to make fast devices for RF applications

Simple case: AlGaAs/GaAs

Heterojunctions: AlGaAs/GaAs

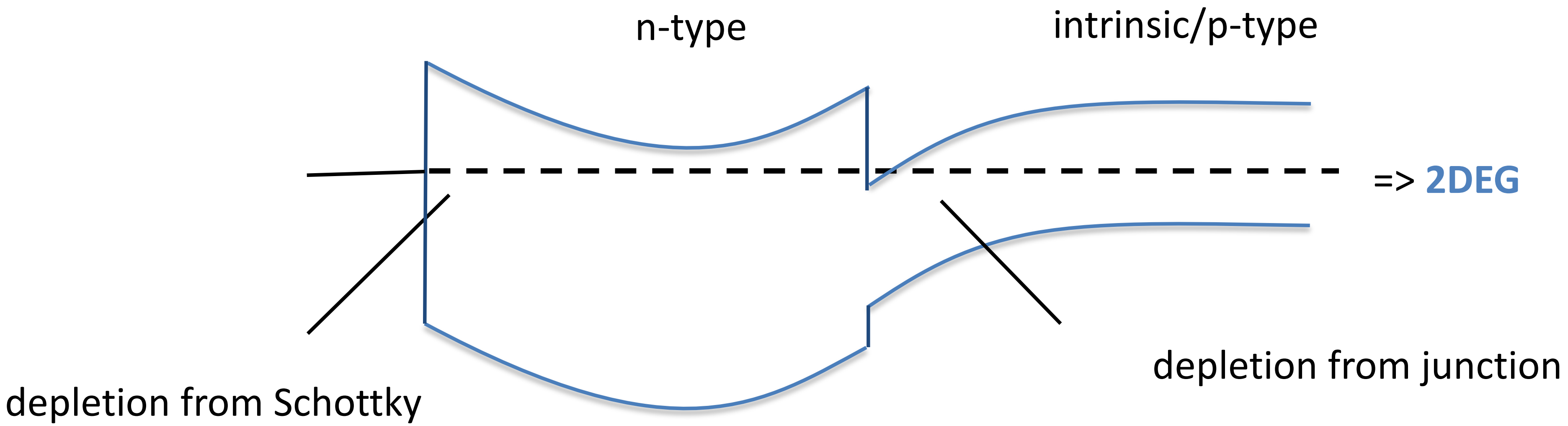
AlGaAs/GaAs





Simple case: AlGaAs/GaAs

+ Schottky gate => **HEMT**



At the semiconductor heterojunction **electrons are transferred** from the material with the higher conduction band energy E_C to the material with the lower E_C where they can **occupy a lower energy state**.

This can be a large number of electrons especially if the semiconductor with the high E_C barrier is doped.

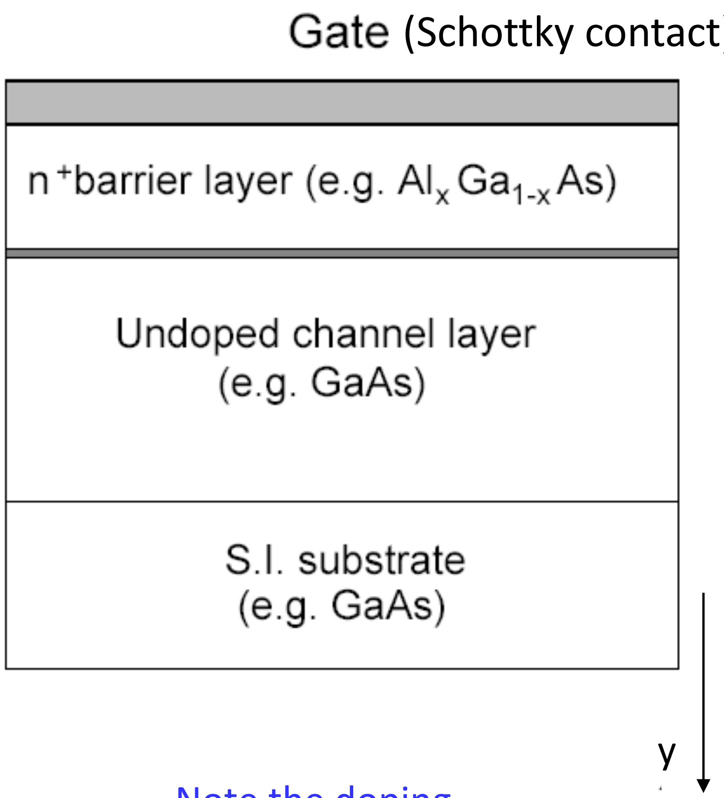
Near the interface a **two dimensional electron gas (2DEG)**, the channel, is created.

High Electron Mobility Transistors (HEMTs)

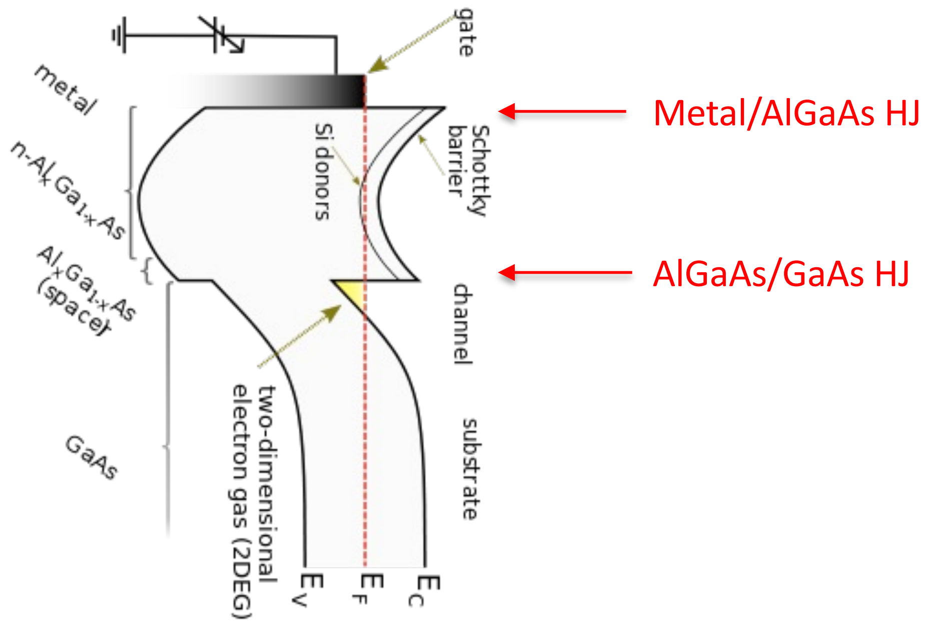
HEMTs are **field effect transistors** where the current flow between two ohmic contacts, source and drain, is controlled by a third contact, the gate.

Most often the gate is a **Schottky contact**, but can also be MISFETs (metal-insulator-semiconductor)

HEMTs are based on **heterojunctions**: epitaxially grown layers with different band gaps Eg



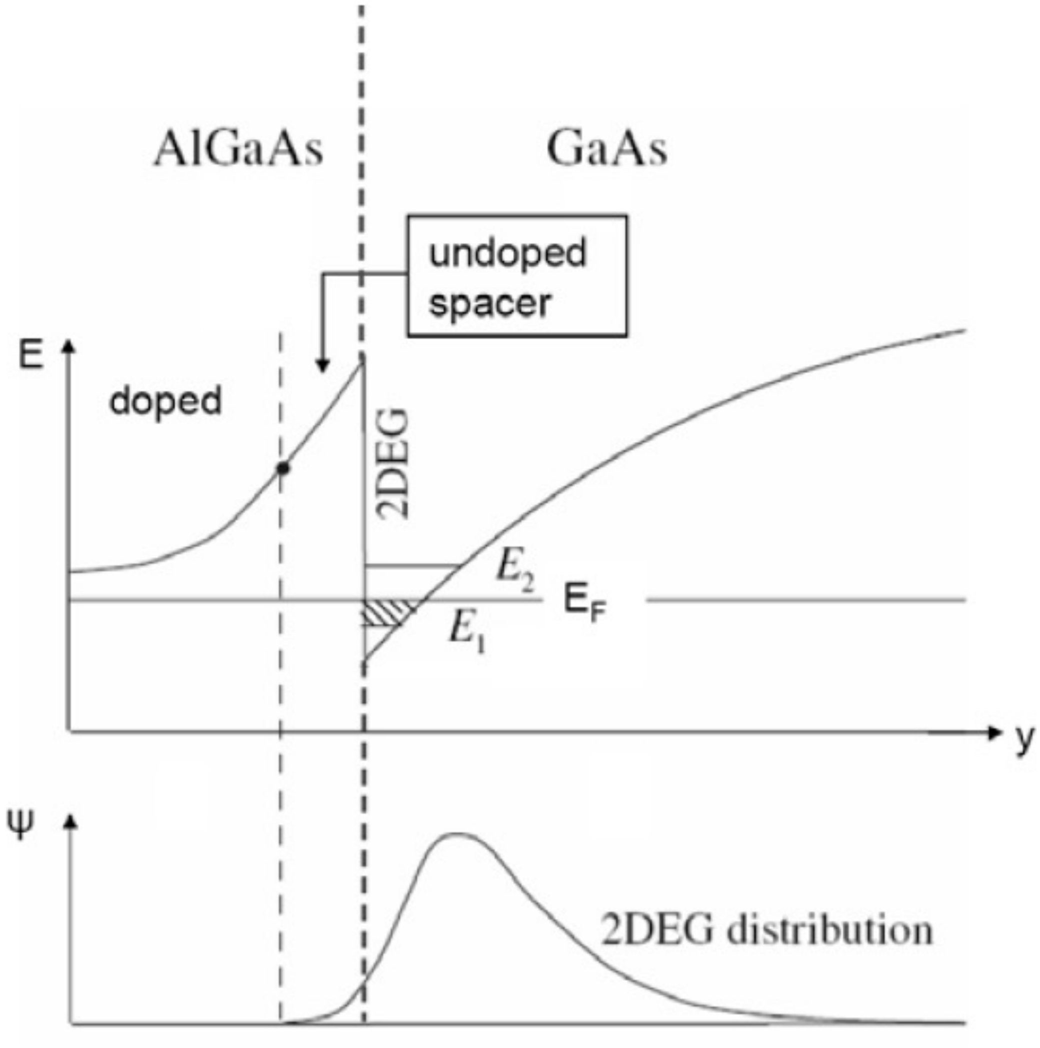
Note the doping



Why is a two dimensional electron gas (2DEG) important?

High Electron Mobility Transistors (HEMTs)

Electrons in GaAs suffer scattering from dopants in the AlGaAs: electron wavefunction overlaps the doped barrier

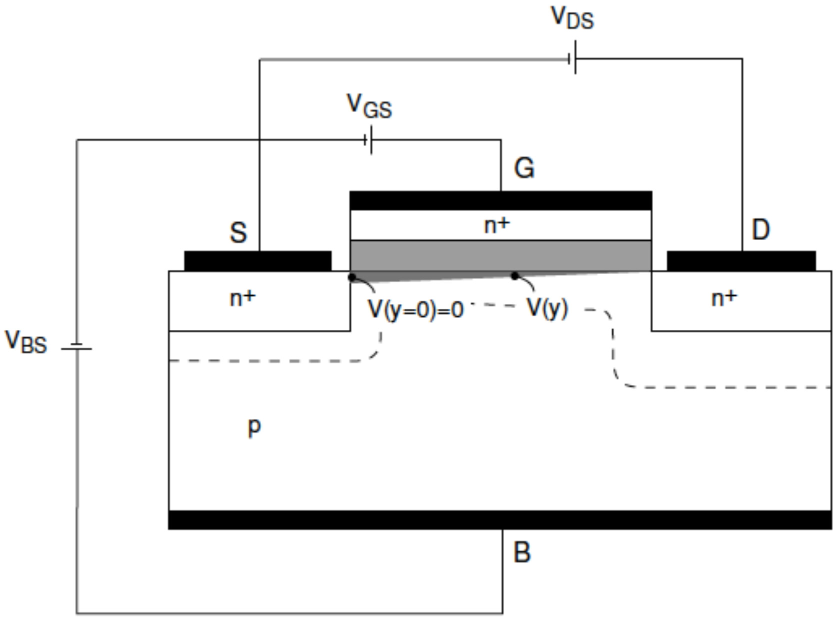


Solutions:

- **Use un-doped spacer**: to reduce scattering from dopants
- Wavefunction not completely confined
  - **Use back barrier of larger Eg to** improve electron confinement

Comparison between MOSFETs and HEMTs

MOSFET



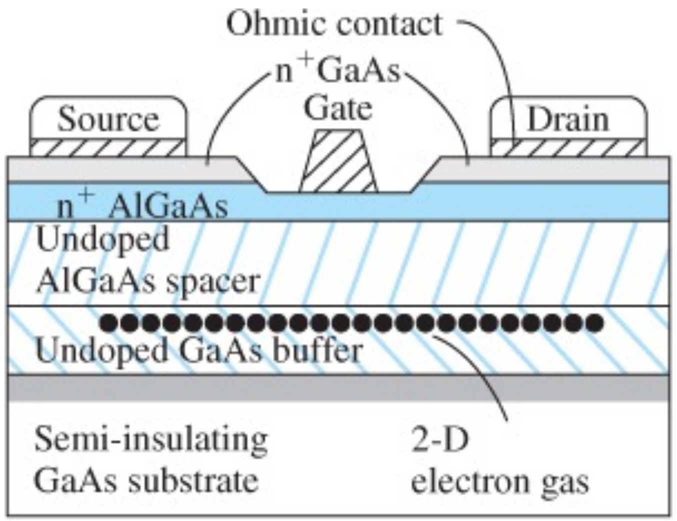
In the inversion channel:

- Mobility below 1000 cm2/Vs (for Silicon)

Enhancement-mode device:

normally-off operation (Vth > 0)

HEMT



Due to the 2DEG:

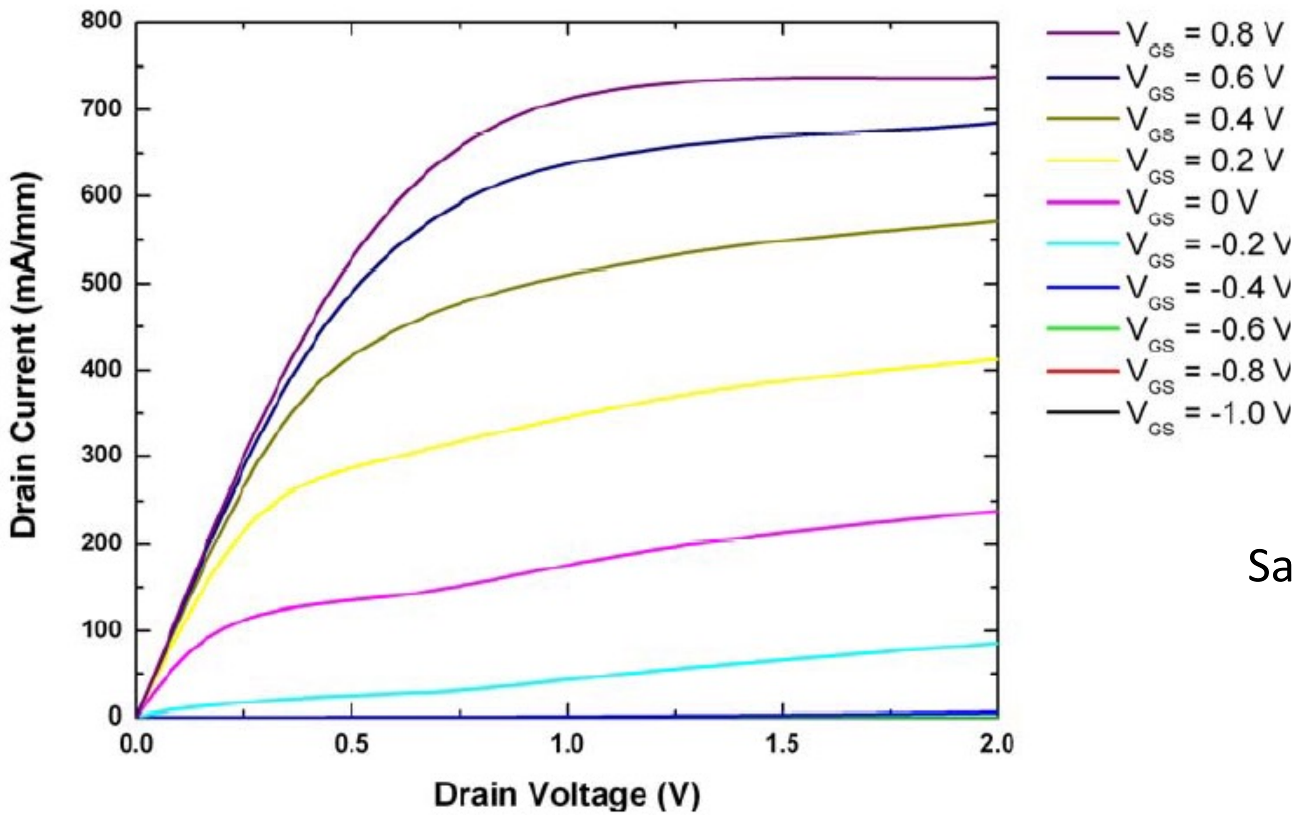
- Superior mobility: over 10000 cm2/Vs
- Higher frequency
- Lower noise figure
- If GaN: higher power density

Depletion-mode device:

normally-on operation (Vth < 0)

High Electron Mobility Transistors (HEMTs)

IV characteristics



Same equations as in a MOSFET:

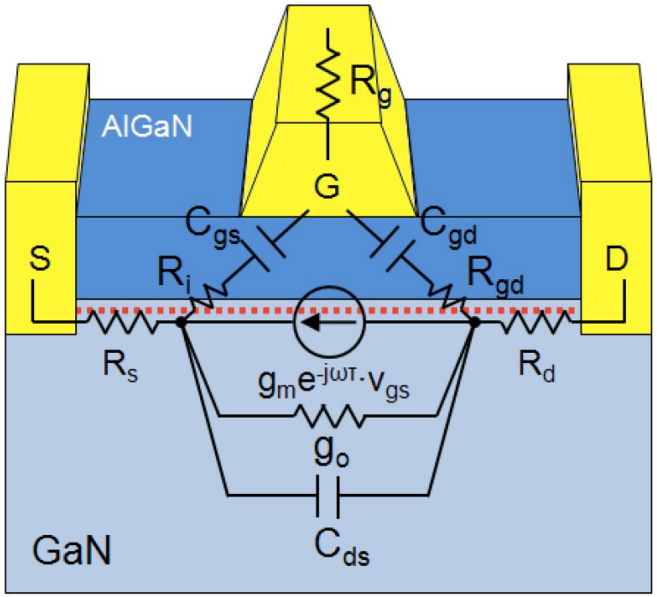
$$g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}} = \frac{W}{L} C_{OX} \mu V_{DS}$$

transconductance g_m

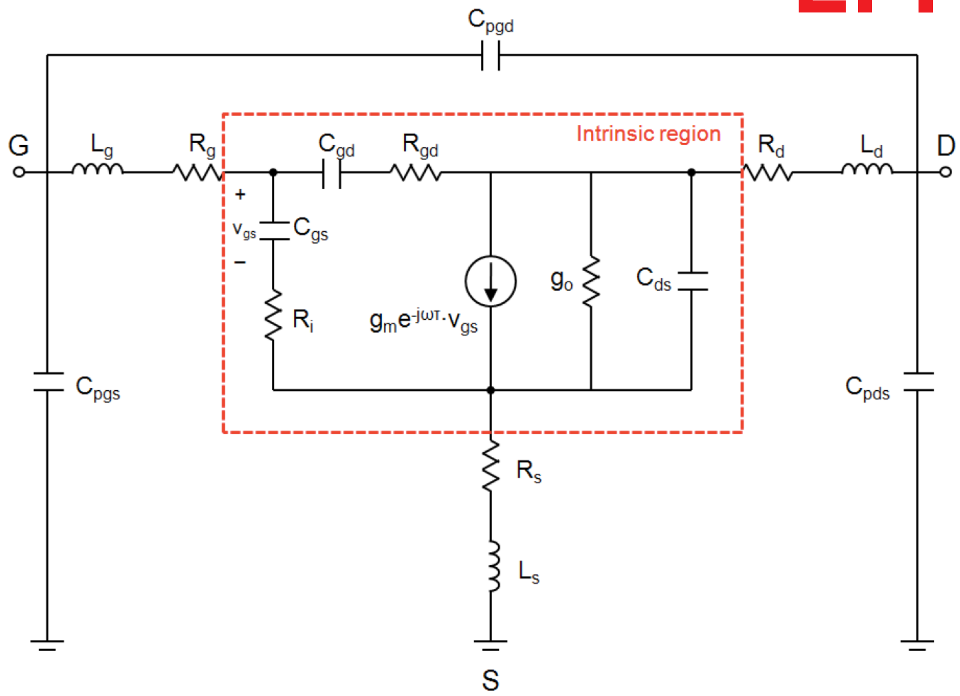
$I_{Dsat} = W_g \mu C_g (V_{GS} - V_T)^2 / 2L_g$

Depletion-mode device: normally-on operation (Vth < 0)

The higher the mobility, the higher transconductance g_m



W. Chung, MIT thesis, 2011



f_T is the frequency at which the magnitude of short-circuit current gain equals unity (or 0 dB)

- f_T is the frequency at which A_I goes to unity when the output is shorted to the ground

$$A_I|_{r_L=0} = \frac{I_d}{I_g}\bigg|_{r_L=0} \rightarrow A_I(f_T)|_{r_L=0} = 1 \rightarrow \; f_T = \frac{g_m}{2\pi(C_{gs}+C_{gd})(1+(R_s+R_d)g_o)+g_m C_{gd}(R_s+R_d)}$$

f_{max} is the frequency at which the unilateral power gain equals unity (or 0 dB)

- f_{max} is the frequency at which A_P goes to unity when the input/source and output/load are matched conjugately

$$A_P(f_{max})\Big|_{z_S=z_{in}^* \,\&\, z_L=z_{out}^*} = 1 \rightarrow \; f_{max} \cong \frac{f_T}{2\sqrt{(R_i+R_s+R_g)g_o+(2\pi f_T)R_g C_{gd}}}$$

Optimization of f_{MAX} relies on the maximizing f_T and reduction of R_i, R_s, R_g, C_{gd}, and g_0

High Electron Mobility Transistors (HEMTs)

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LETTER
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$L_g = 25$ nm InGaAs/InAlAs high-electron mobility transistors with both f_T and f_{max} in excess of 700 GHz

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In this paper, we report an $L_g = 25$ nm InGaAs/InAlAs HEMT on InP substrate that delivers excellent high-frequency characteristics. The device exhibited a value of maximum transconductance (g_{m_max}) = 2.8 mS μm^{-1} at $V_{DS} = 0.8$ V and on-resistance (R_{ON}) = 279 Ω μm. At $I_D = 0.56$ mA μm^{-1} and $V_{DS} = 0.5$ V, the same device displayed an excellent combination of $f_T = 703$ GHz and $f_{max} = 820$ GHz. To the best of the authors' knowledge, this is the first demonstration of a transistor with both f_T and f_{max} over 700 GHz on any material system.

The development of terahertz (THz) microelectronics has yielded new areas of research and applications in the sub-millimeter-wave regime (sub-MMW; 300 GHz–3 THz), such as security/medical imaging systems, collision avoidance radars, next-generation transport communications, and wireless-local-area-networks.[1–6] In order to fully exploit the sub-MMW band, it is crucial to develop semiconductor transistor technologies with both current-gain cutoff frequency (f_T) and maximum oscillation frequency (f_{max}) close to 1 THz simultaneously. In this regard, both InGaAs-based high-electron mobility transistors (HEMTs) and double-heterojunction-bipolar-transistors (DHBTs) on an InP substrate are strong candidates. To date, there have been many impressive accomplishments regarding the high-frequency response of both device technologies, delivering an f_T of 710 GHz in the InGaAs HEMTs[1], an f_T of 695 GHz in the DHBTs[2], and an f_{max} in excess of 1 THz for both.[3,4,7,8)]

The epitaxial layer structure used in this work was grown on a 3 inch semi-insulating InP substrate using metal-organic chemical-vapor-deposition. From top to bottom, the epitaxial layer structure consisted of a 30 nm thick heavily-doped multi-layer cap ($In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$), a 3 nm thick InP etch-stopper, a 9 nm thick $In_{0.52}Al_{0.48}As$ barrier/spacer with Si δ-doping, a 9 nm thick indium-rich InGaAs quantum-well channel, and a 200-nm $In_{0.52}Al_{0.48}As$ buffer on the InP substrate. Details on the material growth were reported in Ref. 18. Key aspects are as follows: (i) a multi-layer cap to lower S/D ohmic contact resistance, and (ii) an $In_{0.53}Ga_{0.47}As/In_{0.8}Ga_{0.2}As/In_{0.53}Ga_{0.47}As$ (1/5/3 nm) composite-channel to improve carrier transport properties. As reported previously,[18)] the Hall mobility (μ_{n_Hall}) was measured to be 13 500 cm^2 V^{-1} s^{-1} with a two-dimensional electron gas density of approximately 3×10^{12} cm^{-2} at 300 K.

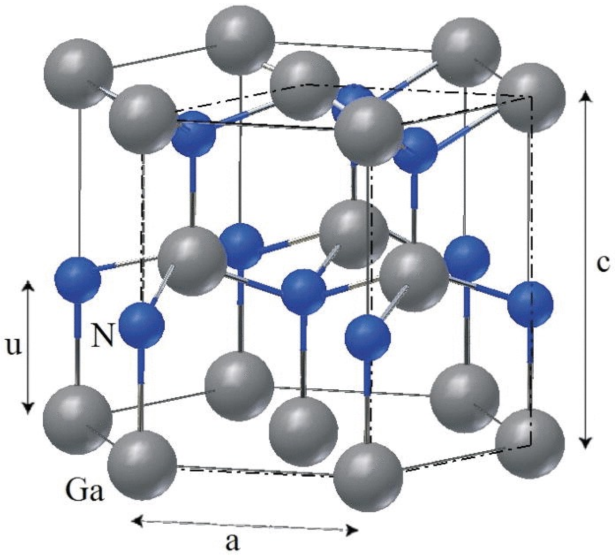
The device fabrication was nearly the same as in previous

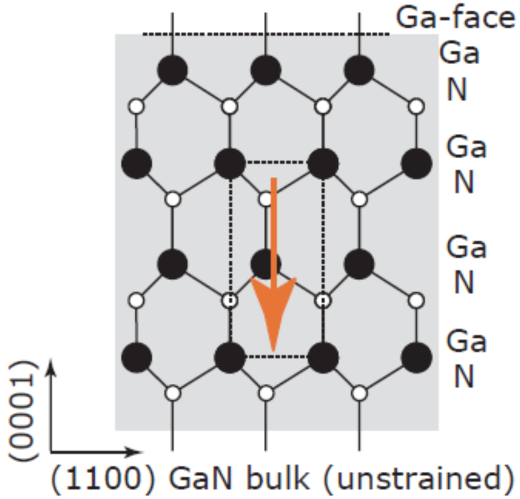
Extremely high mobilities

GaN materials for electronics

What is truly unique of III-Nitrides?

Wurtzite structure





Spontaneous polarization and piezoelectric constants of III-V nitrides

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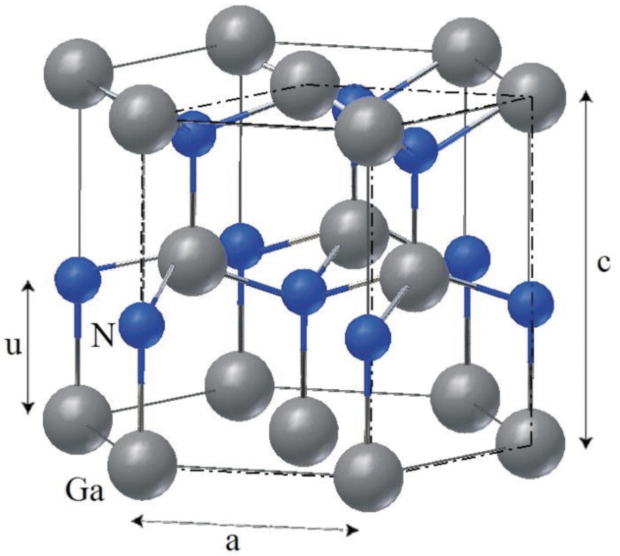
$$\mathbf{P}_e(\lambda) = -\frac{2e}{(2\pi)^3}\int_{BZ} d\,\mathbf{k}\frac{\partial}{\partial \mathbf{k}'}\,\phi^{(\lambda)}(\mathbf{k},\,\mathbf{k}')\Big|_{\mathbf{k}'=\mathbf{k}}$$

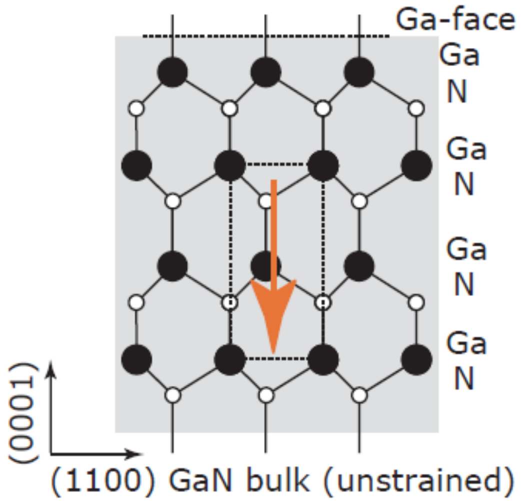
	P^{eq}	Z^*	$du/d\epsilon_3$	e_{33}	e_{31}	$e_{33}^{(0)}$	$e_{31}^{(0)}$
AlN	–0.081	–2.70	–0.18	1.46	–0.60	–0.47	0.36
GaN	–0.029	–2.72	–0.16	0.73	–0.49	–0.84	0.45
InN	–0.032	–3.02	–0.20	0.97	–0.57	–0.88	0.45

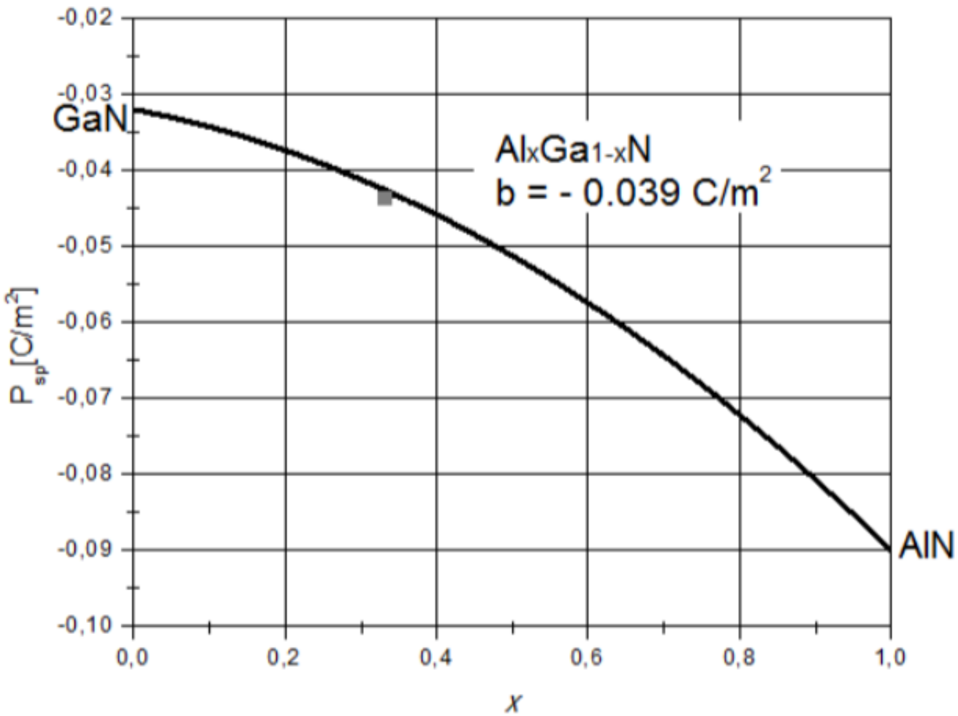
Case for GaN: Basics of III-Nitrides

1. Spontaneous Polarization

Wurtzite structure







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

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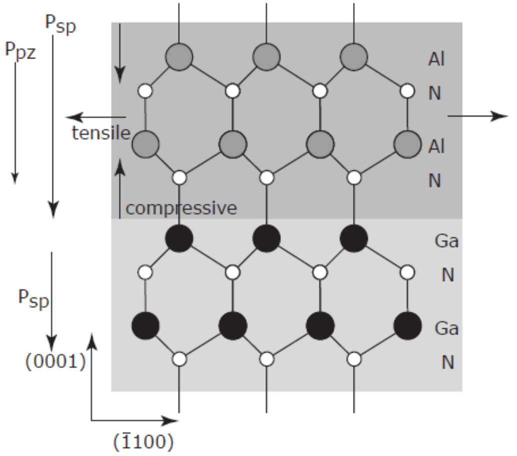
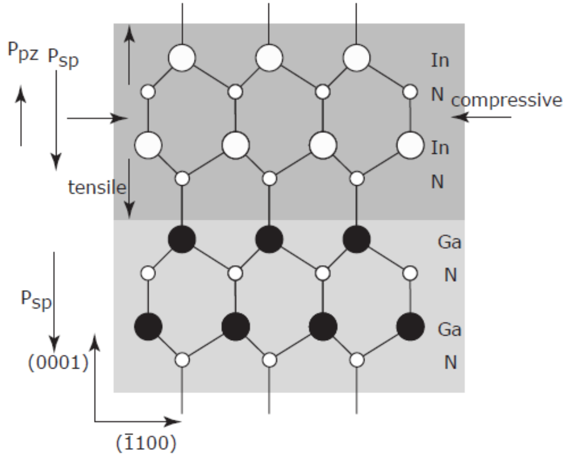
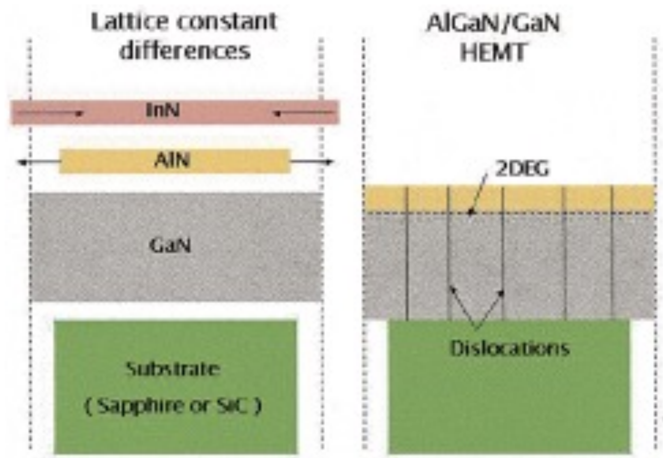
2. Piezoelectric Polarization



AlN/GaN (strained to GaN)



InN/GaN (strained to GaN)



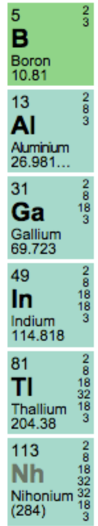


TABLE IV. Calculated stress, polarization, electric field, sheet charge density, and sheet carrier density of relaxed and strained Ga-face and N-face AlGaN/GaN heterostructures.

Top/bottom layer	Face	Stress	Strain 10^{-3}	P_{SP} 10^{-6} C/cm^2	P_{PE} 10^{-6} C/cm^2	σ 10^{-6} C/cm^2	E 10^6 V/cm	n_s 10^{13} cm^{-2}
AlGaN/GaN $x=0.3$	Ga	Relaxed	0	−4.5	0	1.6	1.36	*e* 0.83
	N	Relaxed	0	4.5	0	−1.6	−1.36	*h*
AlGaN/GaN $x=0.3$	Ga	Tensil	7.3	−4.5	−1.1	2.7	6.8	*e* 1.51
	N	Tensil	7.3	4.5	1.1	−2.7	−6.8	*h*

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

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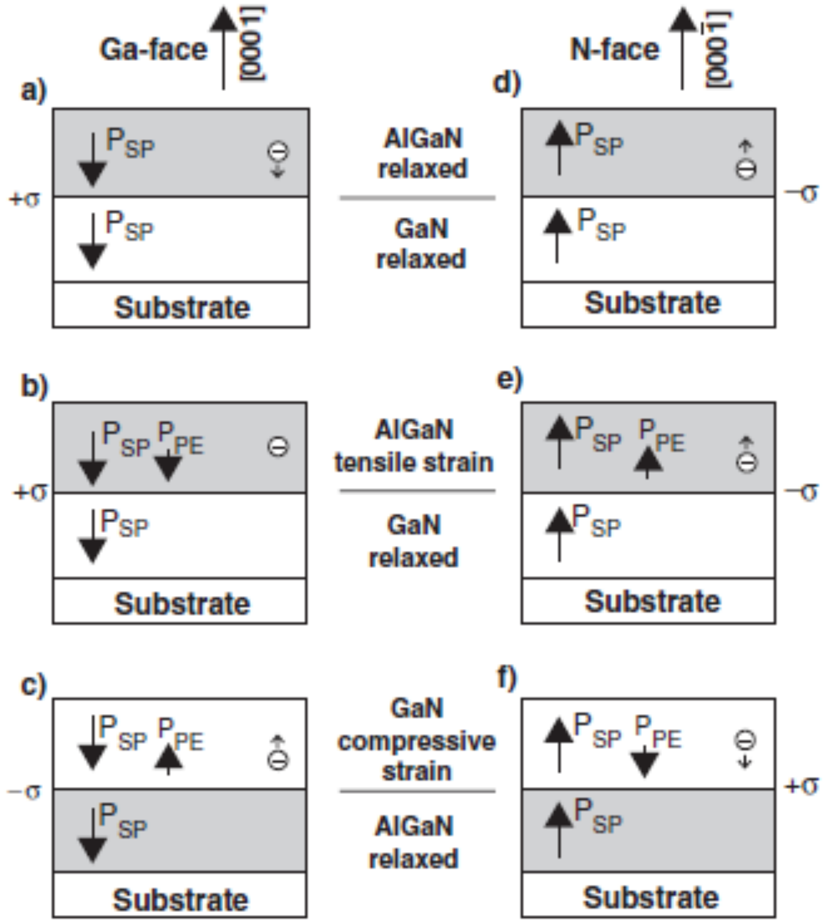
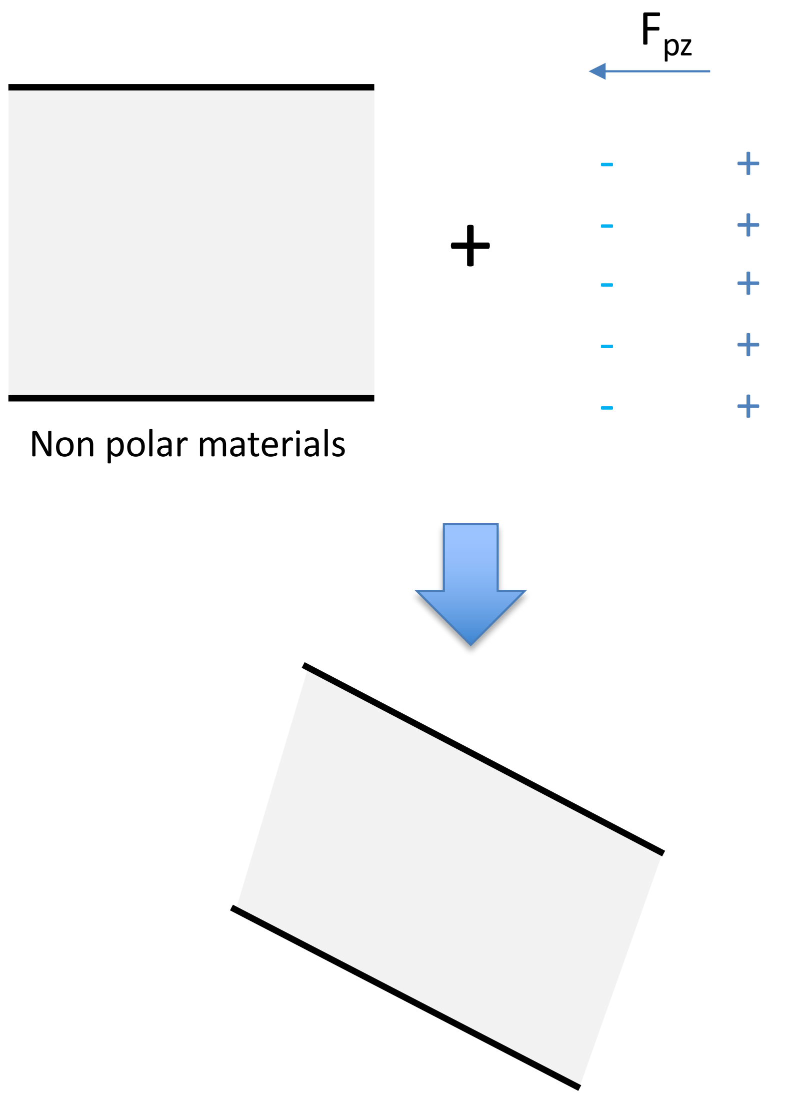
Spontaneous and piezo contributions



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

What does it do to the band structures?



Polarization fields create slopes in the bands!

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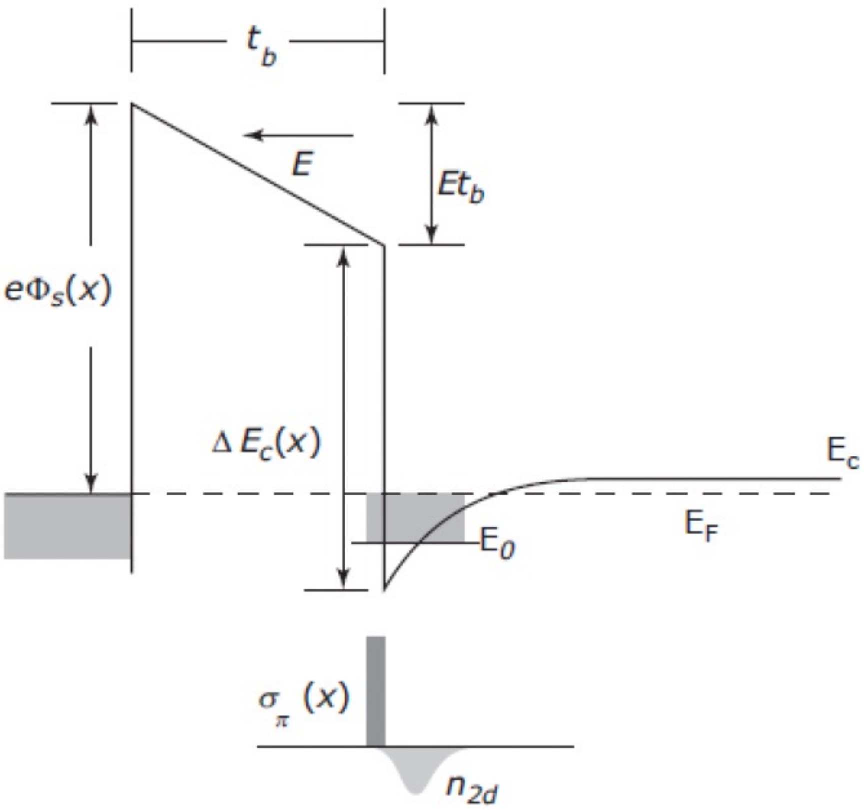
Simplified analytical description of GaN HEMT: charge control



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

From Gauss' law:

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

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

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

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

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

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

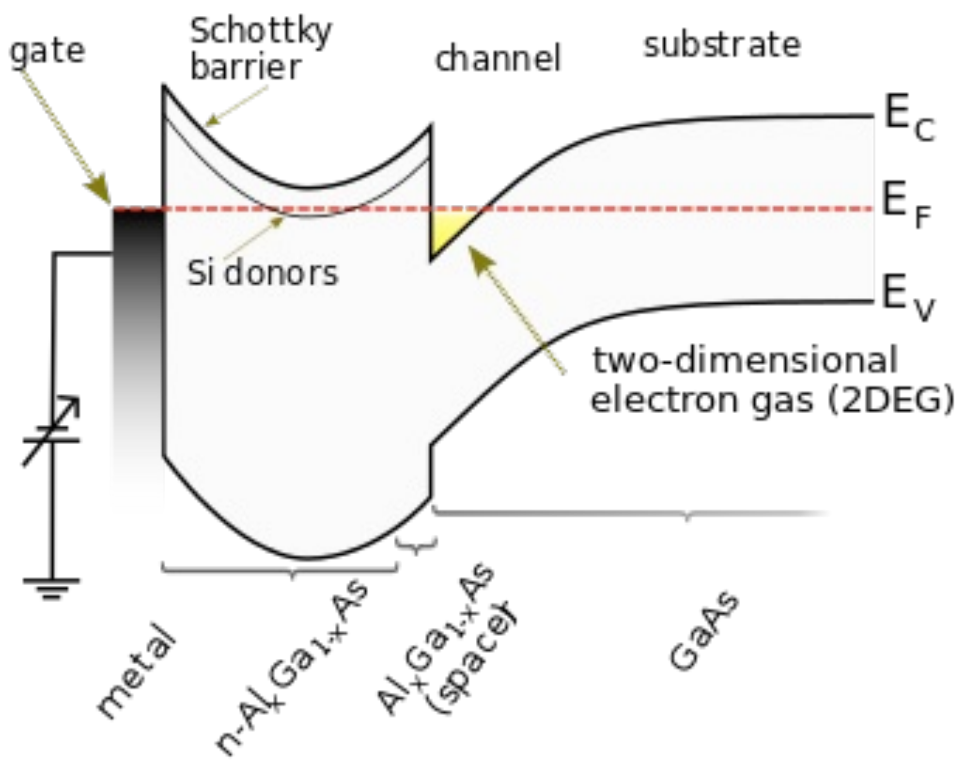
$\sigma_\pi(x)$ total polarization charge (piezo and spontaneous)

$\epsilon(x)$ absolute electric permittivity

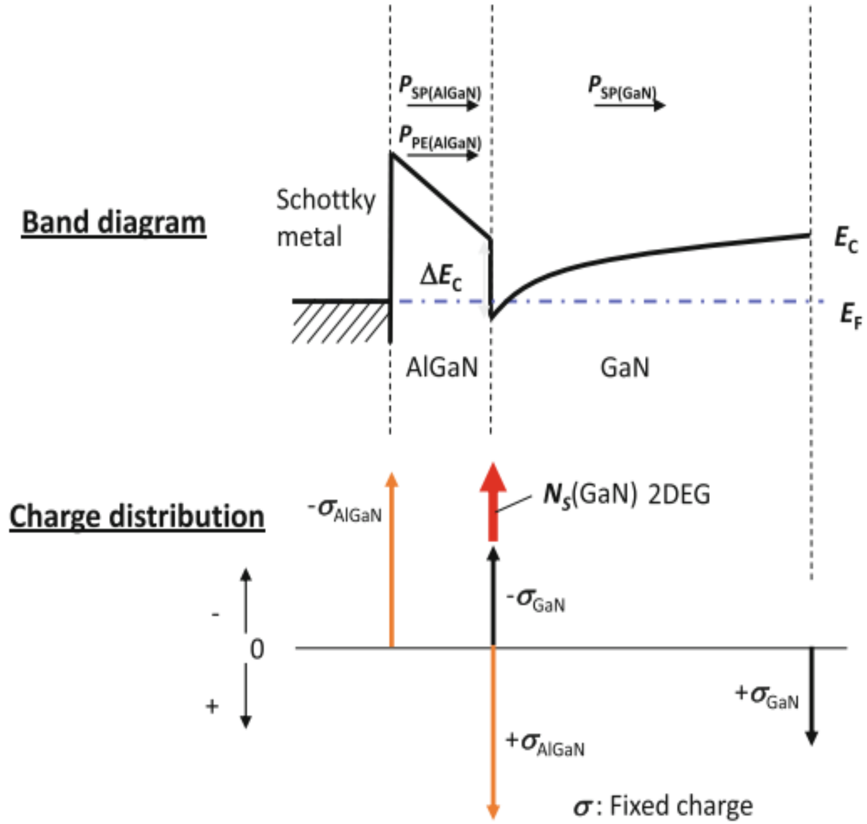
D. J. C. Wood, Polarization Effects in Semiconductors, 1st ed. Springer US, 2008, ISBN: 978-0-387-68319-5.

Summary: difference between Arsenides and Nitrides

AlGaAs/GaAs



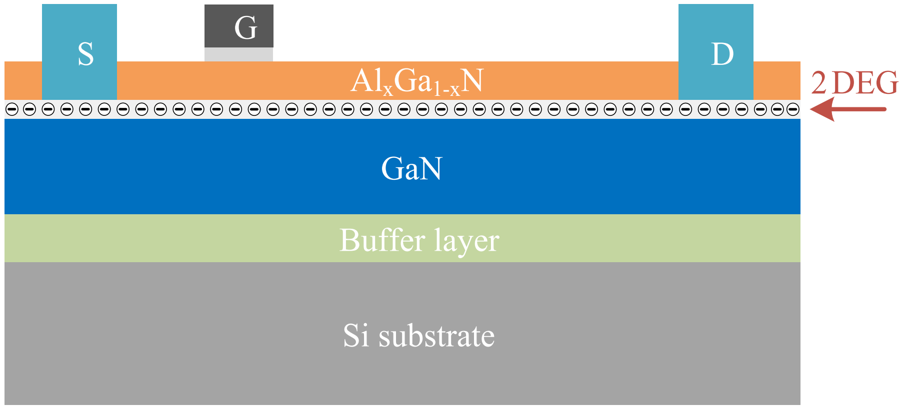
AlGaN/GaN

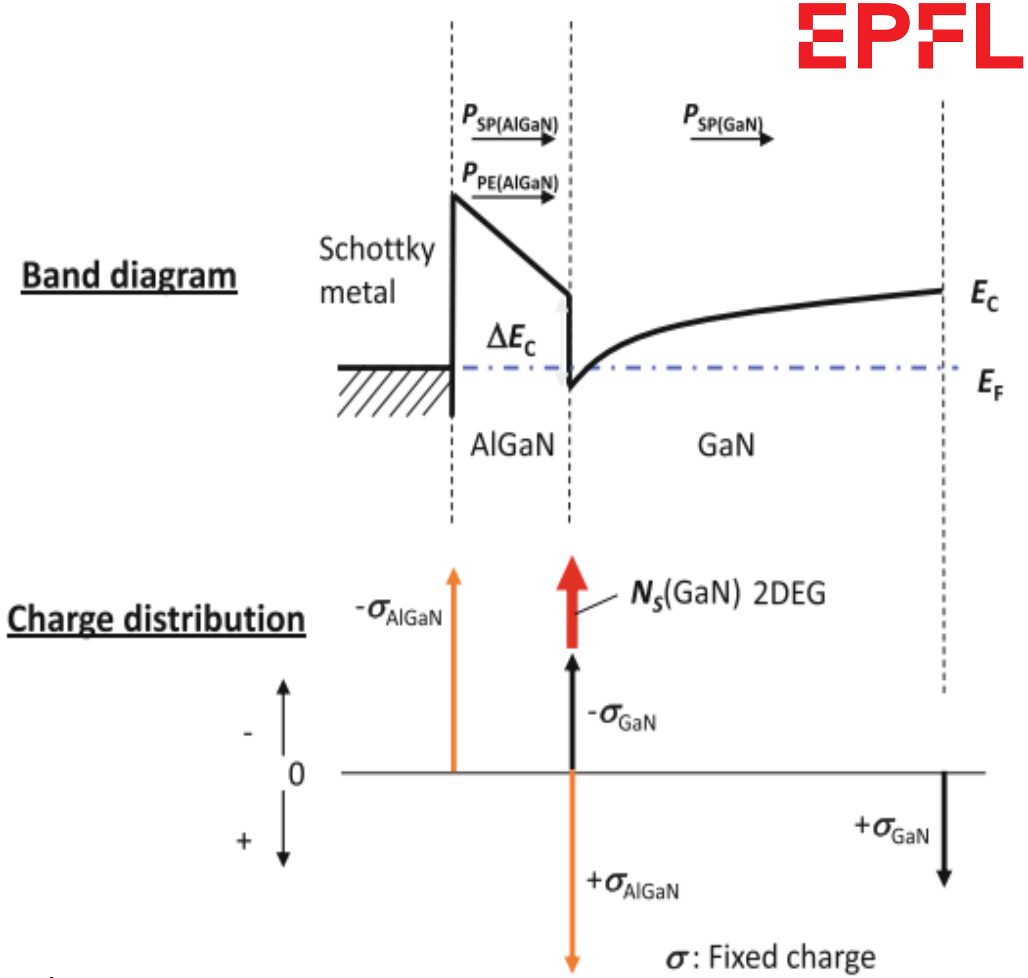


Why are these structures important?

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