EE669: VLSI Technology

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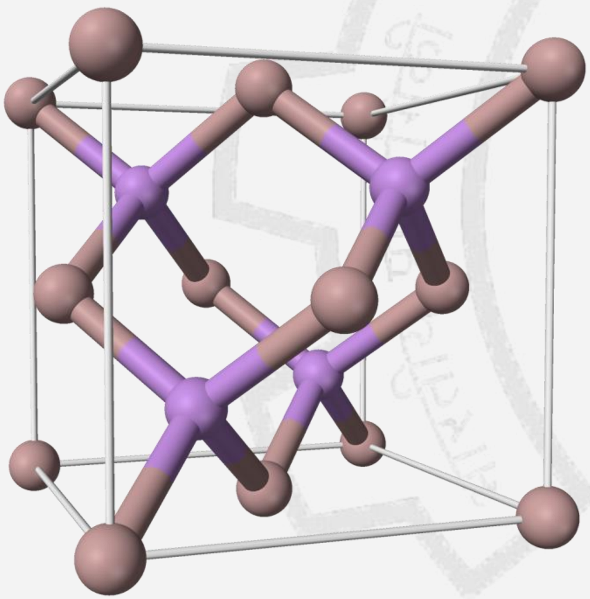
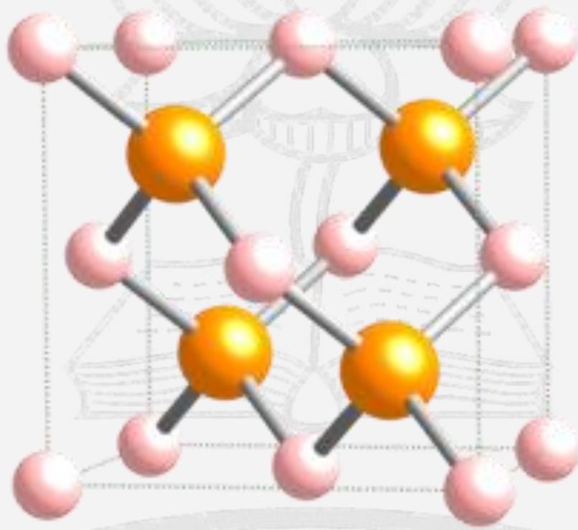
Office hour: Friday 10:00 – 11.00 AM, EE Annex, Room: 104

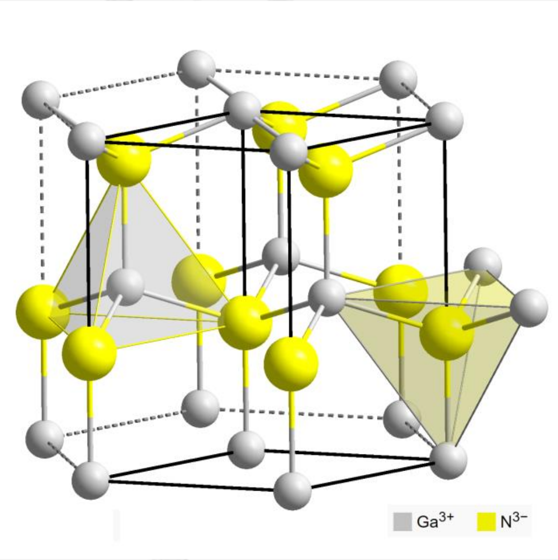
Power of III-V (compound) semiconductor



GaAs



InP



GaN

Some astonishing numbers

Population by Rural Urban Residence – India - 2011

Persons:

- Total : 1,210,193,422
- Rural: 833,087,662
- Urban: 377,105,760

Rural Urban Distribution Persons (in %):

- Total : 100.0 %
- Rural: 68.84 %
- Urban: 31.16 %

➢ **Approximate number electronic gadgets 1.6 billion**

Each gadget wastes approx. 5 watts of power per day at the adaptor (during conversion)

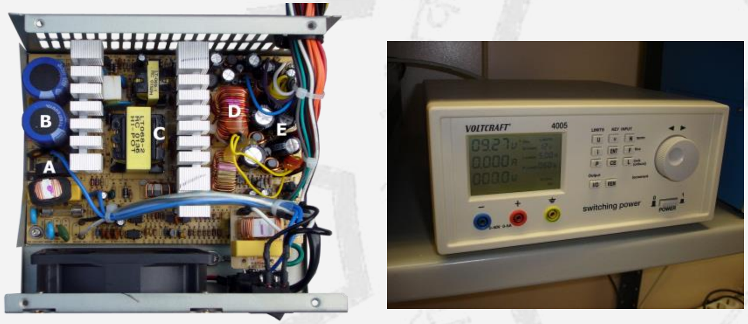
❑ **Total waste per day: 8 Giga watt**

❑ **Total waste per year: ~3 T Watt ONLY due to power conversion in electronic gadgets**

Source: Census 2011 – Provisional Population Total - India

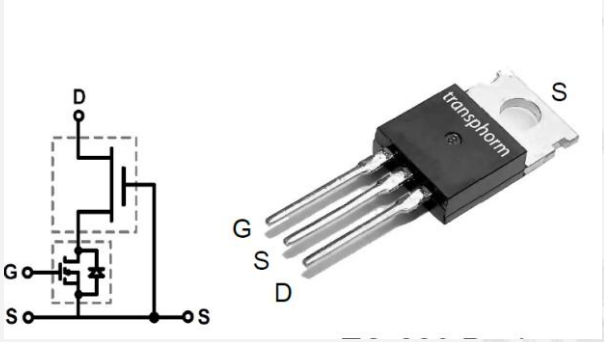
How are we going to address this serious issue

Average efficiency 40–50%



Switch Mode Power Supply

Efficiency: 80-90%



GaN based power converter

Efficiency > 95%

About 32 billion kilowatt-hours (kWh) per year, could be saved in the United States by replacing all linear power supplies. Source: Wikipedia

Differences between MOSFETs and HEMTs

HEMTs

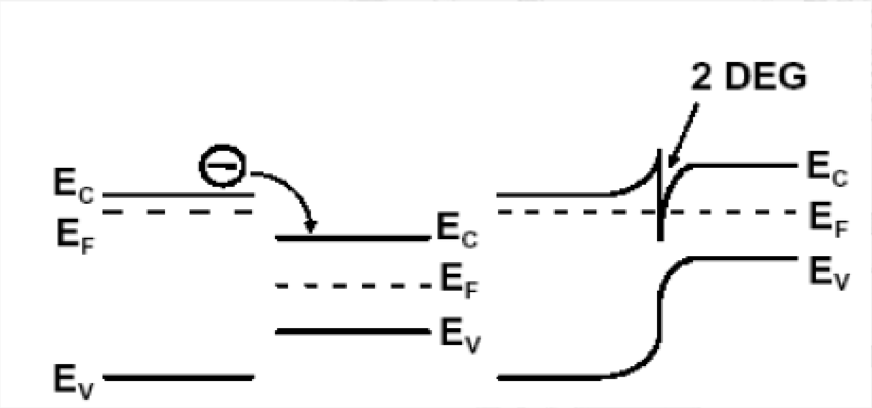
- Operate in the microwave range (300MHZ-300GHz)
- Heterojunction is used as the channel

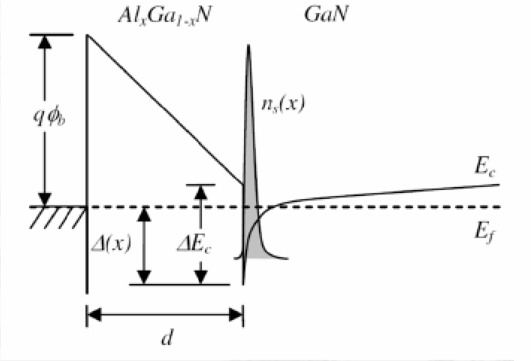
MOSFETs

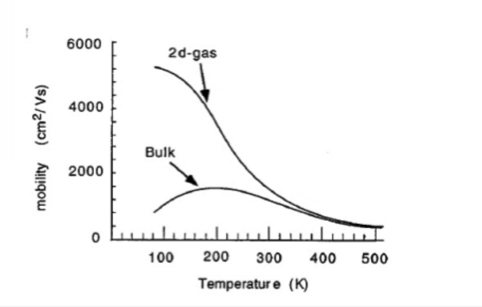
- Operation in the UHF range (300MHZ-3Ghz)
- Doped region is used as the channel

Operation principles (2 DEG)

- Discontinuity through the conduction band of the two semiconductors determines a charge transfer, creating a triangular potential.
- Electrons are confined in the triangular potential in discrete quantum state.
- Mobility of the electrons in 2DEG is higher than in a bulk.

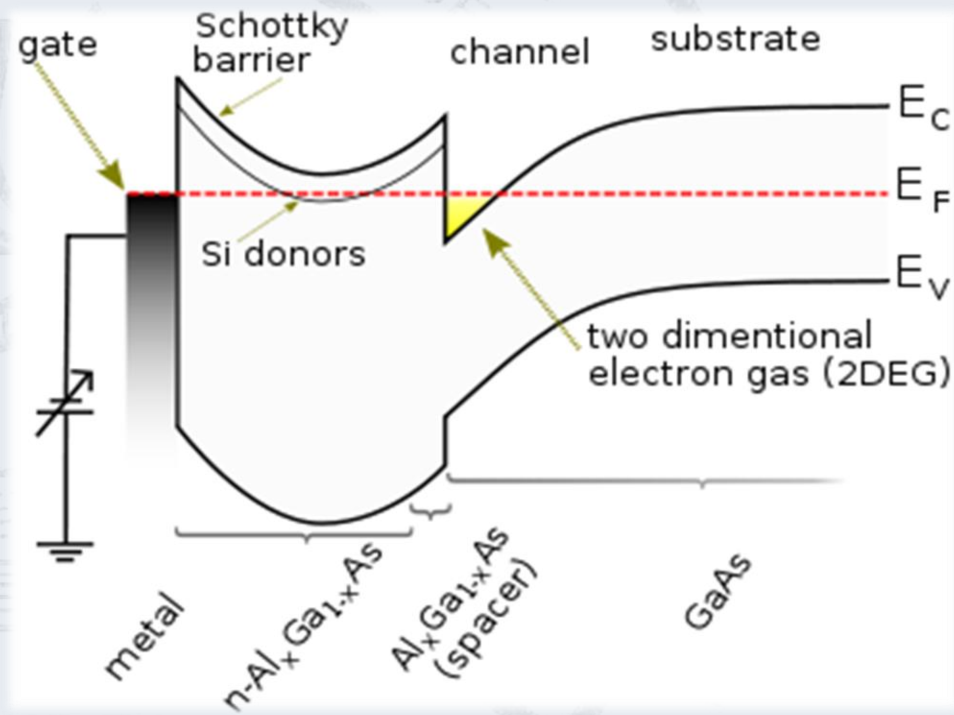






How do HEMTs work?

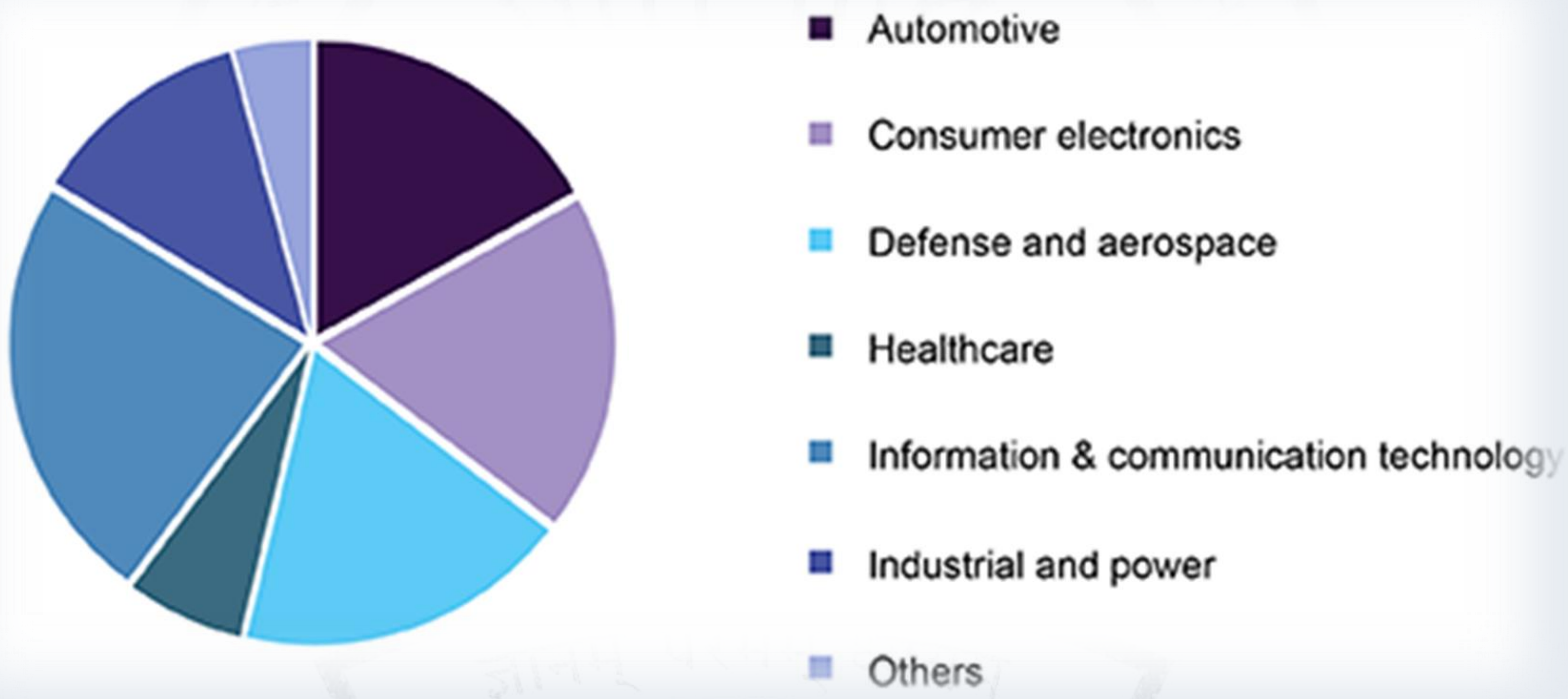
- HEMT's take advantage of 2DEG which is created at the AlGaAs/GaAs heterojunction.
- The 2DEG is confined at the heterojunction and free to move parallel to the channel.
- This results in a higher electron mobility
- Good for large gain and high frequency characteristics.



Energy band diagram for AlGaAs/GaAs heterojunction at thermal equilibrium

You don’t even require the doping in GaN based heterostructure!!!

Asia Pacific GaN semiconductor device market by application



Solid state lighting


Nobelpriset i fysik 2014
The Nobel Prize in Physics 2014
Nobelpriset i fysik 2014
KUNGL.
VETENSKAPS
AKADEMIEN
Isamu Akasaki
Meijo University, Nagoya, Japan
Nagoya University, Japan
Hiroshi Amano
Nagoya University, Japan
Shuji Nakamura
University of California,
Santa Barbara, CA, USA

Outline

- Why III-Nitride semiconductor??
- AlGaN/GaN heterostructure: Advantages and Disadvantages
- Issues with growth of epitaxial layers
- MBE growth of GaN, AlGaN/GaN heterostructure on various substrates
- Nanowires: Promising solution to circumvent the challenges in heterostructure growth
- New horizon yet to be explored
- Summary

Materials Properties Comparison

Material	μ	ε	Eg	BFOM Ratio	JFM Ratio	Tmax
Si	1300	11.4	1.1	1.0	1.0	300 C
GaAs	5000	13.1	1.4	9.6	3.5	300 C
SiC	260	9.7	2.9	3.1	60	600 C
GaN	1500	9.5	3.4	24.6	80	700 C

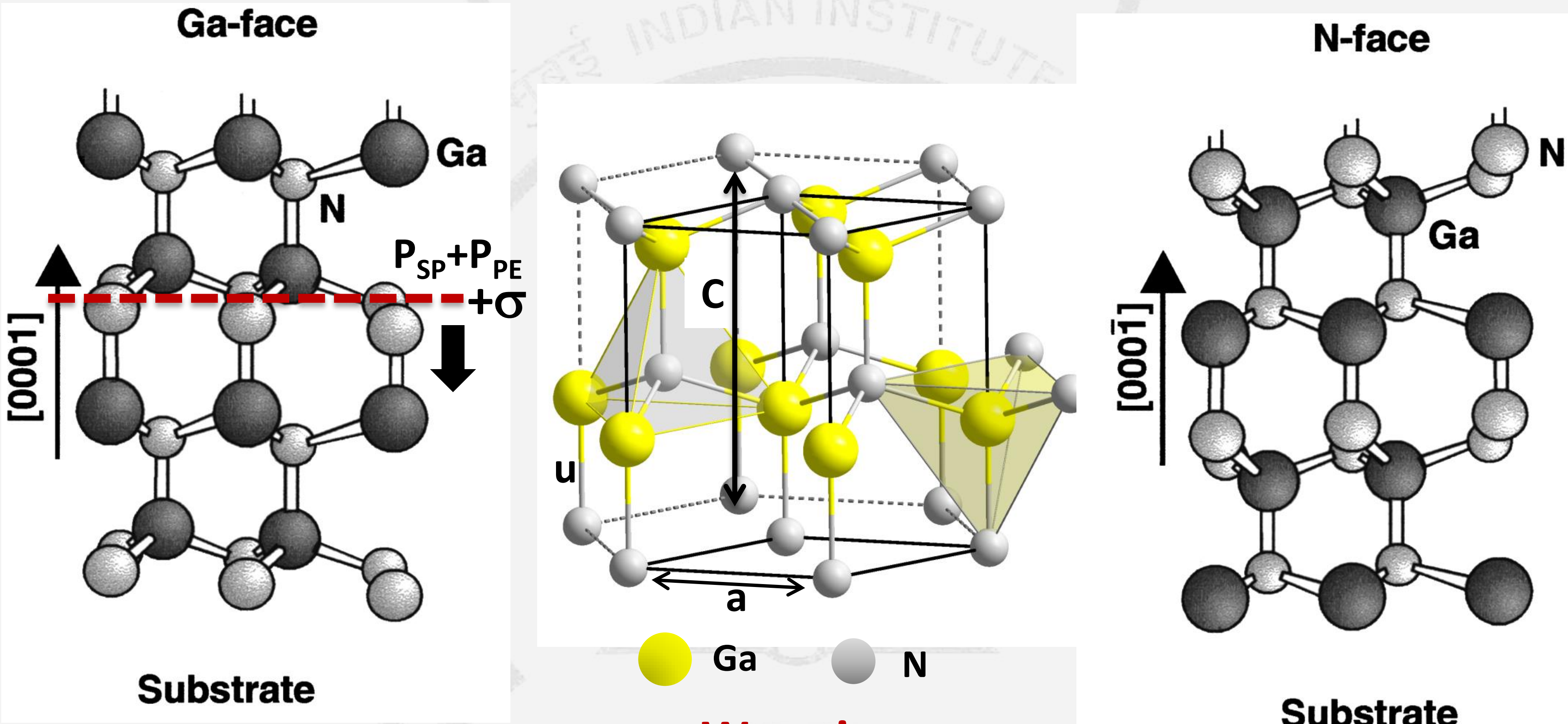
BFOM = Baliga's figure of merit for power transistor performance [$K*\mu*E_g^3$]

JFM = Johnson's figure of merit for power transistor performance

(Breakdown, saturation electron velocity product) [$E_{br}*V_{sat}/2\pi$]

Source: UCSB

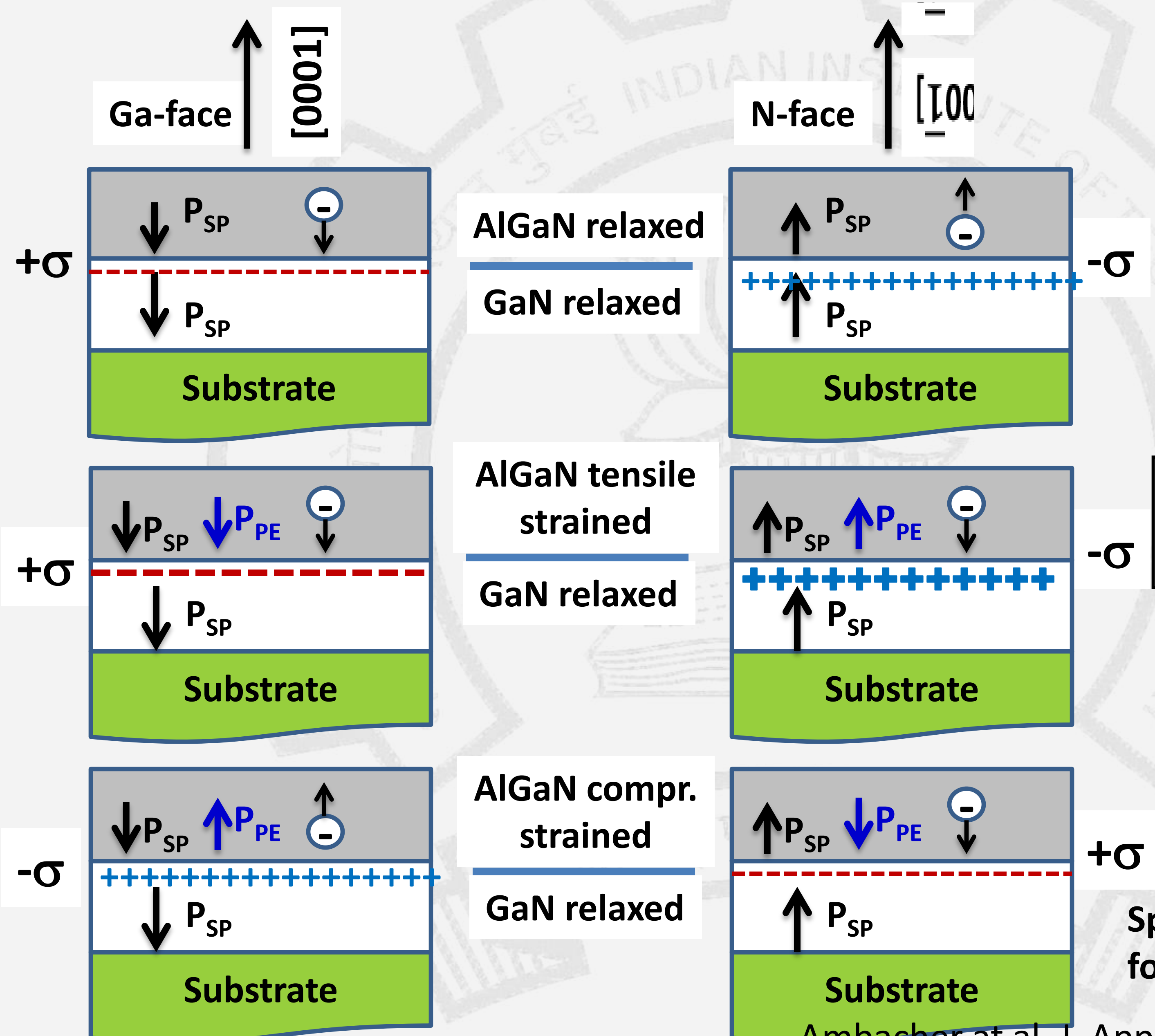
Structure of GaN



Wurtzite

The (0001) and $(000\bar{1})$ surfaces of GaN are **nonequivalent** and differ in their chemical and physical properties. Crystallographic polarity along these axes results spontaneous polarization.

Polarization in GaN/AlGaN heterostructure



$\mathbf{P_{SP}} = P_{SP}\mathbf{z}$

$\boxed{\mathbf{P} = \mathbf{P_{SP}} + \mathbf{P_{PE}}}$

$$\mathbf{P_{PE}} \Downarrow \quad 2\frac{a-a_0}{a_0}\left(e_{31}-e_{33}\frac{C_{13}}{C_{33}}\right)$$

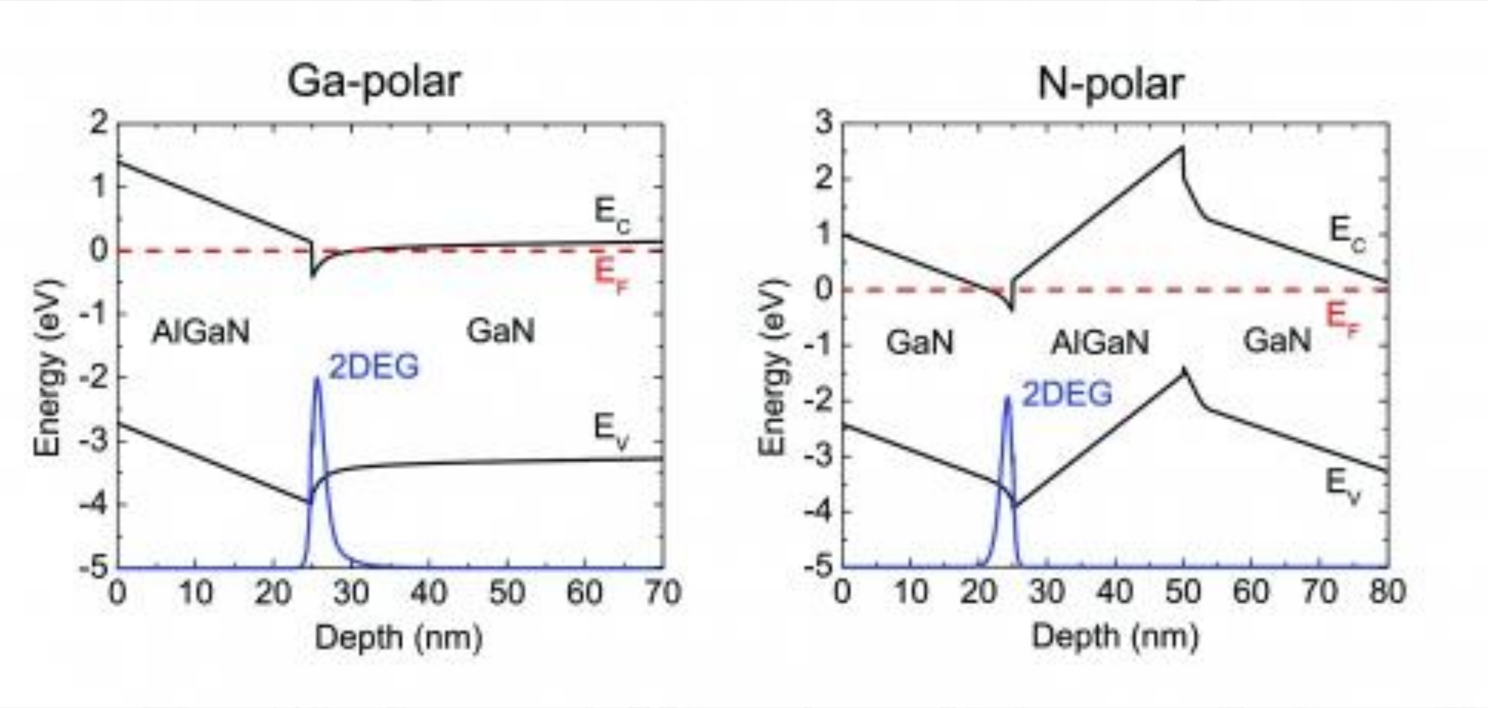
$\left(e_{31}-e_{33}\frac{C_{13}}{C_{33}}\right)<0$

<u>**for AlGaN over the whole range of compositions**</u>

Spontineous polarization for GaN and AlN<0

Ambacher at al. J. Appl. Phys, **85** 3222 (1999)

Looking at band structure of AlGaN/GaN HEMT

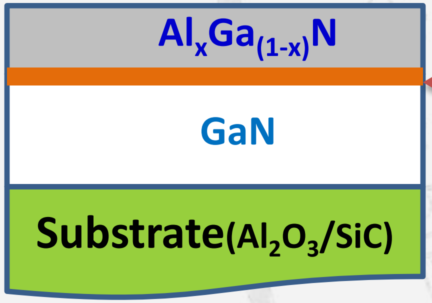


- Discontinuity at the conduction band of the two semiconductors determines a charge transfer, creating a triangular potential.
- Electrons are confined in the triangular potential in discrete quantum state.
- Mobility of the electrons in 2DEG is higher than in a bulk.

Heart of HEMT: 2DEG

For high power, high frequency HEMTs based on $Al_xGa_{(1-x)}N/GaN$:

- high x_{Al},
- coherently strained,
- trap free AlGaN/GaN heterojuction,
- (abrupt + smooth on an atomic level)

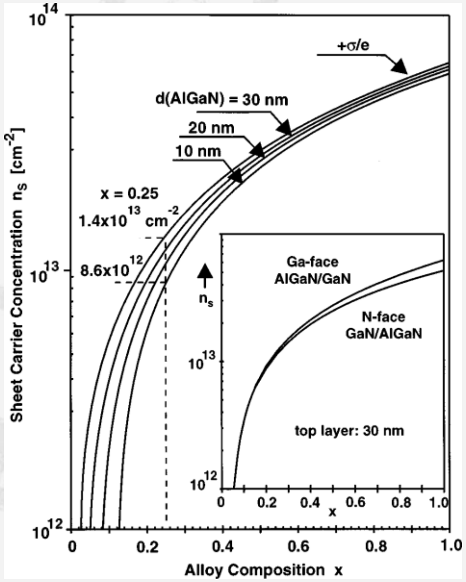


2DEG
(density and mobility)

- ✓ *carrier confinement,*
- ✓ *high breakdown voltage,*
- ✓ *high currents*

Determined by

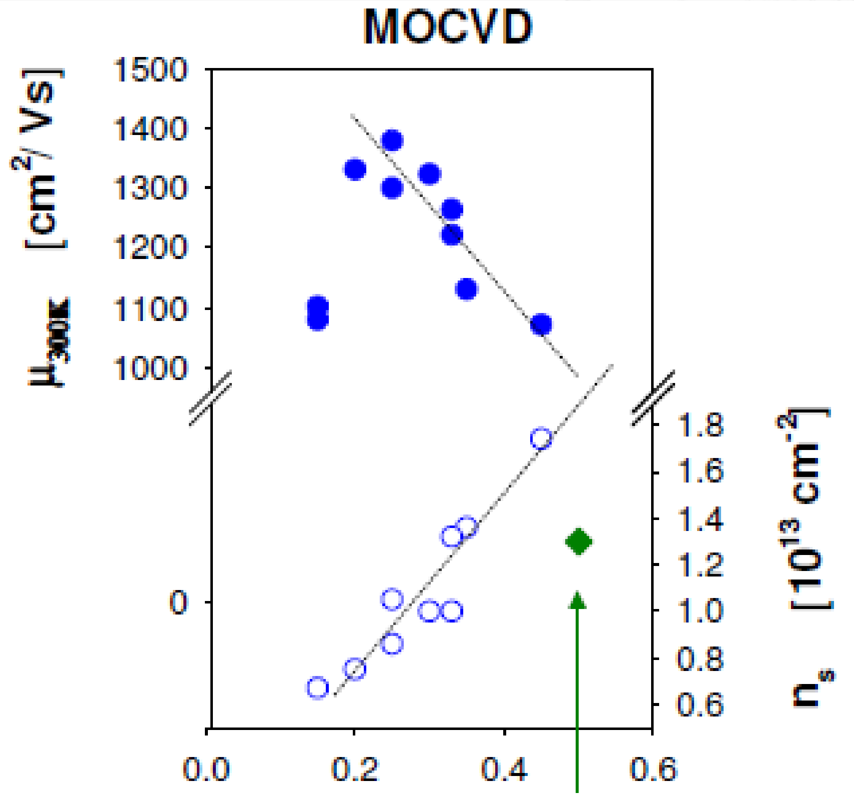
- x_{Al}
- interface roughness
- alloy scattering
- dislocation, etc.



Sheet carrier concentration of the 2DEG confined at a Ga-face GaN/AlGaN/GaN interface for different thickness of the AlGaN barrier.

Ambacher et al. J. App. Phys. 85, 3222 (1999)

2DEG: Influence of the Al-composition



Source: UCSB

x_{Al}

Layer relaxed

For $x_{Al} > 0.2$: $\mu_{300} \sim 1/x_{Al}$

$x_{Al} \uparrow$
- interface problems
- - strain induced defects
- - higher impurity incorporation
- - alloy ordering/clustering

$n_s \sim x_{Al}$ — charge increases due to spontaneous polarization and piezoelectric effects

For $x_{Al} < 0.2$: $\mu_{300} \sim x_{Al}$

- ✓ better confinement of the 2DEG at higher x_{Al}
- ✓ low x_{Al} = low n_s: less efficient screening of defects

AlGaN/GaN HEMTs transistor don’t need doping to obtain a high electron density.

Optimum Al conc. 25-30%