# 화합물 반도체 ( IV-1 )
# – *Piezoelectricity*

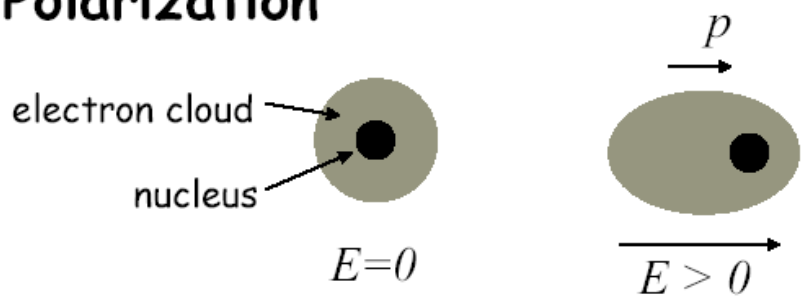
2007 / 가을 학기

# Basics of Polarization ( I )

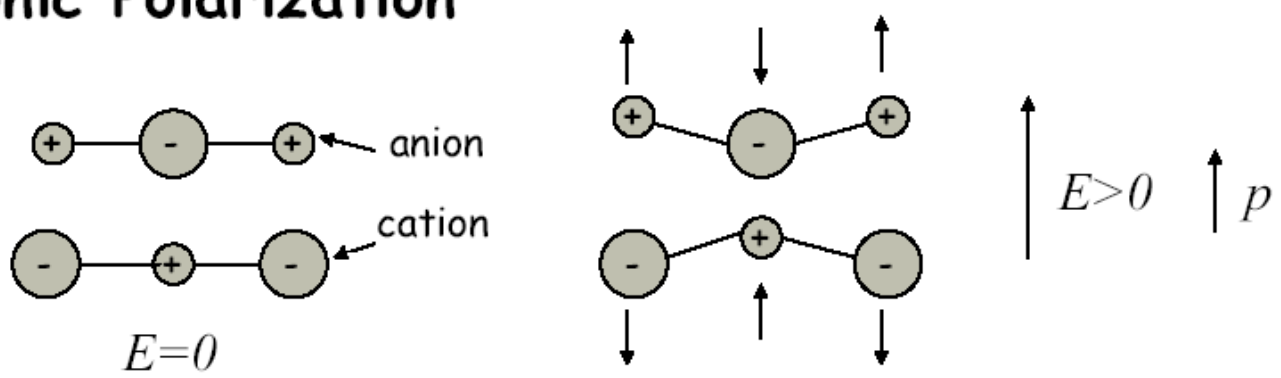
Dipole moment = charge x distance (units: C-m)

Polarization = dipole moment / volume = density of dipole moment
Units: $C/m^2$

## Electronic Polarization

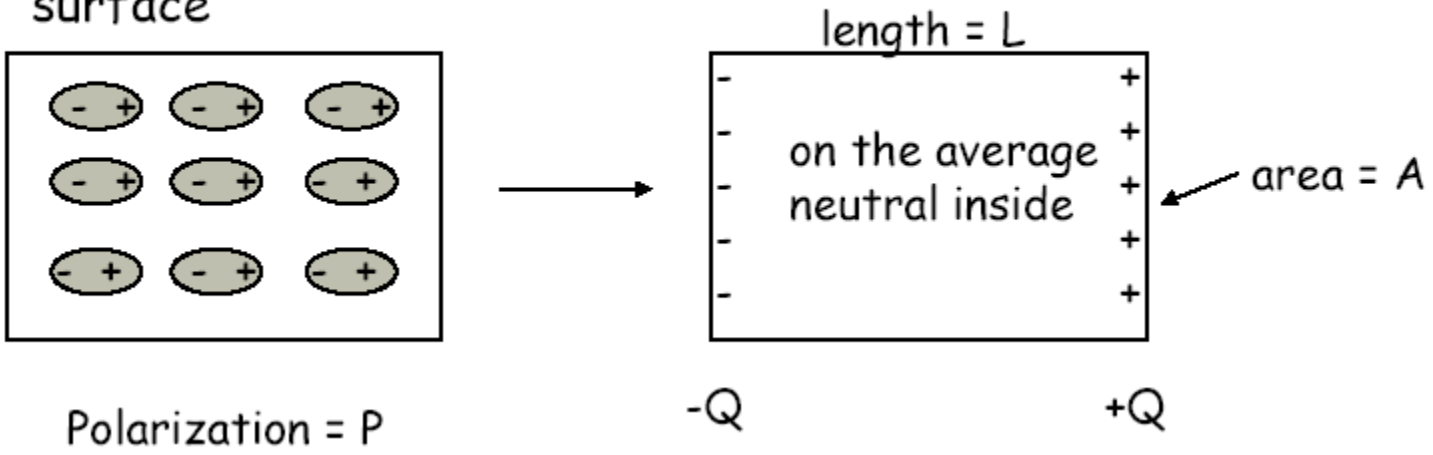



## Ionic Polarization



# Basics of Polarization ( II )

- A uniformly polarized medium has charge accumulation at the surface




dipole moment = QL

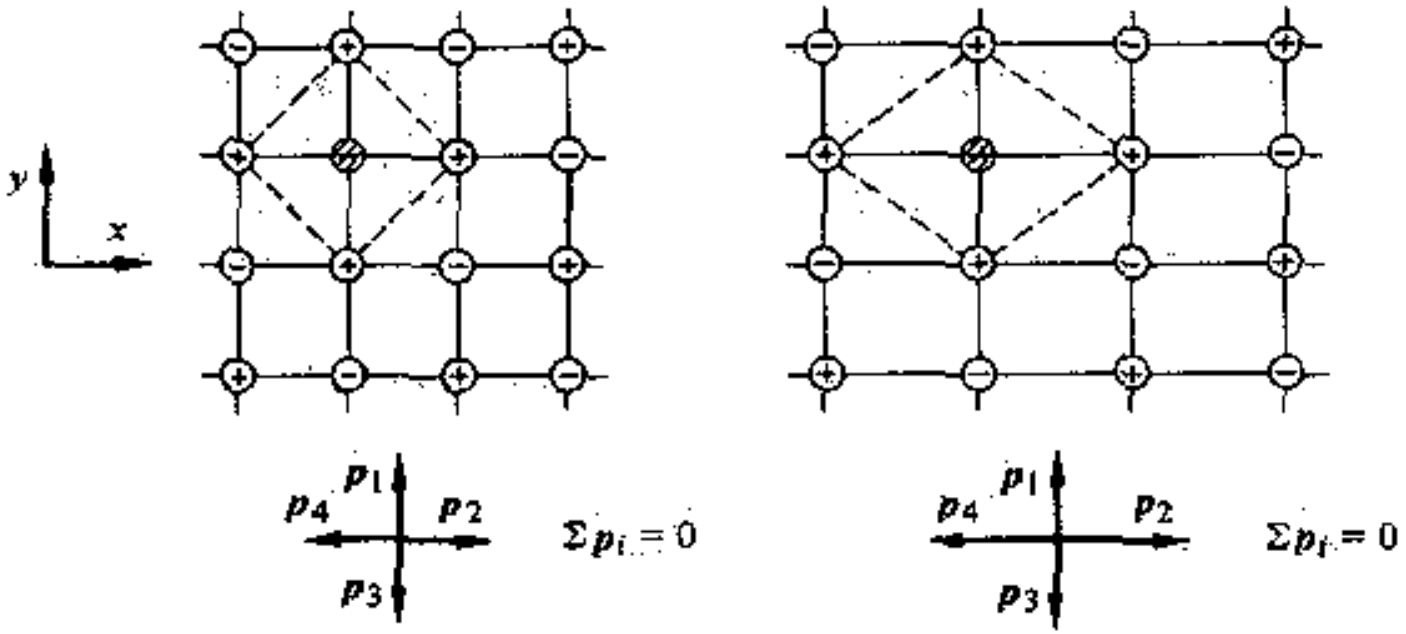
Polarization P = QL/(LA) = Q/A  Surface charge due to polarization Q = PA

## *Piezoelectricity ($P_{SP}$=0.25C/m$^2$ in $BaTiO_3$)*

Mechanical stress --> motion of ions --> polarization.

- Only possible in crystal structures with no centre of inversion (out of all point groups, 12 have centre of inversion).
- Polarization --> internal electric field or voltage

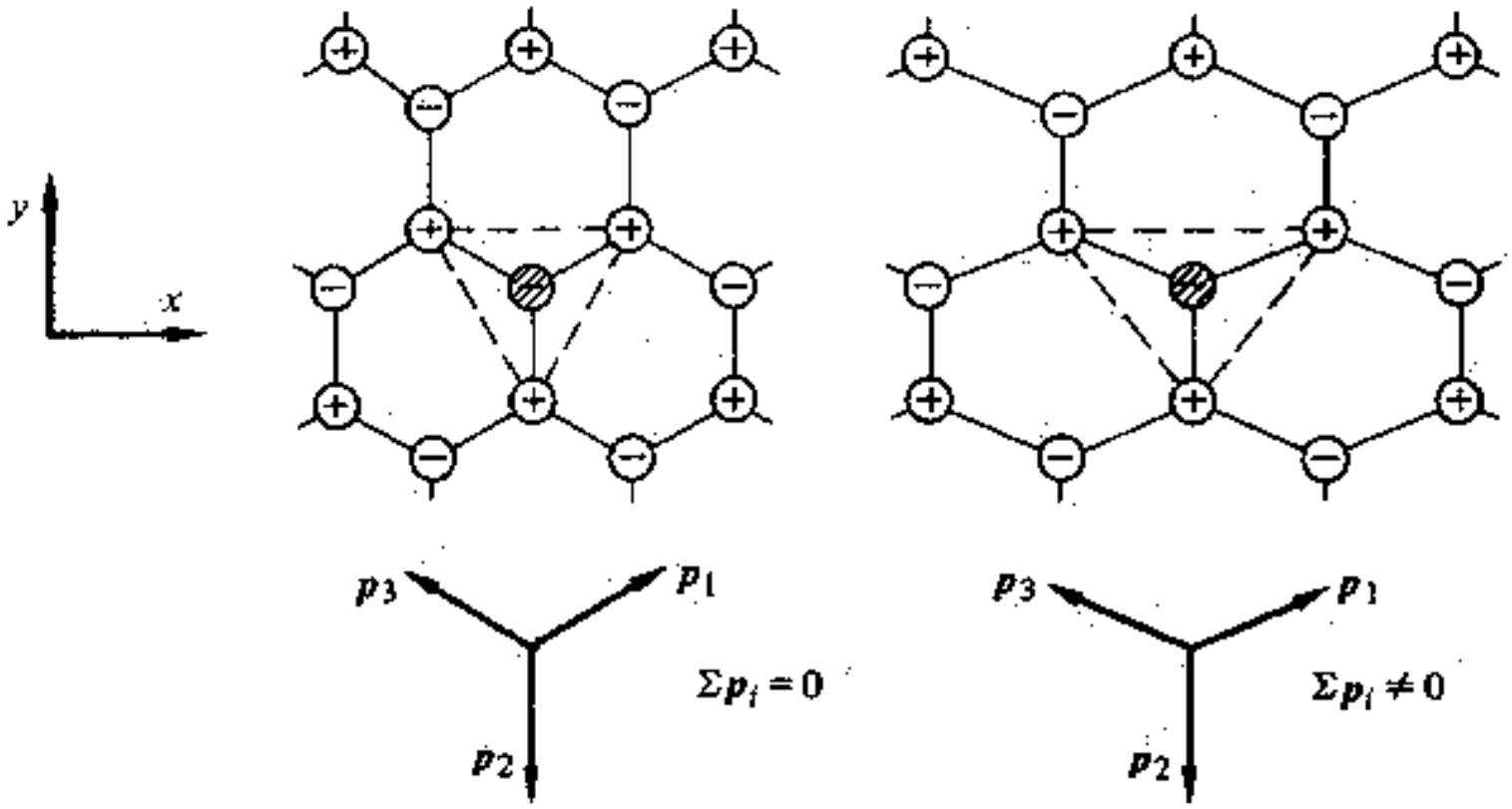
# *Piezoelectricity (I)*




**Structure 1: ⊖ (Cross-Hatched), Reference Ion**

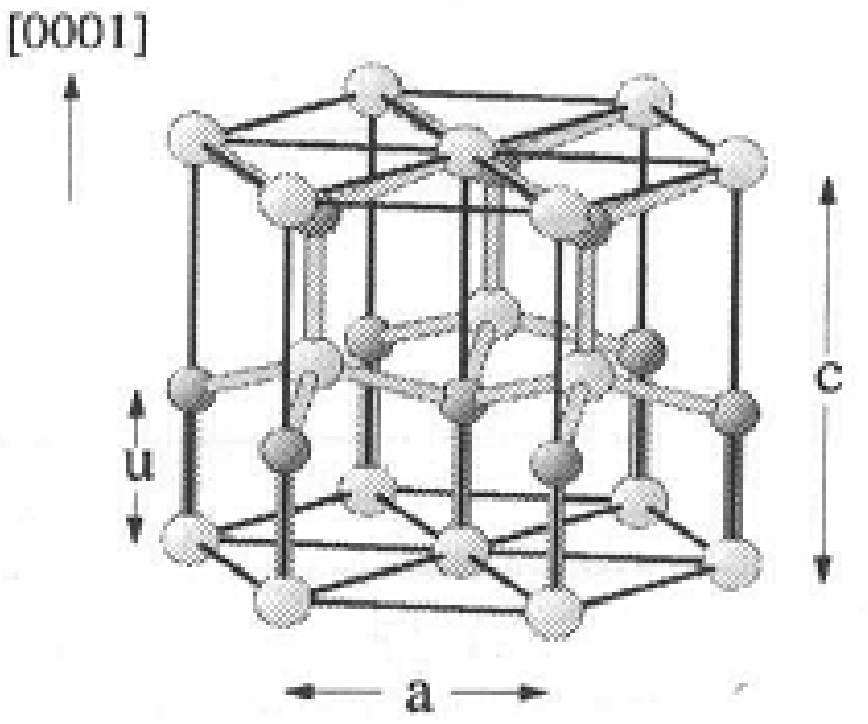
**Center of Inversion ⇨ No Piezoelectricity**

# *Piezoelectricity (II)*




**Structure 2: ⊖ (Cross-Hatched), Reference Ion**

# *Piezoelectronic Properties of Compound Semiconductors*




*Hexagonal Wurtzite Structure*

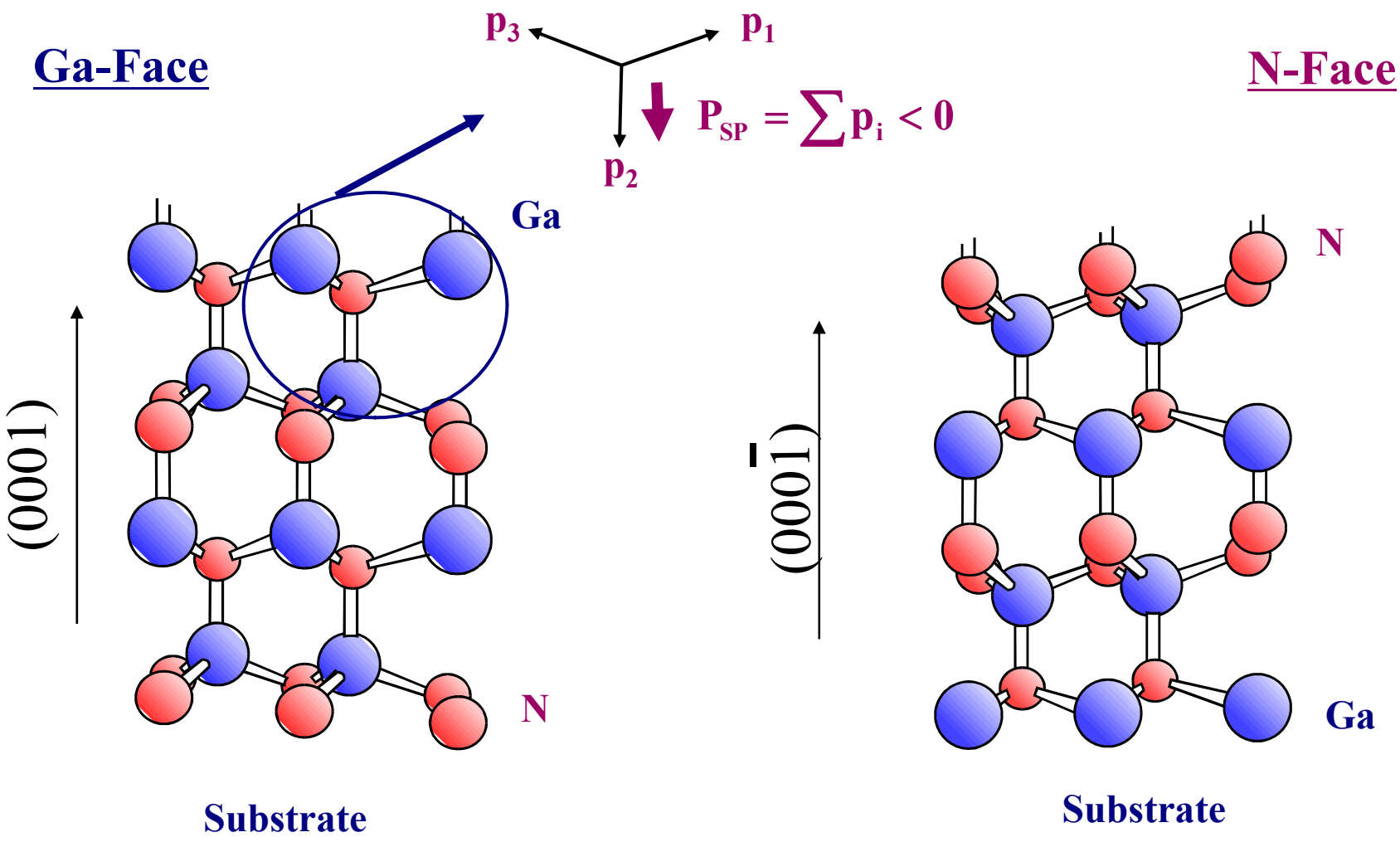
**GaAs**

- Zinc blende structure
- No PE or SP effect in <100> direction
- PE coefficient <111> ~0.15 $C/m^2$
- No PE/SP 'doping' reported

**GaN/AlN**

- Wurtzite structure
- c-axis growth direction
- PE coefficient in c-direction ~1 $C/m^2$
- PE/SP 'doping' demonstrated

# *Polarity of Wurtzite GaN*



# Spontaneous and Piezoelectric Polarization

## Piezoelectric Polarization : $P_{PE}$

$$P_{PE} = e_{33}\varepsilon_z + e_{31}(\varepsilon_x + \varepsilon_y)$$

$$\varepsilon_z = (c - c_0)/c_0\,,\ \ \varepsilon_x = \varepsilon_y = (a - a_0)/a_0\,.$$

Also, $\varepsilon_z = -2\dfrac{C_{13}}{C_{33}}\varepsilon_x$

Therefore, $P_{PE} = 2\dfrac{a - a_0}{a_0}\left(e_{31} - e_{33}\dfrac{C_{13}}{C_{33}}\right)$

where $\varepsilon_z$ : strain, $e_{33}$ : piezoelectric coefficient

$C_{13}$ : elastic constant

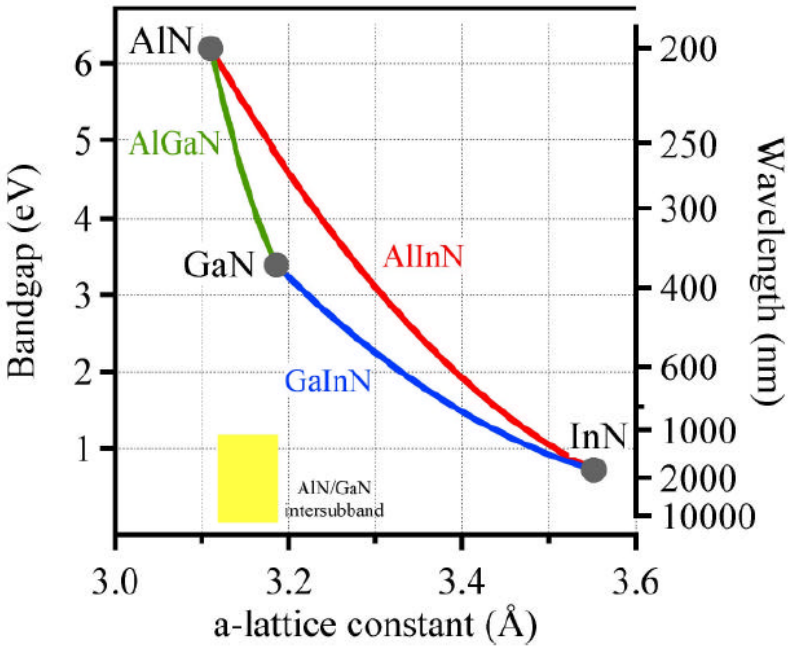
| Wurtzite | AlN | GaN | InN |
|---|---|---|---|
| $a_0$ (Å) | 3.112 | 3.189 | 3.54 |
| $c_0$ (Å) | 4.982 | 5.185 | 5.705 |
| $P_{SP}$ (C/m$^2$) | -0.081 (5x10$^{13}$ cm$^{-2}$) | -0.029 | -0.032 |

**Sapphire ; $a_0$ (Å) = 4.758, $c_0$ (Å)= 12.991**

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

For tensile strained AlGaN, $P_{PE}$ is negative.

(positive direction : cation to the nearest anion along c axis)

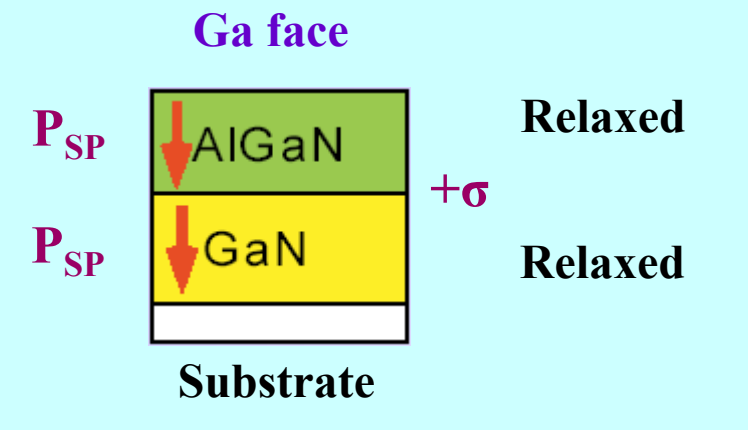


# *Basic Parameters of Wurtzite GaN, AlN, and InN*

| Parameters | GaN | AlN | InN |
|---|---|---|---|
| $a_{lc}$ (Å) at $T=300$ K | 3.189 | 3.112 | 3.545 |
| $c_{lc}$ (Å) at $T=300$ K | 5.185 | 4.982 | 5.703 |
| $E_g$ (eV) | 3.510 | 6.25 | 0.78 |
| $\alpha$ (meV/K) | 0.909 | 1.799 | 0.245 |
| $\beta$ (K) | 830 | 1462 | 624 |
| $\Delta_{cr}$ (eV) | 0.010 | −0.169 | 0.040 |
| $\Delta_{so}$ (eV) | 0.017 | 0.019 | 0.005 |
| $m_e^{\parallel}$ | 0.20 | 0.32 | 0.07 |
| $m_e^{\perp}$ | 0.20 | 0.30 | 0.07 |
| $c_{13}$ (GPa) | 106 | 108 | 92 |
| $c_{33}$ (GPa) | 398 | 373 | 224 |
| $P_{sp}$(C/m$^2$) | −0.034 | −0.090 | −0.042 |
| $e_{31}$ (C/m$^2$) | −0.33 | −0.48 | −0.57 |
| $e_{33}$ (C/m$^2$) | 0.65 | 1.55 | 0.97 |

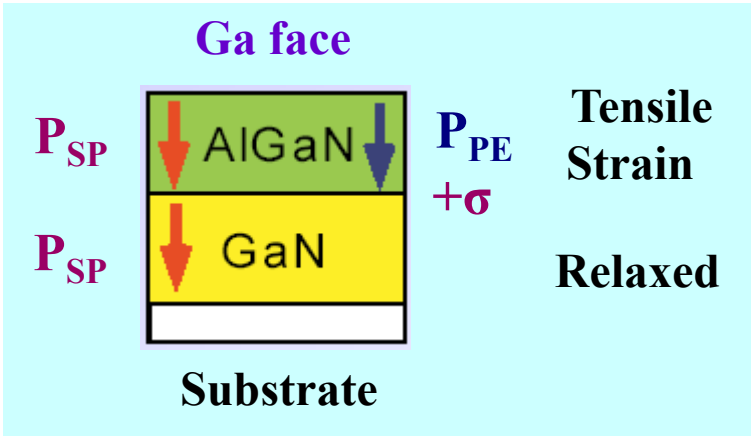
(Ref.) I. Vurgaftman and J. R. Meyer, **"Band parameters for nitrogen-containing semiconductors,"** Journal of Applied Physics, p. 3675-3696, Sept. 2003

# Polarization-Induced Sheet Charge – Ga Face

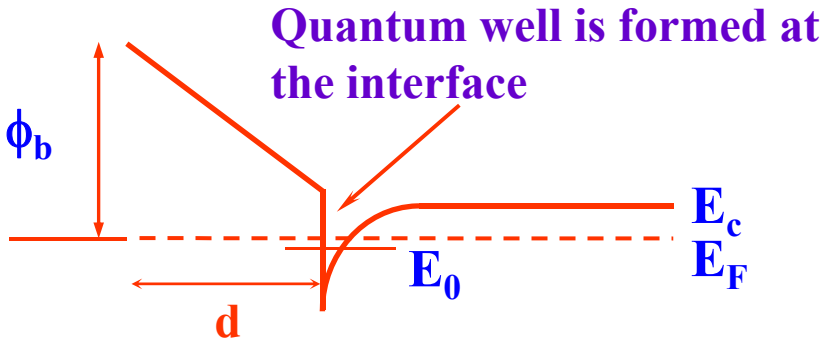


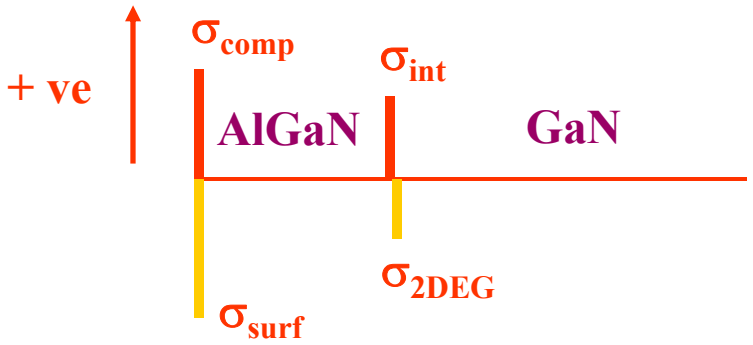

$$\sigma = P(\text{top}) - P(\text{bottom})$$
$$= (P_{SP} + P_{PE})_{top} - (P_{SP} + P_{PE})_{bottom}$$

⇨ Two-Dimensional electrons at AlGaN/GaN interface

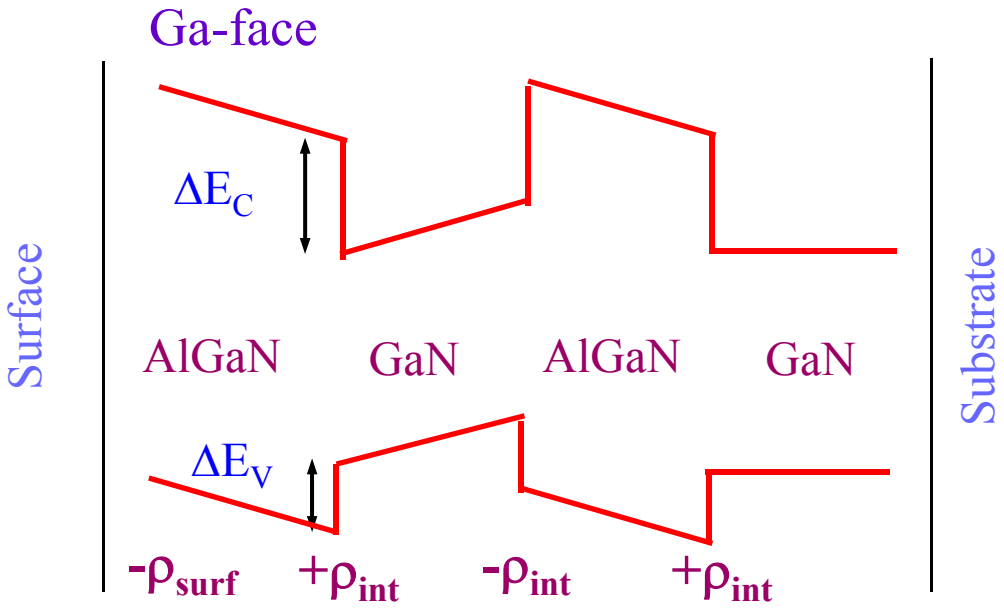



2D electrons at AlGaN/GaN interface



# Band diagram under polarization



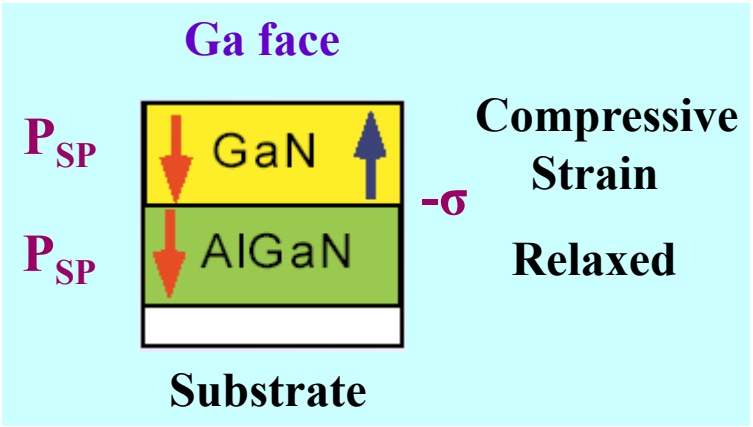

AlGaN/GaN/AlGaN/GaN band line-up with polarization, no charge transfer, no interface charge (2DEG)

$$\Delta E_C = 0.7[E_g(x) - E_g(0)]$$

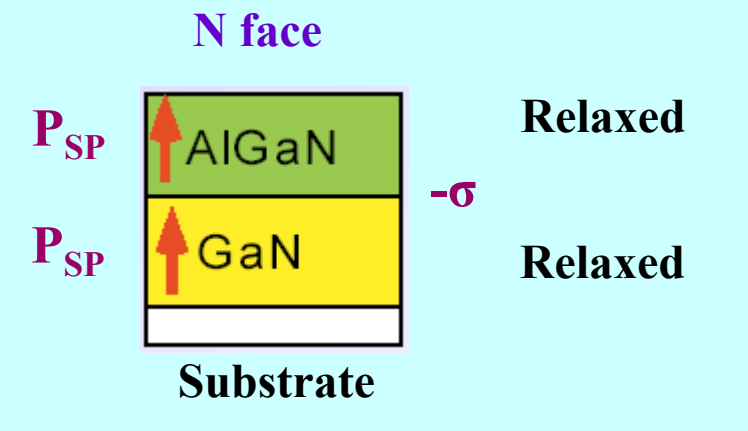
$$E_g(x) = 6.13x + 3.42(1-x) - x(1-x)$$

where $x$ = Al alloy composition

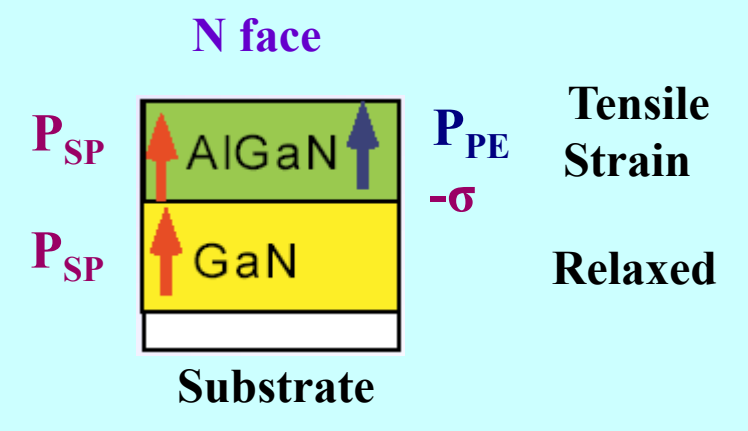
**2D holes at GaN/AlGaN interface**



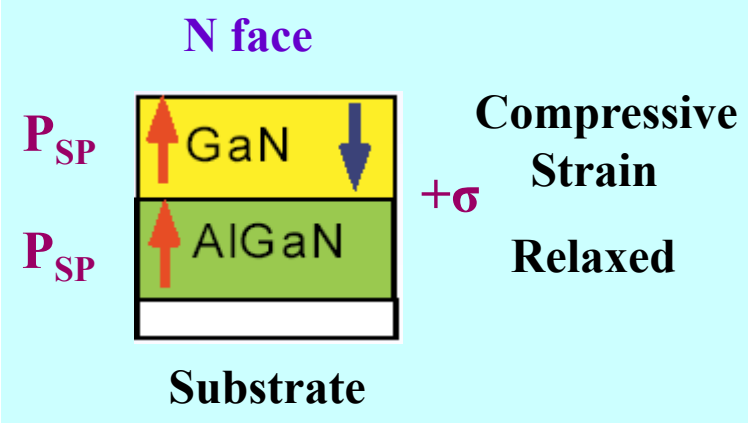
# *Polarization-Induced Sheet Charge – N Face*




⇨ Two-Dimensional holes at AlGaN/GaN interface

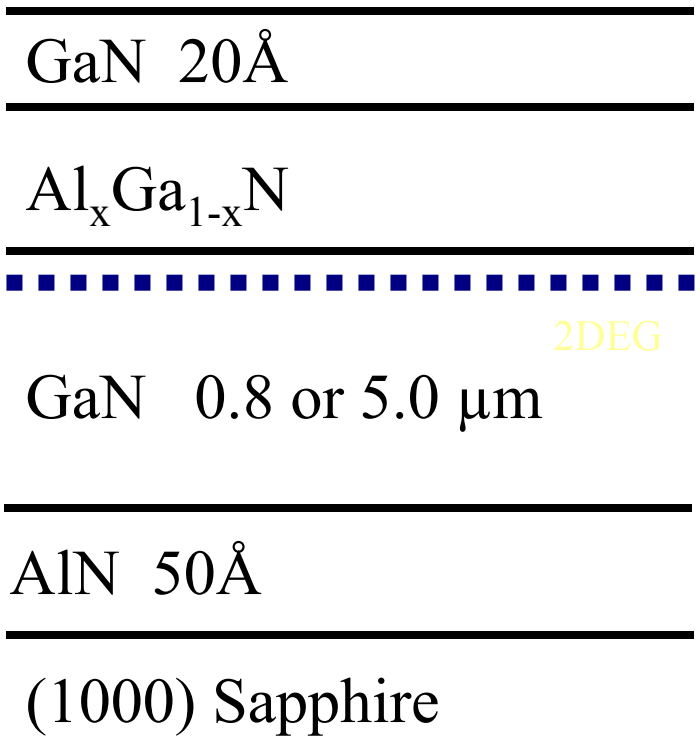



2D holes at AlGaN/GaN interface




2D electrons at GaN/AlGaN interface

# *Normal Piezo HFET (Ga-Face) on AlN buffer*




5.0 μm GaN buffer
AlGaN: x=0.42 20nm

At 300 K
$\mu = 1450\ cm^2/Vsec$ $n_s=1.1x10^{13}\ cm^{-2}$

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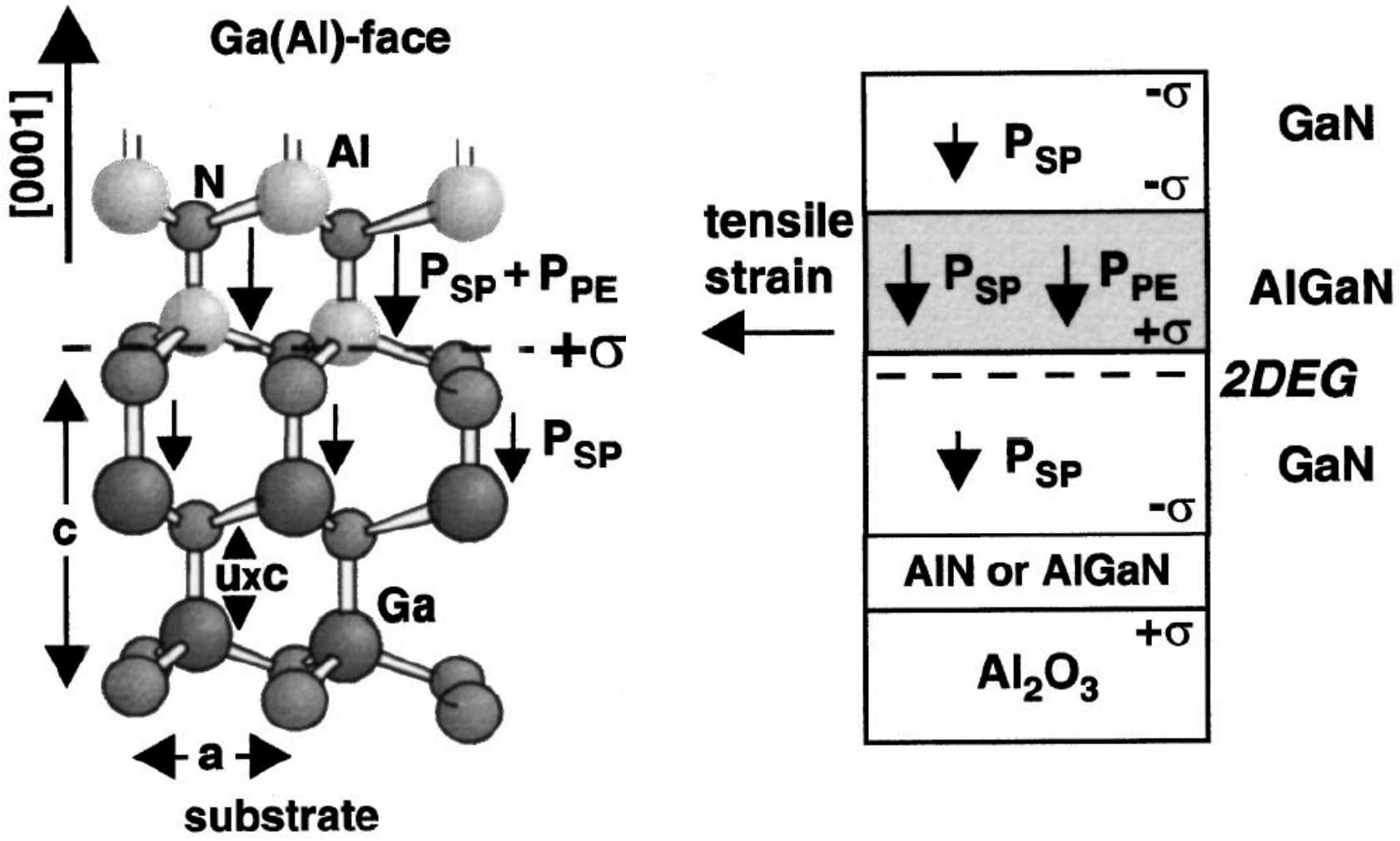
0.8 μm GaN buffer
AlGaN: x=0.36 30nm

At 300K
$\mu = 1478\ cm^2/Vsec$ $n_s=8.8x10^{12}\ cm^{-2}$

Piezo induced HFET 2DEG on **Ga-face** AlN nucleation layer

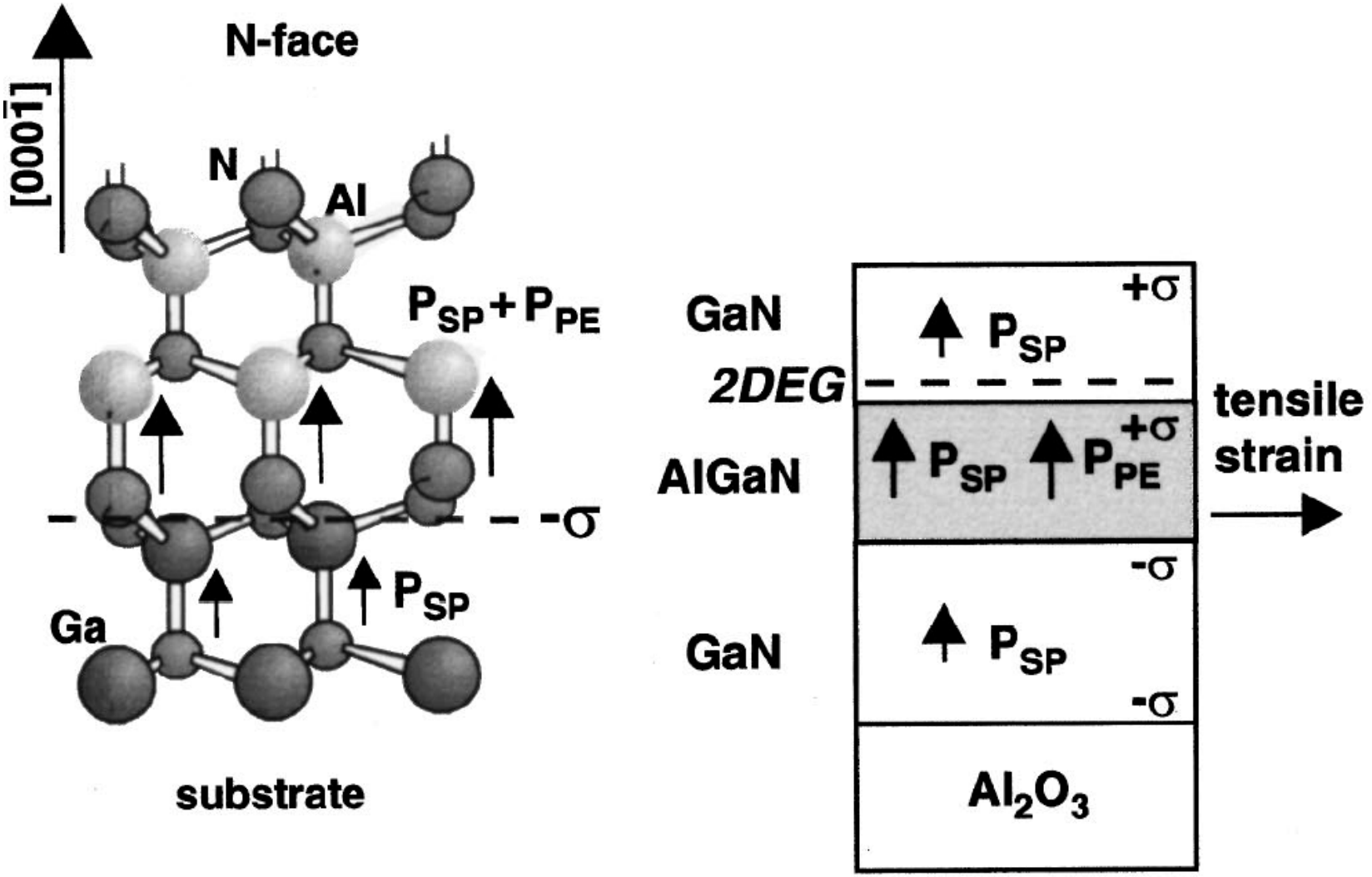
No 2DEG when using GaN (N-face) buffer

# *Normal 2DEG on Ga-Face GaN/AlGaN*

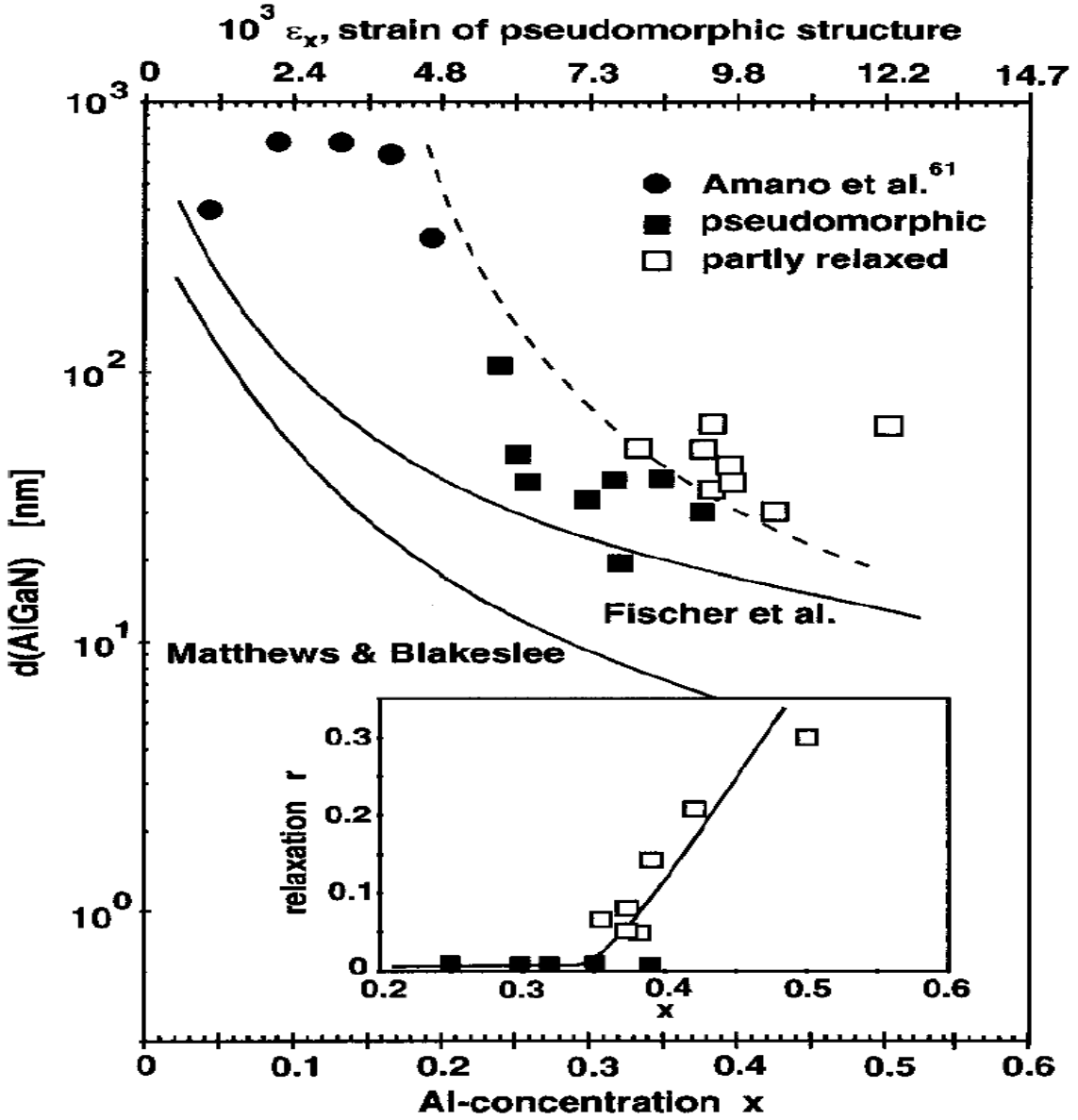



**Ref : O. Ambacher, et al, J. Appl. Phys, p. 334, 2000**

# *Inverted 2DEG on N-Face GaN/AlGaN*

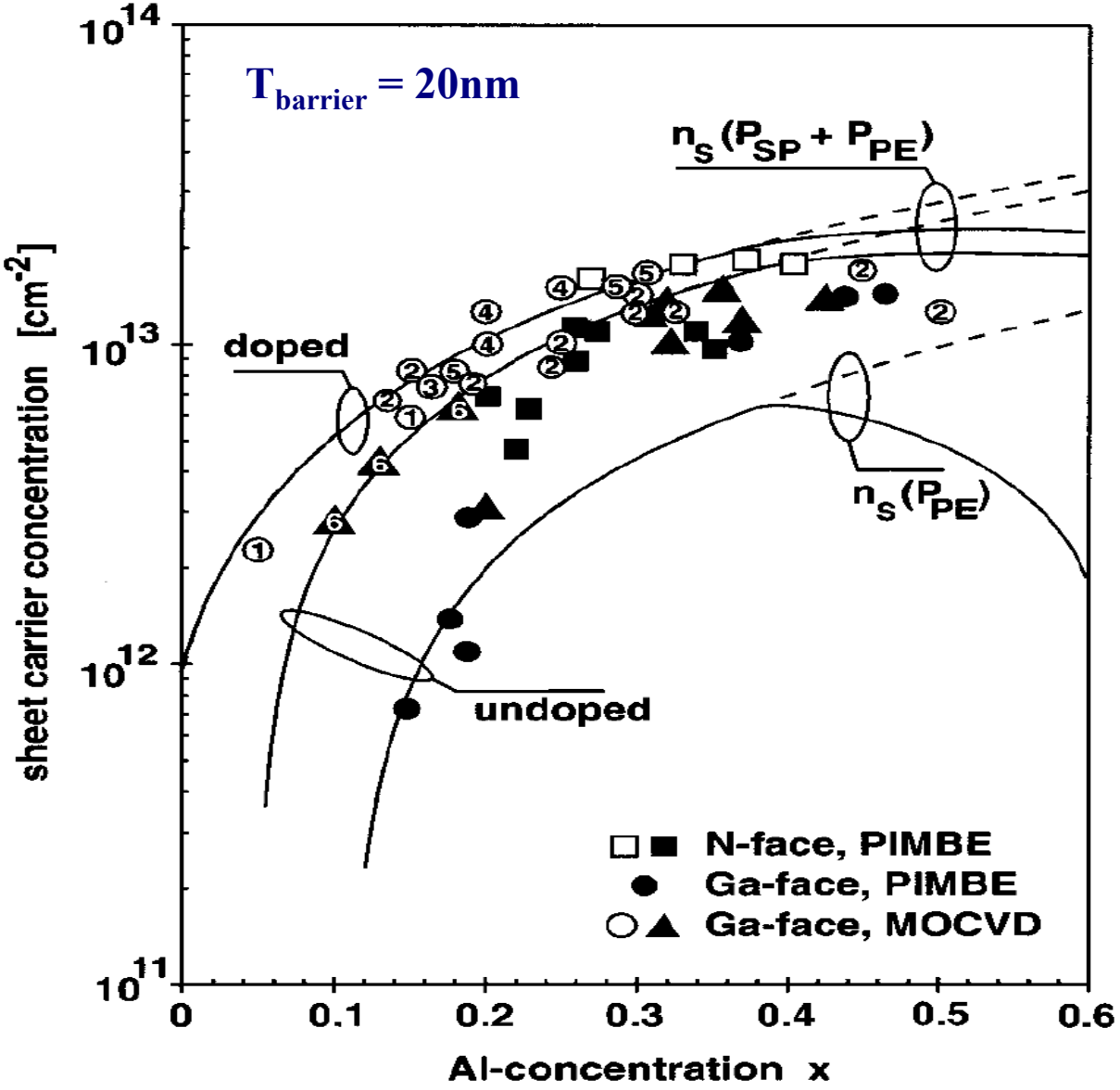


# *Critical Thickness of AlGaN on GaN*



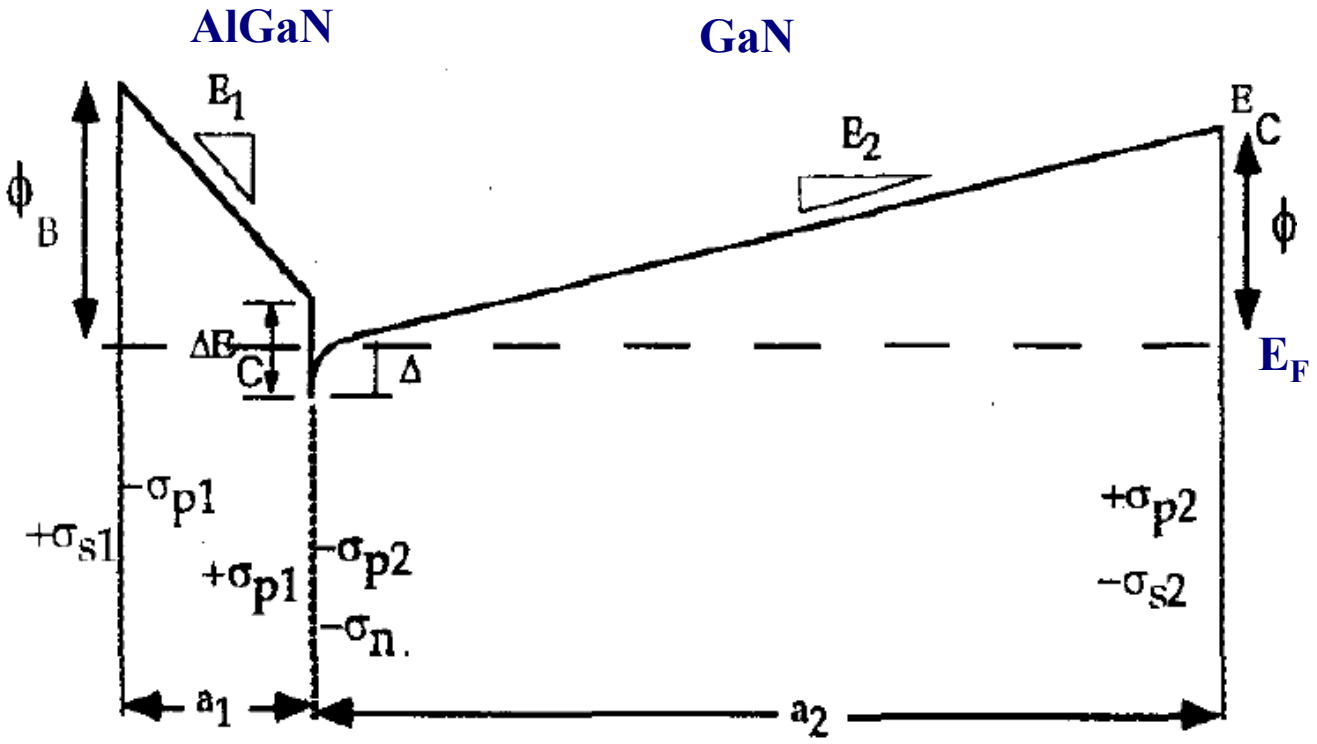

**Ref : O. Ambacher, et al, J. Appl. Phys, p. 334, 2000**

# *Maximum 2DEG Concentration in AlGaN/GaN Structure*




Ref : O. Ambacher, et al, J. Appl. Phys, p. 334, 2000

# *Band Diagram of GaN/AlGaN Modulation Doped Structure*



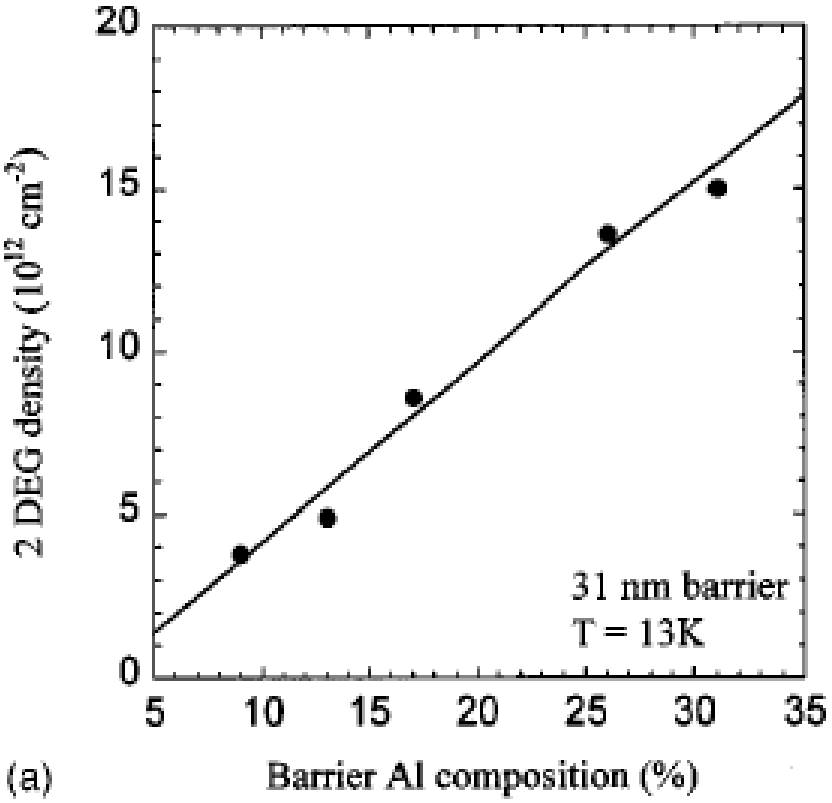

$$\sigma_n = qn_s = \frac{\sigma_{P1} - \sigma_{P2} - c_1\psi - c_2\phi}{1 + c_1 \dfrac{\pi\hbar^2}{q^2 m^*}}$$

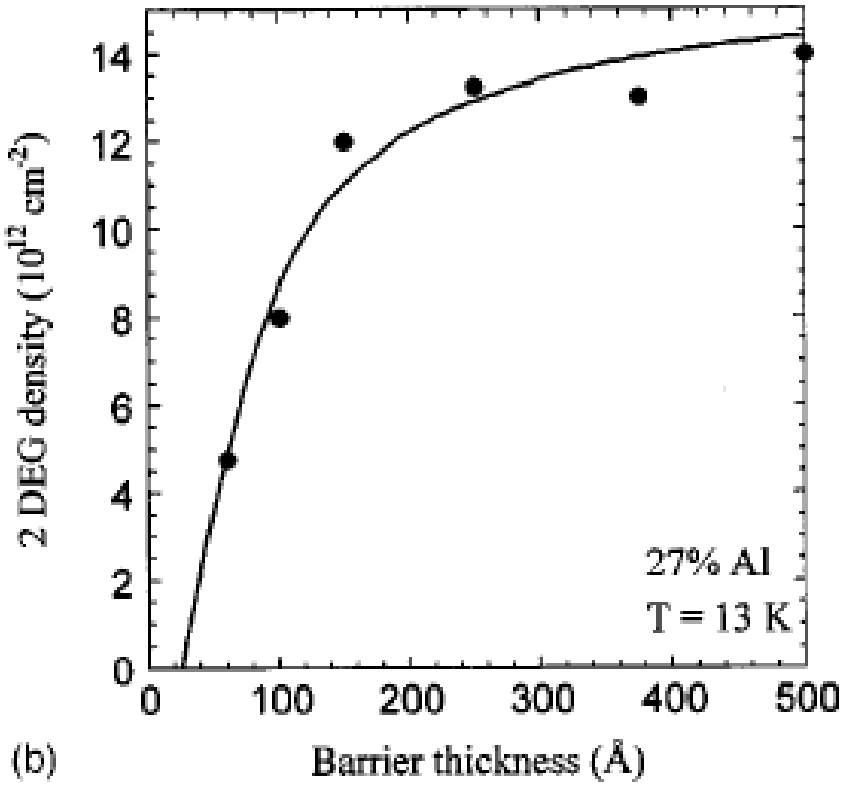
where $\psi = \phi_B - \Delta E_C$,

$c_1 = \varepsilon_1/a_1$, $c_2 = \varepsilon_2/a_2$

Ref : T. R. Prunty, et al, 2000 IEEE/Cornell Conf. on High Performance Devices

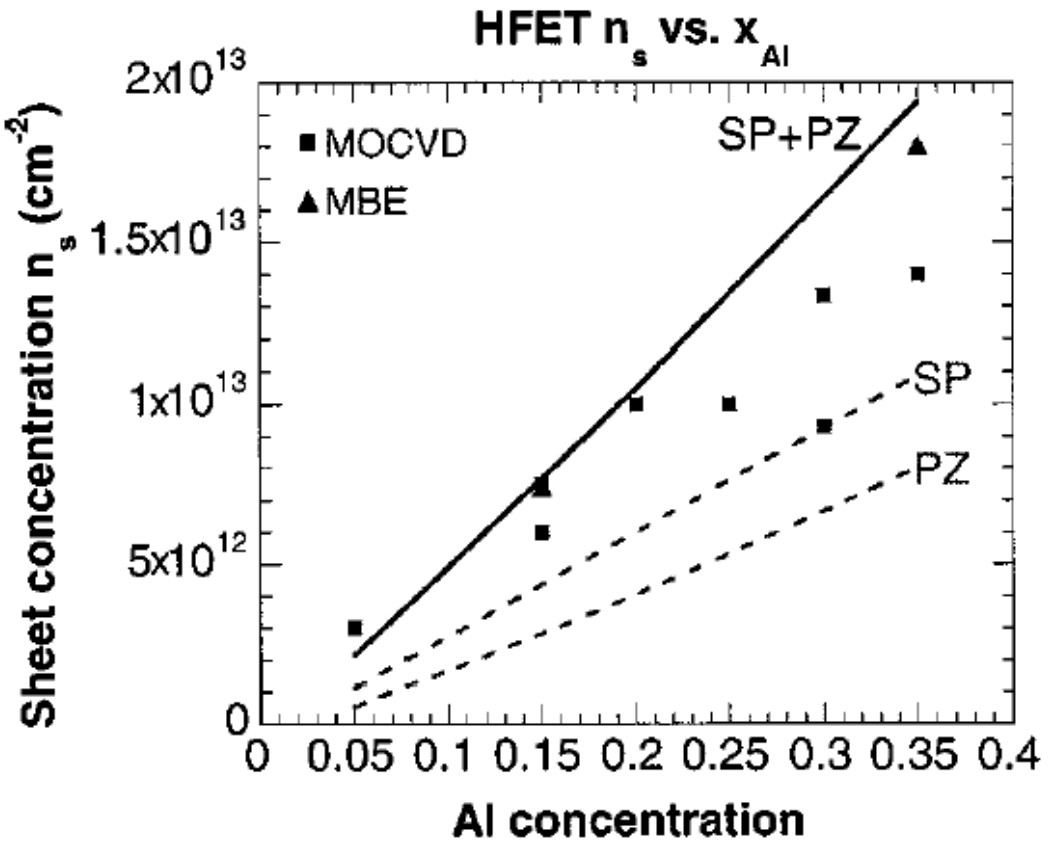
# *2DEG of GaN/AlGaN Modulation Doped Structure*




Schottky Barrier Height on AlGaN : $\phi_B = (1+\ 1.9\ x)$ eV

# 2DEG Concentration in AlGaN/GaN HEMT Structure




**AlGaN Barrier**

$N_d = 1x10^{18}cm^{-3}$

d = 300Å

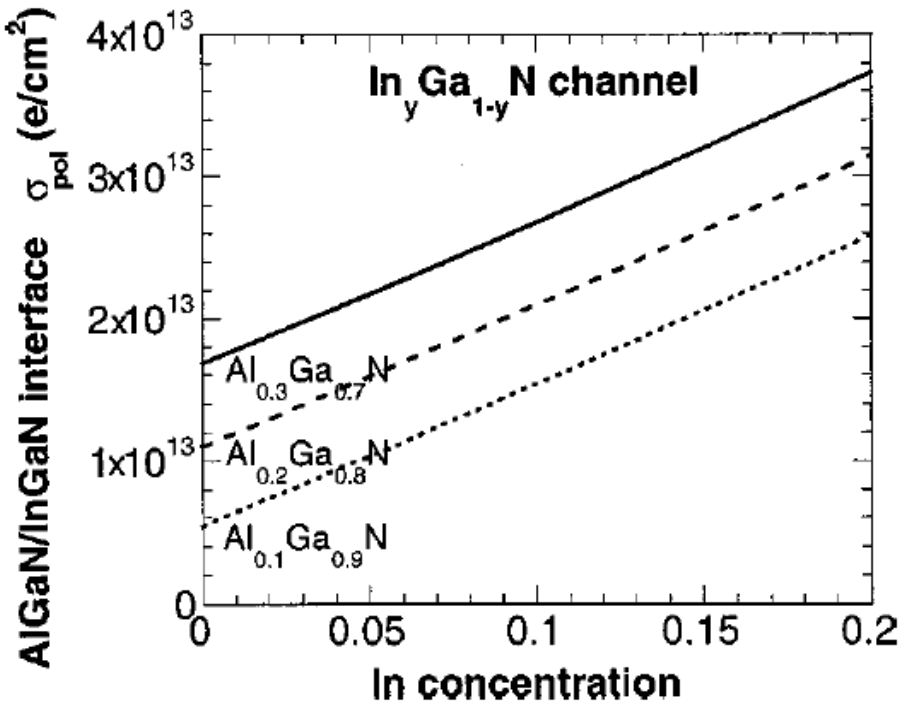
Ref : E. T. Yu et al., J.V.S.T.-B, p. 1742, 1999

$$\sigma_{pol}/e = -2[e_{31} - (c_{13}/c_{33})e_{33}](a_{GaN}/a_{AlN} - 1)x + P_{sp,z}^{GaN} - P_{sp,z}^{AlGaN}$$

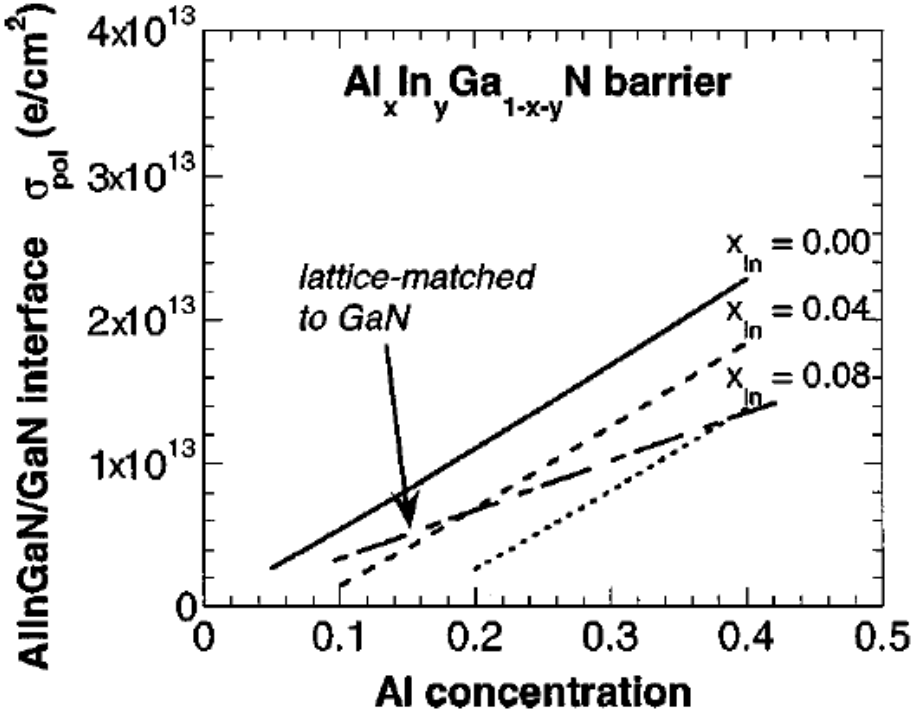
$$n_s = \sigma_{pol}/e - (\epsilon_{AlGaN}/de^2)(e\phi_b + E_F - \Delta E_c) + \tfrac{1}{2}N_d d$$

# *Polarization Sheet Charge in GaN HEMT Structure*

## *InGaN/AlGaN Structure*

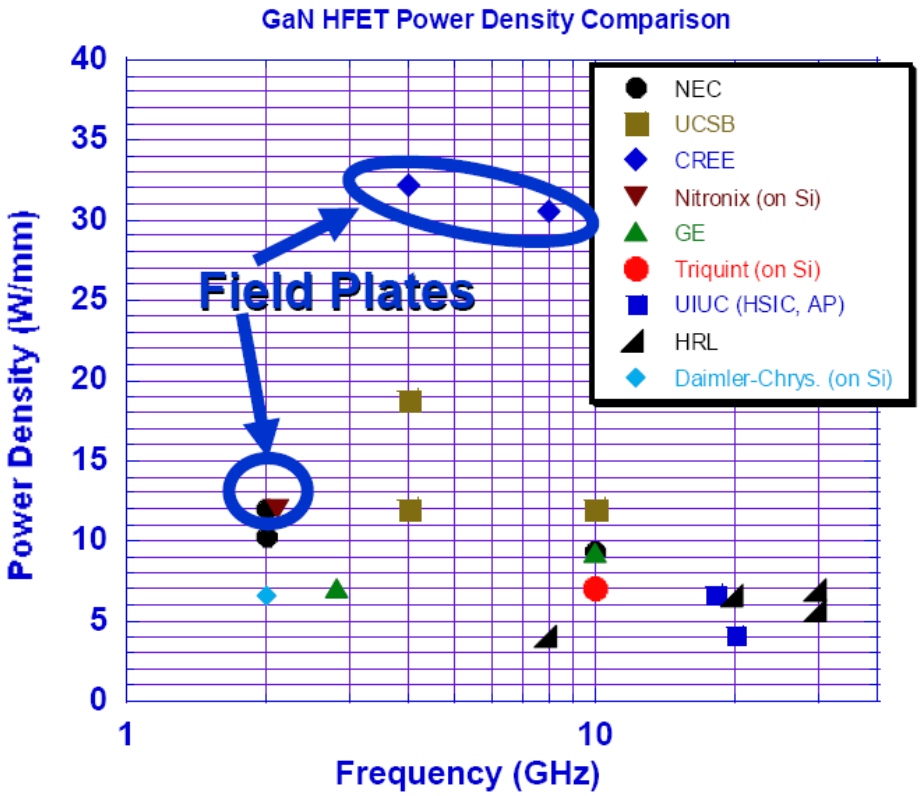


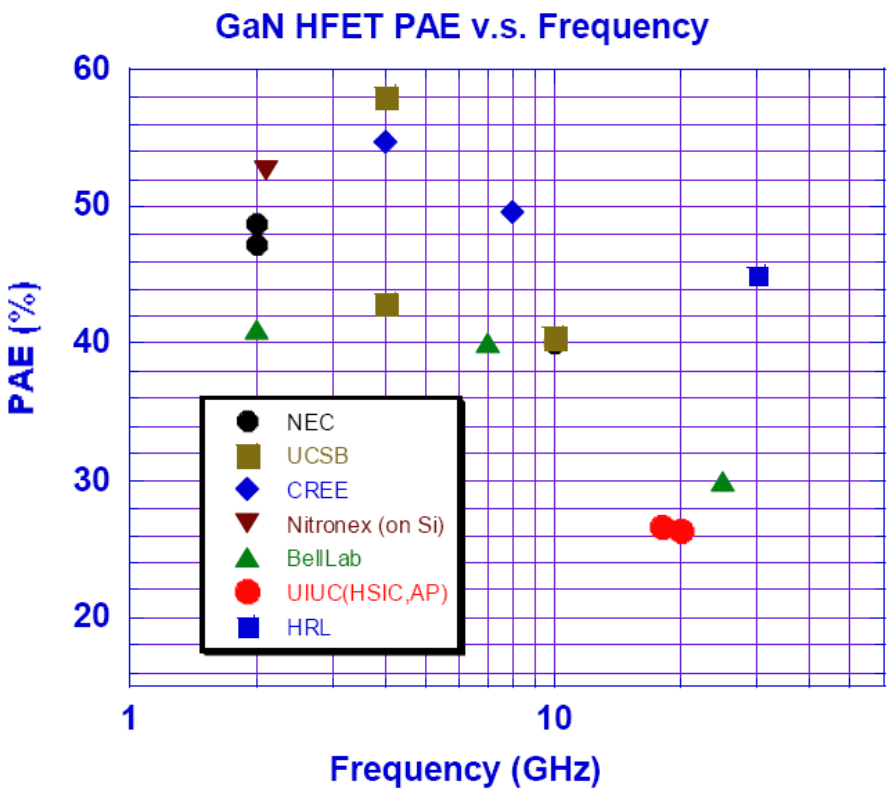

## *GaN/AlInGaN Structure*




Ref : E. T. Yu et al., J.V.S.T.-B, p. 1742-1749, 1999

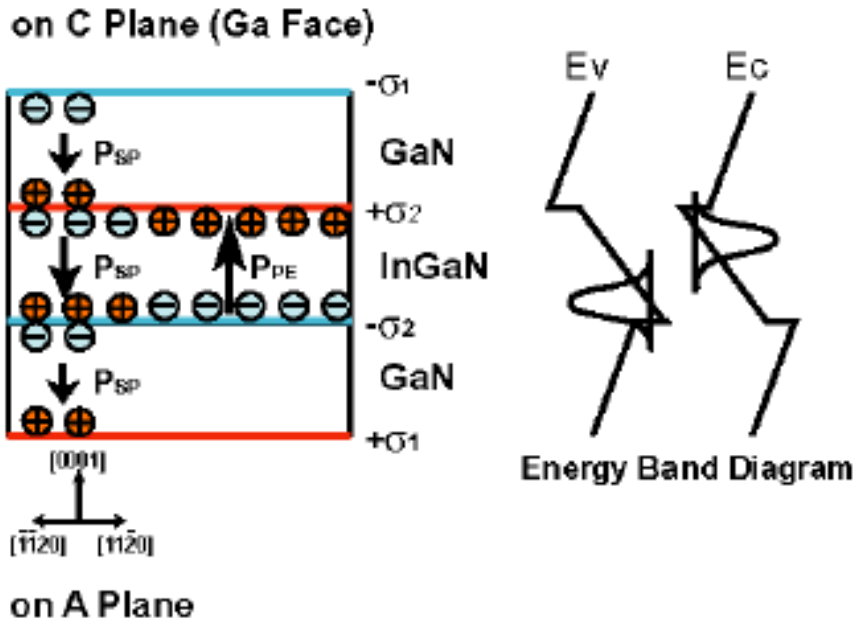
# *Power Density Performance for AlGaN/GaN HFET*




- Advantages
  - – High bandgap material, High breakdown field, >10x power density
  - – Good thermal conductivity, High temperature operation
- Challenges
  - – Large wafer availability, Manufacturability, Reliability

# *Quantum-Confined Stark Effect*




Spontaneous and piezoelectric polarization cause:

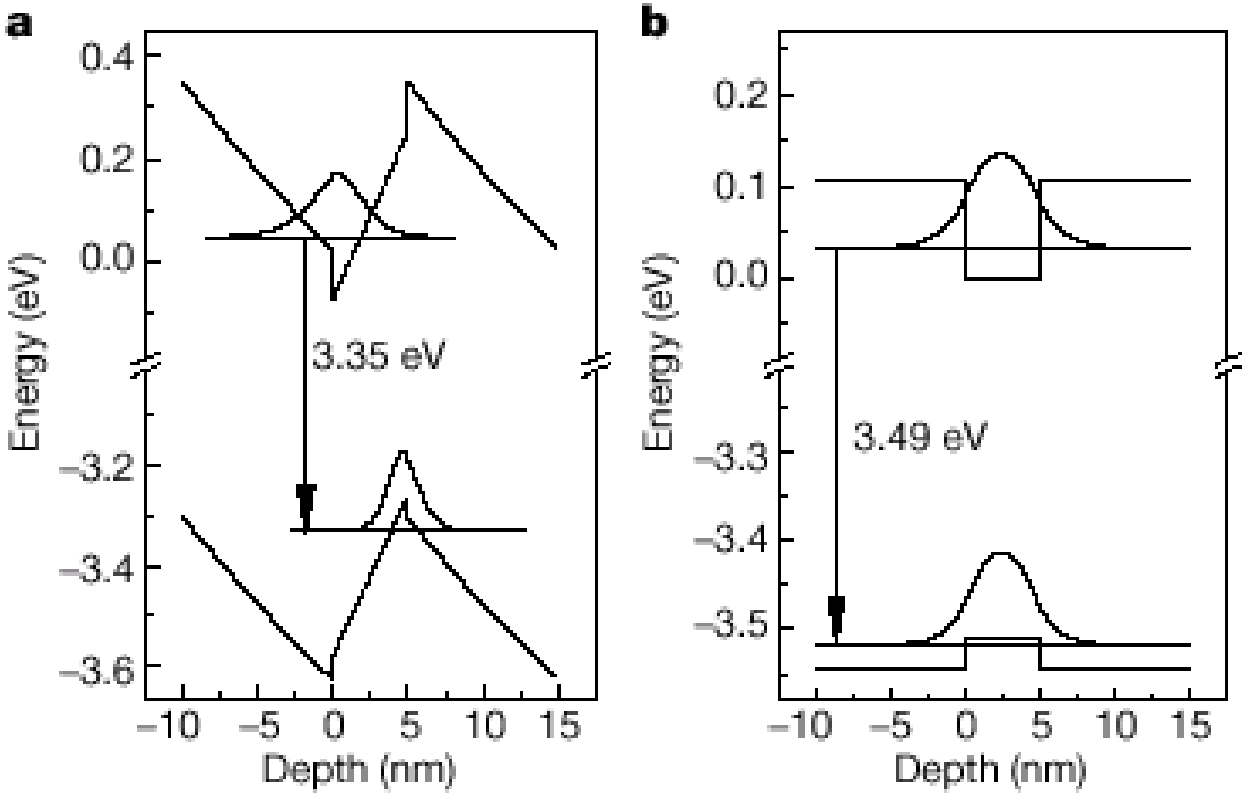
1. band bending
2. charge separation in QW

- **Red shift of the emission**
- **Low recomination efficiency**
- **High threshold current**

Avoiding the QCSE

- Induce growth in non-polar GaN directions such as [1$\underline{1}$00], on substrates such as $LiAlO_2$ [à la Paul-Drude-Institut, Berlin, Germany]
- Homoepitaxial Growth on non-polar GaN substrates derived from **bulk** crystal growth
- Growth of lattice-matched quaternary $Al_xIn_yGa_{1-x-y}N$ compositions

# *Light Emission from GaN/AlGaN Quantum Well*

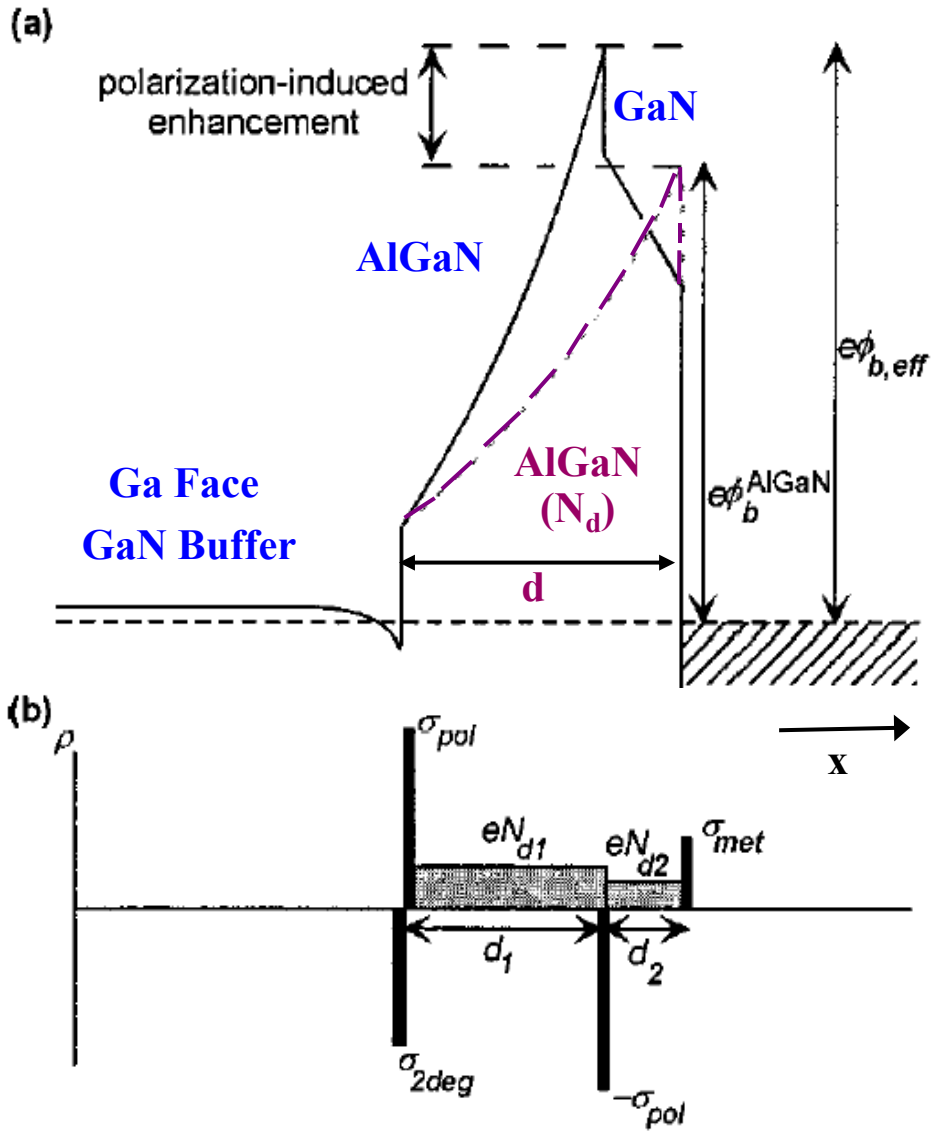



Wurtzite GaN/AlGaN

Cubic GaN/AlGaN
- on $LiAlO_2$ (100)

Ref : P. Waltereit et al., Nature, p. 865-867, 2000

# *Schottky Barrier Enhancement with Polarization Effect ( I )*

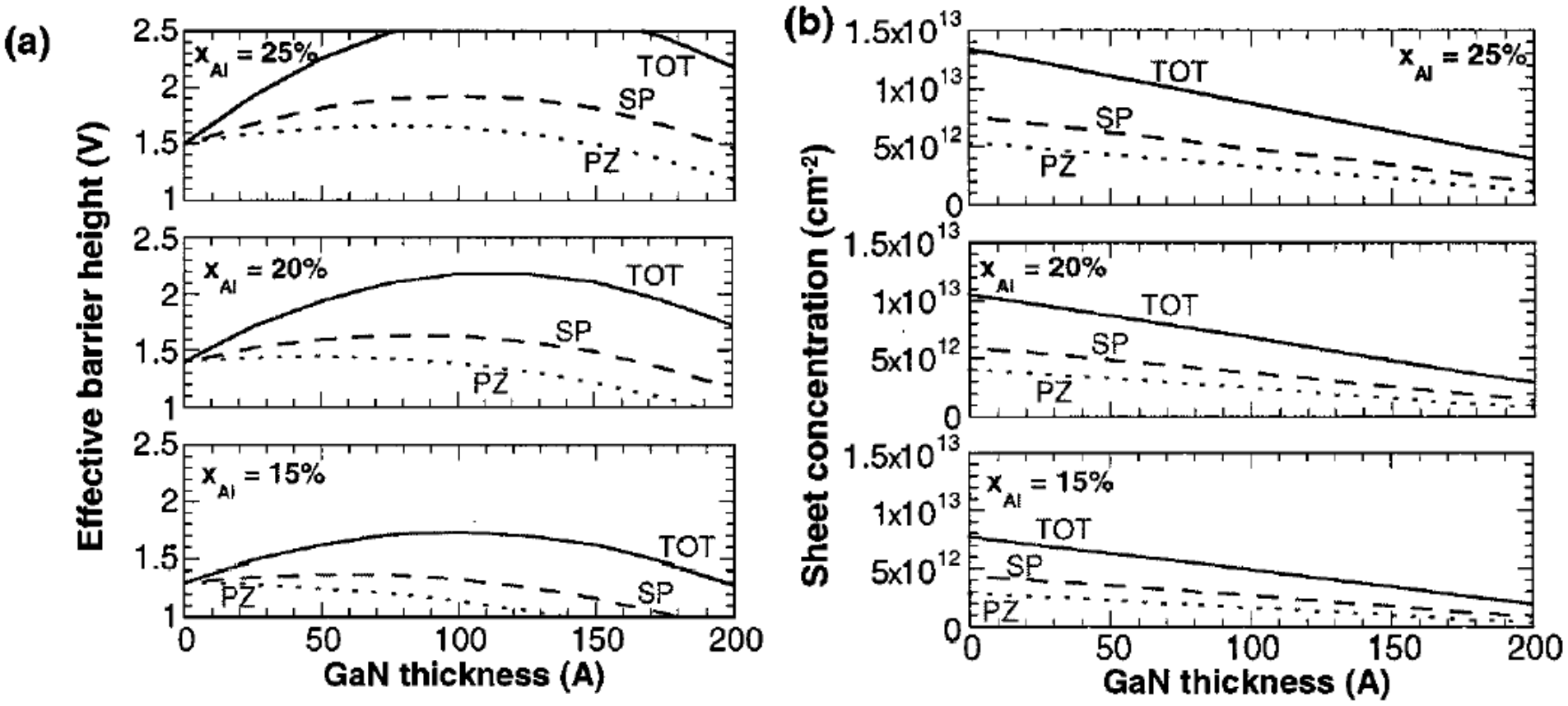



**$e\Phi_b$ :** Schottky Barrier Height or Surface Potential

Ref : E. T. Yu et al., J.V.S.T.-B, p. 1742-1749, 1999

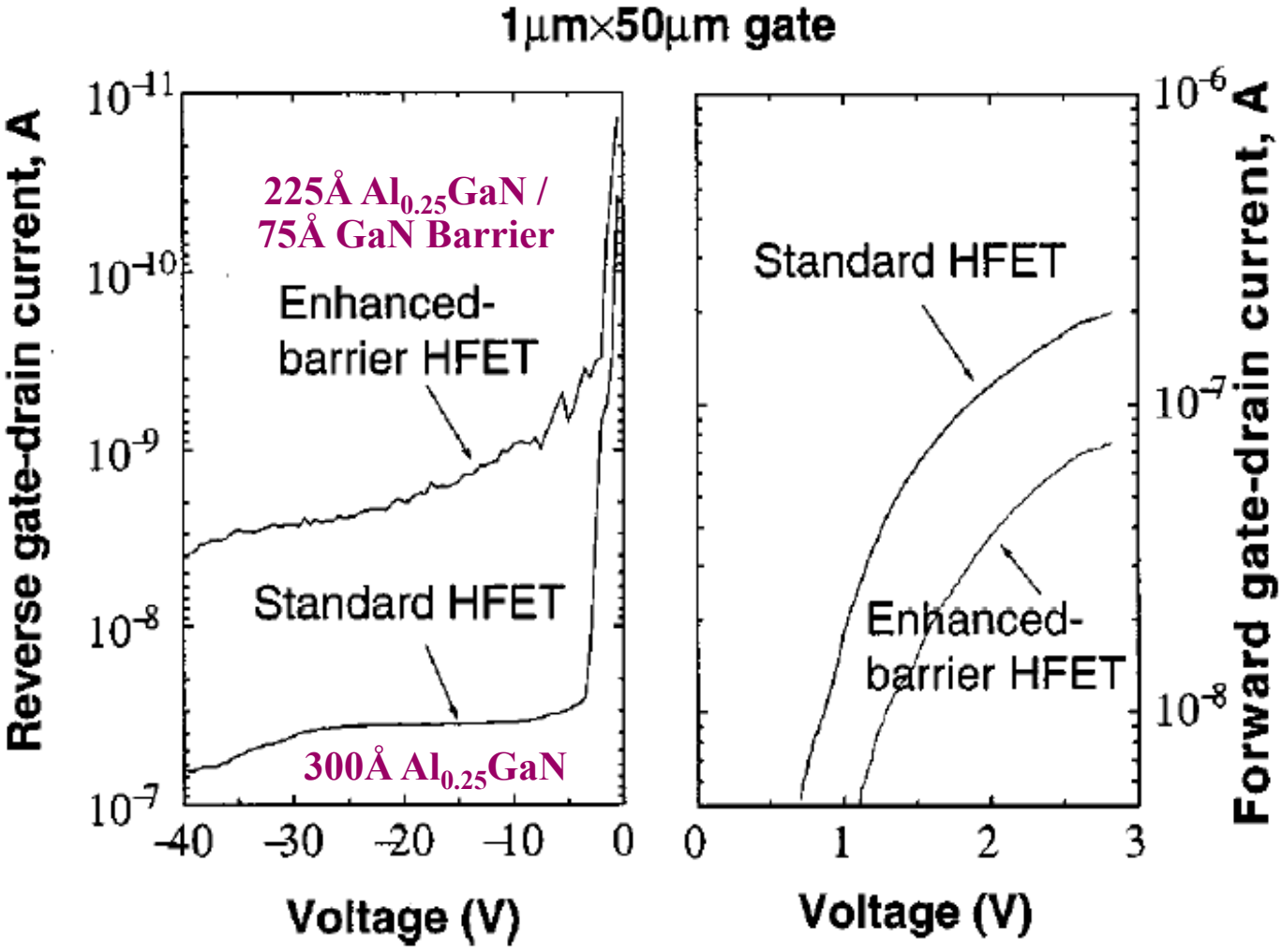
# *Schottky Barrier Enhancement with Polarization Effect ( II )*

**Barrier : $N_{d1} = 1x10^{18}cm^{-3}$, $N_{d2} = 5x10^{17}cm^{-3}$, $d_1+d_2 = 300Å$, $\phi_b^{GaN} = 1.0V$**




Ref : E. T. Yu et al., J.V.S.T.-B, p. 1742-1749, 1999

# *Enhanced Barrier HFET*




Ref : E. T. Yu et al., J.V.S.T.-B, p. 1742-1749, 1999