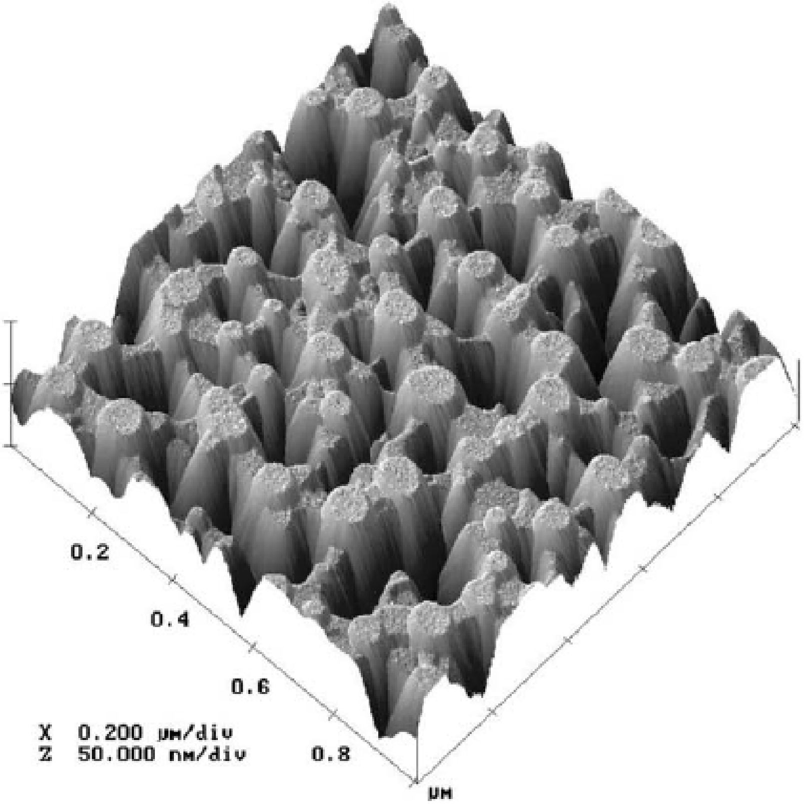
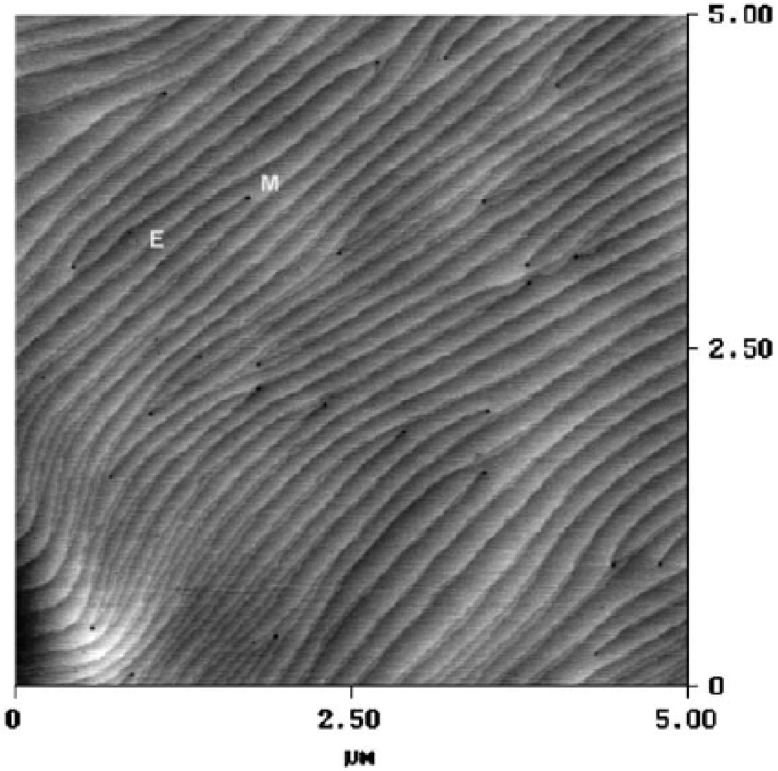
화합물 반도체 (II-4)
Heterostructure Growth

2007 / 가을 학기

Reduced Dislocation Densities with SiH_4 Treatment



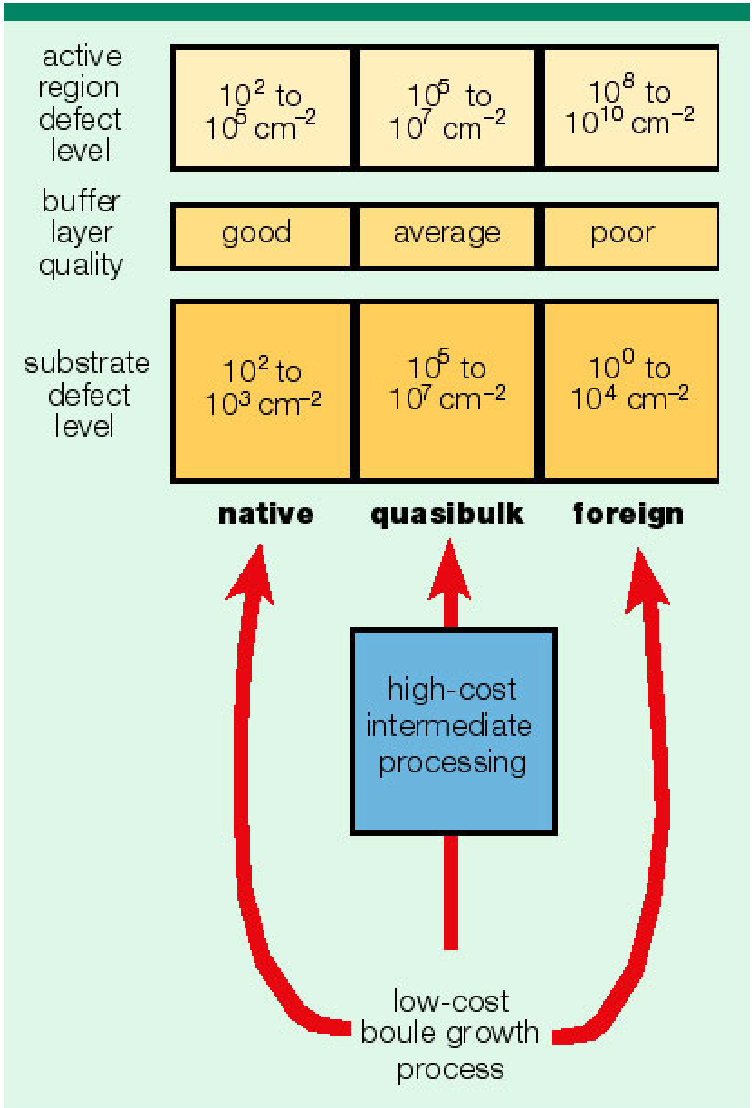
Etched surface with SiH_4 treatment at 1100°C for 300s



TD densities ~ 1×10^{8} cm^{-2}
(without SiH_4 treatment, ~ 1×10^{9} cm^{-2})

Ref.: K. Pakula, et al., Journal of Crystal Growth 267, pp. 1–7, 2004

Bulk GaN Growth



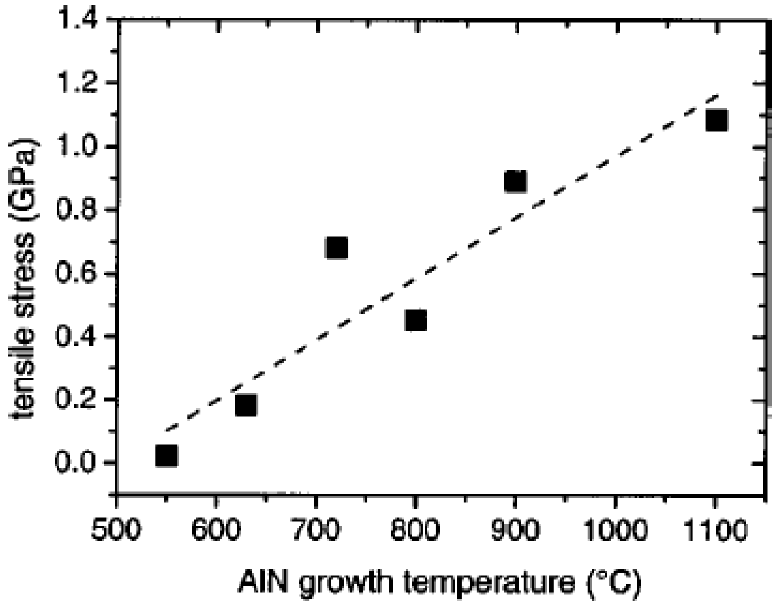
	native	quasibulk	foreign
active region defect level	10^2 to 10^5 cm^{-2}	10^5 to 10^7 cm^{-2}	10^8 to 10^{10} cm^{-2}
buffer layer quality	good	average	poor
substrate defect level	10^2 to 10^3 cm^{-2}	10^5 to 10^7 cm^{-2}	10^0 to 10^4 cm^{-2}

- Bulk GaN growth with pressures of 15,000 atm and temperatures of 1600°C ➡10 mm in diameter with TD densities of 100 cm^{-2} (commercialized by Topgan for research)

- 1~2 inch bulk AlN growth with sublimation recondensation process ➡ appropriate for Al-rich AlGaN growth for DUV laser diodes (commercialized by Crystal IS)

Ref. : Compound Semiconductor
Magazine, Juy, Oct. 2004

Stress Reduction with Low-Temperature AlN Interlayer



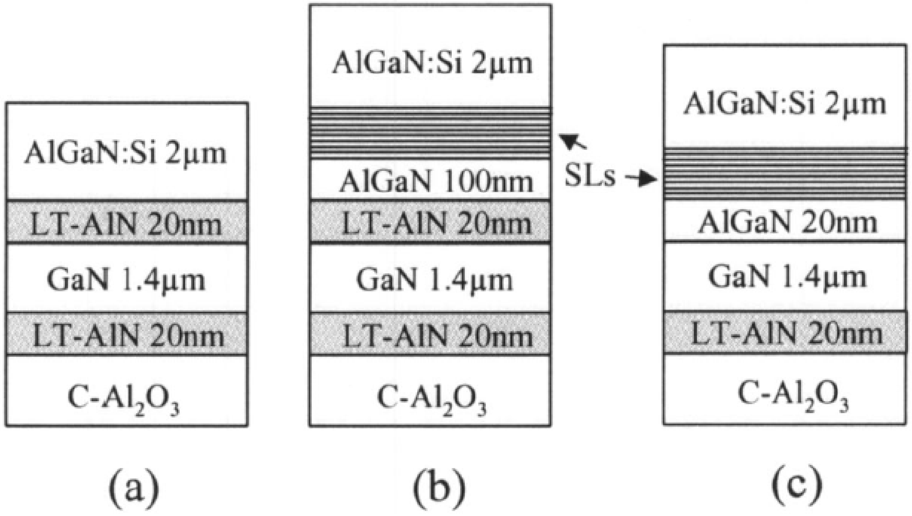
Average tensile stress of 1.3μm thick GaN layer grown on 12nm thick AlN buffer

- Relaxed AlN buffer at low temp growth

Sample	T_{AlN} [°C]	Curvature radius [m]	Total stress [GPa]	a-AlGaN [Å]	a-GaN [Å]
A	630	14.7	−0.01	3.1653	3.1899
B	900	7.9	0.46	3.1665	3.1923
C	1145	2.9	1.13	3.1923	3.1923

Ref.: J. Blasing, et al., Appl. Phys. Lett., pp. 2722–2724, 7 October 2002

AlGaN Grown on GaN with Various Interlayers

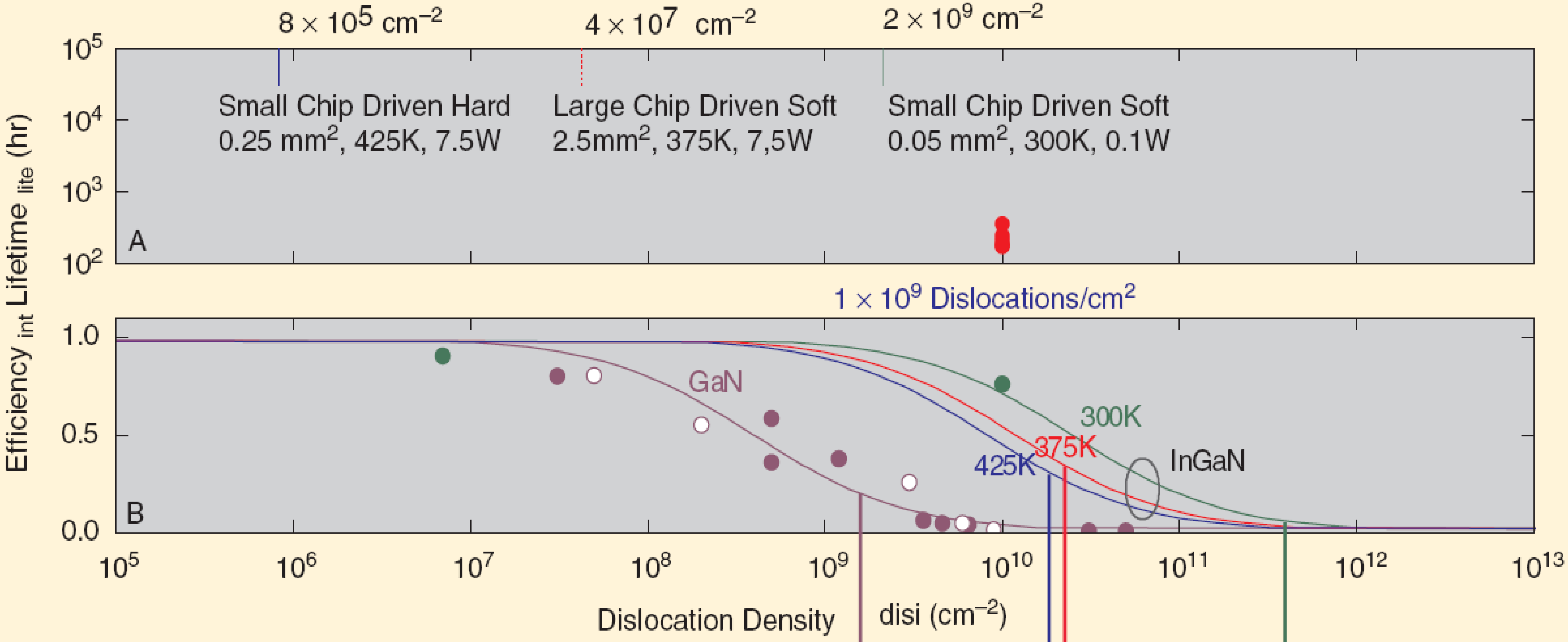


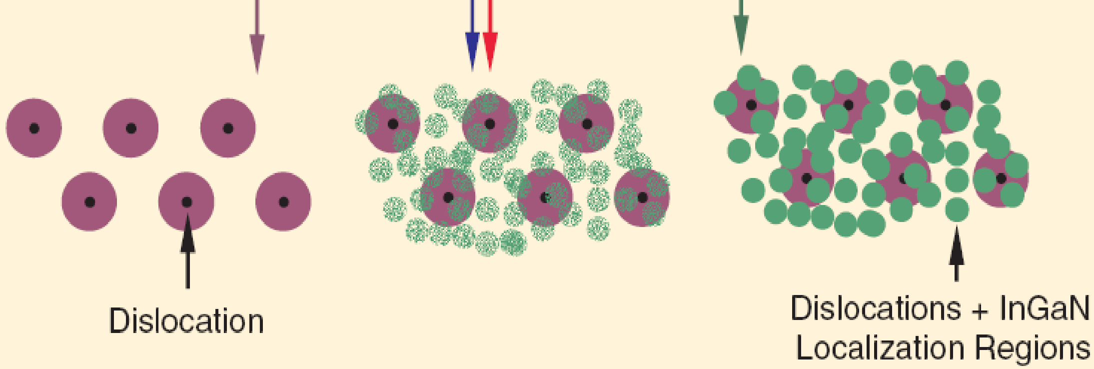
Ten period
AlN 4nm/AlGaN 36nm
Superlattices
($Al_{0.2}GaN$)

Interlayer	Surface	FWHM in (0002) ω scan (arcmin)	FWHM in $(20\bar{2}4)\omega$ scan (arcmin)	Density of etch pits (cm^{-2})	Mobility (cm^2/V s) and concentration (cm^{-3})
No	Crack network	9.5	14.6		
LT-AlN	Several cracks	12.4	18.2	6×10^9	
LT-AlN and SLs	Crack free	12.1	16.9	4×10^9	Mob.: 87, Con.: 3.0×10^{18}
SLs	Crack free	6.4	11.8	2×10^9	Mob.: 161, Con.: 2.5×10^{18}
Directly on Sapphire	Crack free	14.6	23.3	7×10^9	Mob.: 38, Con.: 2.2×10^{18}

Ref.: Q. C. Chen, et al., Appl. Phys. Lett., pp. 4961–4963, 23 December 2002

Effects of Dislocations on Light Emission Efficiency

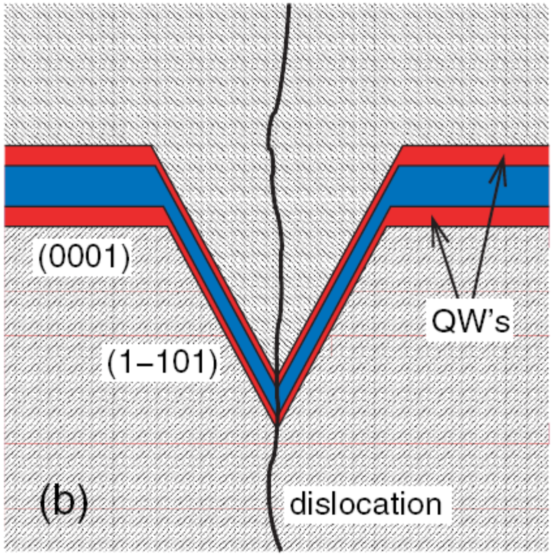


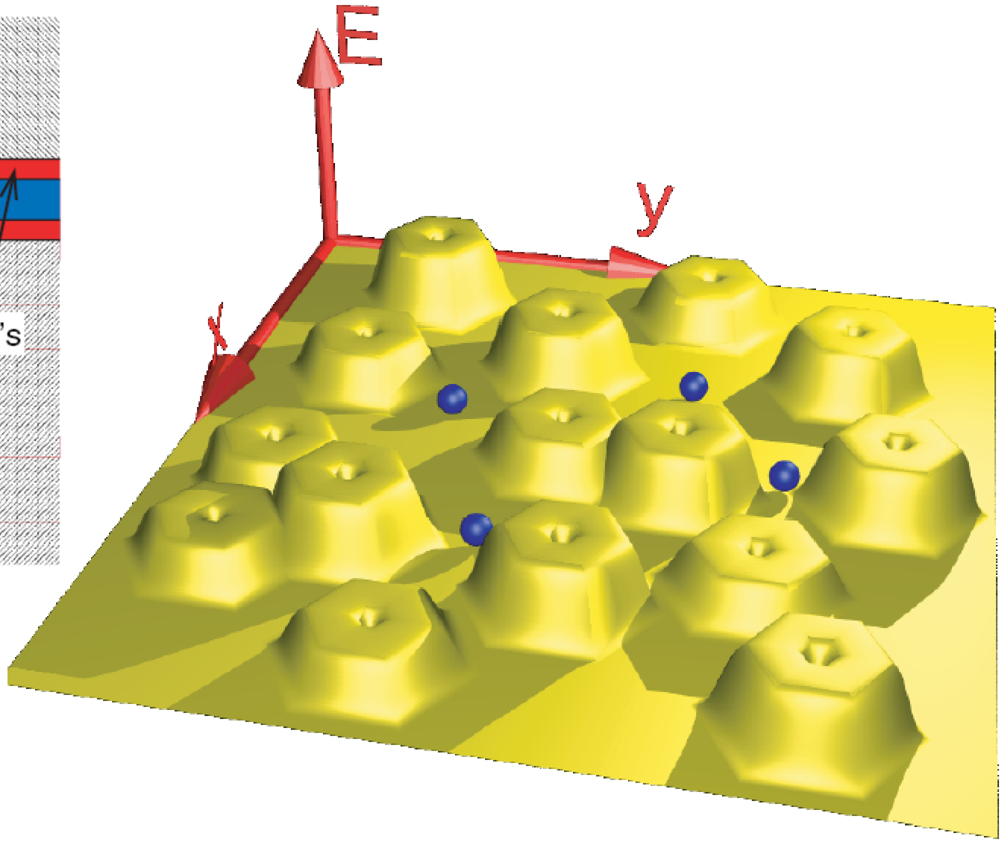


Ref. : Jeff Y. Tsao, "Solid State Lighting," IEEE Cir. & Dev. Magazine, pp. 28-37, May/June 2004

New Model for Suppression of Nonradiative Recombination

High resolution TEM
Near-field micro-PL

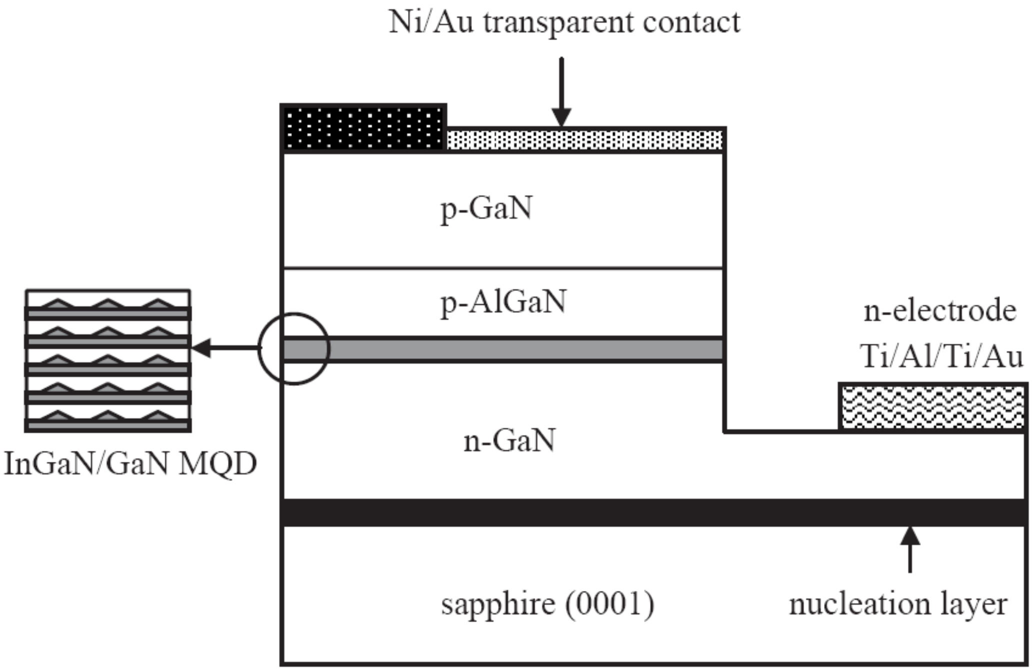


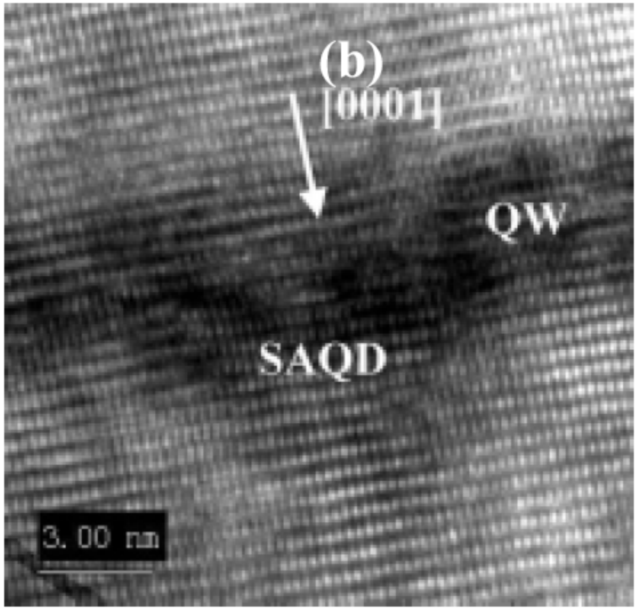


- **hexagonal V-shaped pits decorating the defects**
- **narrow sidewall QW**
  - **⇨ large effective band gap**
  - **⇨ suppressing nonradiative recombination**

Ref) A. Hangleiter, et al., Phys. Rev. Lett. 95, 127402, 2005

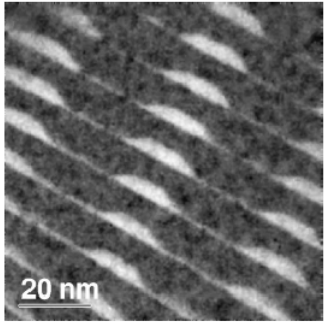
InGaN Multi-Quantum Dot LED (I)





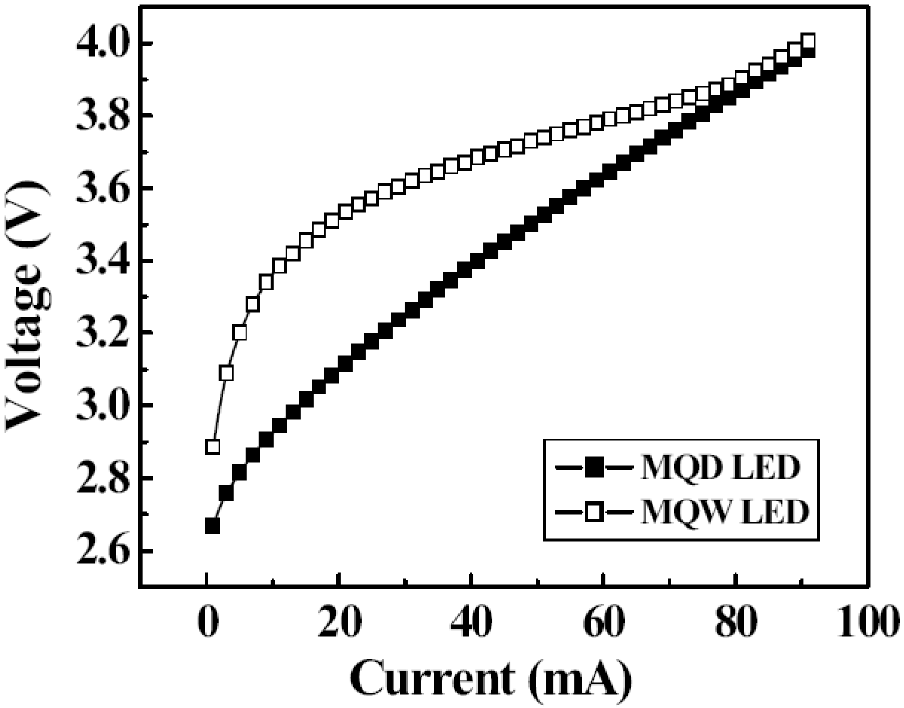
- **2.4nm InGaN well/15nm thick GaN barrier**

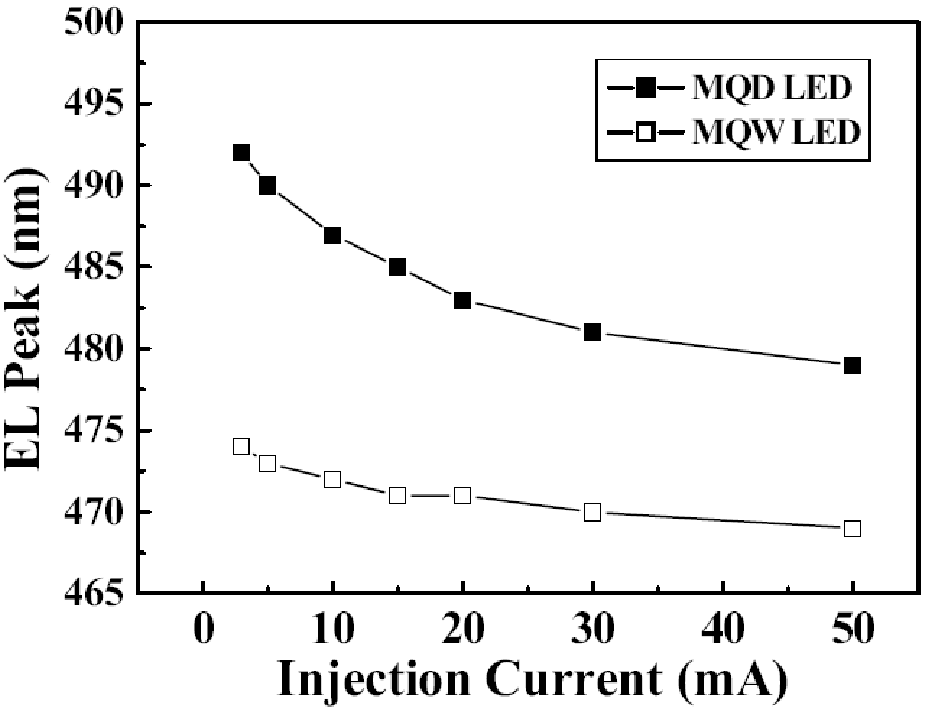
- **GaN QDs embedded inside an AlN matrix (large stess)**
- **Plasma MBE-grown (APL 87, 203112 2005)**



- **interrupted growth to achieve InGaN dots-in-a-well structure**
- **typically a pyramidal dot with a 3nm height and a 10nm diameter**
- **QD density : $10^{10} \sim 10^{11}$ cm^{-2}**

InGaN Multi-Quantum Dot LED (II)



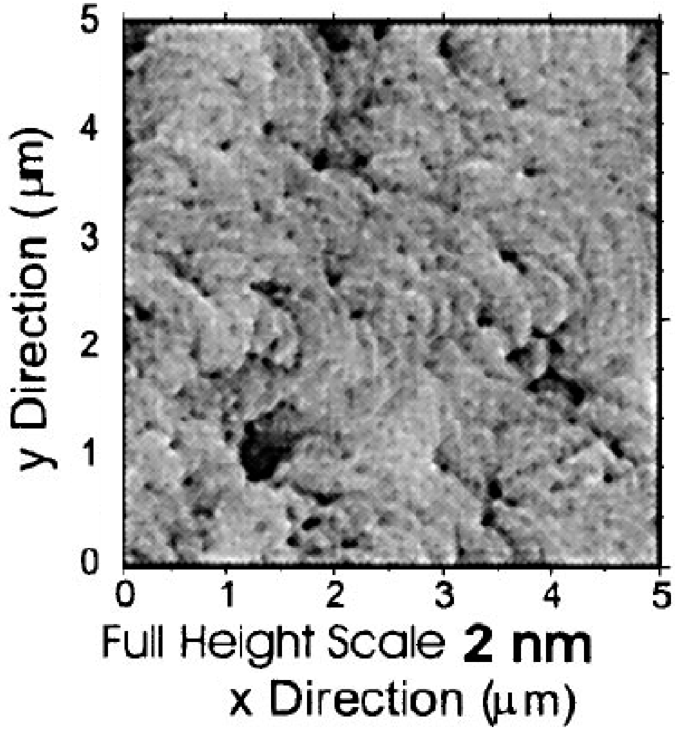


- **Smaller forward voltage 3.1V in MQD LED ➡ cellar phone applications (?)**
- **Large EL blueshift in QD reveals that deep localization of excitons (or carriers) originates from QDs.**

Ref) L. W. Ji, et al., Phys. Stat. Sol. (c) 1, No. 10, pp. 2405, 2004

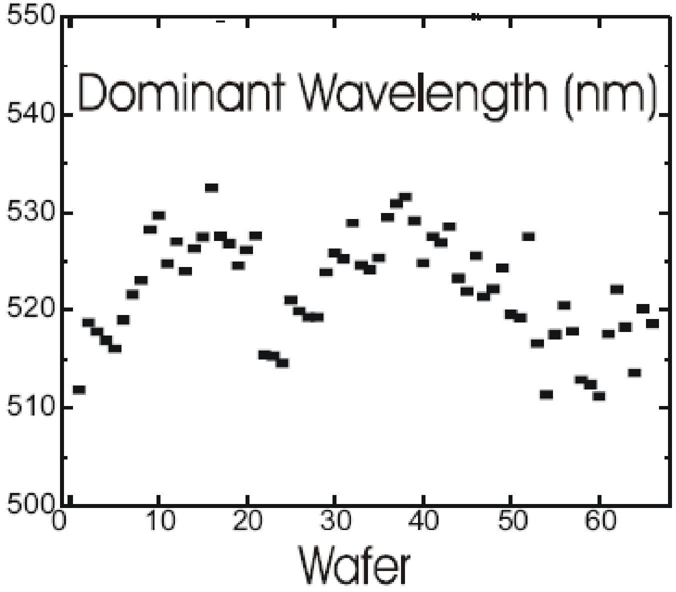
High Performance Green LED with Smooth Surface

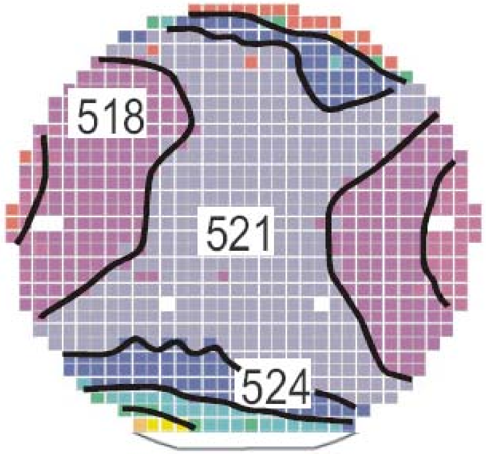
Very Smooth MQW Active Regions (AFM Surface Morphology)



- Small density of pits due to V defects ; $3.6\text{x}10^8\text{cm}^{-2}$
- Very smooth surface morphology rms surface roughness ; 0.14nm

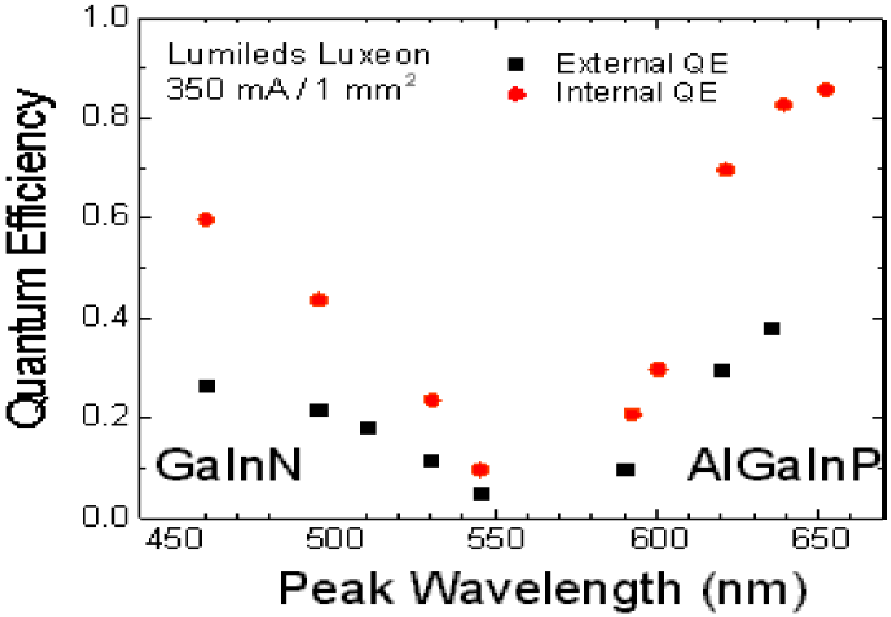
- high performance green LED (525nm)
- uniform & 98% high yield process (λ, power, V_F, I_R)
- At 20mA, V_F =3.2V, power=1.6mW in bare chip

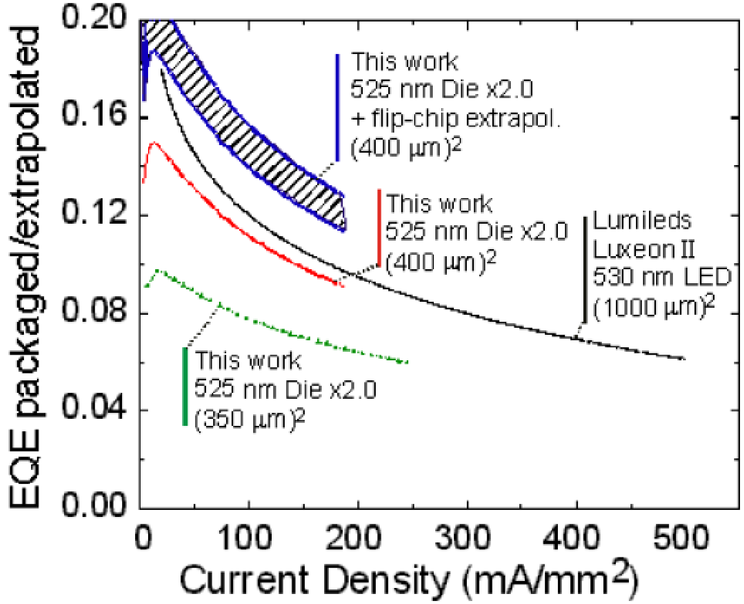




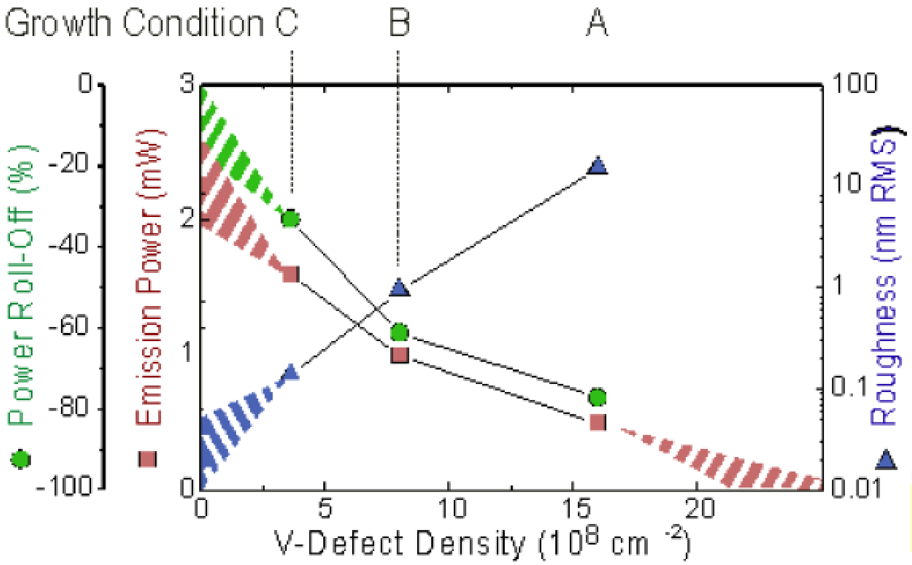
Ref : C. Wetzel, et al., Phys. Stat. Sol. (c) 2 , pp. 2871, 2005

High Power Green Light Emitting Diode

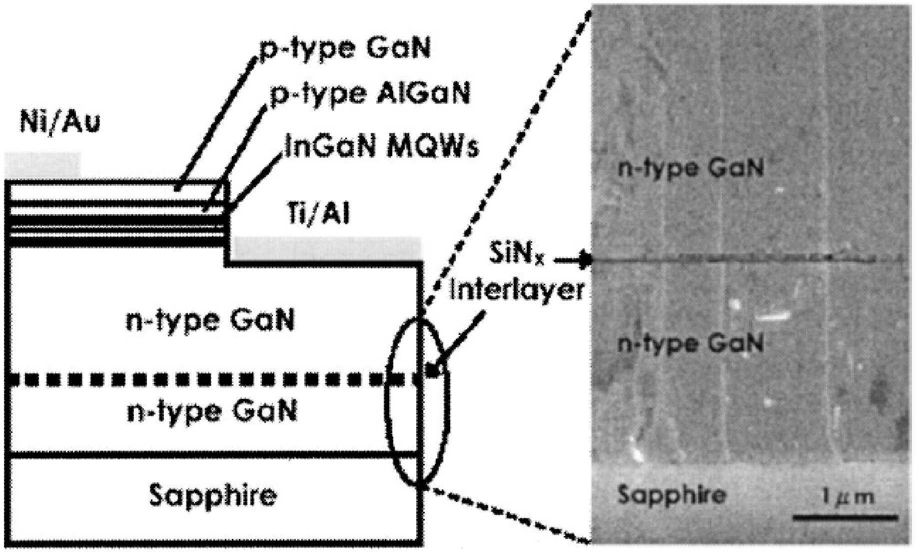


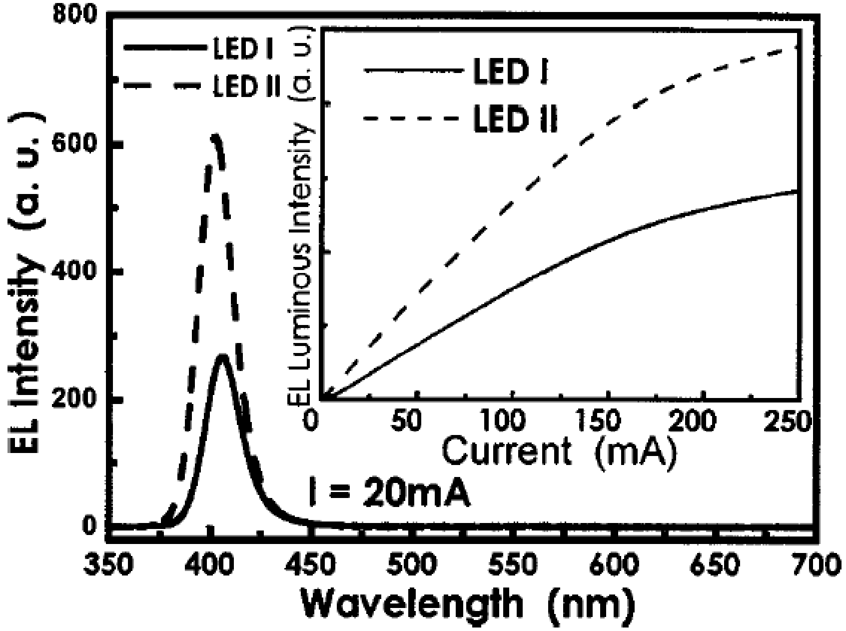


Ref : C. Wetzel, et al., MRS Internet J. Nitride Semicond. Res. 10, 2 (2005)



Effects of Dislocations on LED Performance



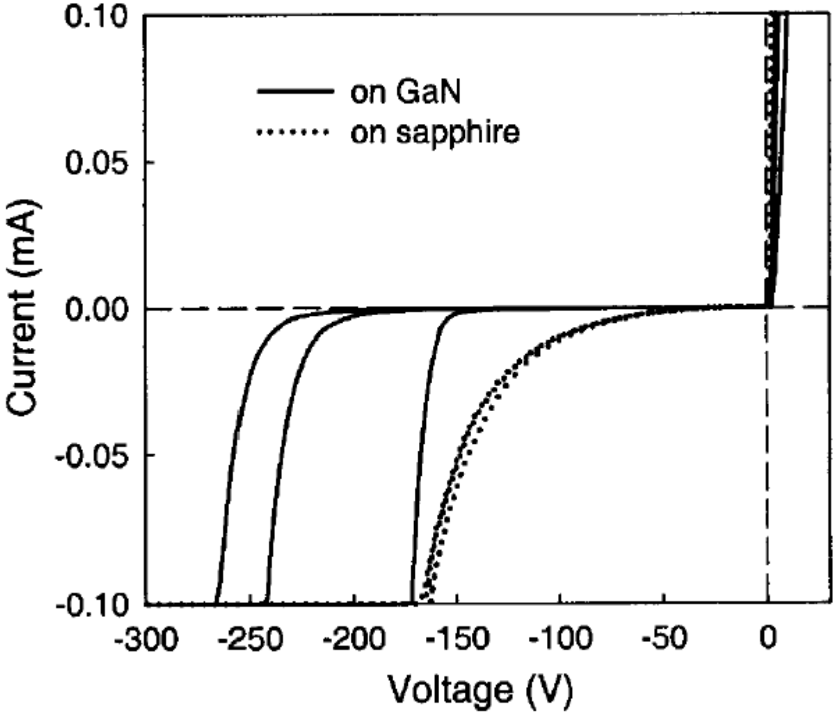


Ref. : Ru-Chin Tu, et al., Appl. Phys. Lett. pp. 3608-3610, 27 October 2003

Effects of Dislocations on Reverse Leakage Current

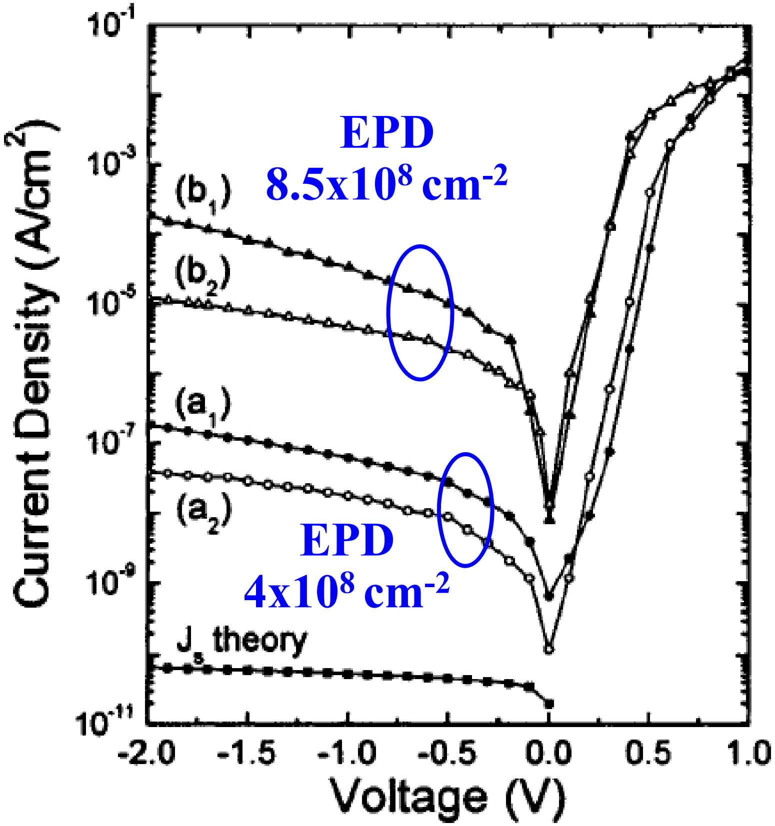
GaN PIN Rectifier

(4µm 1x10^{17}cm^{-3} N^{-} Region)



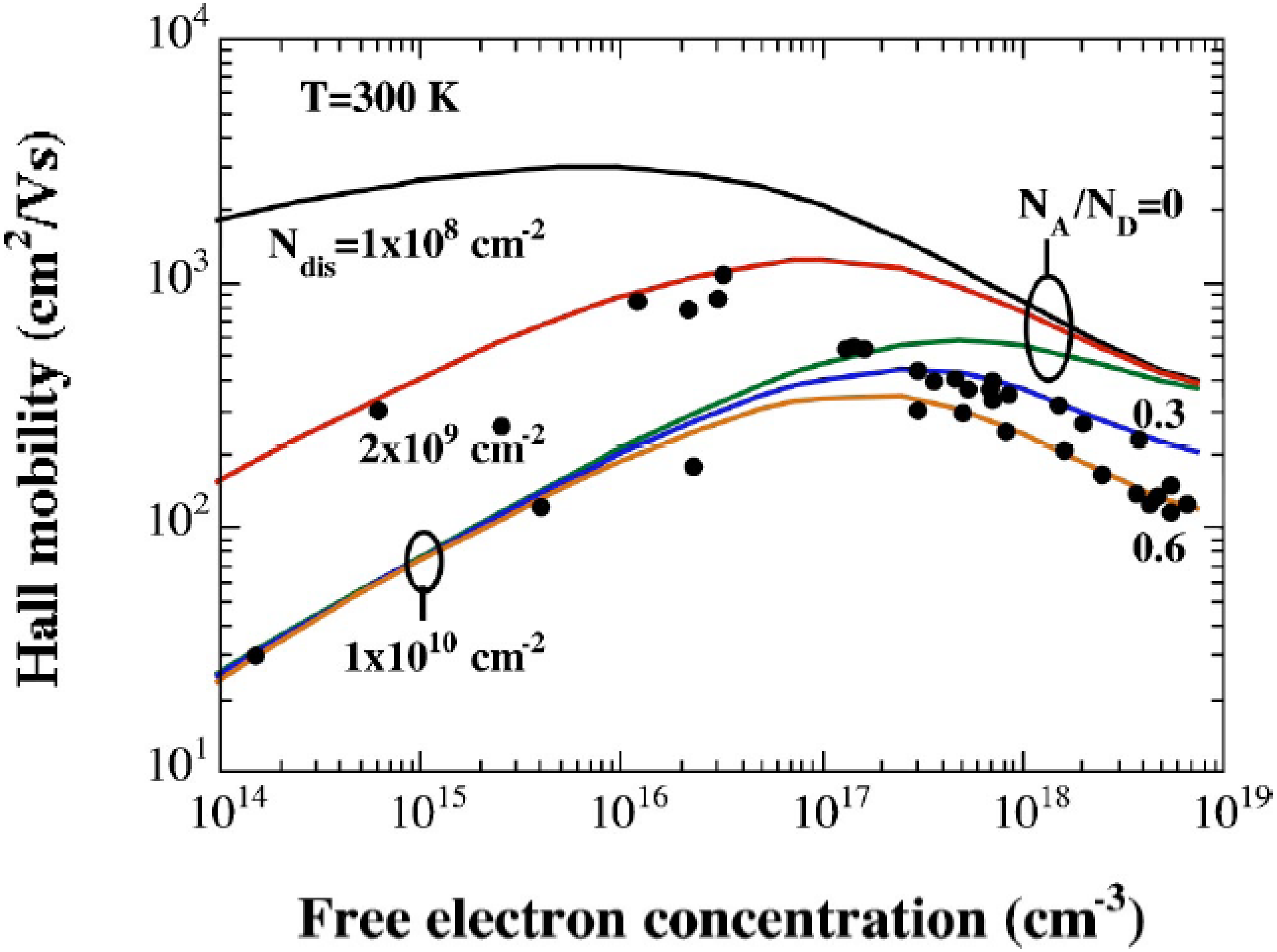
Ref. : X. A. Cao, et al., Appl. Phys. Lett. 87, 053503, 2005

Au/n-GaN Schottky diodes



Ref. : Y. Huang, et al., J. Appl. Phys., pp. 5771-5775, 1 Nov. 2003

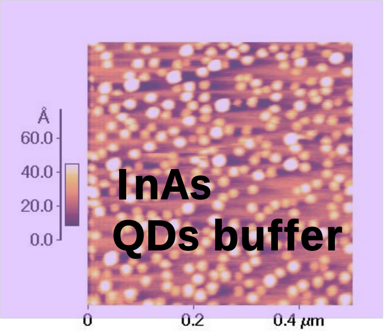
Effects of Dislocations on Hall Mobility

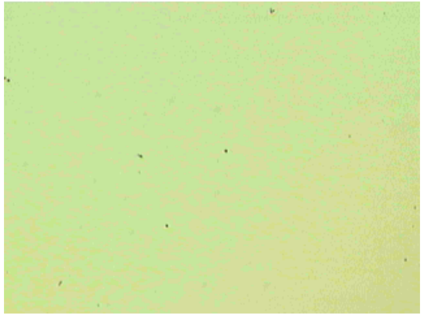


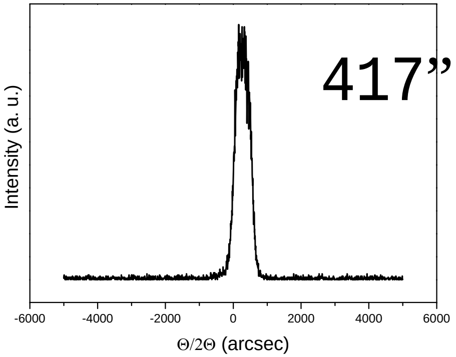
Ref. : M. N. Gurusinghe, et al., Physical Review B 67, 235208, 2003

Hetero-Epitaxy with the Defect-Free QD Buffer layer

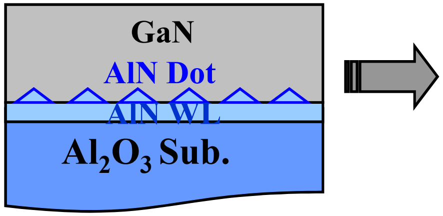
GaSb epilayer on GaAs sub.

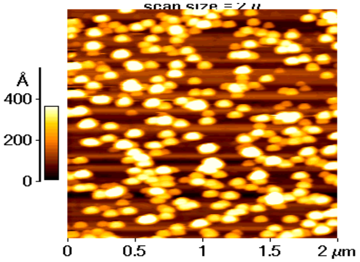


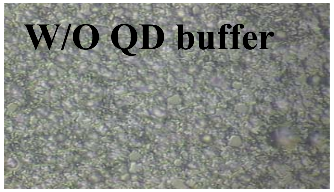


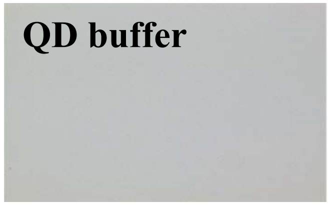


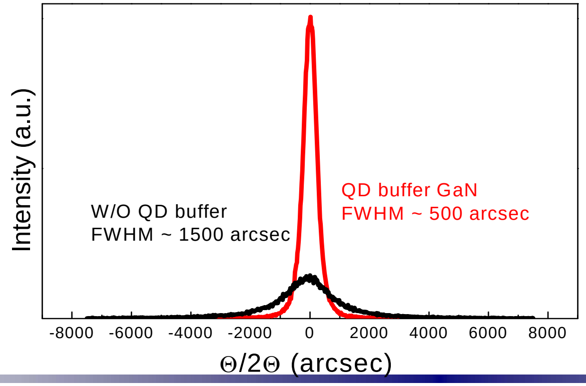
GaN epilayer on Sapphire sub.



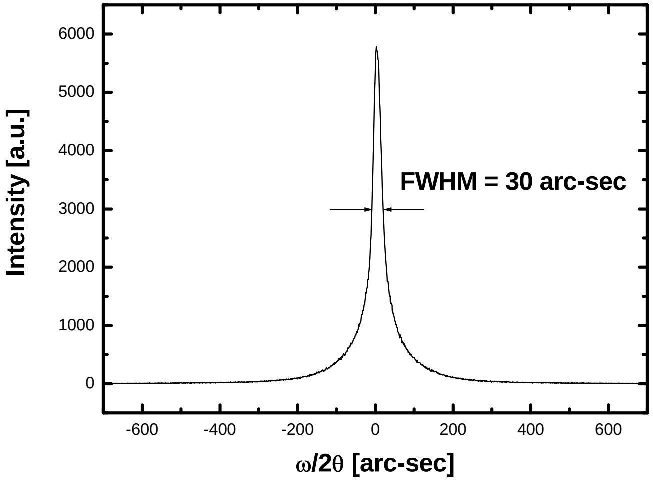




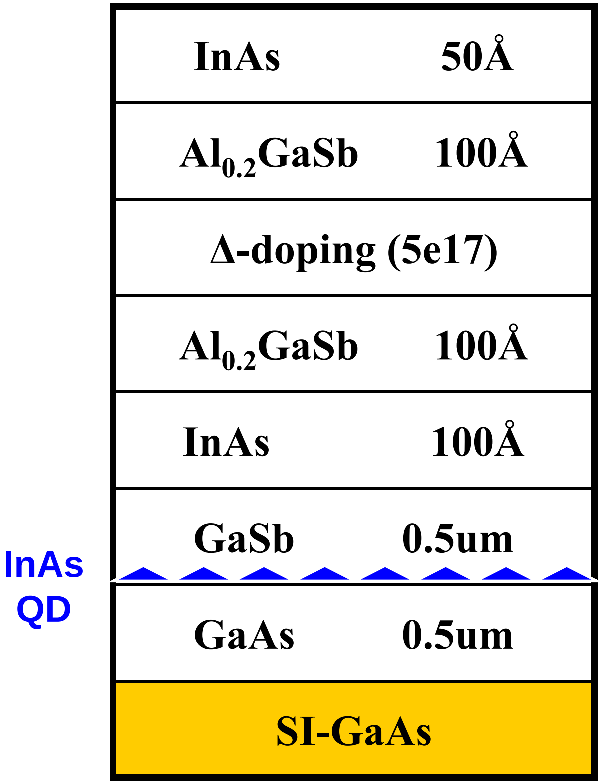




The recent GaN epilayer quality after further optimization



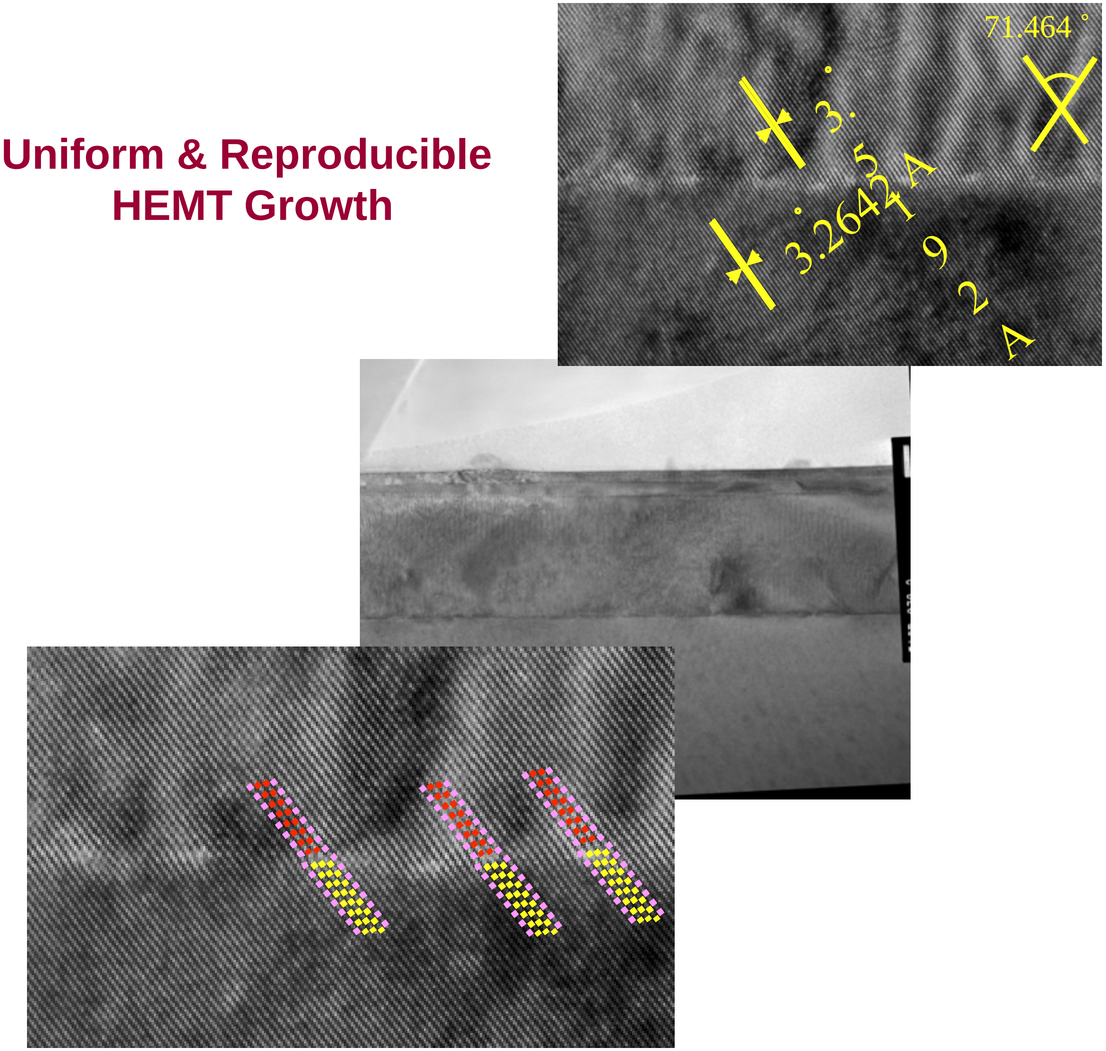
Thin barrier InAs HEMT grown using InAs QD/GaSb Buffer



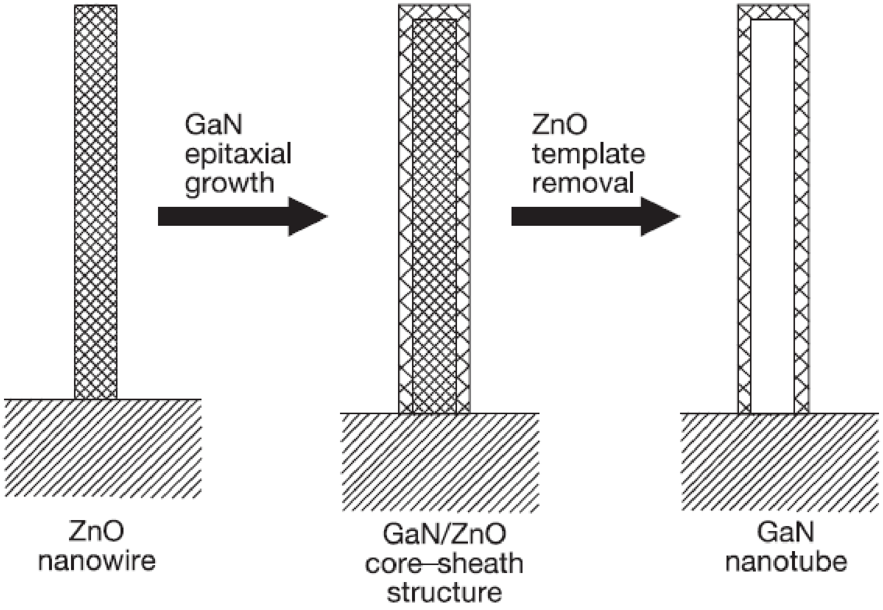
Layer	Thickness
InAs	50Å
$Al_{0.2}GaSb$	100Å
Δ-doping (5e17)	
$Al_{0.2}GaSb$	100Å
InAs	100Å
GaSb	0.5um
GaAs	0.5um
SI-GaAs	

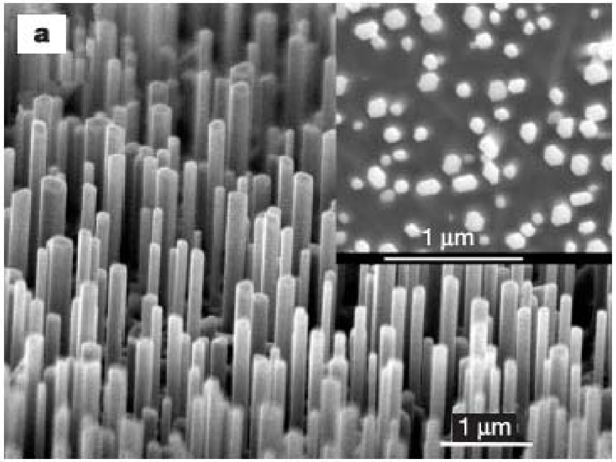
n_s = 3.33x10^{12} cm^{-2}
μ = 8064 cm^2/V-s

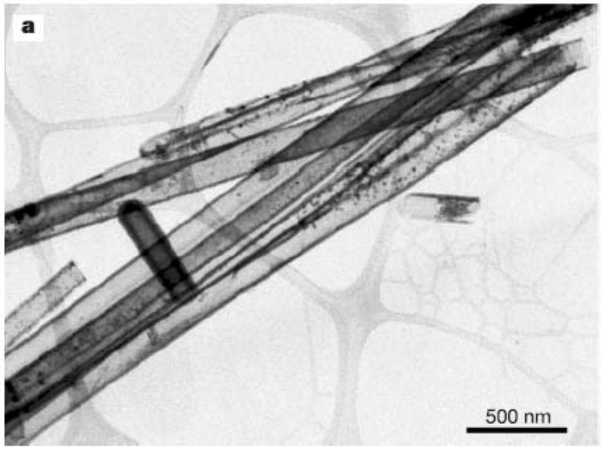
Uniform & Reproducible HEMT Growth



GaN Nanotube

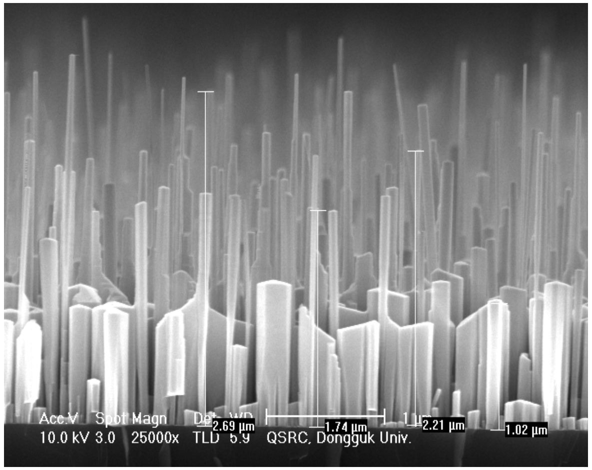


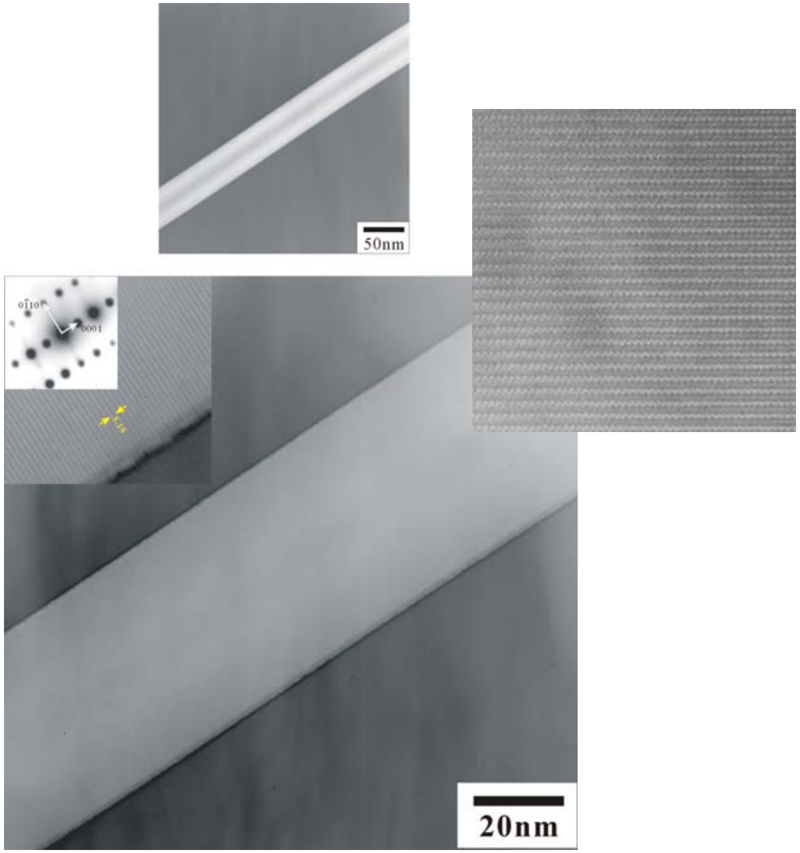




**Ref: J. Goldberger, et al., NATURE,
pp. 599-602, APRIL 2003**

Nano-rod Formation on Si substrate with no Catalysis

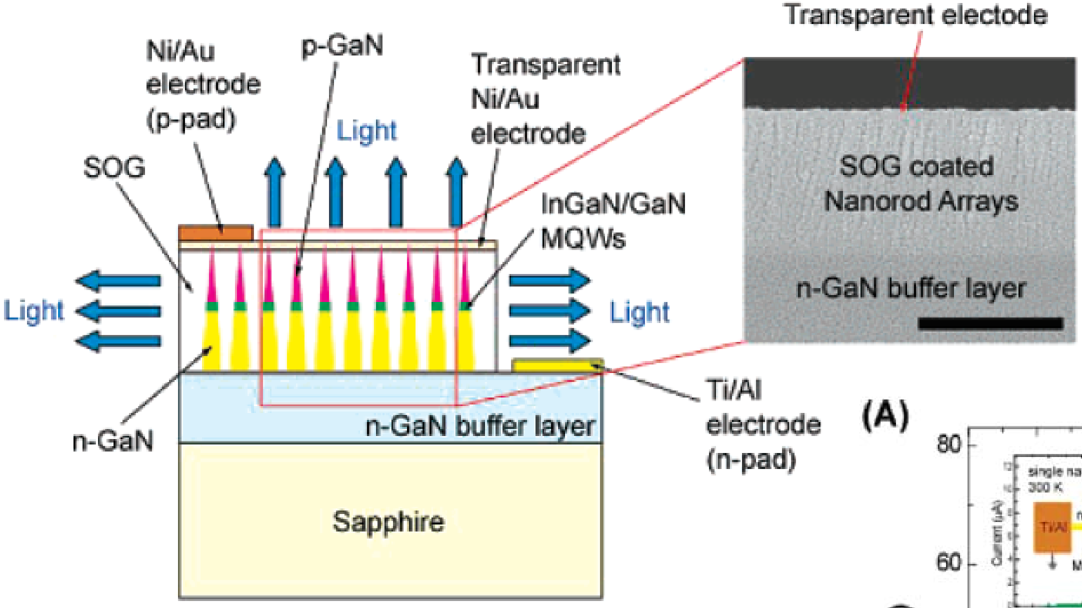


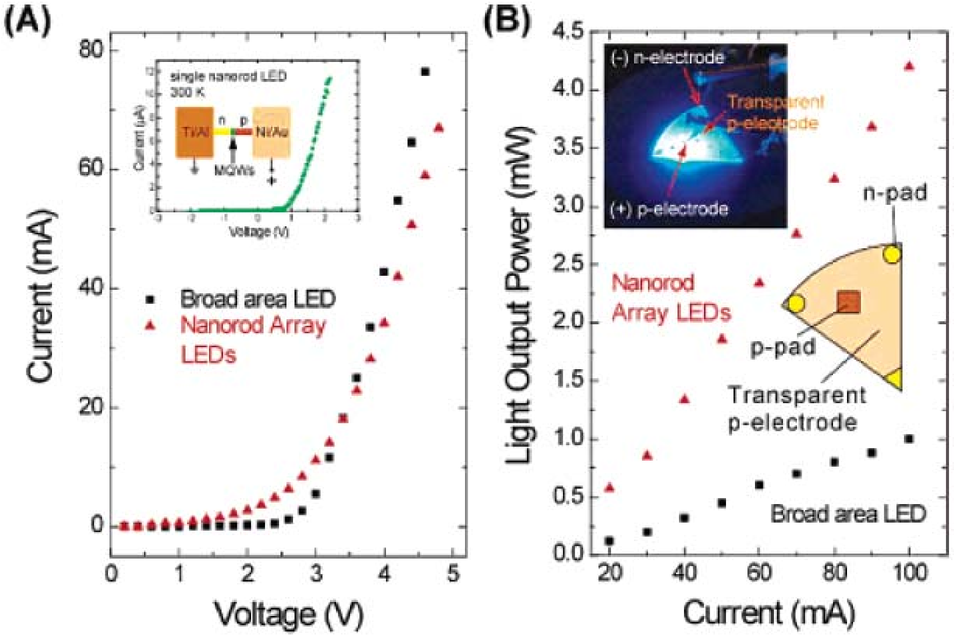


- **Defect free material/structures are obtained**
- **Partially relaxed structure**
- **Diameter ranging from 5 nm~350 nm can be controlled : f_{Ga}/f_N**
- **Feasible for vertical device structures**

(I)QD Nucleation **(II)Columnar Growth** **(III)Selective Nanorod Growth** **(IV) Lateral Nanorod Growth**

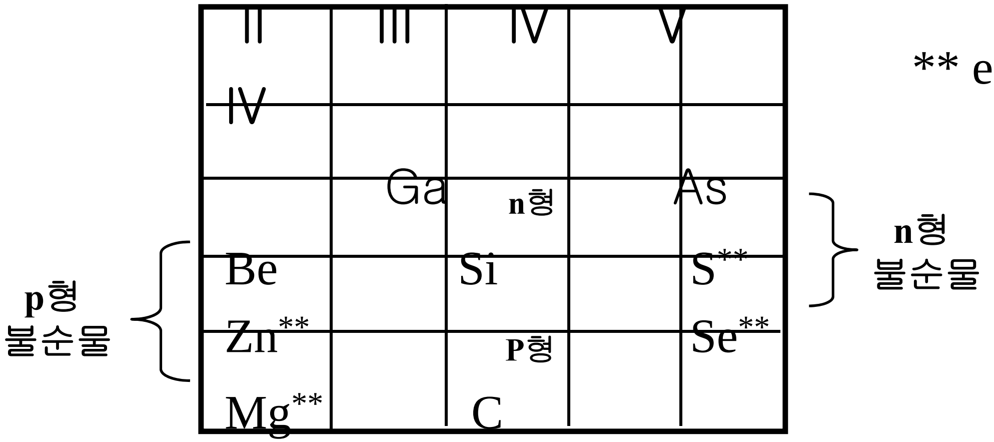
High Brightness InGaN/GaN MQW Nanorod LED





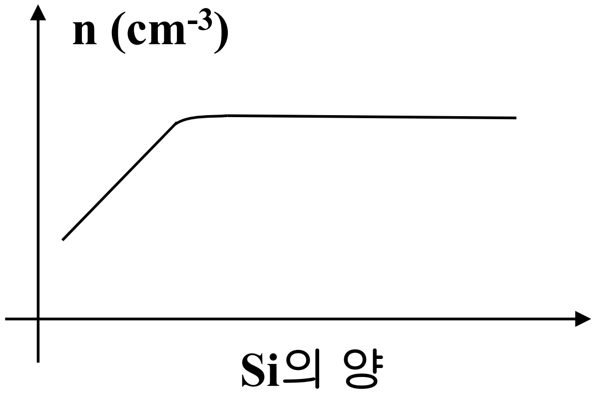
Ref: Hwa-Mok Kim, et al., NANO LETTERS, pp. 1059-1062, 2004

GaAs (InP)의 shallow impurities



** elements; large diffusion constant
→ thin epitaxy에 부적합

*** Si ; amphoteric impurities (n-& p-type) ; self-compensation**



- MBE ; Si (n-type), Be (p-type)

- MOCVD ; Si (n-type), C (p-type)

↓

CCl_4 gas: 1. very small diffusion constant

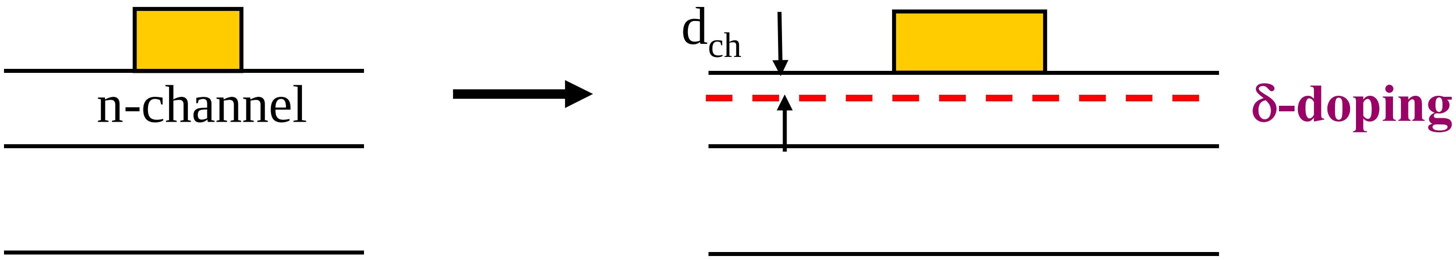
2. high doping

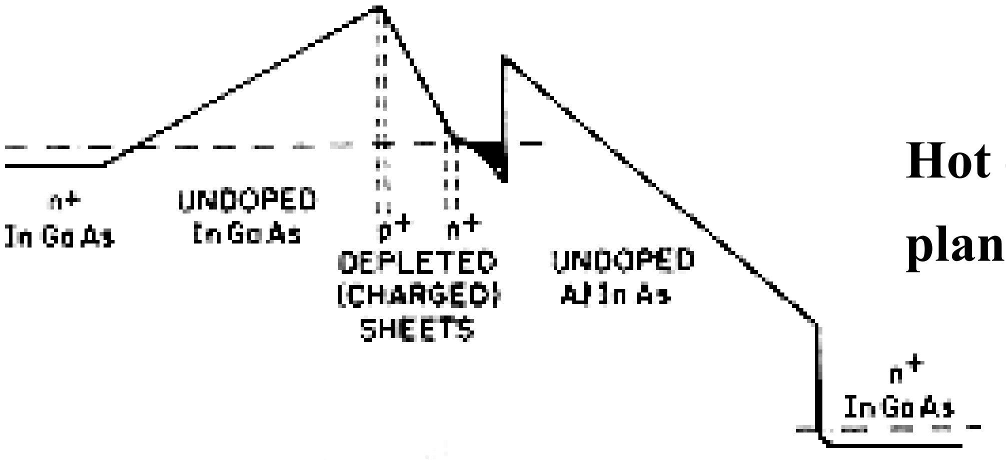
* HBT에서는 very thin, high doped P-base 필요→ MOCVD & C (Kopin)

δ doping/Planar doping

δ-doping 형성 : 일정한 plane에 doping (planar doping)

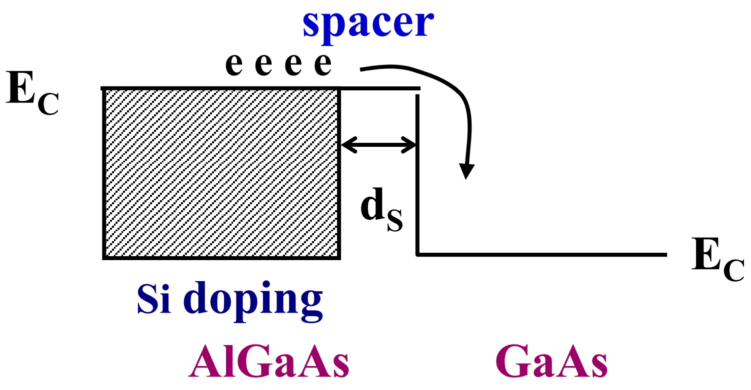
- growth 를 중지한 상태에서 donor /acceptor 불순물을 도입.

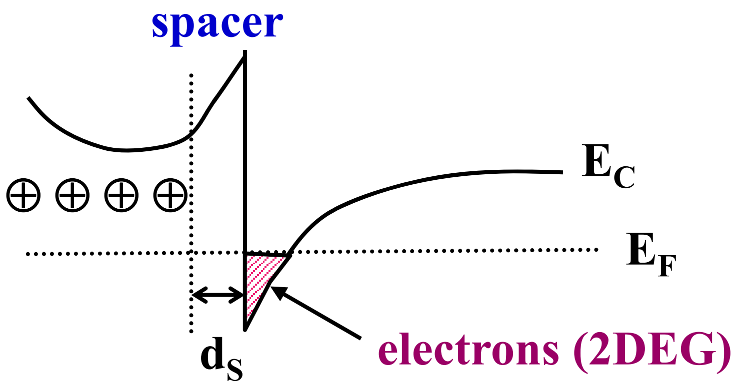




Hot electron transistor with planar doped barrier emitter

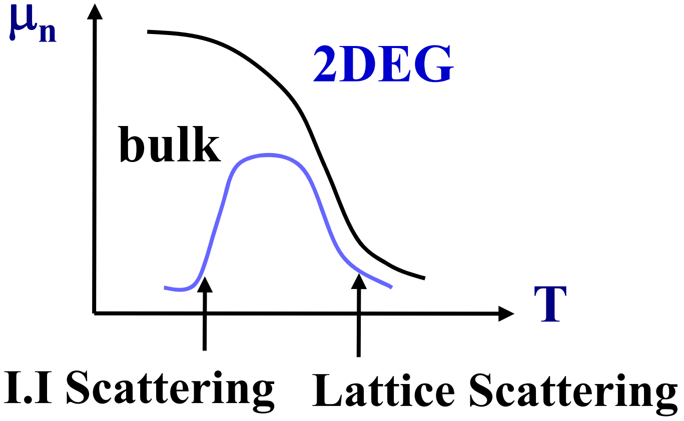
Modulation Doping (I)





channel electron은 ionized-doner에 의한 impurity-scattering을 겪지 않음

→ μ_n ↑, V_{drift} ↑ with modulation doped structure



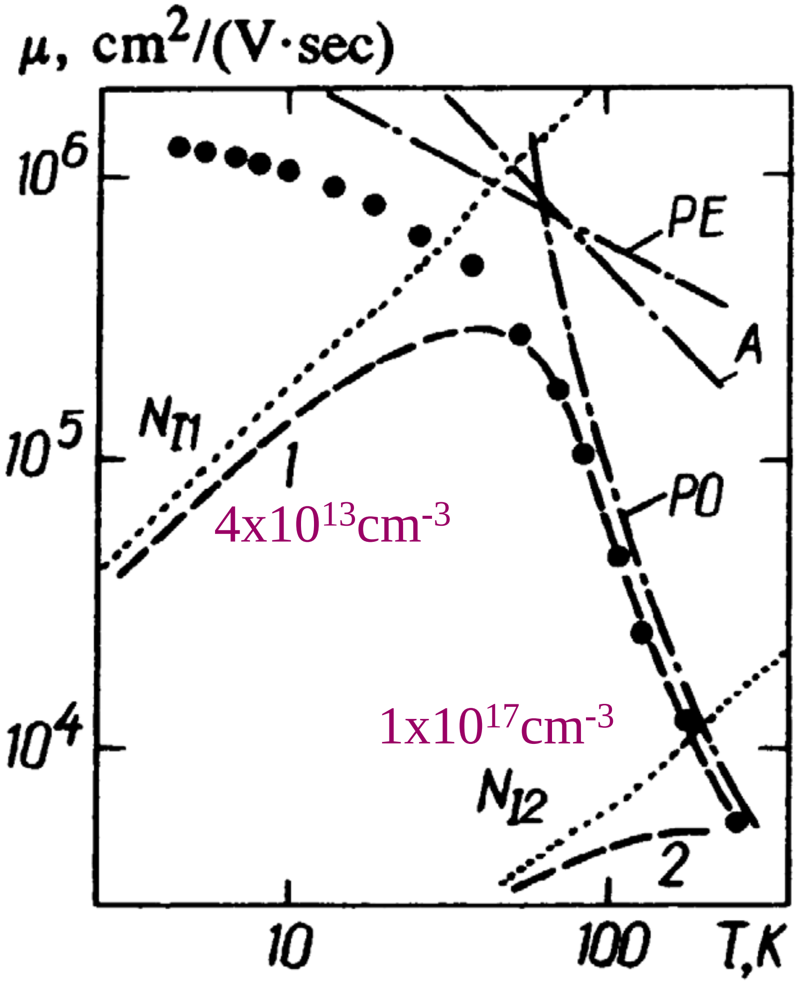
d_s ↑ ⟶ μ_n ↑ ; I-I scattering 감소

(예) d_s =200 Å (77K) μ_n ~150,000cm^2/V·s

(4K) μ_n > 1,000,000cm^2/V·s

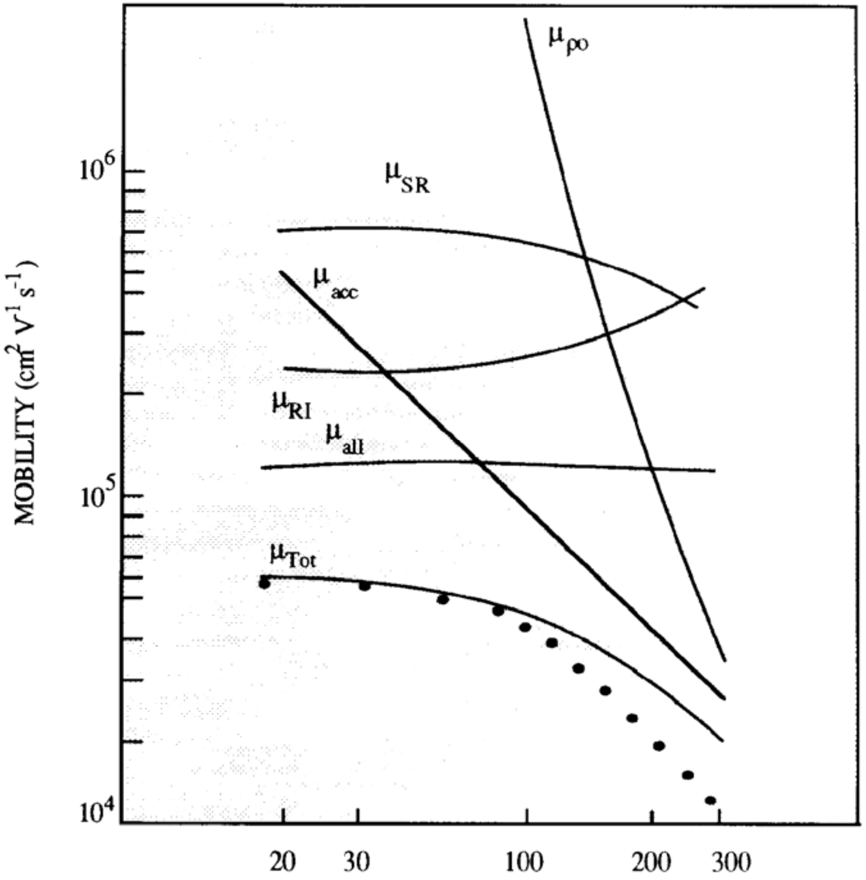
Modulation Doping (II)

GaAs/AlGaAs MD Structure



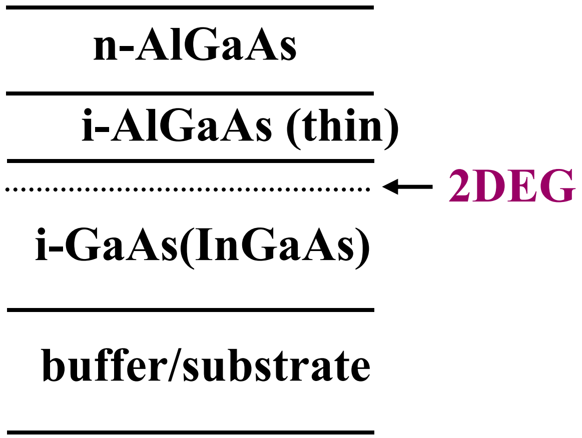
InGaAs/InAlAs MD Structure

- alloy scattering limited



MD Structure의 여러 구조(1)

< Normal HEMT >



n-AlGaAs

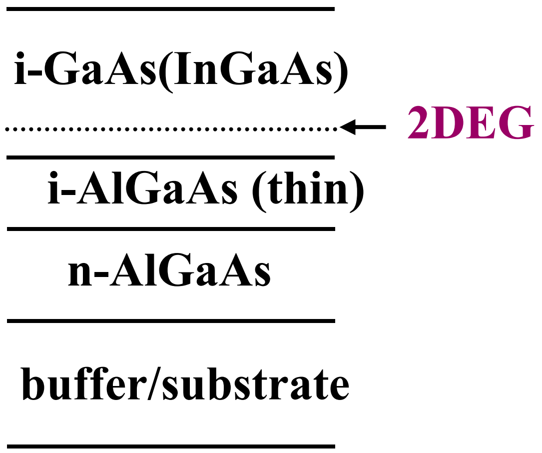
i-AlGaAs (thin)

← 2DEG

i-GaAs(InGaAs)

buffer/substrate

< Inverted HEMT >



i-GaAs(InGaAs)

← 2DEG

i-AlGaAs (thin)

n-AlGaAs

buffer/substrate

- large mobility

→ smallest sheet resistance

→ thermal noise 감소

(저잡음 소자, LNA)

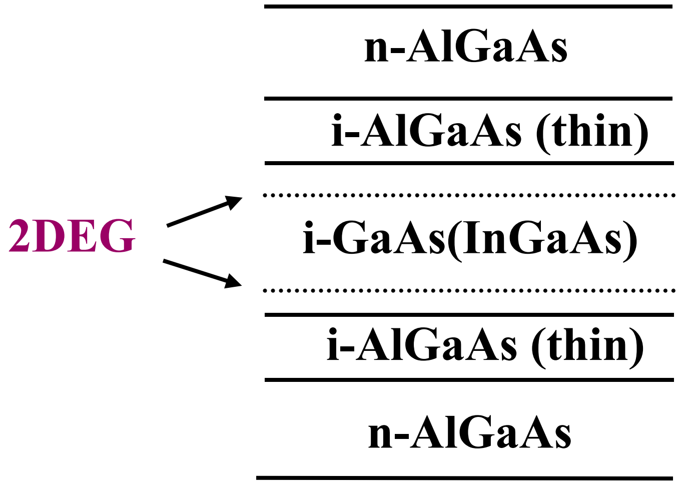
- small mobility due to

1. **rough AlGaAs surface**
2. **dopant (Si) diffusion**
   & segregation

-better ohmic contact

MD Structure의 여러 구조 (2)

< Double-Heterostructure HEMT >

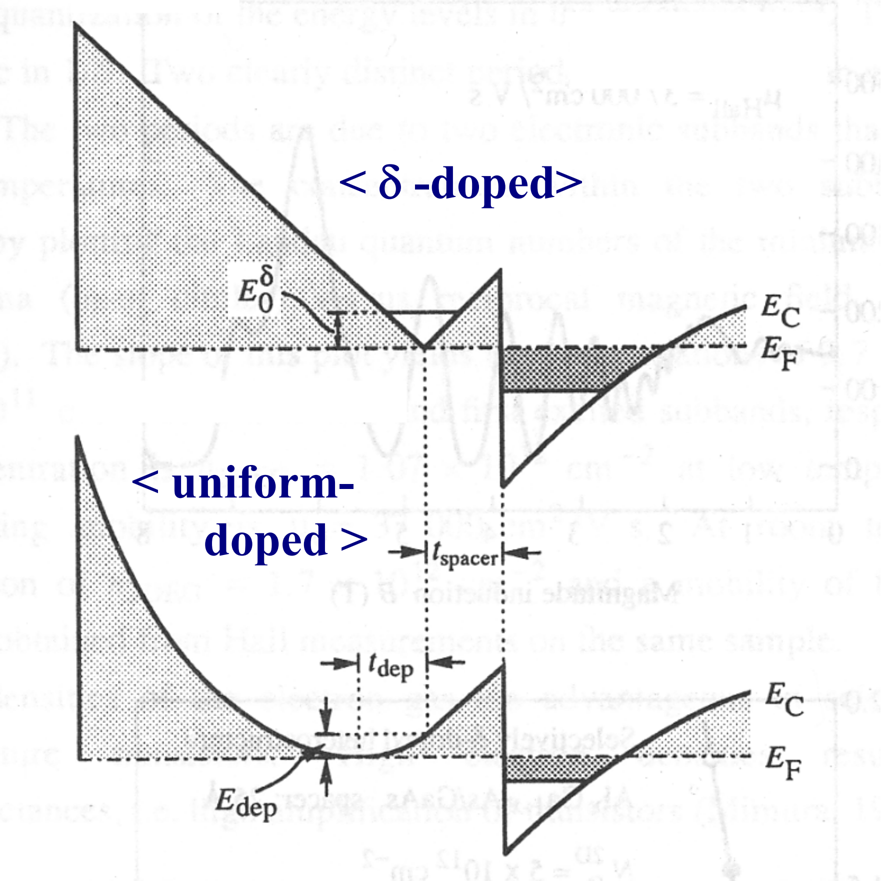


- **largest 2DEG concentration (n_S)**

→ $I_D = q\, n_S\, v_S\, W$ 증가

→ **power device**

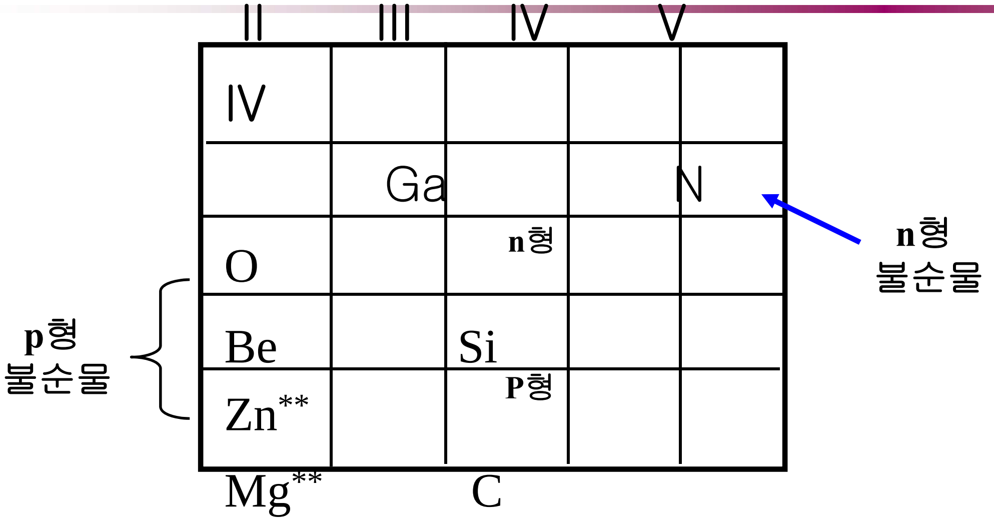
➢ **barrier의 doping 방법**


< δ -doped>

< uniform-doped >

- **barrier의 δ-doping은 channel 전하량 (n_s)를 증가시킴.**

Various Impurities in GaN



II III IV V

IV

Ga N

O n형

Be Si

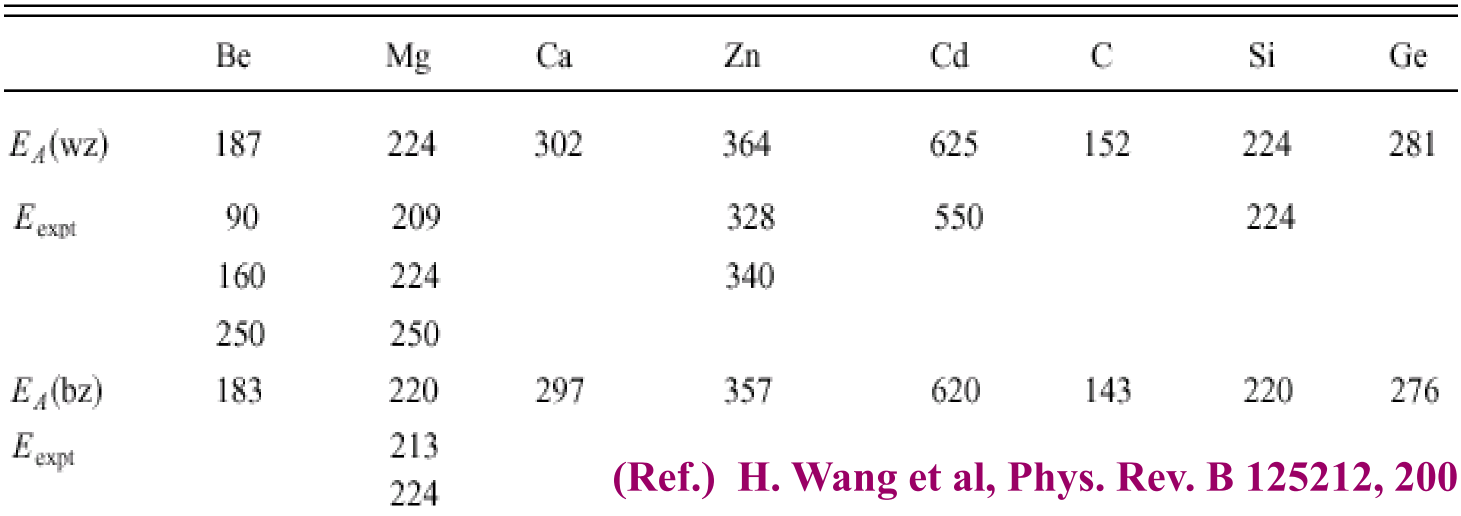
Zn** p형

Mg** C

p형 불순물

n형 불순물

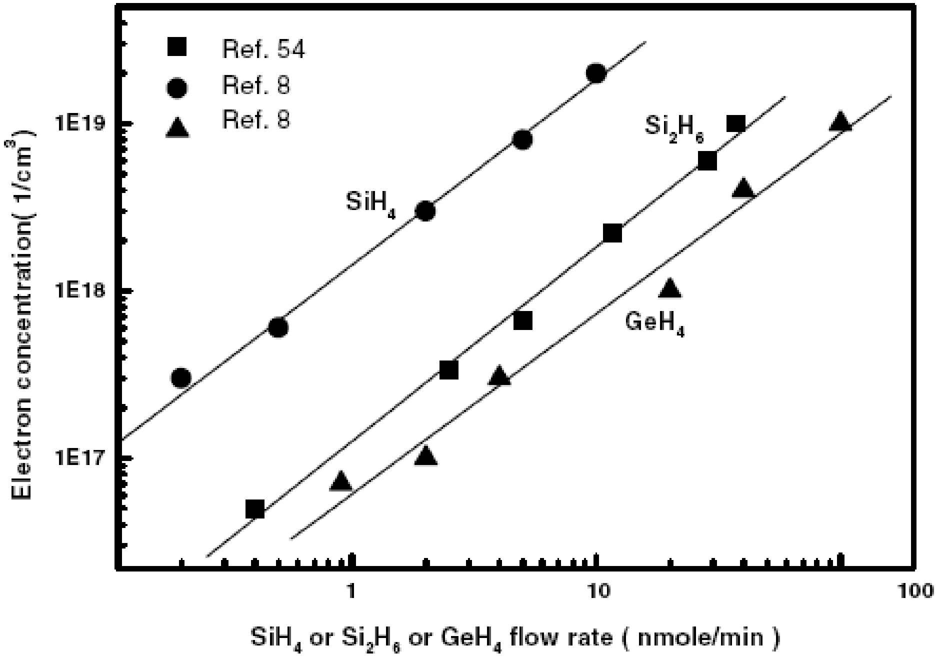
Acceptor Ionization Energies (E_A, meV) in wurtzite(wz) and zinc-blende(bz) GaN



	Be	Mg	Ca	Zn	Cd	C	Si	Ge
E_A(wz)	187	224	302	364	625	152	224	281
E_{expt}	90	209		328	550		224	
	160	224		340				
	250	250						
E_A(bz)	183	220	297	357	620	143	220	276
E_{expt}		213						
		224						

(Ref.) H. Wang et al, Phys. Rev. B 125212, 2001

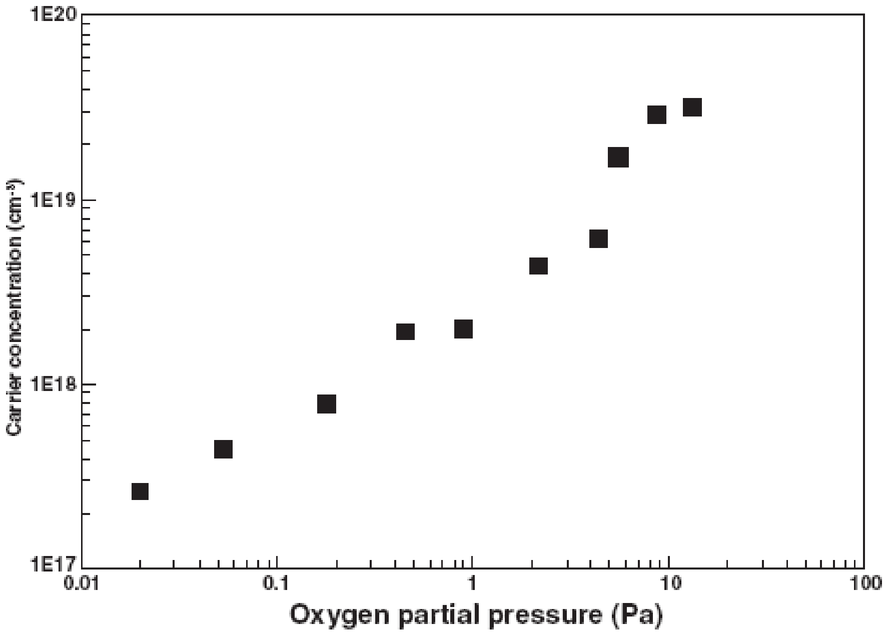
N-Doping of GaN in MOCVD Growth



Oxygen in GaN

– Shallow n-type impurity

– 27meV Activation Energy



(Ref.) J. K. Sheu, et al, J. Phys.: Condens.

Matter 14 (2002) R657–R702

Ion Implantation & Annealing for Selective Doping

Ion Implantation – selective area doping
– doping profile control → **Main Technology for Si**
(even for GaAs & InP)

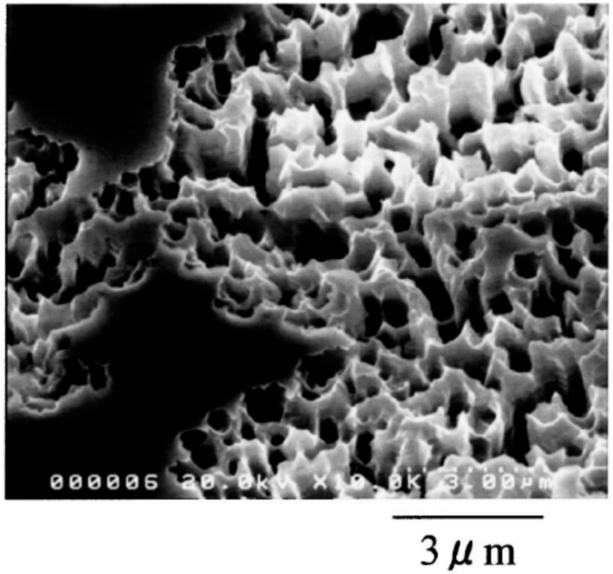
Problems in ion implantation
for CS Technology

1. **Damage Annealing**
2. **Surface Degradation during high temperature annealing**
3. **Furnace Annealing versus RTA**

Various Encapsulant during
High Temp. Annealing

Si_3N_4, SiO_2, AlN, · · · · ·

Surface Morphology of GaN
after 30s RTA at 1200°C



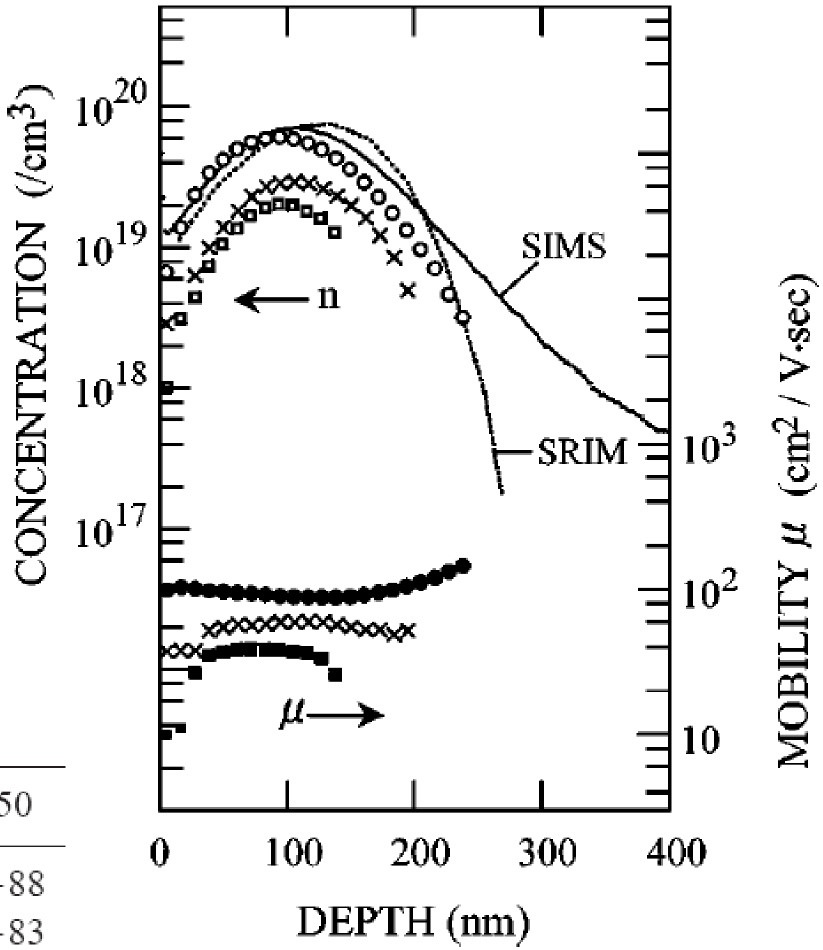
Si Implant and RTA with Si_3N_4 Encapsulant

(Ref.) S. Matsunaga, et al, J. Appl. Phys., pp. 2461-2466, Mar. 2004

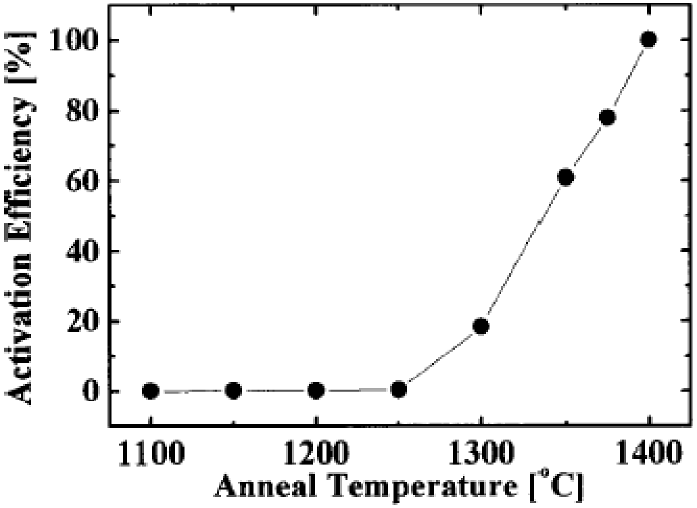
Ion Implantation & Anneal Condition

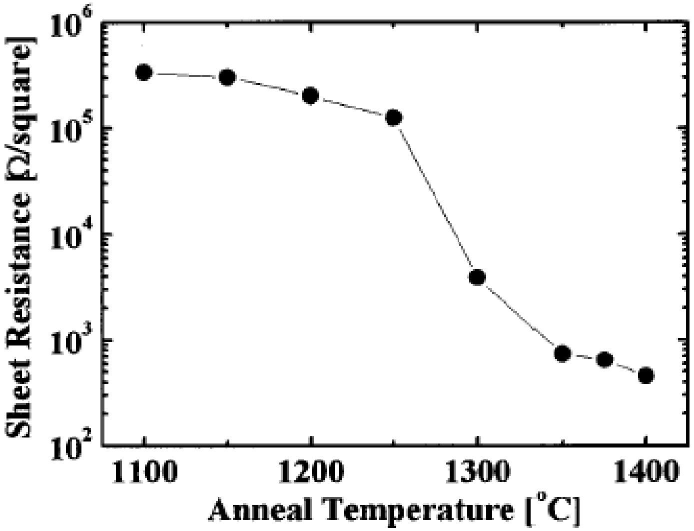
- 150 keV, $1x10^{15}/cm^2$ Si^+ Ions implant
  (Room Temp. Implant)
- Substrate tilted 7° from the incident Si^+ ion beam to minimize the channeling effect.
- 140-nm-thick Si_3N_4 film as an encapsulant
- RTA with N_2 flowing

	RTA temperature (°C)		
Properties	1150	1200	1250
ρ_s (ohm/sq)	870–2200	240–370	82–88
μ_{eff} (cm^2/V s)	36–20	61–57	97–83
N_s ($\times 10^{14}/cm^2$)	2.0–1.5	4.3–3.0	7.9–8.6

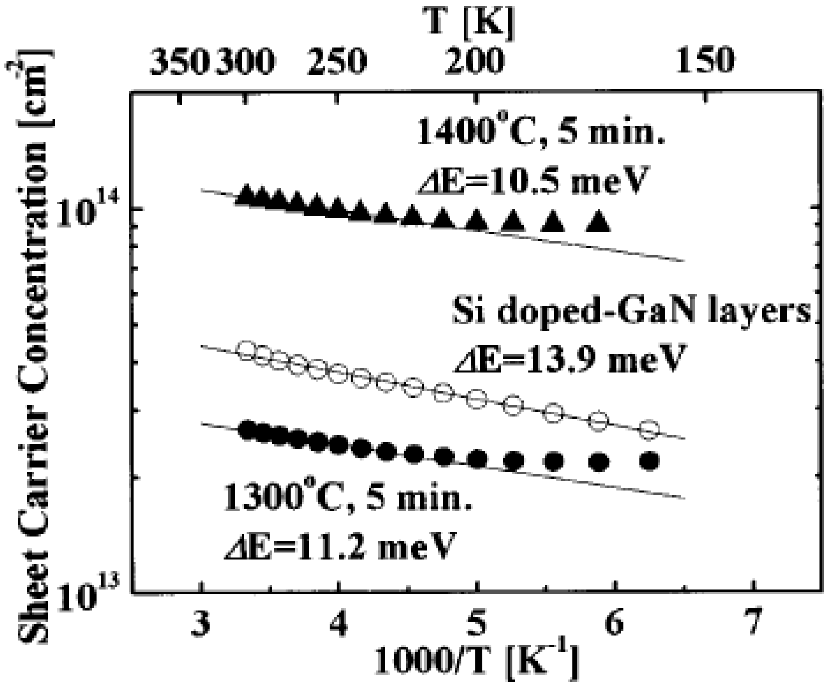


Low Dose Si Implantation & Annealing





- $1\times10^{14}/cm^2$ $^{28}Si^+$ ions implant
  (Room Temp. Implant)
- 500 nm sputtered SiO_2 capping
- annealed for 5 min under N_2 ambient.



(Ref.) Y. Irokawa, et al, J. Appl. Phys. 97, 083505, 2005