RF응용 GaN 에피 기술

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한국나노기술원

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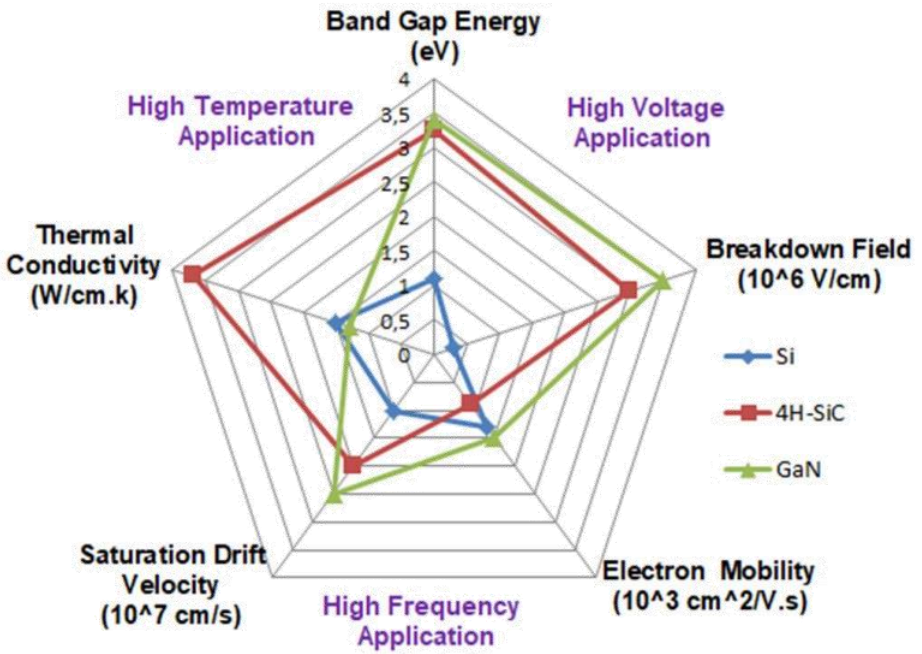
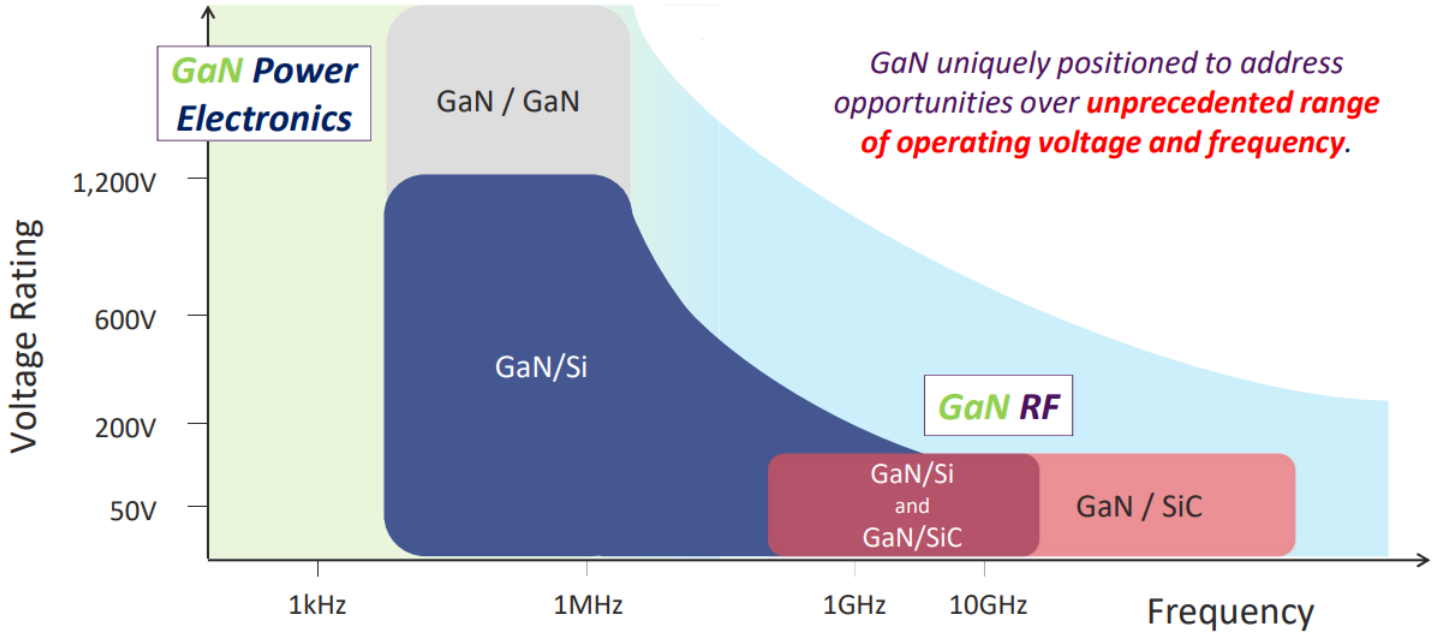
- Summary

GaN HEMT

- Wide-bandgap semiconductor → High Voltage and High Temperature
- Polarization-induced 2DEG channel → High Current and High Frequency

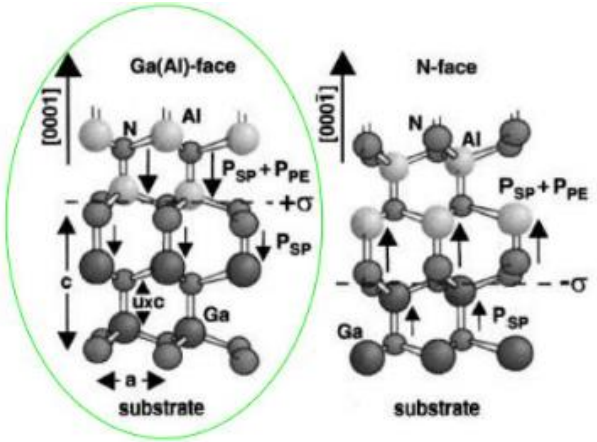




source : IQE 2019

GaN HEMT

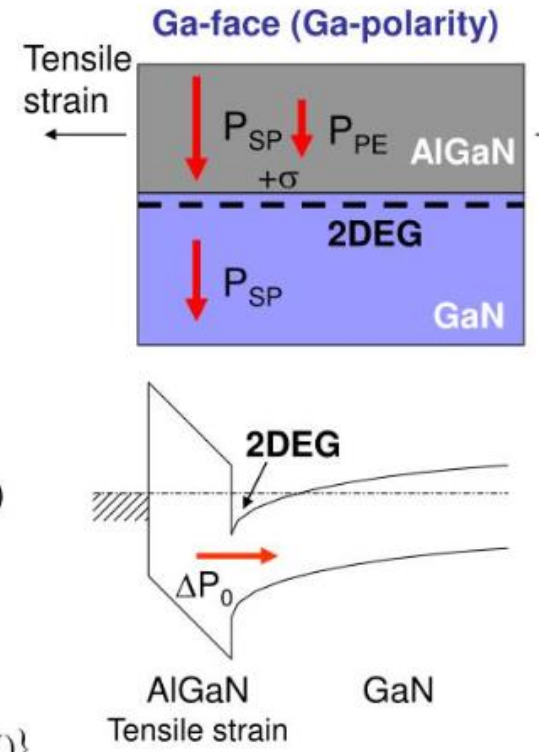
- Wide-bandgap semiconductor → Deep Trap
- Polarization-induced 2DEG channel → Trap sensitive / Normally on

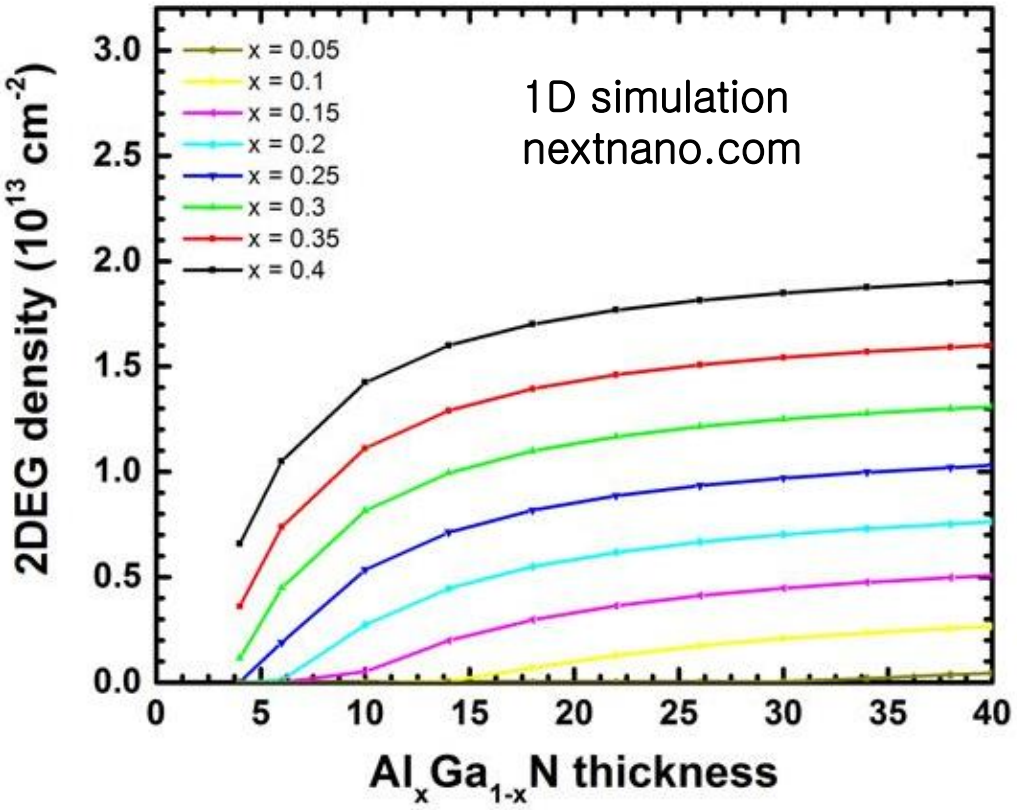


P_{SP} : Spontaneous polarization
P_{PE} : Piezoelectric polarization (strain)

Fixed polarization charge is induced at the AlGaN/GaN interface

$$\sigma = P(GaN) - P(AlGaN)$$
$$= P_{SP}(GaN) - \{P_{SP}(AlGaN) + P_{PE}(AlGaN)\}$$



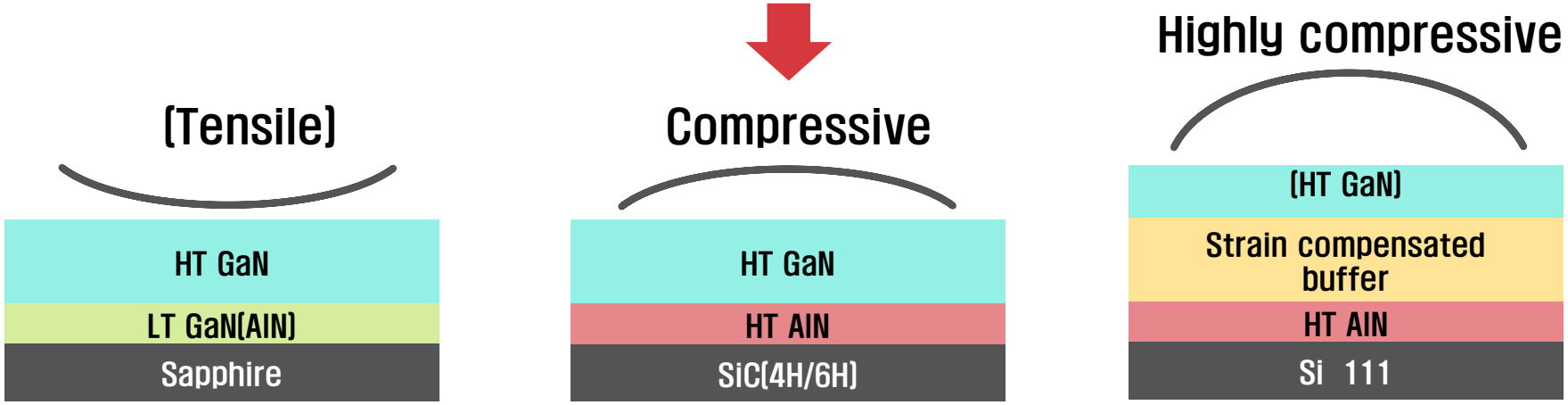


GaN HEMT

GaN HEMT on different substrates

	Sapphire	Si(111)	4H-SiC
Lattice mismatch GaN/substrate	-16	16.9	3.5
Thermal mismatch GaN/substrate	-34	54	25
Thermal conductivity [$Wcm^{-1}K^{-1}$]	0.5	1.49	4.5
Wafer size	4~6”	6~8”	4~6”
Cost	low (4”)	low	high

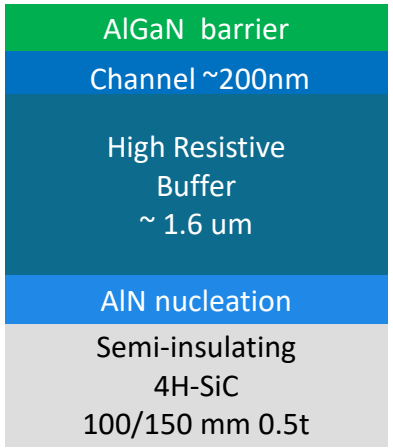
AlGaN/GaN HEMT channel growth

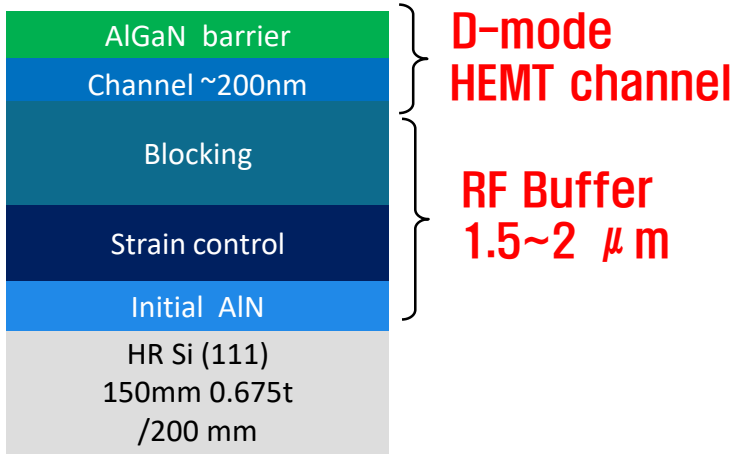


GaN HEMT

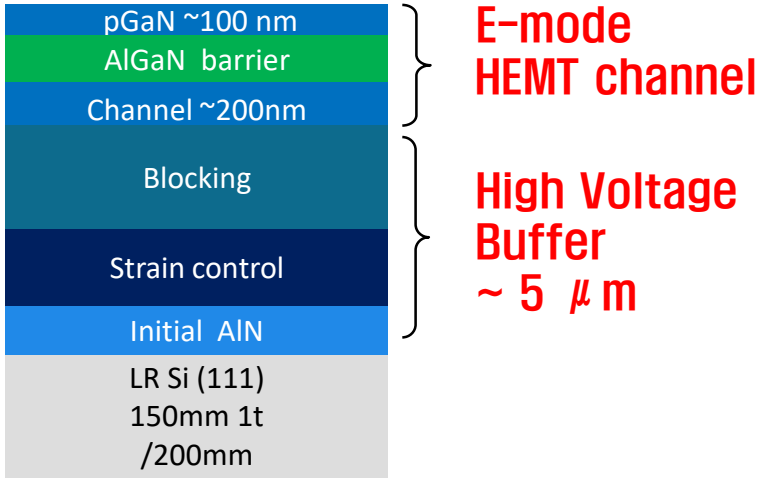
Major applications (RF vs Power)

RF applications





Power applications



Lateral BV > 150 V for S-band

$Al_{0.25}Ga_{0.75}N$ barrier ~20 nm

Rch ~350 Ω/□

Vertical BV > 650 V

$Al_{0.2}Ga_{0.8}N$ barrier ~15 nm

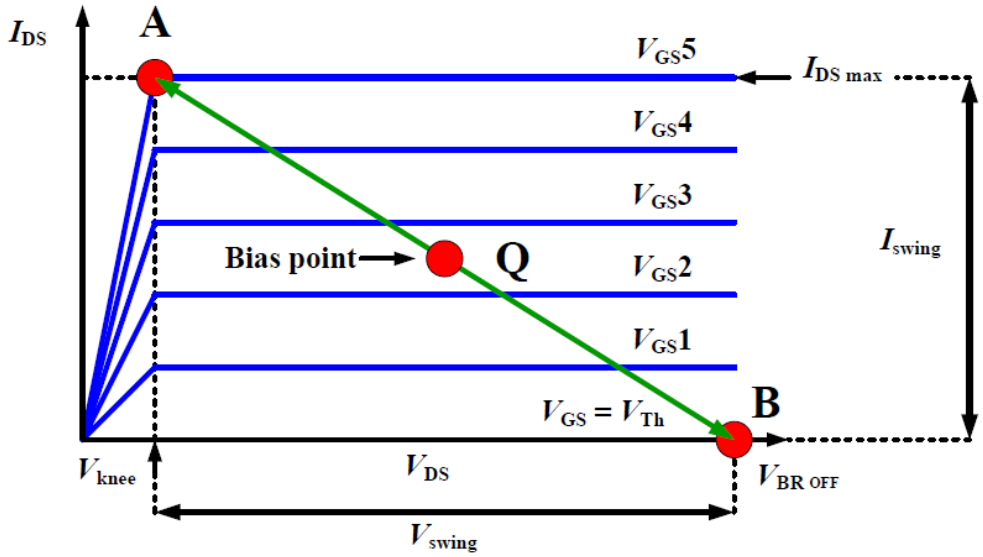
Vt > 1V

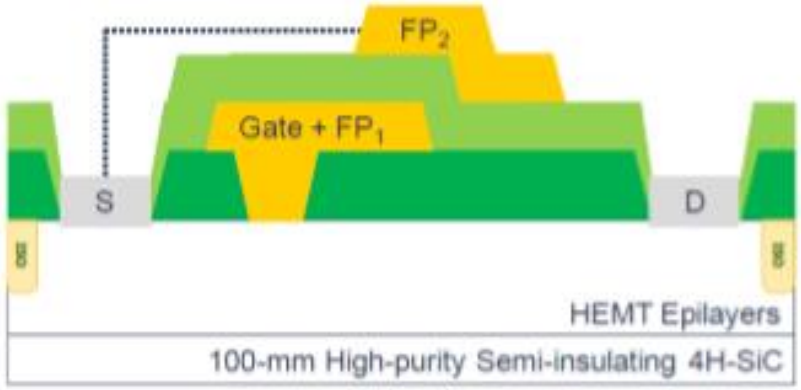
GaN HEMT RF applications

RF applications : Power Amplifier

- RF applications for Power amplifier
- High output power and PAE
→ Reduced trap and Increased Breakdown voltage

- GaN HEMT on SiC substrates
- Reduced TEC and lattice mismatch
- Good thermal conductivity
- Semi-insulating substrates

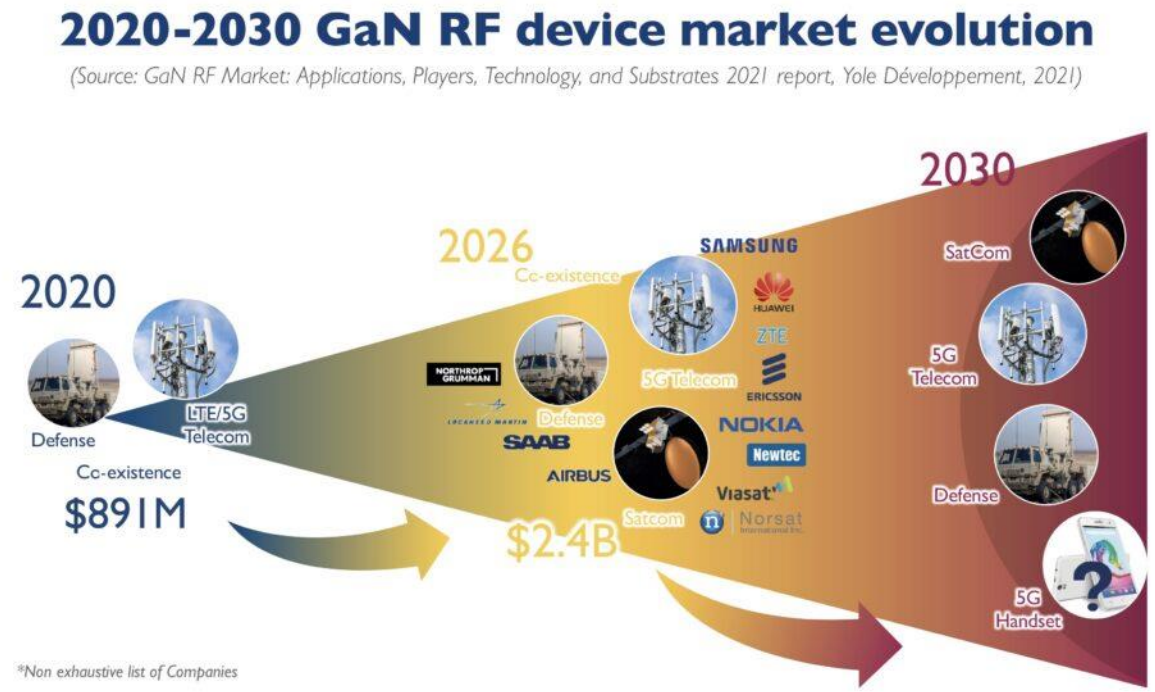


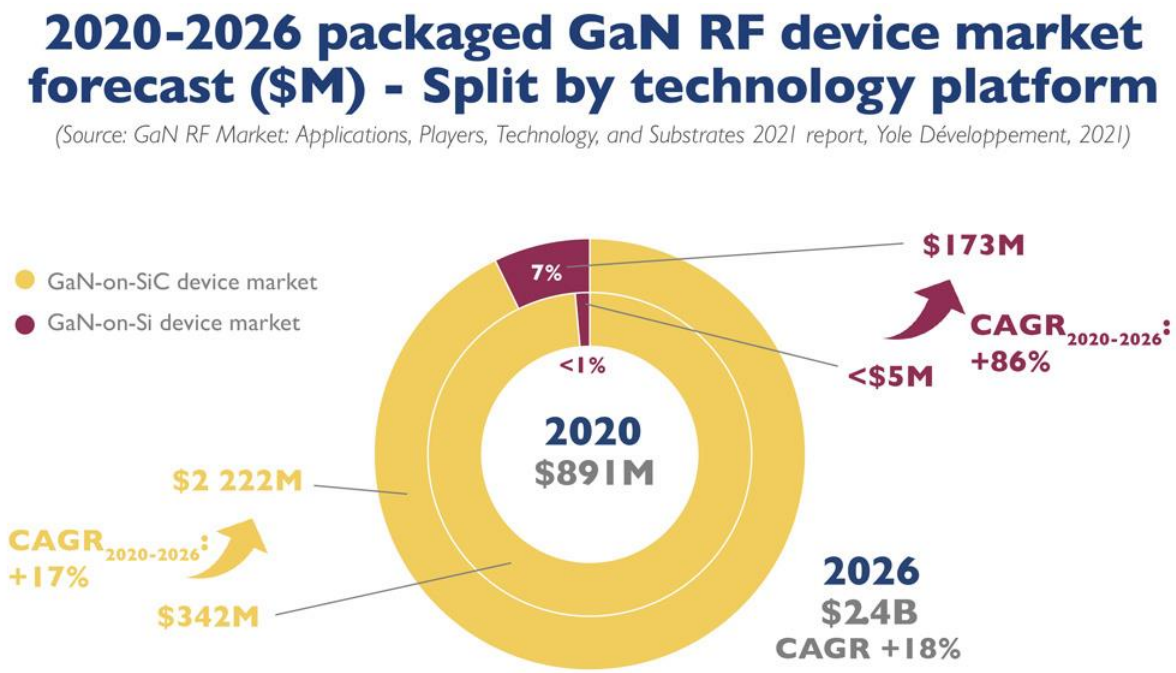


source : Wolfspeed

GaN HEMT RF applications

RF applications : Device Market



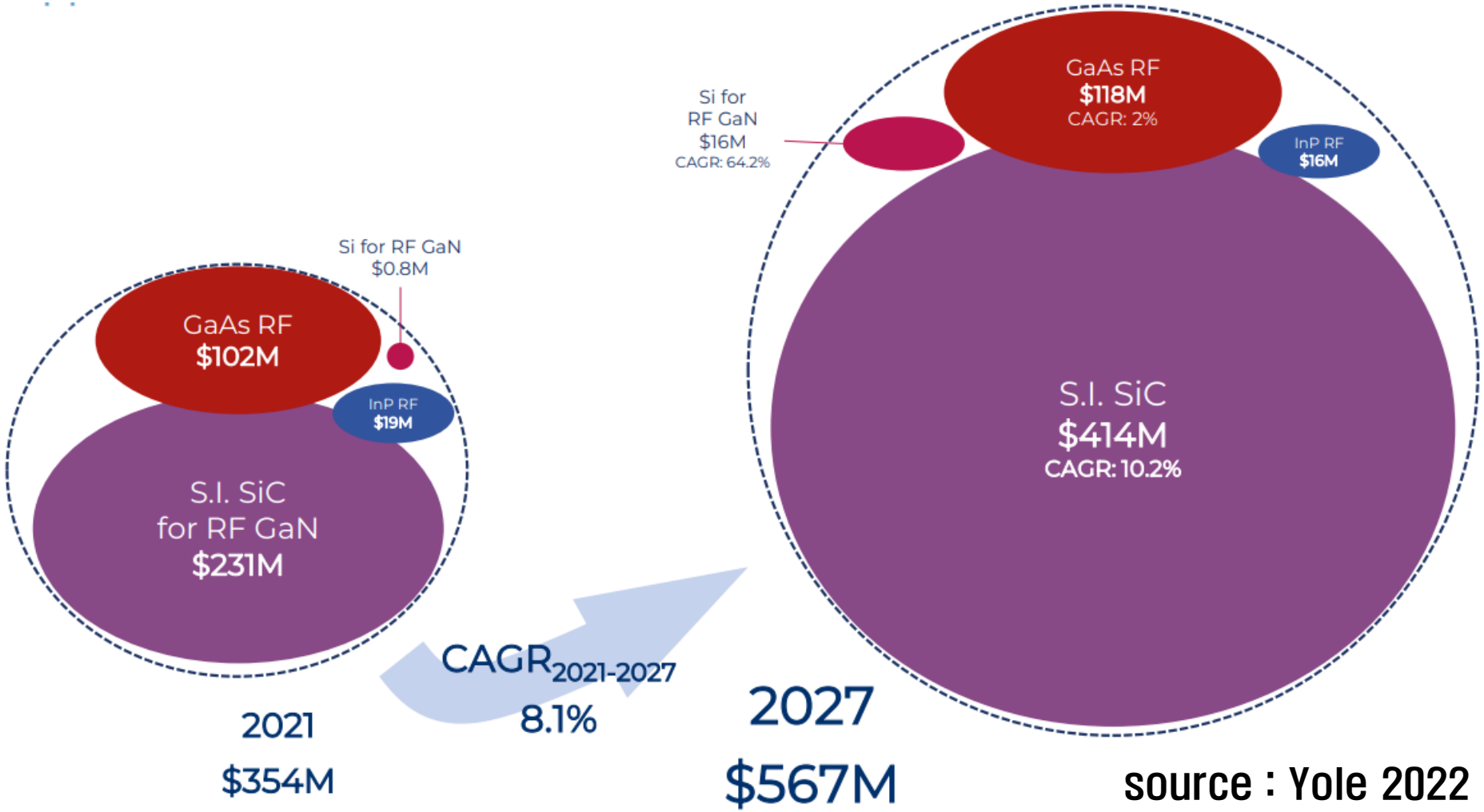


- Defense market
- 5G / mmWave applications

- GaN on SiC : 4” → 6” (8”)
- GaN on Si : 6” → 8” (12”)

GaN HEMT RF applications

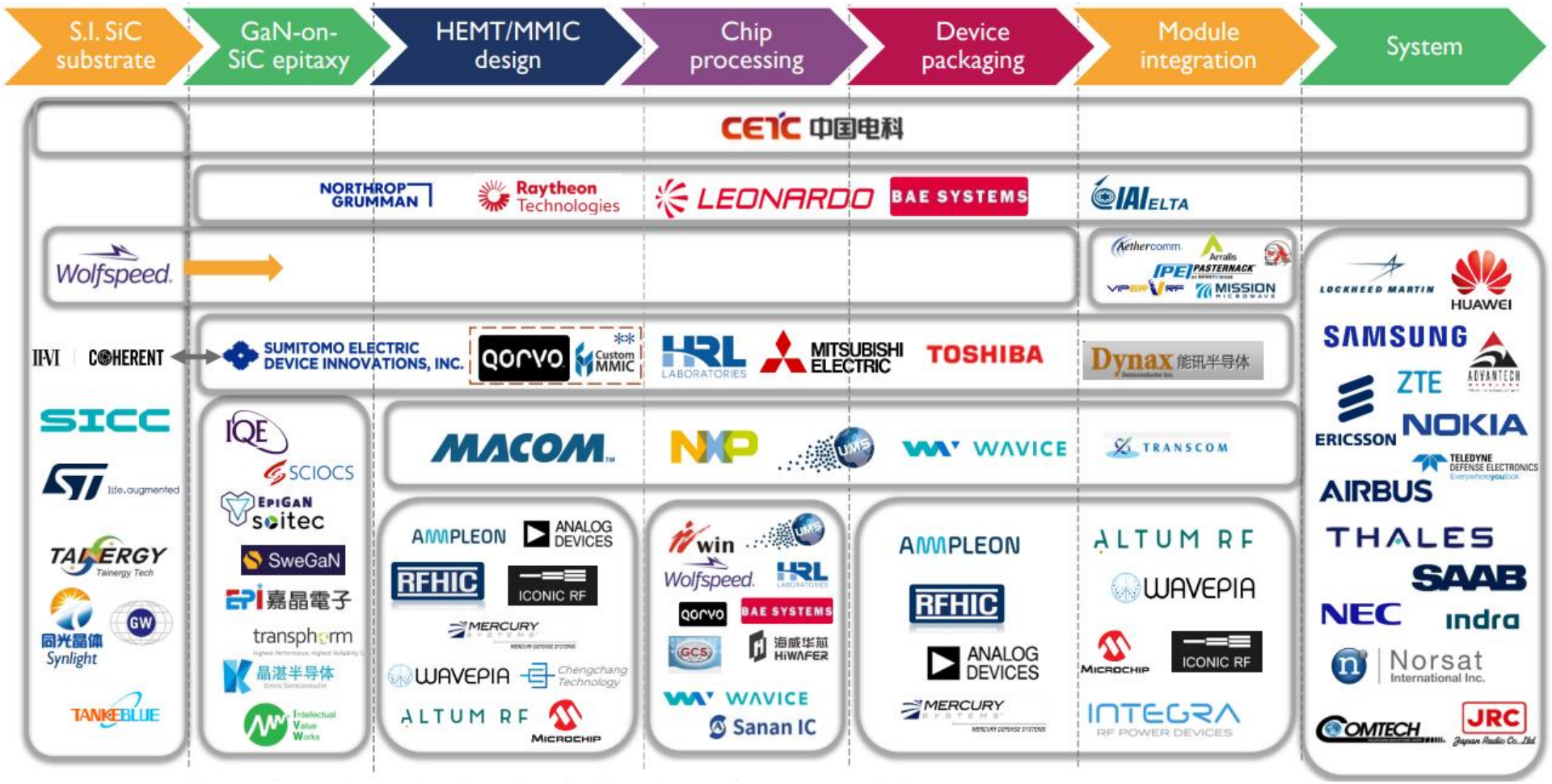
RF applications : Substrate market



source : Yole 2022

GaN HEMT RF applications

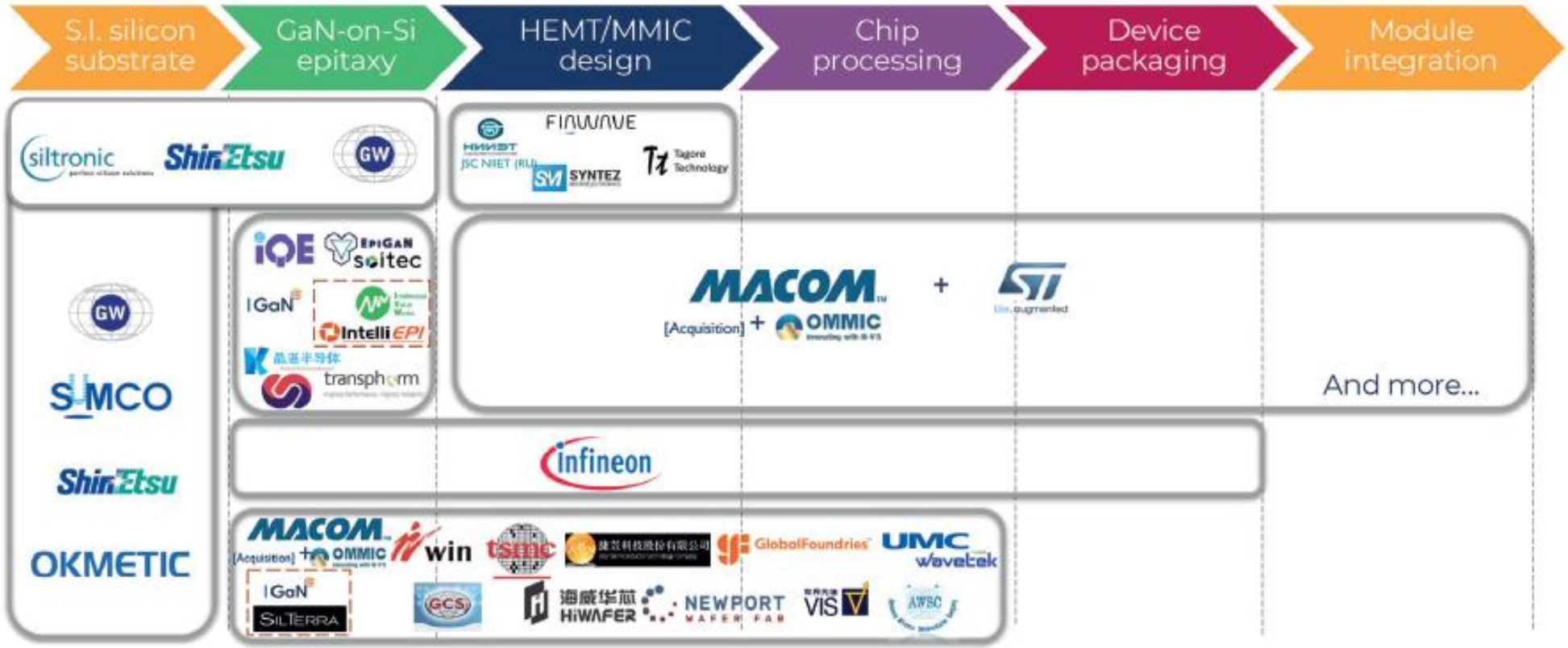
Supply Chain (GaN on SiC)



source : Yole 2022

GaN HEMT RF applications

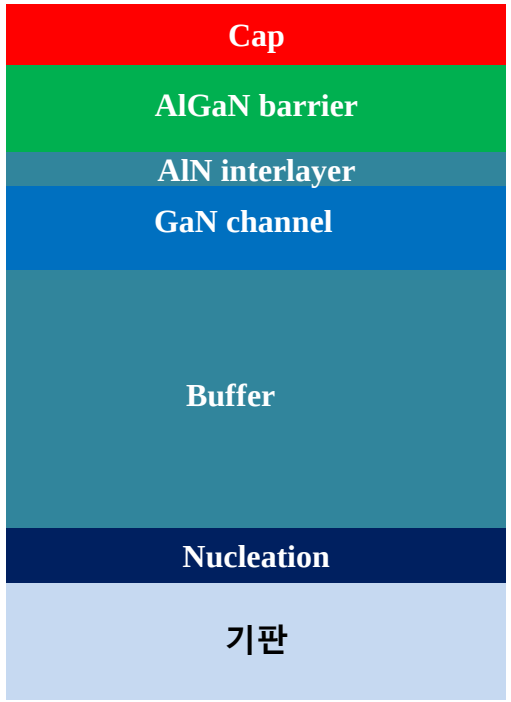
Supply Chain (GaN on Si)



source : Yole 2023

RF GaN HEMT 에피 기술

에피 구조 (상용)



Layer	Typical	option
Cap	GaN 1~3 nm	(In-situ SiN)
AlGaN barrier	Al 25% 20nm	Al 조성/두께
AlN interlayer	1 nm	
GaN channel	200 ~300 nm	
Buffer	1~ 1.8 um (Fe doped)	
Nucleation	AlN	
기판	100 mm 0.5t 4H-SiC	High purity Vanadium doping

Control 영역
Rs, Vth

Buffer leakage
Trapping

RF GaN HEMT 에피 기술

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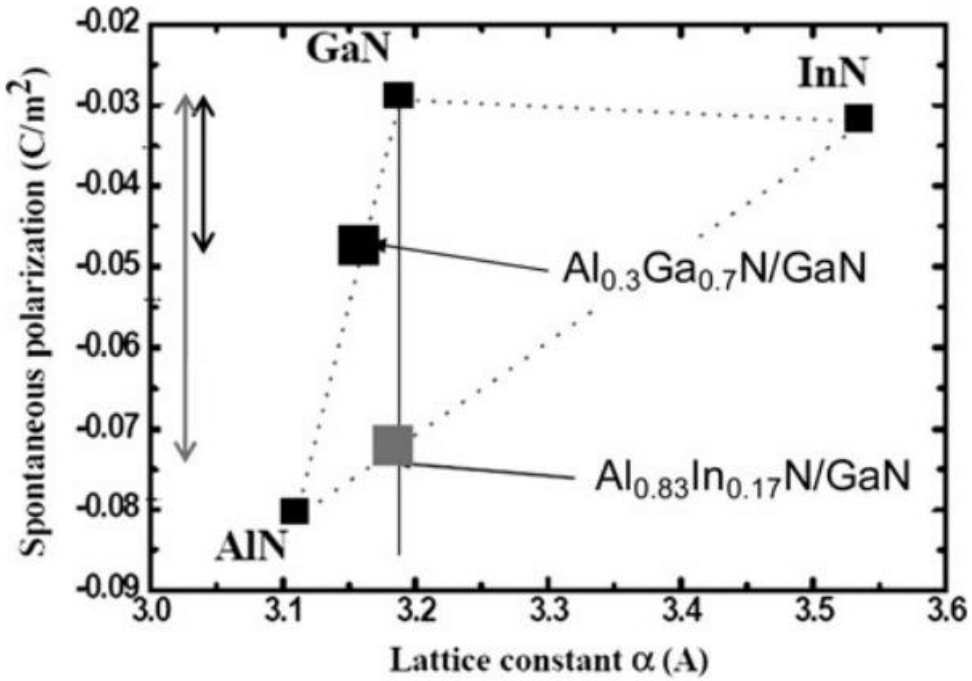
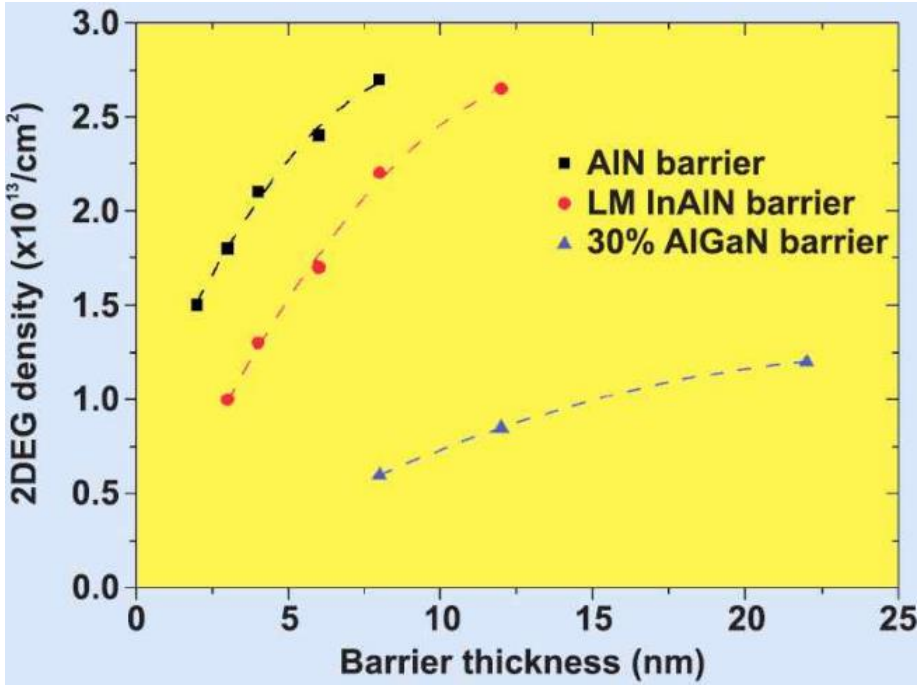
에피 spec (상용 예)

items	spec	typical	Method
Wafer bow/warp	< ±50 um	< ±30 um	Curvature measurement
GaN XRD FWHM	002 < 250 arcsec 102 < 300 arcsec		XRD
AlGaN 조성 AlGaN 두께	< 1% < 10%	25 % 20 nm	XRD / PL XRR
Rs	< 10 %	330 Ω/□	Eddy current
Rs 균일도	< 3%	1.5 %	
ns	< 10 %	0.9 x 10^{13} cm^{-2}	Non-contact mobility measurement (microwave reflectance)
mobility	> 1800 cm^2/Vs	2000 cm^2/Vs	
Buffer breakdown	> 200 V @1uA/mm		Test structure

RF GaN HEMT 에피 기술

Polarization induced 2DEG





International Journal of Microwave and Wireless Technologies, 2011, 3(3),301 - 309

RF GaN HEMT 에피 기술

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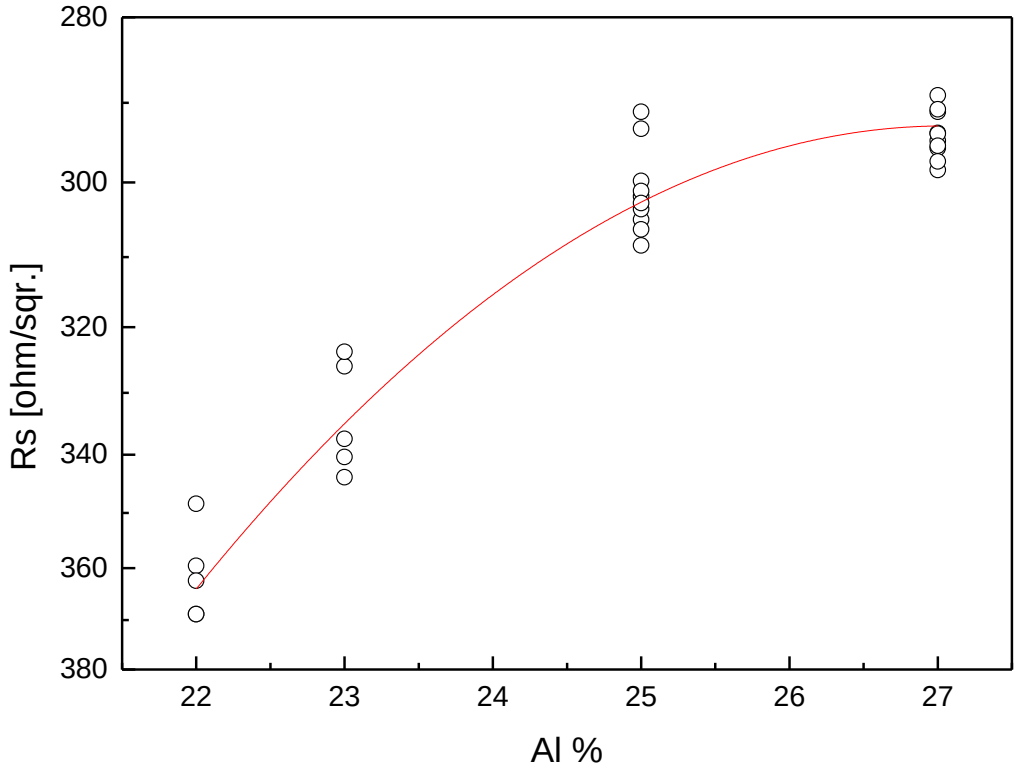
Barrier

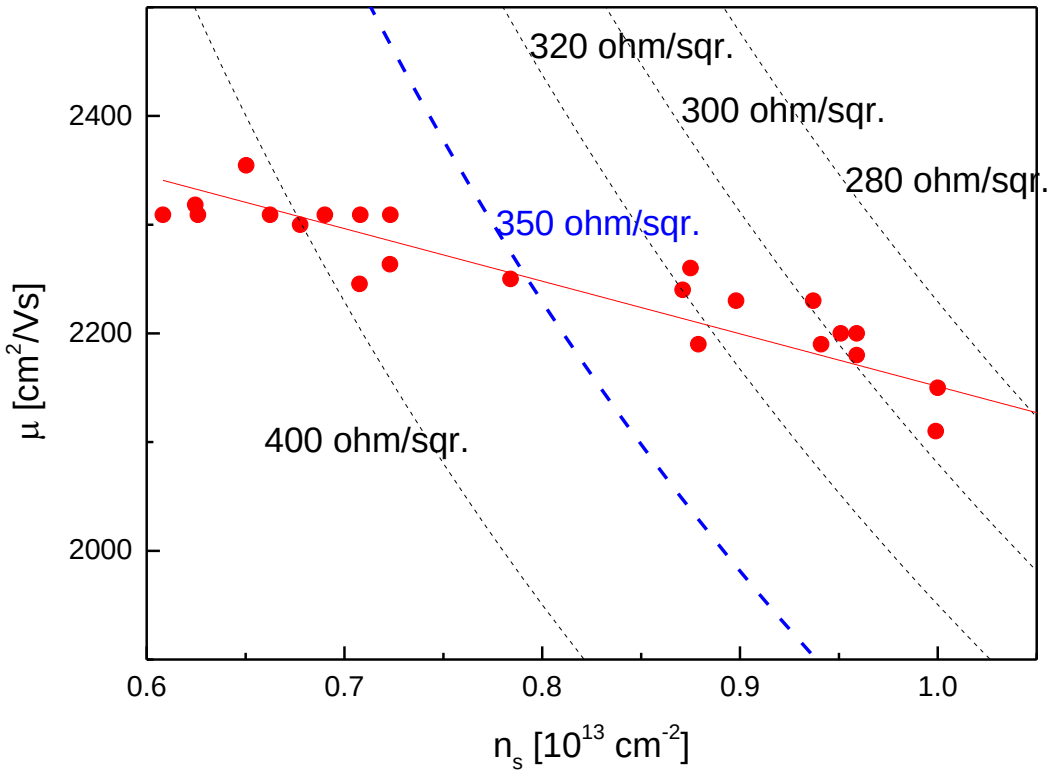
Barrier	$Al_{0.25}GaN$	AlN	$In_{0.17}AlN$
Thickness [nm]	20	4~6	10
Rs [Ω/□]	< 400	< 350	< 250
Ns [10^{13} cm^{-2}]	~0.9	> 1.5	>1.5
Mobility [cm^2/Vs]	> 1800	> 1000	> 1800

source : EpiGaN

RF GaN HEMT 에피 기술

AlGaN/AlN/GaN HEMT channel





RF GaN HEMT 에피 기술

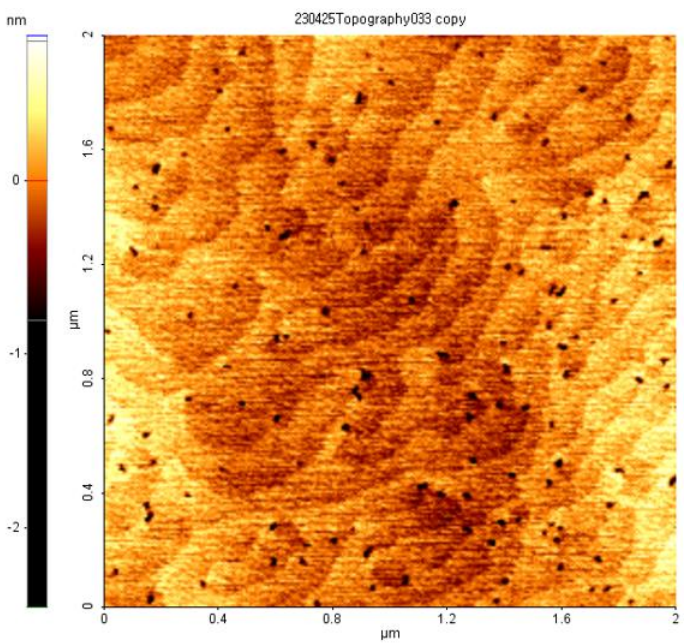
Cap

Cap	GaN	In-situ SiN
Thickness [nm]	1~3	2~20 nm
2DEG	↓	↑
Barrier protection	○	○ AlN barrier
High temperature protection	X	○
Passivation	X	Process depend

RF GaN HEMT 에피 기술

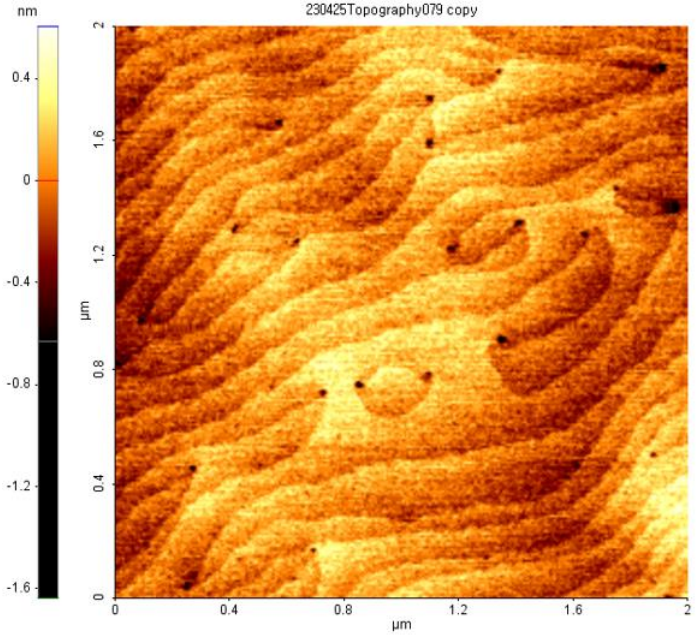
GaN Cap

Cap thickness 증가



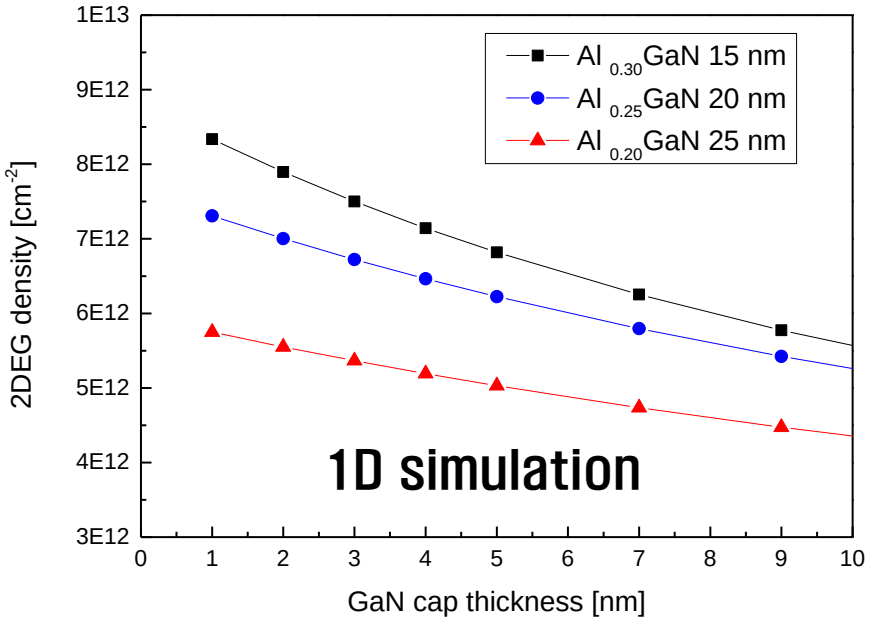
Rq 0.225 nm

Rs 305 Ω/□



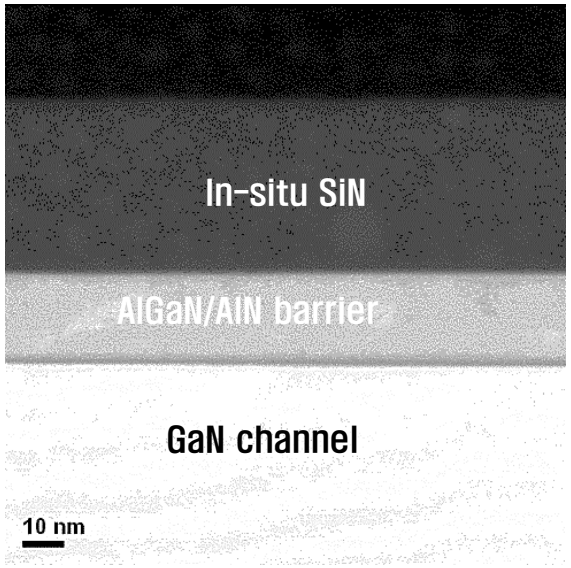
Rq 0.153 nm

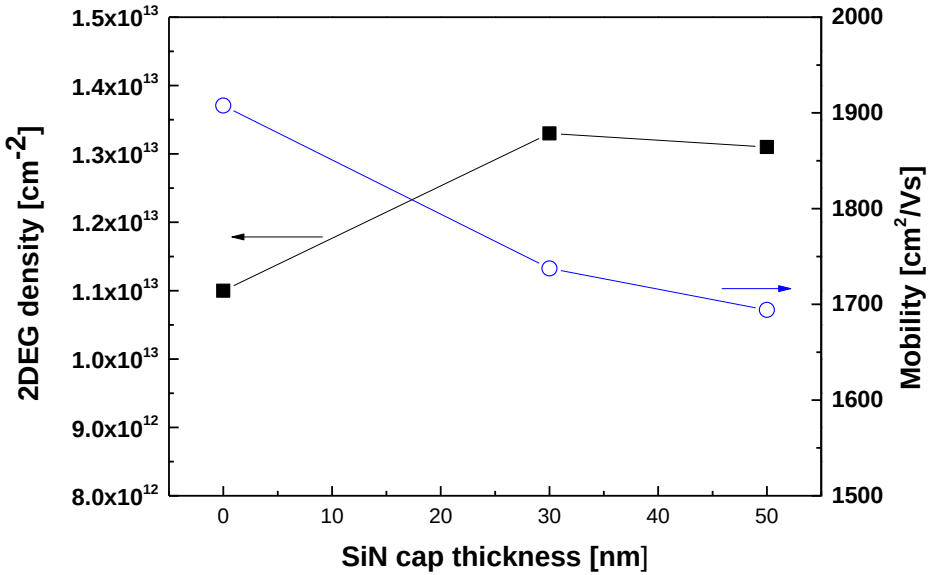
Rs 320 Ω/□

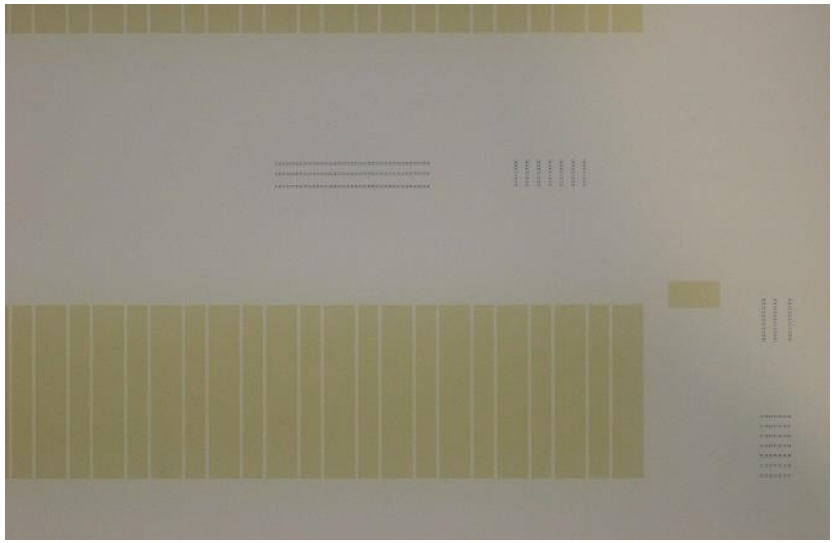


RF GaN HEMT 에피 기술

SiN Cap







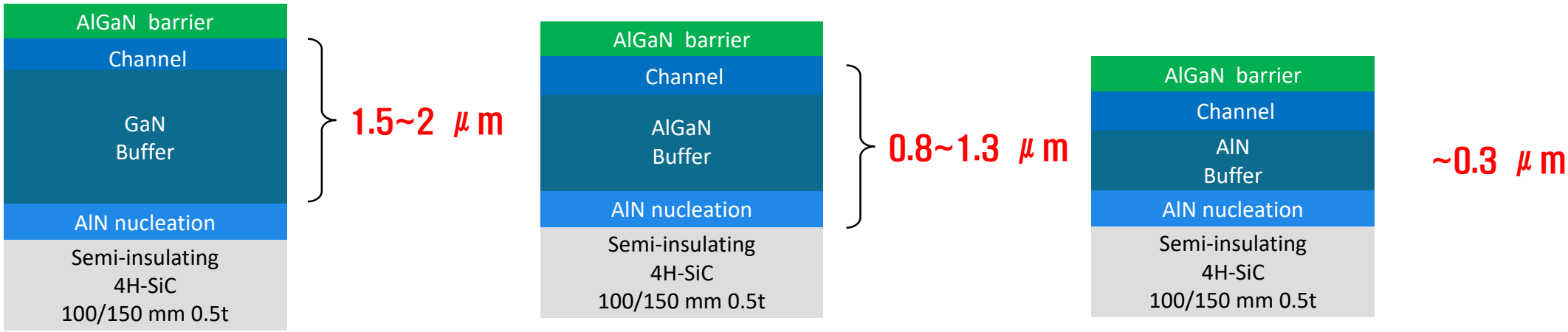
High Temperature processing

RF GaN HEMT 에피 기술

Buffer

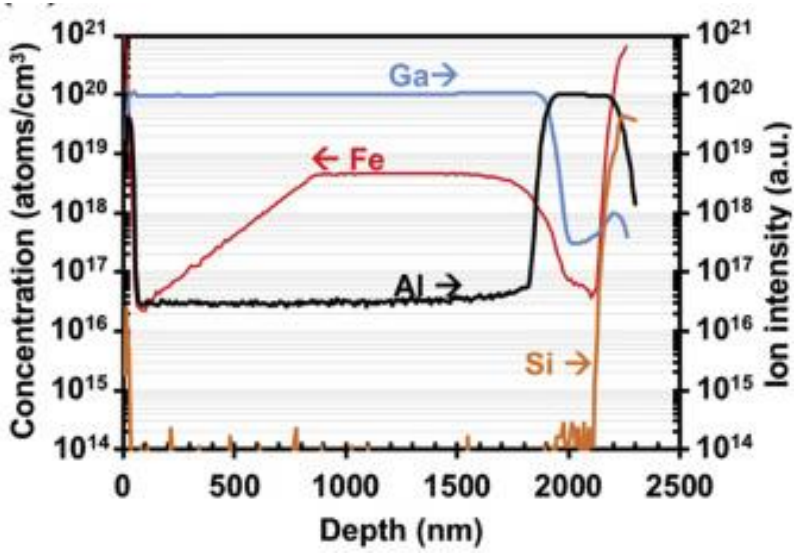
High resistive and Reduced Buffer trapping

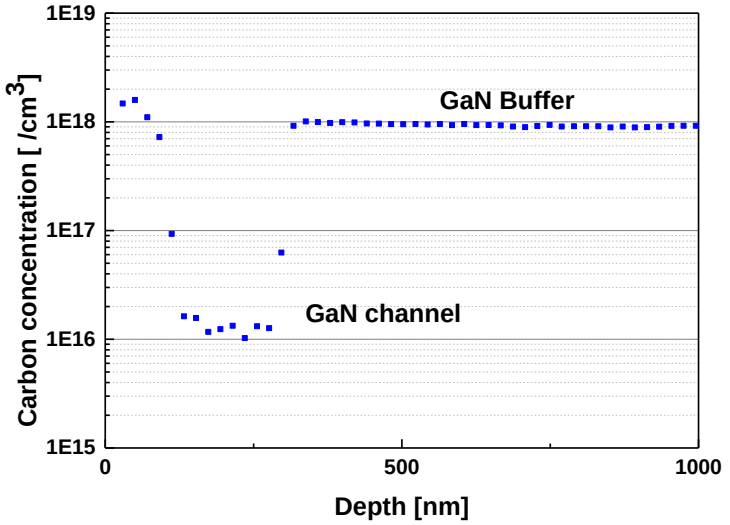
Buffer	Resistivity control	Issues	
GaN	Fe doping	Fe memory effect	Commercial
	Carbon doping	Process control	GaN on Si
AlGaN	Increase Band-gap	Thermal conductivity	DHEMT structure
AlN	AlN buffer	AlN strain control	
	Buffer free	High quality AlN	SWEGAN

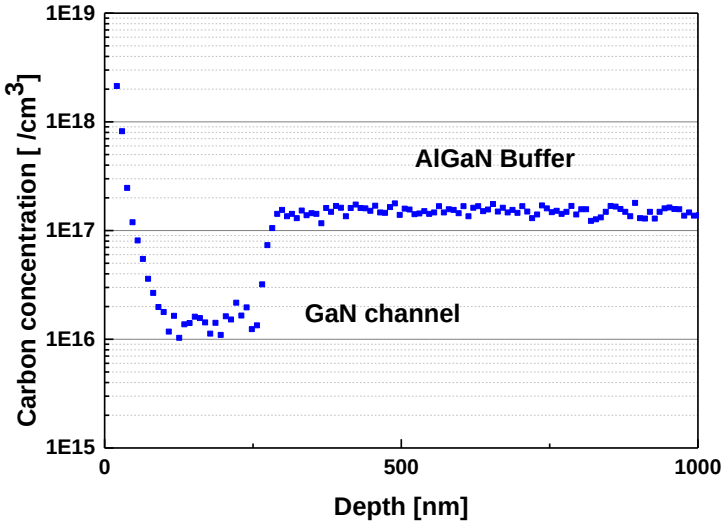


RF GaN HEMT 에피 기술

GaN channel / Buffer



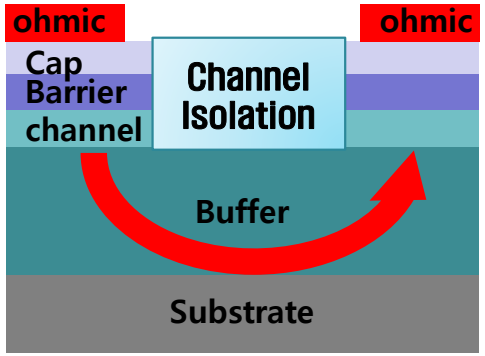


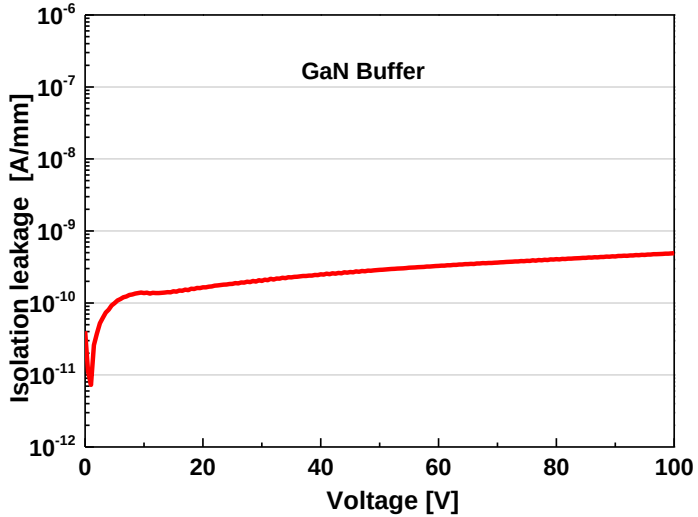


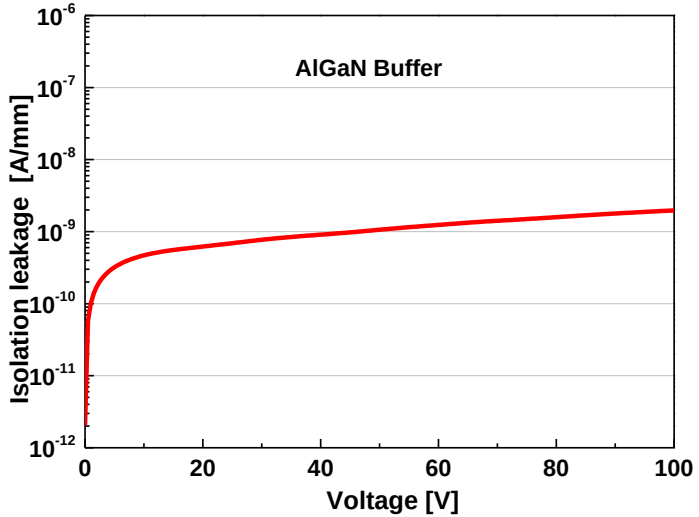
Materials Science in Semiconductor Processing,
Volume 119,2020,105228,

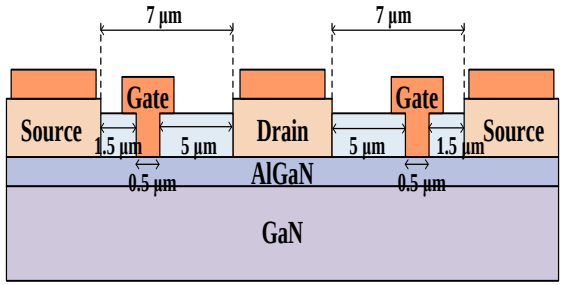
RF GaN HEMT 에피 기술

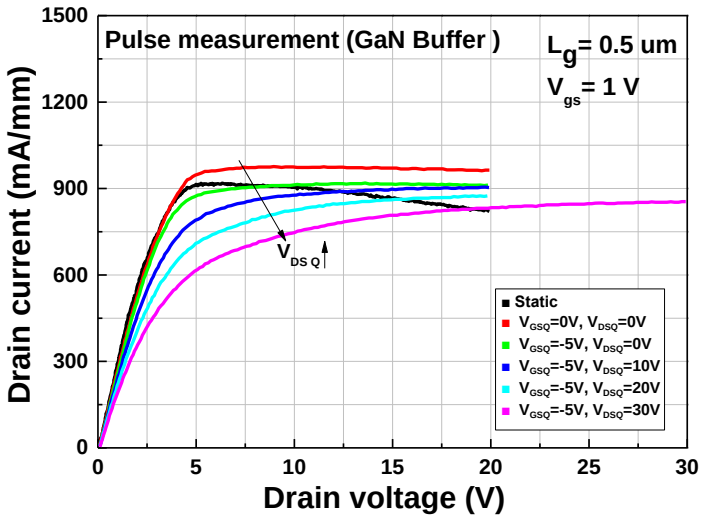
Buffer leakages / Trap

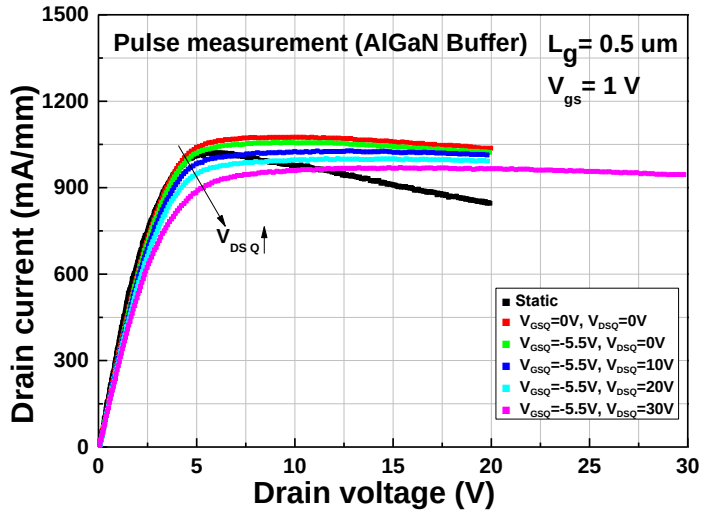








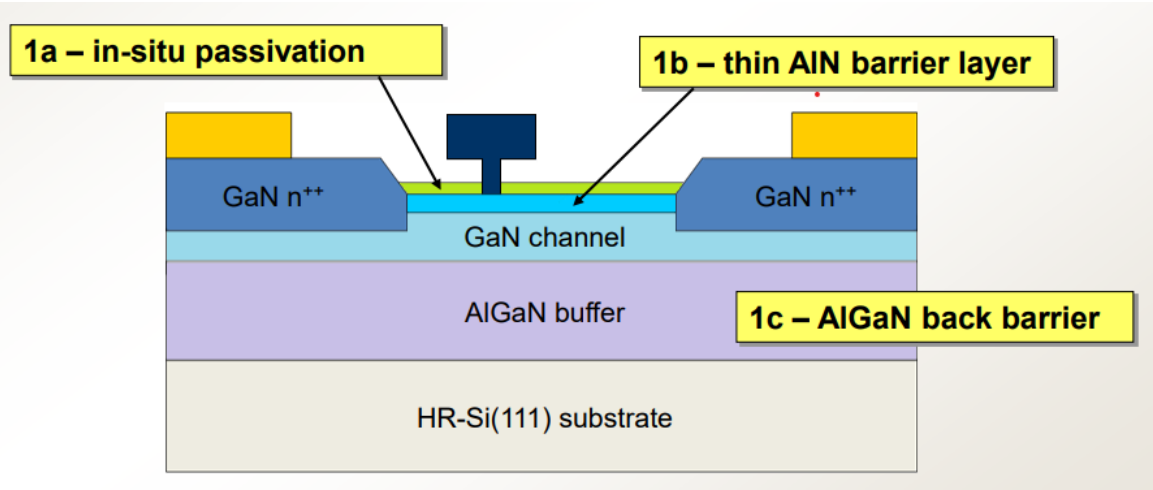




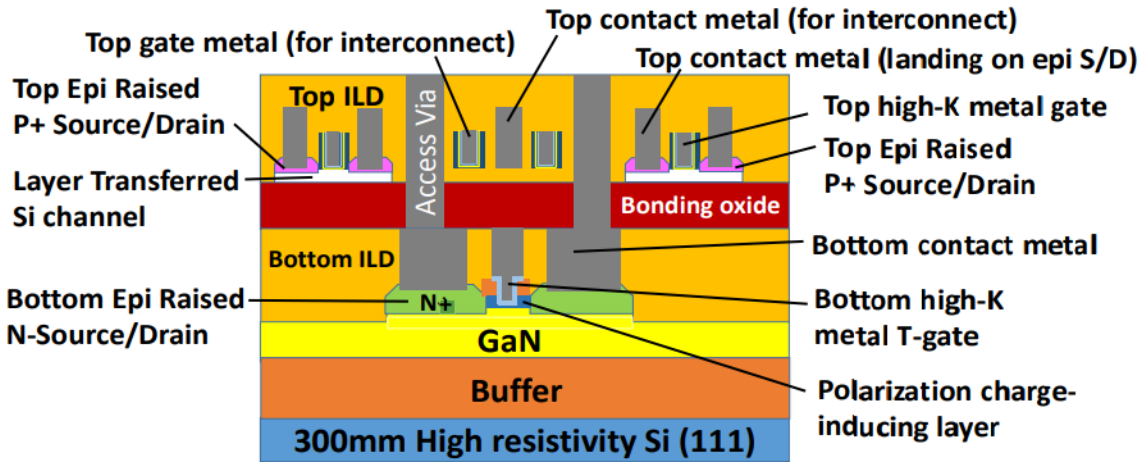
RF GaN HEMT 에피 기술

GaN HEMT on Si for RF

- High resistive Si (111) substrates
- Wafer scaling
- Si CMOS process / Integration



OMMIC 2018

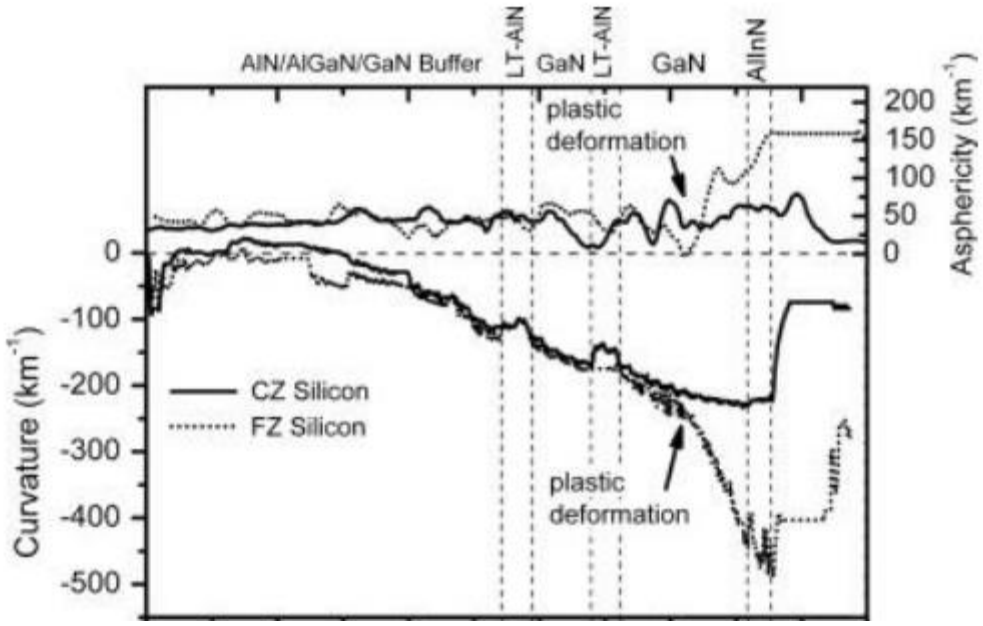


Intel IEDM 2019

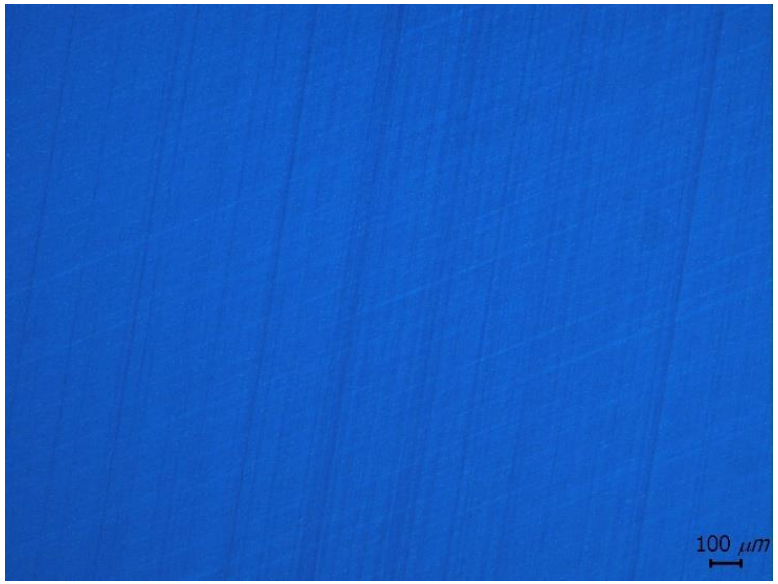
RF GaN HEMT 에피 기술

High resistive Si

- Plastic deformation → Growth thickness / strain control



Journal of Crystal Growth 370, p278

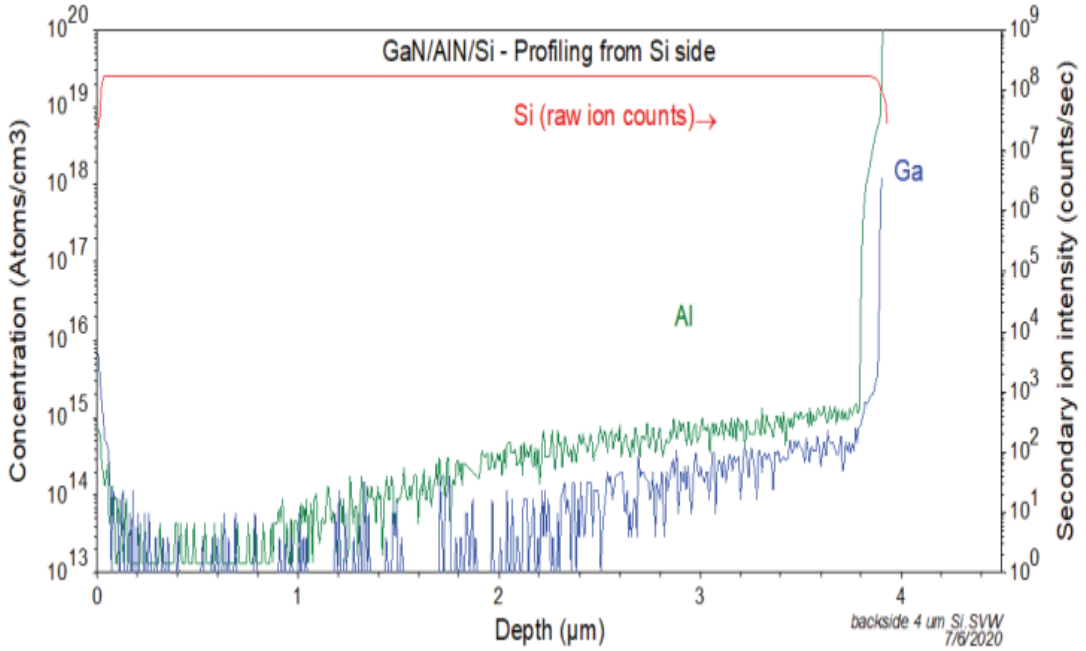


Plastic deformation (Slip)

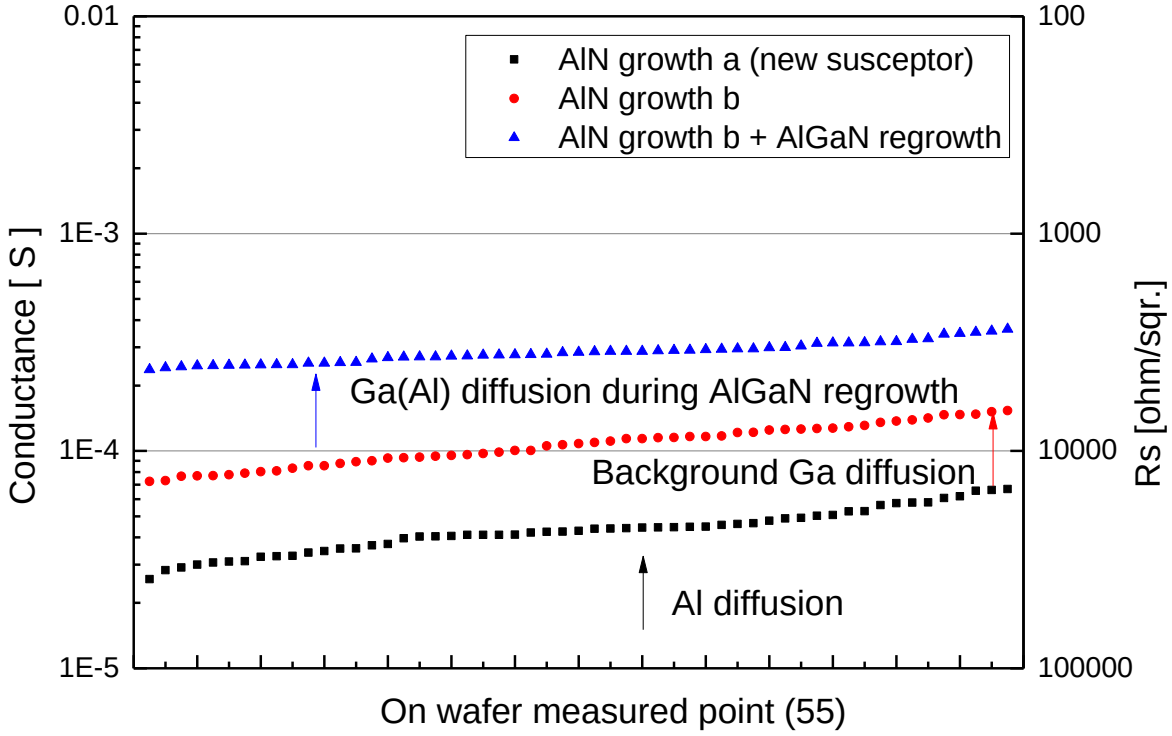
RF GaN HEMT 에피 기술

High resistive Si

- Parasitic channel formation @Si interface → Al/Ga diffusion control



https://www.eag.com/app-note/sims-analysis-of-al-and-ga-diffusion/



KANC 기술 개발 현황

한국나노기술원 (KOREA Advanced NanoFab Center)

나노소자, 화합물 반도체분야의 연구개발 및 지원 공공 인프라

경기도 수원시 영통구 광교로 109

연구개발 (R&D)	▪ 나노패턴 형성 공정 ▪ 보유장비 : E-beam lithography, KrF, stepper Aligner, Nano-Imprinter 등	▪ 에피 및 증착공정 ▪ 보유장비 : MOCVD, MBE, Evaporator, Wet-station 등	▪ 표면, 구조 및 특성 분석 ▪ 보유장비 : TEM, FIB, SEM CL 및 AFM 등
Wafer → Device	나노리소패턴 지원라인 / SI&MEMS 지원라인	나노R&D 지원라인 / 나노산업화 지원라인	특성평가 지원라인 / 후공정 지원라인
산업화	▪ 8 기반의 Si&MEMS 공정 ▪ 보유장비 : I-line Stepper, CD-SEM, Sputter, Wet-station 등	▪ 산업화 지원을 위한 증착 및 에칭 공정 ▪ 보유장비 : Implanter, Sputter, LPCVD, ICP Etcher 등	▪ 후공정 및 신뢰성 측정 ▪ 보유장비 : Wire bonder, Dicing machine, Prober, 신뢰성 측정장비 등

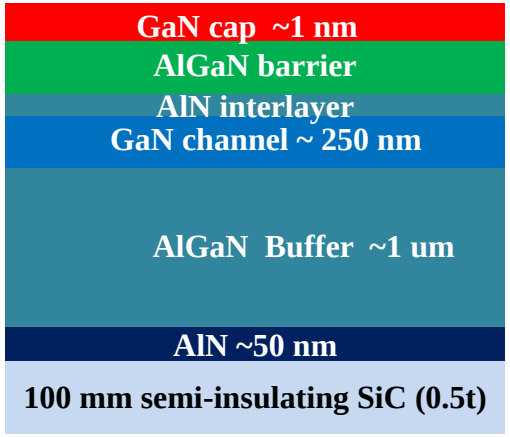
KANC 기술 개발 현황

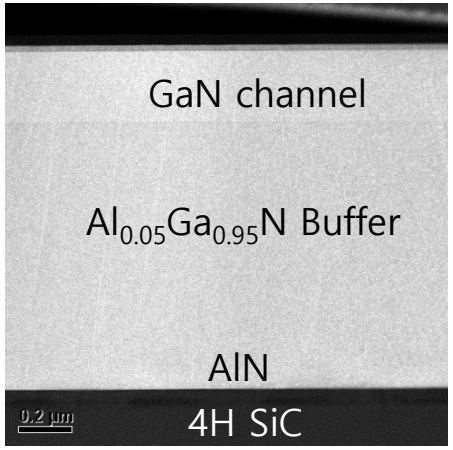
MOCVD for GaN HEMT growth

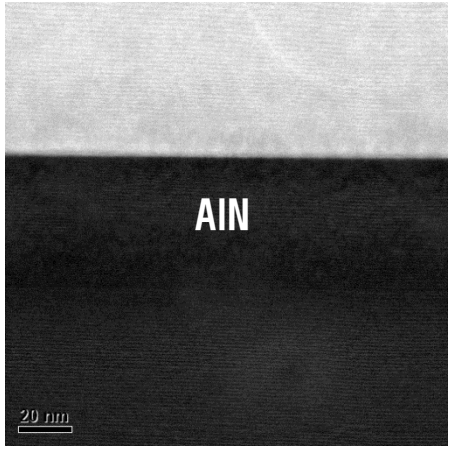
	제조사 /Model	Capacity	현황
	Aixtron/Crius	7 x 4” 3 x 6”	2018 set-up 2019~ 운영 중 GaN HEMT 에피 공정
	Veeco/K465i High thru-put Automatic 3Run	12 x 4” 5 x 6” 3 x 8”	2022 하반기 도입 2023 GaN HEMT 에피 공정 구축 진행중 Pilot 물량 대응 가능

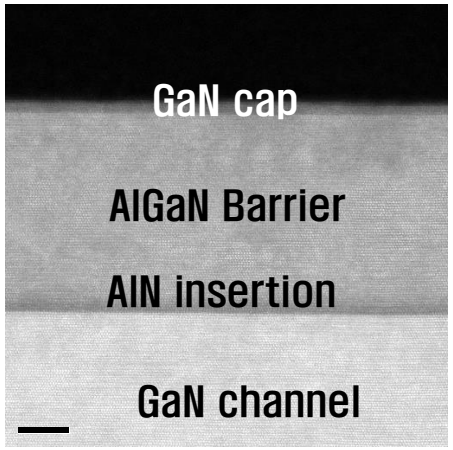
KANC 기술 개발 현황

GaN HEMT on SiC 구조









Layer	standard	option
GaN cap	1 nm	
AlGaN barrier	Al 27% 22 nm	Al 22~30 % 10~25 nm
AlN insertion	1 nm	
GaN channel	250 nm	150 ~ 300 nm
Buffer	$Al_{0.05}Ga_{0.95}N$ ~1 μm	GaN 1.3 ~ 1.6 μm Carbon doping 9E17 ~ 8E18 cm^{-3}
AlN nucleation	50 nm	
SiC	100 mm 0.5t	150 mm 0.5t

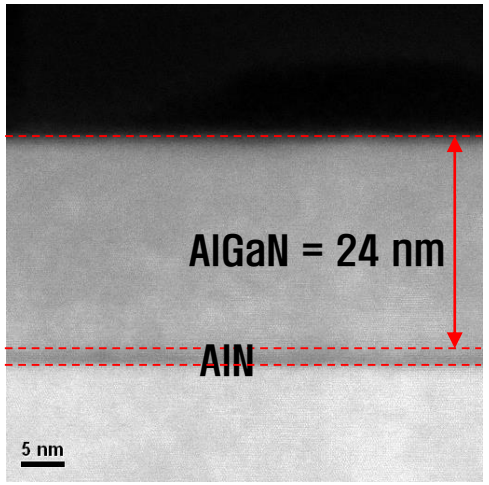
KANC 기술 개발 현황

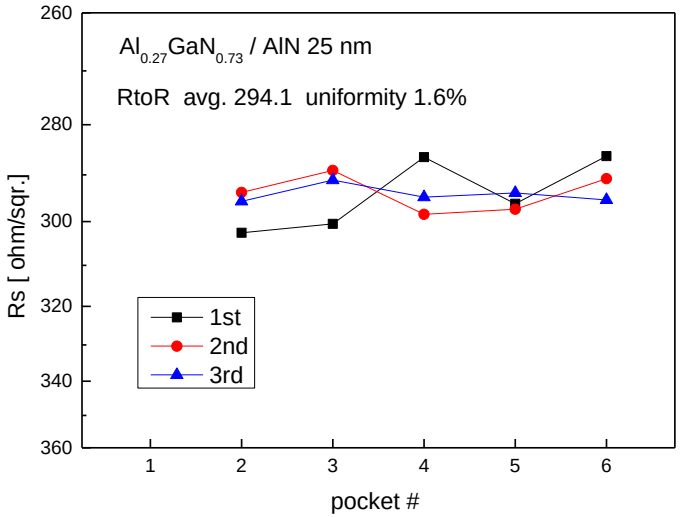
GaN HEMT on SiC spec

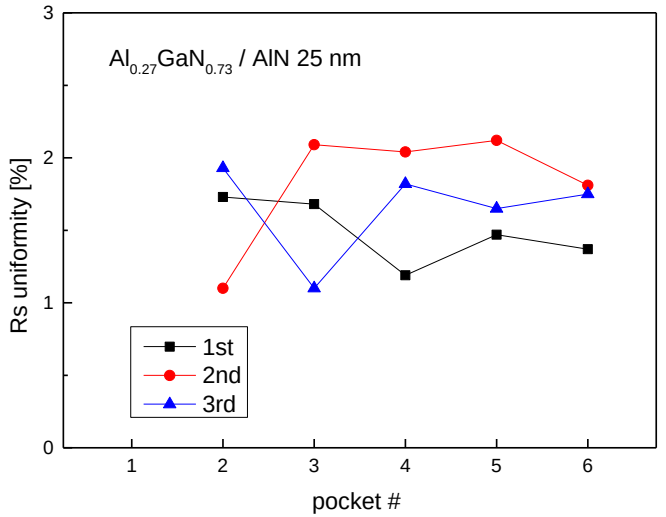
items	spec	typical	KANC
Wafer bow	< ±50 um	< ±30 um	< ±30 um
GaN XRD FWHM	(002) < 250 arcsec (102) < 300 arcsec		(002) < 250 arcsec (102) < 350 arcsec (GaN Buffer) < 450 arcsec (AlGaN Buffer)
AlGaN 조성 AlGaN 두께	< 1% < 10%	25 % 20 nm	25~27 % 20~25 nm
Rs	< 10 %	330 Ω/□	290 ~330 Ω/□
Rs 균일도	< 3%	1.5 %	< 3%
ns	< 10 %	0.9 x 10^{13} cm^{-2}	0.9 x 10^{13} cm^{-2}
mobility	> 1800 cm^2/Vs	2000 cm^2/Vs	2000 cm^2/Vs

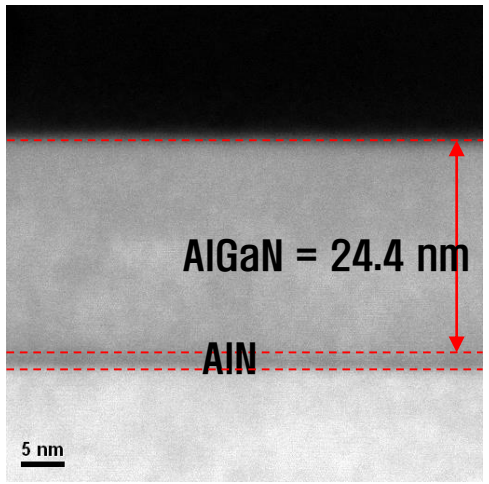
KANC 기술 개발 현황

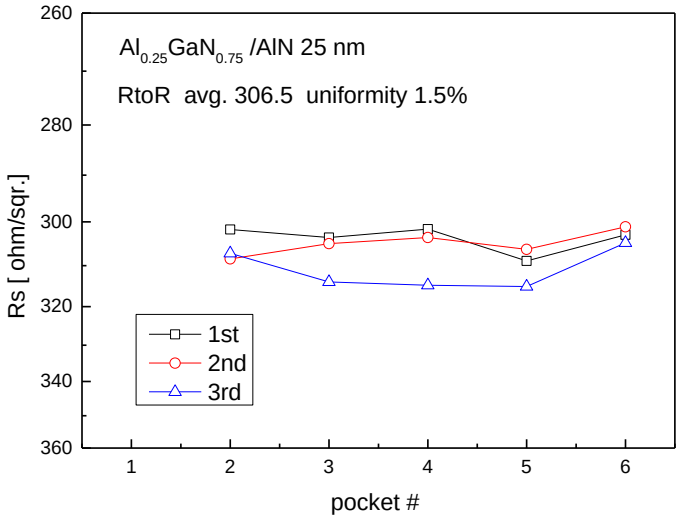
Rs 균일도/재현성

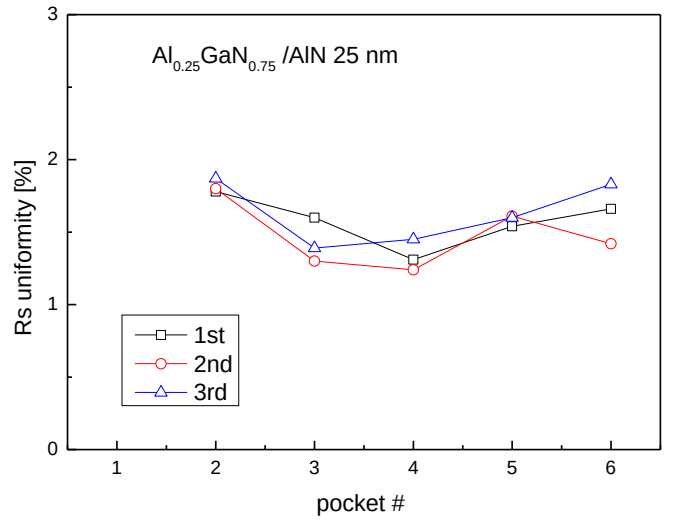






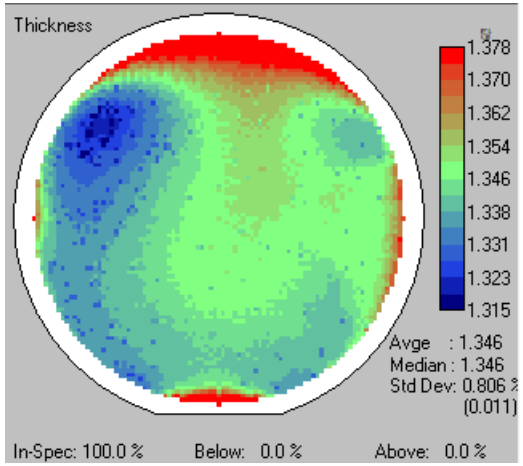


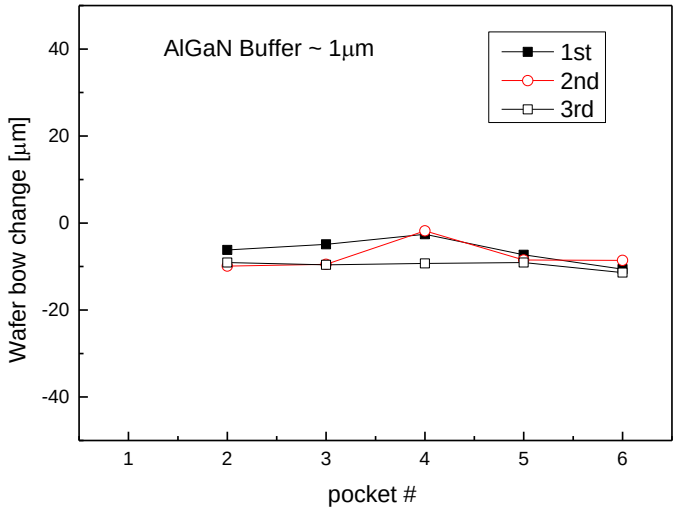


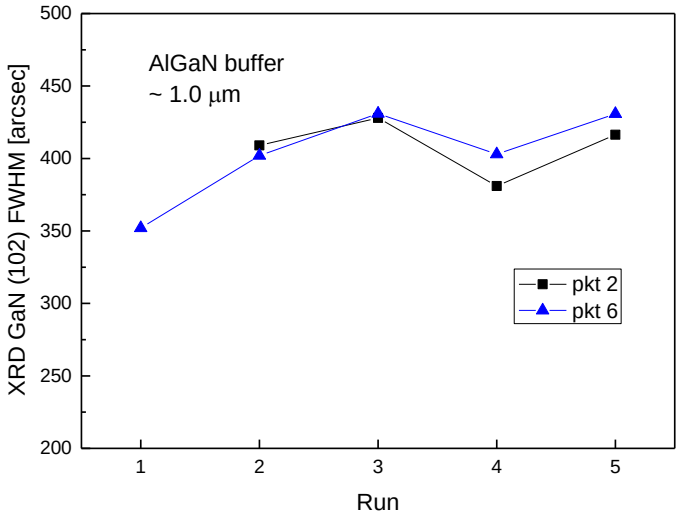


KANC 기술 개발 현황

AlGaN Buffer



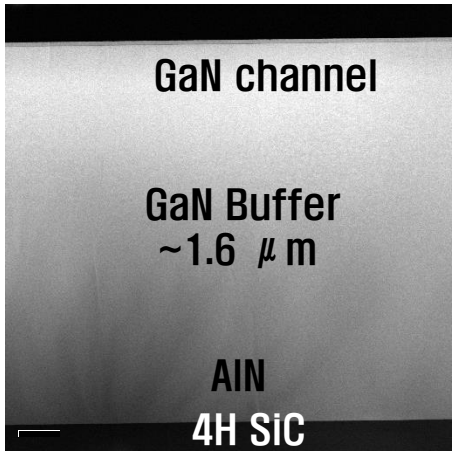


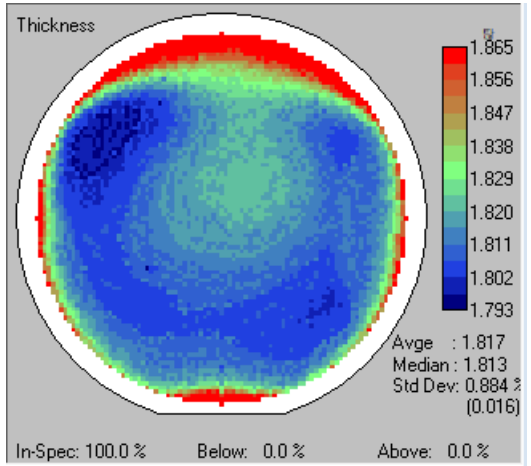


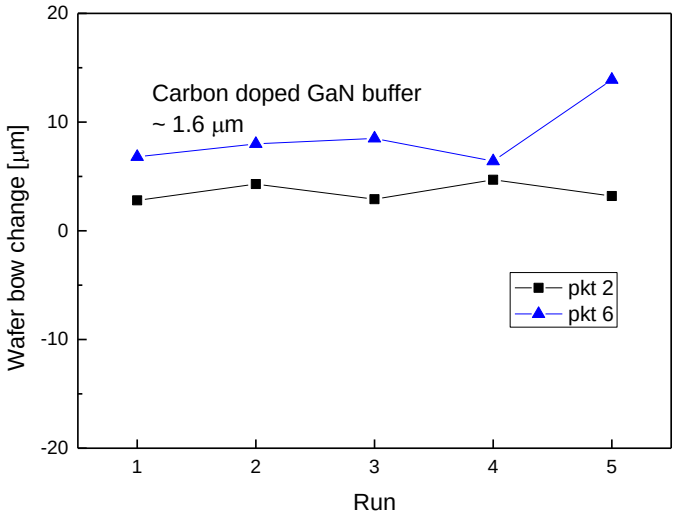
- 두께 균일도 < 2%
- 웨이퍼 휨 < ± 20 um
- GaN (102) FWHM < 450 arcsec

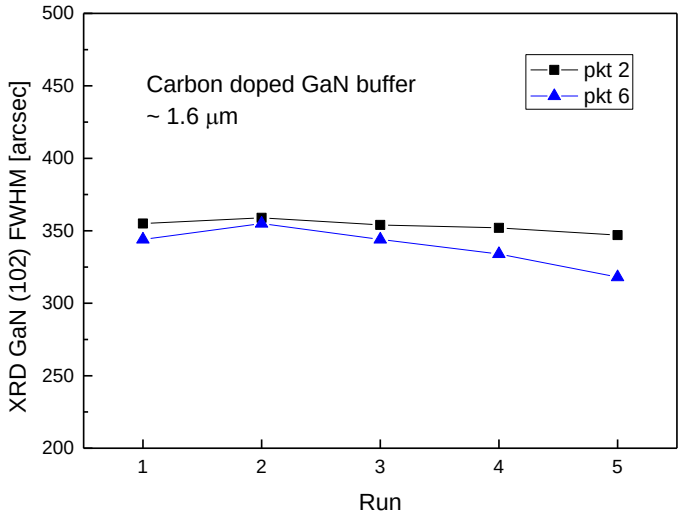
KANC 기술 개발 현황

GaN Buffer







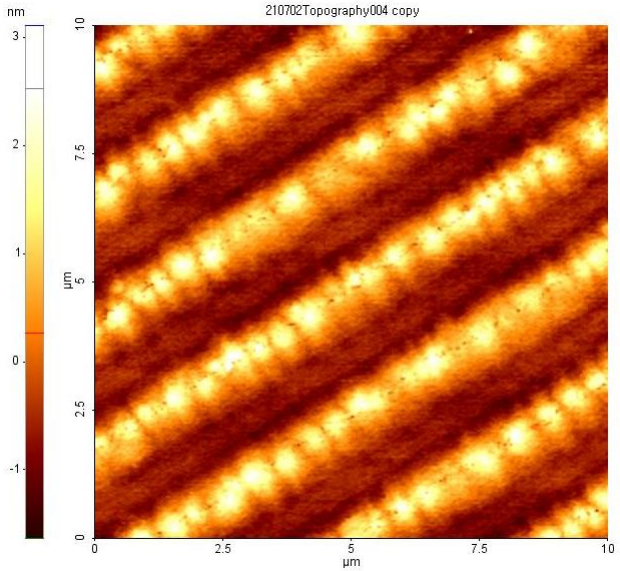


- 두께 균일도 < 2%
- 웨이퍼 휨 < ± 20 um
- GaN (102) FWHM < 350 arcsec

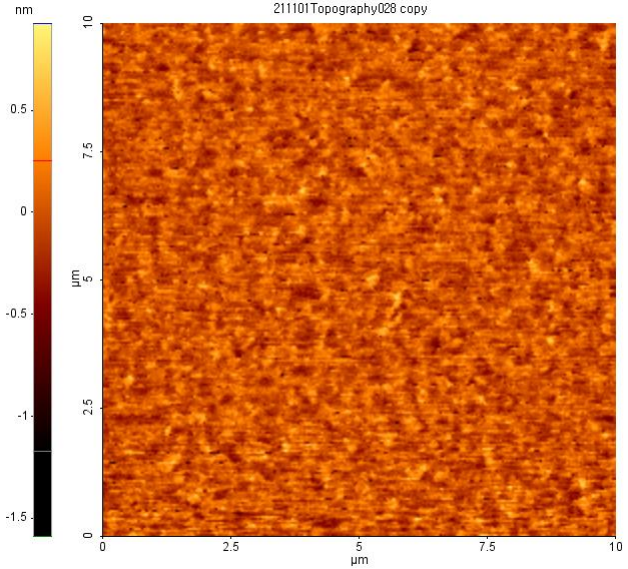
KANC 기술 개발 현황

AlN nucleation

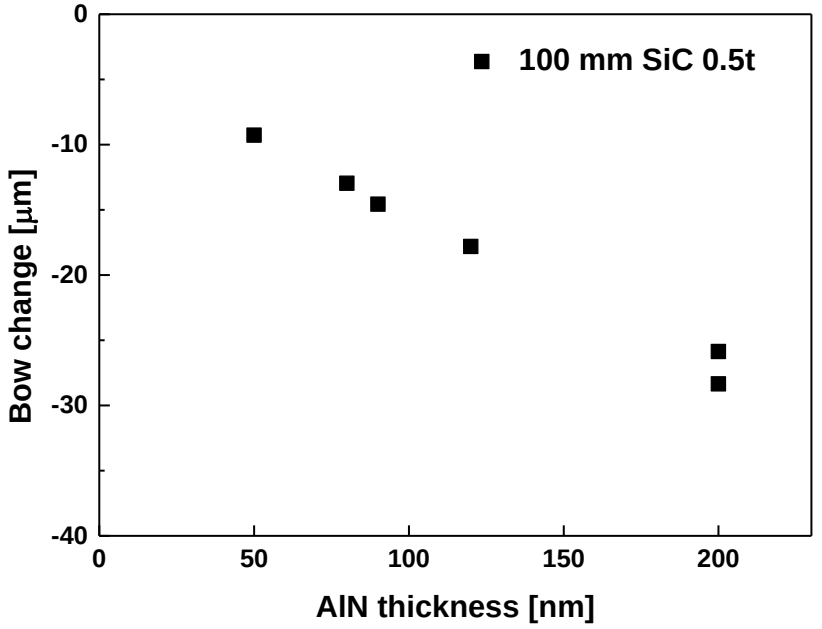
AlN migration 개선



Rq = 0.834 nm



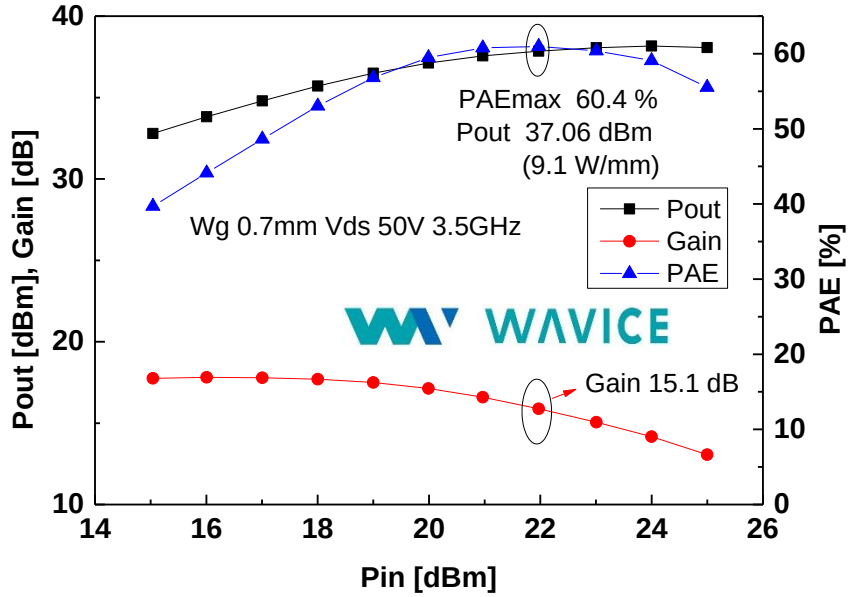
Rq = 0.185 nm



KANC 기술 개발 현황

소자 특성

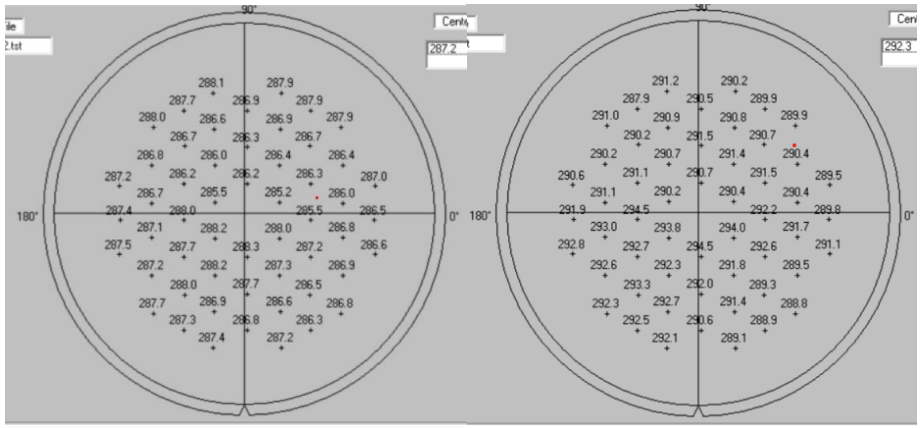
	Cree 0.4 um process	KANC epi @ wavice 0.4 um process
BV @1mA/mm [V]	> 150	> 150
RF Power [W/mm]	10	9
PAE [%]	> 62	60.4
Vds =50V @ 3.5GHz		



- 국내 GaN RF 양산 Fab 웨이비스 공정 적용 소자 특성 확인

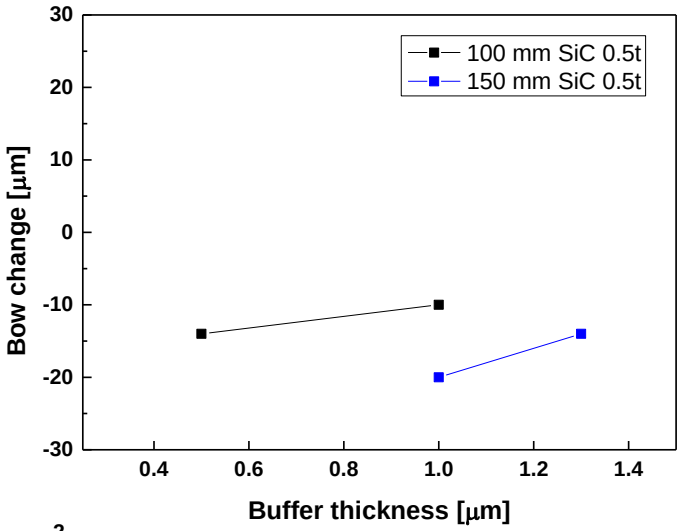
KANC 기술 개발 현황

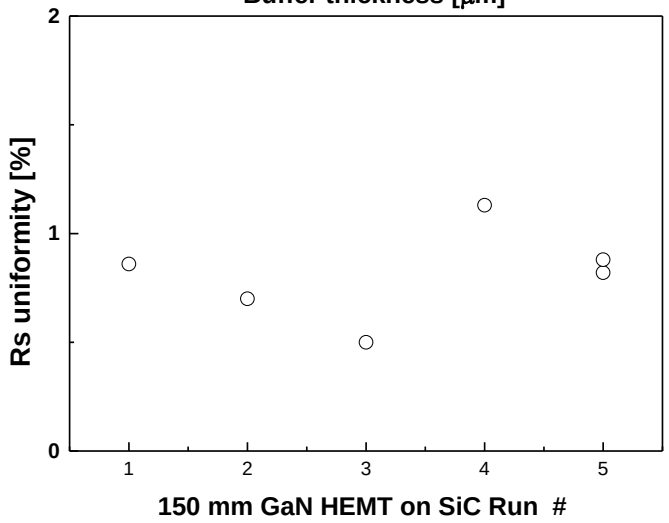
150 mm wafer scaling



4” 287 Ω/□
0.26%

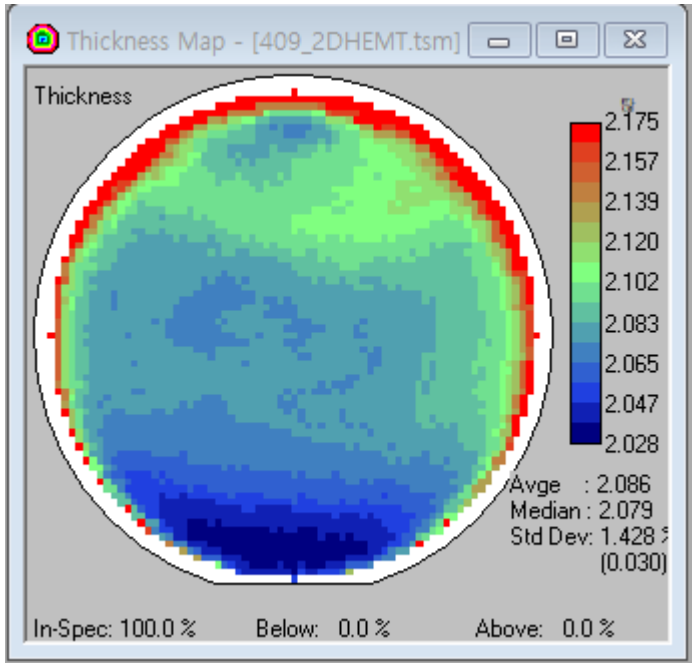
6” 291 Ω/□
0.5%

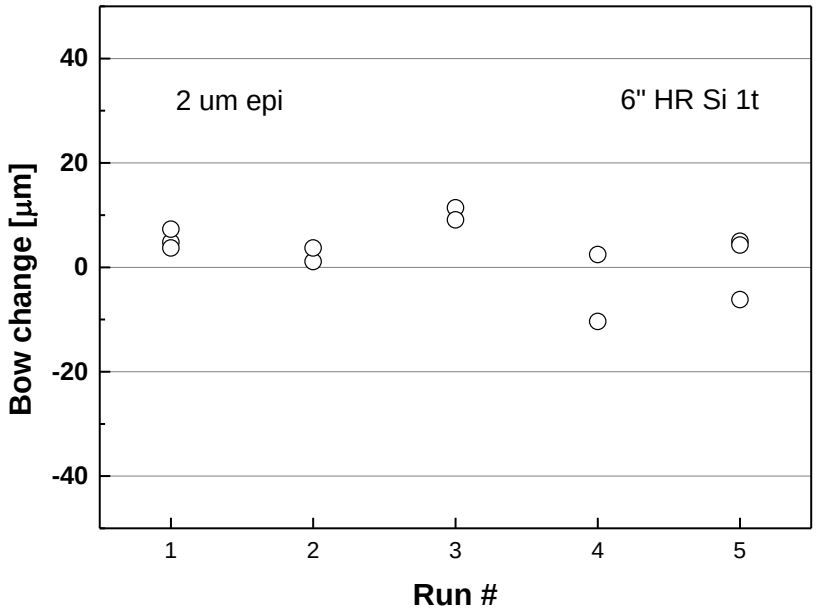


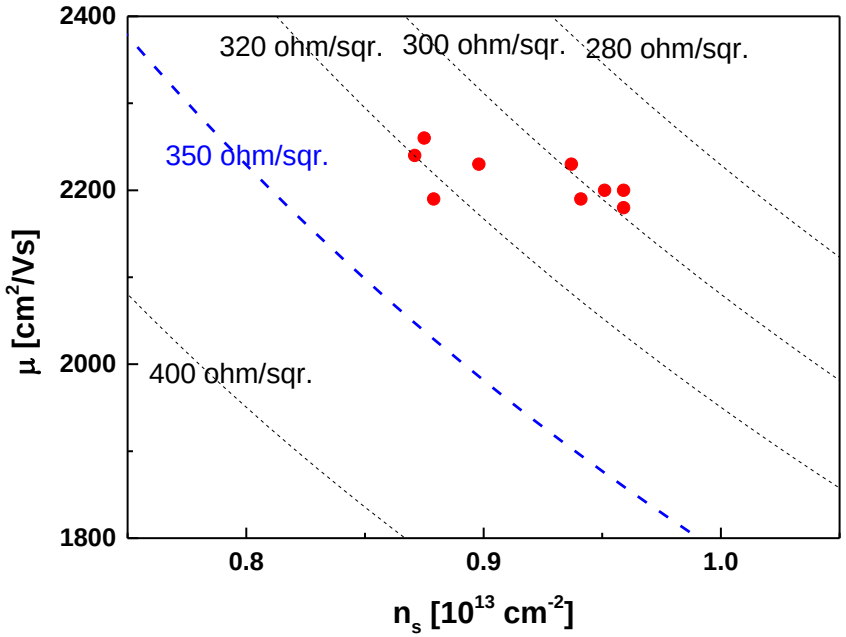


KANC 기술 개발 현황

GaN HEMT on Si







- 두께 균일도 < 2%
- 웨이퍼 휨 < ± 20 um

Summary

- 국내 GaN RF 에피 기술 확보 및 에피 소재 공급망 구축 필요
- 한국나노기술원은 GaN RF 에피 소재 산학연 지원을 위한 기술 개발을 진행중
- 기판-소자 연계 산학연 공동 연구 및 협업 확대 필요

감사합니다

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홍익대 차호영 교수