SAND2016-9835C

Growth and Electrical Properties of AlGaN-based PN Diodes and High-Electron-Mobility Transistors


Veeco D-125 MOCVD system

Andrew Allerman, M. H. Crawford, A. M. Armstrong, A. G. Baca, J. R. Dickerson, M. P. King, R. J. Kaplar, and S.R. Lee

Sandia National Laboratories, Albuquerque, NM

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M. Smith, K. Cross, V. Abate and L. Alessi

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Outline

- Wide bandgap AlGaN alloys for power electronics
- PN diodes $Al_{0.3}Ga_{0.7}N$
  - Growth of thick, N- drift layers
  - Breakdown voltage and forward ON resistance
- Al-rich $Al_xGa_{1-x}N$ ($x > 0.7$) heterostructures for HEMTs
  - 2DEG formation (growth conditions, doping & structure)
  - Initial transistor characteristics
- Summary

Ultra-wide-bandgap semiconductors (UWBS, >4eV) for power electronics

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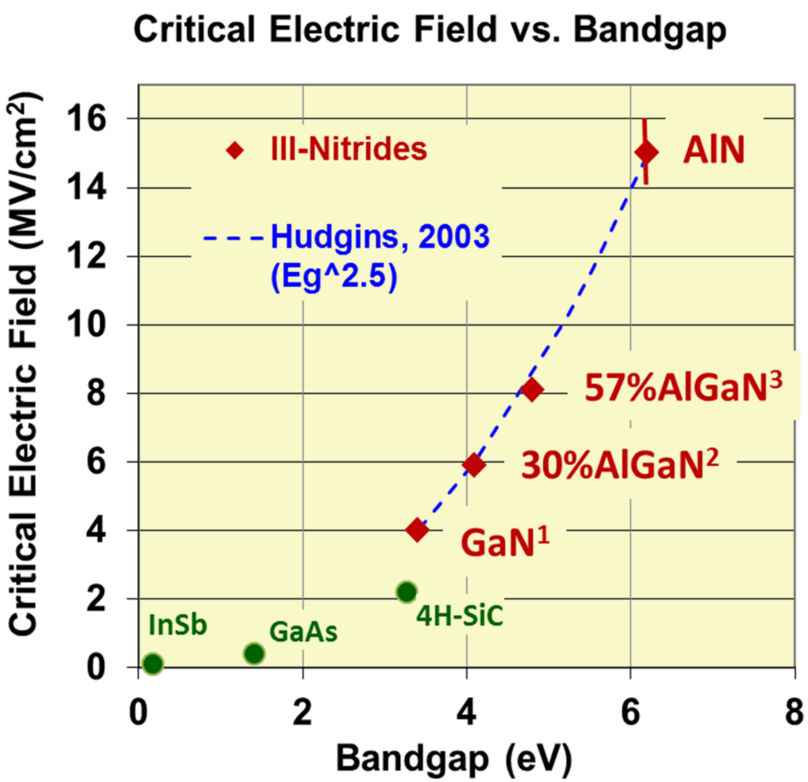
Critical Electric Field (MV/cm)

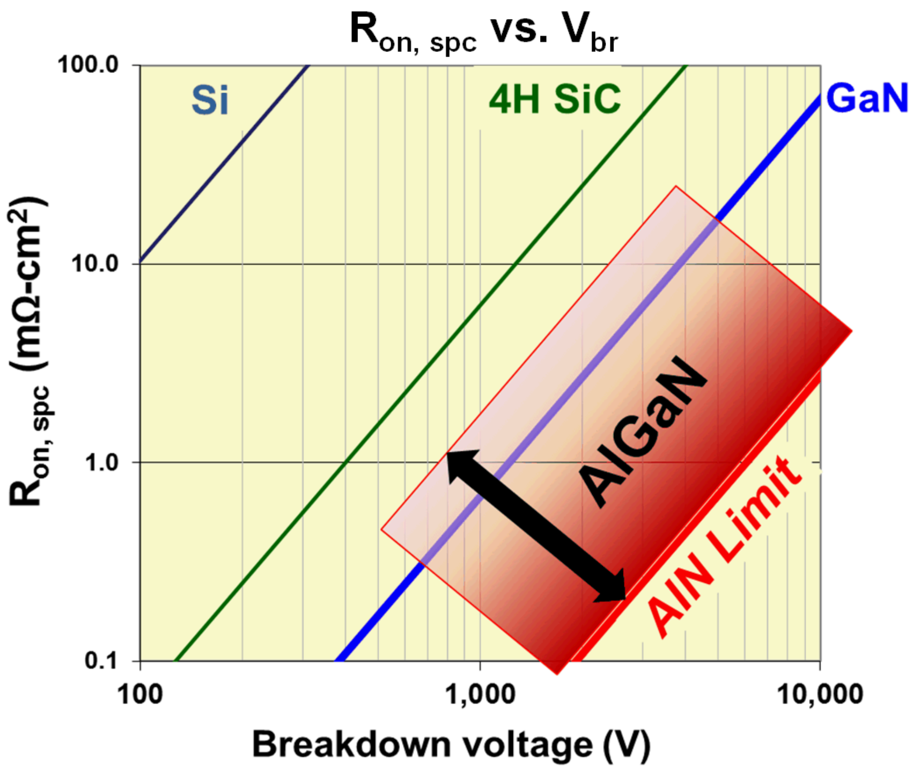
$$E_C \propto E_g^{2.5}$$ (Direct gap)



1-Armstrong, EL 2016, 2-Allerman, EL 2016, 3-Nisikawa, JpnJAP 2007

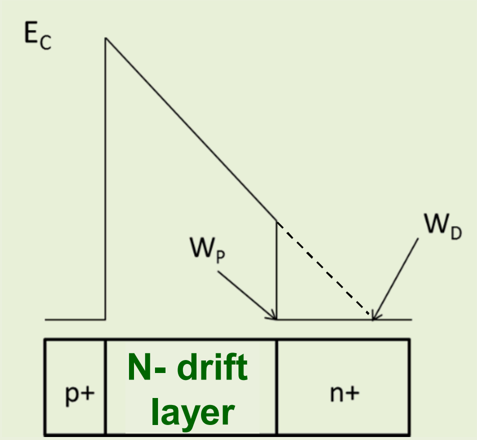
Unipolar Figure of Merit (vertical devices)

$$UFOM = \frac{V_{br}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_C^3 \propto E_g^{7.5}$$



Breakdown voltage of drift layer: doping and thickness

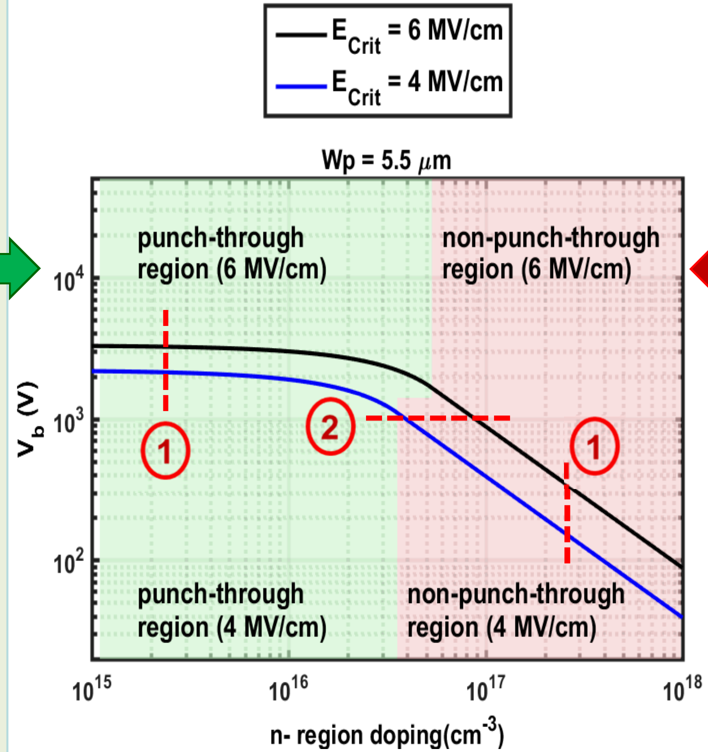
Punch-Through
$W_P < W_D$



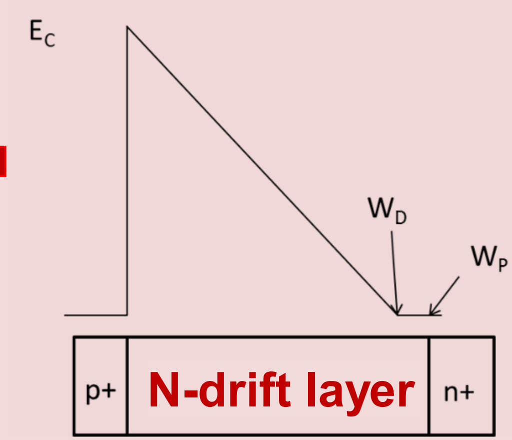
$$V_{br} = E_C W_P - \frac{qN_D W_P^2}{2\varepsilon}$$

- N_d is lower than optimal

➡ ***Thickness determines V_{br}***



Non-Punch-Through
$W_P \geq W_D$



$$V_{br} = \frac{\varepsilon E_C^2}{2qN_D}$$

- Drift layer is thicker than optimal

➡ ***N_d determines V_{br}***

Prior AlGaN PIN diode results (Nishikawa, NTT, 2007)

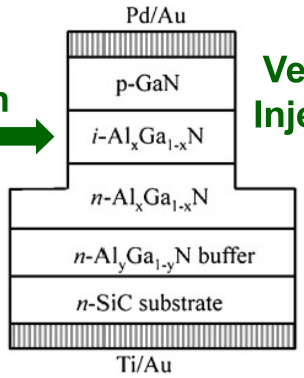
$Al_xGa_{1-x}N$ *Vertical* PN diode (0 < Xal < 0.57)

- Drift Layer: ~ 0.2 μm, N_o ~ $2x10^{16}$ cm^{-3}
- N-SiC substrates, $R_{on,sp}$ = 1.45 mΩ-cm^2 (X_{al}=0.22)

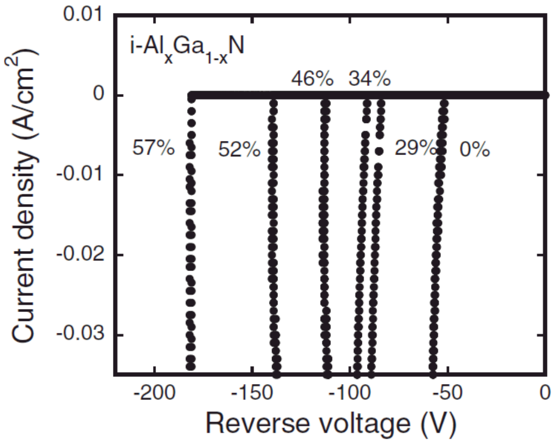
Drift region

Conducting SiC substrate

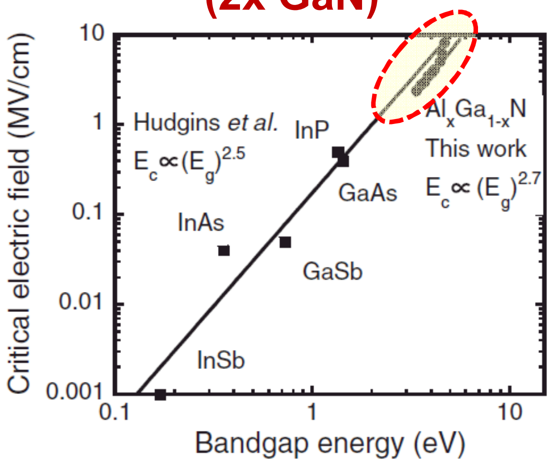
Vertical Injection



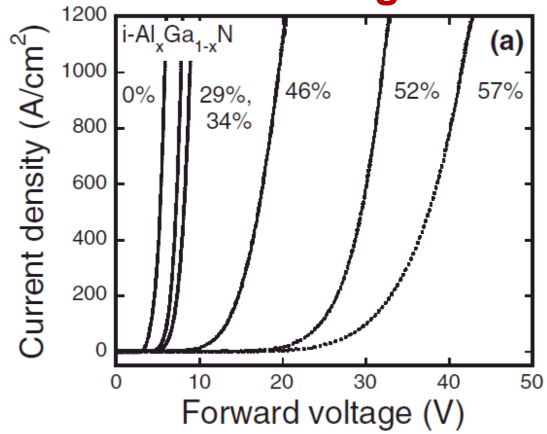
Reverse Breakdown < 200V



E_{crit} ~ 8 MV/cm (2x GaN)



Higher forward turn-on for increasing Al



➡ **Breakdown voltage increases with larger bandgap**

➡ **Critical electric field scales as $E_g{}^{2.7}$**

Control of N-type doping of drift region ($Al_{0.3}Ga_{0.7}N$)

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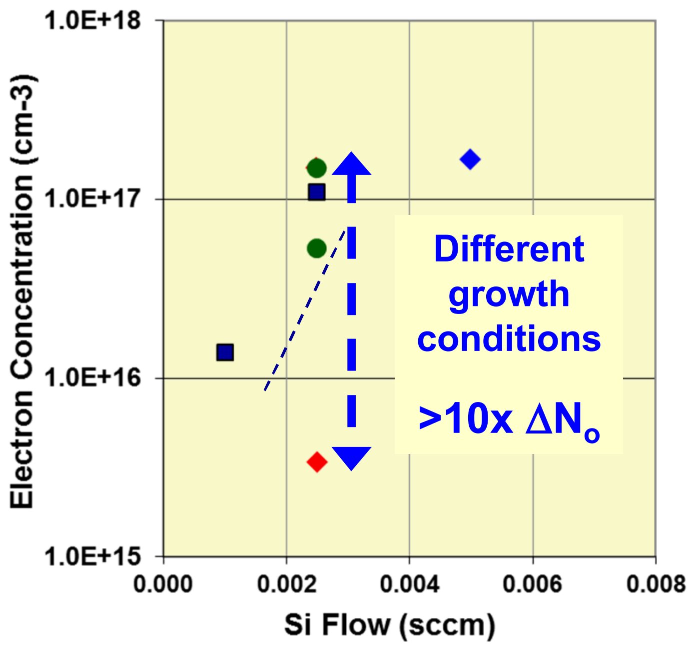
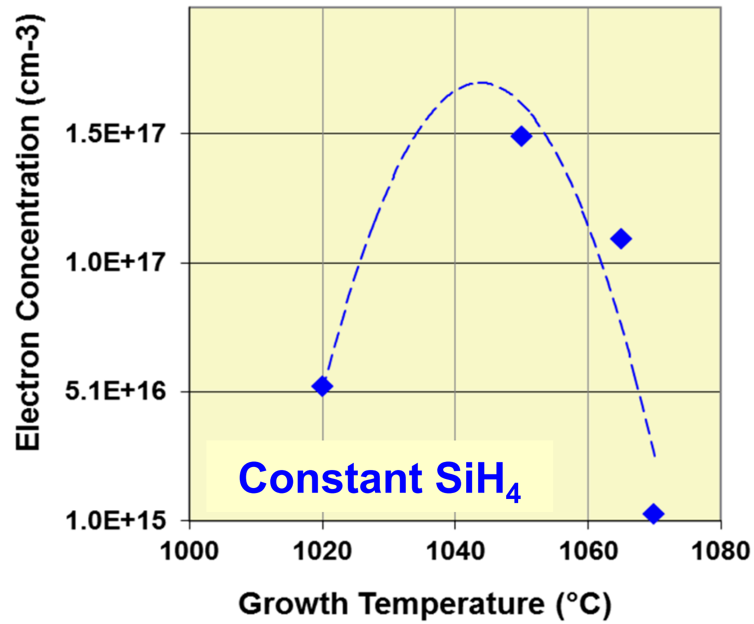
➡ *Si incorporation is linear in SiH_4 flow but…*

Electron concentration (hall) vs. SiH_4 flow (30%AlGaN)



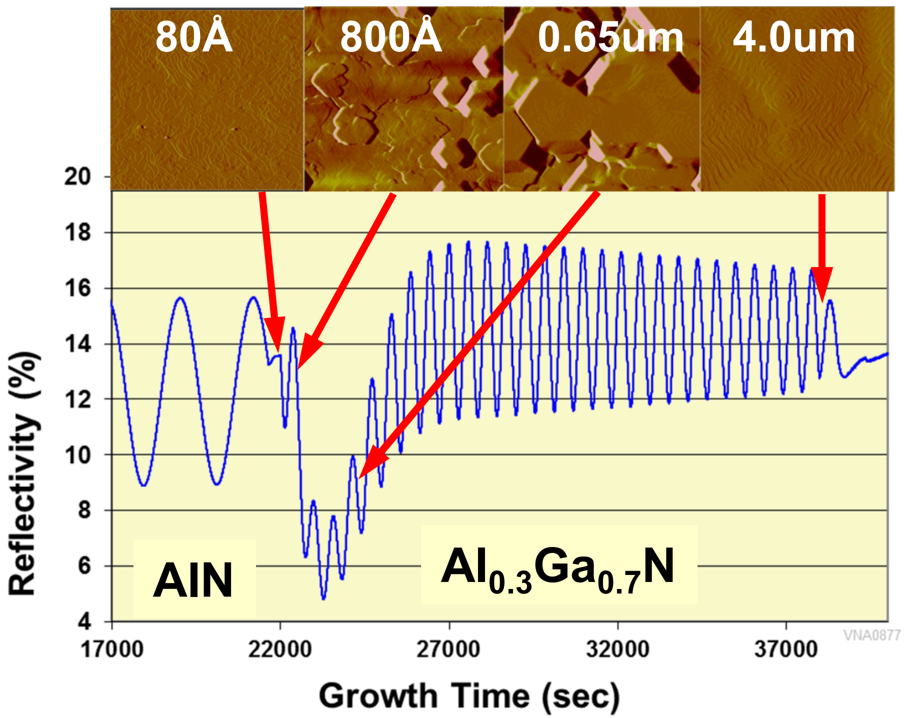
Electron concentration (hall) vs. growth temperature (30%AlGaN)



➡ *… electron concentration is highly dependent on growth condition (i.e. the density of compensating defects)*

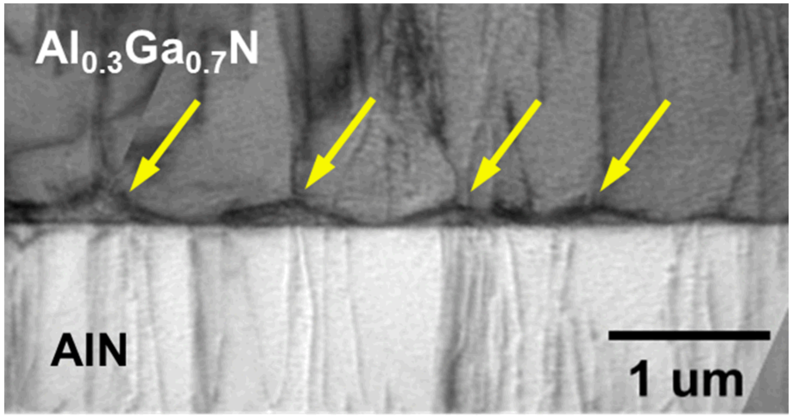
Relaxation and TDD reduction in $Al_{0.3}Ga_{0.7}N$ on AlN

In-situ Reflectance and AFM



- **Surface roughens (3D growth) and then planarization (2D growth)**
- **$Al_{0.3}Ga_{0.7}N$ layer is >80% relaxed, TDD ~ 2-4x10^9 cm^{-3}**

Cross-section TEM



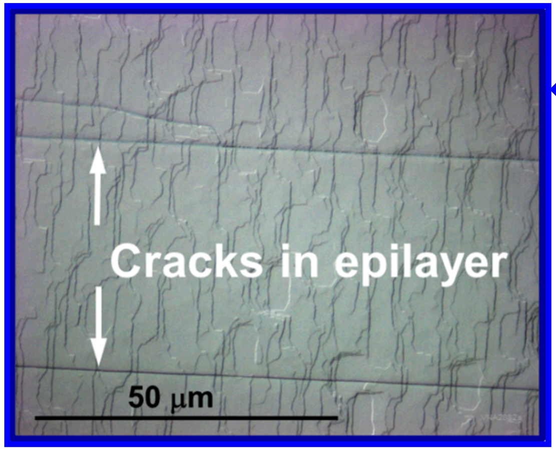
S. Lee, D. Follstaedt, J. Floro 2009

- **Strain is relieved by interfacial misfit dislocation networks with hexagonal boundaries**
- **Threading dislocations "bundle" into triangular features**

➡ ***2D to 3D to 2D growth relieves strain & lowers TDD***

Reduce cracking and bow by using 3x thicker sapphire

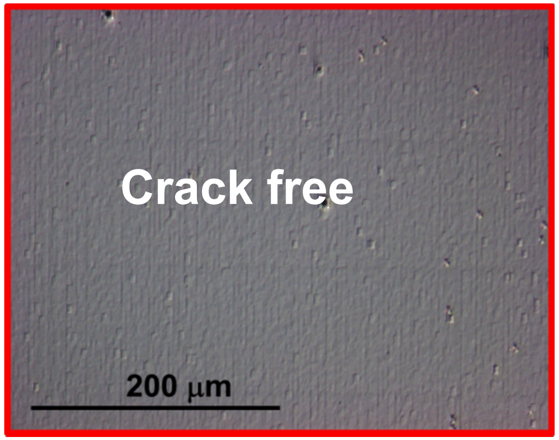
Optical Image of $Al_{0.3}Ga_{0.7}N$ surface



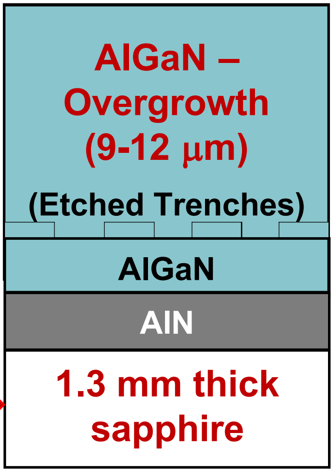
0.4 mm thick sapphire

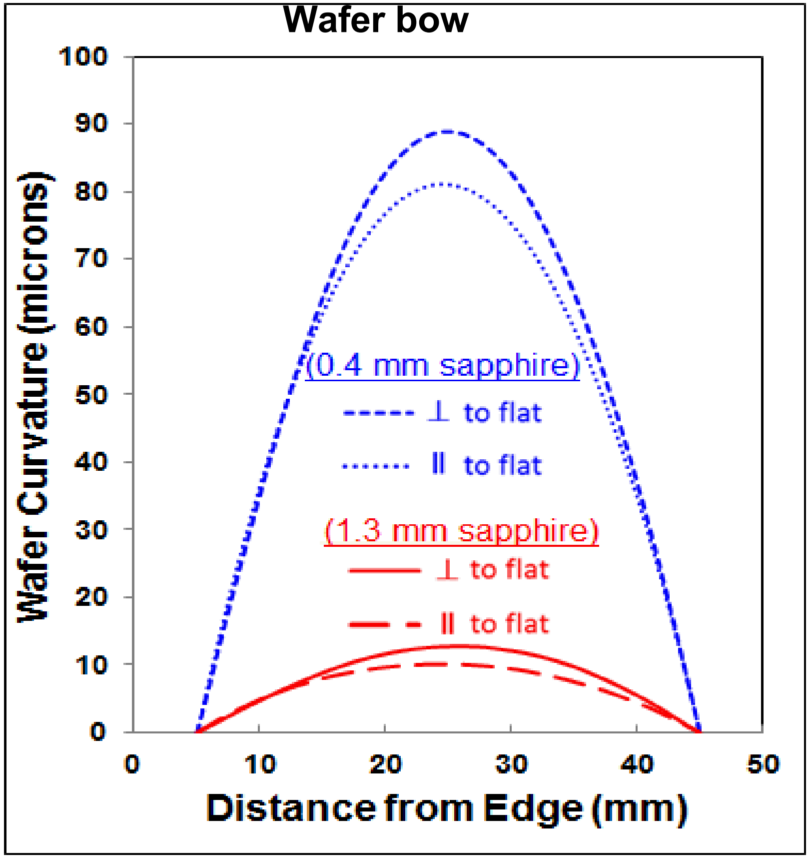
Cracking

& bowing



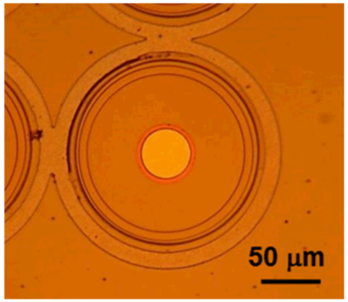
1.3 mm thick sapphire



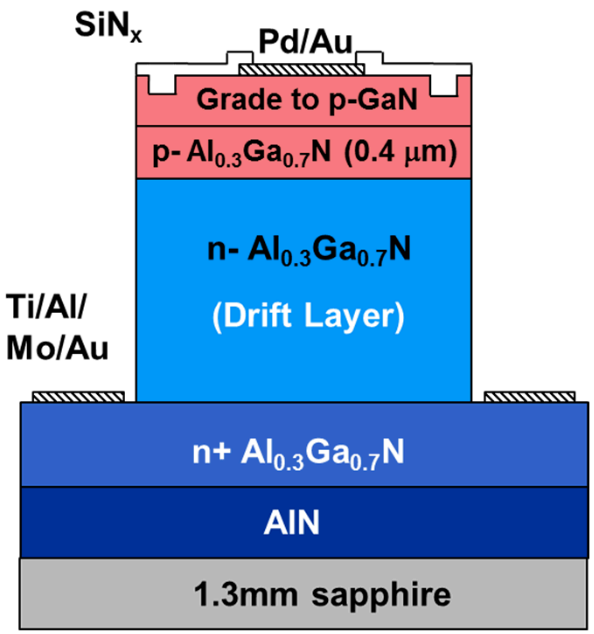


➡ *3x thicker sapphire reduces cracking & wafer bow*

$Al_{0.3}Ga_{0.7}N$ "Quasi-Vertical" PN diode on sapphire



Optical image of diode

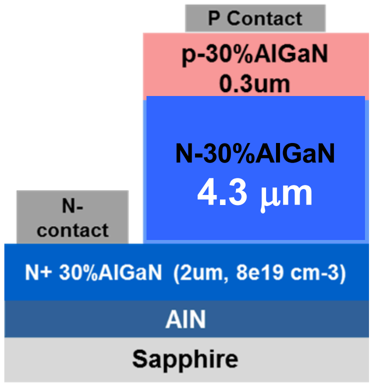


Quasi-Vertical PN diode structure

$Al_{0.3}Ga_{0.7}N$ PN diode design & fabrication

- **Implanted junction edge termination**
- **Mesa / p-metal: 150 / 50 µm**
- ***Drift Layer: 4.3, 5.5, 7.5, 9, 11 and 15.5 µm***
- **Crack-free (except 15.5 µm drift layer)**
- **Total epi thickness: 7 – 18, 22 µm**
- **Drift layer doping: mid 10^{15} – mid 10^{16} cm^{-3}**
  Mobility: 150 cm^2/Vs
- **Sheet resistance: 40-80 Ω/sqr.**
- ***Threading dislocation density: 1-3 x 10^9 cm^{-2}***

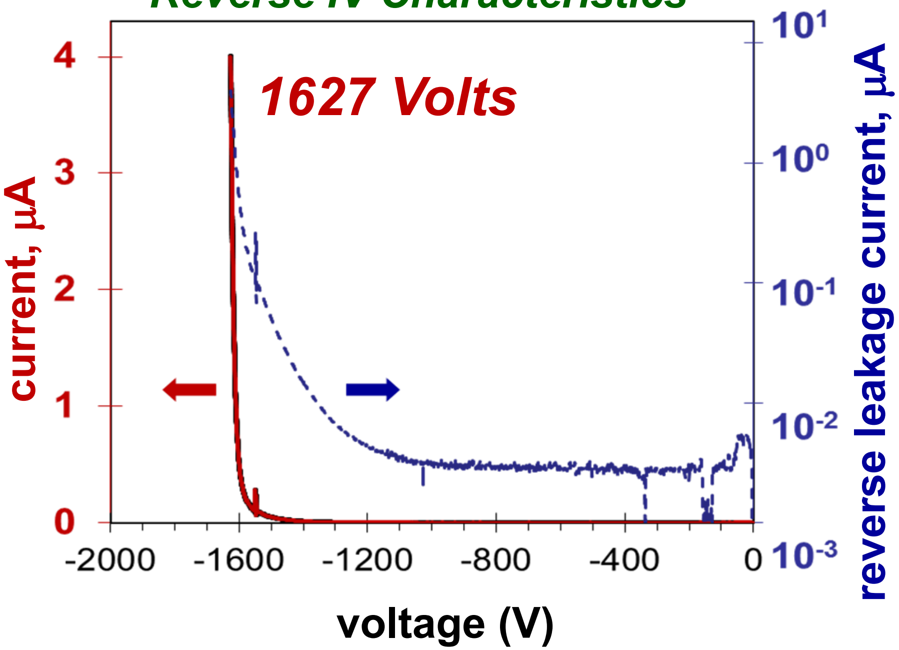
$Al_{0.3}Ga_{0.7}N$ "Quasi-Vertical" PN diode on sapphire



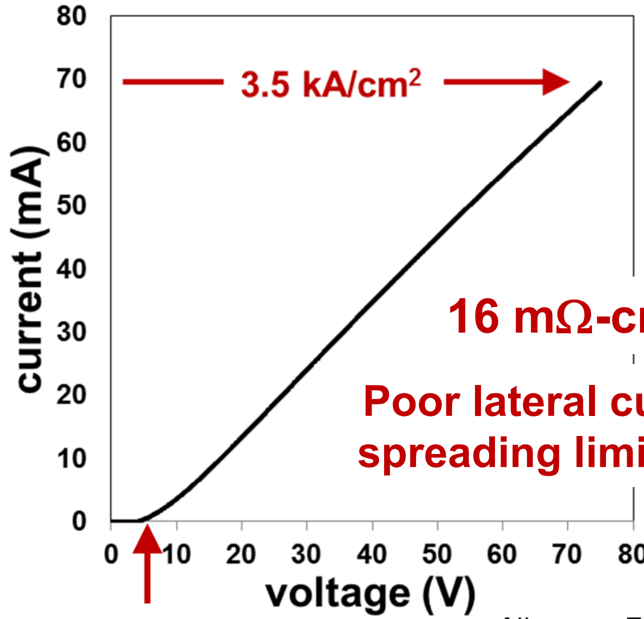
- **Drift layer: 4.3 µm, TDD ~ 1-2e9 cm^{-2}**
  N_o~ 5-7e16 cm^{-2}, µ ~ 150 cm^2/Vs,

➡ ***V_{br} > 1600 Volts***
➡ **$I_{reverse}$ < 3nA (to 1200V)**
➡ **E_C ~ 5.9 MV/cm**
➡ **$V_{br}^2/R_{on,sp}$ = 150 MW/cm^2**

Reverse IV Characteristics



Forward IV Characteristics



Allerman, Elec. Lett. 2016

$Al_{0.3}Ga_{0.7}N$ "Quasi-Vertical" PN diode – thicker drift layers

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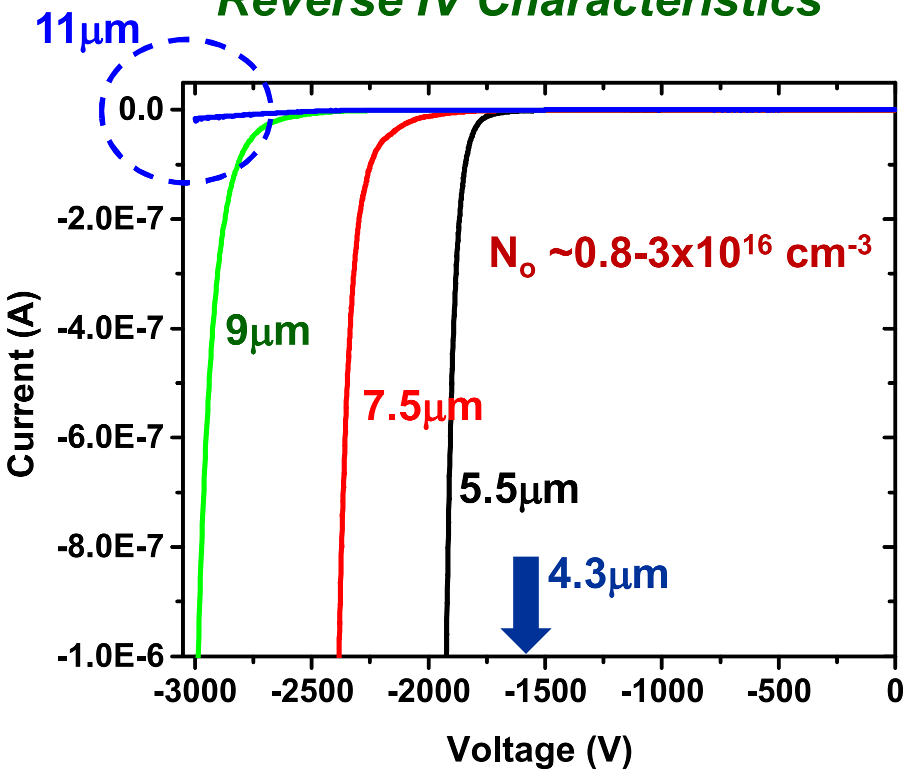
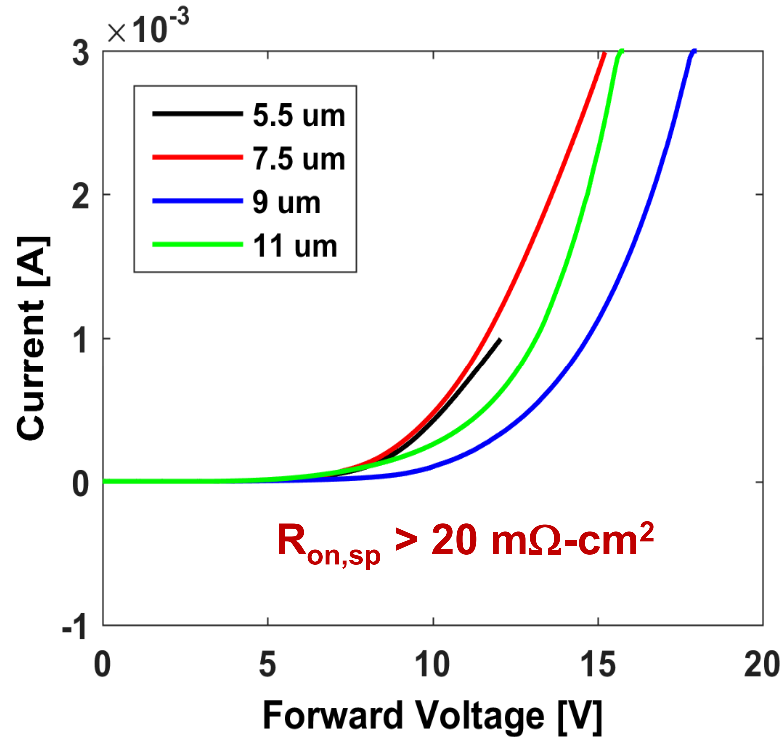
Reverse IV Characteristics



Forward IV Characteristics



- Breakdown voltages ~ 3000V (Drift: 9 &11μm)
- V_{br} increases with drift layer thickness for N_o

Breakdown voltages reported for III-Nitride PN diodes

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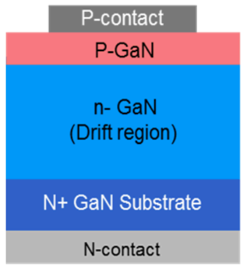
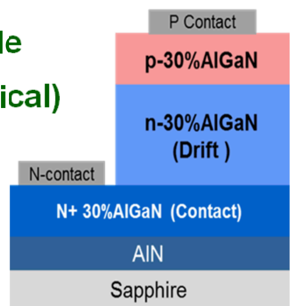
GaN diode (vertical)



AlGaN diode (Quasi-vertical)



III-N PN diodes with > 3 kV breakdown voltage

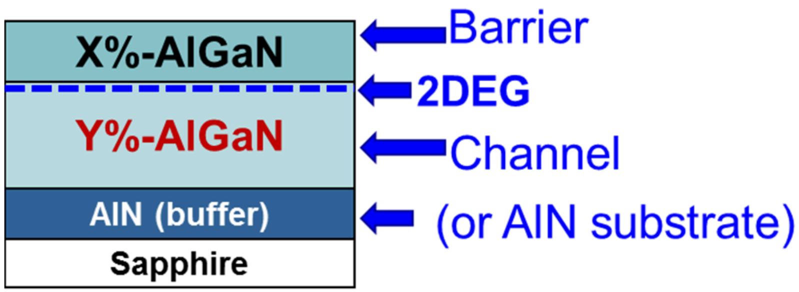
Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7	2/9/16e15	33	GaN	Hosei Univ.	EDL 36p1180_2015
4.0	2-5e15	40	GaN	Avogy	EDL 36p1073_2015
3.9	3e15	30	GaN	Sandia	EL 52p1170_2016
3.7	5e15	>30	GaN	Avogy	EDL 35p247_2014
3.48	1/3/12e15	32	GaN	Hosei Univ.	IEDM15-237_2015
>3	**0.8-3e16**	**11**	**30%-AGaN**	Sandia	This work
3.0	**0.8-3e16**	**9**	**30%-AGaN**	Sandia	This work
3.0	1/10e15	20	GaN	Hitachi	Jpn J Appl Phys 52 p028007_2013

Advantages of wide-bandgap III-Nitride

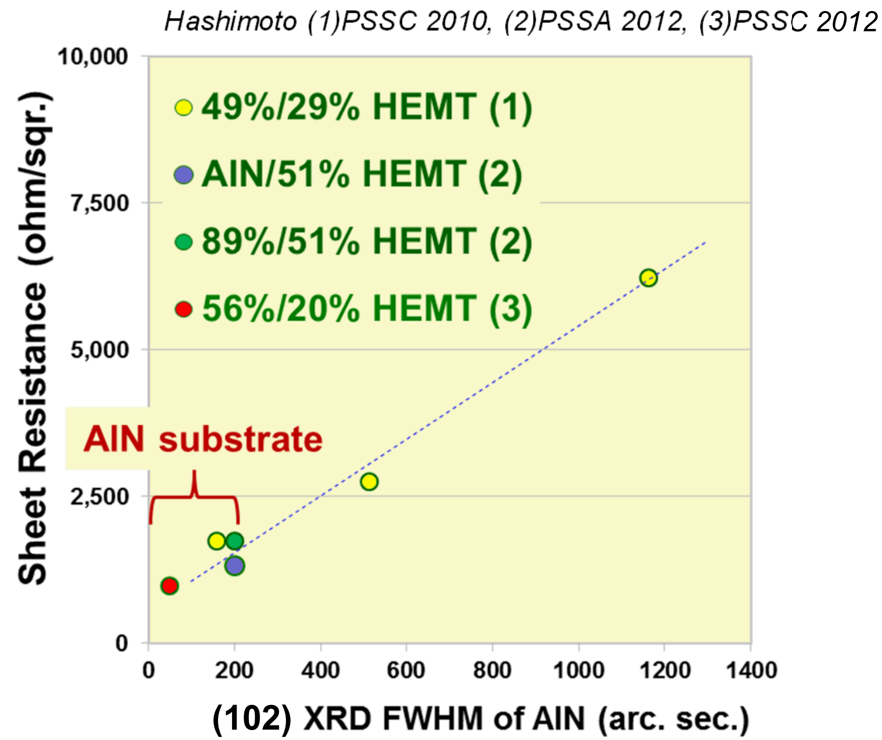
	GaN	$Al_{0.3}Ga_{0.7}N$	
N_o (cm^{-3})	low e15	low e16	] ← Larger E_c (larger E_g)
Drift (μm)	20-30	~10	]
TDD (cm^{-2})	≤ 1e6	low 1e9	← ??

Al-rich AGaN heterostructures and 2DEG formation

Typical heterostructure



Sheet Resistance vs. Dislocation Density



Al-rich AlGaN Heterostructures

- N_s: 0.2 – 2.5 x 10^{13} cm^{-2}
- Mobility: 140-170 (259, X_{al}=0.2) cm^2/Vs
- No 2DEG reported for channel X_{al} > 0.6
- Ohmic contacts are difficult
- Low threading dislocation density (TDD) is critical
- *AlN Substrates are expensive & small*

Q: Is there an alternative to AlN substrates?

Why higher Al compositions for AlGaN heterostructures?

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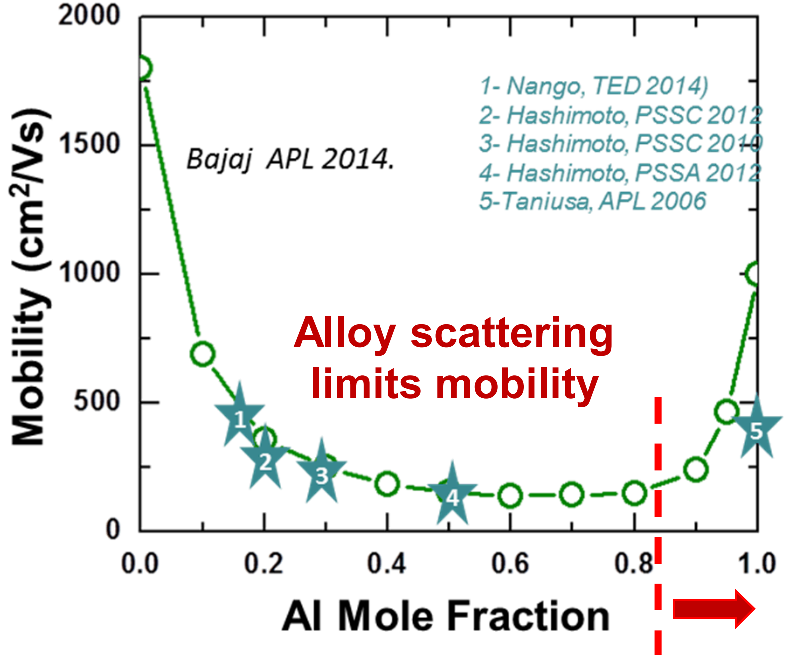
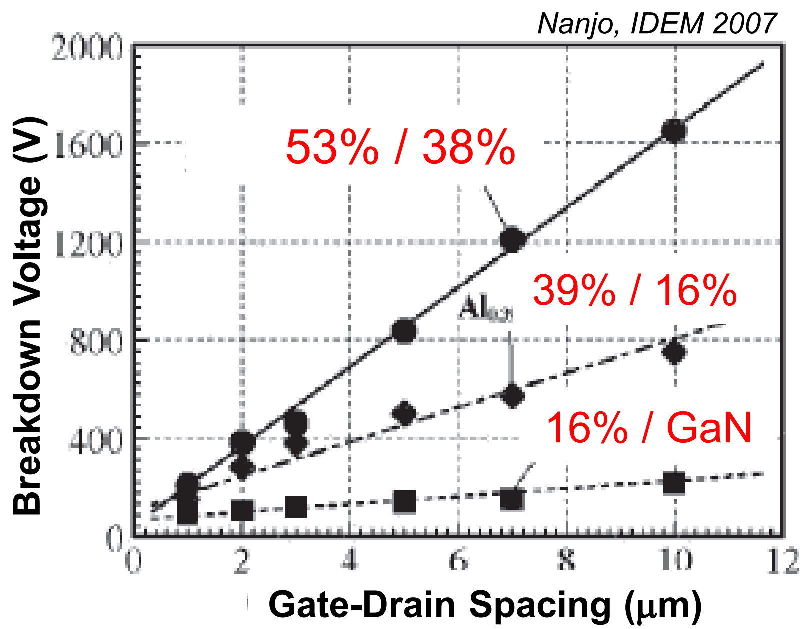
Calculated Electron Mobility vs. AlGaN Channel Composition



Breakdown voltage of AlGaN HEMTs vs. G-D spacing



Higher Al compositions:
➡ ***higher mobility is predicted***

Higher Al compositions:
➡ ***higher breakdown voltages***

SNL AlGaN overgrowth of patterned AlGaN templates

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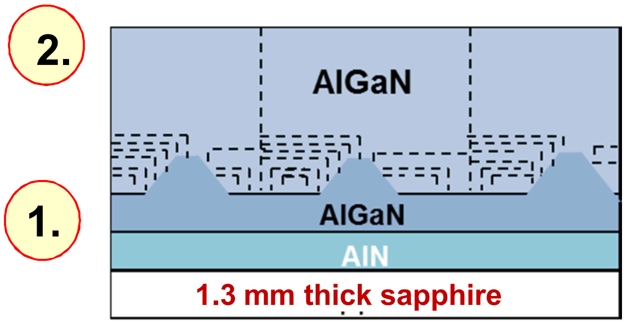
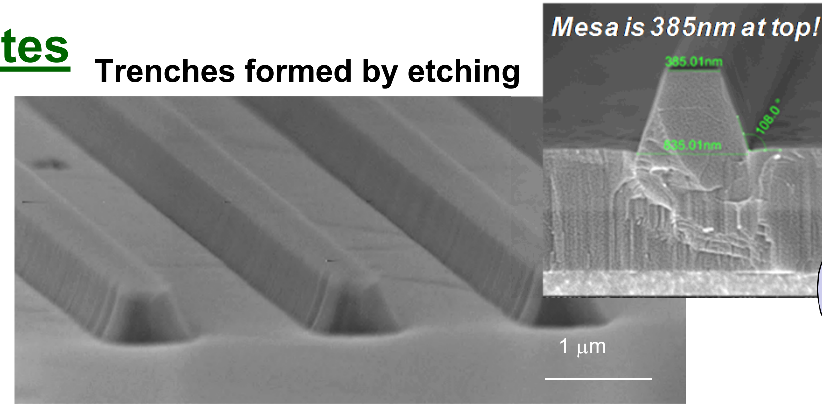
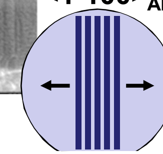
AlGaN Growth on Patterned Templates

AlGaN with reduced dislocations



Trenches formed by etching



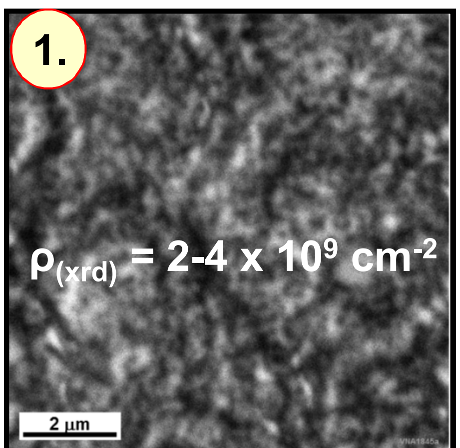


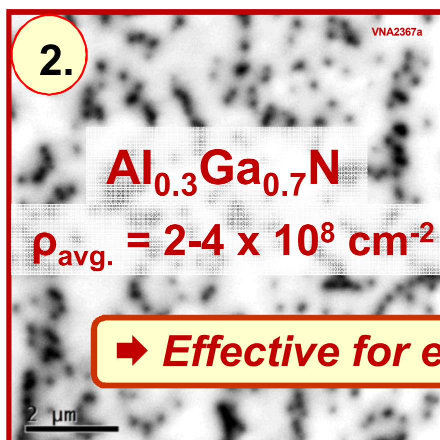
Trench Alignment

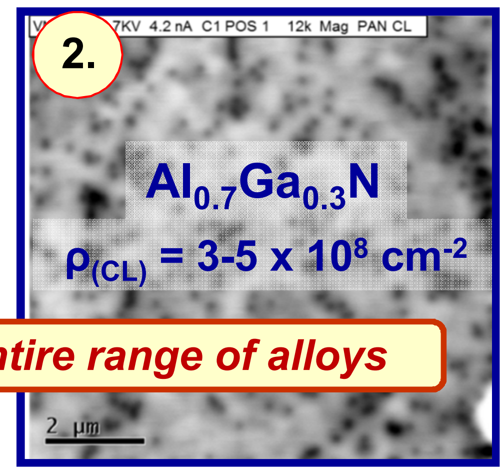
➡ ***Sub-micron features are key for uniform reduction of dislocations***

Allerman et. al., JCG 2014

Cathodoluminescence







➡ ***Effective for entire range of alloys***

10-20X reduction

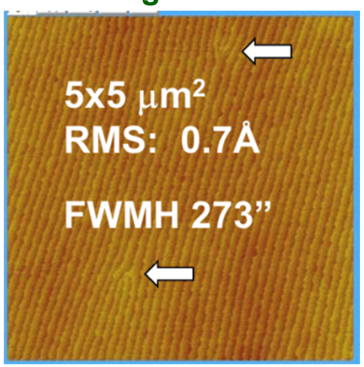
10-15x reduction

AlN overgrowth process (Allerman, JCG 2014)

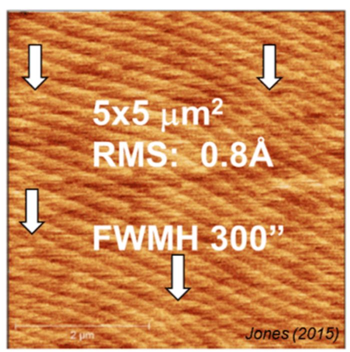
Etched Pattern

- 1x1 (mesa, trench, µm)
- 0.2 – 0.7 µm etch depth
- Overgrowth @ 1100°C

SNL overgrowth 1100°C



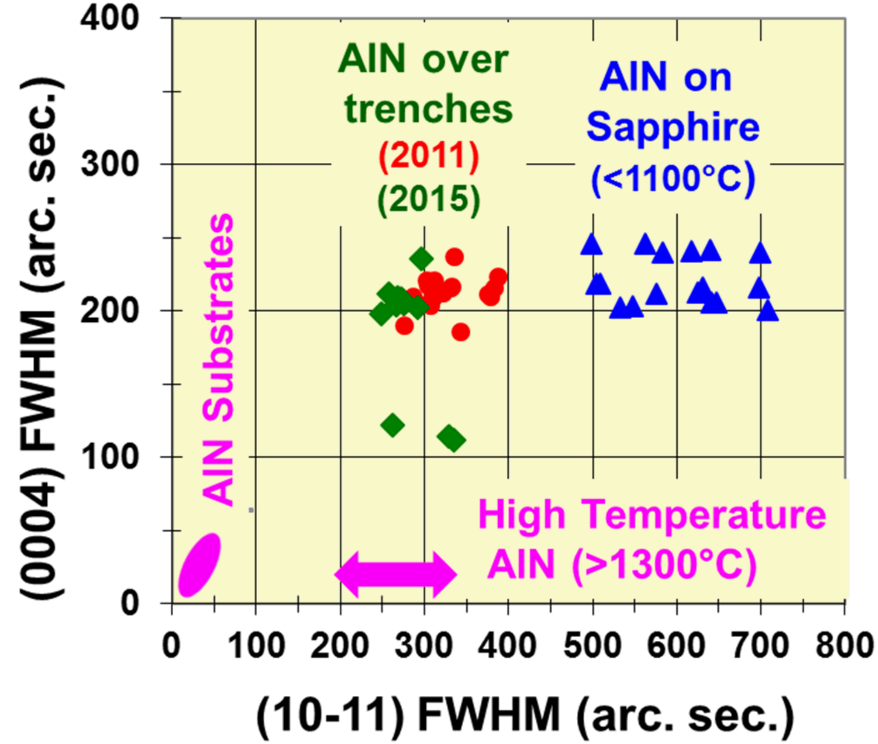
High Temp. AlN



Jones, 2015

➡ **SNL overgrowth @ 1100°C produces AlN similar to HT-AlN**

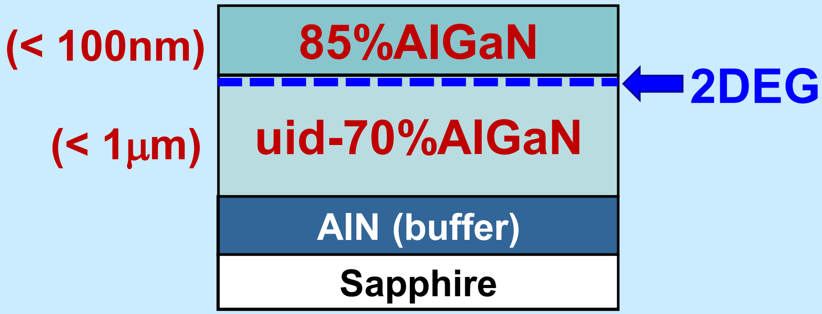
X-ray diffraction peak – width of AlN epilayers



- AlN overgrowth: TDD ~3-5x10^8 cm^{-2}

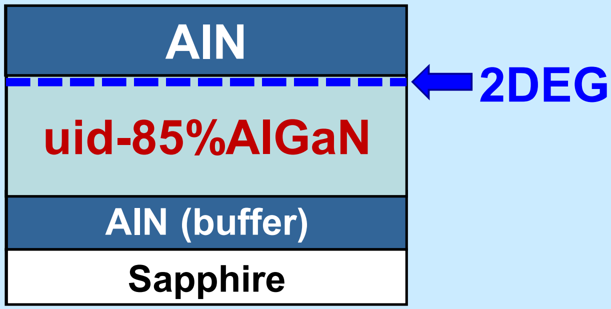
Al-rich AlGaN HEMT heterostructures

85% / 70% AlGaN HEMT



- $Al_{0.85}Ga_{0.15}N$ dopes N-type
- Expect lower mobility with lower Al compositions
- Structure could be grown pseudomorphic to AlN substrates

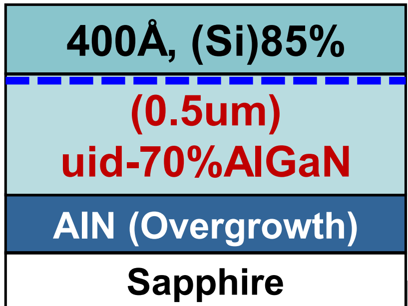
AlN / 85% AlGaN HEMT

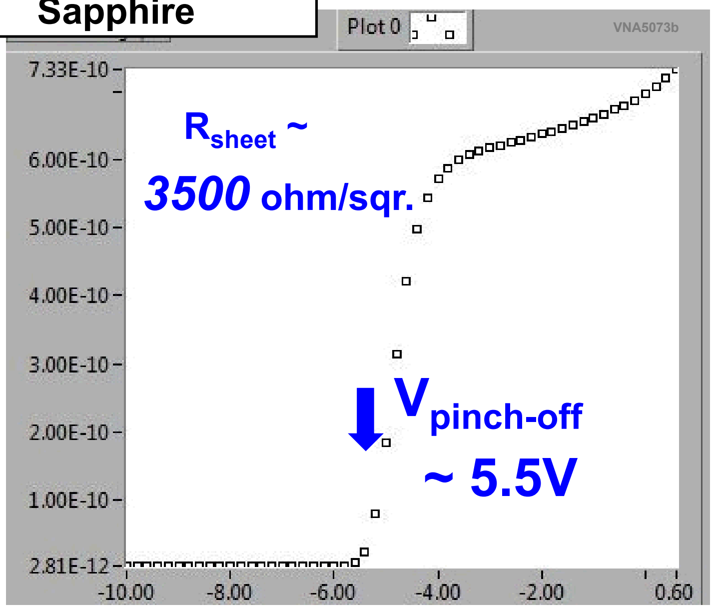


- AlN is hard to dope N-type
- Expect higher mobility with higher Al composition
- Well matched for pseudomorphic growth on AlN substrates

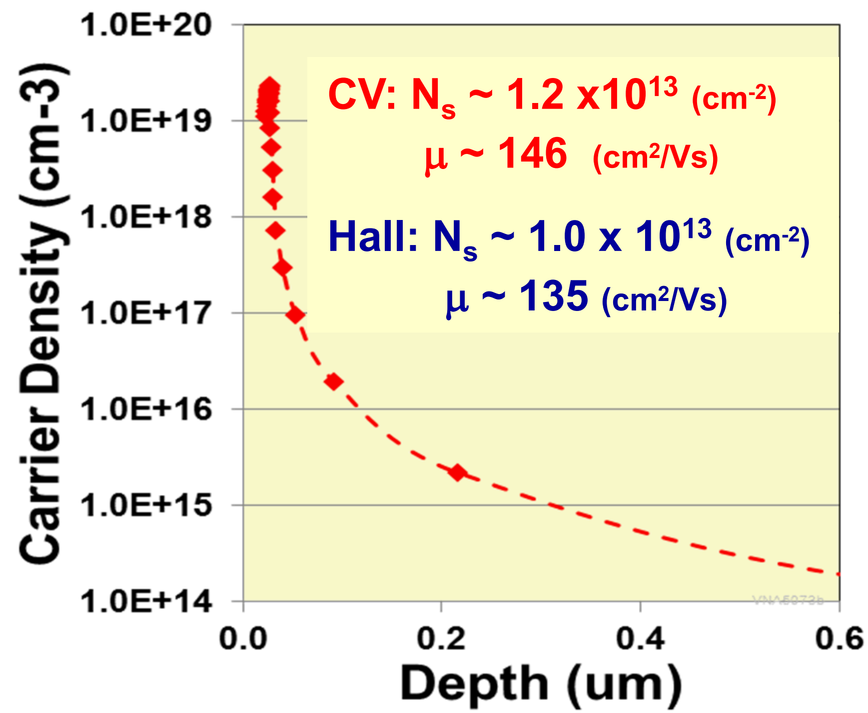
CV of 85% / 70% AlGaN heterostructure

CV of 85% / 70%AlGaN MODFET





Carrier Density Profile (CV)

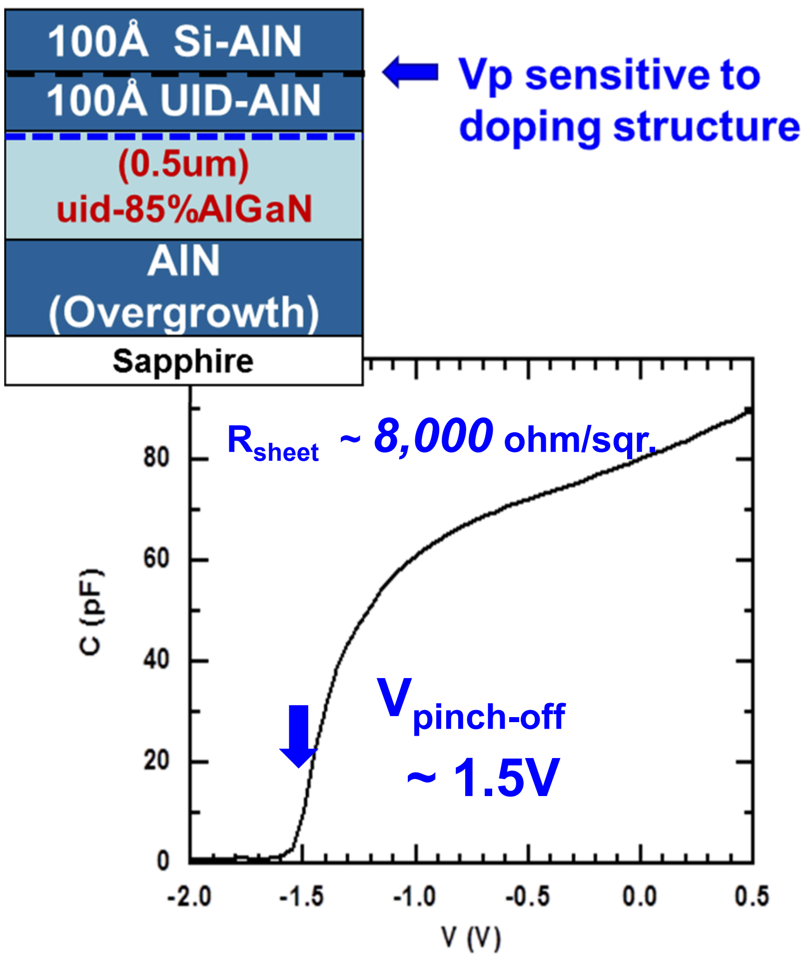


- N_s & μ are similar to HEMTs with lower Al channels

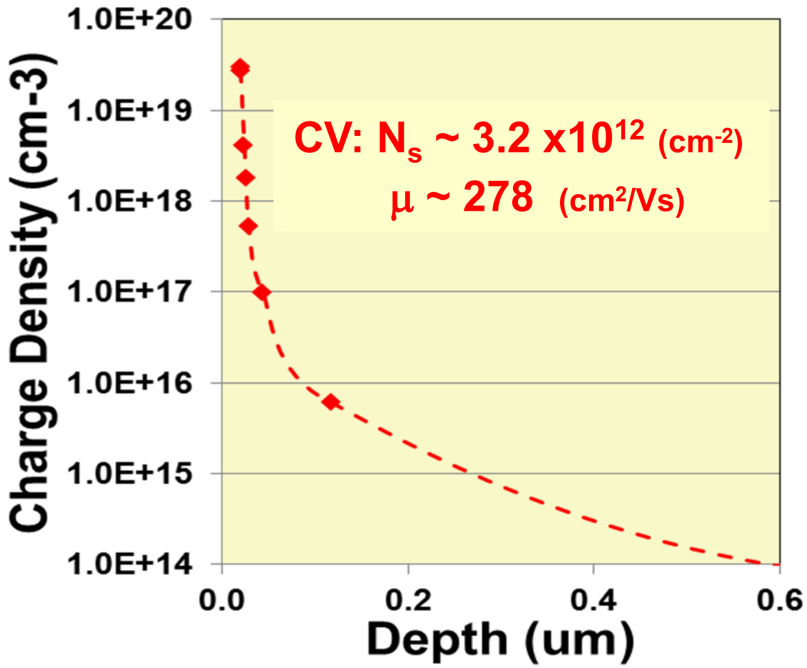
➡ Demonstration of 2DEG in $Al_xGa_{1-x}N$ channel for x > 0.6

CV of AlN / 85% AlGaN heterostructure

CV of AlN / 85%AlGaN MODFET



Carrier Density Profile (CV)



- No indication of parasitic channel
- *Mobility is notably higher*

➡ 2DEG can be formed over the full range of compositions

Si-doped and UID-barrier of 85% / 70% AlGaN heterostructure

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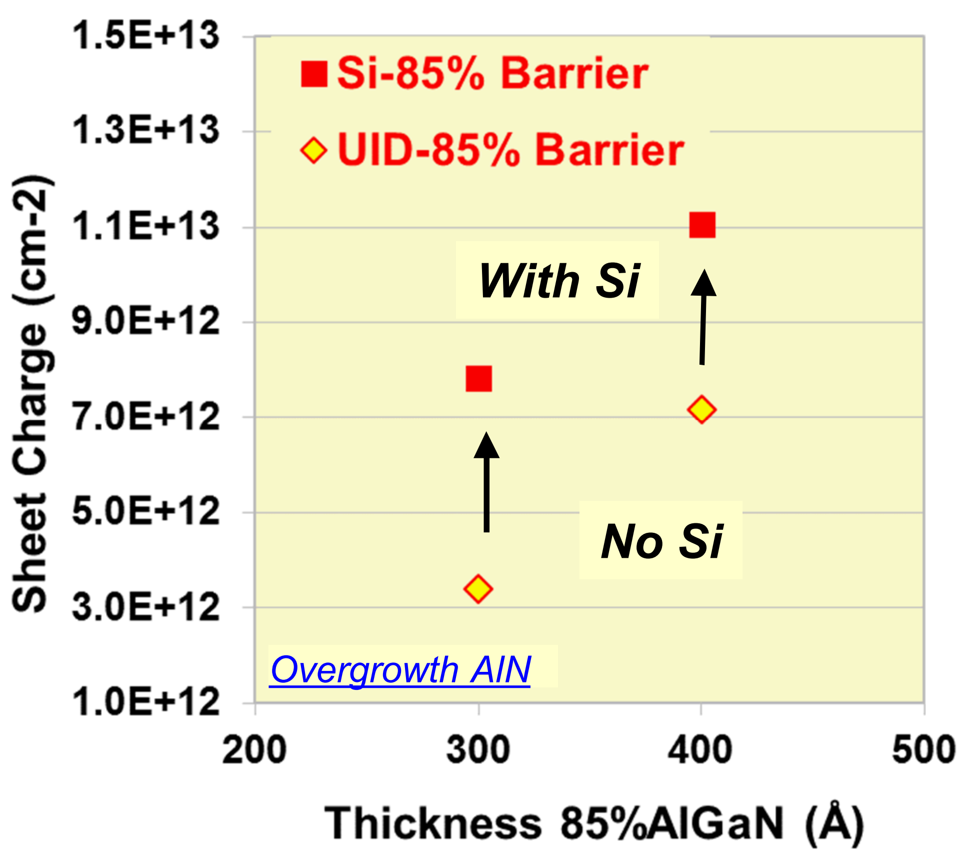
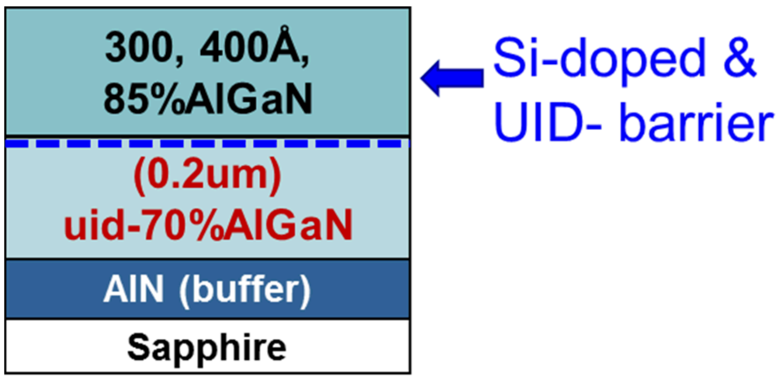
V(pinch-off) with & without Si doping of 85% Barrier



85% / 70% HEMT structure



- 2DEG formation by polarization fields (No Si)
- Si adds charge to the channel

Si-doped and UID-barrier of AlN / 85% AlGaN heterostructure

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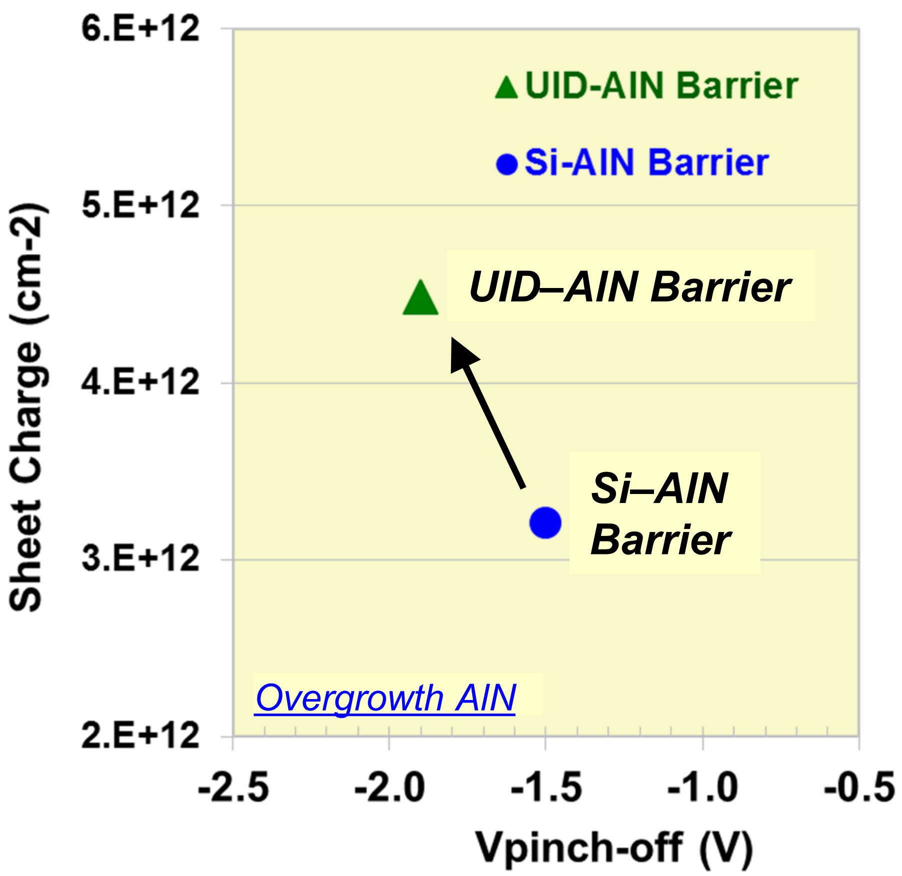
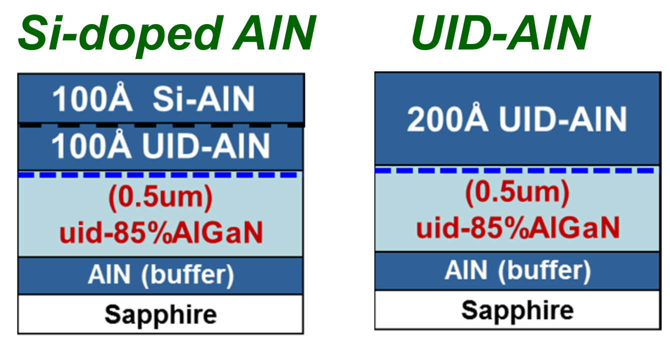
Sheet Charge vs. Vpinch-off with & without Doping of AlN Barrier





Si-doped vs. UID- AlN barrier

- **2DEG formation is very sensitive to Si-doping of AlN barrier.**
- **Sheet charge is higher w/o Si-doping**
- **2DEG formed by polarization fields (NO Si doping).**
- **Formation of compensating defects in Si-AlN reduce sheet charge.**

Pinch-off voltage and sheet charge with barrier thickness

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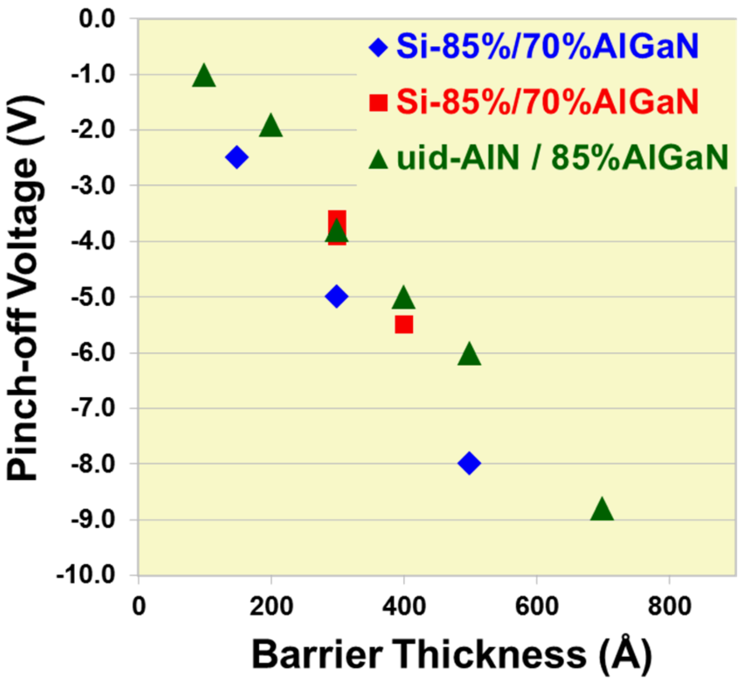
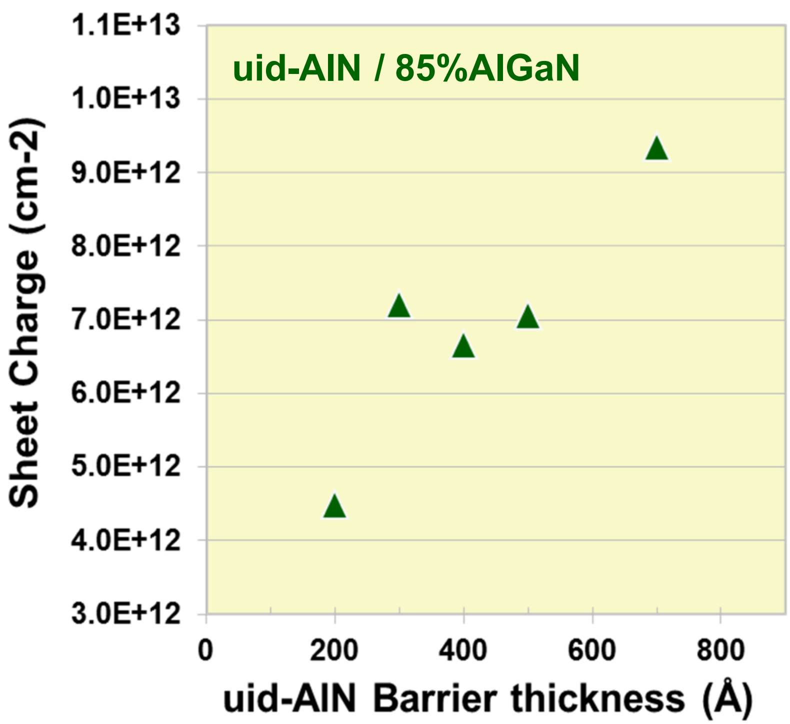
V(pinch-off) vs. UID-AlN Barrier Thickness



- **Pinch-off voltage can be controlled with barrier thickness.**
- **No 2DEG with 1000Å barrier**

Sheet Charge vs. UID-AlN Barrier Thickness



- **N_s approaching 10^{13} (cm^{-2})**
- **Mobility: 157 – 289 (cm^2/Vs)**

Pinch-off voltage and sheet charge of 85% / 70% AlGaN heterostructure vs. TDD

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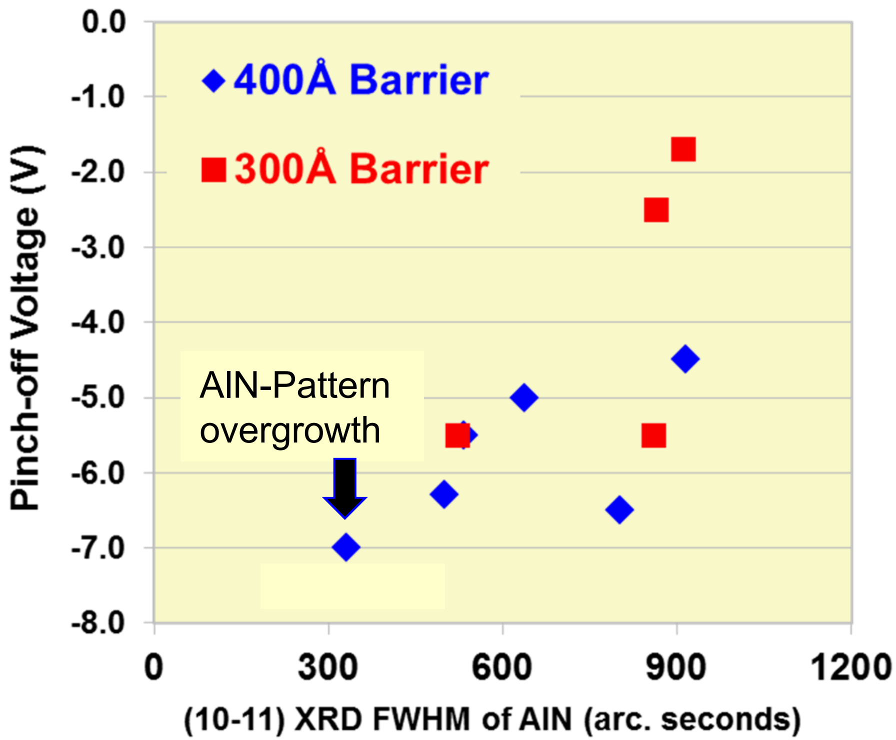
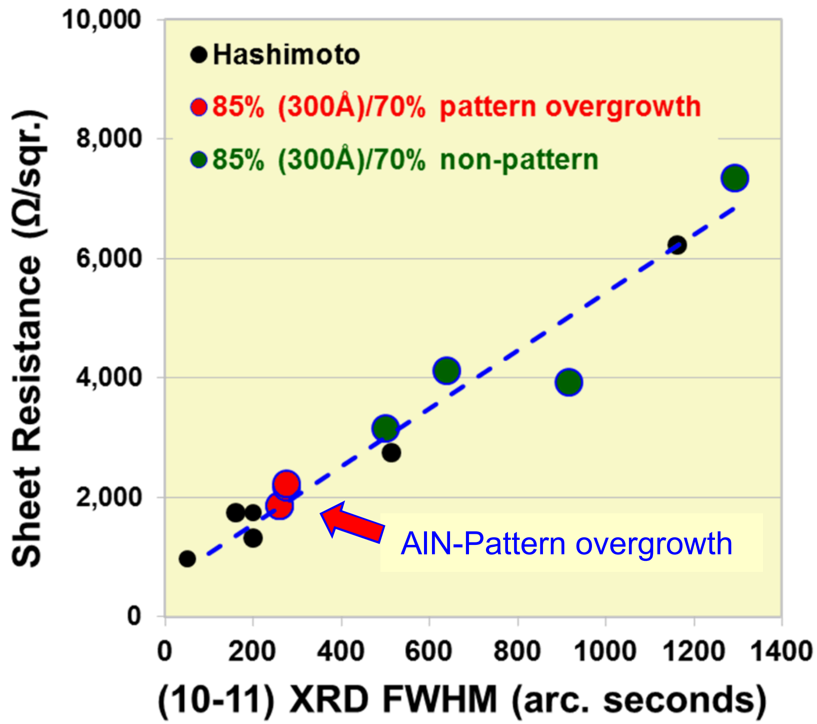
V(pinch-off) vs. TDD of AlN



Sheet Resistance (R_s) vs. TDD of AlN



➡ **Pinch-off voltage and sheet resistance depend on *dislocation density***

HEMT device from an AlN / 85%AlGaN heterostructure

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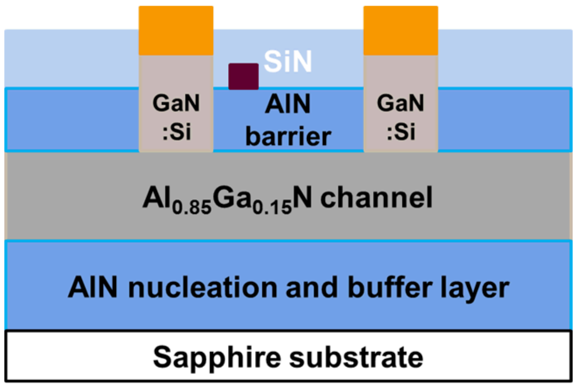
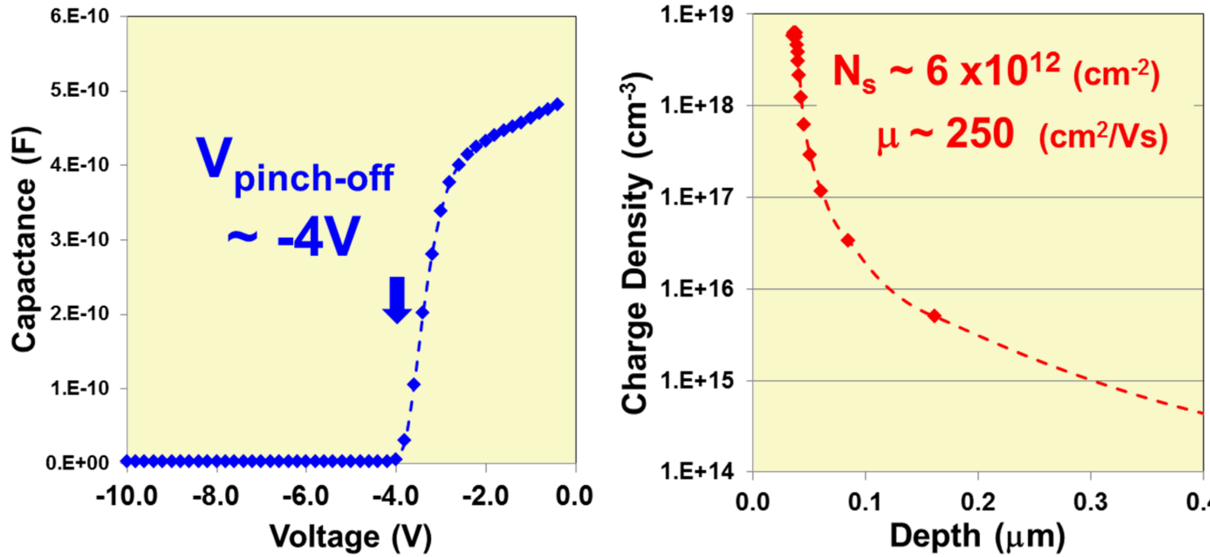
AlN / 85%HEMT structure



CV Characterization



- uid-AlN (475 Å) / 85%AlGaN (0.4 μm) heterostructure
- Gate-Drain spacing: 10 μm
- Regrown contacts (Si-GaN)

- Sheet resistance: 4200 ohm/sqr.
- Pinch-off voltage: -4 V
- Sheet charge density: 6×10^{12} cm^{-2}
- Inferred mobility: 250 cm^2/Vs

HEMT characteristics based on an AlN – $Al_{0.85}Ga_{0.15}N$ heterostructure

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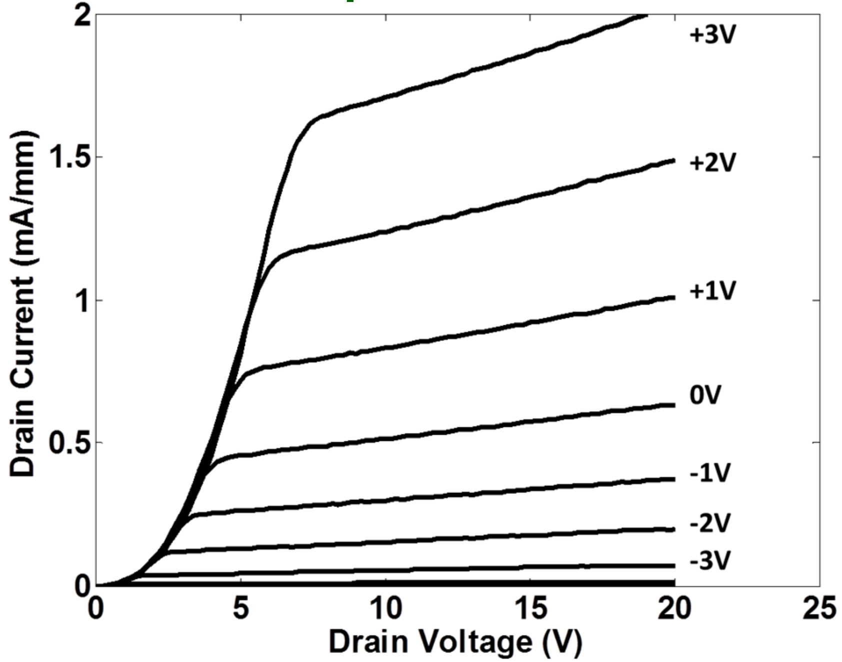
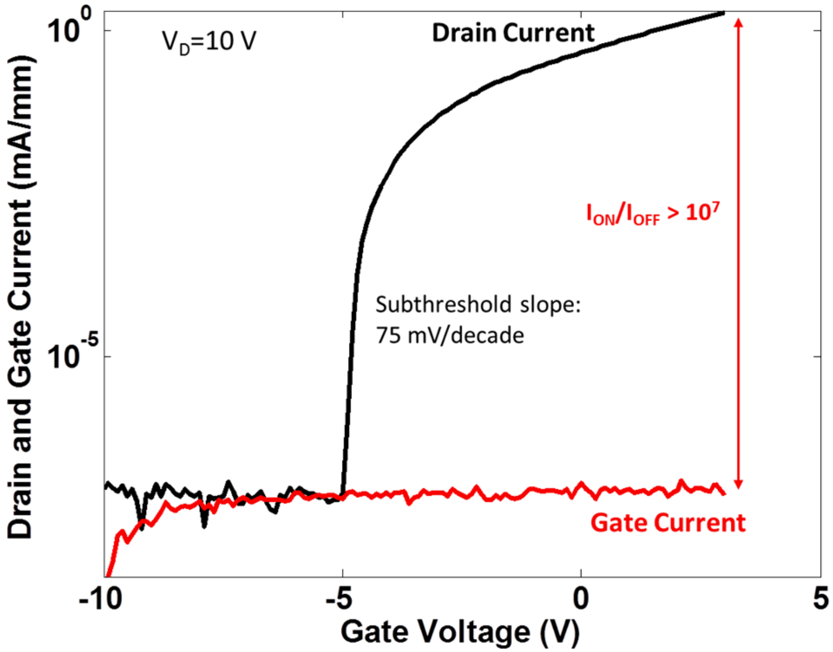
FET Operation



On/Off State Characteristics



- **Good pinch-off (-4.5V)**
- **Knee voltage linear with gate voltage**
- **Low drain current**
- **Contacts are not ohmic**

- **Low drain and gate leakage current**
- **Sub-threshold slope: 75mV/decade**
- **I_{ON}/I_{OFF} ratio > 10^7**
- **$V_{breakdown}$ = 810 V (no field plate)**

Summary

- **Quasi-vertical $Al_{0.3}Ga_{0.7}N$ PIN diodes**
  - Breakdown voltage of > 3000V, (E_c ~ 5.9 MV/cm, drift layer: 11μm)
  - Low reverse leakage current (few nA) with TDD ~ 1-2e9 cm^{-2}
  - High ON resistance (>20 mΩ-cm^2) due to poor lateral current spreading
- **2DEG formation in high Al (X_{al} > 70%) AlGaN heterostructures**
  - With and without Si doping of barrier layer
  - Mobility 150-300 cm^2/Vs, N_s ~ $1x10^{13}$ cm^{-2}
  - Similar sheet resistances AlN and sapphire substrates
- **Demonstrated AlGaN-based HEMT operation with largest bandgap**
  - Low drain & gate leakage, I_{ON}/I_{OFF} ratio > 10^7, V_b = 810 V (no field plate)
  - Low current due to rectifying contacts