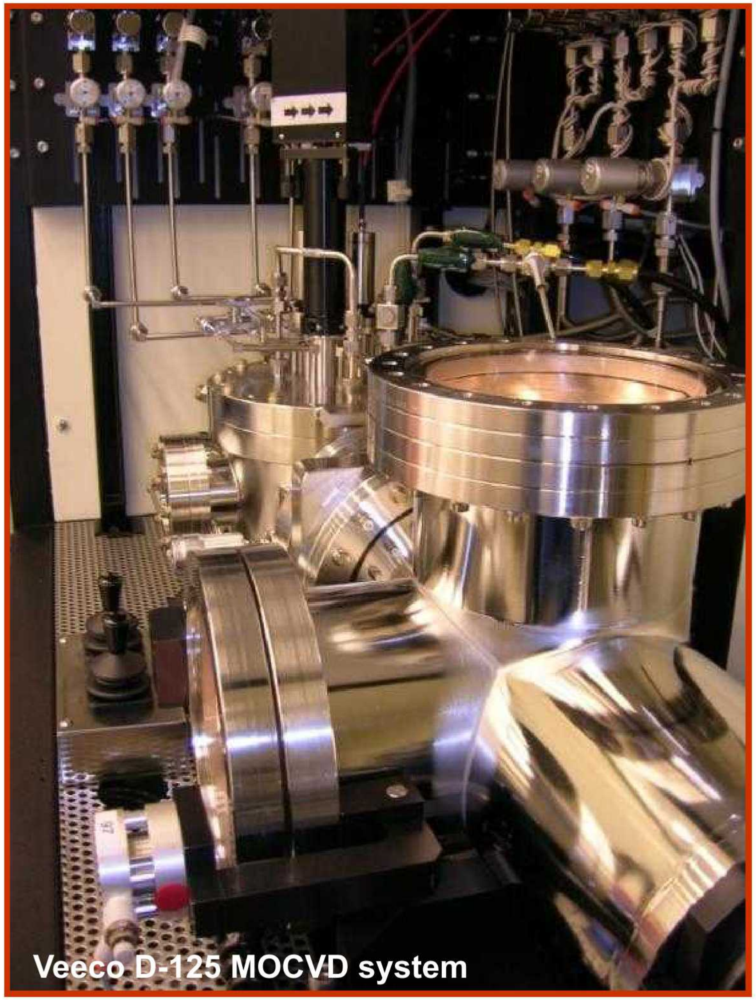
SAND2019-5382PE



Veeco D-125 MOCVD system

MOCVD Growth of AlGaN Alloys for Power Transistors

Andrew Allerman, M. Crawford, A. Armstrong, G. Pickrell, R. Kaplar, A. G. Baca, B.A. Klein, J. R. Dickerson, S. R. Lee, V. M. Abate, M. L. Smith and C. E. Glaser

Sandia National Laboratories, Albuquerque, NM

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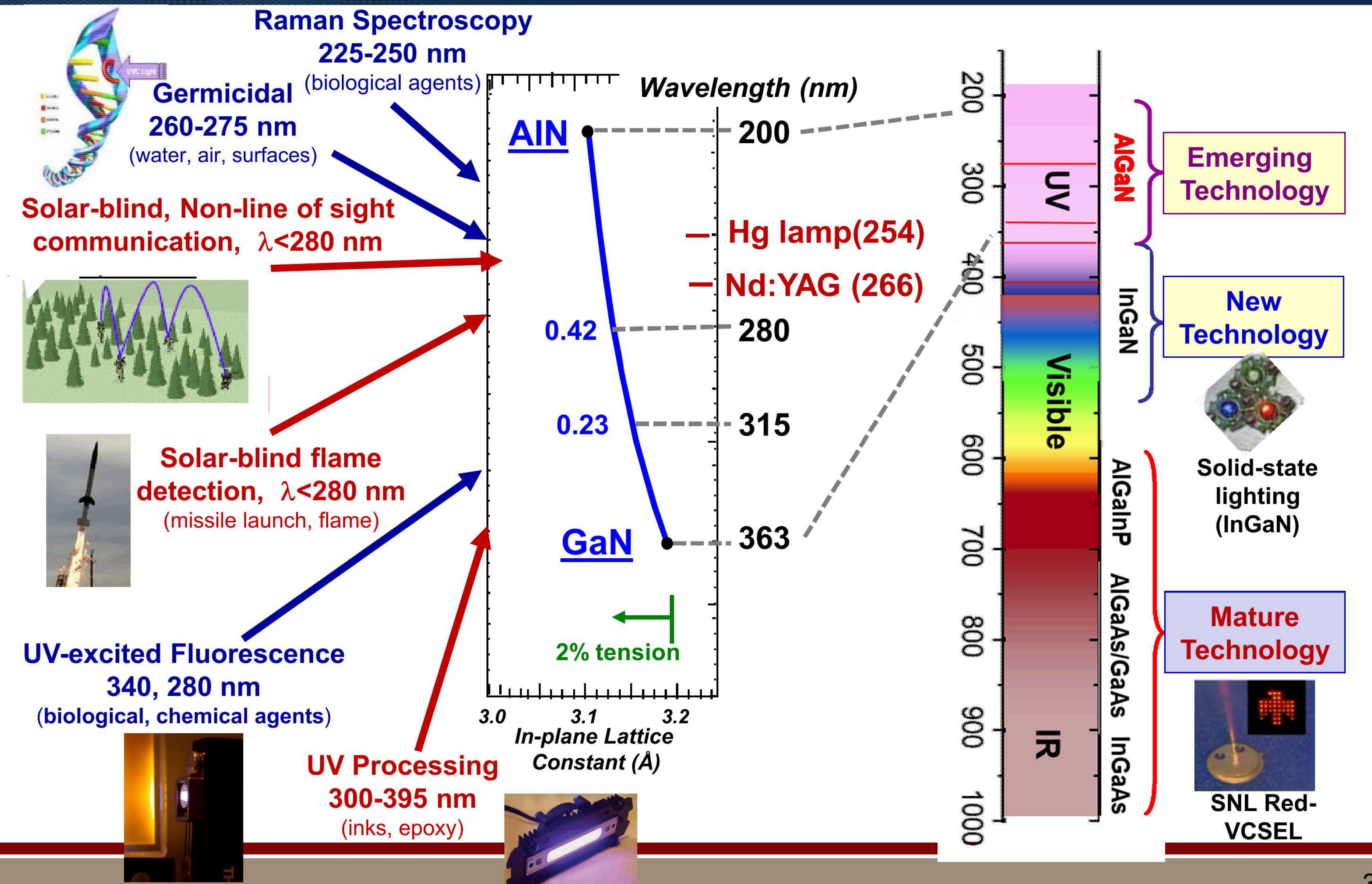
Outline

- **Introduction**
  - AlGaN alloys for power electronics and laser diodes
- **"Quasi-vertical" ($Al_{0.3}Ga_{0.7}N$) PN diodes on sapphire**
  - Continuously grown diodes
  - Diodes with ***regrown*** p-anode
- **Vertically conducting ($Al_{0.3}Ga_{0.7}N$) PIN diodes**
  - Growth on patterned n-GaN substrates
- **"Quasi-vertical" ($Al_{0.7}Ga_{0.3}N$) PN Diodes on sapphire**
  - Continuously grown diodes with different approaches to forming p-anode
- **Summary**

AlGaN alloys for Deep Ultraviolet Light Emitters and Detectors



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

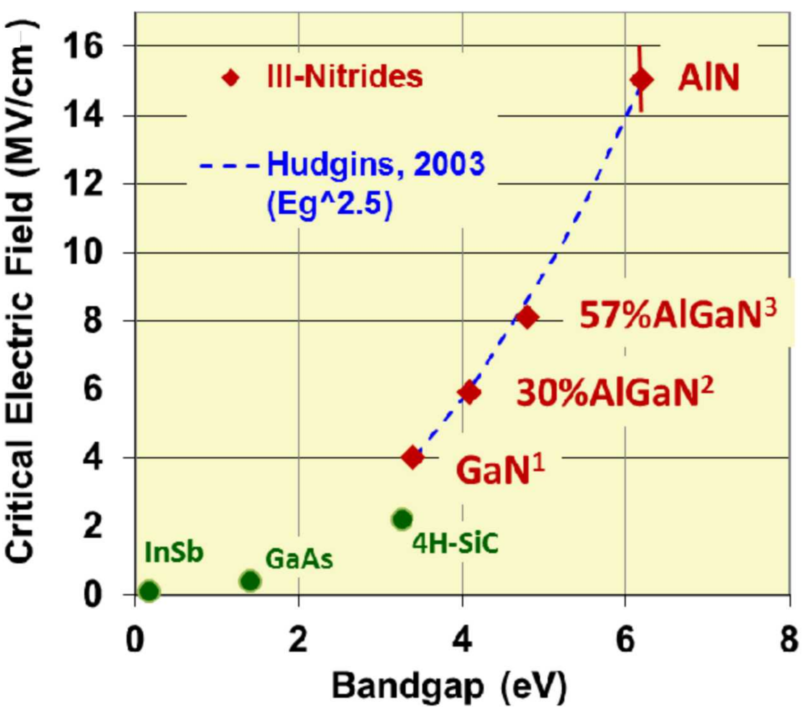
Critical Electric Field (MV/cm)

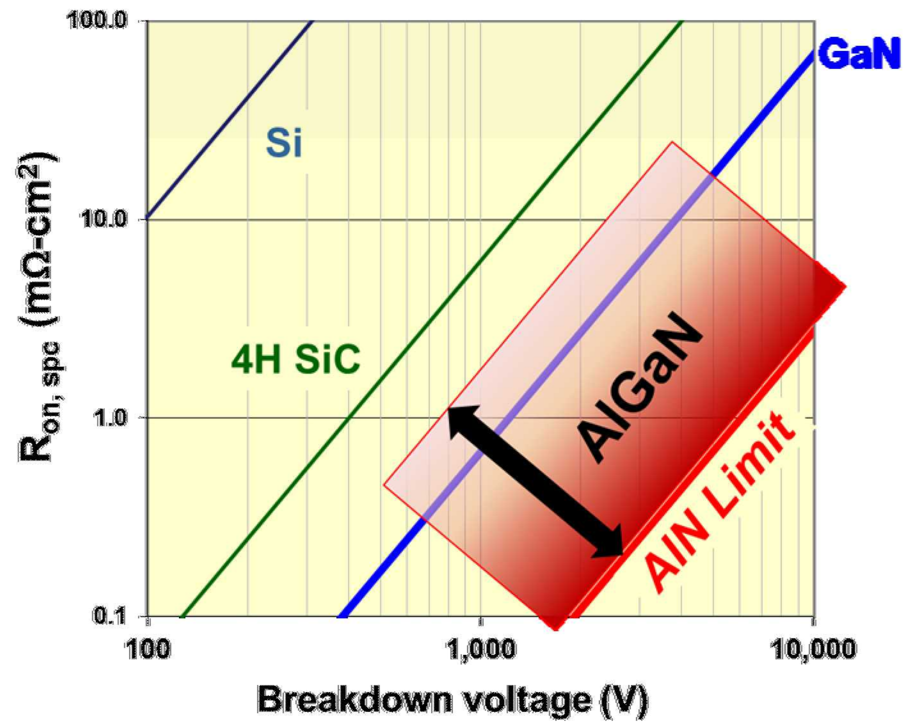
$$E_C \propto E_g^{2.5}$$ (Direct gap)

Unipolar Figure of Merit (vertical devices)

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

Critical Electric Field vs. Bandgap



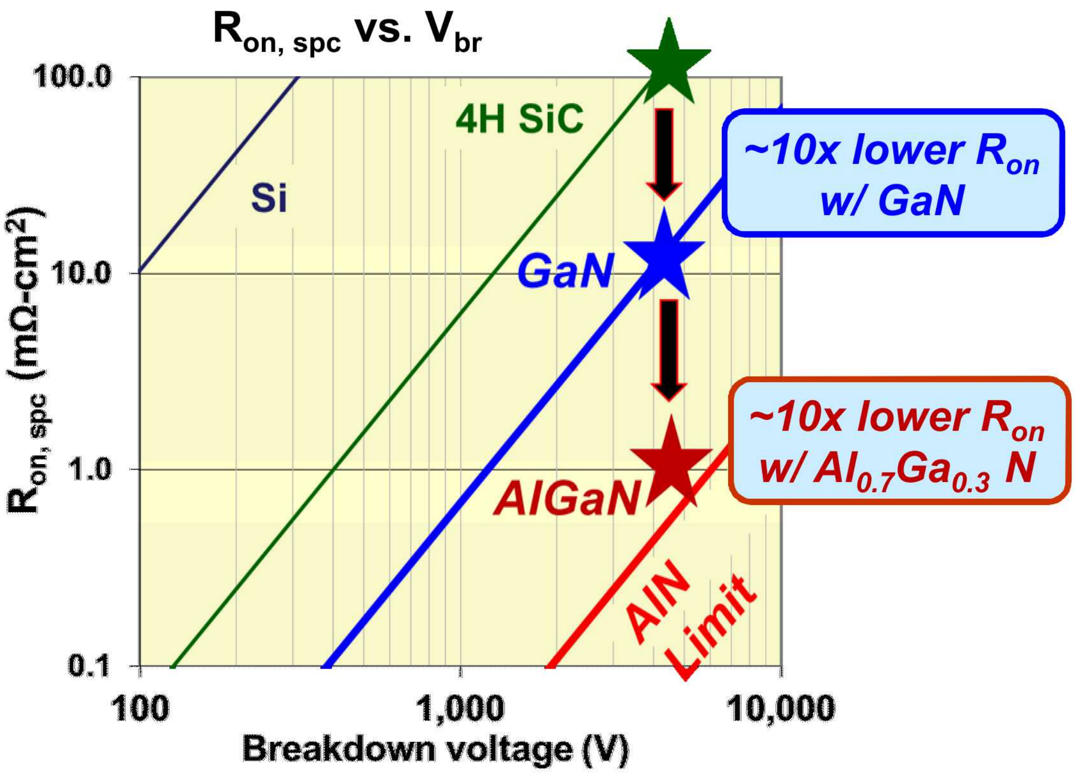


1-Armstrong, EL 2016, 2-Allerman, EL 2016, 3-Nisikawa, Jpn. JAP 2007

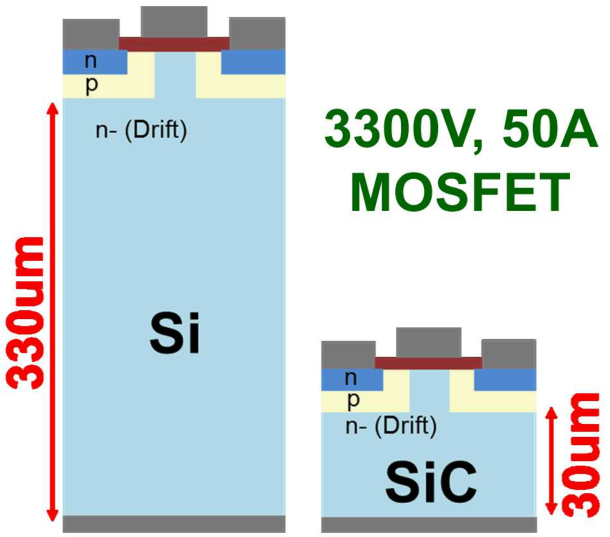
Why wide-bandgap semiconductors for power electronics?

Unipolar Figure of Merit (vertical devices)

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



Si, SiC Power Transistors

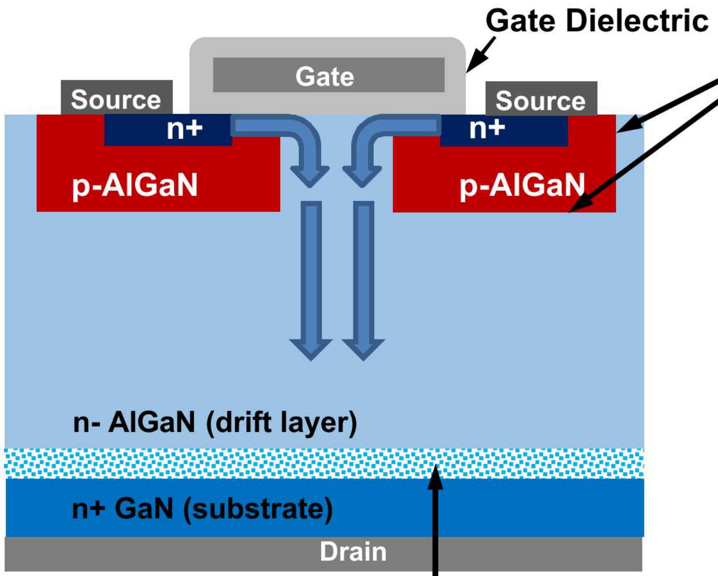


	Si	SiC
V_{drop}:	250V	1.2V
P_{loss}:	12,500W	60W

WBS devices:
➡ *Lower ohmic loss*

Challenges for a AlGaN-based switching transistor

➡ ***Double-well Metal-Insulator-Semiconductor Field-Effect-Transistor (D-MISFET)***



1 **Reverse bias PN junction key to multi-kilovolt blocking voltage (V_{br})**

➡ **Must have low reverse leakage current**

- **P-layers formed by ion implantation and annealing for Si and SiC devices**

➡ **Form the p-well by selective-area-growth (SAG) of p-AlGaN**

2 **Vertically conducting device geometry**

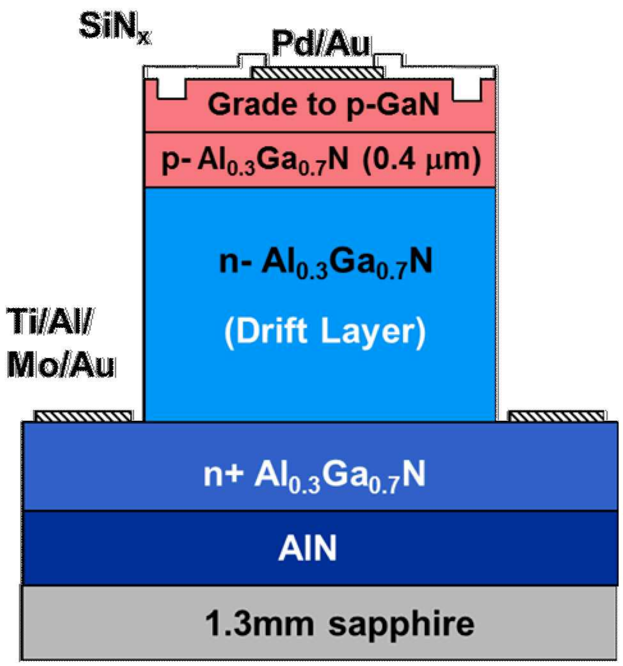
➡ **No AlGaN substrate for vertical conduction (HVPE?)**

- **Substrate removal possible alternative**

➡ **Develop growth of AlGaN on patterned n-GaN substrates**

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

1. Continuously grown Quasi-Vertical diode structure and processing

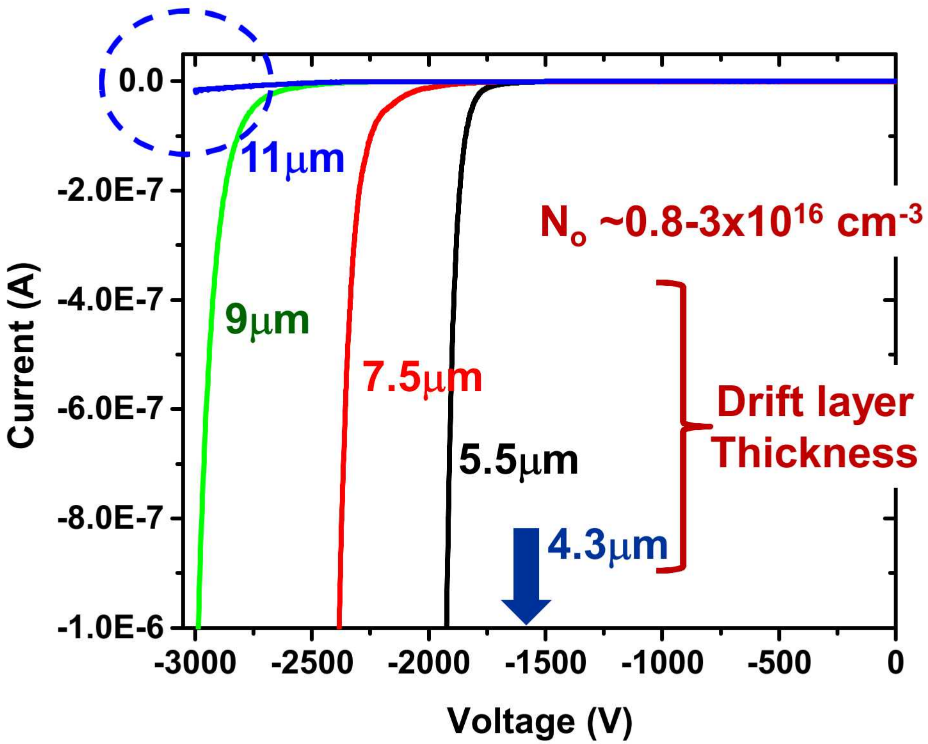


Quasi-Vertical PN diode structure

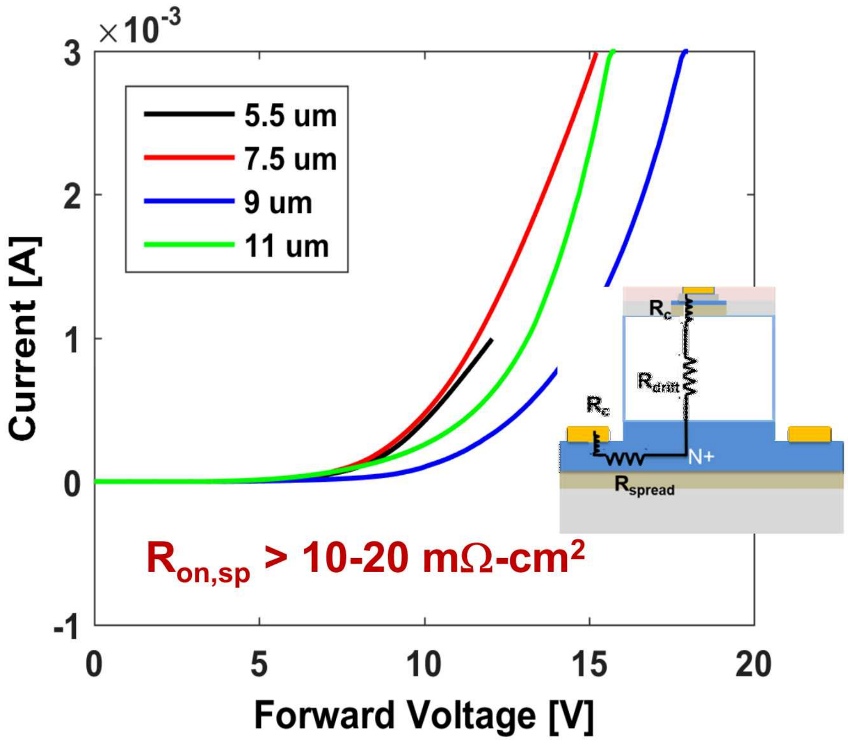
- Implanted junction edge termination
- p-$Al_{0.3}Ga_{0.7}N$: 1025 °C, 6-10 Ω-cm, 0.4 µm
  [Mg] = 2-4e19 cm^{-3}
- *Drift Layer: 4.3, 5.5, 7.5, 9, 11 and 15.5 µm*
- Total epi thickness: 7 – 18, 22 µm
- Crack-free (except 15.5 µm drift layer)
- Drift layer doping: mid 10^{16} cm^{-3}
  Mobility: 150 cm^2/Vs
- *Threading dislocation density: 1-3 x 10^9 cm^{-2}*

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

Reverse IV Characteristics



Forward IV Characteristics

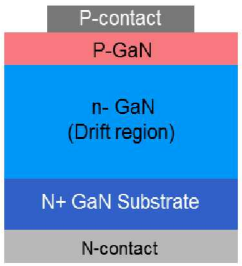


- V_{Rev} ~ 3000V @ 1μA
- E_C ~ 5.9 MV/cm
- Kilovolt class diodes

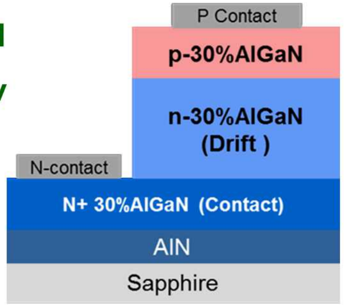
- $R_{on,sp}$ is high due to QV device geometry
- Develop vertically conducting devices

Breakdown voltages reported for III-Nitride PN diodes

GaN diode (vertical)



AlGaN d (Quasi-v



III-N PN diodes with > 3 kV breakdown voltage

Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7 / 5.0	2/9/16e15	33	GaN	Hosei Univ.	EDL-2015 / Jpn J Appl. Phys.-2018
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%-AlGaN**	Sandia	**EL 52p1319_2016**
3.0	**0.8-3e16**	**9**	**30%-AlGaN**	Sandia	**EL 52p1319_2016**
3.0	1/10e15	20	GaN	Hitachi	Jpn J Appl Phys 52 p028007_2013

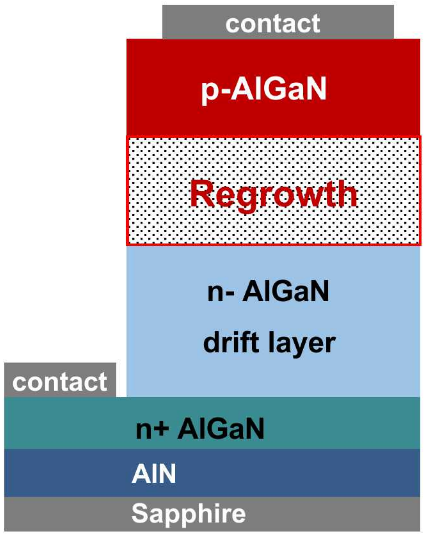
Advantages of wide-bandgap III-Nitride

	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	← Higher reverse leakage

$Al_{0.3}Ga_{0.7}N$ PN Diode: Regrowth on ICP etched drift layer

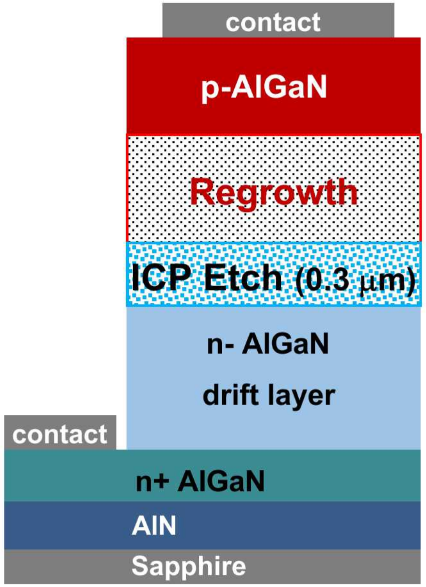
➡ Test p-AlGaN regrowth on *ICP etched* drift layer

A. *“As-grown” Drift*



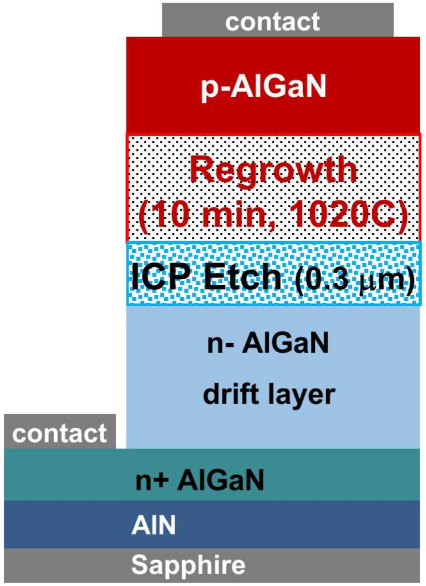
- No ICP etch of drift layer
- Repeat previous regrown diode

B. *ICP-etch ONLY*



- No attempt to remove damage from ICP etch

C. *ICP-etch + Thermal*

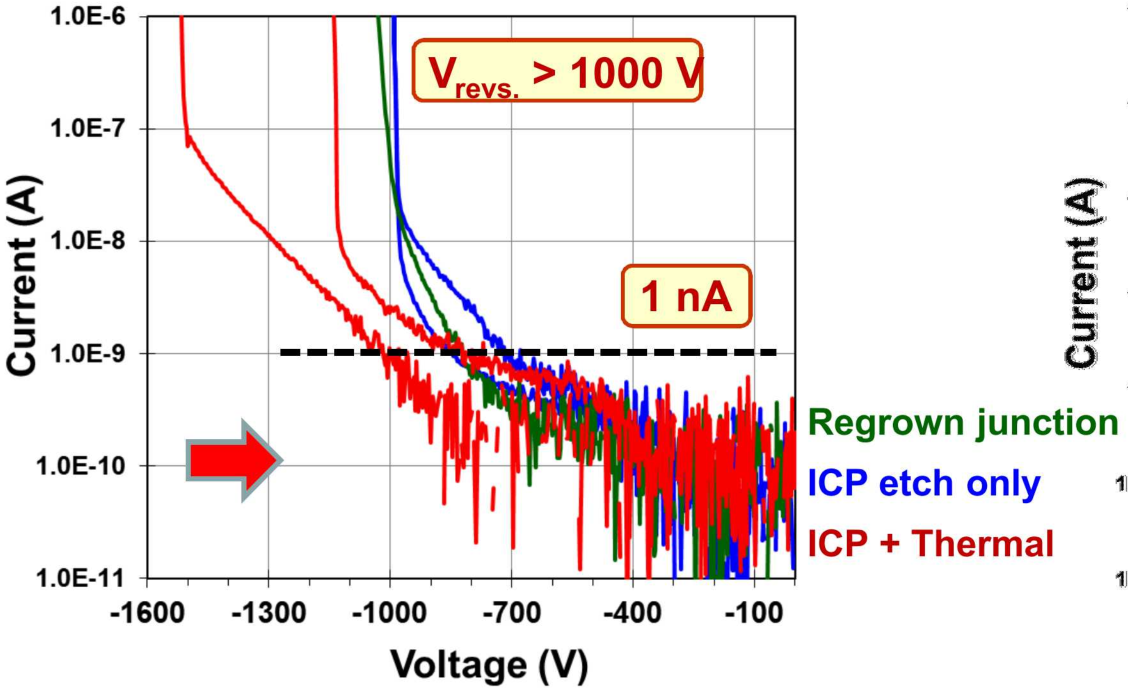


- Warm to 1020C and pause for 10 min. before p-AlGaN

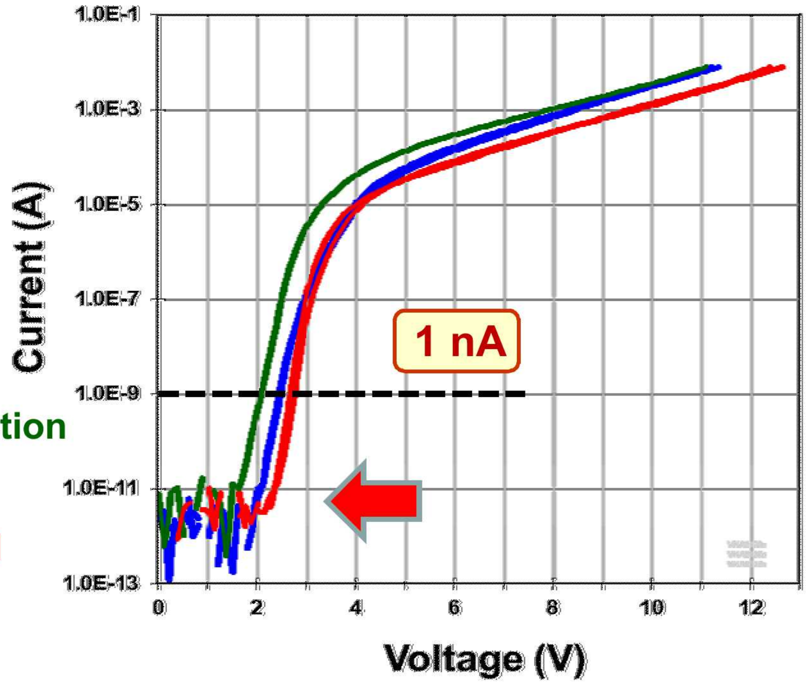
$Al_{0.3}Ga_{0.7}N$ PN Diode: Regrowth on ICP etched drift layer

PN Diode IV Characteristics on an ICP-etched drift layer

Reverse IV Characteristics



Forward IV Characteristics



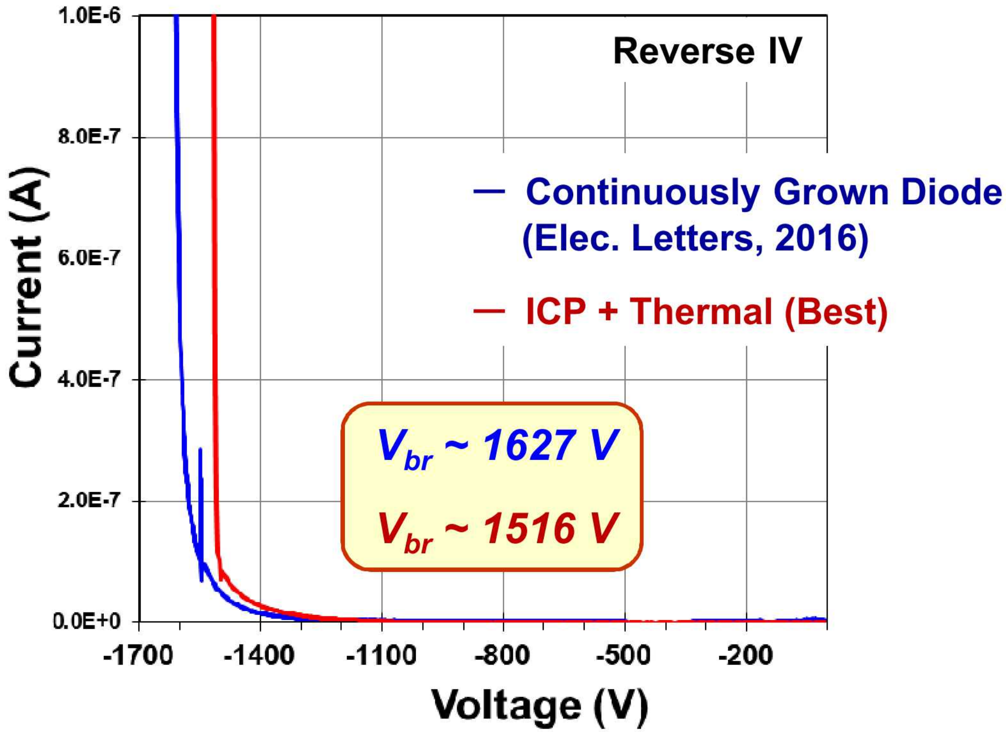
- Regrowth with thermal treatment reached $V_{revs.}$ > 1500V (@ 1μA)
- Regrowth on "as-grown" diode repeated
- ICP-etched reached $V_{revs.}$ ~1000V (@ 1μA)

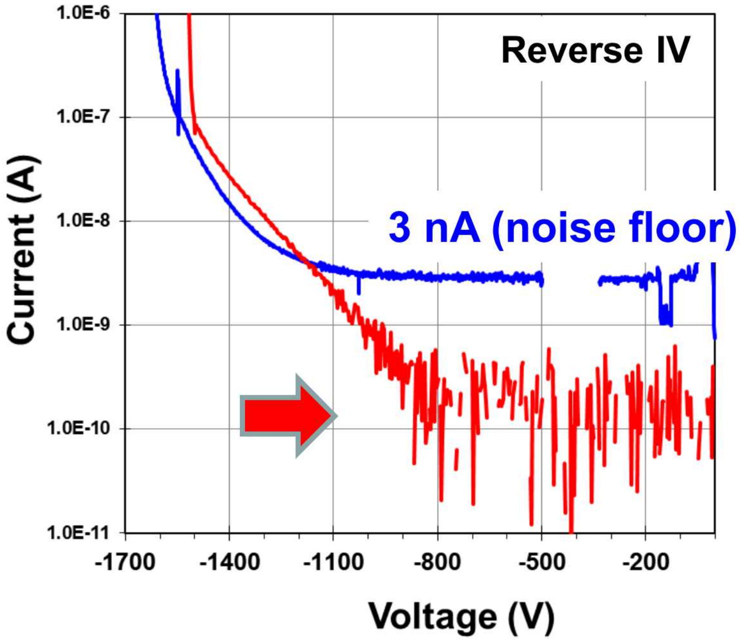
- Very low forward current leakage indicates a good PN junction (*TDD = low 10^9 cm^{-2}*)

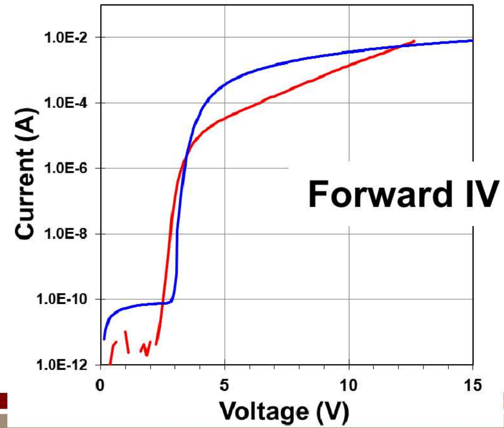
➡ Regrowth of p-AlGaN on *ICP-etched* AlGaN yields kilo-volt class PN diodes with low leakage!

Continuously grown vs. ICP etched and regrown diodes

- ***PN Diode IV Characteristics***

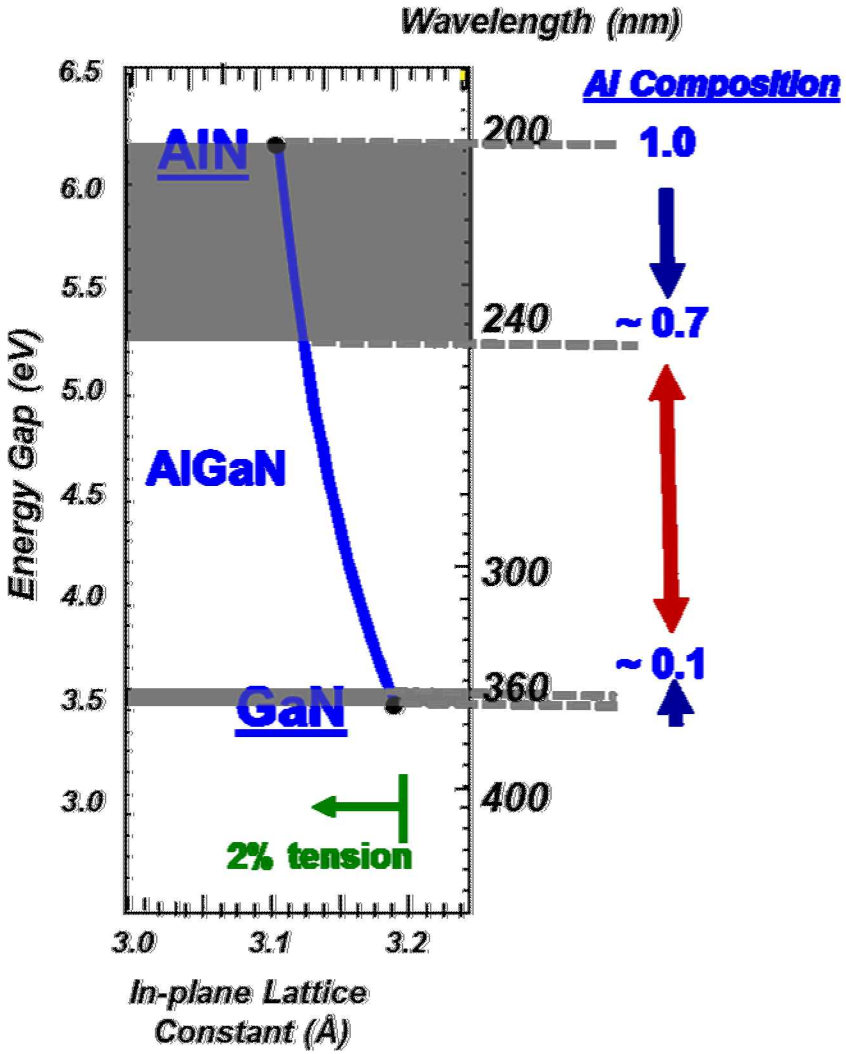






➡ Thermal treatment of ICP-etched drift region can produce AlGaN PN diodes equal to continuously grown diodes (c-plane)

Substrates and AlGaN alloys for vertically conducting laser diodes and power devices



AlN
(Hexatech)

domorphic limit
laxation by dislocation generation)

ary (AlGaN) “substrate” needed for devices
iring microns thick layers (HVPE?)

s tensile strain
to cracking

(Ammono)
GaN

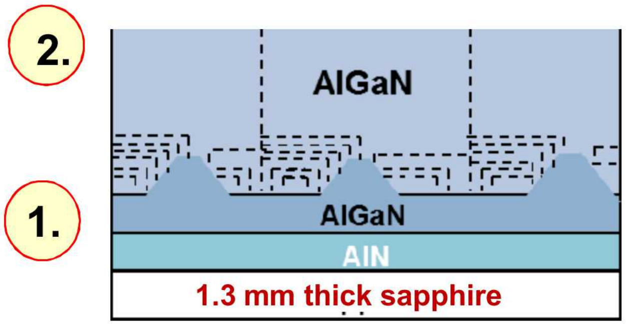
ate a low dislocation template
vices?

Sandia's AlGaN overgrowth of patterned templates

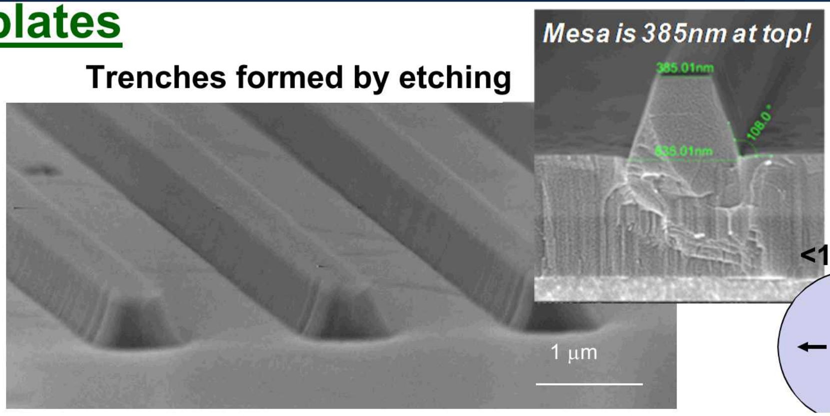
AlGaN Growth on Patterned Templates

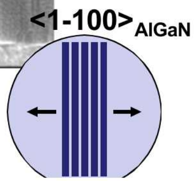
Allerman et. al., JCG 2014

AlGaN with reduced dislocations



Trenches formed by etching

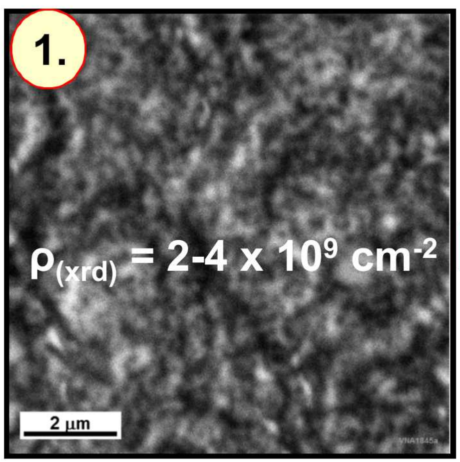


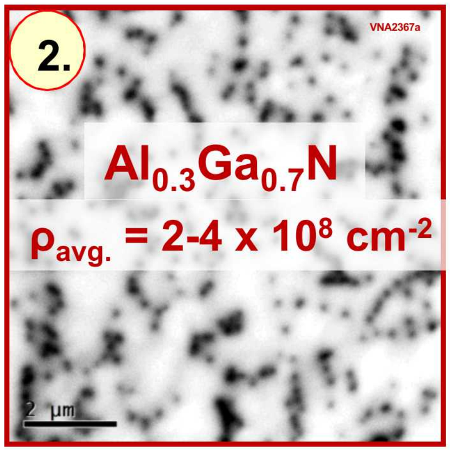


Trench Alignment

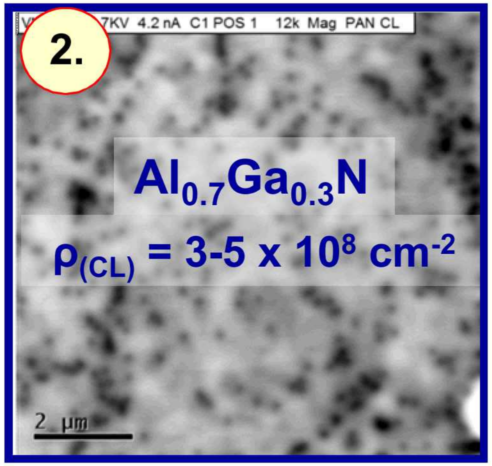
➡ ***Sub-micron features are key for uniform reduction of dislocations***

Cathodoluminescence



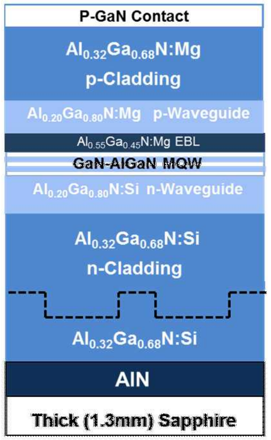


10-20X reduction

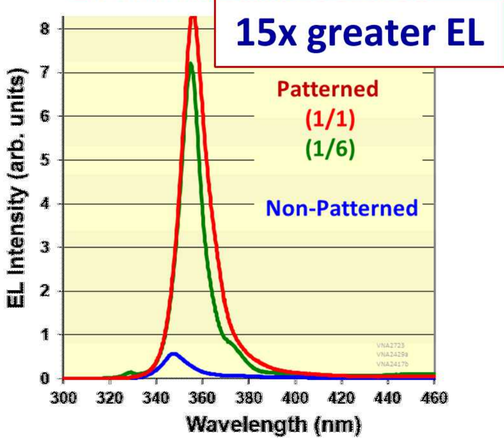


10-15x reduction

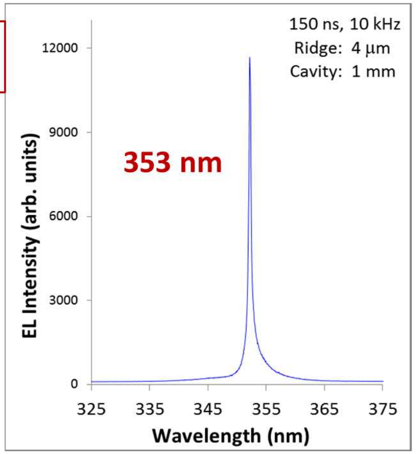
AlGaN Laser Diode



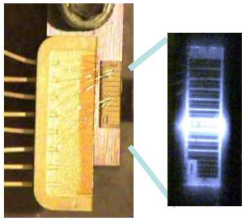
Below Threshold Electroluminescence



Room temperature Pulsed Current Lasing

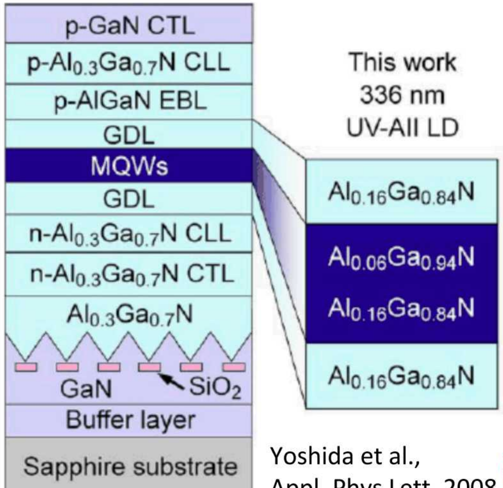


- Ridge Waveguide
- 4 μm x 1 mm
- J_{th}~22kA/cm^2

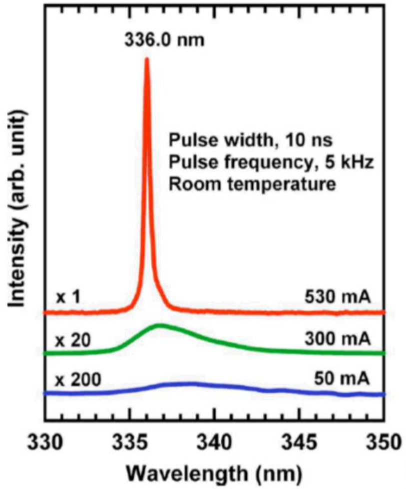


Crawford et al., Appl. Phys Expr. 2015

Record Short Wavelength AlGaN QW Laser Diode (Hamamatsu)



Yoshida et al., Appl. Phys Lett. 2008

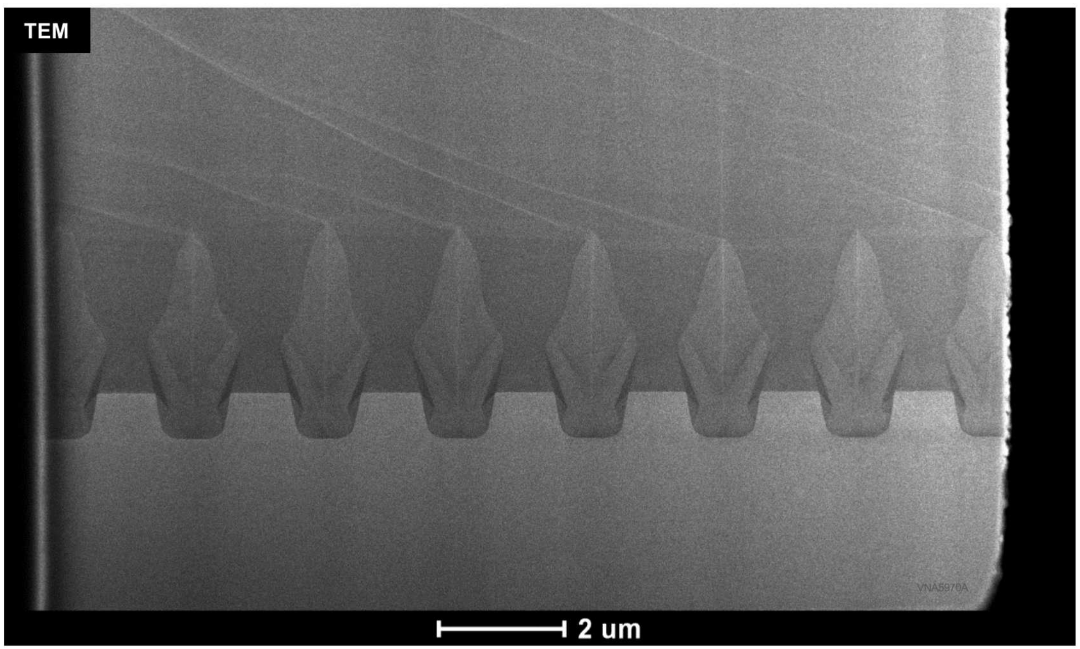


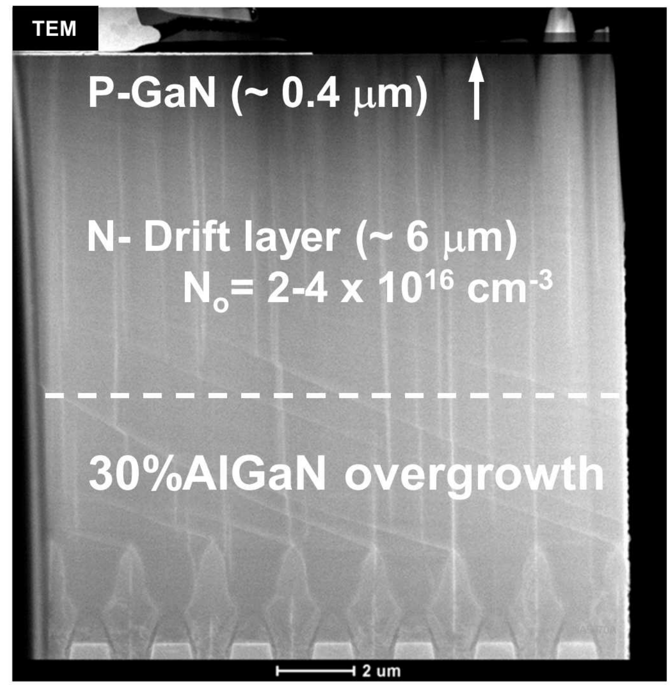
- **Dramatic improvement in below-threshold electroluminescence with 10x reduction in TDD**
- **Patterned over-growth approaches have enabled the shortest wavelength AlGaN ridge waveguide lasers to date**

Vertical $Al_{0.3}Ga_{0.7}N$ PN diode on a conducting GaN substrate

STEM - Vertical PN in 30%AlGaN

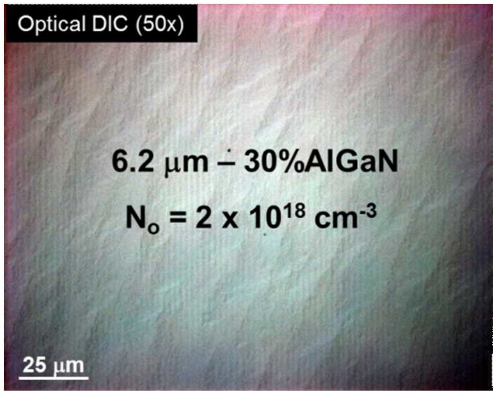
- Large variation in Al composition during film coalescence
- Composition is uniform once coalescence is complete



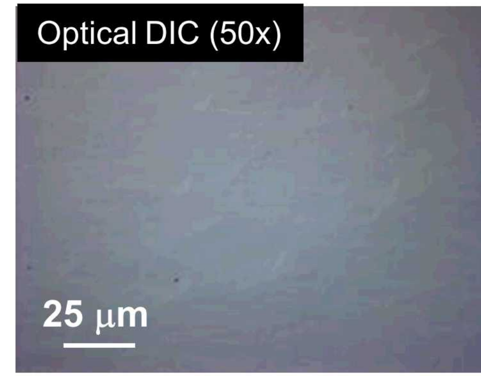


30%AlGaN overgrowth of patterned GaN

30%AlGaN overgrowth on patterned GaN



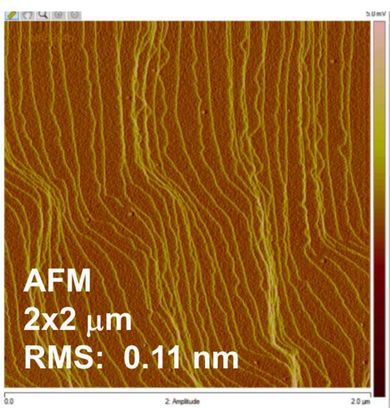
- N-type doping during overgrowth
  - N_o to 2 x 10^{18} cm^{-3}
- X_{al} 0.18 – 0.32 similar morphology
- Planar surface up to X_{al} = 0.45
- More step bunching on GaN (conditions and wafer miscut)

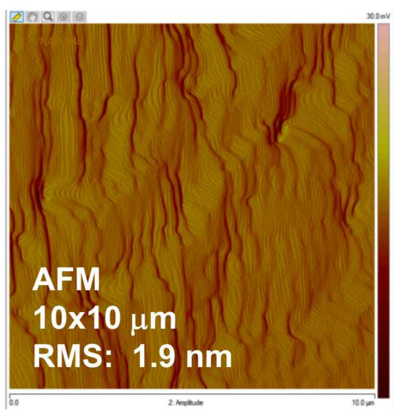


30%AlGaN on patterned GaN

Overgrowth: 6.2 µm

Pattern: 0.67 µm, (1x1)

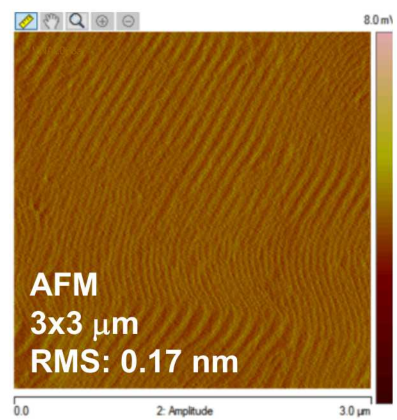


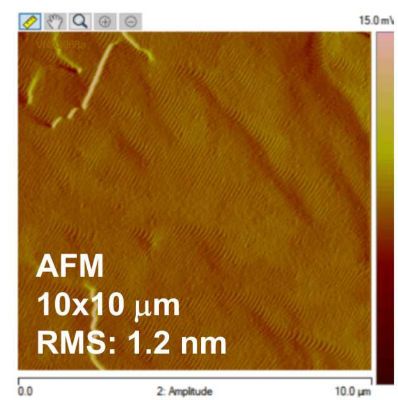


30%AlGaN on patterned AlGaN/sapphire

Overgrowth: 6 µm

Pattern: 0.56 µm, (1x1)



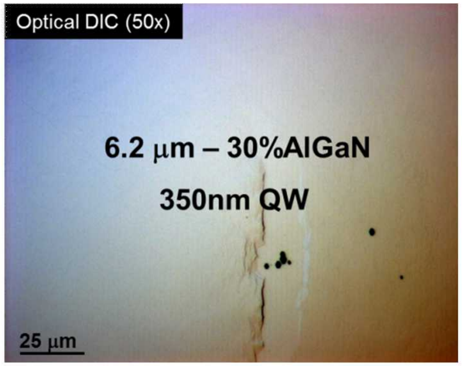


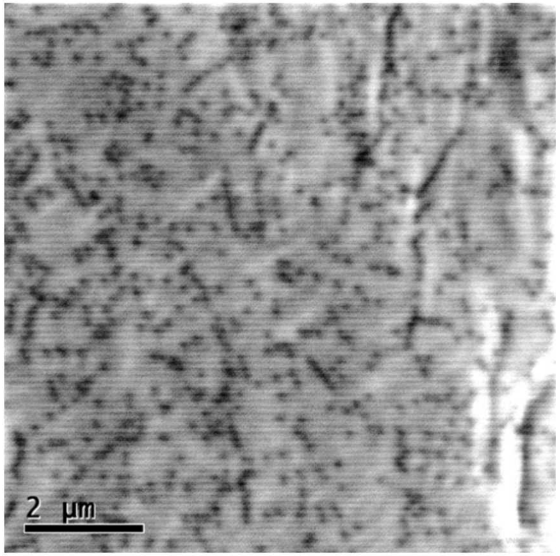
30%AlGaN overgrowth of patterned GaN

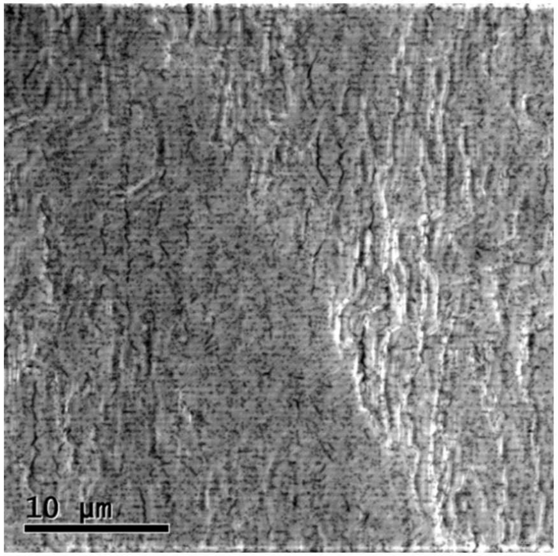
AlGaN on patterned GaN

Overgrowth: 8.3 μm

Pattern: 1.3 μm, (1x1)



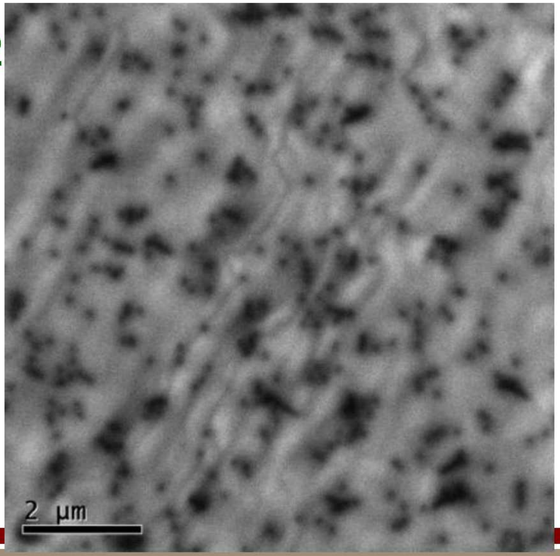


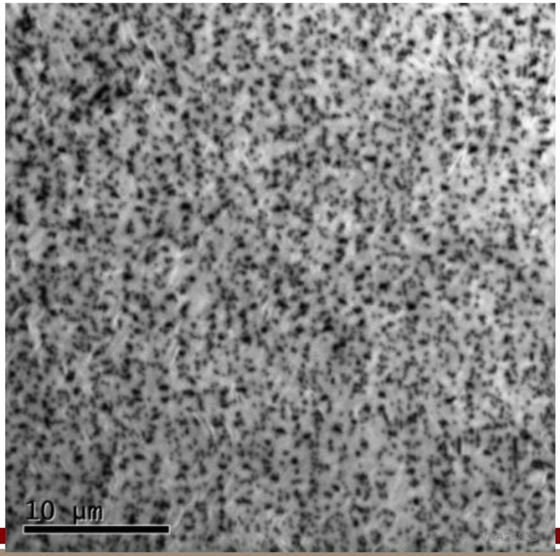


AlGaN on patterned AlGaN/sapphire

Overgrowth: 7 μm

Pattern: 0.66 μm, (1x1)

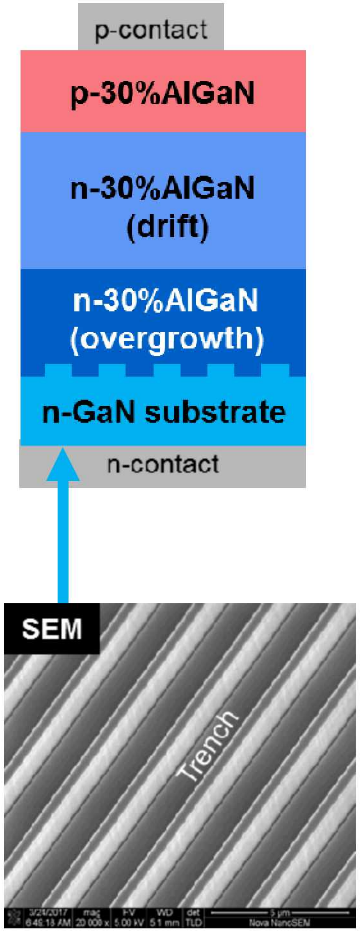




TTD = 2-5 x 10^8 cm^{-2}

➡ **Similar to sapphire**

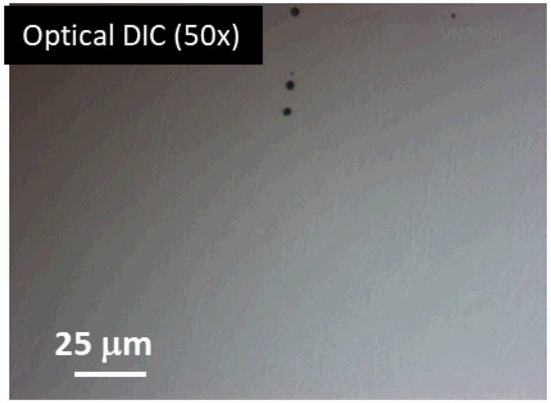
Vertical PN in 30%AlGaN



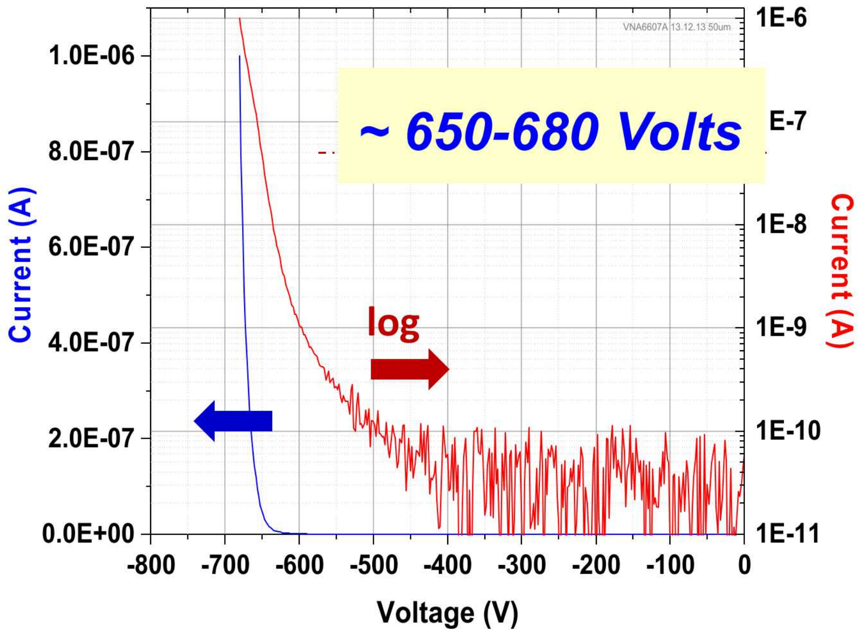
Pattern: 1x1 μm
Etch depth: 1.1 μm

- 30%AlGaN pn diode grown on a N-GaN substrate
- 30%AlGaN overgrowth:
  - Thickness: 6.2 μm
  - N_o: $8 \times 10^{17}\ cm^{-3}$
- Drift region:
  - Thickness: 5.3 μm
  - N_o: $2\text{-}4 \times 10^{16}\ cm^{-3}$
- Total epi: 11.8 μm

$R_{sp\text{-}on} = 1\ m\Omega\text{-}cm^2$



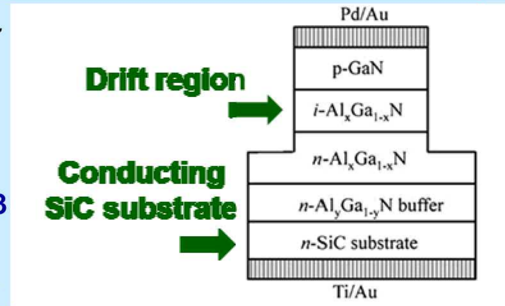
Reverse IV Characteristics



Examples of Al-rich AlGaN PIN and Schottky diodes

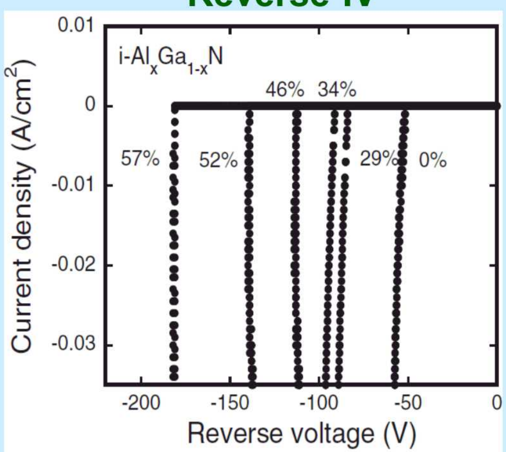
$Al_xGa_{1-x}N$ *Vertical* PN diode (0 < Xal < 0.57)

Nishikawa, Jpn J. App. Phys. 2007

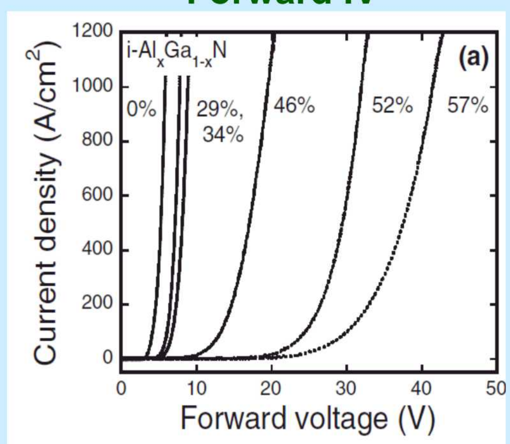


- **Drift Layer: ~ 0.2 μm**
  $N_o \sim 2x10^{16}\ cm^{-3}$
- **$R_{on,sp}$ = 1.45 mΩ-cm² (X_{al} …**

Reverse IV



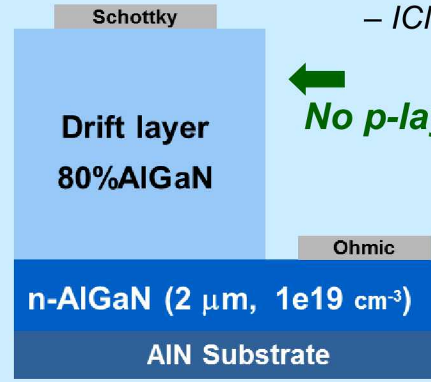
Forward IV



- **V_{revs} < 200V**
- **V_{fwd} ~ 30V (X_{al} = 0.57)**

$Al_{0.8}Ga_{0.2}N$ *Schottky* diode

P. Chow & Hexatech – ICNS, 2017



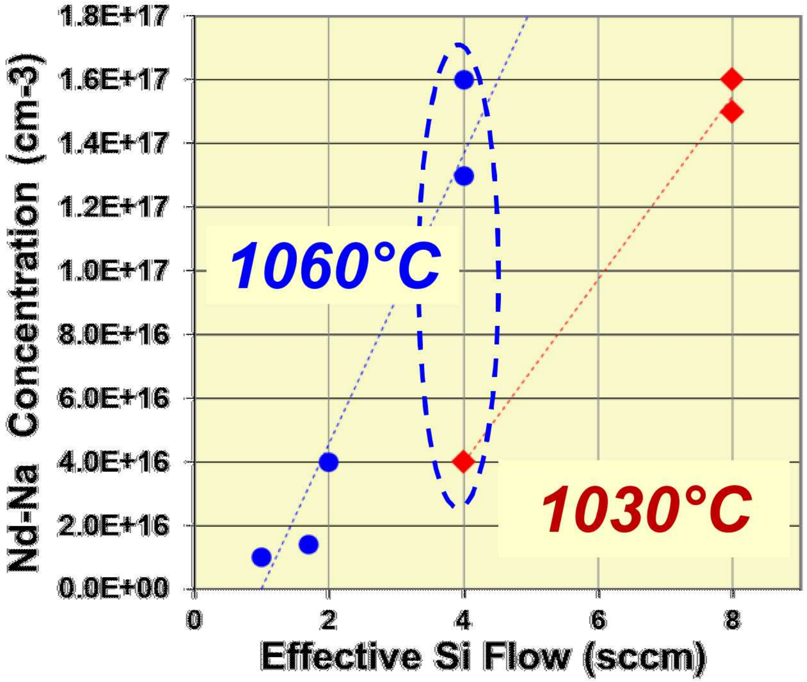
No p-layer

- **Si becomes a D_x center for X_{al} > ~0.85**
- **Drift Layer: 5 μm**
  $N_o \sim 5x10^{17}\ cm^{-3}$
- **$R_{on,sp}$ = 125 - 350 mΩ-cm²**
- **Breakdown: 5000V**

➡ **E_{crit} ~ 10 MV/cm**

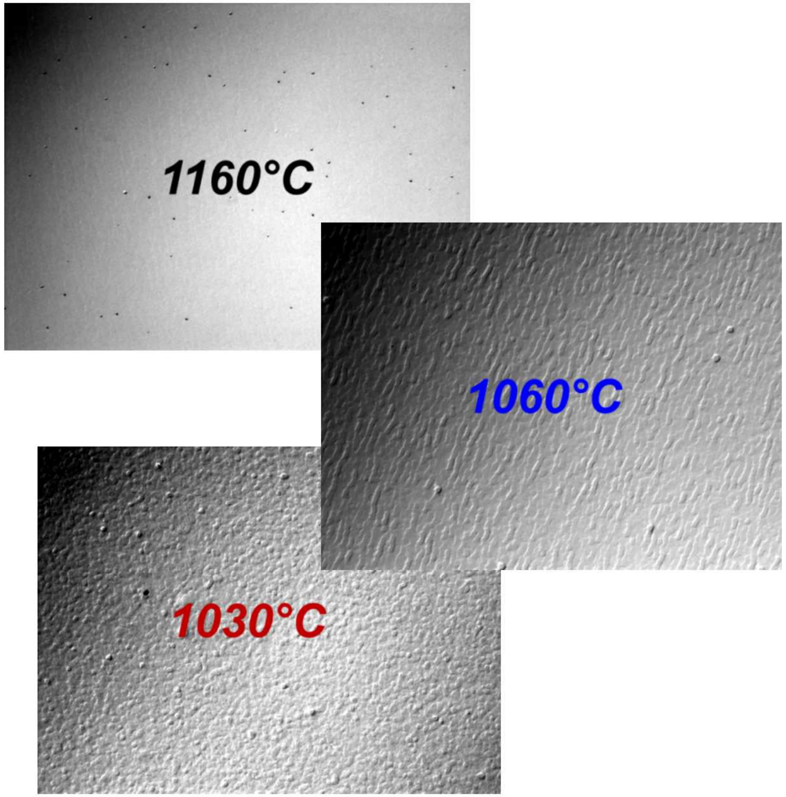
Compensation of Si doped drift region (70%-AlGaN)

Electron concentration (CV) vs. SiH_4 flow (70%AlGaN)



- Compensation is lower at 1060C
- TDD, NH3, pressure *ALL* affect compensation

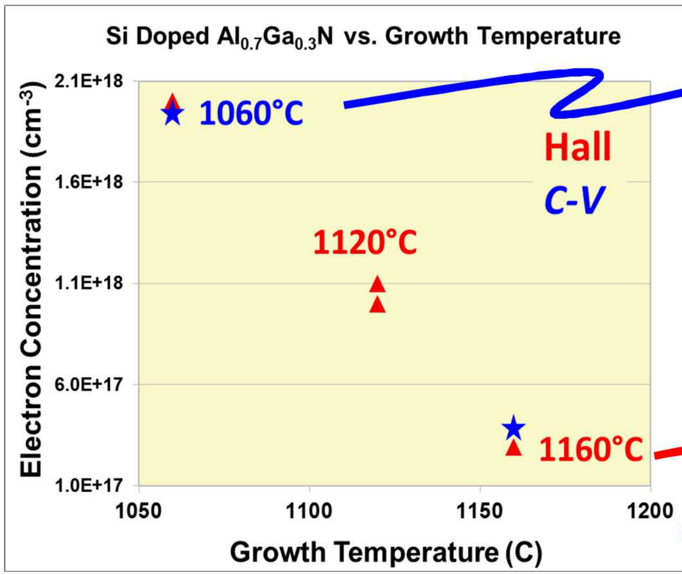
Nomarski DIC (50x) of 70%-AlGaN



- Surface morphology depends on growth temperature (and AlN)

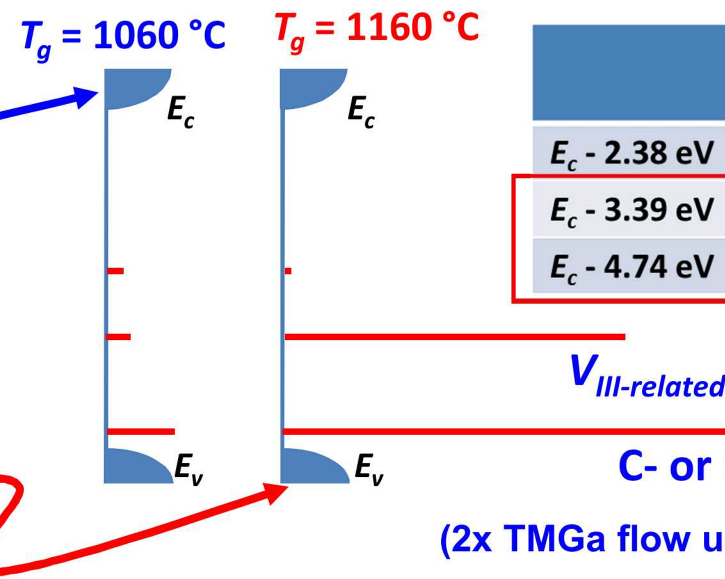
Growth temperature & compensation in Si-doped 80%AlGaN

Electron concentration in Si-70%AlGaN



Armstrong JAP 117 (2015)

Deep level traps in Si-70%AlGaN



	1060 °C N_t (cm^{-3})	1160 °C N_t (cm^{-3})
E_c - 2.38 eV	2.4 x 10^{16}	1 x 10^{16}
E_c - 3.39 eV	3.6 x 10^{16}	5.1 x 10^{17}
E_c - 4.74 eV	1.0 x 10^{17}	6.6 x 10^{17}

$V_{III\text{-related}}$

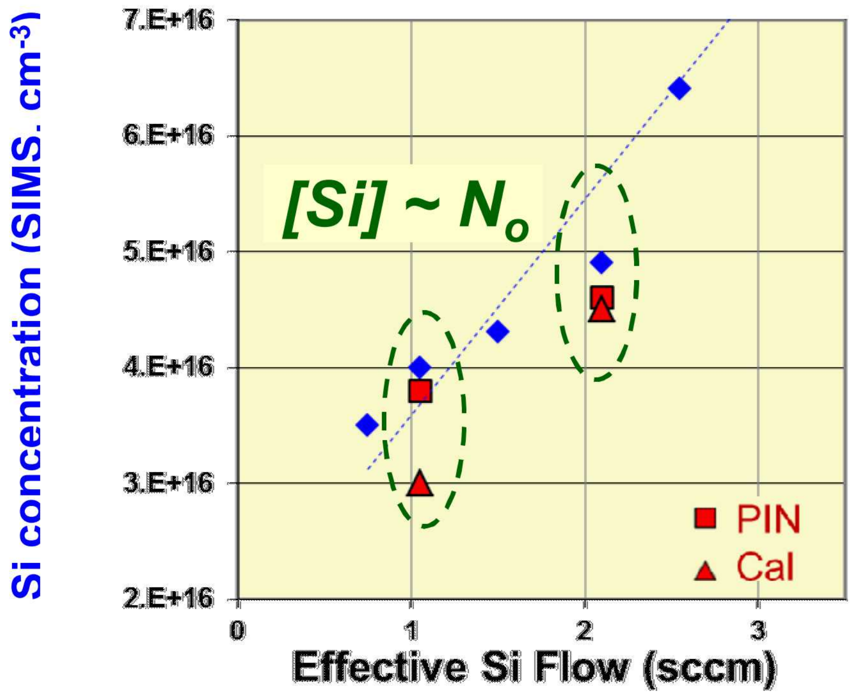
C- or Mg-related

(2x TMGa flow used for HT growth)

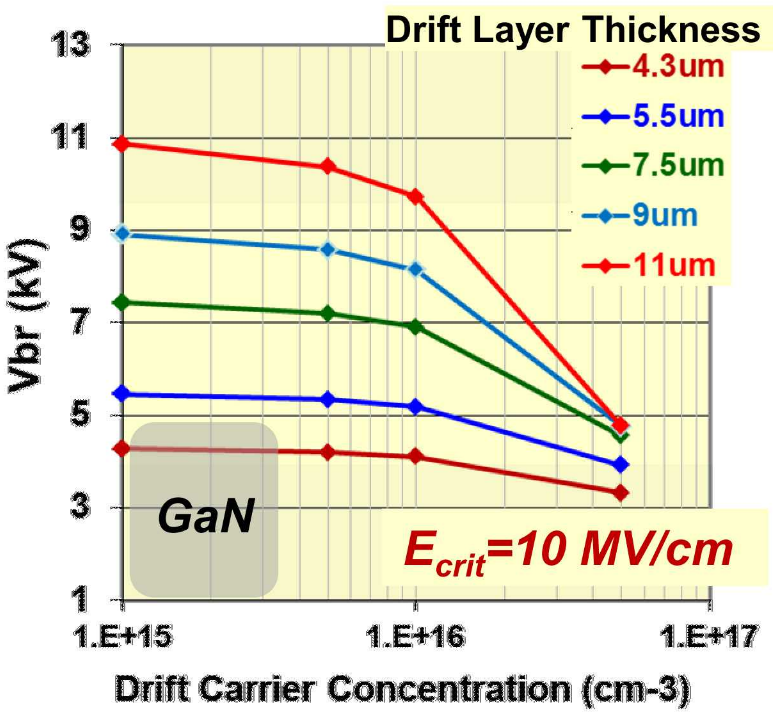
- ➡ **Si dopant compensation strongly depends on growth temperature**
- ➡ **Lowering T_g may inhibit the strong thermodynamic drive to form compensating point defects in UWBGs like Al-rich AlGaN**

Compensation of Si doped drift region (70%-AlGaN)

Si & electron concentration (CV) vs. SiH_4 flow (70%AlGaN)



Calculated V_{br} (kV) for N_o & thickness (70%AlGaN)



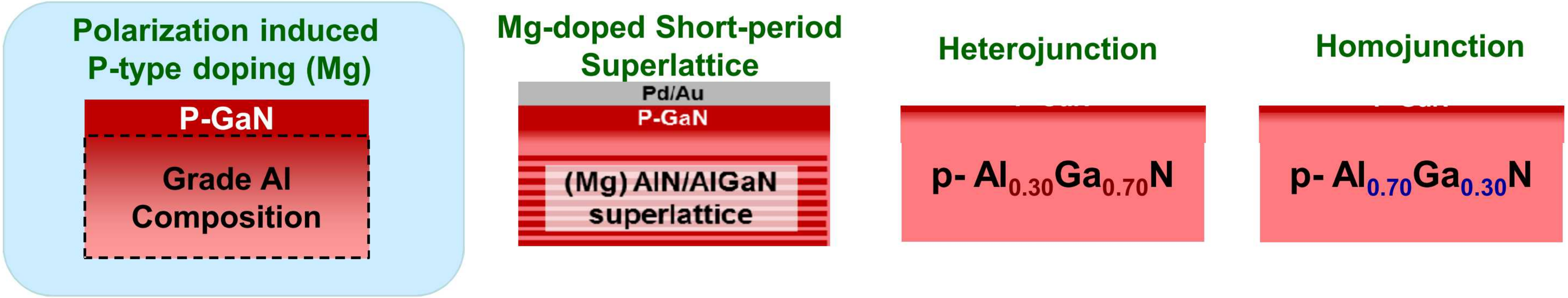
➡ **Donor compensation ~ 1e16 cm^{-3}**

➡ ***Similar to GaN!***

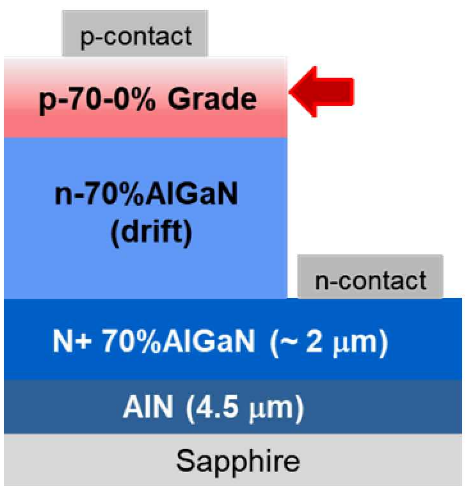
➡ **N_o ~ 1e16 cm^{-3} for ~10 kV**

➡ **Si doping is above the level of compensation**

Thermal ionization is not effective for holes for AlGaN (X_{al} > 0.5)



Polarization doped PN diode



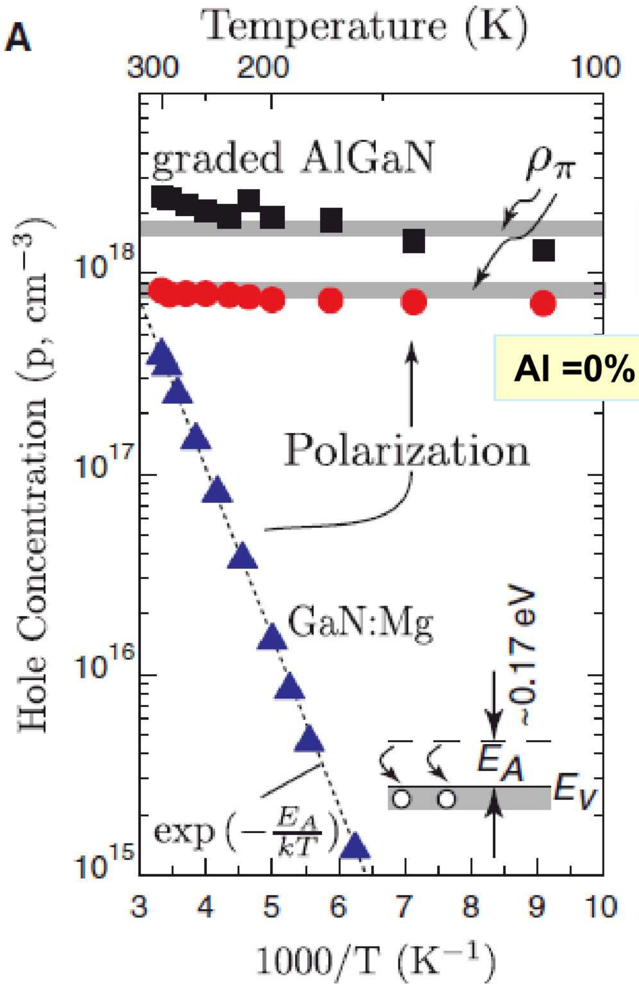
"Quasi-vertical" PIN diode

- **Investigated different Al compositional grades (p-anode)**
- **Drift region (optimized for low compensation):**
  Thickness: 5.4, 6.2 μm (Total: 11-12 μm)
  Doping (Si): 1-3 x 10^{16} cm^{-3}

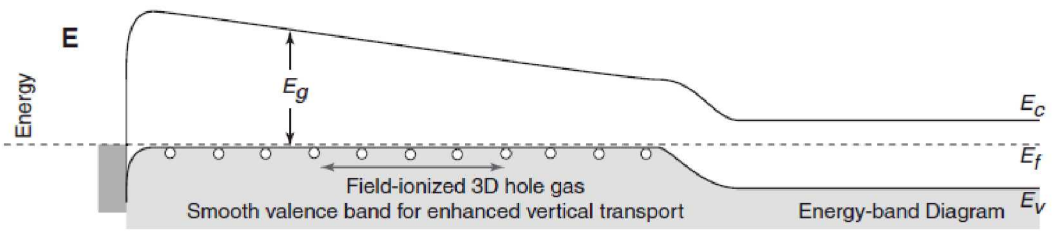
	AlN	$Al_{0.7}Ga_{0.3}N$
Thickness (μm)	4.5	4 - 9
FWHM-(0002)	210"	164"
FWHM- (10-12)	327"	239"
Tg (°C)	< 1100°C	1060°C

$Al_{0.70}Ga_{0.30}N$ Diodes with P-type Polarization Doping

Distributed Polarization Doping with graded AlGaN



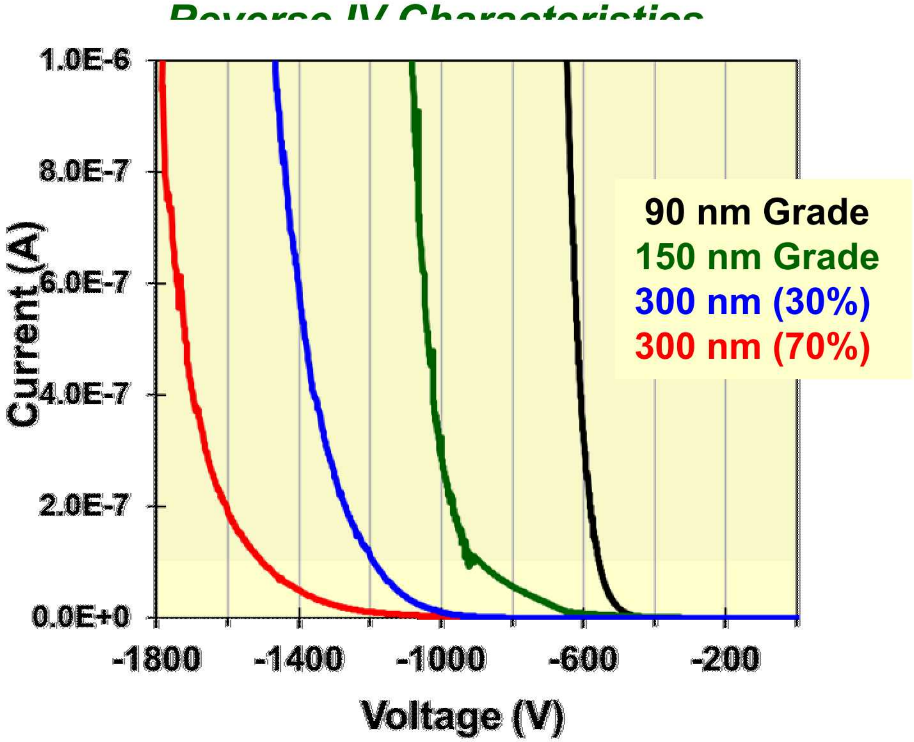
Al =0% → 30%

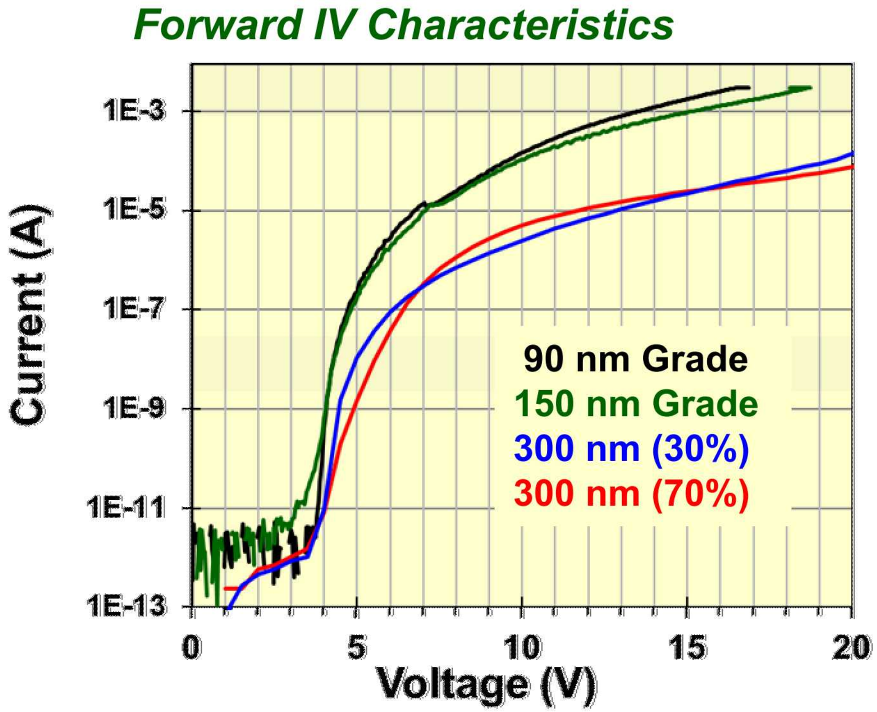


Simon, Science 327, 60 (2010)

- **3D hole doping activated by polarization field**
- **Not limited by thermal activation!**
- **Doping with Mg is required**
- **Not yet demonstrated in AlGaN power diodes**

$Al_{0.7}Ga_{0.3}N$ "Quasi-Vertical" Polarization-doped PN diode





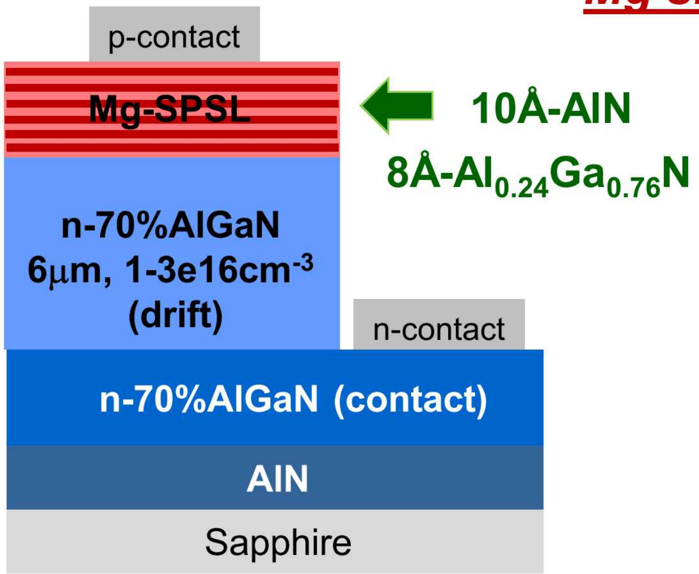
- Reverse voltage ~ -1800V (@ 1μA)
- E_{crit} = < 3 MV/cm (lower than expected)

- Higher series resistance with longer grade (lower Po)
- Low forward leakage

➡ Lower series resistance by adjusting Mg level and grade

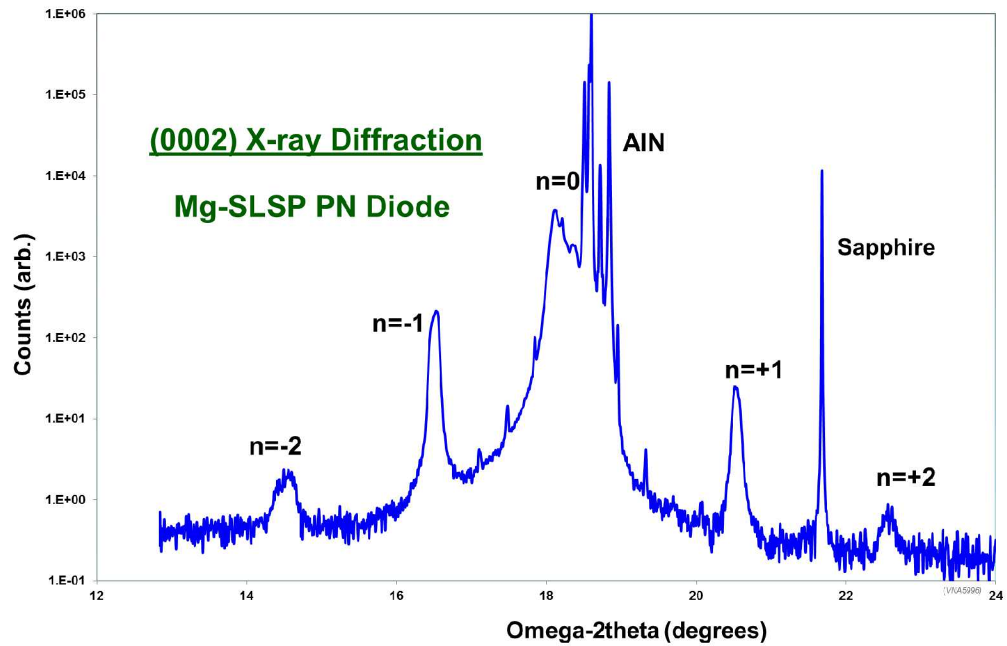
➡ Increase breakdown by optimizing control of the electric field

"Quasi-vertical" Mg-doped short-period superlattice PN diode



Mg short-period superlattice (Mg-SPSL) PN diode

- **P-type resistivity (in-plane): 7-10 Ω–cm**
- **[Mg] ~ 3-4 e19 cm^{-3}**
- **Thickness: 0.3 μm (160 periods)**
- **Average X_{al}: 0.66**
- **Period by XRD: 22.1Å**

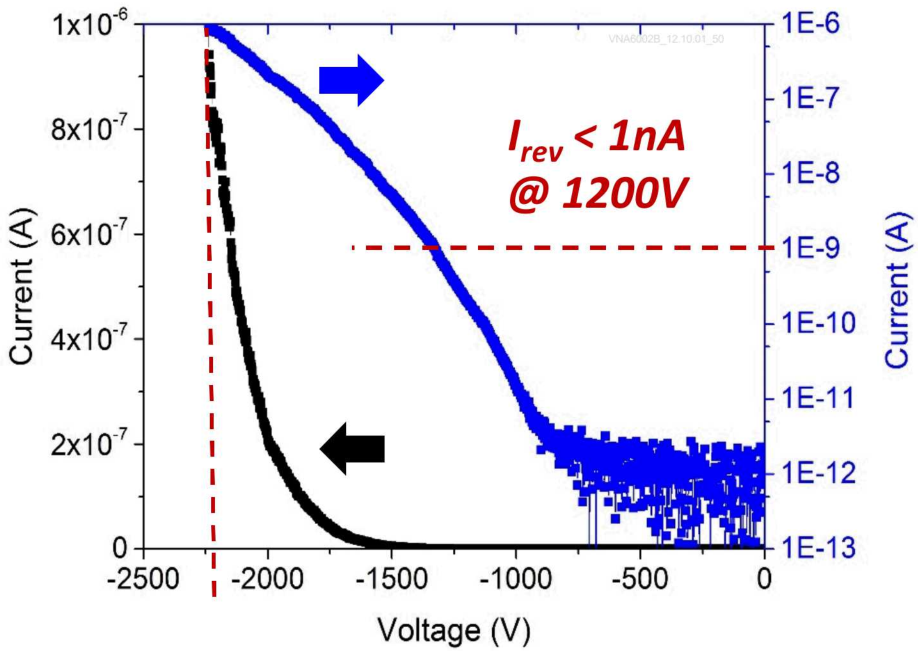


➡ ***Mg-SPSL is reproducible***

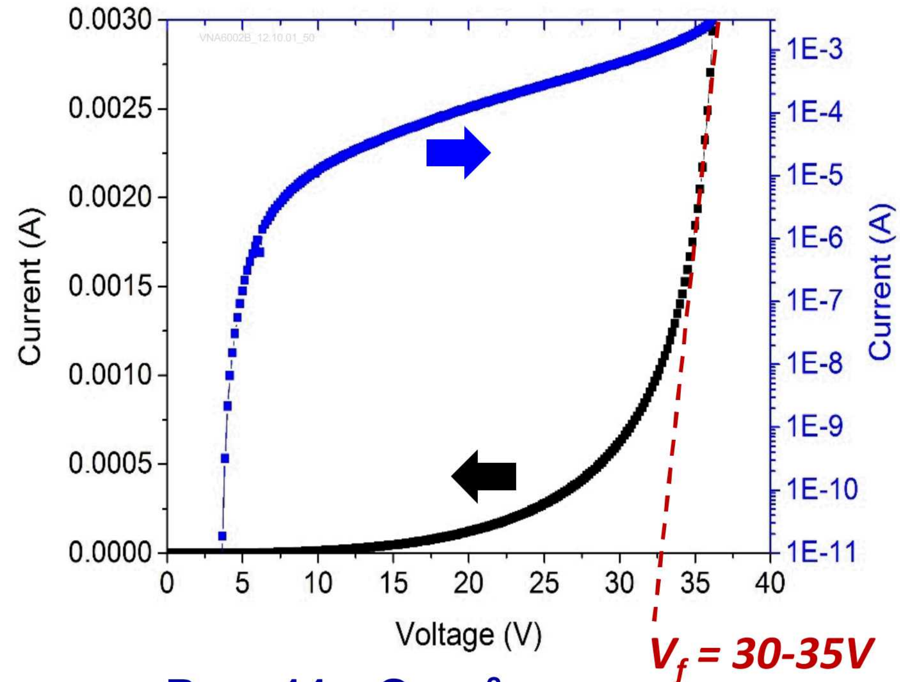
Date	Period (Å)	Resistivity (Ω-cm)
11/2012	19.2	11.5
2/2013	20.7	6.9
3/2014	21.7	10.4
4/2017	19.8	7.1

"Quasi-vertical" Mg-doped short-period superlattice PN diode

Reverse IV Characteristics



Forward IV Characteristics



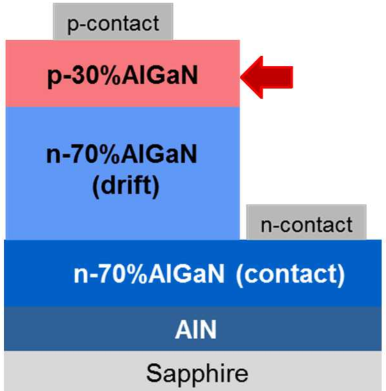
- Reverse voltage ~ -1200V (@ 1nA)
- E_{crit} ~ 3.7 MV/cm (low for 70%-AlGaN)

- R_{on} ~ 14 mΩ-cm²
- High forward voltage ~ 30-35V

➡ Lower forward voltage by adjusting heterobarrier in Mg-SPSL

➡ Increase reverse voltage by optimizing JTE

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



Heterojunction PN diodes (p-30% / n-70%)

- Utilize p-type doping of 30%-AlGaN
- Reverse voltage at 1 μA:

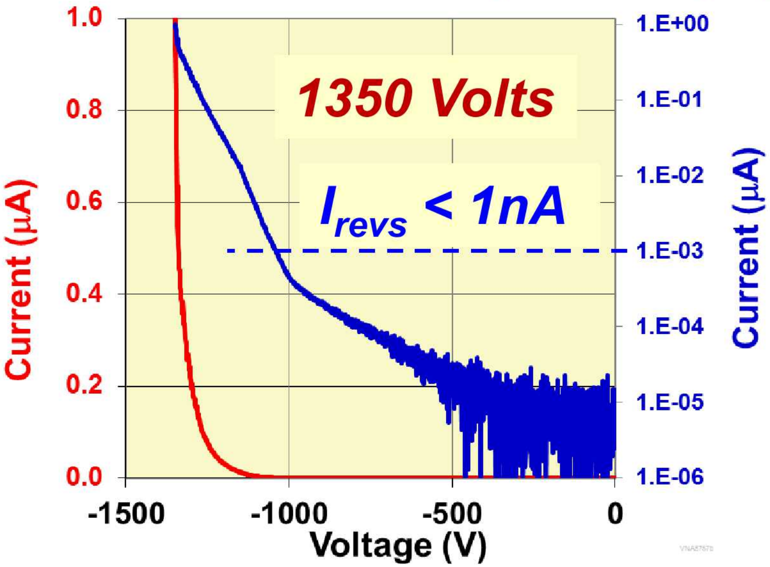
5.5μm ➡ 1300V

8.0μm ➡ 1850V

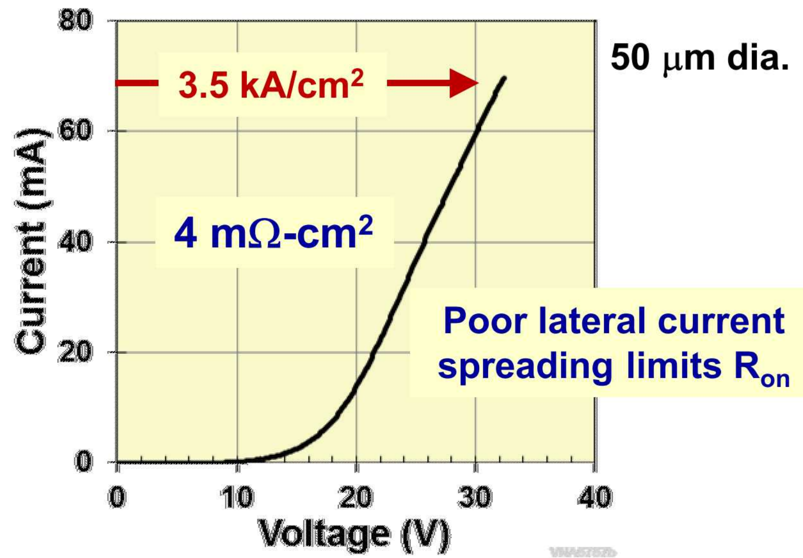
➡ *E_{crit} ~ 2.3 MV/cm (very low)*

Q: JTE, p-30%AlGaN or drift layer?

Reverse IV Characteristics (Drift: 5.5 μm)



Forward IV Characteristics



Summary

- **Quasi-vertical Al_xGa_{1-x} N PIN diodes (X=0.3)**
  - **Reverse voltages > 3000V (@ 1 μA)**
  - **Critical electric field (E_{crit}) = 5.9 MV/cm^2**
- **Quasi-vertical $Al_{0.3}Ga_{0.7}$ N PIN diodes with regrown PN junction on etched drift layer**
  - **Reverse voltages to 1500 V (@ 1 μA)**
    - ➡ ***IV characteristics equal to continuously grown PN diodes***
- **Growth of $Al_xGa_{1-x}N$ (X = 0.3) on patterned N-GaN substrates**
  - **Threading dislocation density of 3-5 x 10^8 cm^{-2}**
  - **$Al_{0.3}Ga_{0.7}N$ overgrowth > 12 mm achieved for vertical PN diodes**
  - **Vertical PIN - 30%AlGaN V_{revs} = 680 V (@1 μA)**