SAND2017-8303C

ULTRAWIDE BANDGAP POWER ELECTRONICS

Sandia National Laboratories


Veeco D-125 MOCVD system

OMVPE Growth of Al-rich AlGaN Alloys for Power Electronics

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U.S. DEPARTMENT OF ENERGY

Outline

- **Wide bandgap AlGaN alloys for power electronics**
- **PN diodes $Al_xGa_{1-x}N$ (x = 0.3)**
  - Growth of thick, N- drift layers
  - Breakdown voltage and forward ON resistance
- **PN diodes $Al_xGa_{1-x}N$ (x = 0.7)**
  - Growth of low compensation of N-type drift layer
  - Approaches for p-side of diode
- **Summary**

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

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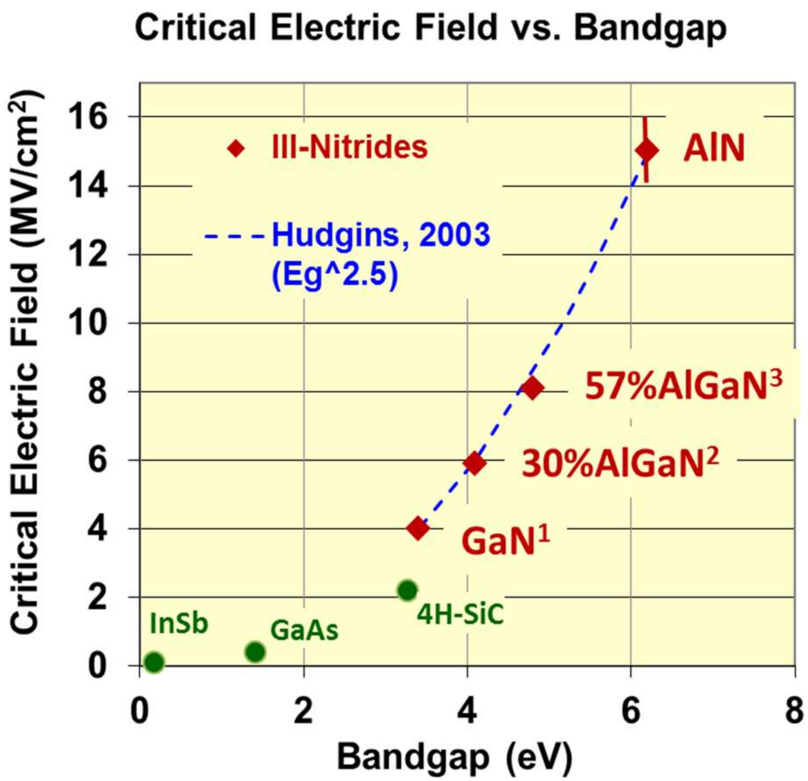
Critical Electric Field (MV/cm)

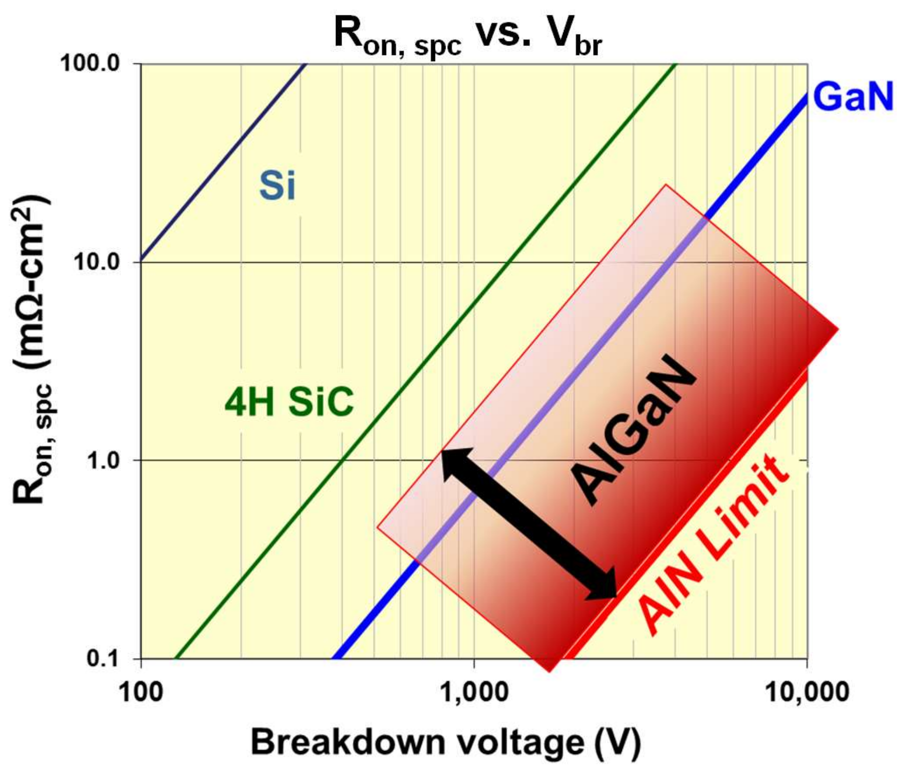
$$E_C \propto E_g^{2.5}$$ (Direct gap)



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

Unipolar Figure of Merit (vertical devices)

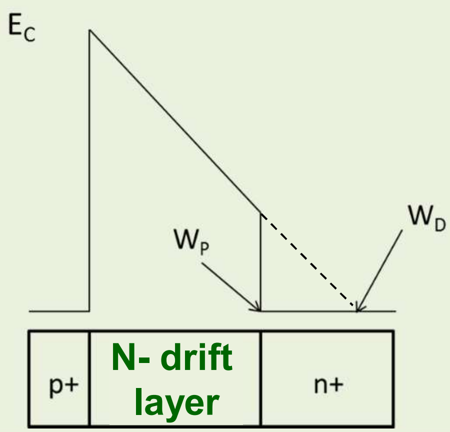
$$UFOM = \frac{V_{br}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_C^3 \propto E_g^{7.5}$$



Breakdown voltage of drift layer: doping and thickness

Punch-Through

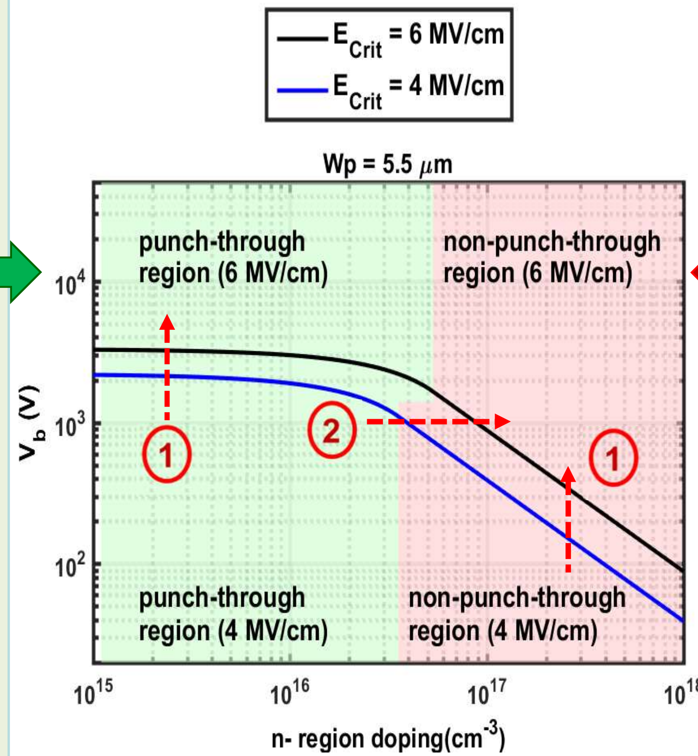
$W_P < W_D$



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

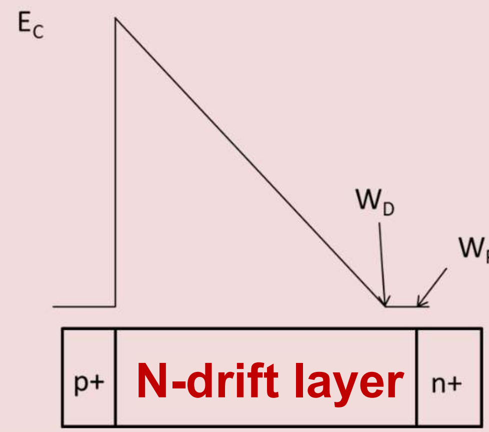
- N_d is lower than optimal

➡ ***Thickness determines V_{br}***



Non-Punch-Through

$W_P \geq W_D$

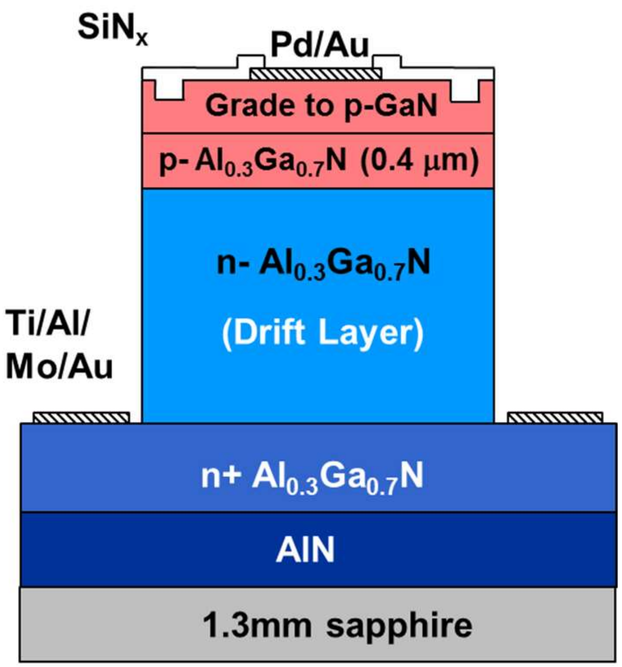


$$V_{br} = \frac{\varepsilon {E_C}^2}{2 q N_D}$$

- Drift layer is thicker than optimal

➡ ***N_d determines V_{br}***

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



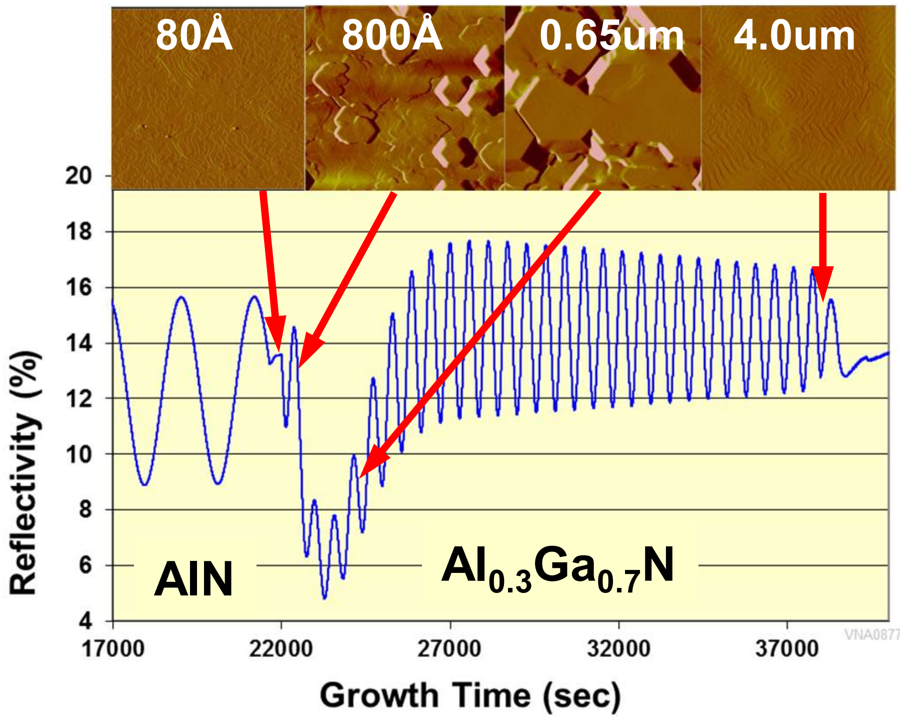
Quasi-Vertical PN diode structure

Quasi-Vertical diode structure and processing

- Implanted junction edge termination
- Mesa & p-metal dia.: 300 - 50 μm
- p-$Al_{0.3}Ga_{0.7}N$: 1025 °C, 2-4 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^{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}*

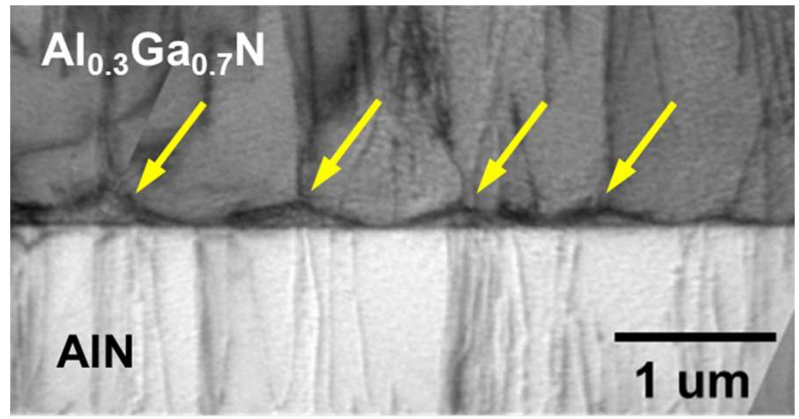
Relaxation and TDD reduction in $Al_{0.3}Ga_{0.7}N$ on AlN

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 ~ $2\text{-}4 \times 10^{9}$ cm^{-3}**

Cross-section TEM



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

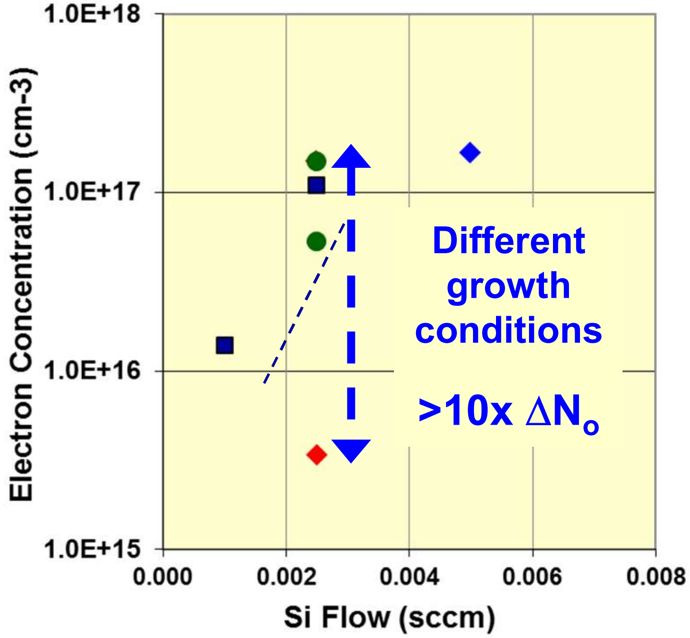
- **Strain is relieved by interfacial misfit dislocation networks with hexagonal boundaries**
- **Threading dislocations “bundle” into triangular features**

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

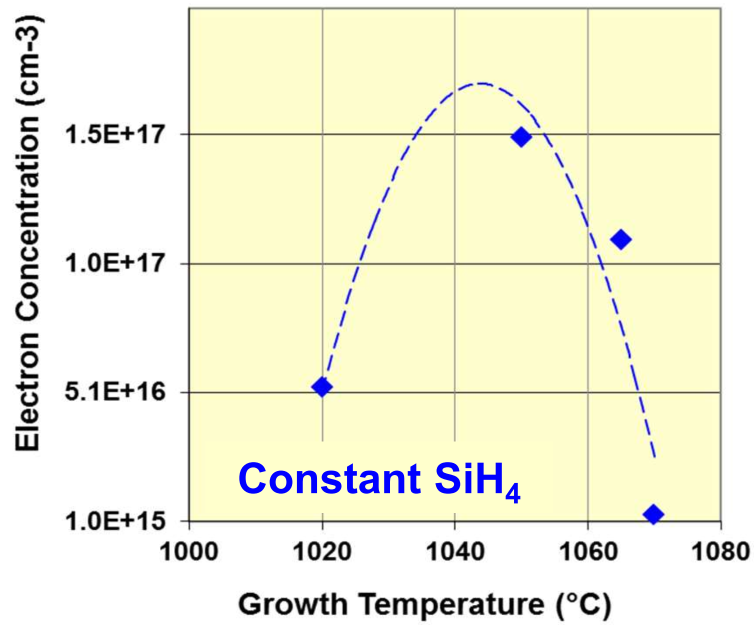
Control of N-type doping of drift region ($Al_{0.3}Ga_{0.7}N$)

➡ *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)*

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

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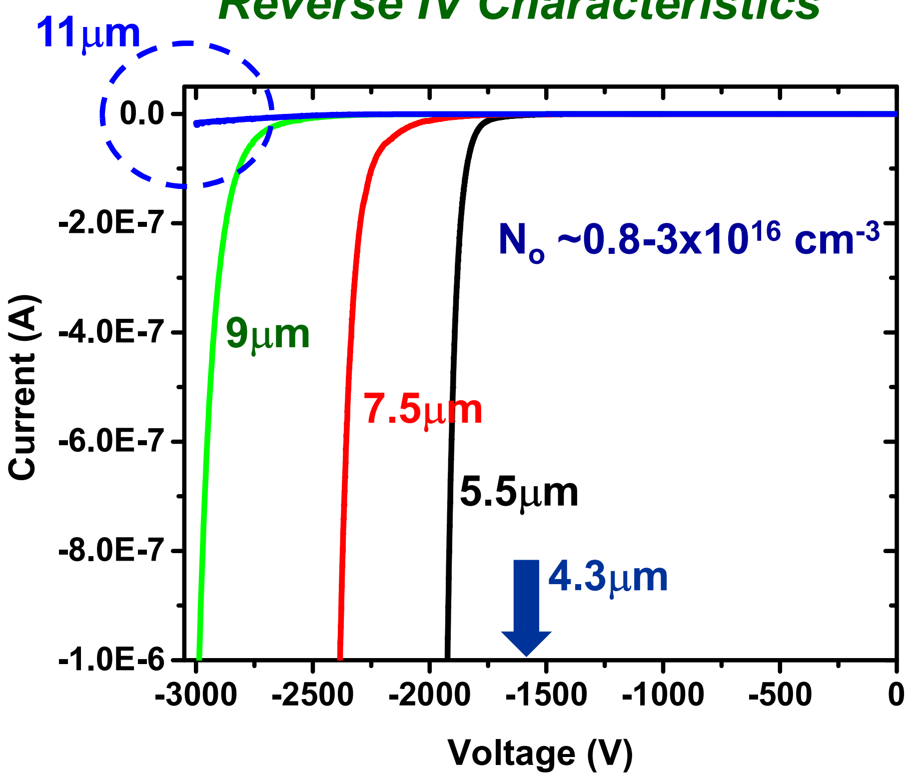
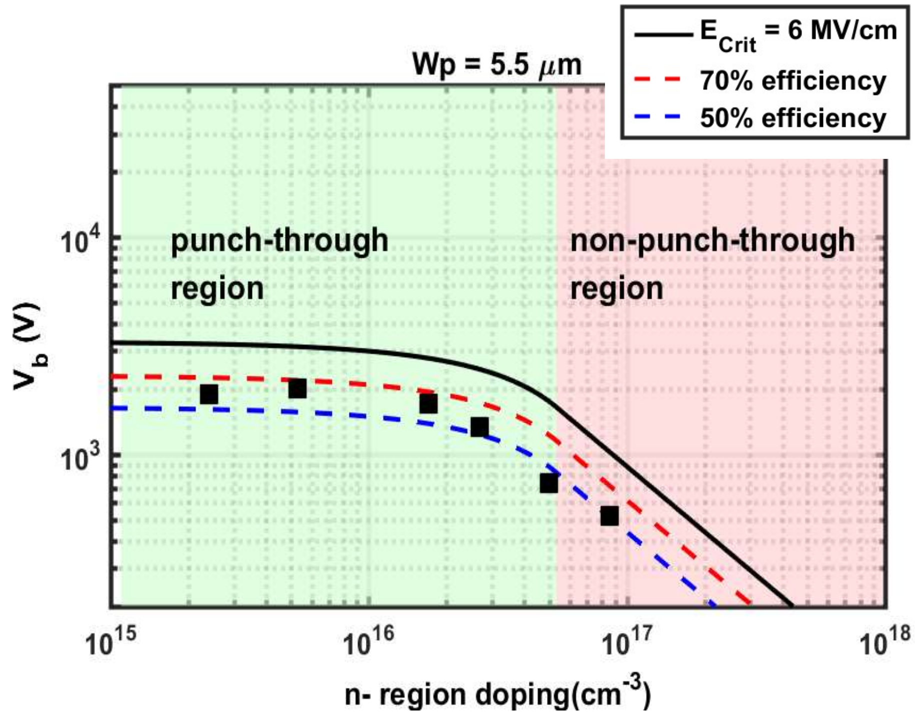
Reverse IV Characteristics



Breakdown Voltage vs. Drift doping



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

➡ E_C ~ 5.9 MV/cm

- **N_o of devices measured by CV**

➡ JTE is 50 – 70% effective (assumes E_{crit} = 6 MV/cm)

Breakdown voltages reported for III-Nitride PN diodes

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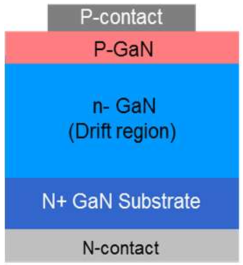
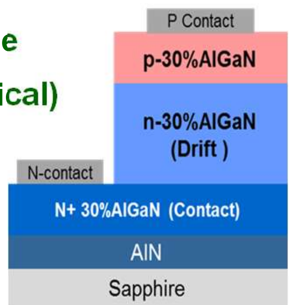
GaN diode (vertical)



AlGaN diode (Quasi-vertical)



III-N PN diodes with > 3 kV breakdown voltage

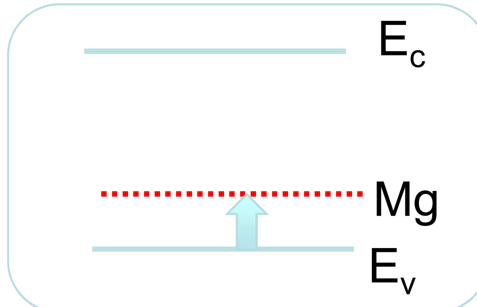
Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7	2/9/16e15	33	GaN	Hosei Univ.	EDL 36p1180_2015
4.0	2-5e15	40	GaN	Avogy	EDL 36p1073_2015
3.9	**3e15**	**30**	**GaN**	**Sandia**	**EL 52p1170_2016**
3.7	5e15	>30	GaN	Avogy	EDL 35p247_2014
3.48	1/3/12e15	32	GaN	Hosei Univ.	IEDM15-237_2015
>3	**0.8-3e16**	**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	← Higher reverse leakage

Approaches to $Al_{0.70}Ga_{0.30}N$ PIN Diodes

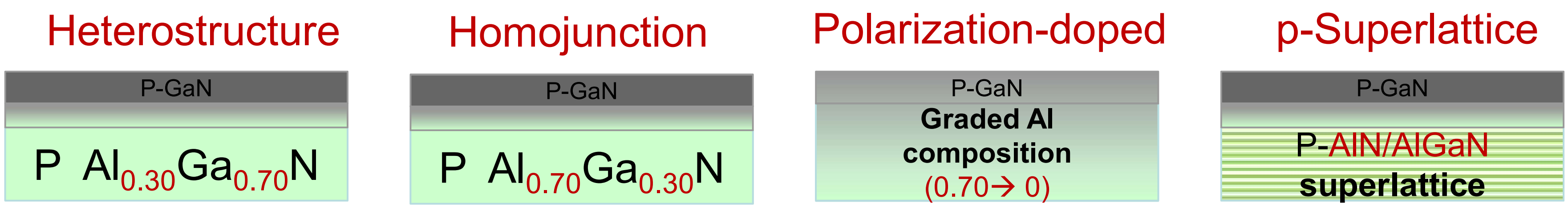
P-type doping very challenging with increasing Al:
E_a (GaN) ~180 meV
E_a (AlN) ~ 500 meV



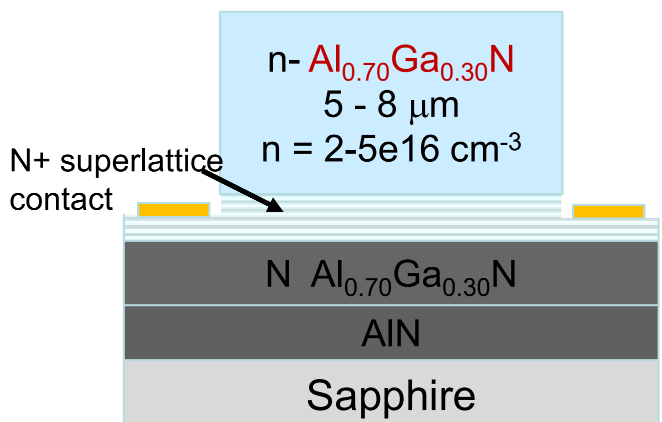
kT ~ 0.026 eV

Thermal activation of holes not viable for high-Al alloys

Device Designs



"Quasi-vertical" on sapphire: Common design except for p-side



Vertical on n-GaN: ultimate goal

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

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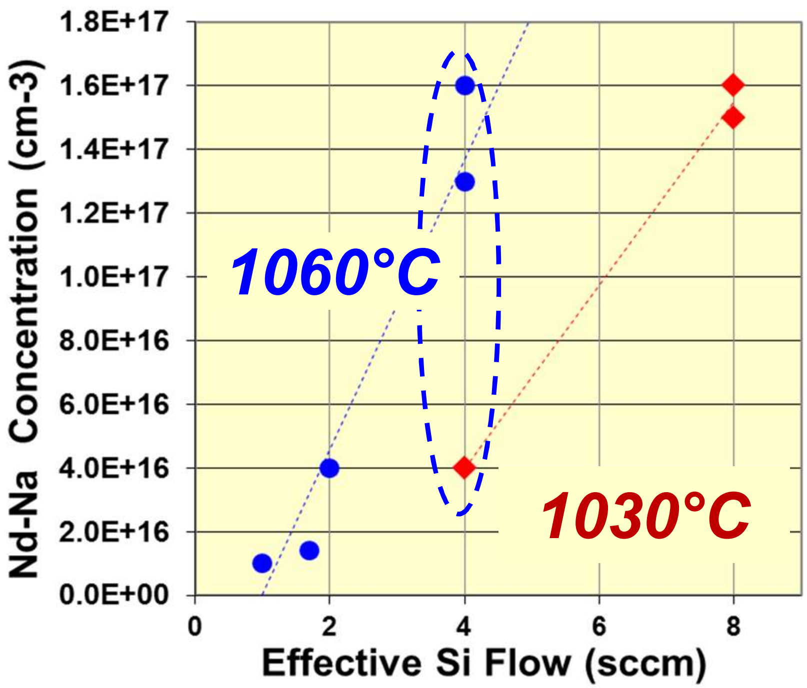
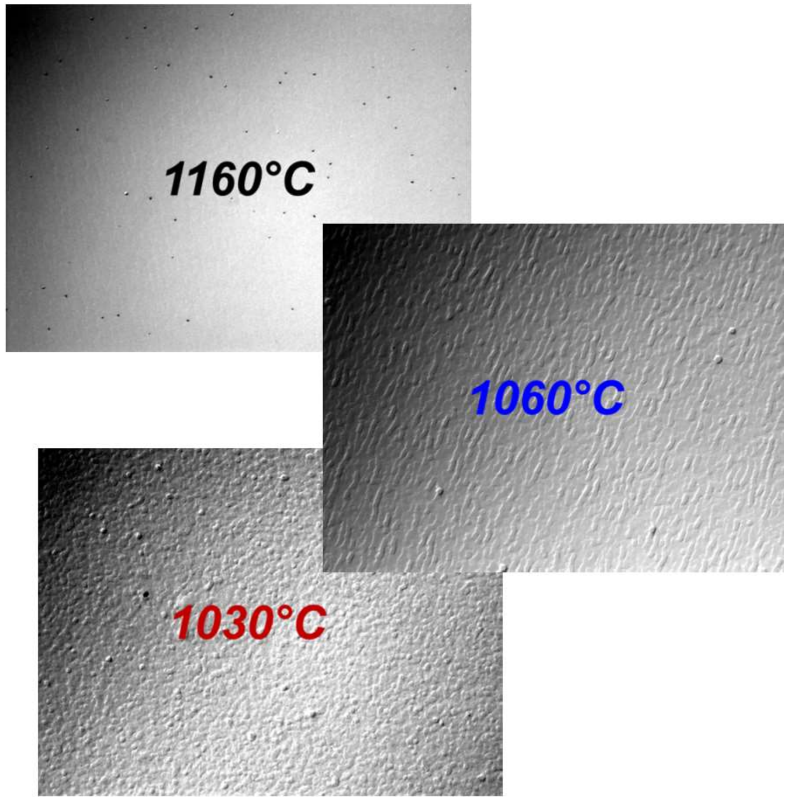
Electron concentration (CV) vs. SiH_4 flow (70%AlGaN)



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

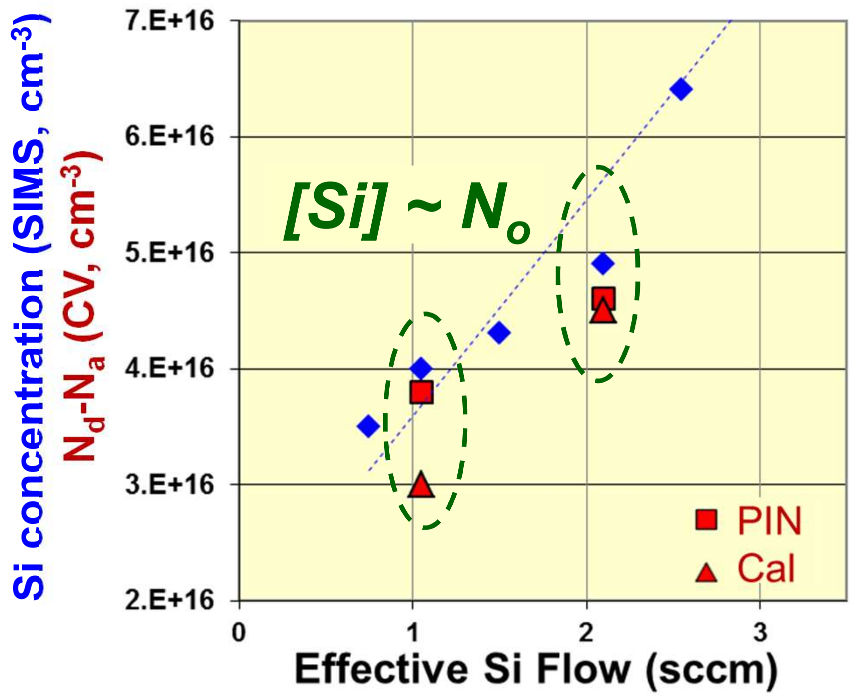
Nomarski DIC (50x) of 70%-AlGaN



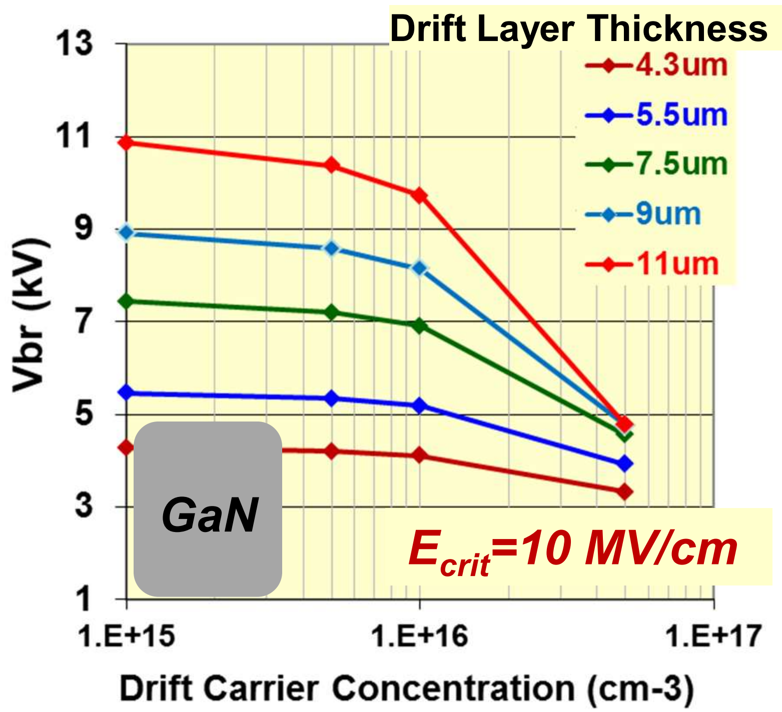
- Surface morphology depends on growth temperature (and AlN)

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

Growth temperature & compensation in Si-doped 80%AlGaN

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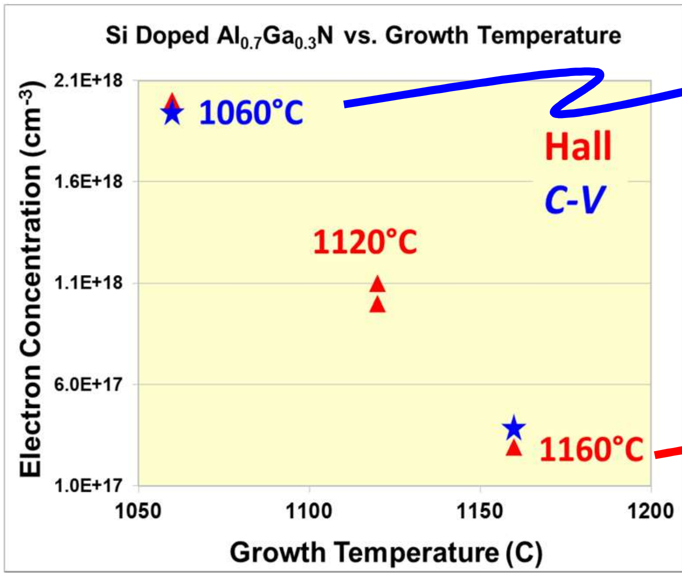
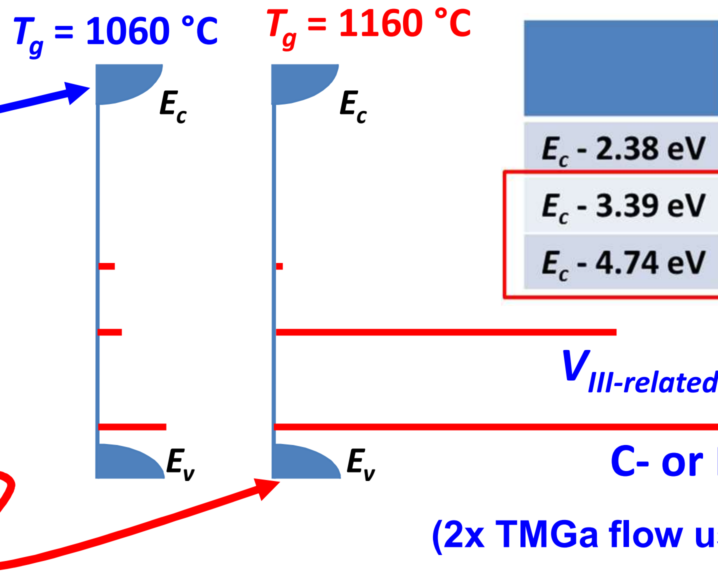
Electron concentration in Si-80%AlGaN



Armstrong JAP 117 (2015)

Deep level traps in Si-80%AlGaN



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

(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

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

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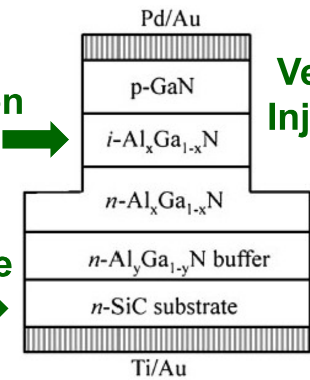
$Al_xGa_{1-x}N$ *Vertical* PN diode (0 < Xal < 0.57)

- **Drift Layer: ~ 0.2 μm, N_o ~ 2×10^{16} cm^{-3}**
- **N-SiC substrates, $R_{on,sp}$ = 1.45 mΩ-cm^2 (X_{al}=0.22)**

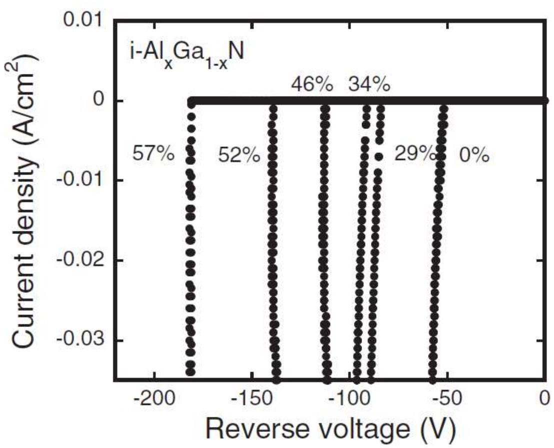
Drift region

Vertical Injection

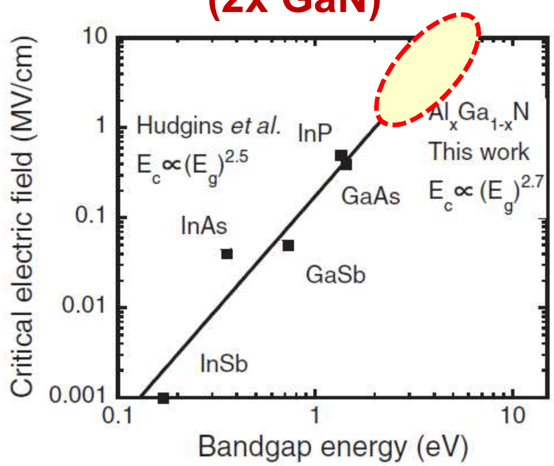
Conducting SiC substrate



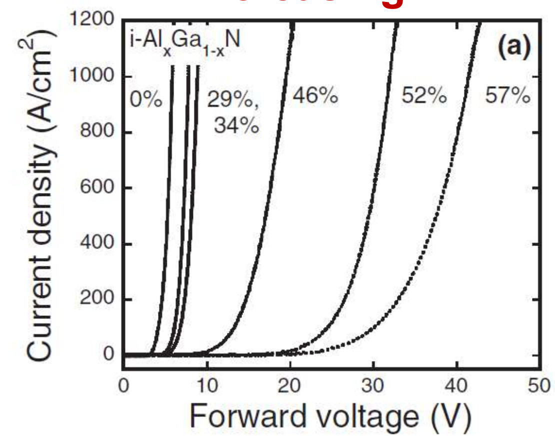
Reverse Breakdown < 200V



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



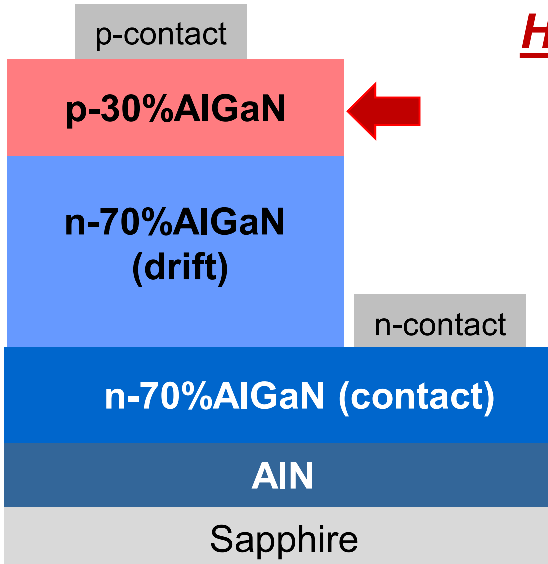
Higher forward turn-on for increasing Al



➡ **Breakdown voltage increases with larger bandgap**

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

"Quasi-vertical" heterojunction PIN in $Al_{0.70}Ga_{0.30}N$



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

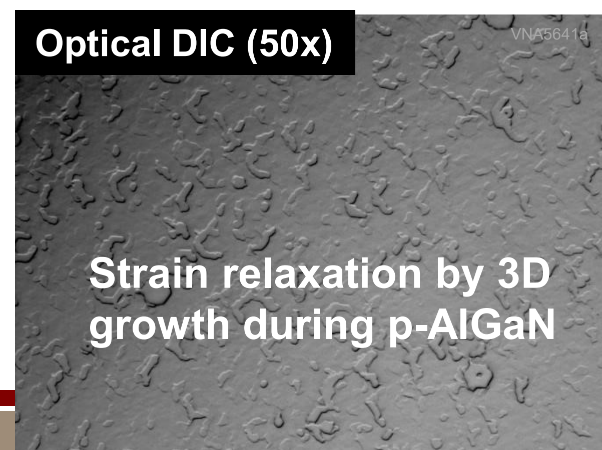
- **Same p-type 30%-AlGaN used in 30%AlGaN homojunction (~ 0.3 μm)**
- **Investigated different transition at pn interface**
- **Drift layer: 4.4 – 9.0 μm (Total: 7.1 – 15.4 μm)**
  - ➡ ***No cracking!***
- **Drift layer doping: 1-3 x 10^{16} cm^{-3}**
  - ➡ ***Suitable for Vbr from 4 – 8 kV***

Projected V_{br} (kV) for N_o, t_{drift}

Drift (um)	5e15	1e16	5e16
4.3	4.2	4.1	3.3
5.5	5.3	5.2	3.9
7.5	7.2	6.9	4.6
9	8.9	8.6	4.8

J. Dickerson

E_{crit} = 10MV/cm



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

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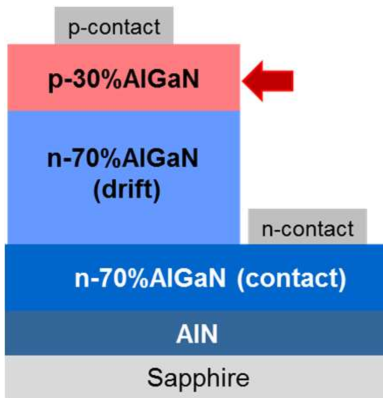


Heterojunction PN diodes (p-30% / n-70%)

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

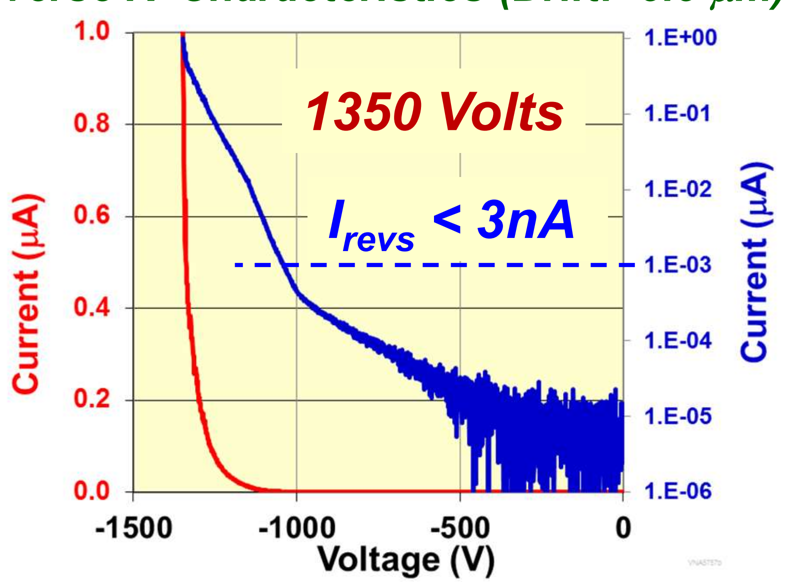
5.5μm ➡ 1300V

8.0μm ➡ 1850V

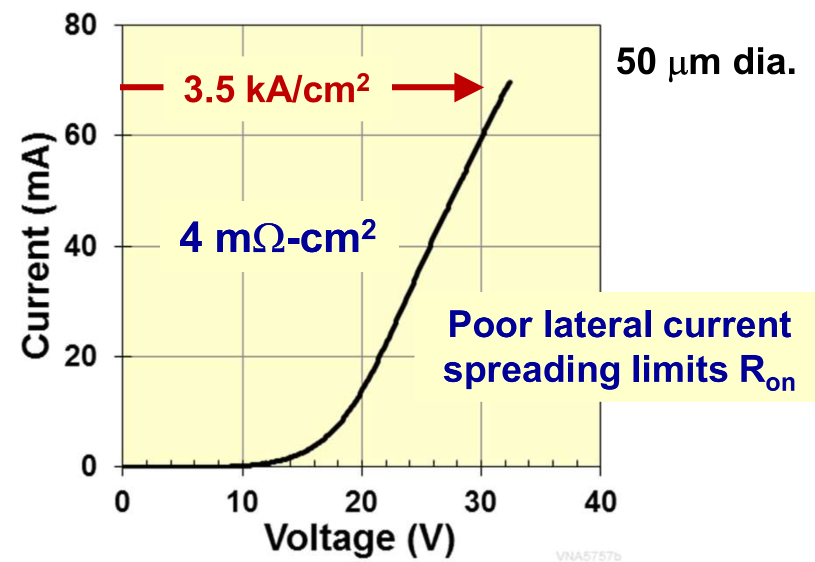
➡ ***E_{crit} ~ 2.3 MV/cm (very low)***

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

Reverse IV Characteristics (Drift: 5.5 μm)



Forward IV Characteristics



Homojunction $Al_{0.7}Ga_{0.3}N$ “Quasi-Vertical” PN diode

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Mg - $Al_{0.70}Ga_{0.30}N$ layer designs

- **Modulate [Mg] to change E field / JTE**
- **Compare V_{br} to heterojunction diode**
- **On same drift layer 5.5 μm as heterojunction diode**

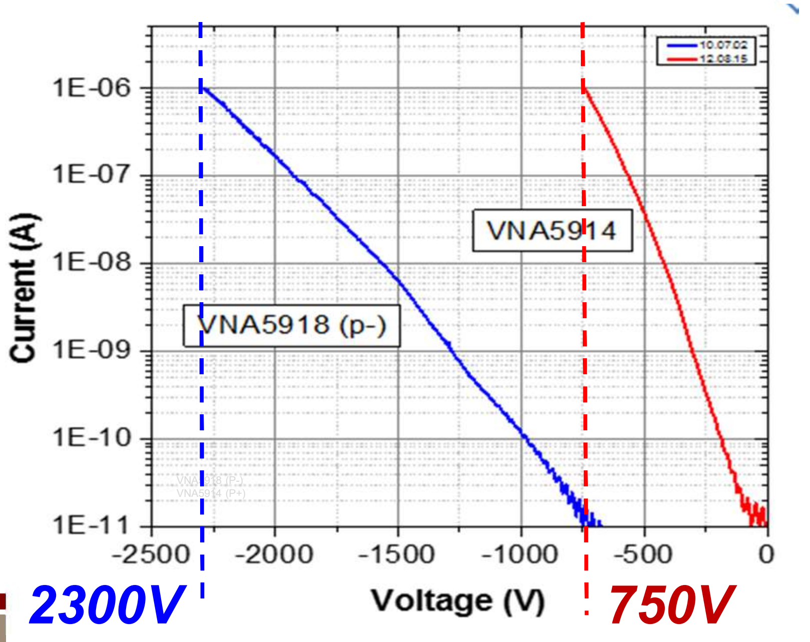
Constant Mg

P-GaN
Grade
0.22 μm, $2e19\ cm^{-3}$

P-minus

P-GaN
Grade
4e19 cm^{-3}, 0.14μm
4e18 cm-3, 0.08μm

Reverse IV Characteristics



IV Characteristics

- **Resistive as expected ➡ V_{fwd} ~130V @ 1μA**
- **Reverse voltage much higher for P-minus (2300V) vs. Constant Mg (750V)**
- ***Drift layer (5.5 μm) can support 2.3kV***

➡ ***Reverse voltage (1.3kV) in HJ diode is JTE or p-side limited***

➡ **Example of importance of controlling electric fields.**

Approaches for hole transport in $Al_{0.7}Ga_{0.3}N$ PN diodes

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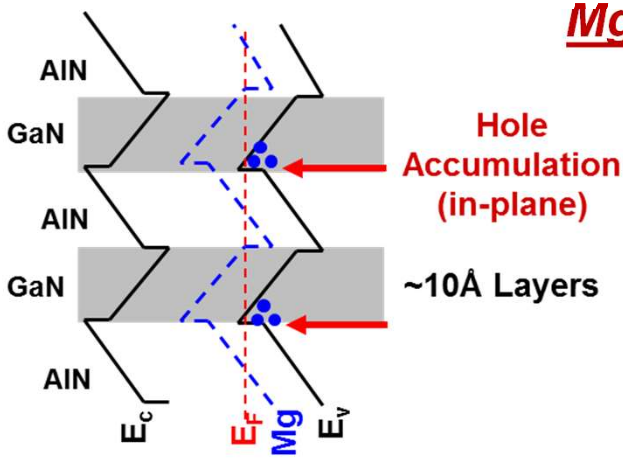
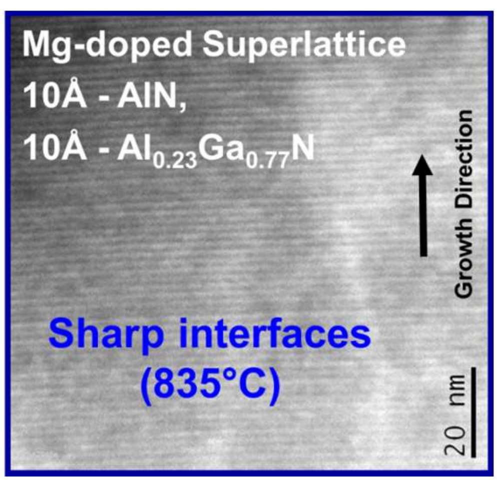
Allerman, JCG 2010



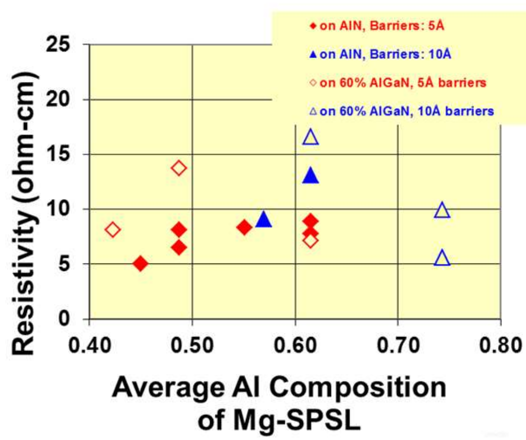
Mg-doped short-period superlattice (Mg-SPSL)

- **Strong polarization fields ionized Mg dopants**
- **Adjust average composition with layer thickness, X_{al}**
- **Low in-plane resistivity (5-10 Ω-cm)**
- **Heterojunctions increase $V_{forward}$ (vertical transport)**

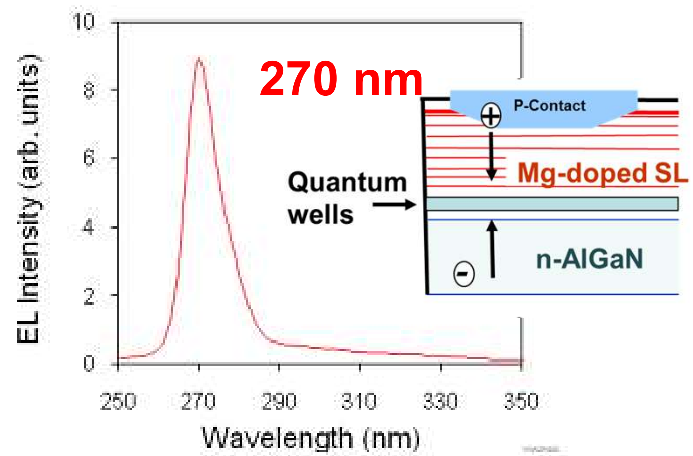
TEM



P-type Resistivity of Mg-SPSL

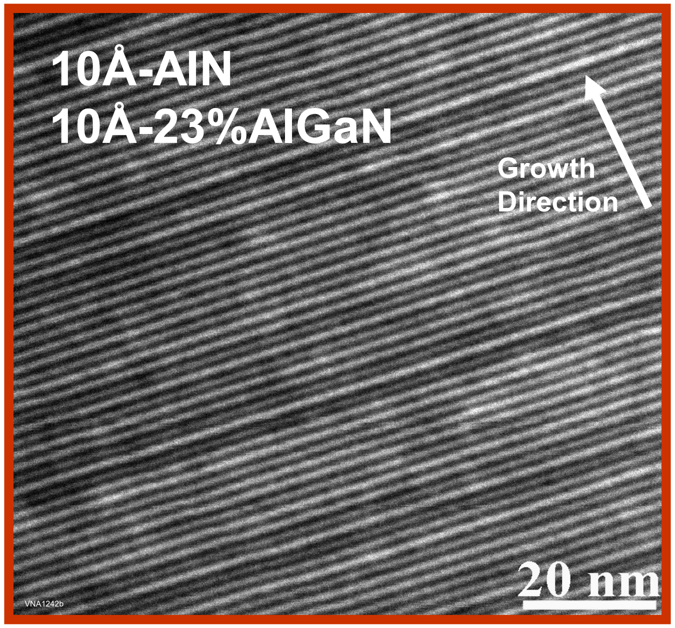


Electroluminescence from p-SPSL LED

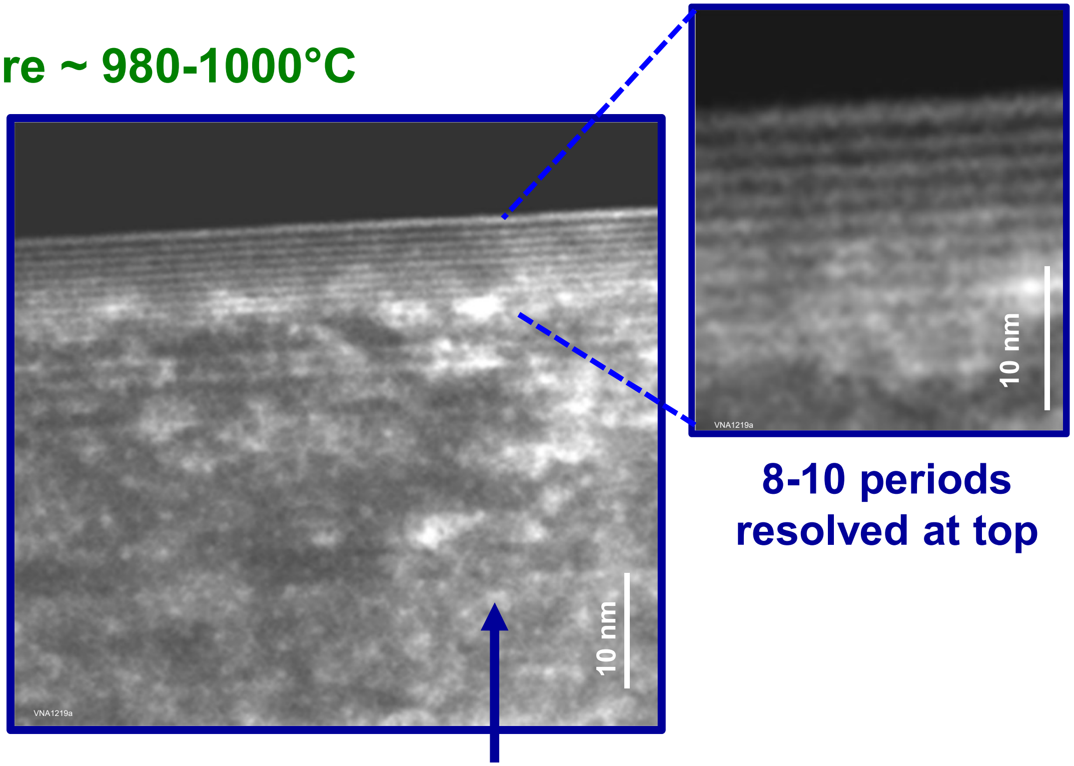


Approaches for hole transport in $Al_{0.7}Ga_{0.3}N$ PN diodes

Growth Temperature ~ 980-1000°C



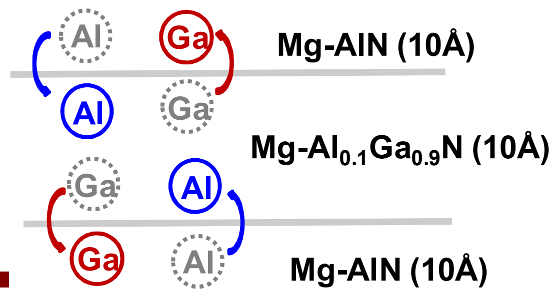
Undoped: Well resolved layers



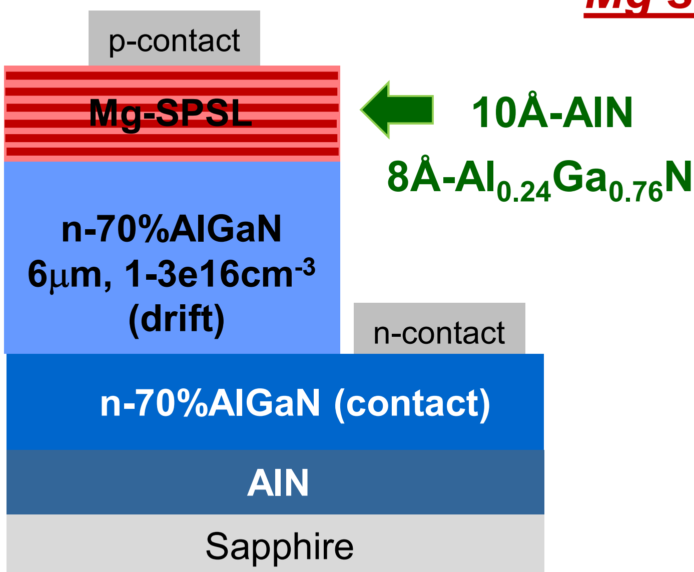
8-10 periods resolved at top

Mg-Doped: Intermixed layers

- ➡ Not intermixing at growth surface
- ➡ Al, Ga diffusion process due to Mg doping



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

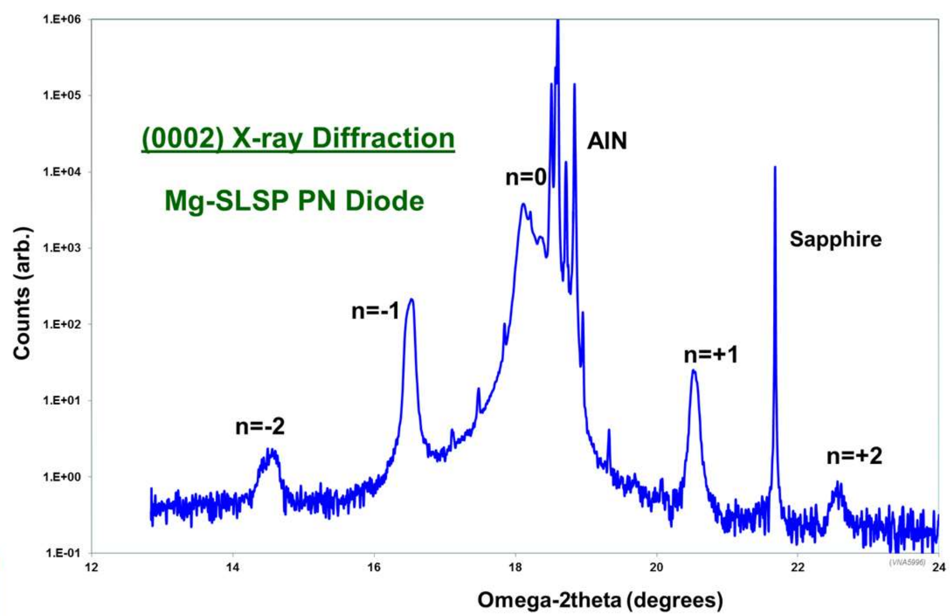


- P-type resistivity: 7-10 Ω–cm
- [Mg] ~ 3-4 e19 cm^{-3}
- Thickness: 0.3 μm (160x)
- Average Xal: 0.66
- Period by XRD: 22.1Å

➡ *Growth temperature: 835 °C*

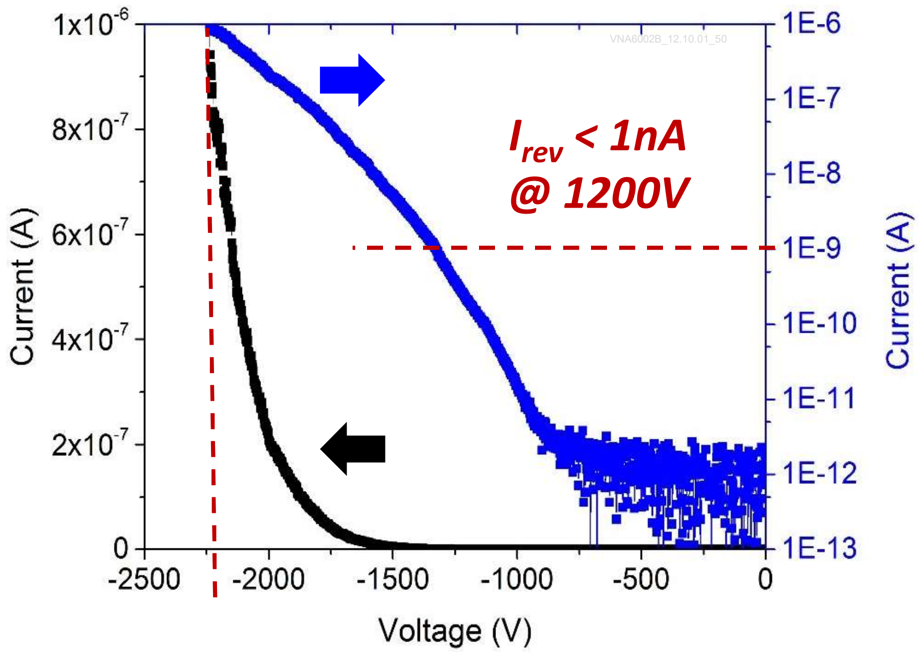
➡ *Mg-SPSL is reproducible*

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

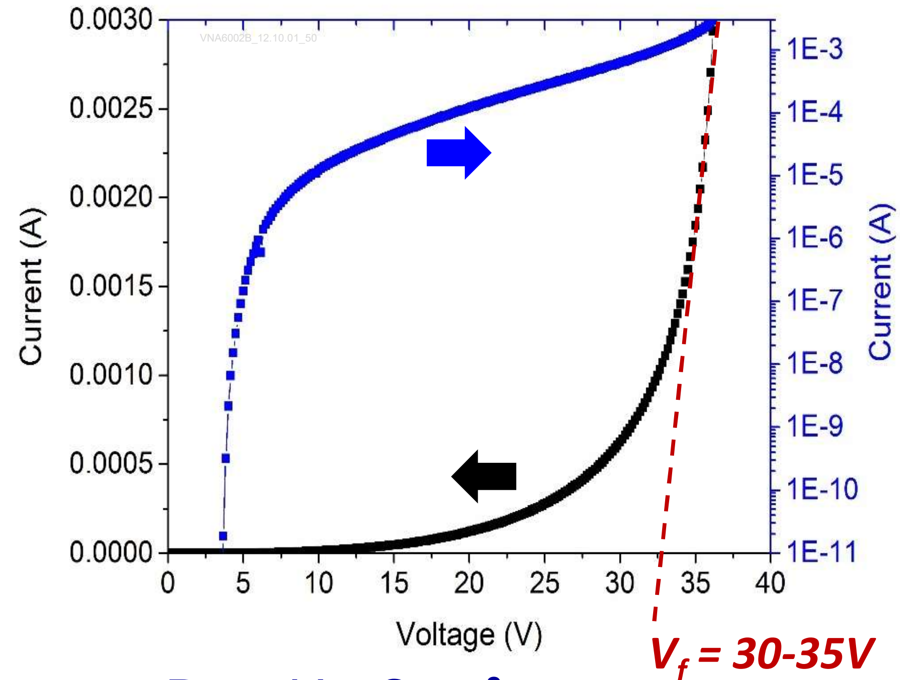
Reverse IV Characteristics



- **Breakdown ~ -2200V (@ 1μA)**

  E_{crit} ~ 3.7 MV/cm

Forward IV Characteristics



- **R_{on} ~ 14 mΩ-cm^2**
- **High forward voltage ~ 30-35V**

➡ **Lower forward voltage by adjusting heterobarrier in Mg-SPSL**

➡ **Increase breakdown by optimizing JTE**

Summary

Sandia National Laboratories

- Quasi-vertical Al_xGa_{0-x} N PIN diodes (X_{al}=0.3)
  - Breakdown voltage > 3000V with n-type drift layer of 11 μm
  - Measured a critical electric field of 5.9 MV/cm^2 for 30%AlGaN

- Quasi-vertical Al_xGa_{0-x} N PIN diodes (X_{al}=0.7)
  - Compensation in drift layer is similar to n-GaN (~ 1e16 cm^{-3})
  - Heterojunction diode (p-30% / n-70%):
    - V_{br} ~ 1350V, V_f = 7-10V, problem with JTE & low Xal p-layer
  - Mg-short period superlattice:
    - V_{br} ~ 2200V, V_f is higher 30-35V