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Veeco D-125 MOCVD system

AlGaN-Based PN Diodes for Power Electronics

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Acknowledgements:
M. Smith, K. Cross, and V. Abate

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

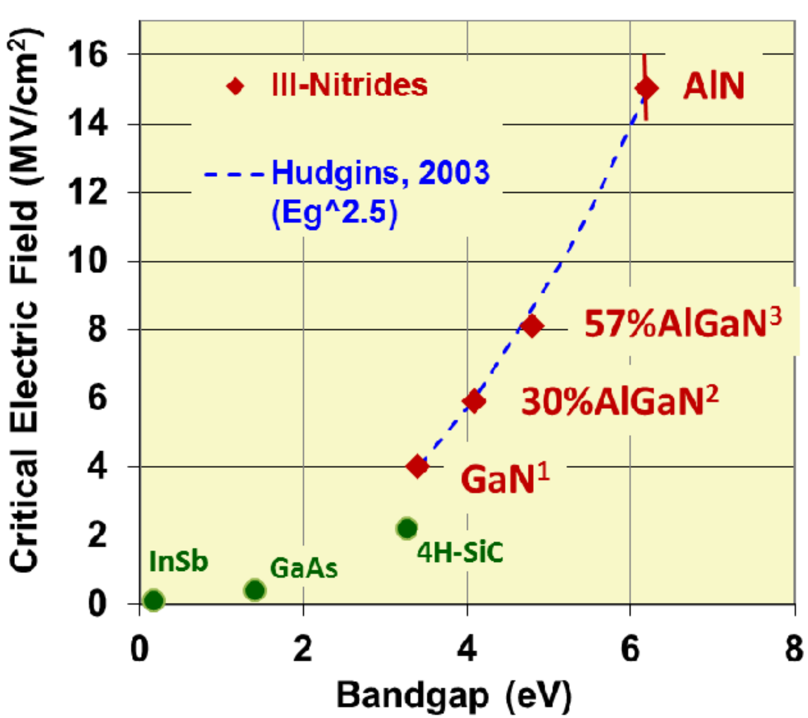
Critical Electric Field (MV/cm)

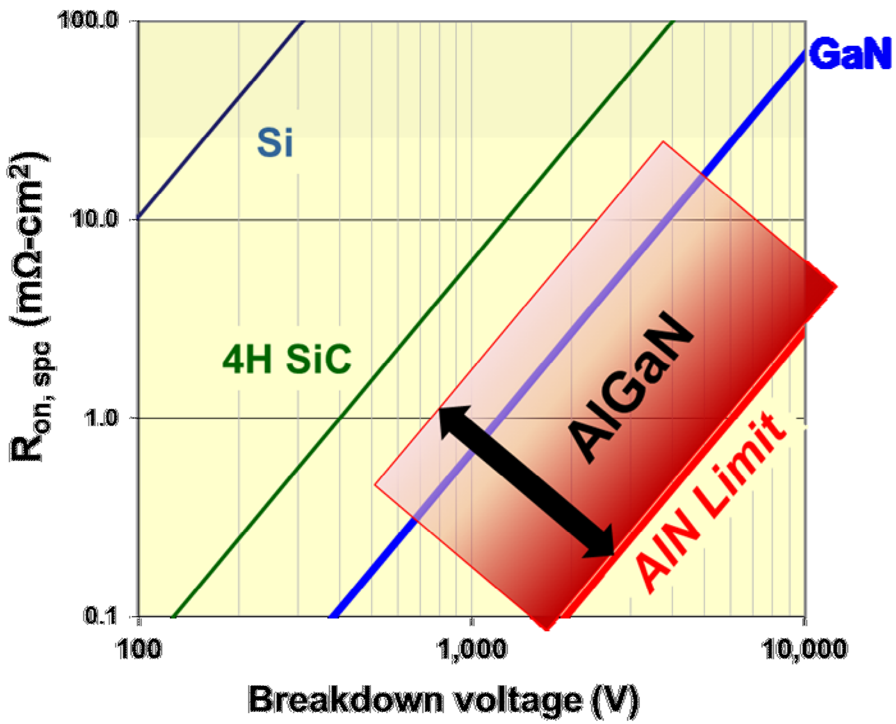
$$E_C \propto E_g^{2.5}$$ (Direct gap)

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



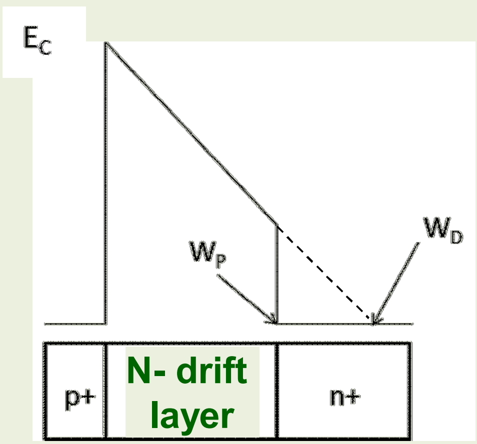


1-Armstrong, EL 2016, 2-Allerman, EL 2016, 3-Nisikawa, JpnJAP 2007

Breakdown voltage of drift layer: doping and thickness

Punch-Through

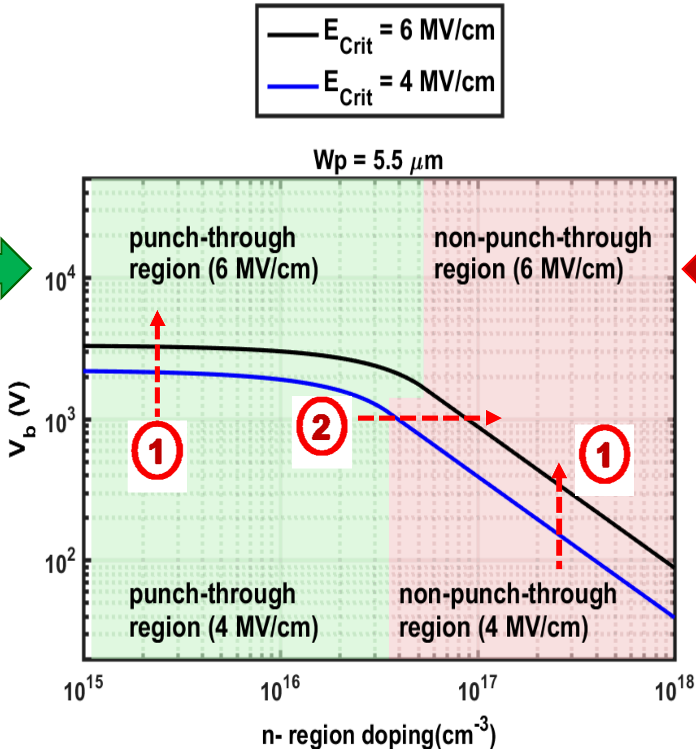
$W_P < W_D$



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

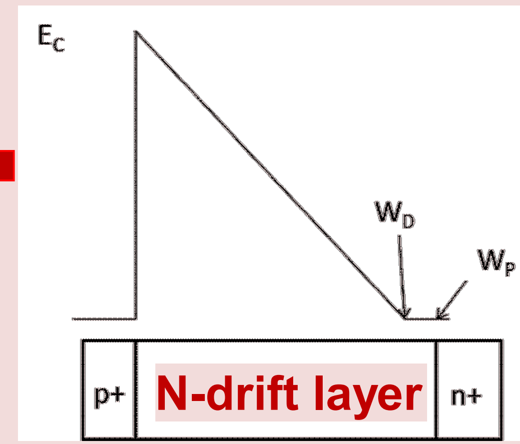
- N_d is lower than optimal

➡ ***Thickness determines V_{br}***



Non-Punch-Through

$W_P \geq W_D$

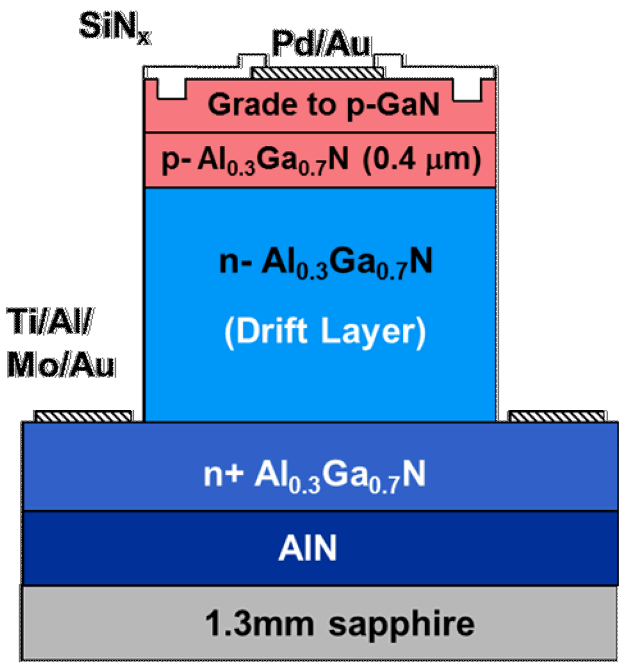


$$V_{br} = \frac{\varepsilon E_C^2}{2 q N_D}$$

- Drift layer is thicker than optimal

➡ ***N_d determines V_{br}***

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



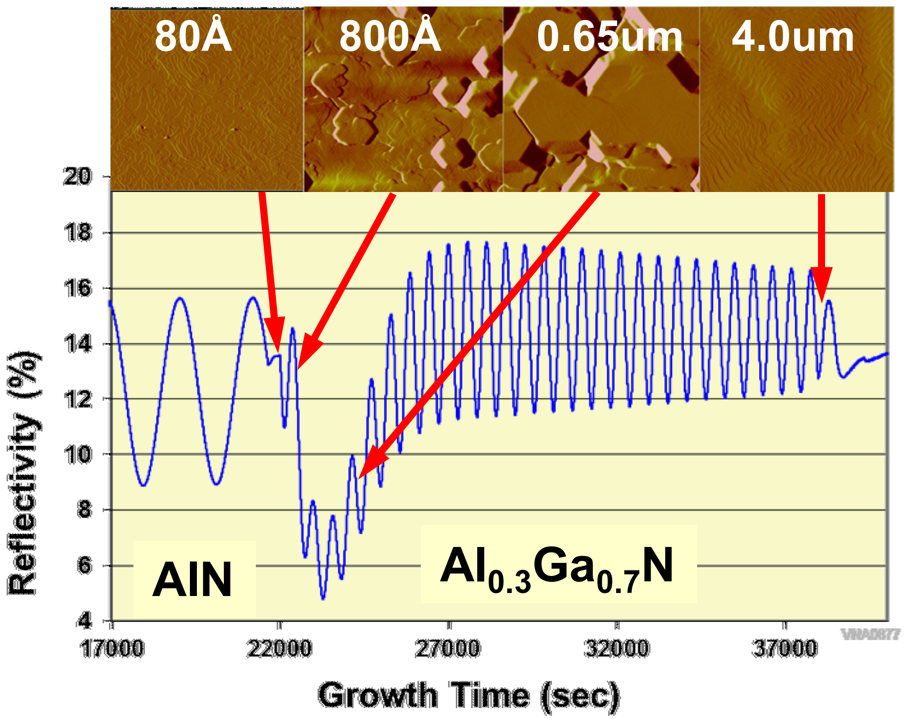
Quasi-Vertical PN diode structure

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, 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^{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}*

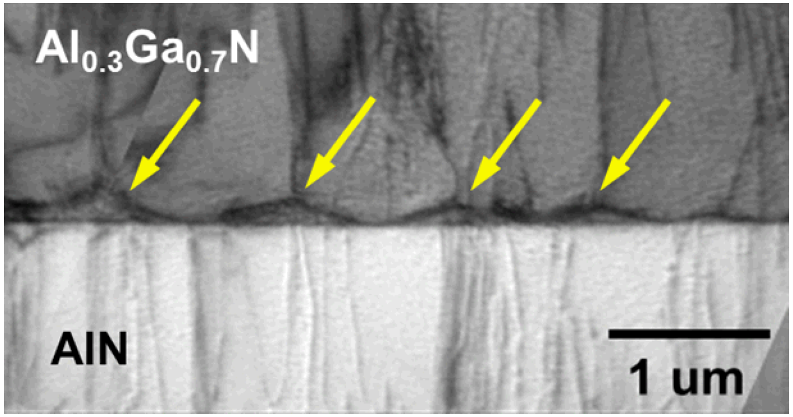
Relaxation and TDD reduction in $Al_{0.3}Ga_{0.7}N$ on AlN

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 ~ 2-4x10^9 cm^{-3}**

Cross-section TEM



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

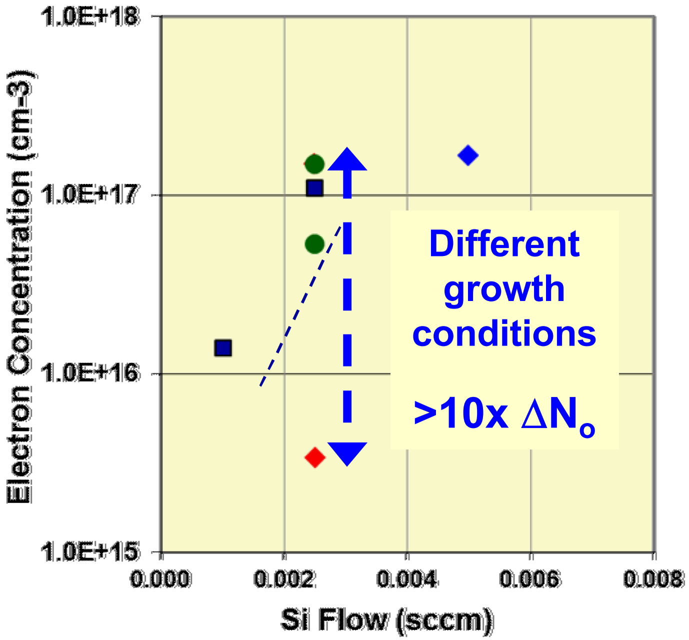
- **Strain is relieved by interfacial misfit dislocation networks with hexagonal boundaries**
- **Threading dislocations “bundle” into triangular features**

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

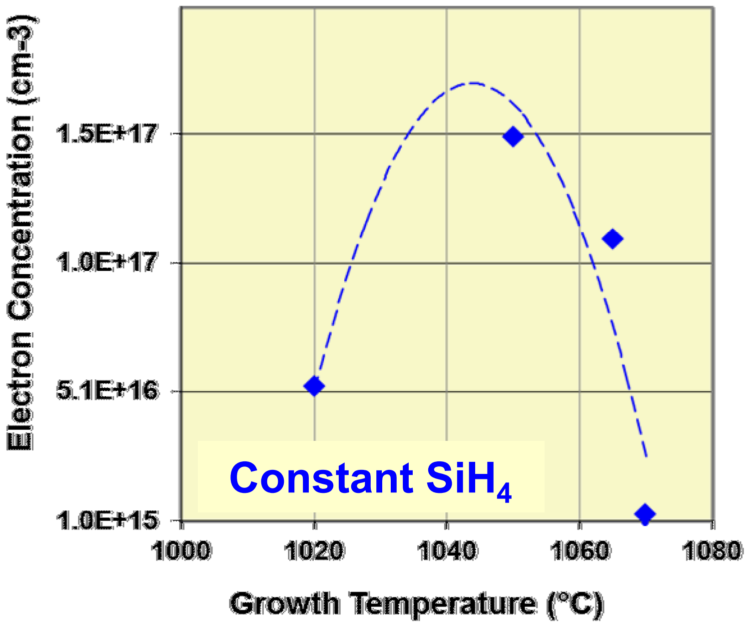
Control of N-type doping of drift region ($Al_{0.3}Ga_{0.7}N$)

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

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



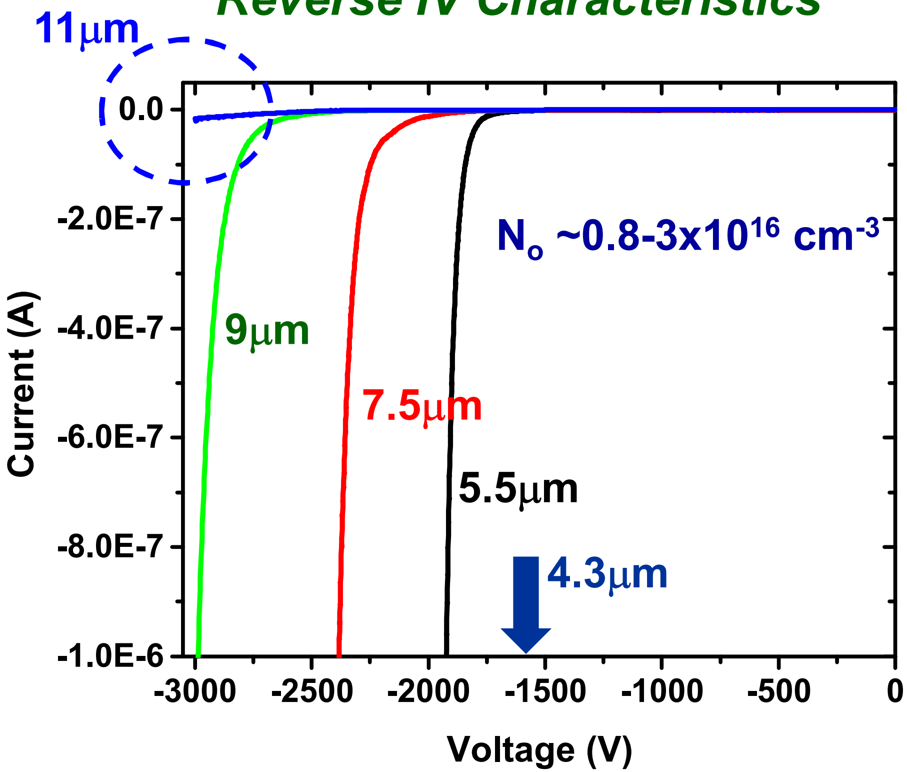
Electron concentration (hall) vs. growth temperature (30%AlGaN)



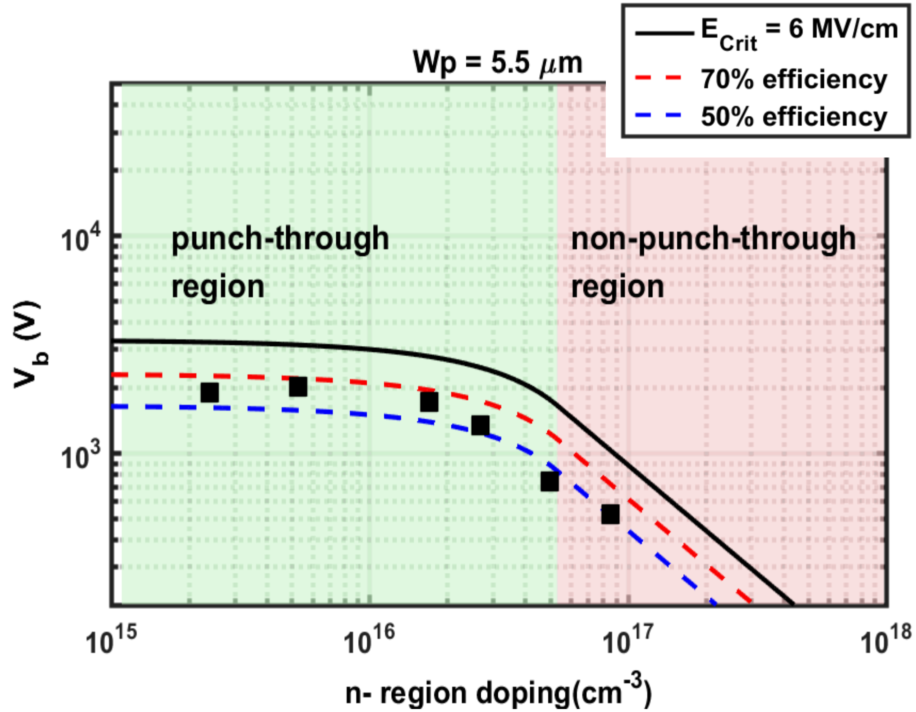
➡ *… electron concentration is highly dependent on growth condition (i.e. the density of compensating defects)*

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

Reverse IV Characteristics



Reverse Voltage vs. Drift doping



- Reverse voltages ~ 3000V @ 1µA

➡ E_C ~ 5.9 MV/cm

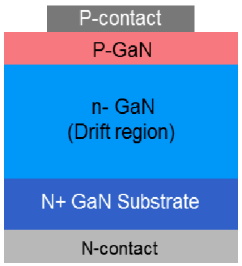
➡ Kilovolt class diodes

- N_o measured by CV

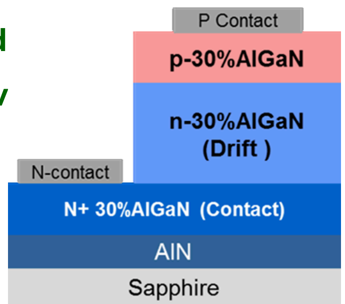
➡ JTE is 50 – 70% effective (assumes E_{crit} = 6 MV/cm)

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	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

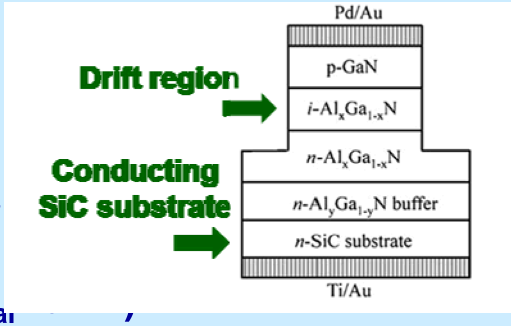
Advantages of wide-bandgap III-Nitride

	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

Prior AlGaN PIN and Schottky diode results

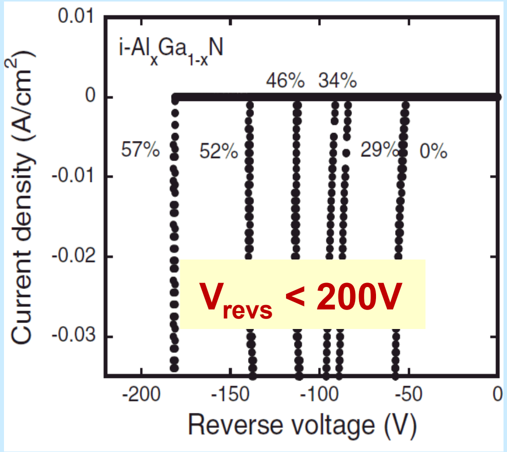
$Al_xGa_{1-x}N$ *Vertical* PN diode (0 < Xal < 0.57)

Nishikawa, Jpn J. App. Phys. 2007

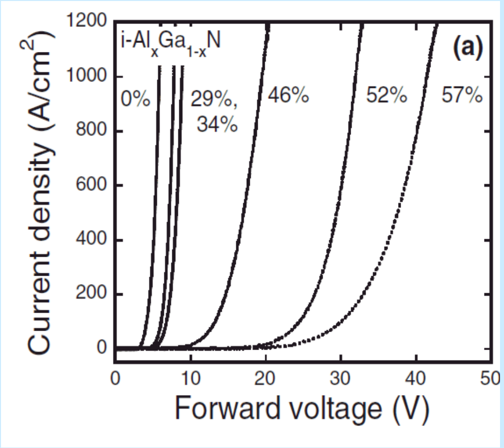


- Drift Layer: ~ 0.2 μm
  N_o ~ $2x10^{16}$ cm^{-3}
- $R_{on,sp}$ = 1.45 mΩ-cm² (X_{al}

Reverse IV



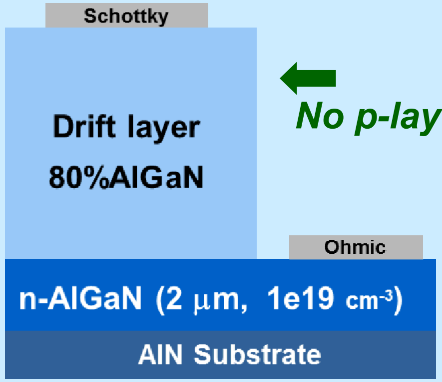
Forward IV



- E_{crit} ~ 8 MV/cm (2x GaN)
- V_{fwd} ~ 30V (X_{al} = 0.57)

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

P. Chow – ICNS, 2017



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

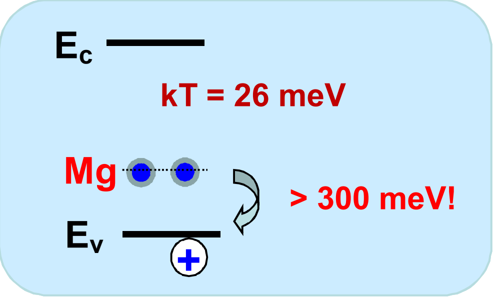
➡ E_{crit} ~ 10 MV/cm

P-type doping of Xal > ~ 50%AlGaN is poor

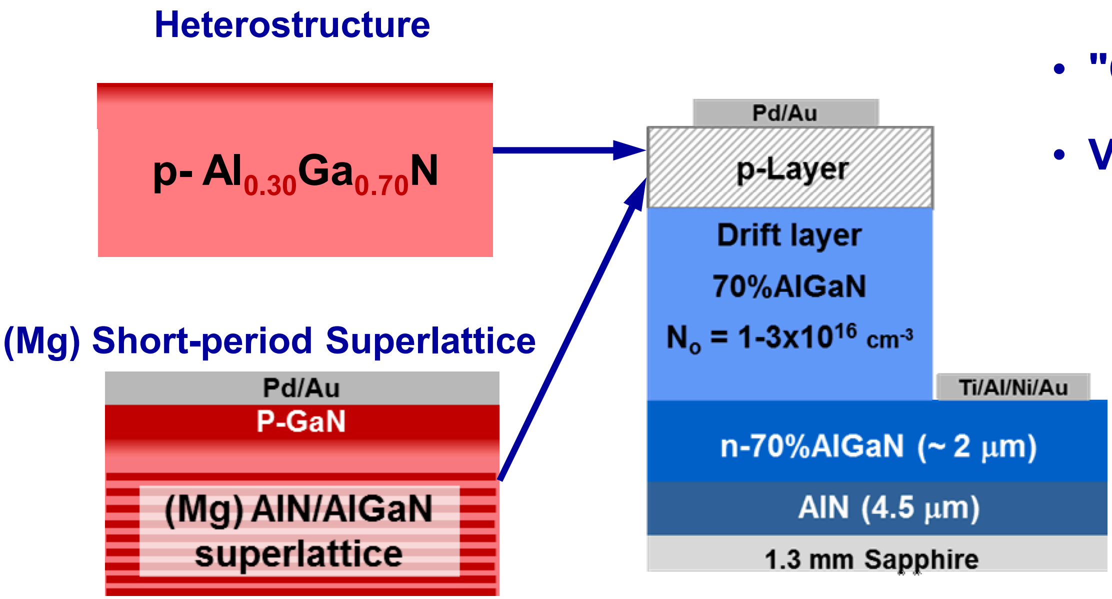
- Large acceptor ionization energies

  E_a (GaN) ~ 180 meV, E_a (AlN) ~ 500 meV

  ➡ Thermal ionization is not effective for holes



P-layer designs and drift region for $Al_{0.7}Ga_{0.3}N$ PIN diodes

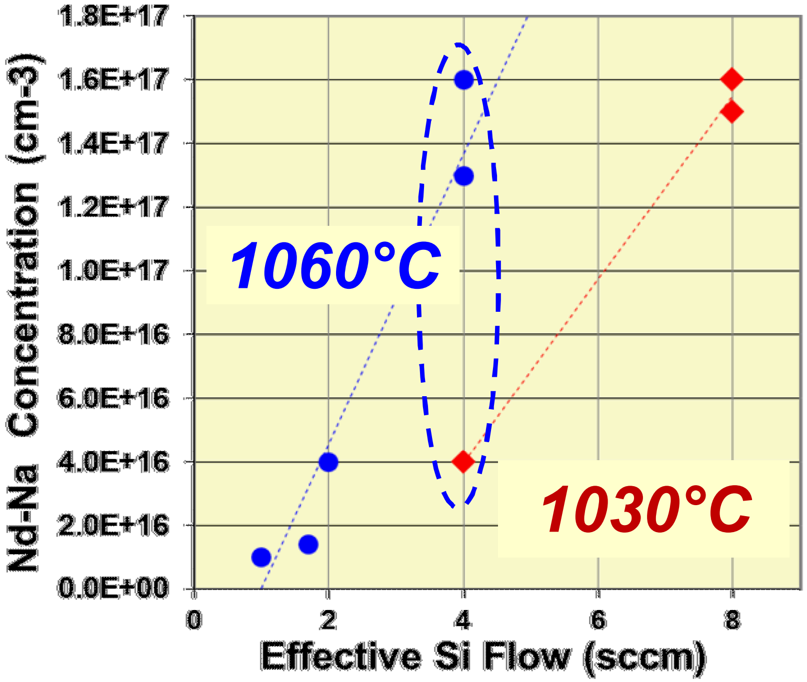


- "Quasi-vertical" design
- Vertical geometry for low R_{on}

	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

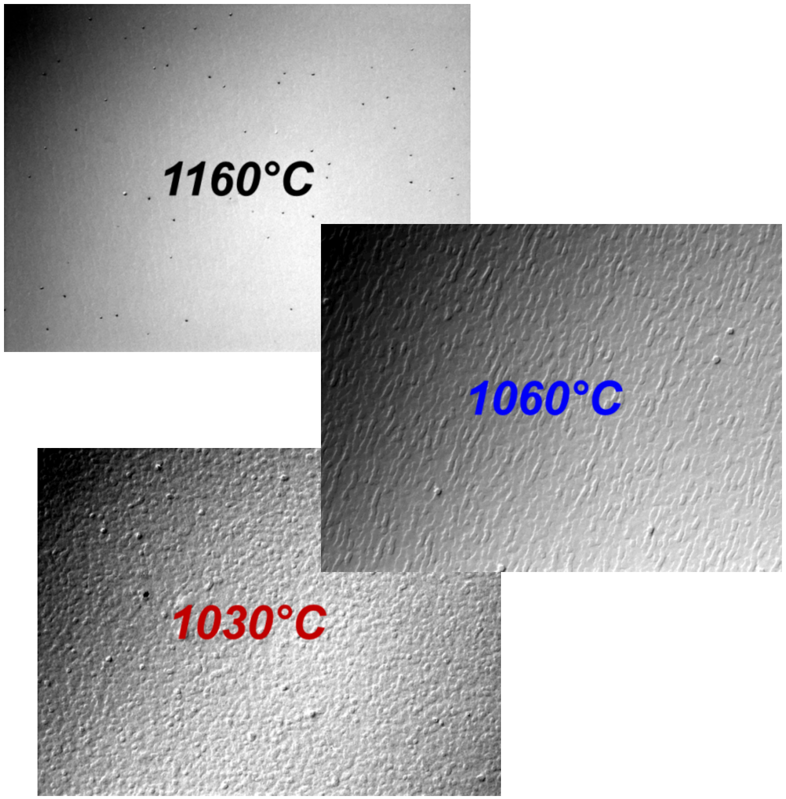
Compensation of Si doped drift region (70%-AlGaN)

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



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

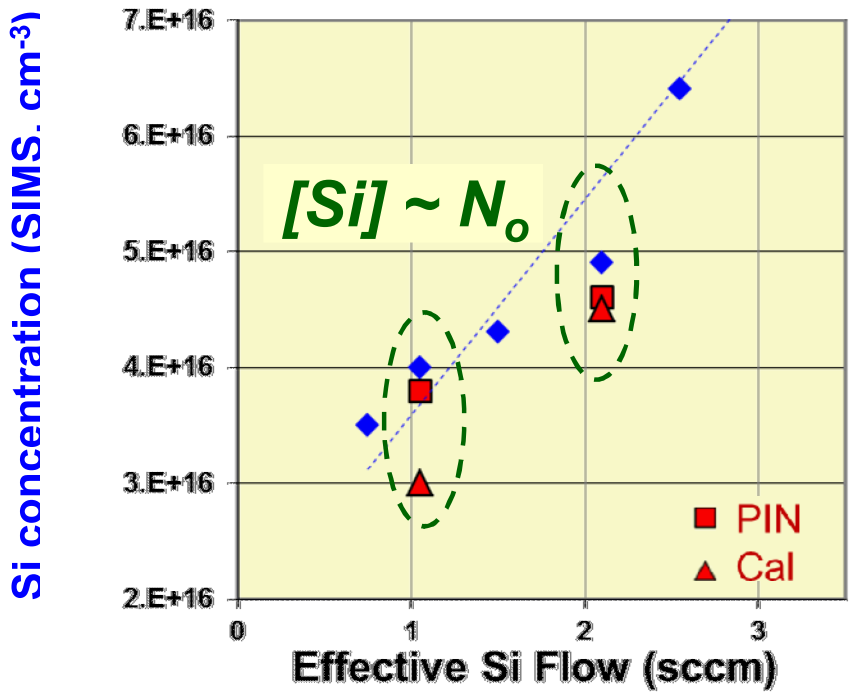
Nomarski DIC (50x) of 70%-AlGaN



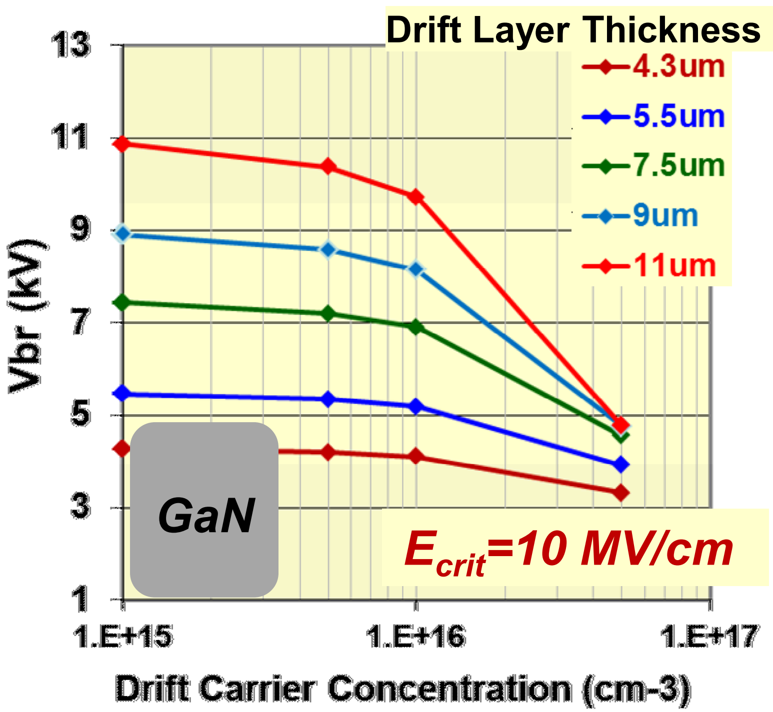
- ➡ Surface morphology depends on growth temperature (and AlN)

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)



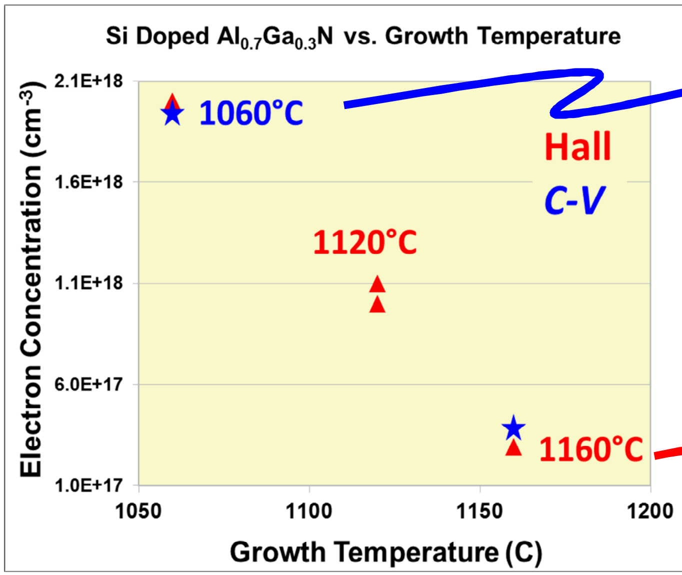
➡ Donor compensation ~ 1e16 cm^{-3}

➡ ***Similar to GaN!***

➡ N_o ~ 1e16 cm^{-3} for ~10 kV

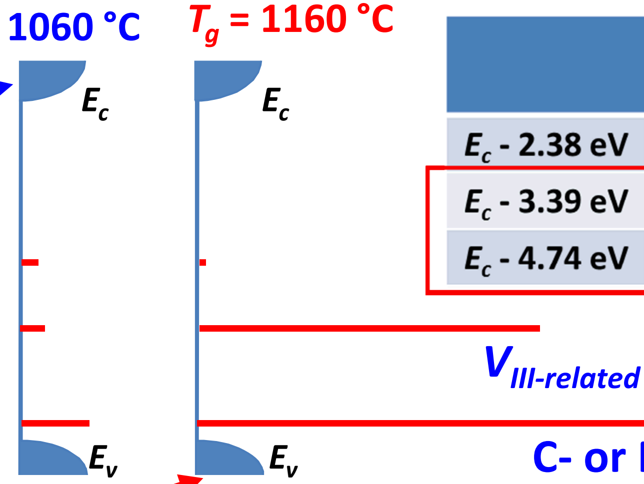
➡ Si doping is above the level of compensation

Electron concentration in Si-80%AlGaN



Armstrong JAP 117 (2015)

Deep level traps in Si-80%AlGaN

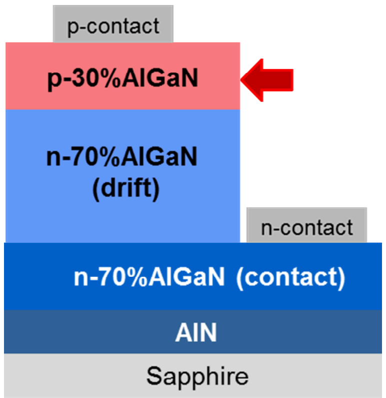


	1060 °C N_t (cm^{-3})	1160 °C N_t (cm^{-3})
E_c - 2.38 eV	2.4 x 10^{16}	1 x 10^{16}
E_c - 3.39 eV	3.6 x 10^{16}	5.1 x 10^{17}
E_c - 4.74 eV	1.0 x 10^{17}	6.6 x 10^{17}

(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**

$Al_{0.7}Ga_{0.3}N$ "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:**

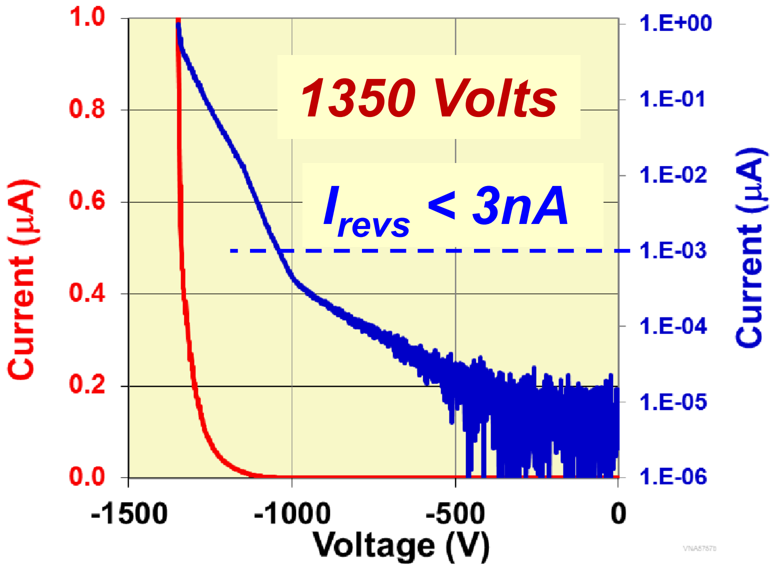
5.5μm ➡ 1300V

8.0μm ➡ 1850V

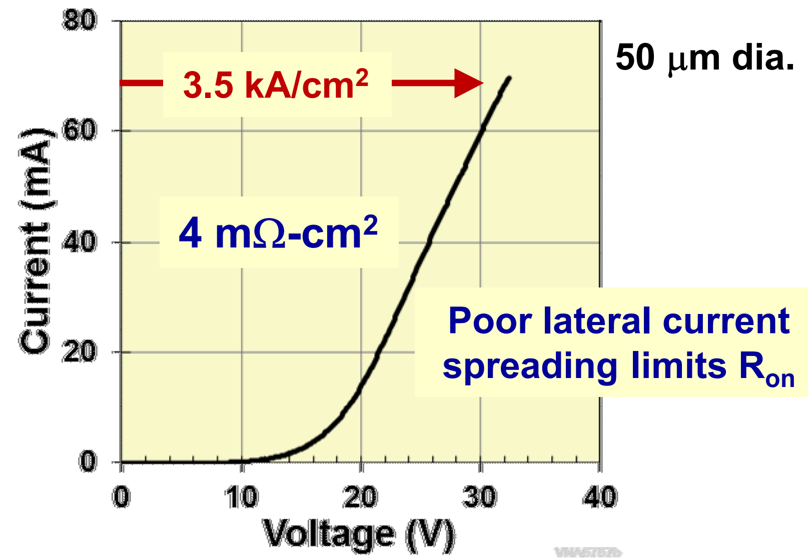
➡ E_{crit} ~ 2.3 MV/cm (very low)

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

Reverse IV Characteristics (Drift: 5.5 μm)

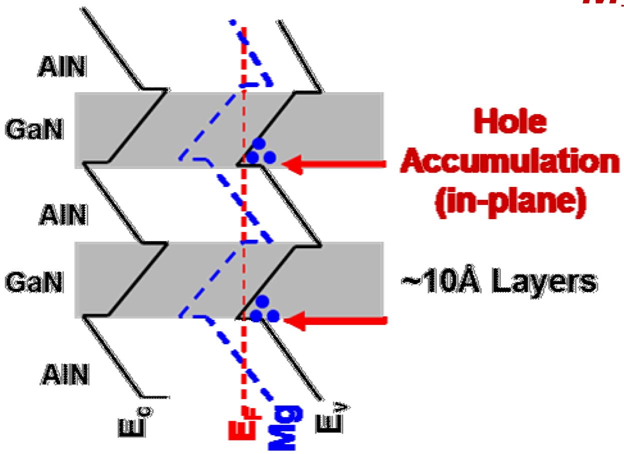


Forward IV Characteristics



Mg-doped short-period superlattice for p-layer in PN diodes

Allerman, JCG 2010

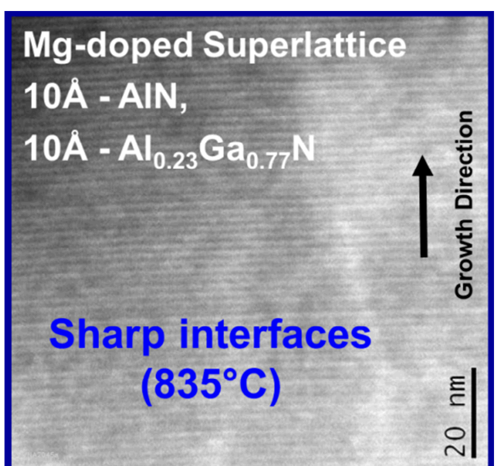


Mg-doped short-period superlattice (Mg-SPSL)

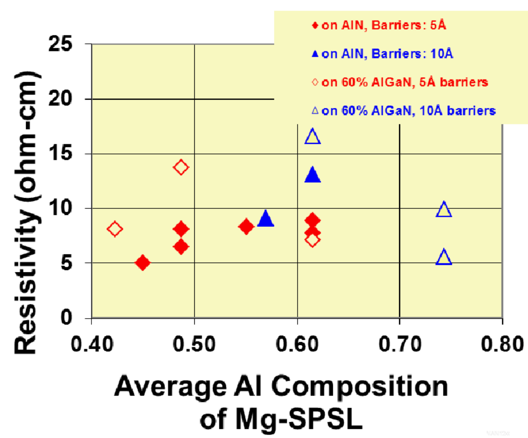
- **Strong polarization fields ionized Mg dopants**
- **Adjust average composition with layer thickness, X_{al}**
- **Low in-plane resistivity (5-10 Ω-cm)**
- **Heterojunctions increase $V_{forward}$ (vertical transport)**

➡ ***Growth temperature: 835 °C***

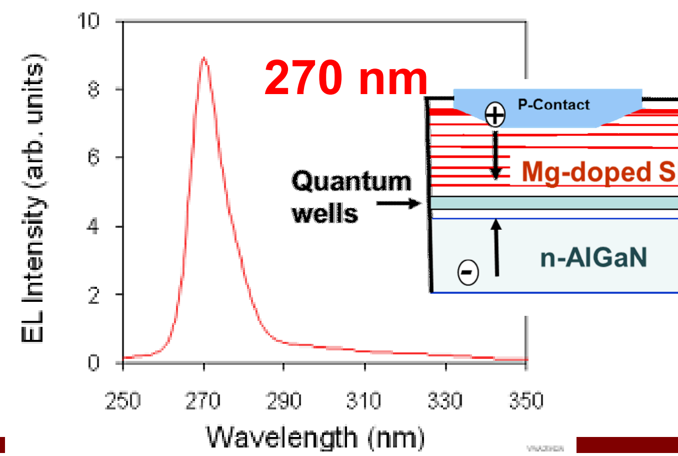
TEM



P-type Resistivity of Mg-SPSL

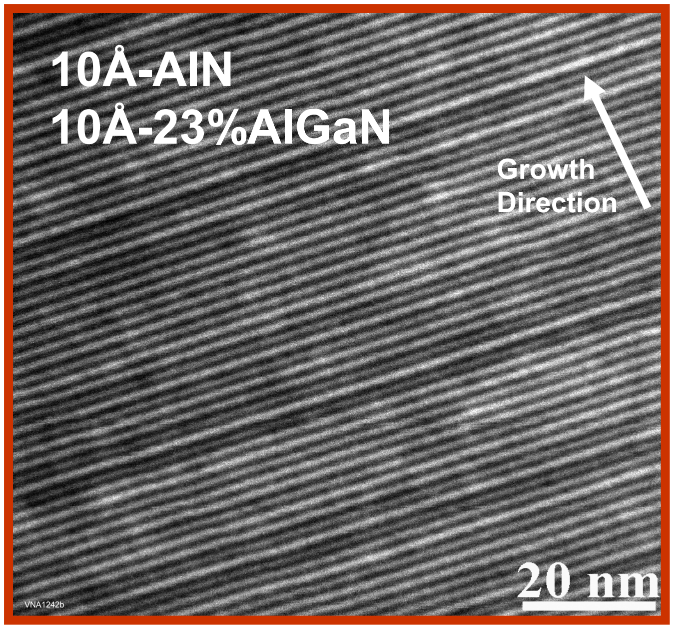


Electroluminescence from p-SPSL LED

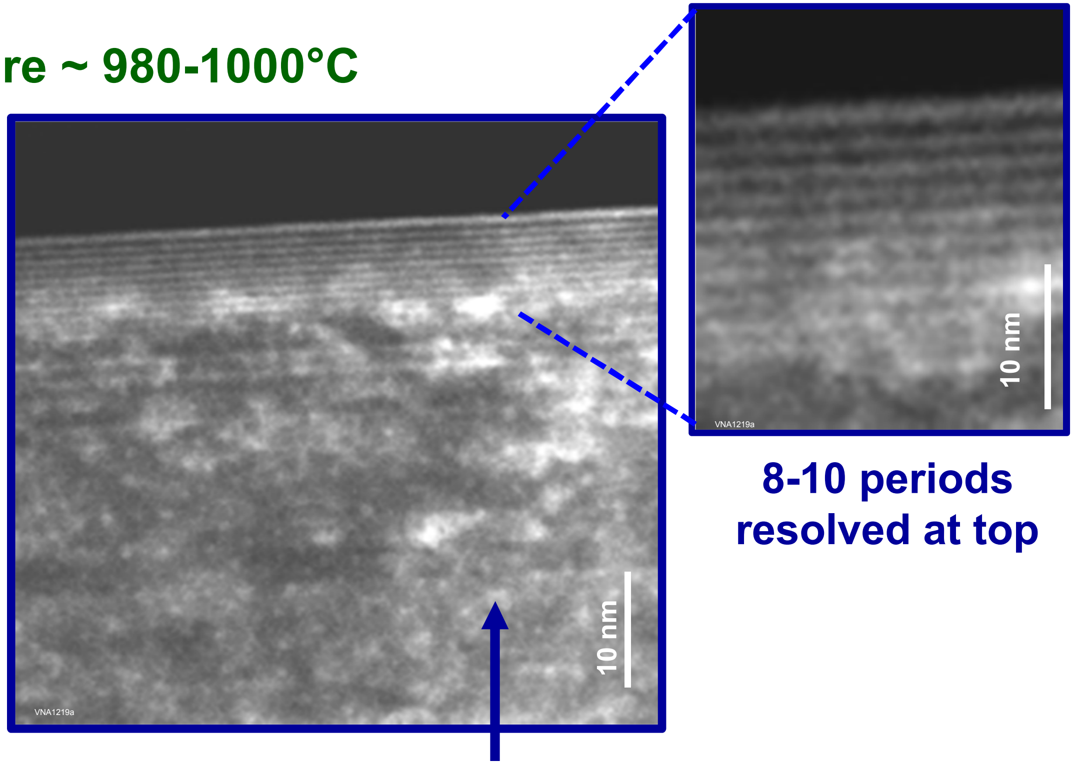


Impurity-induced layer disordering in (Mg)-SPSL

Growth Temperature ~ 980-1000°C



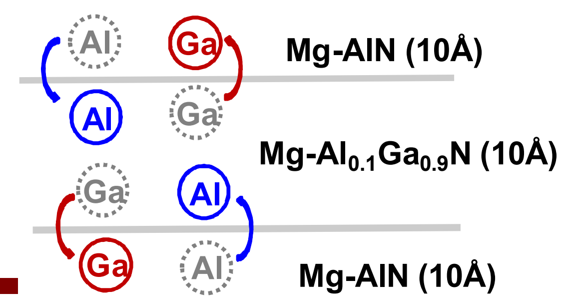
Undoped: Well resolved layers



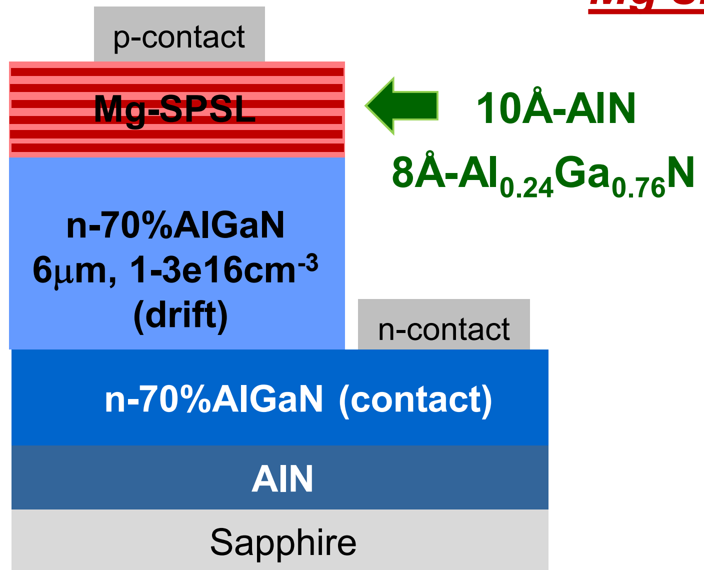
Mg-Doped: Intermixed layers

8-10 periods resolved at top

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

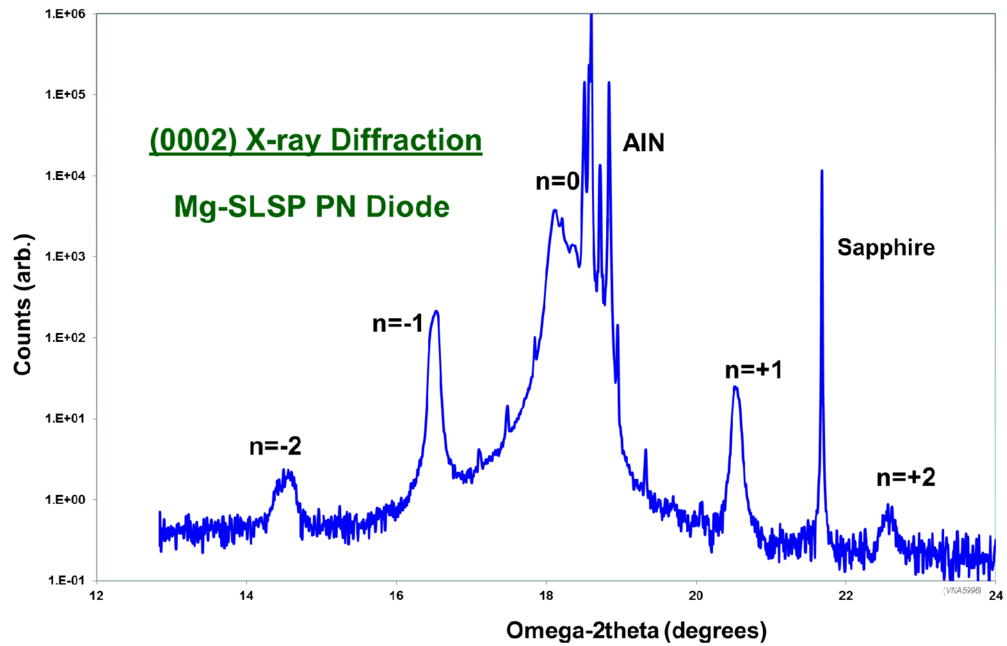


"Quasi-vertical" Mg-doped short-period superlattice PN diode



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**

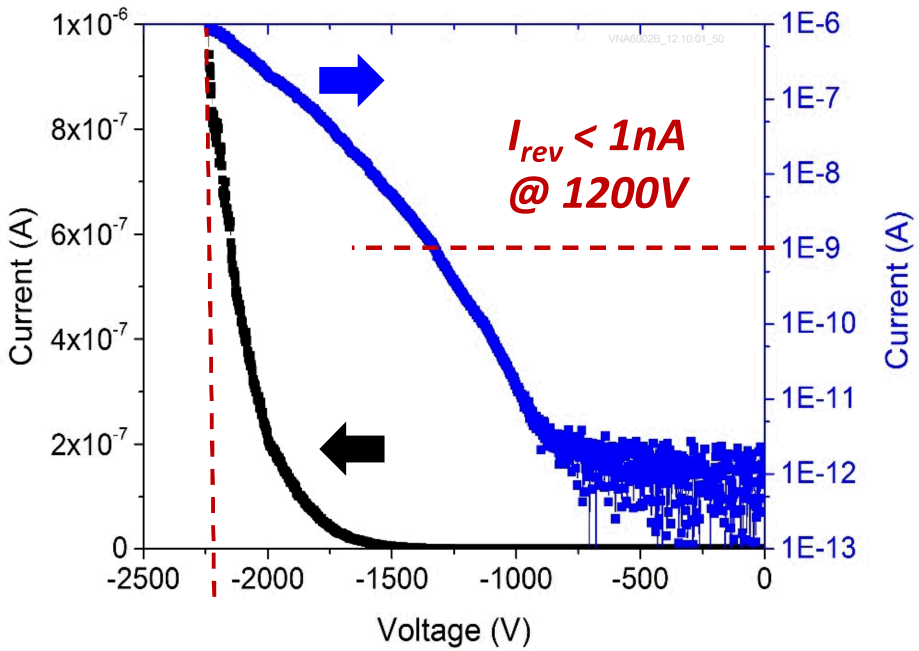


➡ ***Mg-SPSL is reproducible***

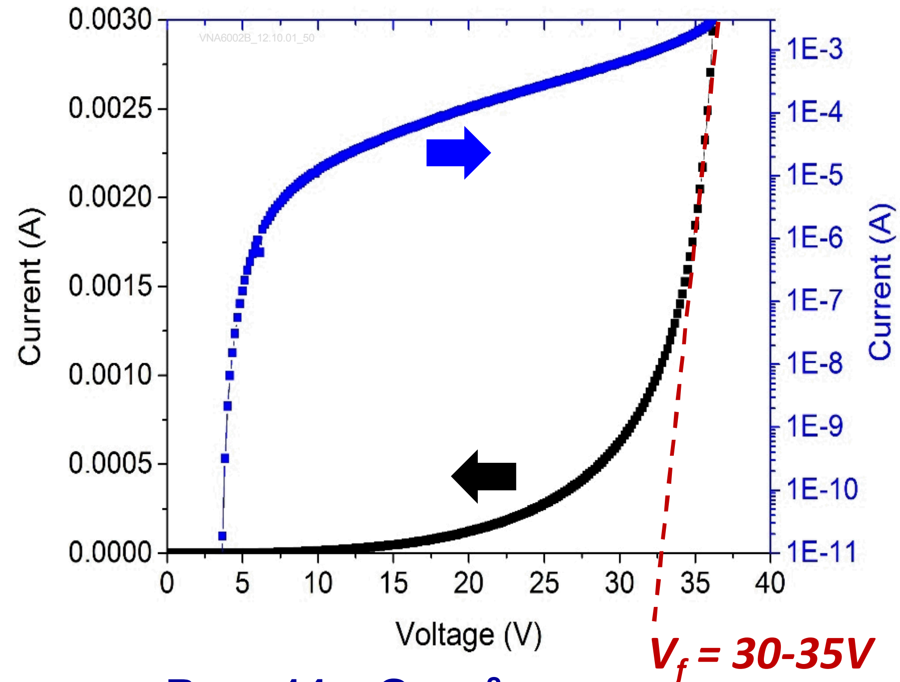
Date	Period (Å)	Resistivity (Ω-cm)
11/2012	19.2	11.5
2/2013	20.7	6.9
3/2014	21.7	10.4
4/2017	19.8	7.1

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

Reverse IV Characteristics



Forward IV Characteristics



- **Reverse voltage ~ -2200V (@ 1μA)**
- **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**

Summary

- Quasi-vertical Al_xGa_{1-x} N PIN diodes (X_{al}=0.3)
  - Reverse voltages > 3000V (@ 1 μA) with n-type drift layer of 11 μm
  - Critical electric field (E_{crit}) = 5.9 MV/cm^2

- Quasi-vertical Al_xGa_{1-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
  - Mg-short period superlattice:
    - V_{br} ~ 2200V, V_f is higher 30-35V