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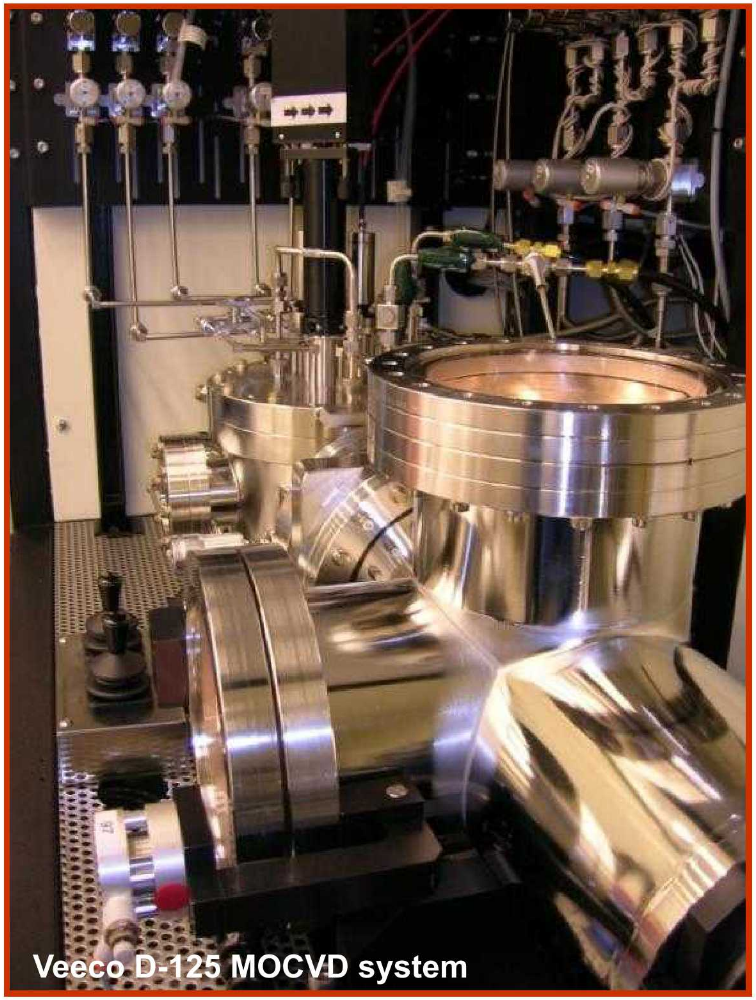

Veeco D-125 MOCVD system

Material Challenges of AlGaN PN Diodes for Power Electronics

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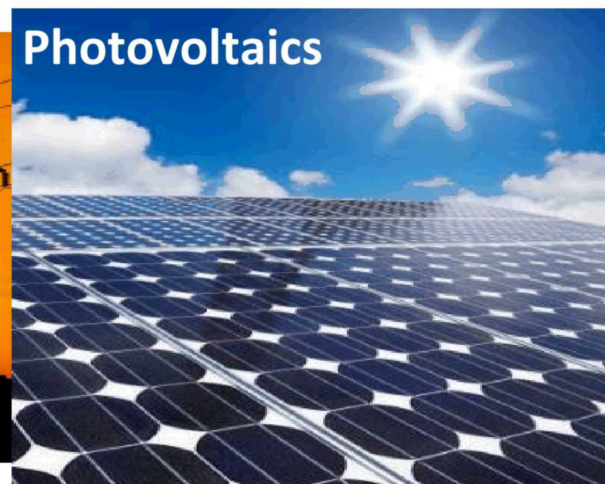
Outline

- Why AlGaN alloys for power electronics
- "Quasi-vertical" ($Al_{0.3}Ga_{0.7}N$) PN Diodes on sapphire
  - Continuously grown diodes
  - Diodes with ***regrown*** p-anode
- Summary

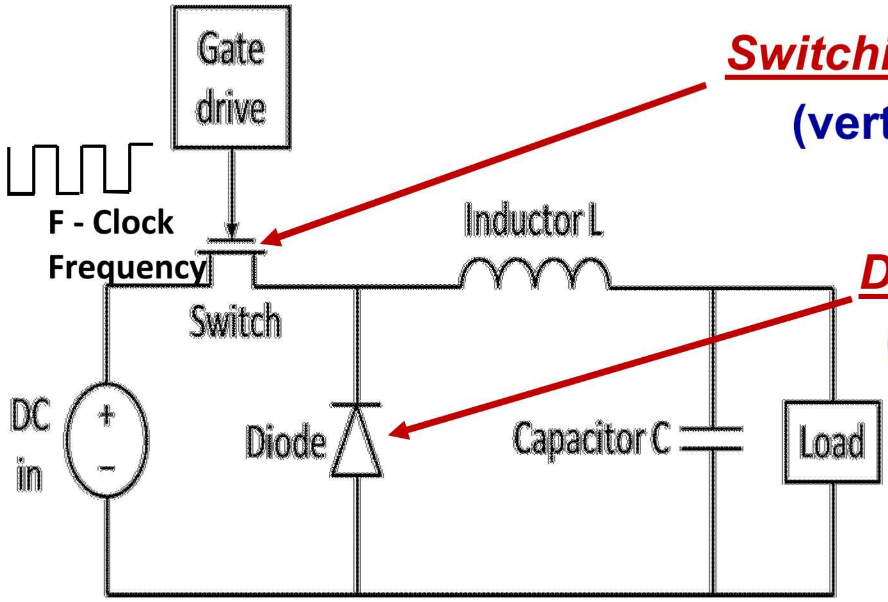
Power electronics are ubiquitous



Active electrical power switching for power management

➡ ***Power is converted between voltage, current, & frequency (DC & AC)***

Example: DC to DC Buck converter



Switching Transistor ➡ ***On/Off switch***

(vertical devices for high-current & voltage)

Diode

(integrated Schottky diode and PN diode: Merged PIN Schottky – MPS diode)

➡ ***Why use AlGaN for power transistors & diodes?***

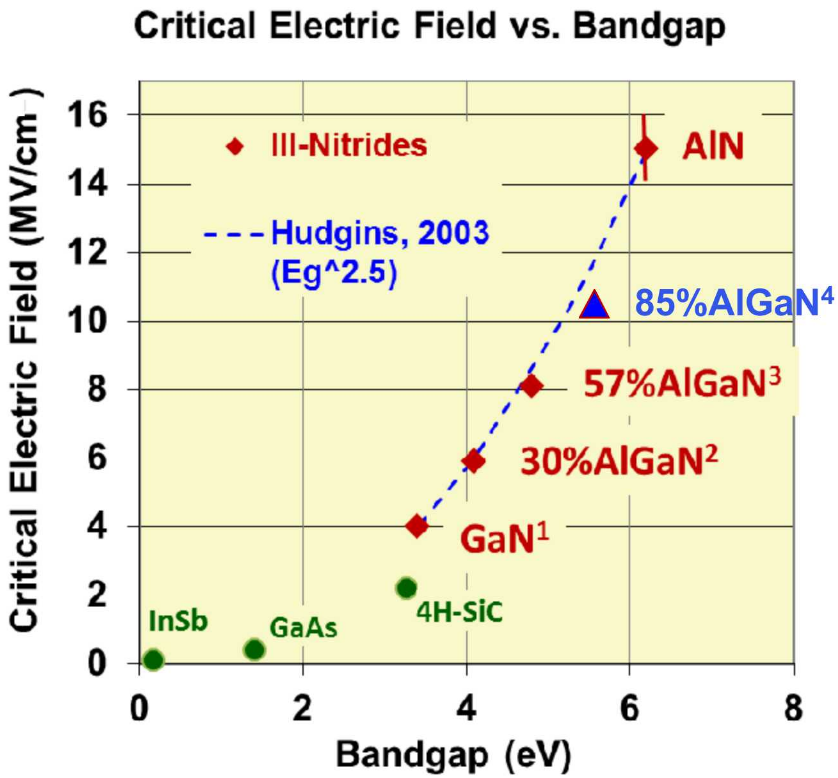
Ultra-wide-bandgap semiconductors (UWBS, >4eV) for power electronics

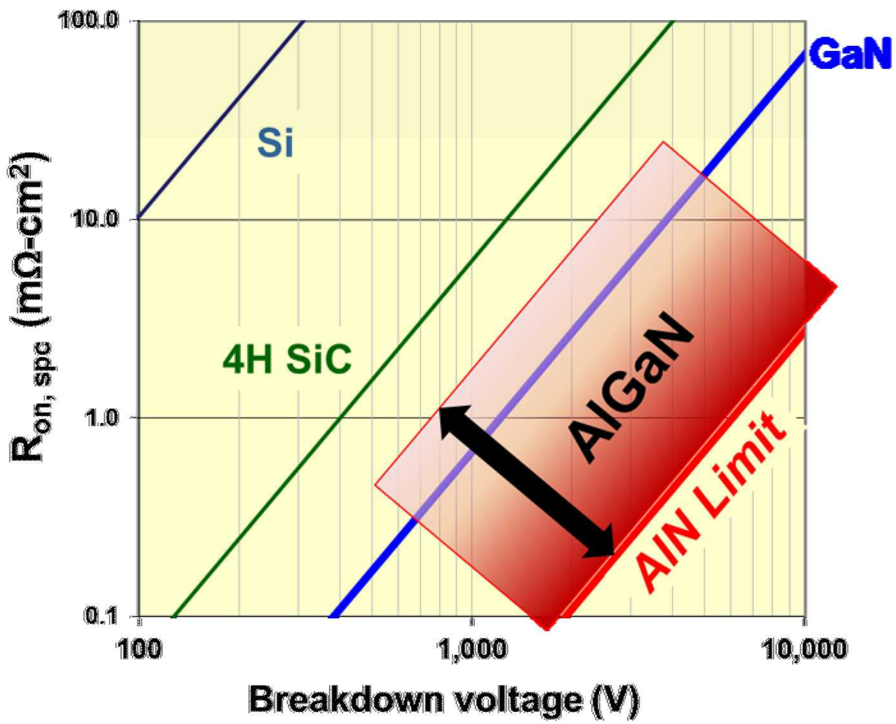
Critical Electric Field (MV/cm)

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

Unipolar Figure of Merit (vertical devices)

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





1-Armstrong, EL 2016, 2-Allerman, EL 2016, 3-Nisikawa, Jpn. JAP 2007, [4](SBD) Chow ICNS 2017

Why ultra wide-bandgap semiconductors for power electronics

Decreasing TRL →

Ultra Wide-Bandgap Semiconductors

Property	Si	GaAs	4H-SiC	GaN	AlN
Bandgap (eV)	1.1	1.43	3.3	3.4	**6.2**
Critical Electric Field (MeV/cm)	0.3	0.4	2.0	**4**	**~15**
Saturated electron velocity (x10^7 cm/sec)	1.0	1.0	2.0	**2.5**	1.4
Thermal conductivity (W/cm·K)	1.5	0.5	**4.5**	4.0	3.4

Larger bandgap
➡ ***Higher temperature***

Larger critical E field
➡ ***Higher voltage***

Higher sat. electron vel.
➡ ***Higher switching speed***

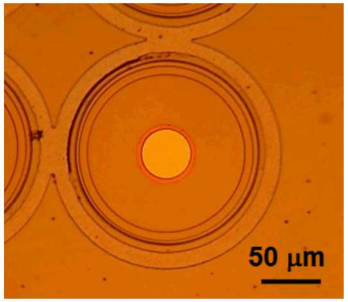
Higher thermal conductivity
➡ ***High power***

Radiation tolerant
➡ ***Stable devices***

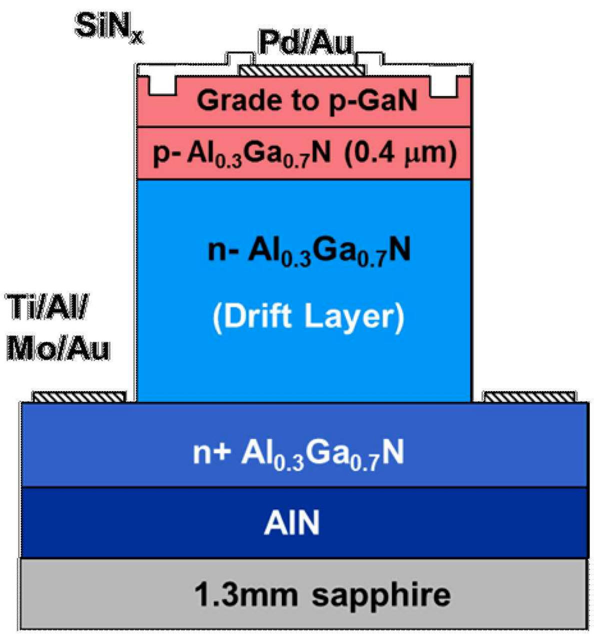
AlGaN alloys & heterostructures
➡ ***Engineered properties***

➡ ***UWBS enable applications NOT possible in Si and GaAs***

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



Optical image of diode

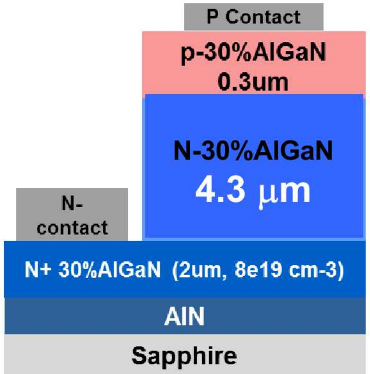


Quasi-Vertical PN diode structure

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

- Implanted junction edge termination
- Mesa / p-metal: 150 / 50 μm
- 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*
- Crack-free (except 15.5 μm drift layer)
- Total epi thickness: 7 – 18, 22 μm
- Drift layer doping: 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

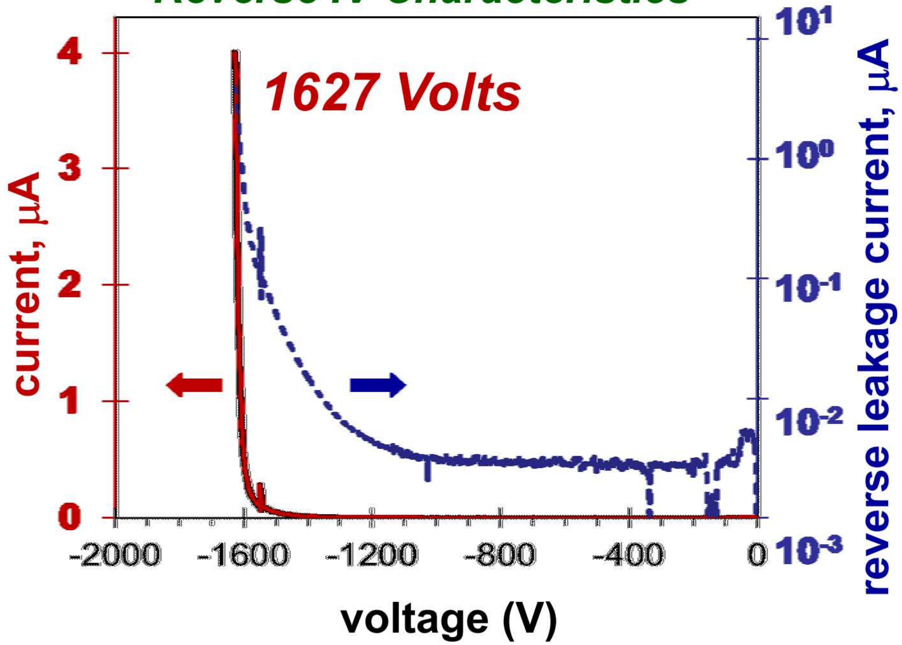


- **Drift layer: 4.3 μm, TDD ~ 1-2e9 cm^{-2}**

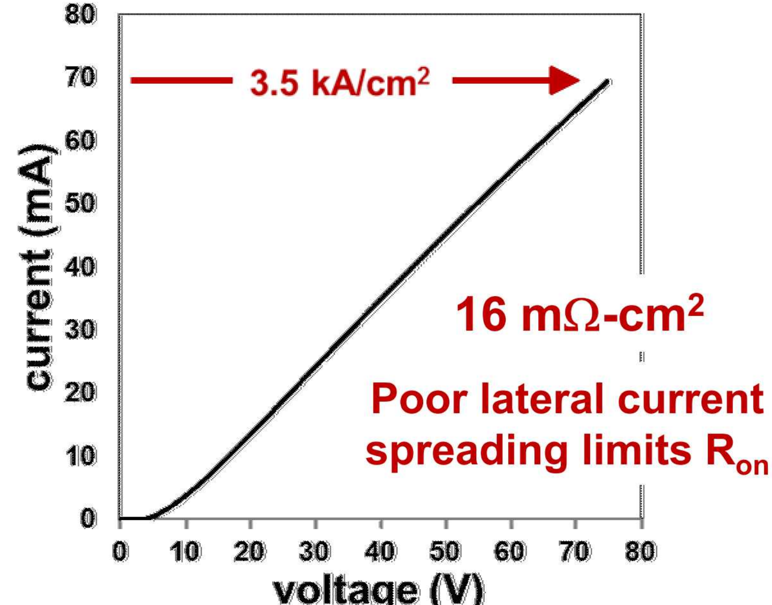
  N_o~ 5-7e16 cm^{-2}, μ ~ 150 cm^2/Vs,

- ➡ ***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



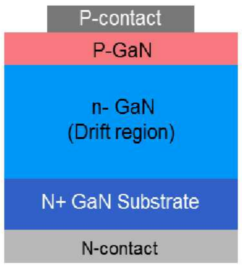
Forward IV Characteristics



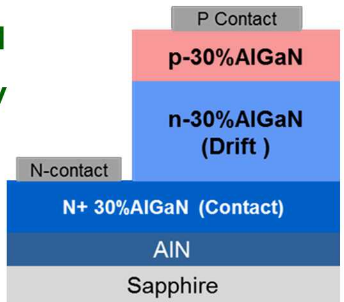
Allerman, Elec. Lett. 2016

Breakdown voltages reported for III-Nitride PN diodes

GaN diode (vertical)



AlGaN d (Quasi-v



III-N PN diodes with > 3 kV breakdown voltage

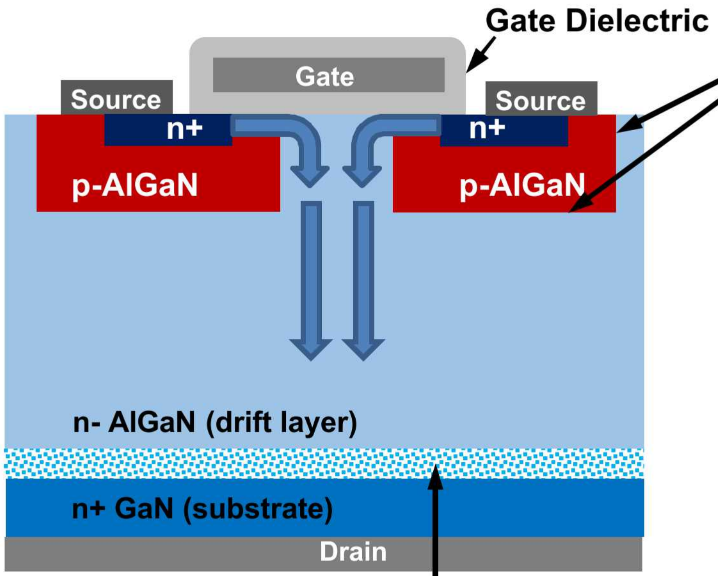
Breakdown (kV)	No (cm-3)	Drift (um)	Material	Group	Ref
4.7 / 5.0	2/9/16e15	33	GaN	Hosei Univ.	EDL-2015 / Jpn J Appl. Phys.-2018
4.0	2-5e15	40	GaN	Avogy	EDL 36p1073_2015
3.9	**3e15**	**30**	**GaN**	**Sandia**	**EL 52p1170_2016**
3.7	5e15	>30	GaN	Avogy	EDL 35p247_2014
3.48	1/3/12e15	32	GaN	Hosei Univ.	IEDM15-237_2015
>3	**0.8-3e16**	**11**	**30%-AlGaN**	Sandia	
3.0	**0.8-3e16**	**9**	**30%-AlGaN**	Sandia	
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	← Similar reverse leakage but higher TDD

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})**

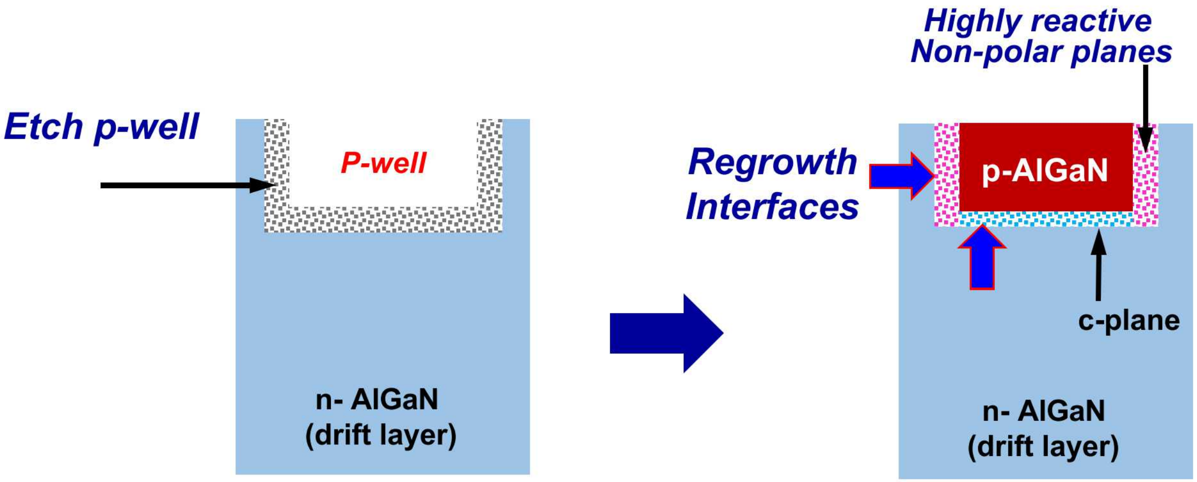
- ➡ **Must have low reverse leakage current**
- **P-layers formed by ion implantation and annealing for Si and SiC devices**
- ➡ **Form the p-well by selective-area-growth (SAG) of p-AlGaN**

2 **Vertically conducting device geometry**

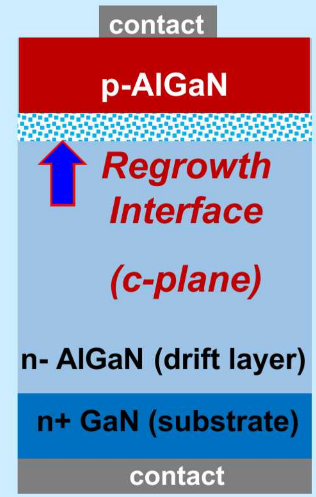
- ➡ **No AlGaN substrate for vertical conduction (HVPE?)**
- **Substrate removal possible alternative**
- ➡ **Develop growth of AlGaN on patterned n-GaN substrates**

Challenges to selective area regrowth of PN junctions

Sources of current leakage at regrown PN interface



- Electrically active impurities (Si, O, etc.)
- Damage to crystal structure from ICP etch resulting in extended (?) and point defects (e.g. vacancies).
- Incorporation rates of impurities and growth rates depend on crystal plane
- Impact of mask on regrowth and subsequent mask removal



Regrowth on c-plane only

➡ ***Start simple, p-AlGaN regrowth only on c-plane drift layers***

Summary

- **Quasi-vertical $Al_{0.3}Ga_{0.7}$ N PIN diodes**
  - **Reverse voltages > 3000V (@ 1 μA) with an 11 μm drift layer**
  - **Critical electric field (E_{crit}) = 5.9 MV/cm^2**

- **Quasi-vertical $Al_{0.3}Ga_{0.7}$ N PIN diodes with regrown P-anode on etched drift layer**
  - **Reverse voltages to 1500 V (@ 1 μA)**
    - ➡ ***IV characteristics equal to continuously grown PN diodes***