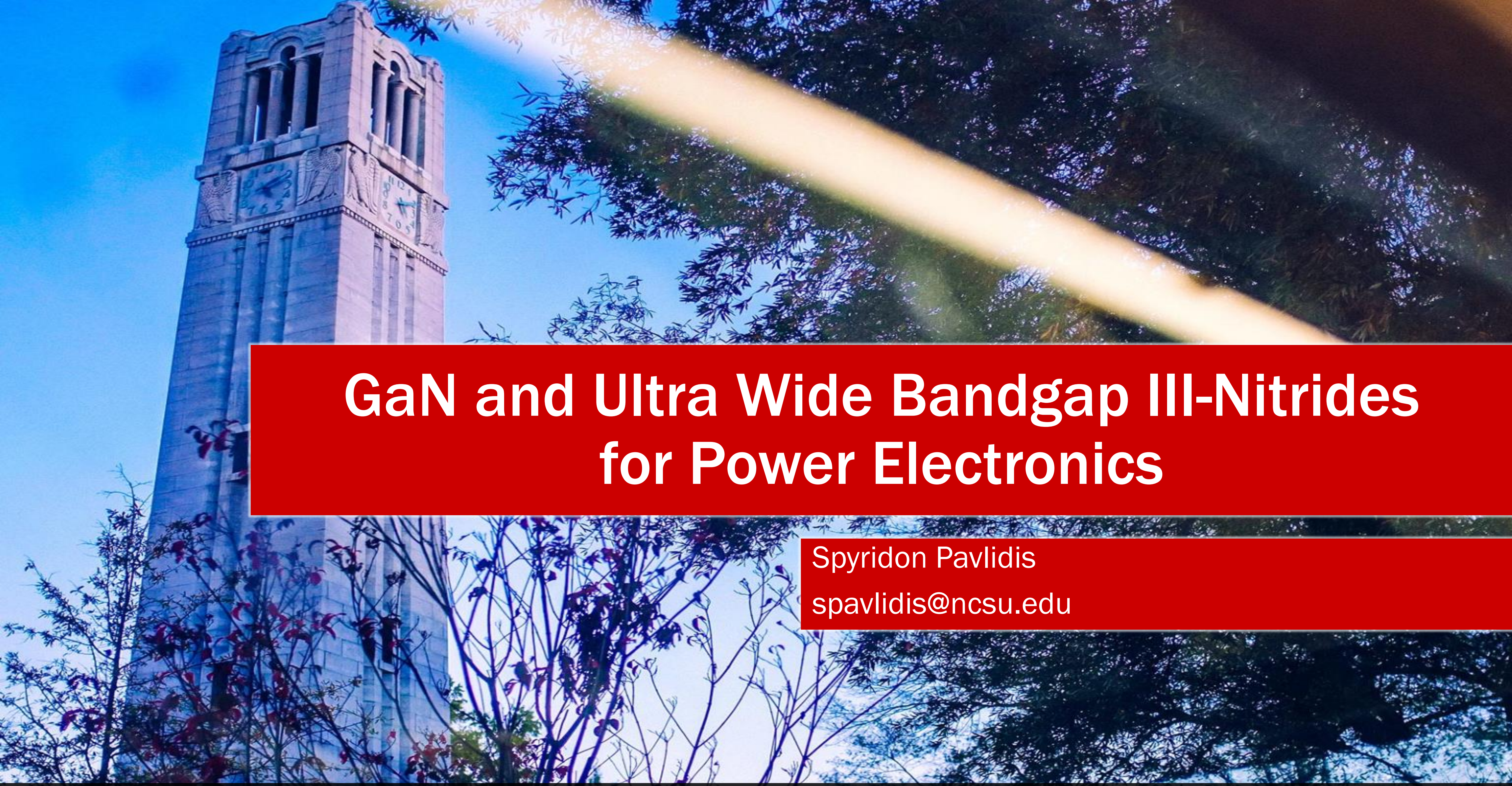


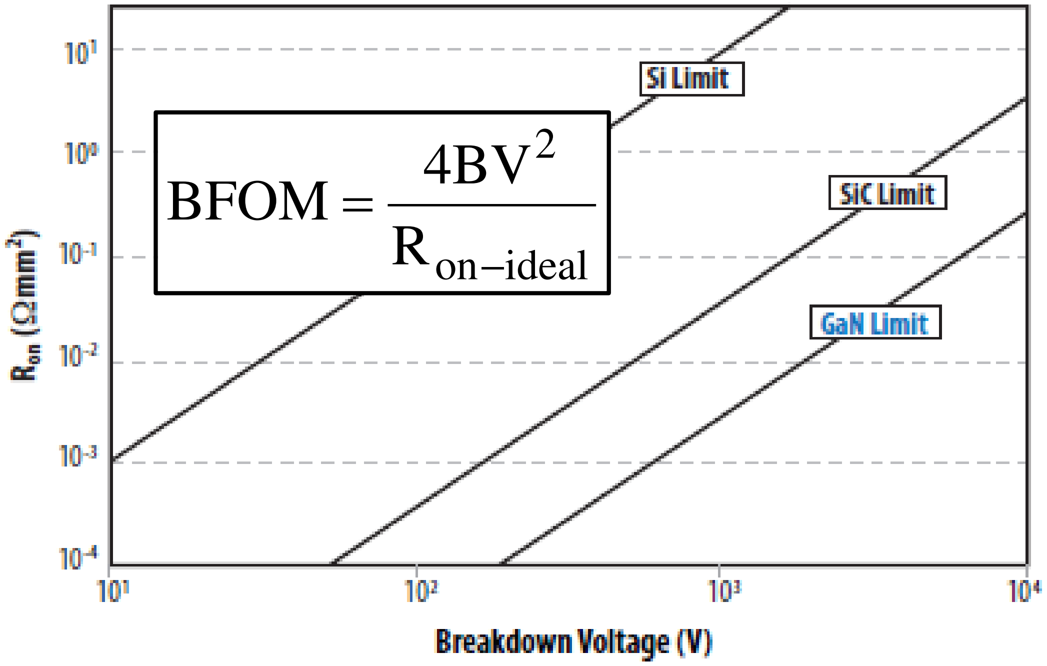
GaN and Ultra Wide Bandgap III-Nitrides for Power Electronics

Spyridon Pavlidis
spavlidis@ncsu.edu

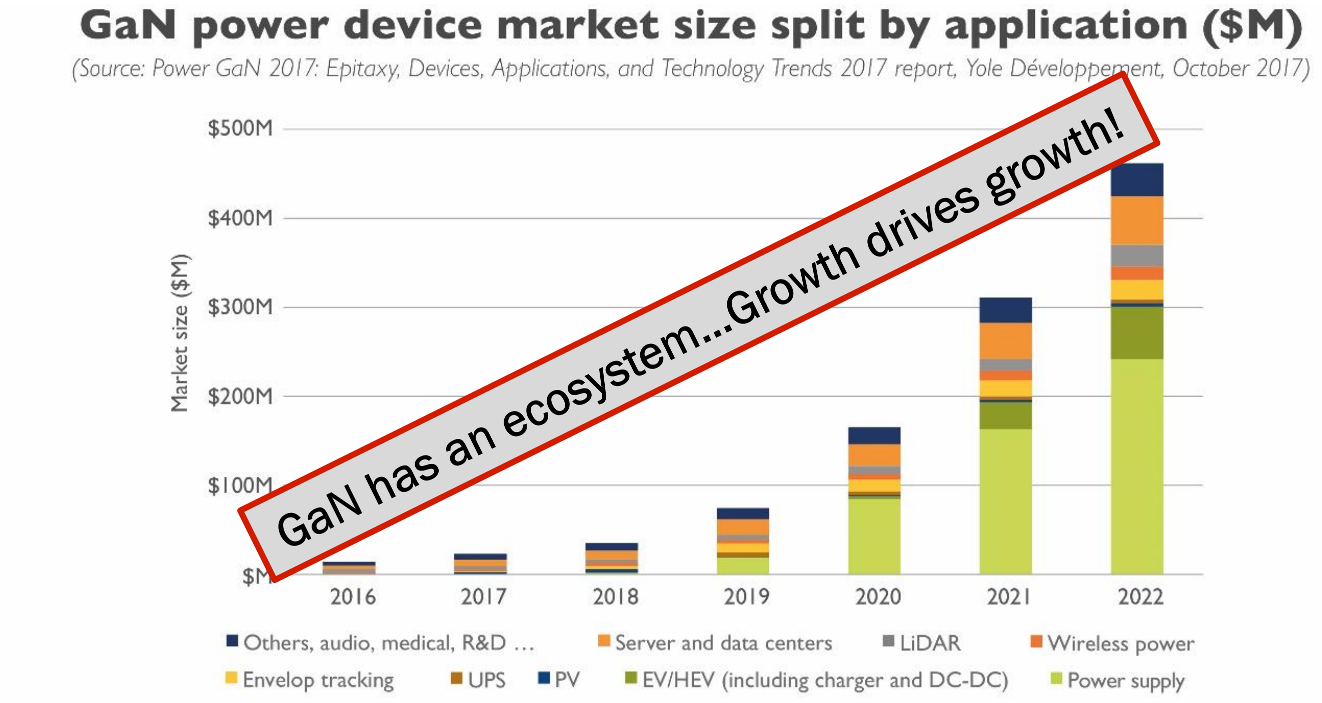
Outline

- Current GaN Power Devices and Performance
- Technological challenges and opportunities for GaN:
    - Device Passivation
    - N-Polar vs. Ga-Polar
    - Ion Implantation
- Ultra Wide Bandgap III-Nitrides (AlGaN → AlN)
    - Device demonstrations
    - Contacts
- Making III-Nitride technology accessible at NCSU

GaN for Power



$$\mathrm{BFOM} = \frac{4BV^2}{R_{on-ideal}}$$



GaN power device market size split by application ($M)

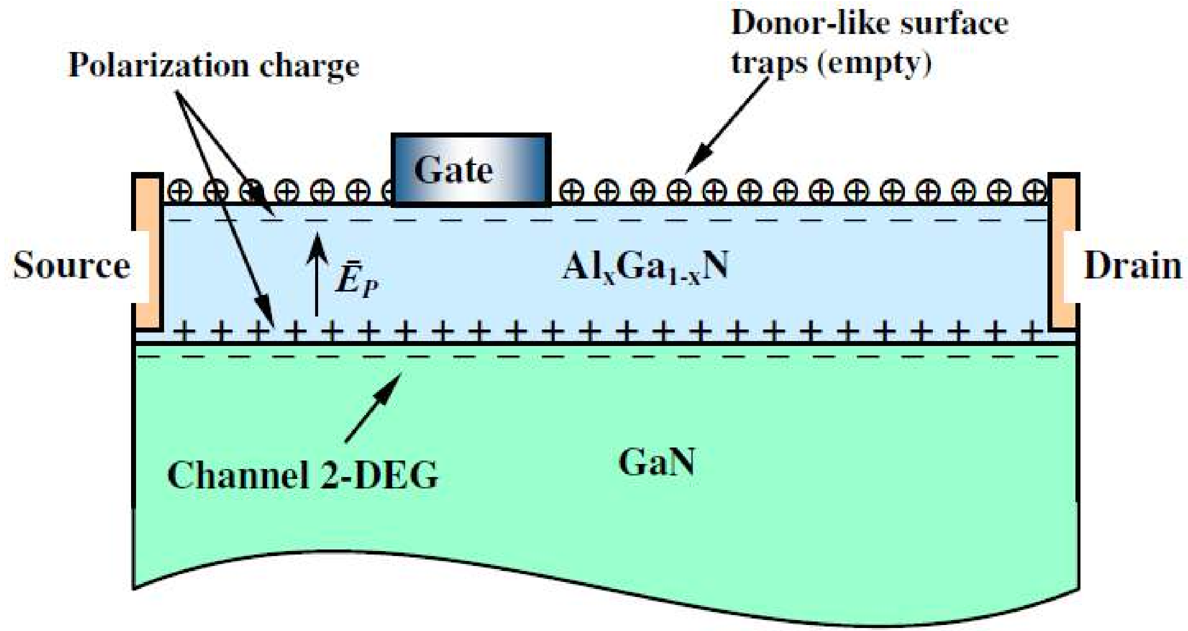
(Source: Power GaN 2017: Epitaxy, Devices, Applications, and Technology Trends 2017 report, Yole Développement, October 2017)

GaN has an ecosystem…Growth drives growth!

- GaN Power Device market size expected to surpass $400M by 2022
- Compared to SiC's ~$1B market size in 2022
- <u>BUT</u> the GaN for RF market is projected to reach $1.3B by 2023
- <u>BUT</u> the GaN-based optoelectronics market is also growing >$1B

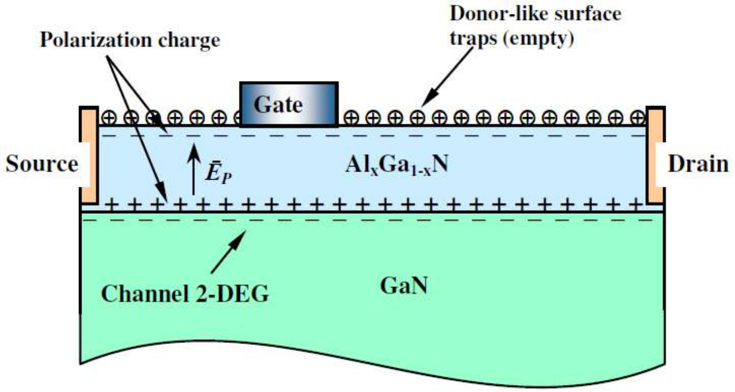
B. J. Baliga, *Fundamentals of Power Semiconductor Devices*, 2nd ed. Boston, MA: Springer International Publishing AG, 2019.
https://epc-co.com/epc/DesignSupport/ApplicationNotes/AN003-UsingEnhancementMode.aspx
http://www.yole.fr/iso_album/illus_power_gan_market_applications_yole_oct2017_updated.jpg

Lateral AlGaN/GaN HEMTs

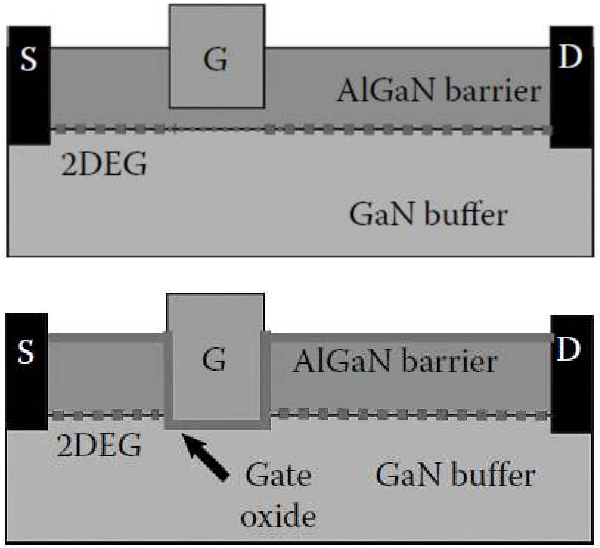


- AlGaN/GaN heterojunction creates quantum well (2DEG) with high electron mobility
- 2DEG is polarization doped:
  - Spontaneous polarization
  - Piezoelectric polarization
- AlGaN/GaN HEMTs are normally-on devices
- Heteroepitaxially grown on Si, SiC or Sapphire substrates

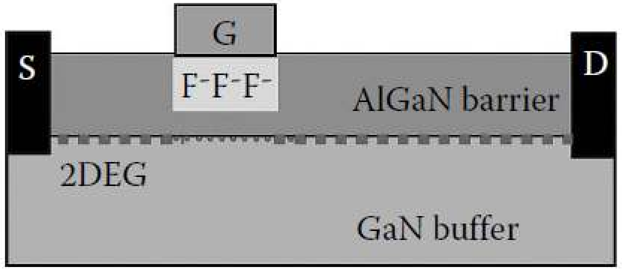
E-Mode AlGaN/GaN HEMTs



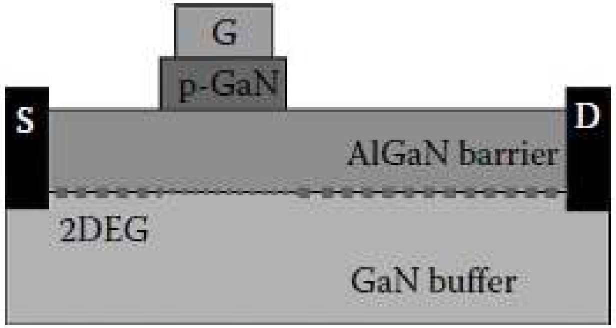
Recessed Gate



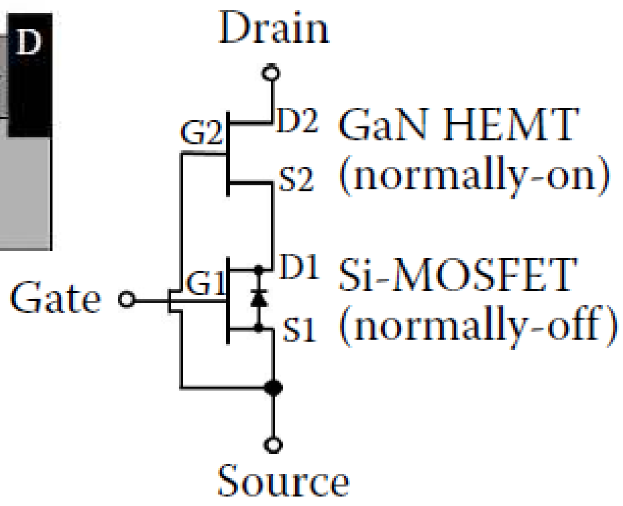
Fluorinated Gate



P-(Al)GaN Gate



Cascode/Baliga Pair



F. Medjdoub, *Gallium Nitride (GaN): Physics, Devices, and Technology*, vol. 47. CRC Press, 2015.

Commercialization Gap

Research

2007

8300V Blocking Voltage AlGaN/GaN Power HFET with Thick Poly-AlN Passivation

Yasuhiro Uemoto, Daisuke Shibata, Manabu Yanagihara, Hidetoshi Ishida, Hisayoshi Matsuo, Shuichi Nagai*, Nagaraj Batta*, Ming Li*, Tetsuzo Ueda, Tsuyoshi Tanaka, and Daisuke Ueda

Semiconductor Device Research Center, Semiconductor Company, Matsushita Electric - Panasonic
1 Kotari-yakemachi, Nagaokakyo, Kyoto 617-8520, JAPAN
*Panasonic Boston Laboratory, Panasonic Technologies Company,
68 Rogers Street Cambridge, MA 02142, USA
Phone: +81-75-956-9083, FAX: +81-75-956-9110, e-mail: uemoto.yasuhiro@jp.panasonic.com

2006

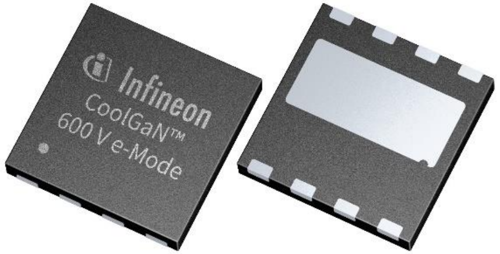
40-W/mm Double Field-plated GaN HEMTs

Y.-F. Wu, M. Moore, A. Saxler*, T. Wisleder and P. Parikh

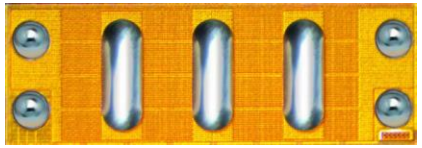
Cree Santa Barbara Technology Center, 340 Storke Road, Goleta, CA 93117
*Cree Inc., 4600 Silicon Drive, Durham, NC 27703

Product

50-600V

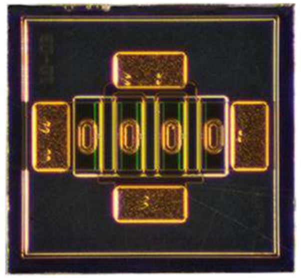


infineon



EPC
EFFICIENT POWER CONVERSION

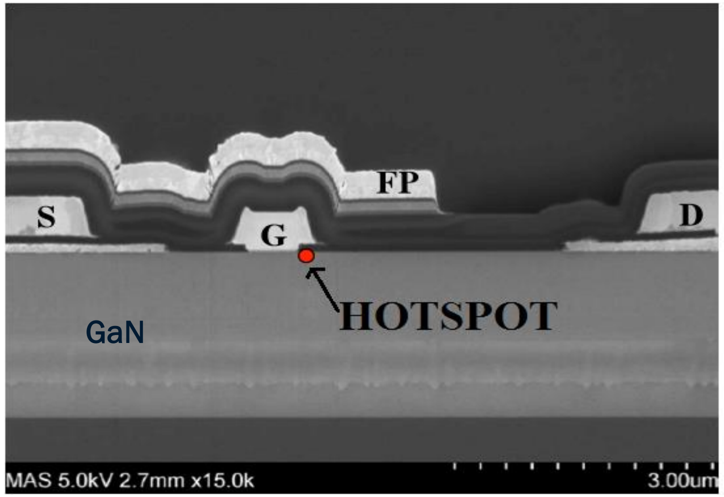
6.6 W/mm

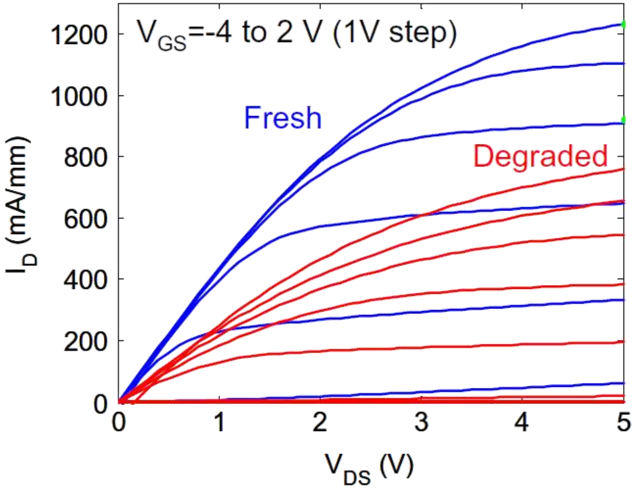


Wolfspeed™
A CREE COMPANY

Thermal Management

IV degradation due to Self-Heating



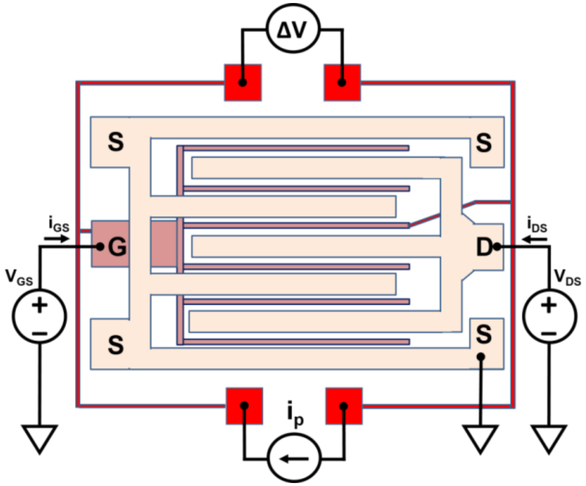


Del Alamo, Microelectronics Reliability, 2009

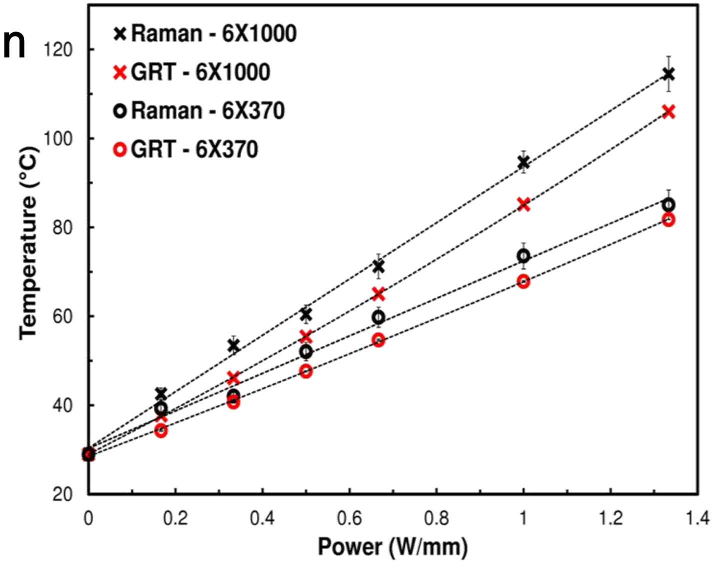
Advanced

Characterization

Gate Resistance Thermometry



Constant 28 V Drain Bias



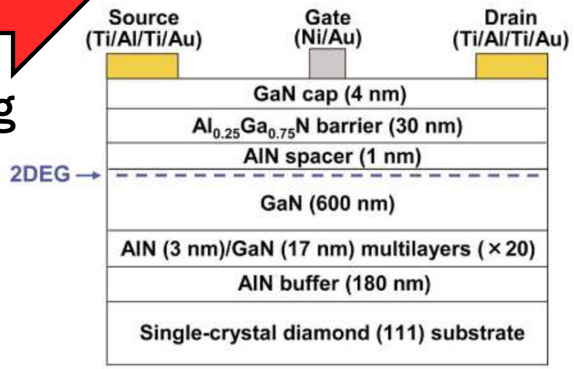
Pavlidis et al., IEEE TED, 64 (1), 78-83, 2017

"ICECool"

Advanced

Cooling

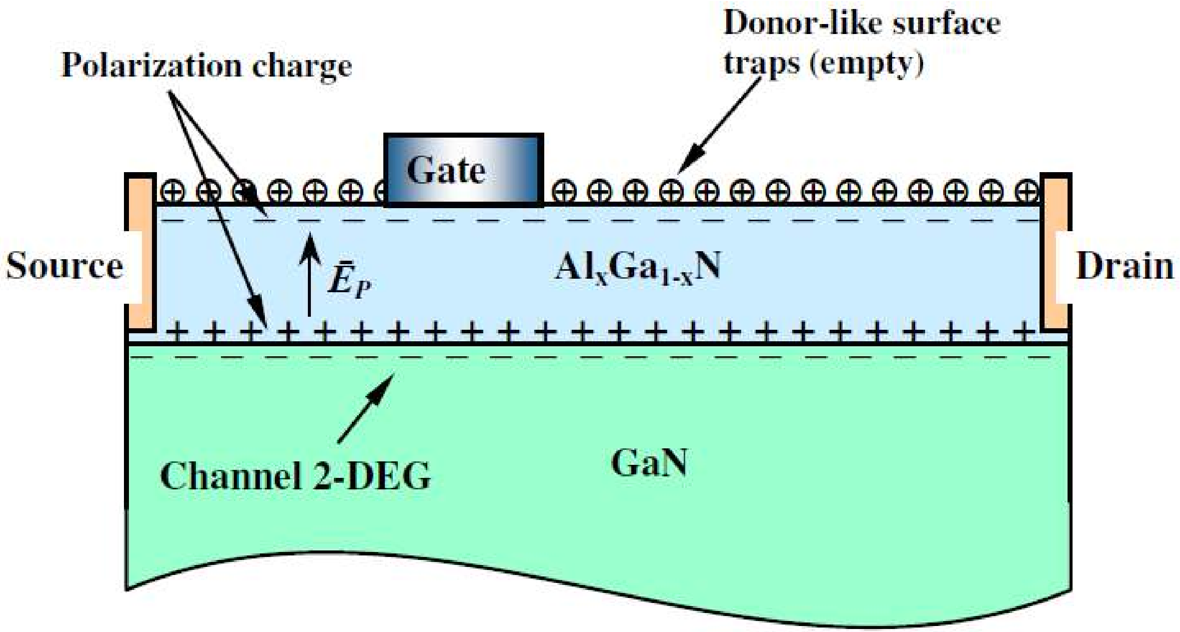
GaN on Diamond



a De Beers Group Company

K. Hirama, *Appl. Phys. Lett.*, vol. 98, no. 16, p. 162112, Apr. 2011.

AlGaN/GaN HEMT Passivation

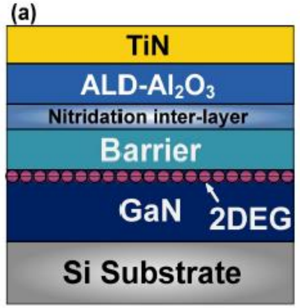


- Two challenges:
  - N- bond is less stable than O-bond
    - GaO_x forms on the surface
  - Charged surface states on the surface
    - Transient effects
    - Fermi level pinning

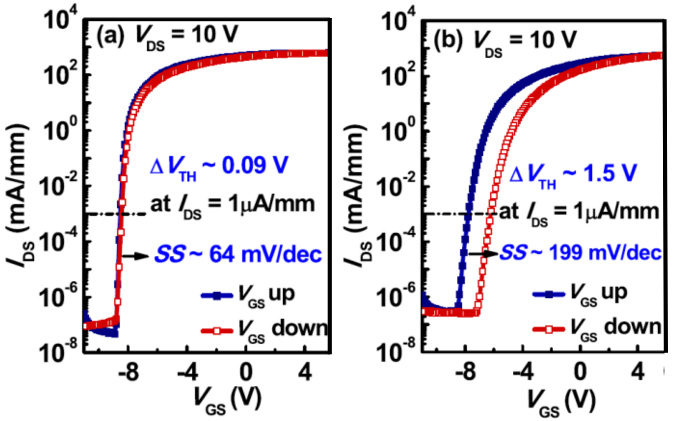
What materials and device fabrication techniques can we use to passivate?

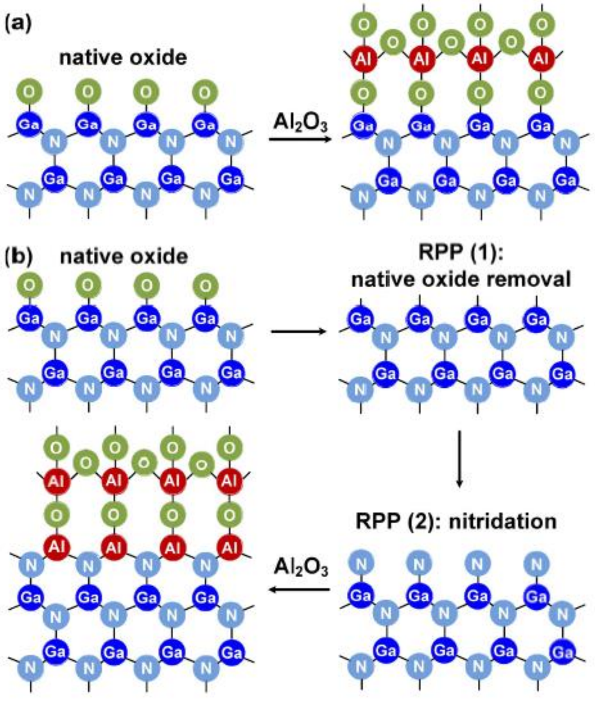
SiN_x Passivation

Produced in a 150mm Si foundry



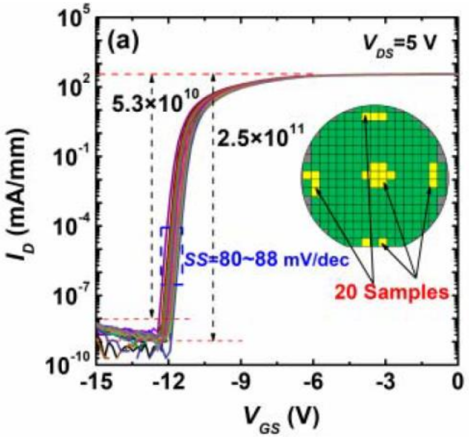
w/ Nitridation **w/o Nitridation**

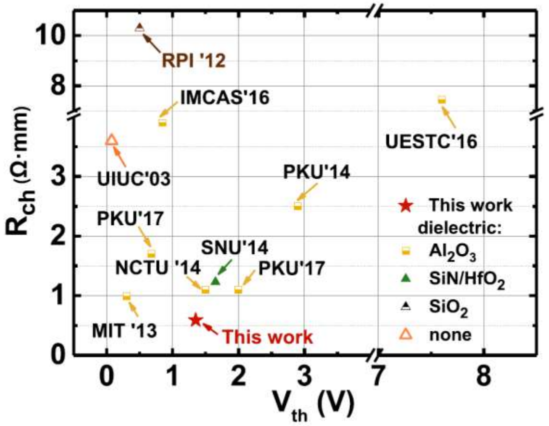


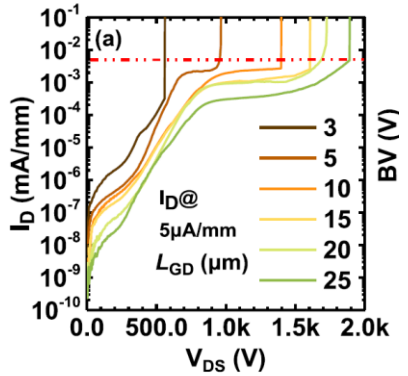


Wafer uniformity

Improved BFOM







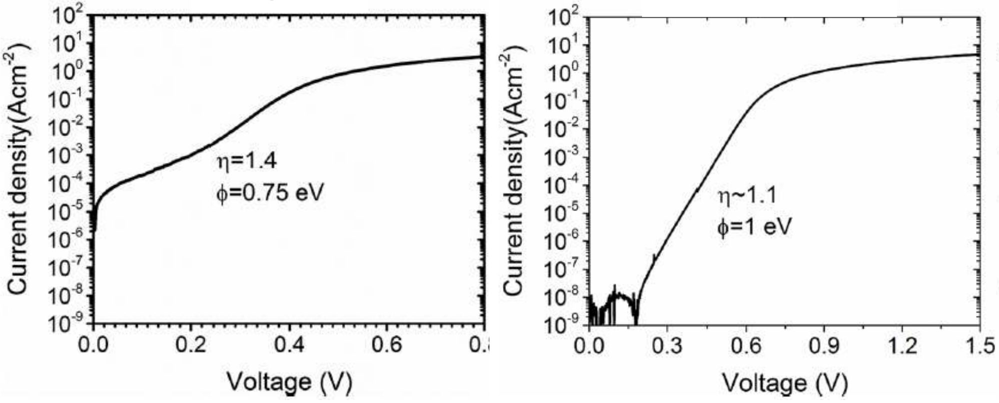
- In-situ nitridation ensures a clean interface between AlGaN and passivation
- LPCVD SiN_x process offers ex-situ nitridation and high-quality passivation

S. Yang *et al.*, *IEEE Electron Device Letters*, vol. 34, no. 12, pp. 1497–1499, 2013.
H. Sun *et al.*, *IEEE Transactions on Electron Devices*, vol. 65, no. 11, pp. 4814–4819, Nov. 2018.
J. Gao *et al.*, *IEEE Transactions on Electron Devices*, vol. 65, no. 5, pp. 1728–1733, May 2018.

Temperature Instability due to Poor Interfaces

- Forward bias non-idealities in photolithography-processed SBDs are reduced via anneal
- Shadow-masked contacts show superior reverse leakage performance
- Acid treatment prior to metal deposition yields ideal Schottky diode behavior

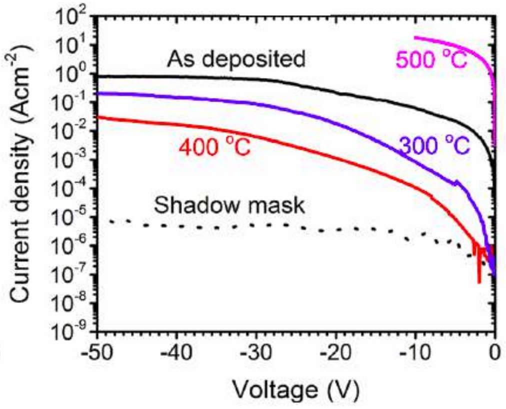
Photolithography



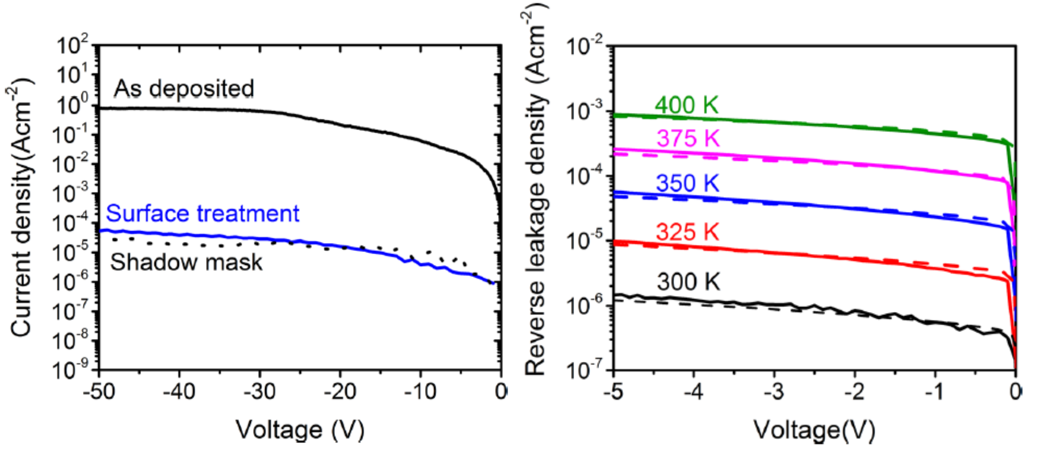
Original

Post-Anneal

Shadow-Mask



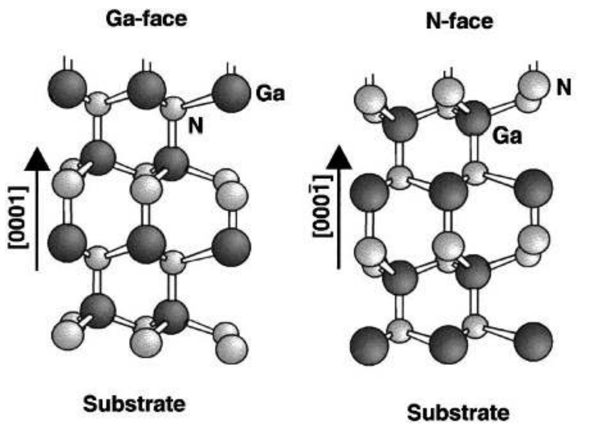
Ideal Diode w/ Acid Treatment



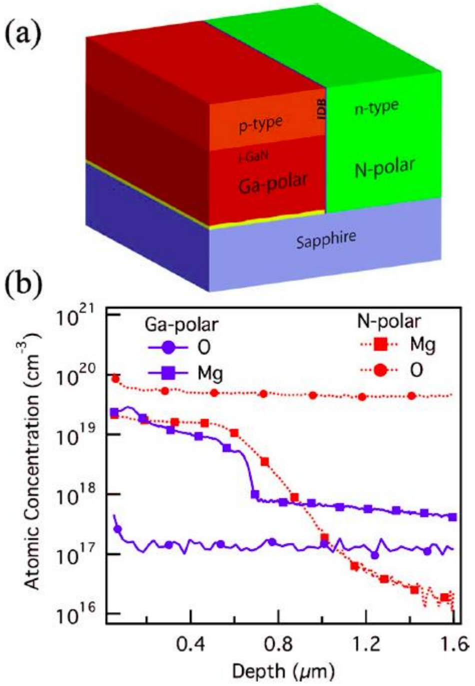
P. Reddy *et al.*, “Defect-free Ni/GaN Schottky barrier behavior with high temperature stability,” *Applied Physics Letters*, vol. 110, no. 1, p. 011603, 2017.

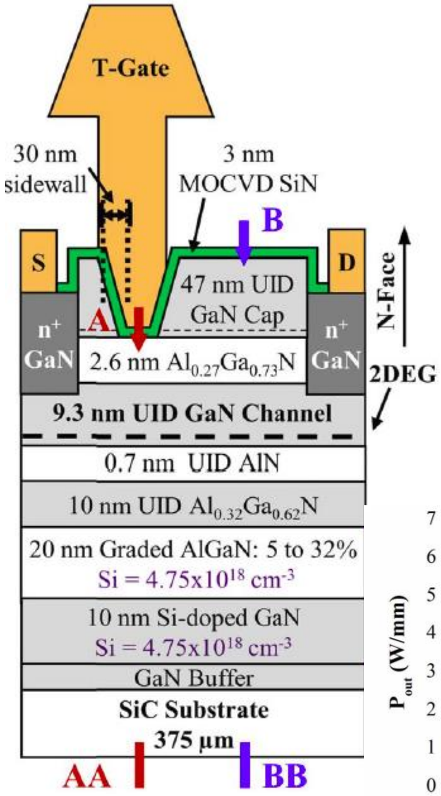
N-Polar GaN

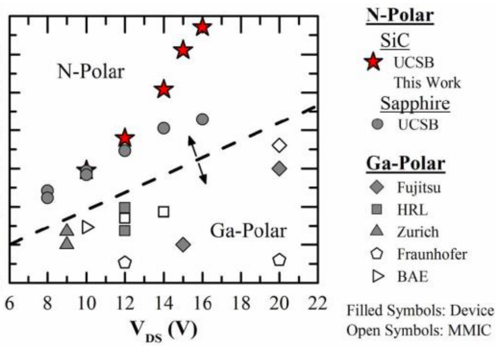
Curiosity → **Performance**



Non-equivalent properties



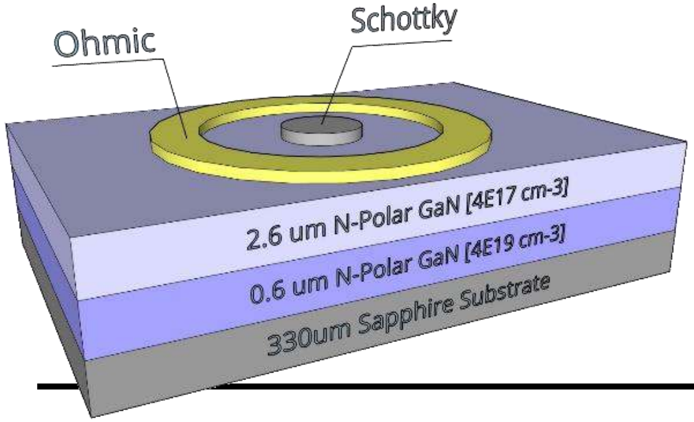




Lower contact resistance improves output power!

O. Ambacher *et al.*, *Journal of Applied Physics*, vol. 85, no. 6, pp. 3222–3233, 1999.
R. Collazo, et al., *Applied Physics Letters*, vol. 91, no. 21, p. 212103, 2007.
S. Wienecke *et al.*, *IEEE Electron Device Letters*, vol. 37, no. 6, pp. 713–716, 2016.

What about N-GaN surfaces?



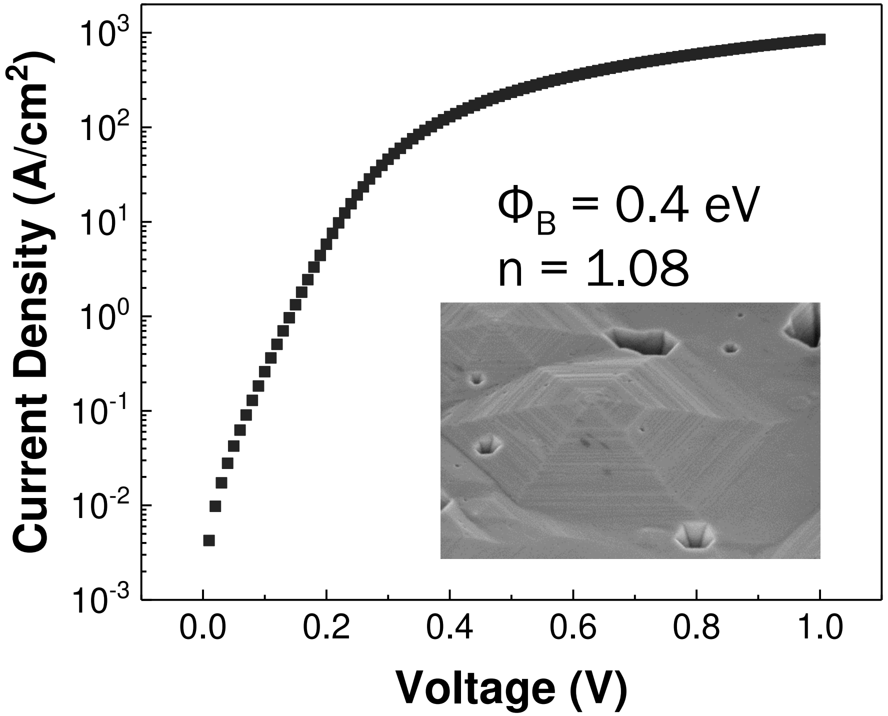
- MOCVD-grown N-polar GaN on sapphire
- O_2-doped

Step	Sample 1 (Control)	Sample 2 (Treated)
Ohmic Contact	Shadow Mask (V/Al/Ni/Au)	Shadow Mask (V/Al/Ni/Au)
Schottky Contact Patterning Method	Shadow Mask	Lithography
Surface Treatment	---	Boiling HCl:H_2O
Schottky Metal Deposition	Ni	Ni
Lift-Off	---	NMP (at 70 °C) then acetone & IPA

D. Khachariya *et al.*, “Chemical Treatment Effects on Schottky Contacts to MOCVD N-polar GaN,” presented at the International Workshop on Nitride Semiconductors, Kanazawa, Japan, 2018.

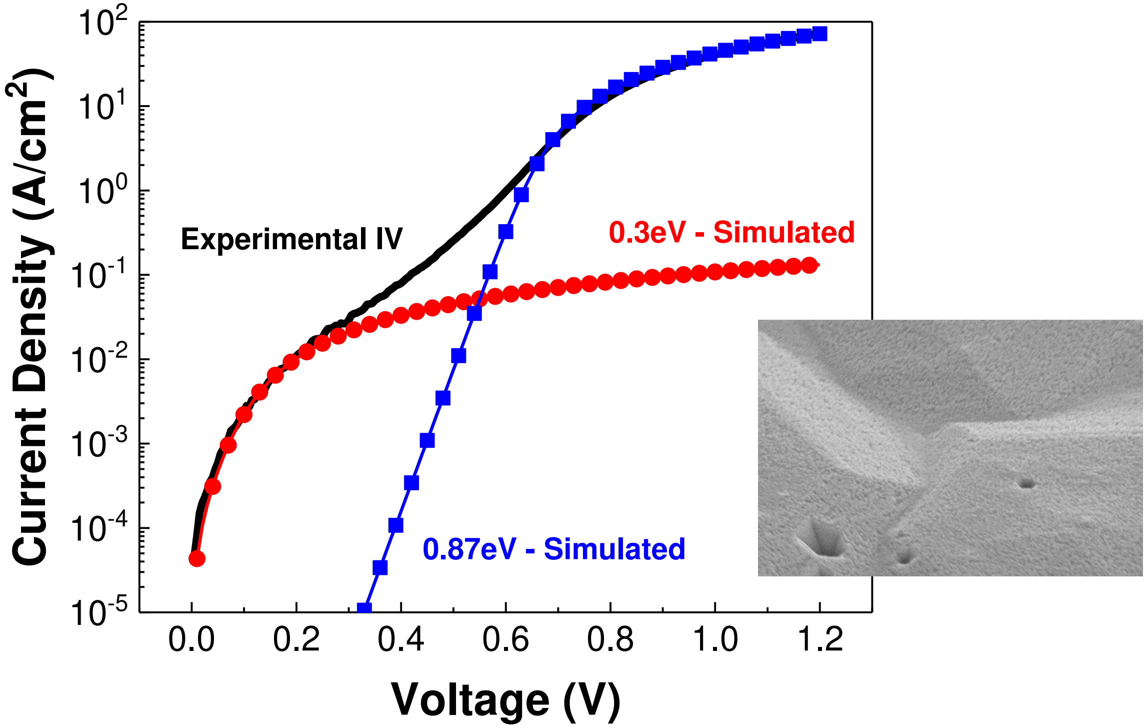
I-V Comparison

Control Sample



Near-ideal ideality factor via shadow masking

Processed Sample



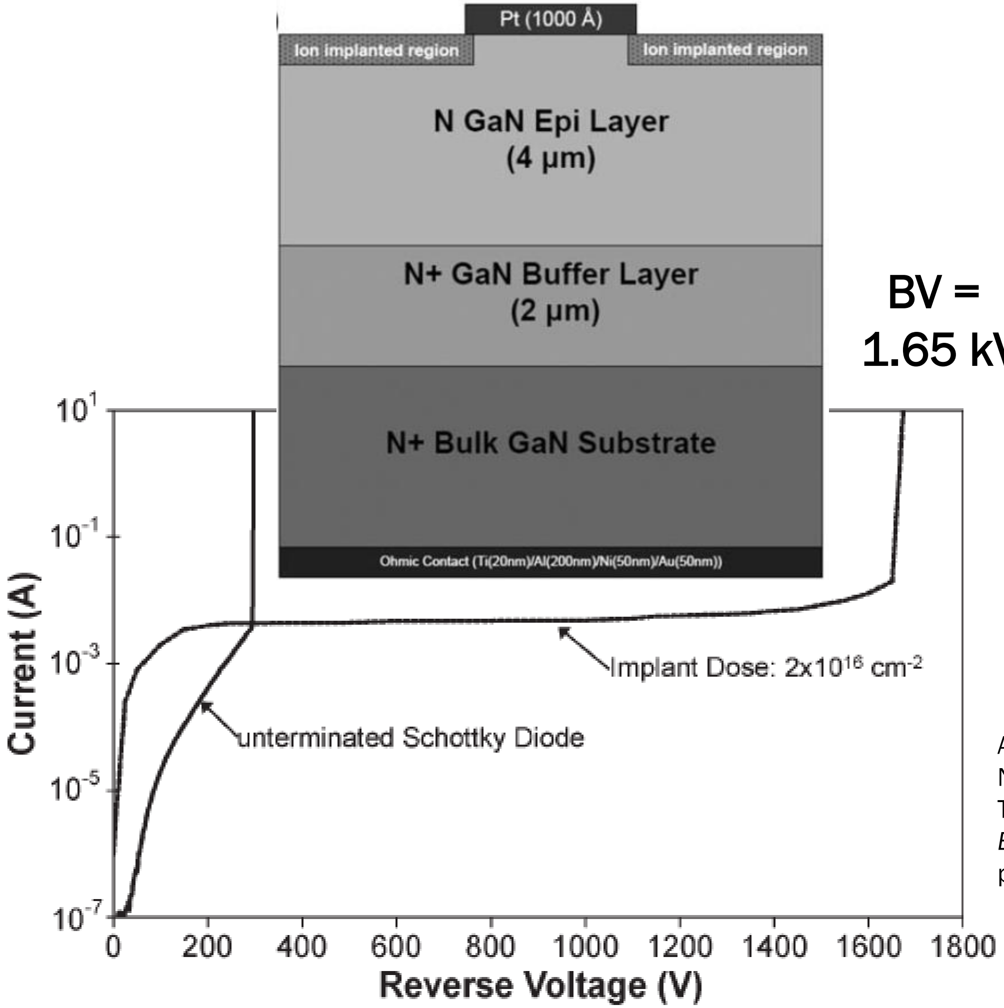
Defective surface introduces non-idealities

D. Khachariya *et al.*, "Chemical Treatment Effects on Schottky Contacts to MOCVD N-polar GaN," presented at the International Workshop on Nitride Semiconductors, Kanazawa, Japan, 2018.

We need passivation!

Ion Implantation Technology for GaN

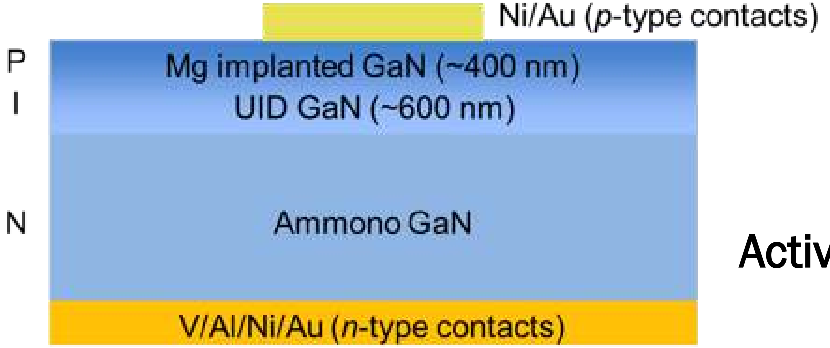
Ar implantation for edge termination



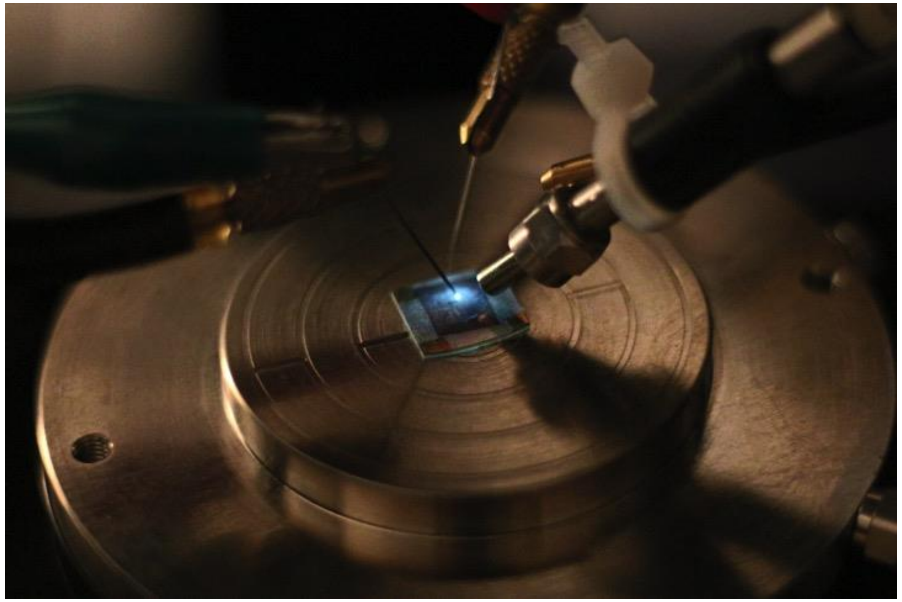
BV = 1.65 kV

A. M. Ozbek and B. J. Baliga, “Planar Nearly Ideal Edge-Termination Technique for GaN Devices,” *IEEE Electron Device Letters*, vol. 32, no. 3, pp. 300–302, 2011.

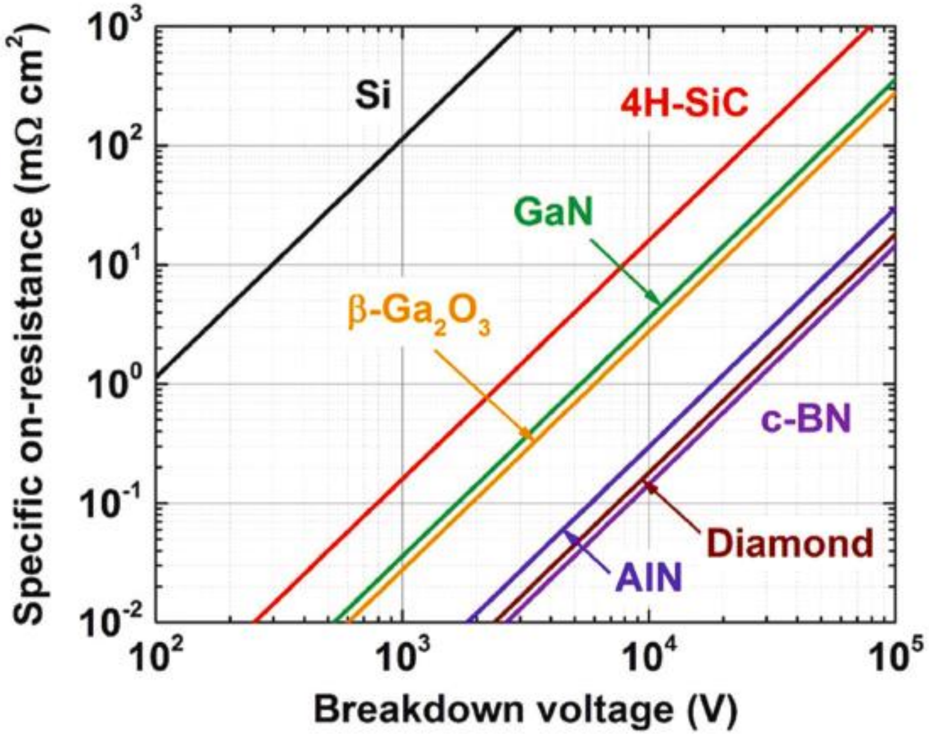
Mg-Implantation for p-GaN

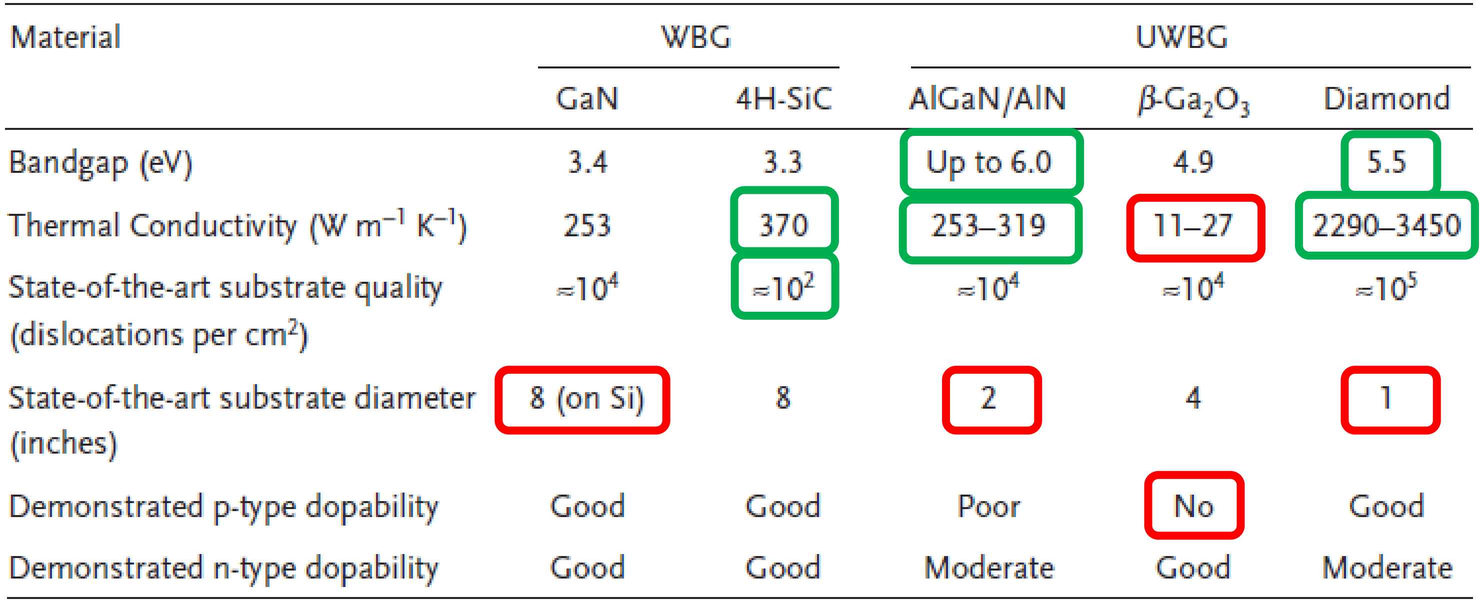


Activation anneal is critical



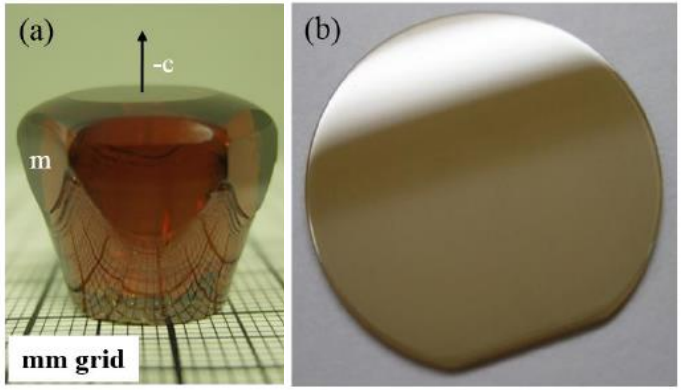
Ultra Wide Bandgap Semiconductors





Material	WBG		UWBG		
	GaN	4H-SiC	AlGaN/AlN	β-Ga$_2$O$_3$	Diamond
Bandgap (eV)	3.4	3.3	Up to 6.0	4.9	5.5
Thermal Conductivity (W m^{-1} K^{-1})	253	370	253–319	11–27	2290–3450
State-of-the-art substrate quality (dislocations per cm^2)	$\approx 10^4$	$\approx 10^2$	$\approx 10^4$	$\approx 10^4$	$\approx 10^5$
State-of-the-art substrate diameter (inches)	8 (on Si)	8	2	4	1
Demonstrated p-type dopability	Good	Good	Poor	No	Good
Demonstrated n-type dopability	Good	Good	Moderate	Good	Moderate

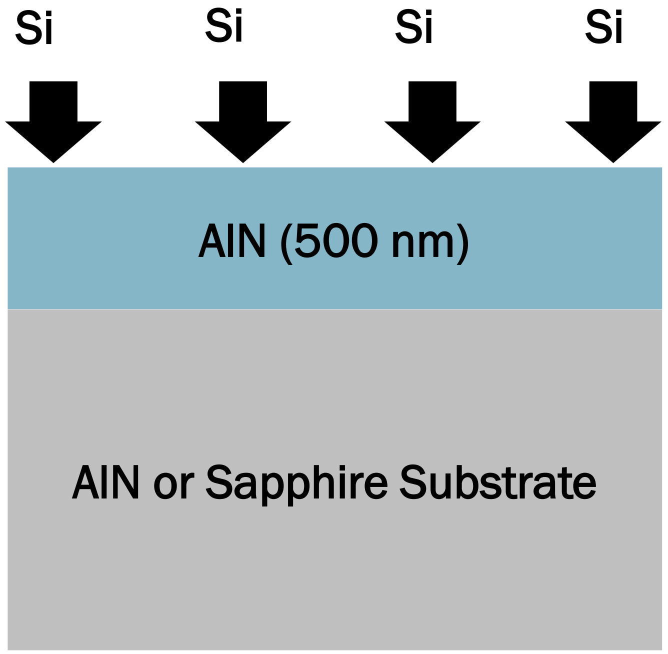
Ultra WBG III-Nitrides (AlGaN and AlN) offer the next frontier of power electronics, and are once again supported by optoelectronics applications (e.g., UV water purification)



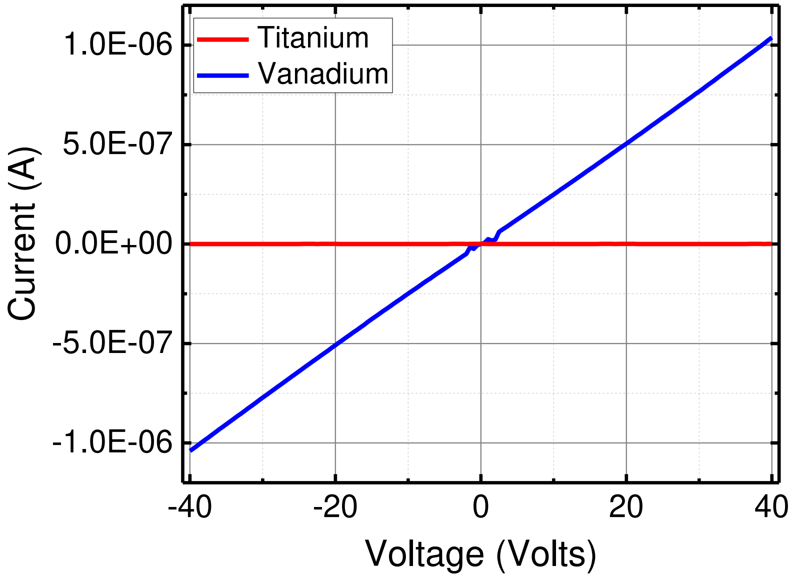
J. Y. Tsao *et al.*, “Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges,” *Advanced Electronic Materials*, vol. 4, no. 1, p. 1600501, 2018.

Ion-Implanted AlN Channels

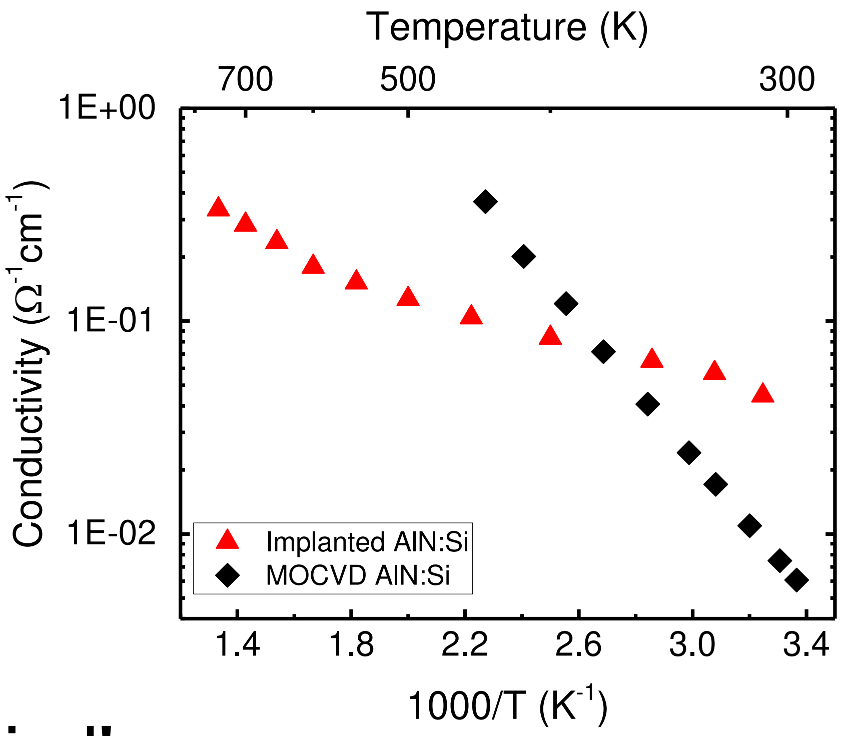
Si implantation
n-type dopes AlN



V-based ohmic contacts
outperform traditional
Ti-based contacts



Ion implantation in AlN
provides a pathway to higher
N_D than epitaxial doping

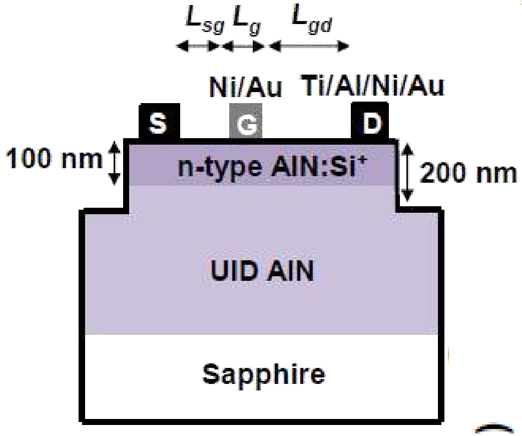


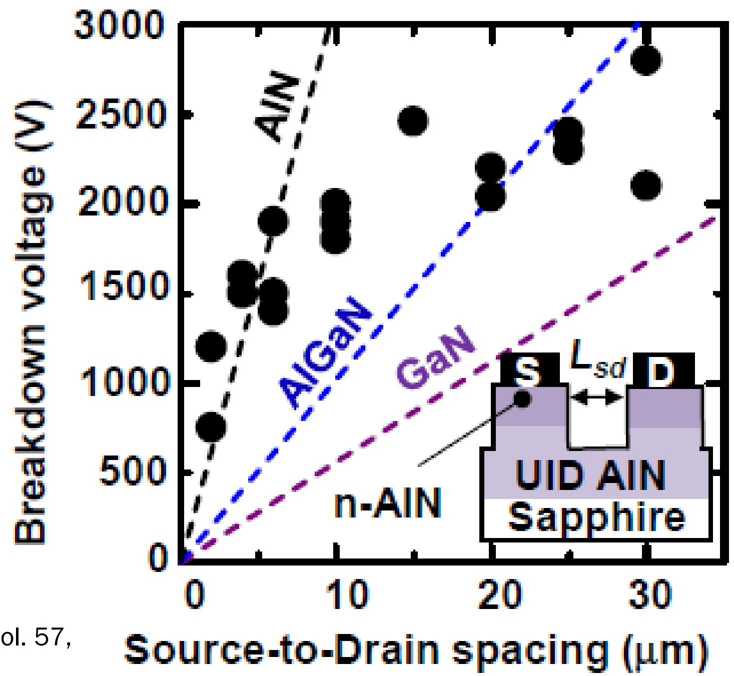
Activation anneal recipe is critical!

M. H. Breckenridge *et al.*, “Electrical and Structural Characterization of Si Implanted Homoepitaxially Grown AlN,” in *2018 IEEE Research and Applications of Photonics In Defense Conference (RAPID)*, 2018, pp. 1–4.

AlN-/AlGaN-Channel Devices

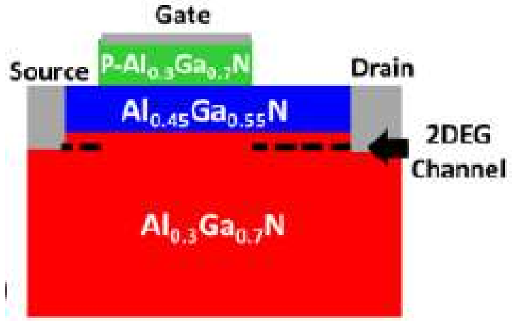
MIT/Tsukuba University (2018)

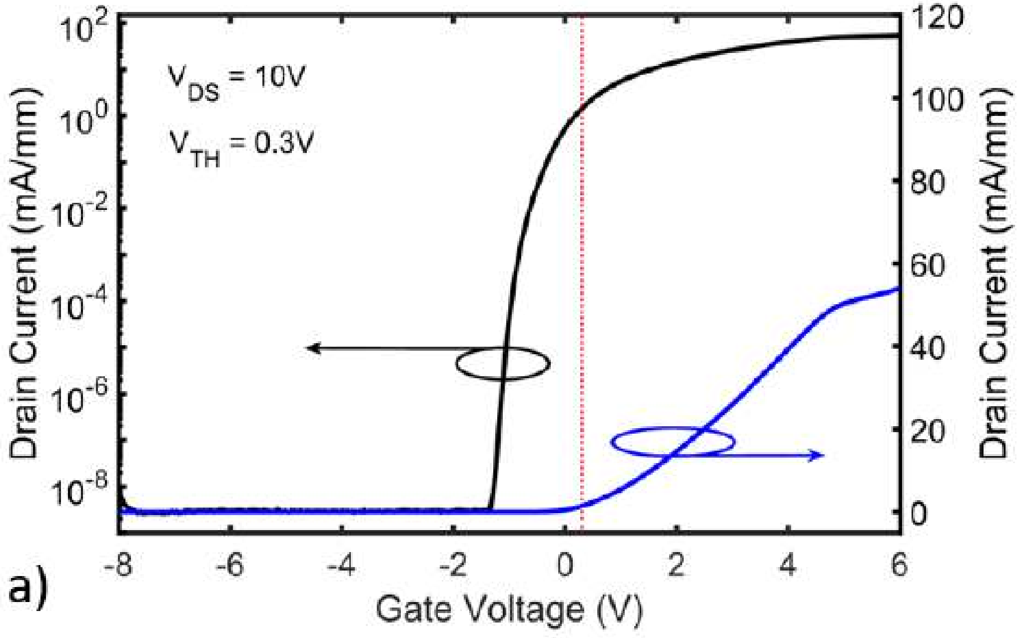




H. Okumura *et al.*," *Jpn. J. Appl. Phys.*, vol. 57, no. 4S, p. 04FR11, Mar. 2018.

Sandia (2018)



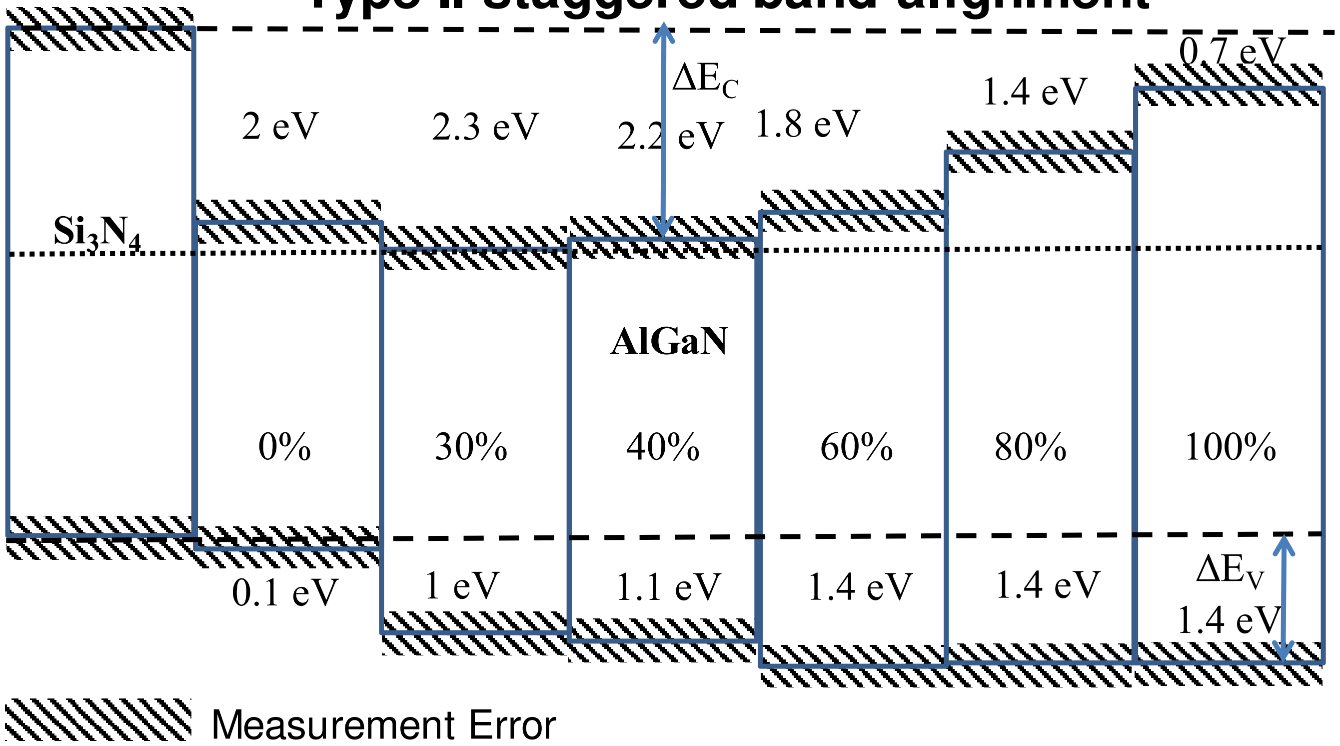


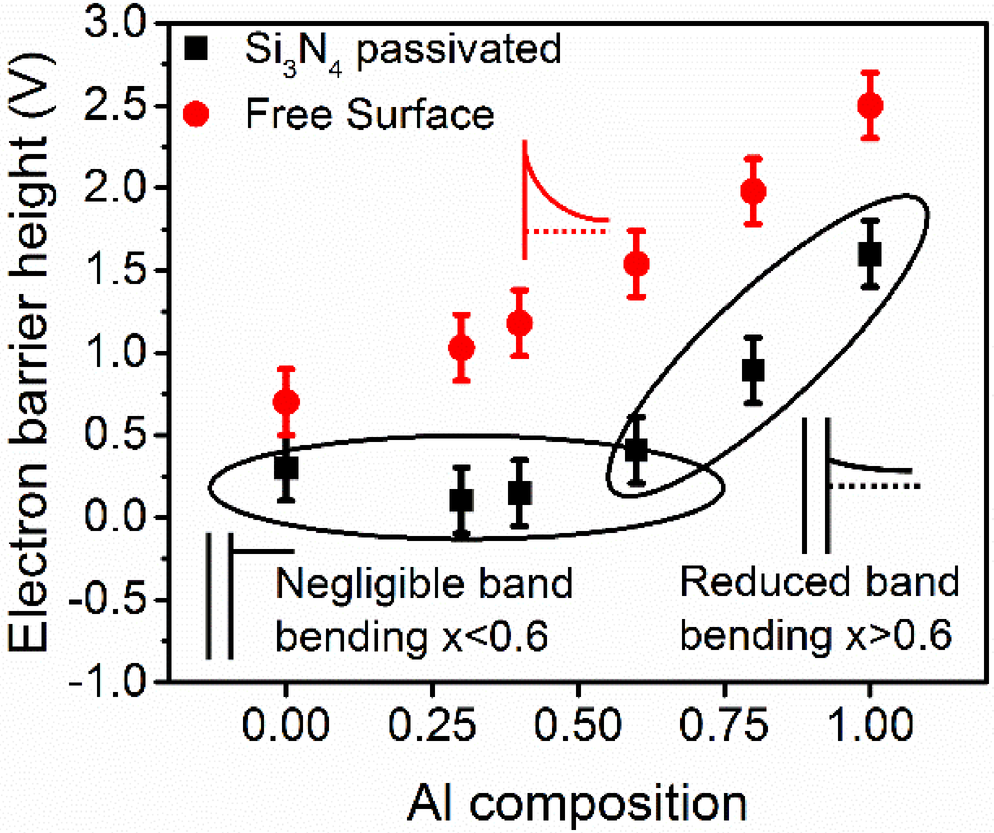
E. A. Douglas et al., *76th Device Research Conference (DRC)*, Santa Barbara, CA, USA, 2018.

Passivation of $Al_xGa_{1-x}N$

- As E_G increases, things become more challenging…

Type II staggered band alignment



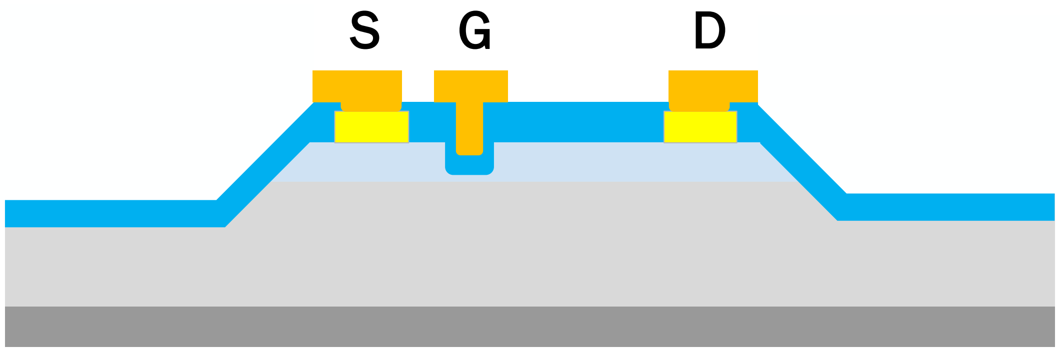


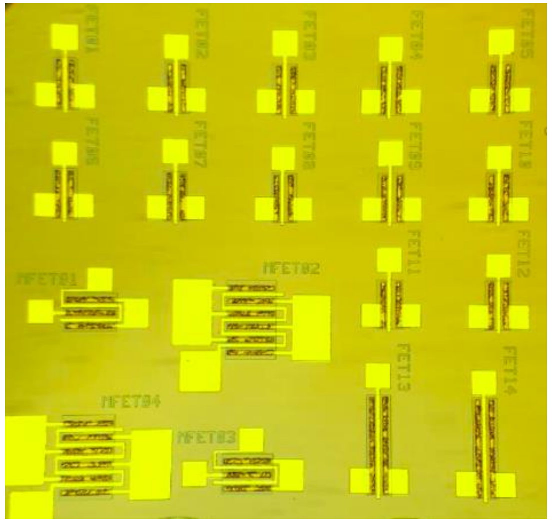
Reddy et al. J. Appl. Phys. **119**, 145702 (2016)

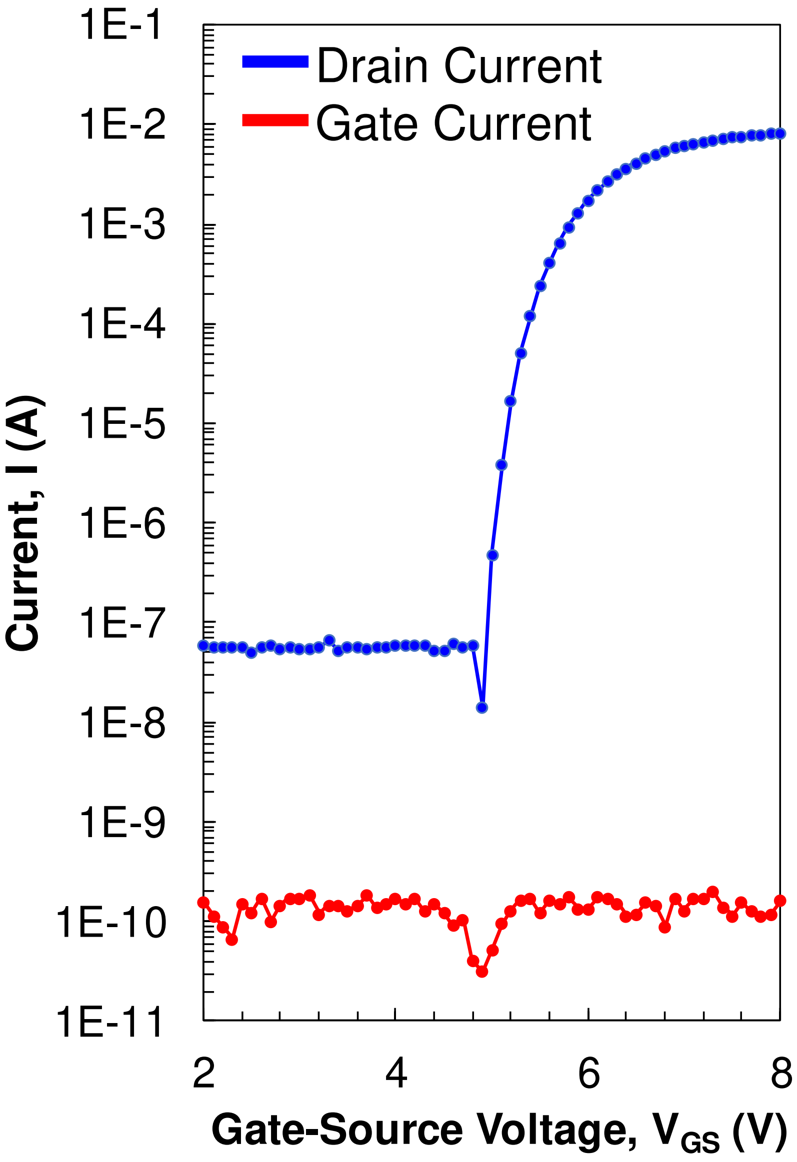
Band bending observed x>0.6

Fabrication Capabilities

E-Mode AlGaN/GaN MIS-HEMT







WBG Device Fabrication Course (& Industry Short Course?)

Measurement Capabilities

On-Wafer

DC I-V

High-Power, High-Speed PIV
220V / 2A / 200 ns PW
2kV / 100A / 1 µsec PW

Transient
1 GHz BW

Tektronix®

FOCUS MICROWAVES

infineon

Wolfspeed™
A CREE COMPANY

MACOM™

Summary

- AlGaN/GaN HEMTs are rapidly penetrating the power device market
  - But we are leaving performance on the table (passivation, thermal and reliability)
- NCSU is tackling these challenges from materials to circuits to systems
  - Example: N-polar GaN vs. Ga-polar GaN vs. mixed polar?
- UWBG III-Nitrides (e.g., AlGaN and AlN) are just around the corner
  - We are developing epitaxy, bulk substrates, implantation contacts and passivation
- Can we derive inspiration from III-Nitrides’ many uses?
  - Mixed optical/electrical systems for higher-speed and integration

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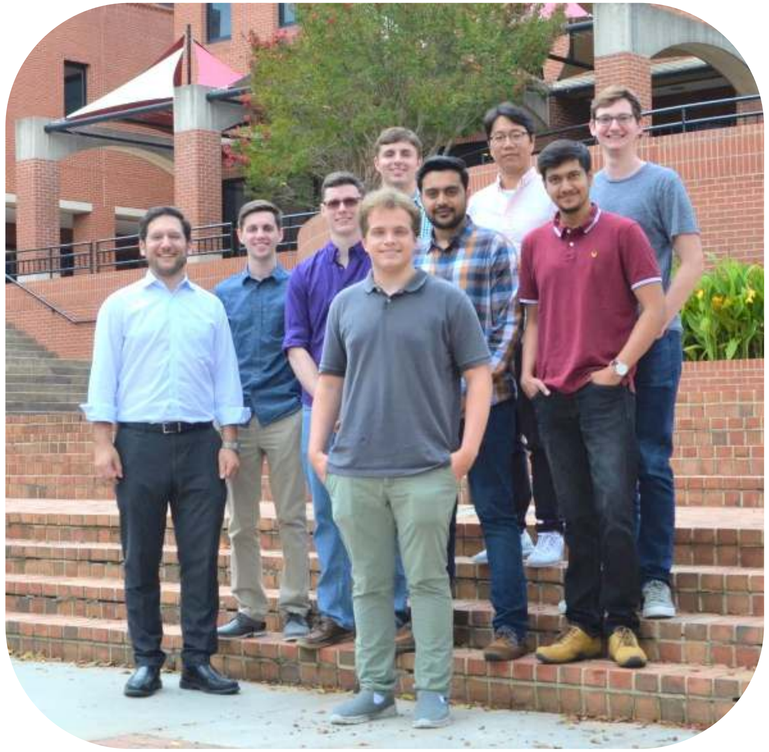
NNF NCSU NANOFABRICATION FACILITY

AIF analytical instrumentation facility

Laboratory for Electronics in Advanced Devices and Systems (NCSU LEADS)



PI: Prof. Spyridon “Spyros” Pavlidis

spavlidis@ncsu.edu