Demonstration of Vertical GaN PN Diode with Step-etched Triple zone JTE

Hyun-Soo Lee, Yuxuan Zhang, Zhaoying Chen, Mohammad Wahidur Rahman, Hongping Zhao, and Siddharth Rajan

Department of Electrical and Computer Engineering, The Ohio State University

Sponsored by the Advanced Research Projects Agency-Energy (ARPA-E), DE-AR0001036
Program Manager: Dr. Isik C. Kizilyalli

Lee.8564@osu.edu

Outline

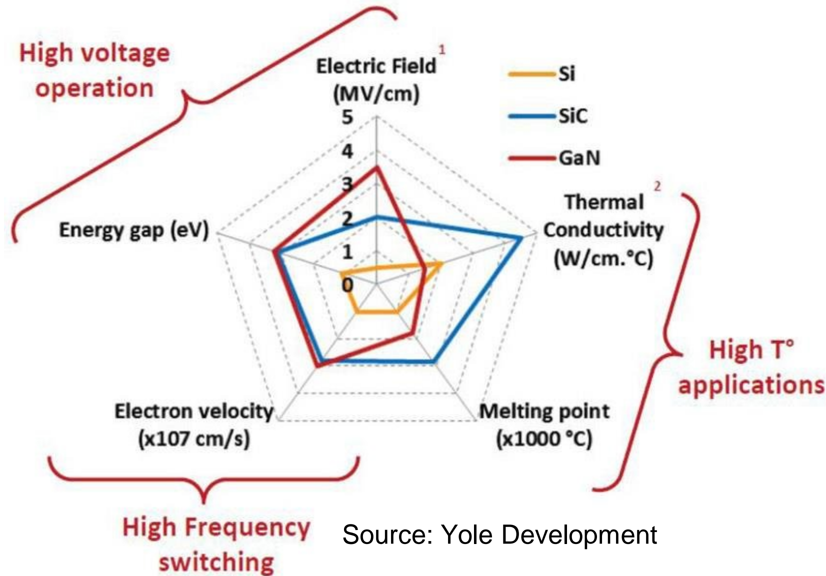
1. Edge Termination for GaN Power Devices

2. Design of Edge Termination

3. Experimental Approach and Results

Lee.8564@osu.edu

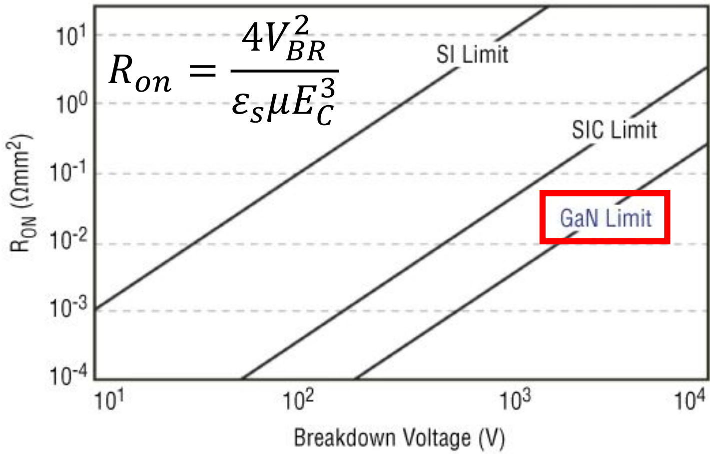
Introduction



Source: Yole Development

Properties	Si	4H-SiC	GaN
E_g [eV]	1.1	3.3	3.4
E_C [MV/cm]	0.3	2.5	3.3
μ [cm²/V·s]	1400	1000	1200
BFOM [$\varepsilon_s \mu E_C^3$]	1	340	870

Source: ON Semiconductor



Source: Efficient Power Conversion Corporation (EPC)

Key factors

1. **High electron mobility and critical electric field**

   → Promising material for power devices

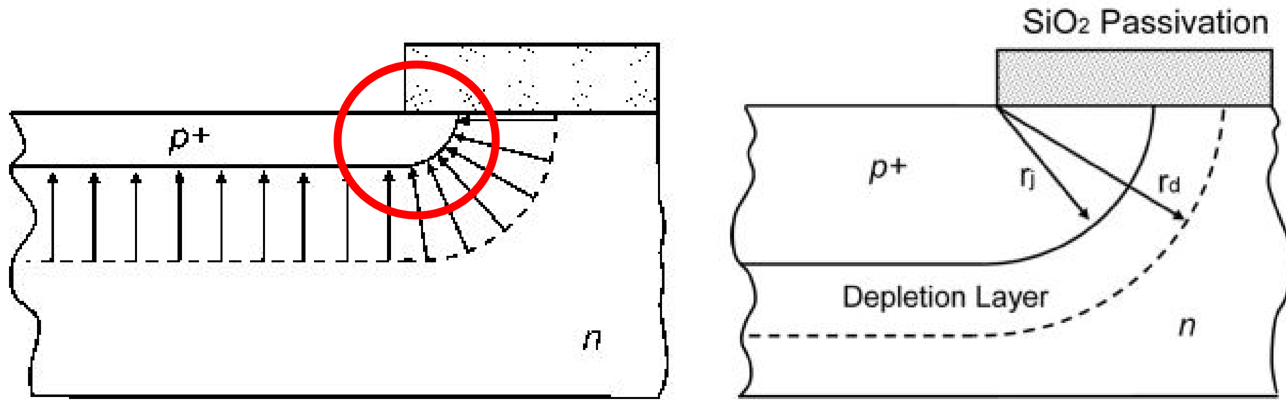
2. **Vertical topology**

   → high current density with small area, easy to package

3. **Bulk substrate with low dislocation density (<10^6 cm^{-2})**

   → Improved reliability, yield, and reverse characteristics

Edge Termination for Vertical Devices



r_d: depletion region edge
r_j: junction depth

$$E_{max,Parallel} = \frac{qN_D r_d}{\epsilon_0 \epsilon_s}$$

$$E_{max,Cylindrical} = \frac{qN_D r_d^2}{2\epsilon_0 \epsilon_s r_j}$$

$$\frac{E_{m,Cylindrical}}{E_{m,Parallel}} = \frac{r_d}{2r_j}$$

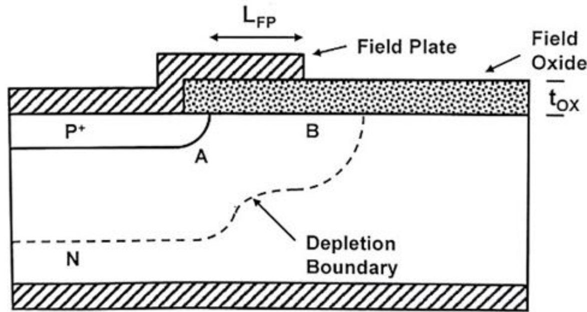
- ❖ **Proper edge termination techniques to achieve ideal breakdown voltage**
- ✓ **Premature breakdown of power devices without edge termination due to effects of field crowding at the junction periphery**
- ✓ **Make near-parallel junction (to avoid cylindrical junction)**
- → If the junction depth is 1 um and the depletion region is 10 um, the maximum electric field at cylindrical junction will be 5 times larger than parallel junction case
- → The maximum electric field at spherical junction is much higher than cylindrical junction case

Source: https://ebrary.net/82339/computer_science/cylindrical_junction

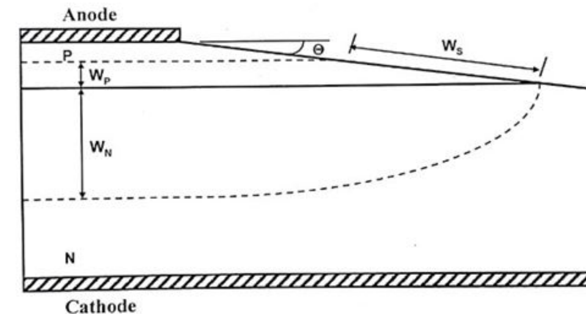
Lee.8564@osu.edu

Edge Termination for Vertical Devices

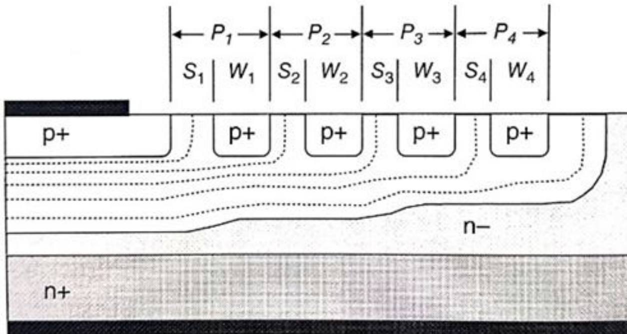
THE OHIO STATE UNIVERSITY



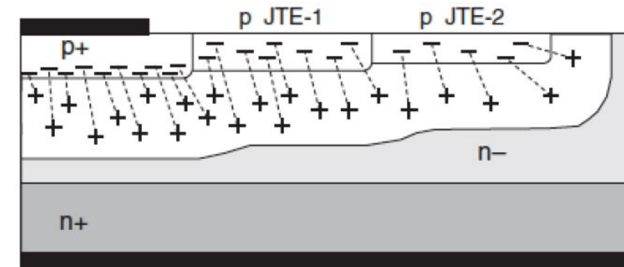
Field plate [1]



Bevel edge termination [1]



Guard ring [2]



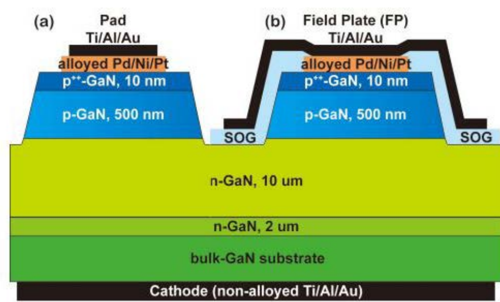
Junction Termination Extension (JTE) [2]

- ➢ **Field plates are limited in the case of high voltage (> 10 kV) devices**
- ➢ **Bevel angle should be small (~10 °), which is hard to process**
- ➢ **Patterned p-type doping using ion-implantation is required for guard ring and JTE**
  → currently challenging for GaN

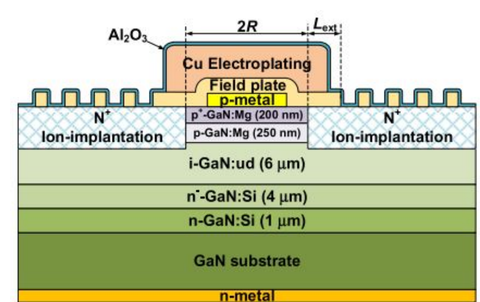
[1] B. J. Baliga, *Silicon Carbide Power Devices.* Singapore: World Scientific, 2005
[2] T. Komoto et al., Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications. Hoboken, NJ, USA: Wiley, 2014

Lee.8564@osu.edu

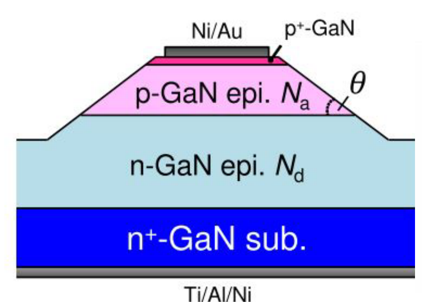
Current Status for GaN Edge Termination



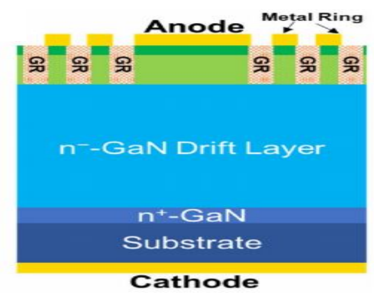
Field plate [1]
Cornell University



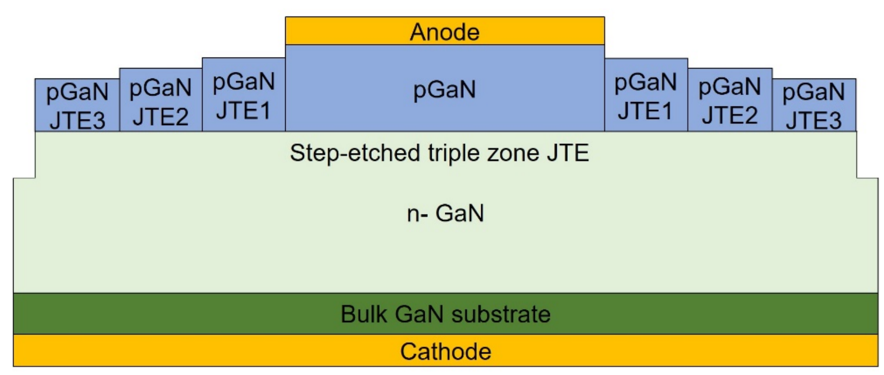
Nitrogen Ion-implantation [2]
Georgia Institute of Technology



Negative bevel edge termination [3]
Kyoto University



Hydrogen plasma-based Guard ring [4]
Arizona State University



Proposed structure
Step-etched triple zone JTE
(STJTE)

- Etching JTE structure that decreases in thickness as it goes outside → the mechanism is same to multiple JTE
- Patterned p-type doping using ion-implantation and precise control of bevel angle are not needed
- Power devices with high breakdown capability (>10 kV) using PN junction JTE unlike Field plate

[1] K. Nomoto et al., *IEEE Electron Device Lett.*, vol. 37, no. 2, pp. 161-164, Feb. 2016.
[2] C.-W. Tsou et al., *IEEE Trans. Electron Devices,* vol. 66, no. 10, pp. 4273-4278, Oct. 2019.
[3] T. Maeda et al., *IEEE Electron Device Lett.*, vol. 40, no. 6, pp. 941-944, June. 2019.
[4] H. Fu et al., *IEEE Electron Device Lett.*, vol. 41, no. 1, pp. 127-130, Jan. 2020.

Lee.8564@osu.edu

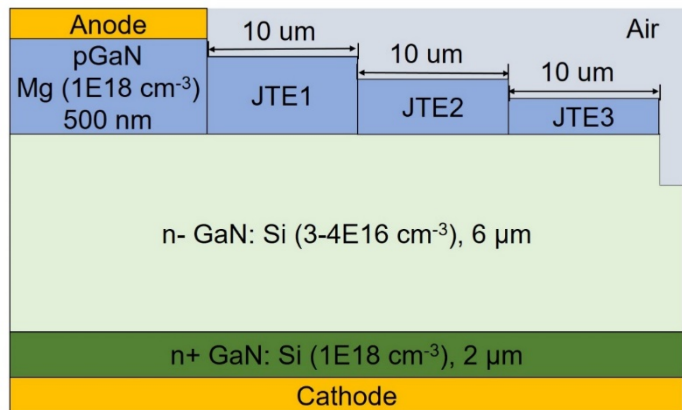
Outline

THE OHIO STATE UNIVERSITY

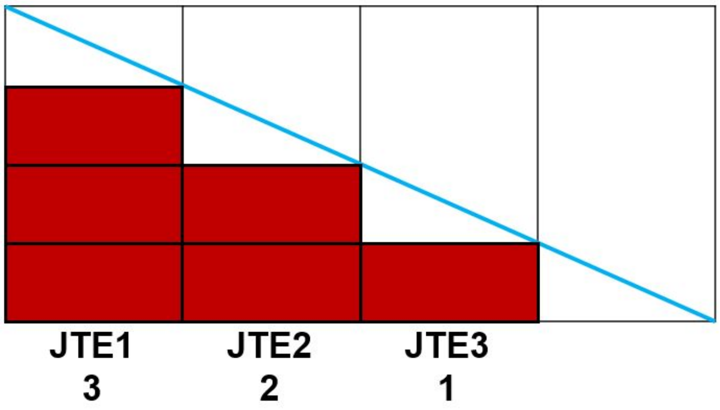
1. Edge Termination for GaN Power Devices
2. **Design of Edge Termination**
3. Experimental Approach and Results

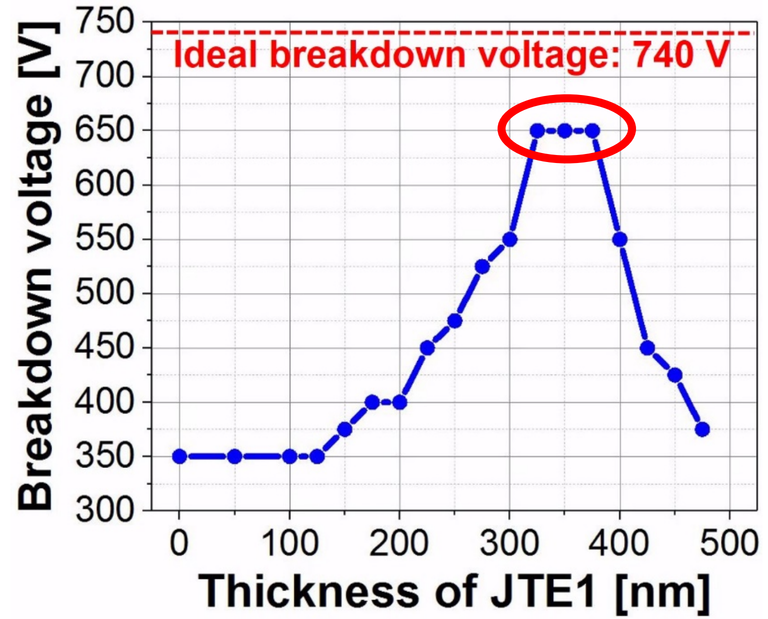
Lee.8564@osu.edu

Design of Junction Termination Layers



STJTE structure for simulation

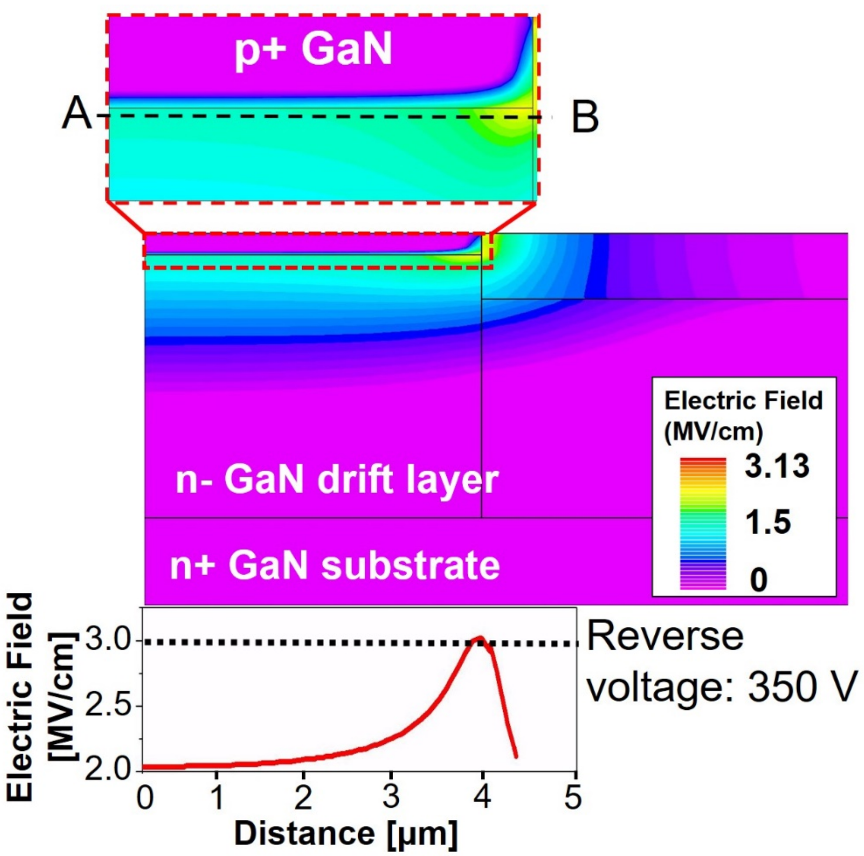


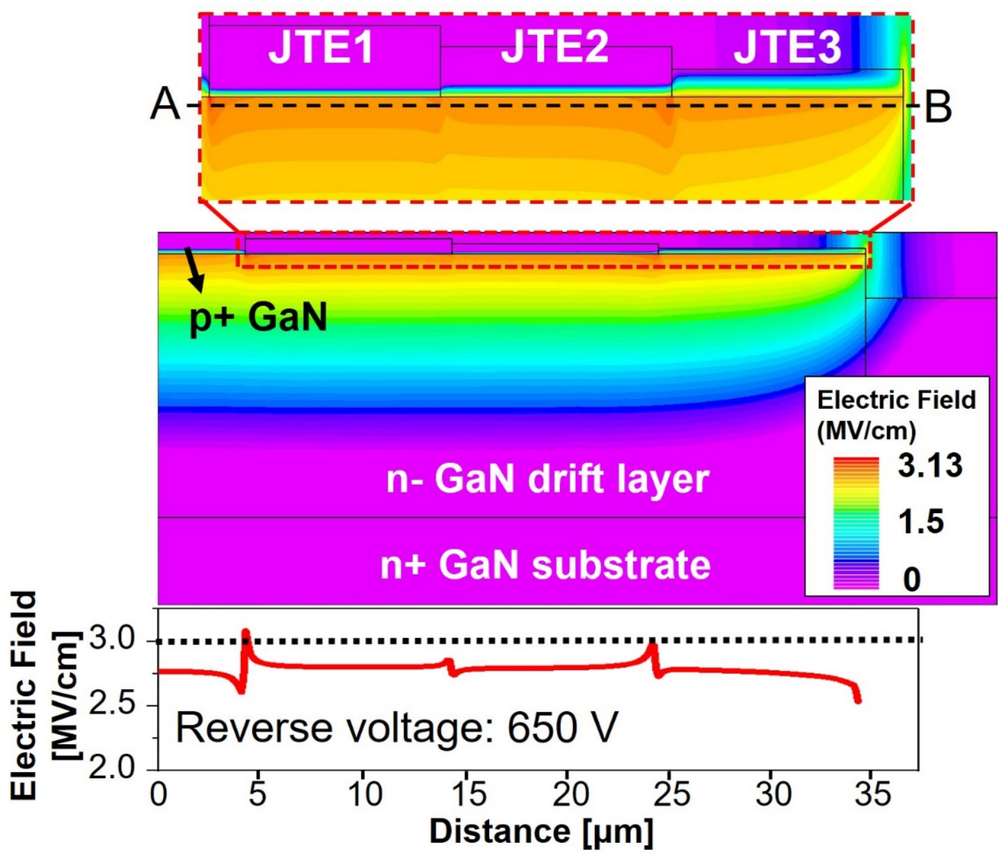


- The total length of JTE region = 5 X the thickness of drift layer = 30 µm
- The ratio of each JTE thickness was fixed as JTE1:JTE2:JTE3 = 1 : 0.7 : 0.4
- The range of JTE1 thickness that has the highest breakdown voltage is 50 nm

Lee.8564@osu.edu

Design of Junction Termination Layers





Conventional structure (without STJTE)
→ **47 %** JTE efficiency

STJTE structure with the optimized JTE thickness
→ **88 %** JTE efficiency

JTE efficiency = [Real breakdown voltage/Ideal breakdown voltage] X 100

Lee.8564@osu.edu

Outline

THE OHIO STATE UNIVERSITY

1. Edge Termination for GaN Power Devices
2. Design of Edge Termination
3. **Experimental Approach and Results**

Lee.8564@osu.edu

Epitaxial Design

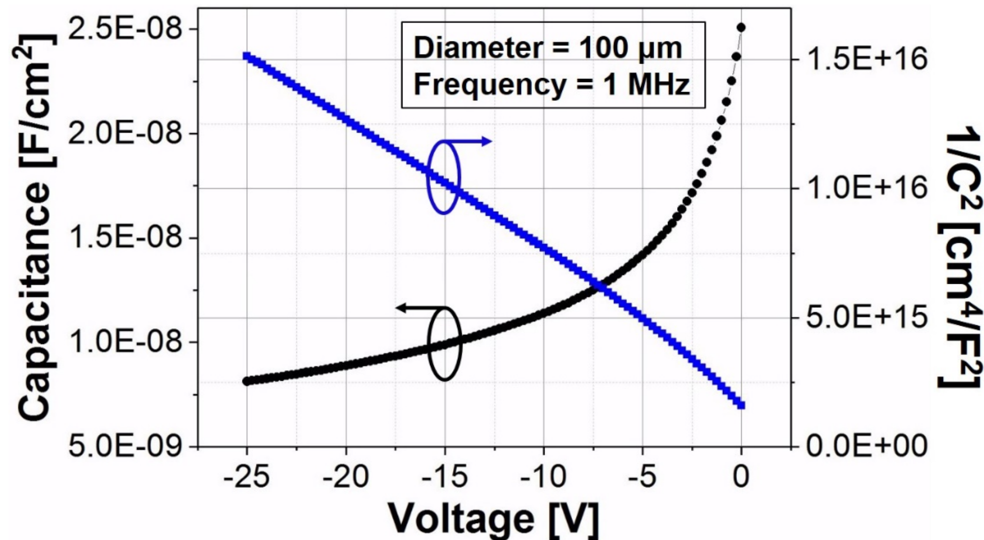
Layer
p+ GaN: Mg (1E19 cm^{-3}) 20 nm
pGaN: Mg (1E18 cm^{-3}) 500 nm
n- GaN: Si (3-4E16 cm^{-3}), 6 μm
n+ GaN: Si (2E18 cm^{-3}), 1.2 μm
Bulk GaN substrate

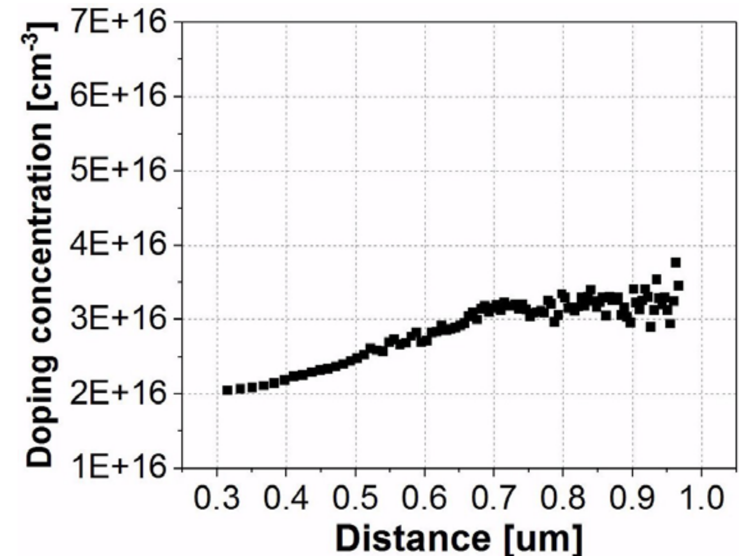
- All epitaxial layers were grown by MOCVD
- Ideal breakdown voltage: 740 V
- Non-punch through case
- p-GaN layer
  - → Mg density = ~5E18 cm^{-3} (SIMS)
  - → Hole density = 1E17 cm^{-3}, Mobility = 18.4 $cm^2/V\cdot s$ (Hall measurement at RT)

Lee.8564@osu.edu

Doping and C-V Characterization

THE OHIO STATE UNIVERSITY

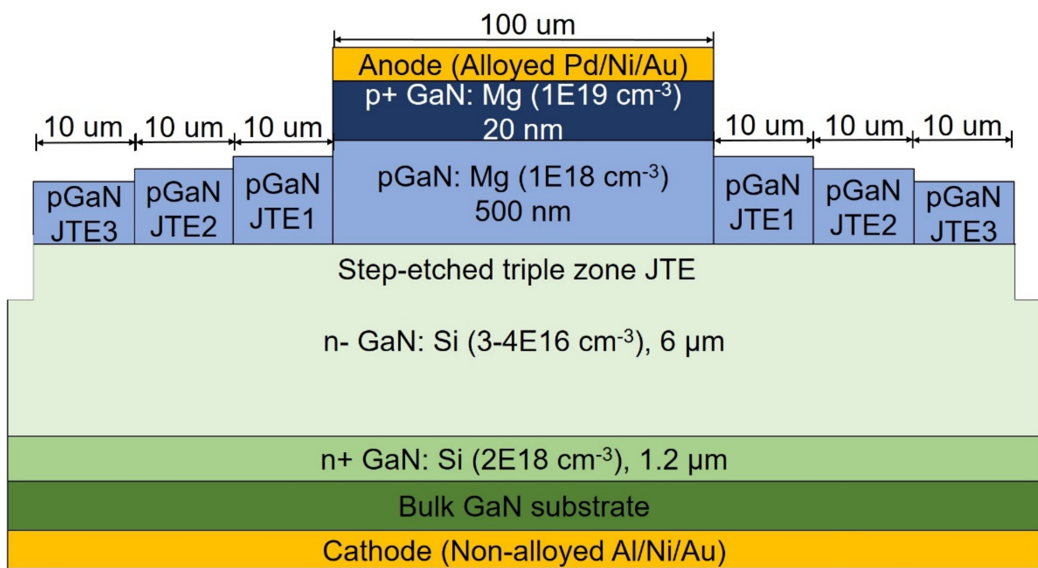


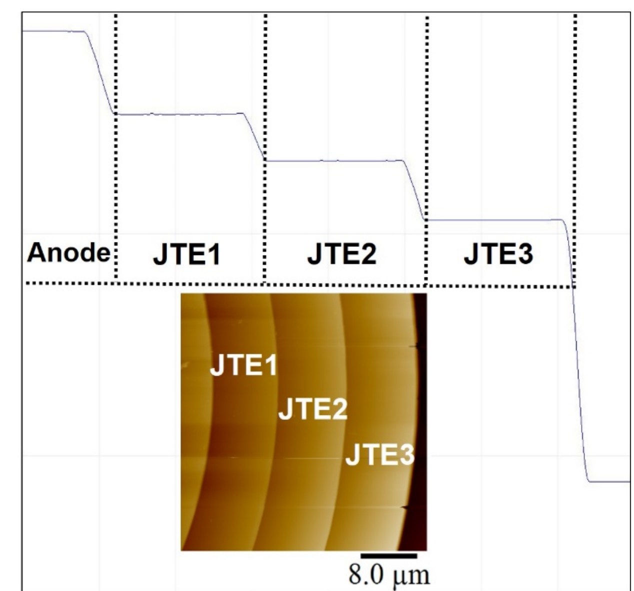


- The net doping concentration (N_D-N_A) in the n-GaN drift layer was estimated to be 2-3E16 cm-3 from C-V measurement
- Our MOCVD growth condition has reasonably low background impurity concentration (C ~ 1E16 cm^{-3} and O < 1E16 cm^{-3}) based on SIMS measurement
- This is in agreement with extracted N_D-N_A from C-V measurement

Lee.8564@osu.edu

Fabrication of vertical GaN pn diode with STJTE



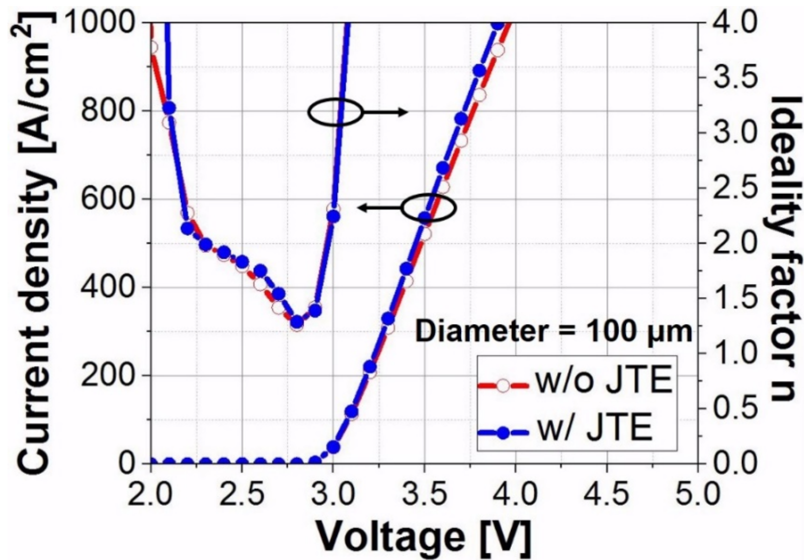


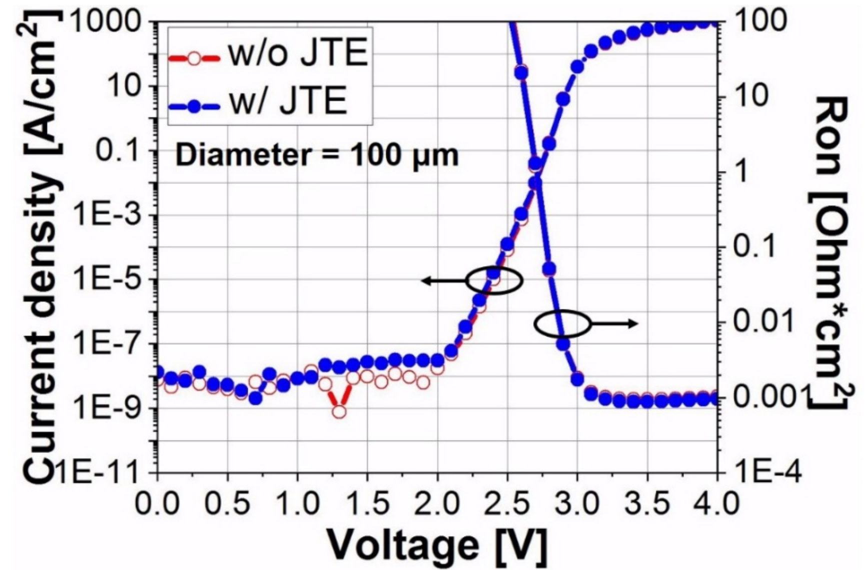
- Low power etching conditions which has ~8.3 Å/s etch rate for etching JTE region was used to minimize etching damage
- p-GaN contact resistance = ~1 mΩ·cm^2 from TLM

Parameters	JTE1	JTE2	JTE3
Optimal thickness (Simulation) [nm]	325 ~ 375	228 ~ 263	130 ~ 150
Fabricated JTE thickness [nm]	335	230	105

Lee.8564@osu.edu

Forward Characteristics

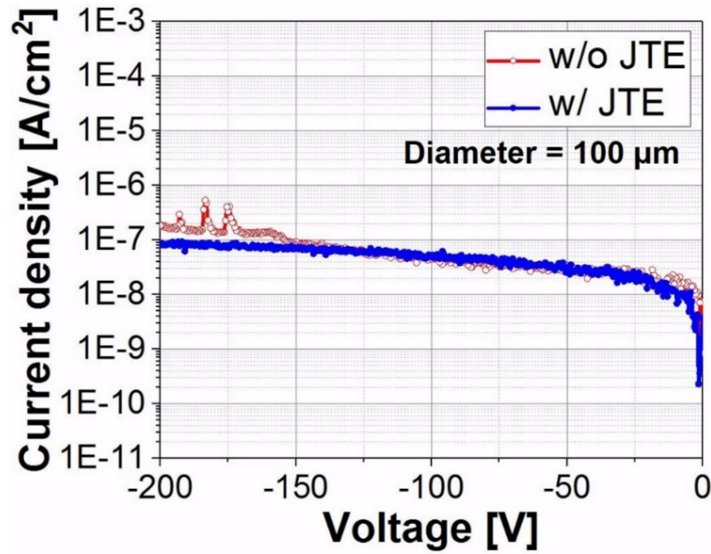


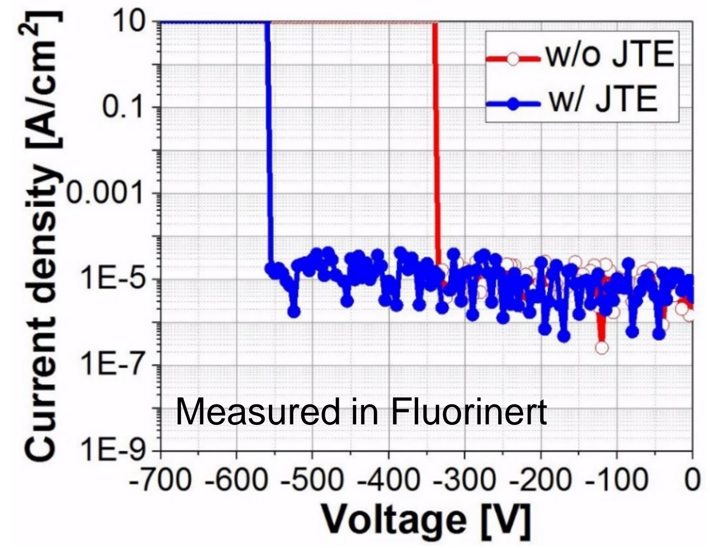


Parameter	Value
Turn-on voltage @ 100 A/cm^2 [V]	**3.1**
The lowest Ideality factor n	**1.3**
on / off ratio	**~10^{11}**
Total specific on-resistance @ 1kA/cm^2 [mΩ·cm^2]	**1.3**
Total specific on-resistance – [p-GaN contact resistance (1 mΩ·cm^2) + thick substrate resistance (0.125 mΩ·cm^2)]	**0.175**
Calculated mobility of n-GaN drift layer [cm^2/V·s]	**715**

Lee.8564@osu.edu

Reverse Characteristics



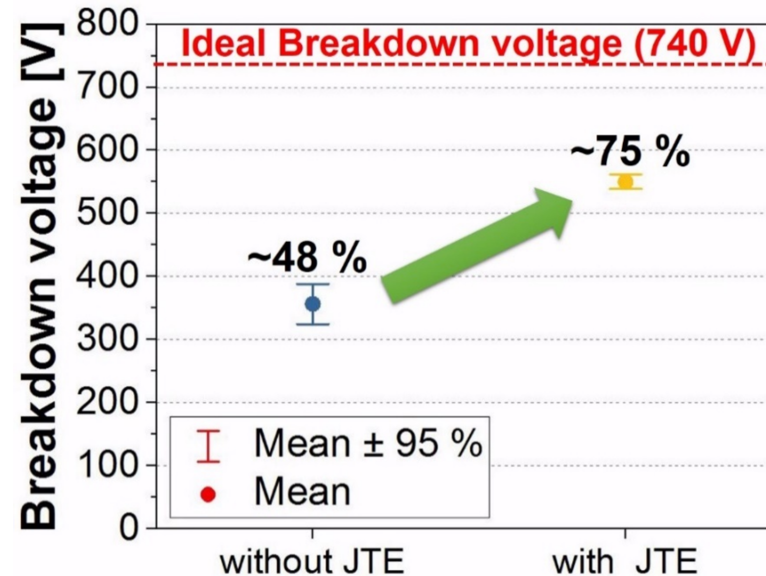


Parameter	Without STJTE	With STJTE
Leakage current @ -200 V [nA/cm^2]	**186**	**86**
Breakdown voltage [V]	**330**	**550**
Simulated breakdown voltage [V]	**350**	**650**

- Higher leakage at > 200 V suggests higher electric field starts peaking in edge regions
- Leakage and breakdown behavior improved significantly after STJTE
- Breakdown improved from 330 V to 550 V with STJTE – breakdown was destructive, not avalanche breakdown

Lee.8564@osu.edu

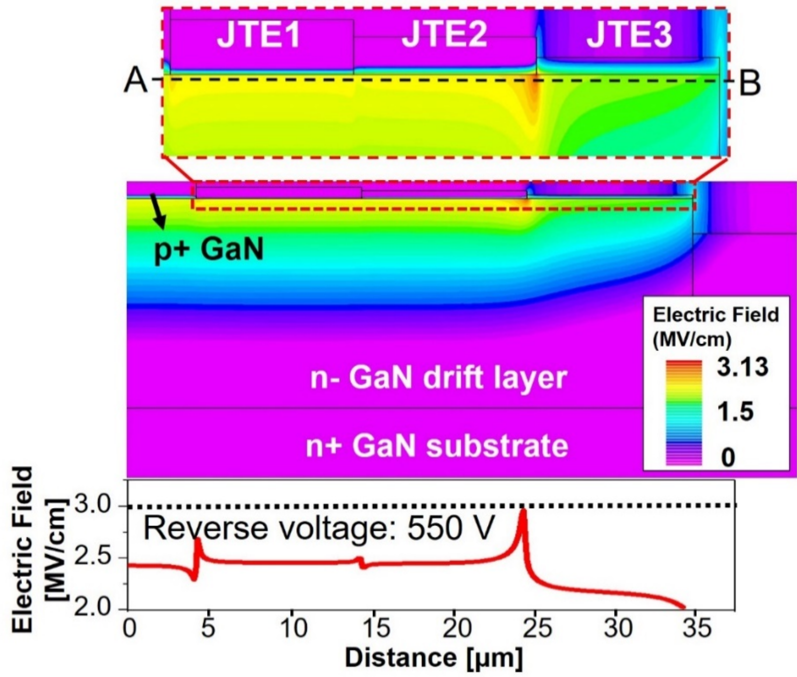
Device Breakdown - Statistics



- 24 devices without STJTE and 80 devices with STJTE were measured
- The standard deviation was 50 V with STJTE
- The average breakdown voltage of without STJTE was 360 V corresponding to ~48 % JTE efficiency (Simulated value = 47 %) → **Well-matched**
- The average breakdown voltage of with STJTE was 550 V corresponding to 75 % JTE efficiency (Optimal simulated value = 88 %) → **Not matched**

Lee.8564@osu.edu

Experimental versus Simulated Breakdown



Parameters	JTE1	JTE2	JTE3
Optimal thickness (Simulation) [nm]	325 ~ 375	228 ~ 263	130 ~ 150
Fabricated JTE thickness [nm]	335	230	**105**

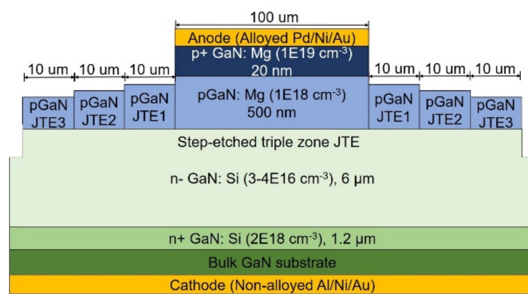
- Due to process variations, the optimal thickness was not achieved
- The simulated breakdown voltage using **actual JTE thickness** was 550 V corresponding to 75 % JTE efficiency → **Well-matched**
- **Excellent match with simulations shows robustness of the proposed approach**

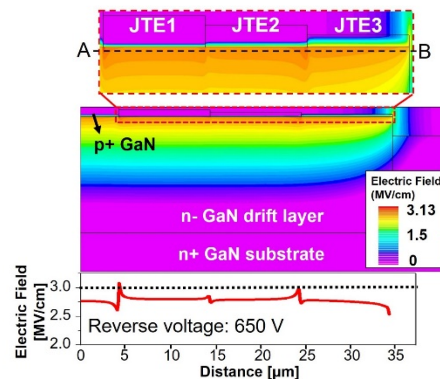
Lee.8564@osu.edu

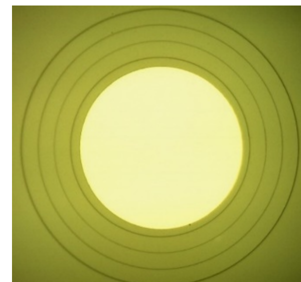
Conclusion

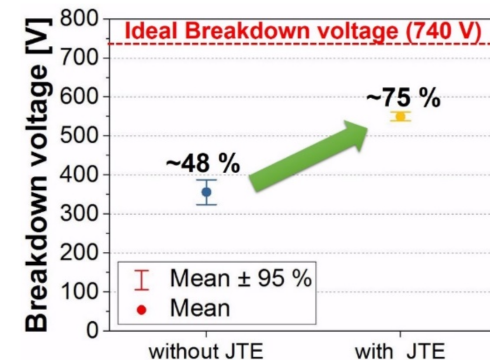
THE OHIO STATE UNIVERSITY

- We have designed and demonstrated for the first time a step-etched edge termination approach for GaN PN diode
- The fabricated vertical GaN PN diode with step-etched triple zone JTE shows breakdown voltage of 550 V corresponding to 75 % JTE efficiency
- Very good match was obtained with the simulations, suggesting near-ideal behavior for the edge termination and minimal effect of etching damage
- Multi-step edge termination could be a promising approach for future multi kV-class GaN vertical power devices









Lee.8564@osu.edu

Thank you

Lee.8564@osu.edu