



**THE OHIO STATE UNIVERSITY**  
COLLEGE OF ENGINEERING

DEPARTMENT OF  
ELECTRICAL AND COMPUTER ENGINEERING

# Monolithic MOCVD-Grown III-Nitride Tunnel Junctions with Ultra-Low Resistance

**Syed M. N. Hasan<sup>1</sup>,**

**Zane Jamal-Eddine<sup>1</sup>, Brendan Gunning<sup>2</sup>, Mary Crawford<sup>2</sup>, Andrew Armstrong,  
Siddharth Rajan<sup>1</sup>, and Shamsul Arafin<sup>1</sup>**

*<sup>1</sup>Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH, USA*

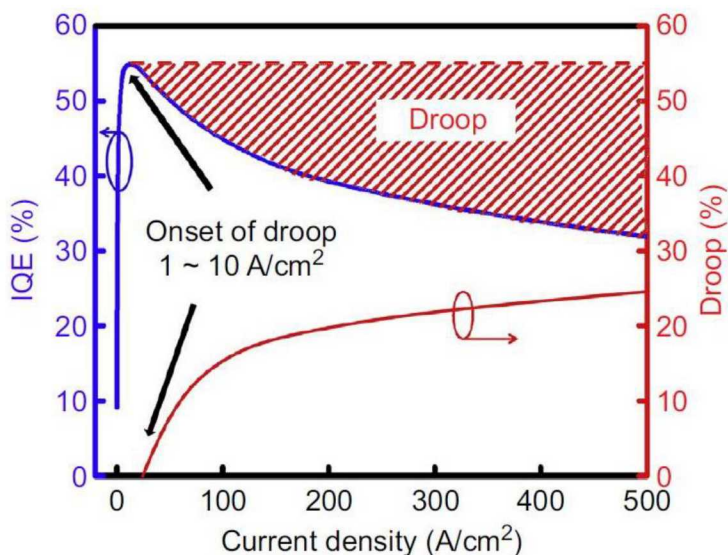
*<sup>2</sup>Sandia National Laboratories, NM, USA*

26<sup>th</sup> June 2020

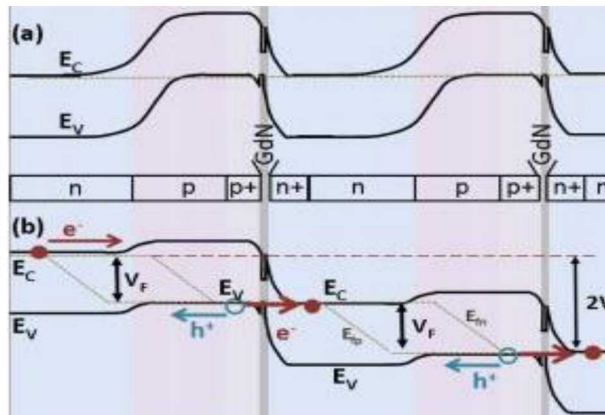
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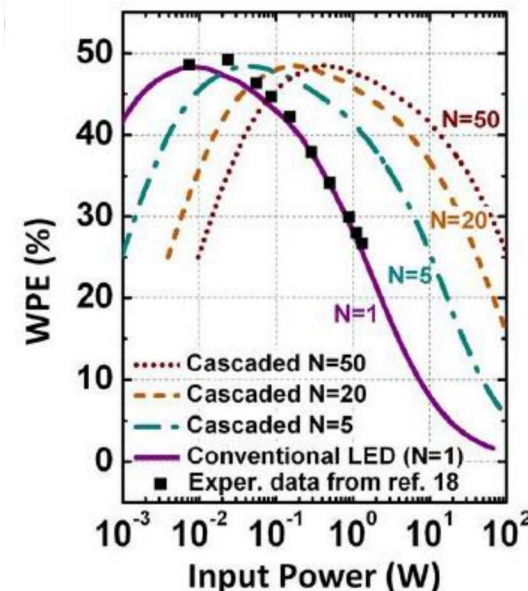
**62<sup>ND</sup> ELECTRONIC MATERIALS CONFERENCE**  
June 24-26, 2020



H Fu, Y Zhao - Nitride Semiconductor Light-Emitting Diodes (LEDs), Elsevier, 2018



Fatih et al. APL 103, 081107 (2013)

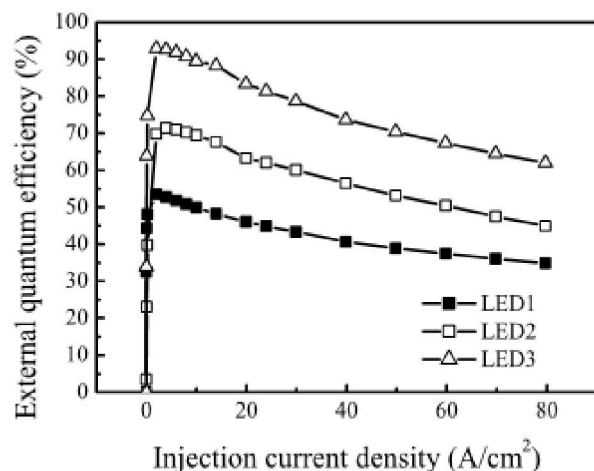


Fatih et al. APL 103, 081107 (2013)

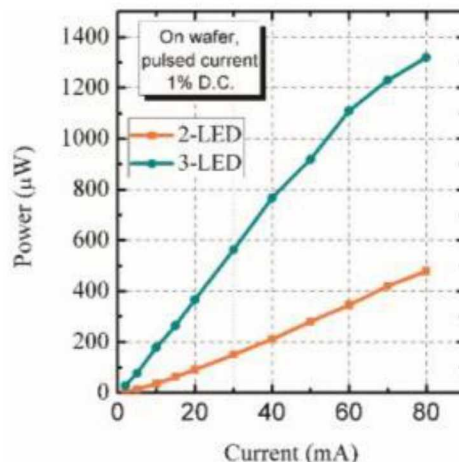
## TJ-enabled cascaded LEDs

- Alleviates hole-pile up and EQE-droop problem at high  $J$
- Multiple LEDs turn-on without increasing  $J$

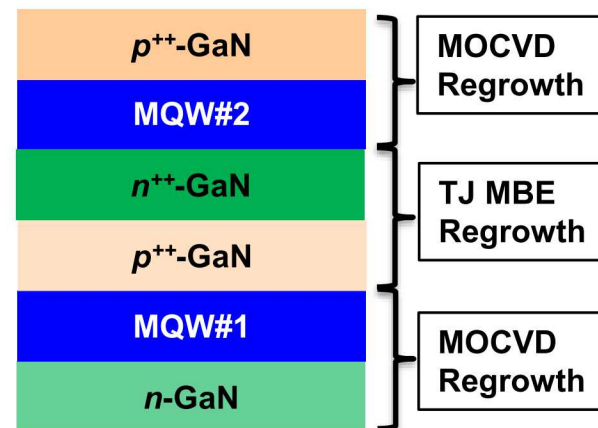
$J$  = current density



Chang et al. IEEE JQE 51, 3300505 (2015)



Fatih et al. APEx 18, 82103 (2015)



Method 1: All MOCVD

High Resistance in TJ

Method 2: All MBE

Low IQE

Method 3: MOCVD-MBE Hybrid

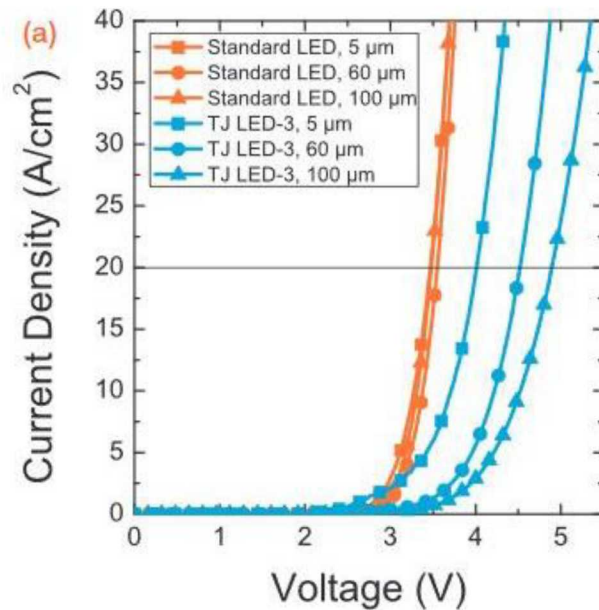
Cost inefficient

Cascaded TJ-LEDs require

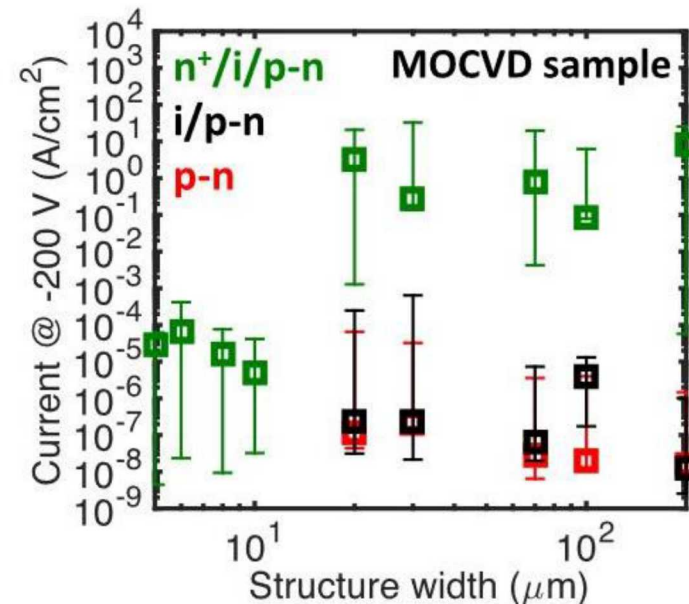
Low-resistance TJ at low  $J$ .

For instance,  $\rho_{\text{TJ}} \leq 1 \text{ m}\Omega\text{-cm}^2$  at  $30 \text{ A}/\text{cm}^2$

$\rightarrow <0.1 \text{ V}$  excess voltage drop in  $3\times$  MJ-LED

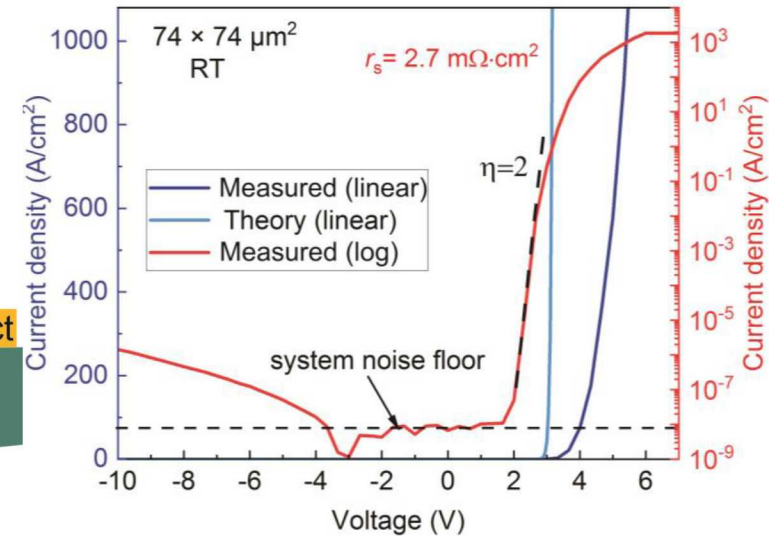
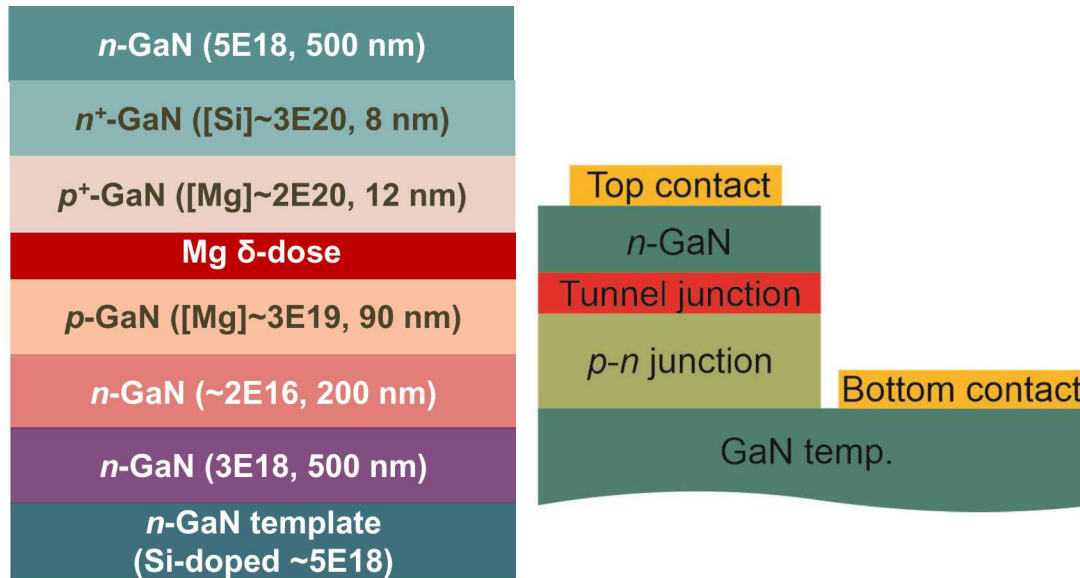


David Hwang et al. APL 11, 012102 (2018)

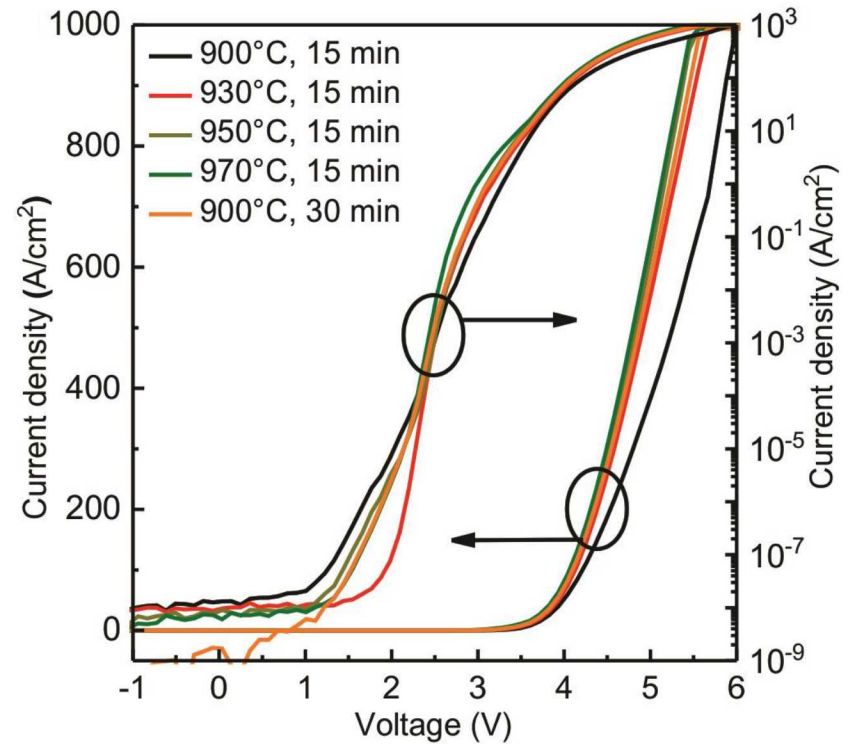
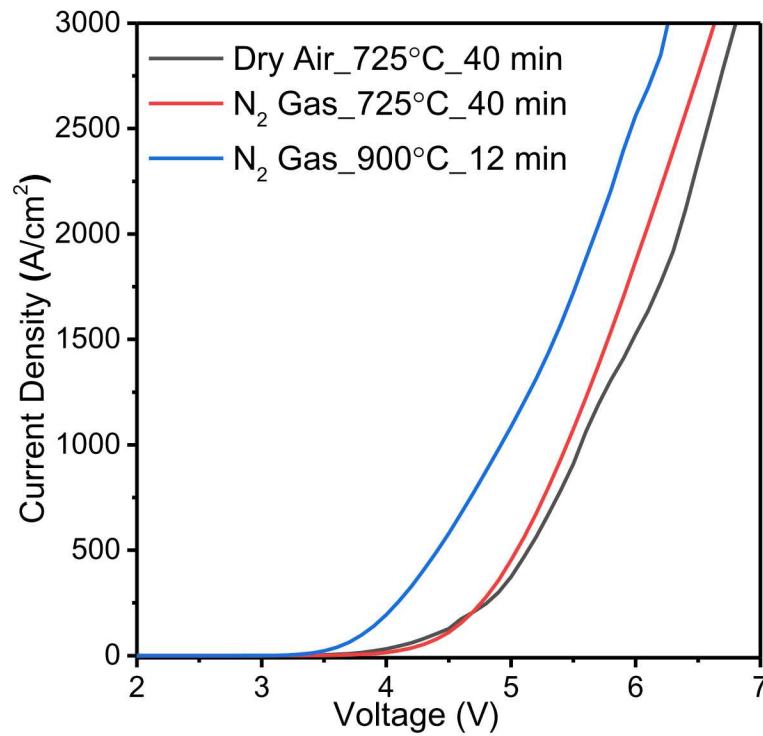


Li, Wenshen, et al. APL 113.6, 062105 (2018)

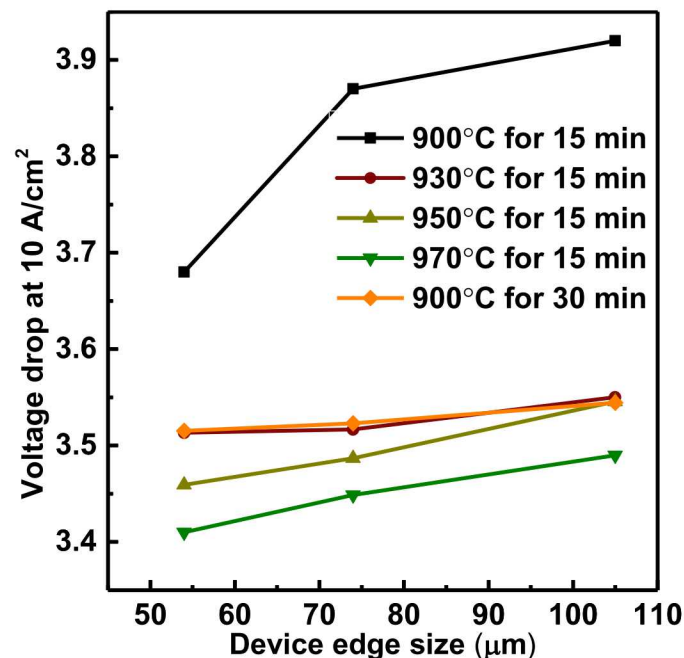
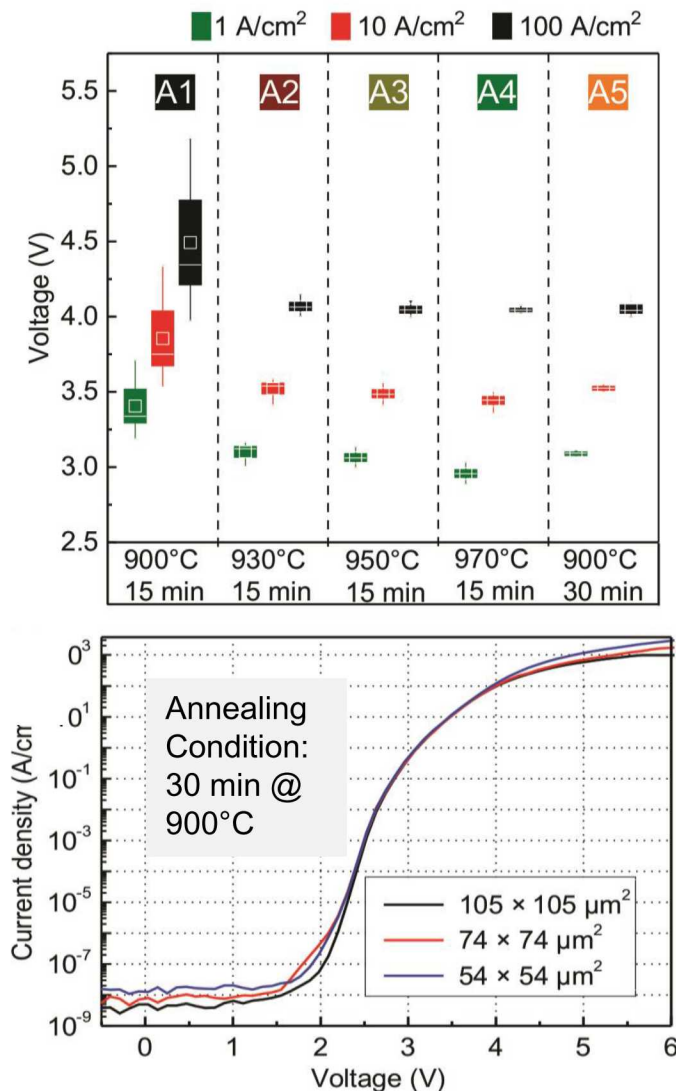
- Less doping level compared to MBE
- Memory effect
- Thermal activation of buried  $p$ -GaN layer



- Samples grown in MOCVD - Taiyo Nippon Sanso SR4000HT reactor at Sandia National Lab.
- Buried p-GaN activated through sidewalls
- Engineering p<sup>+</sup>-GaN layer: i) Thickness  
ii) Mg δ-dose



- $\text{N}_2$  gas more effective than dry air
- Annealing temperature changed to 900°C from 725°C



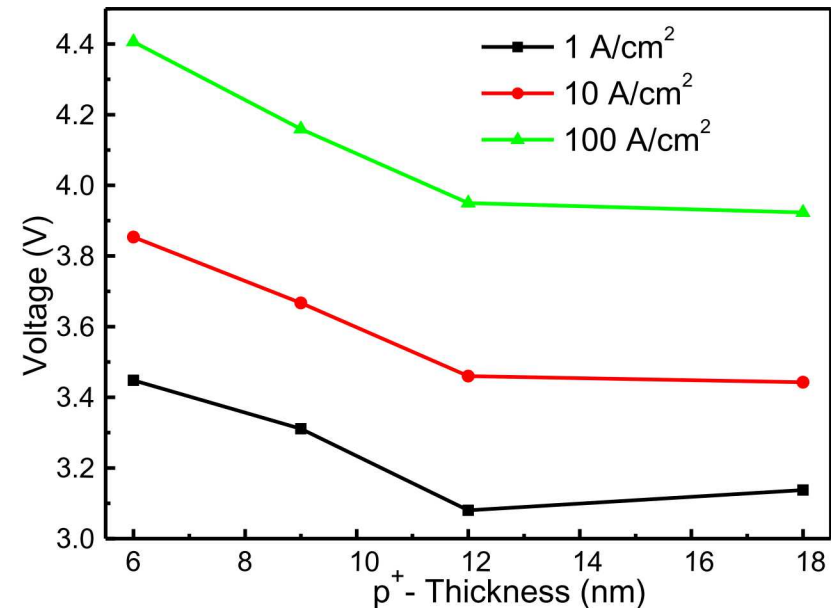
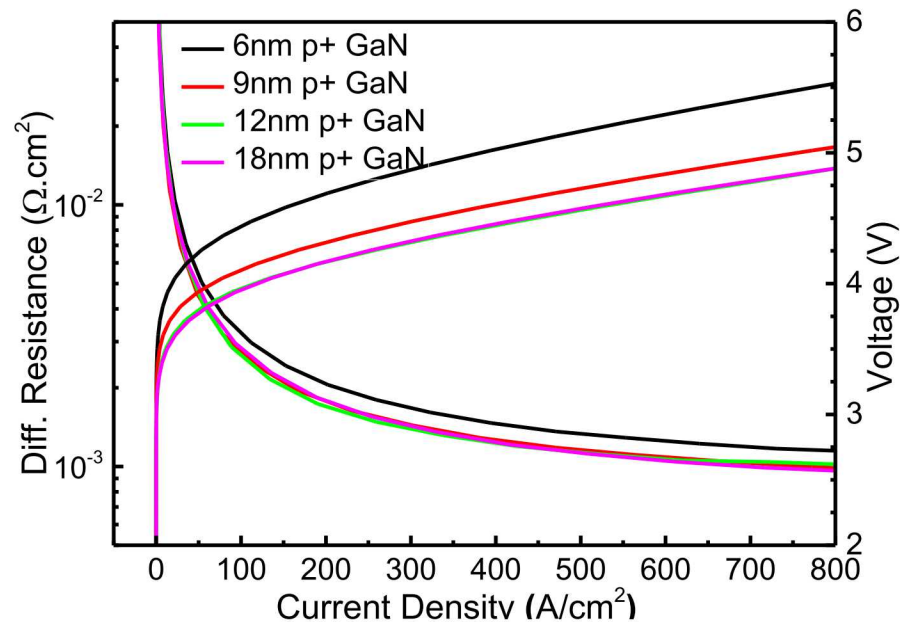
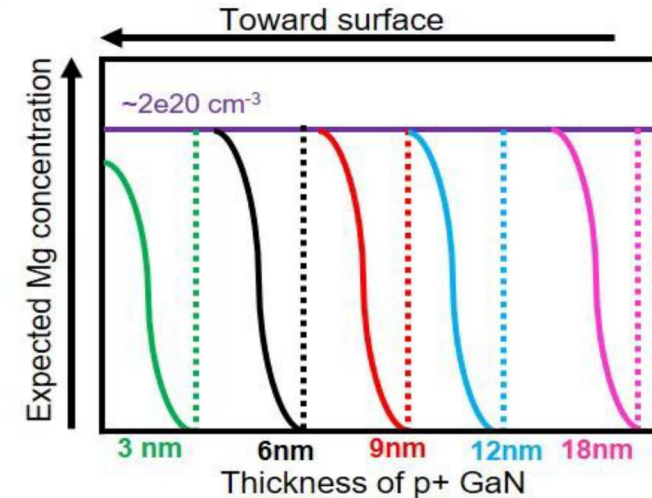
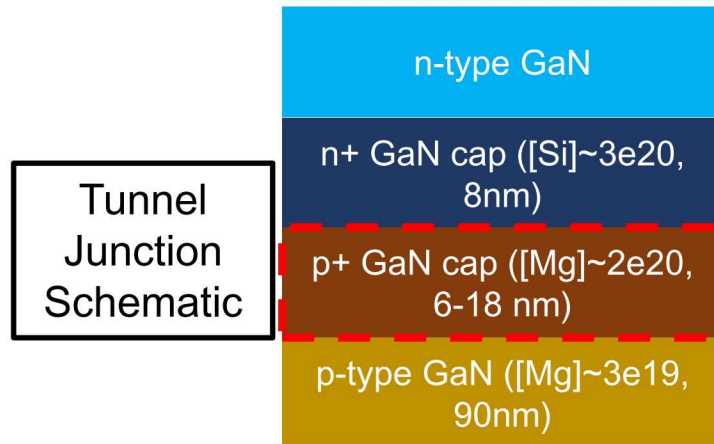
- Optimum annealing condition:
  - 900°C
  - 30 mins
- Size-independent characteristics observed

# Mg Turn On/Off Delay Compensation

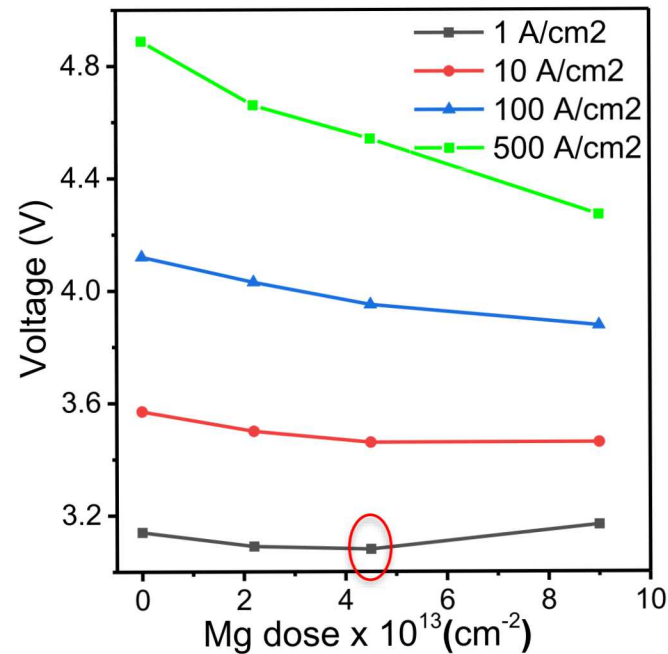
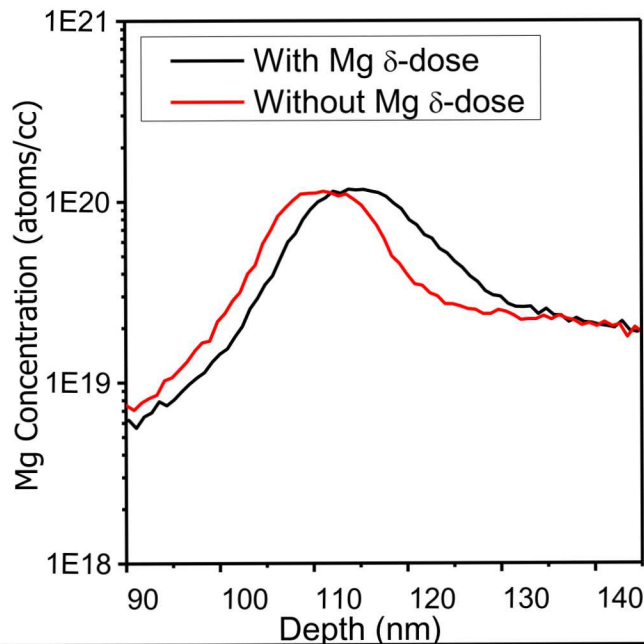
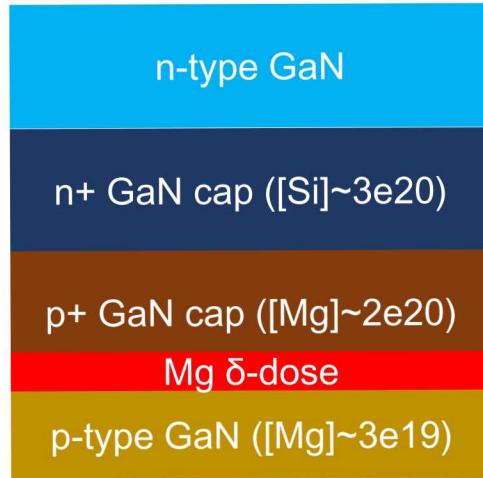


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# Mg $\delta$ -dose Variation

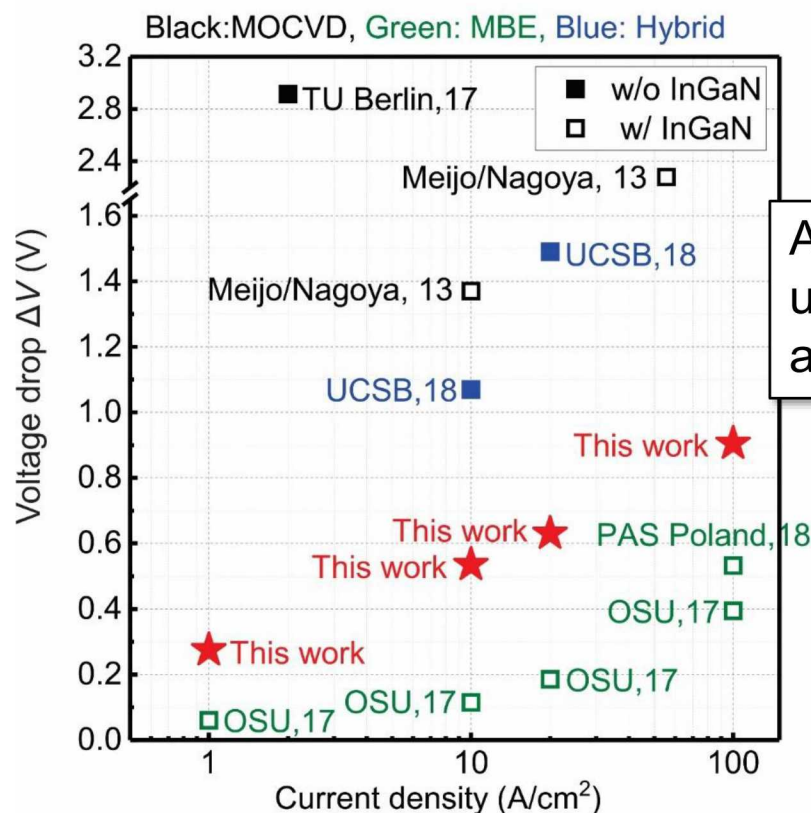


- $\delta$ -dose amplifies Mg ramp rate.
- Effect of Mg  $\delta$ -dose more prominent at high current density
- Optimum  $\delta$ -dose :  $4.5 \times 10^{13} \text{ cm}^{-2}$ .

# State-of-the-Art Results

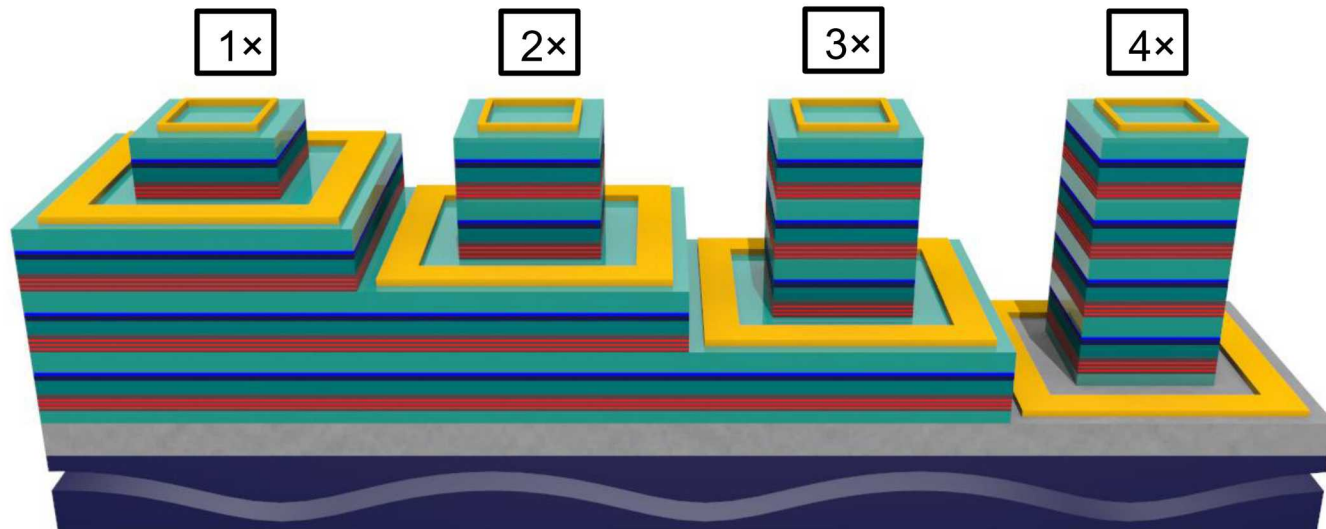


| Current Density (A/cm <sup>2</sup> ) | <i>p-n</i> Diode with Metal Ohmic Contact | <i>p-n</i> Diode with TJ | Voltage Penalty $\Delta V$ (V) |
|--------------------------------------|-------------------------------------------|--------------------------|--------------------------------|
| 1                                    | 2.94 V                                    | 3.08 V                   | 0.14                           |
| 100                                  | 3.48 V                                    | 3.95 V                   | 0.47                           |



Absolute voltage drop calculated using ideal diode eq<sup>n</sup> for this work and similar reported devices.

- Combine optimized TJ structures with LEDs to achieve optical power scaling with cascaded structures
- Investigate low Indium-containing InGaN/GaN TJ to suppress Mg decay tail.
- Explore low-temperature GaN growth to reduce thermal budget and potential impact in overlying epilayers



- Low-resistivity and reduced voltage-penalty for all MOCVD grown TJ demonstrated
- A balance between time and temperature necessary for buried  $p$ -GaN activation
- Thicker  $p$ -GaN layer to compensate the delay in Mg turn on/off
- $\delta$ -dose useful to achieve steep Mg profile

**Thank you for your attention**