MOCVD-based Tunnel Junctions for III-Nitride Emitters

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Interband Tunnel Junctions

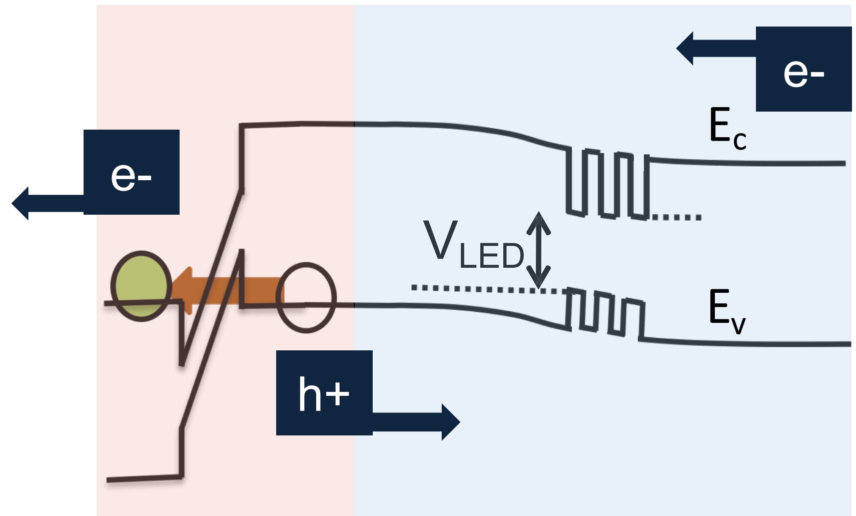
Tunnel Junctions

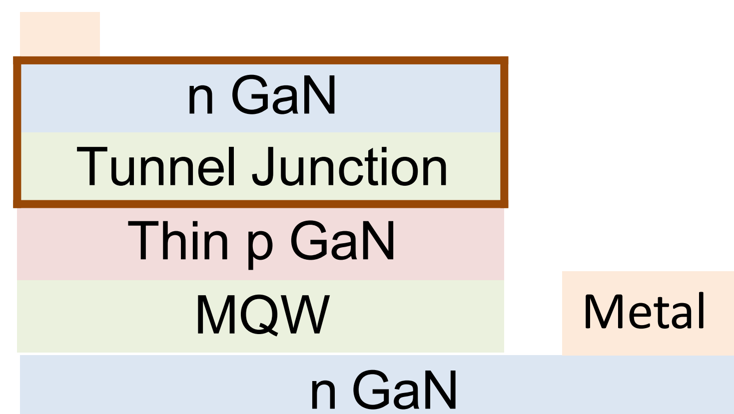
- Under reverse bias electrons tunnel from valence band on p-side of TJ to open states in the conduction band on n-side of TJ
- Tunneling enables effective hole injection to p-side of reverse biased TJ

Tunnel Junctions for application in LEDs

- Holes can be injected from the tunnel junction directly into the active region of the LED
- ***Low-cost process flow*** (top transparent n-GaN spreading layer) – enables new device designs

TJ in reverse bias





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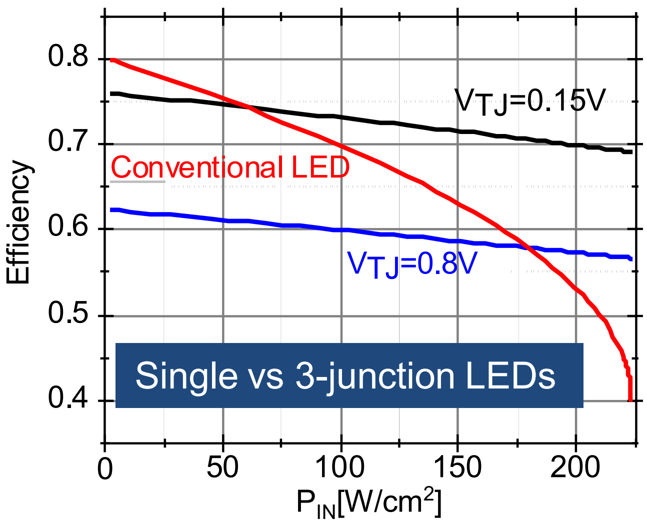
Cascaded LEDs for Efficiency Droop

Akyol et al, Appl. Phys. Lett. 103 , 081107 (2013)

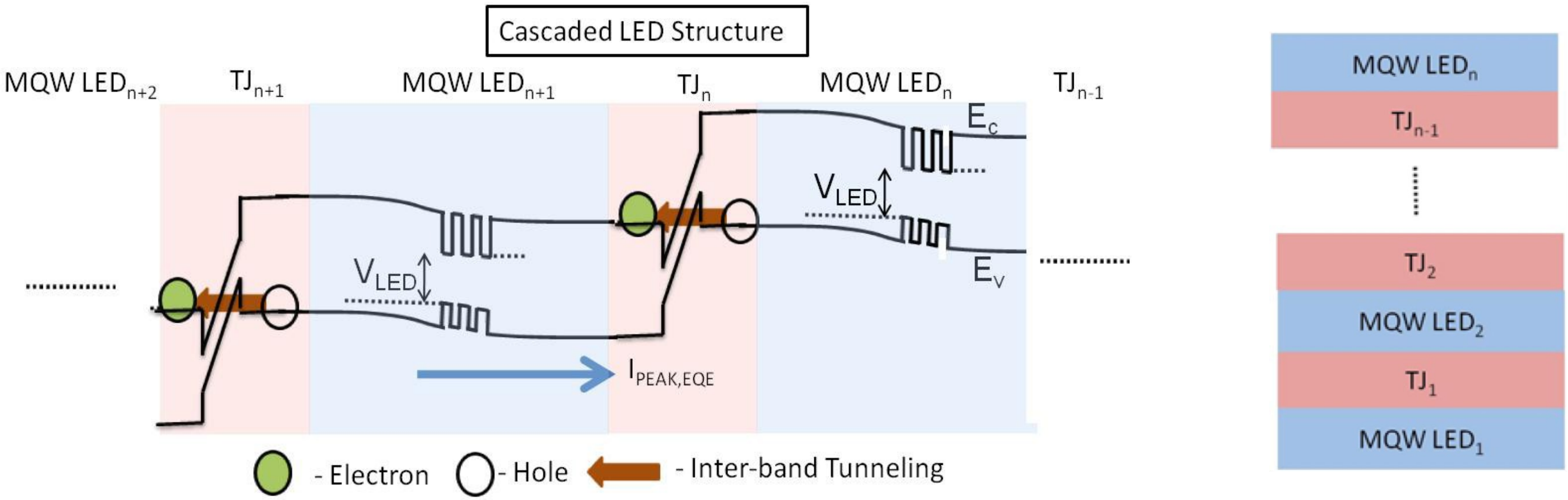


Efficiency droop: Main issue in LED lighting today

- Carrier overflow
- Auger recombination

Cascaded LEDs

- Low current density with multiple active regions
- Each e-h pair injected creates multiple photons
- Also important for longer wavelenths



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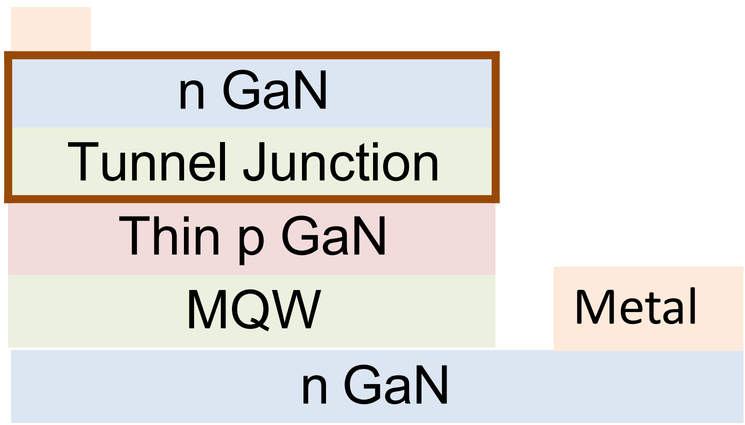
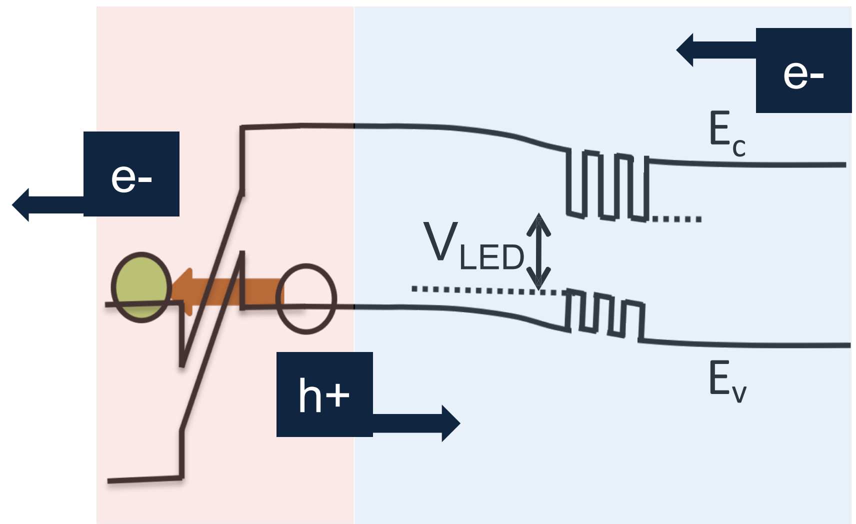
High Current Density – Lasers





- Edge-emitting lasers: ITO can lead to significant losses
- VCSELS need a **transparent top region**
- High power density - **high current density**
- Tunnel junctions can enable very **low resistance transparent contacts**

Tunnel junctions could enable high current density lasers

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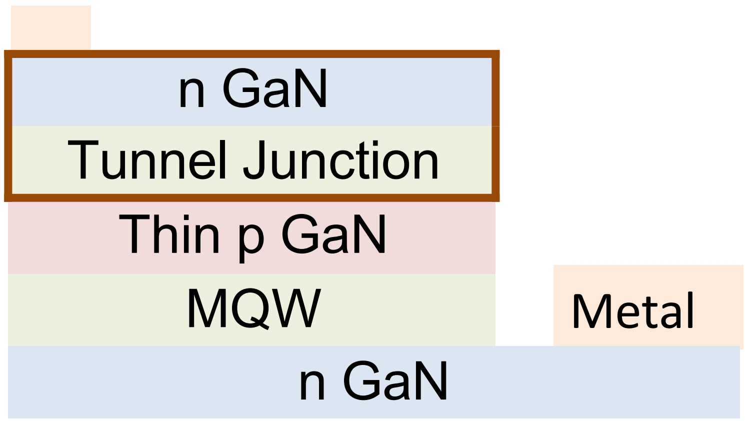
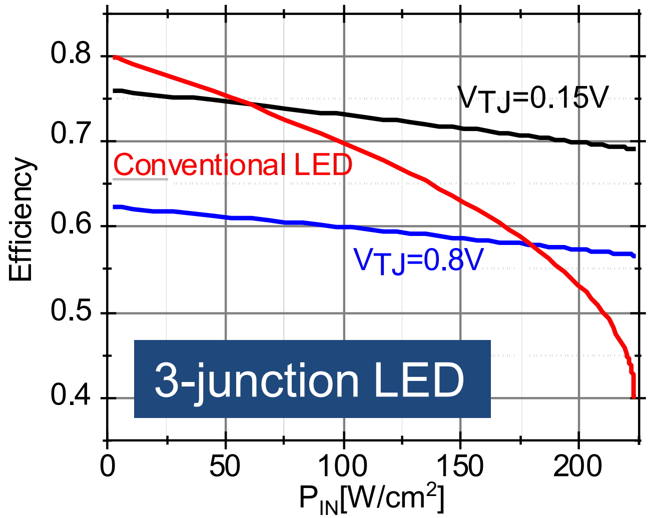
Key challenges for MOCVD Tunnel Junctions





Objective: transparent low voltage loss tunnel junctions < 0.2 V @ 35 A/cm²

Main challenges for all-MOCVD structures

1. High doping density in n+ and p+ tunnel junction
2. Abrupt doping profiles (challenging for MOCVD)
3. Activation of buried p-type region
4. Impact of thermal budget (in multi-active region structure) on quantum well regions

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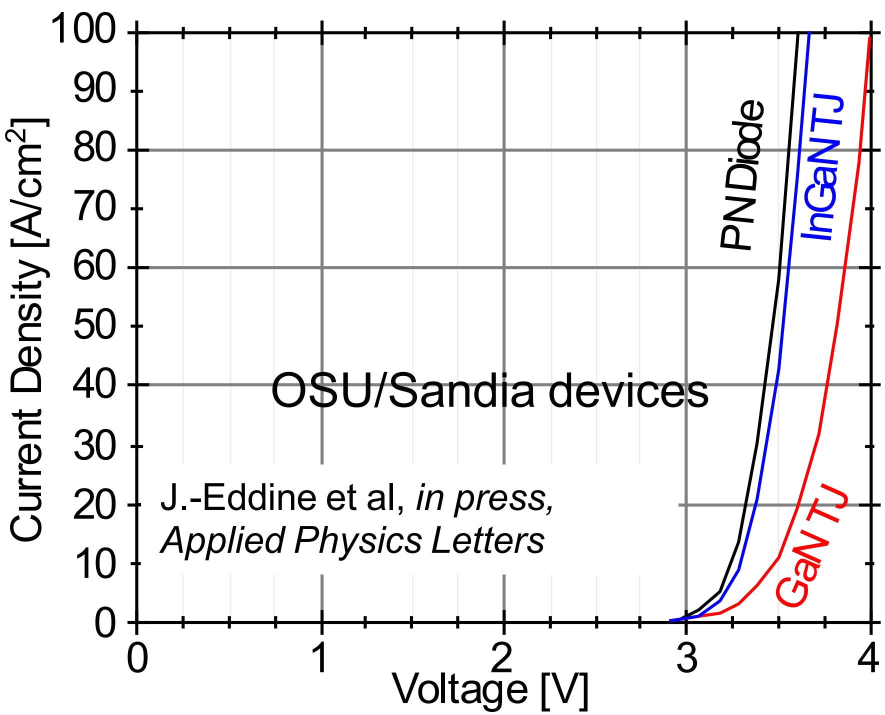
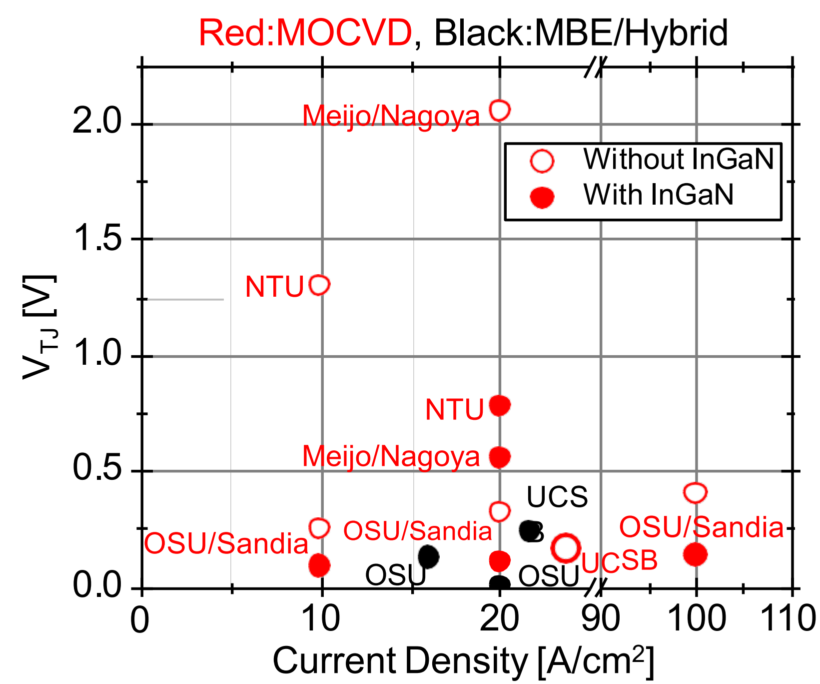
Experimental Results: Record Low MOCVD V_{TJ}

- PN diode shows expected characteristics – turn-on voltage = 3.1V
- TJ resistance was de-embeded using reference PN-diode characteristics
- State-of-art low V_{TJ} demonstrated at 100 A/cm^2

  0.18 V for transparent (< 7%) InGaN interlayer junction (OSU/Sandia)

  0.2 V for GaN homojunction (UCSB/Li et al) - *regrown TJ*

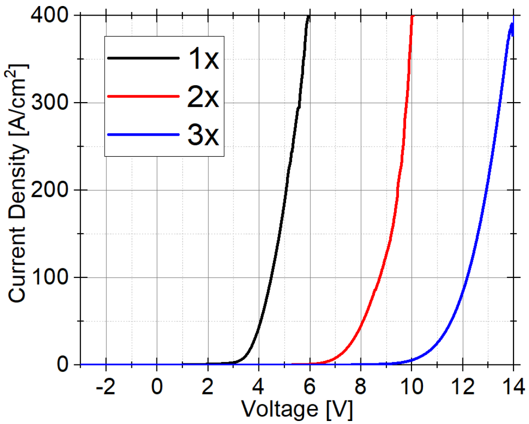


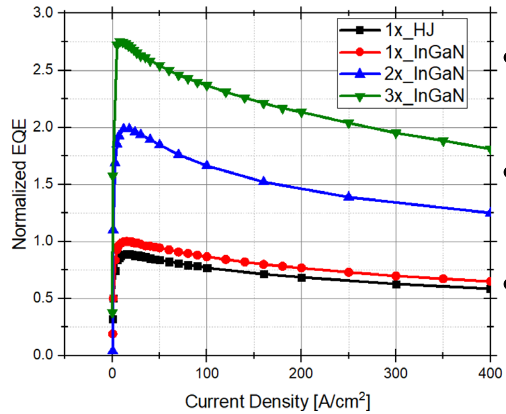


Jamal-Eddine, Zane, et al. "Low voltage drop tunnel junctions grown monolithically by MOCVD." APL 118.5 (2021): 053503.

Multi-active region LEDs and TJ-lasers

3 junction 450 nm LED (Ohio State University/Sandia)





- 3-junction multi-active region LEDs demostrated
- Near-ideal EQE scaling achieved in new generation devices
- HR-TEM shows no additional defects due to doped tunnel junctions

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Multi-active region LEDs and TJ-lasers

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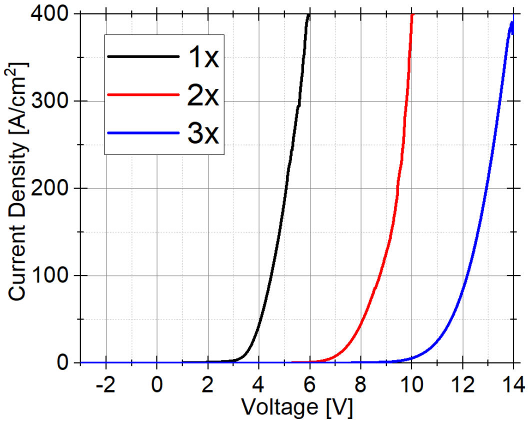

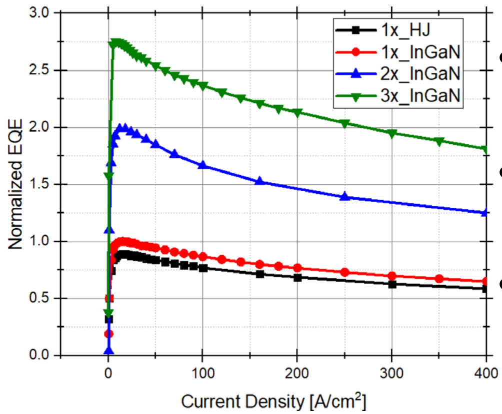

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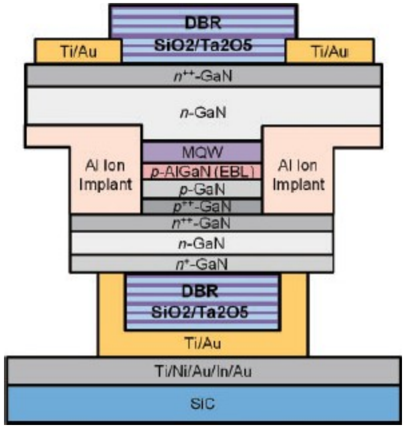
TJ-based VCSEL (UCSB)

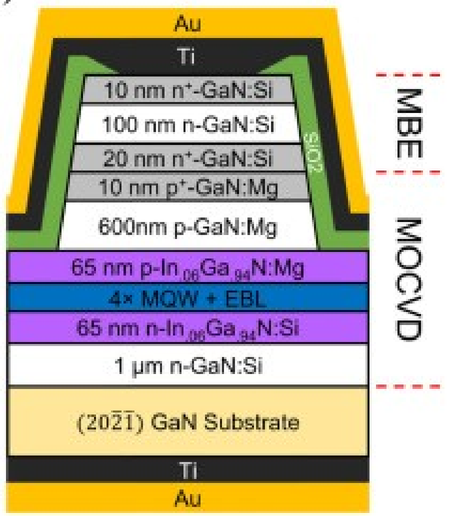
- 2018 - Demonstrated a tunnel-injected VCSEL with buried PN junction
- Edge-emitting laser using a hybrid MBE/MOCVD tunnel junction

Shows potential of tunnel junctions for future laser applications



SeungGeun Lee *et al* 2018 *Appl. Phys. Express* **11** 062703

(a)



Yonkee, Benjamin P., et al. *Optics express* 24.7 (2016): 7816-7822.

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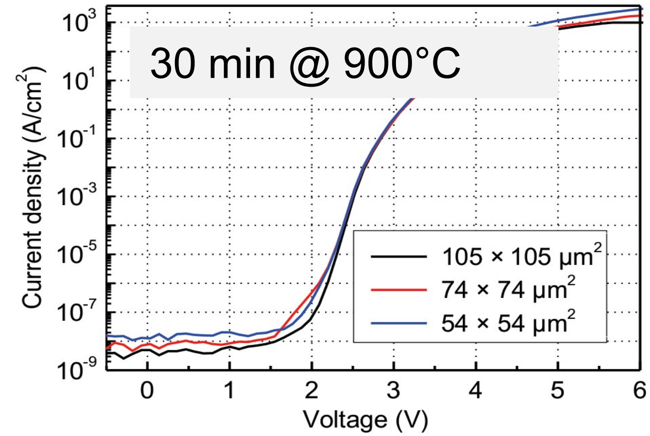
Lateral activation and extended defects

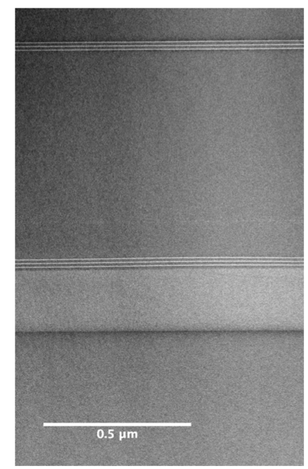


Activation conditions are critical

- Dramatic change in device performance as annealing conditions are optimized
- Lateral activation is complete – devices up to 100x100 um^2 are fully activated

Extended defects/degradation

- No extended defects introduced due to high doping density
- No degradation in active regions grown above the tunnel junction



HR TEM of a 3-junctioN LED

Hasan, Syed MN, et al. Journal of Physics D: Applied Physics (2021).

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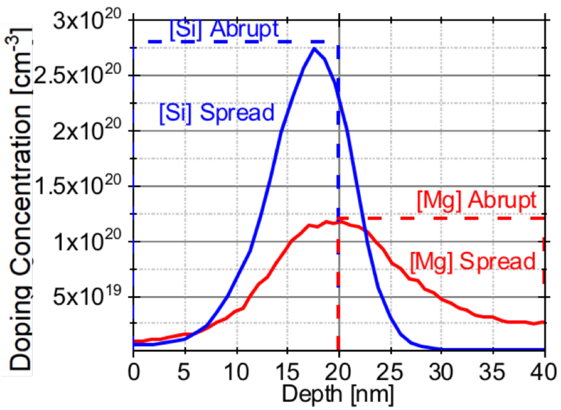
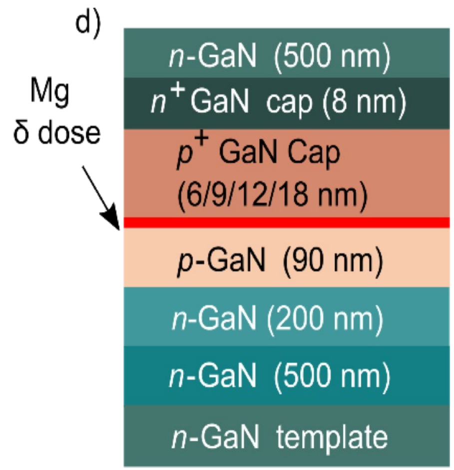
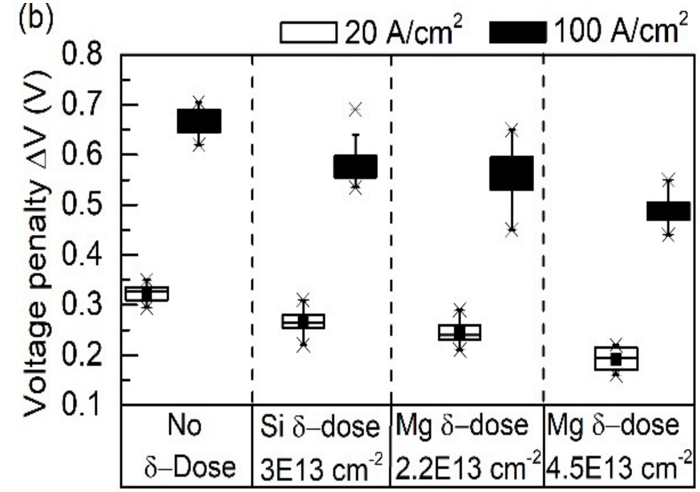
Impact of doping profiles

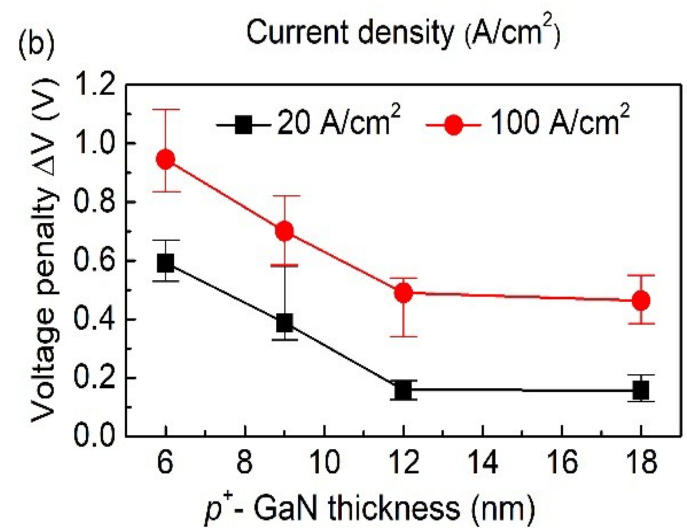






Doping level and position require nanoscale precision

- Significant change in voltage drops as doping levels are increased
- MOCVD doping profiles lead to significant overlap
- Exact position of doping profiles (at nanometer scale) can impact the voltage drop.



Hasan, Syed MN, et al. "All-MOCVD-Grown Gallium Nitride Diodes with Ultra-Low Resistance Tunnel Junctions." J. Phys. D: Applied Physics (2021).

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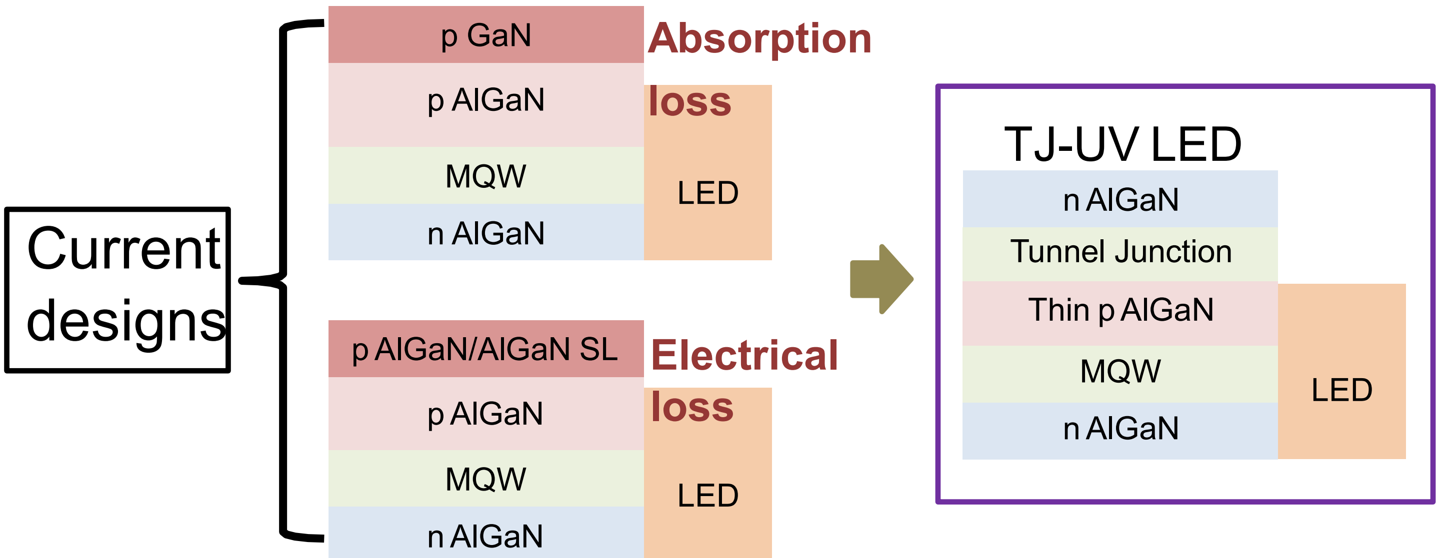
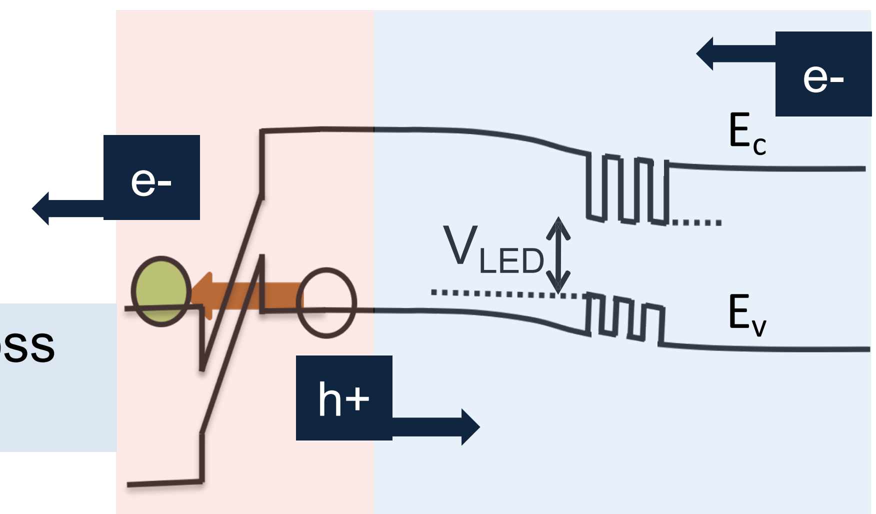
Tunnel-based UV LEDs



- Replace p-type contact using tunneling contact.
- Non-equilibrium injection.

- Reduced light absorption loss
- Better contacts.



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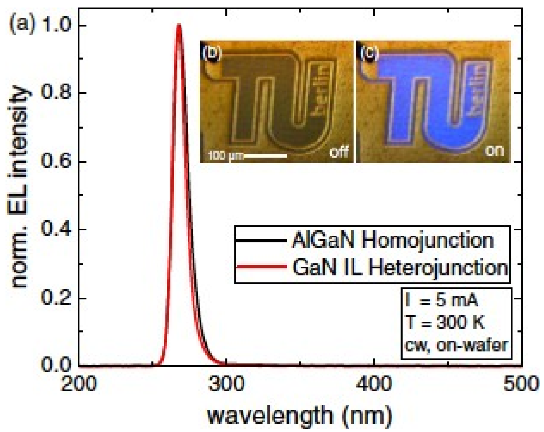
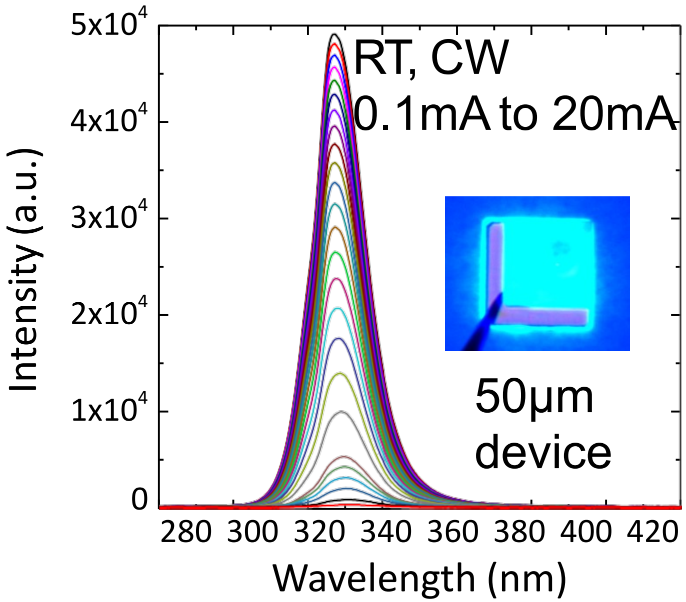
Tunnel Injected UV LEDs

MOCVD TJ UV LED



Kuhn, Christian, et al. *Photonics Research* 7.5 (2019): B7-B11.



Zhang, Yuewei, et al. *Applied Physics Letters* 106.14 (2015): 141103.

- Lowest TJ resistance of **5.6 x 10^{-4} Ohm cm^2** is obtained for $Al_{0.3}Ga_{0.7}N$ TJ
- Polarization-engineered tunnel junctions provide low on-resistance
- All-MOCVD tunnel junctions have been demonstrated recently (TU Berlin) – emission at 260 nm

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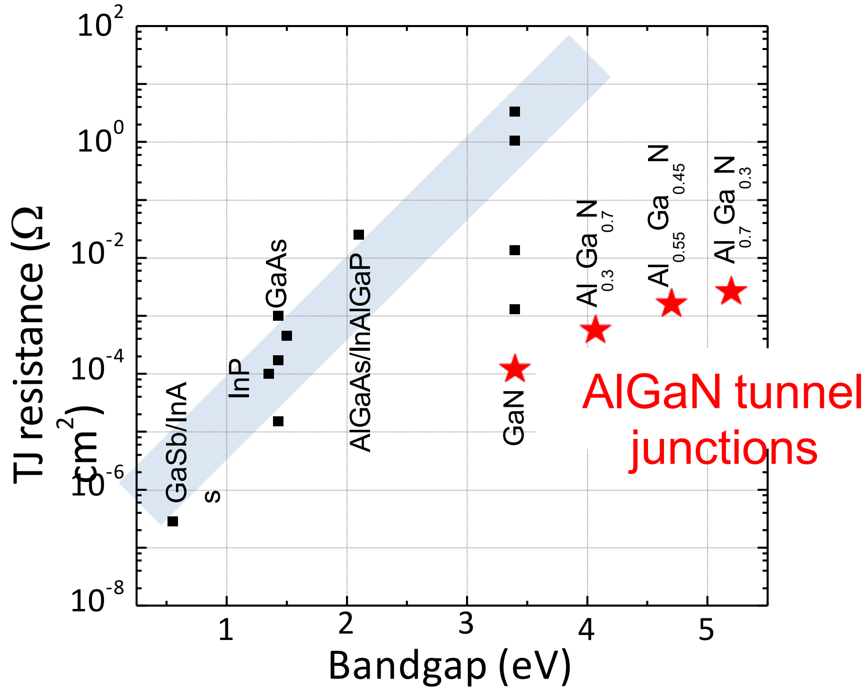
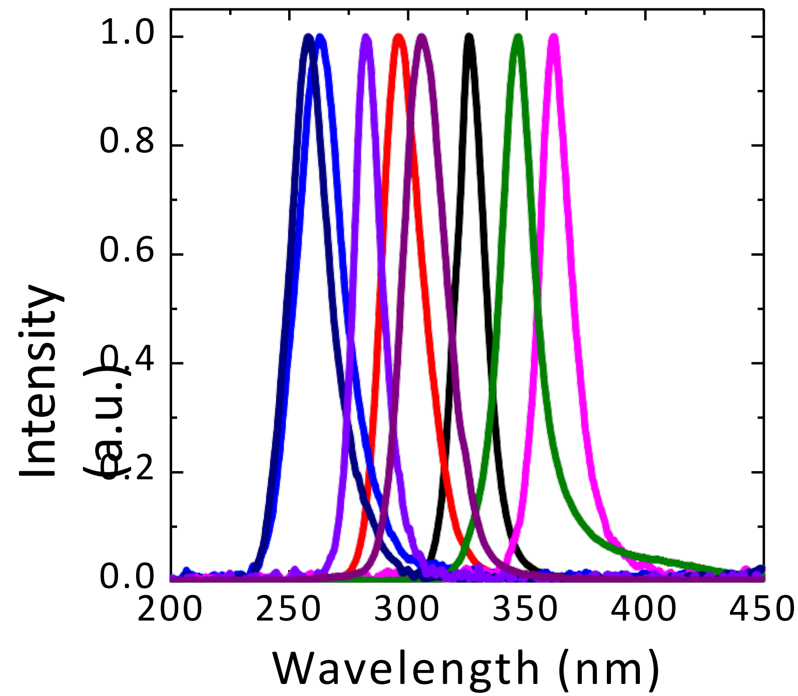
Tunnel-injected UV LEDs





- Demonstration of tunnel junctions for > 5 eV material (70% AlGaN)
- Emission wavelength down to 257 nm demonstrated for tunnel-injected LEDs
- Could enable next-generation highly efficient UV LEDs and lasers

Electrical injection is efficient, but light extraction still remains a significant challenge

Zhang, Yuewei et al, *Japanese Journal of Applied Physics* 58.SC (2019): SC0805.
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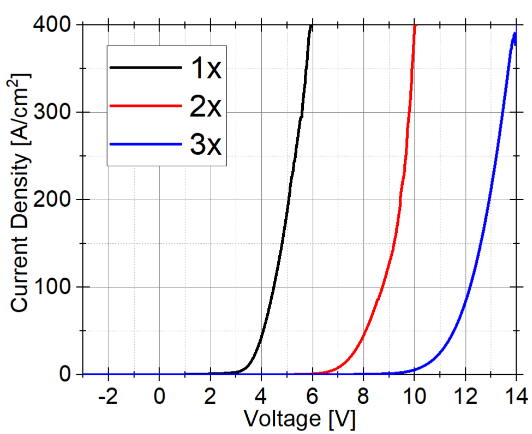
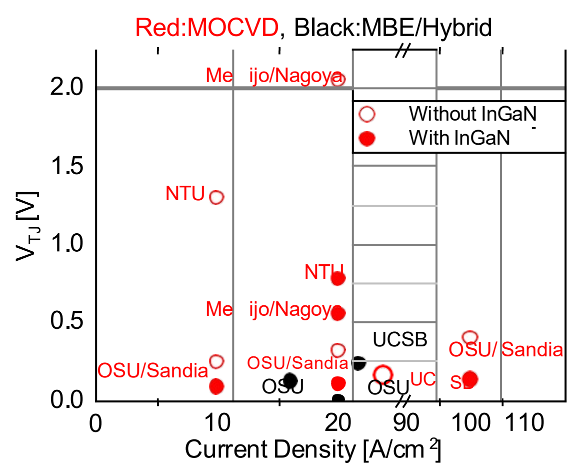
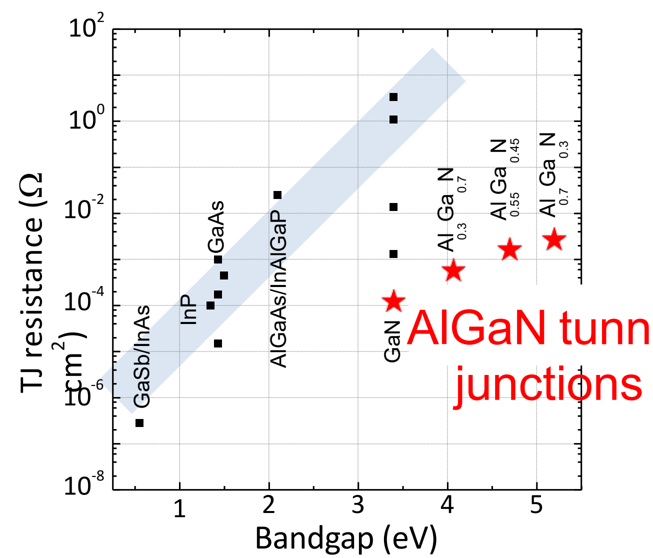
Summary

- Tunnel junctions have made significant progress over the last decade
- Several challenges related to MOCVD tunnel junctions are now resolved
    - MOCVD tunnel junction resistance < 0.2 V at 100 A/cm^2
    - Multi-active region LEDs with excellent EQE scaling
    - Tunnel-injected edge-emitting lasers and VCSELs
    - UWBG AlGaN tunnel junctions up to 70% AlGaN

Tunnel Junctions are an exciting new tool for next-generation III-Nitride LED and lasers!







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