



# Solving Current Droop via Tunnel Junction Cascade LEDs

**Andrew Armstrong**

aarmstr@sandia.gov

Sandia National Laboratories

Albuquerque, NM USA



# Outline

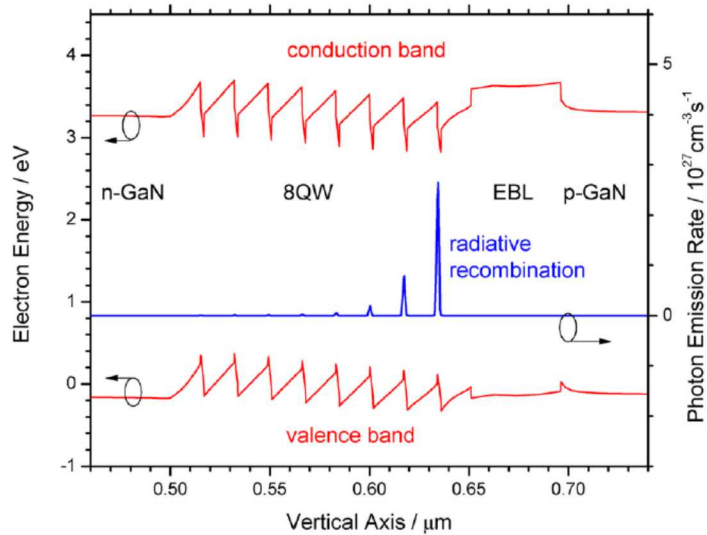
## Outline:

- Tunnel junction (TJ) incorporation into LEDs
- How TJ enable cascade LEDs to solve current droop
- TJ and cascade LED technological viability and materials challenges

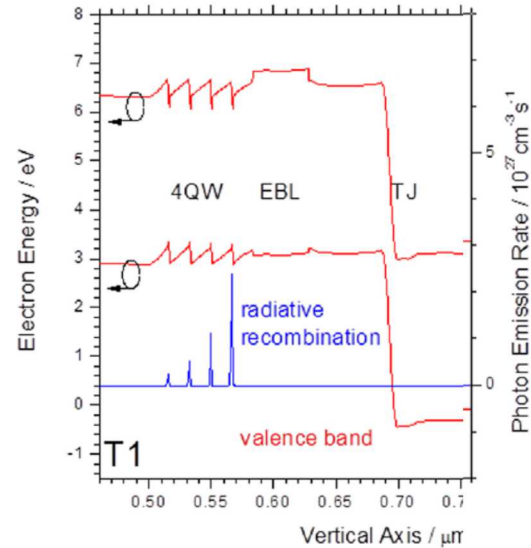


# Tunnel Junction incorporation into LEDs

## Standard LED



## TJ-LED



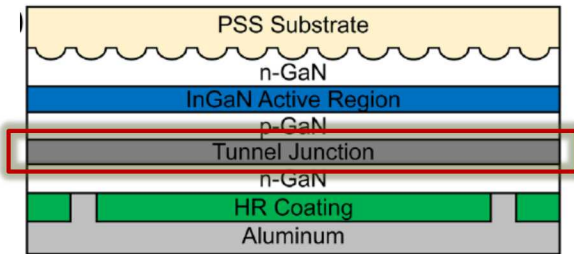
- Cap p-GaN layer with p++/n++ junction
- LED has *n*-type contacts on top and bottom

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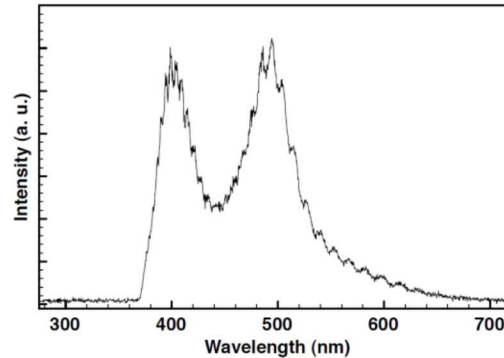
# Tunnel junction applications in LEDs

## Decouple properties of $p$ -contacts and mirrors



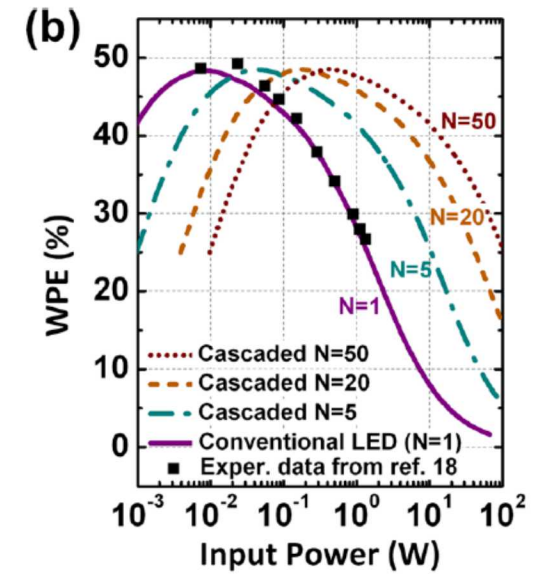
1. Yonkee *et al.* APL 109 191104 (2016).

## Multi-color LEDs



2. Grundmann and Mishra *pss(c)* 4 2830 (2007).

## Droop suppression



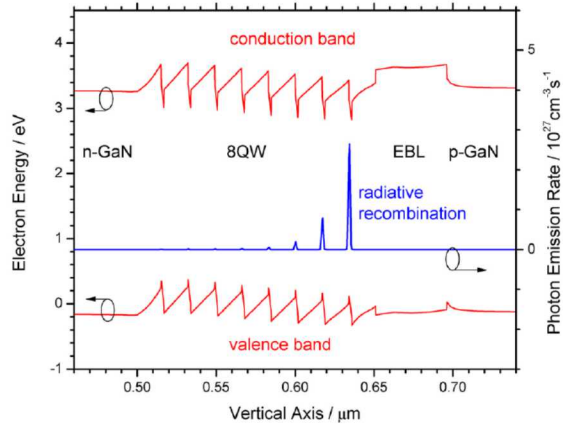
3. Akyol *et al.*, APL 103 081107 (2013).

- Reduce optical losses of large area  $p$ -contacts<sup>1</sup>
- Increase LER by color mixing using direct emitters<sup>2</sup>
- Mitigate current droop<sup>3</sup>

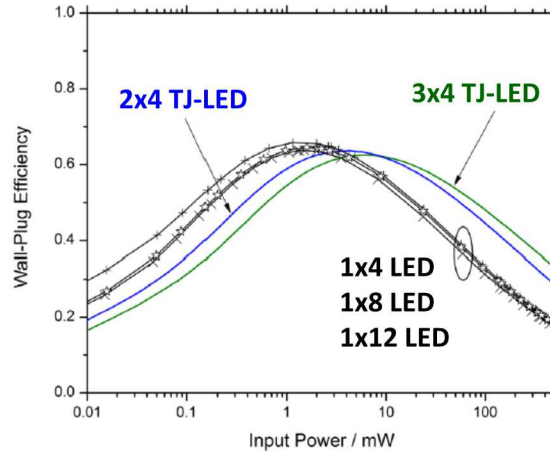


# Avoid droop in cascade TJ-LEDs

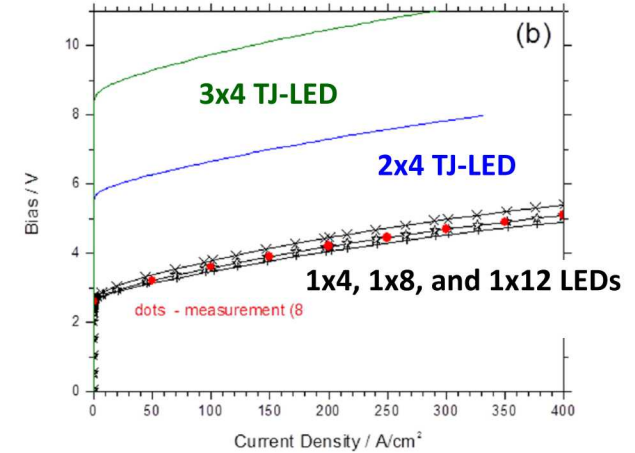
## Standard 8 QW LED



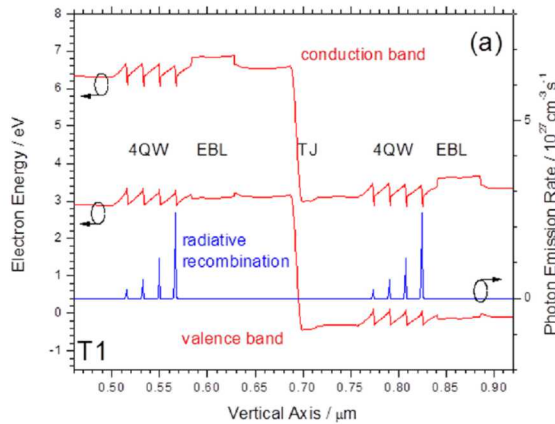
## WPE for LED vs Cascade LEDs



## LIV for LEDs and TJ-LEDs



## 2x4 QW TJ-LED



Piprek APL 104 05118 (2014).

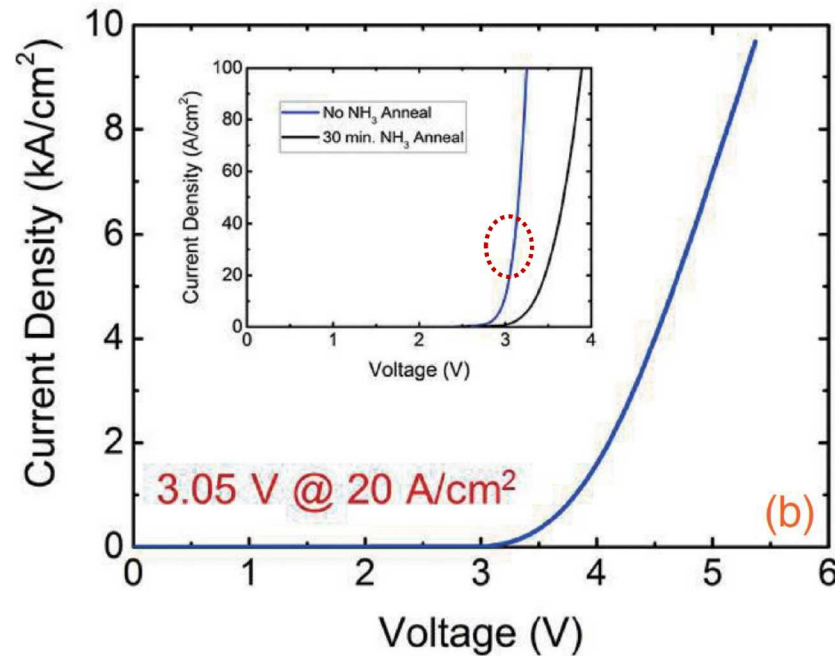
- TJs provide more uniform carrier distribution in QWs
- Improved WPE because same  $J$  populates more  $N \times$  QWs ( $N \times$  higher EQE)
- Price is paid in  $N \times$  higher voltage...
- ...but there is not (necessarily) voltage droop!

Andrew Armstrong - aarmstr@sandia.gov



# TJ performance target for cascade LEDs

## PNP TJ Diode



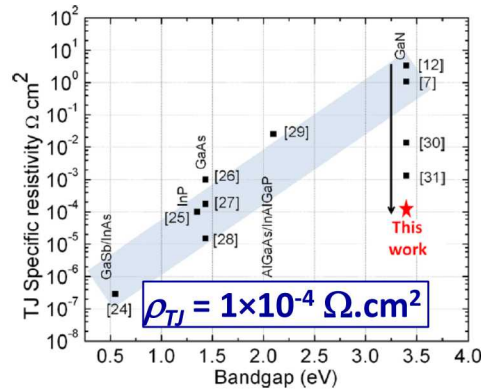
Young APEx 9 022102 (2016).

- TJs for single active region LEDs or LDs focus on  $J > 100 \text{ A/cm}^2$
- Cascade LEDs need low  $\rho_{TJ}$  at low  $J$
- Requires  $\rho_{TJ} < 10^{-3} \Omega \cdot \text{cm}^2$  at  $\sim 30 \text{ A/cm}^2$  for  $< 0.1 \text{ V}$  excess voltage drop in 3x cascade LED



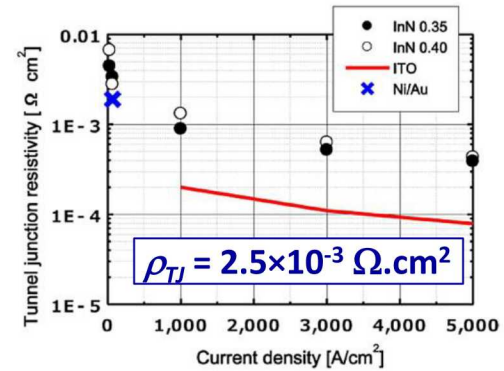
# TJ operation for cascade LEDs

## MBE InGaN/GaN TJ



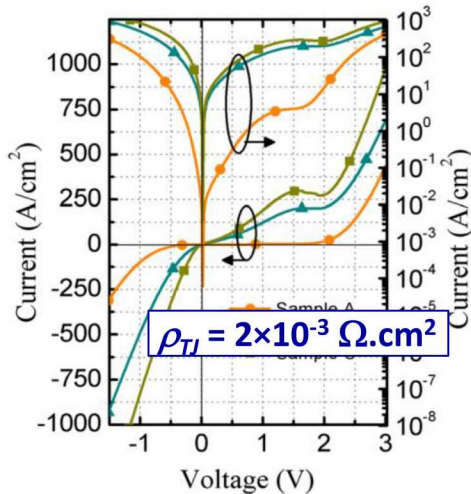
Krishnamoorthy APL 102 113503 (2013).

## MOCVD InGaN/GaN TJ



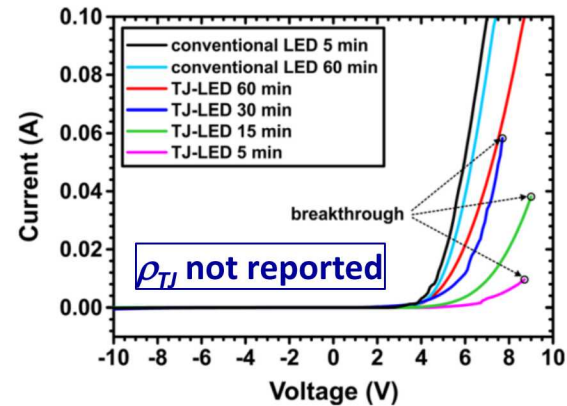
Minamikawa pss(b) 252 1127 (2015).

## MBE GaN TJ



Akyol 108 131103 (2016).

## MOCVD GaN TJ



Neugebauer APL 110 102104 (2017).

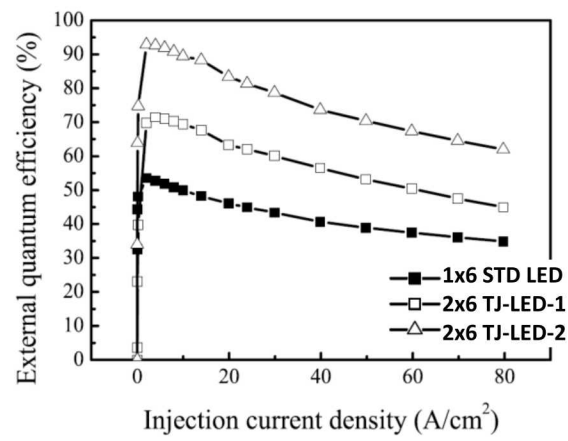
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Viabie TJs for cascade LEDs demonstrated



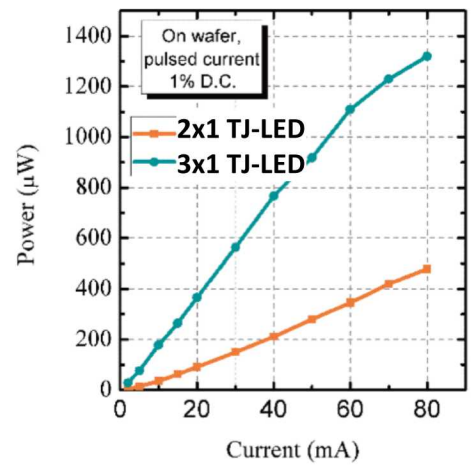
# Cascade LEDs are reality but require R&D investment

## MOCVD Cascade LED



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

## MBE Cascade LED



Akyol et al., APEX 8 082103 (2015).

## MOCVD-MBE Cascade LED

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy | Funding Opportunity Announcement

Department of Energy (DOE)  
Office of Energy Efficiency and Renewable Energy (EERE)  
**Solid-State Lighting Advanced Technology R&D - 2018**

- High TJ resistance:
- Non-abrupt Mg doping
  - [Si] < 10<sup>19</sup> cm<sup>-3</sup>
  - Activation of buried p-GaN

- Low IQE:
- Immature MBE InGaN material
  - Particular impurities (e.g. Ca)?<sup>1</sup>
- Small Area:
- < 200 x 200 µm<sup>2</sup>
  - Lower J for larger area<sup>2</sup>

- Not yet realized:
- Best of both worlds?
  - Multiple regrowth interfaces
  - Epitaxial thermal budget
  - Combined MBE and MOCVD expertise and infrastructure

Many challenges, but they are not fundamental roadblocks

Andrew Armstrong - aarmstr@sandia.gov