Tunneling-based Cascaded LEDs for Efficient Solid State Lighting

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MSE, The Ohio State University

Funding: NSF EECS-1408416

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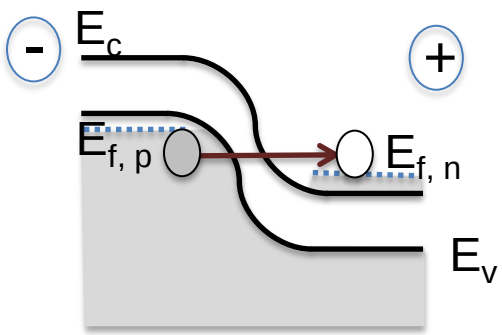
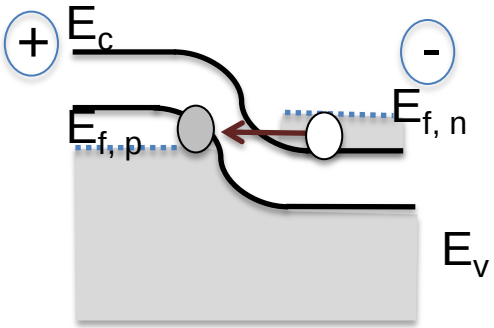
Interband Tunnel Junctions

TJ in reverse bias

TJ in forward bias

Electron ←→ hole carrier conversion





- injection of holes into p- type material
- Applications: LEDs, Lasers

- Recombination of electrons and holes by tunneling
- Applications: Solar cells

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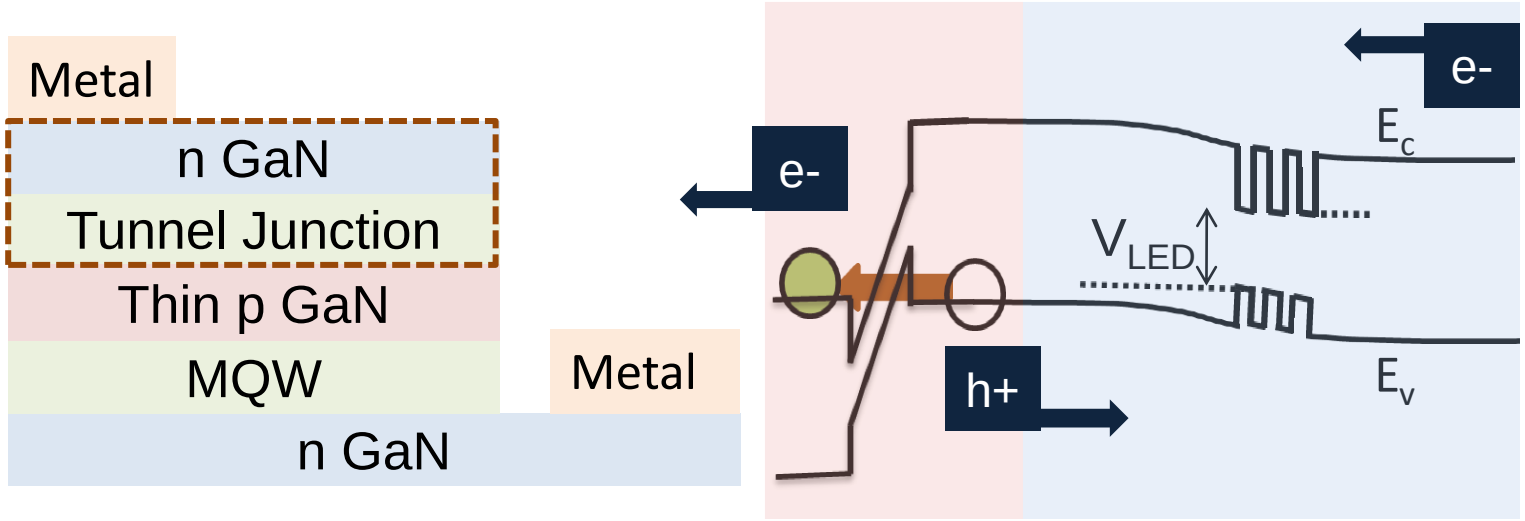
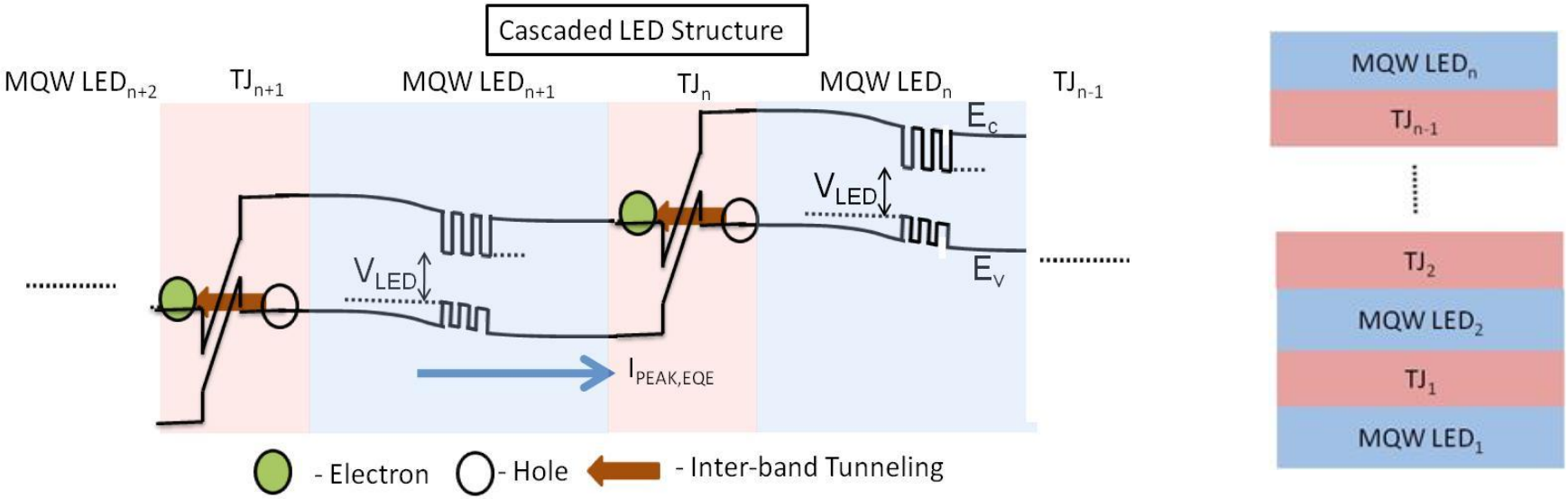
LEDs with tunnel junctions





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Outline

1. Motivation for tunnel junctions
   - Cascaded multi-active region LEDs
   - High current density emitters/VCSELS
   - Reverse polarity designs

2. Current status of tunneling based LEDs
   - Design of tunnel junctions
   - MOCVD-based tunnel junctions
   - High current density/laser structures

3. Challenges and research directions

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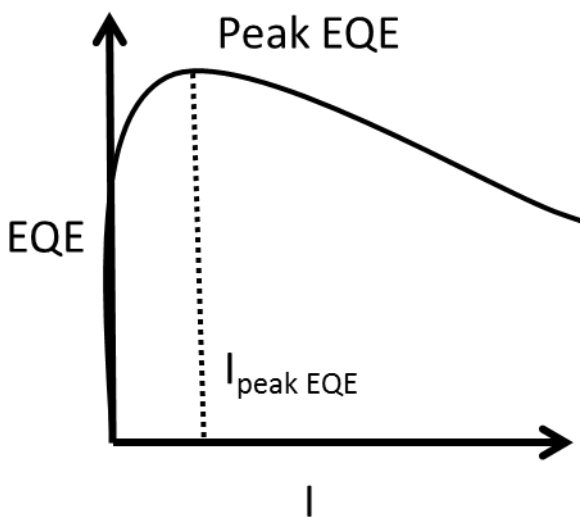
Motivation 1: Cascaded LEDs for Efficiency Droop

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

Reduce chip area
Low current, high power
Reduce LED cost

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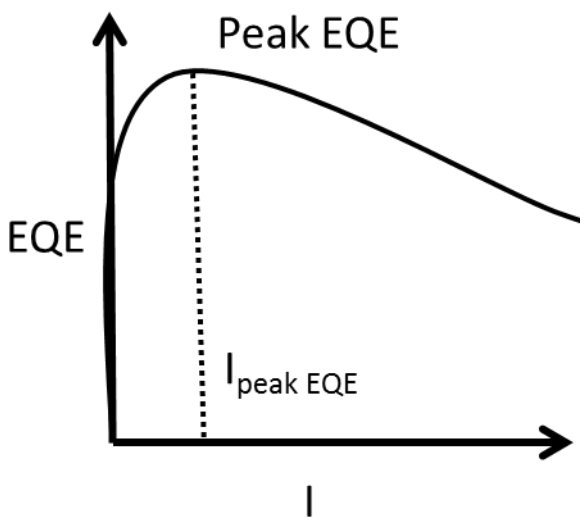

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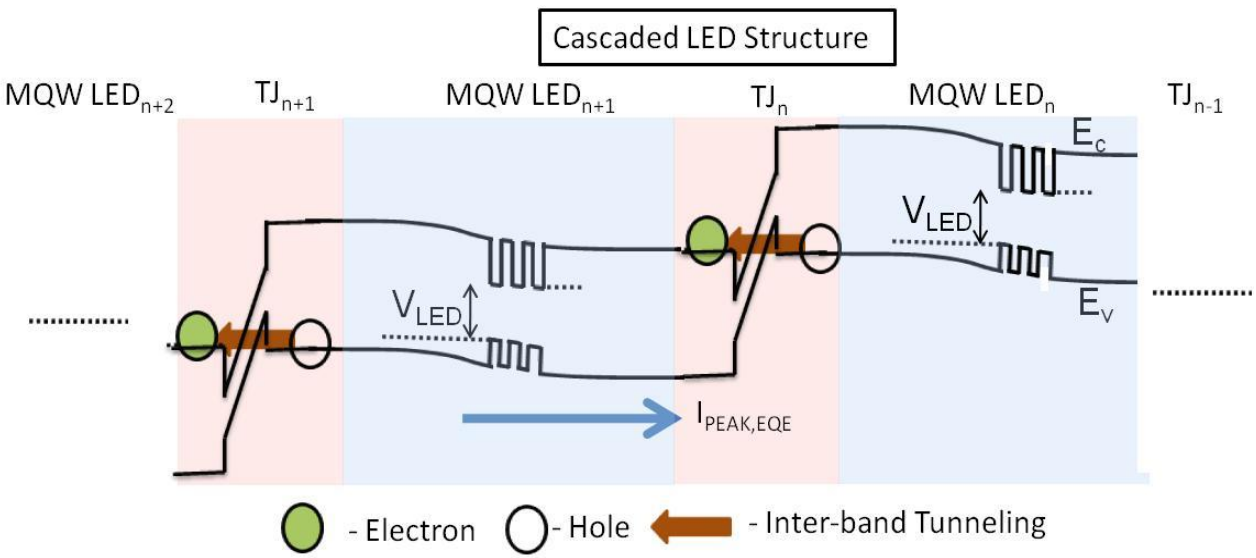

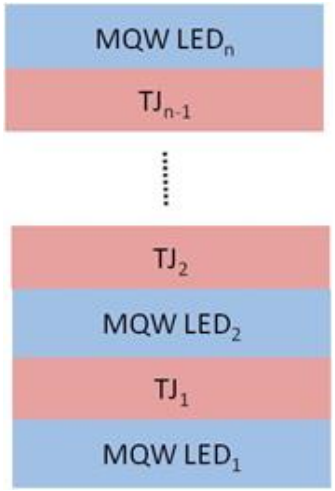

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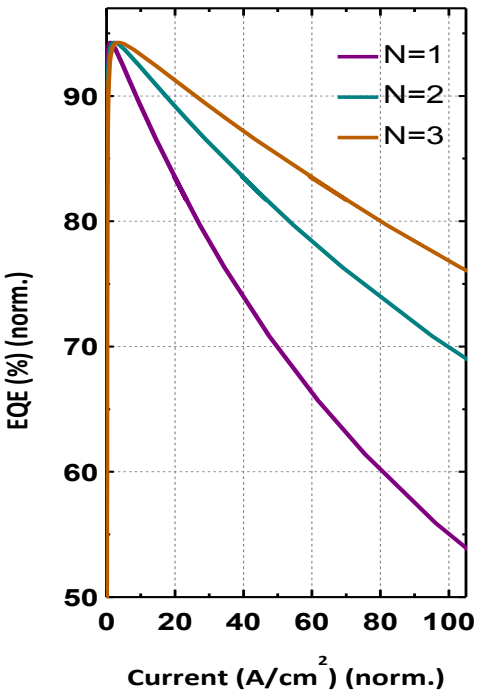
Modeling of multi-junction LEDs

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



Equivalent current = N*I

High equivalent current with high efficiency

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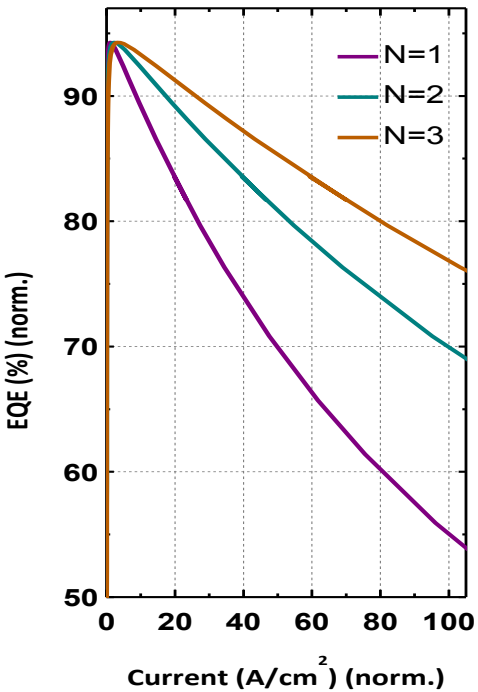

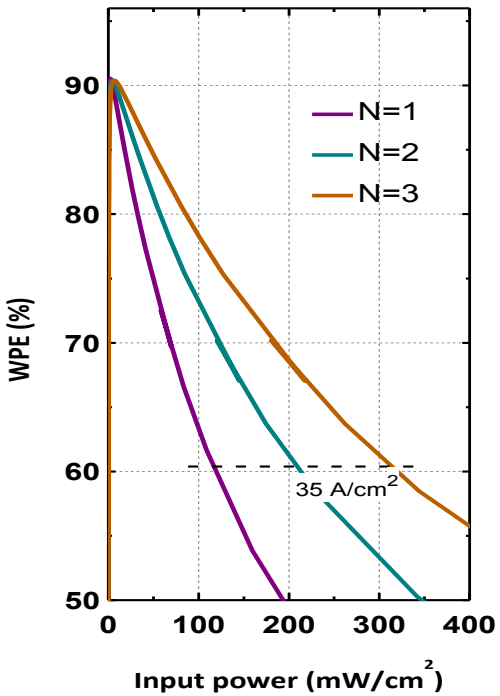

Equivalent current = N*I

High equivalent current with high efficiency

Input power
- Lower current density at higher voltage
- High efficiency at high power

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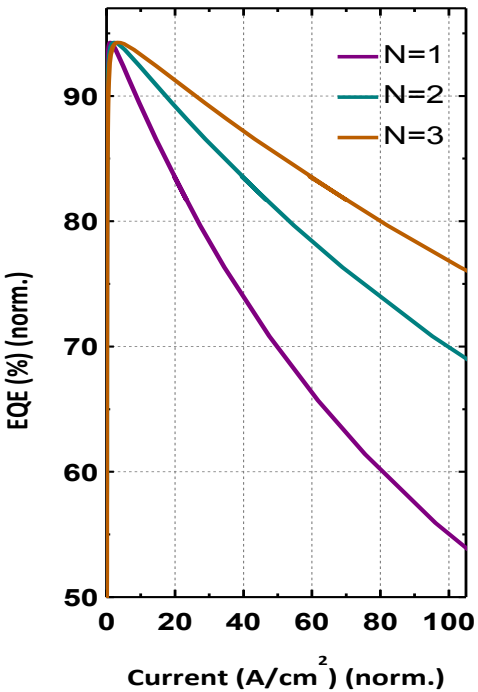

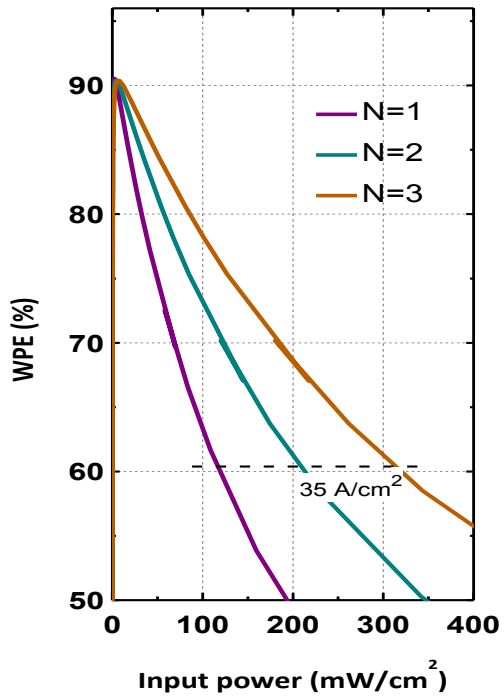

Cascaded LEDs

Objective: high power density

- Use high voltage instead of high current
- Low current density **circumvents efficiency droop**

Equivalent current = N*I

High equivalent current with high efficiency

Input power
- Lower current density at higher voltage
- High efficiency at high power

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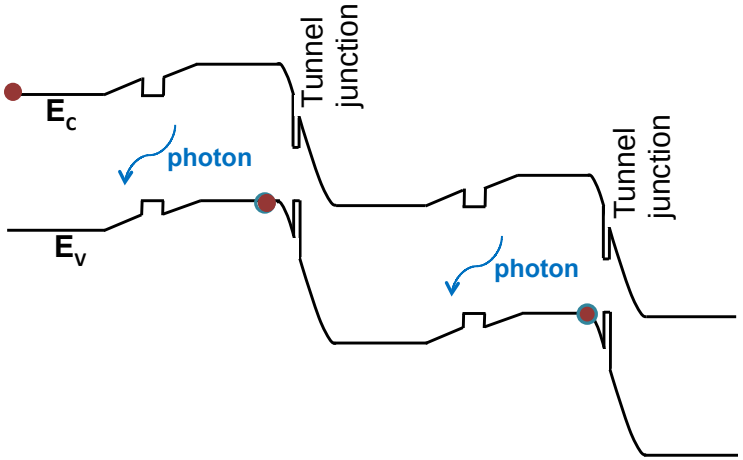
Scaling Laws for Cascaded LEDs

- **Assume identical active regions with series resistance R_s**

Identical *power* density	**Cascaded/ Conventional**
Forward bias	N
Driven Current	1/N
Series resistance	N
Joule Heating (I^2 x R_s)	1/N
Area, cost (post epitaxy)	1/N

- Joule heating **decreases** linearly with 'N'.
- Higher wall plug efficiency (WPE)
- Better thermal management



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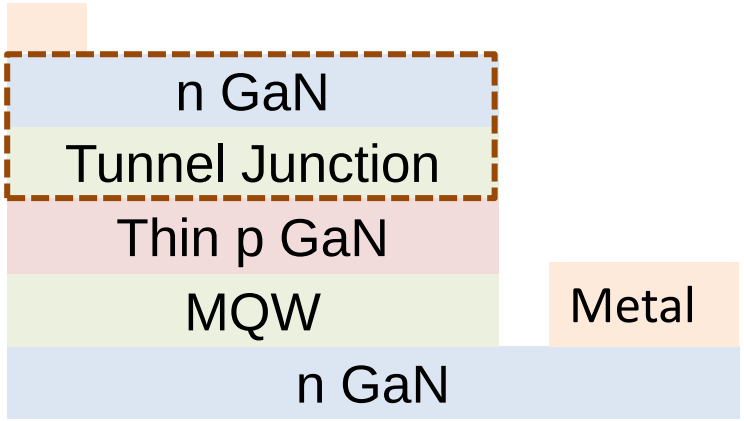
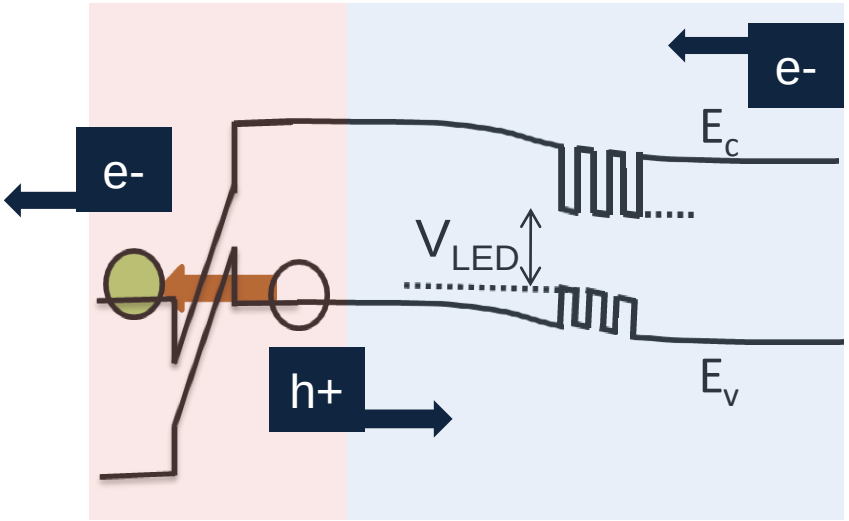
Motivation 2: High Current Density – Lasers





- 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 laser based lighting

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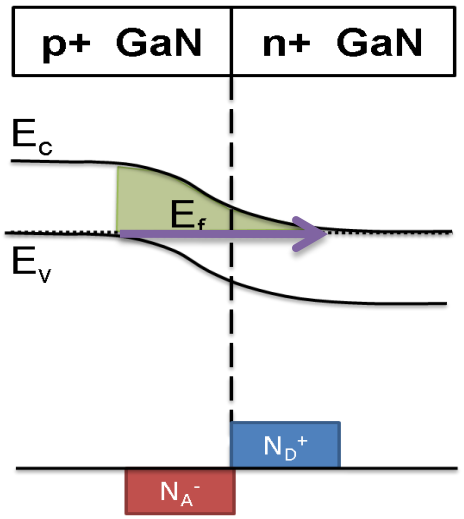
Polarization engineering for tunnel junctions

Standard p+/n+ TJ

- Large Eg → wide depletion region
- Doping limitations
- Large energy barrier for tunneling

Low tunneling current density



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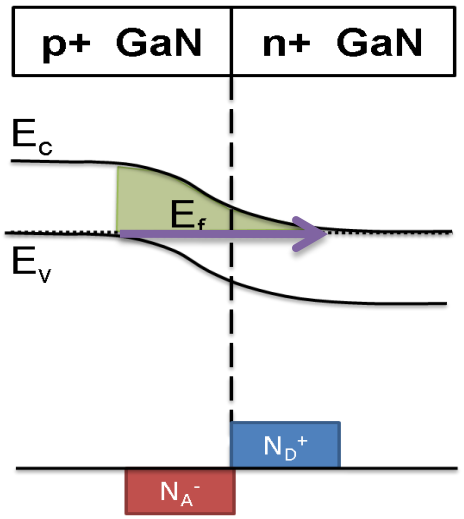
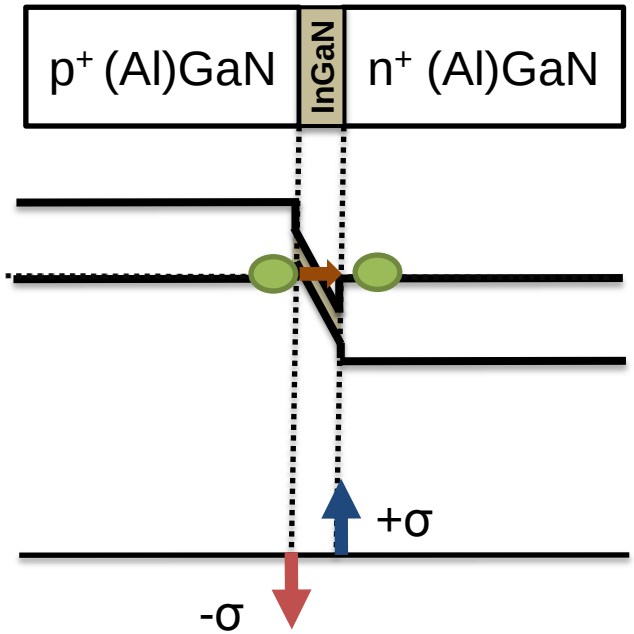


Polarization TJ

- High density polarization sheet charge
  → depletion width greatly reduced.
- Tunnel barrier reduced due to InGaN.



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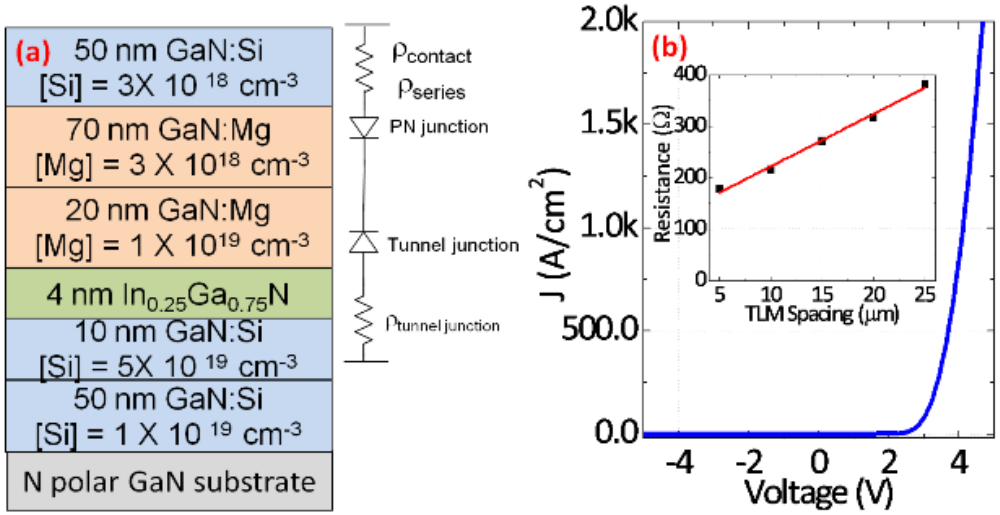
Low resistance GaN/InGaN/GaN TJs (MBE, OSU)

Krishnamoorthy et al, Appl. Phys. Lett. 97, 203502 (2010)



GaN/InGaN/GaN tunnel junctions
All Plasma-assisted MBE

- Voltage drop < 0.1 V
- Resistance ~ 0.1 mOhm-cm^2

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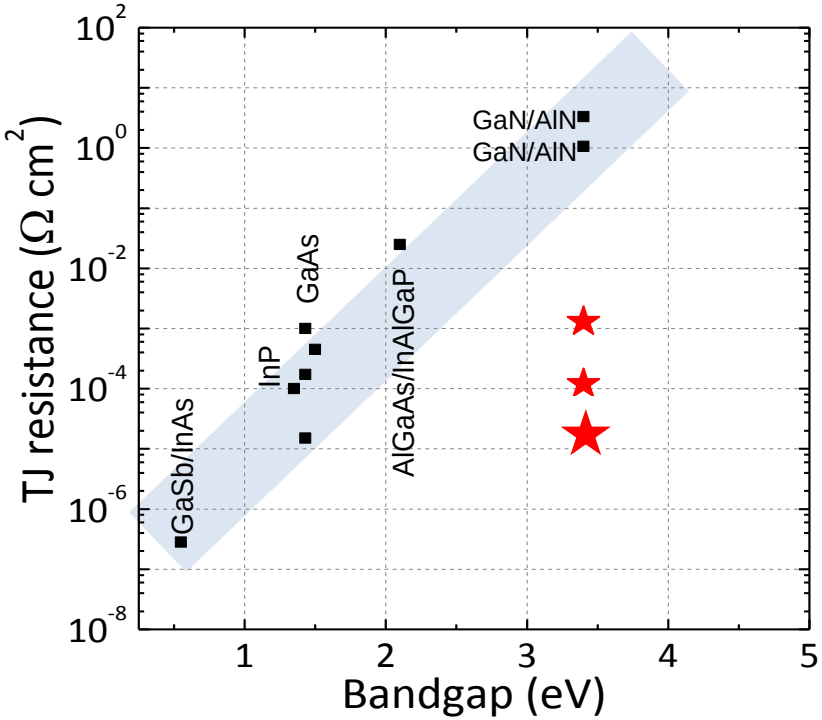
Overview of the tunnel junction technology



GdN/GaN, Nano Lett., 13, 2570 (2013)

InGaN/GaN, APL 102, 113503 (2013)

PN GaN (2015)

Resistance down to 10^{-5} Ohm cm^2 achieved for GaN tunnel junctions.

MBE-based approaches already enable very low voltage drop/resistance tunnel junctions

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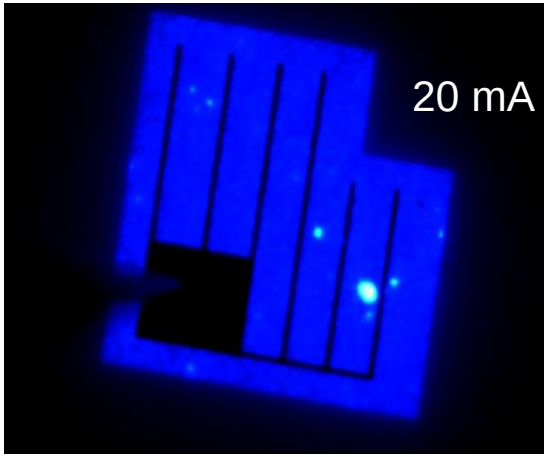
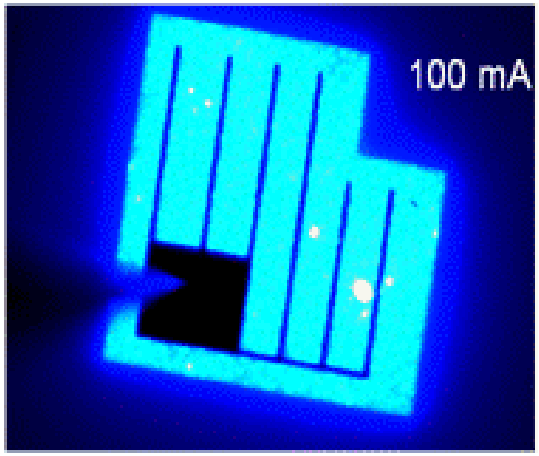
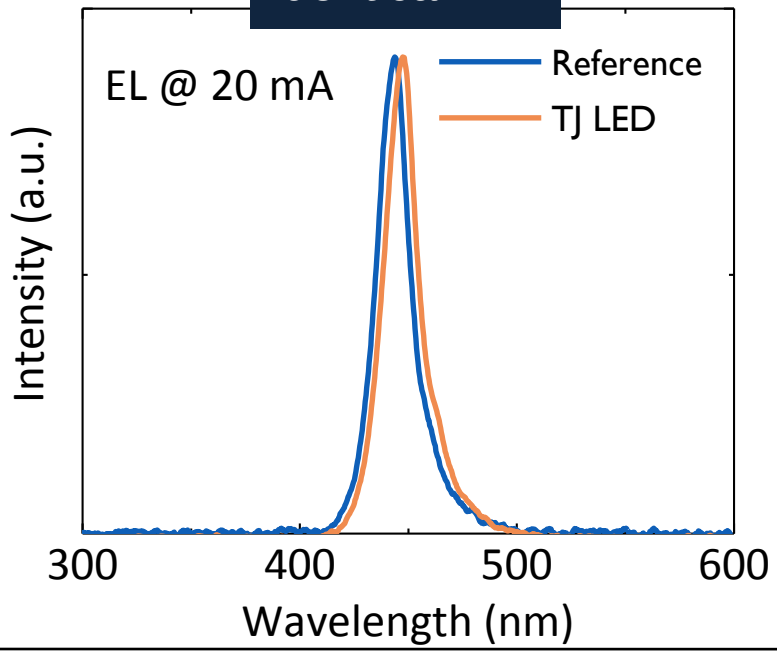
MBE Tunnel Junction on MOCVD LED



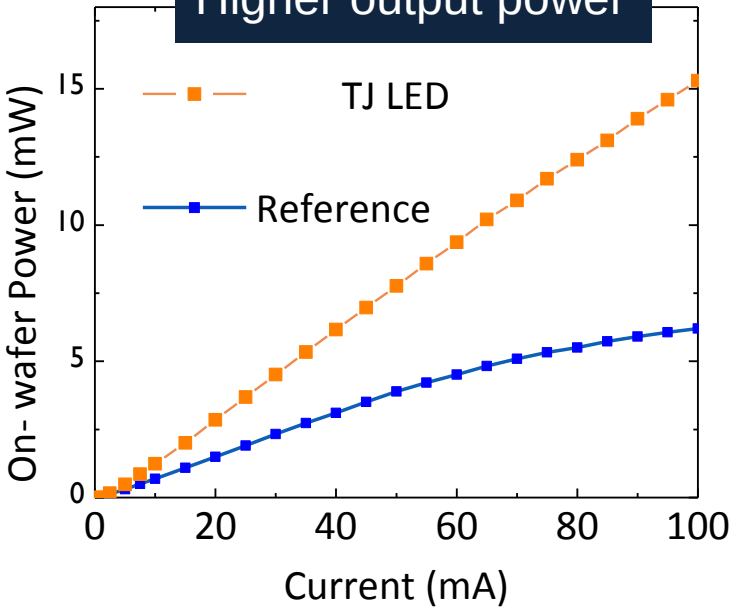


- Only 16% area covered with metal electrode (could be reduced further)
- **<u>Excellent current spreading</u>** due to top tunnel junction
- No flip-chip or ITO needed

Identical EL



Higher output power



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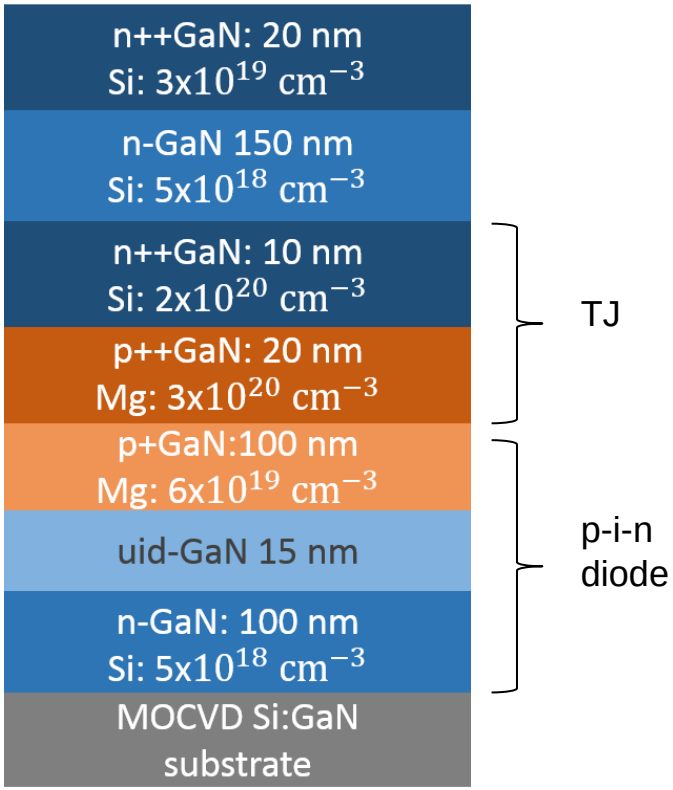
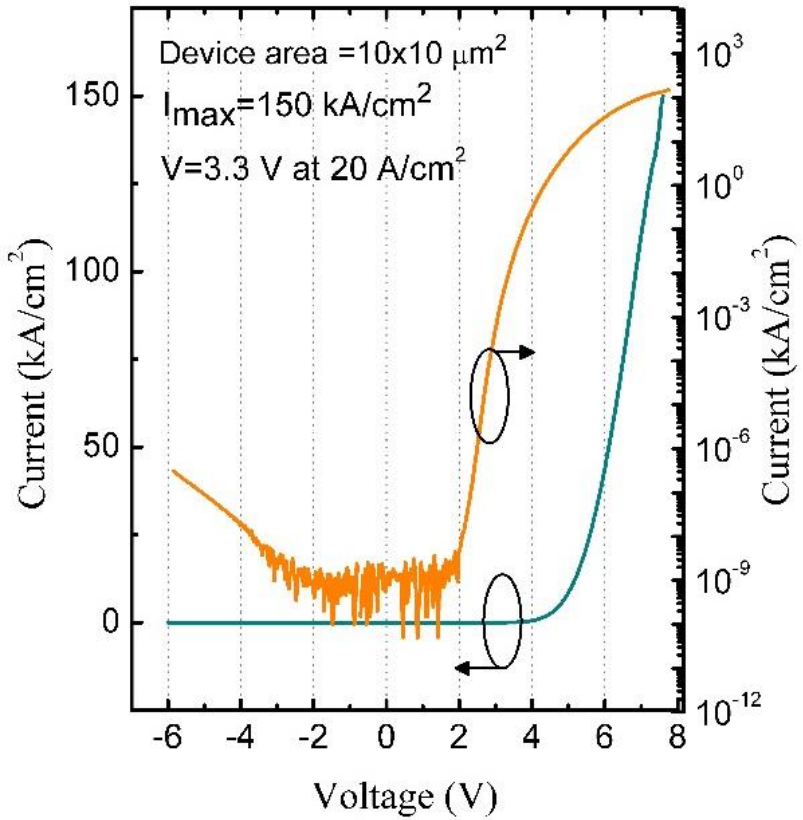
Homojunction Tunnel Junctions on PN junction





n-p-n Diode epitaxial design

- NH_3 MBE homojunctions (EPFL - Grandjean)
- NH_3 MBE/MOCVD hybrid TJ for VCSEL (UCSB)

- CW I-V at RT
- 20 A/cm^2 at 3.3 V
- Record GaN PN current density up to 150 kA/cm^2
- Record tunneling resistance: 1 x 10^{-5} Ω.cm^2 at 150 kA/cm^2

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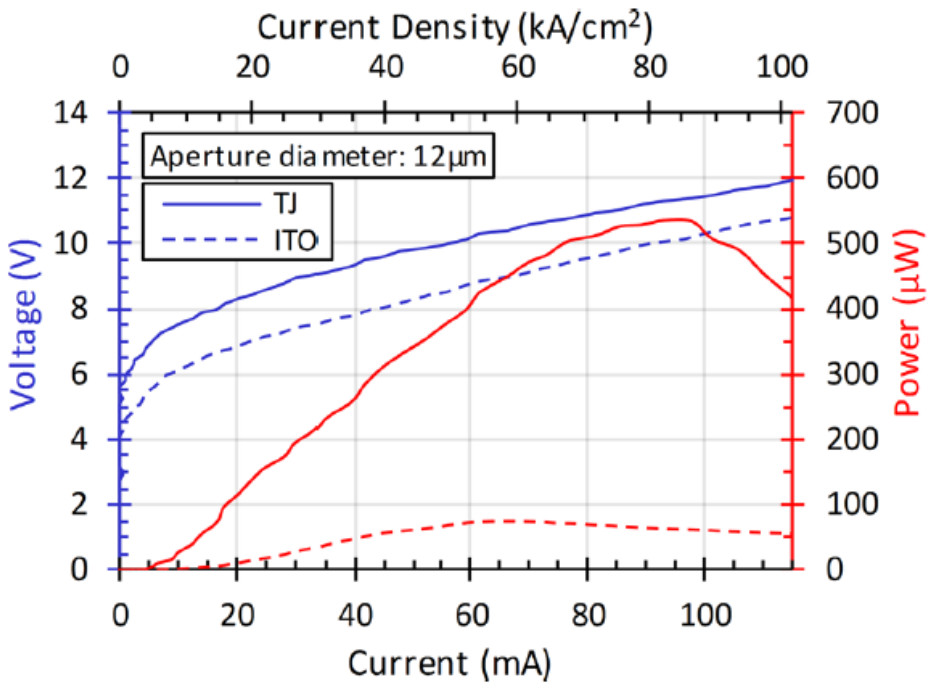
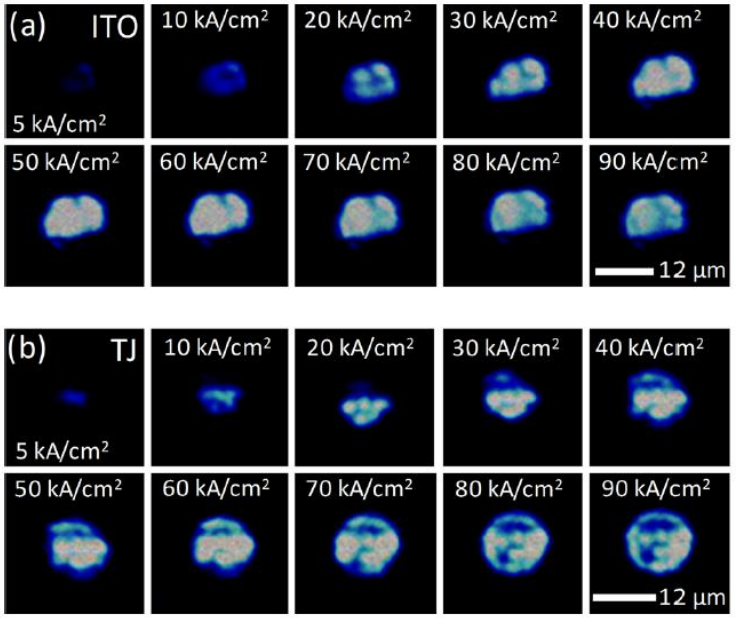
Tunnel junction based laser (UCSB)





MBE/MOCVD hybrid tunnel junction

Improved performance relative to ITO

- Lower threshold current (3.5 vs 8 kA/cm^2)
- Higher efficiency (0.26% vs 0.062%)

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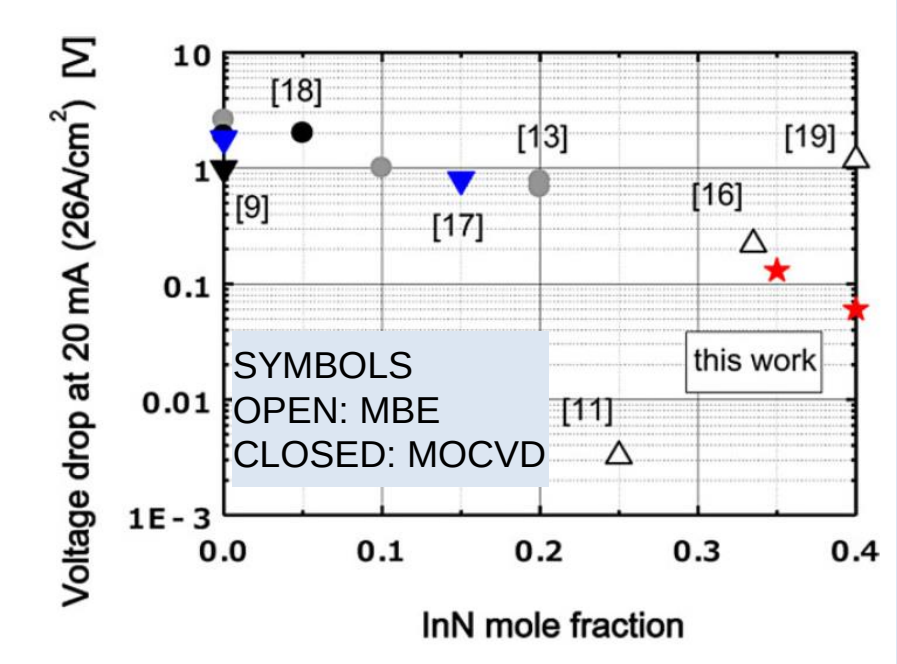
MOCVD TJ development (Meijo/NCKU/Epistar)

Takeuchi/Akasaki groups/Meijo University
Phys. Status Solidi B 252, No. 5 (2015)

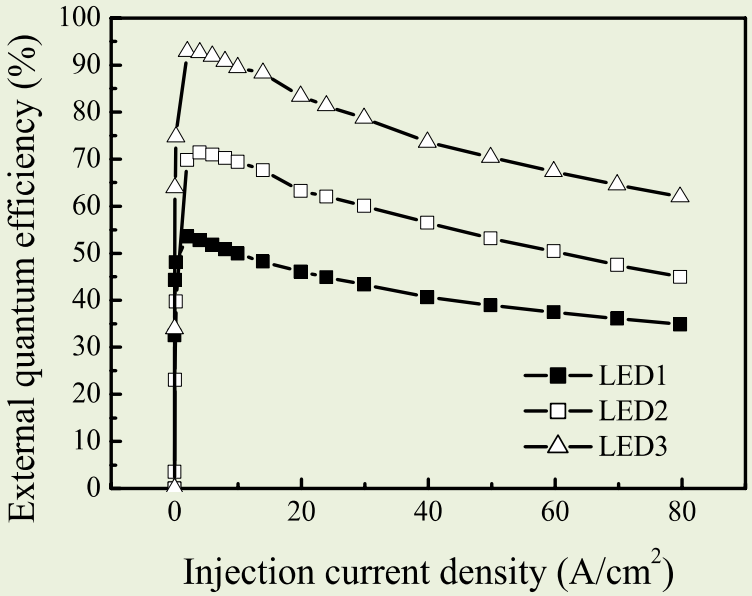


IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 51, NO. 8, AUGUST 2015

Cascaded GaN Light-Emitting Diodes With Hybrid Tunnel Junction Layers

Shoou-Jinn Chang, *Fellow, IEEE*, Wei-Heng Lin, and Wei-Shou Chen

NCKU, Taiwan and Epistar



- Low resistance tunnel junctions demonstrated using all-MOCVD GaN/InGaN/GaN approach
- Proof-of concept cascaded LEDs demonstrated

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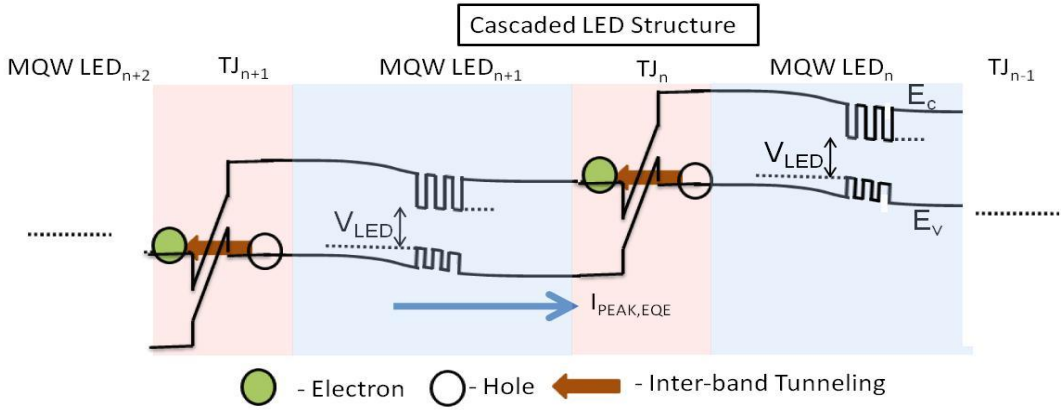
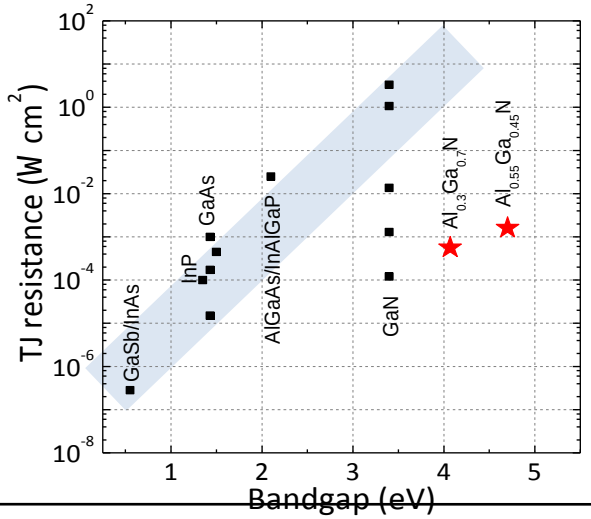
Research needs/directions

1. **Design:** InGaN-based tunnel junctions/homojunctions
2. **Absorption** in tunnel junctions
3. **Activation of buried p-type** regions
4. **Defect control** at tunnel junctions (due to doping and InGaN)
5. **Inverted polarity** structures (p-down)

Tunnel junctions can enable innovative solutions to efficiency droop problem

They are ready to be applied today!





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