III-Nitride Tunnel Junctions for Visible and UV LEDs

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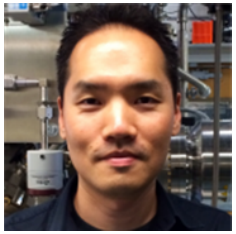
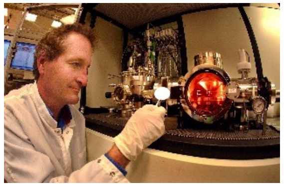
<u>Collaborators</u>

Ohio State University: Jinwoo Hwang's group



Sandia National Laboratories: Brendan Gunning, Andrew Allerman, Andrew Armstrong



Funding: US Department of Energy, NSF, AFOSR

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Outline

- Motivation for Tunneling-based III-Nitride LEDs
- Tunneling Injected UV LEDs
- Tunneling-based Visible LEDs

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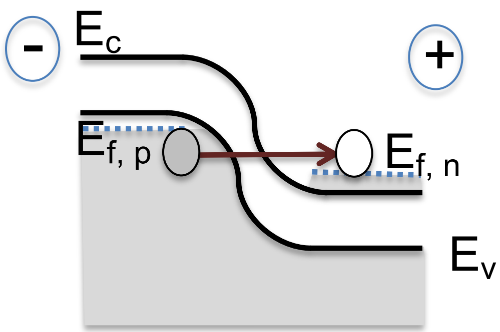
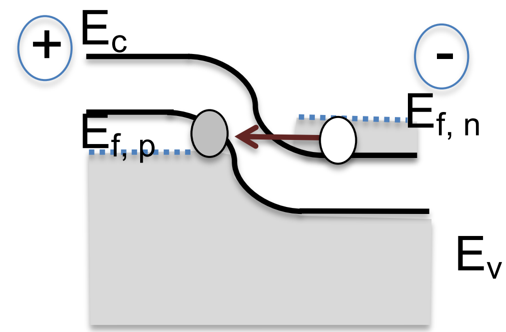
Interband Tunnel Junctions

TJ in reverse bias



Electron ←→ hole carrier conversion

TJ in forward bias



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

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

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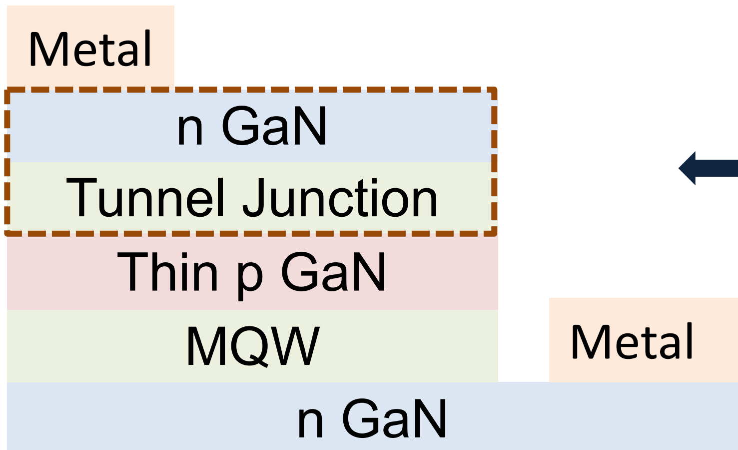
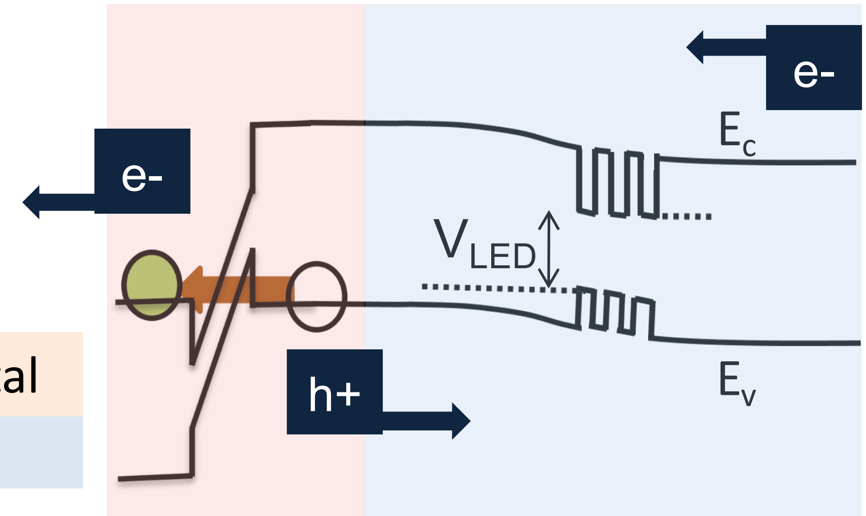
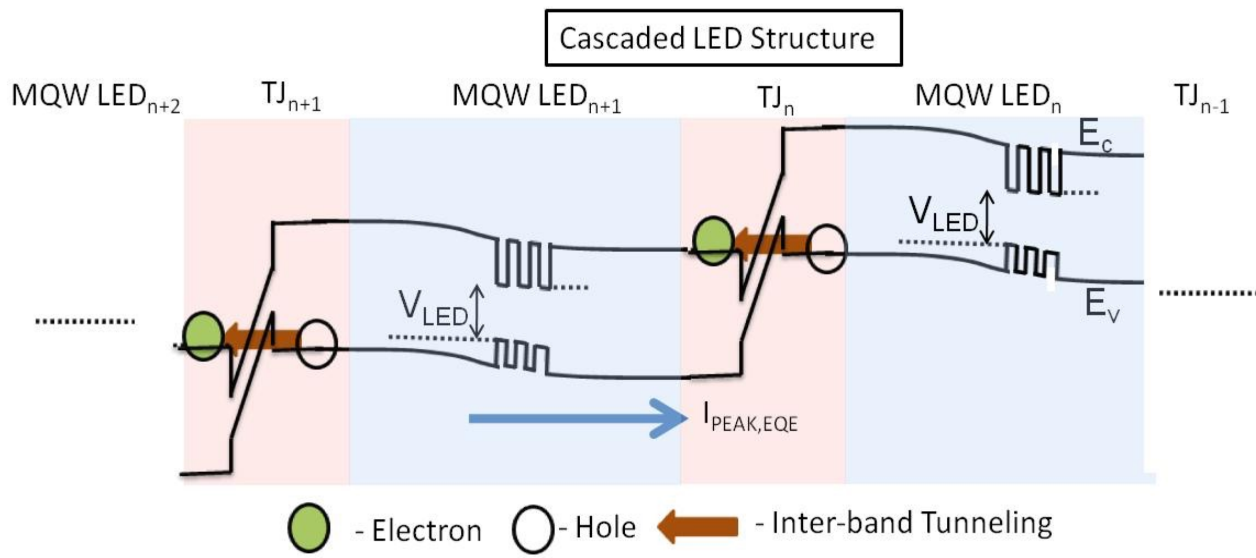
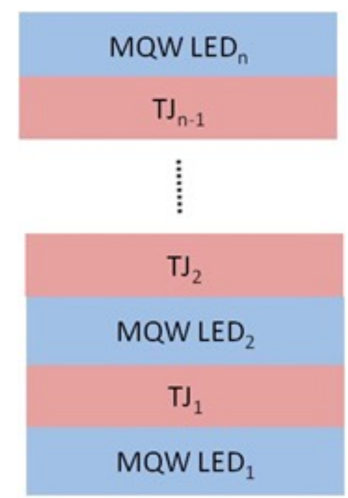
LEDs with tunnel junctions









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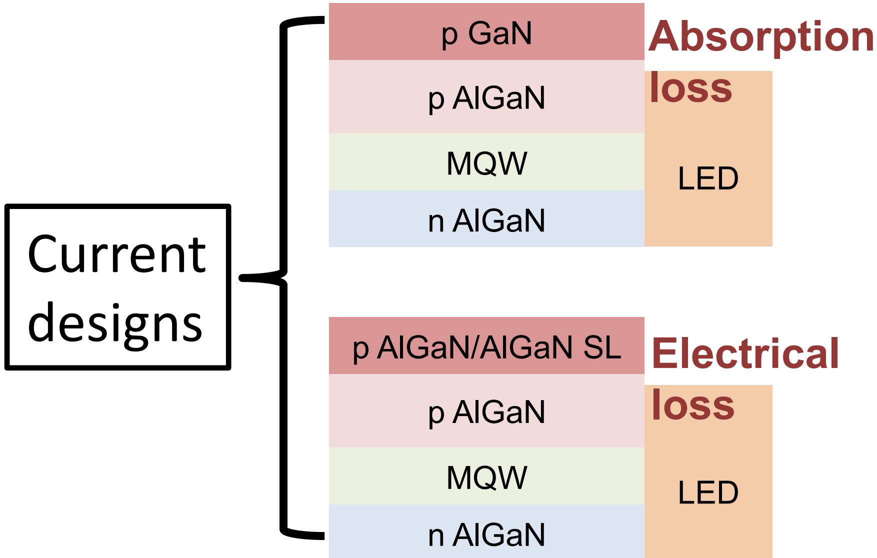
P-contact and light extraction



Increased absorption losses

Increased voltage drop

Trade-off between $\eta_{injection}$ & η_{LEE}

	GaN	SiC	Ga_2O_3	AlN	Diamond	ZnO
Bandgap (eV)	3.4	3.3	4.9	6.1	5.5	3.4
E_A (eV) Holes	0.16	0.20	None	0.5	0.370	0.180
E_D (eV) electrons	0.015	0.085	Low	0.063	1.7	0.04

Acceptor activation limits large band gap materials

Low hole density and large p-type resistance leads to poor UV LEDs

Can we use NON-EQUILIBRIUM INJECTION instead of doping?

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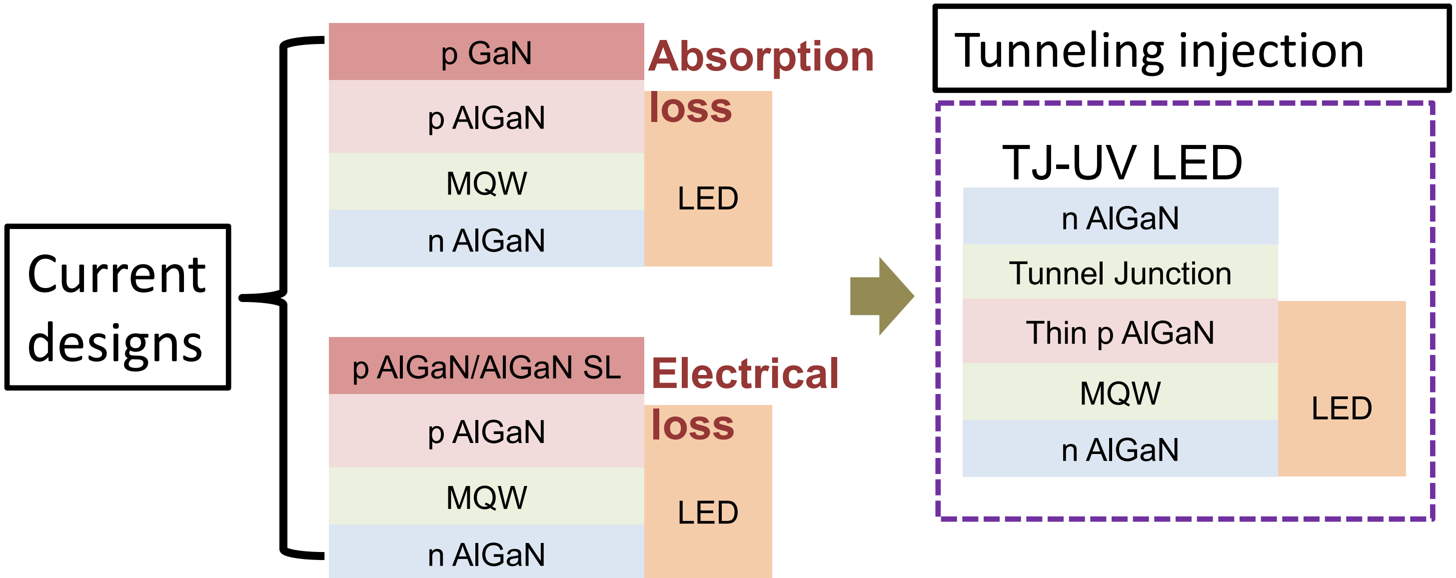
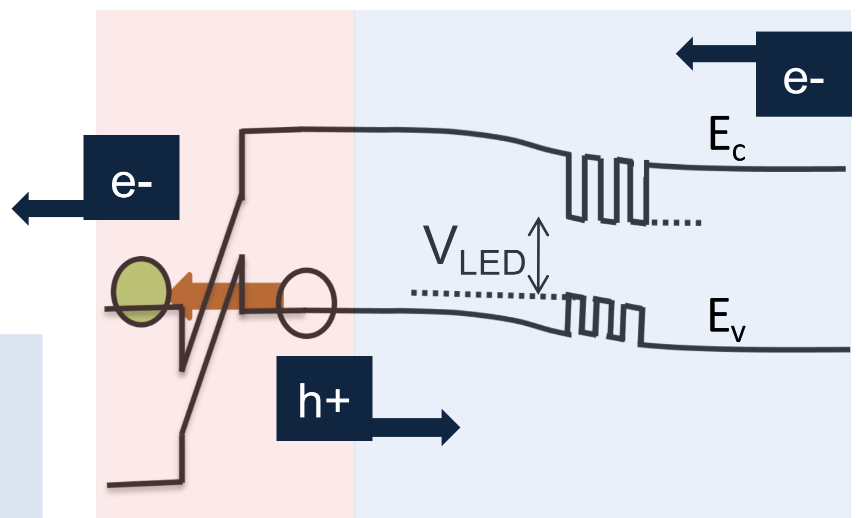
P-contact and light extraction



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

- Reduced light absorption loss
- Enhanced injection efficiency
- Enables new LED/**laser** designs by making p-AlGaN **<u>thin</u>**



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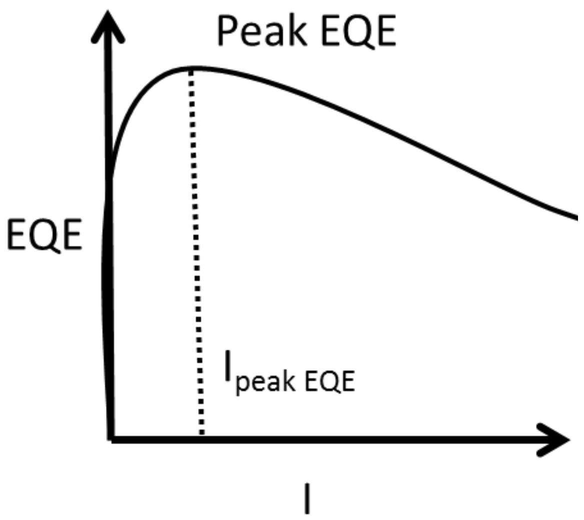
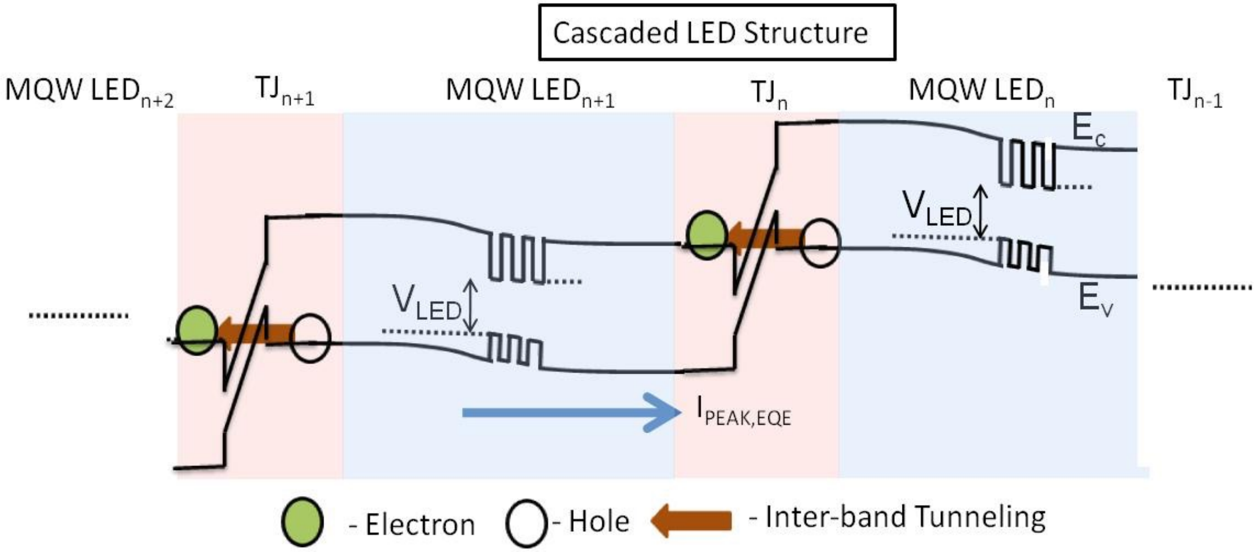
Tunneling-Based GaN Optoelectronics

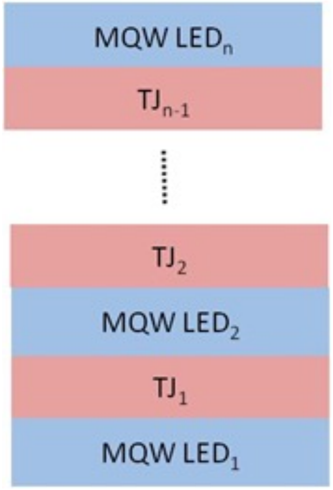


Efficiency droop: Main issue in LED lighting today
- Low efficiency at higher injection current

Cascaded multiple active region LEDs
- Low current density with multiple active regions
- Each e-h pair injected creates multiple photons
- Enables **higher power density point sources**
- Also important for **longer wavelengths**
- Prerequisite for a true RGB white LED

[1] *Appl. Phys. Lett. 103* , 081107 (2013)





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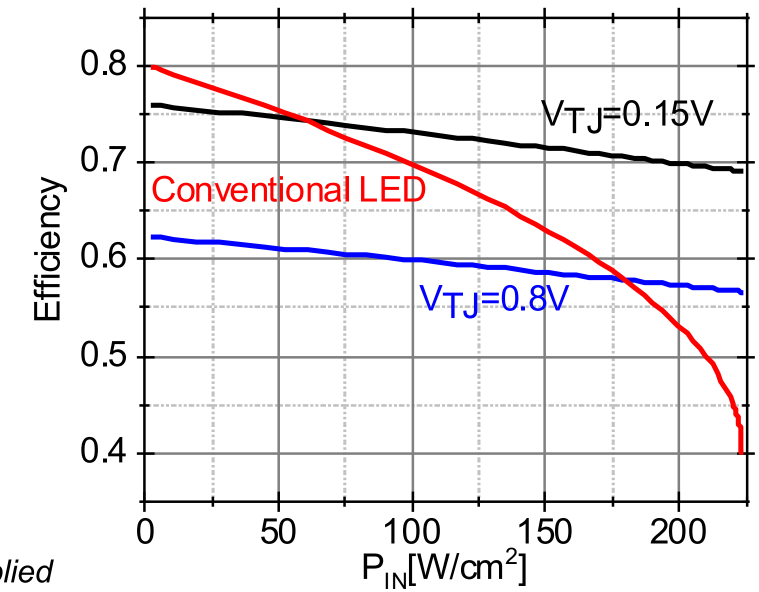
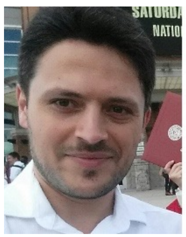
Tunnel Junctions for Cascaded LEDs

Efficient design of cascaded LEDs

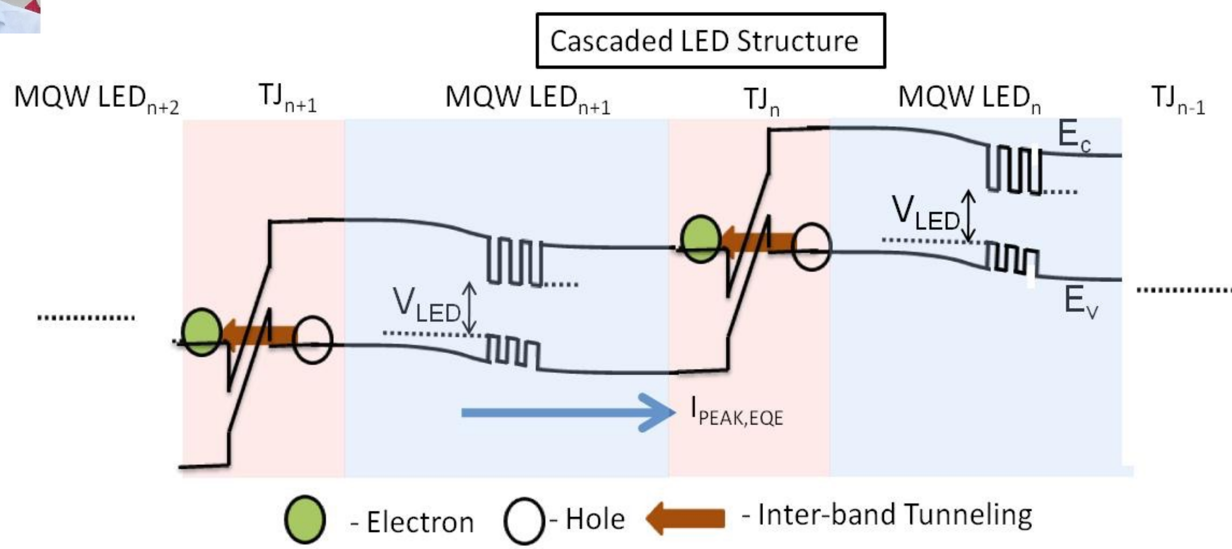
- High output power operation where efficiency droop is significant
- Excess forward voltage due to tunnel junction must be minimized

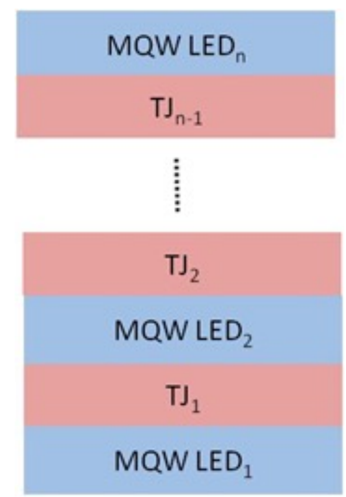




Fatih Akyol
Now at Yildiz Univ.

Akyol, F., Krishnamoorthy, S. and Rajan, S., 2013,. *Applied Physics Letters*, *103*(8), p.081107.





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Outline

- Motivation for Tunneling-based III-Nitride LEDs
- **Tunneling Injected UV LEDs**
- Tunneling-based Visible LEDs

Y. Zhang, OSU (now Apple)

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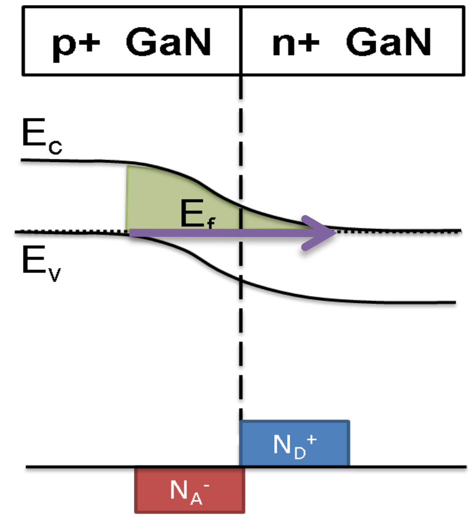
Polarization engineering for tunnel junctions

Standard p+/n+ TJ

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

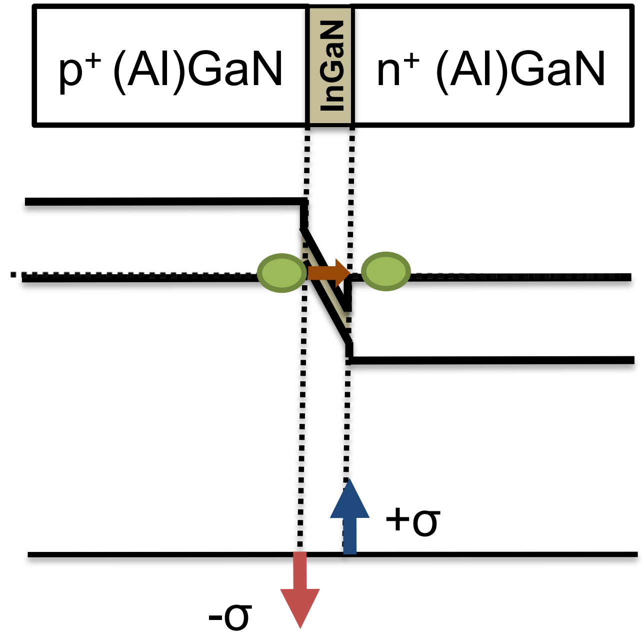
Low tunneling current density



Polarization-engineered TJ

- High density polarization sheet charge

  → depletion width greatly reduced.
- Tunnel barrier reduced due to InGaN.



S. Krishnamoorthy
(Now UCSB)

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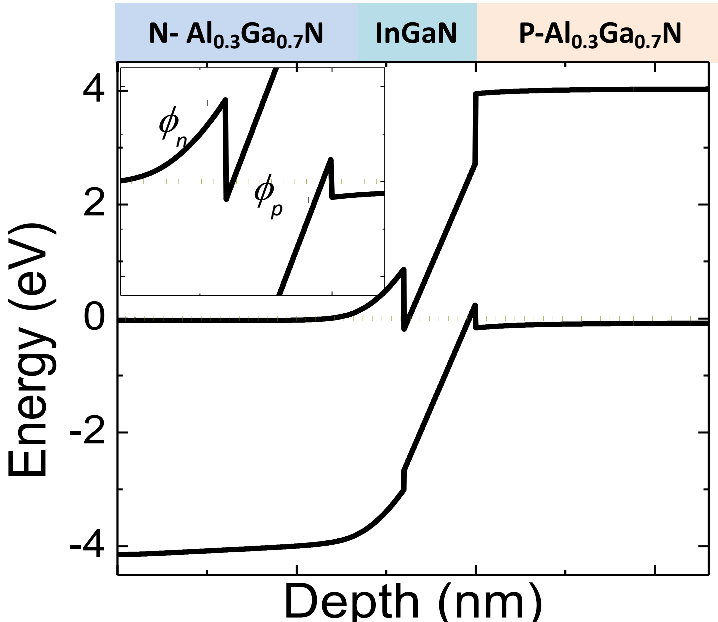
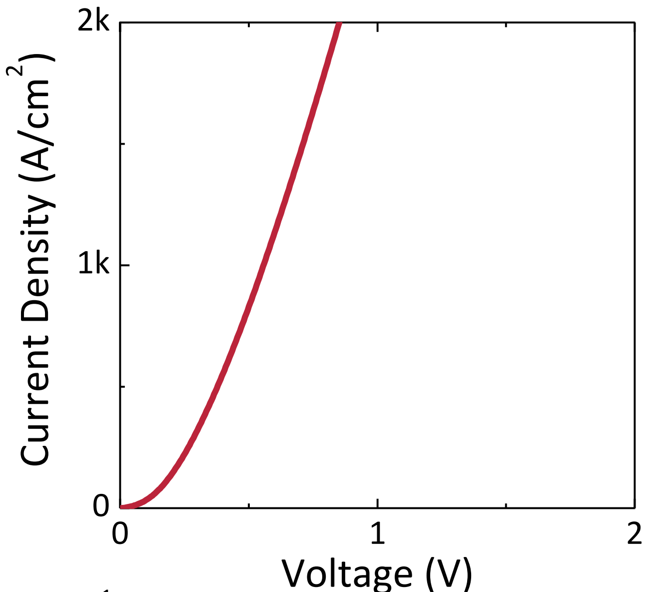
Modeling: tunneling current in AlGaN

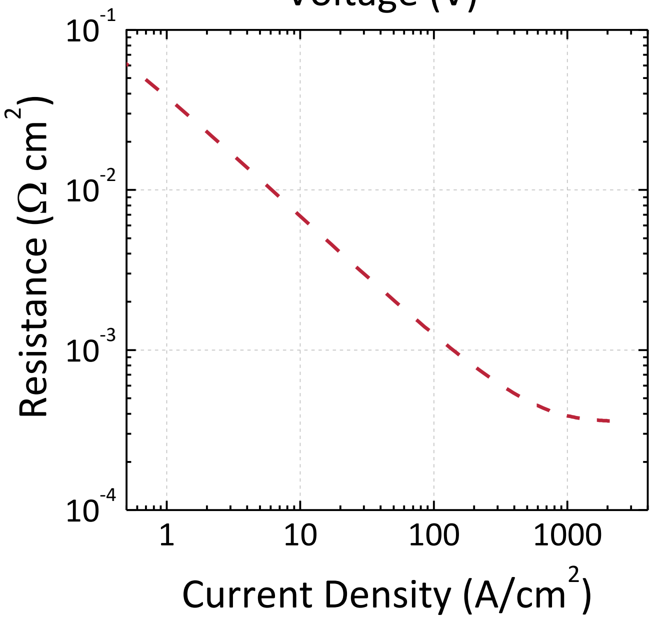


- Self-consistent Schrodinger Poisson solution
- WKB approximation for tunneling probability calculation.

$$J_T = q\iint\left(f_p^n\rho^p - f_n^n\rho^n\right)v_z T_{wkb}\,dE$$

- Resistance reaches 3E-4 Ohm cm^2.
- High current density could be achieved with low voltage drop.





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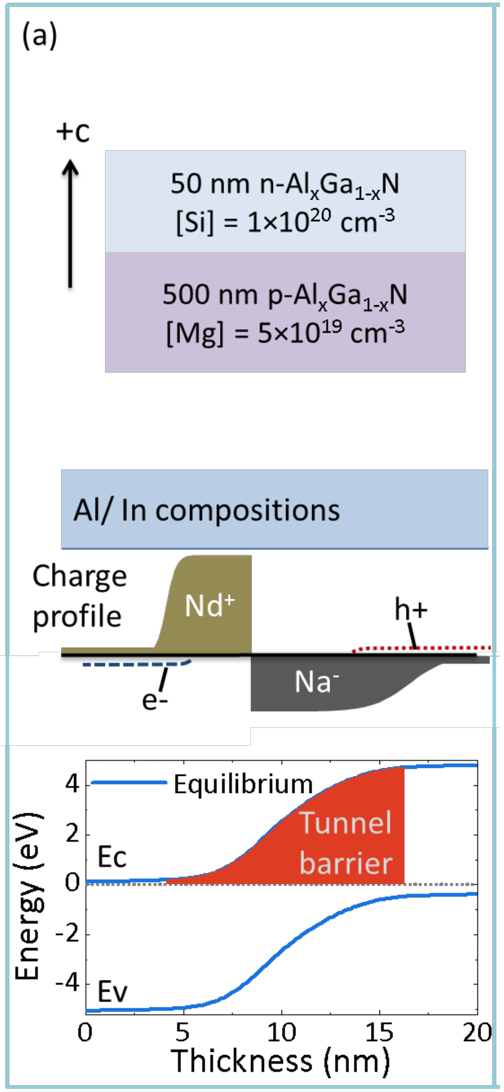
Design of tunnel junction structures



$Al_{0.7}Ga_{0.3}N$
$/(In_{0.3}Ga_{0.7}N)$

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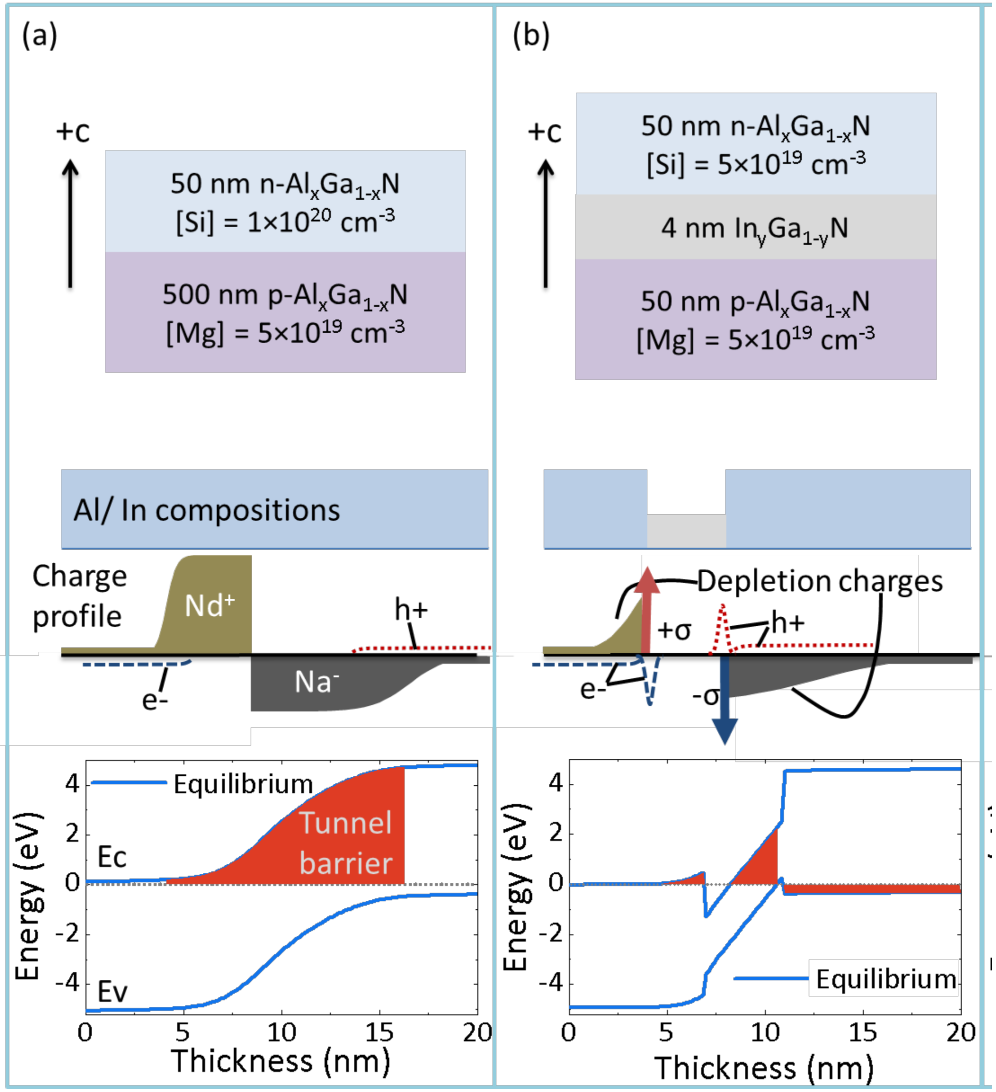
Design of tunnel junction structures



$Al_{0.7}Ga_{0.3}N$ /($In_{0.3}Ga_{0.7}N$)

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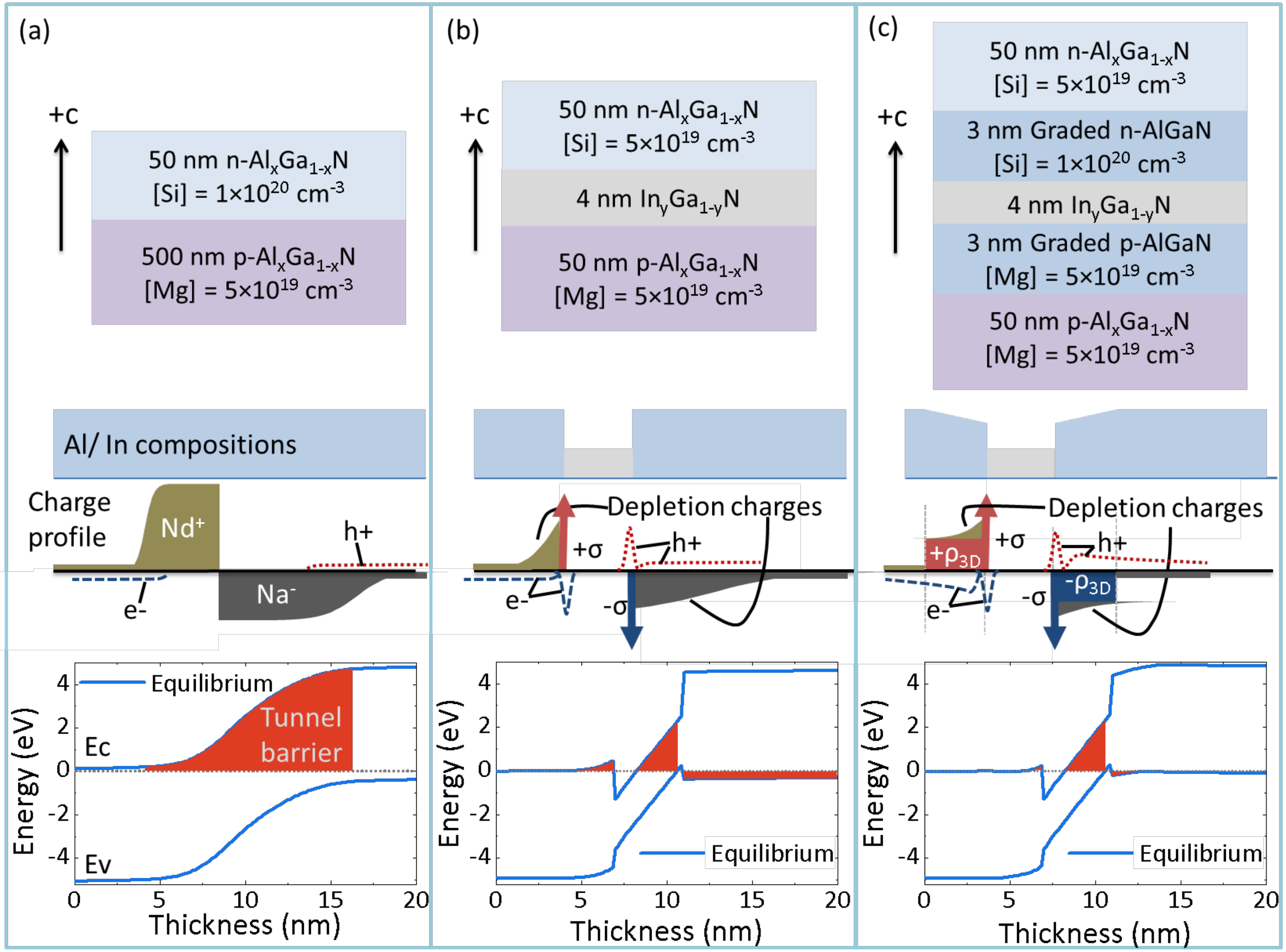
Design of tunnel junction structures

$Al_{0.7}Ga_{0.3}N$
$/(In_{0.3}Ga_{0.7}N)$



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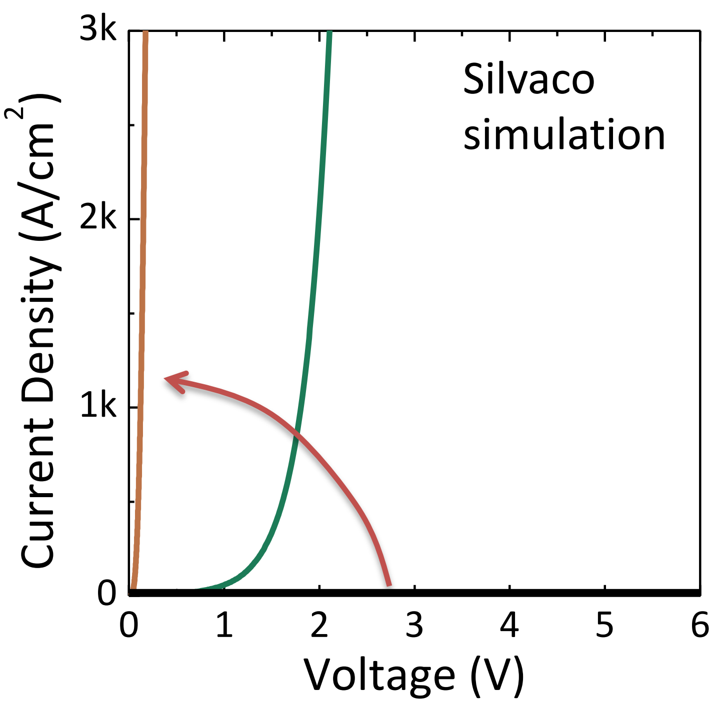
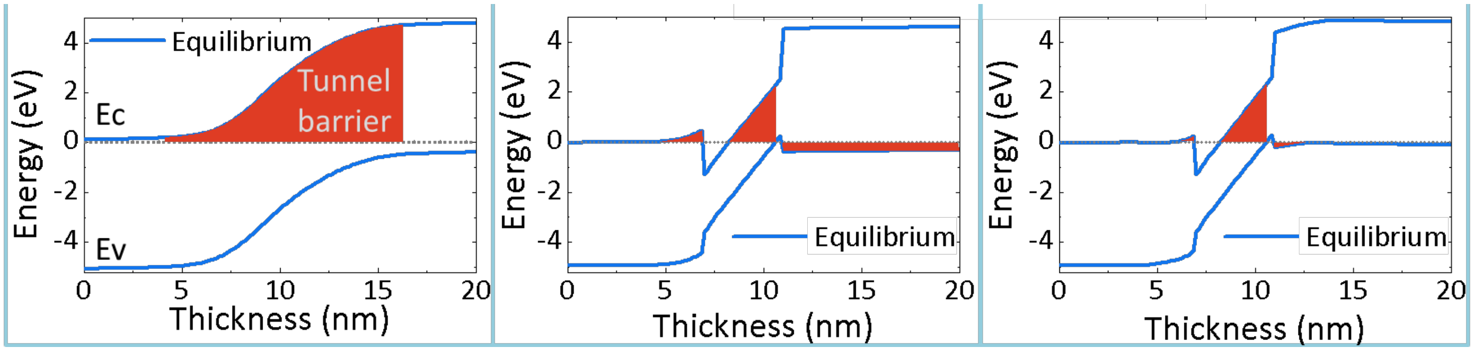
Design of tunnel junction structures

- Polarization engineering enables low tunneling resistance and voltage drop.



$Al_{0.7}Ga_{0.3}N$ /$(In_{0.3}Ga_{0.7}N)$



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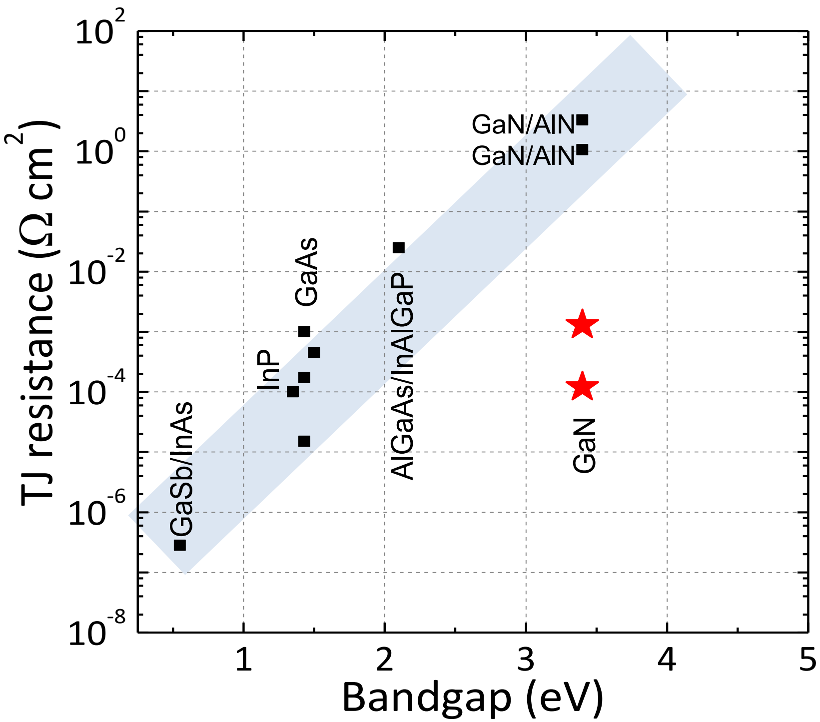
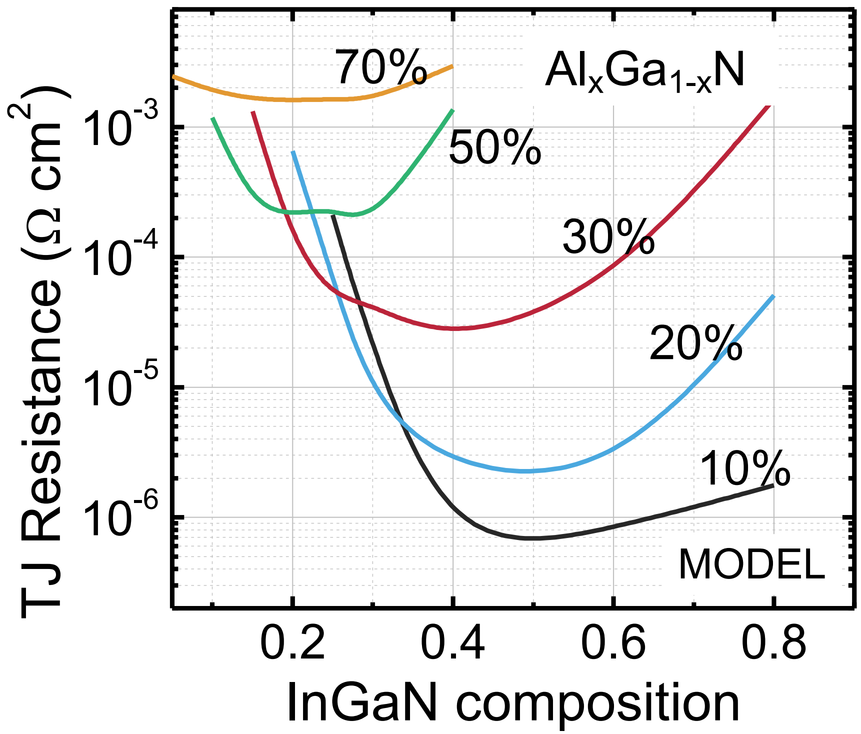
Beyond the GaN bandgap: Design of AlGaN TJs





- Low resistance TJ could be created for high composition AlGaN.
- Hole injection could be achieved through high bandgap AlGaN TJs.

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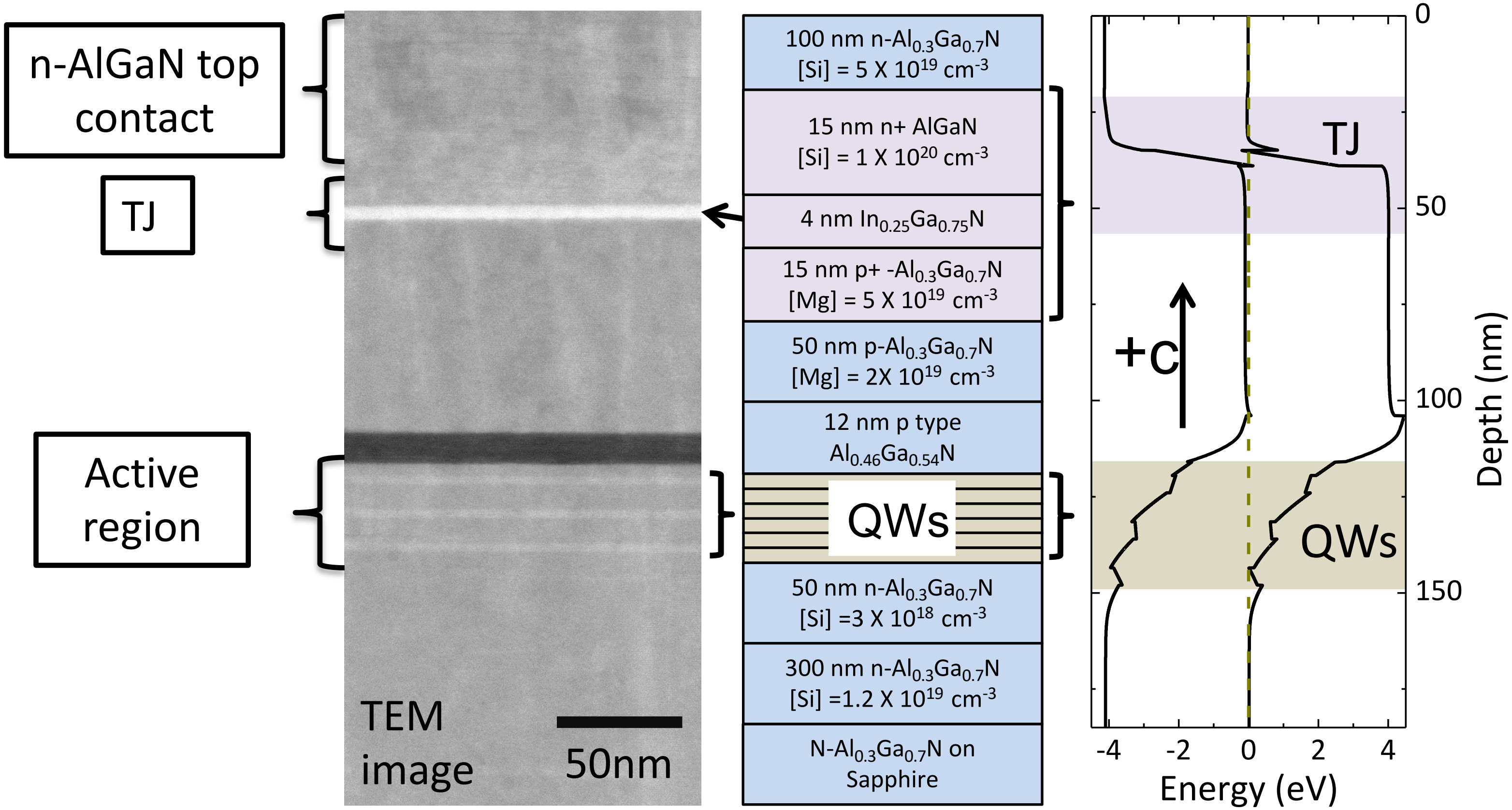
MBE-grown TJ-UV LED



- TJ as a tunneling contact to p-AlGaN
- Enables extraction from top surface→ no need for flip chip bonding
- Low spreading resistance in n-AlGaN → reduced metal coverage

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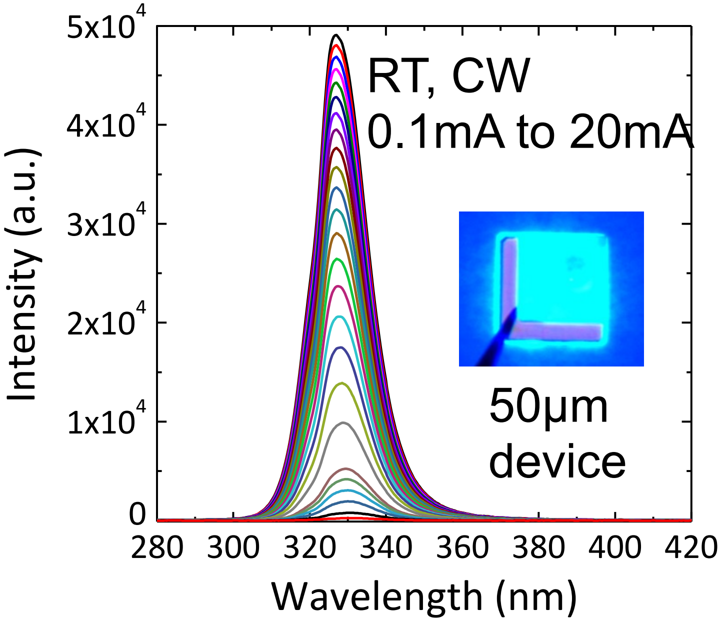
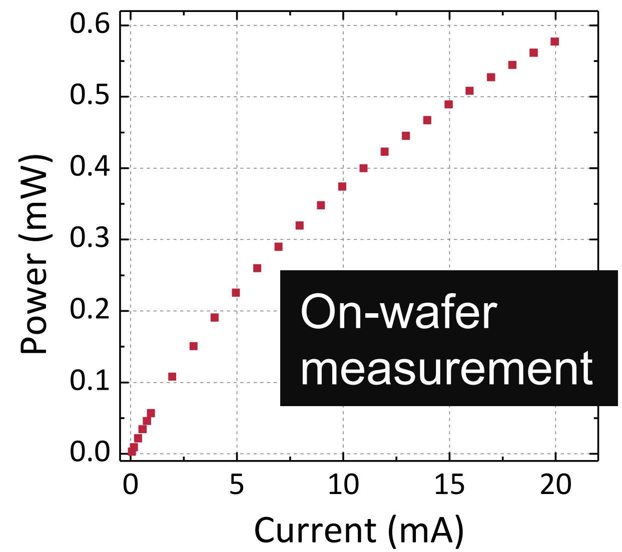
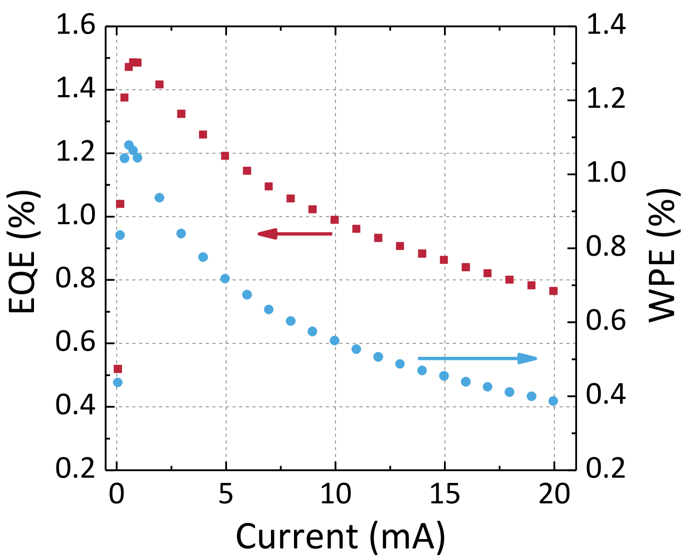
TJ-UV LED – optical characteristics







- Single peak emission at 327 nm
- Peak EQE and WPE are 1.5% and 1.08%, respectively.
- At 120 A/cm^2, voltage is 5.9 V, power is 6 W/cm^2.
- Proof of efficient hole injection through tunneling.

Y. Zhang, Appl. Phys. Lett. **106**, 141103 (2015)

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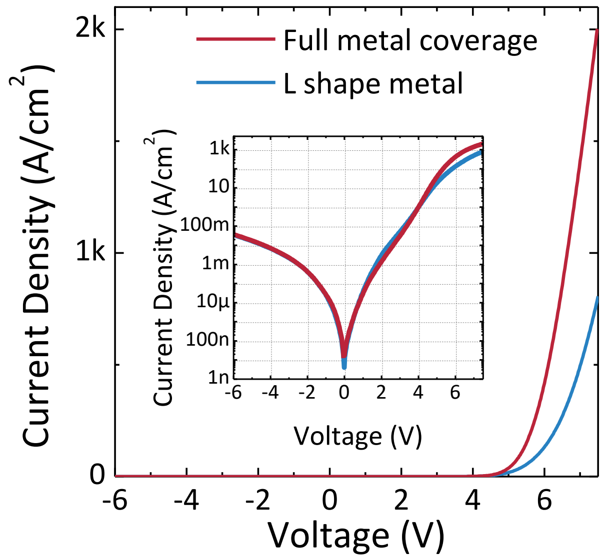
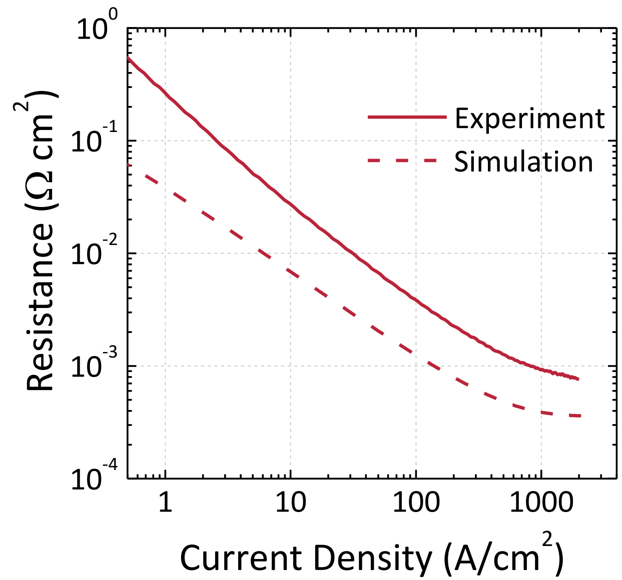
TJ-UV LED – electrical characteristics





- 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 TJ enables orders of magnitude lower resistance.

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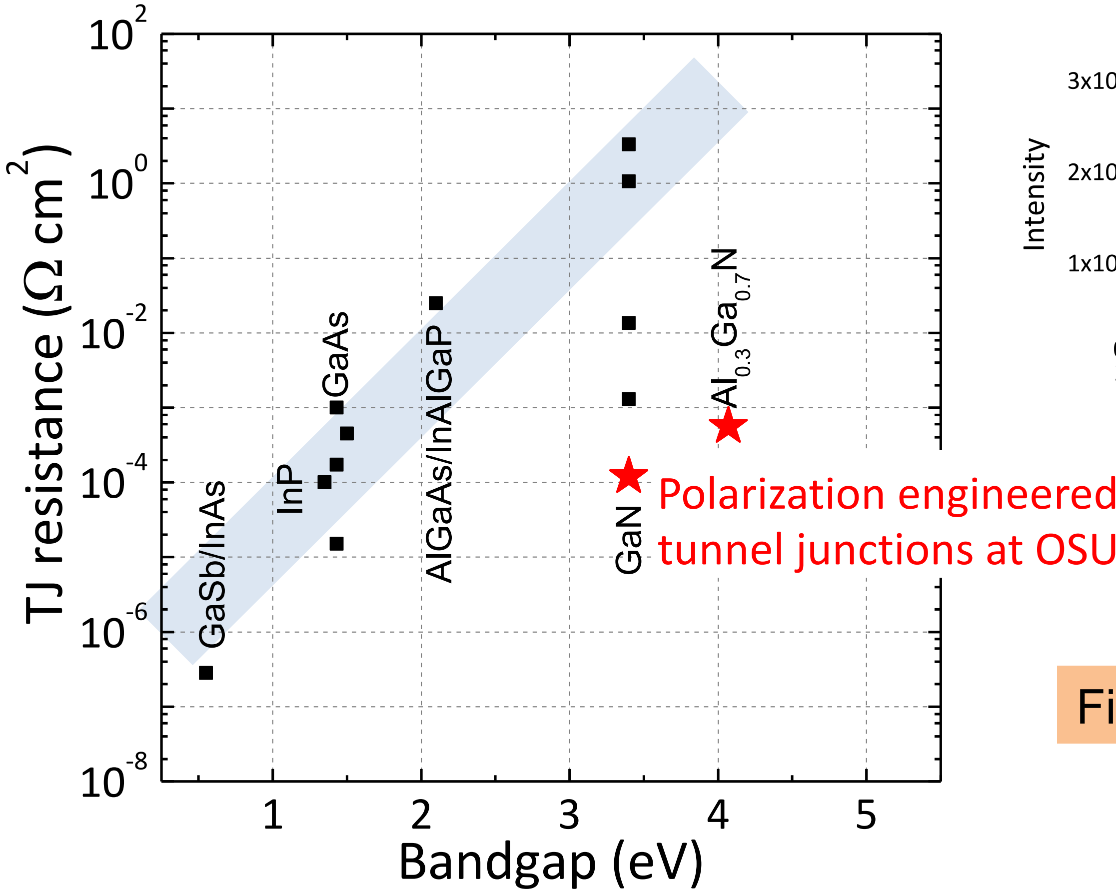
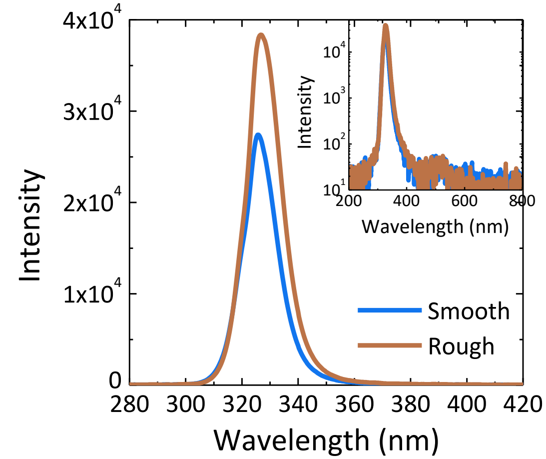
Overview of the tunnel junction technology





325 nm emission

First tunnel-injected UV LED

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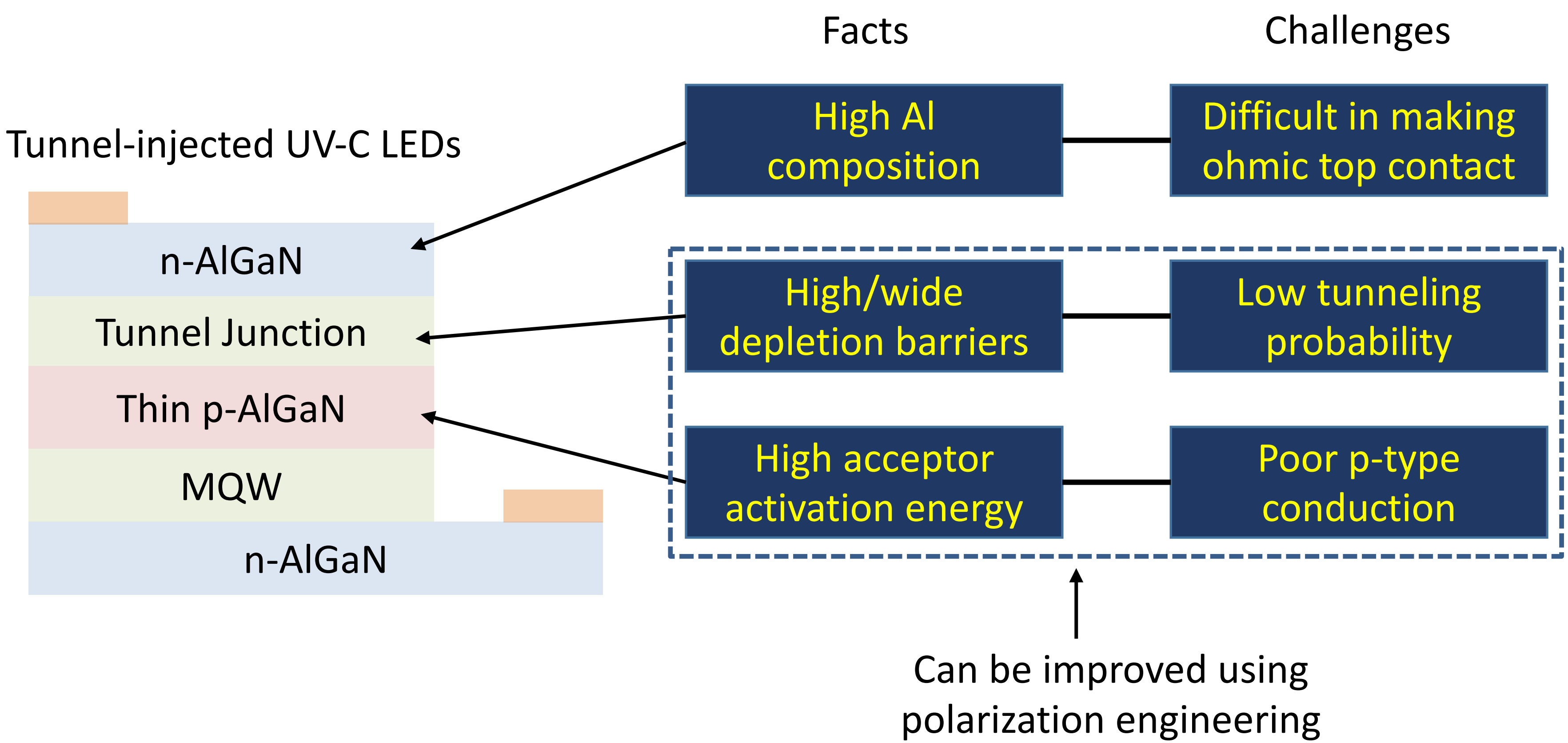
Tunnel-injected UV-C LEDs



Making ohmic contact to ultra-wide bandgap AlGaN top contact layer is challenging.

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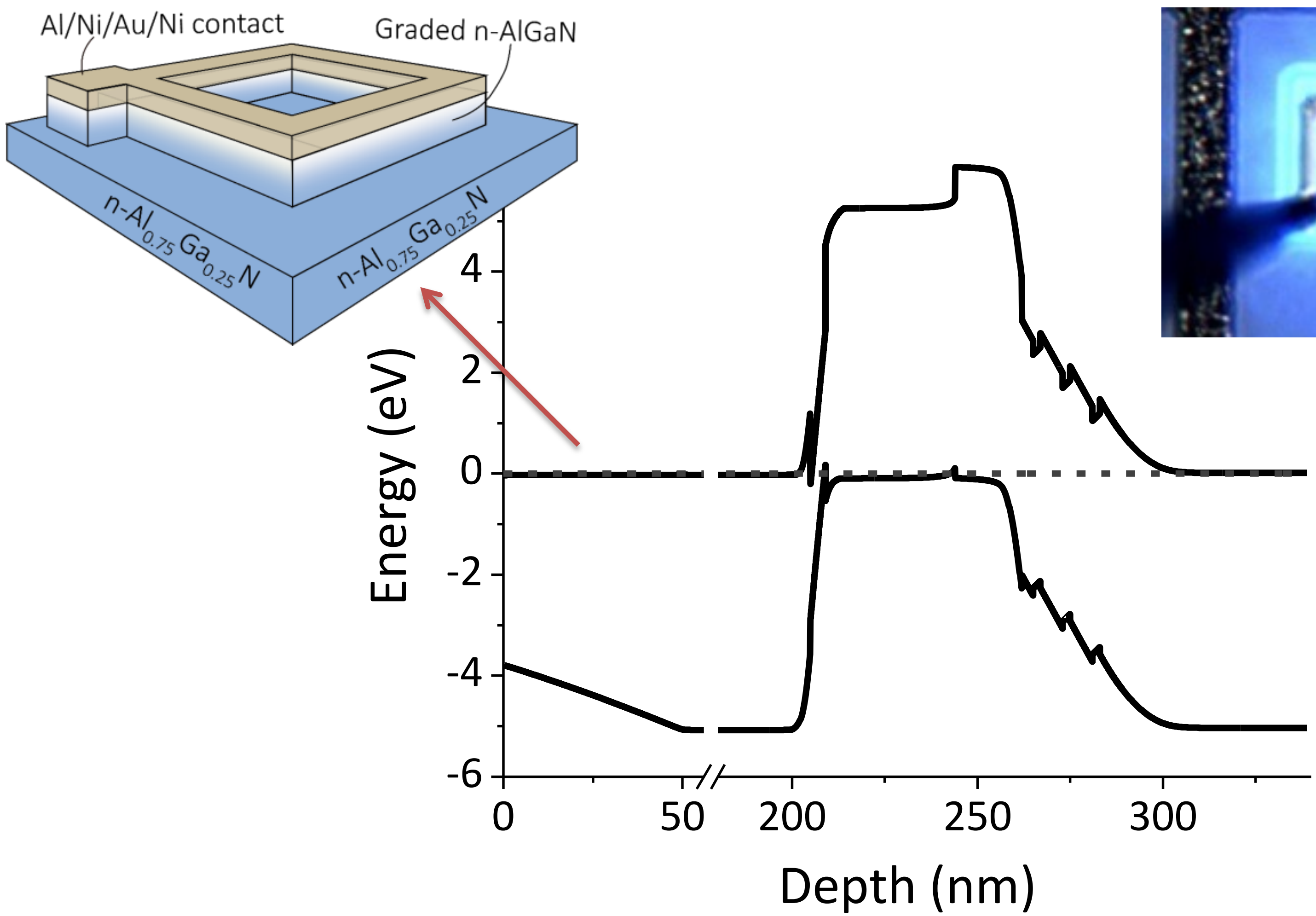
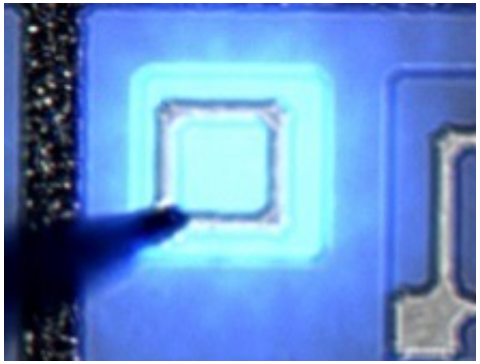
Tunnel-injected deep UV LED structure





- Graded contact can be applied for deep UV LEDs

S. Bajaj, Appl. Phys. Lett. **109**, 133508 (2016)
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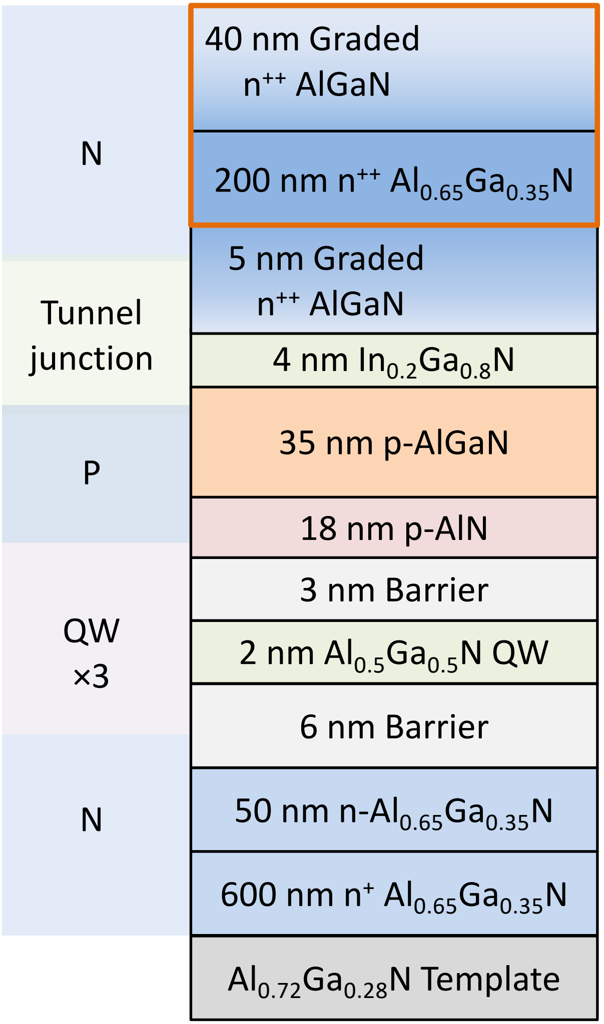
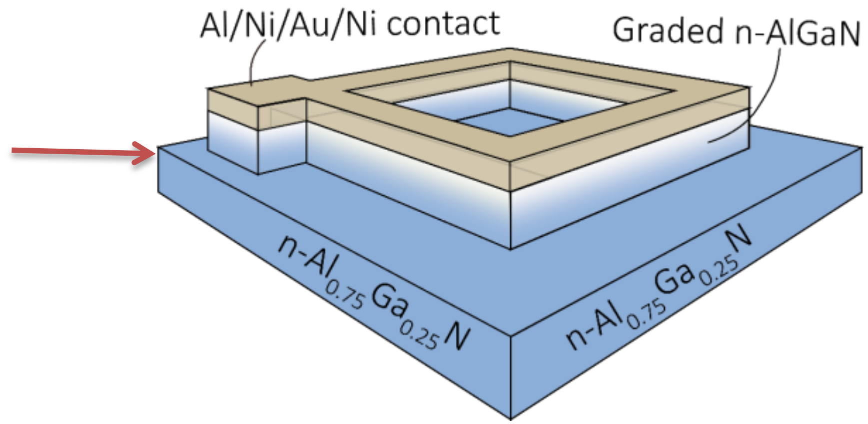
Tunnel-injected deep UV LED structure





- Partial top metal coverage to minimize light absorption.
- Contact through graded n++ AlGaN.
- The n+ AlGaN top layer provides sufficient current spreading.

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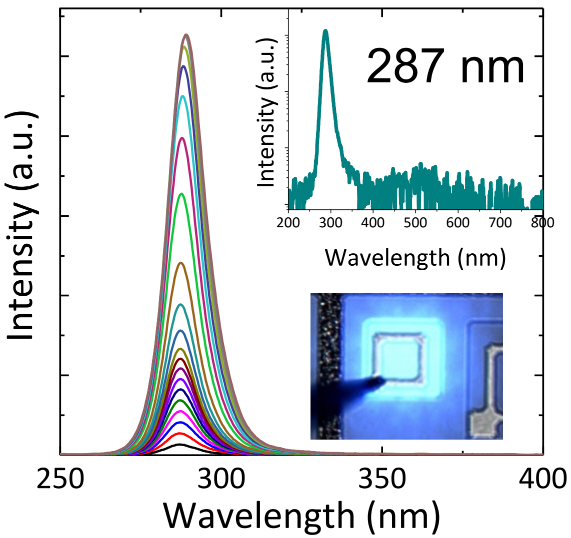
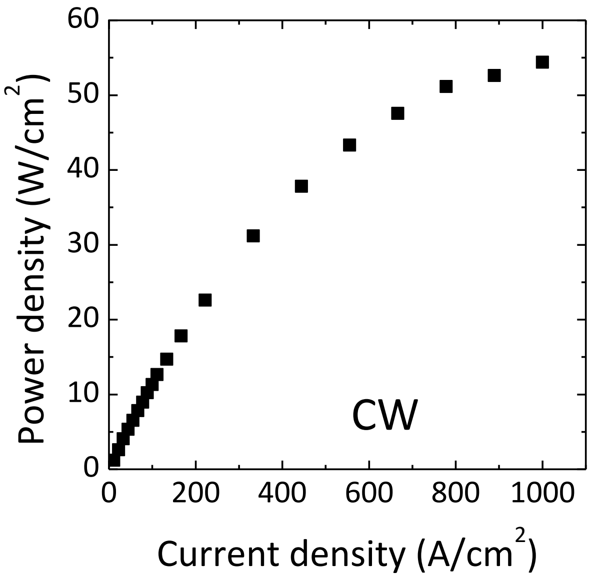
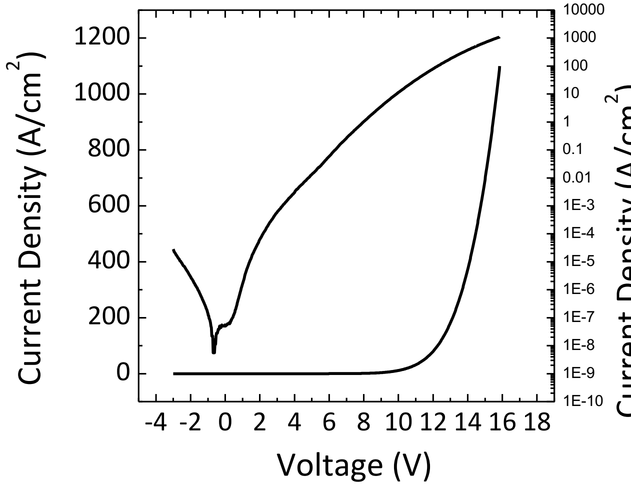
Optical characteristics – sub 290nm TJ-LED







- Achieved uniform single peak emission at 287 nm
- High power density of ~ 55 W/cm^2 achieved 1 kA/cm^2

- Low on-resistance -- **1.7 x 10^{-3} Ohm cm^2** – more than one order lower compared to conventional UV LEDs

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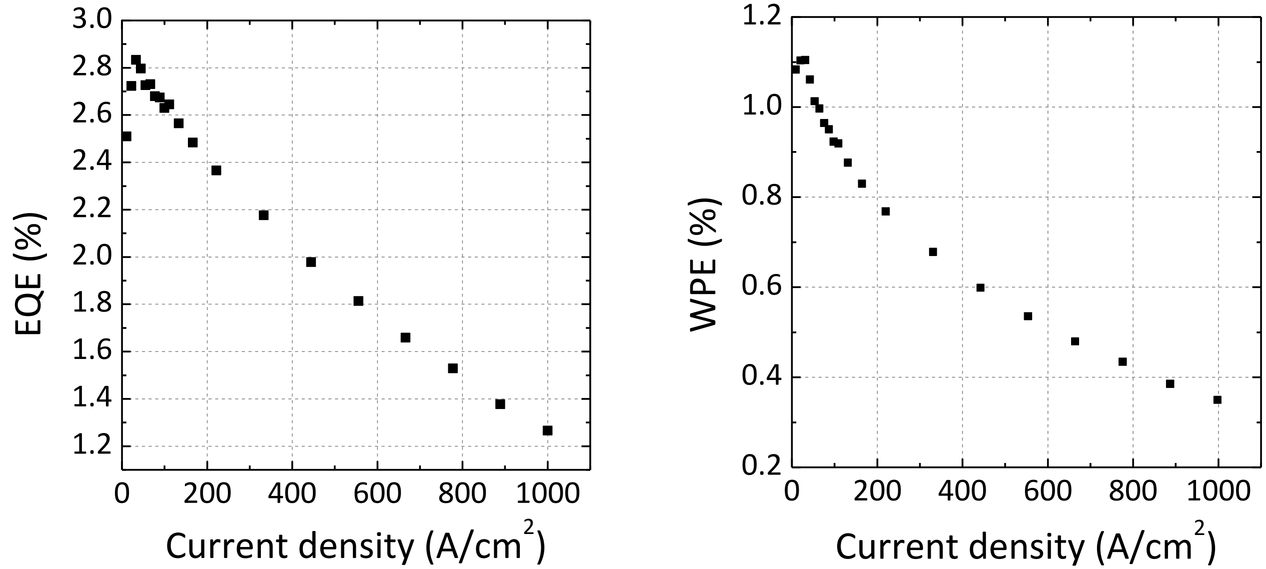
Sub 290nm TJ-LED - Efficiency



WPE=EQE*hν/qV

- Peak EQE is 2.8%, peaks at 30 A/cm^2
  - indication of high carrier injection efficiency.
- Peak WPE is 1.1% -- high voltage drop harms WPE
- Direct demonstration of efficient hole injection into UWBG AlGaN

Power/ efficiency values are underestimated because of on-wafer measurement

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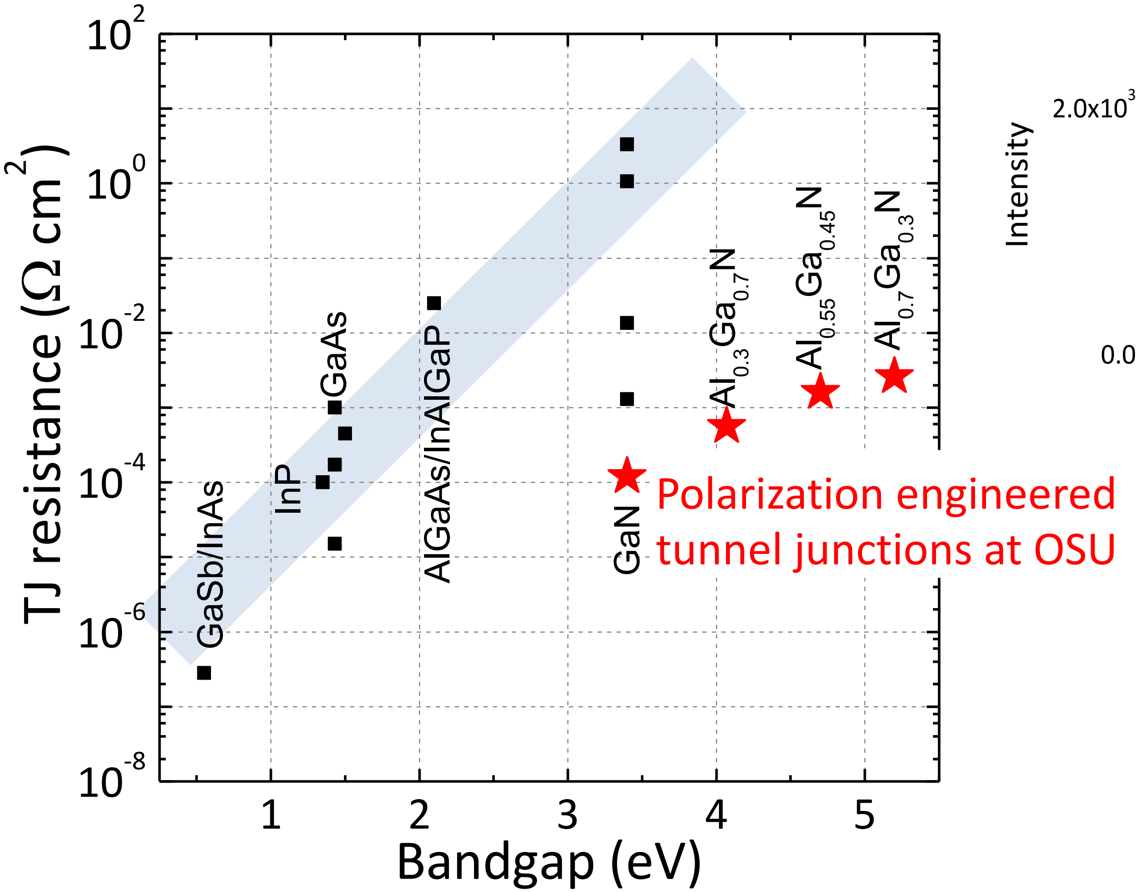
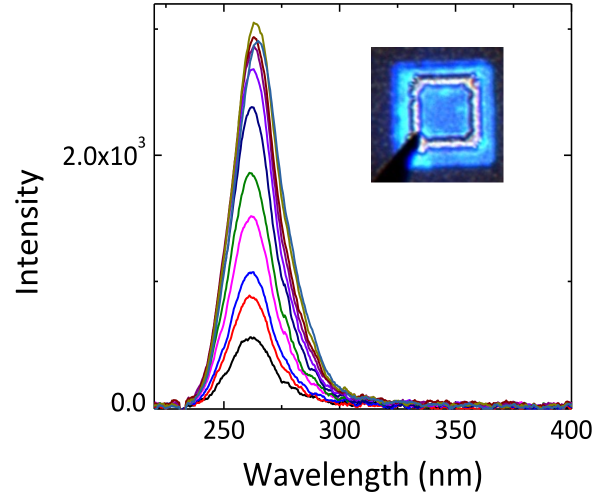
Overview of the tunnel junction technology





257 nm emission

Widest band gap interband tunnel junctions for *any* semiconductor

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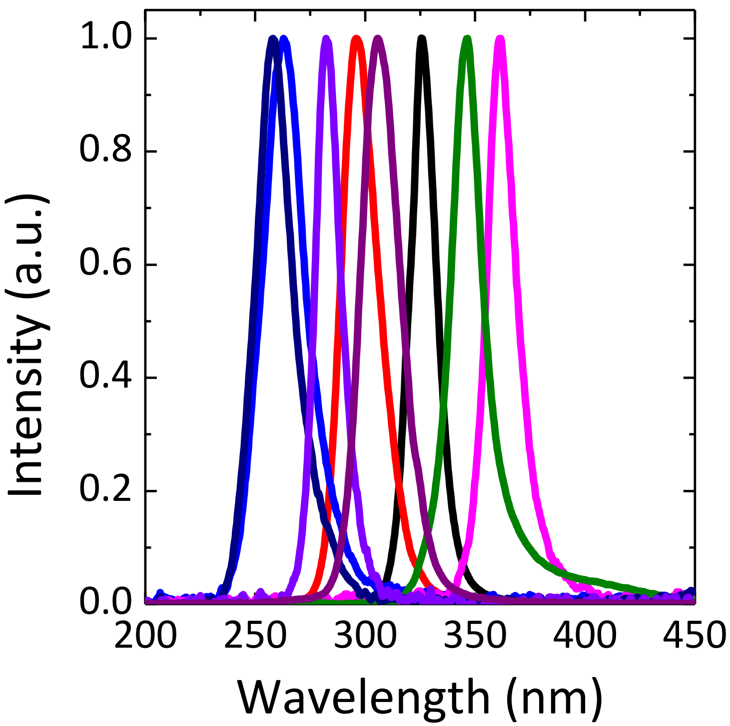
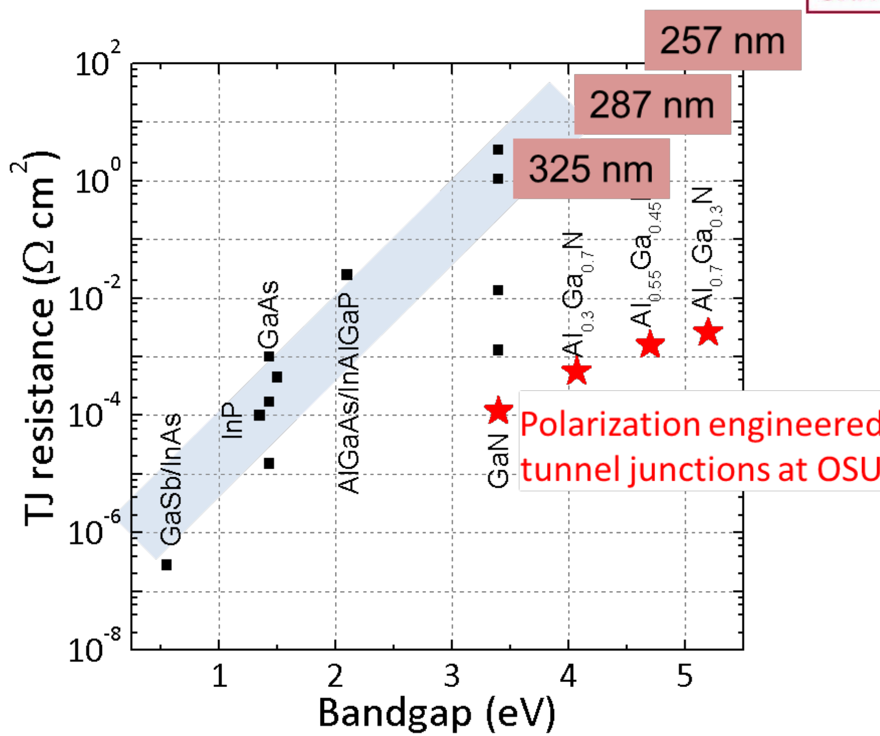
Overview of the tunnel junction technology





GaN TJs:

UCSB, JT Leonard, APL **107** (9), 091105 (2015)
Meijo/ Nagoya, M Kaga, JJAP **52** (8S), 08JH06 (2013)
EPFL, M Malinverni, APL 107, 051107, (2015).
OSU, S. Krishnamoorthy, *Nano Lett.*, *13*, 2570 (2013)
OSU, S. Krishnamoorthy, APL 102, 113503 (2013)
OSU, F. Akyol, APL 108 (13), 131103 (2016).

UV TJs

Y. Zhang, APL, 106 (14), 141103 (2015).
Y. Zhang, APEX 9 (5), 052102 (2016).
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Y. Zhang, APL 109 (19), 191105 (2016).
Y. Zhang, APL 110 (20), 201102 (2017).
S. M. Sadaf, Nano Lett., 17 (2), 1212 (2017).

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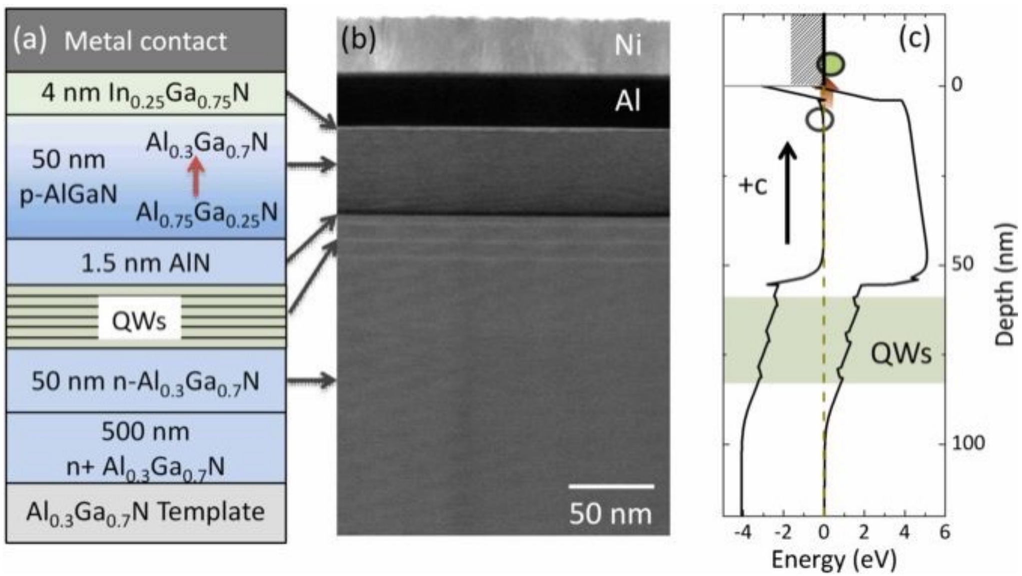
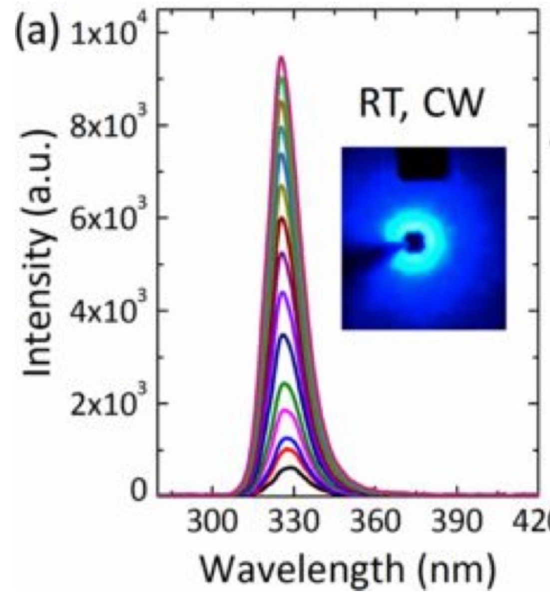
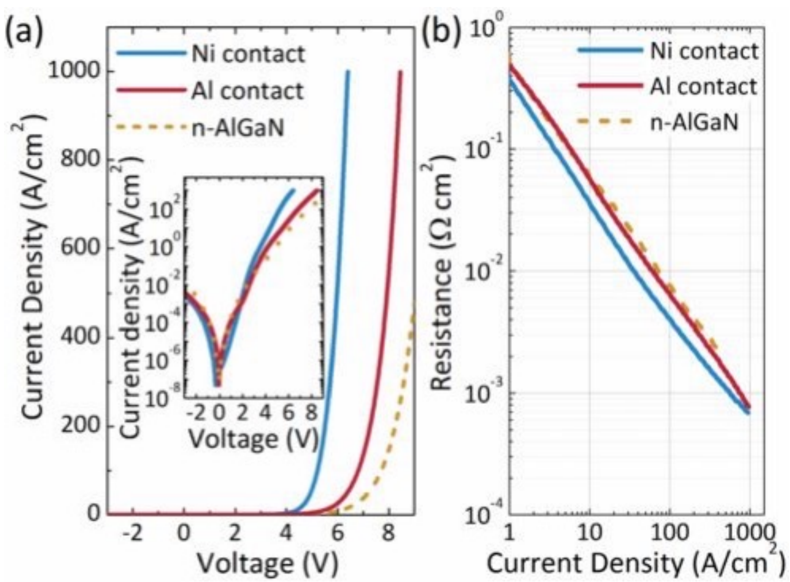
Reflective Metal Tunneling UV LEDs







Metal based tunnel junctions

- Al provides reflective contact
- Low resistance (better than AlGaN TJs)
- Reflective contact *reduces field* intensity near the tunnel junction

Could enable new device topology with reflective Al contacts

APL 110 (20), 201102 (2017).

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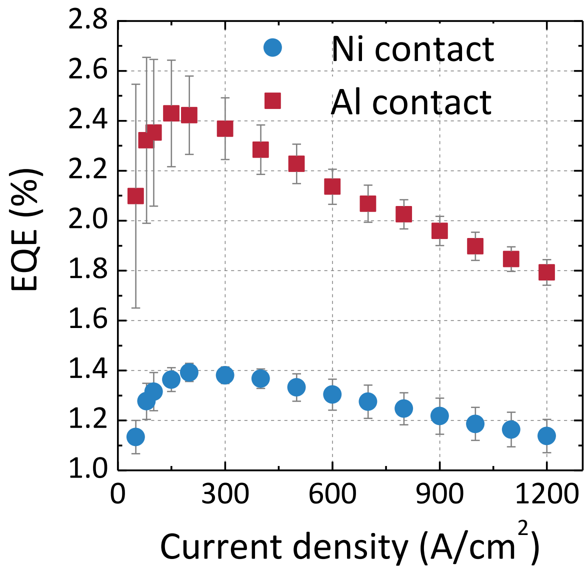
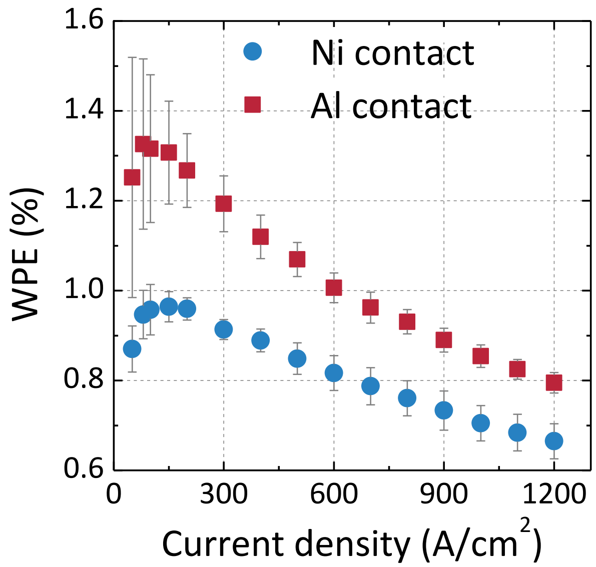
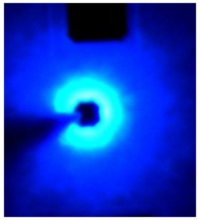
Electroluminescence results



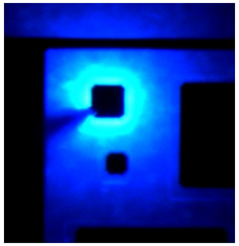


First demonstration of Al/InGaN/AlGaN tunnel junction

- Devices with Al contact showed 75% increase in EQE, and 39% increase in WPE
  – higher reflectivity
- EQE of 2.43%, WPE of 1.33% obtained
- The samples with Al contact showed higher droop, possibly due to higher operation voltage



10x10 um^2



20x20 um^2

Zhang et al, APL 111, 051104 (2017)

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Outline

- Motivation for Tunneling-based III-Nitride LEDs
- Tunneling Injected UV LEDs
- **Tunneling-based Visible LEDs**

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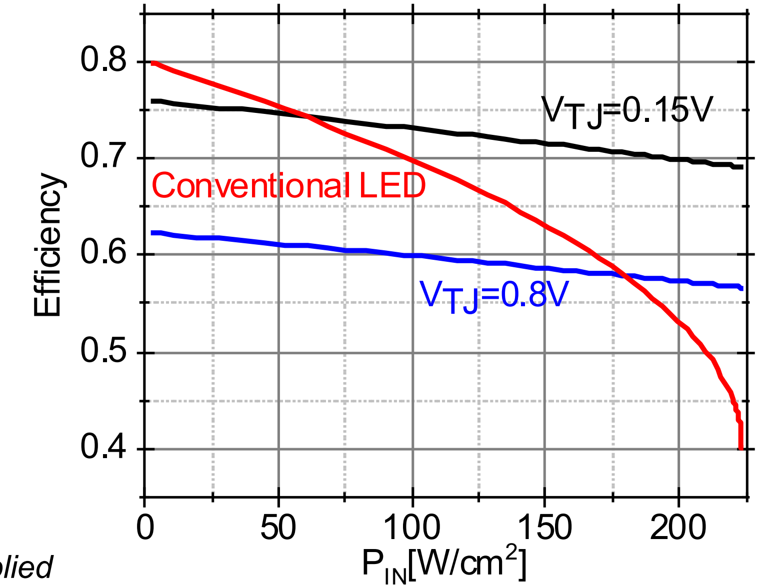
Tunnel Junctions for Cascaded LEDs

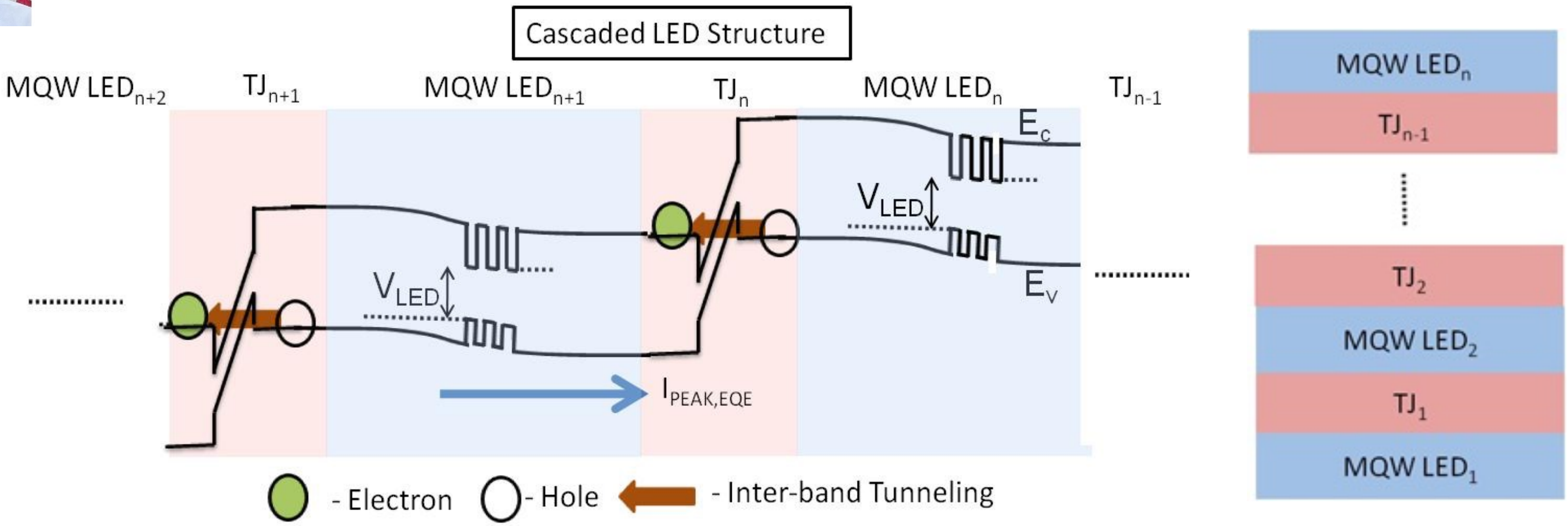
Efficient design of cascaded LEDs

- High output power operation where efficiency droop is significant
- Excess forward voltage due to tunnel junction must be minimized



Fatih Akyol
Now at Yildiz Univ.

Akyol, F., Krishnamoorthy, S. and Rajan, S., 2013,. *Applied Physics Letters*, *103*(8), p.081107.



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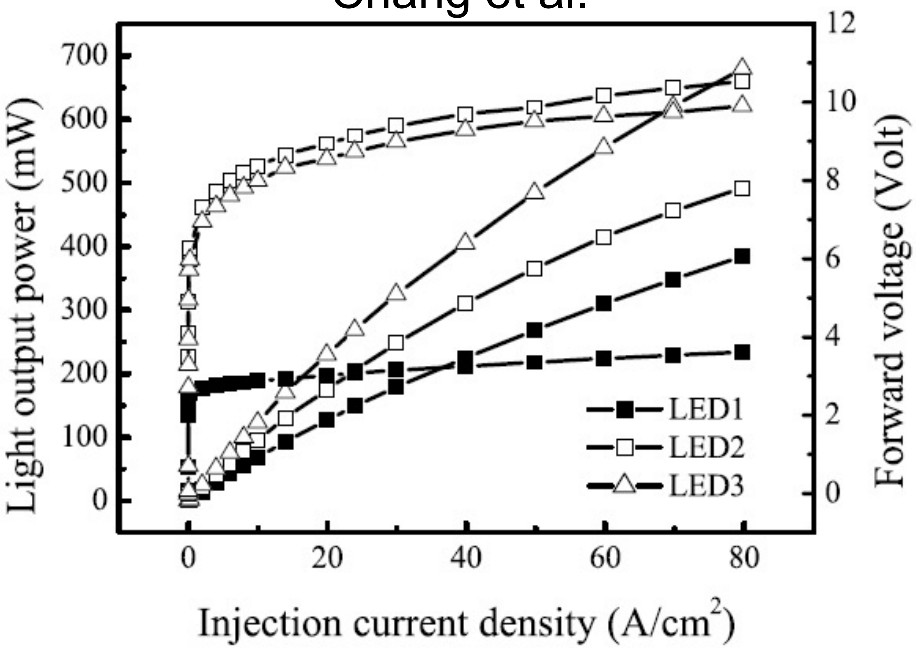
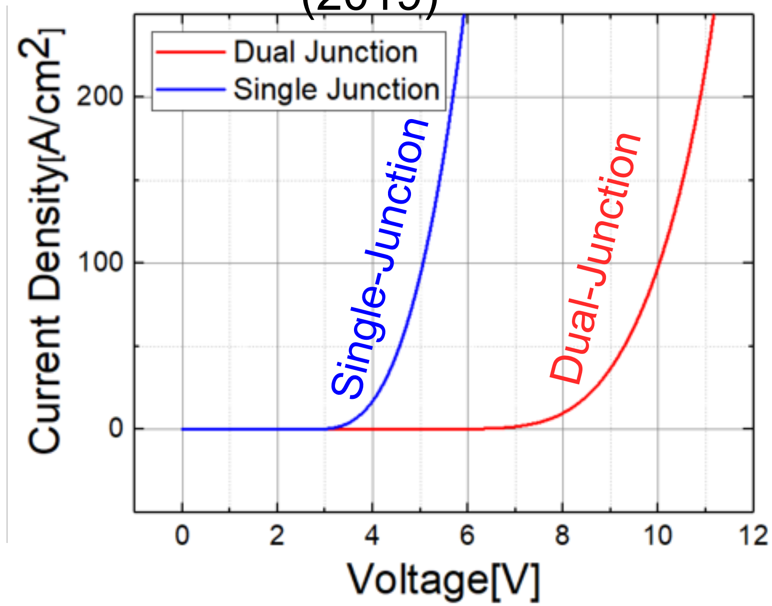
Previous MOCVD Grown Cascaded LEDs

Chang et al.



OSU/Sandia (2019)



Previous demonstration of MOCVD grown cascaded dual-junction LEDs

- High forward voltage was observed due to large excess voltage penalty associated with tunnel junctions
- Large forward voltage prevents WPE improvement
- Excess forward voltage due to tunnel junction must be minimized

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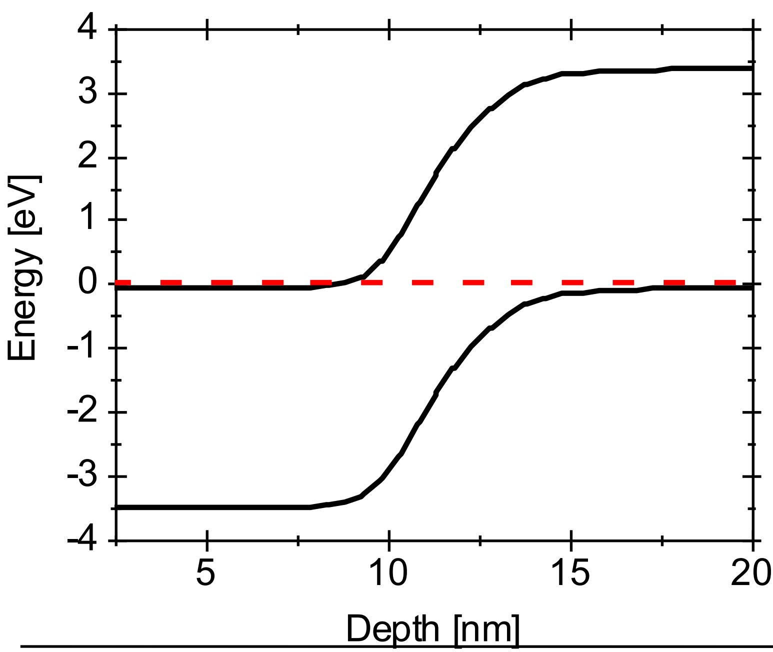
MOCVD-Based Tunnel Junction Structures

Zane J-Eddine
Now at Lumileds

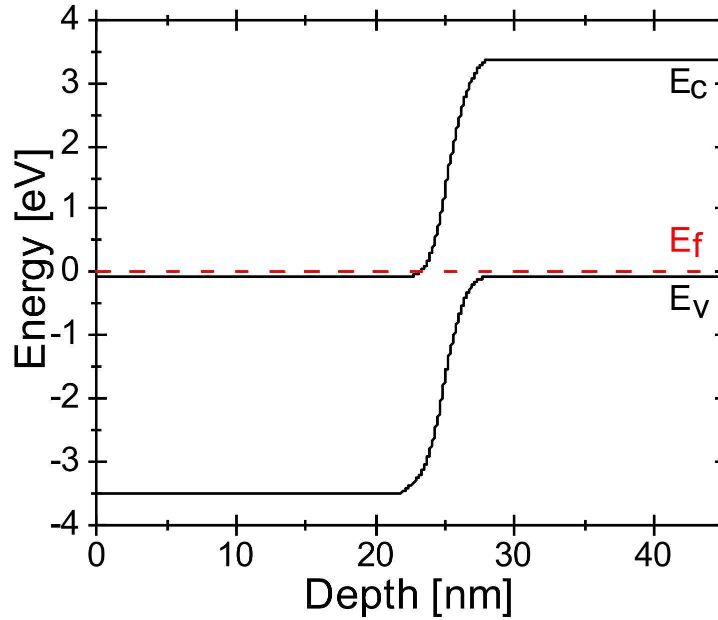
GaN Homojunction

n++GaN [Si]=2.8e20
p++GaN [Mg]=1.2e20



Graded InGaN Tunnel Junction

n++GaN [Si]=2.8e20	
p++$In_{0.07}Ga_{0.93}N$→GaN [Si]=2.8e20	t_{grade}
p++GaN→$In_{0.07}Ga_{0.93}N$ [Mg]=1.8e20	t_{grade}
p++GaN [Mg]=1.2e20	



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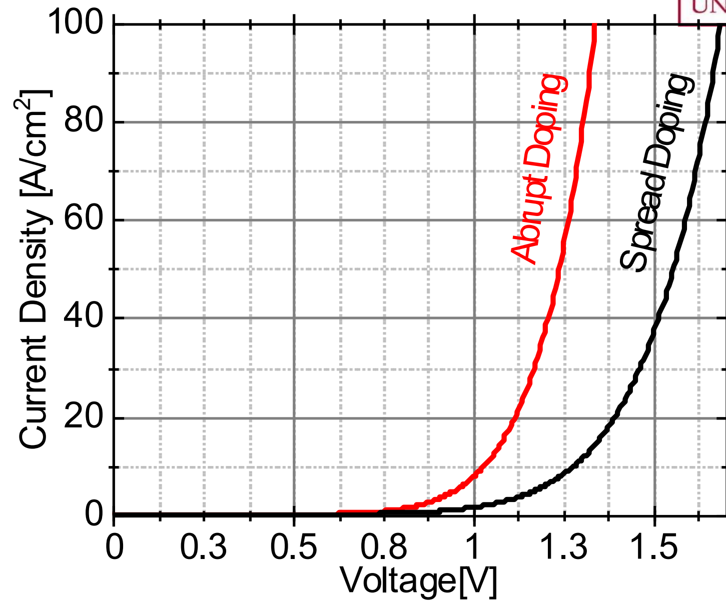
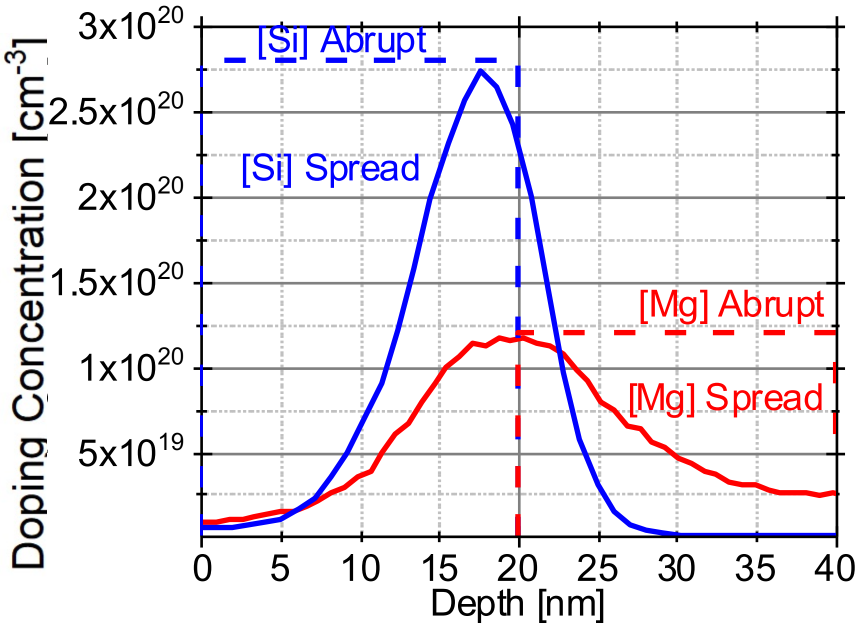
Simulation of TJ: Non-Ideal MOCVD Doping Profiles

- Non-ideal doping profiles due to memory effect
- Non-local tunneling effects
- Activation energy of Mg dopants
- Bandgap narrowing/band-tail effects





- Mg memory effect - Mg tail from p-side of the tunnel junction into n-side
- Non-abrupt profiles were measured directly using SIMS measurements on test epitaxial structures
- Significant increase in V_{TJ} as compared to the ideal (abrupt) doping profiles

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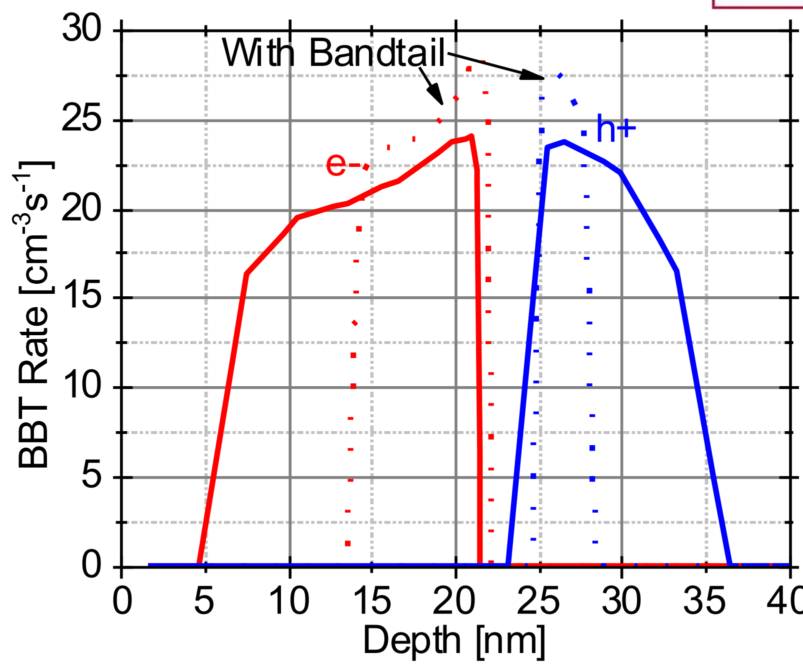
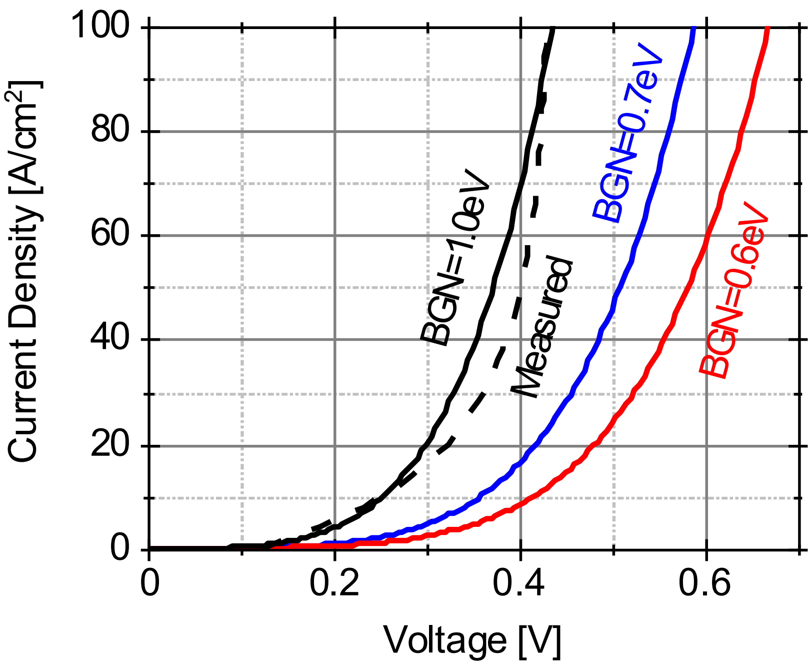
Band Tailing Effects in p++(In)GaN

- Non-ideal doping profiles due to memory effect
- Non-local tunneling effects
- Activation energy of Mg dopants
- Bandgap narrowing/band-tail effects





- Band tailing effects simulated by lowering the Mg acceptor energy (E_A) and bandgap narrowing in the p++ layers (Kane Model)
- Band-to-Band Tunneling (BBT) rates increase as band tail effects are included in the simulation

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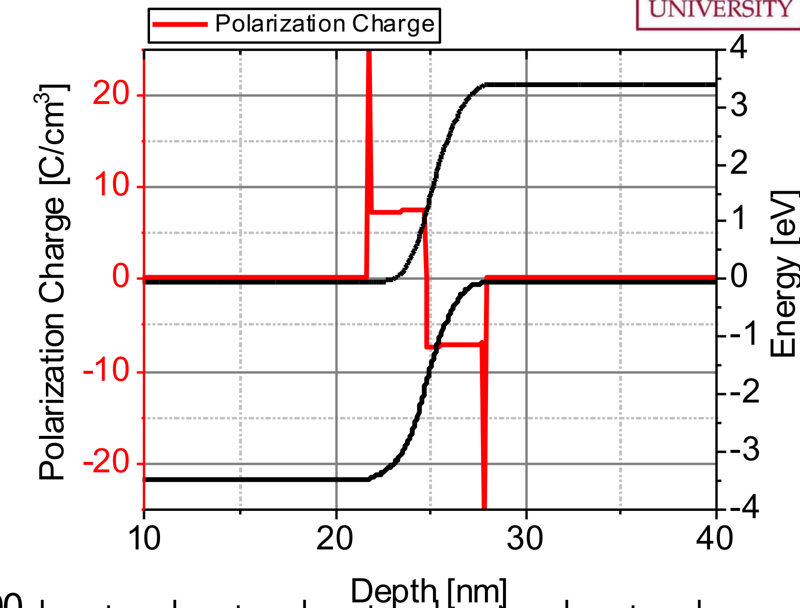
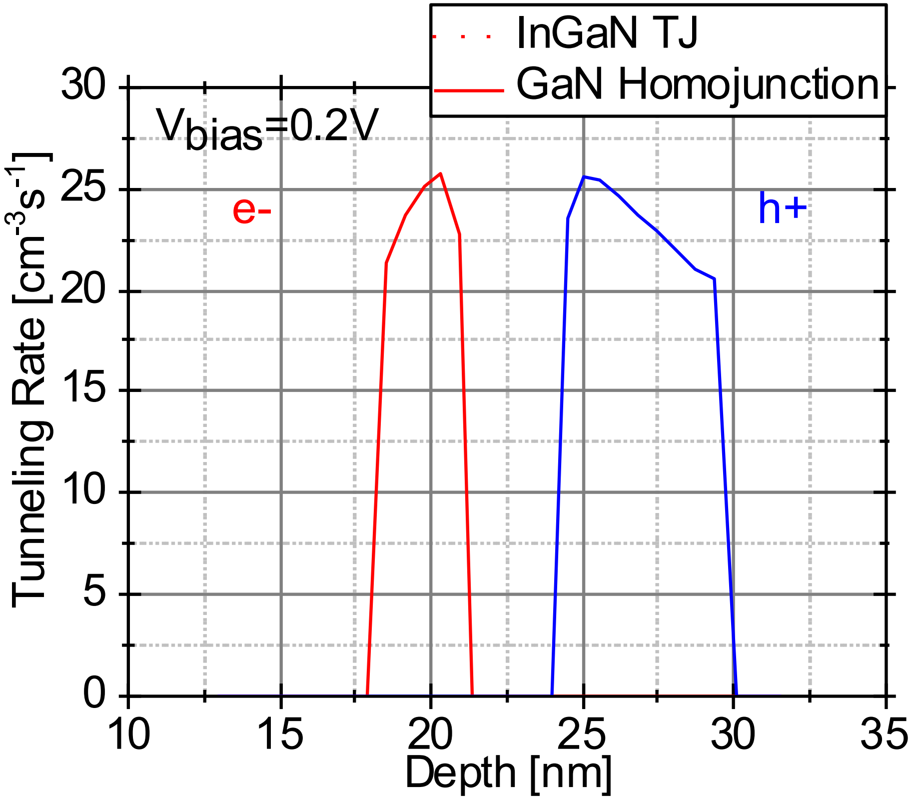
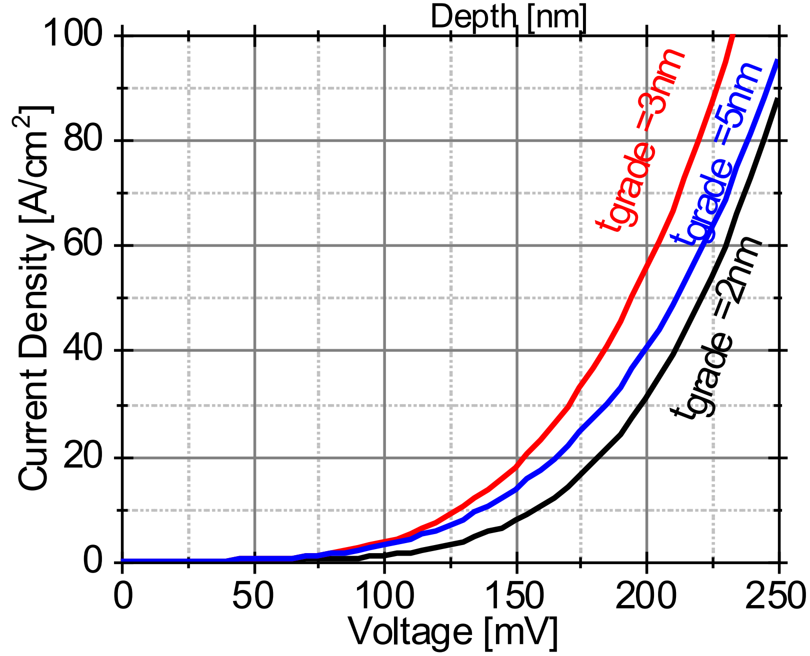
Benefit of Graded InGaN Tunnel Junctions

- Electrostatic ionization of graded InGaN leads to higher fields for tunneling
- Polarization charge + increased Mg doping efficiency in the InGaN leads to higher band-to-band tunneling rates







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Experimental Tunnel Junction Structures

Zane J-Eddine
Now at Lumileds

Brendan Gunning
Sandia

Reference pn-diode

Reference pn-diode
90nm p+GaN [Mg]=3e19
200nm n-GaN [Si]=2e16
500nm n-GaN [Si]=5e18
6µm n-GaN (Template)

GaN Homojunction

GaN Homojunction
450nm n-GaN [Si]=5e18
6nm n++GaN [Si]=2.8e20
12nm p++GaN [Mg]=1.2e20
90nm p+GaN [Mg]=3e19
200nm n-GaN [Si]=2e16
500nm n-GaN [Si]=5e18
6µm n-GaN (Template)

InGaN Heterojunction

InGaN Heterojunction
250nm n-GaN [Si]=5e18
6nm n++GaN [Si]=2.8e20
6nm [Si]=2.8e20 p++$In_{0.07}Ga_{0.93}N \rightarrow GaN$
6nm [Mg]=1.8e20 p++$GaN \rightarrow In_{0.07}Ga_{0.94}N$
6nm p++GaN [Mg]=1.2e20
90nm p+GaN [Mg]=3e19
200nm n-GaN [Si]=2e16
500nm n-GaN [Si]=5e18
6µm n-GaN (Template)

Mg δ-dose (between the p++GaN and 90nm p+GaN layers in both tunnel junction structures)

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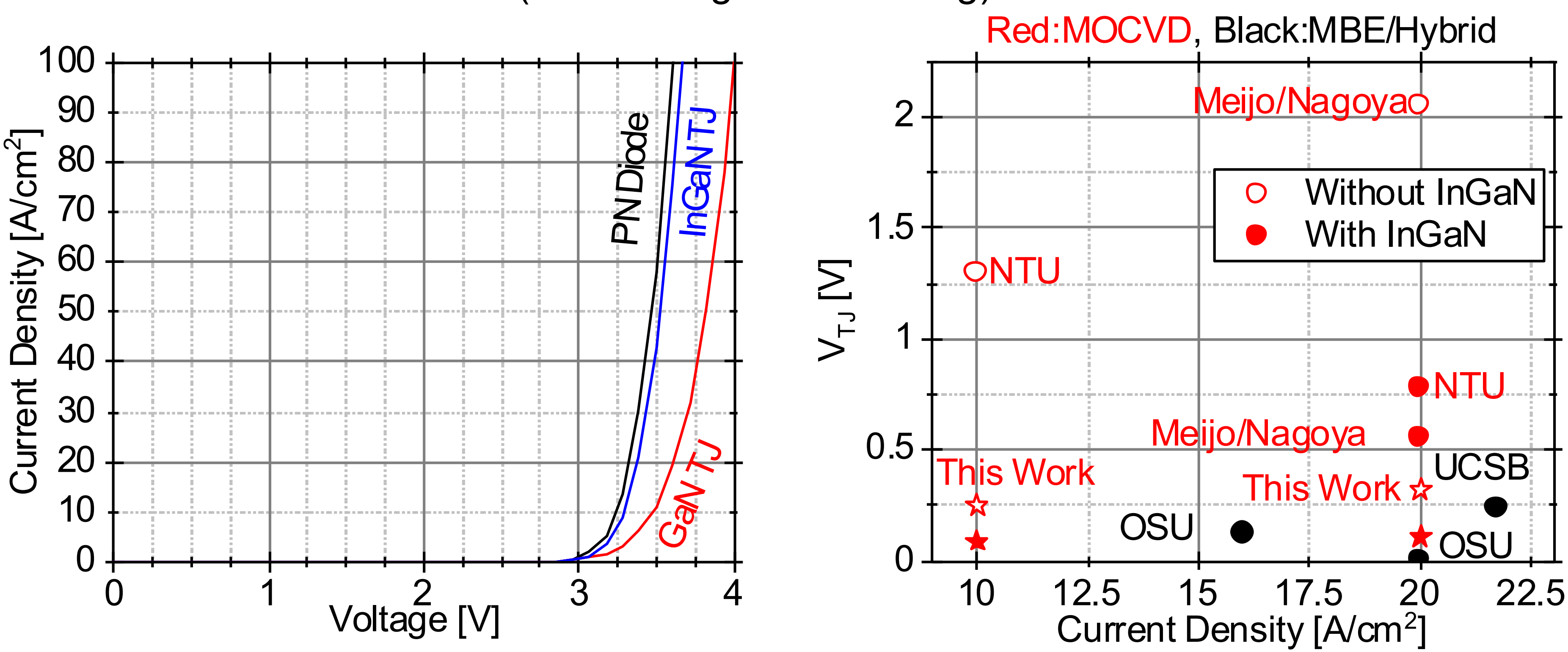
Experimental Results: Record Low MOCVD V_{TJ}

- 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 InGaN interlayer junction**
  - **0.45 V for GaN homojunction**

Collaboration with Sandia (B. Gunning/A. Armstrong)



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

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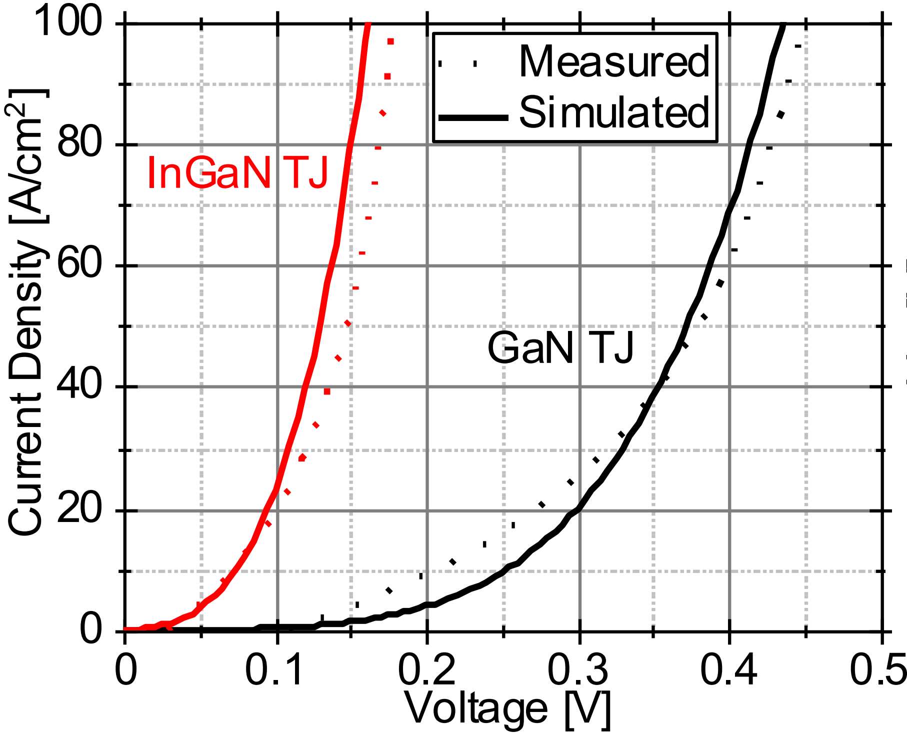
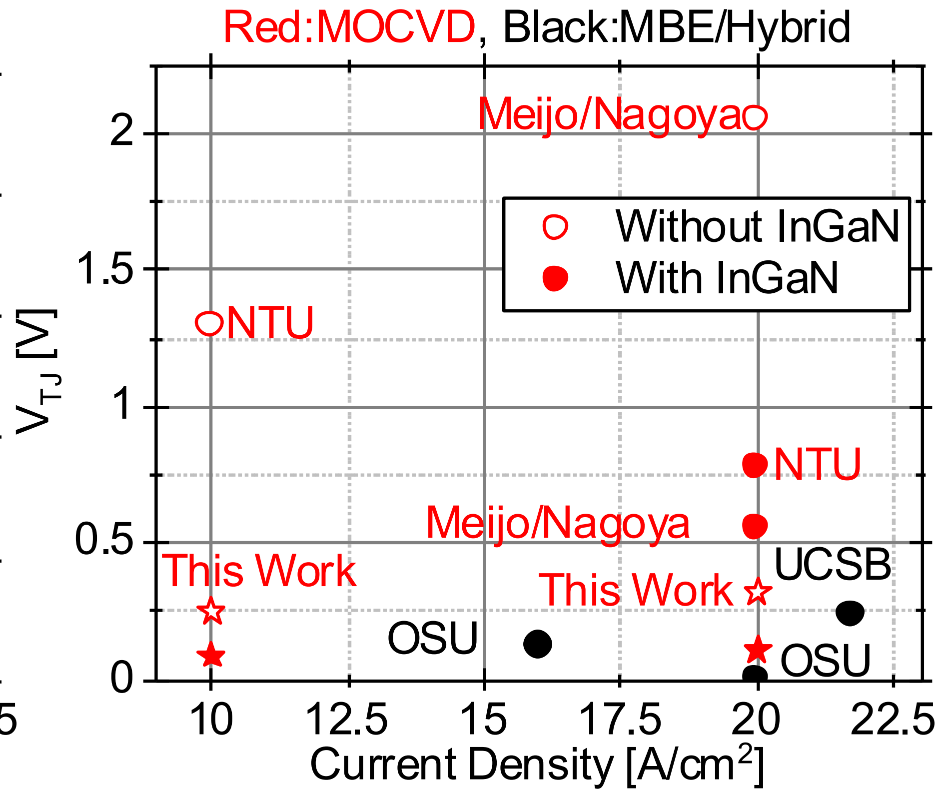
Simulation and Experiment: Comparison

- Low V_{TJ} @ 100A/cm^2 of **0.17V** (InGaN TJ) and **0.45V** (GaN TJ) was achieved experimentally – lowest reported values for all-MOCVD tunnel junctions
- Voltage losses are low enough to give significant benefits to current LED technology
- Excellent agreement between simulation and experiment





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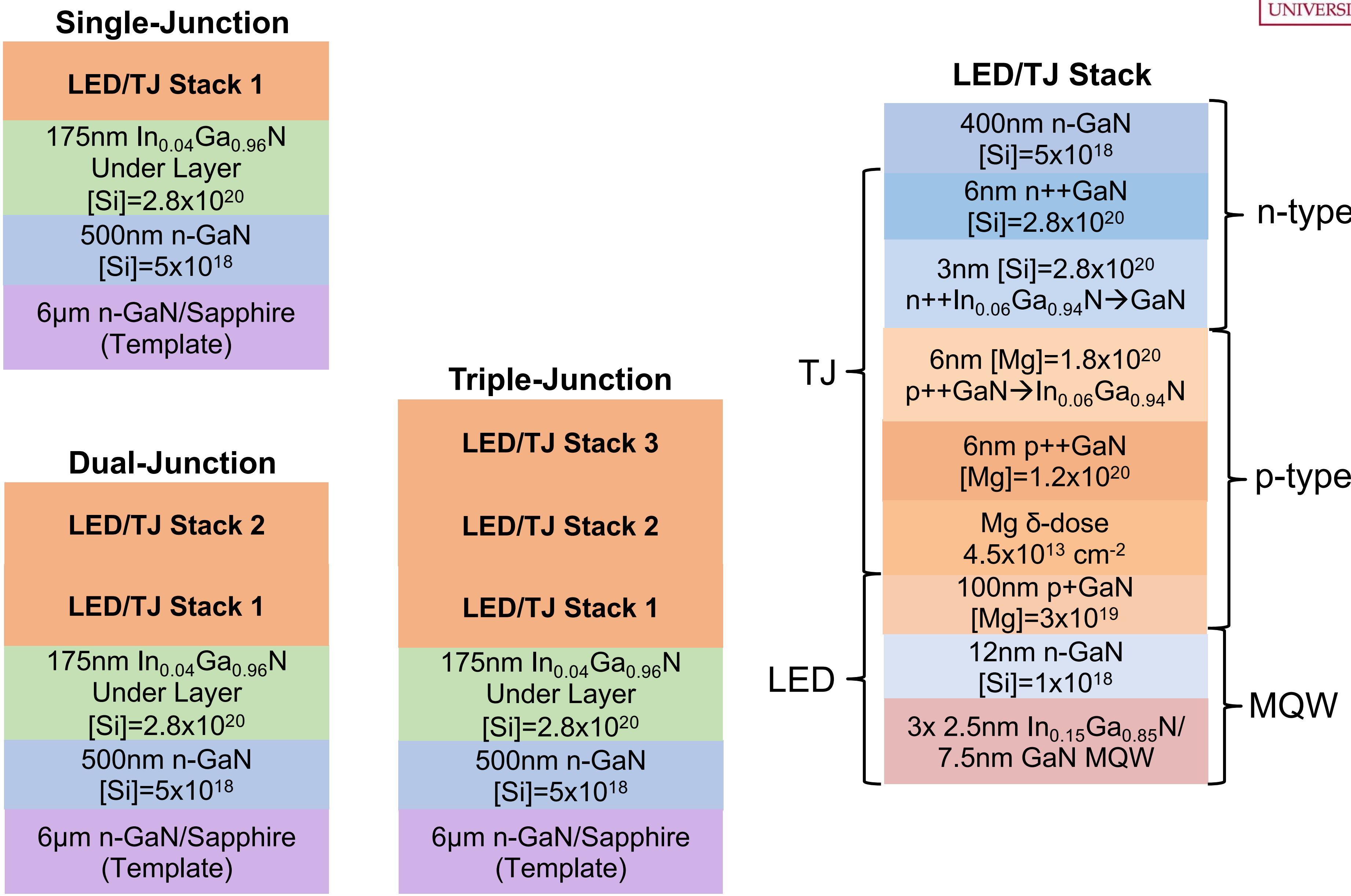
Multi-Junction LED Device Structures



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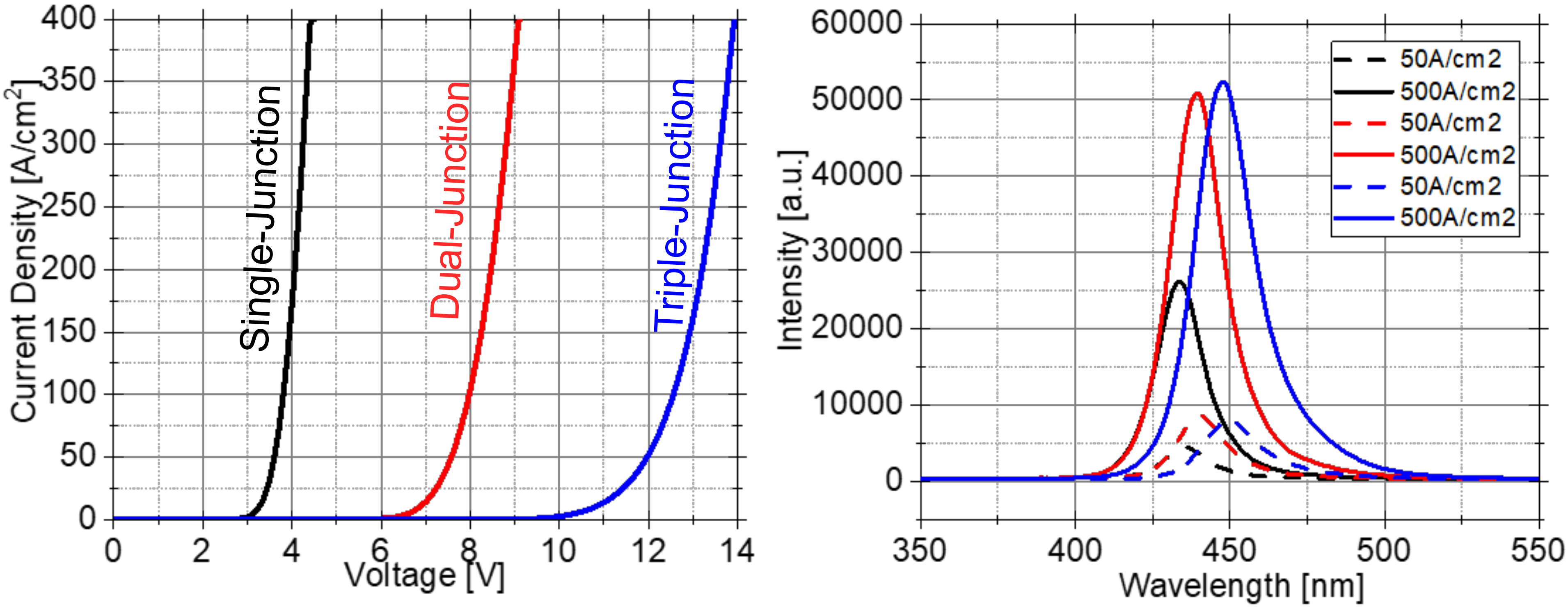
Experimental Results: Multi-Junction LEDs

- Excellent scaling of the forward turn-on voltage
- At 10 A/cm^2 the V_F for the 1/2/3 junction LEDs were 3.3 V/6.9 V/10.8 V
- The EL peak shifts by ~ 6 nm for each additional junction

Collaboration with Sandia (B. Gunning/A. Armstrong)



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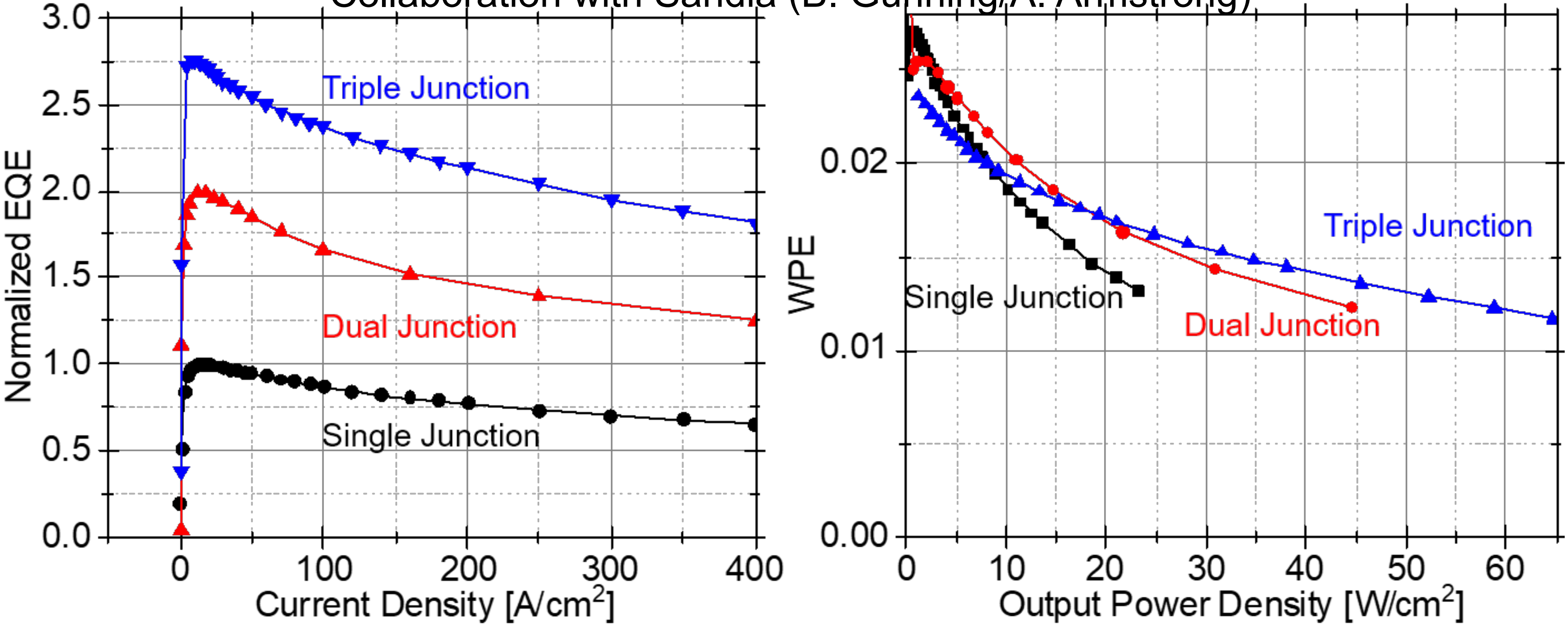
Experimental Results: Multi-Junction LEDs

- Peak EQE scaled 200% for the 2-junction device, and 275% for the 3-junction
- WPE for the dual junction device was found to be greater than in the single junction device above a power density of 5 W/cm^2
- WPE is greater in the triple junction device than in the dual or single junction

Collaboration with Sandia (B. Gunning/A. Armstrong)



Jamal-Eddine, Zane, et al. "Improved forward voltage and external quantum efficiency scaling in multi-active region III-nitride LEDs." *Applied Physics Express* 14.9 (2021): 092003.

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Experimental Results: Multi-Junction LEDs

- State-of-the-art tunnel junctions enable voltage scaling in MOCVD grown multi-junctions approaching that achieved by MBE grown multi-junctions
- First demonstration of EQE scaling of 200% in a 2-junction device
- First demonstration of WPE improvement in III-Nitride multi-junction LEDs

Number of Junctions	Voltage Scaling	EQE Scaling	Reference
2	**210%**	**200%**	**This Work (MOCVD)**
3	**330%**	**275%**	**This Work (MOCVD)**
2	270%	173%	Chang et al. (MOCVD)
2	306%	133%	Chang et al. (MOCVD)
3	312%	N/A	Akyol et al. (MBE)

Jamal-Eddine Z. et al. "Improved forward voltage and external quantum efficiency scaling in multi-active region III-nitride LEDs." *Applied Physics Express* (2021).

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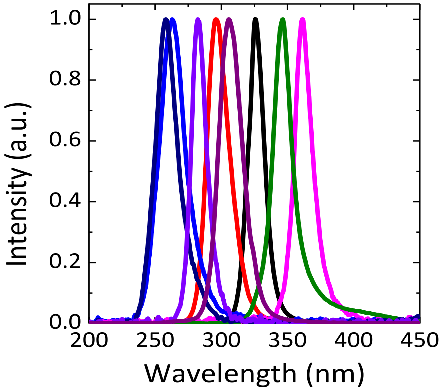
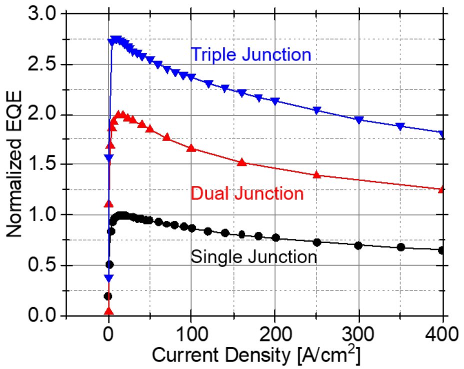
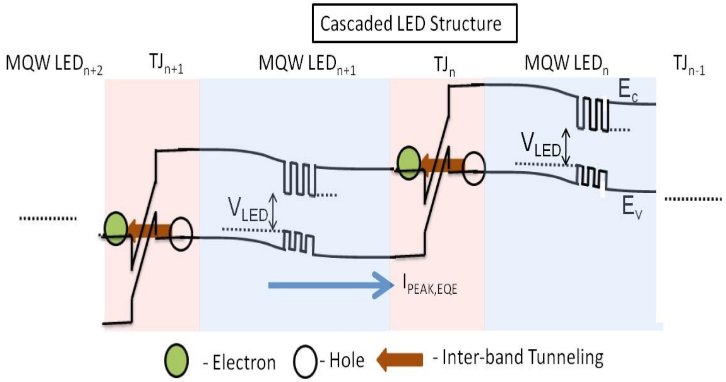
Summary

- Efficient tunnel junctions possible for high Al-content UV LEDs
- Accurate modeling of tunnel junctions using industry-standard Silvaco software
- Visible MOCVD-based LED tunnel junctions with voltage drop < 0.2 V demonstrated
- Near-ideal 3-junction MOCVD-based cascaded LEDs

Tunnel junction-based multi-junction LED devices are promising for next-generation high power LEDs







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