Fin LEDs for High-brightness UV Light Sources and High Temperature Applications

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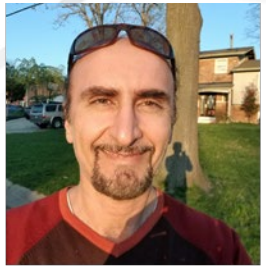

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2021 Joint CORM/CIE US & Canadian National
Committee Conference
11/17/2021

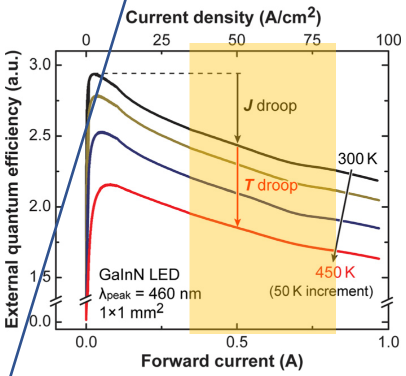
Applications of LEDs-Laser diodes & challenges in emerging technologies

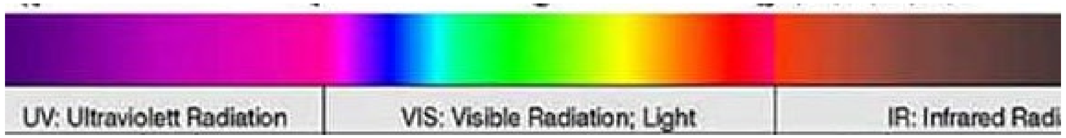
- Optical comm.

- Imaging

- Display

- General lighting





LEDs
LDs → Micro → Sub-micron

EQE >70%

EQE ~20%

EQE ~1%

Major issue: Decline in efficiency
- ○ Droop effect
- ○ LED size reduction

Sub-micron LED/lasers are in nanowatt range.

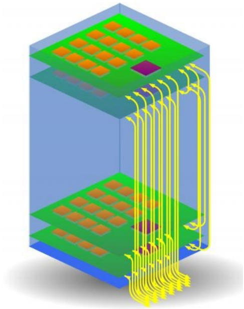
Hope is at micron and sub-micron:
Engineering of Bandgap, Shape, Size, Defects, etc.

Challenge at nanoscale: linking property and structure, which is key for identifying superior designs.

Emerging technologies

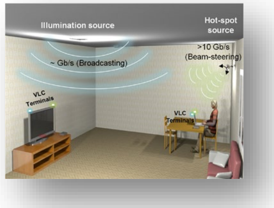
Microwatt range power

- ☐ Intra-chip optical interconnects



- ☐ On-chip Metrology (Optical frequency generators, etc.)
- ☐ Micro displays (augmented reality)

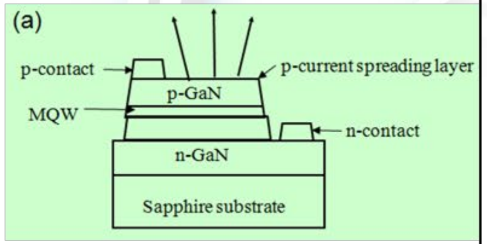
- ☐ Visible light communication

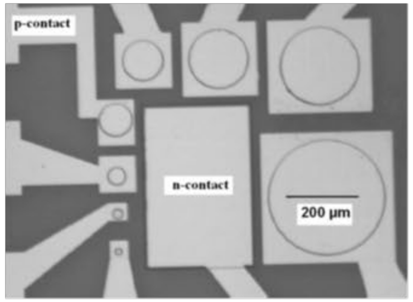


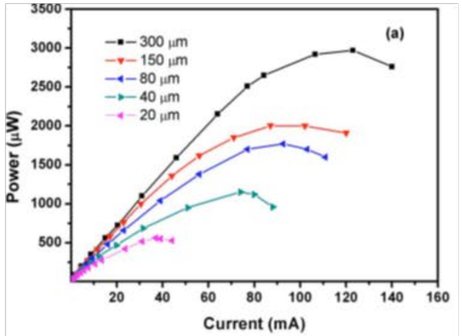
Ref.1) (Kartik Srinivasan grp, NIST) arXiv:2003.12177v1, March 26, 2020.

Persistence of the droop effect at micro- and sub-micron scale

❑ Micro-LEDs

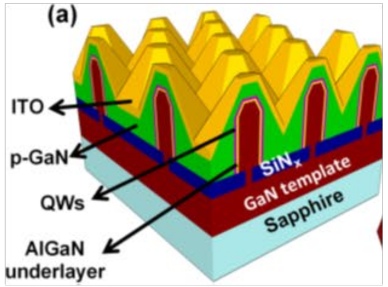


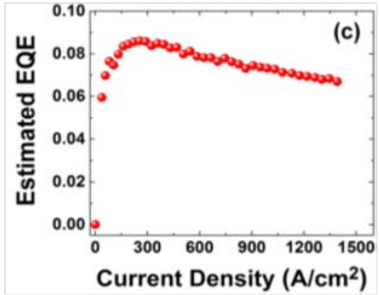




Z. Gong *et al.*, *J. Appl. Phys.* **107**, 013103 (2010)

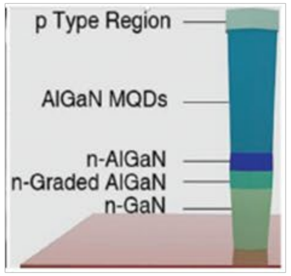
❑ NanoLED with all-fact metal contact

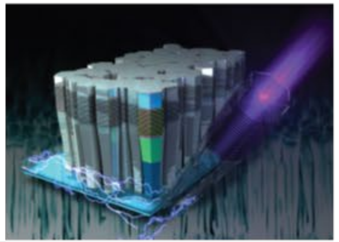


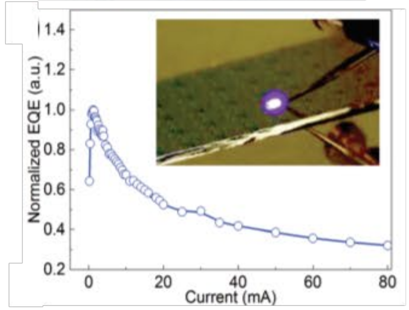


M. Nami *et al.*, *Scientific Reports* **8**, 501 (2018)

❑ NanoLED with end-fact metal contact

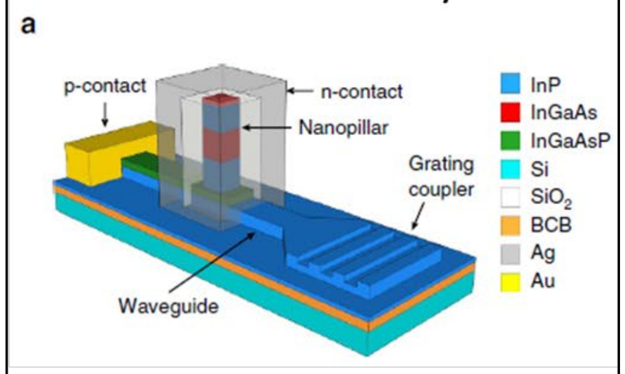


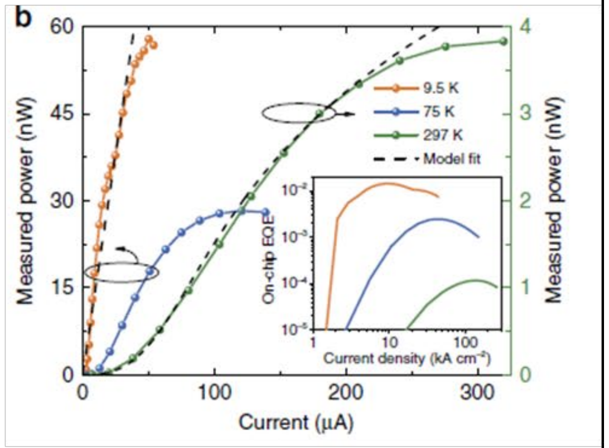




B. Janjua *et al.*, *Nanoscale* **9**, 7805-7813 (2017)

❑ NanoLED with metallic-coated cavity

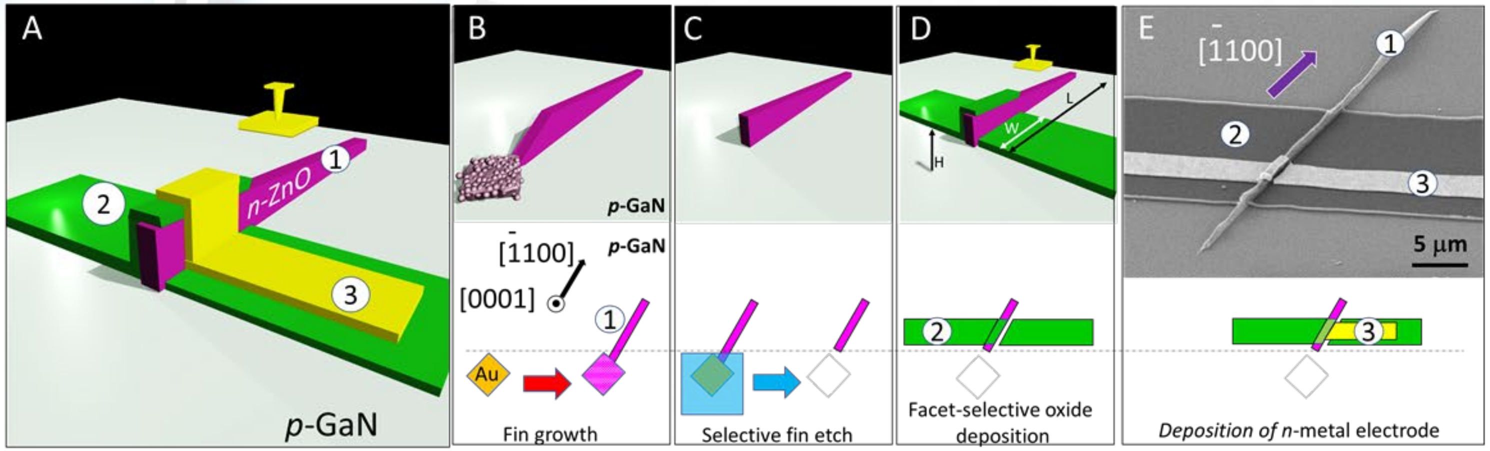


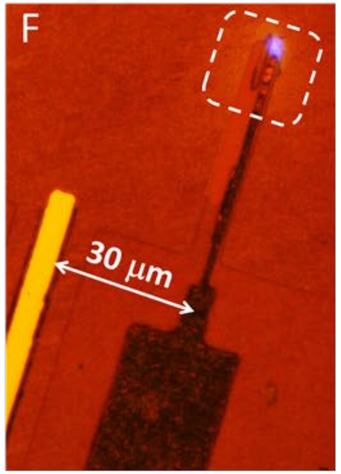


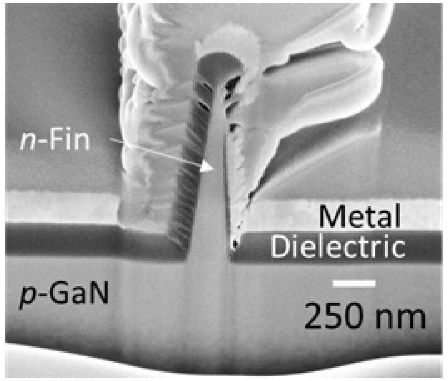
V. Dolores-Calzadilla *et al.*, *Nature Communications* **8**, 14323 (2017)

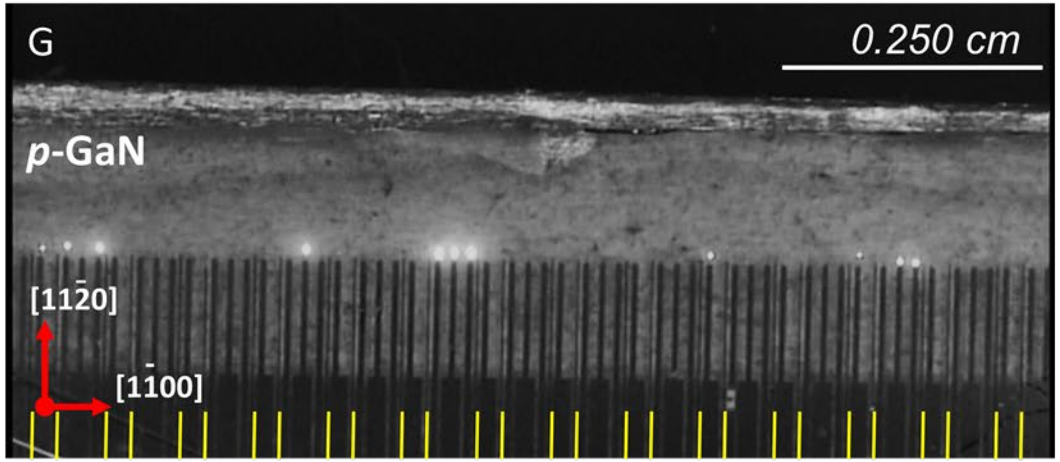
Overview of fabrication of fin LED pixels in an array format

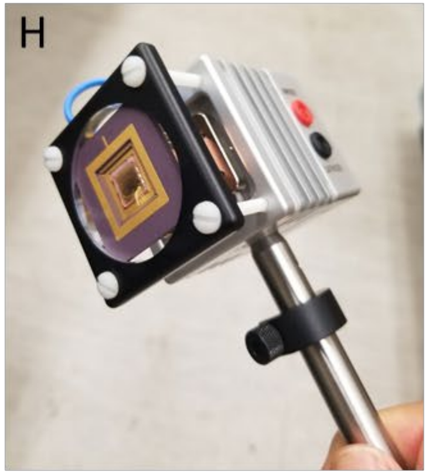
- **Facet-selective electron injection**





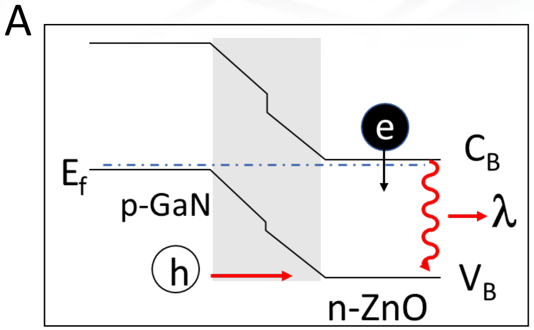


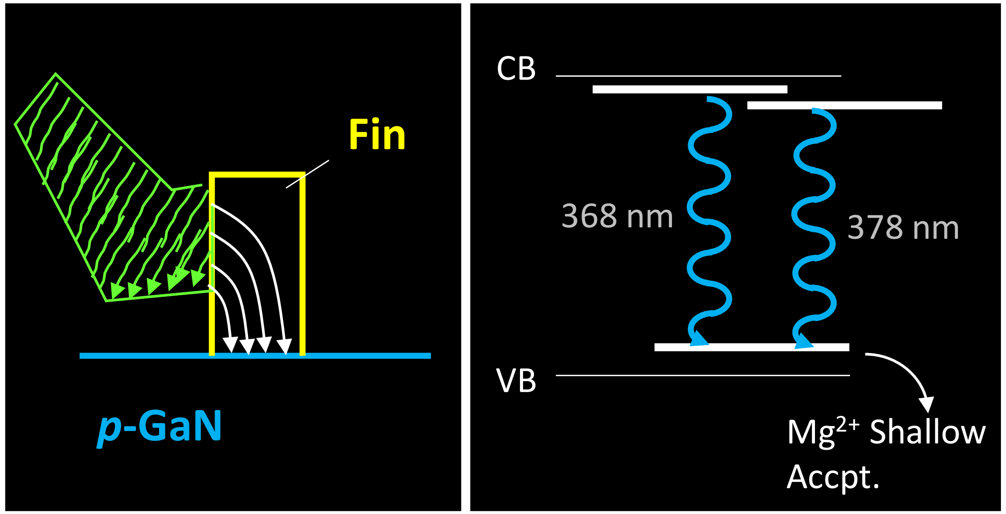


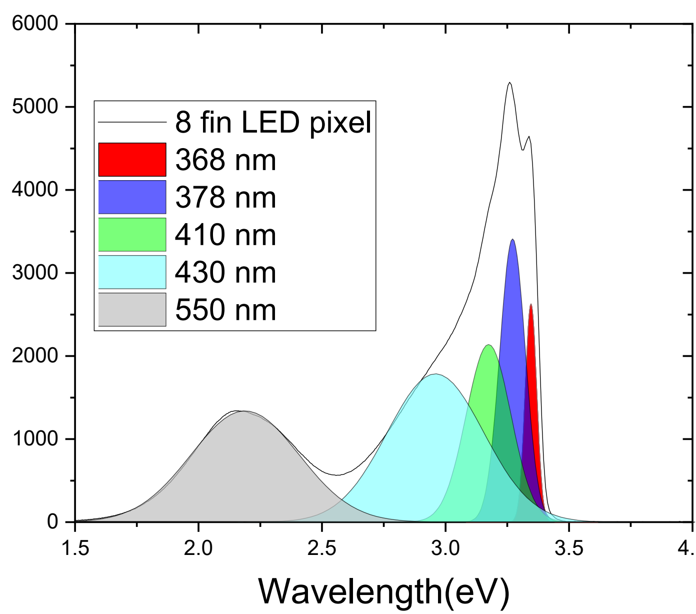


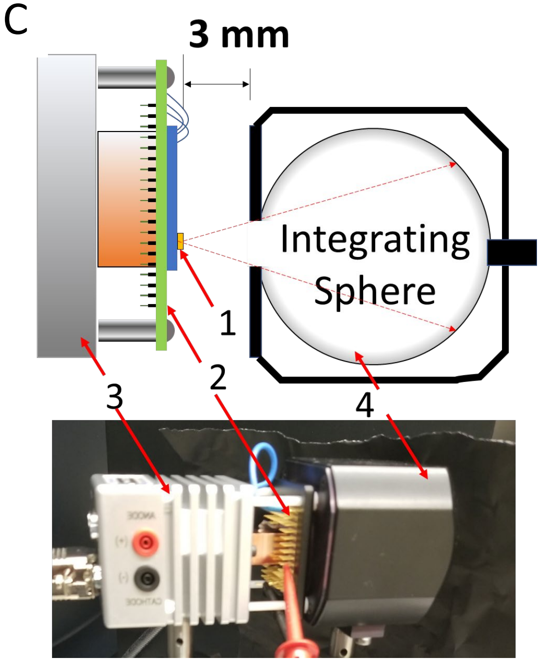
- *LED pixels contain different number of fins from 1 to 10 fins.*

Electroluminescence of fin LEDs







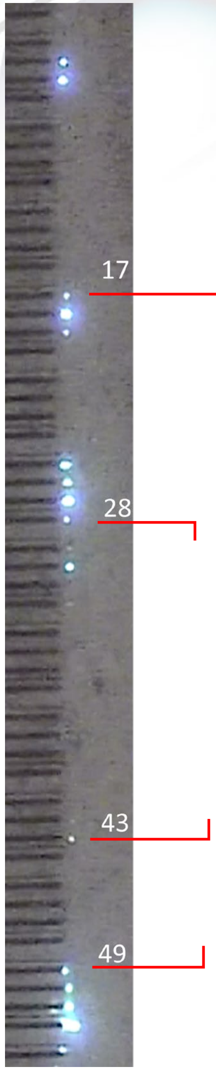


- ○ LED array in front of the integrating sphere

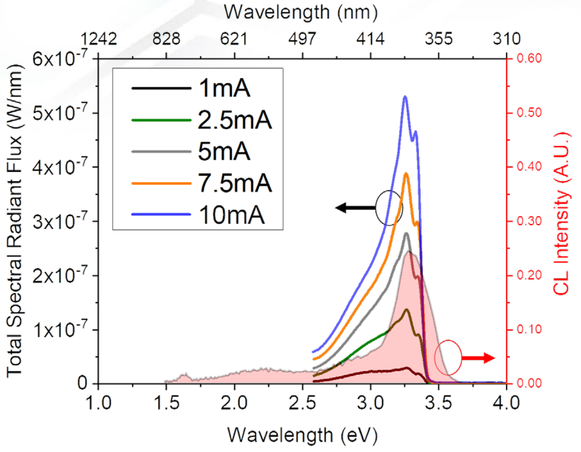
Results shows:

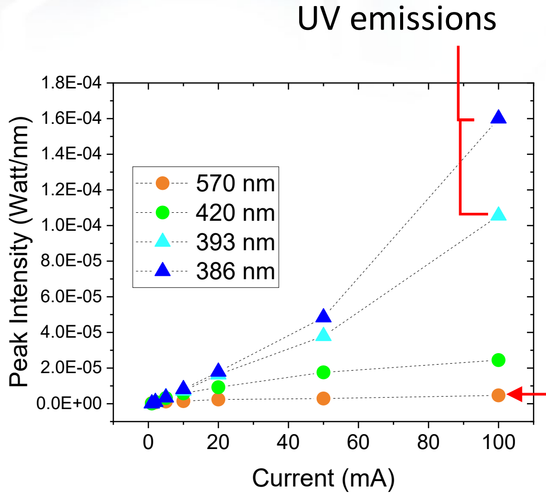
- Majority of e-h recombination occurs in the ZnO fin.
- There are two excitonic UV emissions at 368 nm and 378 nm.
- A shoulder emission exists due to e-h recombination in GaN.

How does EL change with increasing injected current?



☐LED pixel with 8 fins



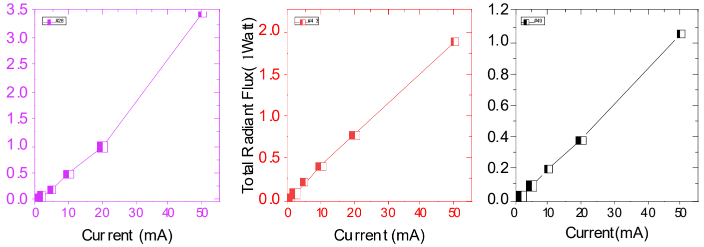


At high injection regime,

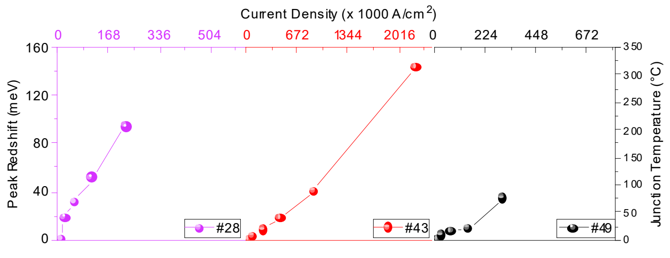
- *the photon generation occurs in the ZnO fin,*
- *the output power grows linearly with the injected current indicating carrier loss due Auger recombination is minimal.*

- *e-h recombination in p-GaN side @420 nm continues to be flat as more e-h pairs are injected.*

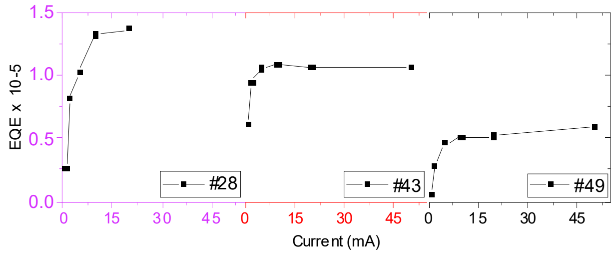
☐ Great performance beyond injected current of 20 mA



- ☐ 1 μWatt to 3 μWatts of power.
- ☐ Total radiant flux increases linearly with injected current density beyond 50 mA (500 kA/cm²)



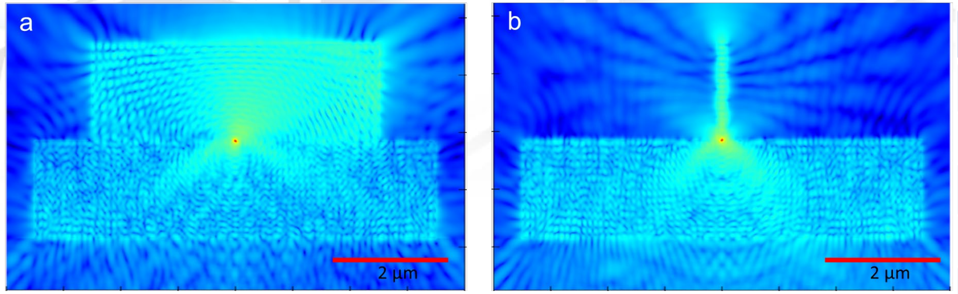
☐ Junction temperature (EL redshift) reaches 100 °C to 300 °C, beyond 500 kA/cm².



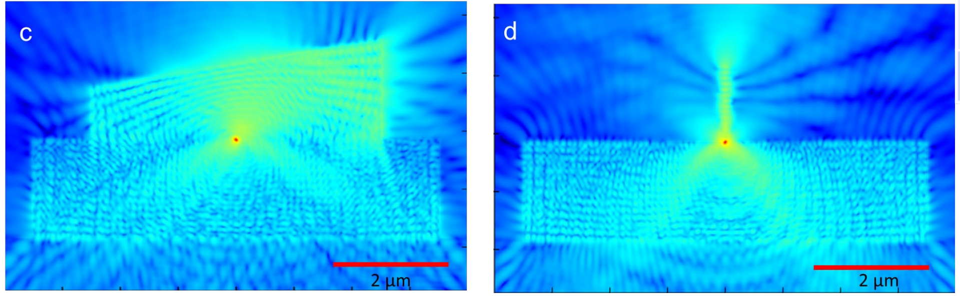
☐ The EQE does not show decline despite the high T and current density.

Light extraction in fin LEDs

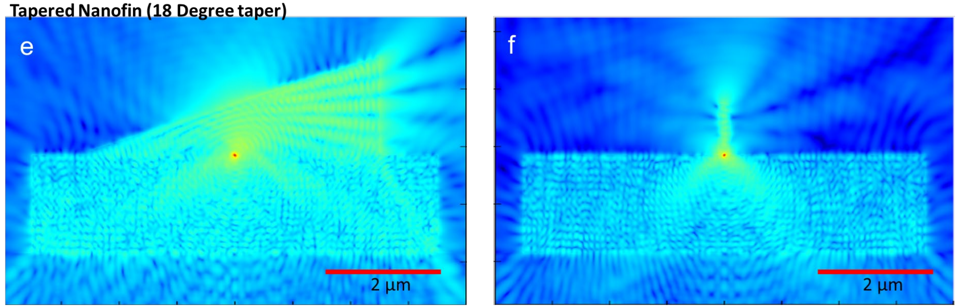
Rectangular Nanofin (No taper)



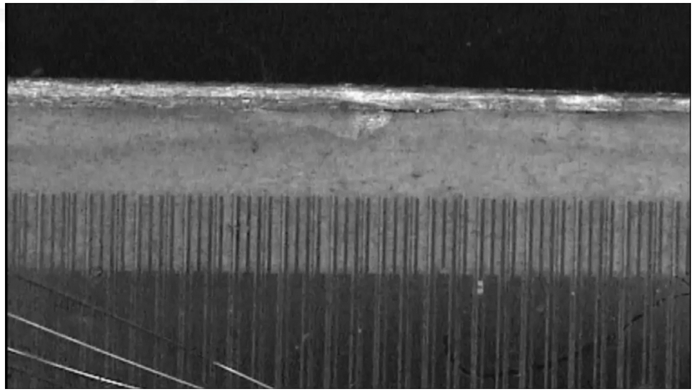
Tapered Nanofin (9 Degree taper)



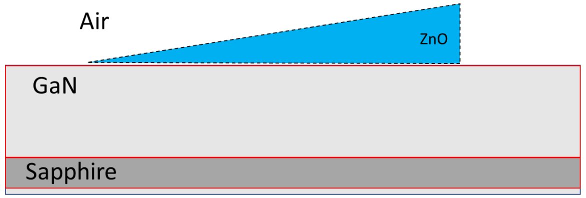
Tapered Nanofin (18 Degree taper)

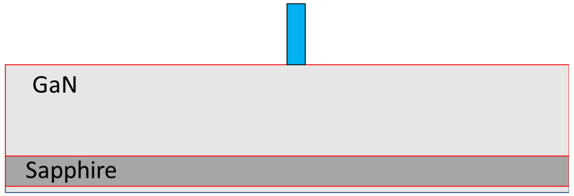


	0 degree	9 degree	18 degree
Front (tall side of the fin)	3.06	4.47	6.17
Back (short side of the fin)	3.06	1.98	1.62
Side (parallel to the fin)	1.33	1.46	1.50
Side (parallel to the fin)	1.33	1.46	1.50
Top (out of plane emission)	9.75	8.6	7.67
TOTAL	18.5%	18%	18.4%



Linear array of fin LED pixels (Field of view= 1 cm)



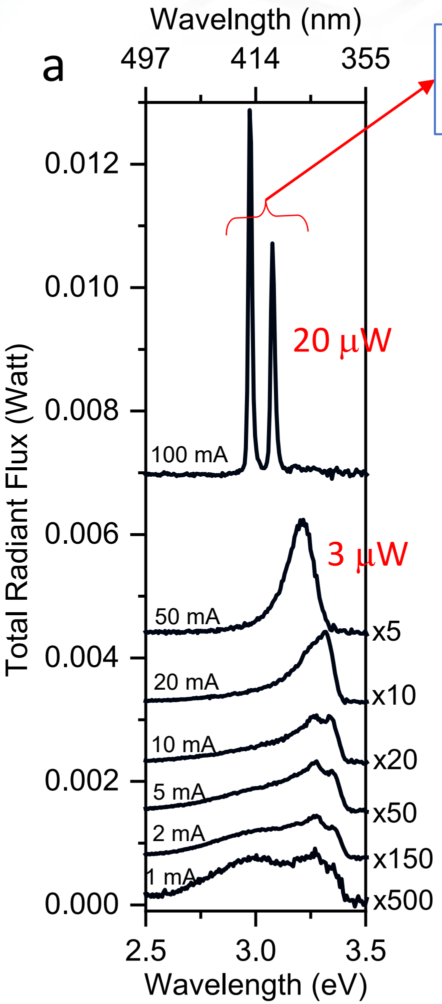


- ☐ Light extraction efficiency is about 18% for this geometry.
- ☐ Can be increased 5x by different surface treatment methods.

Realization of UV surface emitting lasers at microscale:

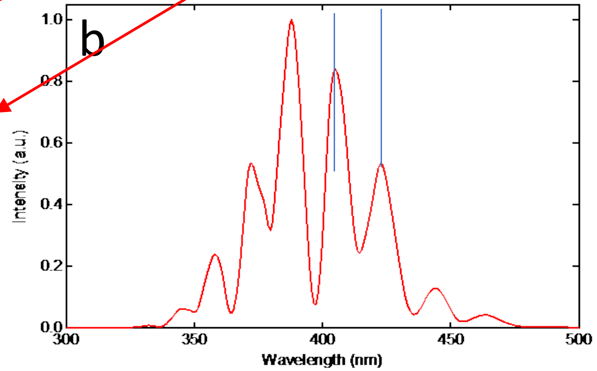
(The absence of droop allows observation of stimulated emission)

- ○ **ZnO fin on GaN as a Fabry–Pérot cavity**

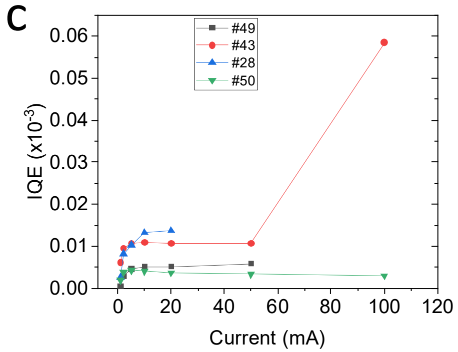


14 nm spacing

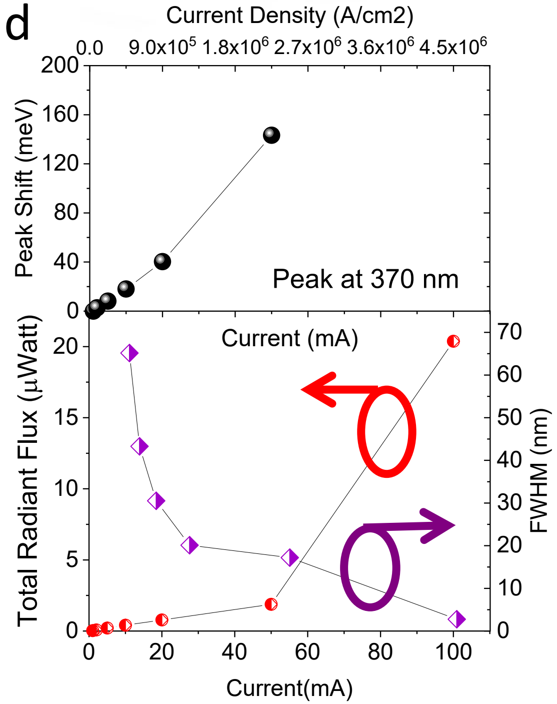
14 nm-16 nm



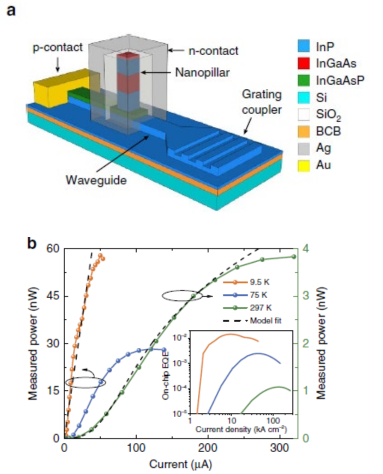
❑ Simulated passive cavity modes:
show a free-spectral range of 14 nm to 16 nm.



❑ Jump in IQE of fin LEDs to lasers



e ❑ Single NanoLED



○ 4 nW at EQE of 10^{-5}

V. Dolores-Calzadilla *et al.*, *Nature Communications* **8**, 14323 (2017)

○ Suppression of non-radiative Auger recombination in fins, allows stimulated emission and lasing, even when fins are very hot!

Why does a fin LED show a droop-free behavior?

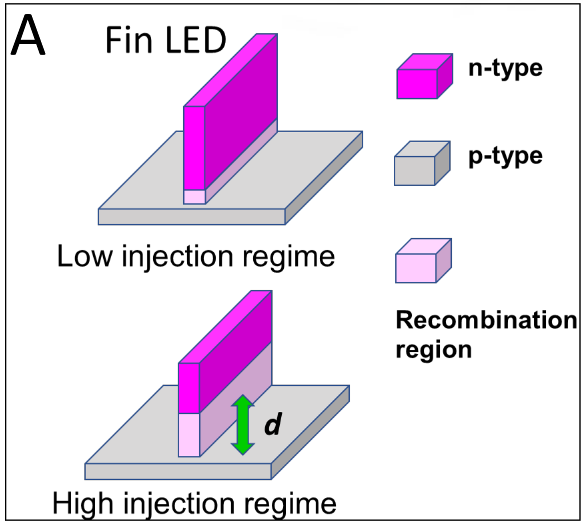
$$J = J_{SRH} + J_{Rad} + J_{Auger} \qquad \text{(eq. 1)}$$

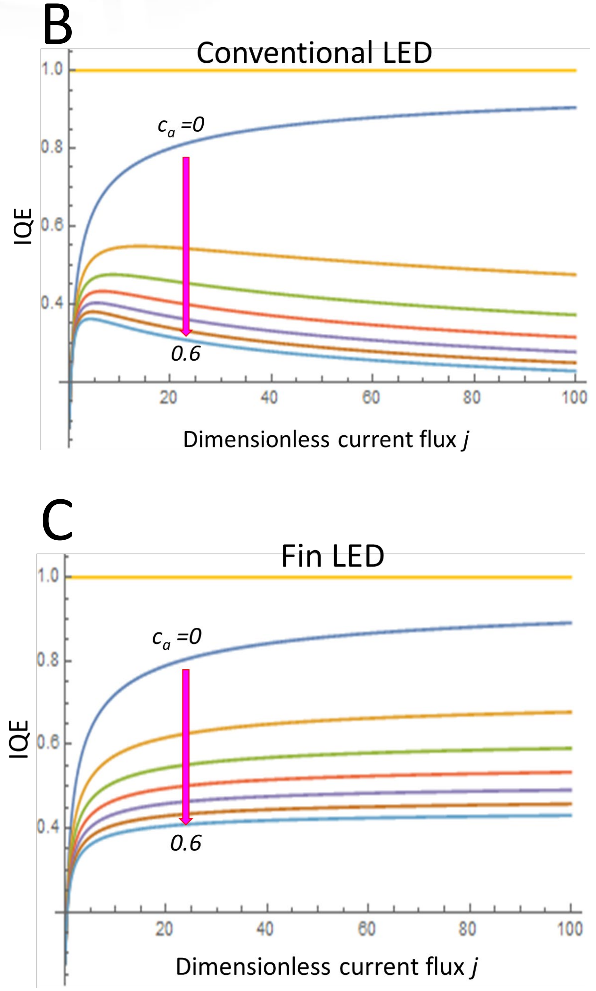
$$J = I/(qd) \qquad \text{(eq. 2)}$$

(*J*: current density flux gradient,
n: carrier density)

(*d* is the length of the recombination region)

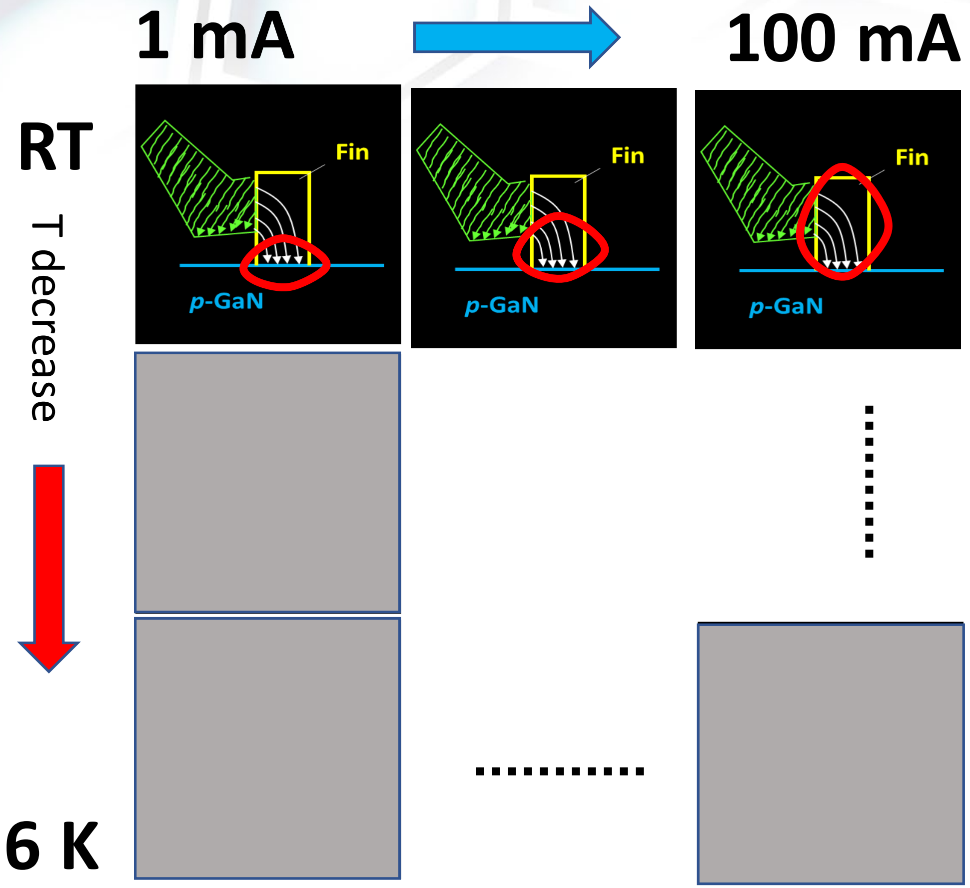
$$\eta_{high} = \frac{N_p}{1 + N_p + c_a N_p^2} = \frac{N_p}{c_a N_p^2} = \frac{N_p^2}{j} = \boxed{\frac{1}{c_a^{2/3} j^{1/3}}}$$

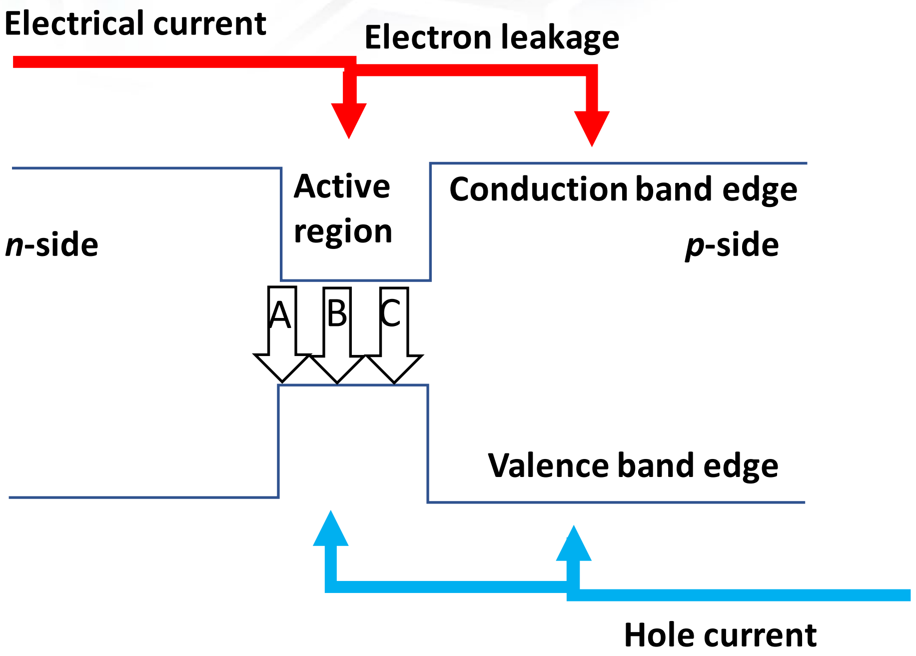


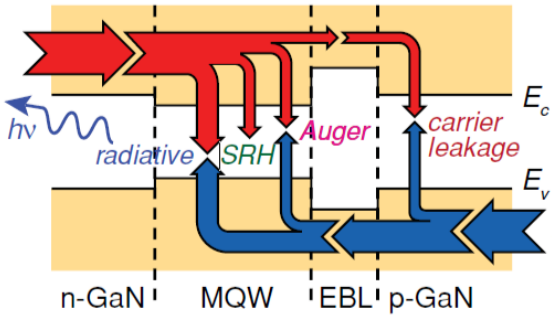


As injected current is raised:
- ○ In Fin LEDs, the recombination region (*d*) increases;
Auger recombination rate saturates.
- ○ In conventional LEDs, *d* stays constant; Auger recombination rate increases.

Fin shape is more effective in e-h collection at high injection levels



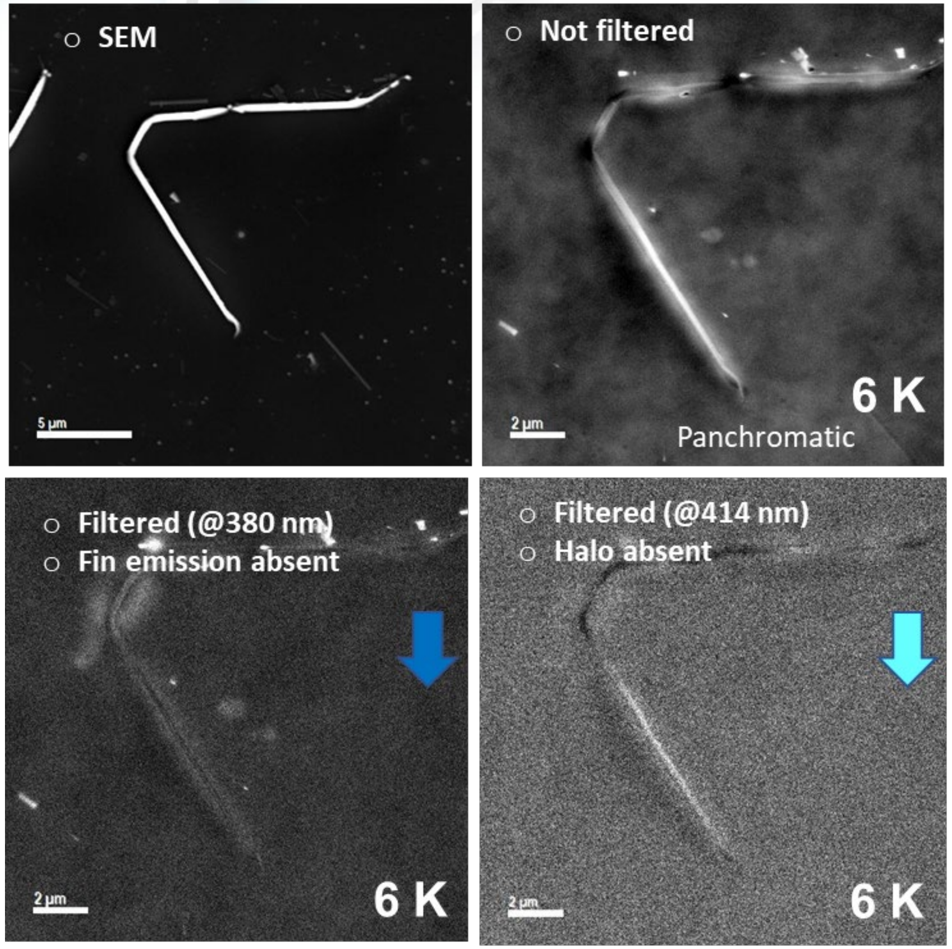


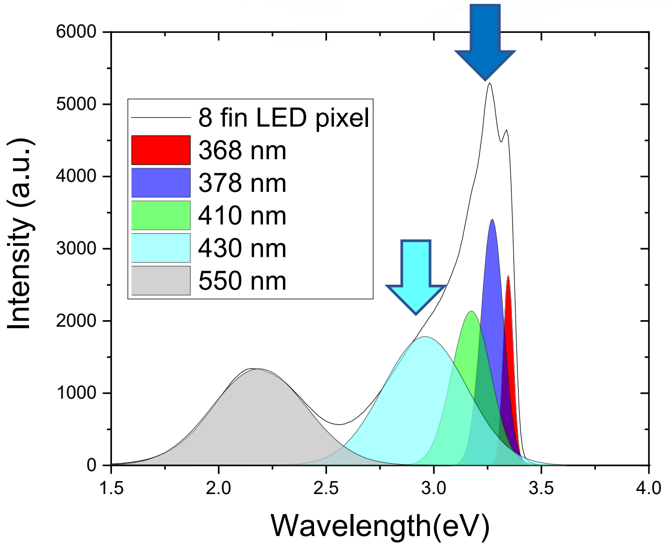


- In Fin LEDs, electron leakage to p-GaN is effectively suppressed.

As temperature declines e-h recombination shifts outside ZnO fin

(no electrical bias)

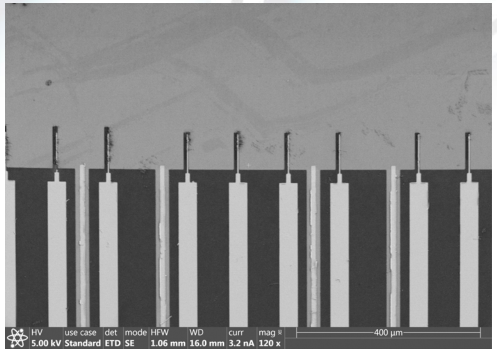


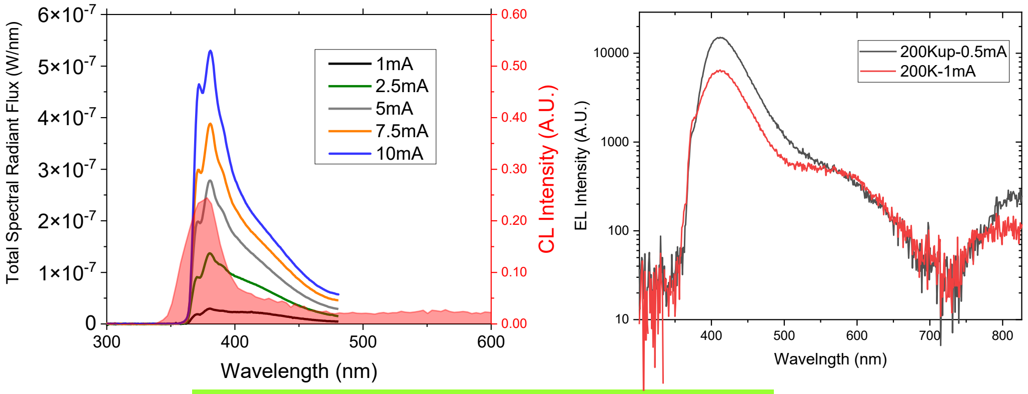


❑ At RT e-h recombination (360-390 nm) occurs in ZnO fin.

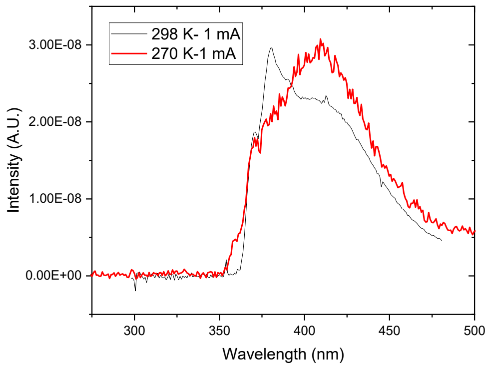
❑ As T is reduced to 6 K, e-h recombination shifts to the p-GaN side.

e-h recombination in ZnO fins under a low bias (temperature range of 6 K- 380 K)



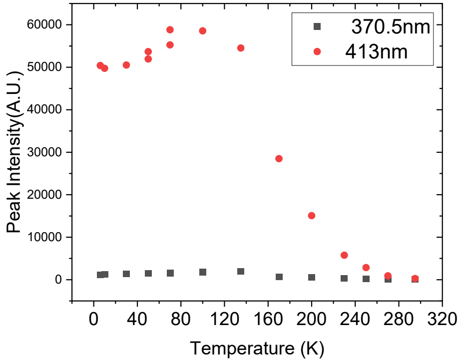


- ○ Impact of current increase (1-100 mA): UV emission in the ZnO fin.

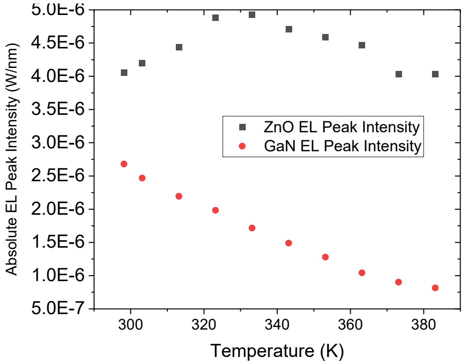


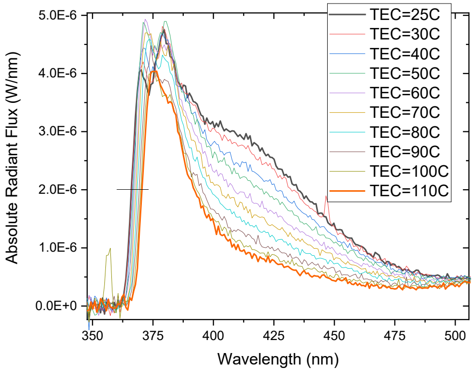
- ○ At fixed current (1 mA), by reducing T, recombination increases in the p-GaN.

@0.5 mA



@1 mA

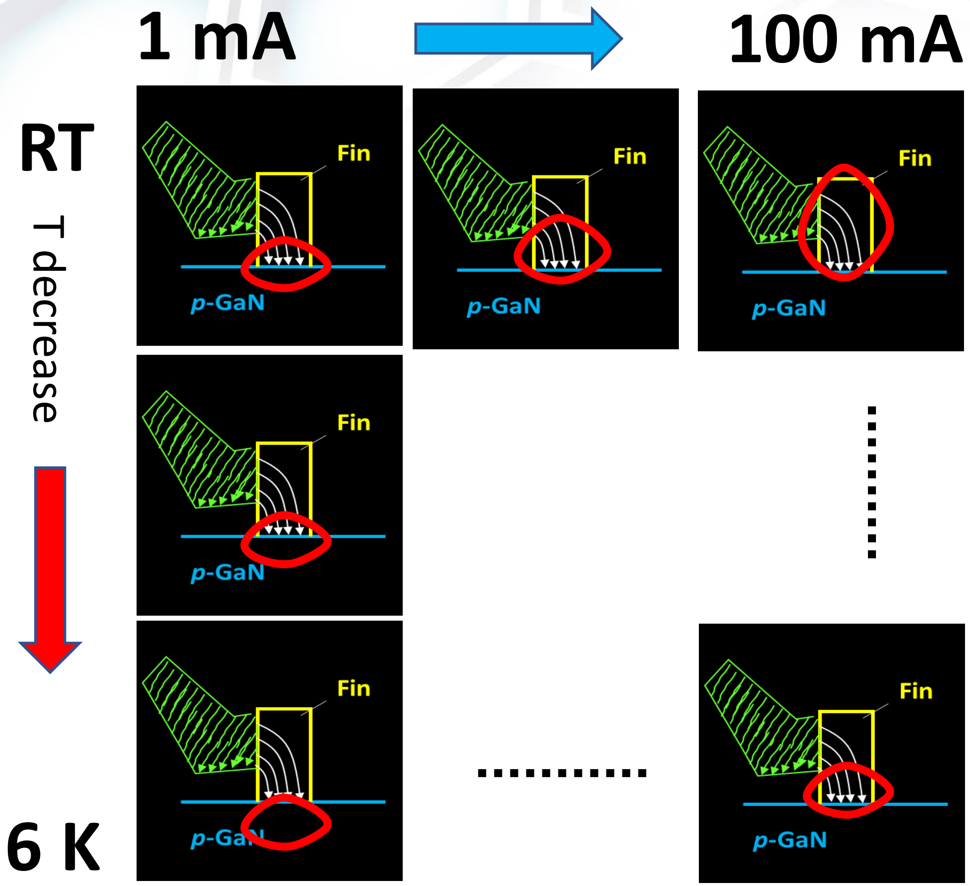


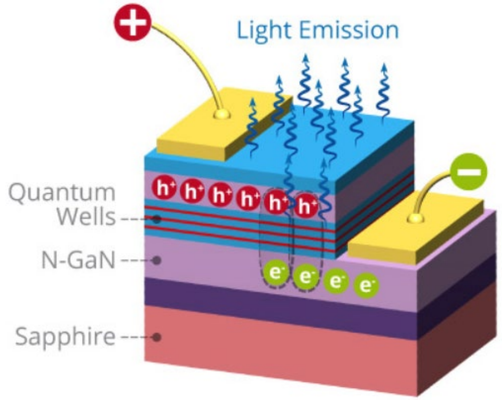


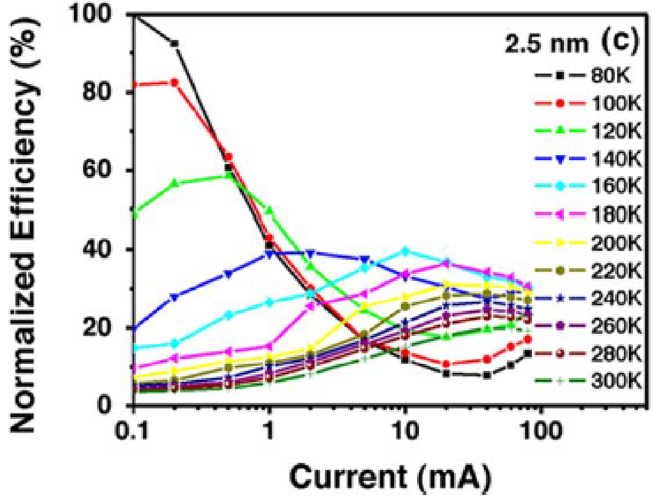
Fin shape is more effective in confining the electrons at:

- *Higher currents and*
- *Higher temperatures.*

Summary: Patterns of e-h recombination: fin LEDs vs. planar LEDs







Wang *et al. IEEE Photonics Technology Letters* **2010,** 22, 236-238.

In planar LEDs, under low temperature condition:

☐ At low current injection (0.1 mA), holes are confined in the QW nearest the p-side, which results in the effective recombination in the QW.

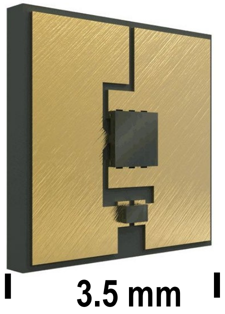
☐ At high current injection (10-100 mA), electrons overflow into the p-side due to large forward voltage at low temperature.

Summary

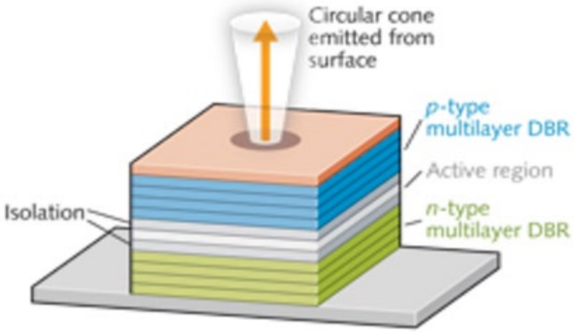
- ☐ Fin shape *pn*- LED controls and suppresses the non-radiative Auger recombination at high current densities.
- ☐ Both temperature and current density droop are mitigated in fin LEDs.
- ☐ Low optical loss in fins at high temperature allows brighter light sources and observation of stimulated emission.

This design could be a precursor for design of brighter LEDs and lasers by mitigating the droop effect.

Thank you!



☐ Study of droop in Fin UV-C LEDs



☐ Surface laser cavities for sensing and metrology