CS International, Invited Talk, April 18, 2023 14:30-14:45pm Brussels

Optimizing the Process for Making MicroLEDs

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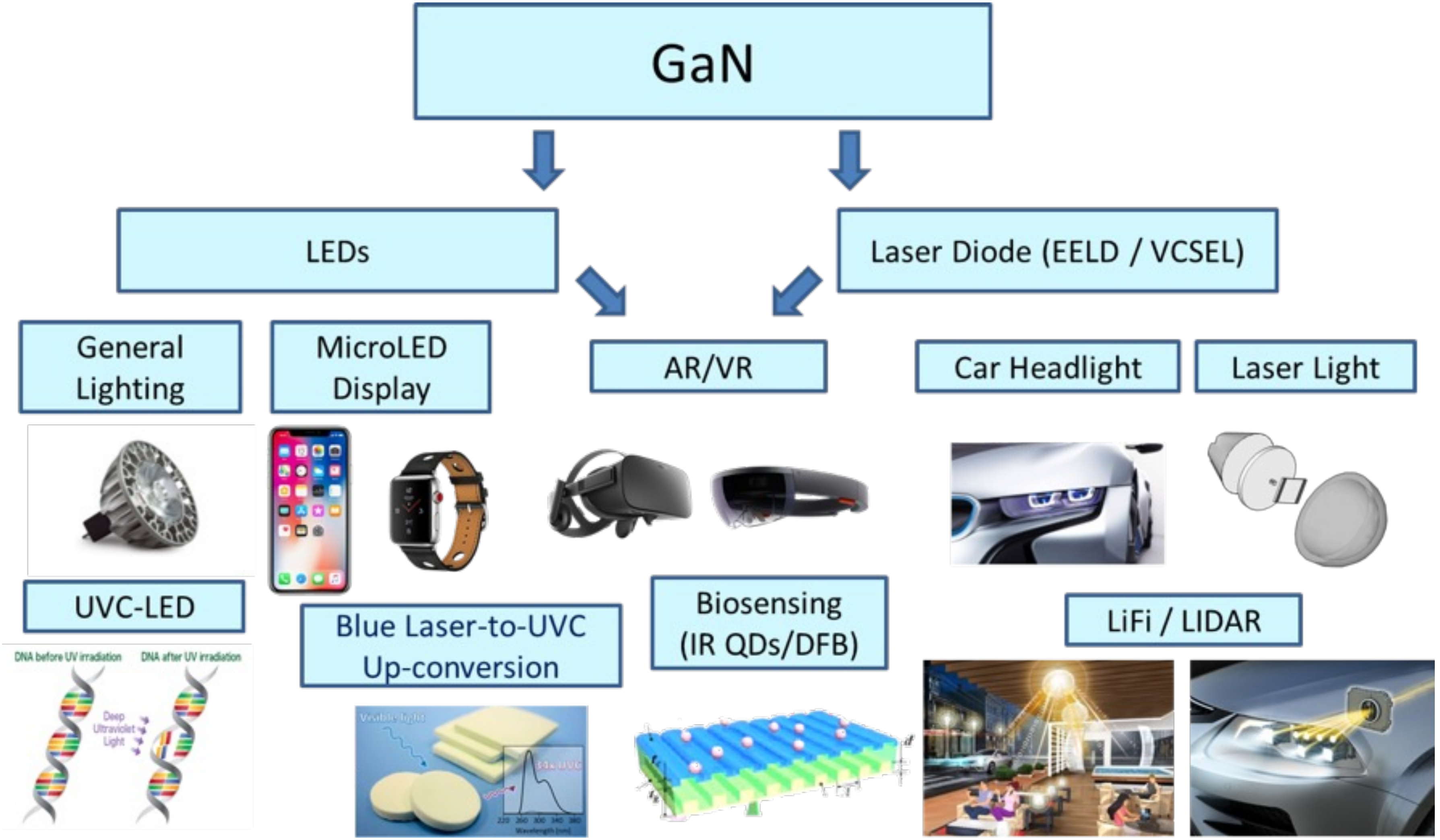
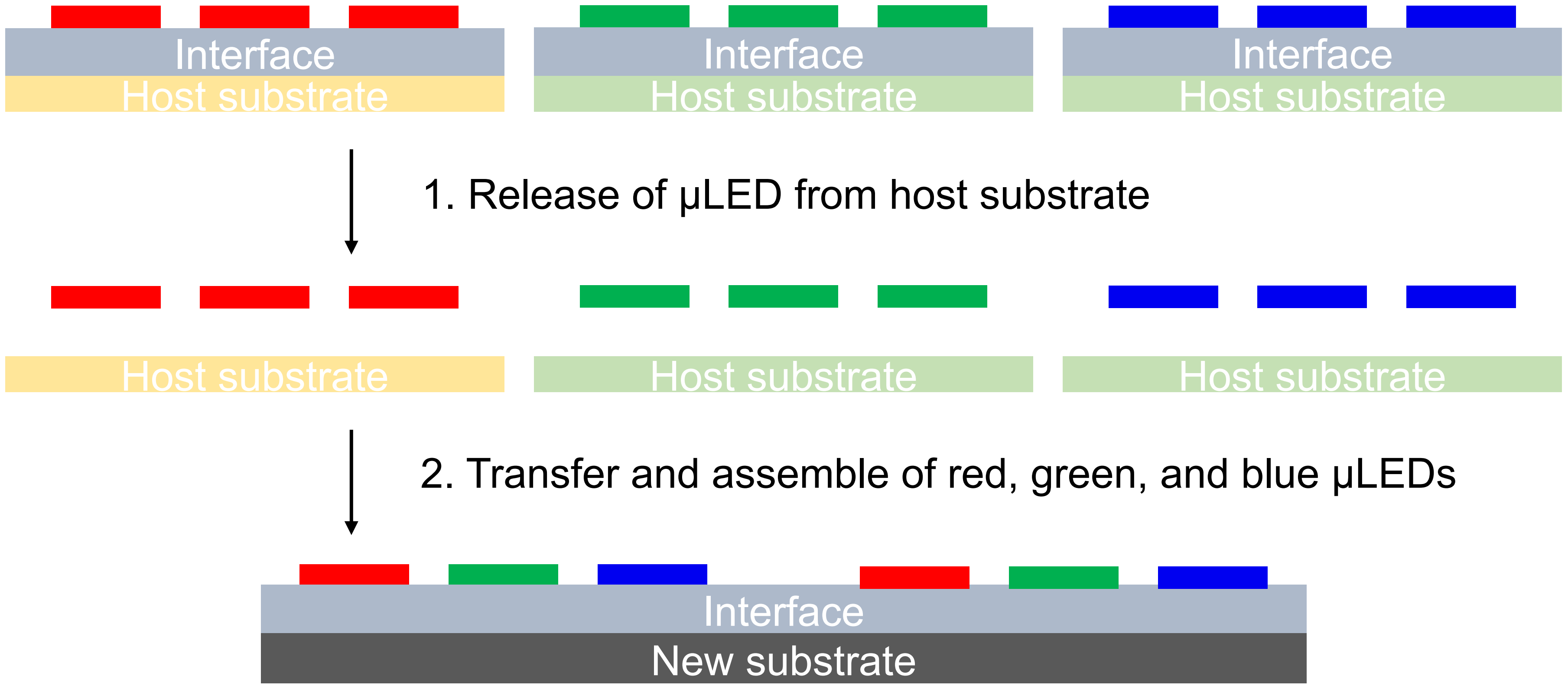
SSLEEC: Application-Driven Optoelectronics Research



UCSB research addresses some key microLED problems

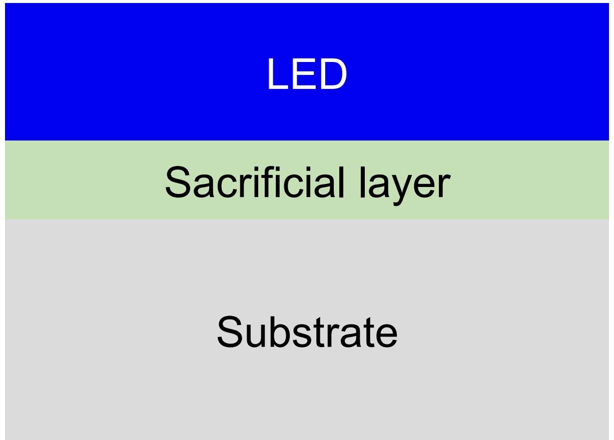
1. Mass Transfer of MicroLEDs with PEC etch and Transfer
   - Photoelectrochemical Etch for low damage chip removal
2. Efficiency drops as the microLED size decreases
   - Effects of sidewall damage are more pronounced when device dimensions smaller than 40 μm
3. Long-wavelength microLEDs-RGB InGaN based
   - Materials for green and red microLEDs
   - Quantum-confined Stark effect (blueshift in wavelength) for InGaN *c*-plane long-wavelength microLEDs

Mass transfer can be broken into two steps.

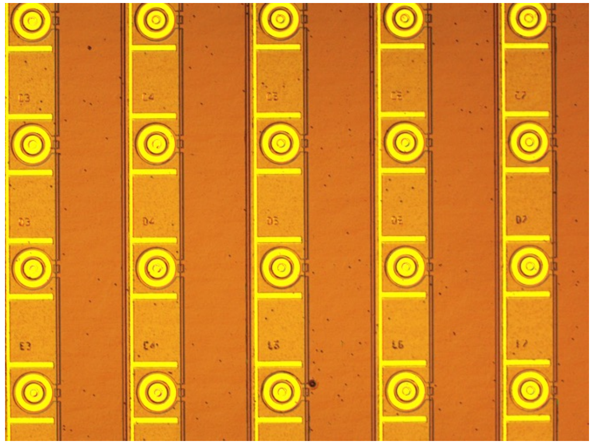


UCSB solution: PEC etching + transfer print

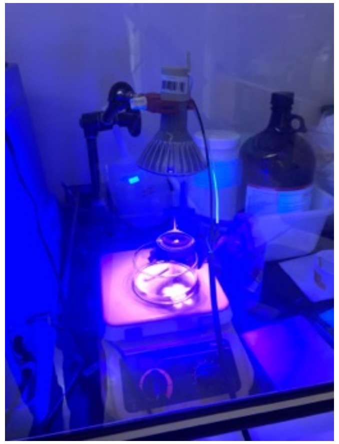
I. Growth of sacrificial layer and LED



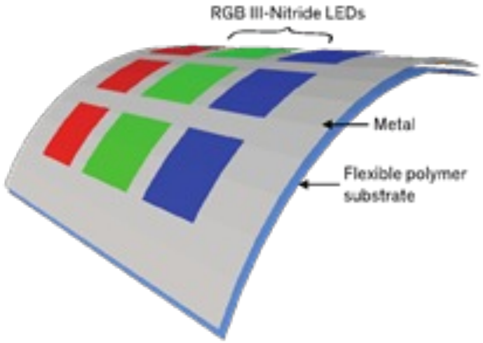
II. Fabrication of releasable structures



III. PEC etch



IV. Transfer print μLEDs
On TruFlex polymer
Backplane (SmartKem)

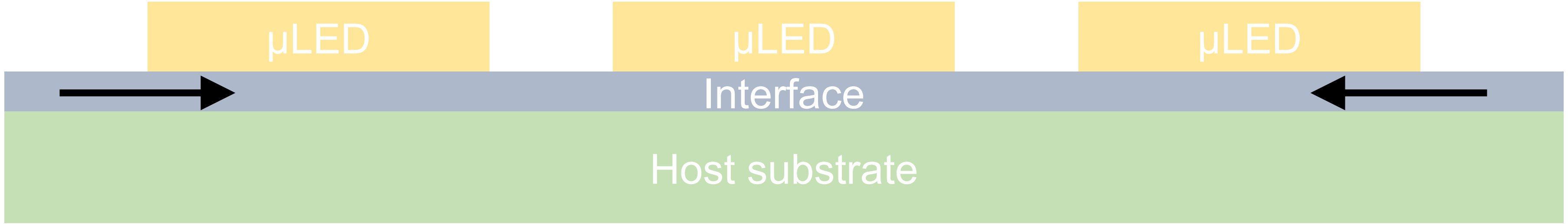


<u>Advantages of UCSB process:</u>

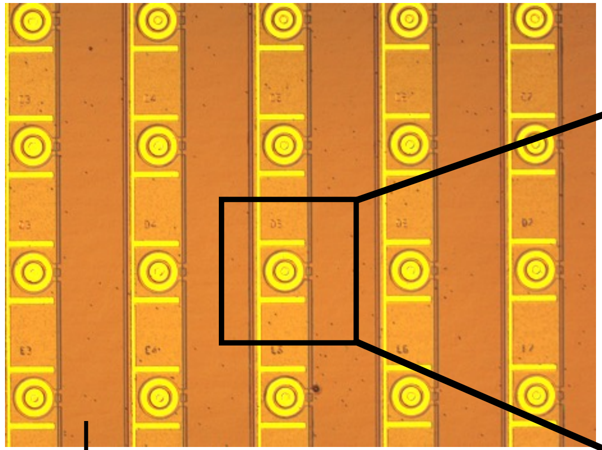
- ✓ **Allows for high quality epitaxial growth (on sapphire, freestanding GaN)**
- ✓ Can assemble μLEDs from different wafers (eg can assemble multi-color pixels)
- ✓ Ultrasmall dimensions can be transferred (< 1 μm)
- ✓ Built-in extraction features for *c*-plane; otherwise, low to atomic roughness on semipolar or nonpolar

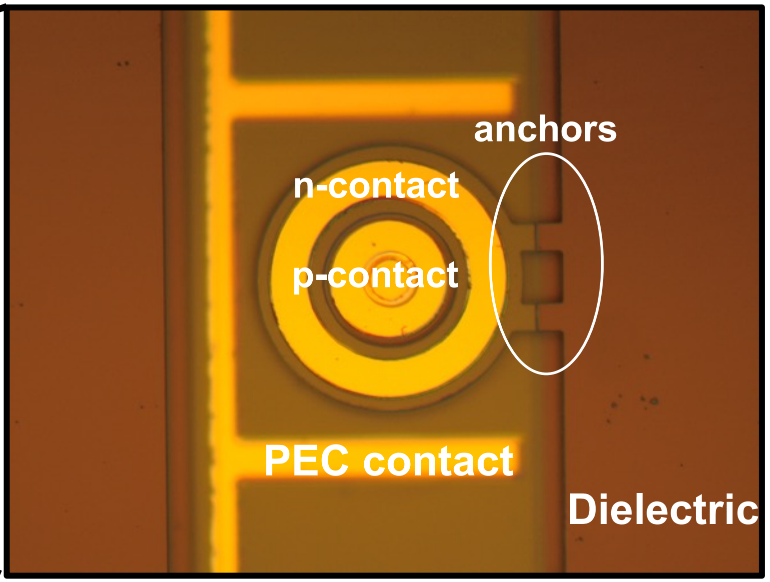
Release of μLED: PEC sacrificial etch (UCSB)

2. **PhotelectroChemical Etch (PEC) Sacrificial etch**
   a. **III-phosphides/arsenides are oxidizable and etchable**
   b. **GaN is not easily etched (or at all), but GaN grown on Si can be removed by selectively etching Si (110) with KOH**



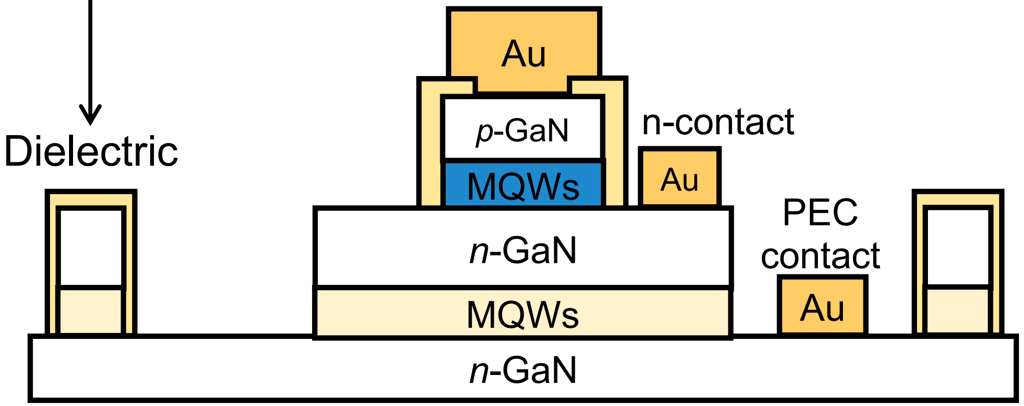
Deposit PEC metal and common *p*- and *n*-contacts





Dielectric covers sidewalls of columns so they are protected from the etch and stay on the substrate.

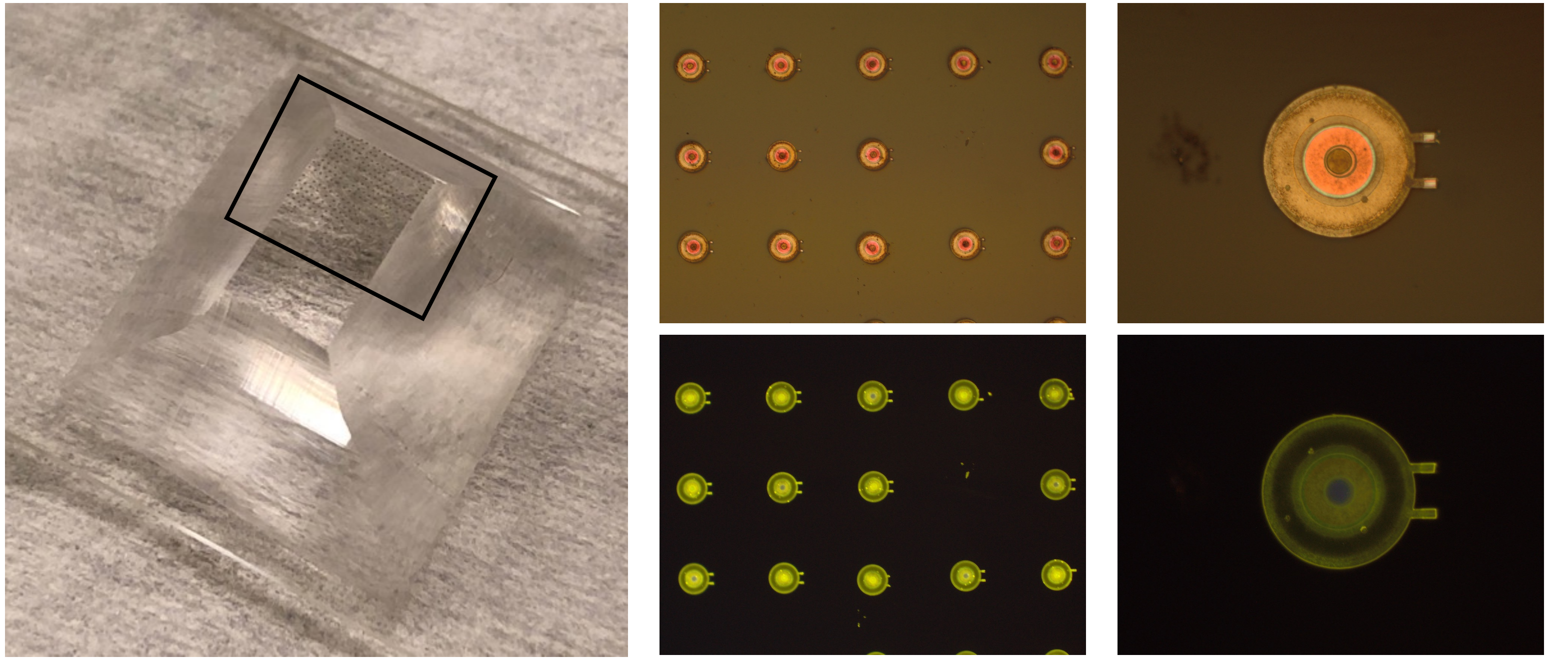
Thin anchors hold patterns onto the substrate and can be broken mechanically.



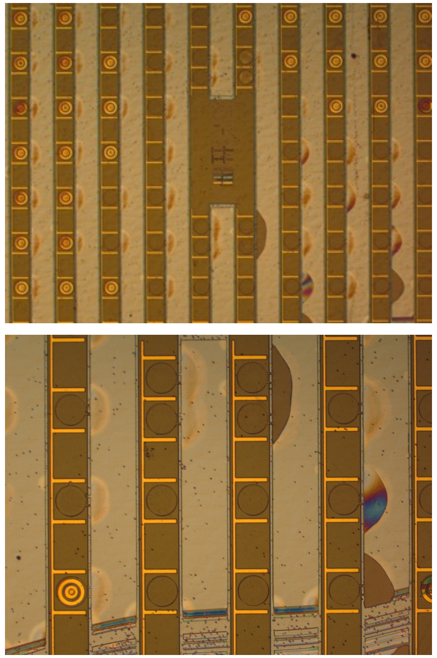
Transfer printing utilizes a PDMS stamp

- µLEDs are loosely bonded to the temporary PDMS substrate and retain periodicity.

<u>µLEDs on PDMS</u>



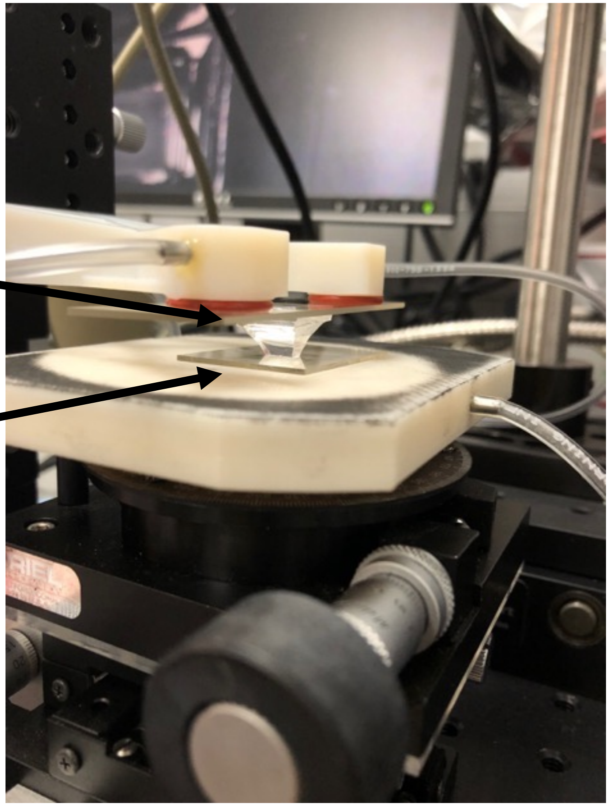
<u>Remaining µLEDs on sapphire</u>

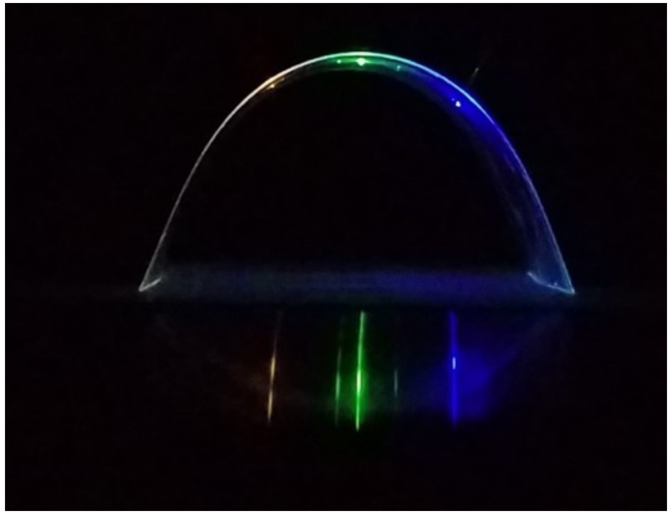


Transferring from PDMS to final substrate

- **The final substrate is prepared by spinning an optical adhesive (NOA61) that is UV-curable.**
- **μLEDs are lowered slowly onto the adhesive and then cured by UV for 1.5 hours.**
- **PDMS is slowly lifted off from the final substrate, and μLEDs remain on the adhesive layer.**

PDMS
μLEDs
Final substrate



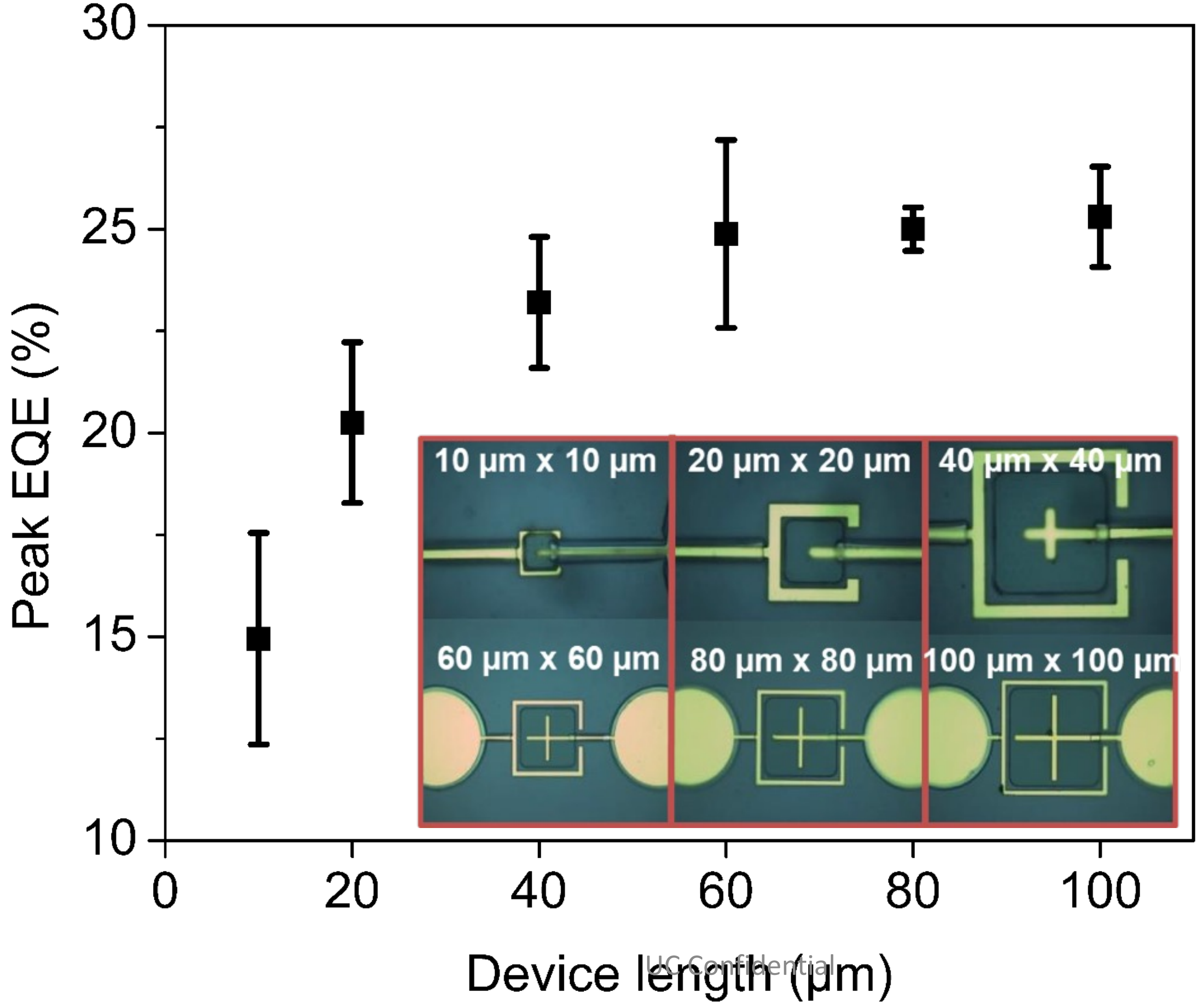


RGB MicroLED integrated on flexible substrates

Sidewall damage reduces the efficiency of microLEDs

UCSB

- The decrease in efficiency is caused by sidewall damage and defects
- The efficiency drop increases as device size shrinks

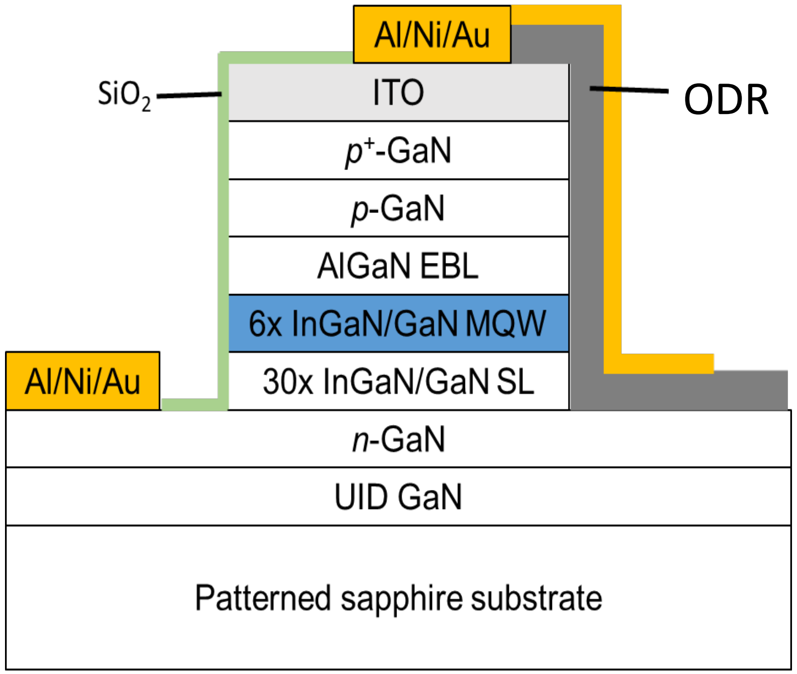


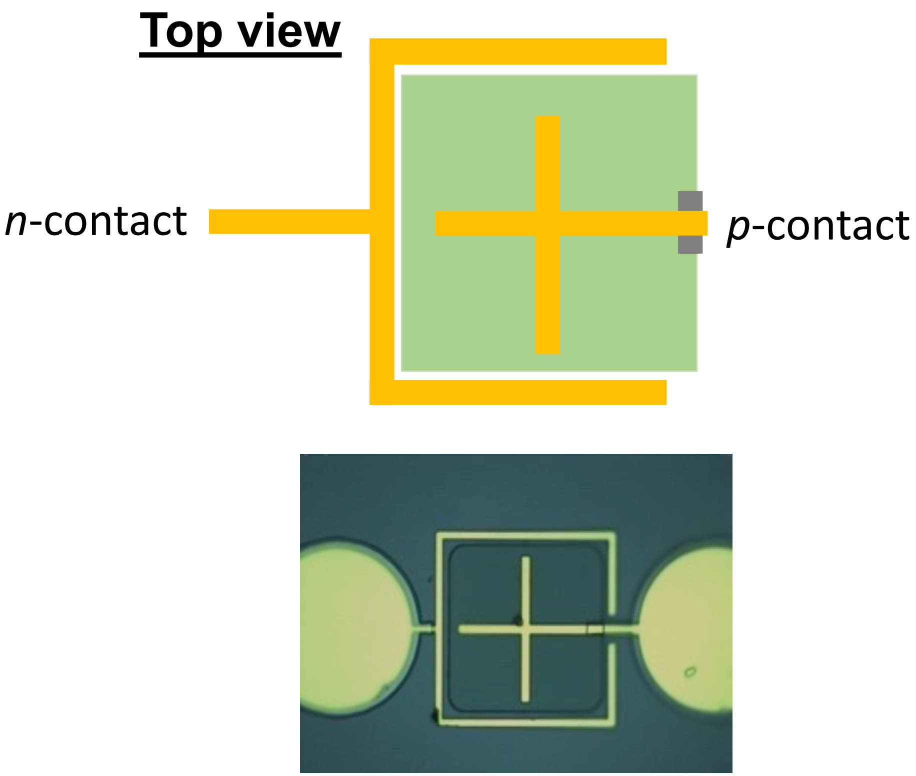
µLED Design in GaN based LEDs

Cross-sectional schematic of processed LEDs with

- indium tin oxide as the transparent *p*-contact
- omnidirectional reflector (ODR) composed of alternating stacks of Ta_2O_5 and SiO_2
- Al/Ni/Au as the *p*- and *n*-contacts
- ALD sidewall passivation-reduces non-radiative sidewall recombination

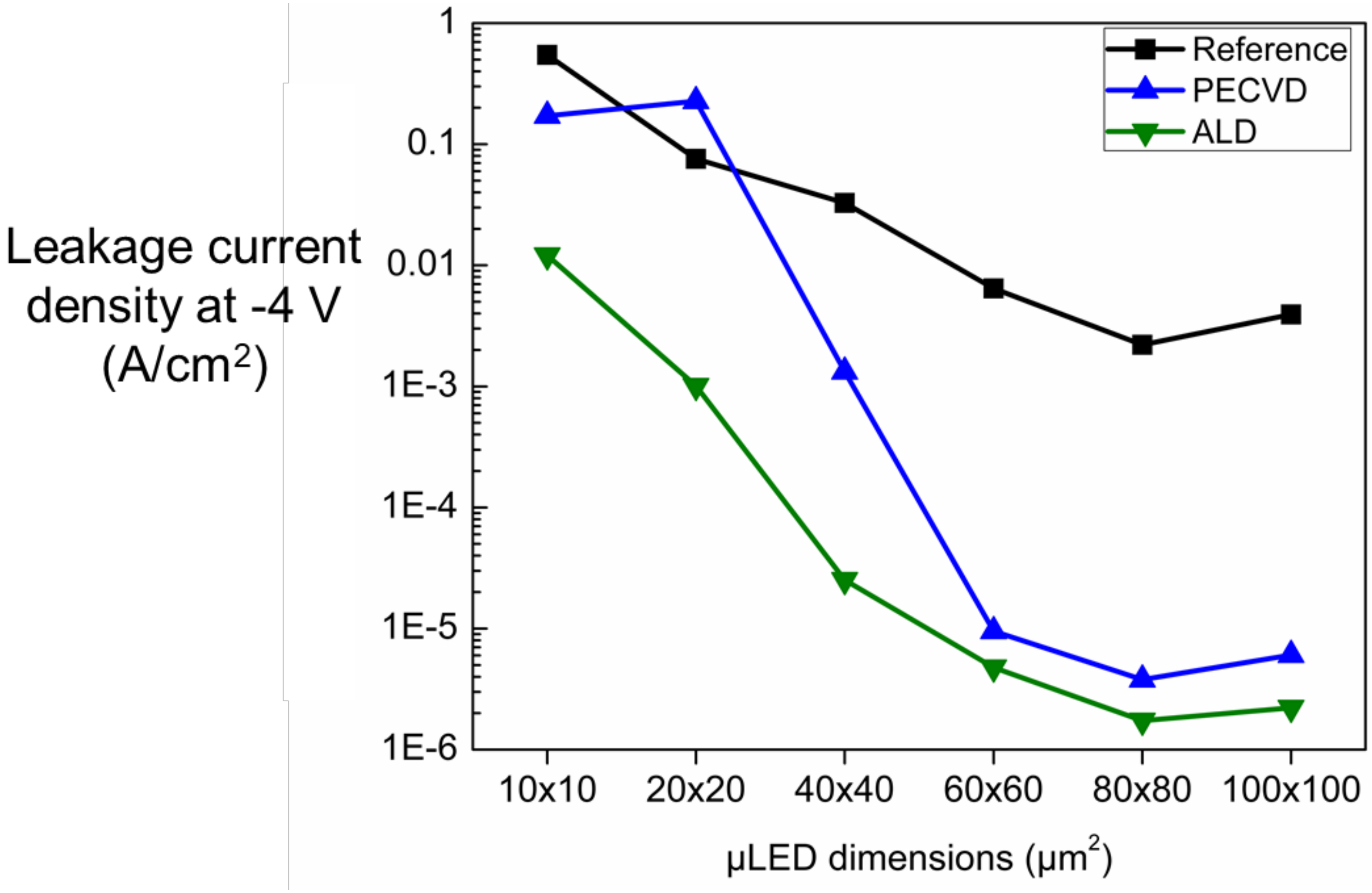
Optical image of µLEDs showing the *n*-contact/pad (left), the ODR (right), and *p*-contact/pad on top of the ODR and mesa





ALD suppressed leakage current effectively

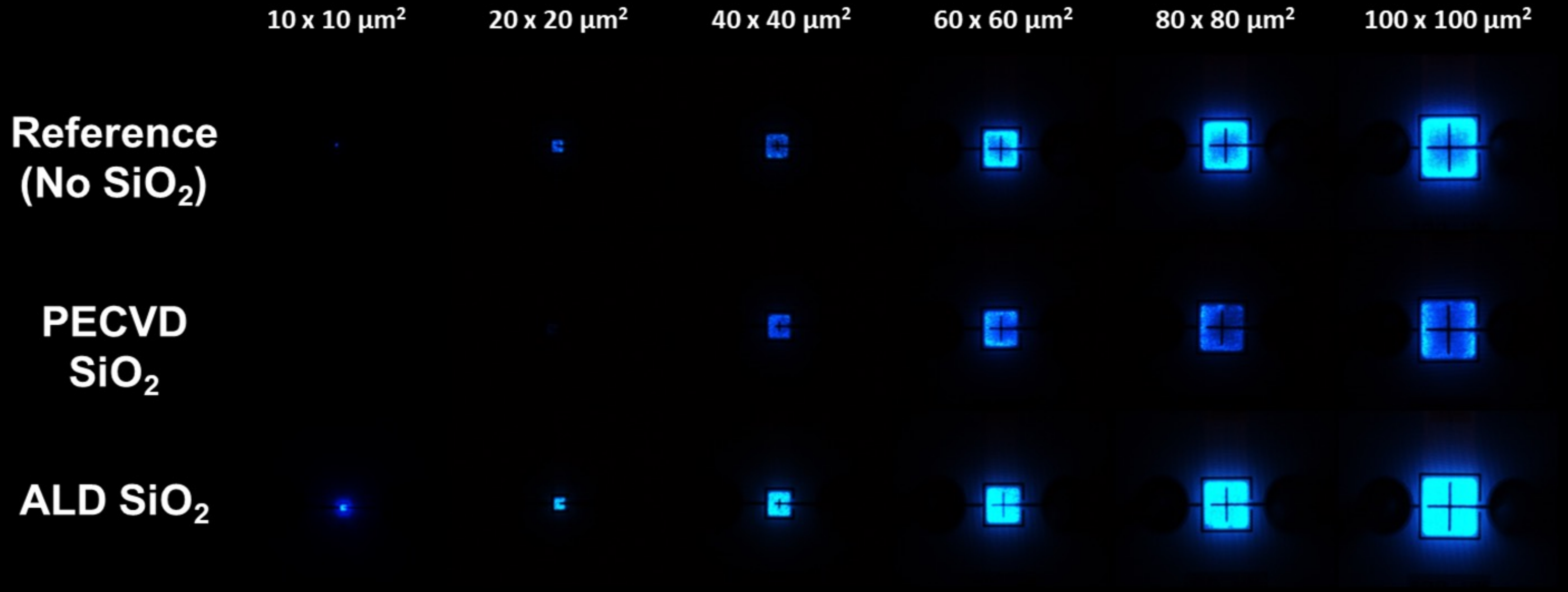
- PECVD failed to suppress leakage for smaller microLEDs
- MicroLEDs with ALD sidewall passivation resulted in the least amount of leakage



M.S. Wong, *Opt. Express*, **26 (16)** (2018)

ALD yielded uniform light emission

- Current crowding did not appear in the µLEDs with ALD passivation
- Uniform light emission with ALD passivation among all sizes

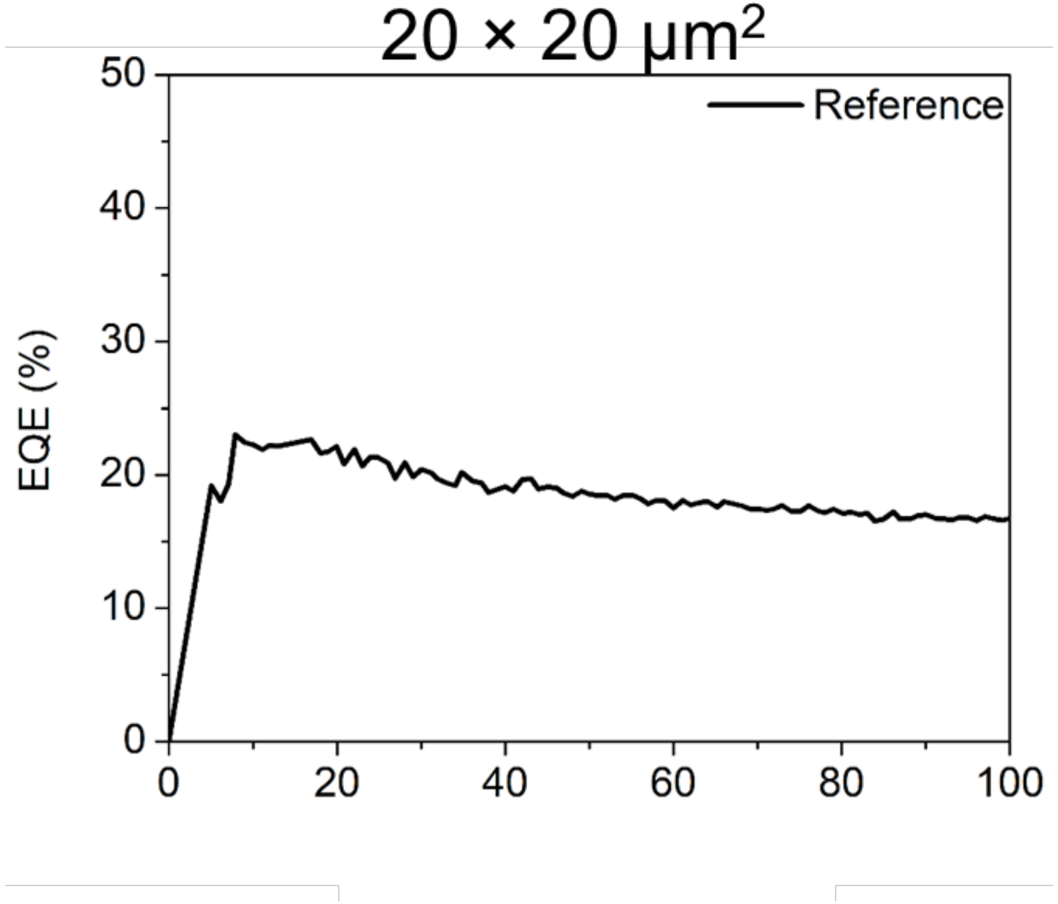


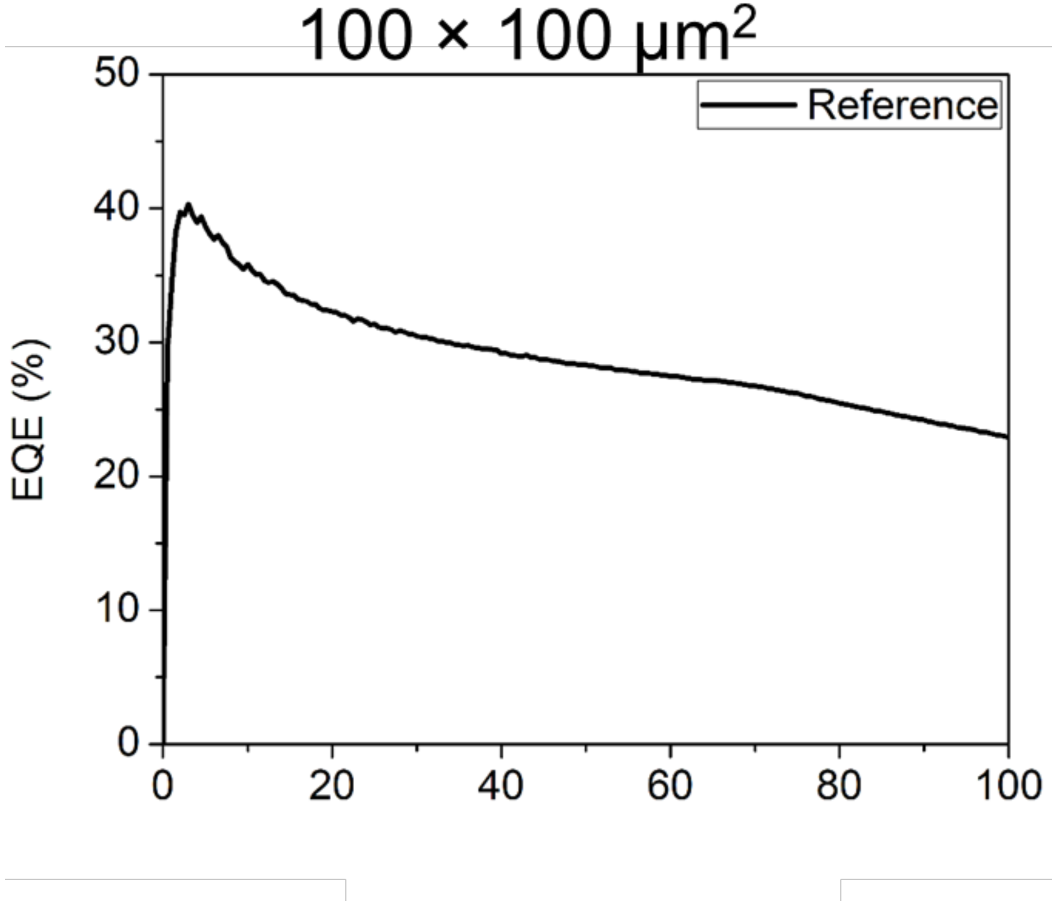
Electroluminescence at 1 A/cm^2

M.S. Wong, *Opt. Express*, **26 (16)** (2018)

Decrease in peak EQE due to sidewall defects

- Without passivation, peak EQE dropped significantly
- From 40% (100 μm) to 24% (20 μm)

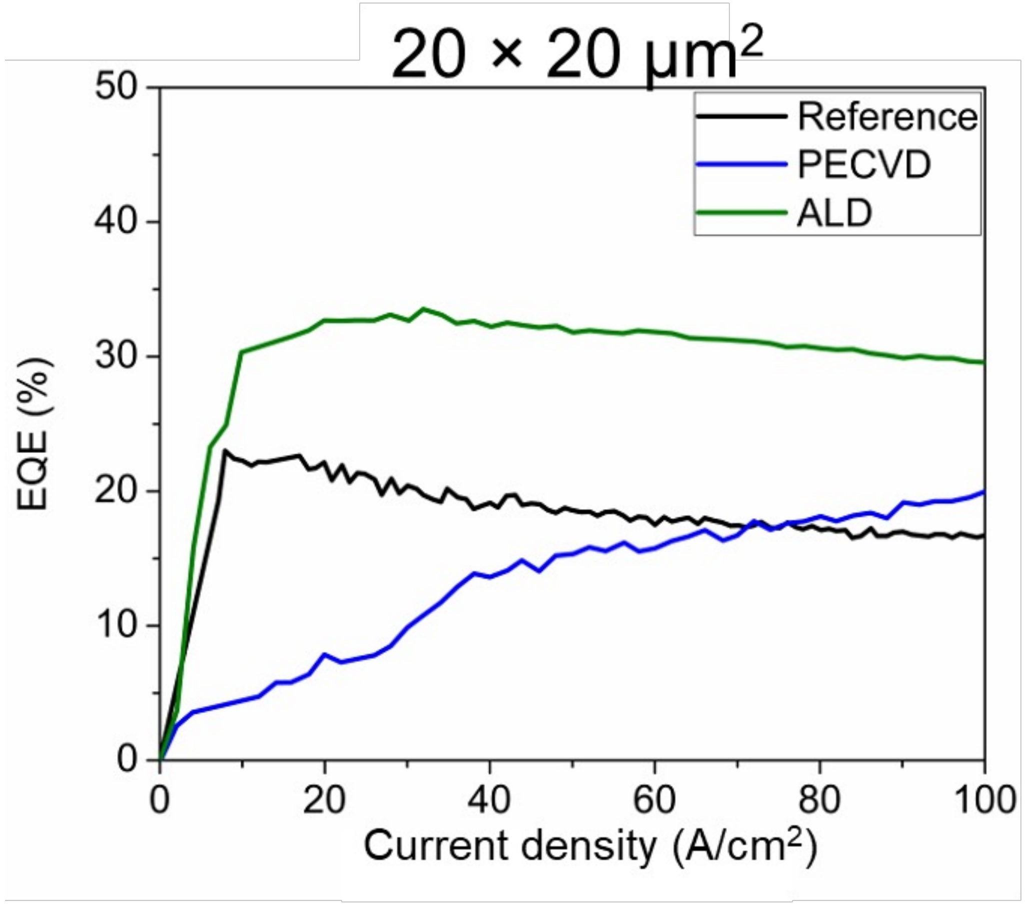


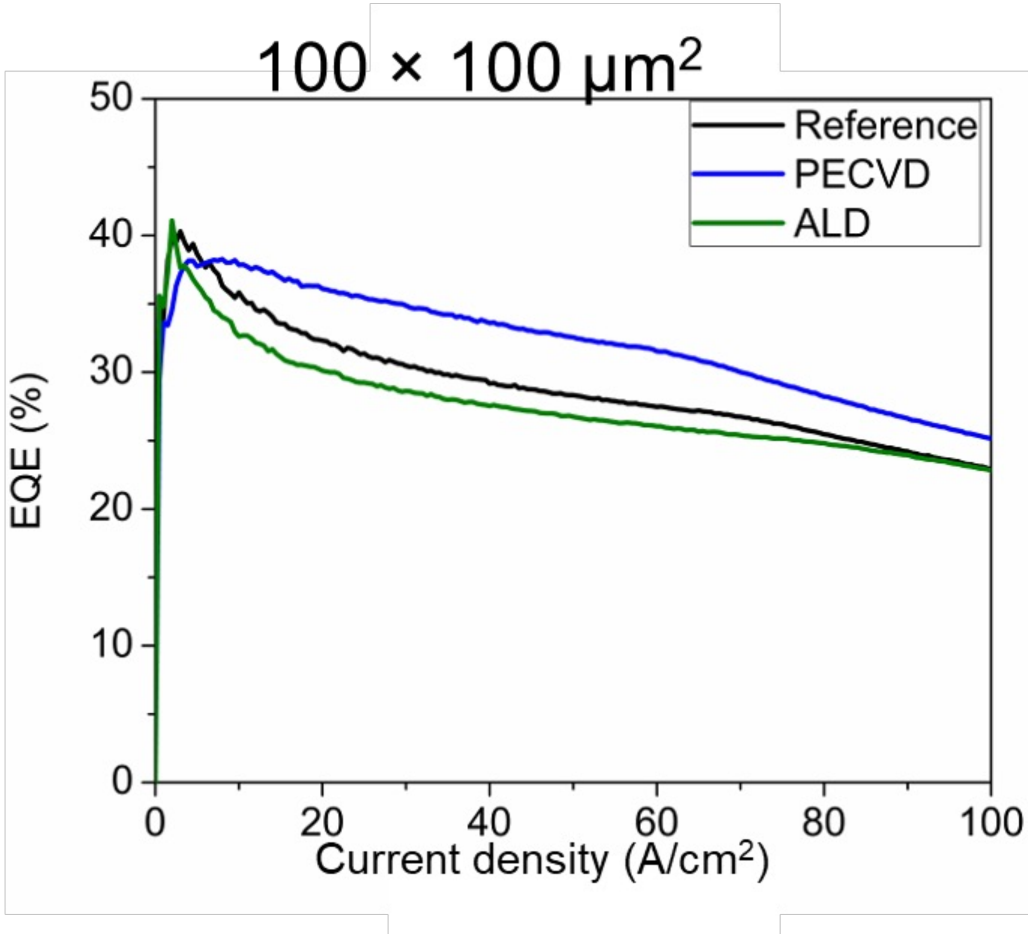


M.S. Wong, *Opt. Express*, **26 (16)** (2018)

ALD passivation improved EQE in 20 × 20 μm^2 microLEDs

- MicroLEDs with ALD passivation, the decrease in EQE was reduced (42% → 33%)
- The low EQE of the 20 x 20 μm^2 PECVD device was due to ITO damage

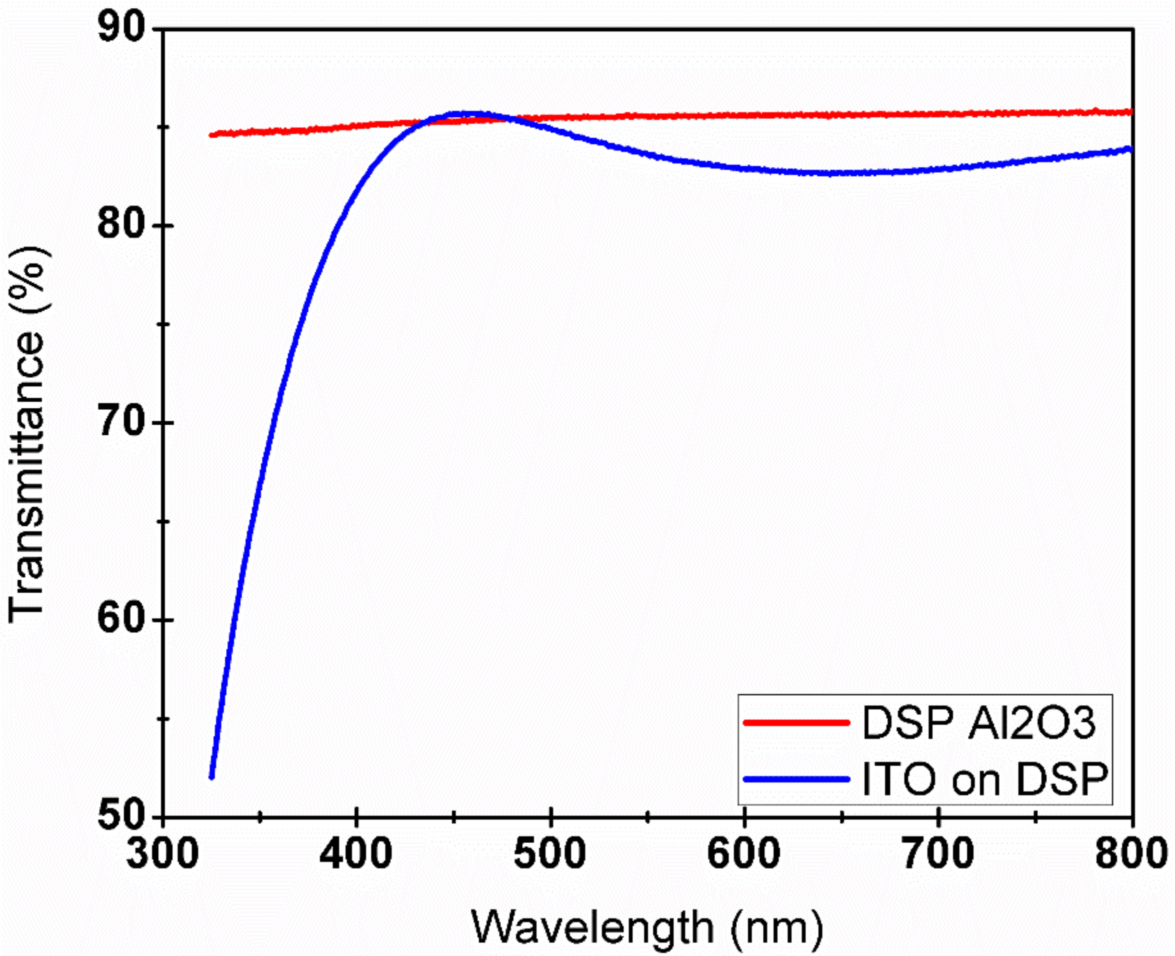




M.S. Wong, *Opt. Express*, **26 (16)** (2018)

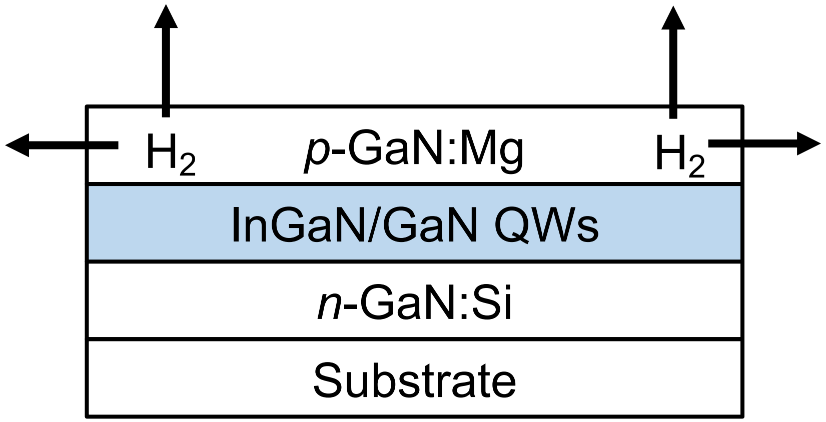
ITO is absorbing -> switch to Tunnel Junctions (TJs)

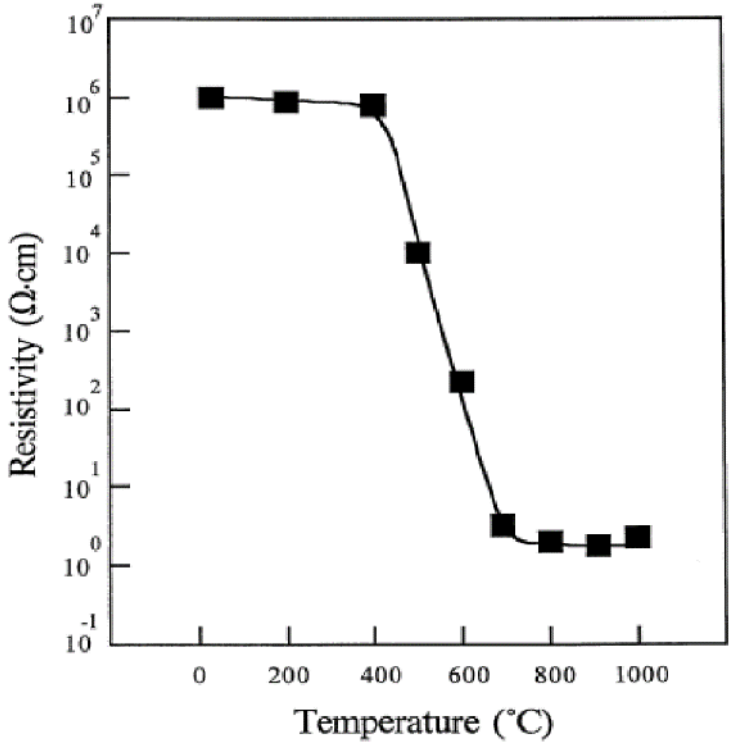
- ITO has >80% transmittance in the visible spectrum
- Optical absorption ~2000 cm^{-1} at 405 nm and ~1000 cm^{-1} at 450 nm



Hydrogen passivation in *p*-GaN during MOCVD

- Magnesium doped *p*-type GaN is passivated by hydrogen
- Thermal activation of *p*-type GaN is required

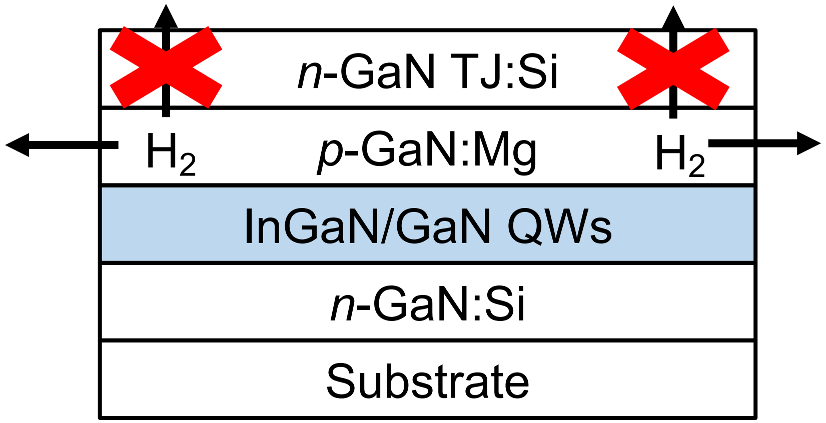


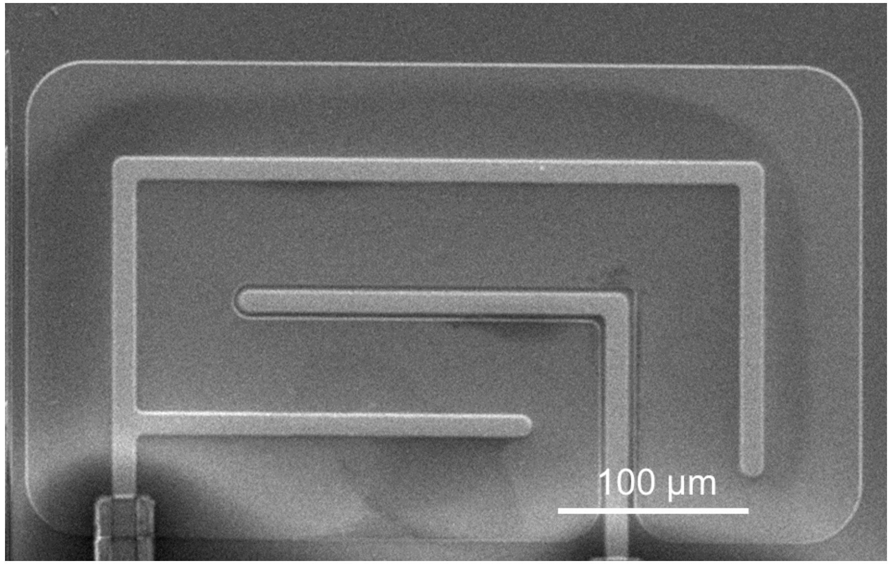


Nakamura, JJAP, 31, L139 (1992)

MOCVD-grown TJs suffer from hydrogen passivation

- *n*-type GaN acts as a diffusion barrier for hydrogen
- Sidewall diffusion is inefficient for conventional LEDs

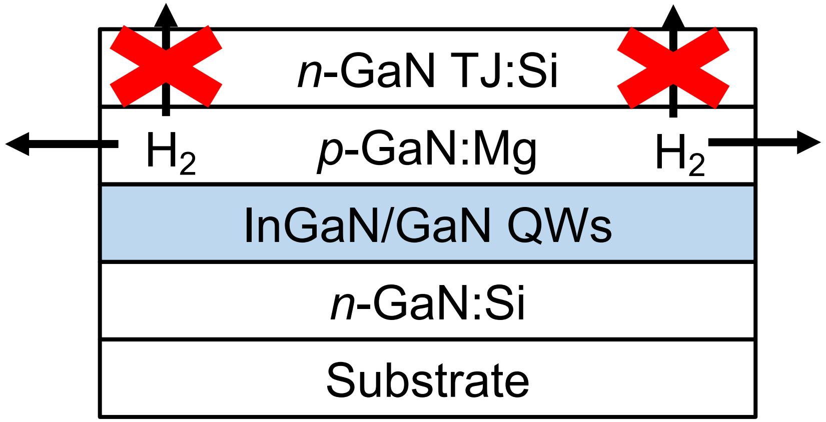


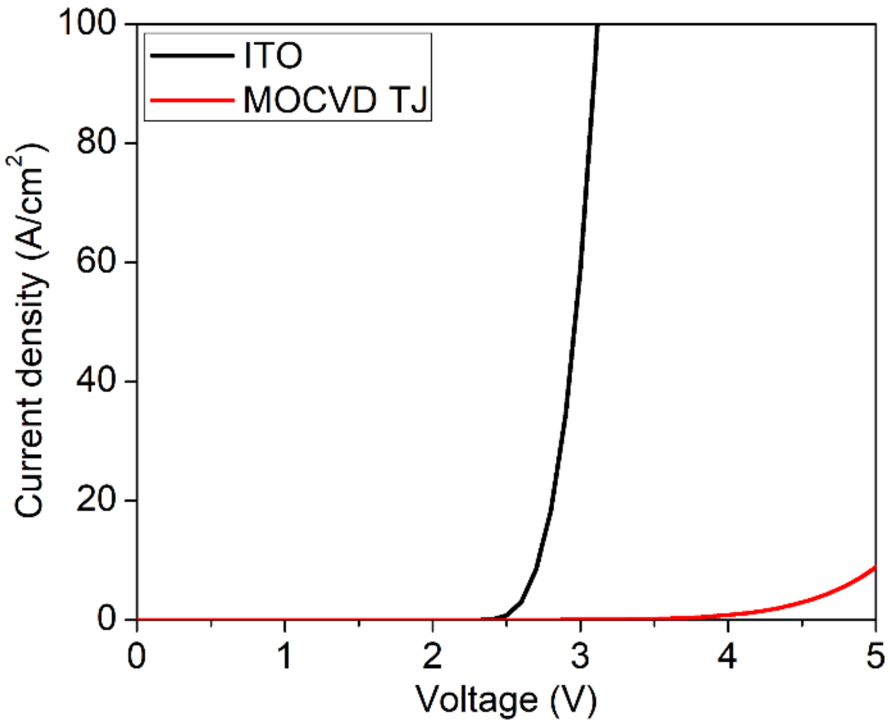


MOCVD-grown TJs suffer from hydrogen passivation

UCSB

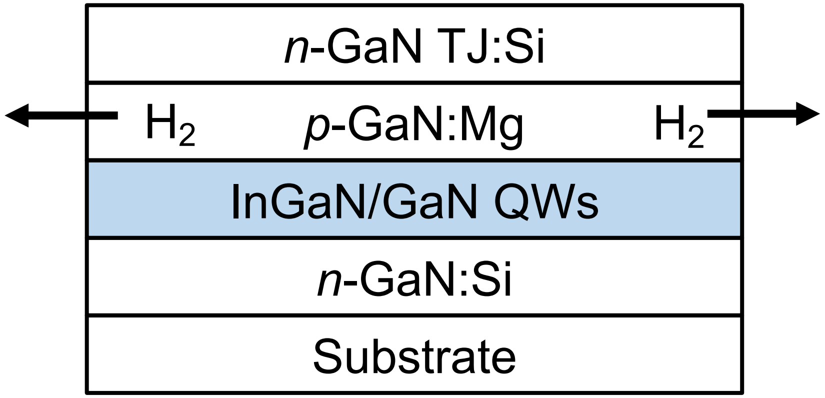
- *n*-type GaN acts as a diffusion barrier for hydrogen
- MOCVD-TJ normally yielded high voltage penalty

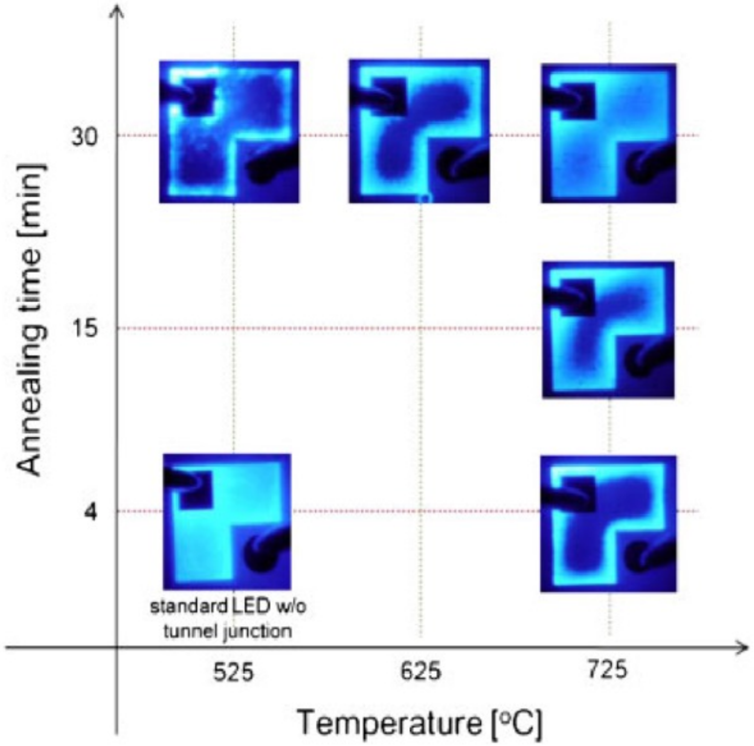




Sidewall activation is possible in microLEDs

- MicroLEDs have small lateral dimensions
- Hydrogen diffusion through sidewalls has been demonstrated

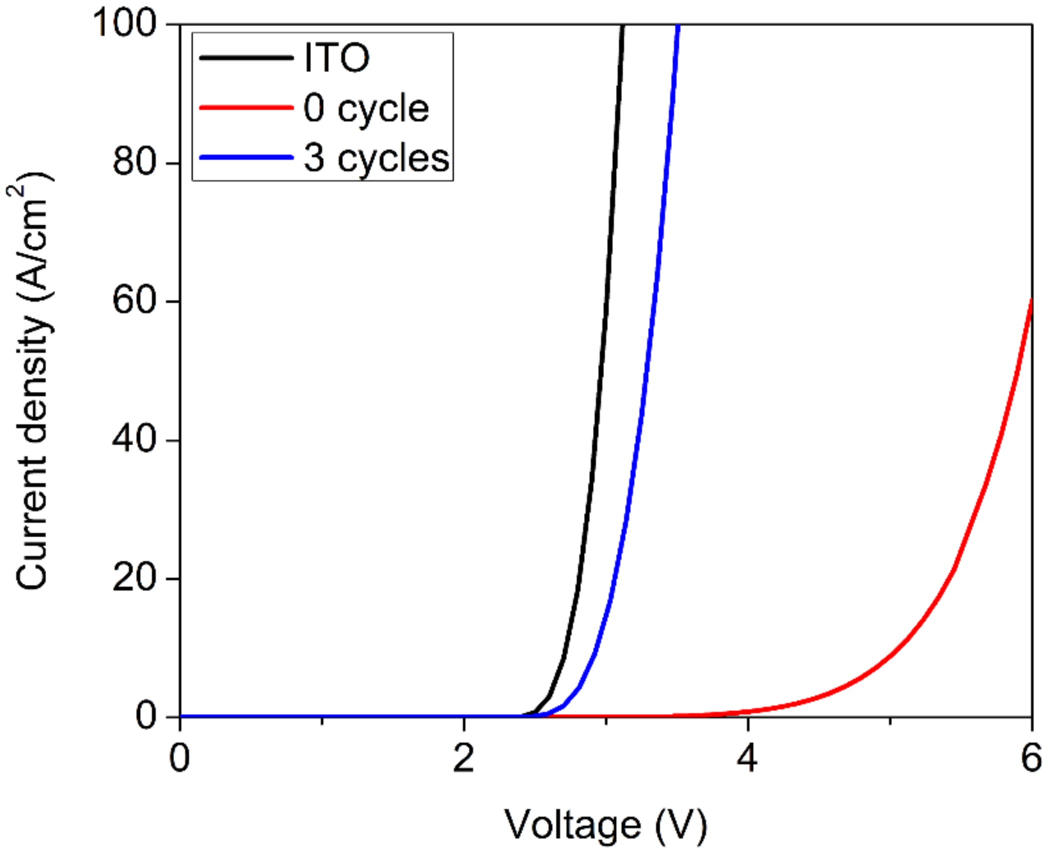


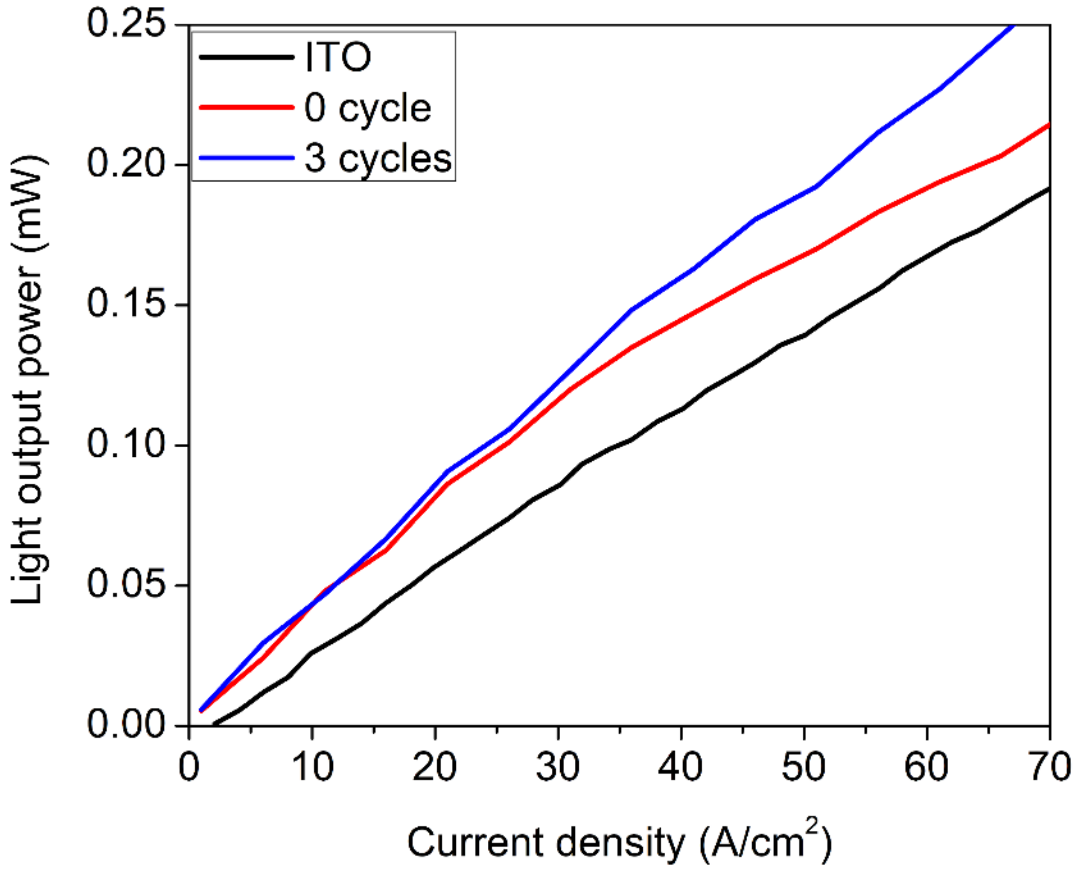


Kuwano, JJAP, 52, 08JK12 (2013)

ITO and TJ devices have comparable performances

- The voltage penalty of 0.2 V is observed in TJ devices with chemical treatments
- More than 40% enhancement in light output power

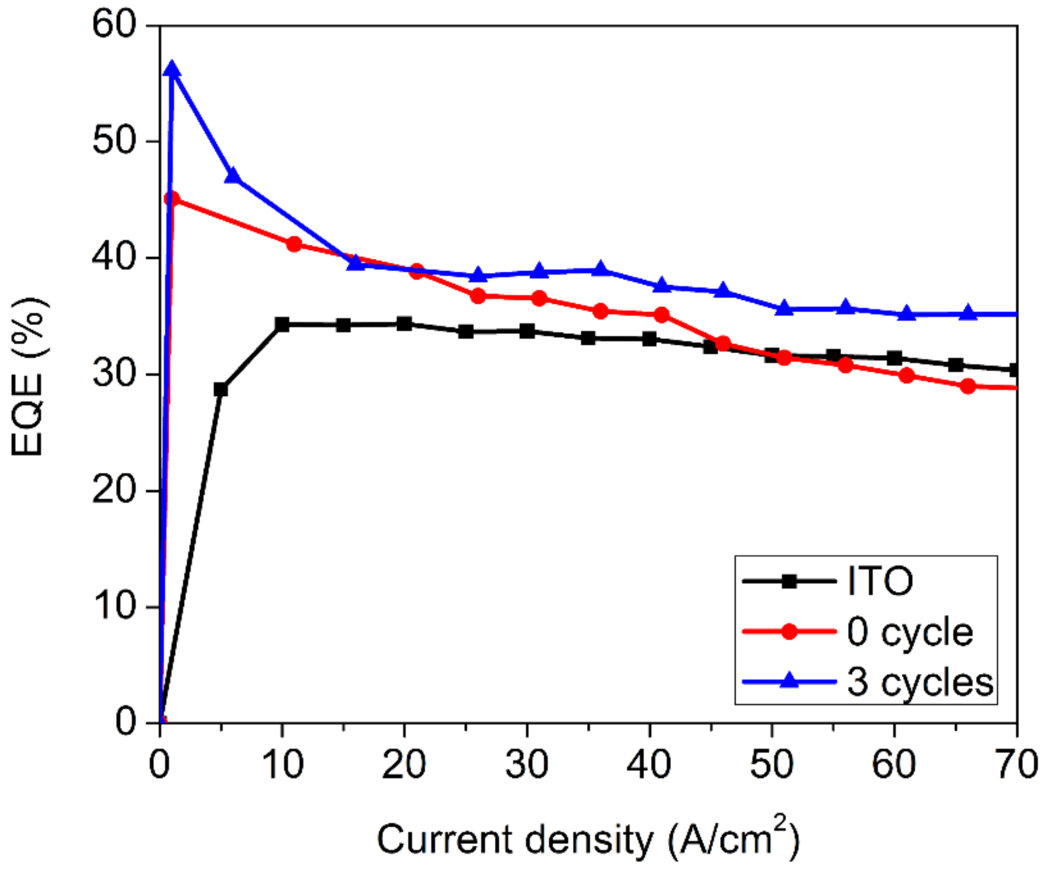


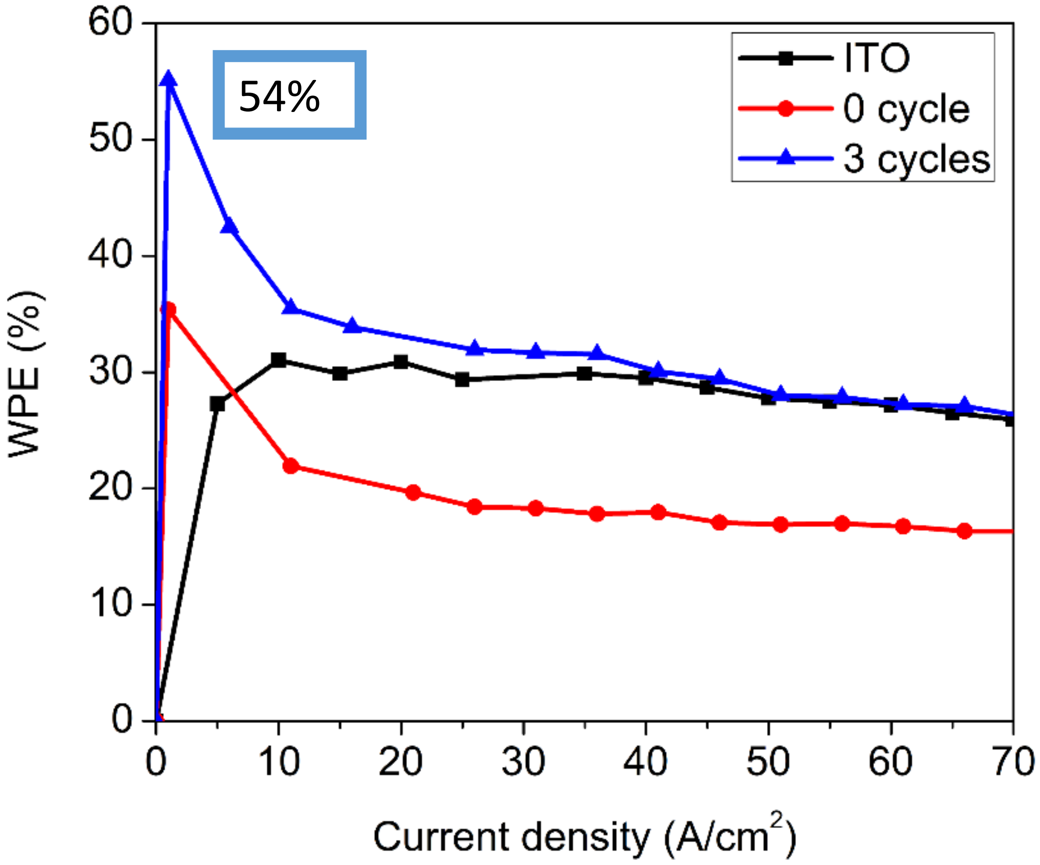


Wong, APEX, 14, 086502 (2021)

TJ devices show better efficiency than ITO devices

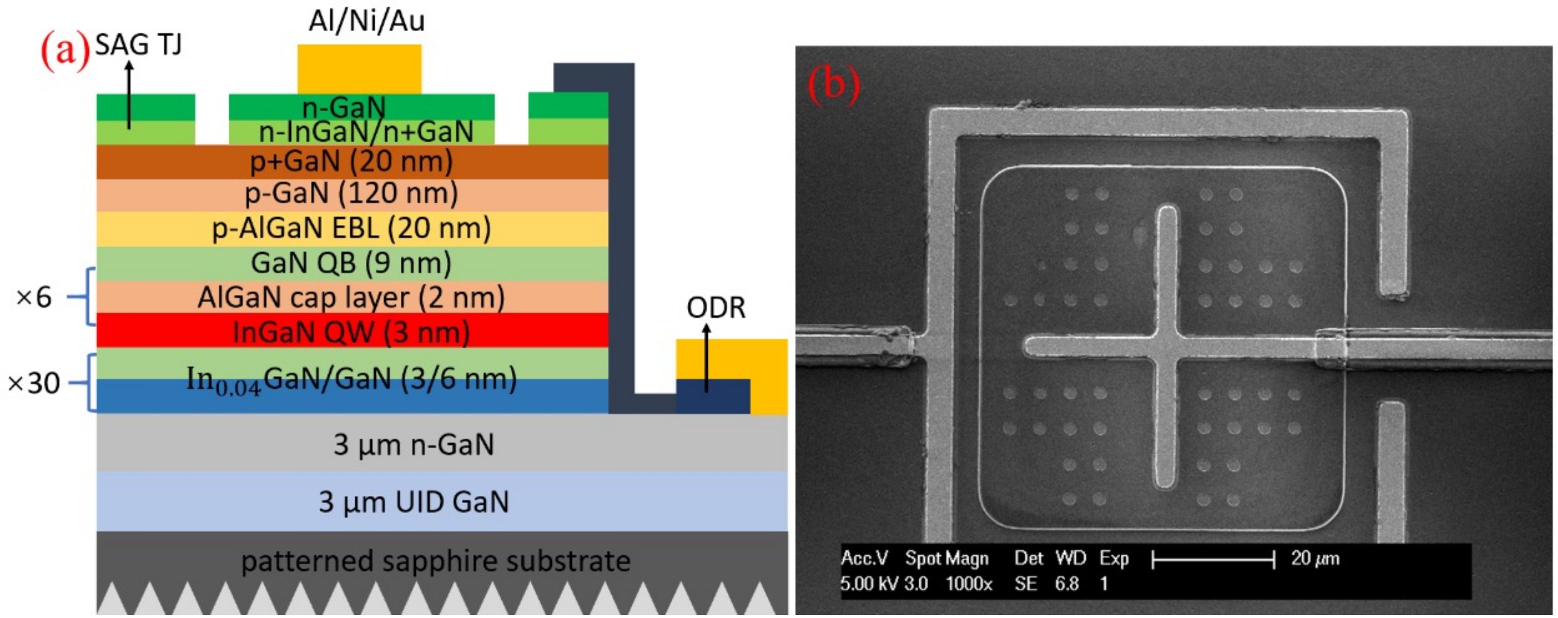
- Both EQE and WPE are higher than those of ITO devices
- WPE is as good as ITO device even at high current density
- 54% Wall Plug Efficiency-best reported MicroLED Efficiency





Wong, APEX, 14, 086502 (2021)

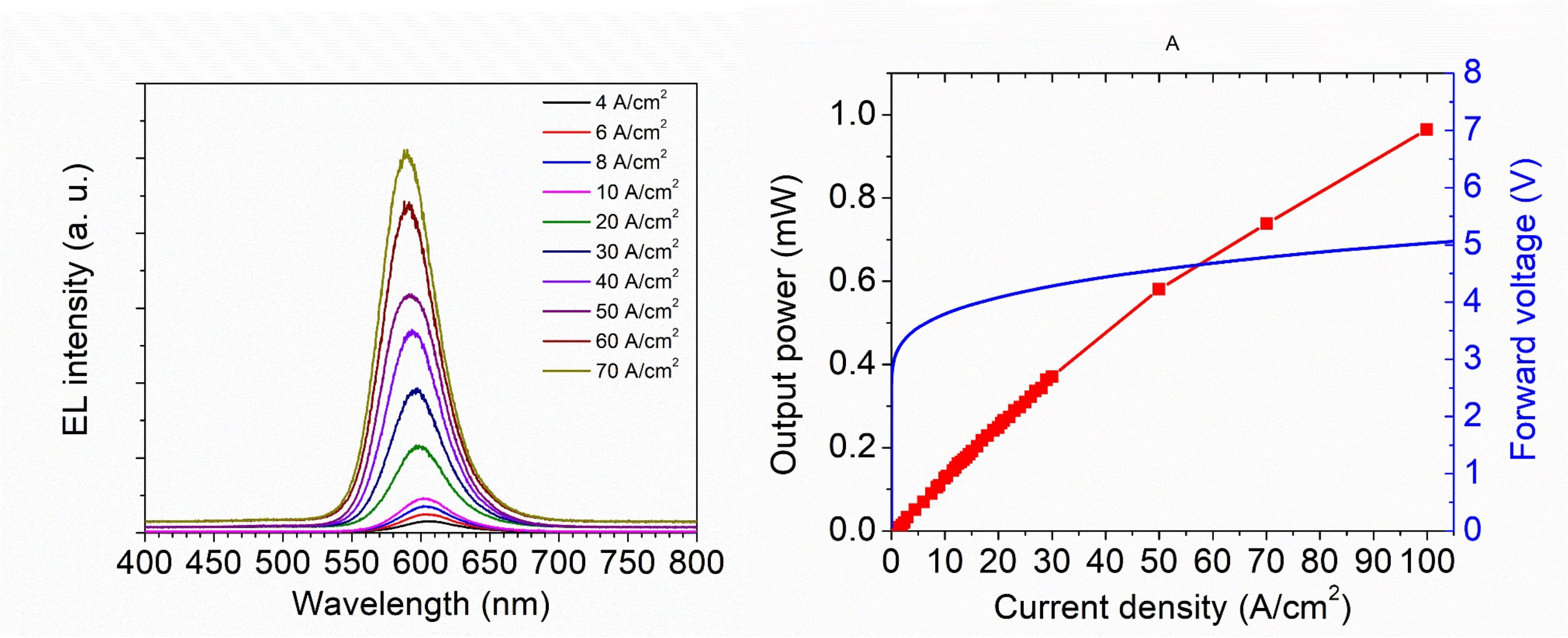
Red InGaN Micro LEDs



(a) Schematic epitaxial stacks and devices structure of InGaN red µLEDs;

(b) (b) SEM image of the 60×60 µm^2 InGaN red µLEDs.

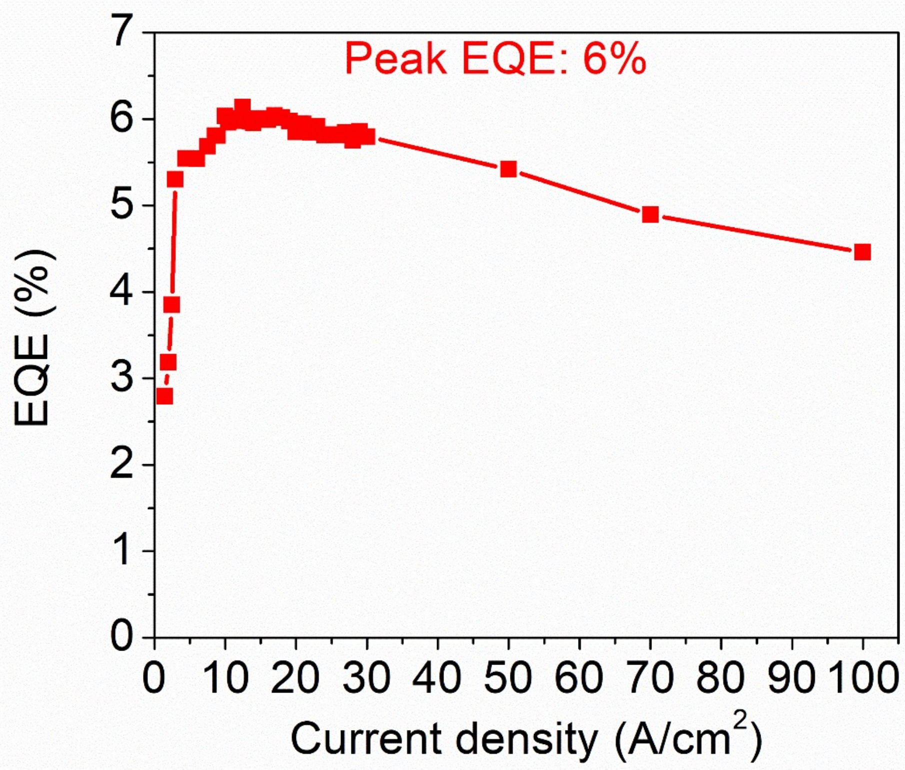
InGaN red micro-LEDs devices results



Singe peaks emission around 608 nm at 4A/cm^2.

InGaN red micro-LEDs packaged results

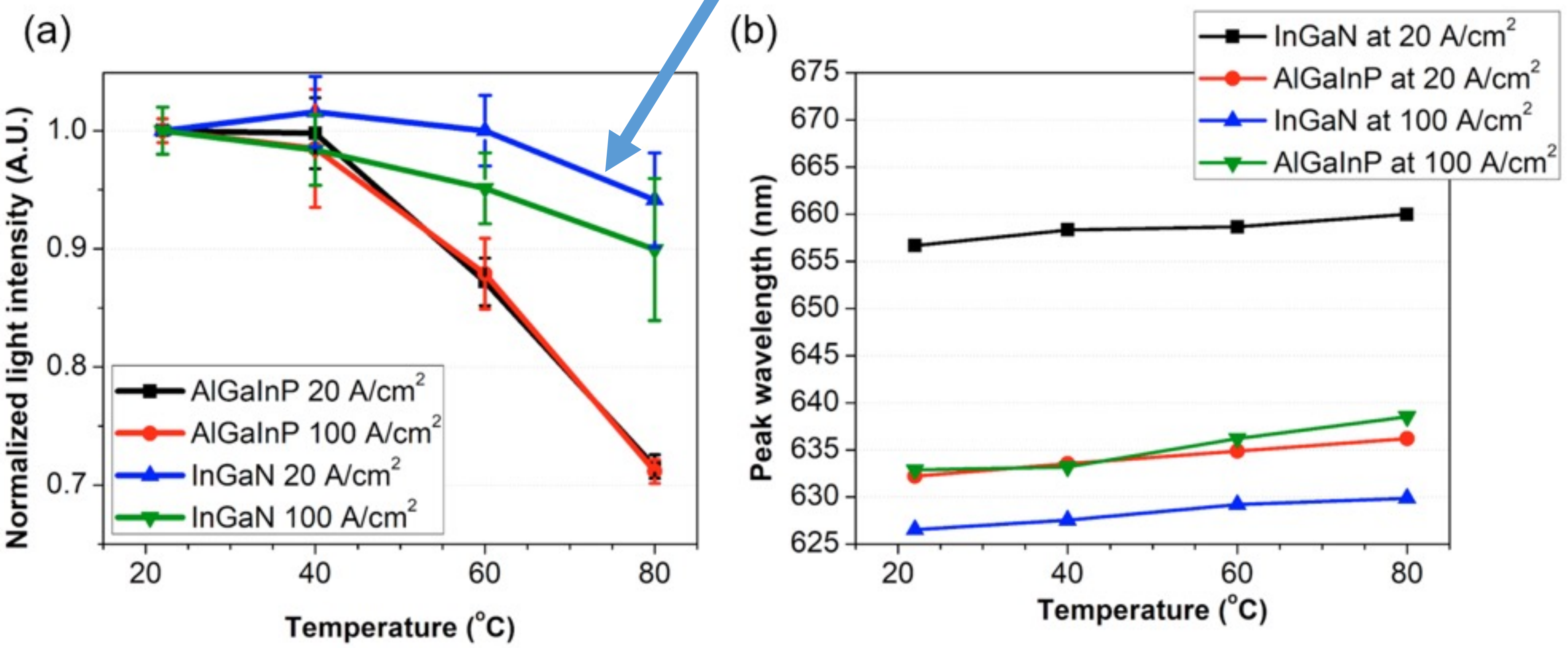
80x80µm^2 red micro-LEDs



Best Reported InGaN
Red MicroLED in the literature

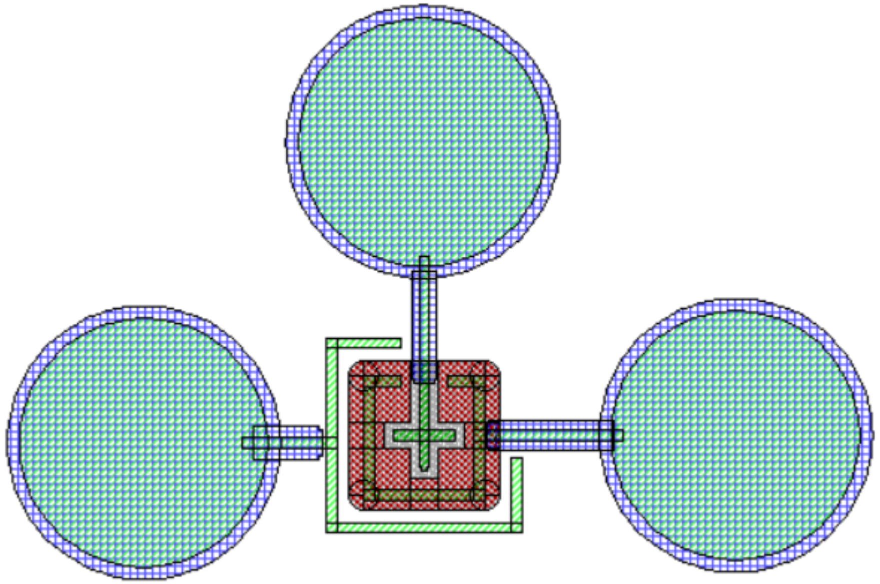
Red InGaN Better Temperature Stability -10% vs. -30%

10% for InGaN versus 30% for AlGaInP

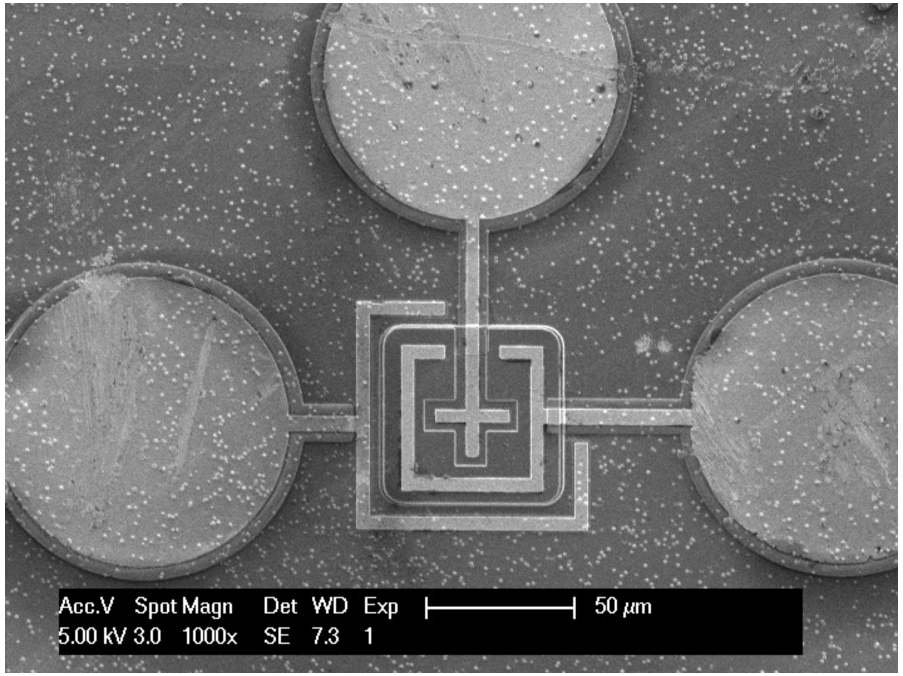


Full TJ Cascaded uLEDs with independent junction control

60*60 micro-LED Mask

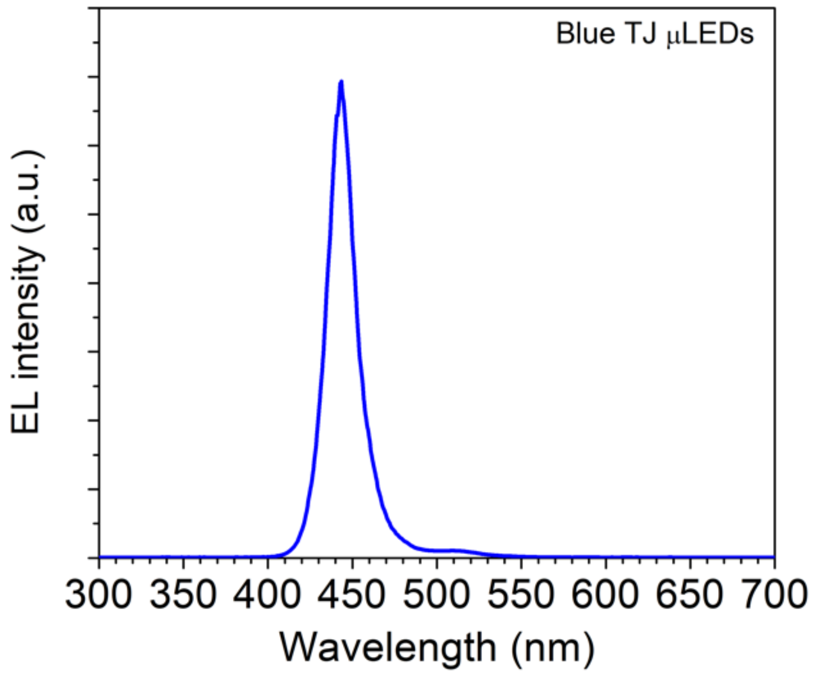


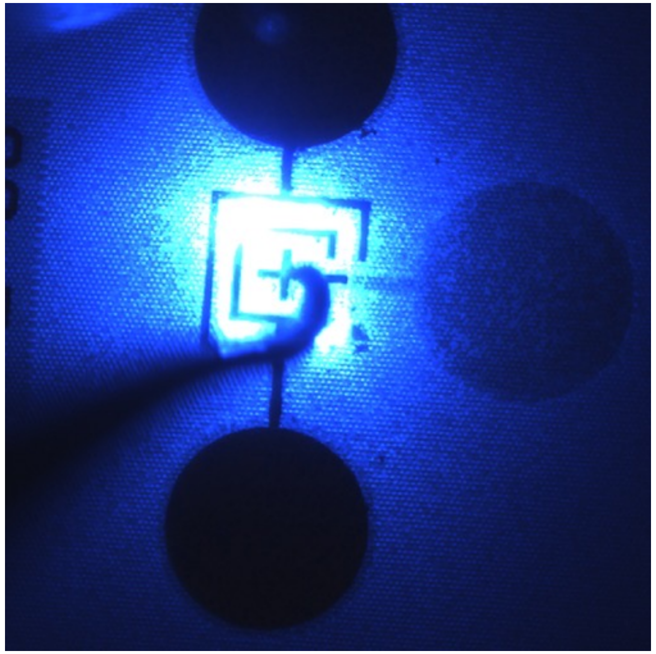
60*60 micro-LED SEM



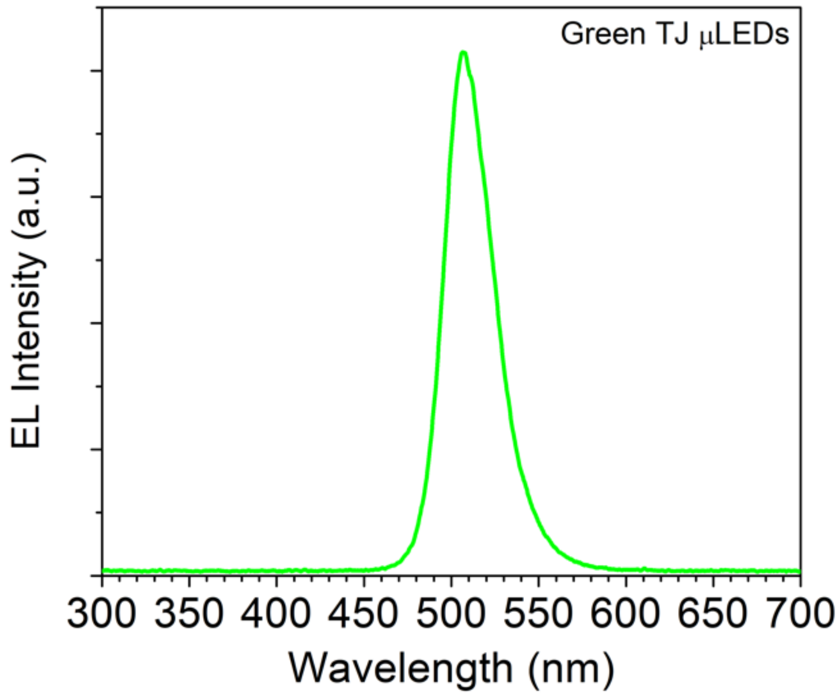
Control blue µLEDs: 449 nm:

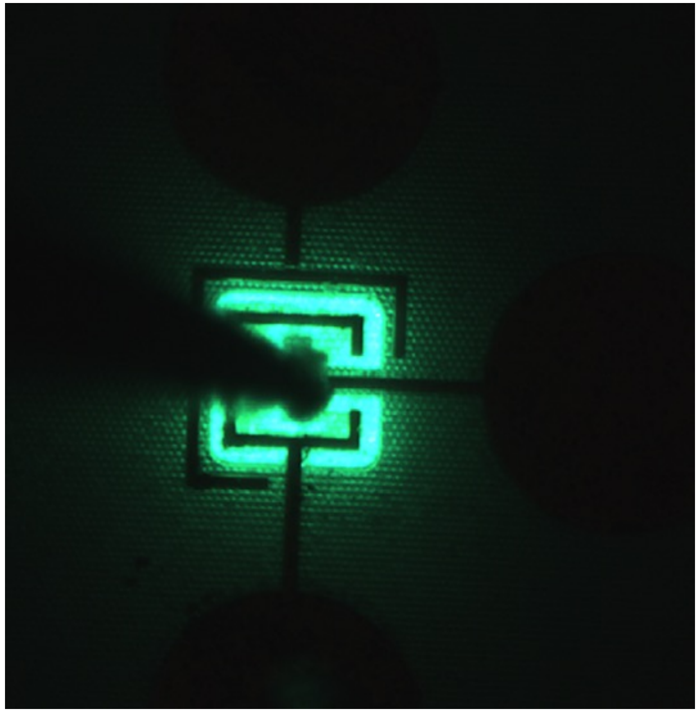
Uniform at low current density





Control green µLEDs: 510 nm; Very uniform emission





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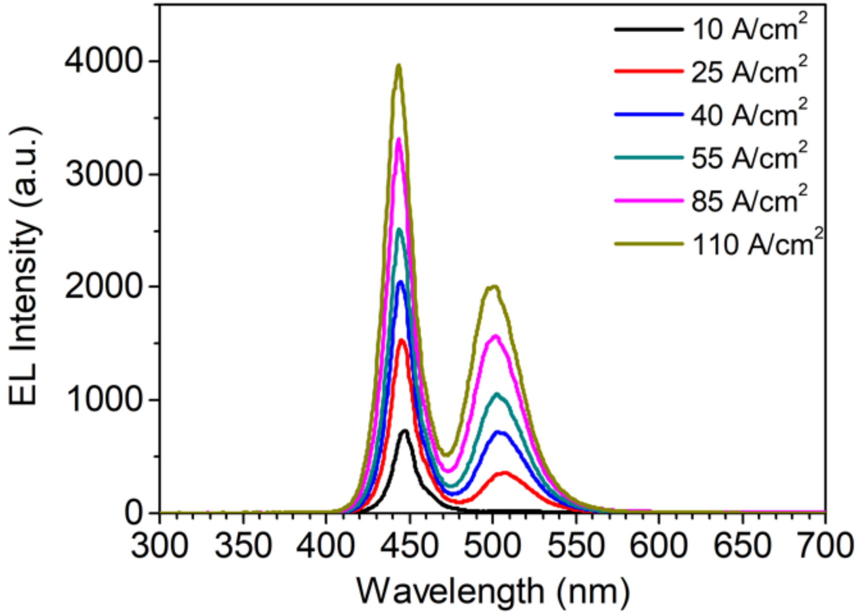
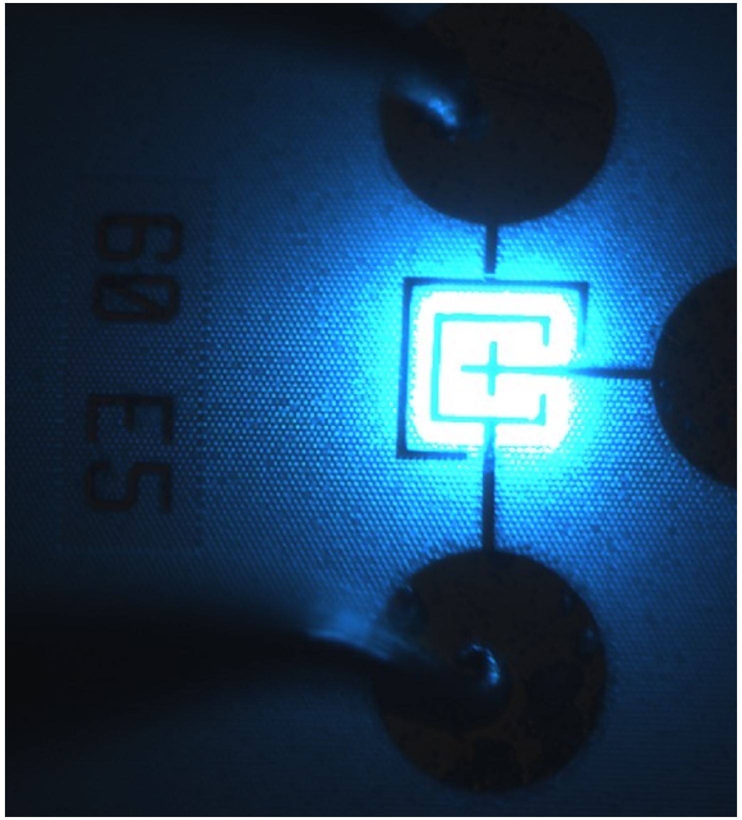
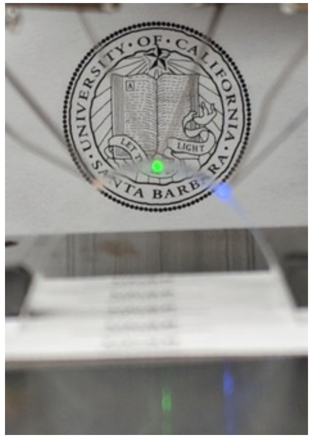
Control blue + green μLEDs Simultaneously

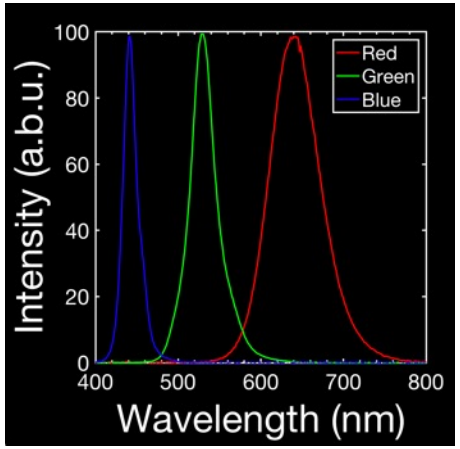




Summary and Future Work

- Utilized PEC Etching for Chip removal
- Demonstrated high EQEs for blue(58%) & Green(24%) µLEDs
- Red MicroLED best reported is 6%, integrate to monolithic RGB pixel
- Proposed tunnel junction use in µLED
- Develop all wavelengths using InGaN for Red, Green and Blue (RGB).
- Integrate RGB µLEDs onto flexible substrate and organic backplane





Thank you for your attention

Questions?