Midinfrared Photonics

TOWARDS HIGHER POWER/EFFICIENCY MULTISPECTRAL MID-INFRARED TYPE-2 III-V SUPERLATTICE LEDS

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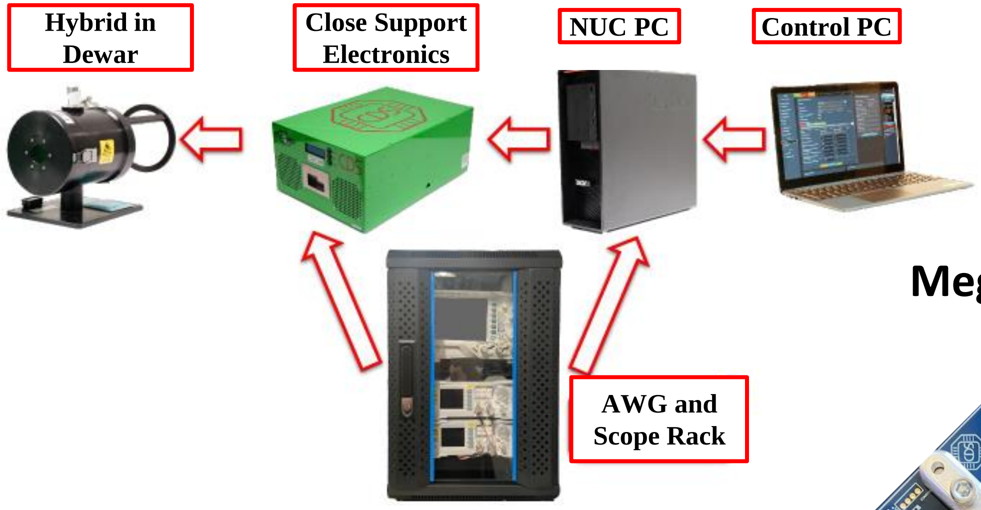
Talk Outline

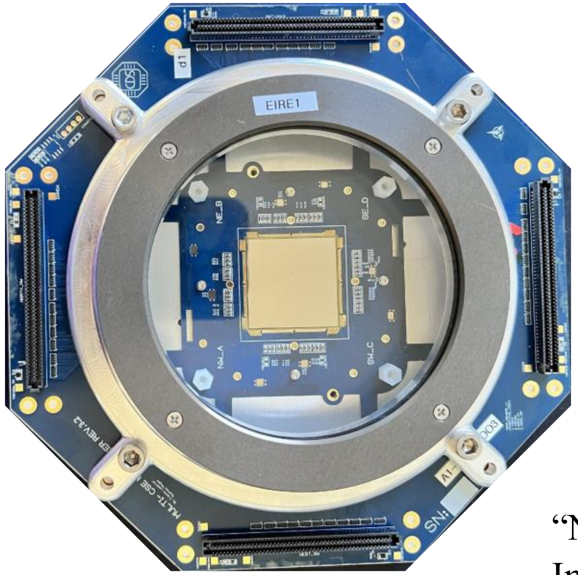
- **Applications**: Mid-ir thermal scene projectors, chemical sensing of gases
- **Limitation:** Mid-IR LEDs have <1% wallplug efficiency
- **Impact:** Thermal droop limits brightness and LED array performance
- **Solutions:** cavities, resonant structures, metamaterial optical structures
- **Future:** VCSELs, droplet quantum dots, and surface polaritonic structures

Thermal Scene Projection



Projector Components

Megapixel Mid-IR LED / ROIC Package

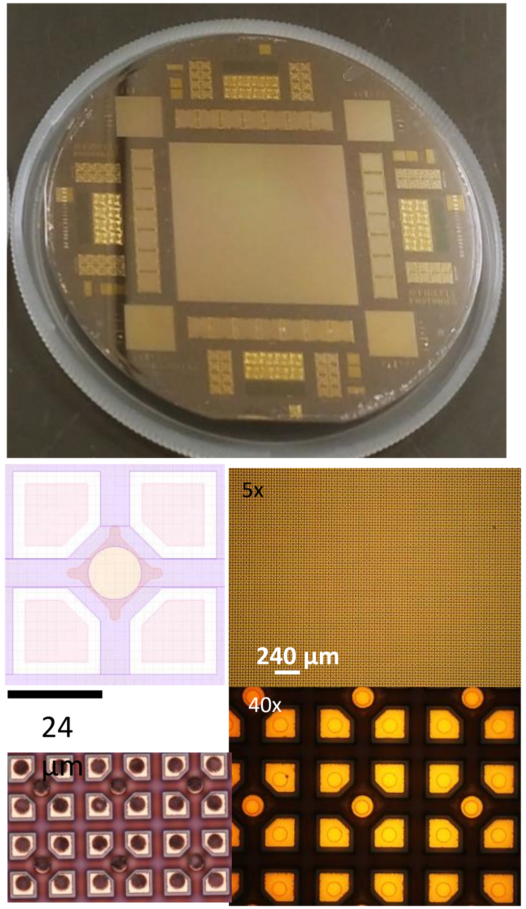


Projected Scenes

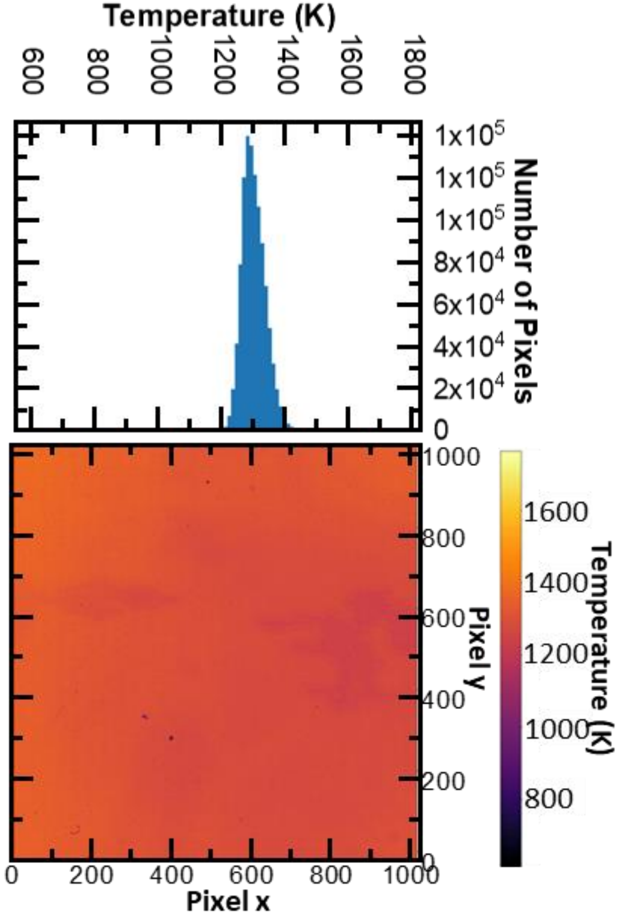
"Next Generation 1024x1024 Individually Addressable Mid-Infrared LED Arrays," in preparation for IEEE J. Quant. Electron.

Megapixel Mid-IR LED/ ROIC Hybrid Performance

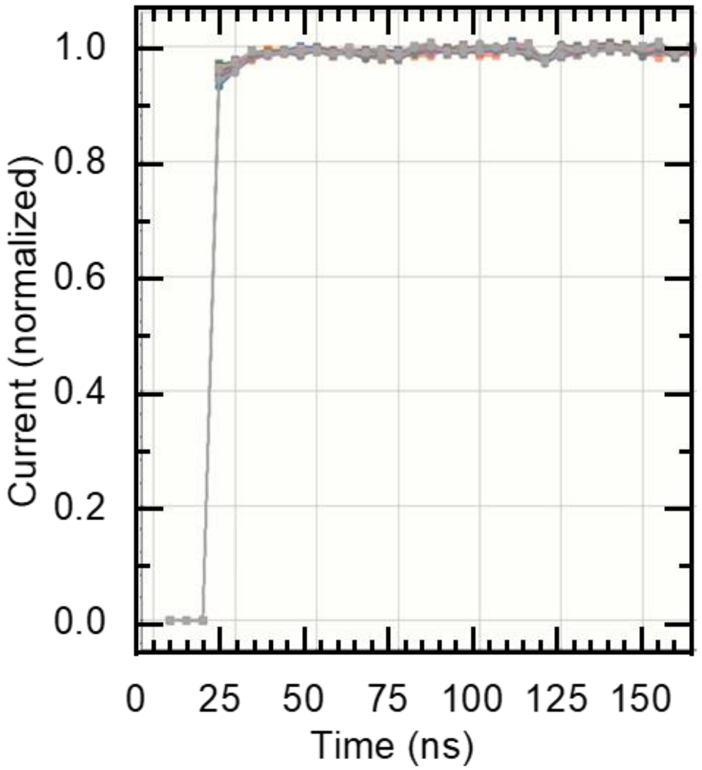
Megapixel LED Array



Hybrid Operability - >99%

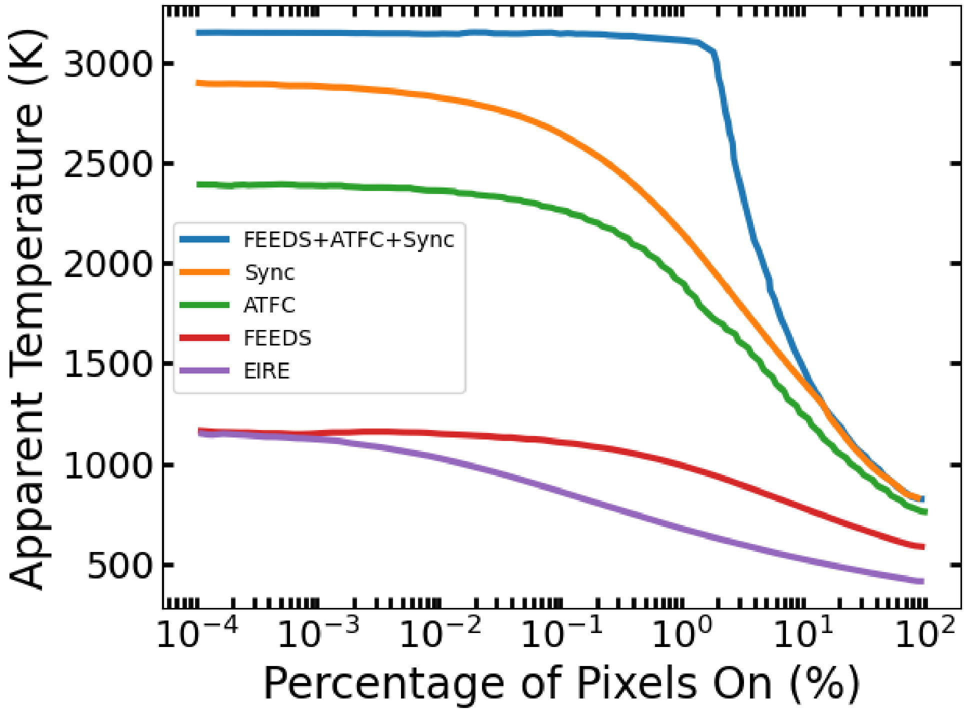


Nanosecond Pixel Risetime (100 MHz)



Thermal Management in Hybrid

- <1% wallplug efficiency of mid-infrared leds limits fraction on due to thermally-induced LED droop
- Motivates improved wallplug efficiency
- Different operational modes:
  - EIRE: baseline demonstration in continuous mode
  - FEEDS: with improved refrigerator
  - ATFC: algorithmic thermal feedback correction
  - Sync: camera and projector synchronized at duty cycle
  - FEEDS+ATFC+Sync: putting it all together



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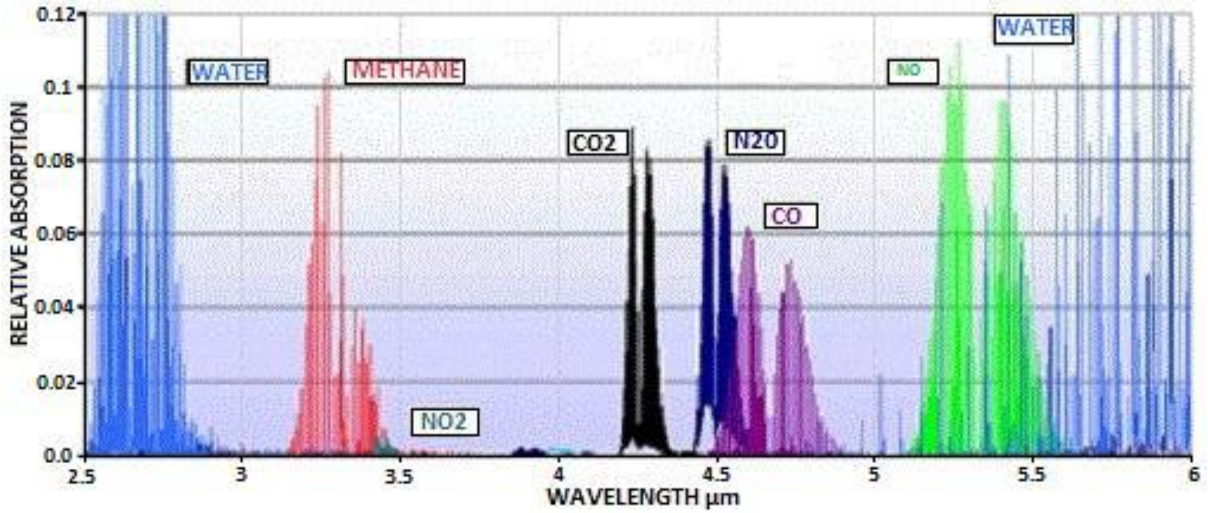
Mid-Infrared LED Uses

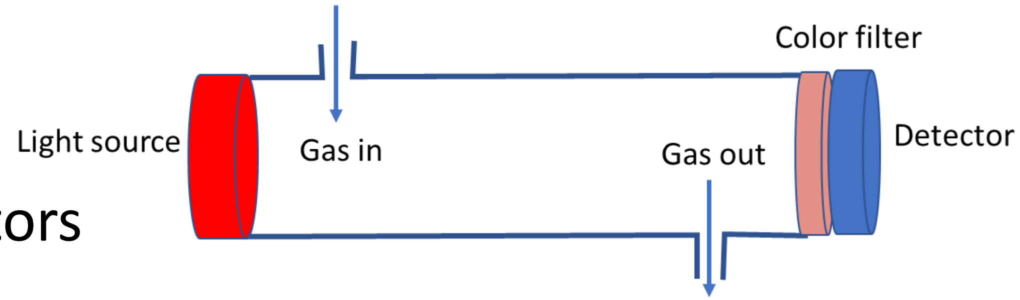
❖ Optical chemical sensing

- Environmental, commercial, medical
- Examples:
    1. Carbon dioxide (CO_2)
    2. Methane (CH_4)
    3. Nitrous oxides (N_2O, NO, NO_2)
    4. Sulfur oxides (SO, SO_2, SO_3)
    5. Volatile organic compounds (VOCs)
- Short settling time, longer battery life, no ignition risk compared to thermal sources

❖ Defense: Interest in use as beacons, flares, illuminators



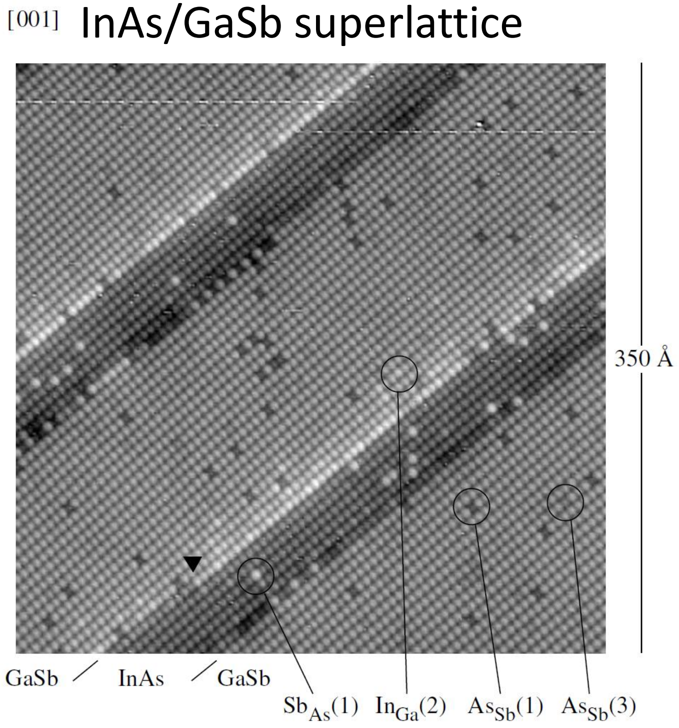
Gibson etal, *Sensors* **13**, 7079-7103 (2013)



NDIR Gas Sensor

Group III-V Superlattices

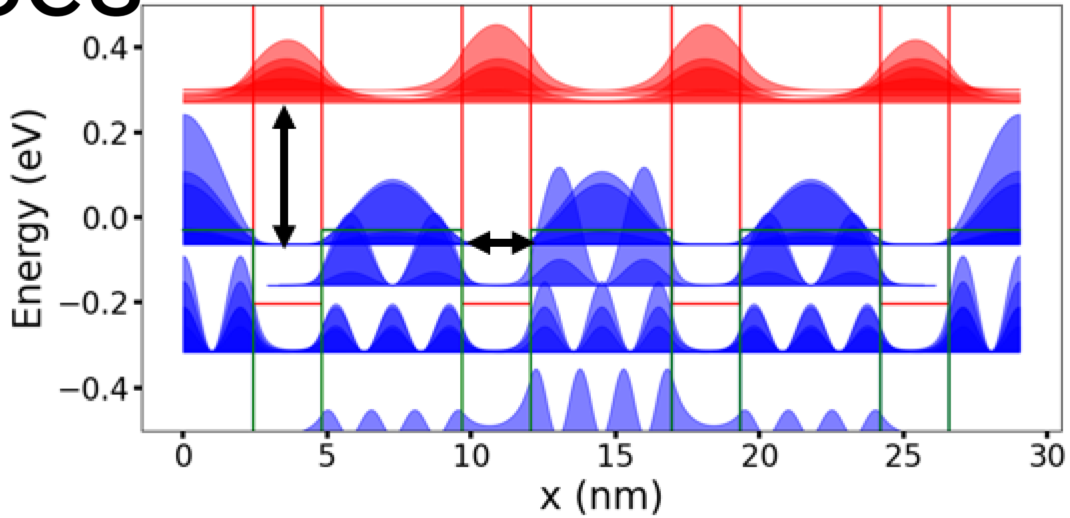
InAs/GaSb superlattice

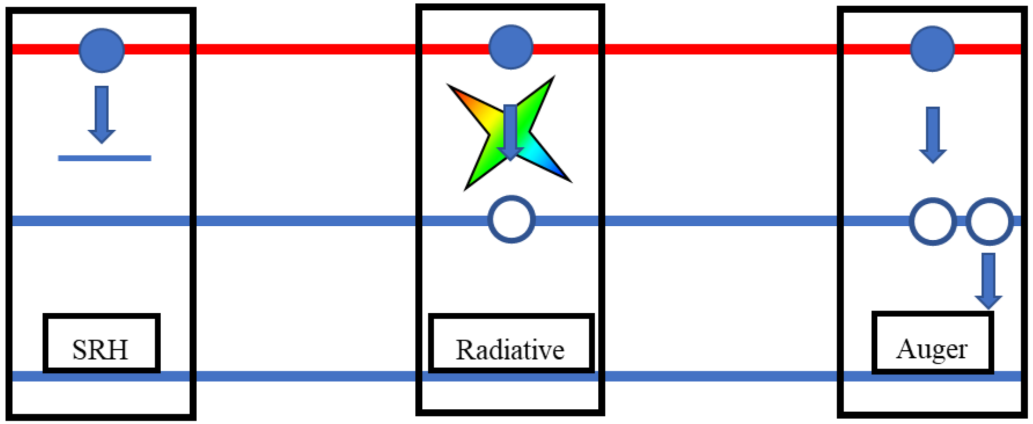


Thin layers a handful of atomic layers thick

[1]Steinshnider etal, *Phys Rev Lett* **85**, 2953 (2000)

InAs/GaSb superlattice
Real space bandstructure



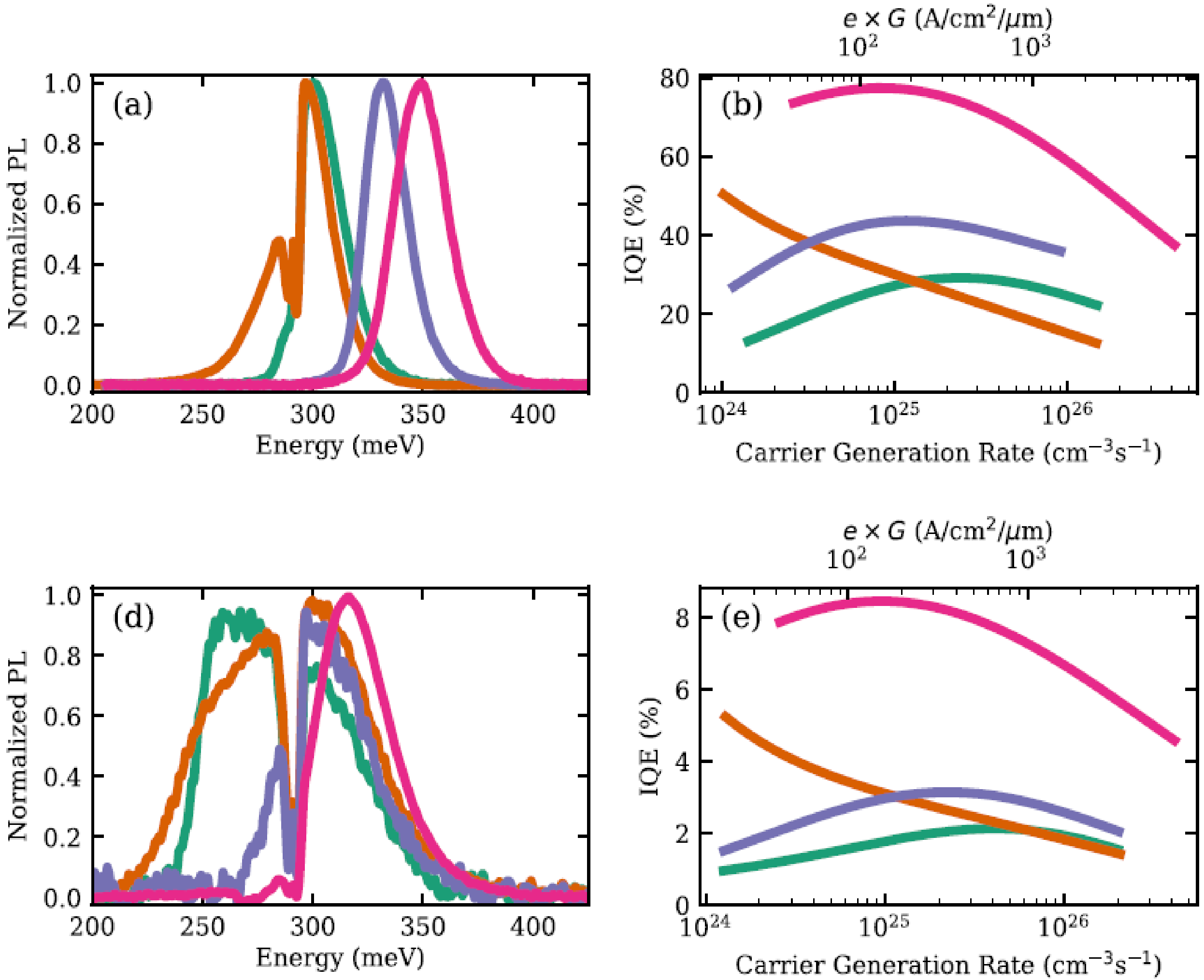


Maximize radiative recombination
Minimize nonradiative recombination (SRH, Auger)

Group III-V Superlattices: Quantum Efficiency

77K data

Room temp data



A – InAs/GaSb

B – InAs/InAsSb

C – InAs/AlGaInSb

D – W-Suplerlattice

Quantum efficiency = photons produced / carrier / stage

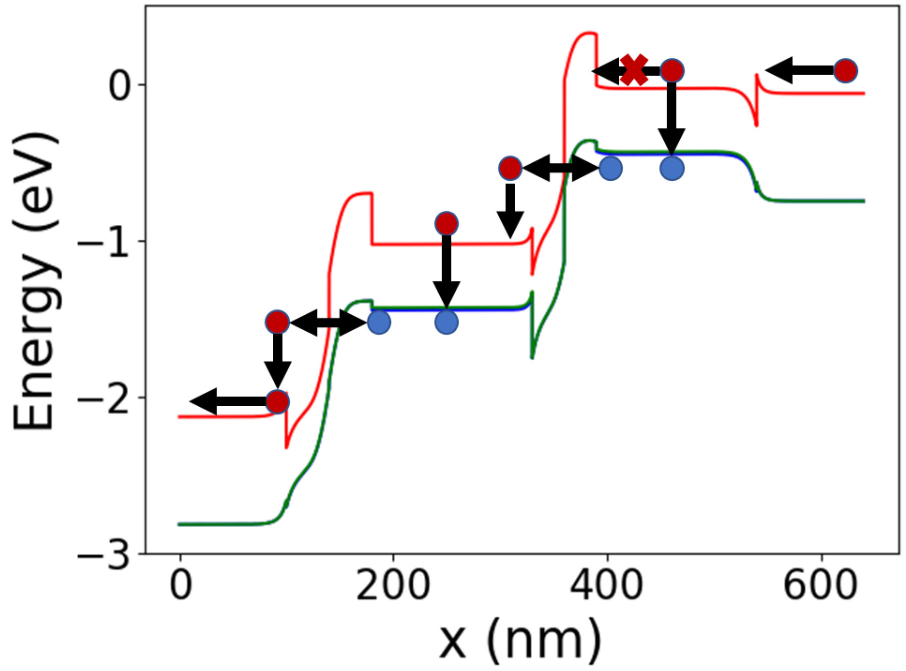
(Wallplug efficiency = power out / power in)

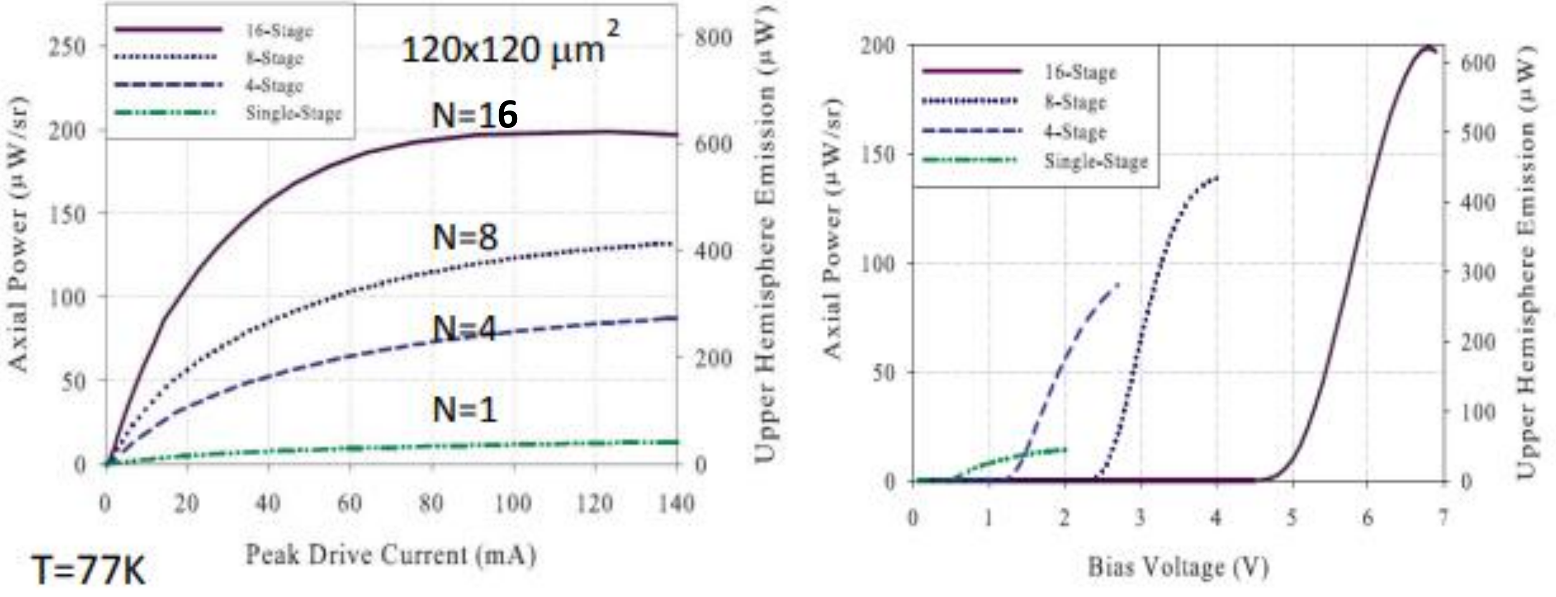
Best internal quantum efficiencies per superlattice family

A.J. Muhowski etal., Appl. Phys. Lett. **117**, 061101 (2020)

C.L. Bogh etal., Opt. Mat. Express **12**, 4261 (2022)

Cascading Emission Regions



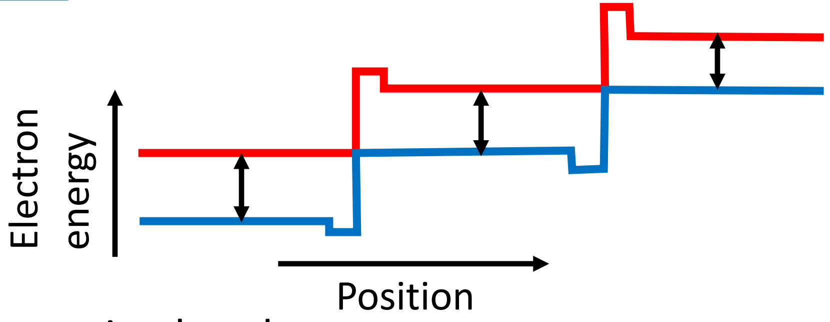


- Emission regions in series via tunnel junctions
- Carrier recycling

- Cascading allows tailoring current-voltage characteristics of device to battery / control electronics
- Reduced current operation reduces ohmic loss

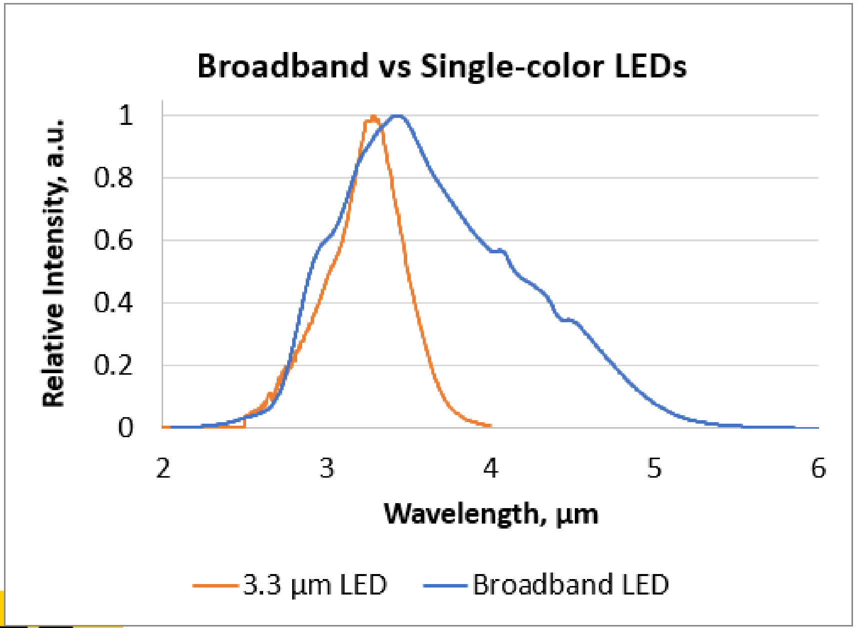
E.J. Koerperick etal., IEEE J. Quantum Elecron. 44, 1242 (2008)

Broadband and Multi-Spectral IRLEDs

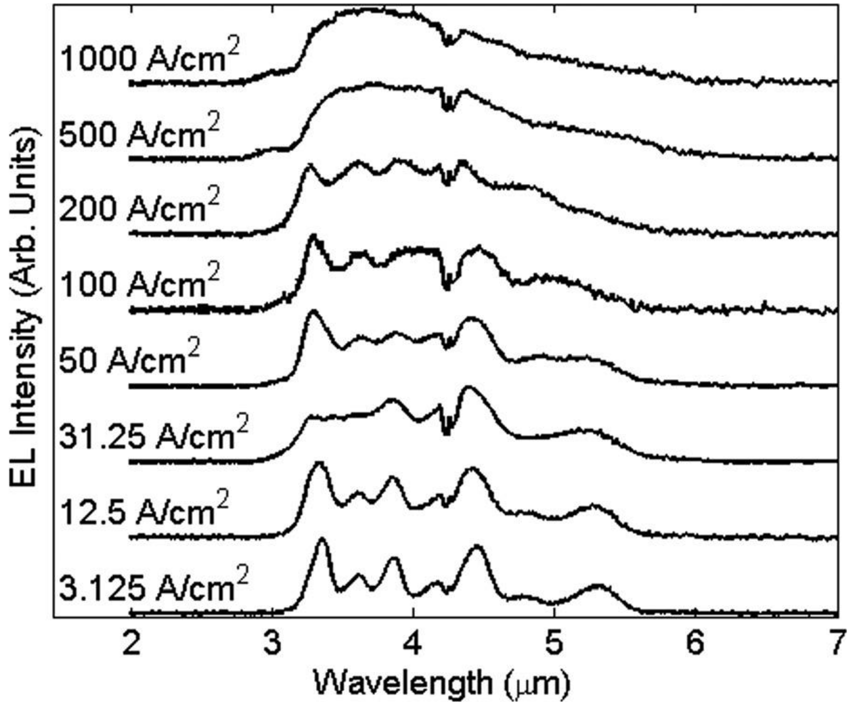


Increasing bandgap energy per stage

Room temperature, 5 stage



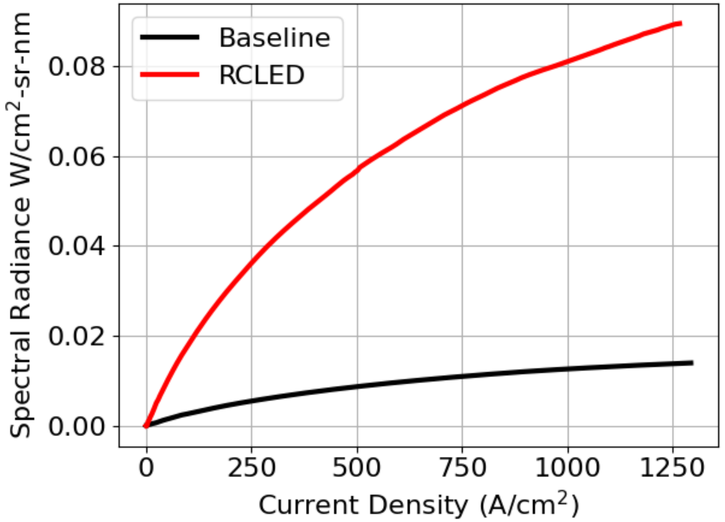
Original demonstration: 8-stage, 77K

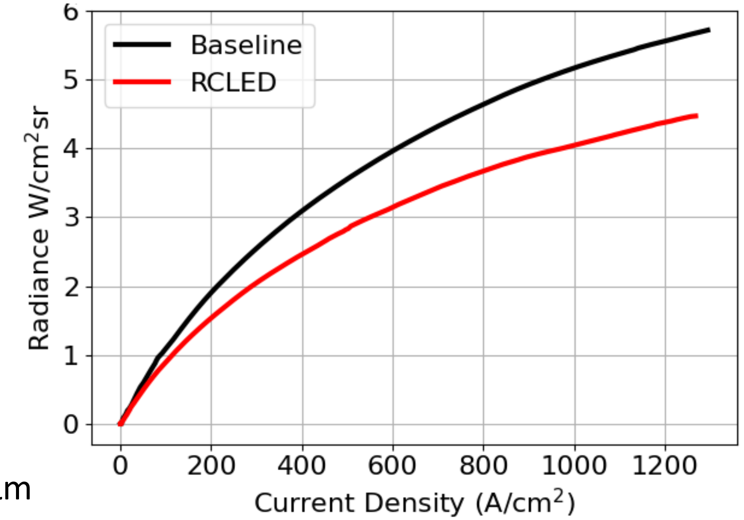


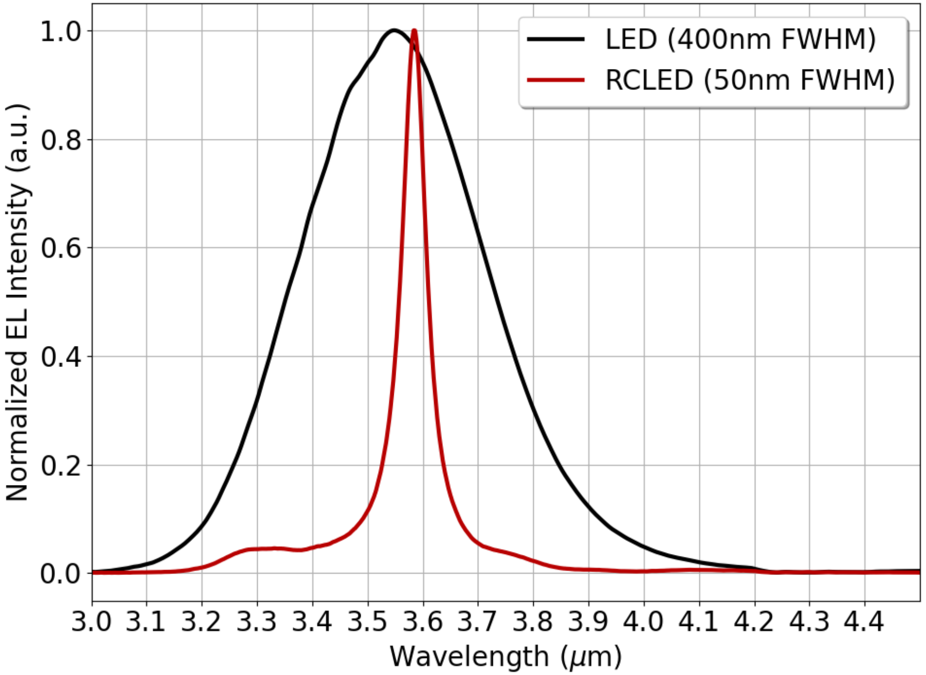
Ricker etal, *J. Appl. Phys.* **121**, 185701 (2017)

Full Cavity: Narrowband Emission With Enhanced Spectral Radiance

- Narrowband emission
- Observed enhanced spectral radiance
- Emission wavelength more stable with temperature





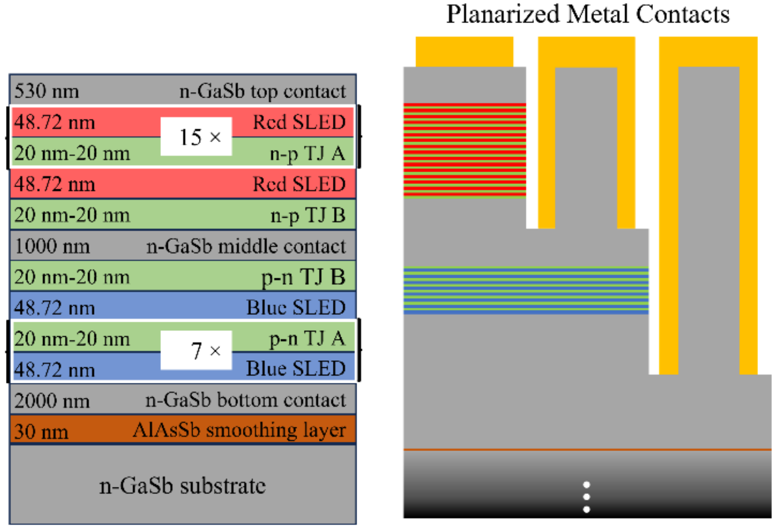


77K, 3.6 μm

K.N. Schrock etal,l J. Appl. Phys. **135**, 183101 (2024)

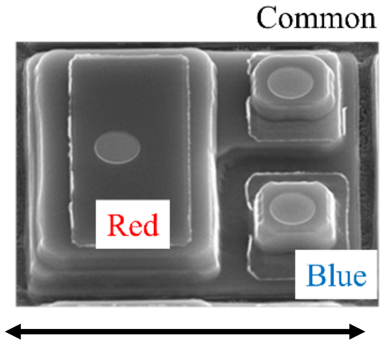
Two Color Monolithic Mid-IR LED without / with Red Cavity Incorporated

Monolithic two-color pixel

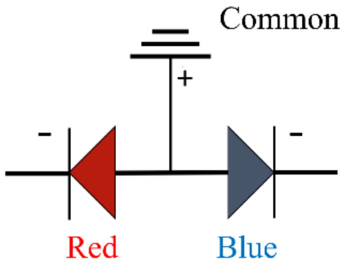


Non-cavity 2 color SLED

(a) (b)

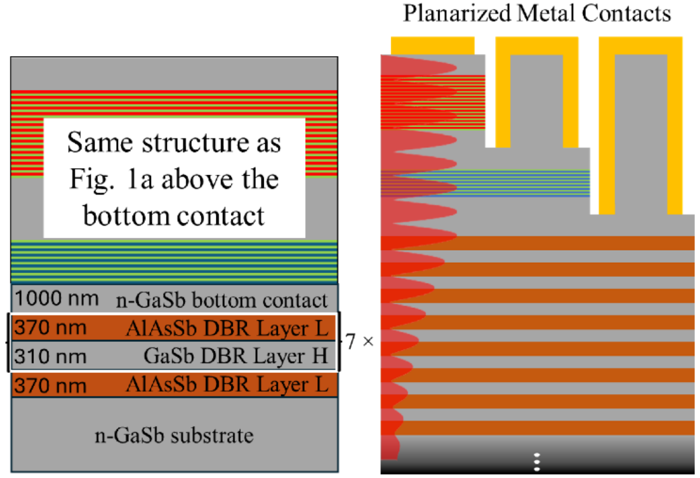


48 µm



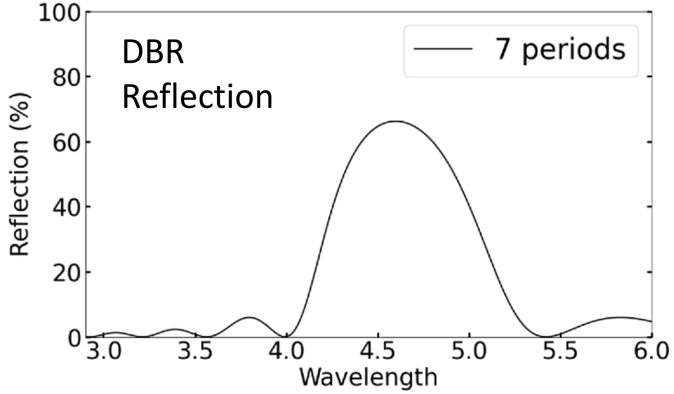
(d)

Monolithic two-color pixel with incorporated red cavity



Cavity 2 color SLED

(a) (b)



(c)

D.A. Montealegre etal, IEEE J. of Quantum Electron. **61** (4), 3200108 (2025)

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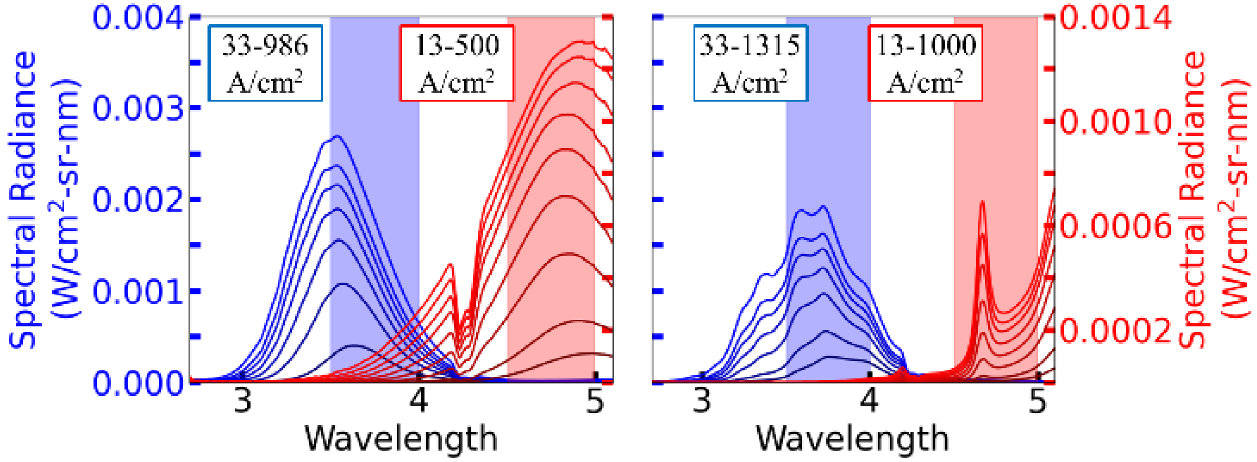
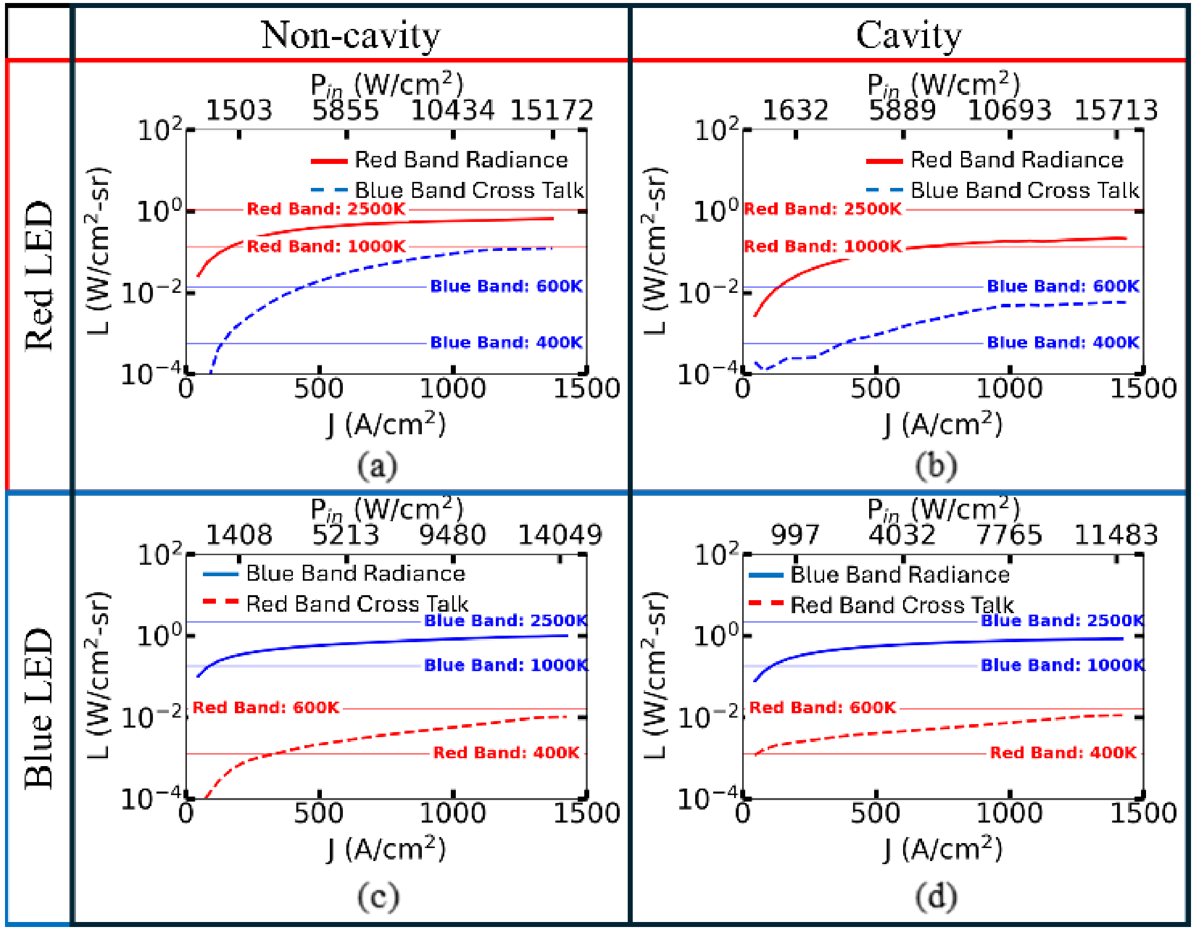
Two Color Monolithic Mid-IR LED with Red Cavity Incorporated





- Independent color control demonstrated in 48 um pixel
- Color crosstalk an issue in two mid-infrared red/blue bands
- Incorporated red cavity can reduce cross talk but at a price

D.A. Montealegre etal, IEEE J. of Quantum Electron. **61** (4), 3200108 (2025)

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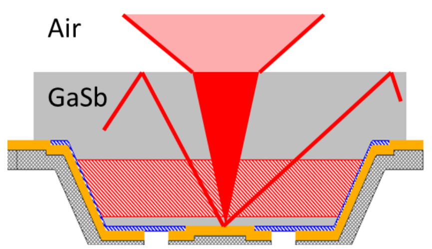
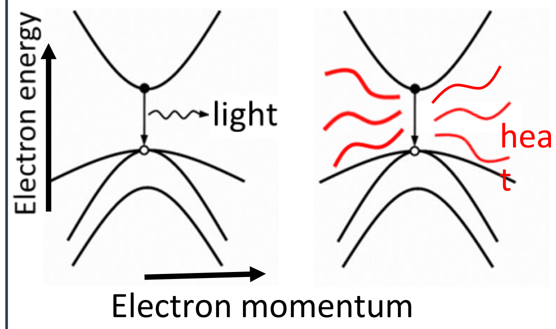
Why is Wallplug Efficiency So Low?

	$\eta_{extraction}$		$\eta_{internal\ quantum\ efficiency}$		η_{ohmic}		$\eta_{quantum\ defect}$	
$\eta_{wallplug\ 77K} \sim$	2-7%	x	80%	x	70%	x	70%	~ 0.7 - 3%
$\eta_{wallplug\ RT} \sim$	2-7%	x	8%	x	70%	x	70%	~ 0.1 – 0.3%

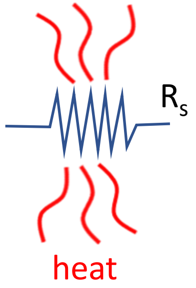


Light extraction efficiency

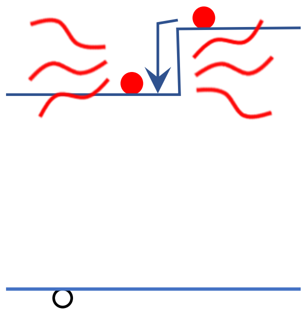
n ≈ 3.8



Internal quantum efficiency



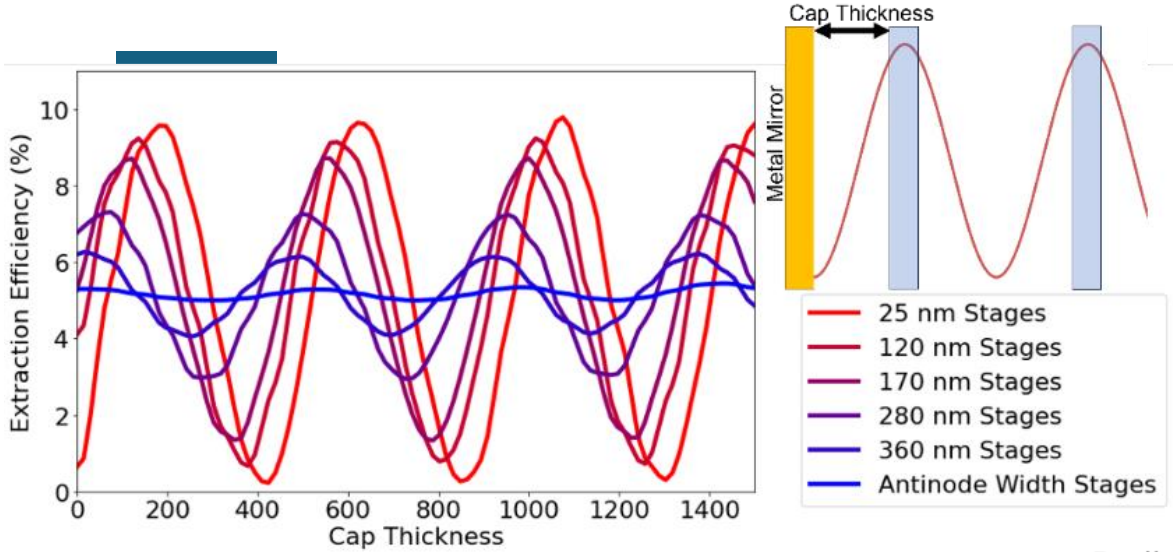
Ohmic efficiency



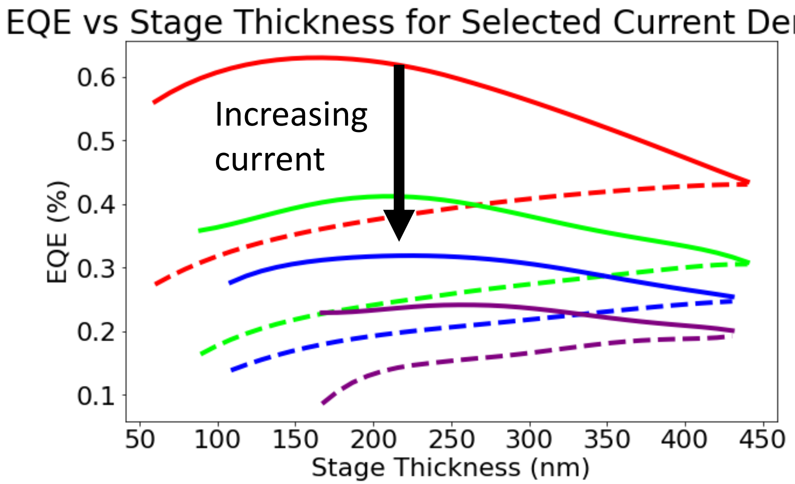
Quantum defect efficiency

Total internal reflection: $\eta_{extraction} \approx 1/2n^2 \approx 3\%$

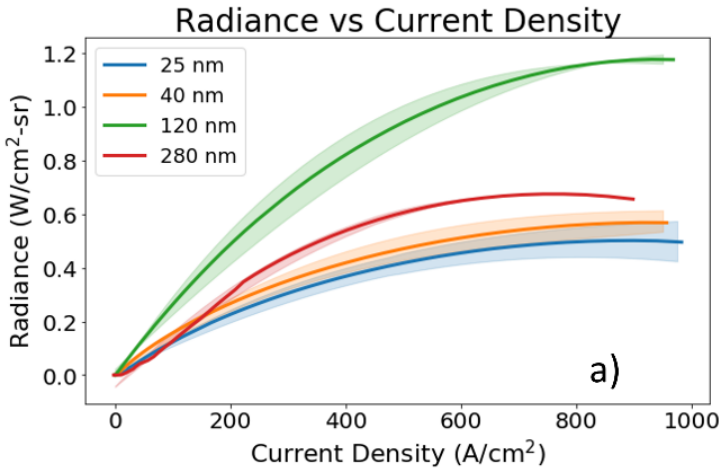
Enhanced Extraction Efficiency in Half Cavity

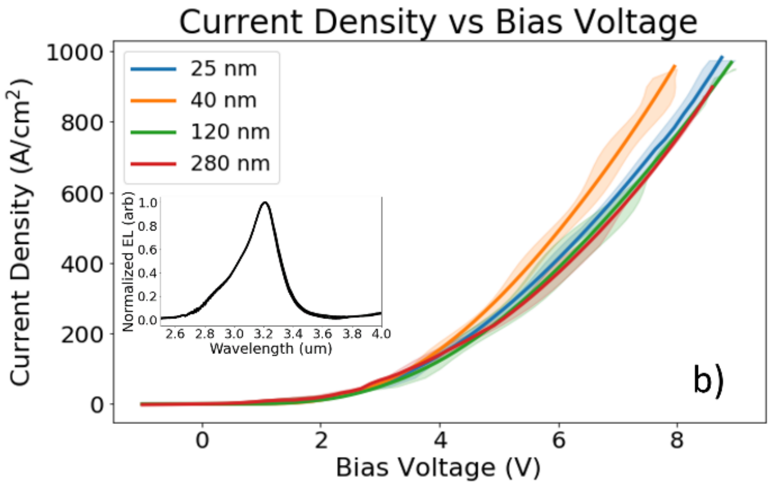


- Half cavity enhances extraction efficiency without narrowing spectrum
- Stage thickness: Auger vs. cavity effect



Room temp, 3.3 um emitter

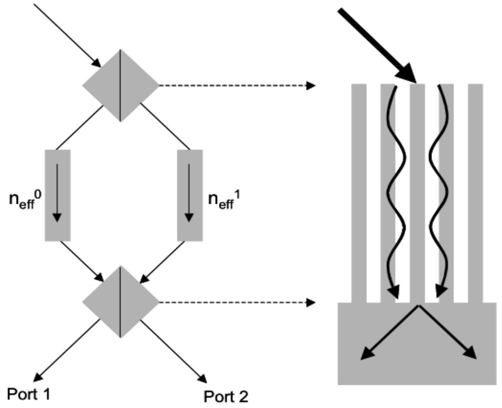


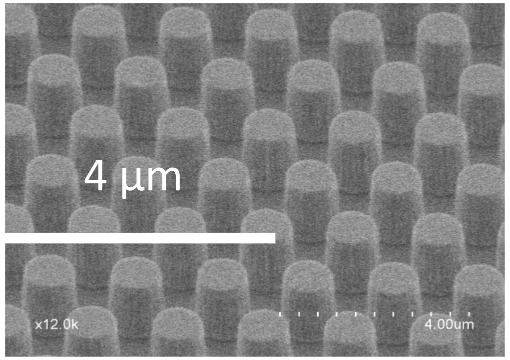


K.N. Schrock etal,l J. Appl. Phys. **135**, 183101 (2024)

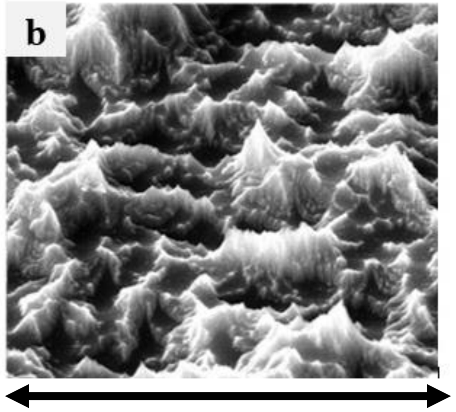
Simplest Strategy: Texture the Backside

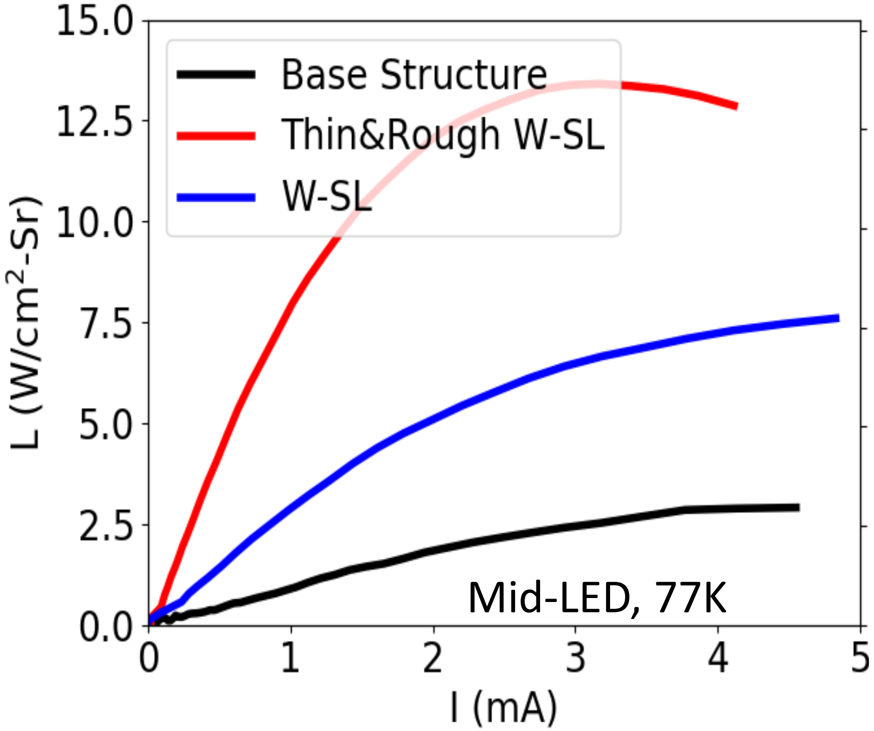
Maximum 2-3x enhancement in extraction





45˚ Angle

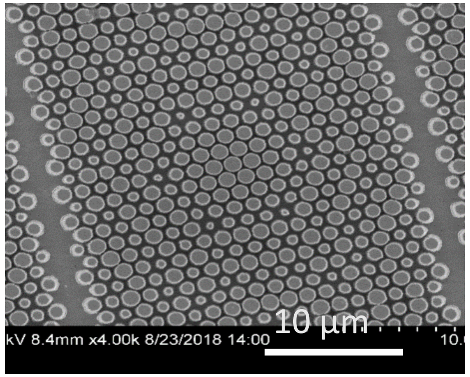




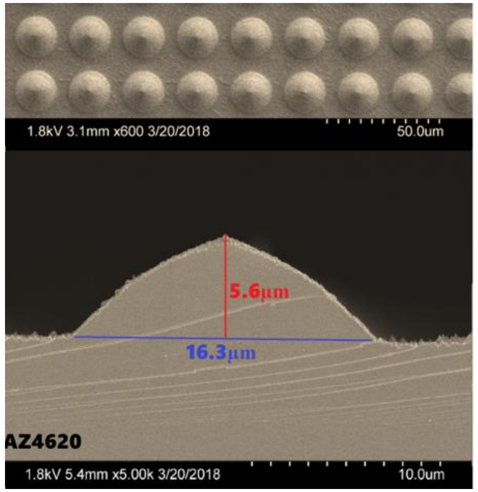
D.A. Montealegre etal, Appl. Phys. Lett. **118**, 071105 (2021)

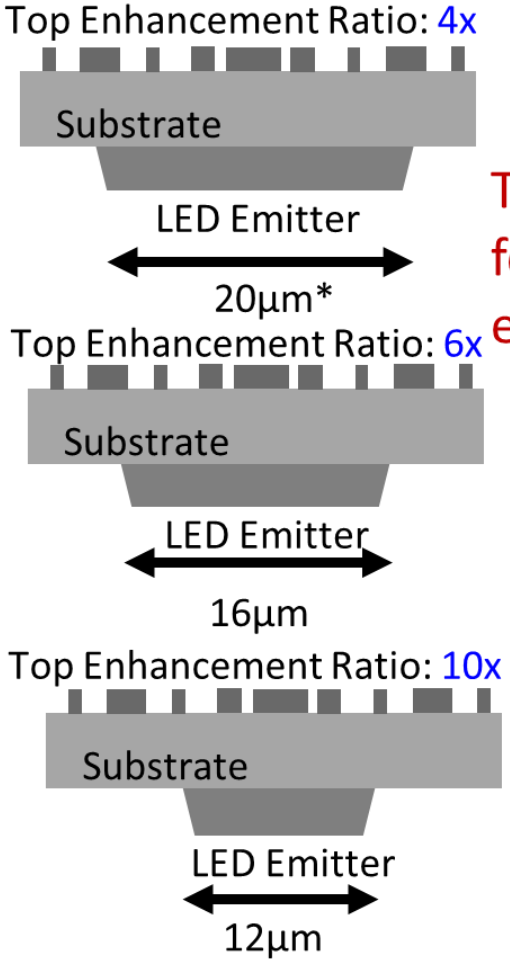
Enhanced Light Extraction with Lenslets

~10% efficient

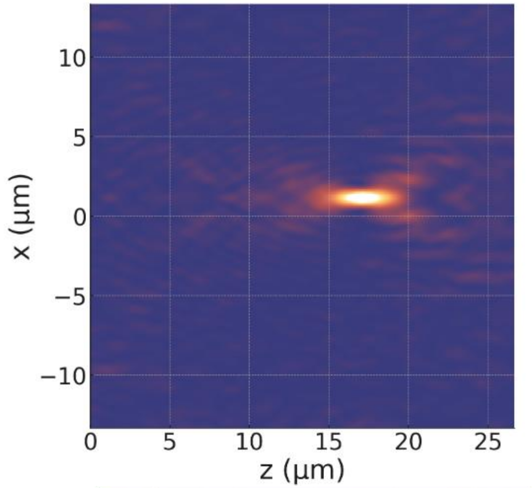


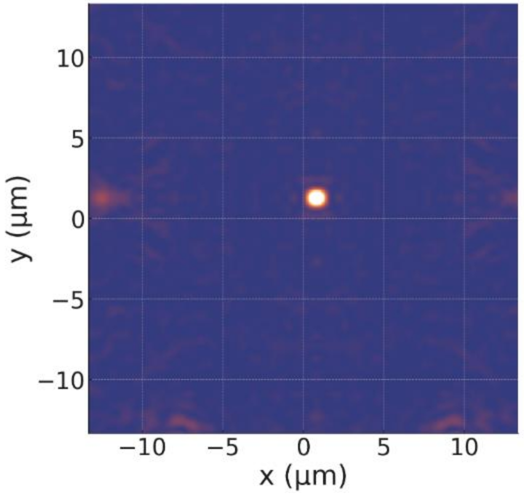
~70% efficient





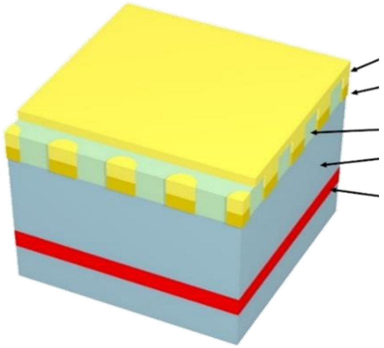
Trade fill factor for extraction efficiency

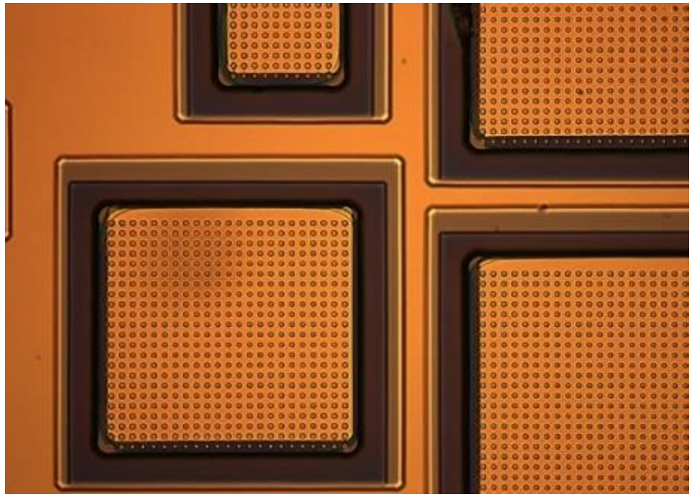


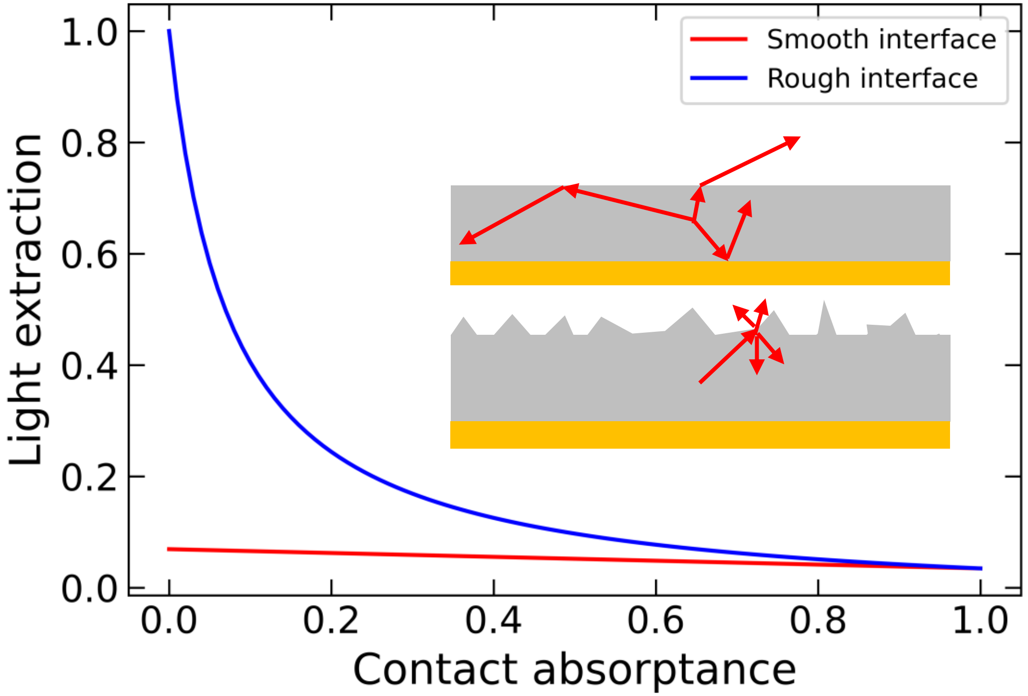


C.L. Bogh, ACS Appl. Electron. Mat. **2**, 2645 (2020)

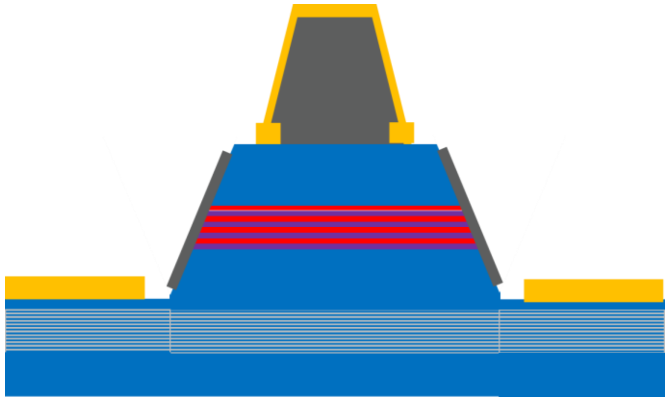
Low Loss Metal Contacts for Enhanced Light Extraction



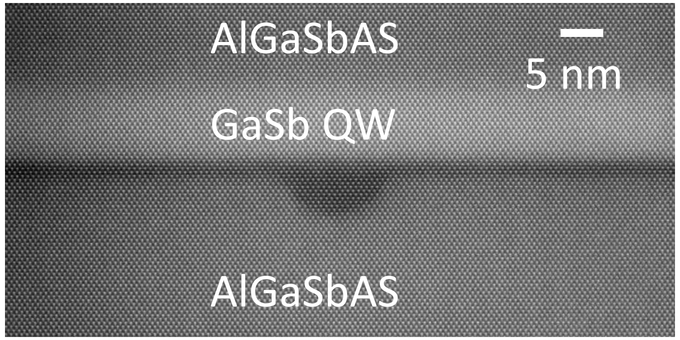


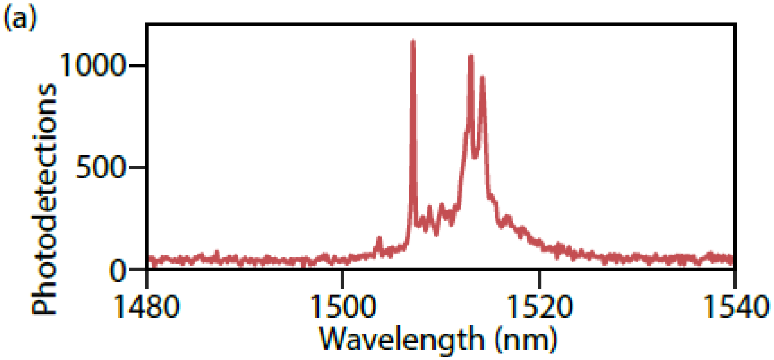


Some Current and Future Directions

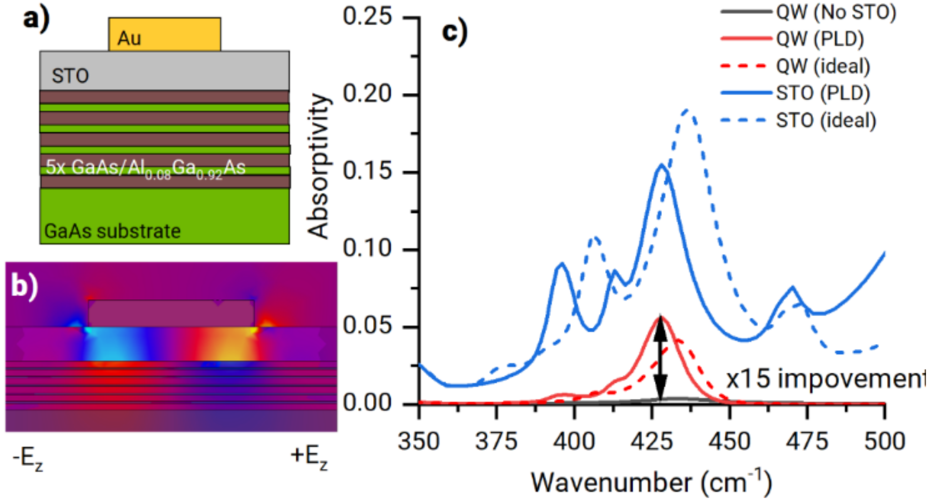


- Mid-infrared VCSEL: stimulated emission to extract light and enhance room temperature quantum efficiency





GaSb droplet epitaxial dots for telecom single photon emitters – 10x less inhomogeneous broadening than SK dots



Surface phonon-polaritons for low loss Purcell enhanced emission / absorption in the long / very-long wave infrared

I.M. Masson etal, ACS Nano, submitted (2025)

M. Pradhan, Submitted to Opt Mat Express (2025)

IOWA

Conclusions

- Demonstrated 1024x1024 mid-infrared hybrid LED arrays with >99% operability
- Achieved nanosecond pixel risetimes and improved thermal management
- Demonstrated broad, narrow, and multi-spectral emitters
- Identified primary efficiency bottlenecks and proposed solutions
- Next: pursue mid-IR VCSELs, droplet epitaxial quantum dots, phonon-polaritonic structures