IOWA

Midinfrared Photonics

Compound Semiconductor Innovation and Antimonide Infrared Emitters

Opportunities and Challenges

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Nov 9, 2022

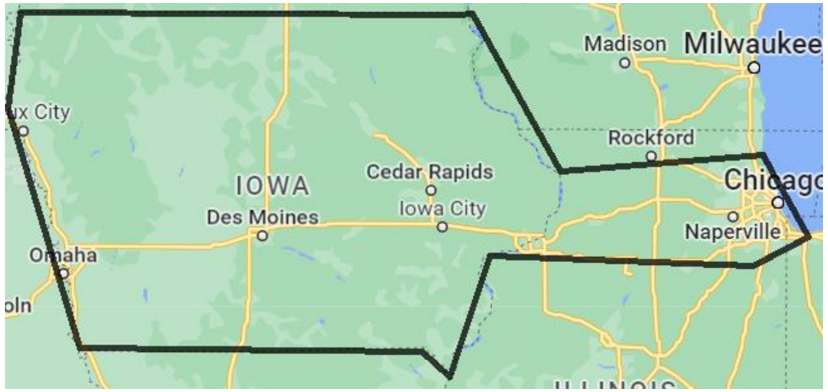
NSF Regional Innovation Engines Competition from Technology Innovation Partnerships (TIP)

- Authorized by CHIPS and Science Act
- $1M Type 1 (<2 yrs), $160M Type 2 (10 yrs)
- **Regional** innovation ecosystems, accelerate translation of use-inspired research to manufactured products
- Solutions to pressing societal problems (e.g. chips shortage!)
- Focus on security, STEM, innovation environment, DEI, underdeveloped heartland regions

Proposed (Type 1) NSF (TIPS) Regional Compound Semiconductor Manufacturing Hub

Purpose and vision: A compound semiconductor innovation ecosystem and manufacturing hub

- An end-to-end foundry for advanced manufacturing of compound semiconductors, including III-V, II-VI, and 2D
- Manufactured semiconductor products
- Expanded compound semiconductor user facilities to grow use-innovation and expand training
- An expanded and diverse semiconductor workforce at all levels



Region: Iowa – Chicago Metropolitan

Iowa City – Chicago high speed rail coming

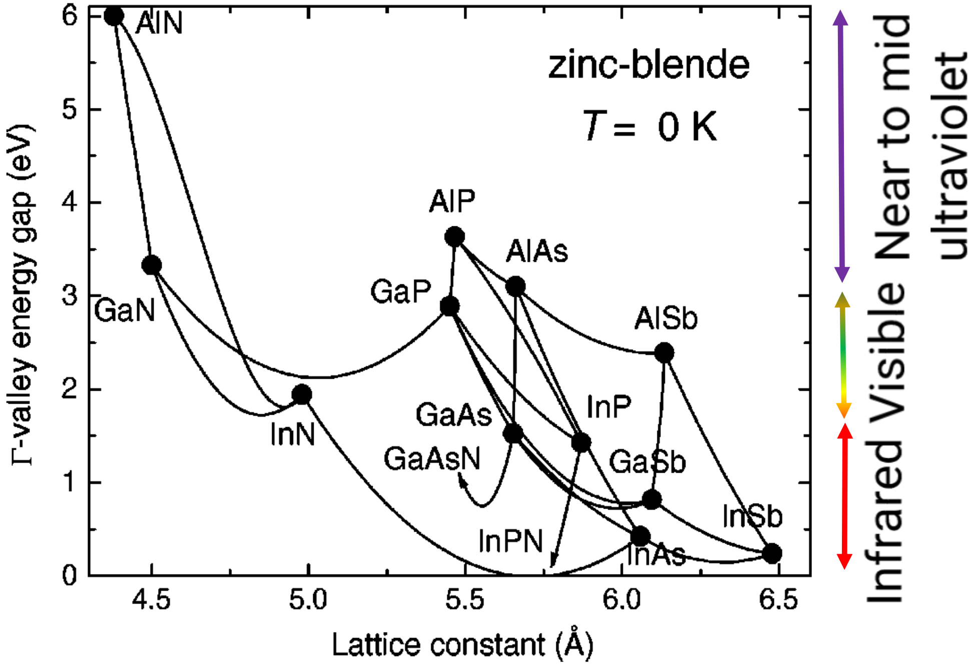
Midwest Advanced Semiconductor Innovation and Manufacturing Workshop

Compound Semiconductor Focus
Coming January 2023
Iowa City, IA

- Emerging Advanced Semiconductor Technologies
- Semiconductor Needs and Opportunities for the Region
- Recruiting and Training Diverse Semiconductor Talent in the Region
- Building a Semiconductor Innovation Ecosystem
- Semiconductor Manufacturing Hub Benefits to the Region

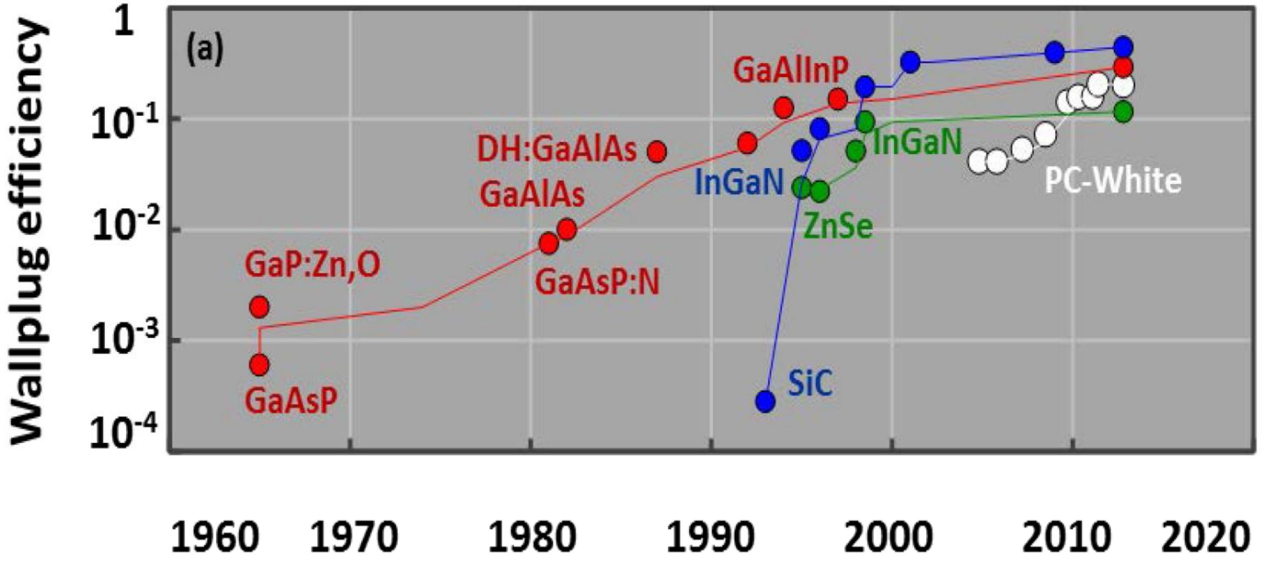
Compound Semiconductor Technology

- Compound semiconductors crystals with unit cell based on two or more elements (III-V, II-VI, 2D, etc; e.g. GaAs, HgCdTe, MoS_2)
- Have key advantages over silicon in speed, power, efficiency, and ability to produce/detect light
- Compound semi technologies include:
  - Visible LEDs (lighting, displays)
  - Telecom (wireless, fiber optics, etc)
  - Other optoelectronics (solar, sensors)
    - UV to Thz
  - Power electronics
- Important to technologies of the future
  - Electric vehicles, self-driving cars, internet of things, quantum computing, more



Group III-V Semiconductors

R&D of Red and Blue LEDs

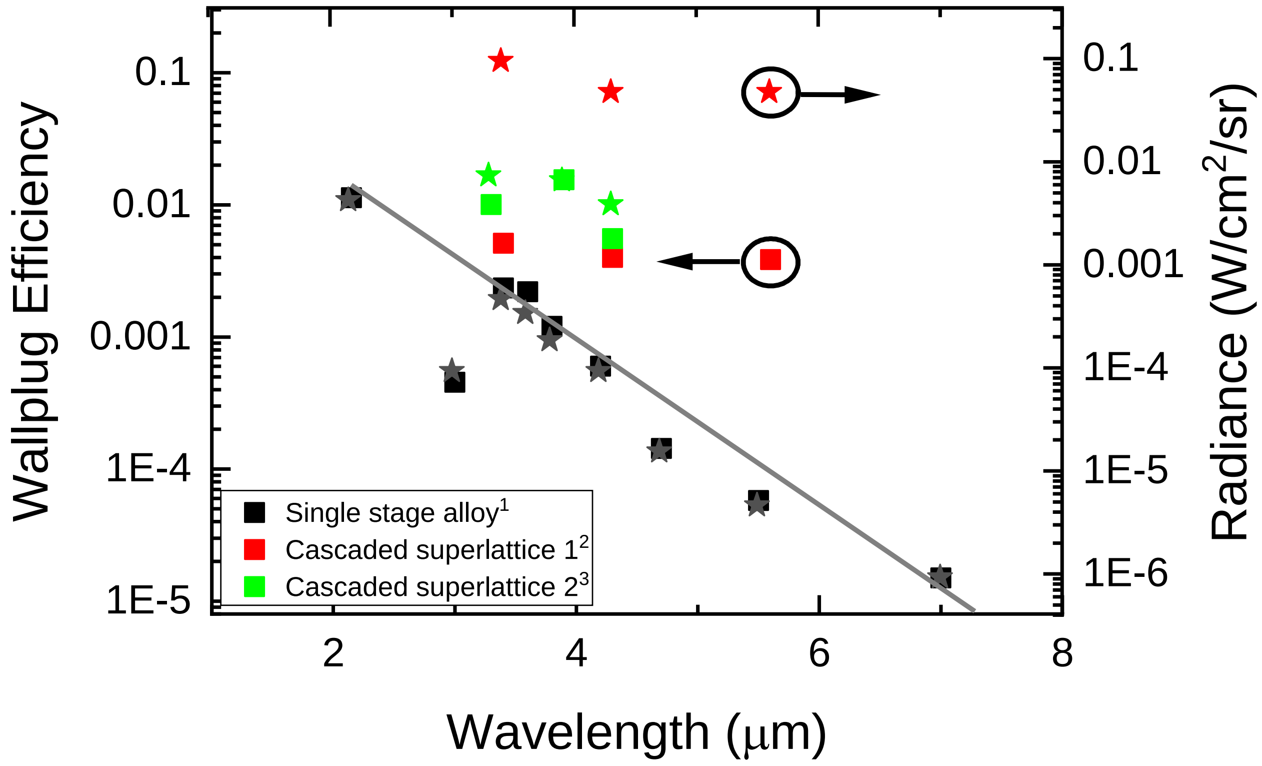


- 30 years for red LEDs to go from few tenths to >10% efficiency
- Less than a decade for blue LEDs to go from a tenth to >50% efficiency

Crawford etal in D.L. Andrews, Ed., “Photonics Volume 3: Photonics Technology and Instrumentation” (Wiley, 2013).

R&D of Mid-Infrared LEDs

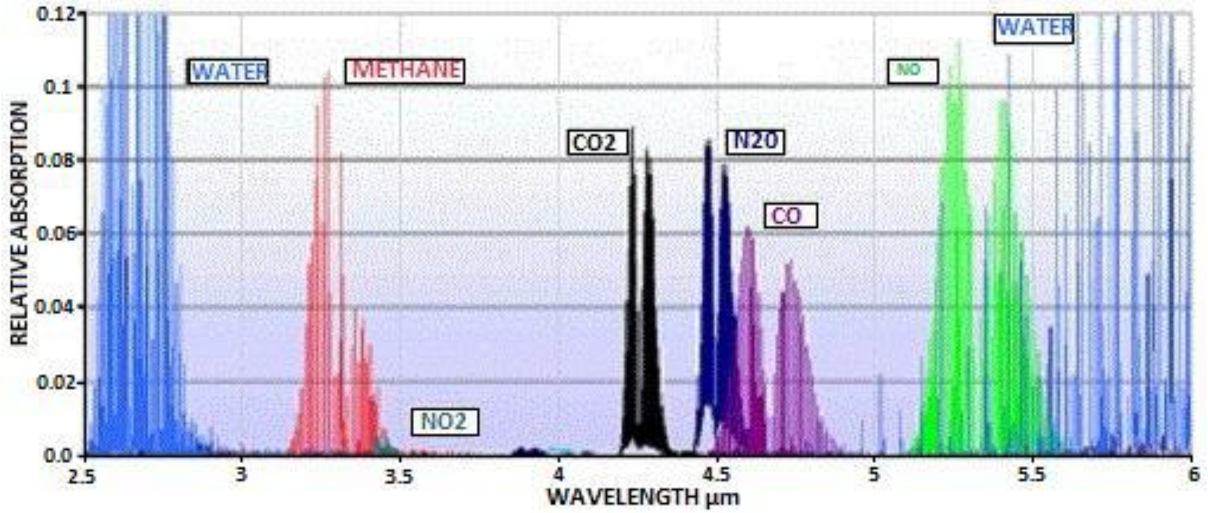
- Single stage alloys developed between ~1990-2005
  - InAsSb/InAsSbP, AlGaInAsSb/GaSb
- Cascaded superlattices developed ~2006-present
- Superlattice LEDs have higher wallplug efficiency and especially higher radiance
- Powers in small chips 1-5 mW, tenths of a percent efficiency, costs of $5-$350
- Packaging, cost, licensing matter in addition to performance



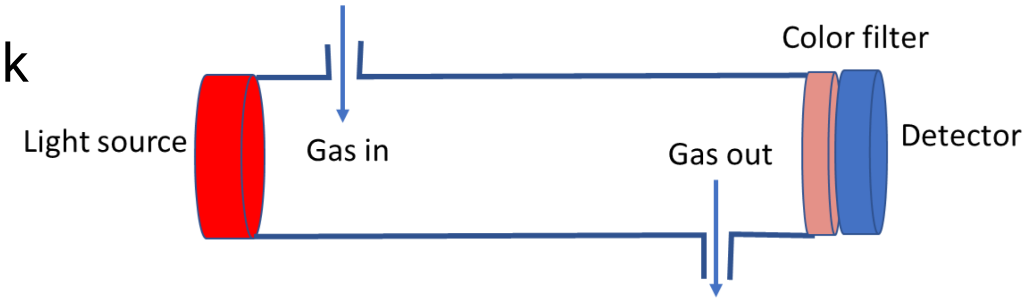
[1] Boston Electronics
[2] Nanoplus
[3] Hammamatsu

Mid-Infrared LED Uses

- Optical chemical sensing
  - Environmental, commercial, medical
  - Examples:
    1. Carbon dioxide (CO2)
    2. Methane (CH4)
    3. Nitrous oxides (N2O, NO, NO2)
    4. Sulfur oxides (SO, SO2, SO3)
    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



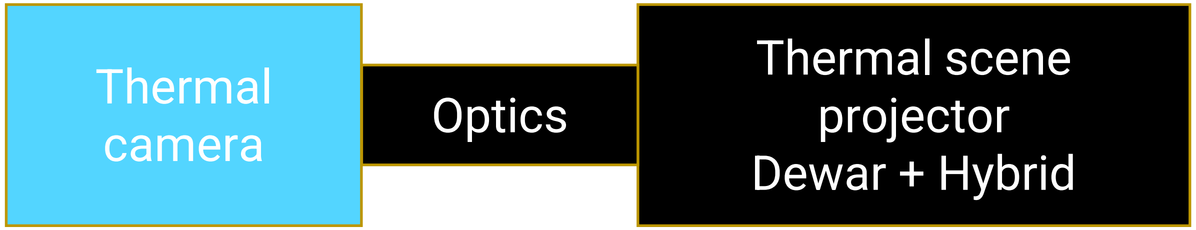
Gibson etal, *Sensors* **13**, 7079-7103 (2013)



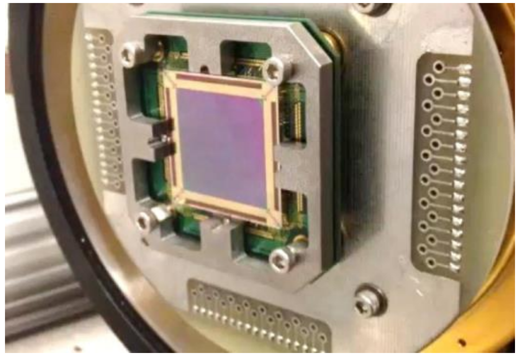
NDIR Gas Sensor

Mid-Infrared LED Uses

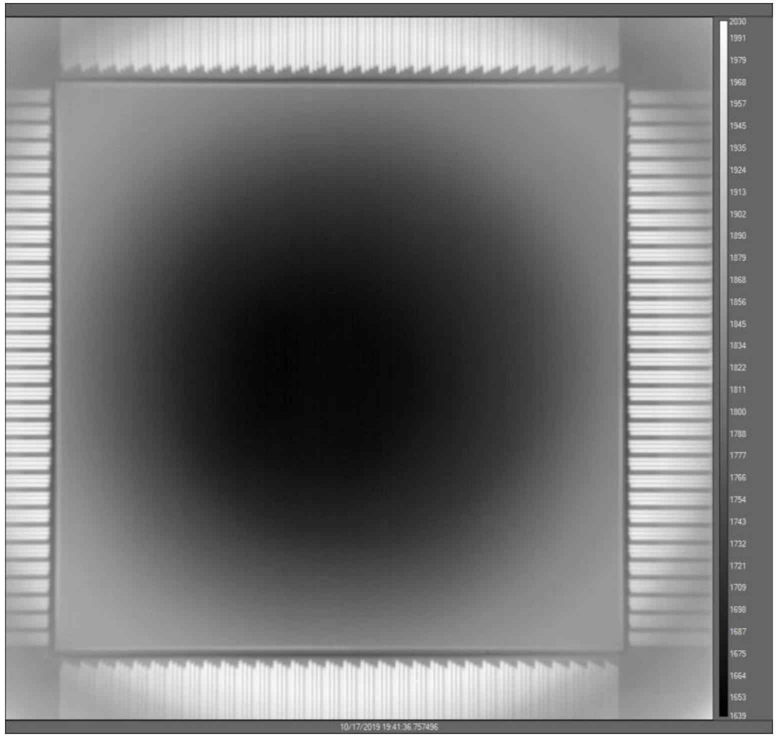
Thermal Scene Projector



- Hardware-in-the-loop testing
- Counter measure simulation
- High frame rates
- High apparent temperature
- Manufacturable Group III-V semiconductor materials

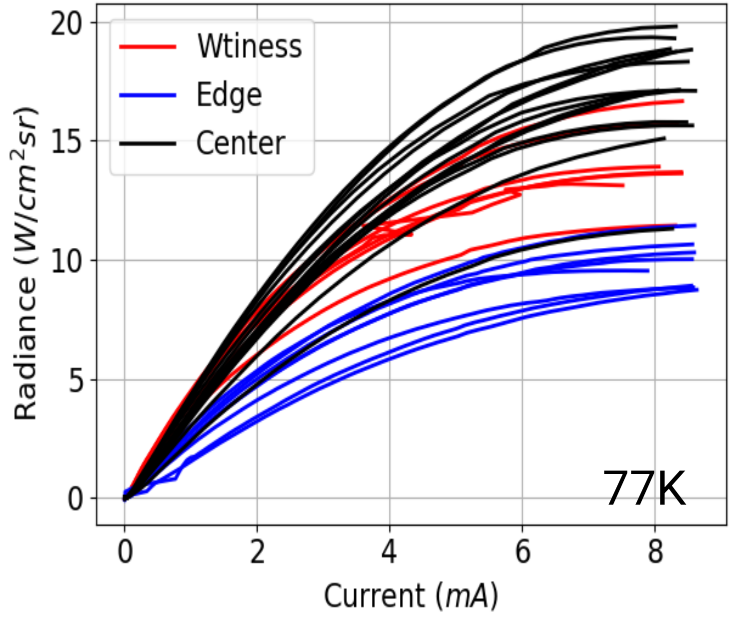


Hybrid = LED array + RIIC

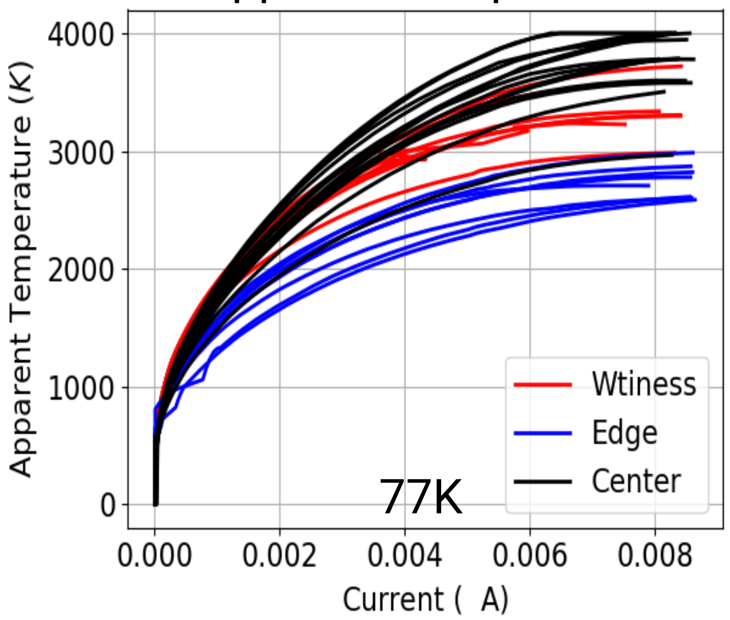


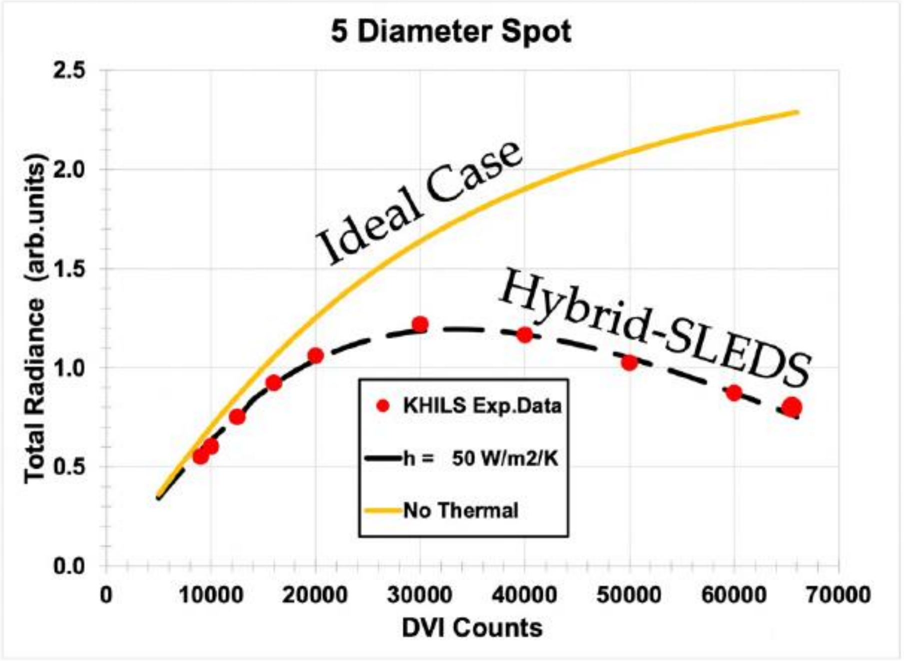
Challenge: Increase IRLED Wallplug Efficiency

Mid-infrared radiance



Corresponding apparent temperature





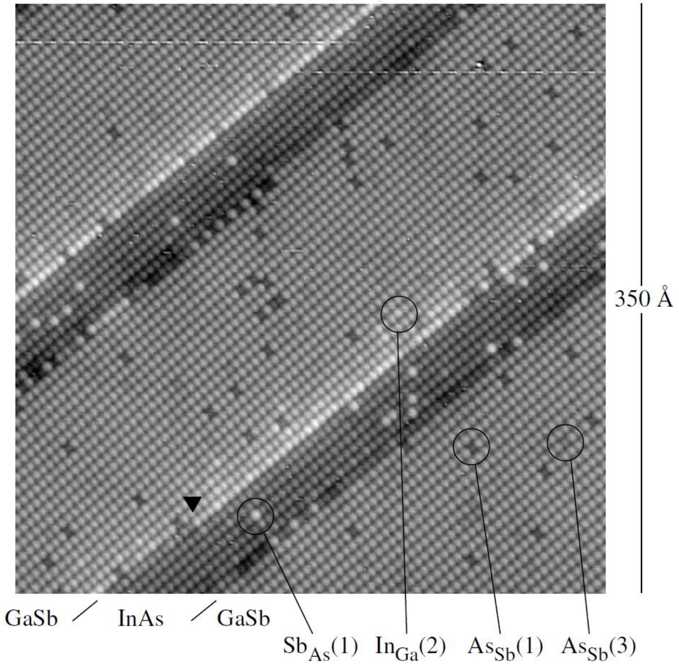
- High radiance, high apparent temperature cascaded superlattice IRLEDs
- Wallplug efficiencies of 1-3%

- High thermal loading causes LED droop
- Power limits how many pixels can be lit up

D.A. Montealegre etal., Proceedings of SPIE **122022**, 122022B (2022)

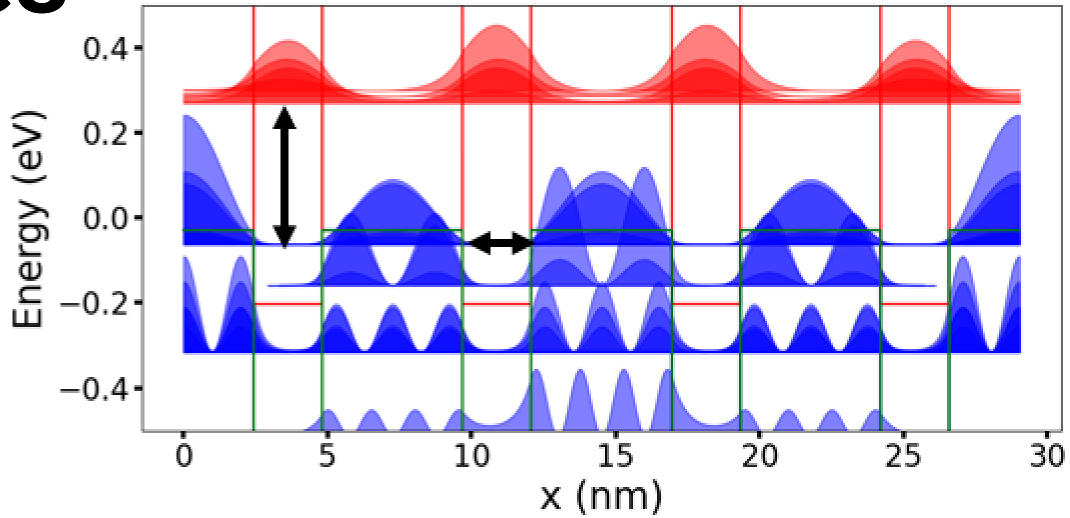
Group III-V Superlattices

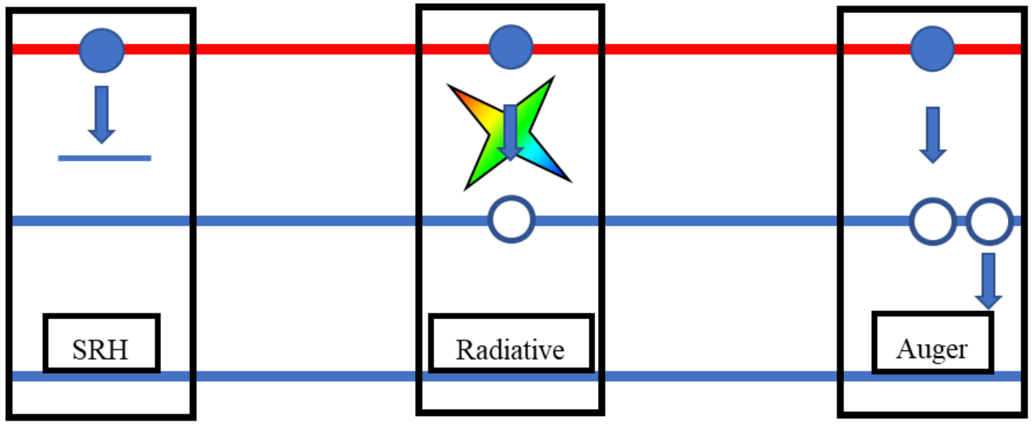
[001] InAs/GaSb superlattice



Thin layers a handful of atomic layers thick

InAs/GaSb superlattice
Real space bandstructure



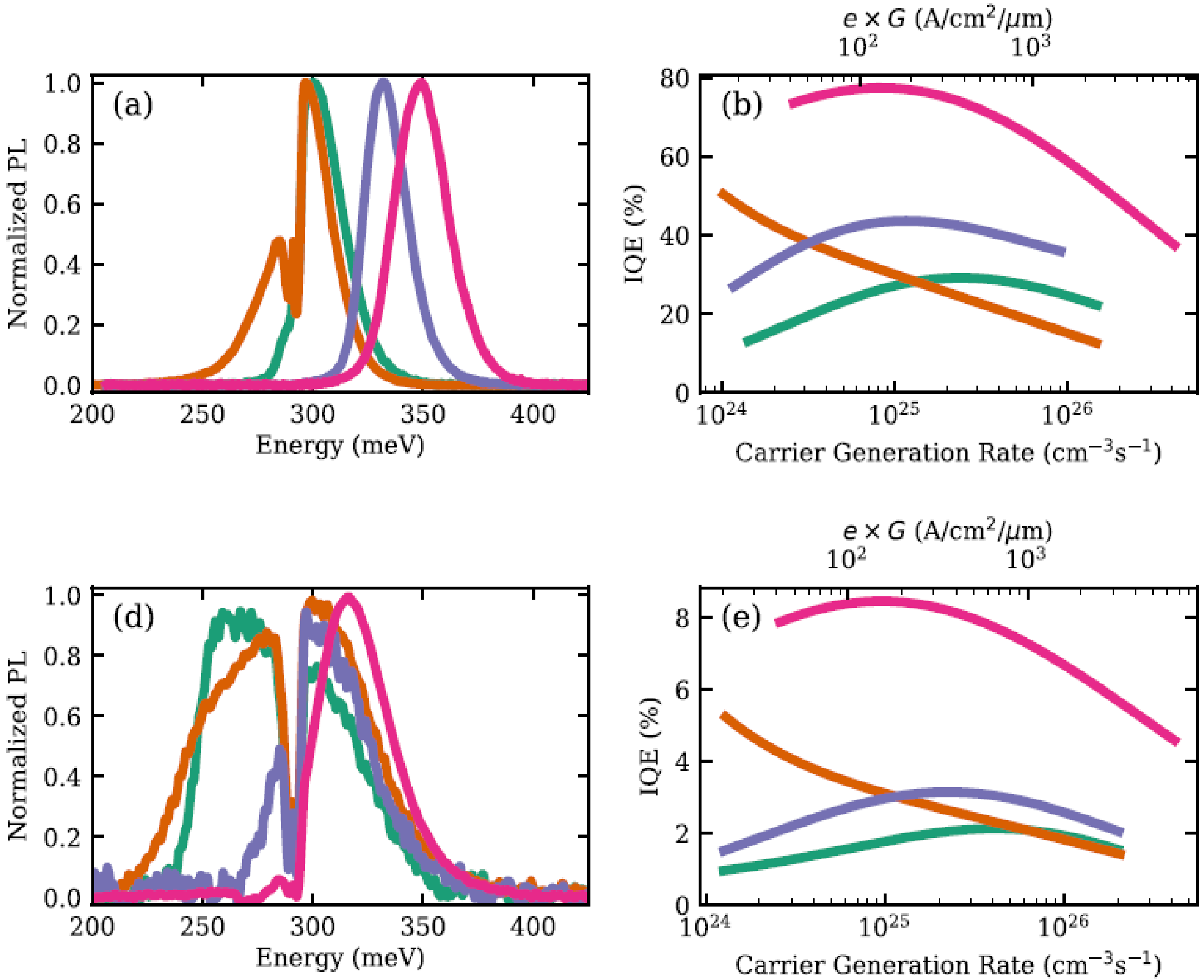


Maximize radiative recombination
Minimize nonradiative recombination (SRH, Auger)

Group III-V Superlattices: Quantum Efficiency

77K data

Room temp data



A – InAs/GaSb

B – InAs/InAsSb

C – InAs/AlGaInSb

D – W-Suplerlattice

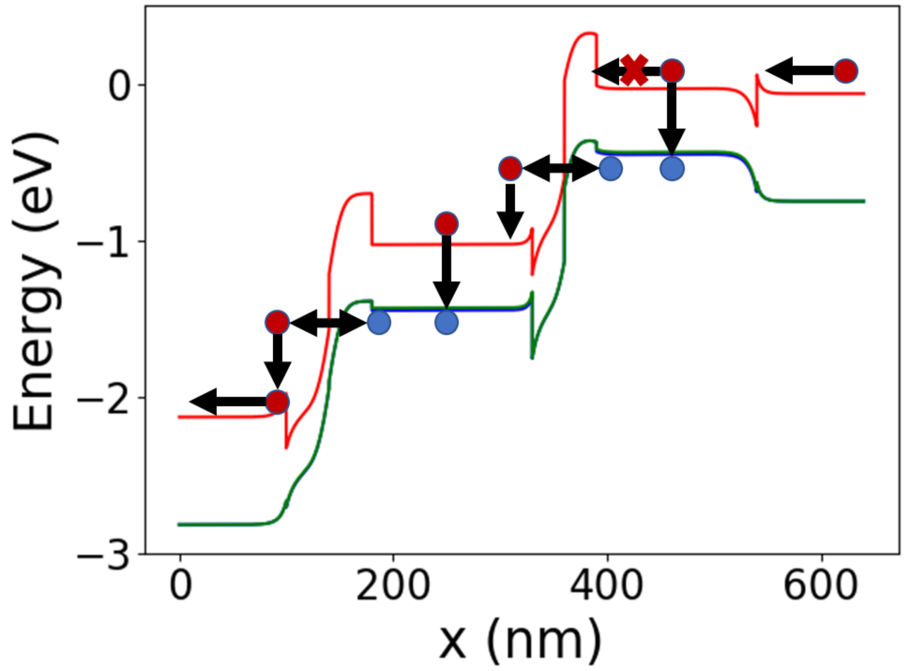
Quantum efficiency = photons produced / carrier / stage

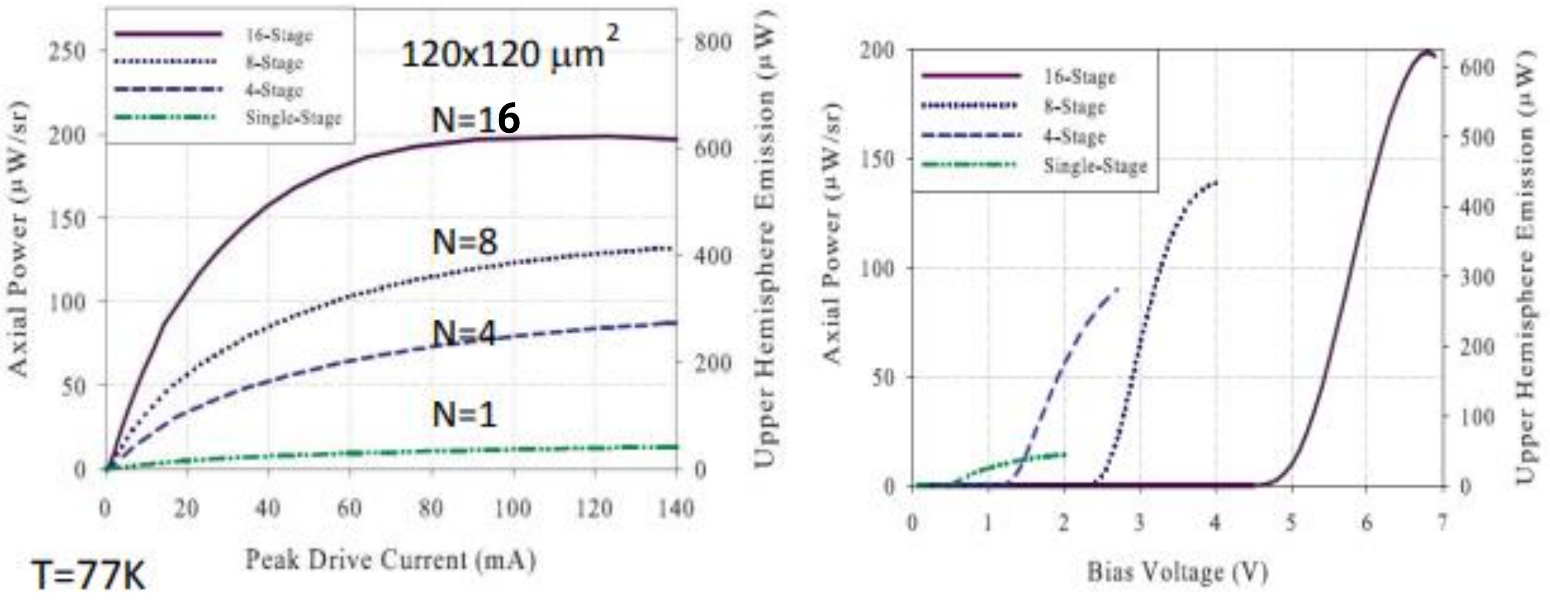
(Wallplug efficiency = power out / power in)

Best internal quantum efficiencies per superlattice family

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

Cascading Emission Regions





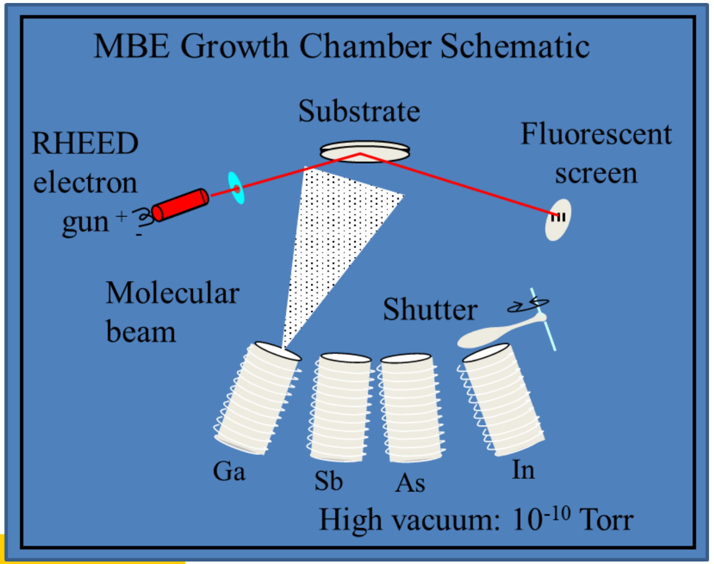
- Emission regions in series via tunnel junctions
- Carrier recycling

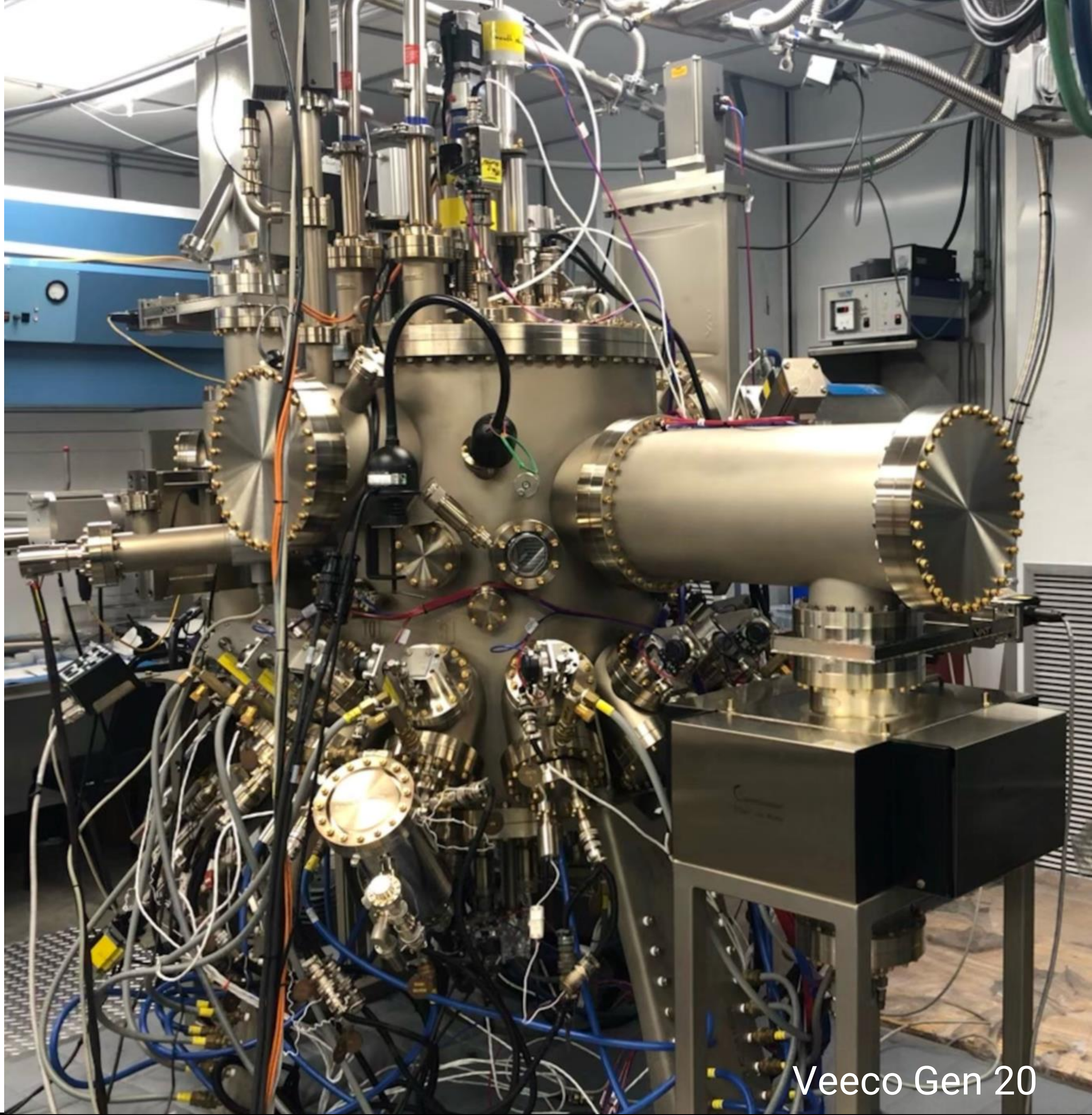
- Cascading allows tailoring current-voltage characteristics of device to battery / control electronics
- Reduced current operation reduces ohmic loss

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

MBE Growth

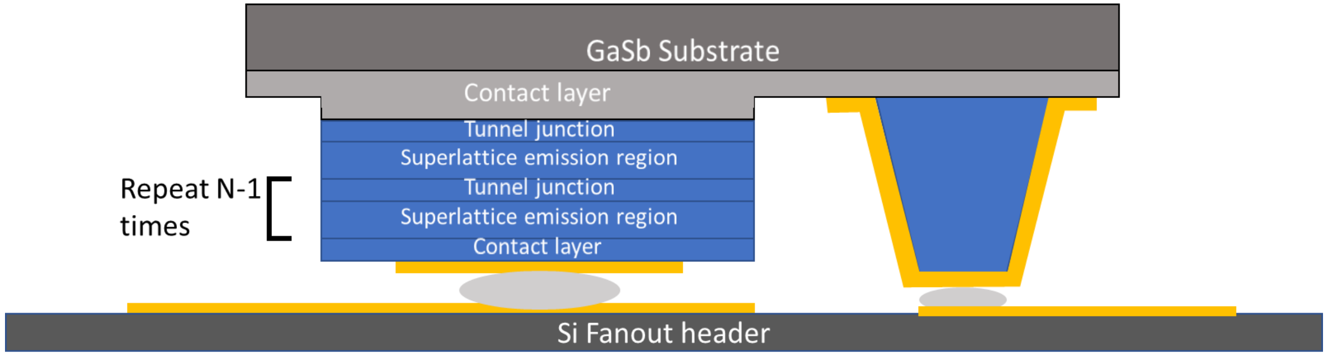
- Material grown at UI Molecular Beam Epitaxy User Facility in the IATL Building
- Ultrahigh vacuum, non-equilibrium epitaxial growth technique
  - Single atomic layer precision
  - High purity layers



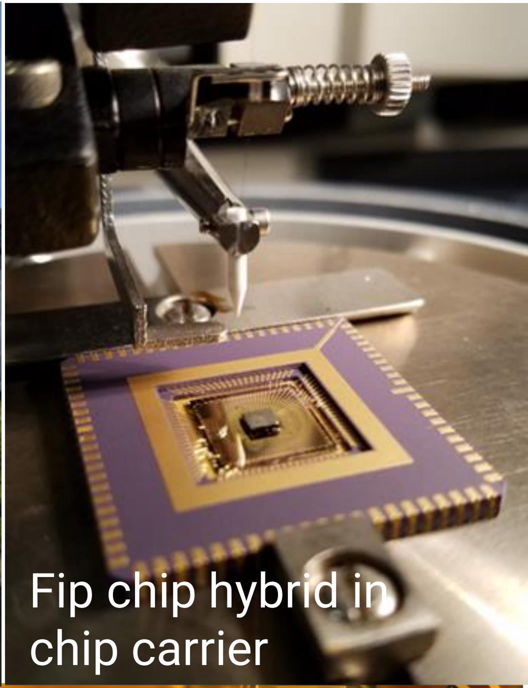


Microfabrication

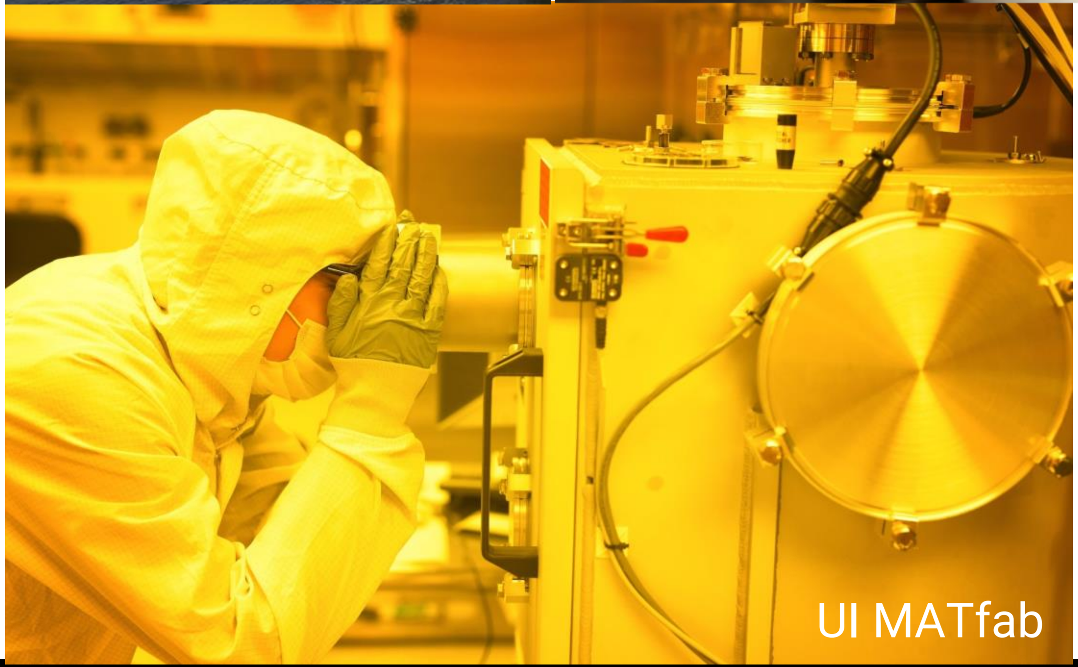
- Devices fabricated at the UI MATfab User Facility in the Iowa Advanced Technology Building (IATL)
- Use photolithography, dry etching, and dielectric encapsulation to flip chip variable sized mesa to fanout header, mounted in a leadless chip carrier



IATL Bldg on Iowa River

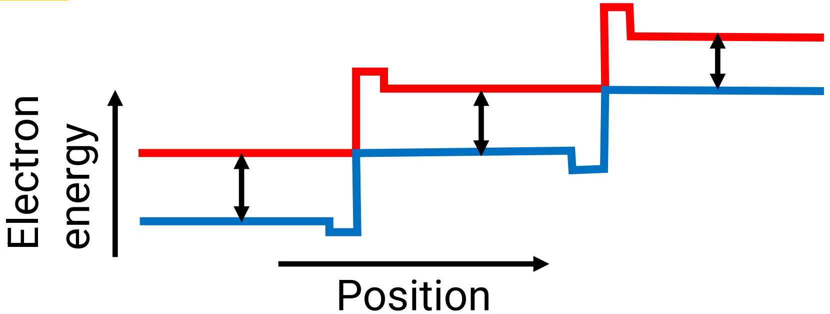


Fip chip hybrid in chip carrier

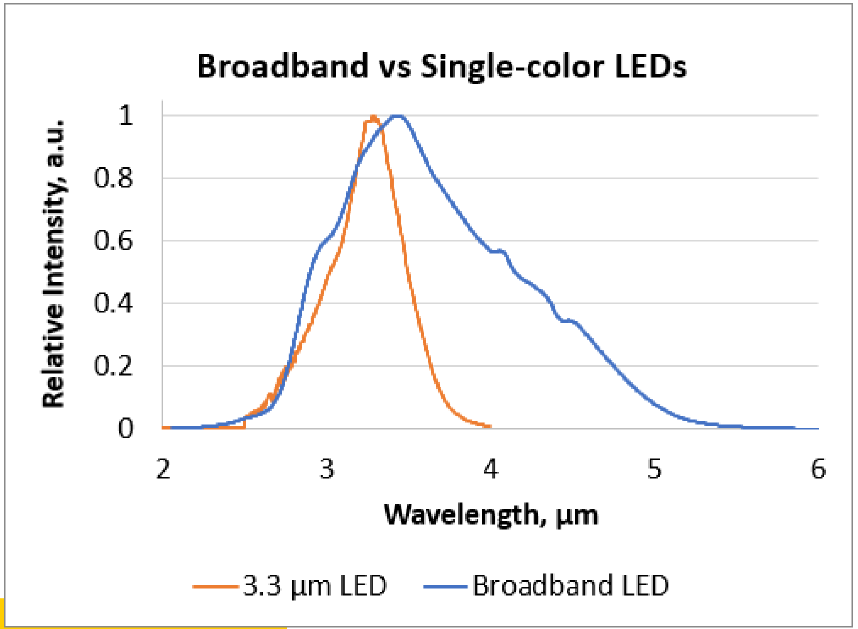


UI MATfab

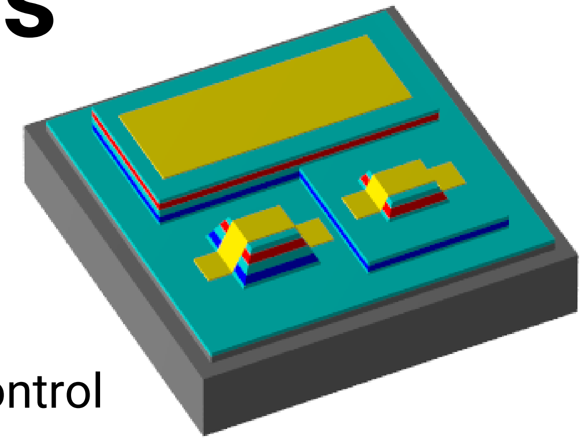
Broadband and Multi-Spectral IRLEDs

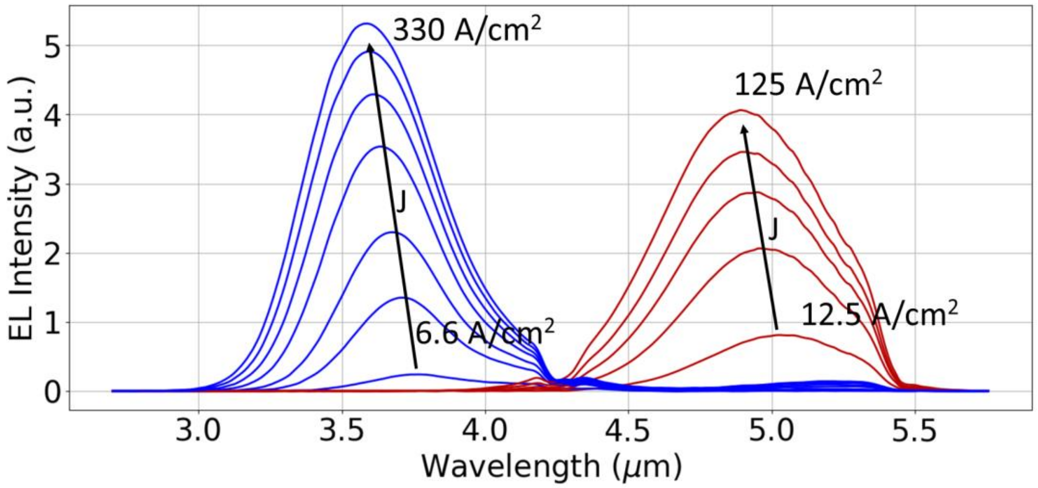


Increasing bandgap energy per stage



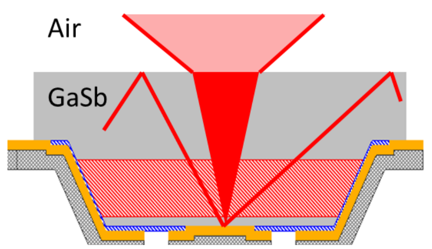
- p-n – n-p heterostructure
- Contacts to top, bottom, middle for independent control





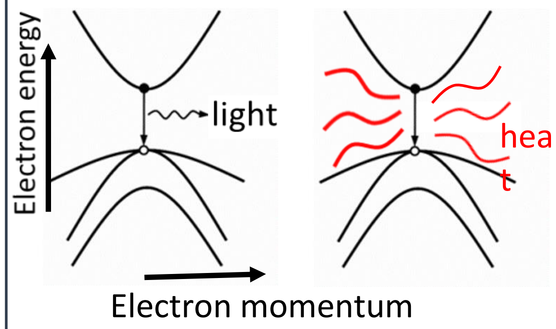
Why is Wallplug Efficiency So Low?

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

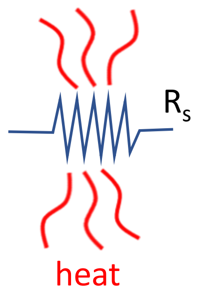


Light extraction efficiency

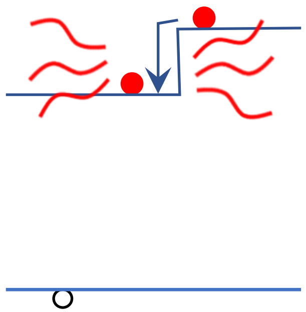
n ≈ 3.8



Internal quantum efficiency



Ohmic efficiency

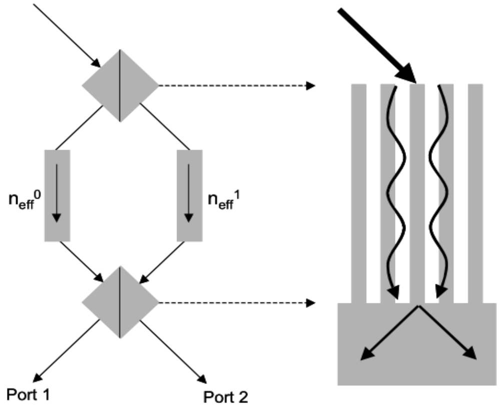


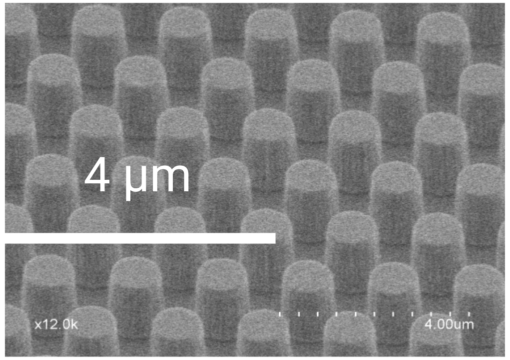
Quantum defect efficiency

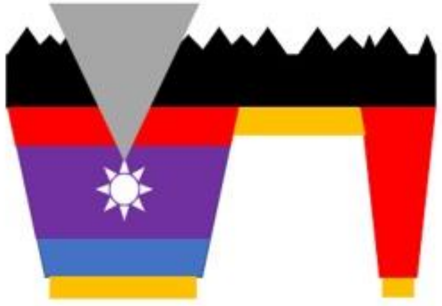
Total internal reflection: $\eta_{extraction} \approx 1/2n^2 \approx 3\%$

Simplest Strategy: Texture the Backside

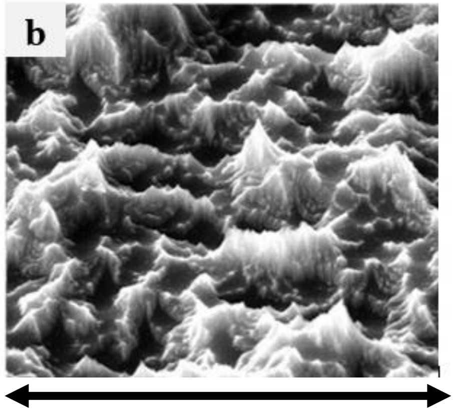
Maximum 2-3x enhancement in extraction



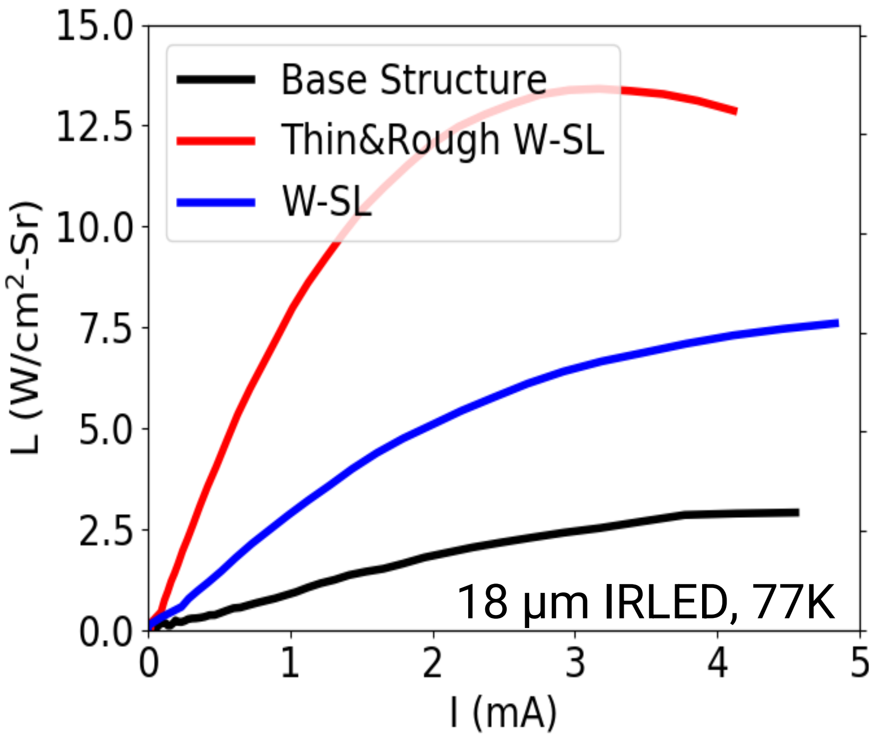




45˚ Angle



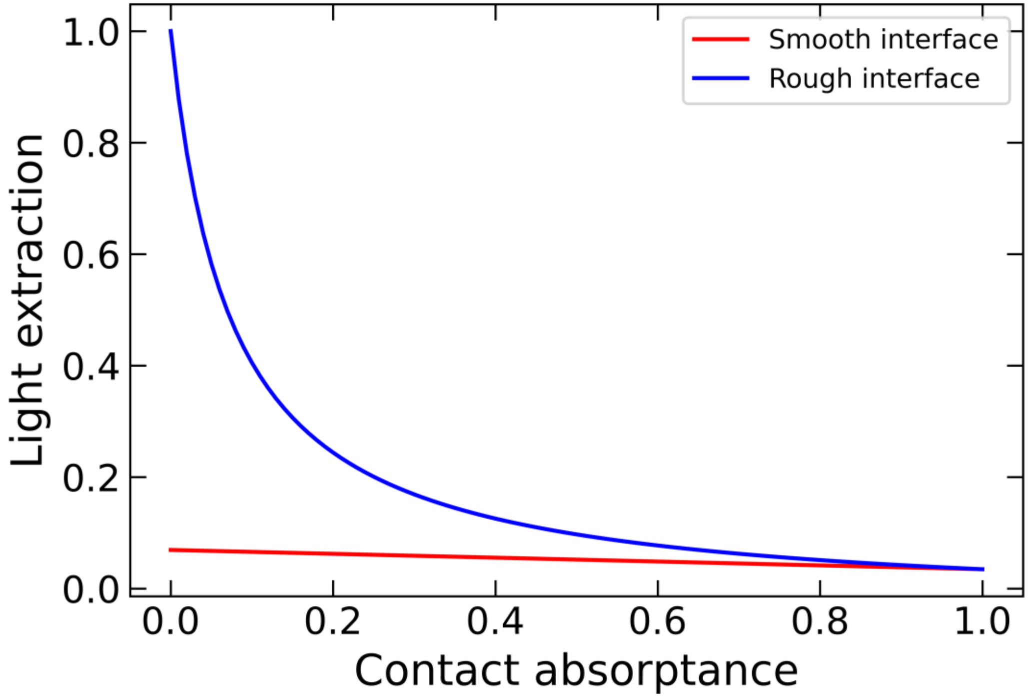
50 μm

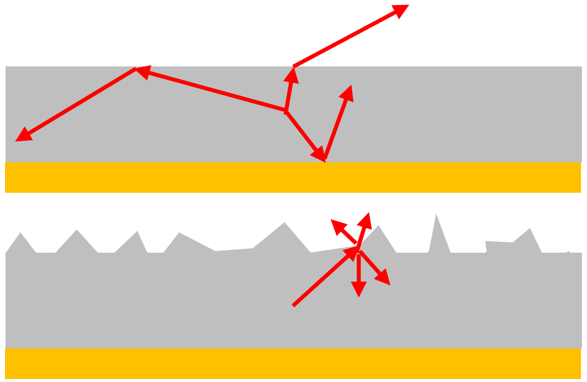


D.A. Montealegre etal, Appl. Phys. Lett. **118**, 071105 (2021)

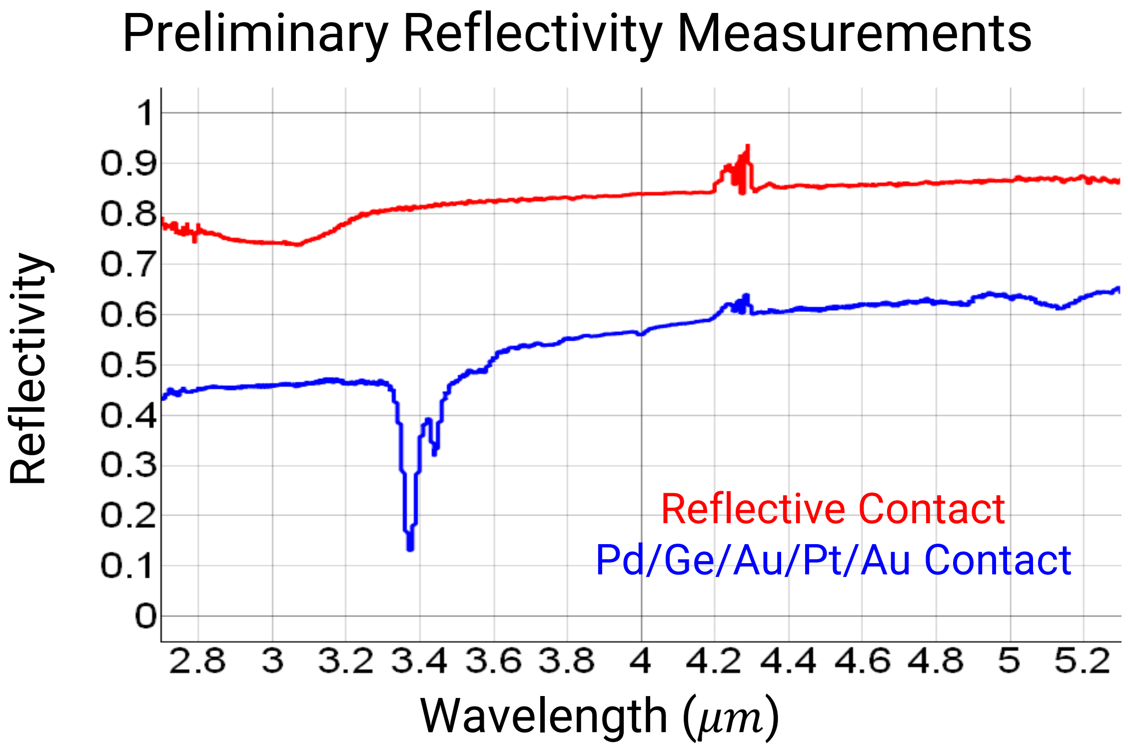
Extraction of Light Versus Absorptive Loss

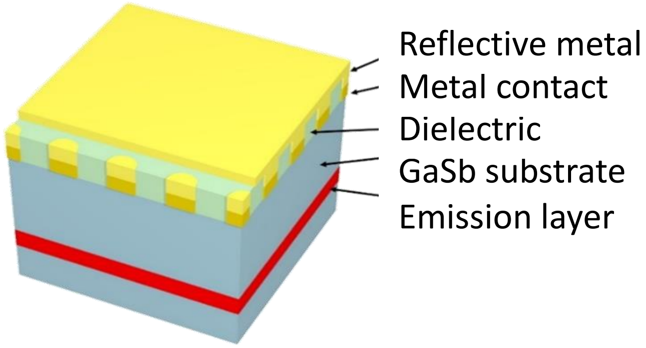
- Zero aborbance + scattering surface = all the light can be extracted
- Optical loss heaviest from metal contacts

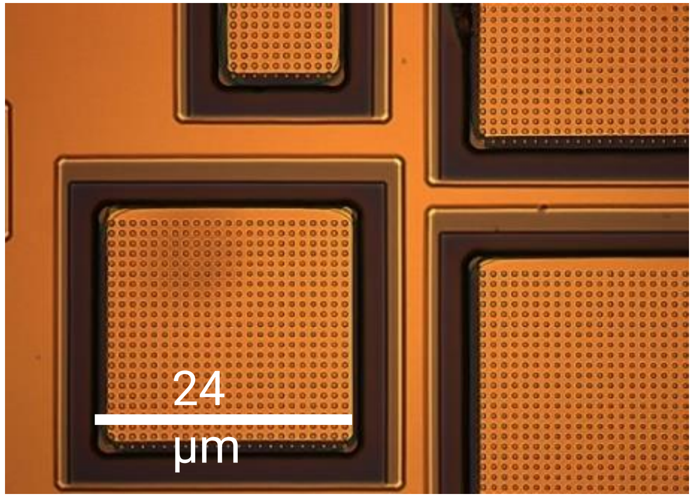




High Reflection Structured Contacts





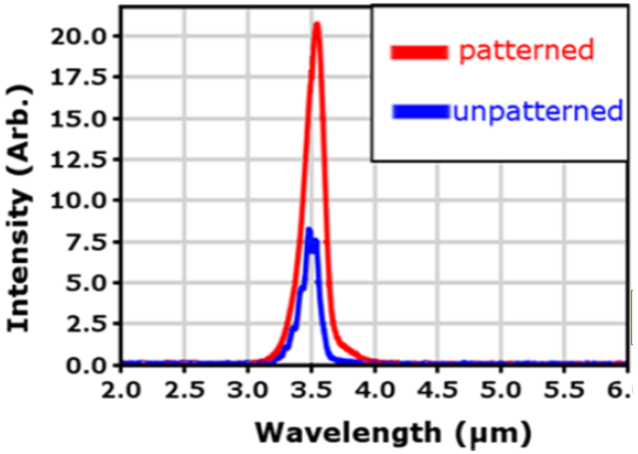


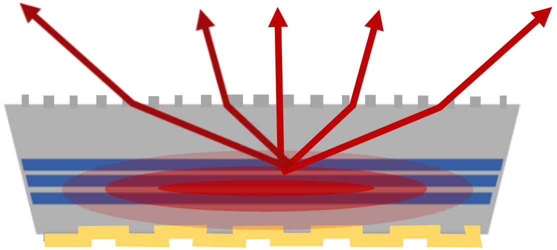
Extraction Enhancement Through a Metalens

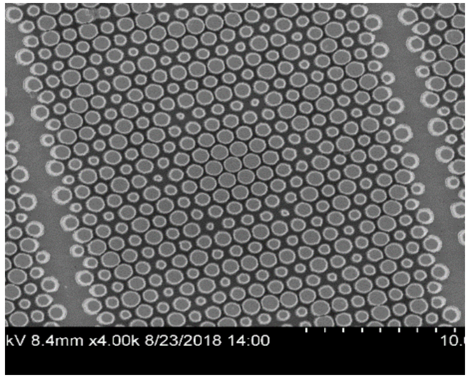
- Metasurface: adds new term to Snell's Law
- Light extraction beyond the critical angle

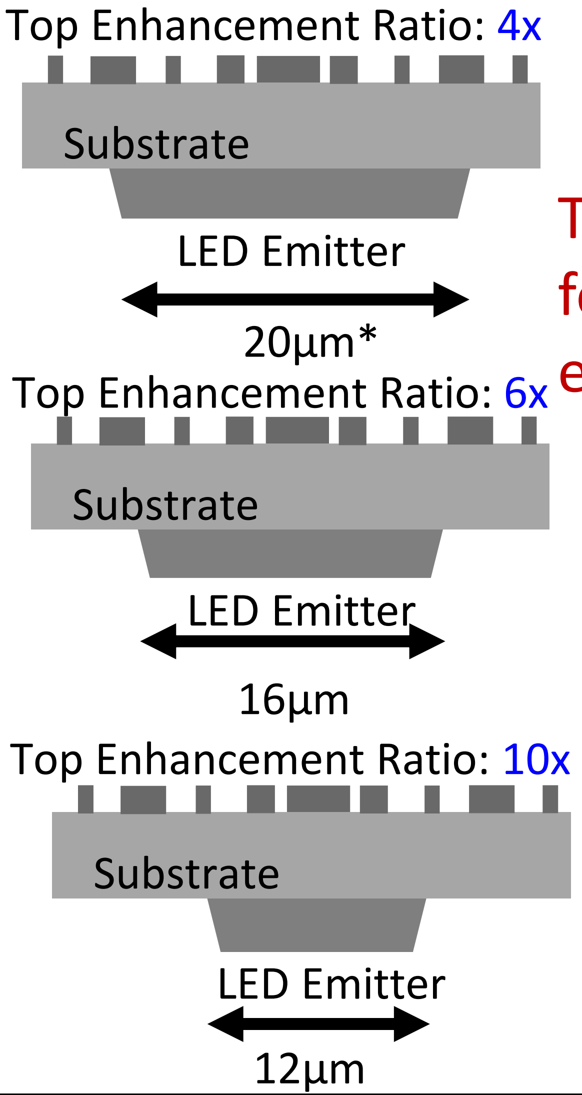
$$n_1 sin\theta_1 = n_2 sin\theta_2 + \nabla\phi(r)$$

Phase gradient along radius



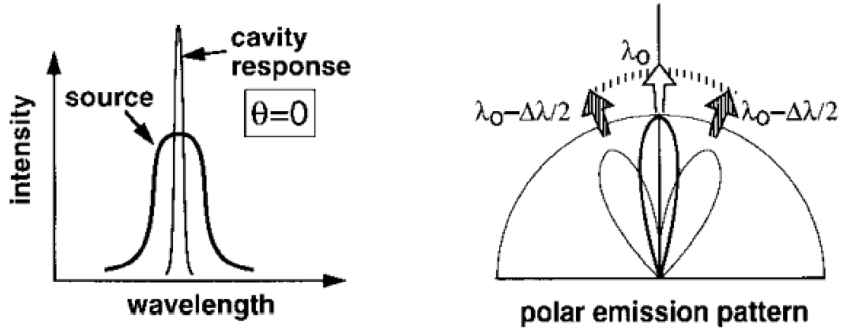






Trade fill factor for extraction efficiency

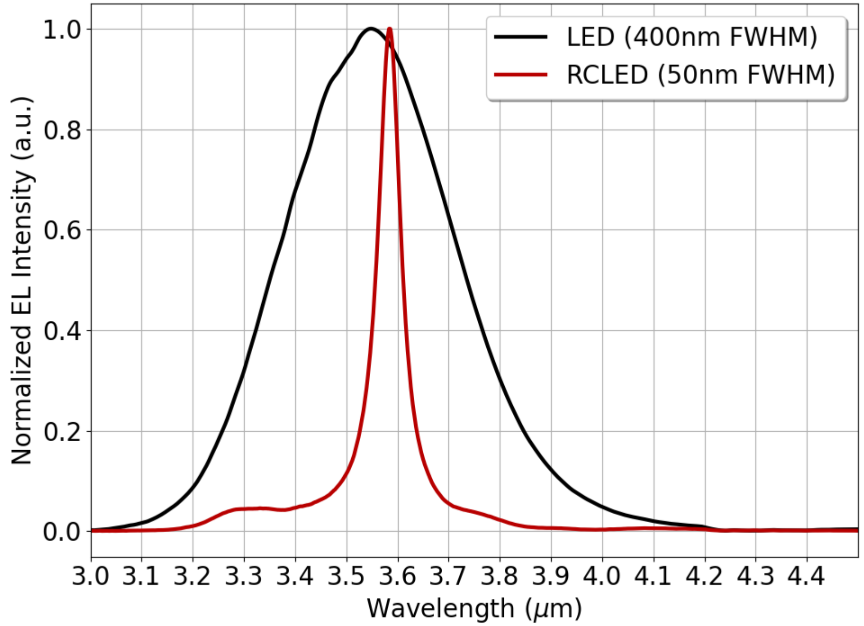
Extraction Enhancement Through Resonant Cavities

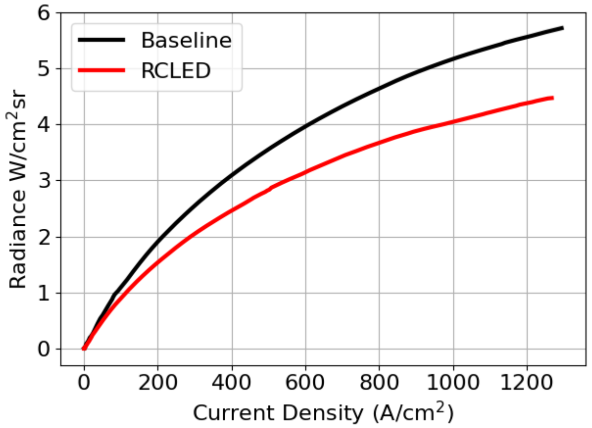


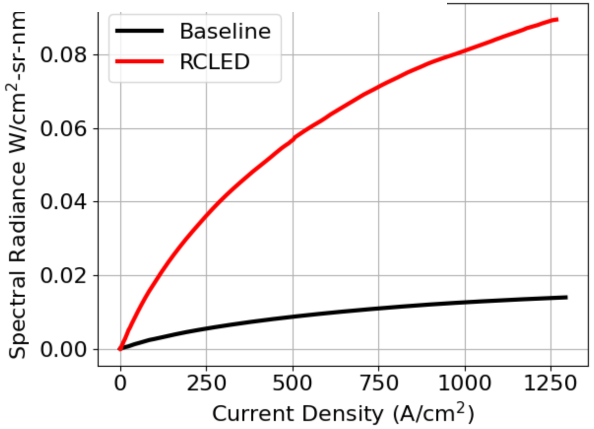
For isotropic emitter, 1-D cavity directs more light in the normal direction and into the escape cone[1]

[1]H. Benisty etal., IEEE J. Quantum Electron. 34, 1612 (1998).

- Observed enhanced spectral radiance
- Superior wavelength stability against current and temperature







Conclusions

- Mushrooming demand for semiconductor chips, and CHIPS and Science act create regional **opportunities**
- Mid-infrared LEDs are growing in efficiency and radiance while remaining low cost
- Applications in gas sensing, defense technologies
- **Challenge**: further increase mid-ir wallplug efficiency by improving light extraction efficiency

Compound Semiconductor Markets and Production

- The CHIPs (and Science) Act of 2022 to promote US leadership
  - Effort to promote semiconductor innovation, and bring back manufacturing to support secure supply chains
- Contract foundry production moving to Asia Pacific
  - Market share domination by North America, but production dominated by Asia Pacific
- Compound semiconductor market versus silicon
  - Complex, fragmented, and smaller than the consolidated silicon industry

Regional Importance and Impact

- Iowa as a manufacturing state
- Iowa and Chicago have a strong history of research and innovation on compound semiconductor photonics
- Iowa (an EPSCoR state) as a rural underdeveloped region
- Chicago: critical industrial and research mass, diverse urban populations; benefits from regional manufacturing hub and semiconductor workforce development
- The innovation hub will address regional gaps

Core Partners

Core Partners Green = Joined Engine Gold = Expressed Interest Red = Has Not Been Contacted Yet or Has Not Responded	
	Academic: Iowa State University, University of Illinois-Chicago, Northwestern University, Grinnell College, Luther College, Coe College, Cornell College, Kirkwood Community College, City Colleges of Chicago **National Labs:** Ames National Labs **Startup:** Firefly Photonics, Sivananthan Labs, NOUR, EpiSensors, EpiSolar, EPIR Technologies, QuantCad **Industrial:** Collins Aerospace, John Deere, Winnebago, BAE, Crystal Group, Littlefuse, Motorola, Moxie Manufacturing, DRS, Microlink Devices, Ford Motors, Caterpillar, Weiler, American Ordinance, Ramco Innovation **Nonprofit and Government:** Iowa Economic Development Authority, Technology Association of Iowa, Center for Industrial Research and Service, Iowa Innovation Council, TEConomy Partners, VentureNet Iowa, Iowa State House and Senate, Chicago City Government, United States House and Senate, Iowa and Chicago Chambers of Commerce

Comparison to Mid-Infrared Lasers

Interband Cascade Lasers

DFB: P = 5 mW, WPE = 0.8%, λ = 4.5 µm, linewidth < 2×10^{-3} Å (Nanoplus)

FP: P = 20 mW, WPE = 5.6%, λ = 4.5 µm, linewidth 60 nm (Nanoplus)

Quantum Cascade Lasers

DFB QCL: P = 20 mW, WPE= 0.2%, λ = 4.6 µm, < 2×10^{-3} Å (Hammamatsu)

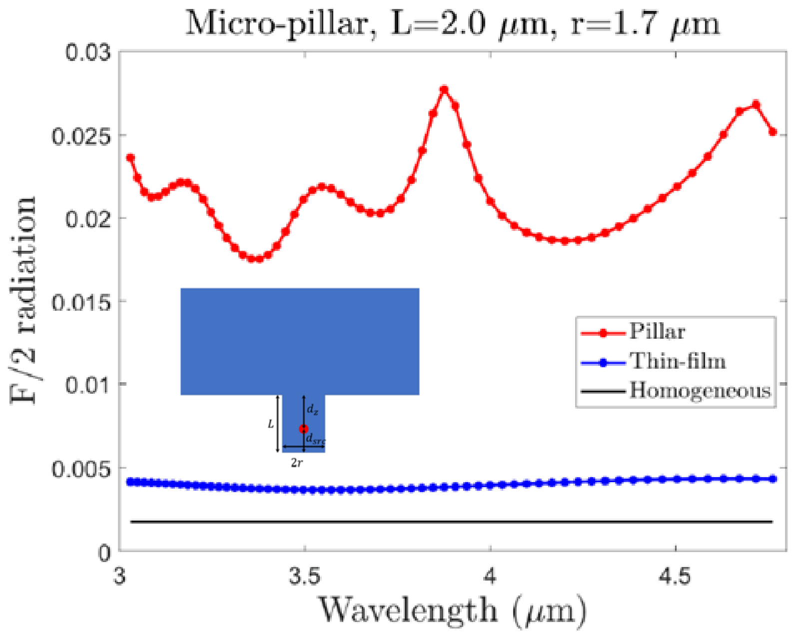
FP QCL: P = 1.2W, l = 4.05 um, WPE = 9% , linewidth 60 nm

(Thorlabs)

Cost: $1K - $10K

Towards Micropillar IRLEDs

- The micropillar acts as a waveguide to extract more light in escape cone
- Simulations show improvements in efficiency of 5 to >10x
- Initial results show promise



2 μm diameter, 8 μm pitch