InAs/GaSb Mid-Wave Cascaded Superlattice Light Emitting Diodes

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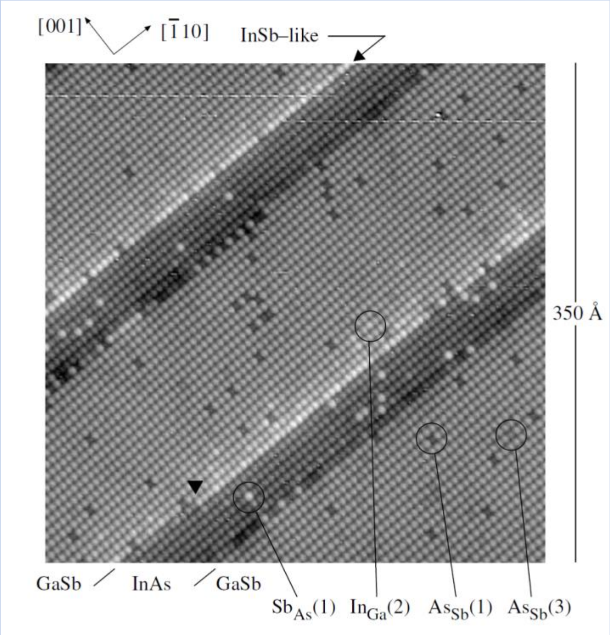
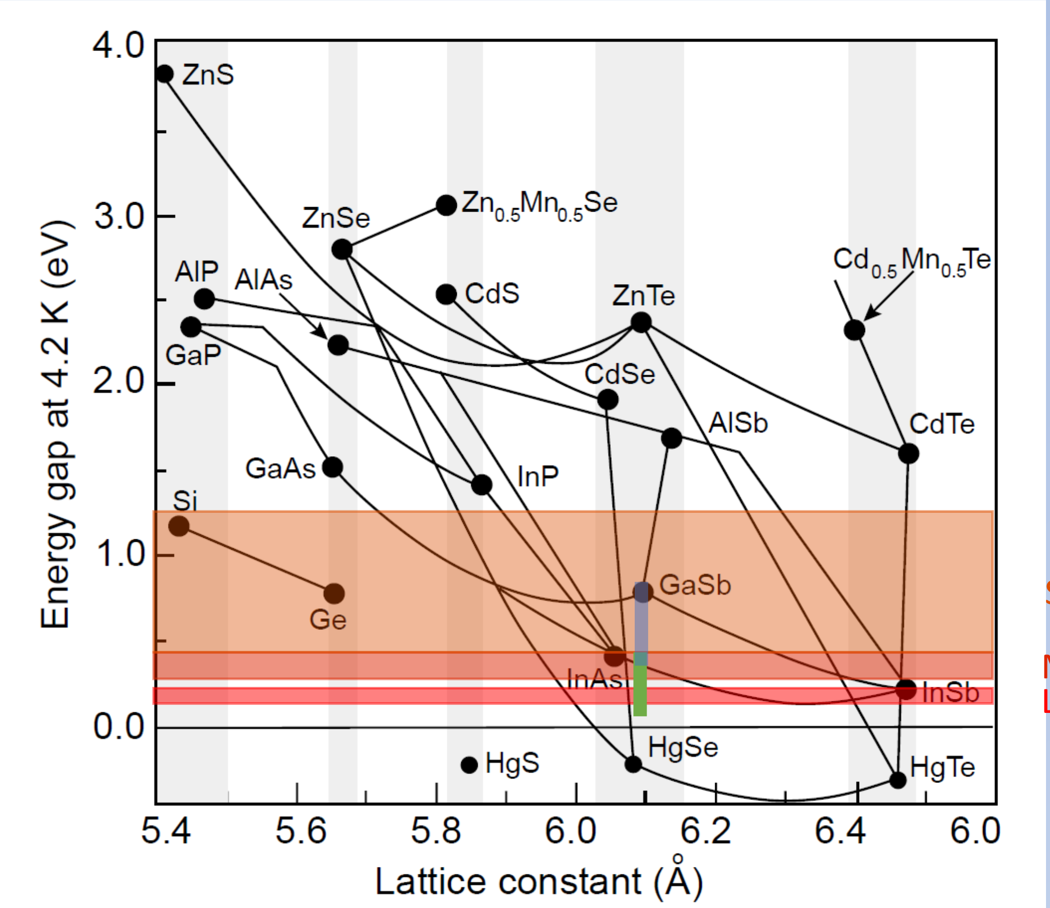


InAs/GaSb type II superlattices generated early interest due to their tunability over the mid- and long-wave infrared

InAs/GaSb 3-30 μm

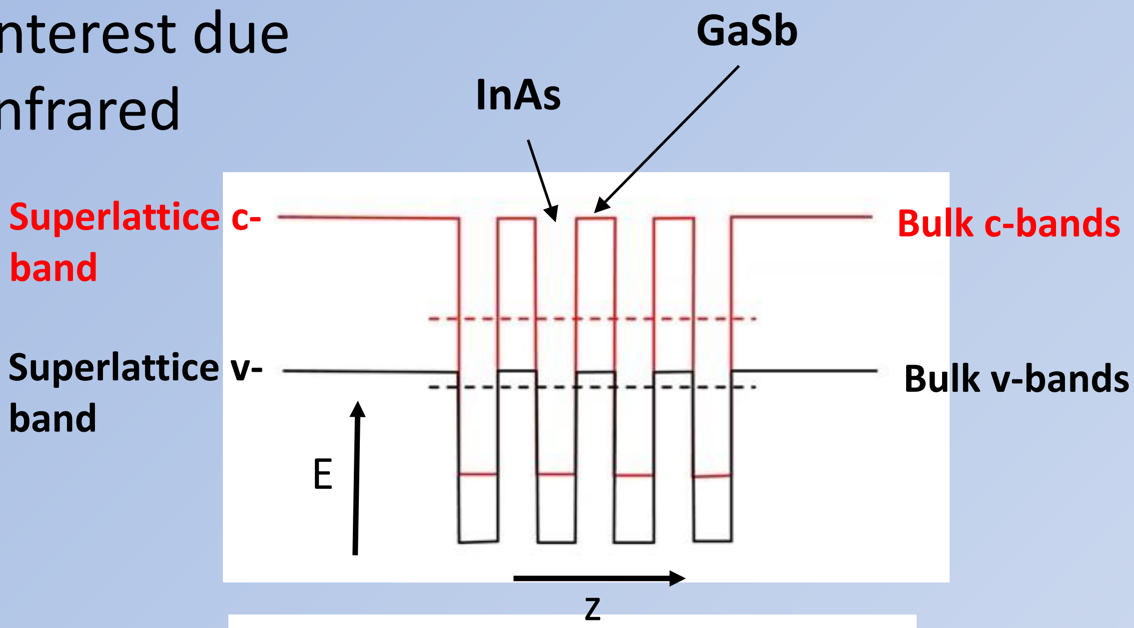
GaInAsSb 1.7-4.9 μm

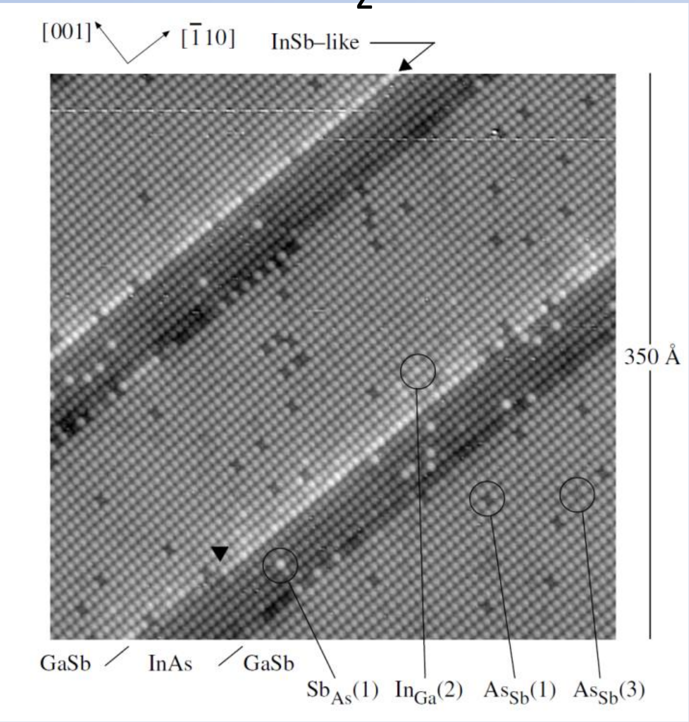


SWIR: 1-3 μm

MWIR: 3-5 μm

LWIR: 8-12 μm





STM cross section of InAs/GaSb[1]

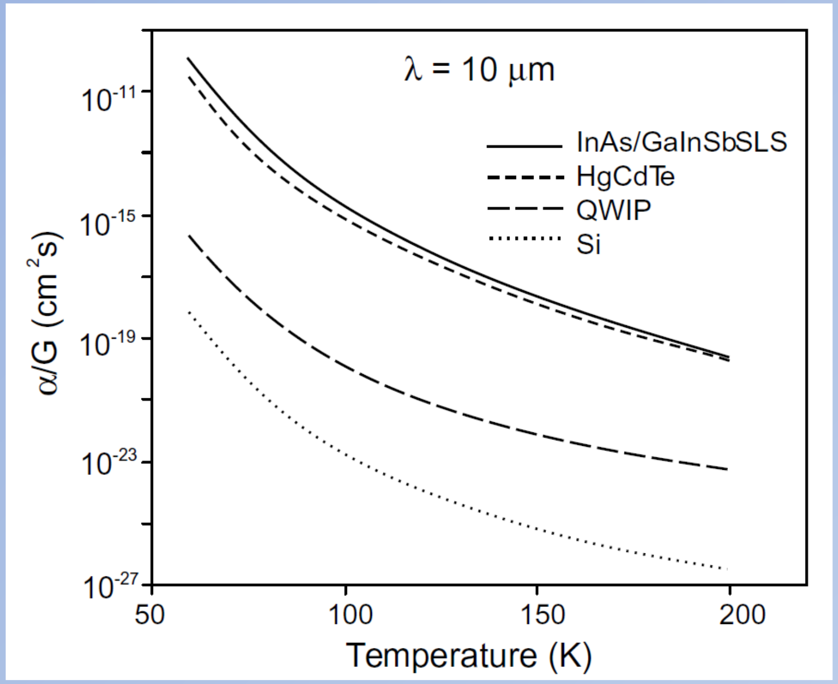
[1]Steinshnider etal, *Phys Rev Lett* **85**, 2953 (2000)

Type II superlattices have been shown in theory to be potentially better detector materials the $Hg_xCd_{1-x}Te$

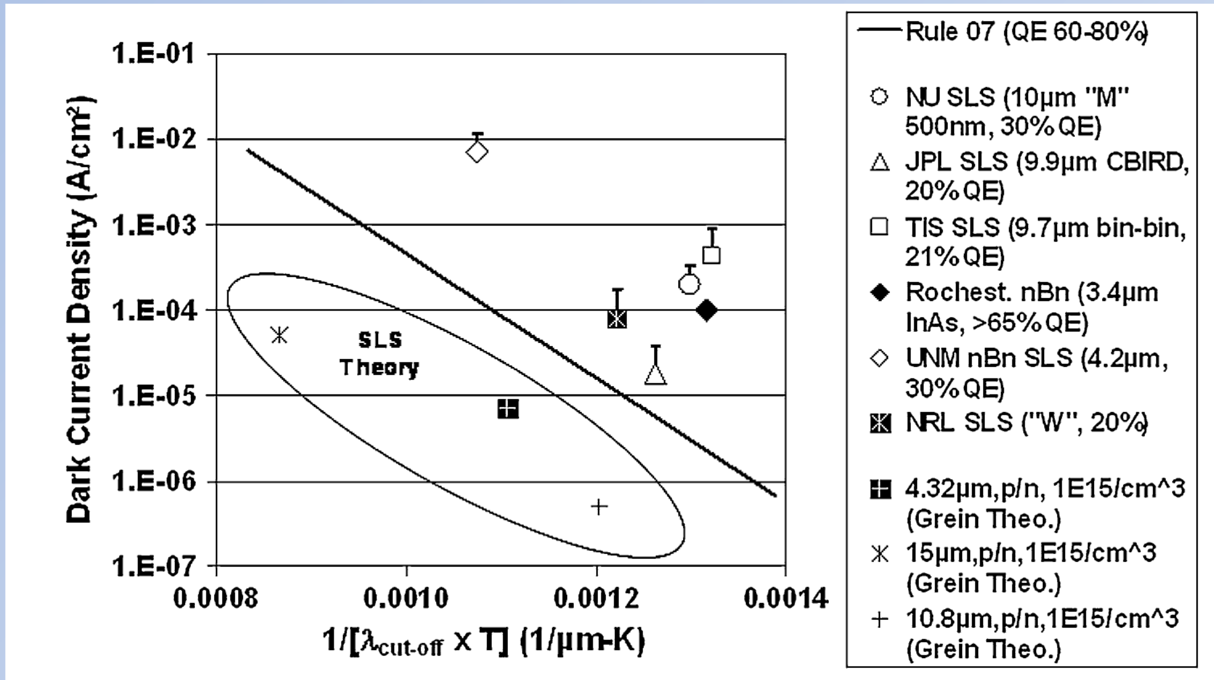
$$D^* \equiv \text{Specific detectivity} \propto \sqrt{\frac{\alpha}{G}} \propto \frac{R_i}{I_n}$$

$\alpha \equiv$ absorption coefficient
G $\equiv$ carrier generation rate

$R_i \equiv$ current responsivity
$I_n \equiv$ dark current noise



A. Rogalski etal, *Infrared Phys Technol* **48**, 39 (2006)



W.E. Tennant, *J Electron Mater* **39**, 1030 (2010)

The carrier generation/recombination rate in a semiconductor is determined by total carrier lifetime

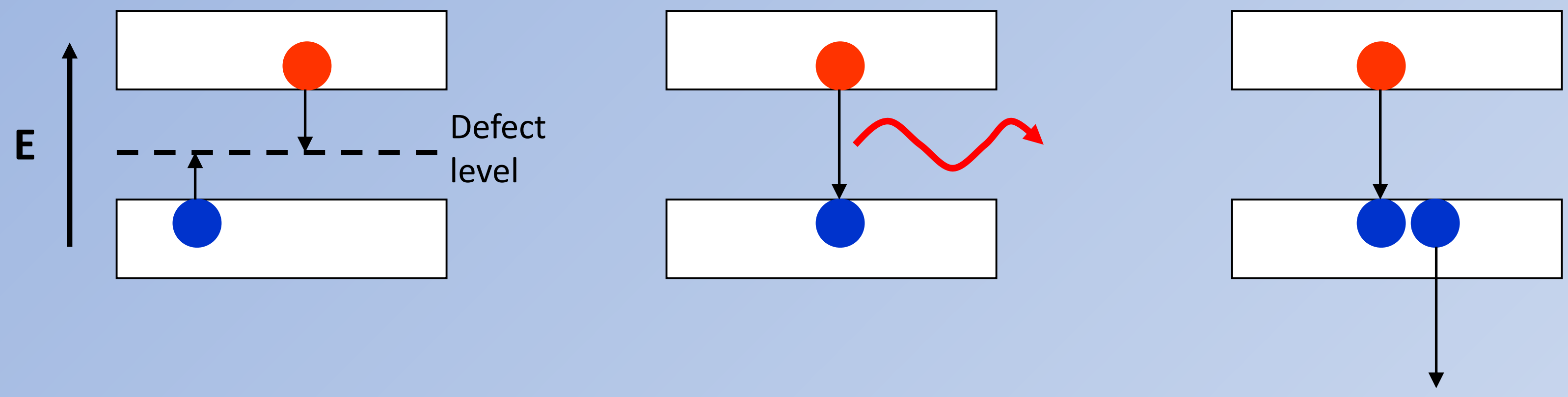
$$G \propto \frac{1}{\tau_{total} n}$$

n is carrier density

τ_{total} is total (minority) carrier lifetime

$$\frac{1}{\tau_{total}} = A_{SRH} + B_{rad}n + C_{Auger}n^2$$

SRH rate = A_{SRH} **Radiative rate =$B_{rad}n$** **Auger rate =$C_{Auger}n^2$**



The carrier generation/recombination rate in a semiconductor is determined by radiative and nonradiative (**S**hockley-**R**ead-**H**all, Auger) processes

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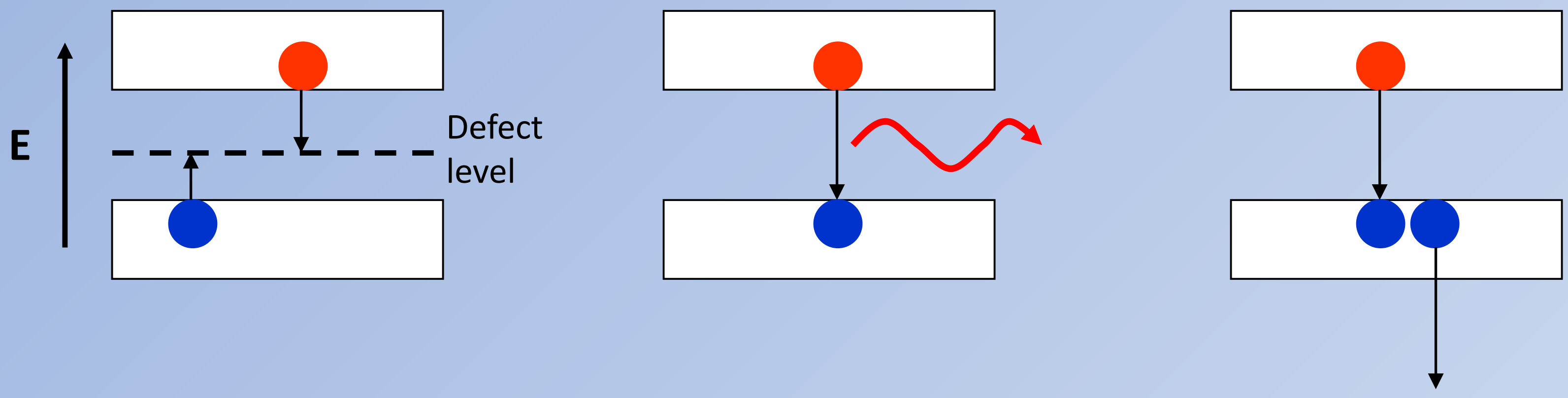
Radiative recombination

SRH rate = A_{SRH} **Radiative rate = $B_{rad}n$** **Auger rate = $C_{Auger}n^2$**



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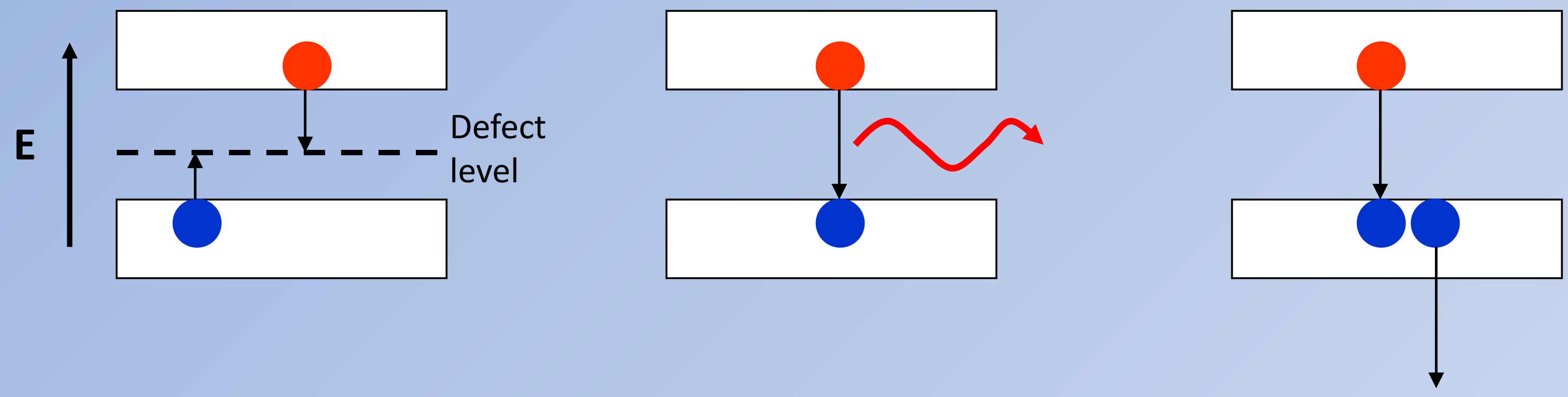
Nonradiative recombination

SRH rate = A_{SRH} **Radiative rate =$B_{rad}n$** **Auger rate =$C_{Auger}n^2$**



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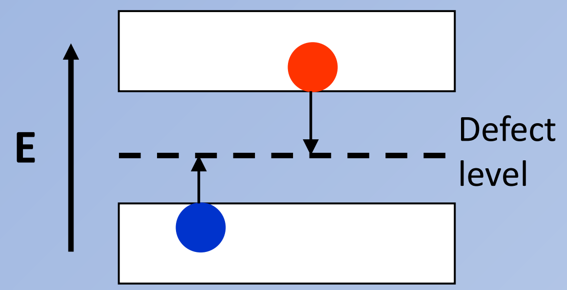
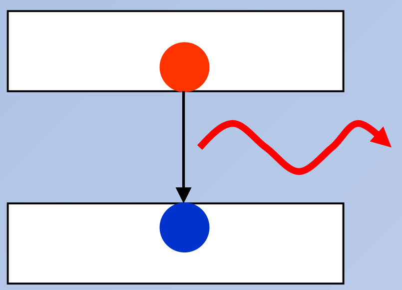
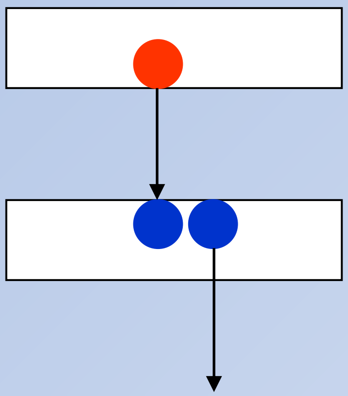
SRH rate = A_{SRH}



Radiative rate =$B_{rad}n$

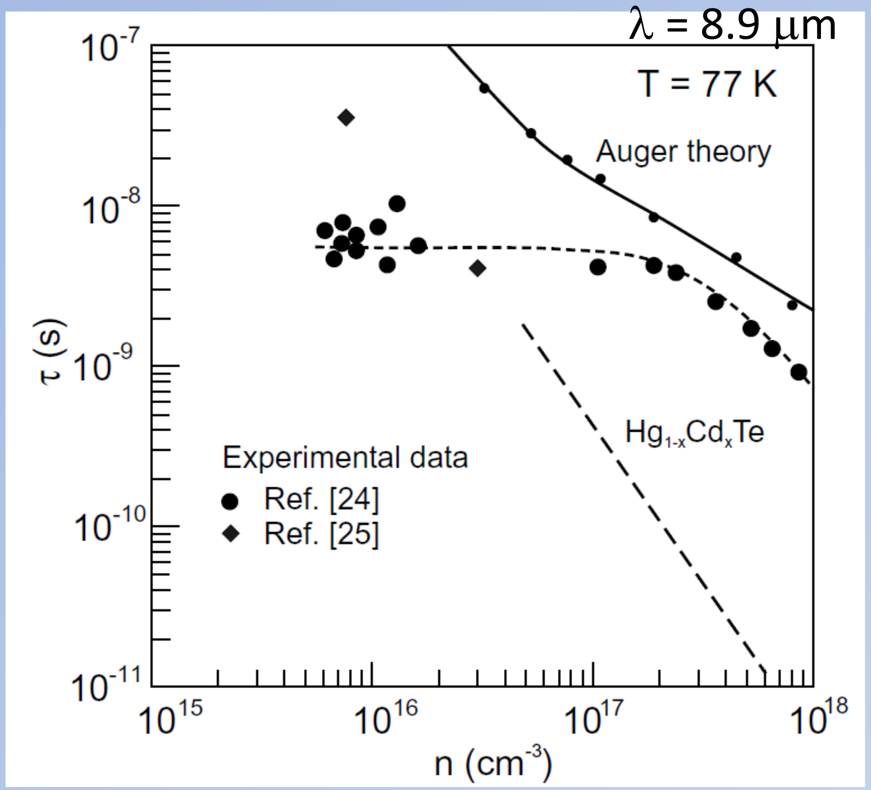


Auger rate =$C_{Auger}n^2$



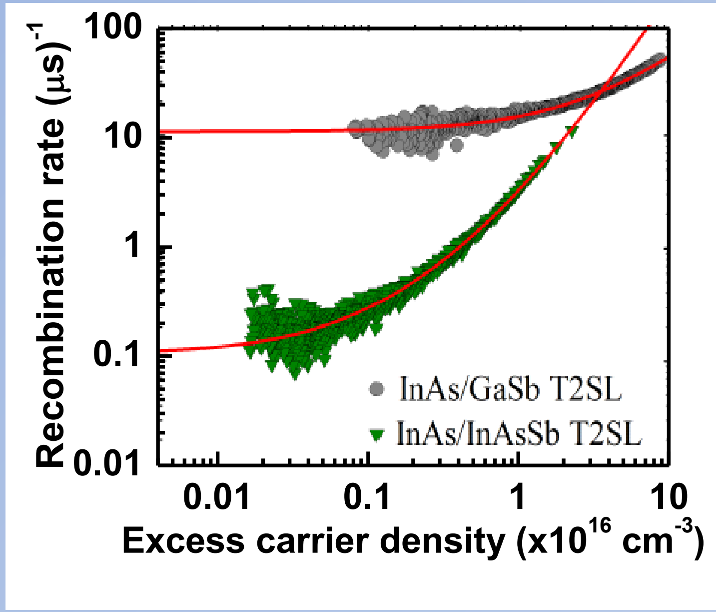
- What makes InAs/GaSb superlattices so promising in theory is the possibility of using bandstructure engineering to suppress Auger recombination.

What holds InAs/GaSb superlattices back in practice is fast SRH (defect-assisted) nonradiative recombination; in contrast, SRH rate in $Hg_xCd_{1-x}Te$ is often treated as zero.



Youngdale etal *Appl Phys Lett* **78**, 7143 (1995)

Carrier lifetime studies in mid-wave ir InAs/GaSb superlattices at 77K confirm the small Auger coefficients but large SRH coefficients



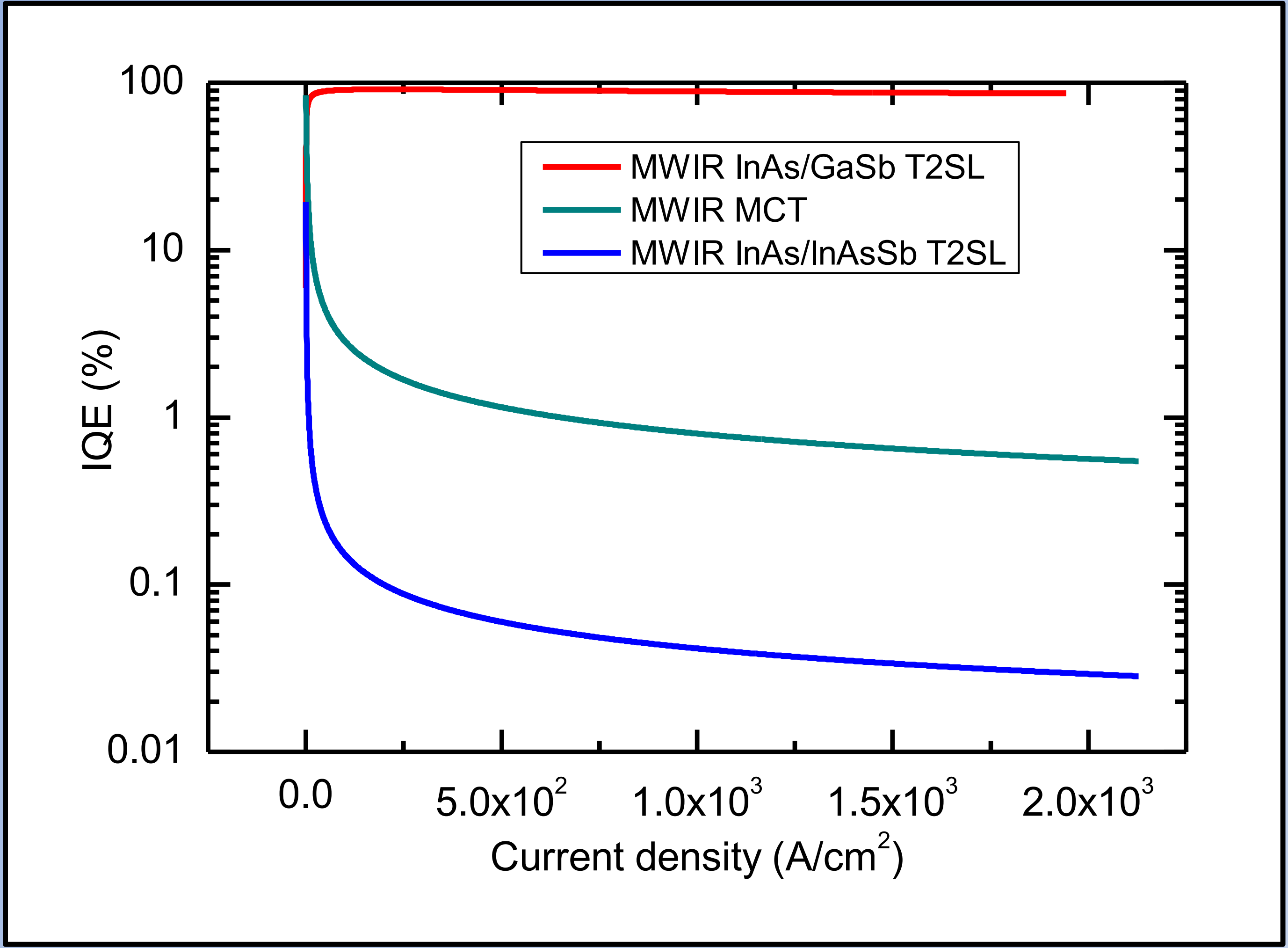
B.V. Olson etal, *Appl. Phys. Lett.* **101**, 092109 (2012).

$$\frac{1}{\tau_{total}} = A_{SRH} + B_{rad}n + C_{Auger}n^2$$

	A_{SRH}^{-1} (ms)	B_{rad} (cm^3/s)	C_{Auger} (cm^6/s)
InAs/GaSb T2SL	0.092	8×10^{-10}	$< 10^{-28}$
InAs/InAsSb T2SL	9.0	1.7×10^{-10}	6.0×10^{-25}
MWIR HgCdTe[1]	∞	2.2×10^{-10}	4.0×10^{-26}

[1]M.A. Kinch, *J Electron Mater* **29**, 809 (2000)

For light emitting diodes, which operate at high carrier densities rather than low (detectors), radiative and Auger rates are much more important, and SRH unimportant



Internal **Q**uantum **E**fficiency:

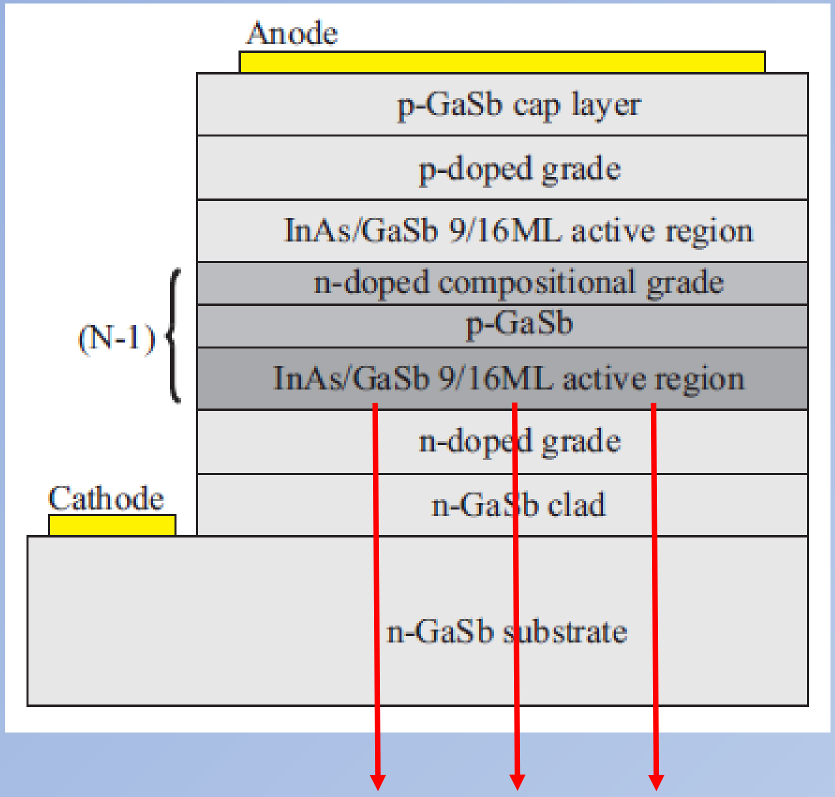
$$IQE \equiv \frac{photons\ emitted}{injected\ carrier}$$

$$IQE = \frac{B_{rad}n}{A_{SRH} + B_{rad}n + C_{Auger}n^2}$$

n is carrier density

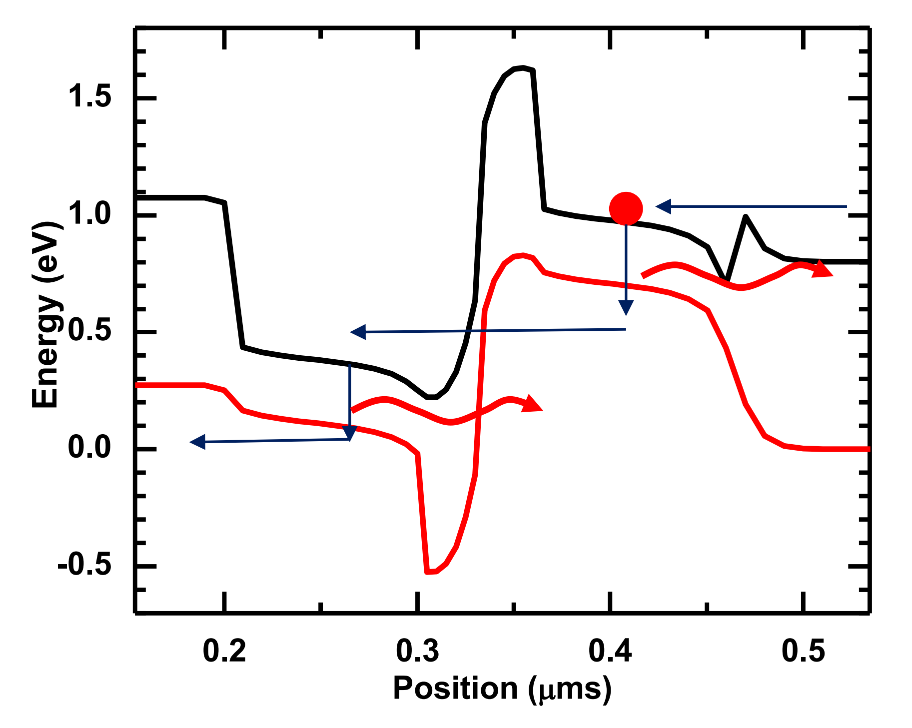
Due to the favorable Auger characteristics, we have used InAs/GaSb superlattices as the material of choice for high power light emitting diodes

Cascaded superlattice LED (SLEDs) Mesa Diode



Epitaxial structure fabricated into back-emitting LED

Diagram of a (biased) tunnel junction



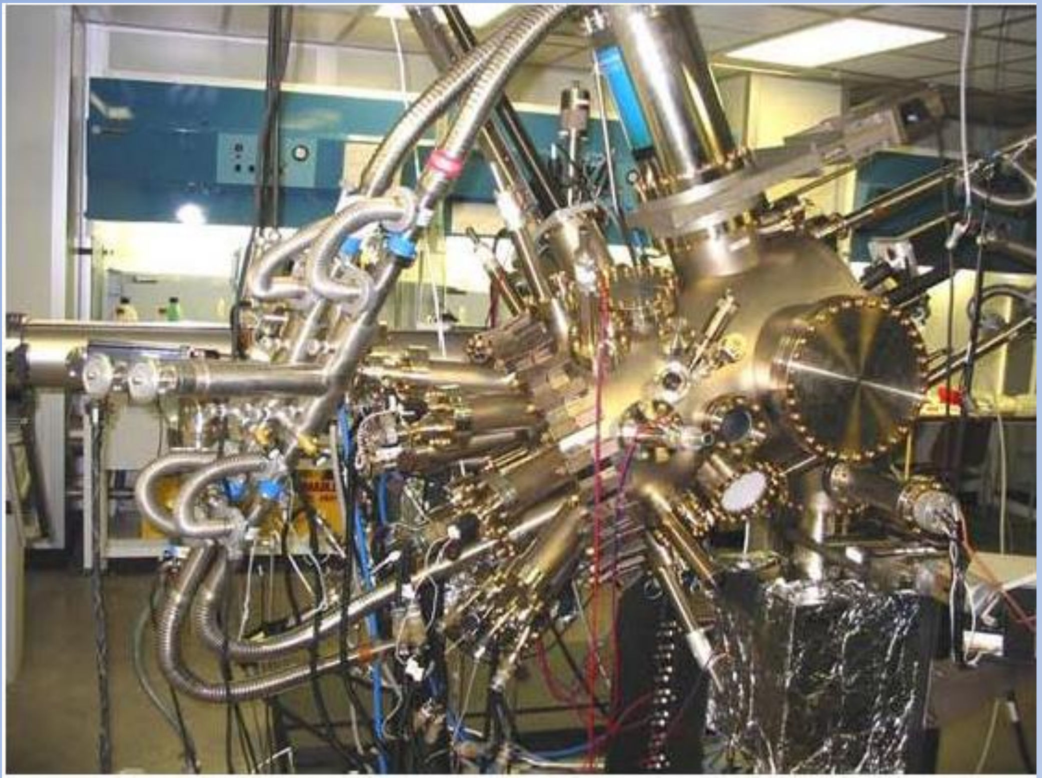
- N cascaded emission regions means each carrier can emit N photons instead of just one:

$$IQE_{N-stage} = N\ IQE_{1-stage}$$

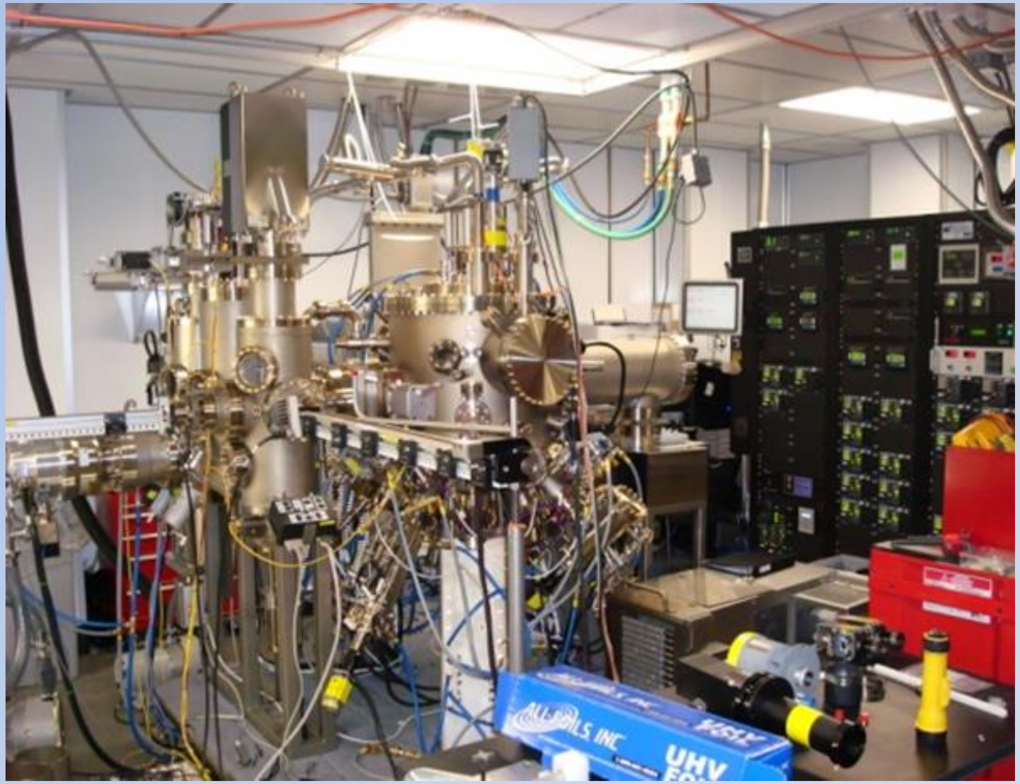
L.M. Murray etal, *J. Vac. Sci. Technol. B* **30**, 021203 (2012)

MBE growth facility at the University of Iowa

EPI930

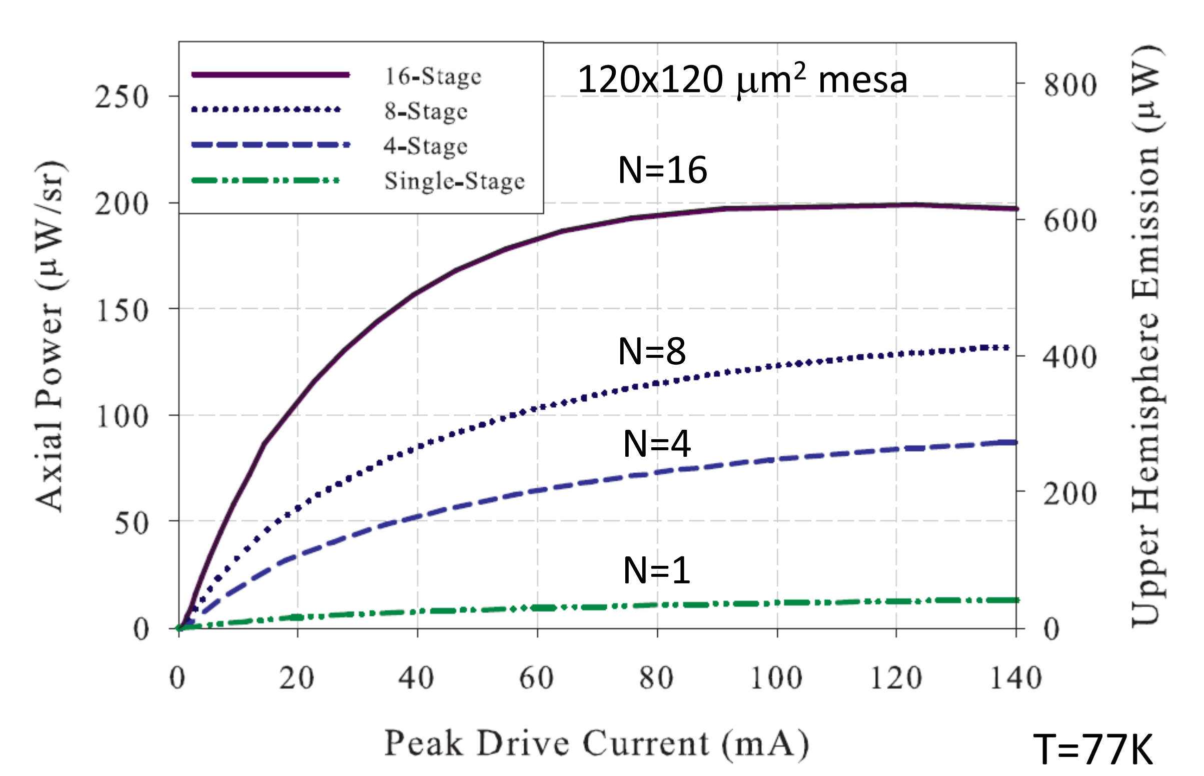


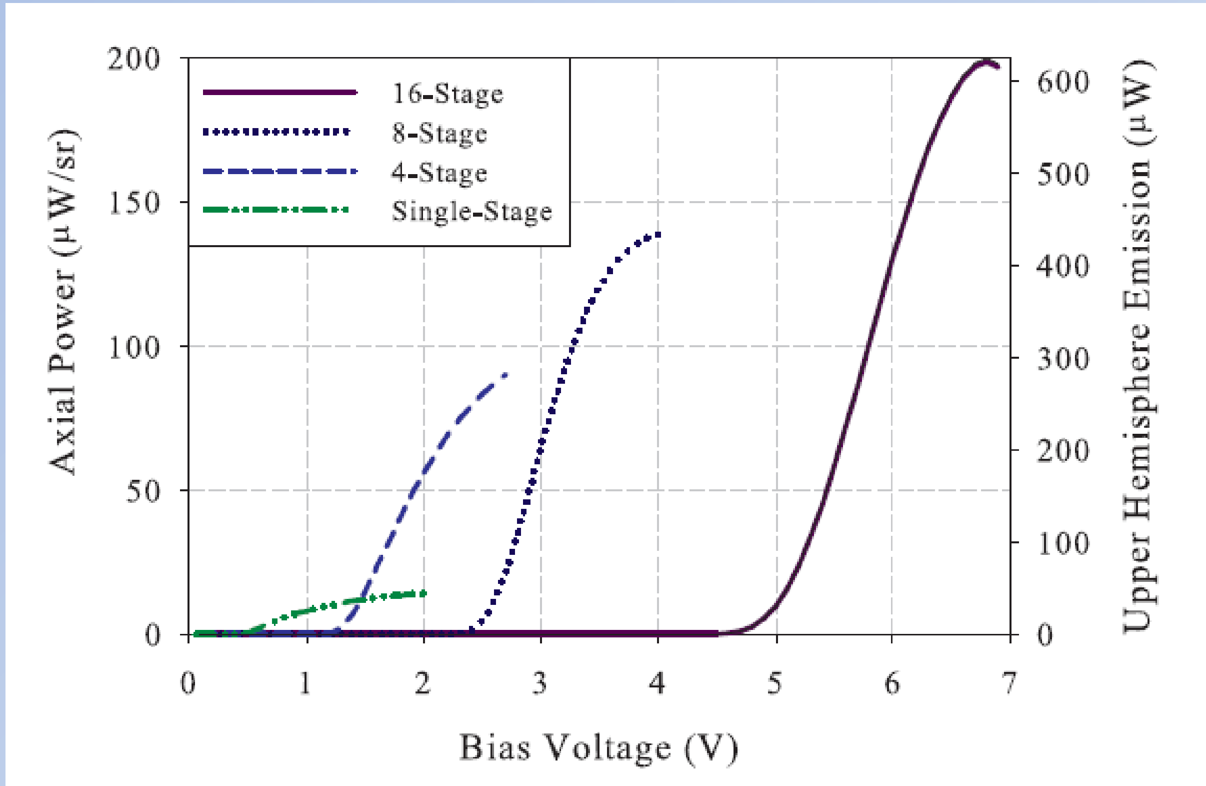
GEN20



The MWIR (and LWIR) cascaded InAs/GaSb superlattices mesa diodes exhibit high output power, and predicted scaling of output power with stages N

Cascaded SLEDs with variable number of stages:



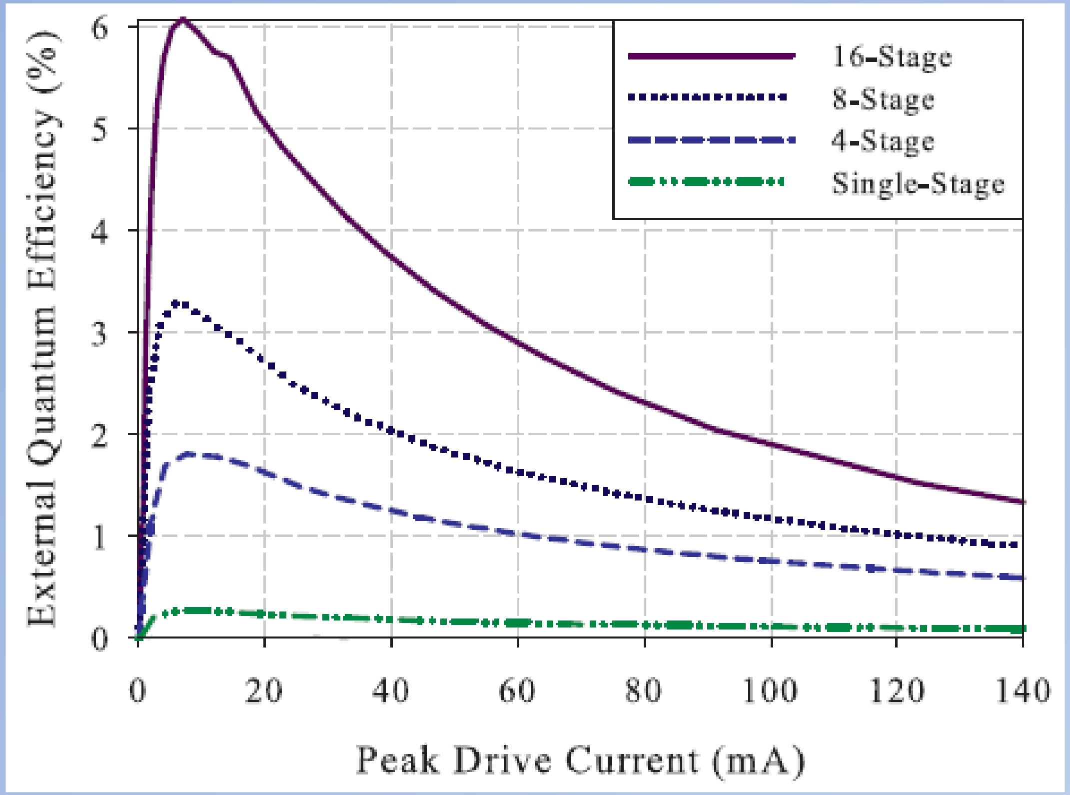


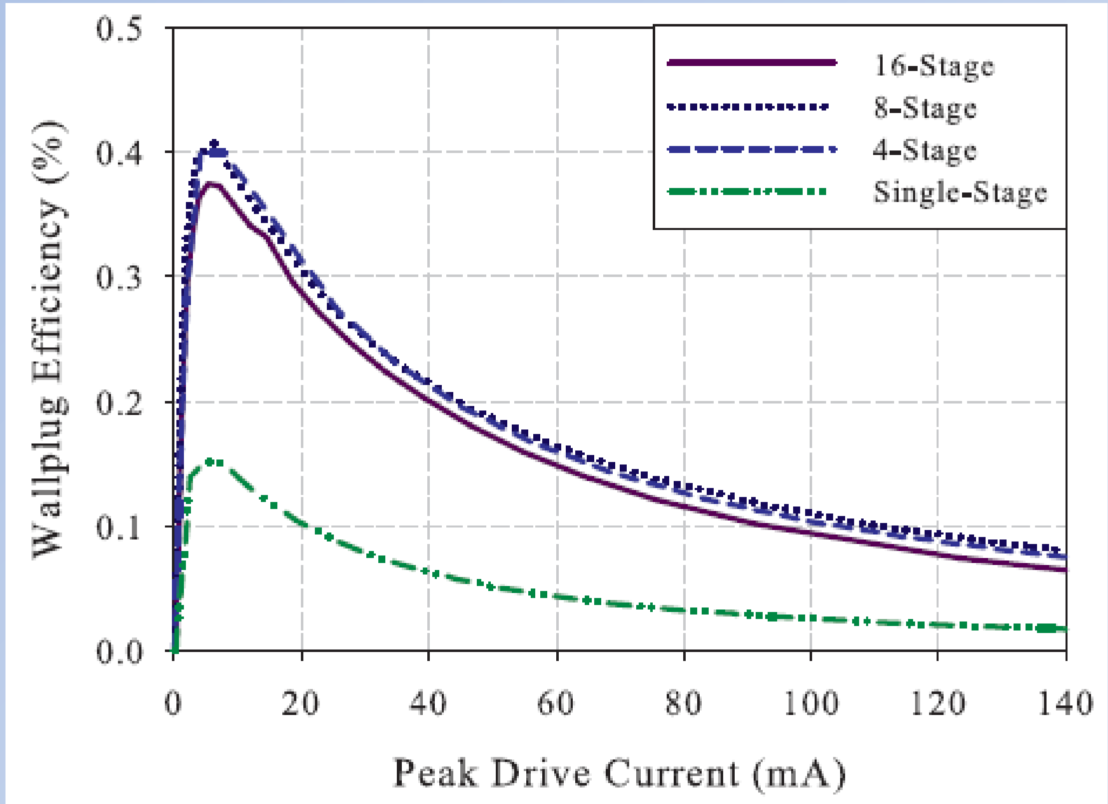
E. Koerperick etal, *IEEE J Quant Electron* **44**, 1242 (2008)

Cascading helps external quantum efficiency, and wallplug efficiency by allowing operation at lower currents

$$External\ quantum\ efficiency \equiv \frac{photons\ extracted}{electrons\ injected}$$

$$Wallplug\ efficiency \equiv \frac{light\ power\ out}{electrical\ power\ in}$$

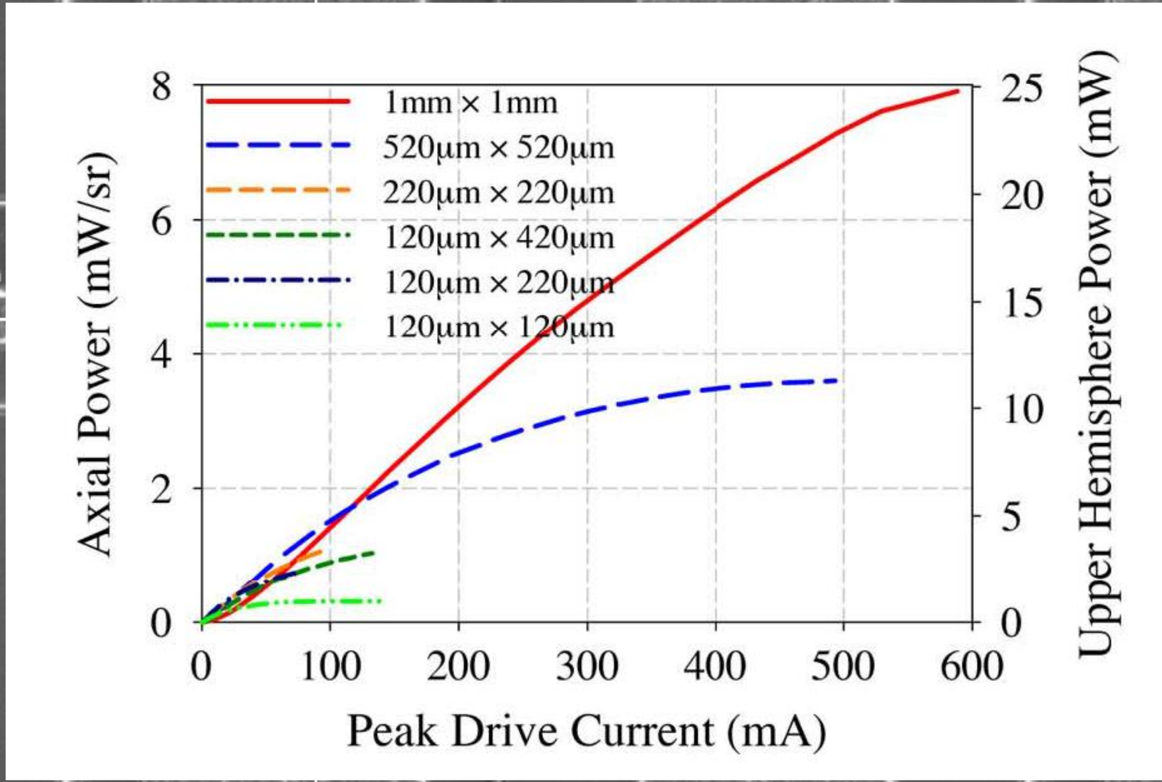




E. Koerperick etal, *IEEE J Quant Electron* **44**, 1242 (2008)

Output power scaling with mesa size

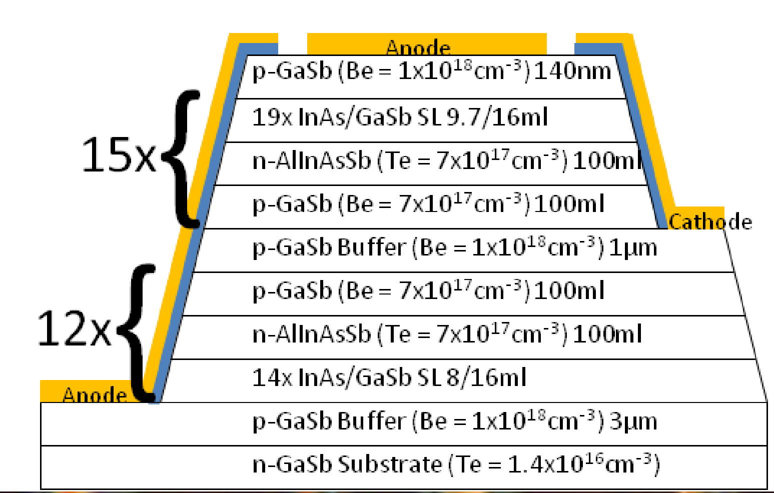
Sixteen stage SLEDs with variable mesa size (77K):

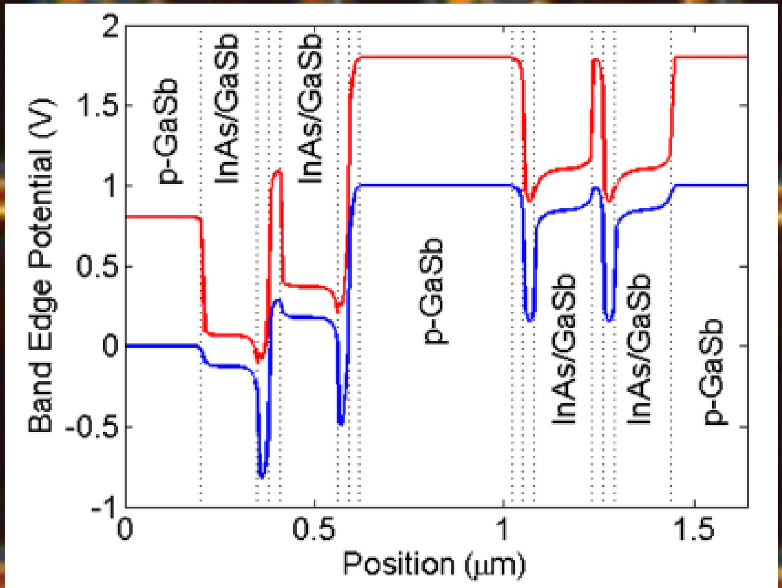


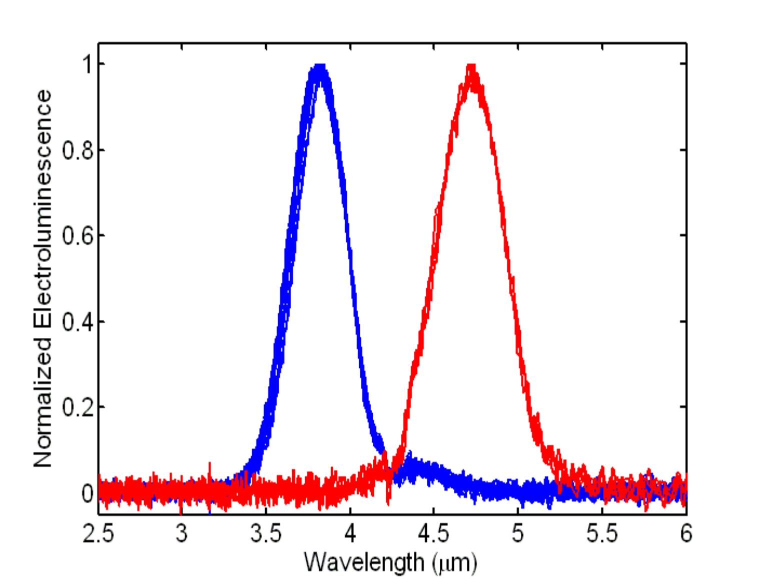
E. Koerperick etal, *IEEE J Quant Electron* **45**, 849 (2009)

We have grown/fabricated InAs/GaSb MWIR two-color SLEDs independently operable at each color

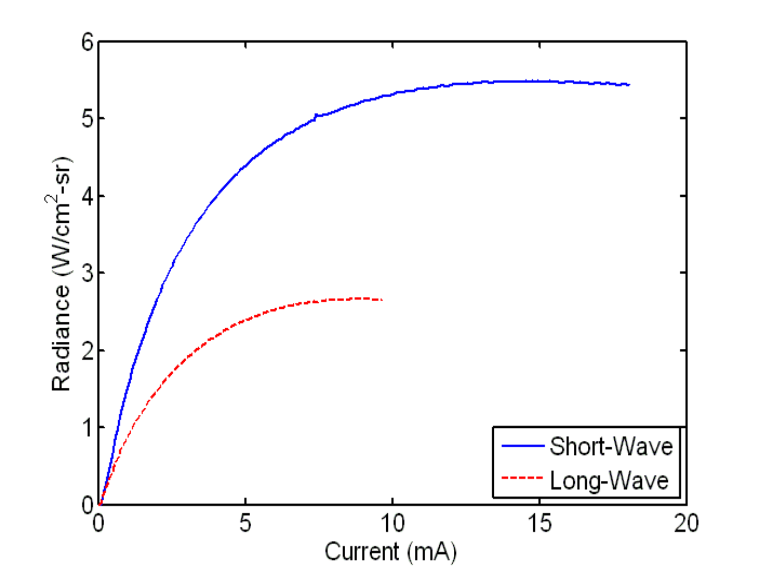
28 stage device over 9 μm thick
with over 500 interfaces







Operable at either color

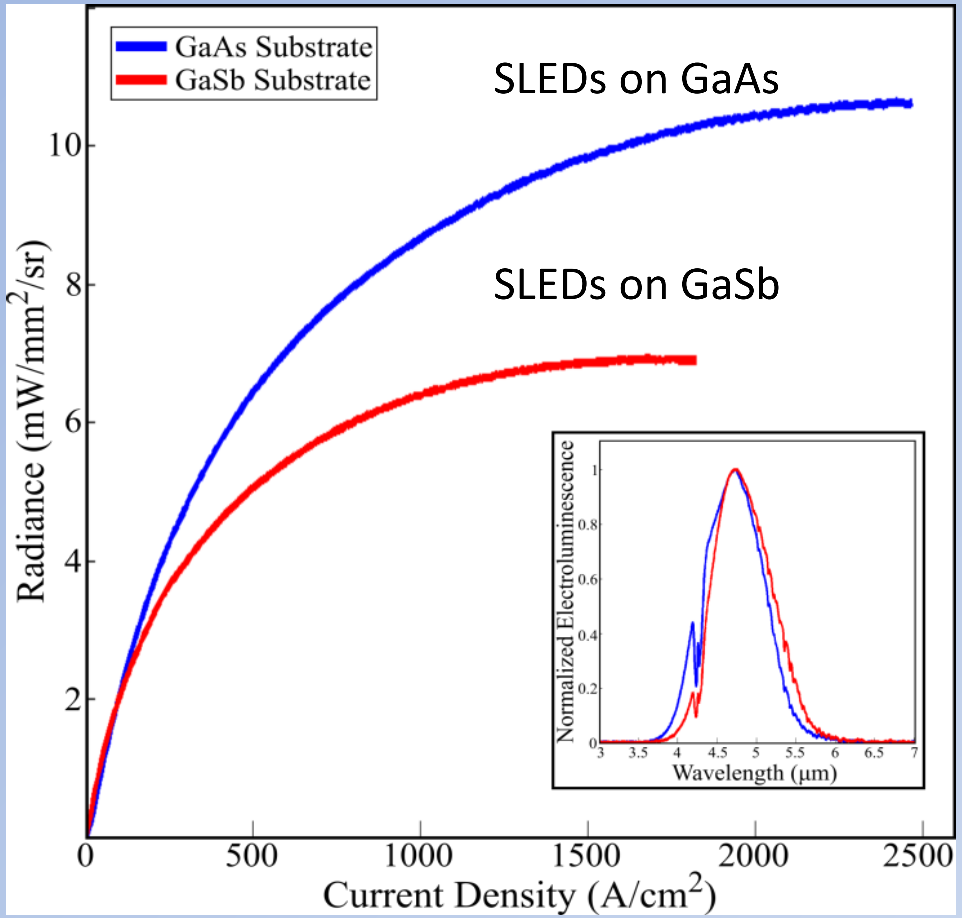


Output-current at each color

R.J. Ricker etal., IEEE J. Quant Electron 51, 3200406 (2015)

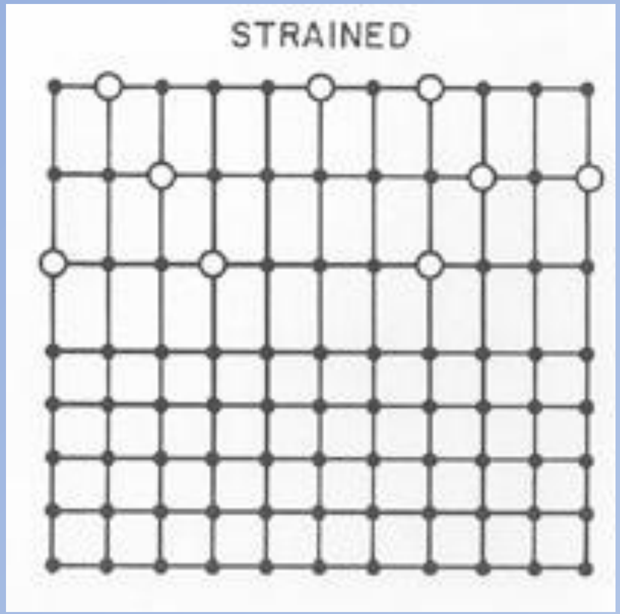
We have investigated growth of SLEDs on lattice-mismatched GaAs substrates. Surprisingly, more light came out than those grown on lattice-matched GaSb.

Light out versus current at 77K N=4

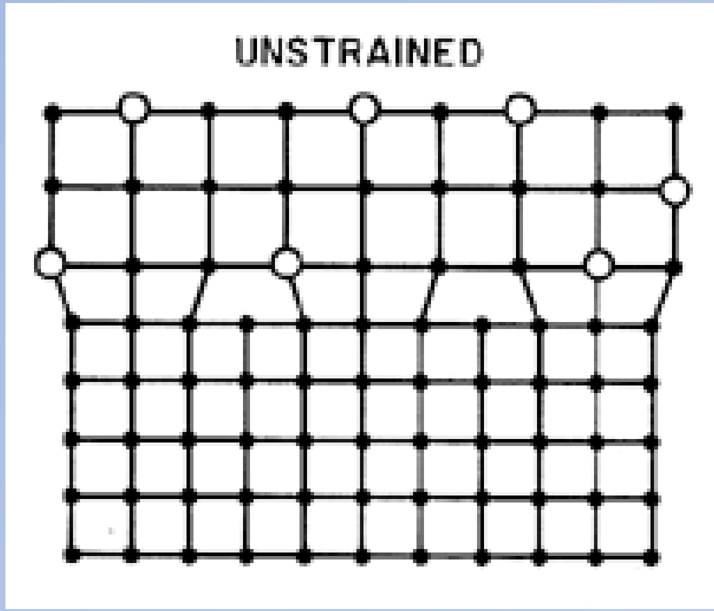


S. Provence etal, *J. Appl. Phys.* **118**, 123108 (2015).

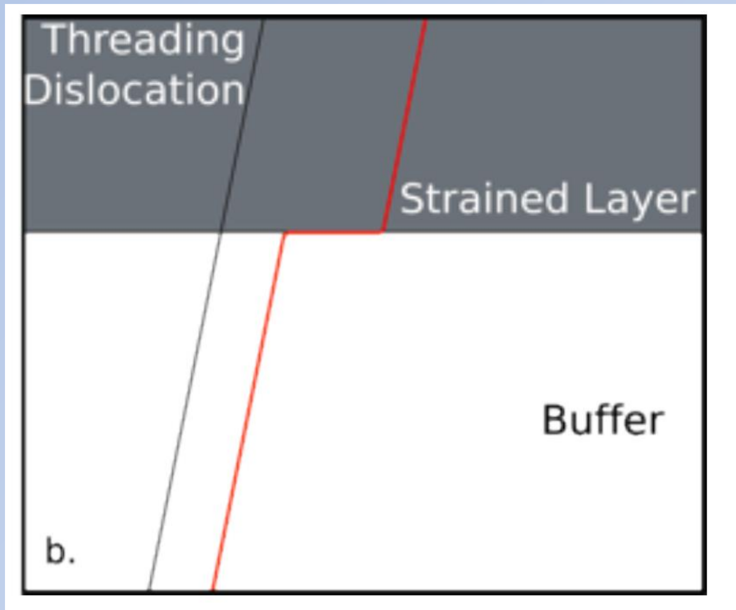
Why is it surprising that more light came out of material grown on lattice-mismatched GaAs (metamorphic growth) than lattice-matched GaSb (pseudomorphic growth)?



- Pseudomorphic growth: epilayer is fully strained to substrate

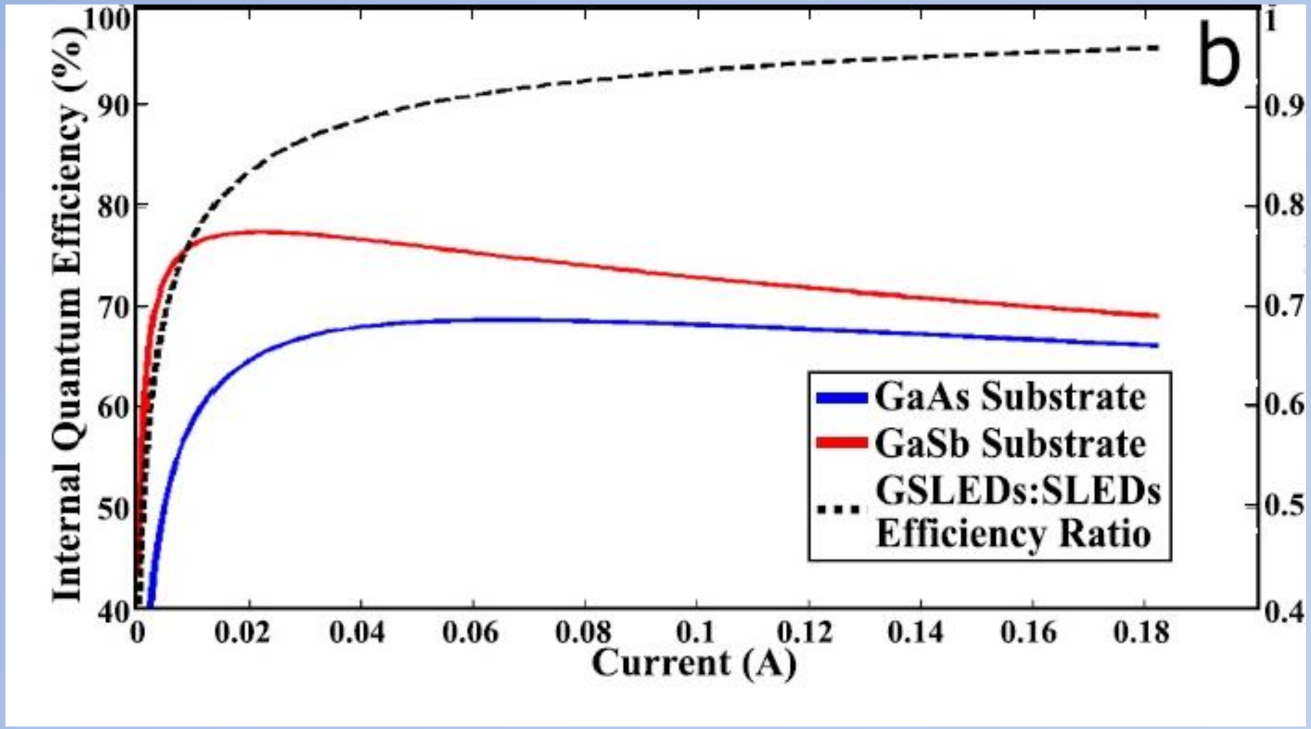


- Metamorphic growth: epilayer is fully relaxed through formation of misfit dislocations



- Misfit dislocations are not necessarily contained at interface, but can thread through epilayer creating defect states

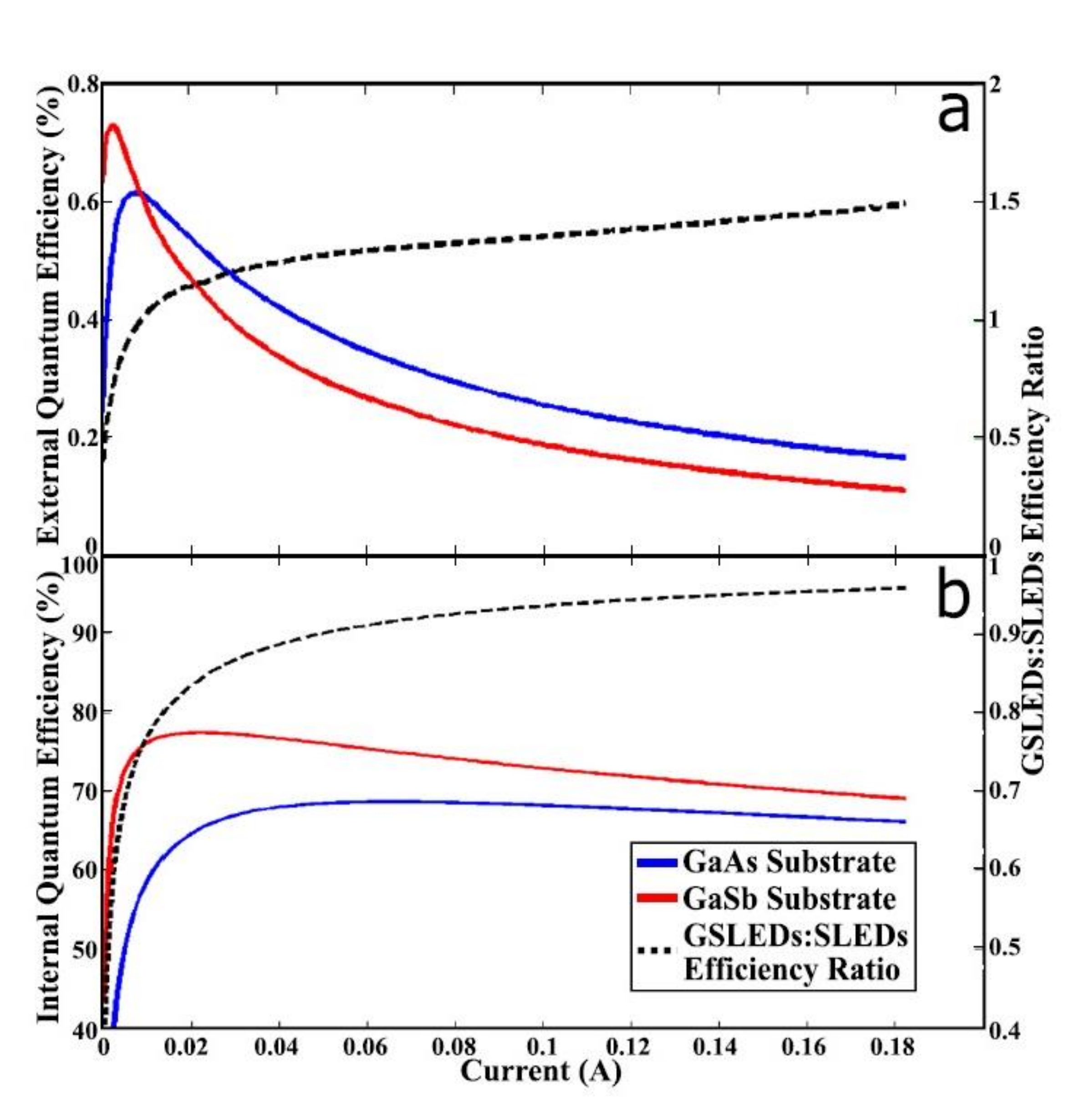
The misfit dislocations in SLEDs on GaAs increase the SRH nonradiative recombination rate, but SRH does not play an important role in the internal quantum efficiency



S. Provence etal, *J. Appl. Phys.* **118**, 123108 (2015).

- ❖ Per stage internal quantum efficiency (photons produced / injected carrier) calculated from measured recombination coefficients is similar for SLEDs on GaAs and GaSb except at low current injection.

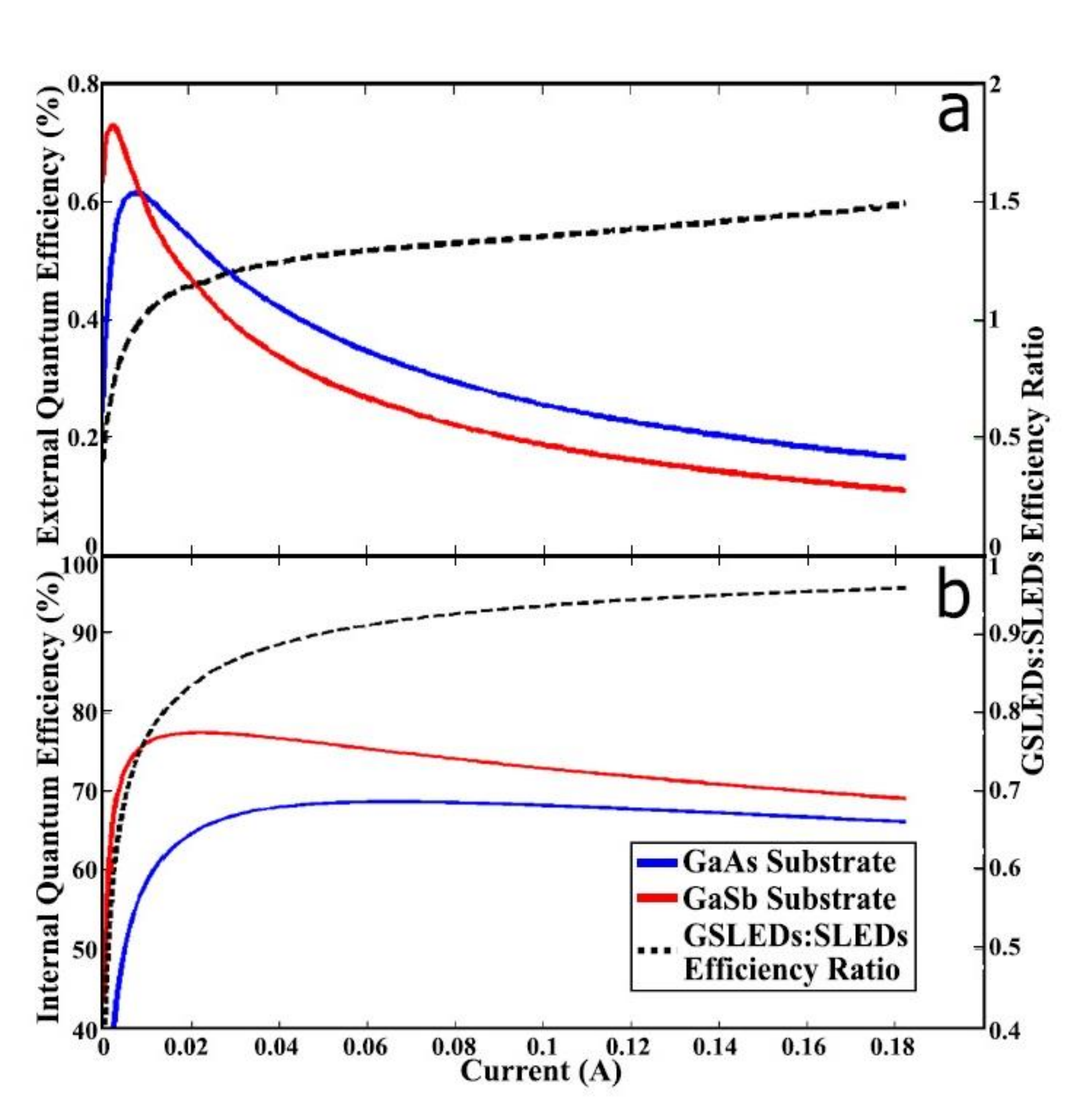
The misfit dislocations in SLEDs on GaAs increase the SRH nonradiative recombination rate, but SRH does not play an important role in the internal quantum efficiency



- Measured external quantum efficiency (extracted photons / injected carrier) is slightly higher for SLEDs on GaAs.
- The difference in EQE is attributed mainly to higher transparency of GaAs substrate compared to GaSb.

S. Provence etal, *J. Appl. Phys.* **118**, 123108 (2015).

Also revealed by this comparison is the need for us to improve our extraction efficiency

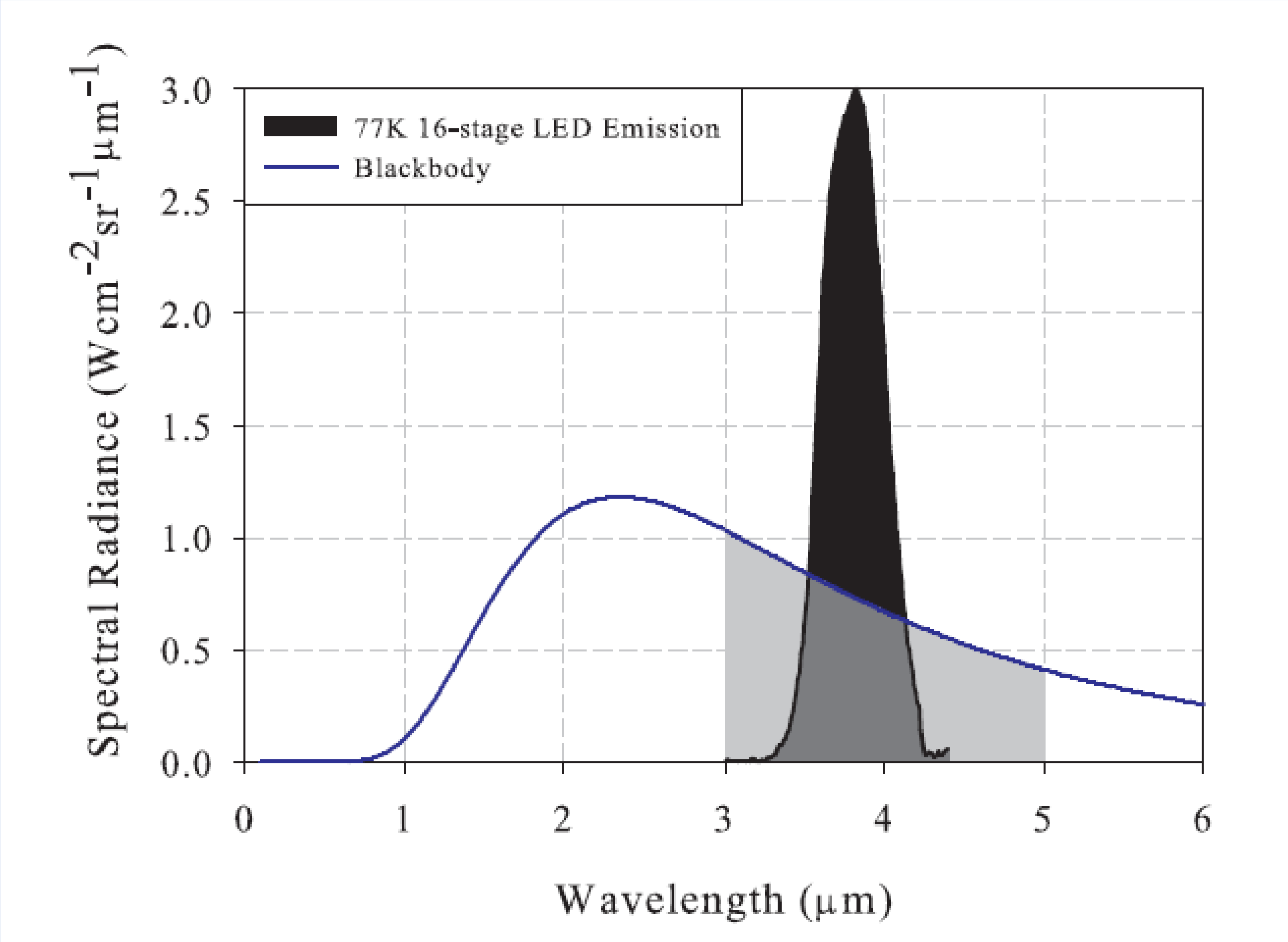


- ❖ Light is hard to extract from the LEDs because the high index of refraction of the material tends to trap light through total internal reflection.
- ❖ LED output could be increased 10-100x by frustrating Snell's Law.
- ❖ Droop in EQE is attributed to sample heating, and power loss to high contact layer sheet resistance

S. Provence etal, *J. Appl. Phys.* **118**, 123108 (2015).

Thermal scene generation: generating scenes with apparent temperatures through high radiance LED arrays

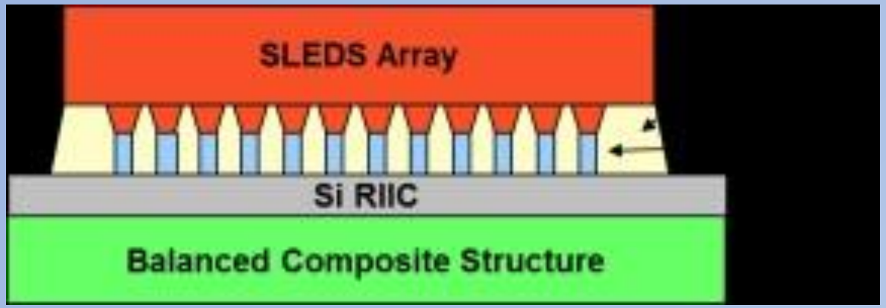
- Infrared LEDs emulate a blackbody in the sense of spectral radiance integrated over the mid-infrared – “power in a bucket” is the description sometimes used.
- Apparent temperatures of 2500 K state-of-the-art, equal to standard incandescent sources
- Apparent temperature of 6,000 K would equal the surface of the sun.



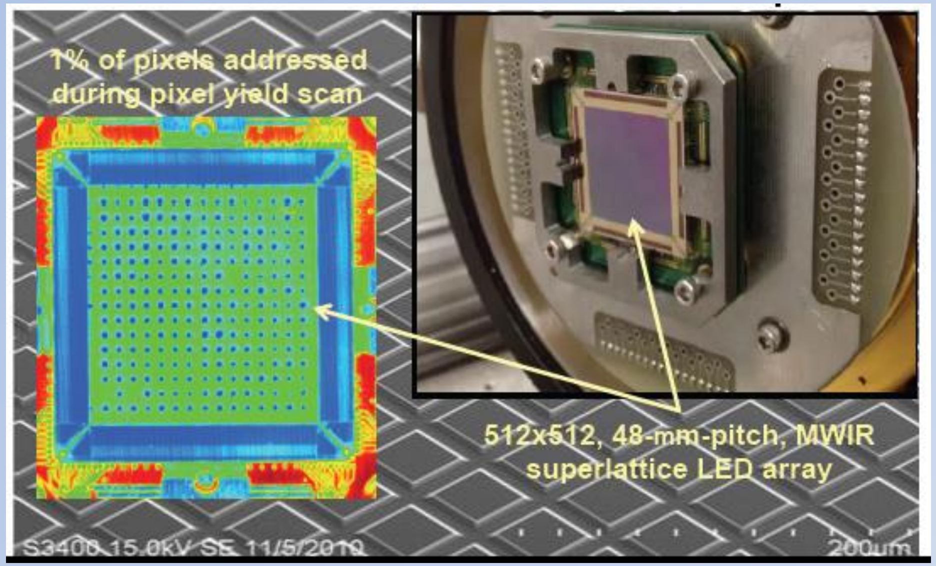
E. Koerperick etal, *IEEE J Quant Electron* **44**, 1242 (2008)

Thermal scene projectors with 1500 K apparent temperature and 512x512 array demonstrated

Hybridization of SLEDs array and Si CMOS:



From J. Ejzak etal, submitted to *IEEE J. of Display Technology* (2015)



D.T. Norton etal, *IEEE J. of Quantum Electron.* ***49**, 753 (2013)*

- InAs/GaSb SLED used in LED array for thermal scene generation
- Pixel yield greater than 95%

Conclusions

- Auger nonradiative recombination dominates over Shockley-Read Hall nonradiative recombination in LEDs. This makes InAs/GaSb a remarkable emitter compared to dominant detector materials such as HgCdTe or InAs/InAsSb.
- The unimportance of SRH in SLEDs opens the door to growth of SLEDs metamorphically on a variety of other advantageous substrates.
- The quantum efficiency of cascaded SLEDs scales with the number of stages N, while wallplug efficiency is technically independent of N
- We have demonstrated SLEDs with two independently operable colors, 512 x 512 SLEDs arrays, and SLEDs apparent temperatures of 2500K.
- Thermal scene generation is composed arrays of light emitters that generate an apparent temperature through radiance in wavelength range, or “power in a bucket.”
- There are still potential major improvements in SLEDs output power