Mid-Infrared Semiconductor Lasers: Recent Advances and Future Pursuits

Linda J. Olafsen

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Collaborators

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James Tour (Rice)

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REU 2009: Nethmi Ariyasinghe (USC), Lauren Ice (Arizona State), Ben Ball (RPI)
REU 2010: Lauren Bain (University of North Carolina)
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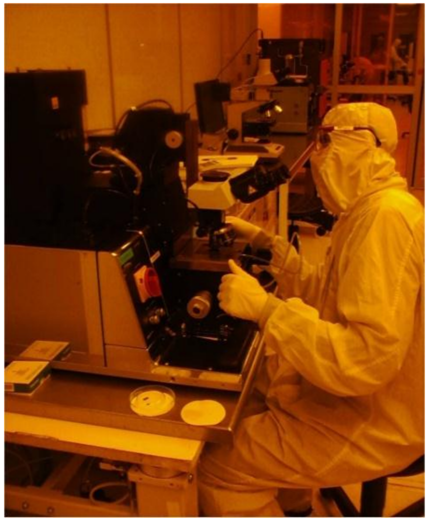
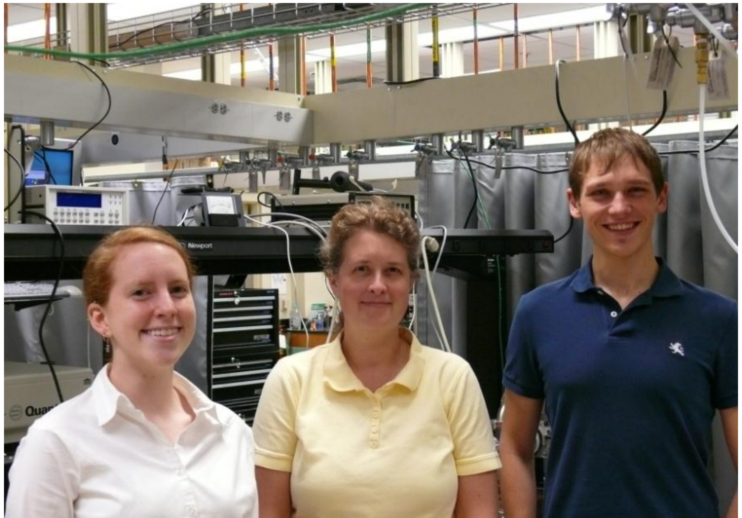




Graduate Physics at Baylor

***Ph.D.* and Masters in Science**

- ***General GRE required***
- ***Physics GRE optional***
- ***Most students serve as Graduate Teaching Assistants***

Research areas:

Astrophysics and Space Sciences, Plasma Physics (Hyde, Matthews, Wang)
Atomic and Molecular Physics (Ariyasinghe)
Condensed Matter Physics (Benesh, J. Olafsen, L. Olafsen, Park, Russell, Zhang)
Elementary Particle Physics (Cleaver, Dittmann, Hatakeyama, Wang, Ward, Wilcox)
Gravitation and Cosmology (Cleaver, Wang, Ward)
Non-Linear Dynamics (J. Olafsen)

First Year Recommended Course Plan

Fall Term (10 hrs)
5320 Classical Mechanics I (3 hrs)
5360 Mathematical Physics I (3 hrs)
5370 Quantum Mechanics I (3 hrs)
5180 Graduate Physics Colloquium (1 hr)

Spring Term (10 hrs)
5330 Electromagnetic Theory I (3 hrs)
5340 Statistical Mechanics (3 hrs)
5371 Quantum Mechanics II (3 hrs)
5180 Graduate Physics Colloquium (1 hr)

Qualifying Exam

- During the summer between your first and second years
- The exam consists of four parts:
  - Classical Mechanics
  - Quantum Mechanics
  - Electricity and Magnetism
  - Mathematical methods/Thermodynamics and Statistical Mechanics

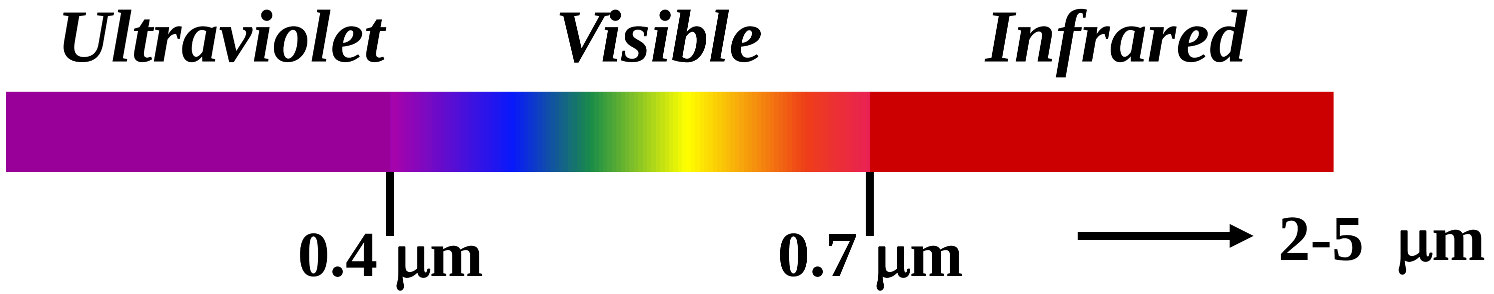
The Qualifying exam must be passed to remain in the Ph.D. program. Two attempts, once a year for the first two years, are the maximum allowed.

Outline

- Objectives
- Applications
- Semiconductor basics
- 3-5 μm semiconductor lasers
- Resonant optical pumping of type-II W lasers
- Temperature limitations
- New research directions
    - Integrated absorber lasers
    - Interband cascade lasers
    - Graphene contacts
- Conclusions

Objectives

- Understanding carrier dynamics in wave-function engineered structures
- Development of efficient mid-infrared (λ = 3-5 μm) semiconductor lasers emitting high cw output powers (≈1 W) at or above thermoelectric cooler temperatures ($T_{op} \geq 200$ K)
- Development of near-infrared light emitting diodes (LEDs) and detectors



Applications

- Chemical sensing
  - Atmospheric pollution
  - Industrial process monitoring and control
  - Drug monitoring
  - Detection and monitoring of chemical weapons facilities
  - Glucose monitoring
  - Breath monitoring (asthma, ulcers, cancer)
- IR Countermeasures
- Laser Surgery
- Spectroscopy

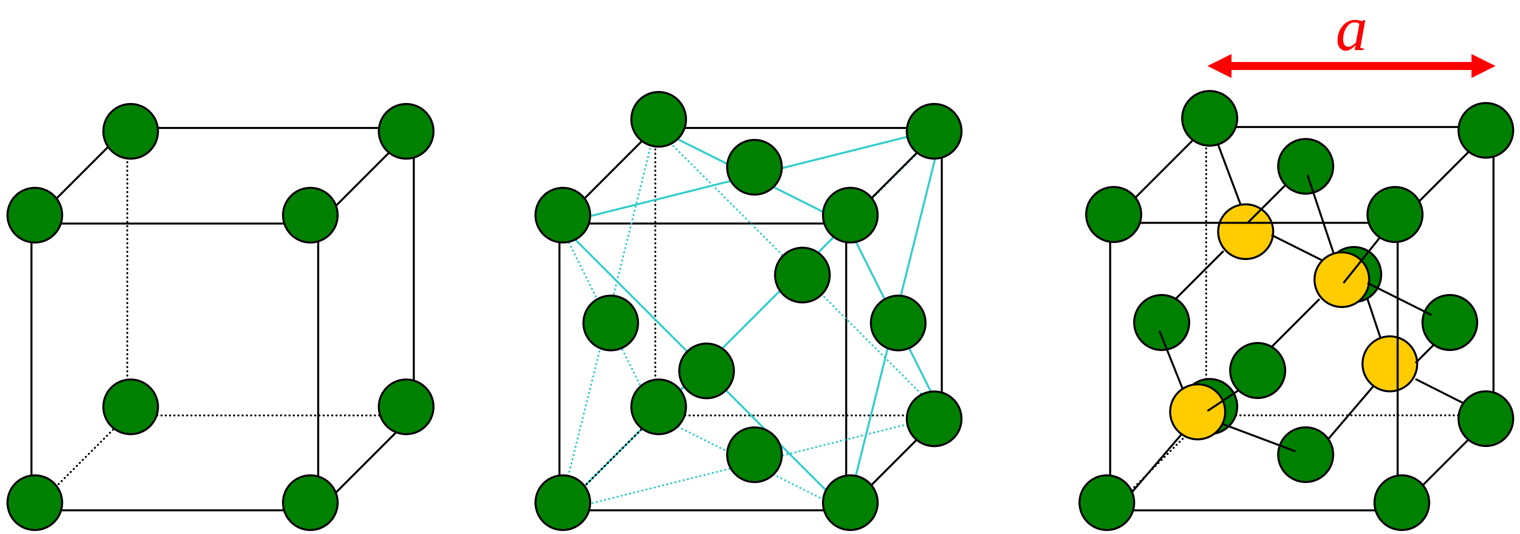
Baylor University PHYSICS

Enhanced Chemical Detection

Molecule	Wavelength (μm)	Sensitivity (ppm-m)
CO_2	1.432	17
	1.957	0.25
	2.779	0.0025
	4.235	0.00003
CO	1.567	3.6
	2.333	0.09
	4.602	0.0002
CH_4	1.651	0.07
	3.281	0.0007
H_2O	1.365	0.006
	1.847	0.004
	5.935	0.0004
N_2O	1.953	10
	2.257	0.07
	4.468	0.0001

- Chemical detection 10^2-10^4 times more sensitive in mid-IR than near-IR
  - High-*T* sources required
- Monitoring of pollution, industrial processes, drugs, biological agents, *etc*.
- Chemical weapons monitoring, explosives detection, leak detection
- Other mid-IR laser applications: spectroscopy, laser surgery

Lattice structure

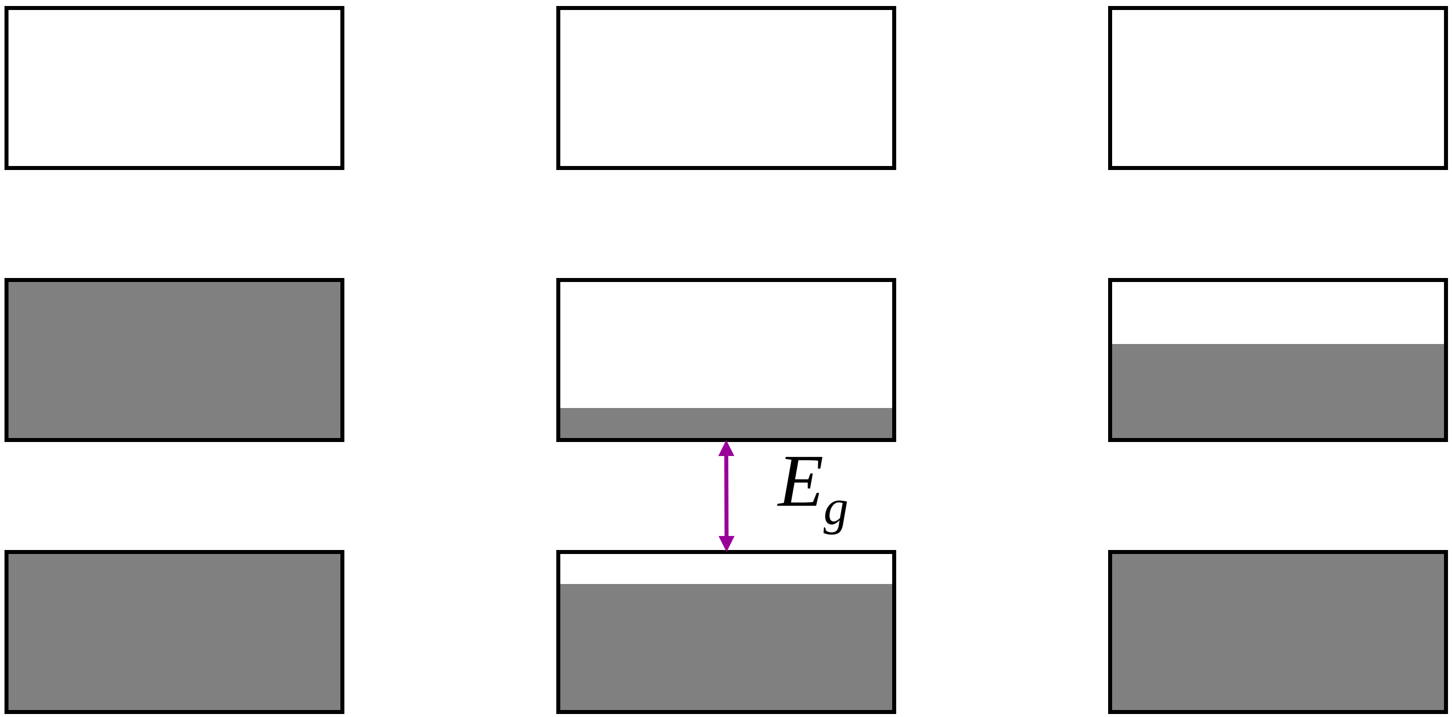


simple cubic *face-centered cubic* *zincblende*

Group III-e.g., Ga, Al, In

Group V-e.g., As, Sb

Energy bands

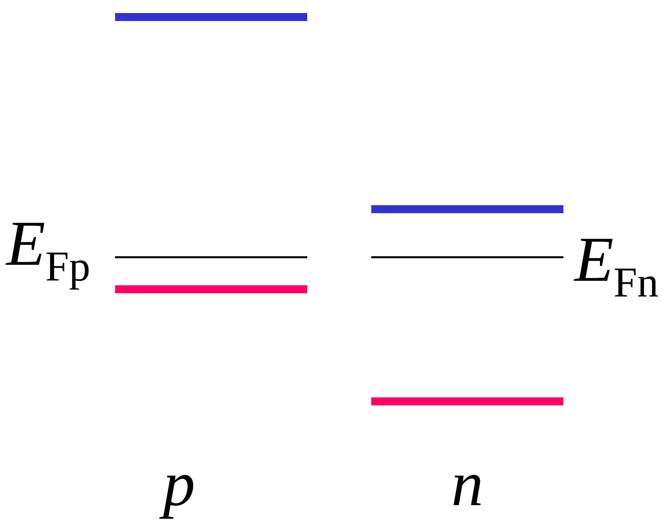


insulator	**semiconductor**	**metal**
glass	*silicon*	*gold*
wood	*germanium*	*copper*
brick	*gallium arsenide*	*silver*

Semiconductor heterostructures

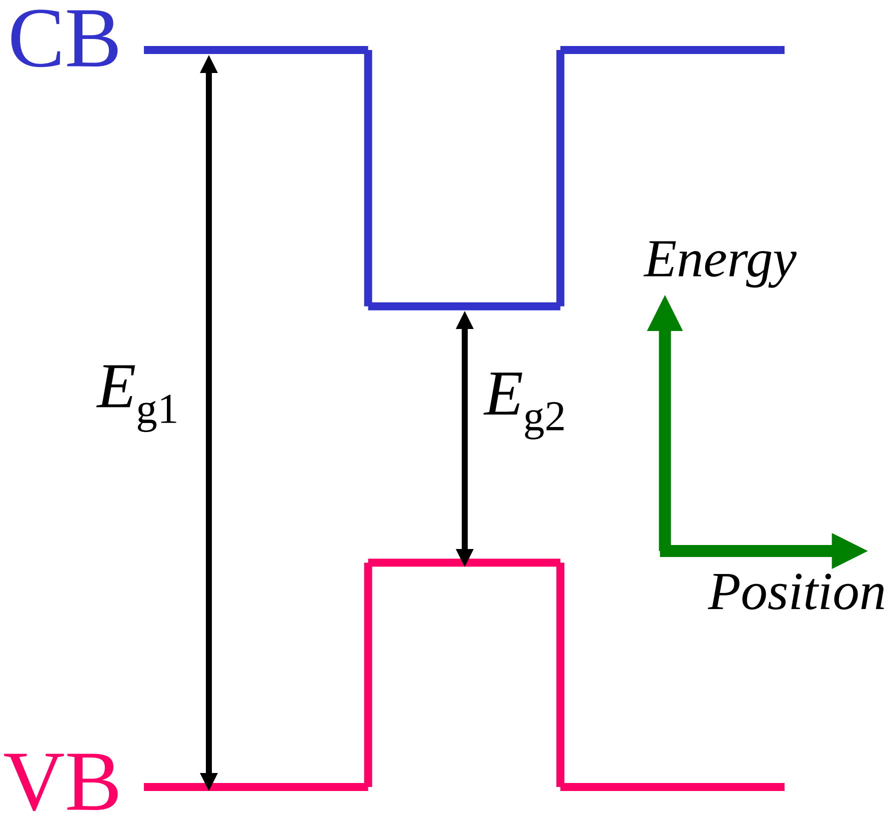
Bringing layers of different doping or different band gap together

- *p*-*n* junctions
- quantum wells

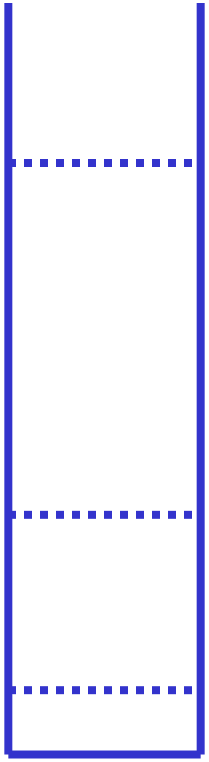


CB: conduction band

VB: valence band



Infinite square well



$$V(x)=\begin{cases}0, & 0<x<L\\ \infty, & x<0,\ x>L\end{cases}$$

$$-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi(x)+V(x)\psi(x)=E\psi(x)$$

$$E_n=\frac{n^2\hbar^2\pi^2}{2mL^2}$$

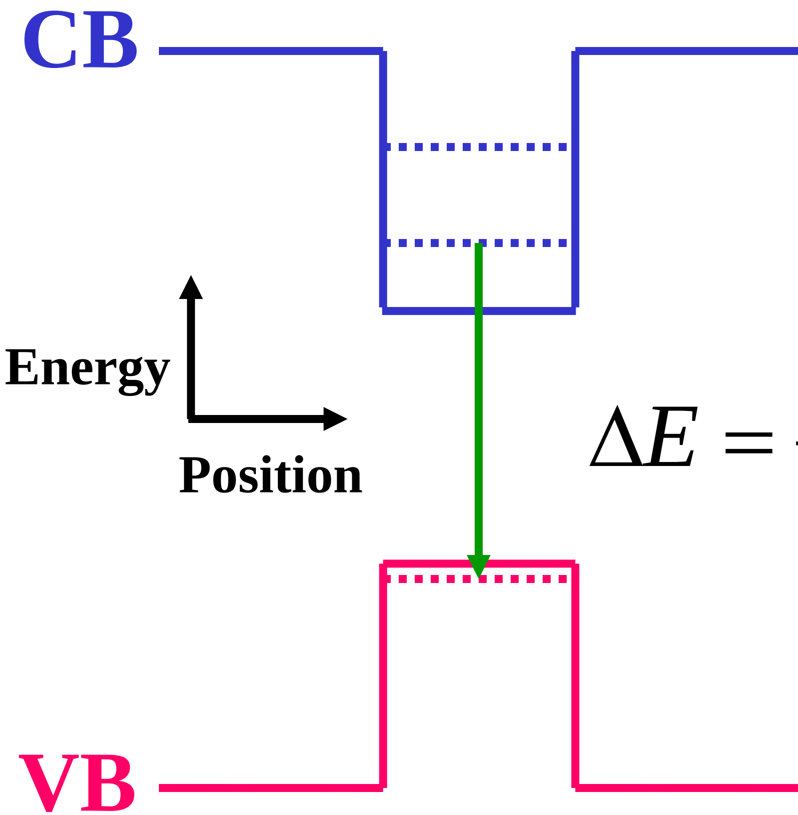
Generating 3-5 μm lasers

Three primary semiconductor approaches:

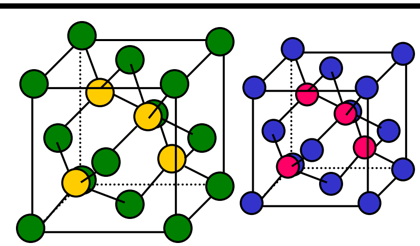
- Type-I (direct) interband GaSb-based lasers
  - Grown on GaSb or “virtual” substrates
  - Incorporate strain
- Quantum cascade lasers
  - Lattice-matched to InP substrates
- Type-II (indirect) “W” wells
  - Latticed matched to GaSb substrates

Alternate approaches (typically based on harmonic generation): optical parametric oscillators, optical parametric amplifiers, periodically-poled lithium niobate, frequency doubling in longer wavelength QCLs (e.g., 8 μm → 4 μm)

Approach I: Direct gap



$$\Delta E = \frac{hc}{\lambda}$$

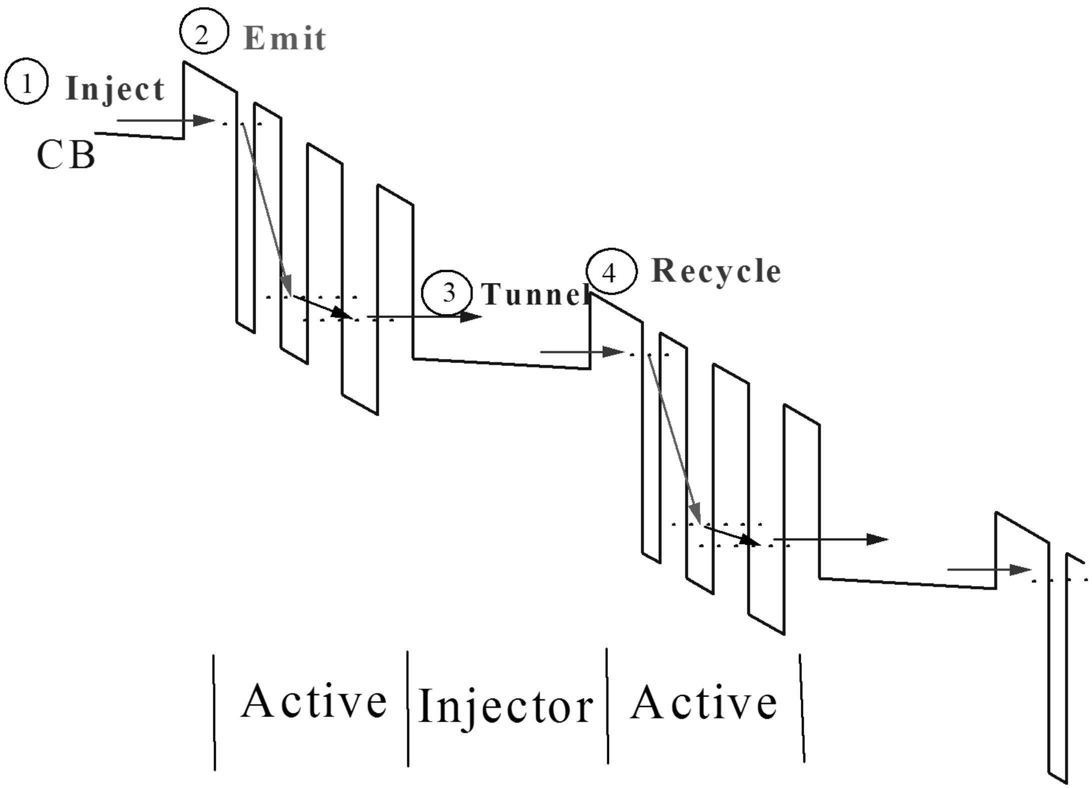


Lattice mismatch

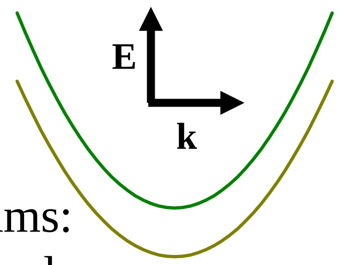
- GaSb-based wells
- **Interband** transitions
- Longest wavelengths limited by direct gap
- Able to reduce gap through strain incorporation
- Wavelengths extended to ~3.5 µm using compositionally graded metamorphic buffer layers
- No clear path to extend to the ~5 µm range

- Leading research teams:
  Belenky *et al.*, SUNY Stonybrook

Approach II: QCLs



- Quantum cascade lasers
- Multiple photons out for each injected electron
- Excellent in 8-12 μm range and longer wavelengths
- InAlAs/InGaAs lattice-matched to InP substrates
- Limitations: phonon scattering, well depth

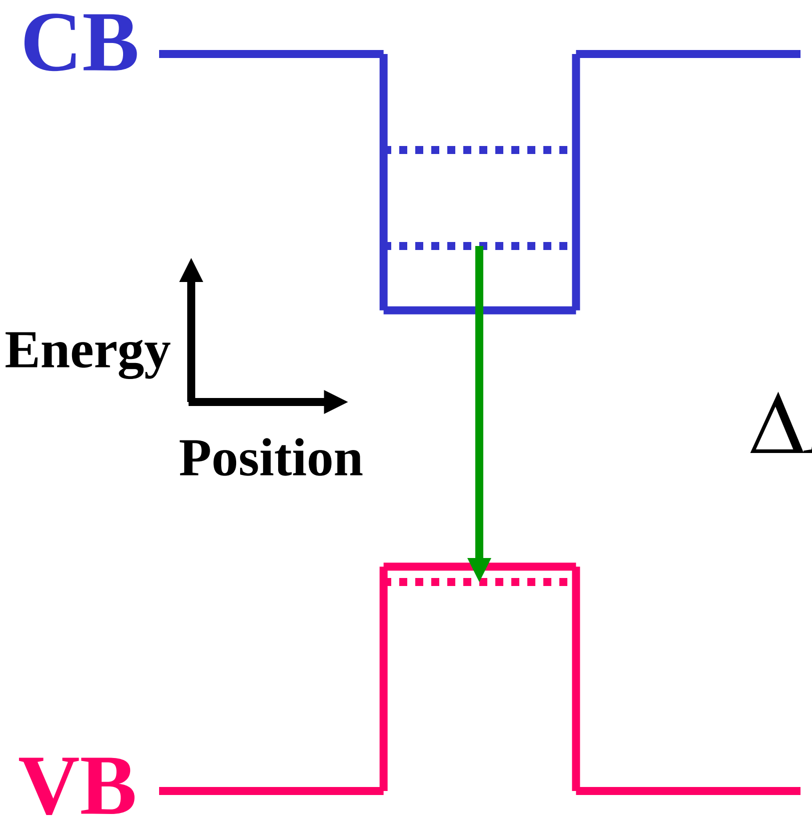


Electrons are injected from the left, photons are emitted when the electron makes a diagonal **intersubband** transition, and then the electron further relaxes via phonon emission and tunneling through and injector region for recycling at the next identical period of the structure.

- Leading research teams: Capasso *et al.*, Harvard; Faist *et al.*, ETH-Zürich; Razeghi *et al.*, Northwestern

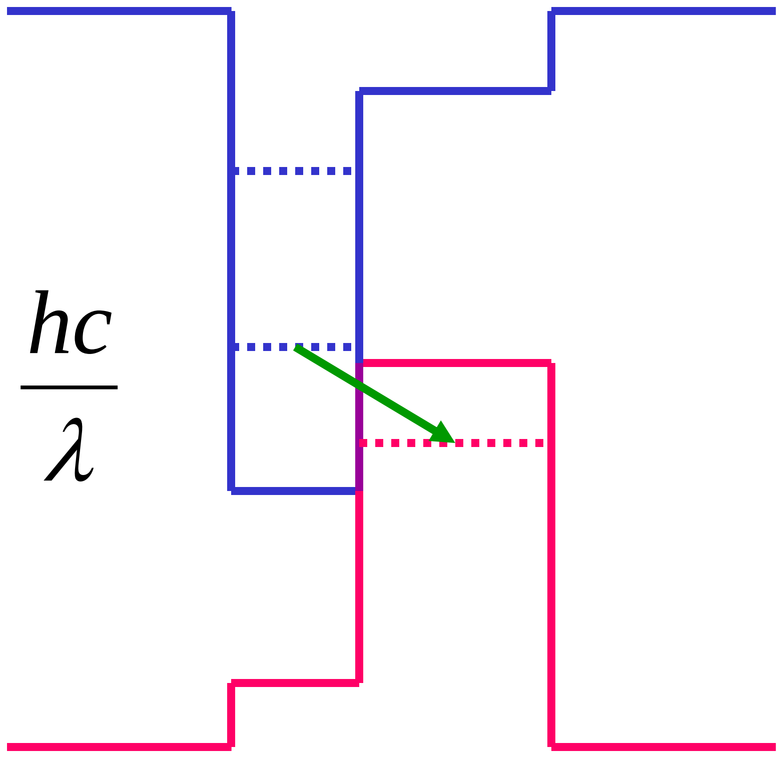
J. Faist, *et al.*, "Quantum cascade laser," *Science* **264**, 553–556 (1994).

Band offsets



TYPE I

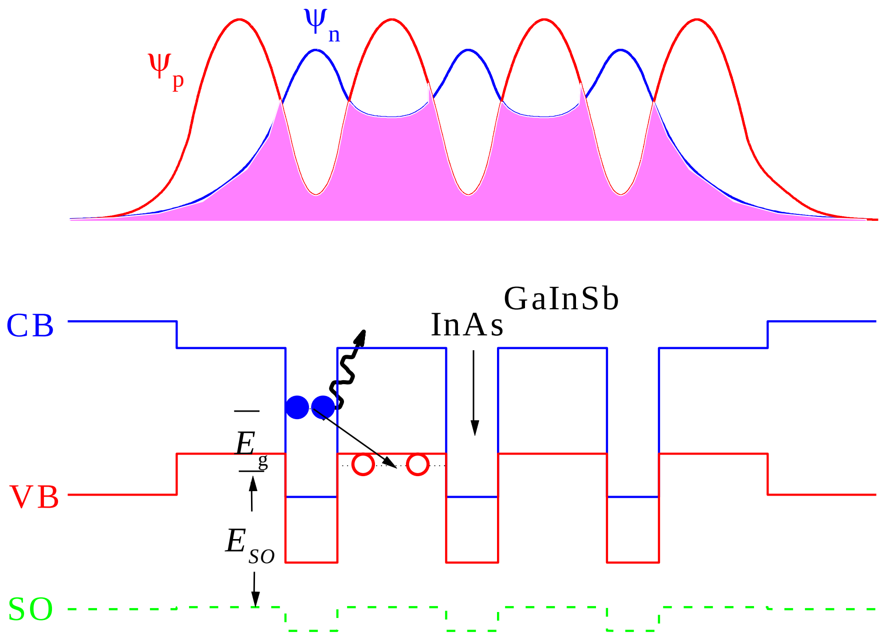
$$\Delta E = \frac{hc}{\lambda}$$



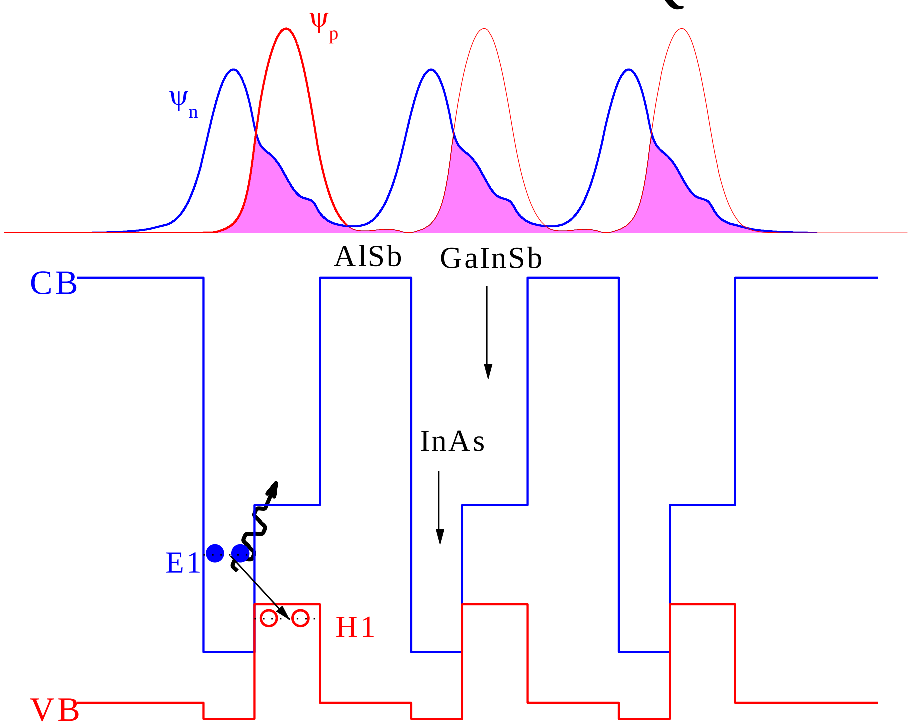
TYPE II

3D vs. 2D Density of States

TYPE-II SL



3-CONSTITUENT MQW



<u>Advantages</u>:

(1) Excellent electrical confinement

(2) Suppressed Auger

<u>Disadvantage</u>:

3D Density-of-States

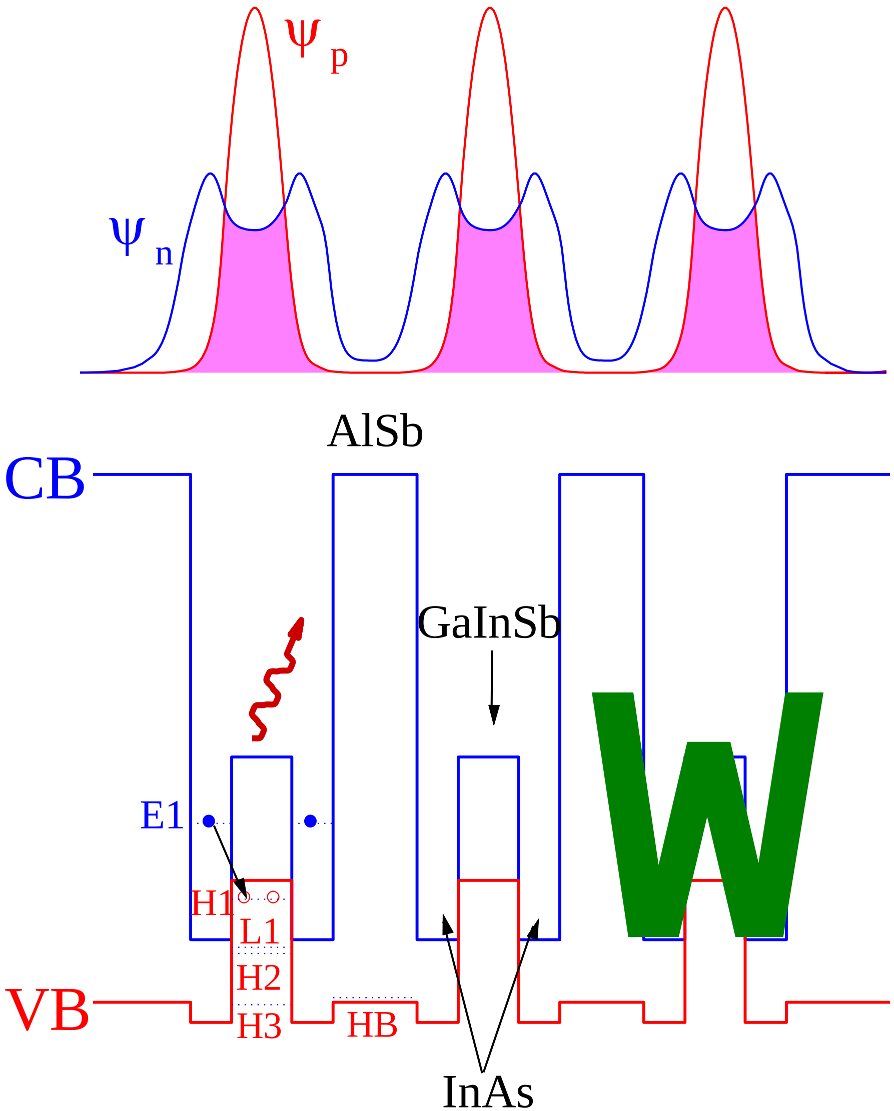
<u>Advantage</u>:

2D DOS for electrons and holes

<u>Disadvantage</u>:

Reduced wavefunction overlap

Approach III: Type-II "W" Laser



Advantages:

(1) Strong wavefunction overlap

(2) 2D for both electrons and holes

(3) Excellent electrical confinement

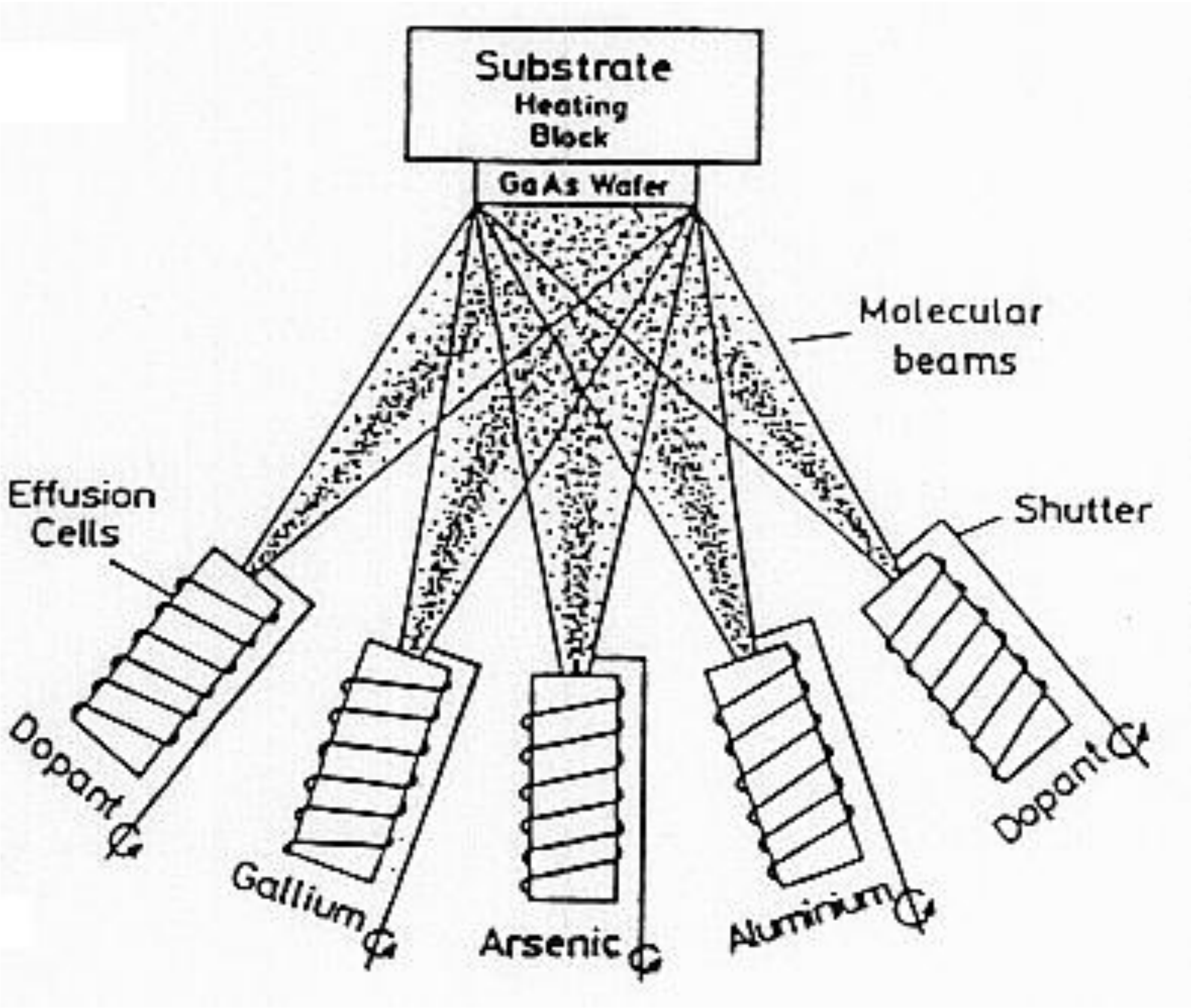
(4) Auger suppression

– *Factor of 5-10 improvement confirmed in lasers*

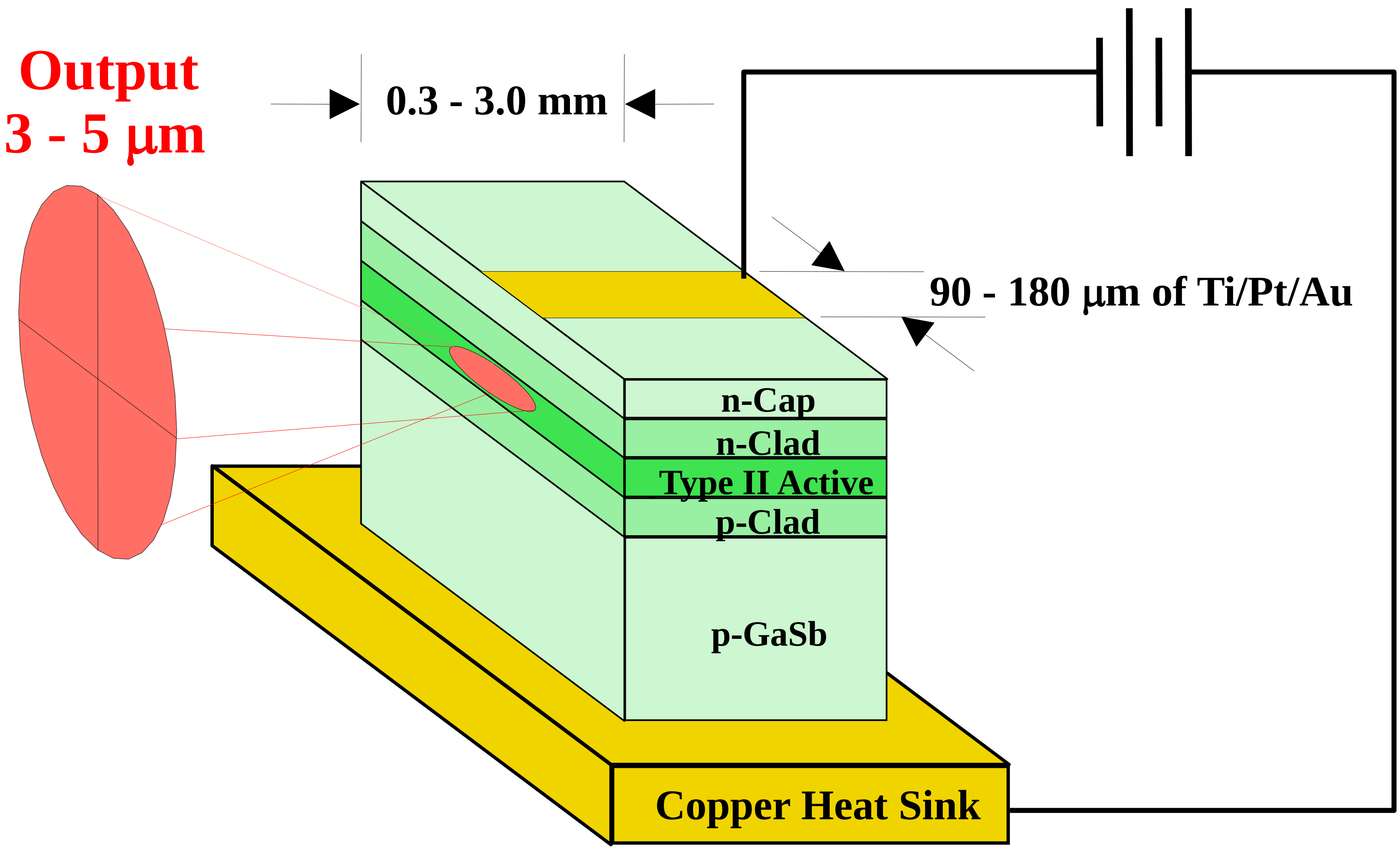
Meyer et al. APL ***67****, 757 (1995)*

U.S. Patent # 5,793,787

Molecular Beam Epitaxy



Electrical injection



Optical Pumping

Advantages

- Epitaxy greatly simplified
- Little to no post-growth processing
- Higher operating T_{max}/less heating

Disadvantages/Issues

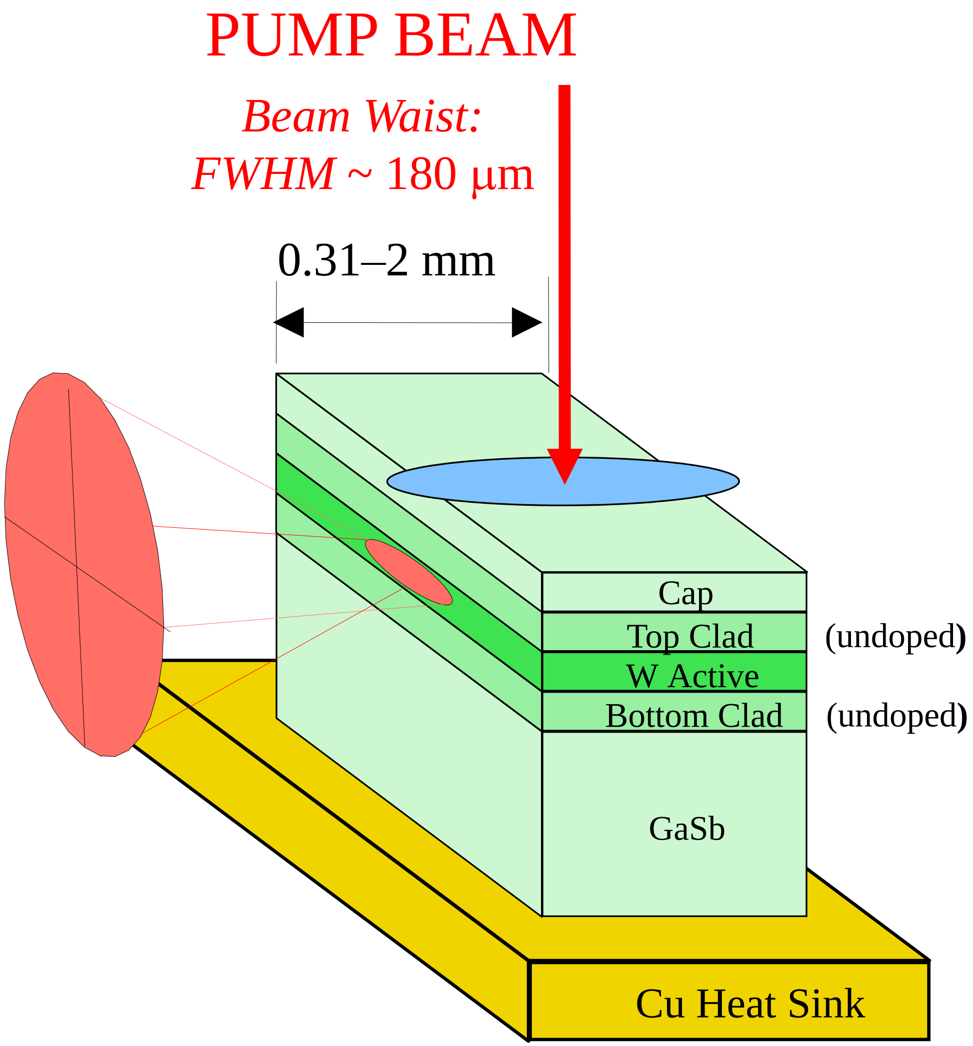
- Photon decrement
- Efficient absorption of pump beam
- Free carrier absorption losses
- Near-infrared pump sources

Optical Pumping *(with OPO)*

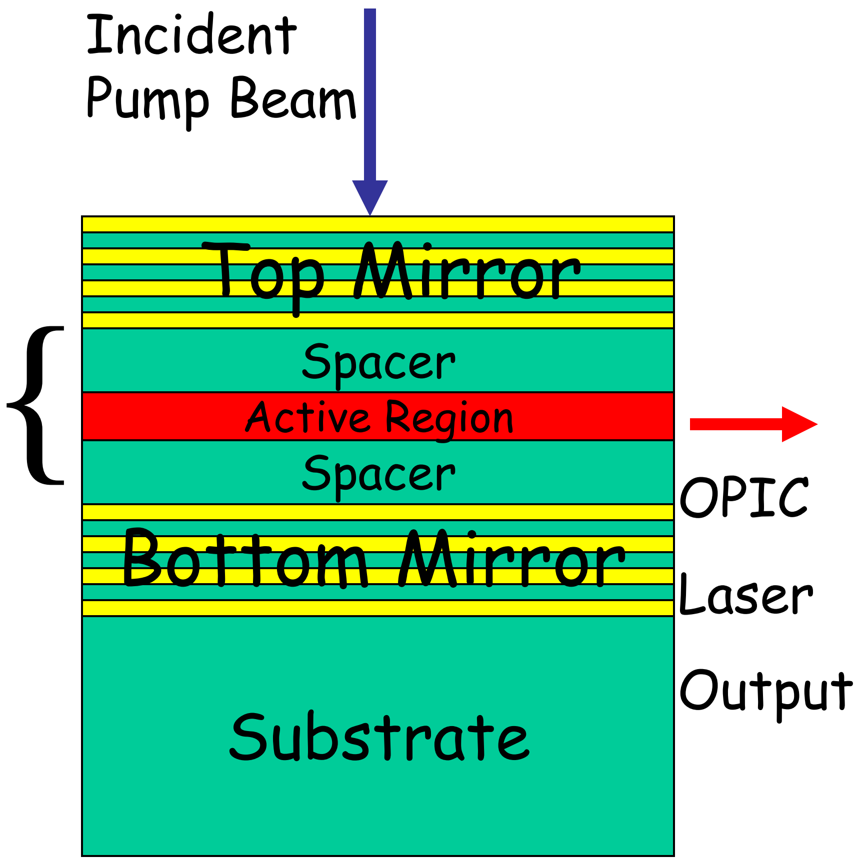
In previous experiments,
only fixed pump wavelengths
were available…

Pulsed: 2.1 μm Ho:YAG
_cw_: 1.84 μm Diode Array
or 1.06 μm Nd:YAG

*Pulsed output from **O**ptical*
***P**arametric **O**scillator*
Tunable across
Pump λ < 1600 - 2100 nm
Pulse duration ~4 ns



Optical Pumping Injection Cavity



Principal: Etalon cavity is tuned to pump λ to bring about several passes through the active region between two distributed Bragg reflectors (DBRs).

Goals

- Long pump λ
- Thin active region
- High pump absorbance

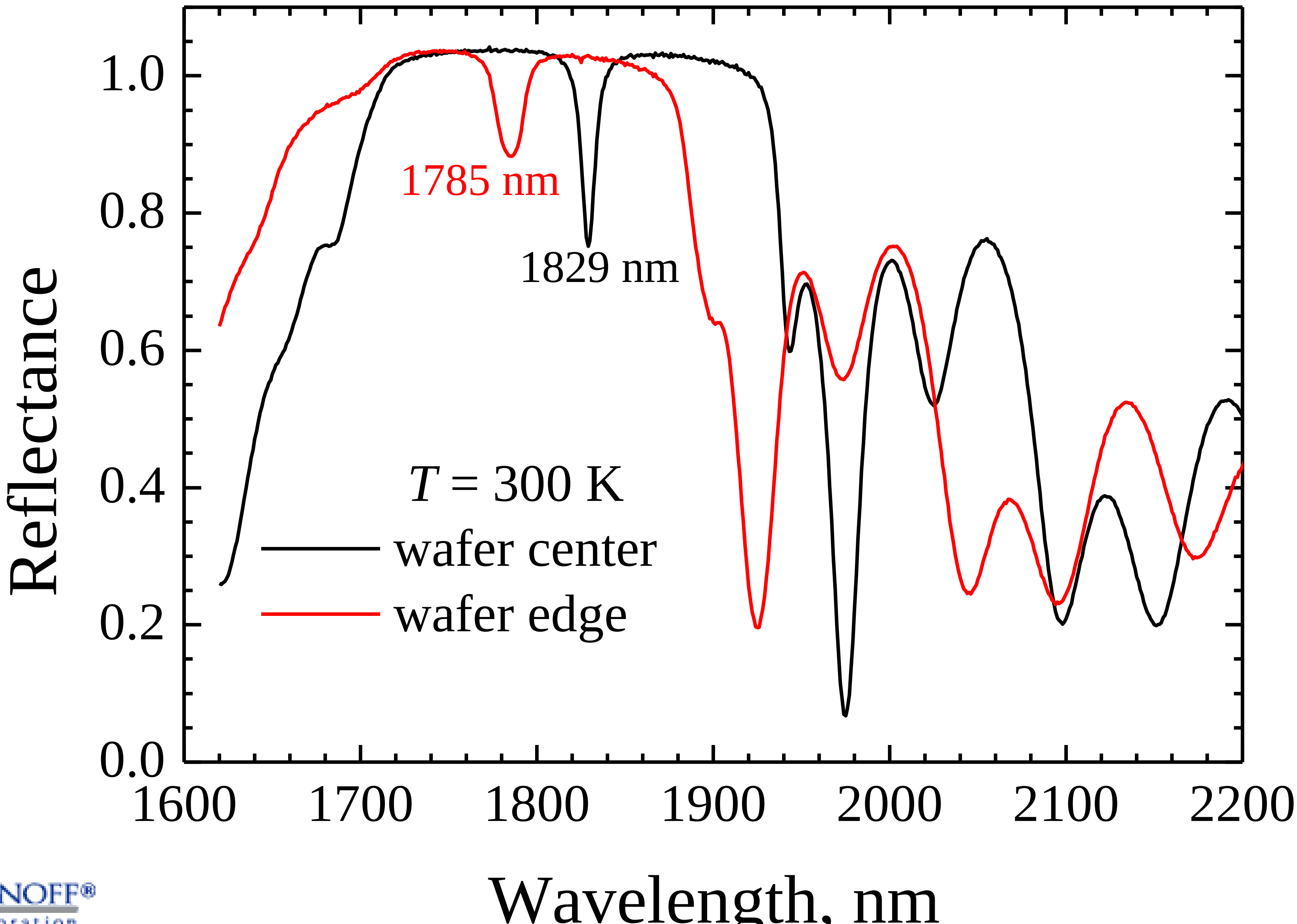
Advantages

- Lasing threshold is reduced
- Internal loss due to free carrier absorption is reduced

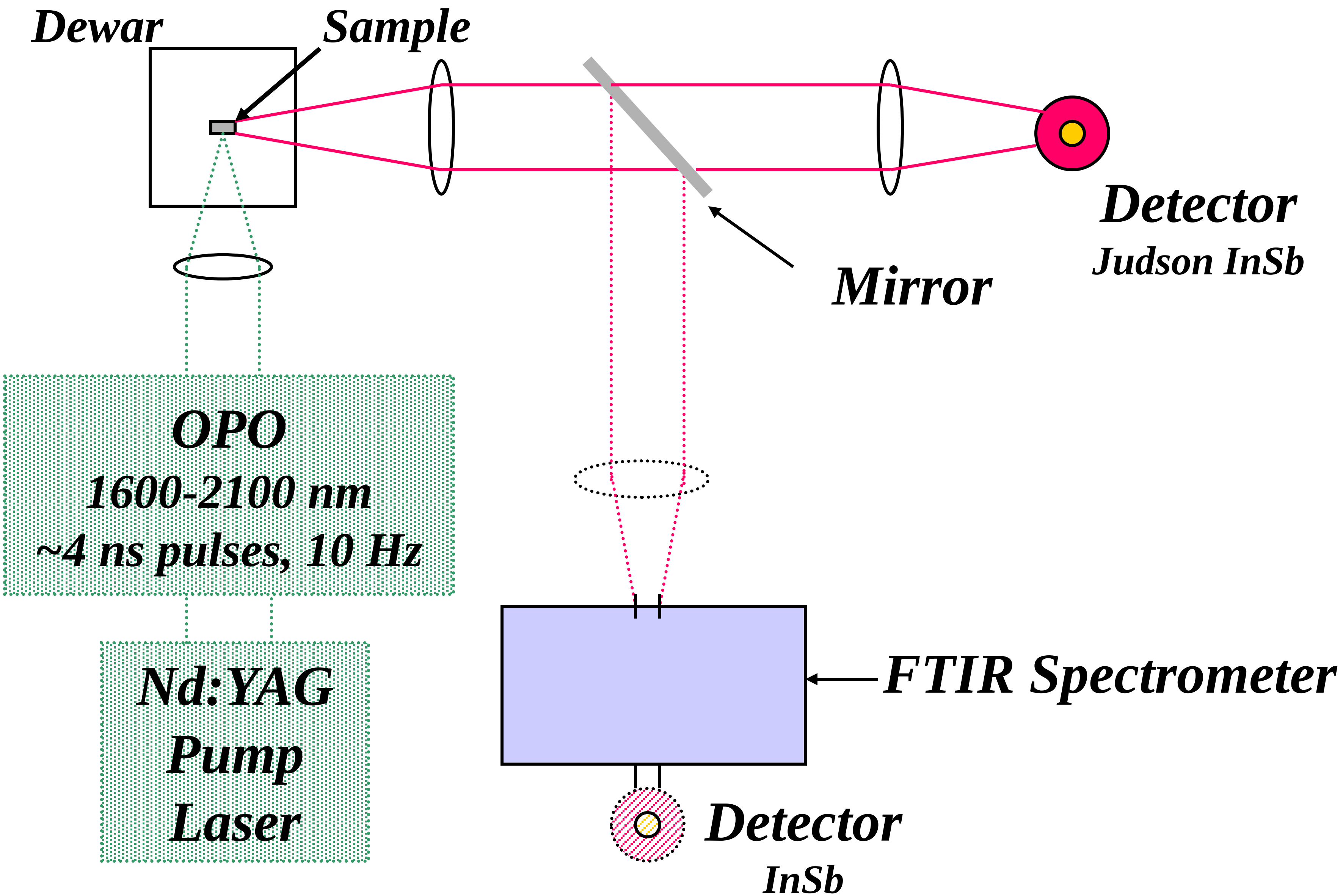
Details of sample structure (nominal)

	Material	Thickness (nm)	Periods	Comment	
¼ Wave Stack	GaSb	145.1	10	Top quarter wave stack	
	$AlAs_{0.08}Sb_{0.92}$	175.8			
Etalon	GaSb	521.3	1	Spacer	
	$AlAs_{0.08}Sb_{0.92}$	10	1	Hole Blocking Layer	
	AlSb	4	1	Strain Balance Layer	
	InAs	2.1	10	W-well Active Region	W
	GaSb	3.4			
	InAs	2.1			
	AlSb	4.0			
	$AlAs_{0.08}Sb_{0.92}$	10	1	Hole Blocking Layer	
	GaSb	521.3	1	Spacer	
¼ Wave Stack	$AlAs_{0.08}Sb_{0.92}$	175.8	18	Bottom quarter wave stack	
	GaSb	145.1			
	$AlAs_{0.08}Sb_{0.92}$	175.8	1	Finishing Mirror	
	n – GaSb			Substrate	

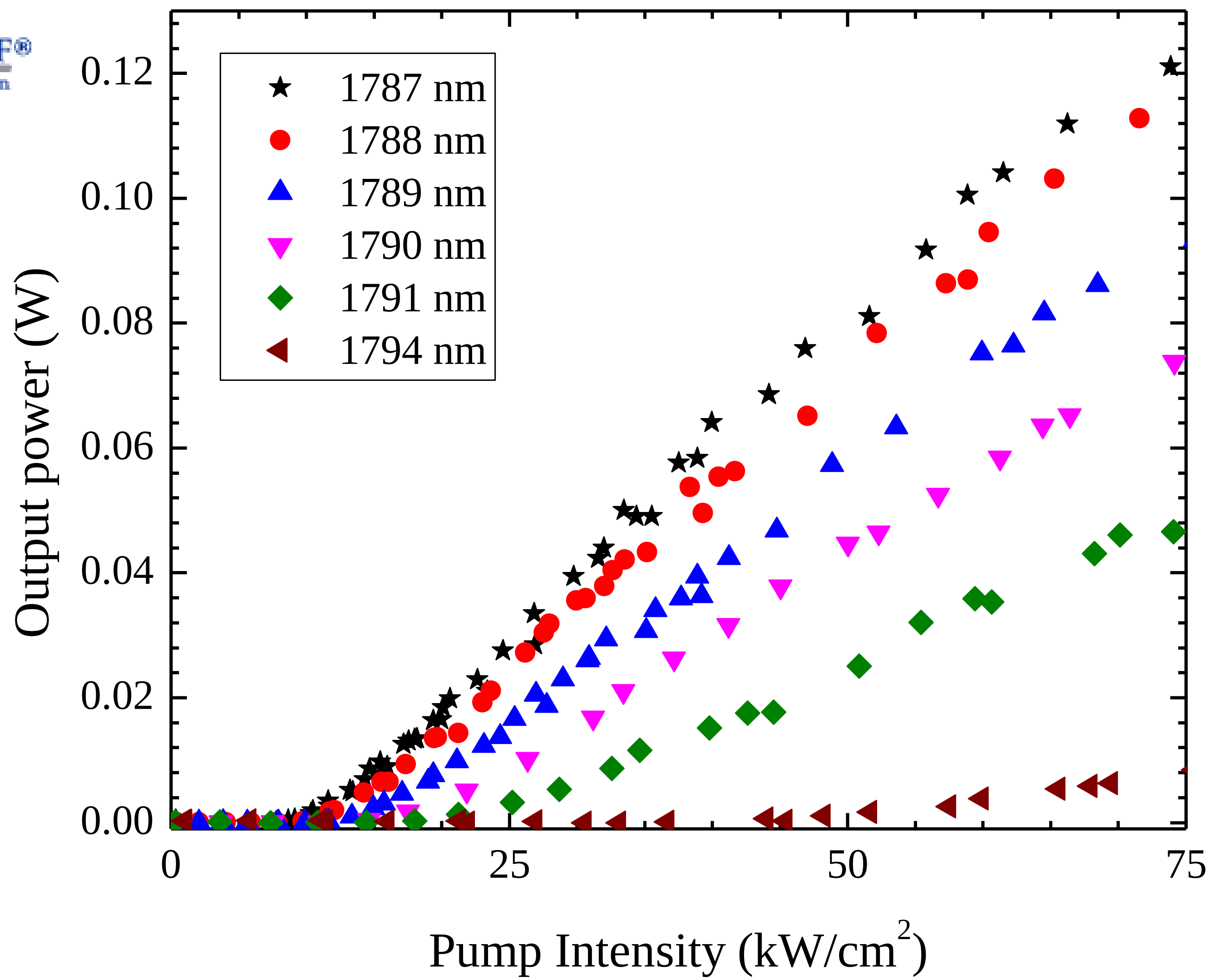
Reflectivity



Experimental Set-up

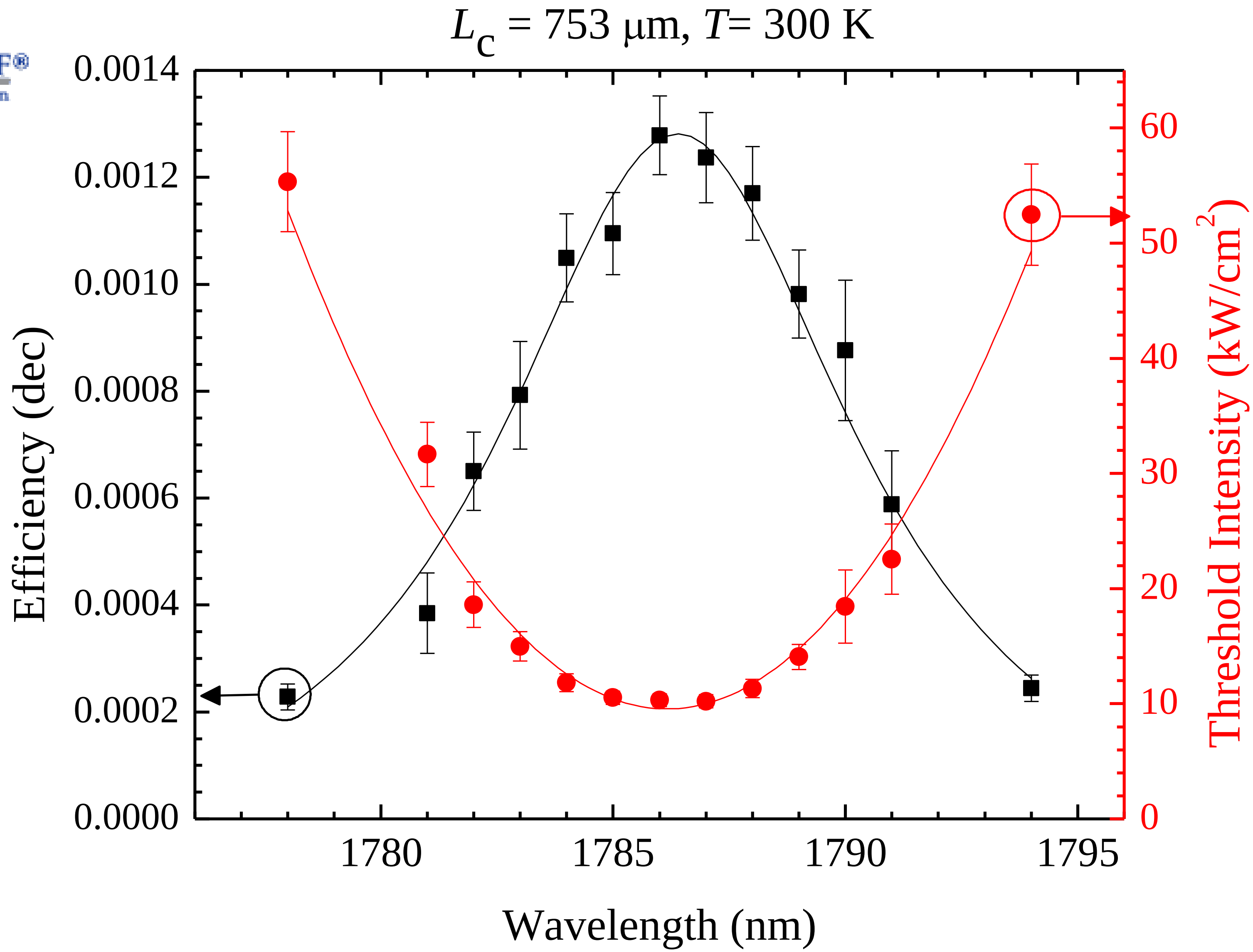


Light-Light Curves at 300 K



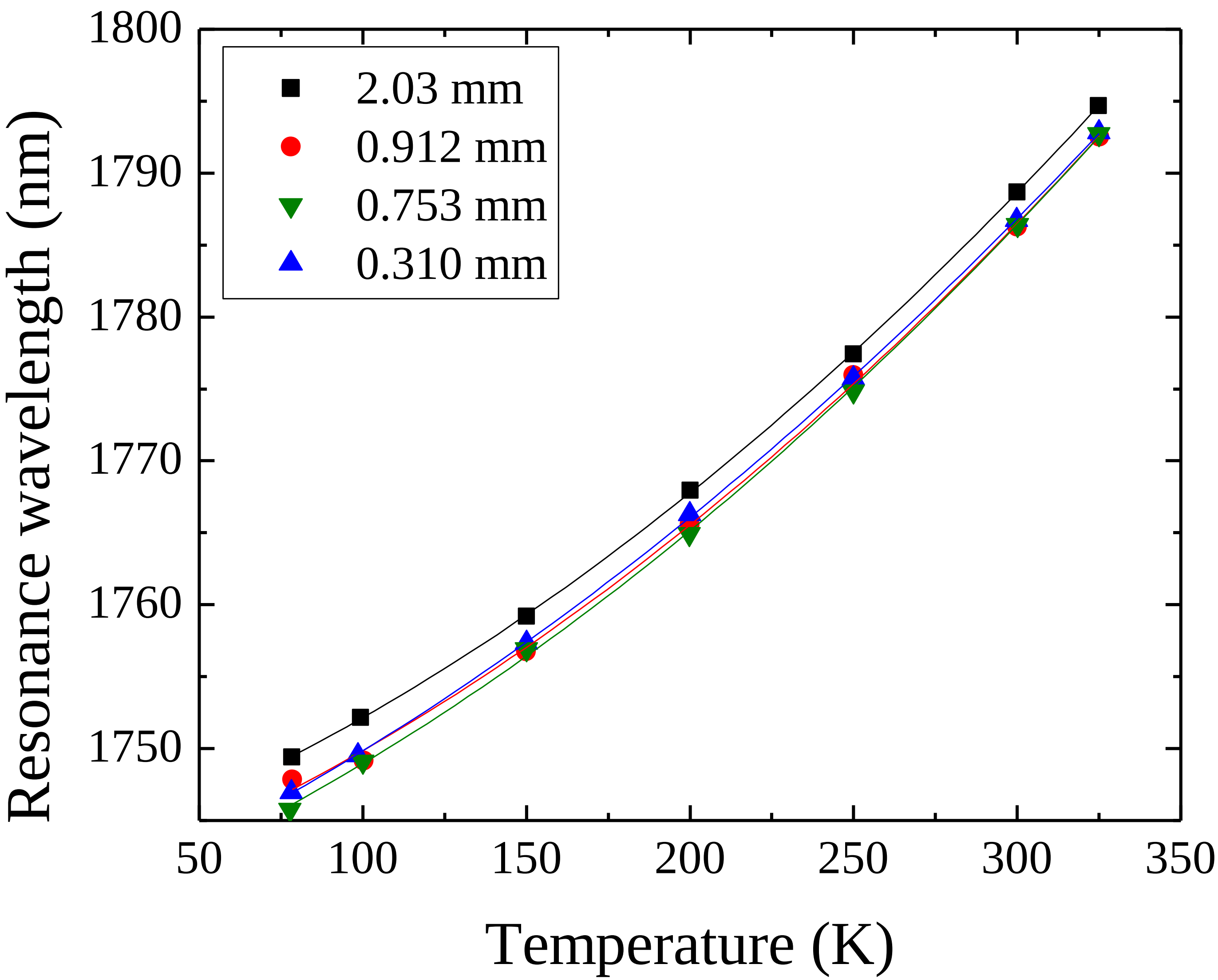
L_C = 753 μm

Resonant pump wavelength



McAlpine, *et al.*, *J. Appl. Phys.* **96**, 4751–4754 (2004); Olafsen and McAlpine, *J. Appl. Phys.* **108**, 053106 (2010)

Resonant pump wavelength vs. T



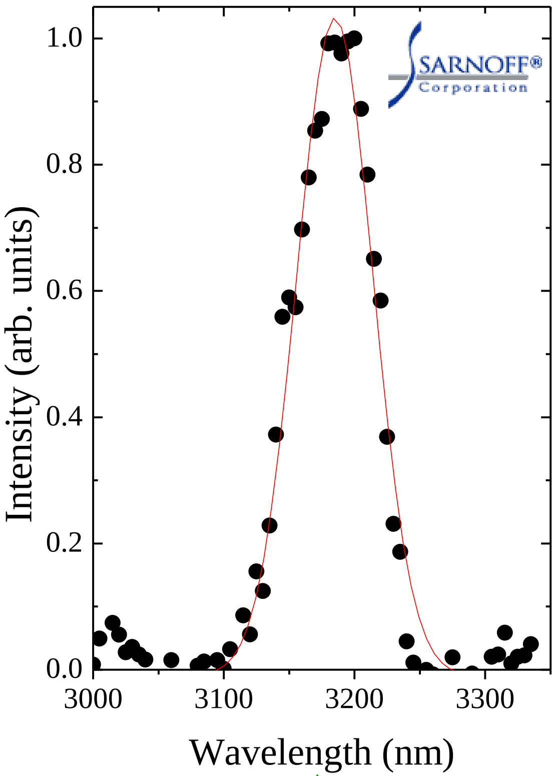
L. J. Olafsen, L. D. Ice, and B. Ball,
IEEE J. Sel. Top. Quantum Electron. **17**, 1453–1459 (2011).

- The resonance pump wavelength of OPIC lasers is consistently observed to demonstrate quadratic temperature dependence for a variety of cavity lengths and locations on the epitaxial wafer.
- As the optical pumping is at very low duty cycle, **the nonlinear behavior is attributed not to heating, but to gain-induced changes in the index of refraction** that result from the increased pump intensities and consequent carrier concentrations arising from temperature increases.

Spectra

Resonant pumping

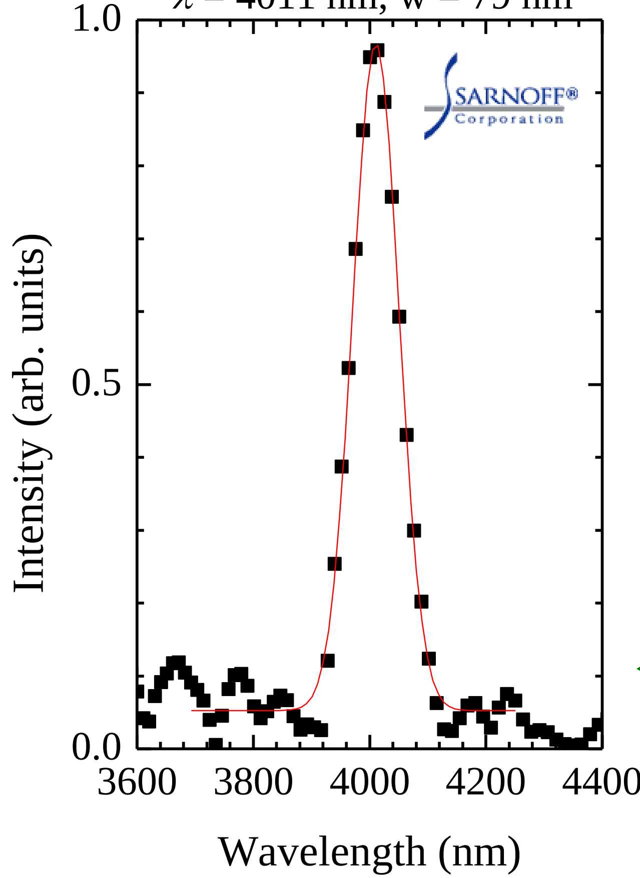
T = 300 K
λ = 3185 nm, FWHM = 69 nm



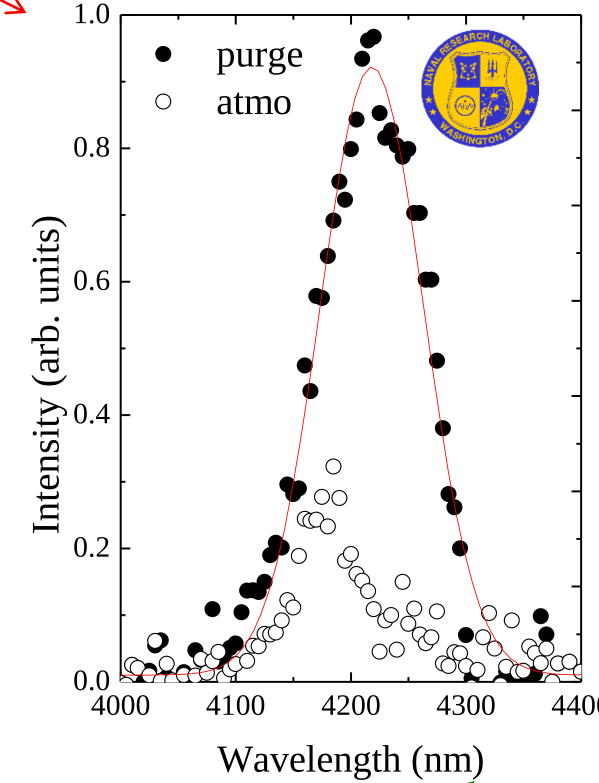
Epi-up

1850 nm pumping

T = 310 K
λ = 4011 nm, w = 79 nm



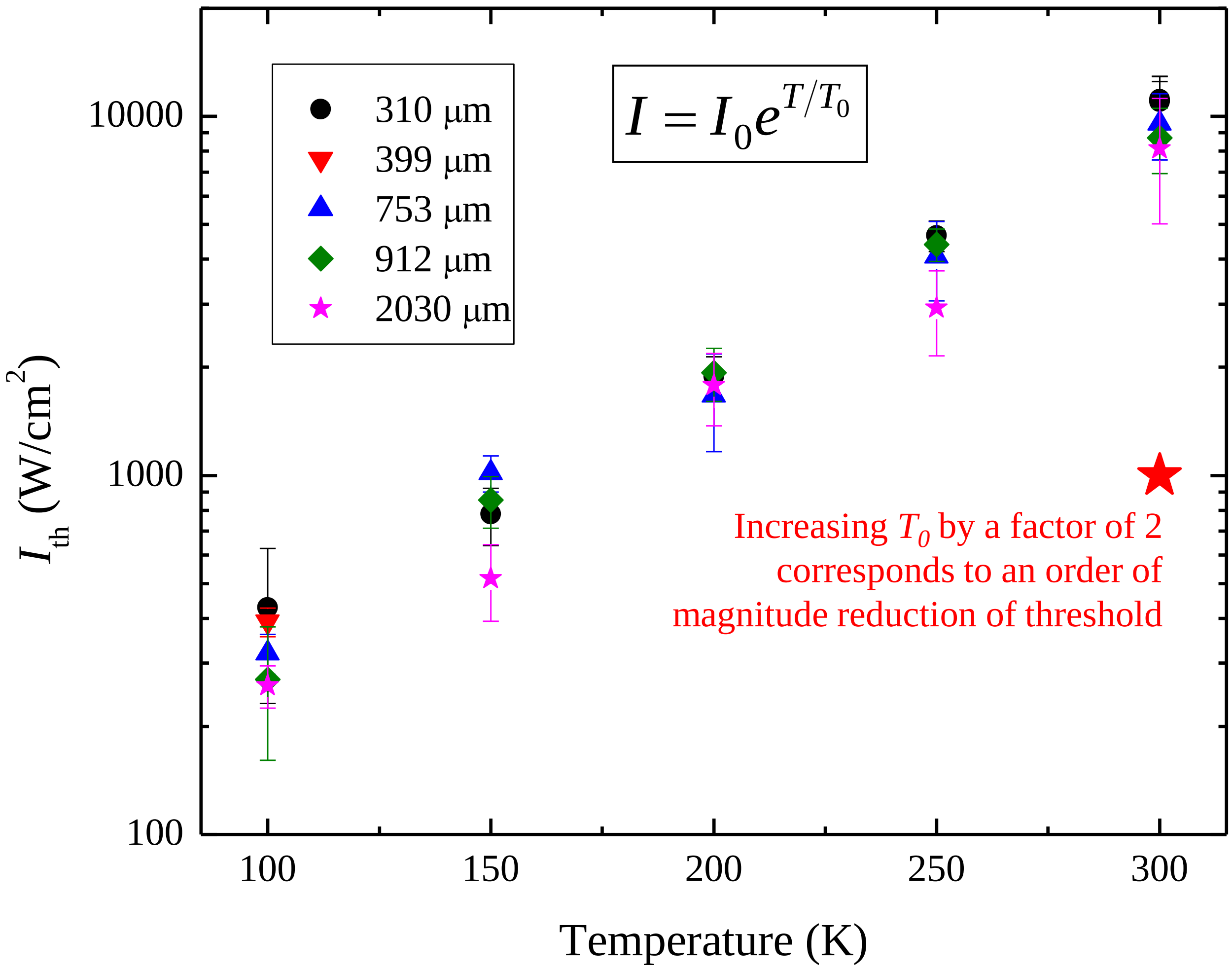
T = 200 K
λ = 4218 nm, FWHM = 106 nm



Epi-down
Broadened OPIC

McAlpine, *et al.*, *Mater. Res. Soc. Symp. Proc.* **799**, 211 (2004)

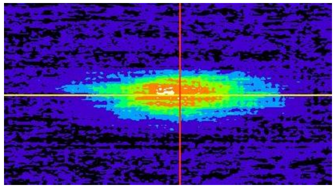
Threshold intensity (at λ_R) vs. T



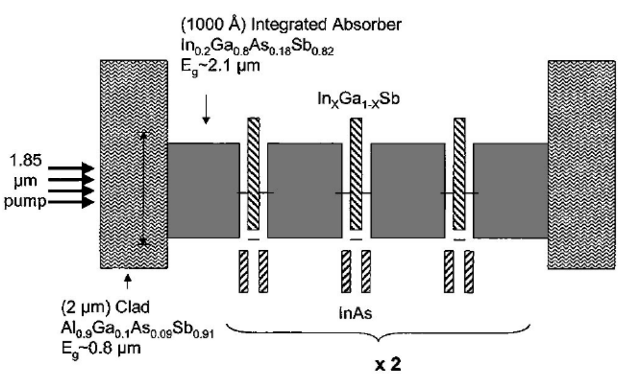
- The threshold intensity varies exponentially with temperature, scaled by a characteristic temperature T_0.
- Characteristic temperatures for various cavity lengths of this OPIC device were on the order of 50-60 K.
- **T_0 for antimonide-based heterostructures appears to max out around 60 K**
- **Limitation for high temperature operation may be attributable to pinning of carrier concentration above threshold.**

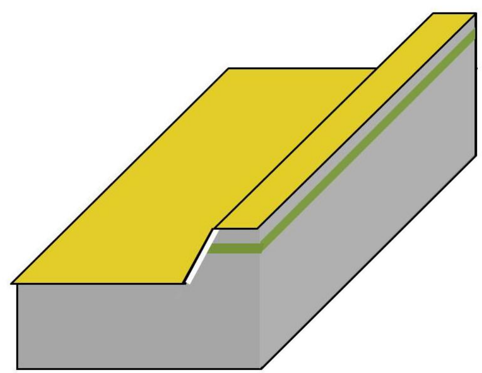
L. J. Olafsen, L. D. Ice, and B. Ball, *IEEE J. Sel. Top. Quantum Electron.* **17**, 1453–1459 (2011).

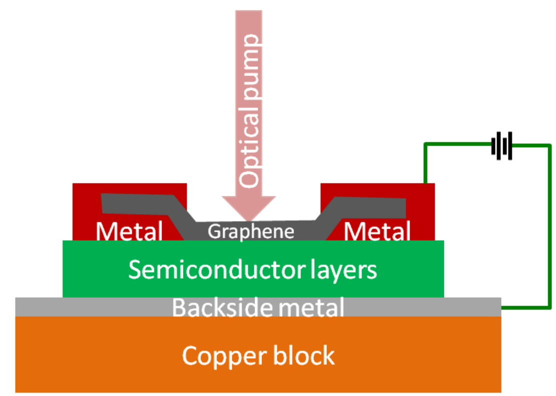
Research directions



- Investigating the limitation to high temperature operation in type-II W antimonide-based quantum well lasers is central to the laboratory’s current research program.
- New and renewed **collaborations** (AFRL, NRL, Rice, Baylor, UT Austin) allow us to attack this problem using a range of **devices** (optically pumped, electrically injected, dual optical pumping/electrical injection) with a variety of **experimental tools** (tunable optical pumping, electrical injection, step-scan Fourier transform infrared spectroscopy, beam profiling with IR camera, fabrication of transparent contacts).

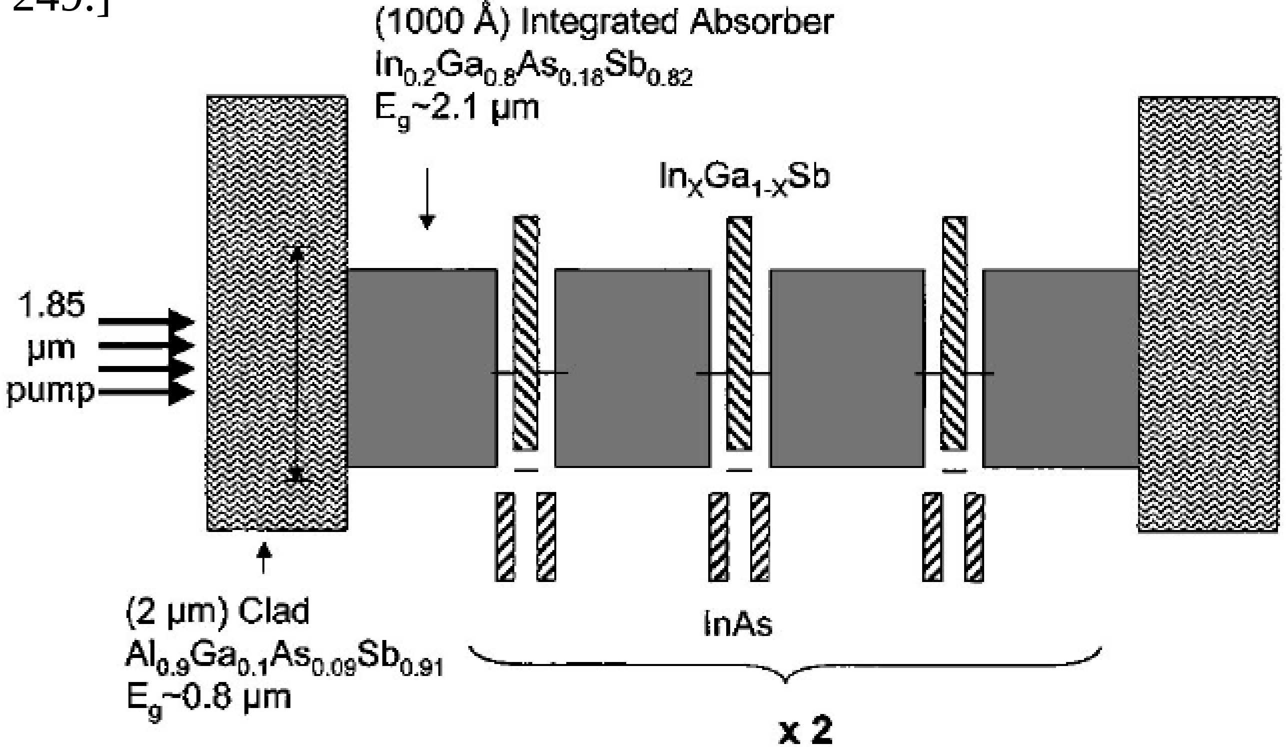






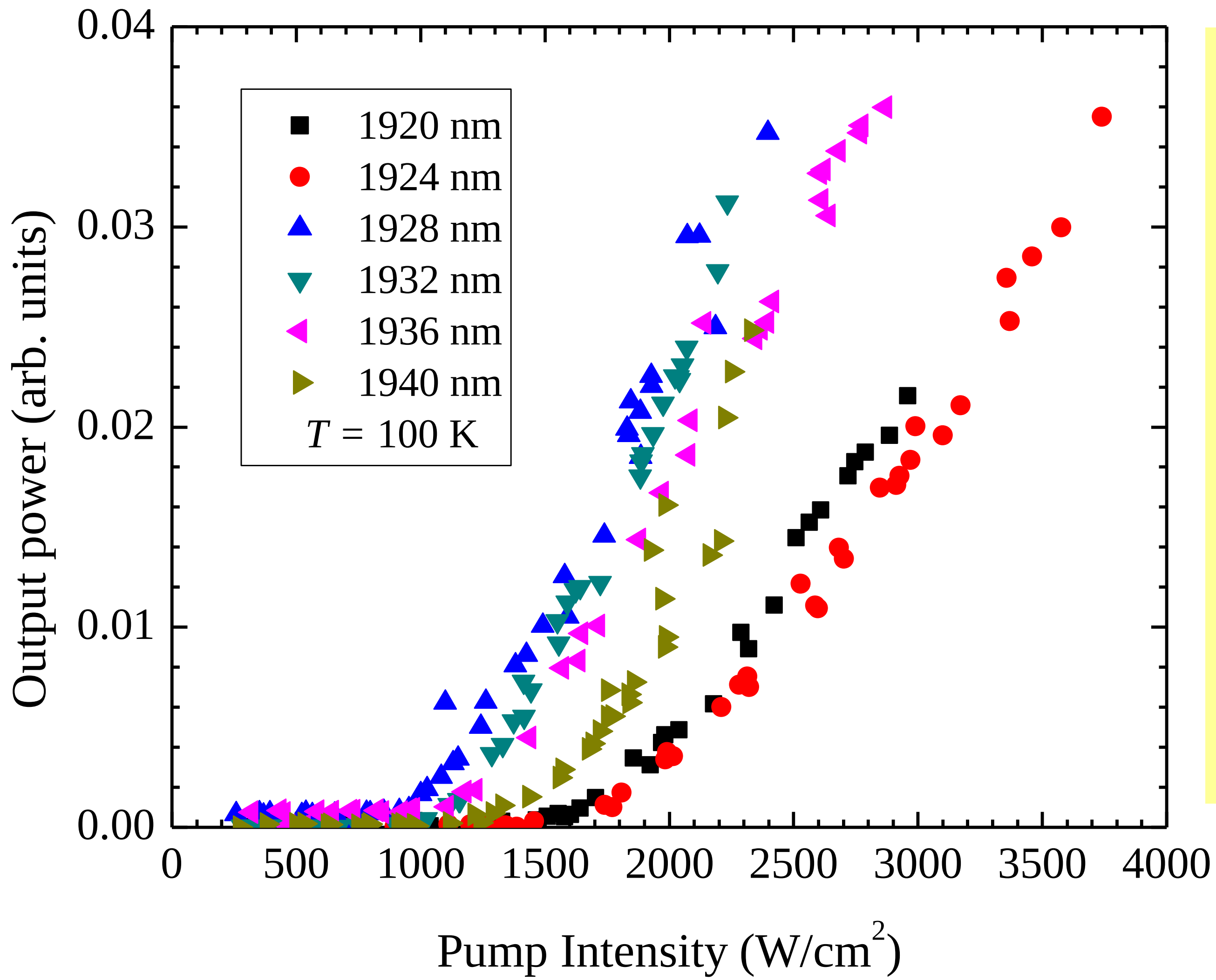
Integrated Absorber

- W quantum wells periodically inserted into thick $In_xGa_{1-x}As_ySb_{1-y}$ waveguide/absorber layers, which are specifically designed to absorb the pump radiation and that are lattice matched to the GaSb substrate
- Initially proposed/designed at MIT Lincoln Laboratory [A. K. Goyal, *et al*., *Conference Proceedings* (Laser and Electro-Optics Society (LEOS) Annual Meeting, Puerto Rico, 2000), p. 249.]



A. P. Ongstad, *et al*., *J. Appl. Phys*. **92**, 5621 (2002)

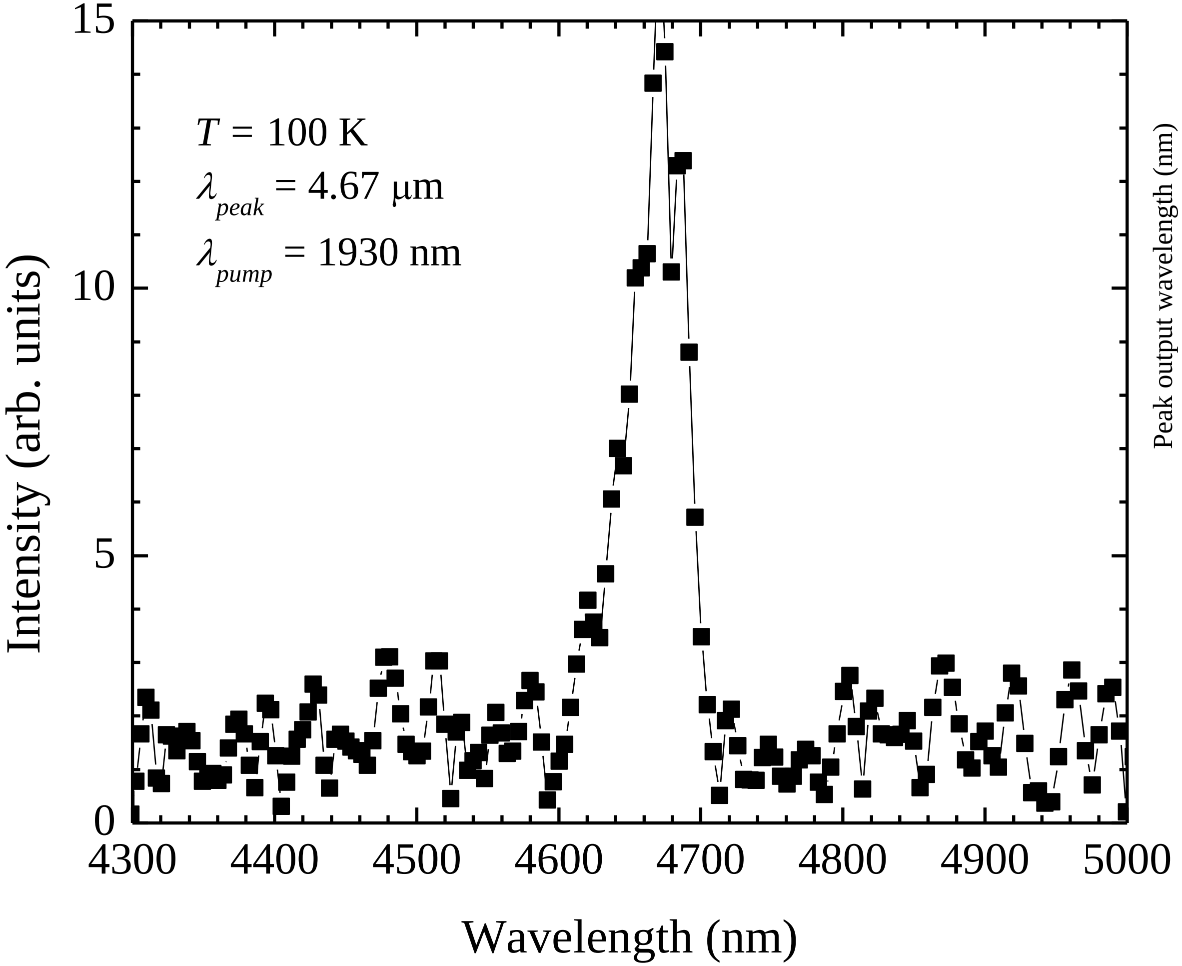
IA Light-light curves

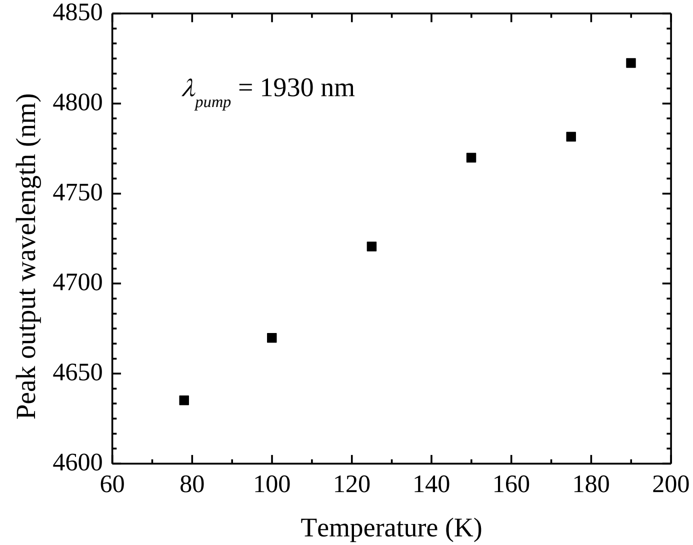


- 4.0 mm cavity, edge emitter
- 10 Hz, ~4 ns pulse width, variable pump wavelength
- AFRL optically pumps at 1940 nm at much higher duty cycles (e.g., 20%)
- Data at left not corrected for collection efficiency or pump-sample overlap

L. J. Olafsen, J. Kunz, A. P. Ongstad, and R. Kaspi, "Tunable excitation of mid-infrared optically pumped semiconductor lasers," to be submitted to *Proceedings of the SPIE* (2013).

IA spectra



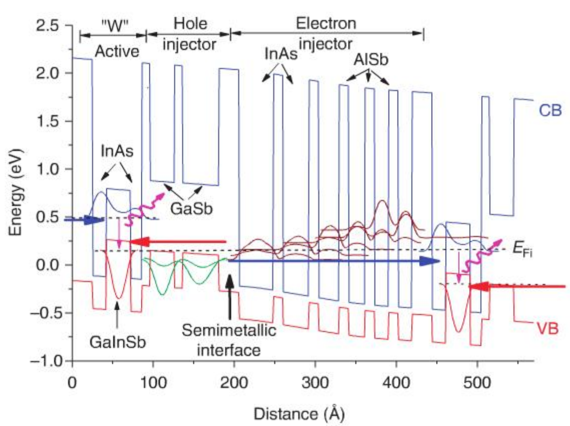


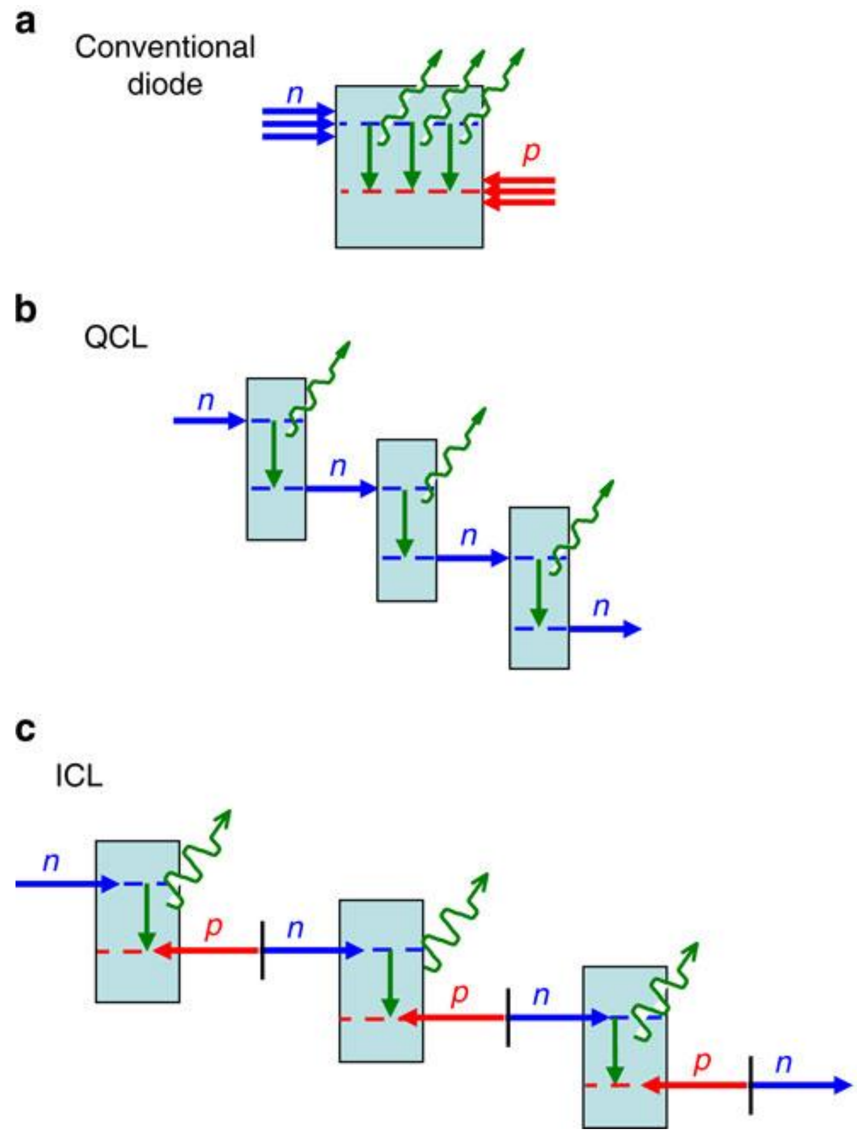
T_{max} of 190 K typical of type-II W integrated absorber lasers.

L. J. Olafsen, J. Kunz, A. P. Ongstad, and R. Kaspi, "Tunable excitation of mid-infrared optically pumped semiconductor lasers," to be submitted to *Proceedings of the SPIE* (2013).

Interband Cascade Laser

- Theorized by Rui Yang (now at University of Oklahoma) in 1995
- First demonstrated in 1997 (Houston, Sandia)
- Near-room-temperature operation at 3.6 μm achieved in 1998 (Olafsen *et al.*, Naval Research Lab)
- Over the next ~10 years, pursued by Army Research Lab/Maxion Technologies/Jet Propulsion Laboratory
- NRL made breakthrough by rebalancing internally generated carriers, resulting in very low power consumption (2010, 2011)

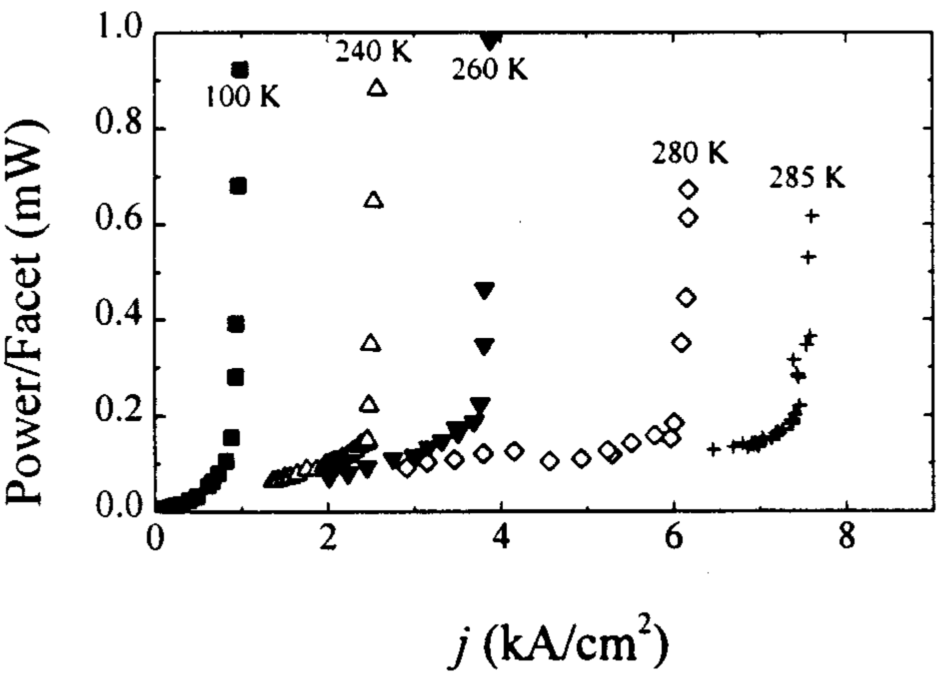


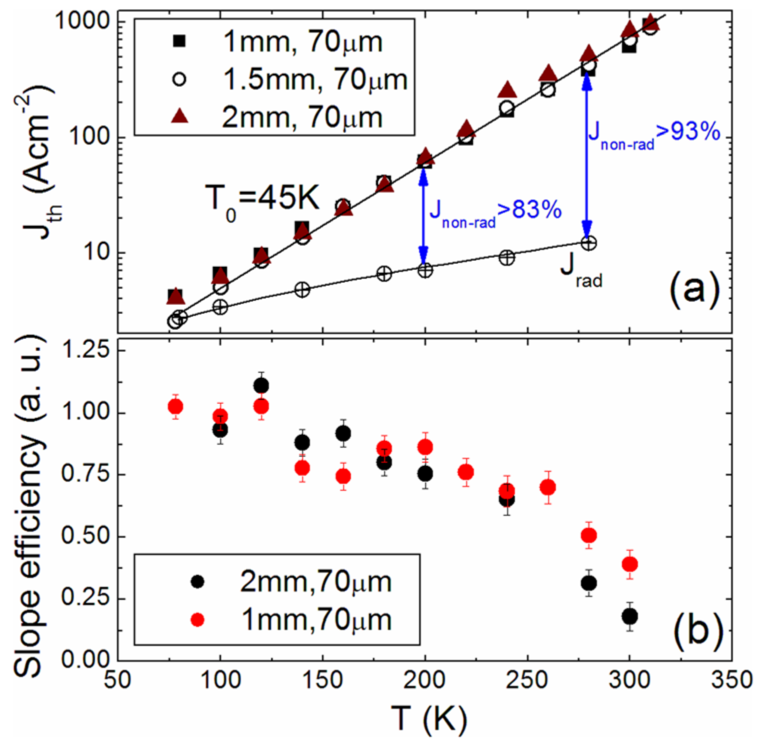


Vurgaftman, et al., *Nature Communications* **2**, 585 (2011).

Spontaneous vs. stimulated emission

Ideally, the spontaneous emission "pins" as a diode laser reaches threshold, so that additional current increases above threshold contribute to an increase of laser light. However, without this pinning, **spontaneous emission continues to increase at the expense of stimulated emission**.

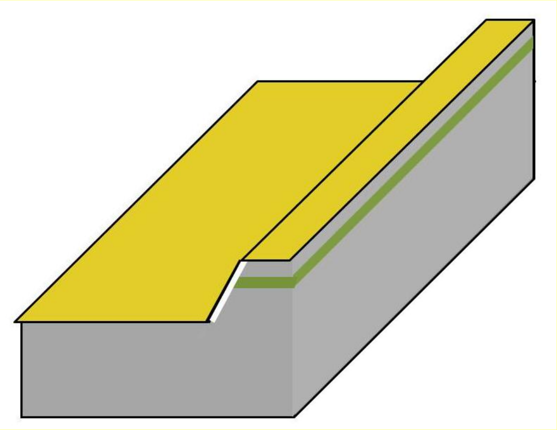




Olafsen, *et* al., *Applied Physics Letters* **72**, 2370–2372 (1998); Ikyo, *et al.*, *Applied Physics Letters* **99**, 021102 (2011).

Split ridge ICLs

To determine this unknown degree of Fermi level pinning, the intensity and spectrum of the electroluminescence will be studied as a function of pump intensity (below and above threshold), operating temperature, ridge width and cavity length, and epitaxial composition. The relative contributions of these parameters to the above threshold spontaneous emission and carrier concentrations will be compared to determine the reason for lack of pinning, *or to understand why the ICLs violate classical laser diode theory*.



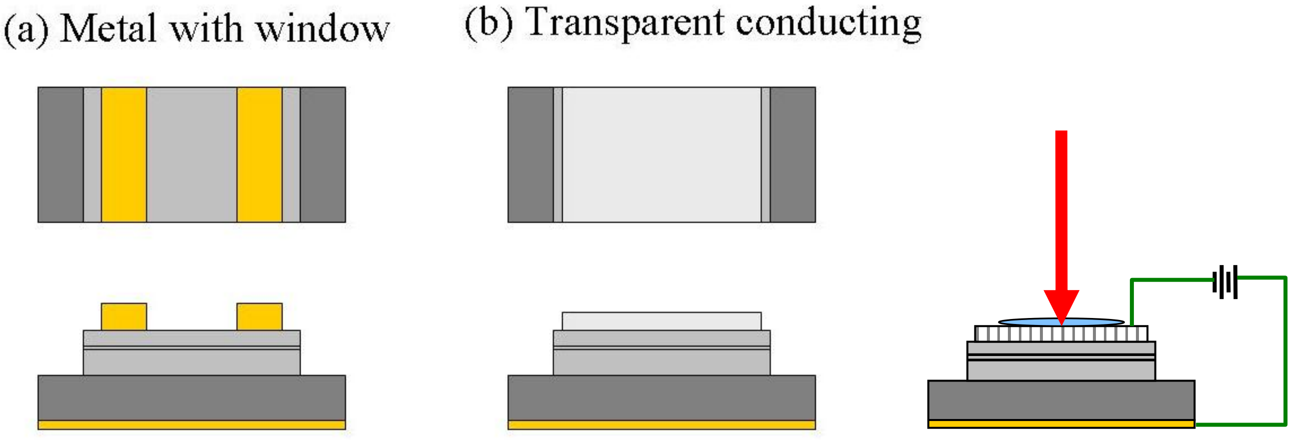
APPROACH:

Schematic of a split ridge laser structure, in which the laser bar is split lengthwise so that electroluminescence may be measured along the laser as it operates above threshold. The gold top layer provides an electrical contact, while an insulated passivation coating (in white) along the (left) sidewall in the illustration prevents shorting across the active layers of the device.

Colombelli, *et al.*, *Applied Physics Letters* **77**, 3893–3895 (2000).

Transparent contacts

- To collect spontaneous emission from the surface, or to conduct pump probe measurements that employ both optical pumping and electrical injection, a mask (left) or transparent contact (center, right) is necessary.
- Transparent conducting oxides and graphene can be applied uniformly and hence achieve uniform electrical and optical fields, unlike contacts that utilize a window approach and rely on the conductivity of the underlying semiconductor to achieve field uniformity through current spreading. The transparent contact would demonstrate great advantages so that the pump and probe areas could be equal without reliance on current spreading for a nominally uniform electrical pulse.



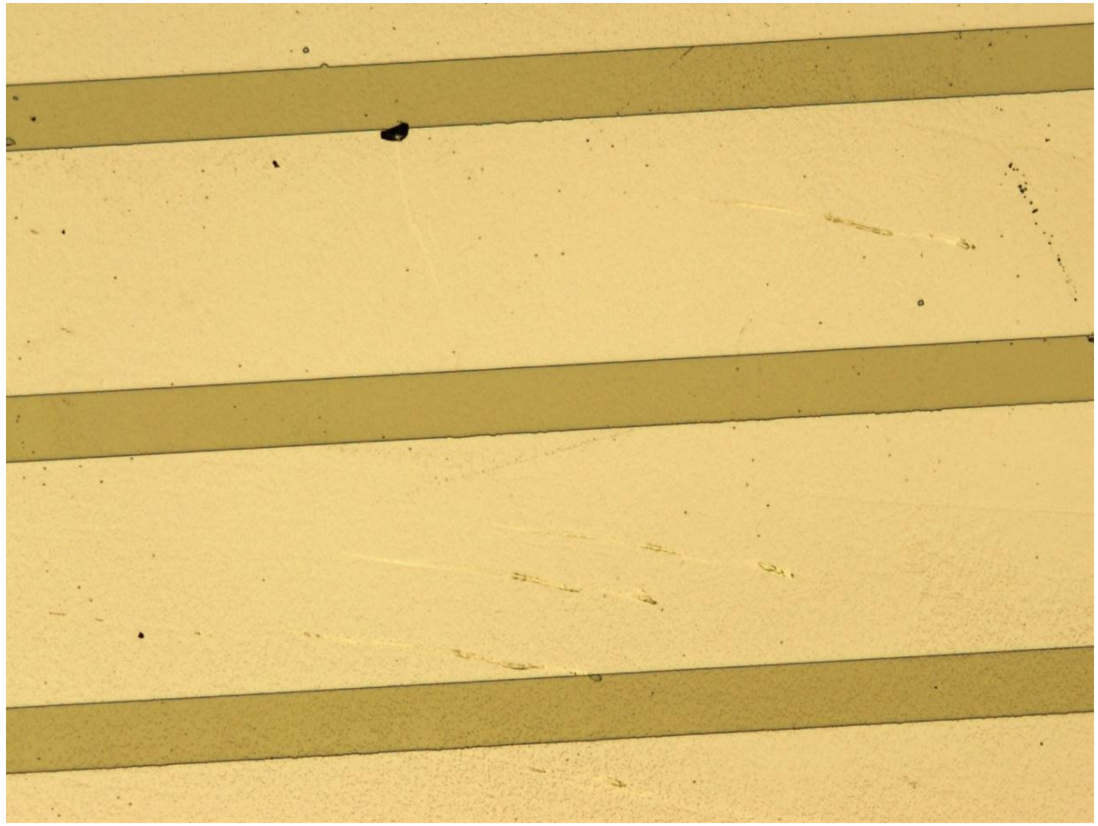
Supported by URC grant (2011): "Transparent Contacts for Dual Optical and Electronic Excitation in Mid-Infrared Semiconductor Lasers" (included training and preliminary work at Microelectronics Research Center, UT-Austin).

Transparent contacts

<u>*Candidate materials:*</u>

Indium tin oxide (ITO), Tin oxide (SnO_2), Indium oxide (InO), Zinc oxide (ZnO)

Graphene



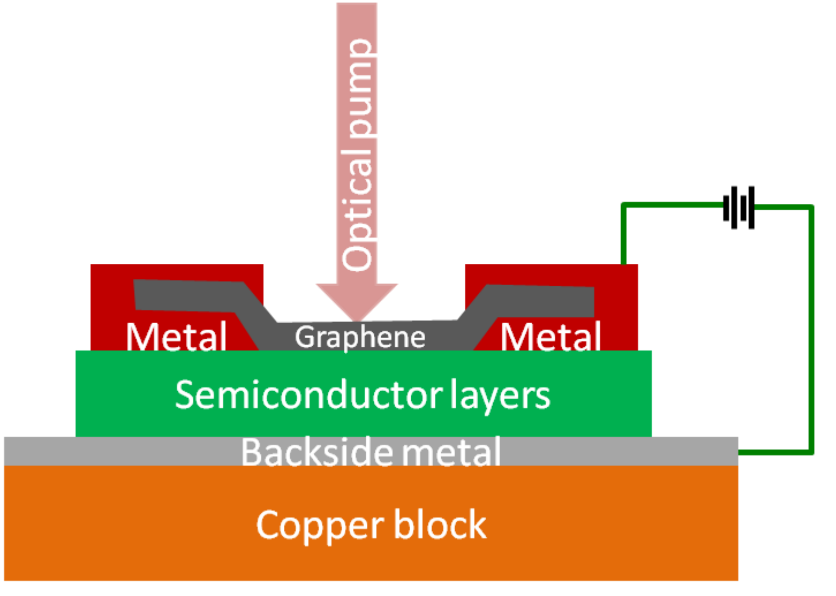
(left) Ph.D. candidate Jeremy Kunz working with the MJB4 mask aligner at the Microelectronics Research Center. (right) Image of 100 μm bars of electron-beam evaporated zinc oxide separated by 400 μm on a GaSb surface.

Supported by URC grant (2011): "Transparent Contacts for Dual Optical and Electronic Excitation in Mid-Infrared Semiconductor Lasers" (included training and preliminary work at Microelectronics Research Center, UT-Austin).

Graphene on semiconductor

- Perfect graphene is a two-dimensional hexagonal lattice.
- Transparency: each layer absorbs $\pi\alpha \approx 2.3\%$, where α is the fine structure constant (Nair, *et al.*, *Science* **320**, 1308 (2008)).
- Excellent potential for heat dissipation, despite being a single atom thick.
- Can be deposited in single or few layers with high degree of order (compared with 100-200 nm typical thicknesses for transparent conducting oxides).

- Graphene layers will be grown at Rice and then transferred onto the GaSb-capped laser structures.
- The extent of active region heating (typically 30-70K) can be determined by measuring wavelength spectra at high and low duty cycle.



Exploratory grant proposal awarded by NSF; with Prof. James Tour, Rice University ("EAGER: Enhanced Optoelectronic Devices Through Integration of Single-Crystal Graphene and Bernal Bilayer and Trilayer Graphene")

Conclusions

- Type-II W lasers are excellent candidates for efficient lasing in the 3-5 μm wavelength range
- OPIC lasers can be resonantly pumped to minimize threshold and maximize efficiency. OPIC lasers have demonstrated characteristic temperatures ~60 K, comparable with the best performing antimonide-based lasers. Above-room-temperature operation has been achieved and emission wavelengths extend beyond 4 μm.
- Integrated absorber lasers with type-II W active regions demonstrate T_{max} of 180-200 K. Investigating further with low duty cycle tunable optical pumping to elucidate the limiting mechanism.
- Spontaneous emission from split ridge interband cascade lasers is being measured to understand the lack of carrier concentration/Fermi level pinning and its effect on high temperature laser performance.
- Graphene is a promising candidate for a transparent contact on GaSb-capped semiconductor lasers.