TYPE-II ANTIMONIDE MID-IR LASERS

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WPI: L. R. Ram-Mohan

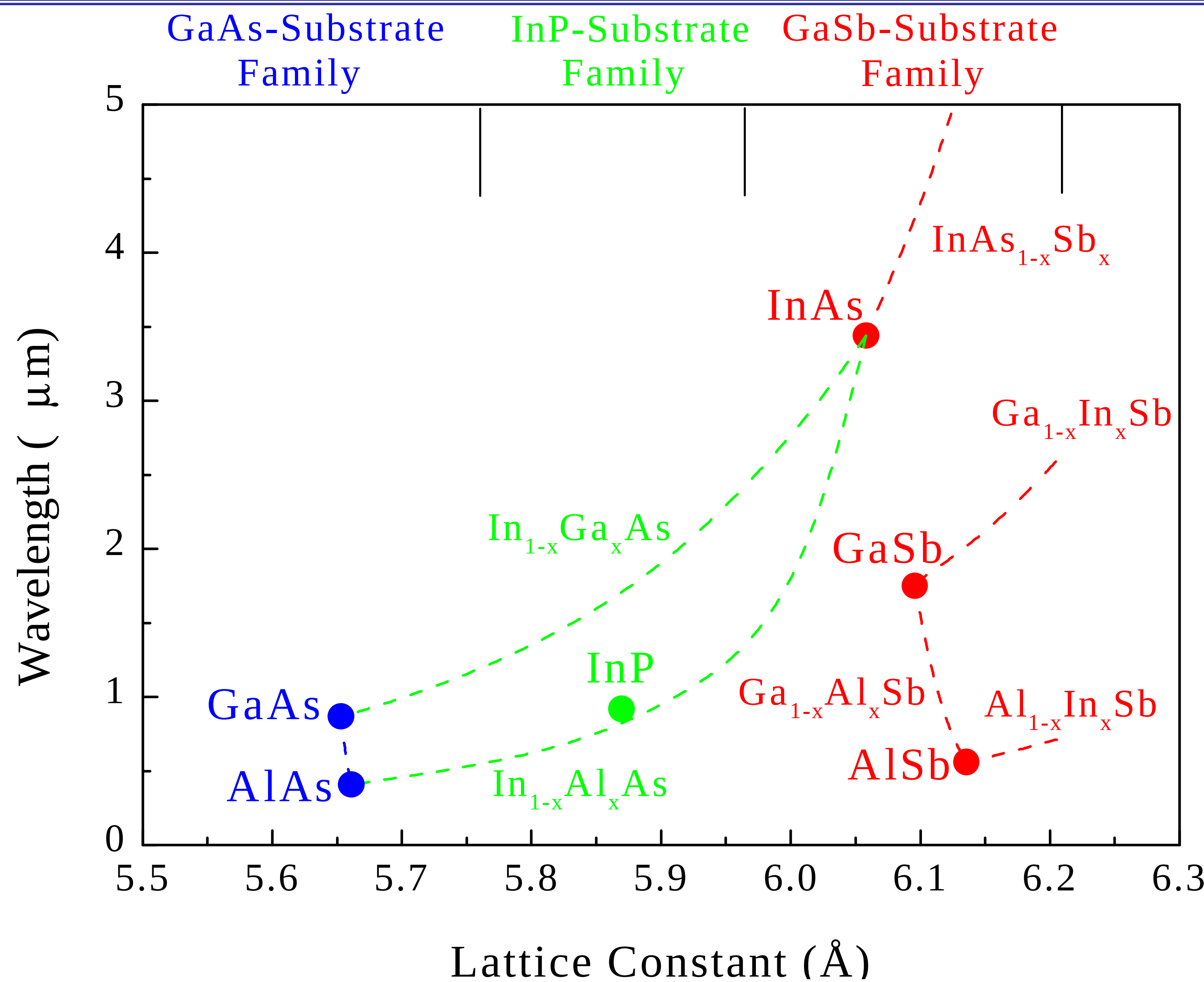
OUTLINE

- Scope/Historical perspective/Rationale
- Optically-pumped type-II lasers (including VCSELs)
- Type-II diodes & Interband Cascade Laser (ICL)
- Limitations to performance (Auger recombination, internal losses, *etc.*)
- Status summary

SCOPE

- This talk will review:
  - InAs/GaSb-based type-II mid-IR lasers
- This talk will not review:
  - Type-I mid-IR lasers (antimonide or otherwise)
  - InAs/InAsSb-based type-II lasers
  - InP-based mid-IR intersubband quantum cascade lasers

III-V WAVELENGTH vs LATTICE CONSTANT



HISTORICAL BACKGROUND

- First type-II laser proposal: *Kroemer & Griffiths (1982)* [Single heterojunction, *e.g.*, InP/InAlAs – lasing first demonstrated: Lugagne-Delpon *et al. (1992)*]
- First experimental lasing of a type-II heterostructure (antimonide): *Baranov et al. (1986)* [Lasing at a single InGaAsSb/GaSb interface ($\lambda \approx 2$ μm); recent 3 μm lasing at a single InAs/GaInAsSb heterojunction: *Moiseev et al. (1995)*]
- First theoretical analysis of mid-IR type-II InAs/GaInSb superlattice lasers: *Grein et al. (1993)*
- First type-II InAs/GaInSb laser demonstration: *Miles et al. (1994)* [Multiple superlattices (≈ 4½ periods each) separated by GaInAsSb confining layers]
- Theory for type-II W laser: *Meyer et al. (1994)*
- First demonstration of W laser: *Malin et al. (1995)*
- Proposal of interband cascade laser: *Yang (1994)*
- First ICL demonstration: *Lin et al. (1997)*

HRL TYPE-II LASER DEVELOPMENT (1994-1997)

- Pioneering development of InAs/GaInSb MBE growth, first use of InAs/AlSb superlattice optical cladding layers

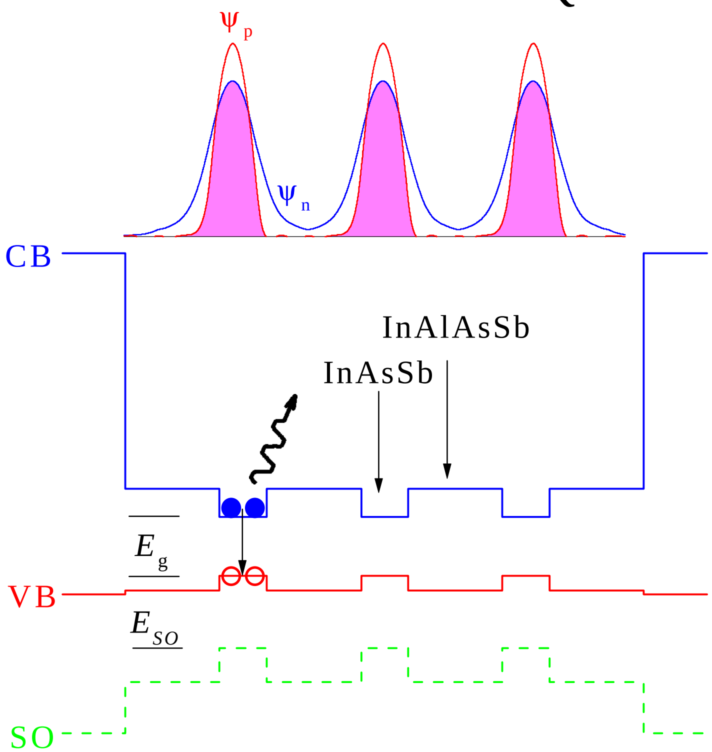
- First demonstration of type-II InAs/GaInSb lasers *[Miles et al., APL 66, 1921 (1995); Hasenberg et al. EL 31, 275 (1995); Chow et al., APL 67, 3700 (1995)]*

- Diode performance [*Hasenberg et al., JQE 33, 1403 (1997)* – Multiple superlattices (≈ 4½ periods each) separated by GaAlSb, GaInAsSb or GaInAlAsSb confining layers]:
  - Pulsed: T_{max} = 255 K, P_{max}(160 K) = 60 mW (λ = 3.2 μm), diode operation to λ = 4.3 μm
  - cw: T_{max} = 180 K (λ = 3.2 μm)

TYPE-I vs TYPE-II LASER STRUCTURES

TYPE-I

InAsSb/InAlAsSb QW



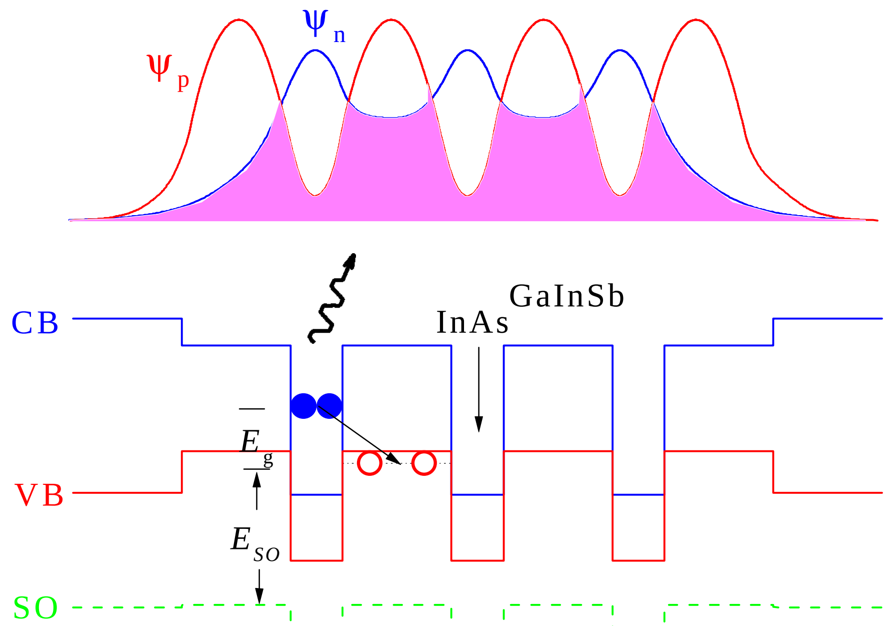
Potential Disadvantages:

(1) Poor electrical confinement

(2) High Auger loss rate ($E_g \approx E_{SO}$)

TYPE-II

InAs/GaInSb Superlattice

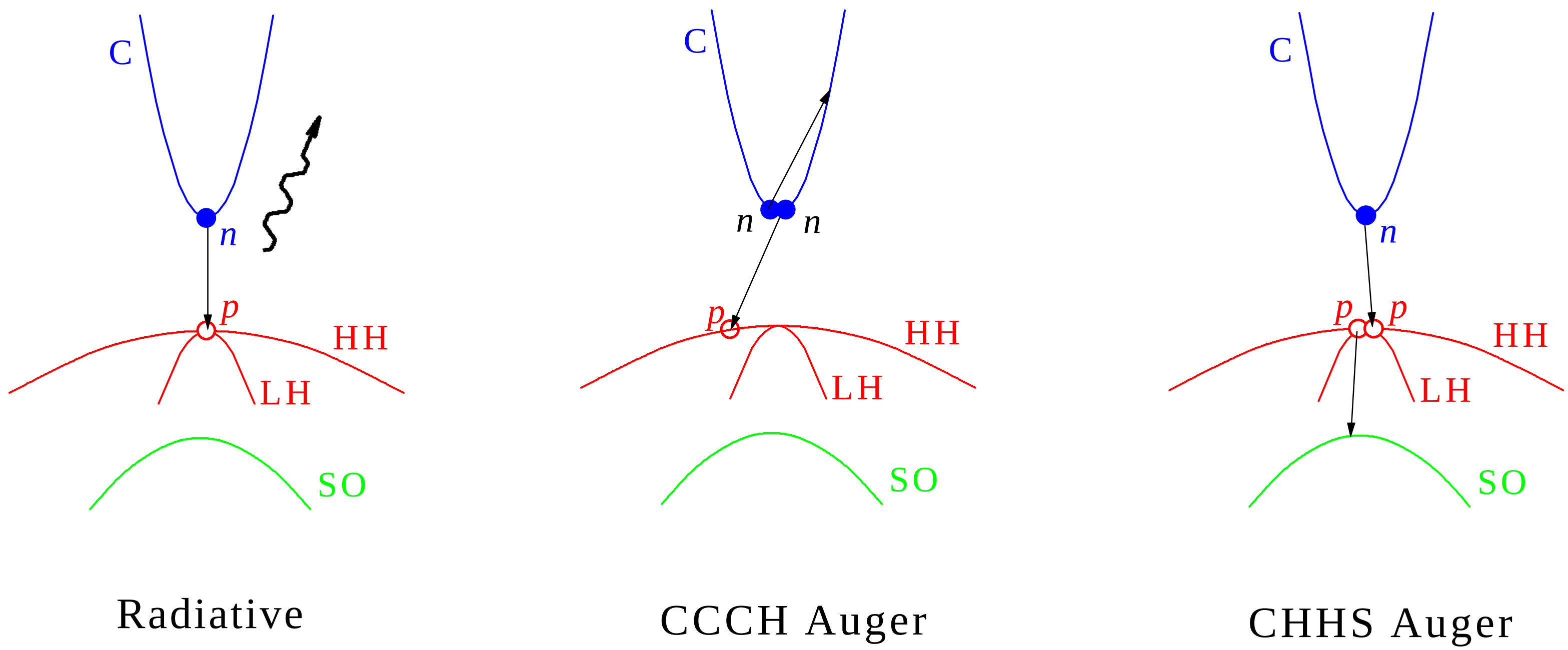


Advantages:

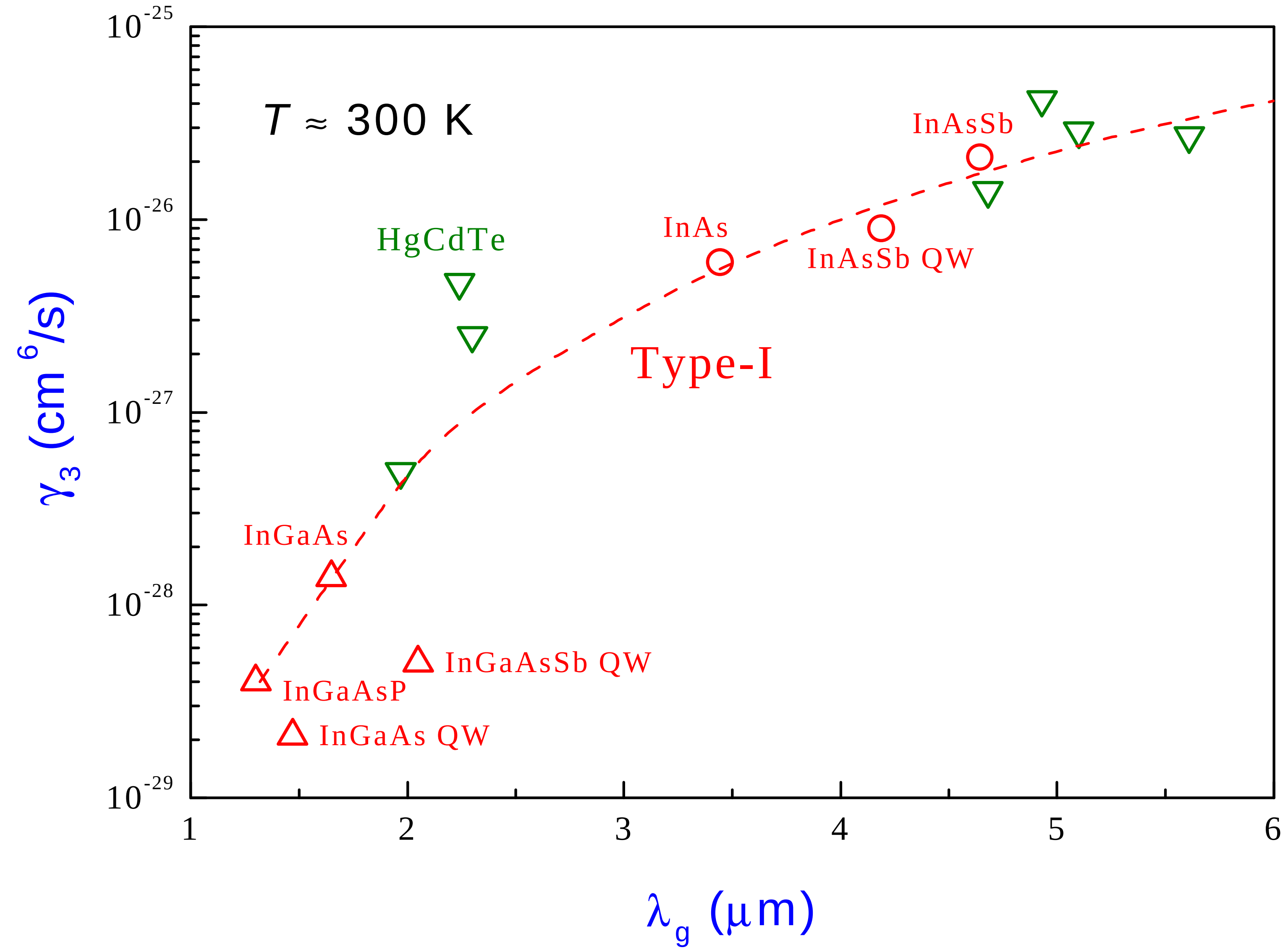
(1) Excellent electrical confinement

(2) Suppressed Auger (E_g « E_{SO})

AUGER NONRADIATIVE LOSS

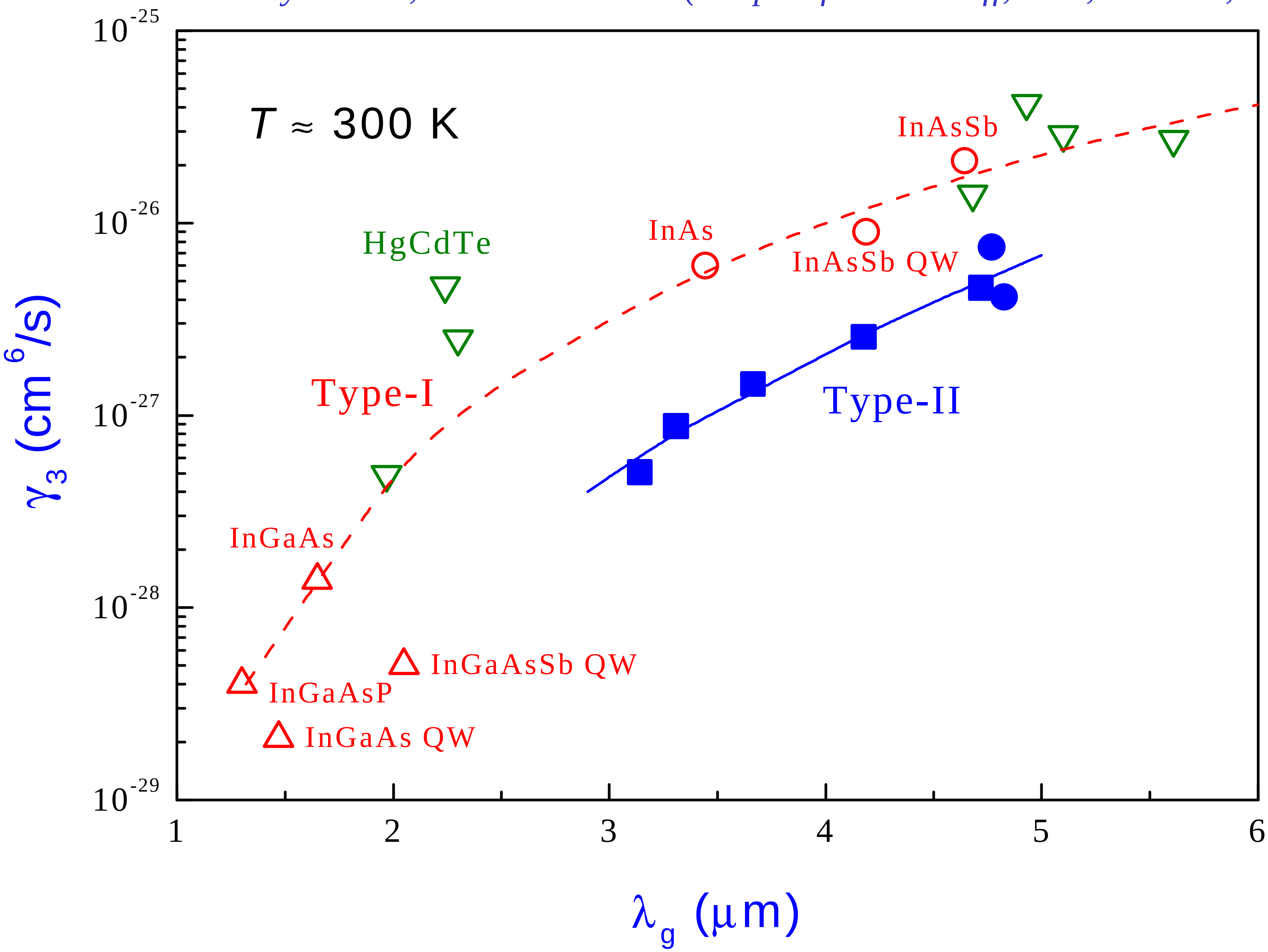


AUGER IN TYPE-Is



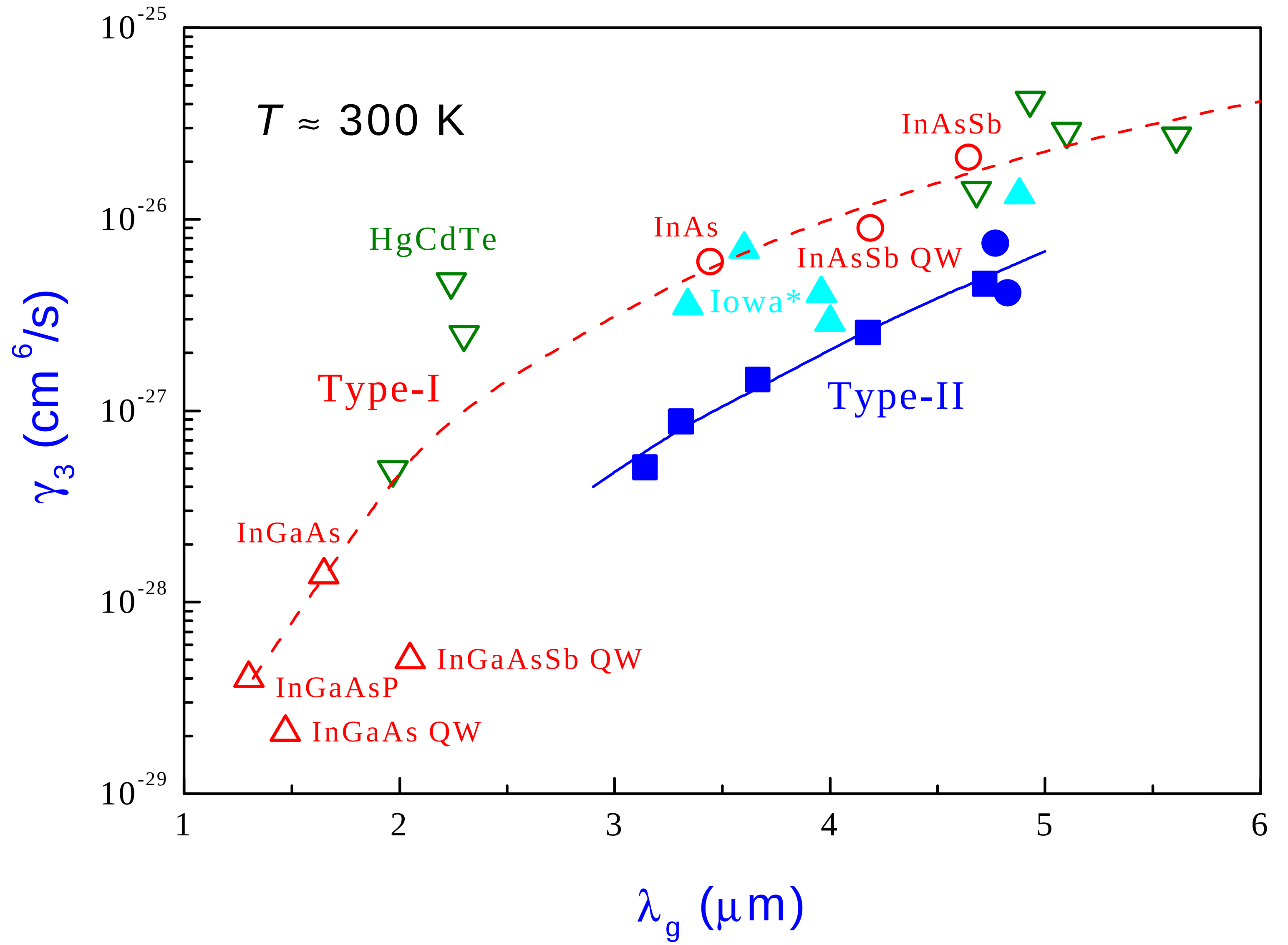
AUGER SUPPRESSION IN TYPE-IIs

Meyer et al., submitted to APL (samples from Sarnoff, NRL, Houston, HRL)



AUGER SUPPRESSION IN TYPE-IIs

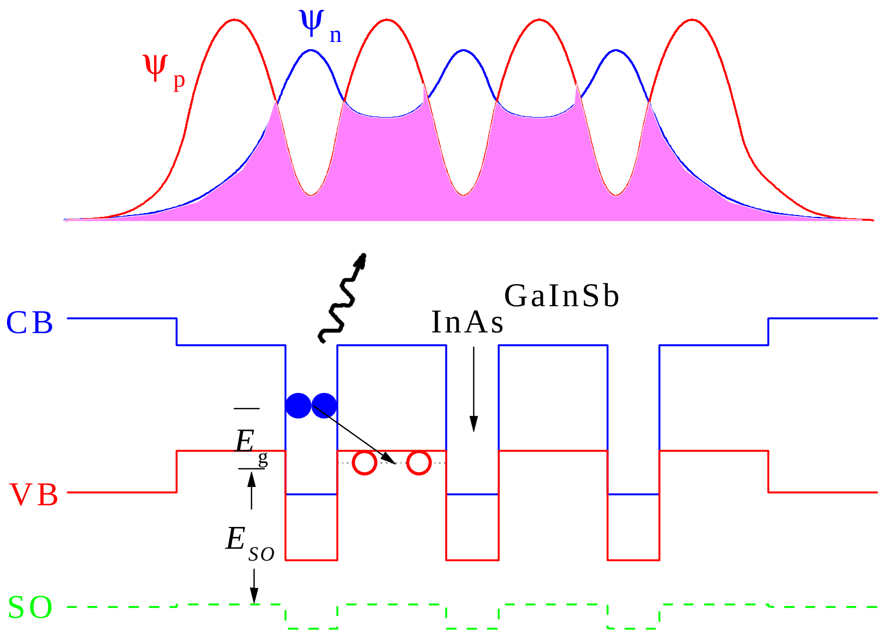
**Boggess, Flatte, Hasenberg et al. (from pump-probe experiments)*

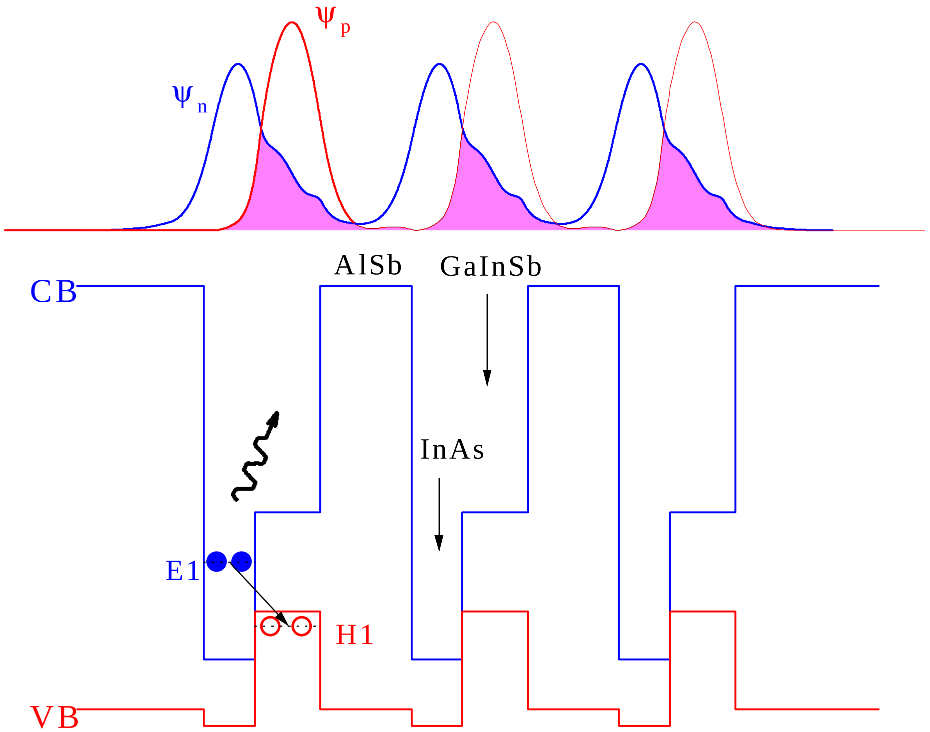


TYPE-IIs – 3D vs 2D DENSITY OF STATES

TYPE-II SL

3-CONSTITUENT MQW





Advantages:

(1) Excellent electrical confinement

(2) Suppressed Auger

Disadvantage:

3D Density-of-States

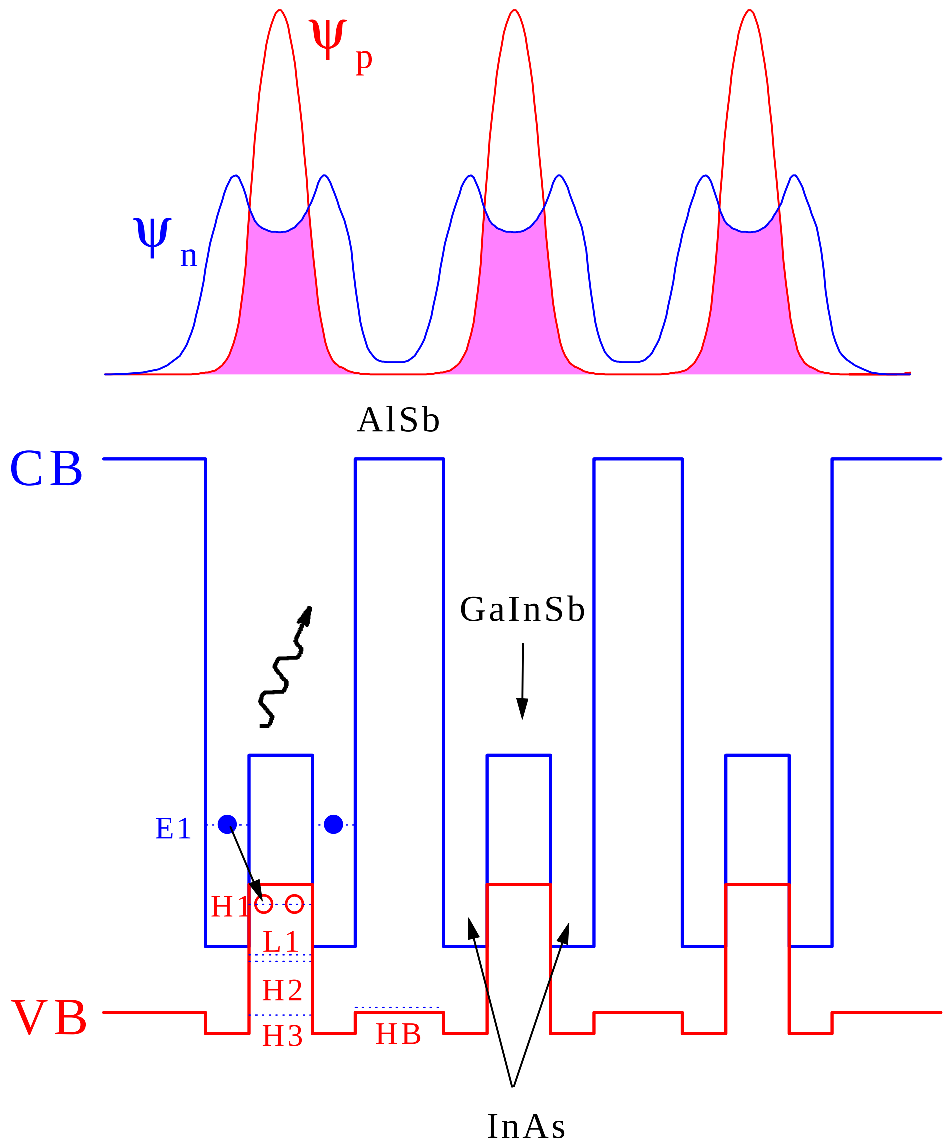
Advantage:

2D DOS for electrons and holes

Disadvantage:

Reduced wavefunction overlap

TYPE-II "W" LASER



<u>Advantages:</u>

(1) Strong wavefunction overlap

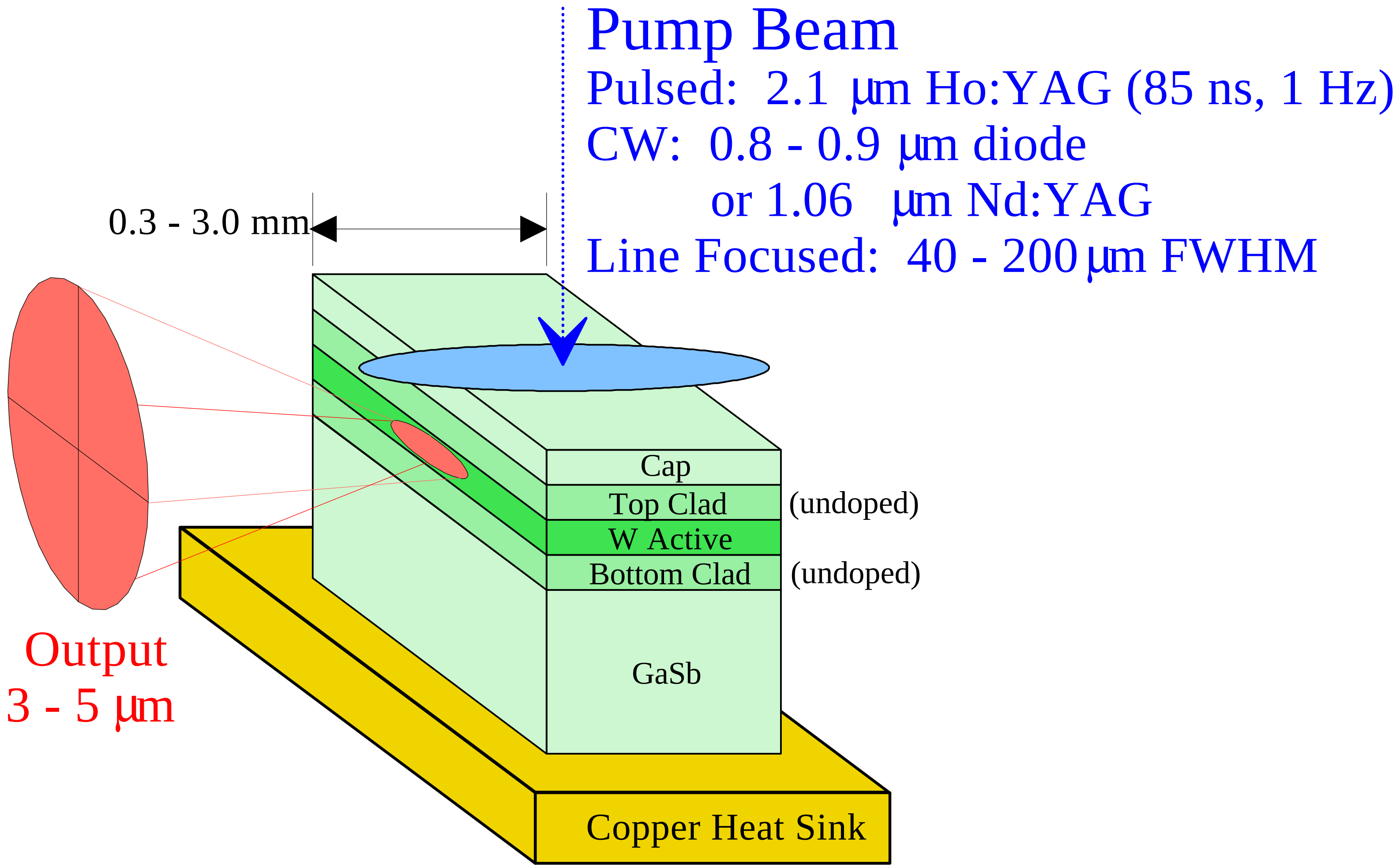
(2) 2D for both electrons and holes

(3) Excellent electrical confinement

(4) Auger suppression – *Factor of 5-10 improvement confirmed in lasers*

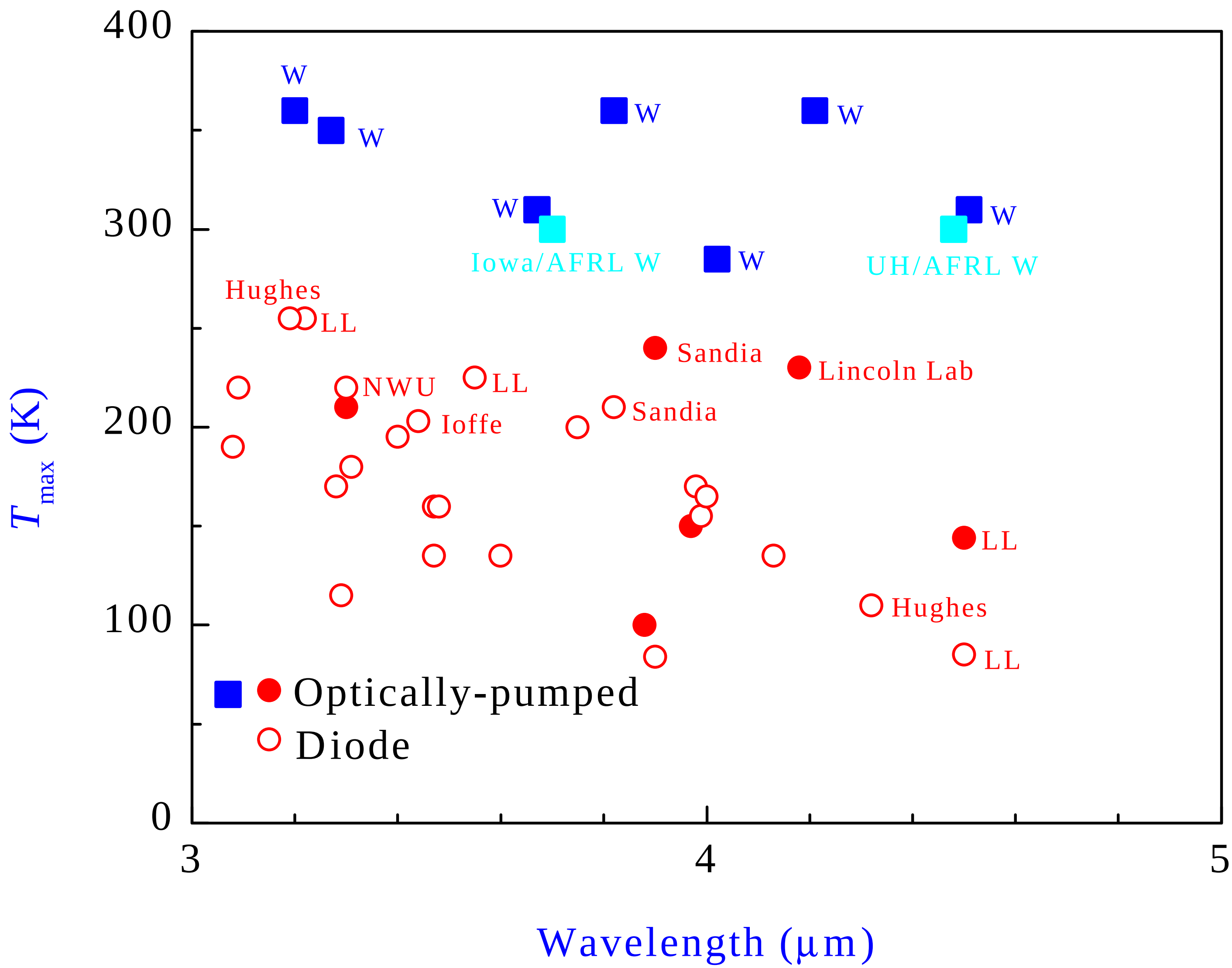
Meyer et al. APL 67,757 (1995)

OPTICALLY-PUMPED TYPE-II LASERS



III-V INTERBAND MID-IR LASERS (Pulsed)

W samples for NRL characterization grown by Sarnoff, NRL, and Houston



III-V MID-IR LASERS (Pulsed)

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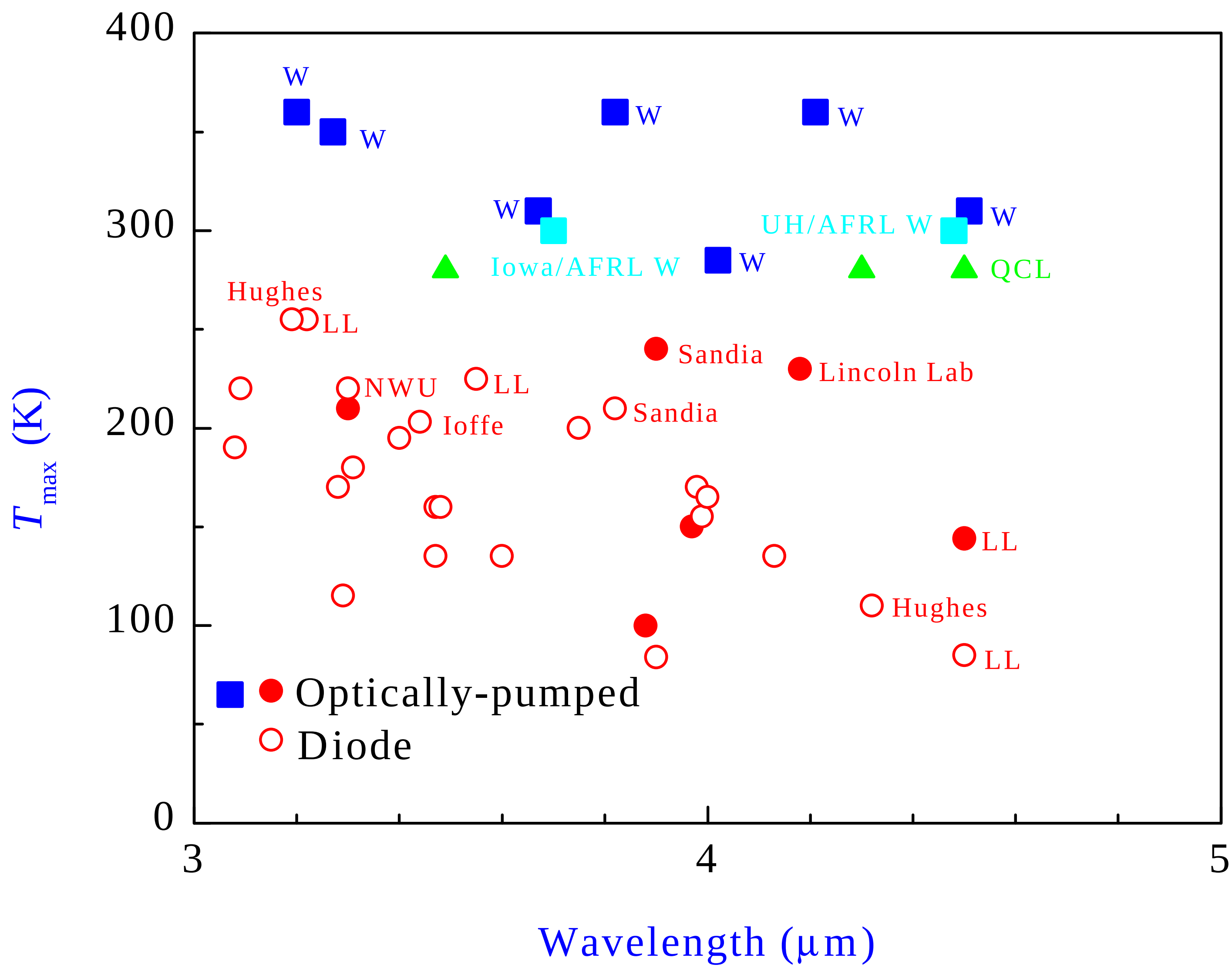
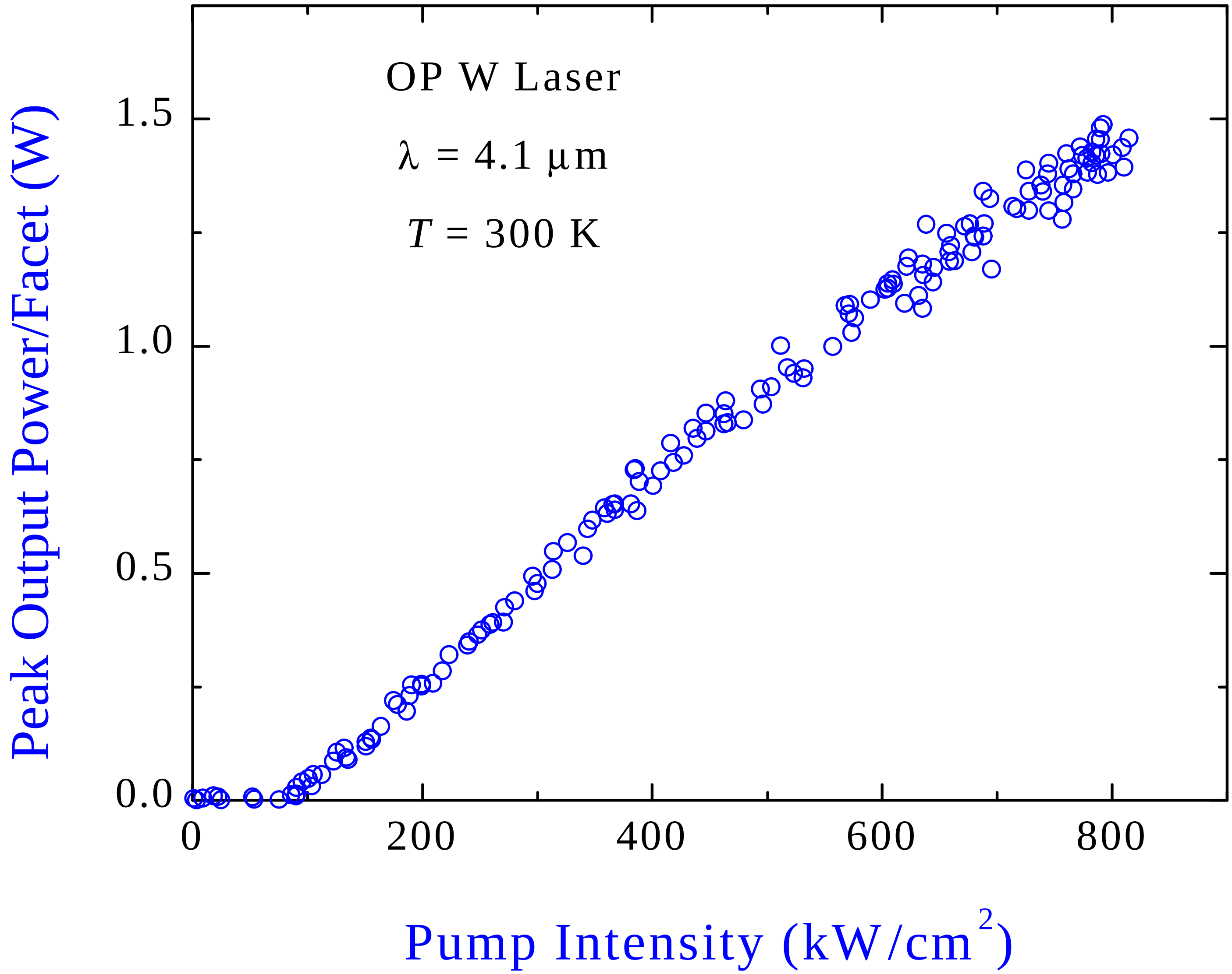


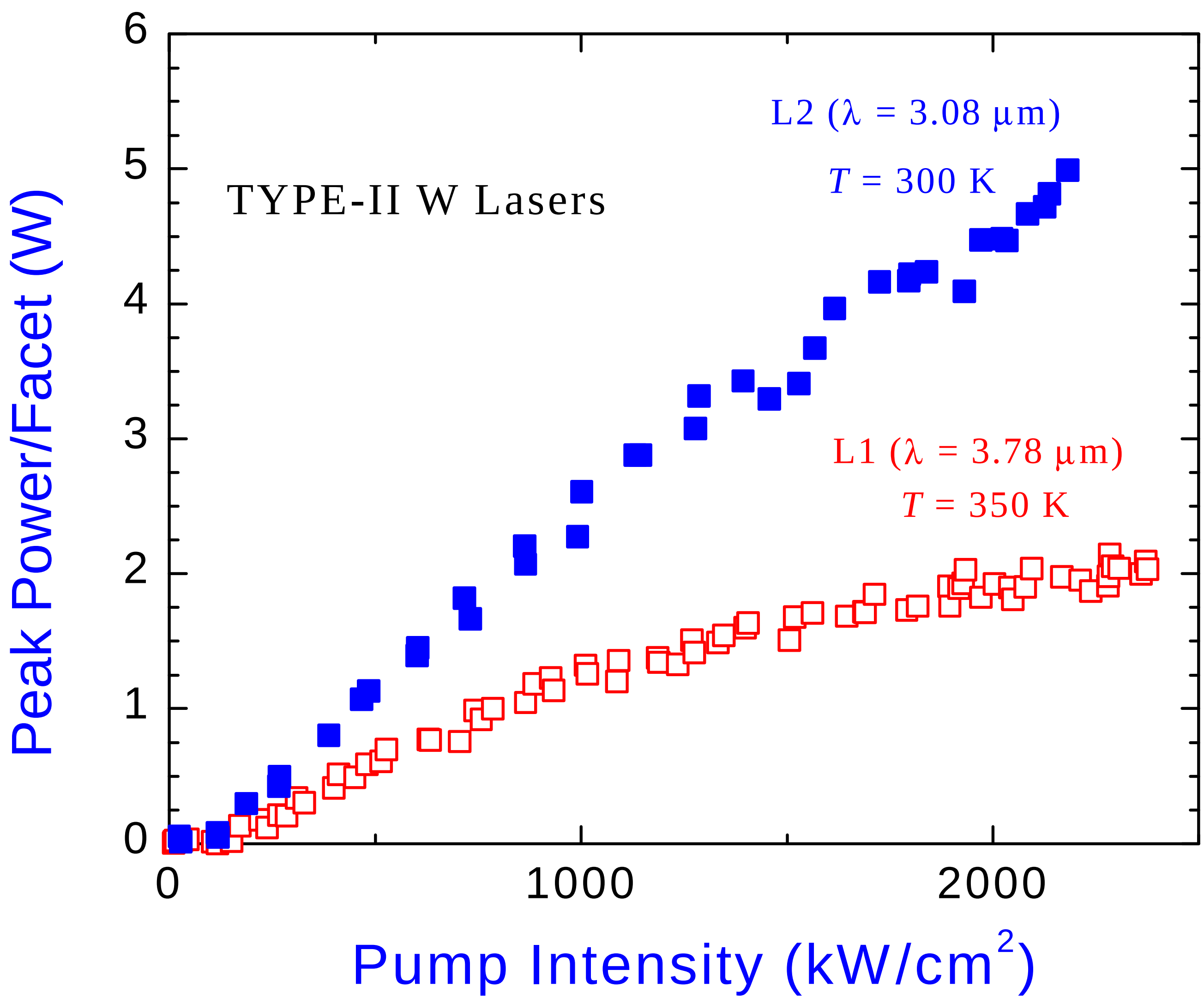
ROOM TEMPERATIRE PEAK POWER

Bewley et al., submitted to APL (MBE growth at NRL)



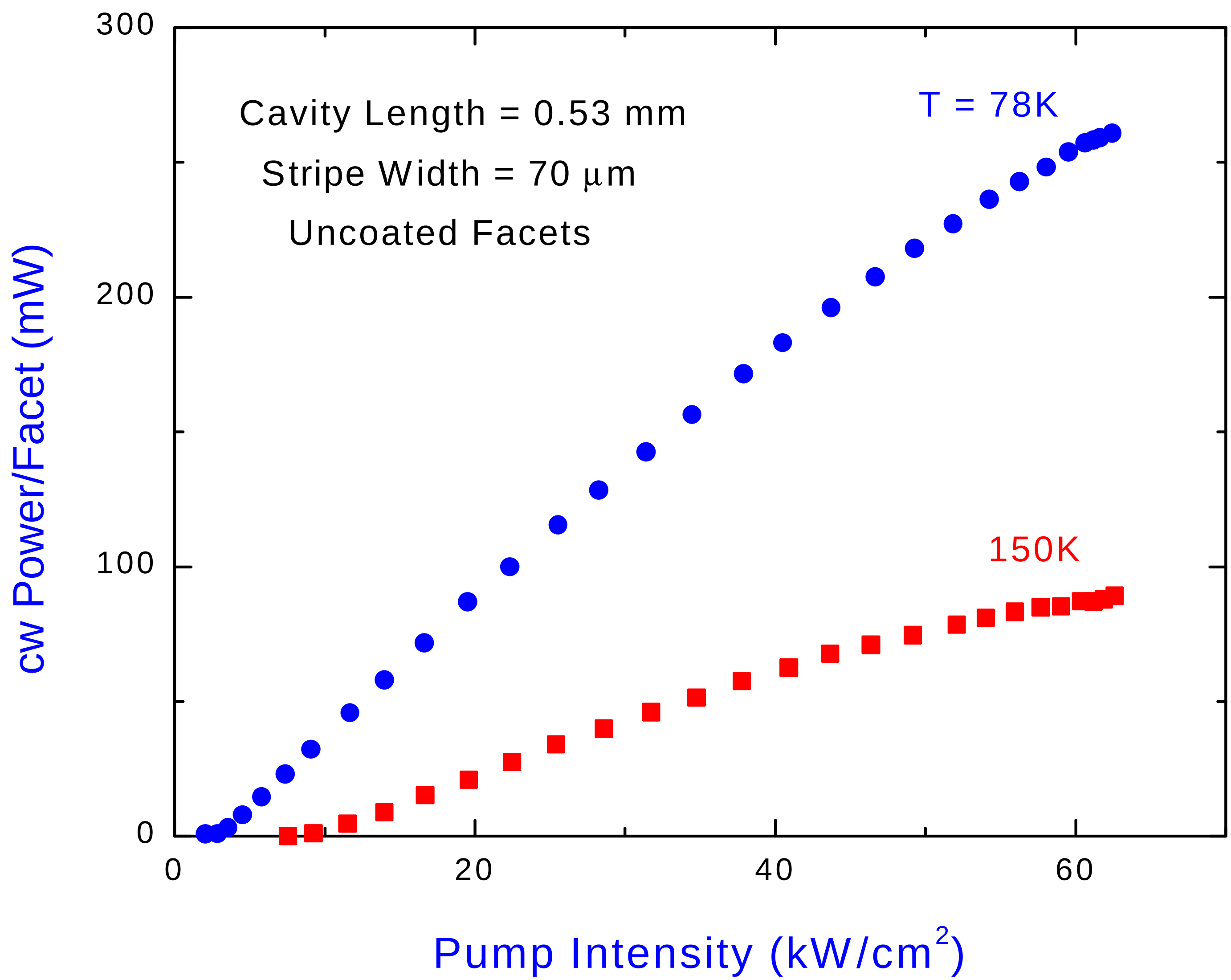
HIGH-POWER W LASERS (PULSED)

Bewley et al., submitted to APL (MBE growth at Sarnoff)

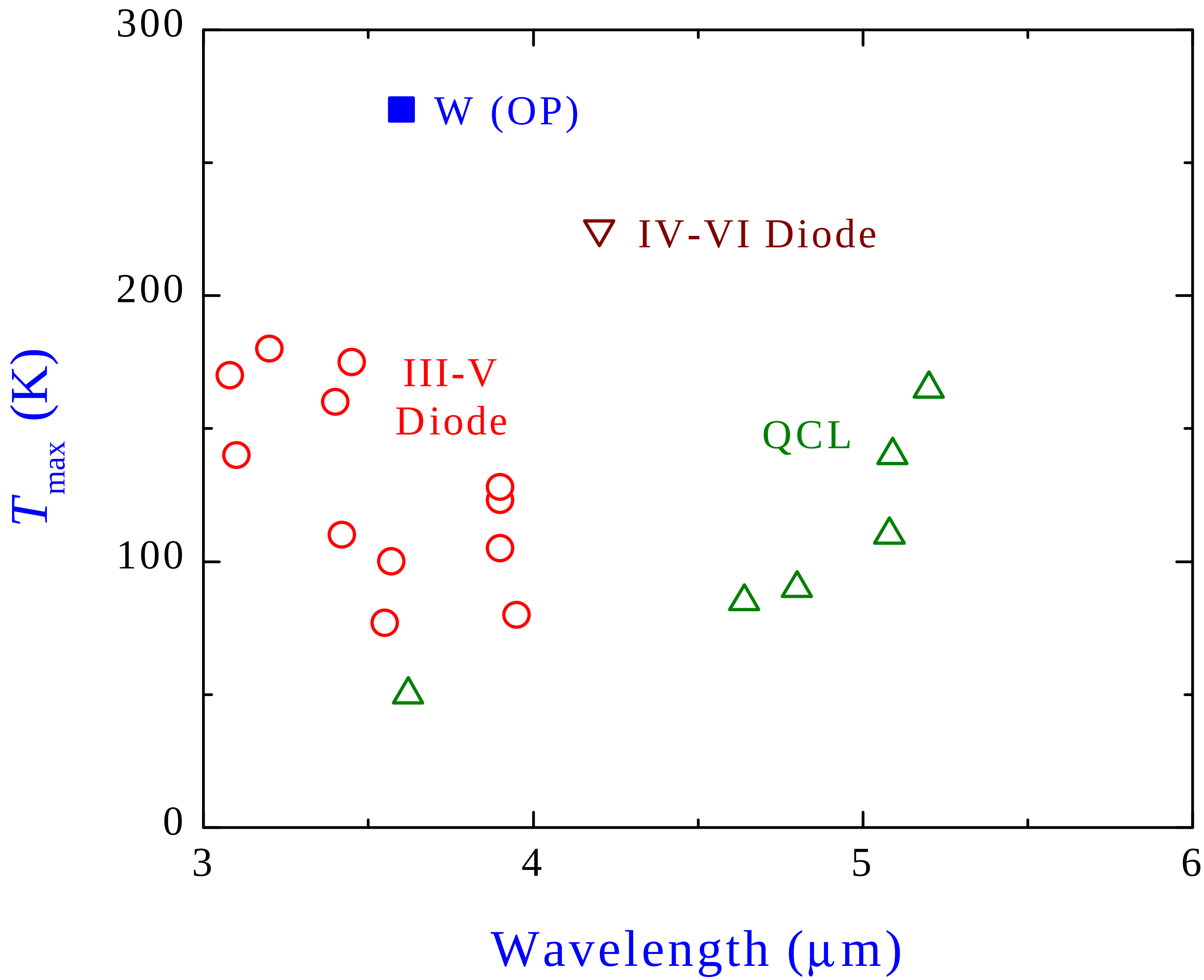


OPTICALLY-PUMPED W (cw)

MBE growth at Sarnoff



MID-IR LASERS (cw)



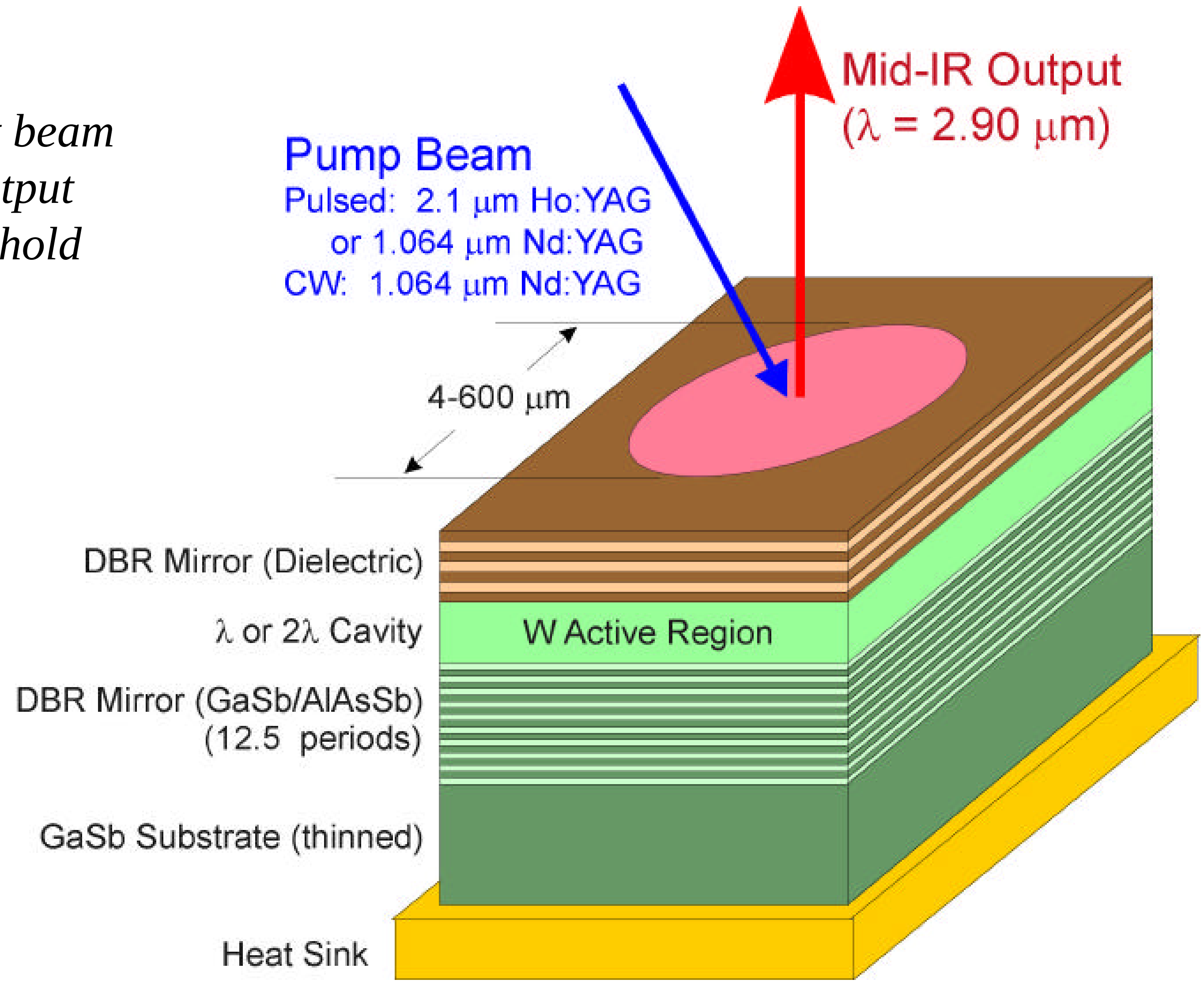
HOUSTON/LINCOLN LAB HIGH AVERAGE POWER

- Recent quasi-cw testing of optically-pumped W lasers *[Le et al. 72, 3434 (1998)]* yielded high output powers at $\lambda = 4$ μm:
  - 100 μs pulses, 10% duty cycle: Peak $P_{out} = 1.5$ W at $T = 71$ K
  - 20 μs pulses, 50% duty cycle: Average $P_{out} = 0.37$ W at $T = 82$ K

MID-IR VCSELs

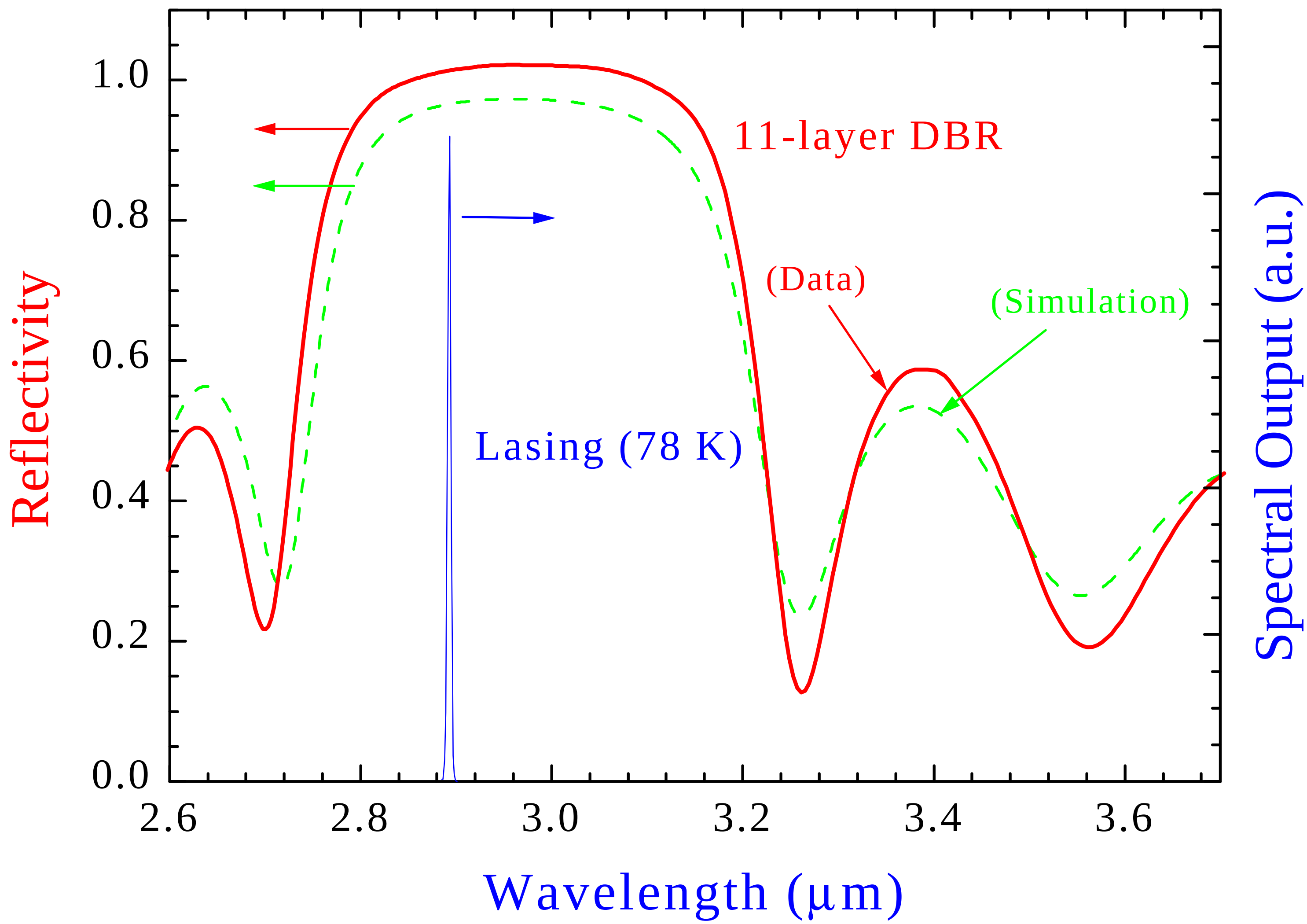
Motivations:

- *Circular output beam*
- *Single-mode output*
- *Ultra-low threshold*
- *2D arrays*

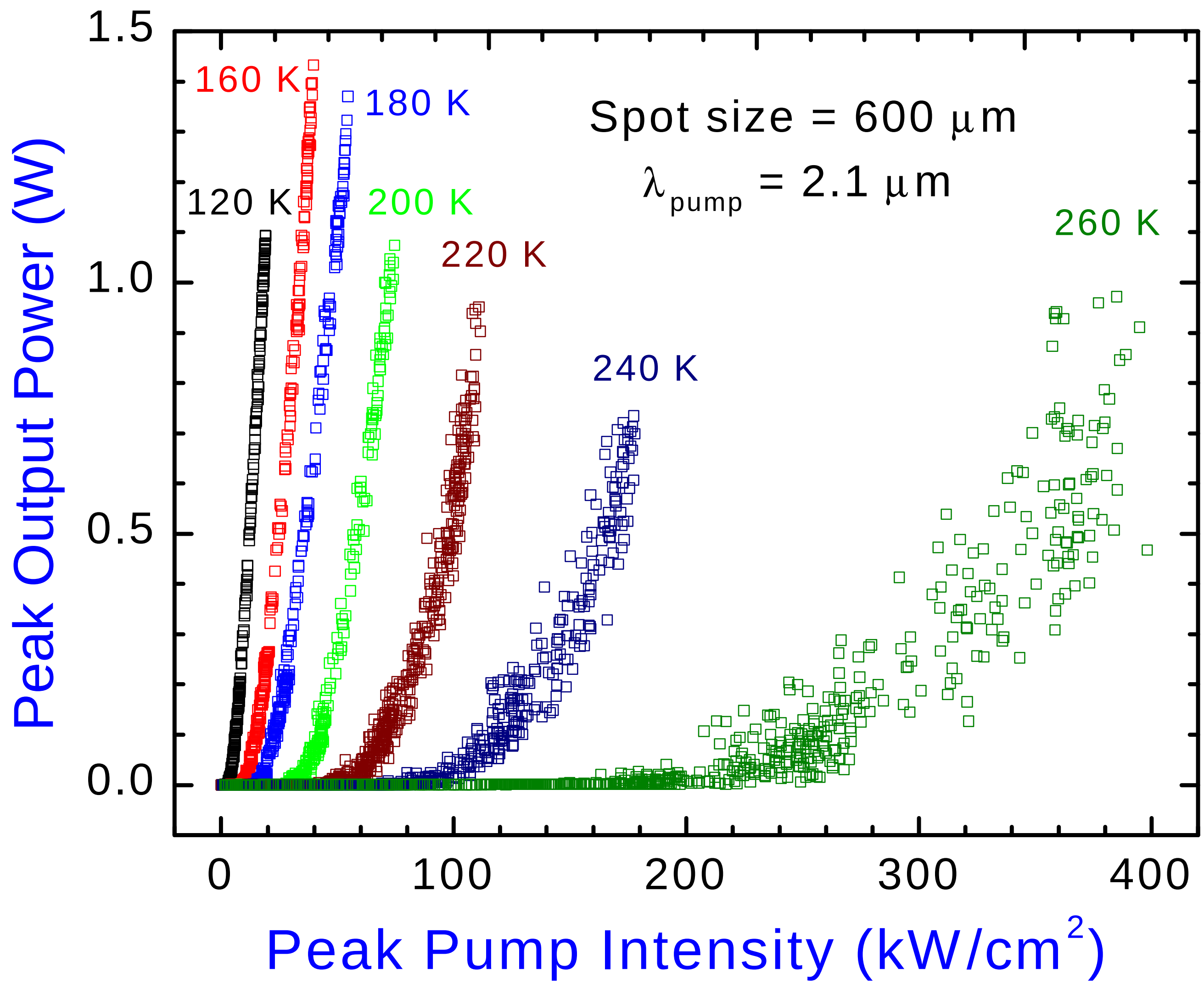


MIRROR/LASING SPECTRA

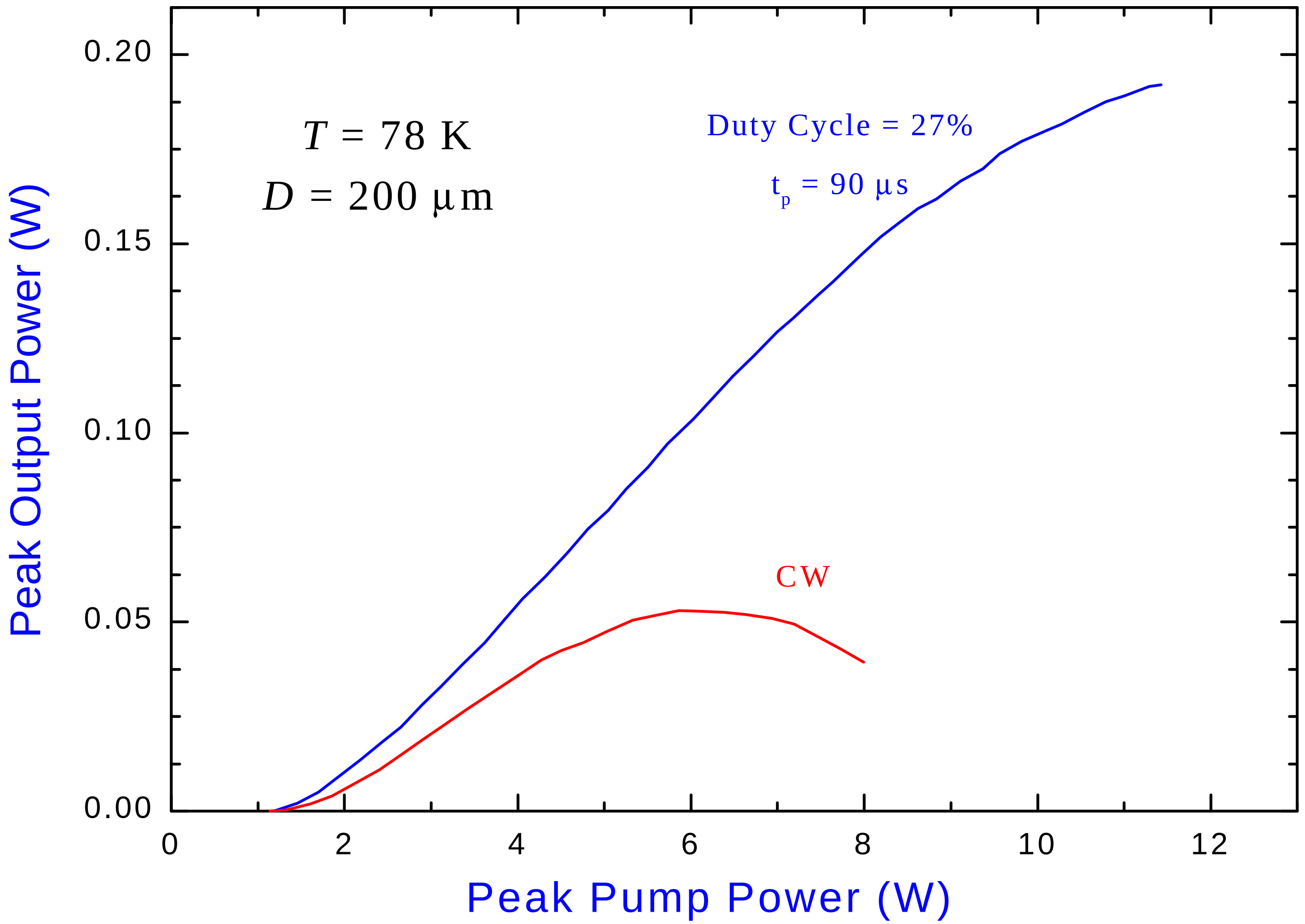
Felix et al., APL 71, 3483 (1997) (MBE by D. H. Chow, Hughes)



VCSEL – PULSED L-L (l = 2.9 mm)

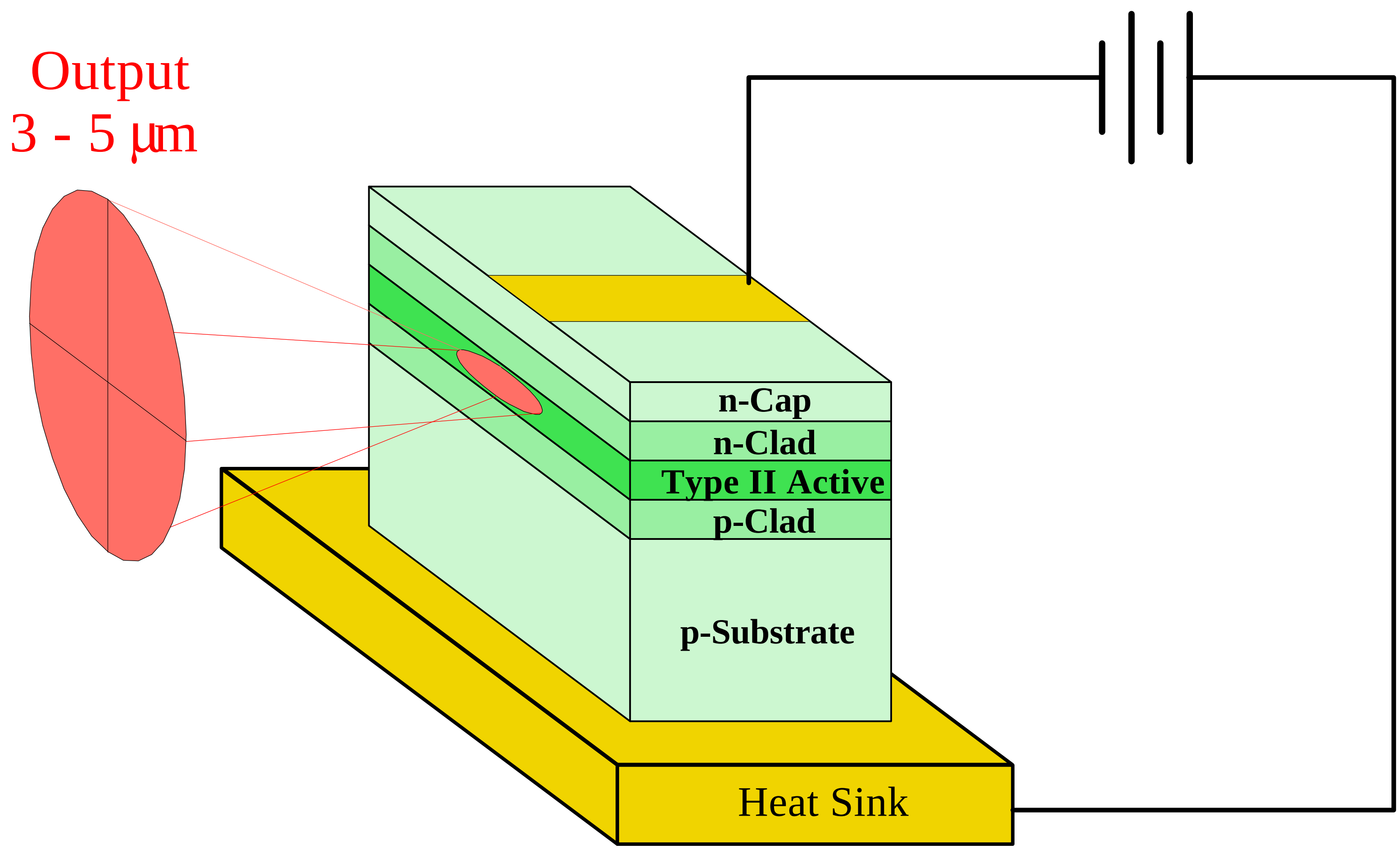


CW, QUASI-CW VCSEL OPERATION



For *D* = 6 µm: P_{th}^{cw} = 4 mW!

TYPE-II DIODE LASERS



TYPE-II DIODES

Electrically-pumped (non-cascade) type-IIs relatively inactive since HRL work:

- U. Montpellier *[Baranov et al., APL 71, 735 (1997)]* (InAs/GaSb superlattice active region): Lasing up to 300 K at $\lambda = 1.95$–2.35 µm; strong 300 K electroluminescence at $\lambda = 2.83$–3.70 µm

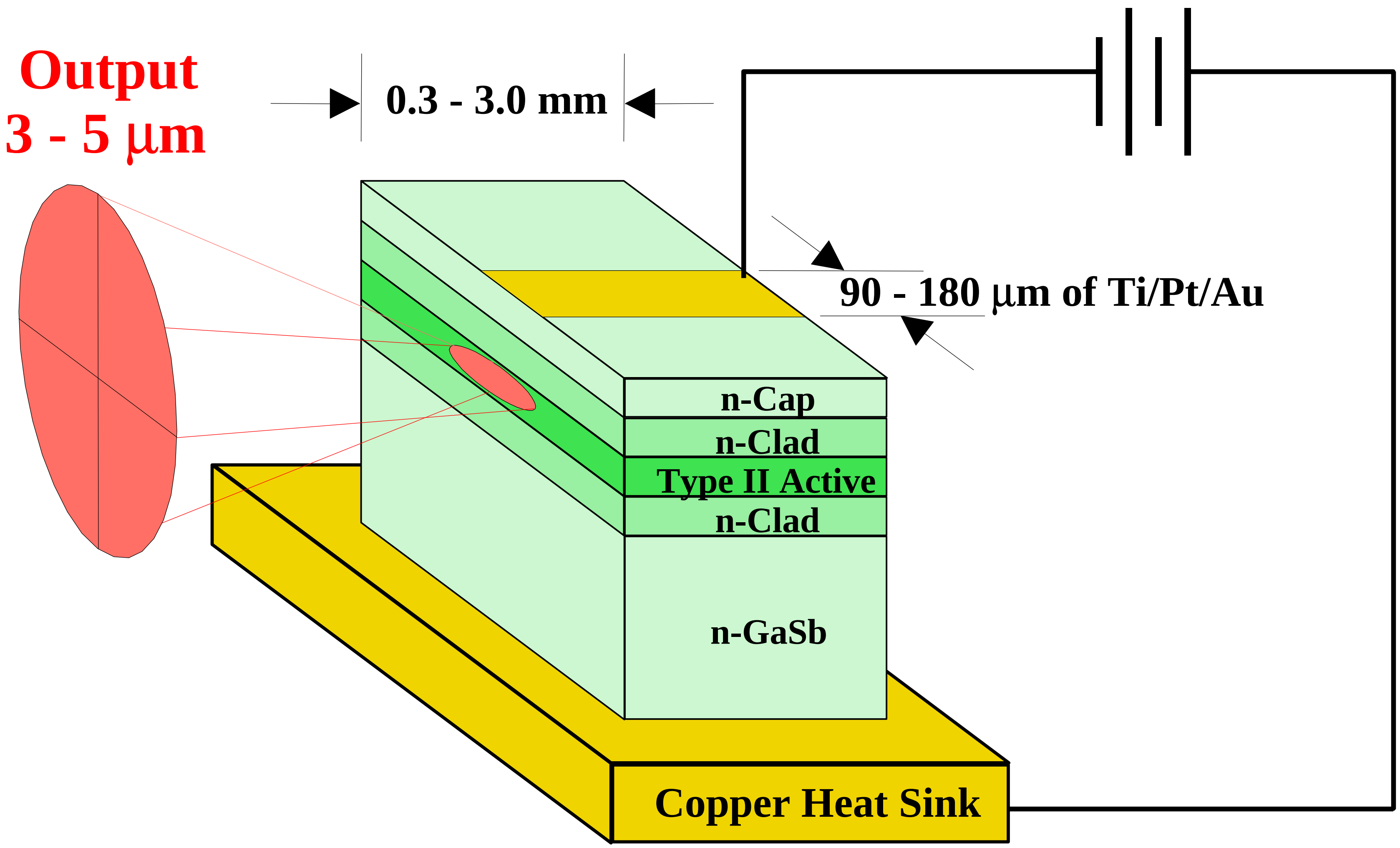
- NRL/U. Houston *[Bewley et al., APL 71, 3607 (1997)]* (InAs/GaSb/GaInSb/GaSb SL active): $T_{max} = 260$ K ($\lambda = 2.92$ µm); $P_{out} >$ 400 mW per facet (100 K), >100 mW (200 K); $j_{th} = 1.1$ kA/cm^2 at T = 200 K

- U. Iowa *[Flatte et al., APL 71, 3764 (1997)]* (InAs/GaInSb/InAs/AlGaInAsSb W active): Lasing up to 180 K at $\lambda = 2.7$ µm

- Northwestern U. *[Mohseni et al., DLTR abstract (1998)]* (InAs/GaInSb/GaSb SL active): $P_{out} = 110$ mW at 77 K ($\lambda = 3.9$ µm); lasing up to 130 K

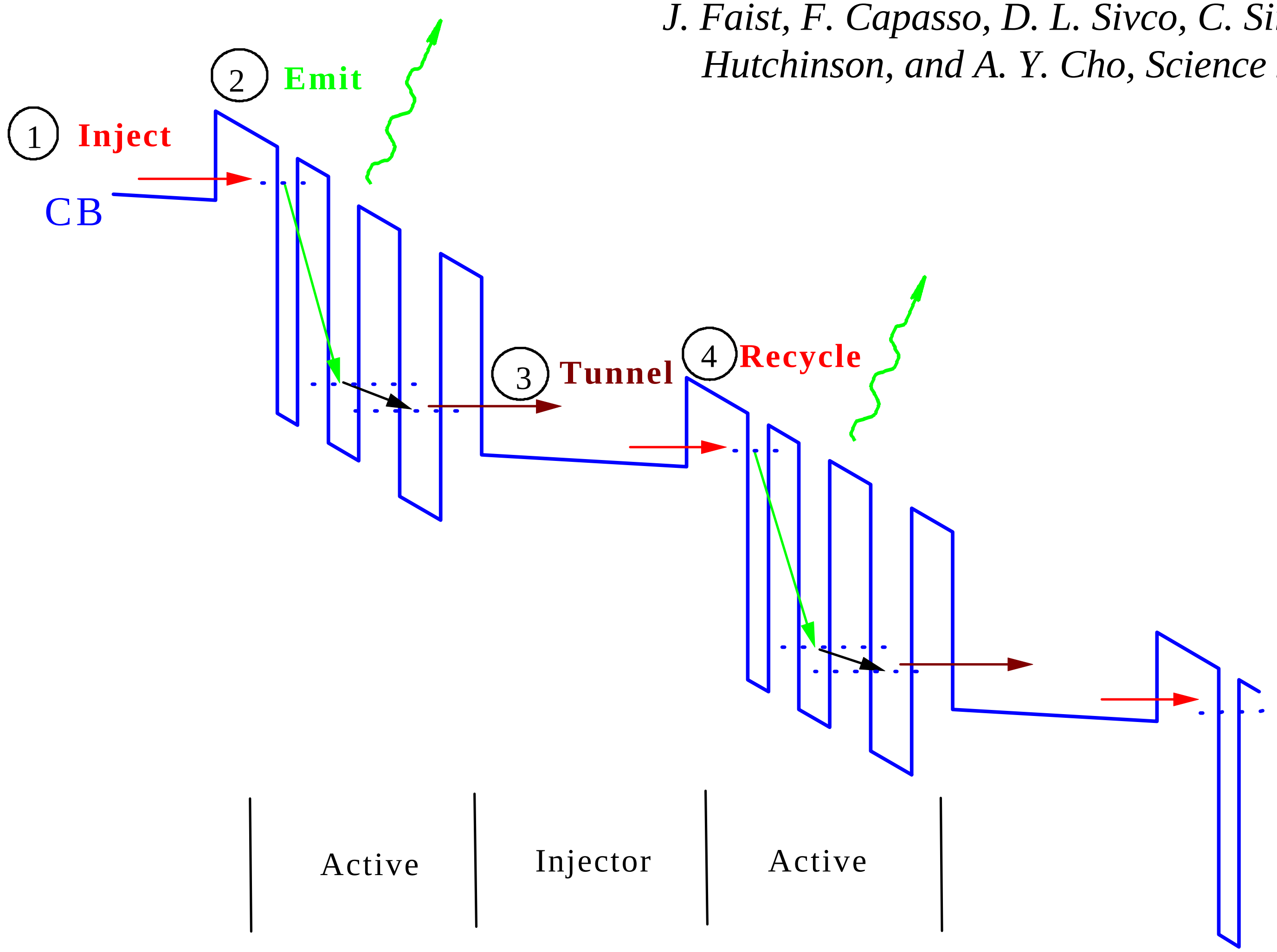
Designs still preliminary – *Large further improvements expected*

INTERBAND CASCADE LASERS

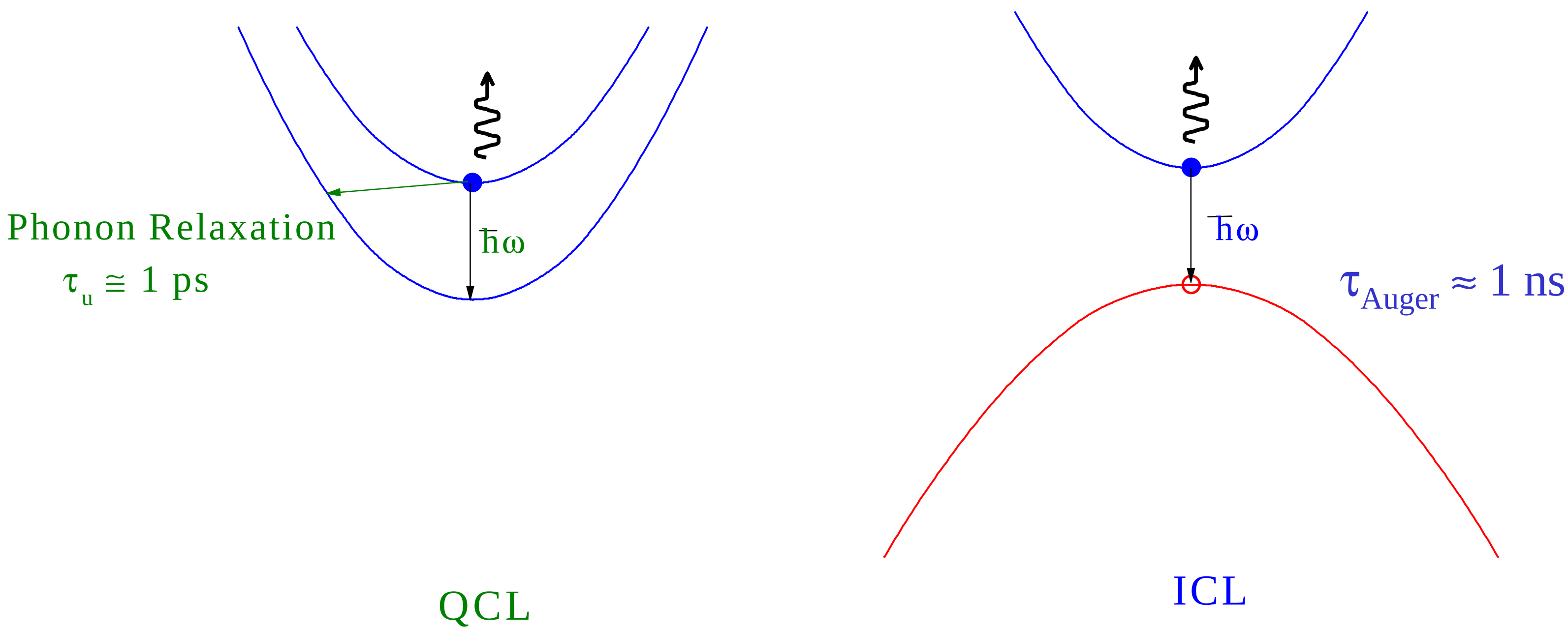


QUANTUM CASCADE LASER (Intersubband)

J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, Science 264 (1994)



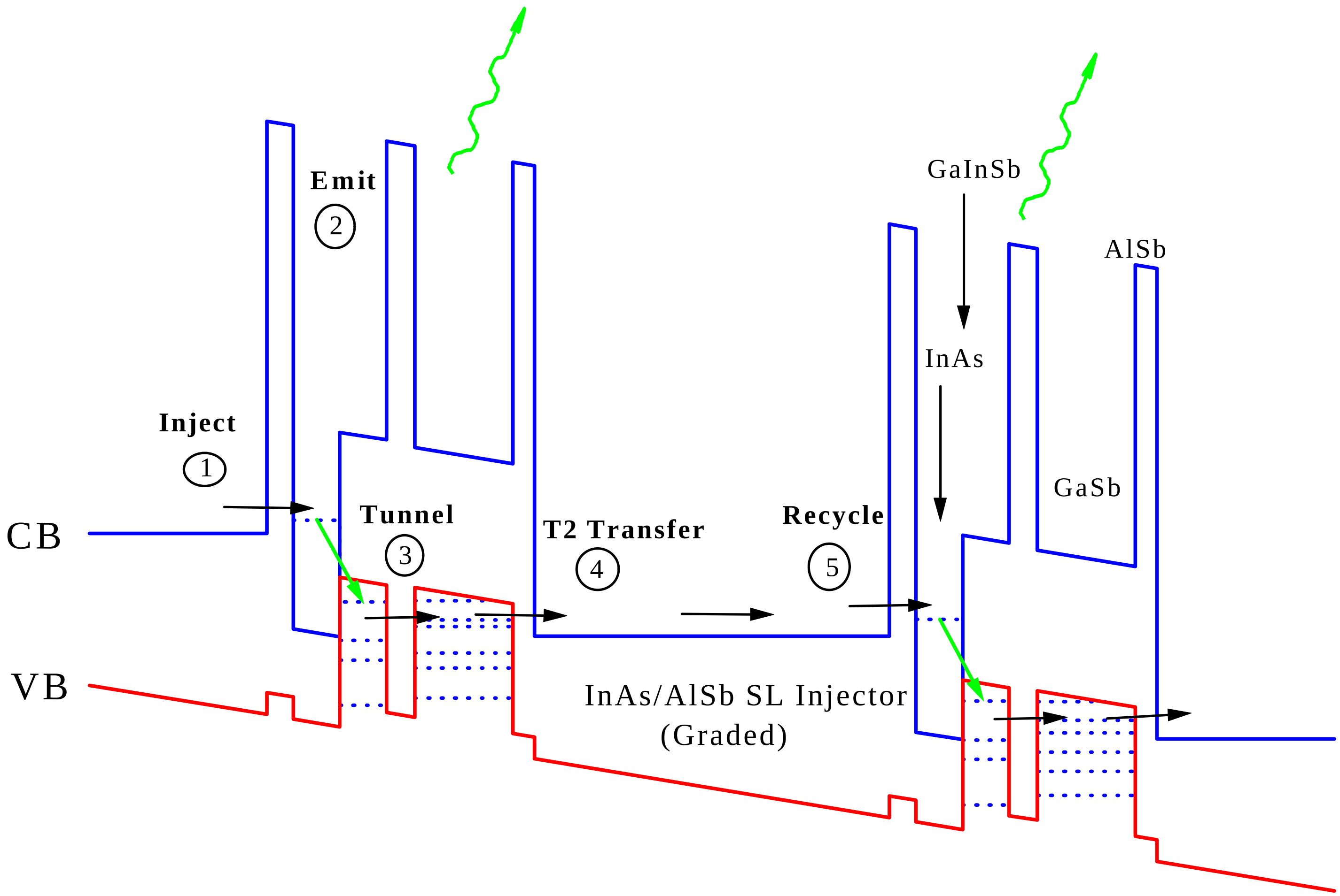
CASCADE LASERS: INTERSUBBAND vs INTERBAND



ICL avoids short phonon relaxation lifetime – Means much lower j_{th}

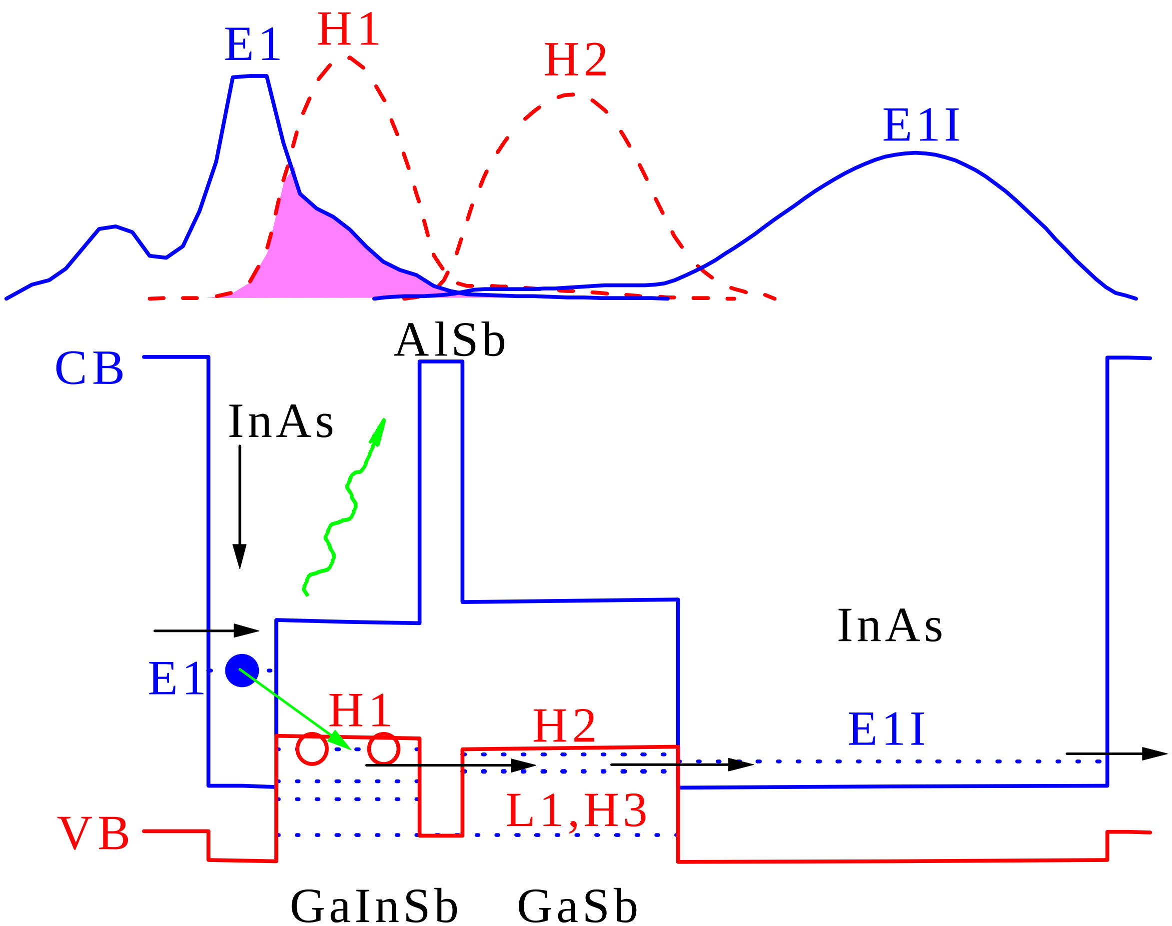
INTERBAND CASCADE LASER – CONCEPT

First proposed: *R. Q. Yang, Superlatt. Microstruct. 17, 77 (1995)*
Improvements: *J. R. Meyer, I. Vurgaftman, R. Q. Yang, and L. R. Ram-Mohan, EL 32, 45 (1996)*

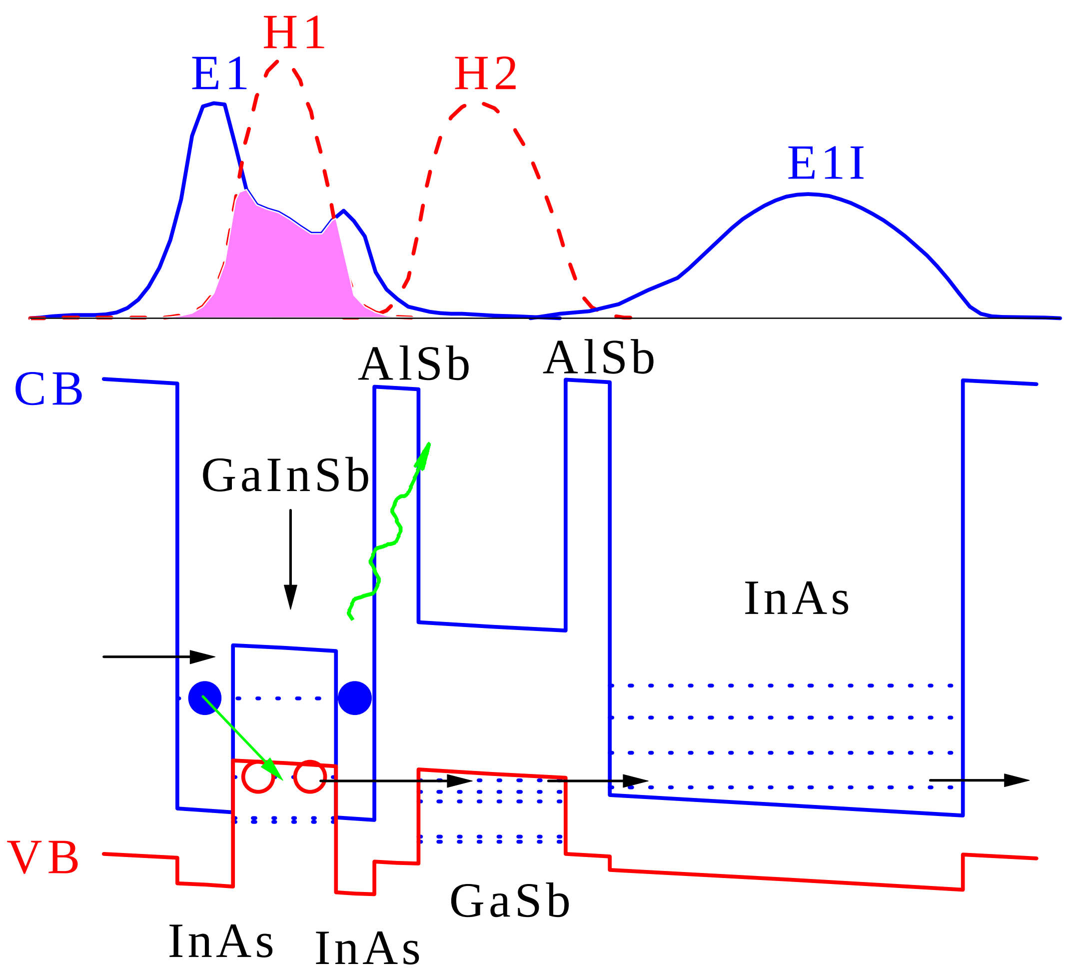


Advantages: (1) High output power, (2) High slope, (3) Low threshold, (4) High T_{max}

ICL - ACTIVE REGION



W-ICL FOR ENHANCED GAIN



ICL DEMONSTRATIONS

- *(1-97)* UH/Sandia (λ = 3.8 μm) – The first ICL
  [Lin et al., Electron. Lett. 33, 598 (1997)]

- *(4-97)* NRL/UH W (λ = 3.0 μm) – P_{max}(180 K) = 170 mW/facet (Advantage 1), *dP/dI*(100 K) > 1 photons/electron (Advantage 2) *[Felix et al., Phot. Tech. Lett. 9, 1433 (1997)]*

- *(5-97)* UH/UH (λ = 3.9 μm) – P_{max}(80 K) = 480 W/facet (Advantage 1), *dP/dI* (80 K) up to 2.2 photons/electron (Advantage 2)
  [R. Q. Yang et al., APL 71, 2409 (1997); B. H. Yang et al., APL 72, 2220 (1998)]

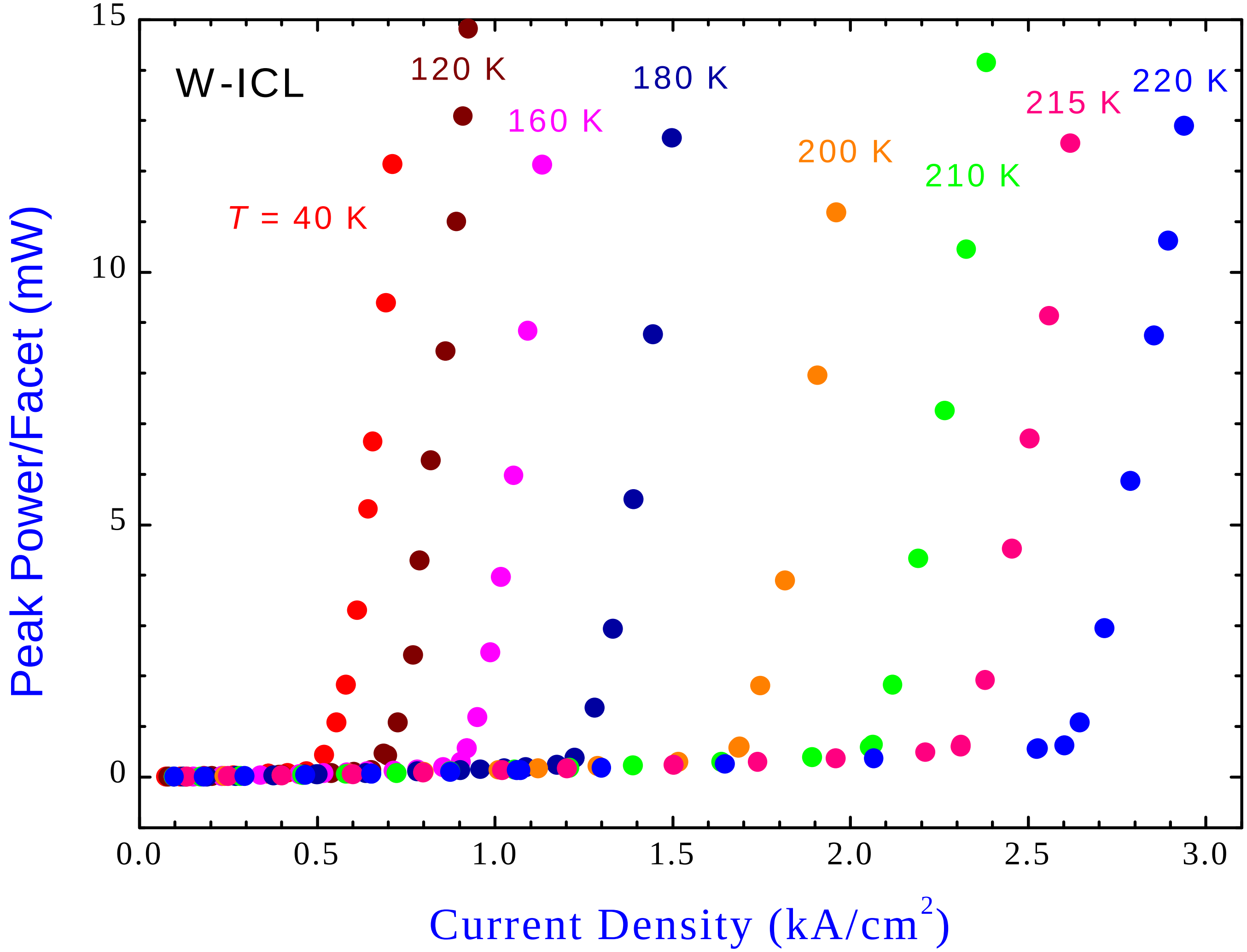
- *(9-97)* NRL/UH (λ = 3.9 μm) – Retested early non-W ICL (T_{max} = 70 K)

- *(10-97)* Sandia ($\lambda \approx$ 4 μm) – 10-stage Type-I ICL
  [Kurtz et al., APL 72, 2093 (1998)]

- (11-97) NRL/UH (λ = 3.6 μm) – W-ICL, Suppressed-leakage design
  [Olafsen et al., APL 72, 2370 (1998)]

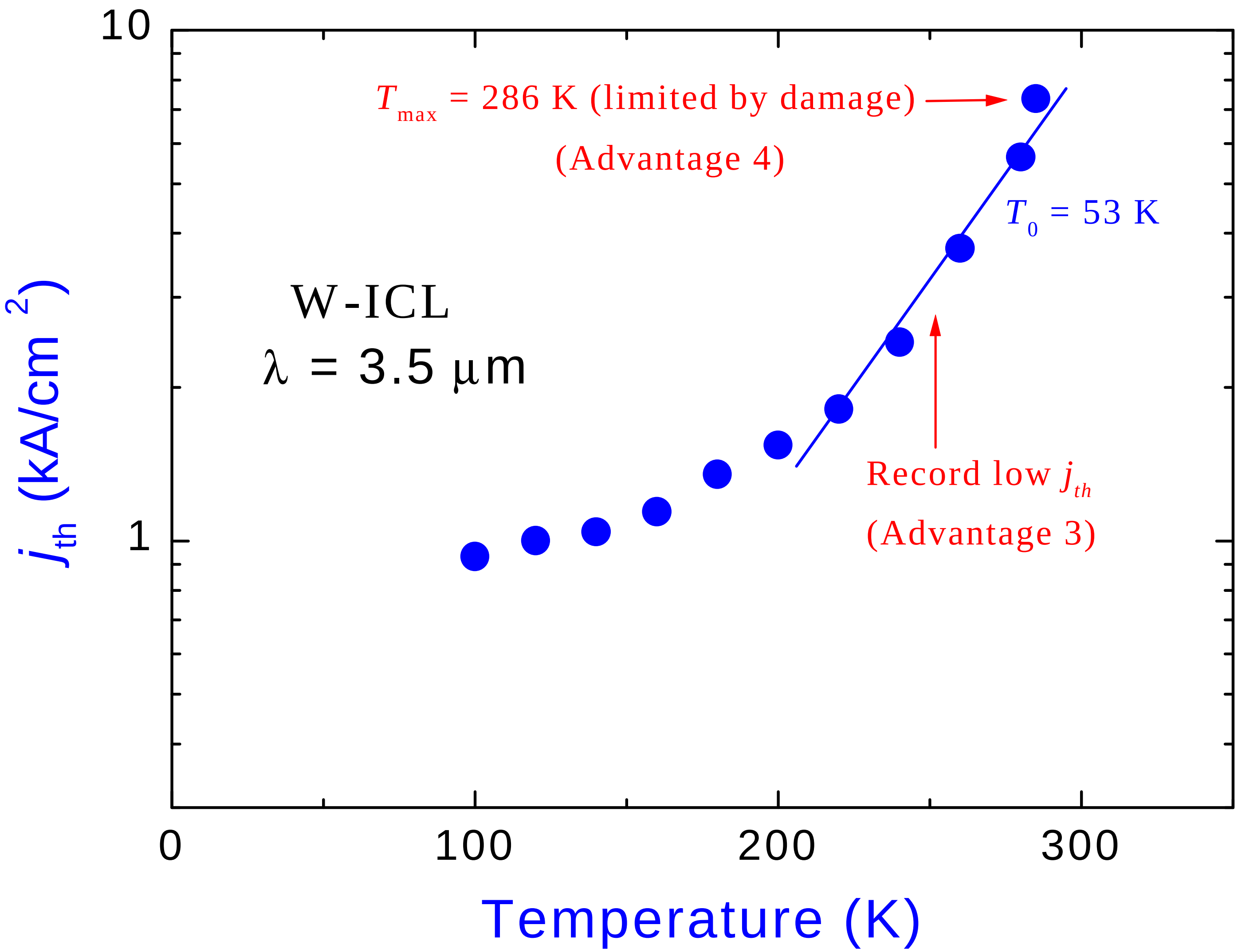
L-I vs TEMPERATURE

Felix et al., Phot. Tech. Lett. 9, 1433 (1997) (with U. Houston)

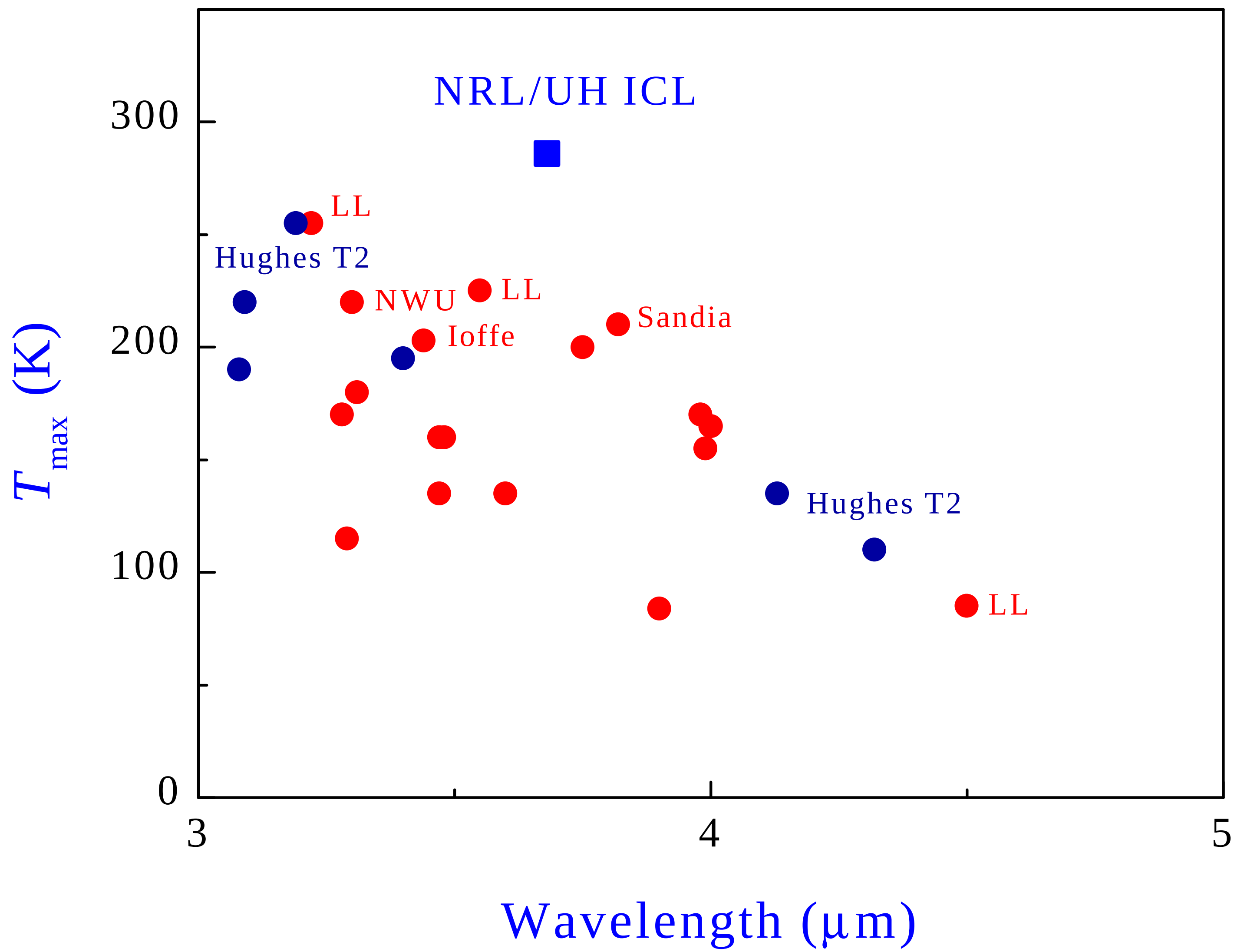


ICL LASING THRESHOLD vs T

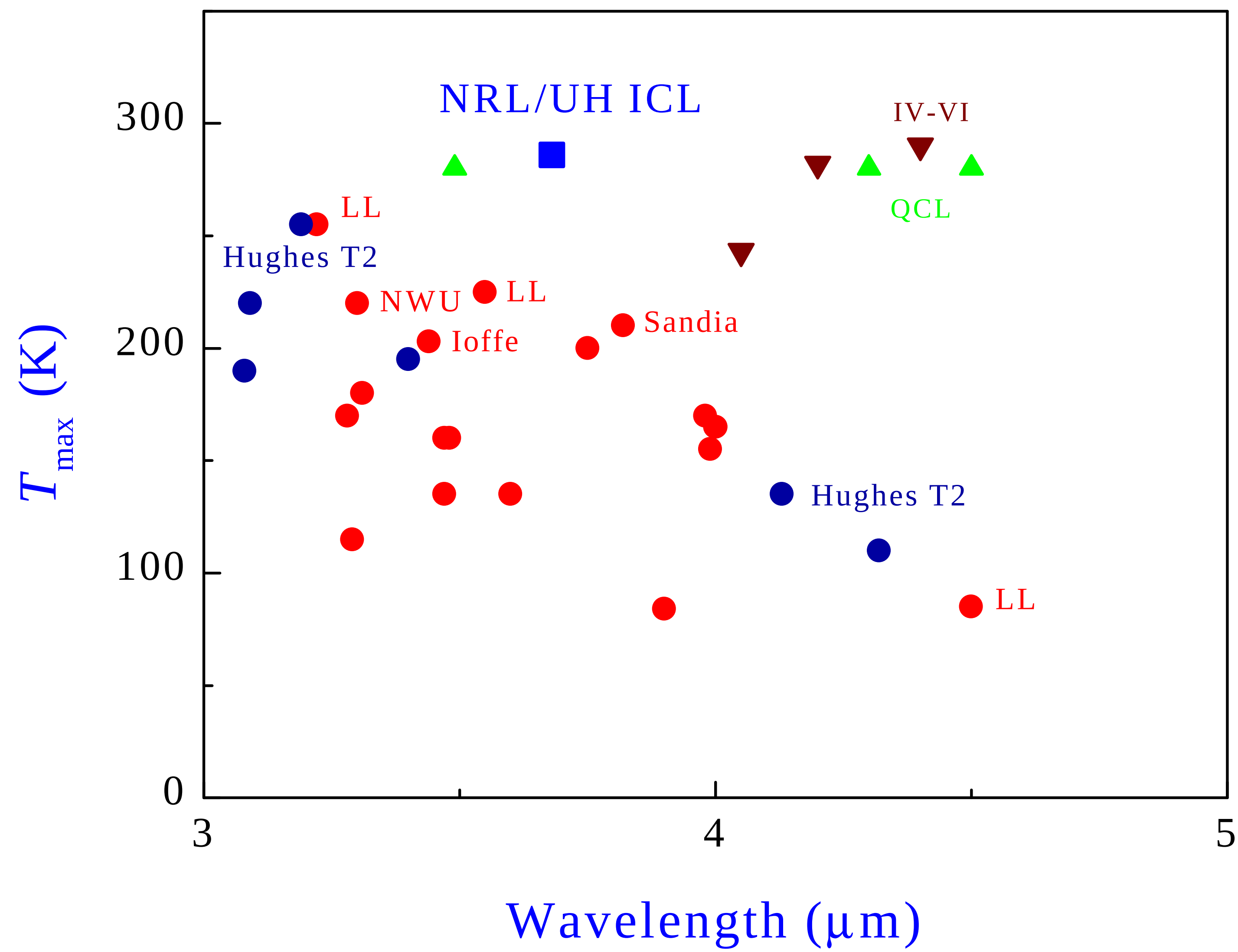
Olafsen et al., APL 72, 2370 (1998)



III-V INTERBAND DIODES (Pulsed)

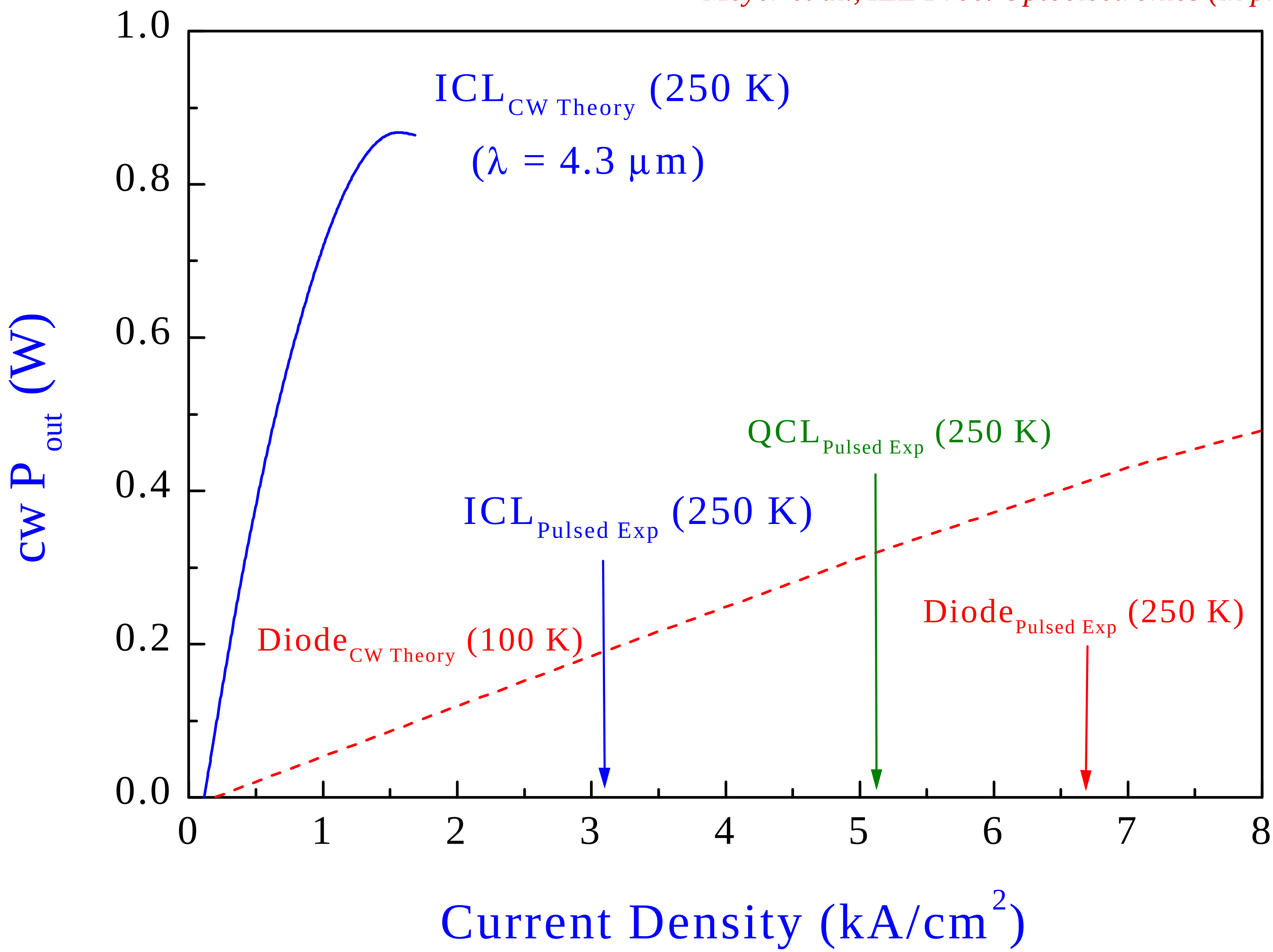


ALSO QCL PLUS LEAD SALTS (Pulsed)



ICL – PREDICTED cw OUTPUT POWER

Meyer et al., IEE Proc. Optoelectronics (in press)

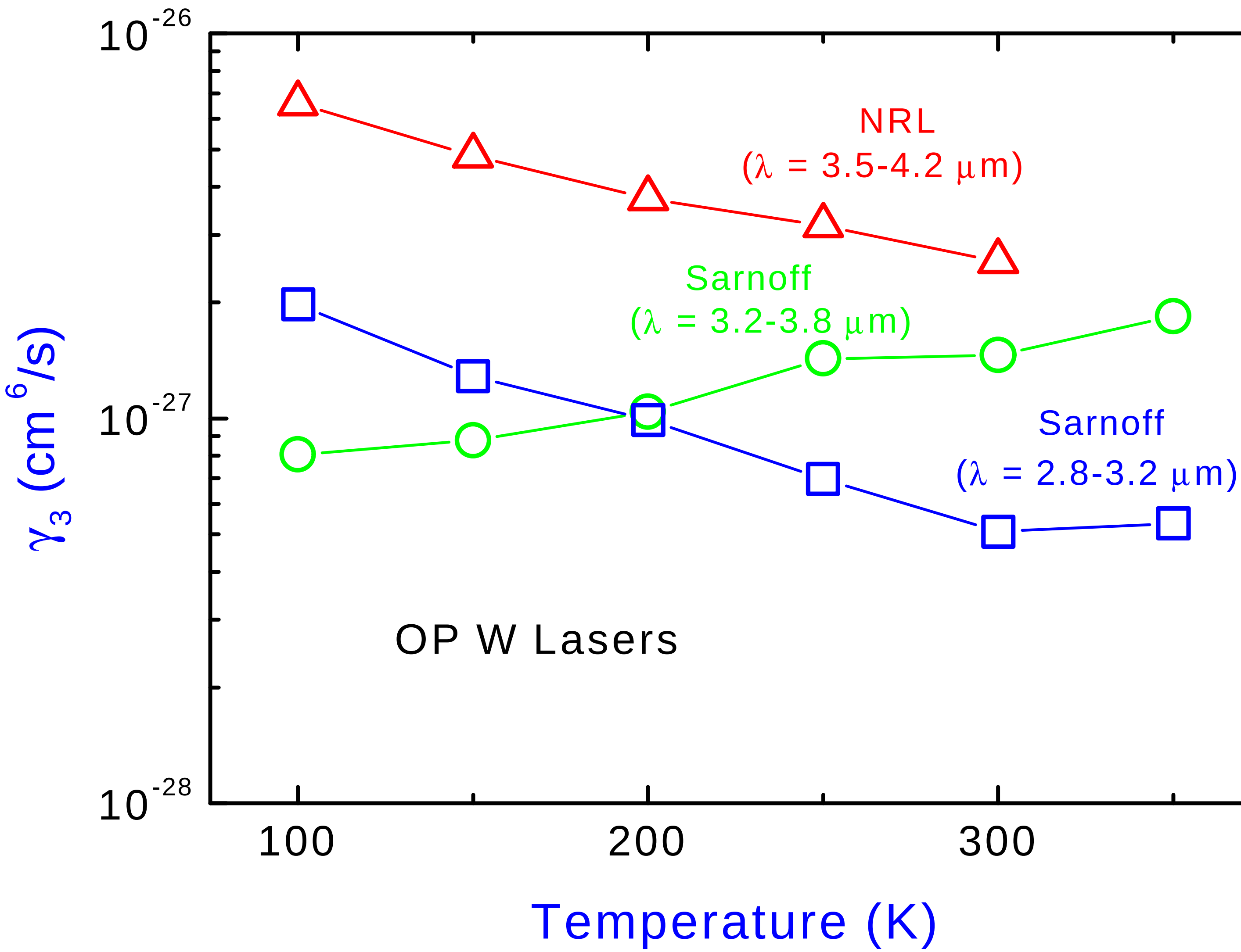


T2 IR LASERS – ISSUES LIMITING PERFORMANCE

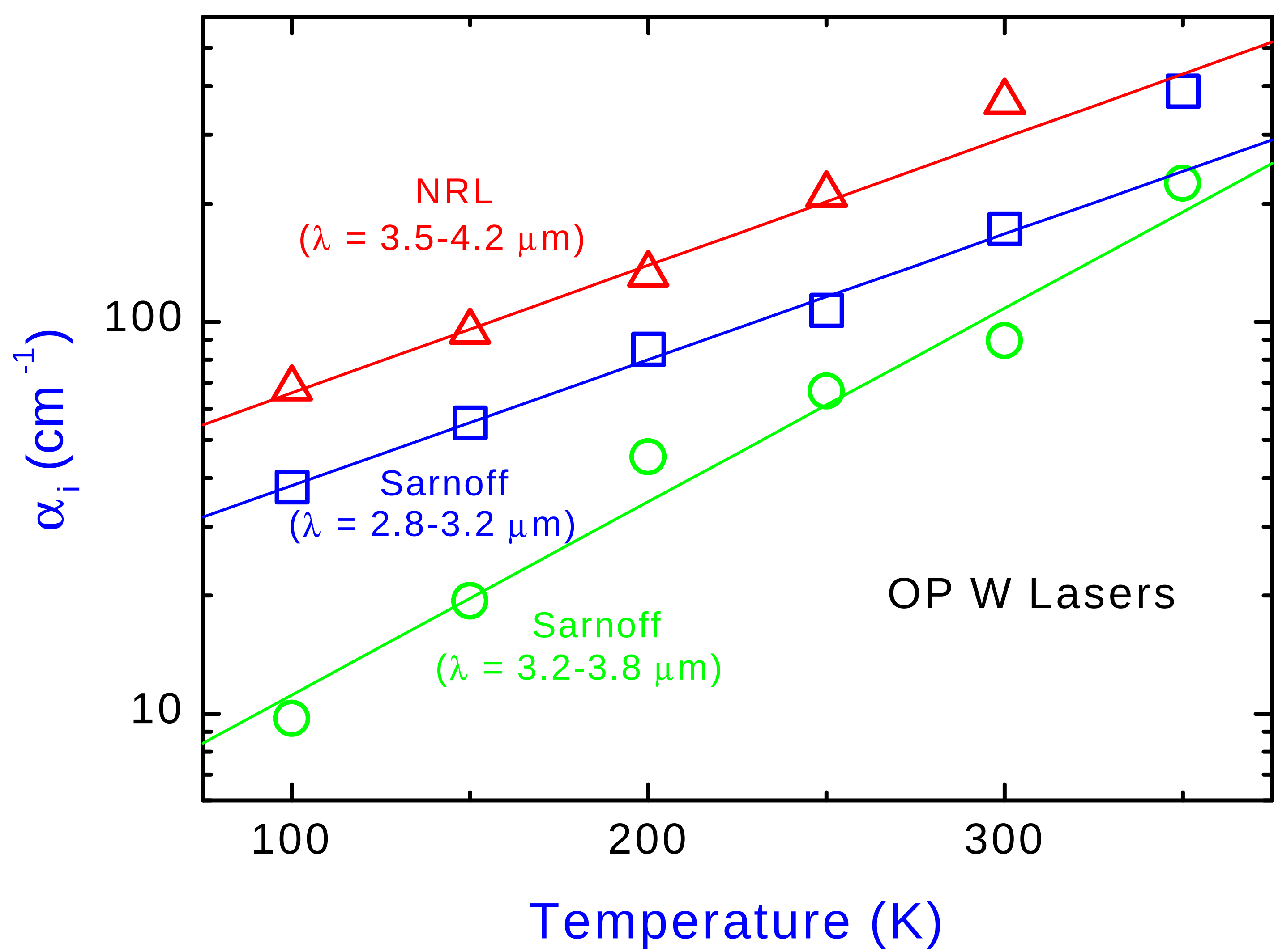
- Growth quality – Interfaces, dislocations/defects, yield, *etc*.
- Processing – Immature for antimonides as compared to GaAs, InP
- Auger non-radiative recombination – Limits j_{th}, T_{max}
- Internal loss – Limits efficiency & output power, especially at higher T
- Band structure
  - Theory – Is $k \cdot p$ reliable for thin layers, higher-order valence bands?
  - Characterization – Almost no data available for intervalence energies
- Electrical injection – Optimize growth-direction transport, resonant tunneling in complex multi-layer devices
- Thermal management – Optimize heat-sinking (Diamond, epi-down mounting, *etc*.) – Thermal conductivity of some constituents unknown

AUGER COEFFICIENT vs TEMPERATURE

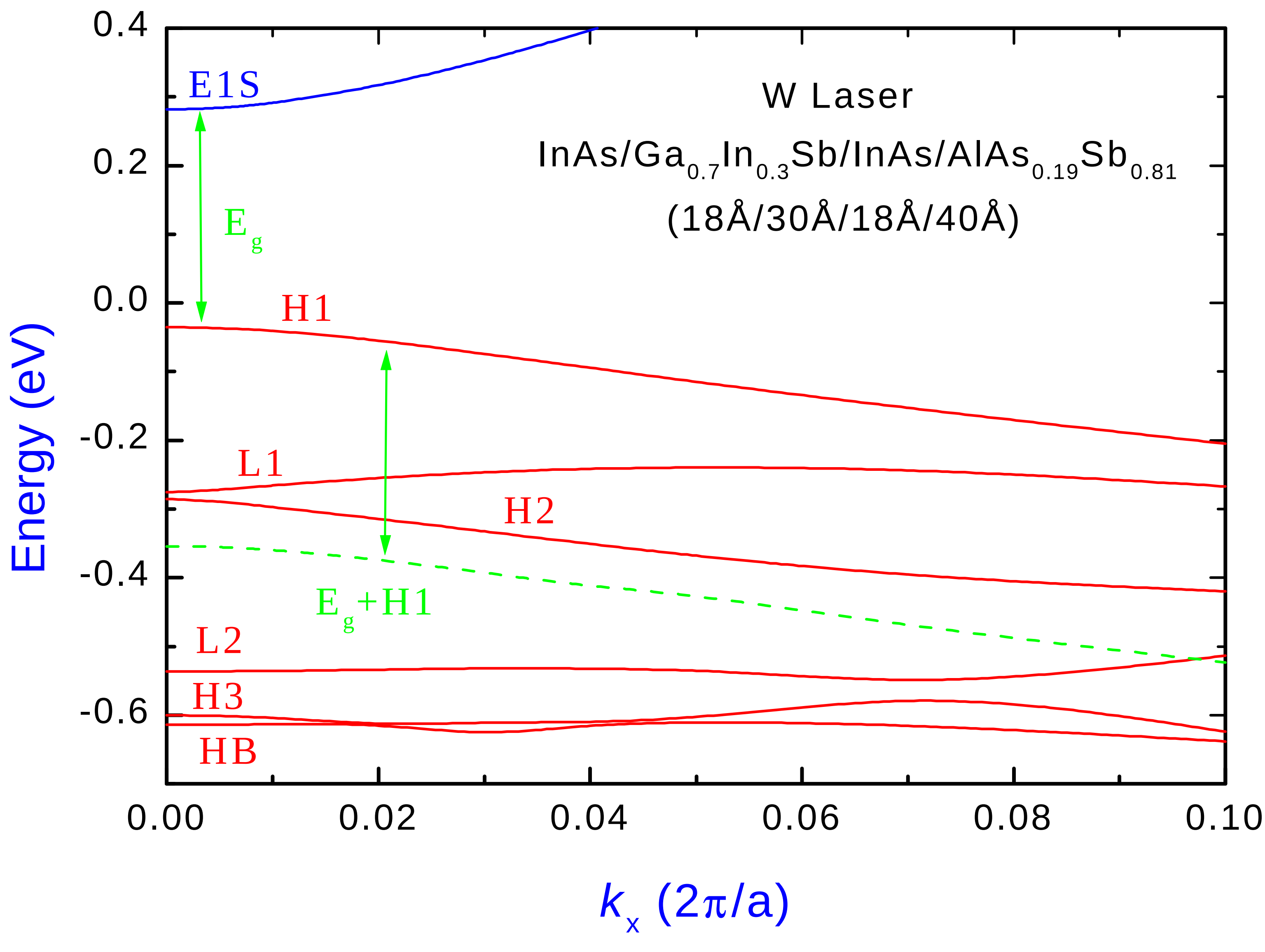
Bewley et al., submitted to APL



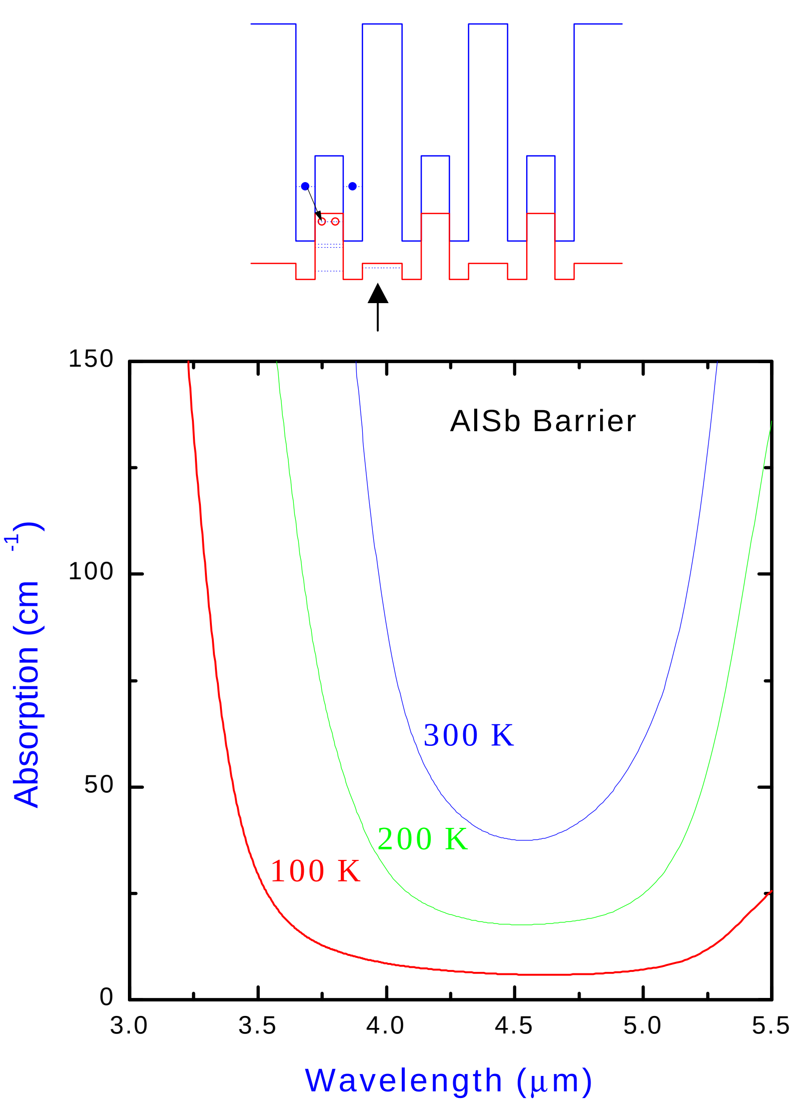
INTERNAL LOSS vs TEMPERATURE

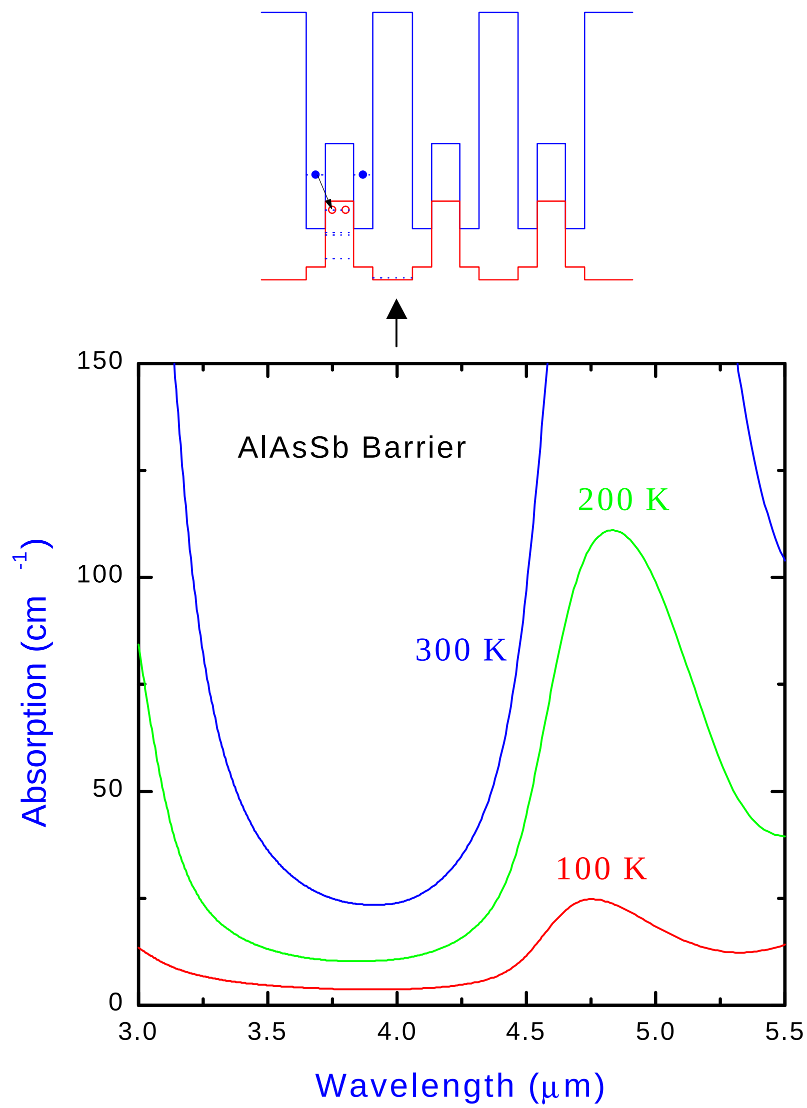


DISPERSION WITH AlAsSb BARRIER



LOSS MINIMIZATION





ANTIMONIDE QCLs (INTERSUBBAND)

- Primary limitation of InGaAs/InAlAs intersubband QCLs is high j_{th} due to phonon relaxation – Precludes high-temperature cw lasing

- *HOWEVER*, Antimonide quantum cascade lasers (AQCLs) with InAs QWs ($m^* \approx 0.023 m_0$) may have much lower j_{th} than InP-based QCLs with $In_{0.53}Ga_{0.47}As$ QWs ($m^* \approx 0.040 m_0$)

- Small mass yields enhanced intersubband phonon lifetime: $\tau_{32} \propto 1/m^*$

- Also enhanced dipole matrix elements: Gain $\propto |z_{32}|^2 \propto 1/m^*$

- Hence net threshold scales quadratically with mass:

$$j_{th} \propto \frac{\lambda \gamma_{ij} (\alpha_R + \alpha_{int})}{|z_{ij}|^2 \tau_j (1 - \tau_i / \tau_{ij})} \propto m^{*2}$$

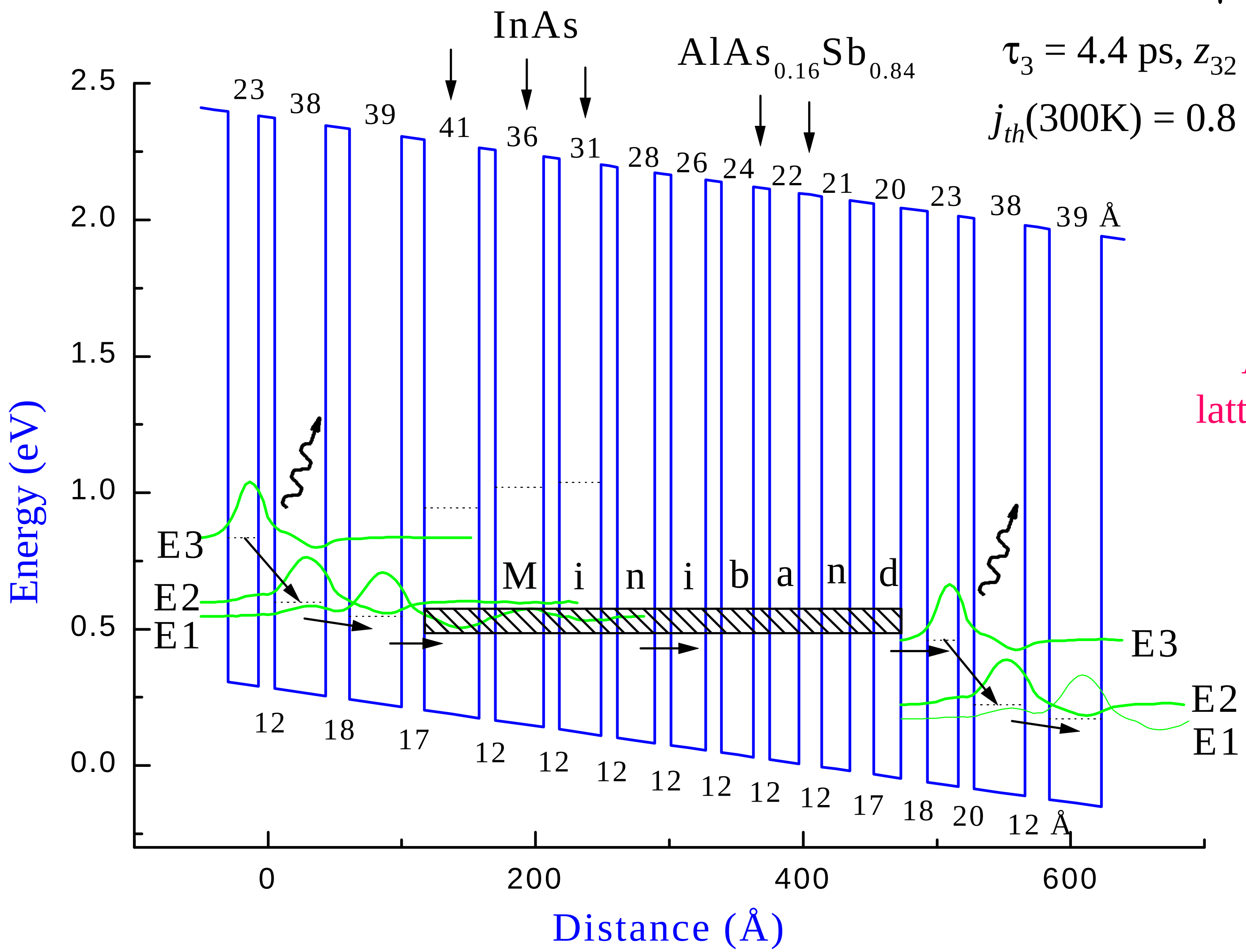
"DIAGONAL" DESIGN

Vurgaftman et al., APL 73, 711 (1998)

λ = 5.3 μm

τ_3 = 4.4 ps, z_{32} = 13 Å

j_{th}(300K) = 0.8 kA/cm²



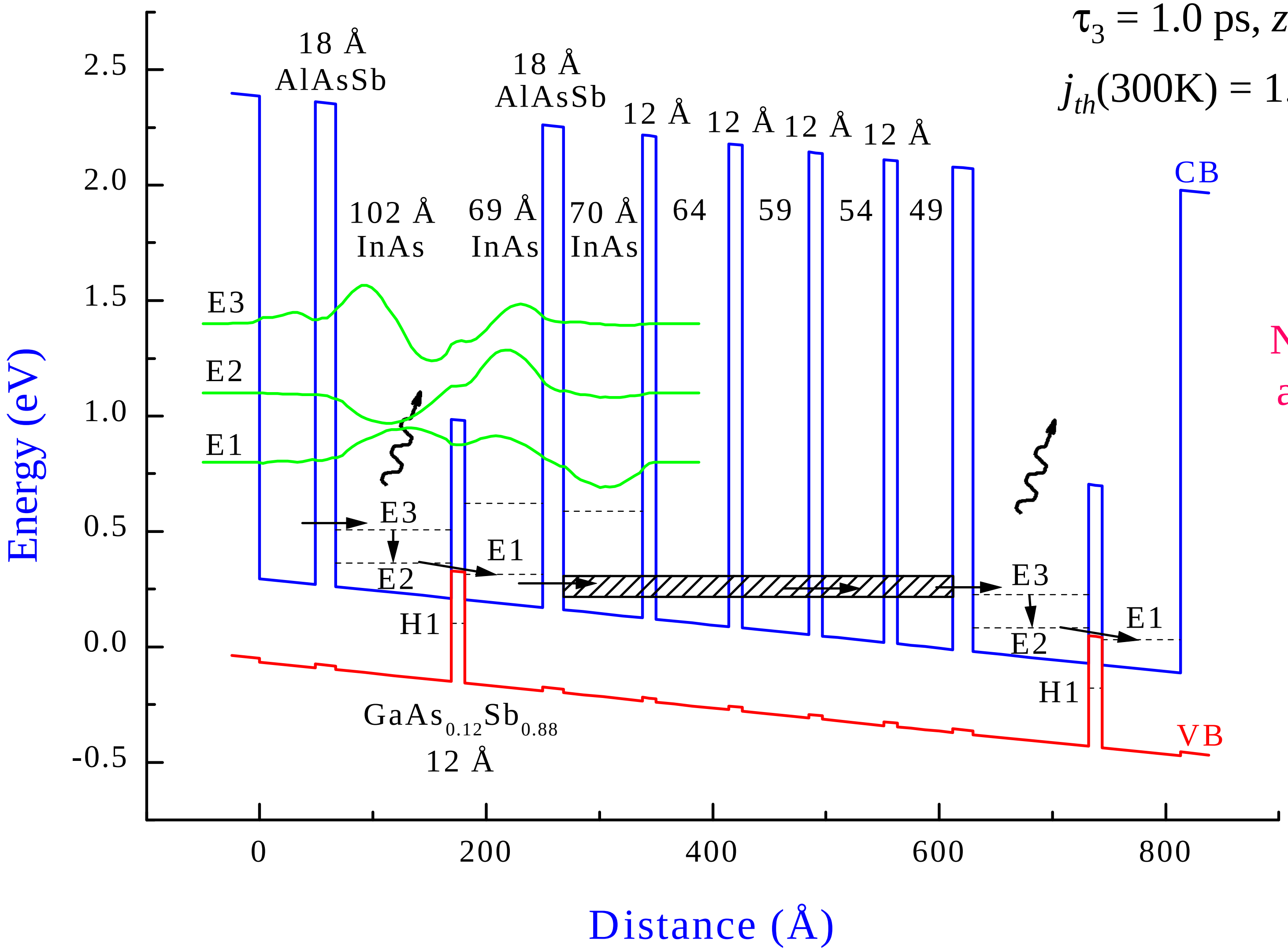
All layers lattice-matched to InAs

“VERTICAL” DESIGN

$\lambda = 8.8\ \mu m$

$\tau_3 = 1.0$ ps, $z_{32} = 46$ Å

$j_{th}(300K) = 1.2$ kA/cm^2



No intervalence absorption loss

AQCLs vs InGaAs/InAlAs QCLs

Theory vs theory at T = 300 K:

	λ (μm				j_{th} (kA/cm^2)	
					Exp	*Theory*
InGaAs/InAlAs	4.3	Diagonal	1.5	10	No 300 K	
AQCL	5.3	Diagonal	4.4	13		0.8
InGaAs/InAlAs	5.2	Vertical	0.8	16	7.5	3.1
AQCL	5.3	Vertical	0.8	37		0.8
InGaAs/InAlAs	8.5	Vertical	0.6	26	8	5.4
AQCL	8.8	Vertical	1.0	46		1.2

Reduction from j_{th} = 3-8 kA/cm^2 in InGaAs/InAlAs QCLs to 1-2 kA/cm^2 in AQCLs critical for high-temperature cw

T2 MID-IR LASER STATUS – OPTICAL PUMPING

- Pulsed
  - $T_{max} \geq 360$ K, P_{max}(300 K) > 5 W/facet far exceeds any other semiconductor technology for $\lambda \geq 3$ μm

- cw, quasi-cw
  - 80 K efficiency & P_{max} of UH/LL/AFRL W lasers comparable to best type-I results
  - $T_{max} = 270$ K significantly exceeds all type-I, QCL, and lead salt results
  - Modeling predicts that $P_{max} \geq 0.5$ W/facet at $T \geq 250$ K will be achievable with optimized QW design & thermal management

T2 LASER STATUS – ELECTRICAL PUMPING

- Pulsed
  - Hughes T_{max} = 255 K (λ = 3.2 μm) equals best type-I
  - ICL T_{max} = 286 K (λ = 3.5 μm) exceeds type-I, comparable to lead salts, but well behind QCL ($T_{max} \geq 320$ K) – ICL performance limited by damage rather than intrinsic properties
  - UH ICL *dP/dI*(80 K) = 2.2 photons/electron exceeds theoretical limit for conventional diodes, but well behind QCL (> 4 photons/electron)

- cw, quasi-cw
  - Hughes T_{max} = 180 K slightly ahead of type-I & QCL, behind lead salts
  - 80 K: Some high-duty-cycle UH ICL data, but type-I & QCL still far ahead ($P_{max}^{cw} \geq 200$ mW)
  - ICL modeling predicts P_{max} > 0.5 W/facet at $T \geq 250$ K for optimized devices

- Novel configurations
  - Antimonide versatility enables: Single-HJ lasers, VCSELs, ICLs, AQCLs, *etc.*

BOTTOM LINE

- Type-II mid-IR lasers have displayed rapid progress since their first demonstration in 1994

- They have the potential to become the dominant 3-5 μm source, but both optically- and electrically-pumped devices still have a long way to go