Mid-IR Interband Cascade Lasers for Chemical Sensing

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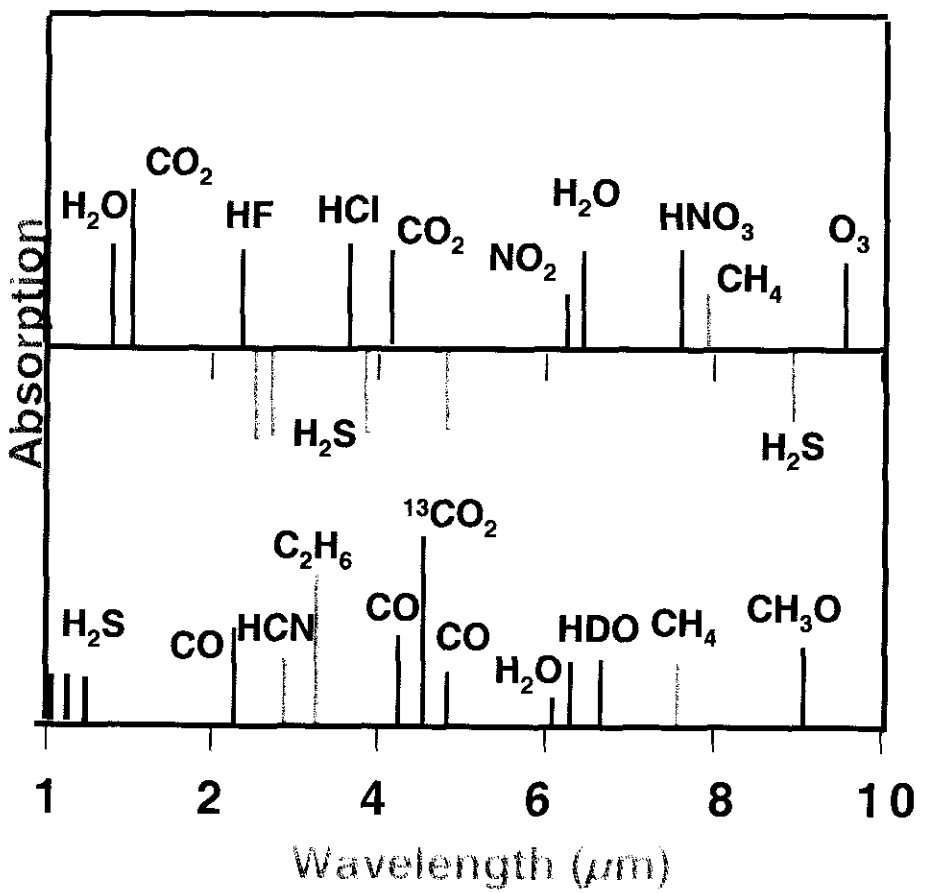
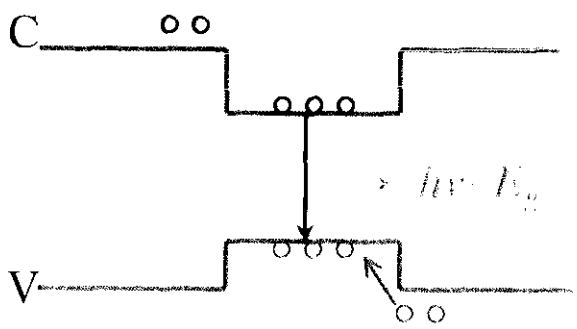
Presentation at Habitation 2004, Orlando, FL
Jan. 6, 2004

Why Mid-IR Lasers?



- Molecules possess strong fundamental vibration-rotation lines in the mid-IR
  - » Hydrocarbon signatures at 3–4 μm
- Mid-IR improves sensitivity by orders of magnitude over near-IR spectroscopy
  - » H2CO at ~3.53 μm, detection limit <10 ppb
- There is less spectral interference in the mid-IR

What are the Challenges for Mid-IR Lasers?



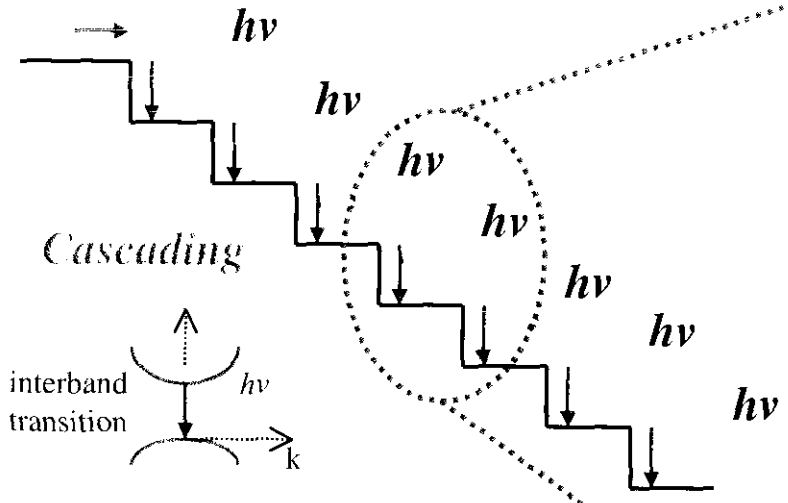
- Electrons & holes combine to give photon emission
- Light emission wavelength $\lambda \propto 1/E_g$

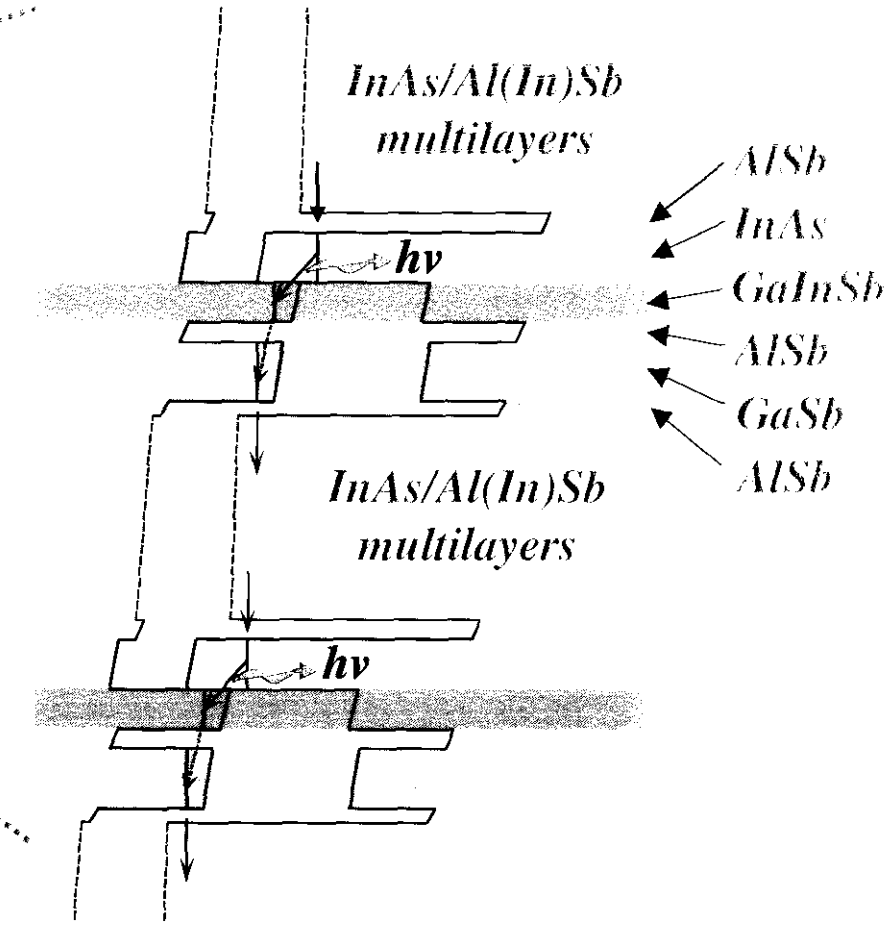
Mid-IR lasers require narrow E_g materials

- **Narrow E_g materials are *hard to grow* and *hard to process* into devices**
- **Visible & near-IR lasers are well established**
  - » Large commercial investment drivers (consumer products, optical commun.)
  - » Negligible market thus far for longer wavelength lasers
- **Semiconductor lasers develop other problems as λ increases**
  - » Non-radiative losses increase rapidly
  - » Inadequate electrical confinement
  - » Poor efficiency in utilizing bias voltage
  - » Free carrier absorption loss
  - » Non-uniform distribution of injected carriers

Interband Cascade (IC) Laser – Promising Approach

[original concept, R. Q. Yang, Superlattices and Microstructures, **17**, 77 (1995)]

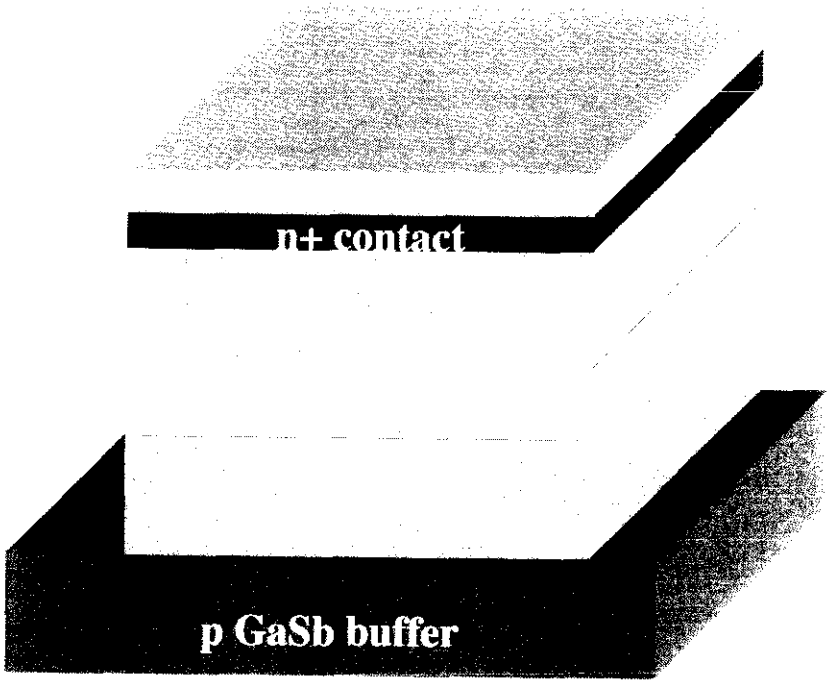




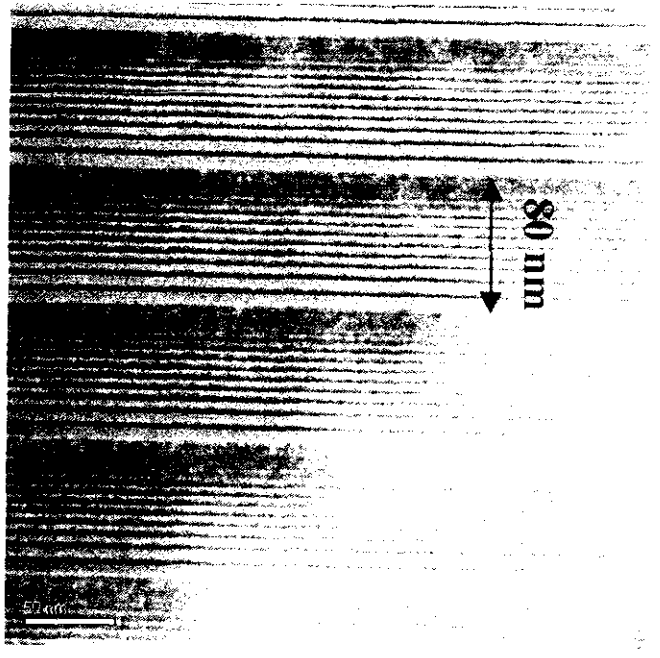
- **cascade process —**
  - » high efficiency, large output power, uniform injection over every stage
- **interband transition —**
  - » circumvents fast phonon scattering
- **quantum engineering at sub-nanometer scale and Sb-based type-II QW system**
  - » suppresses non-radiative Auger losses
  - » allows for wide wavelength tailoring range
  - » excellent carrier confinement because of band-gap blocking feature

Low threshold current, high efficiency, high output power mid-IR lasers

Typical IC Laser Structure and MBE Growth



TEM image



Four Cascade Stages

> The structure is grown on a GaSb substrate

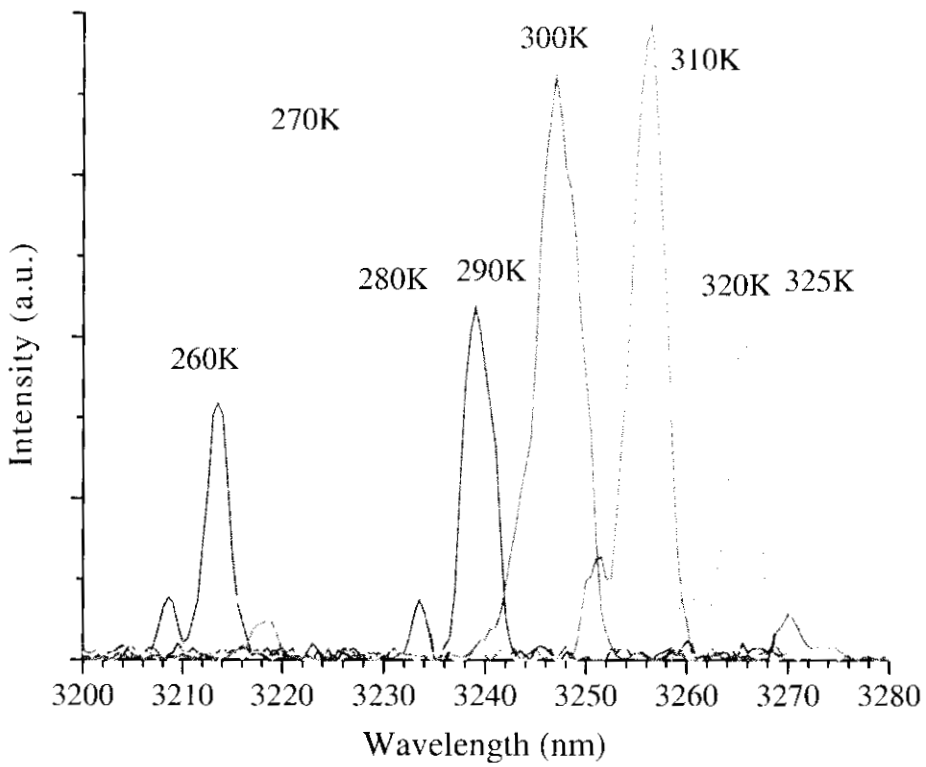
>

> requiring sophisticated growth technology such as molecular-beam epitaxy (MBE) with precise controls

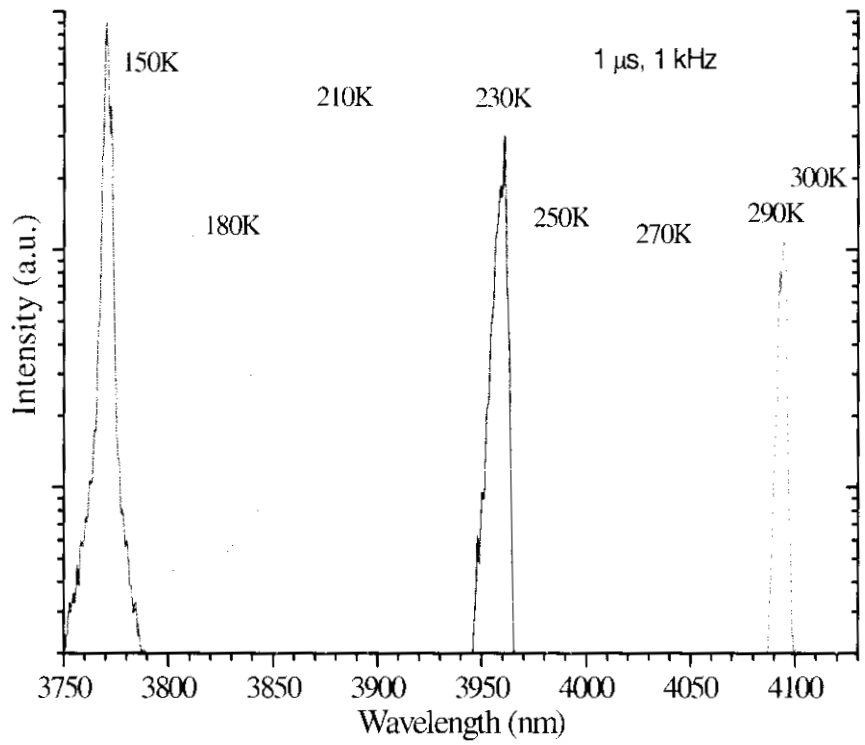
- tunnel barriers layers can be as thin as 12 Å – four atomic layers
- quantum well layers are on the order of 30 Å
- changes of ±1 Å can shift the lasing wavelength out of a molecular resonance

High temperature operation

15 stage 150 μm x 0.8 mm mesa stripe

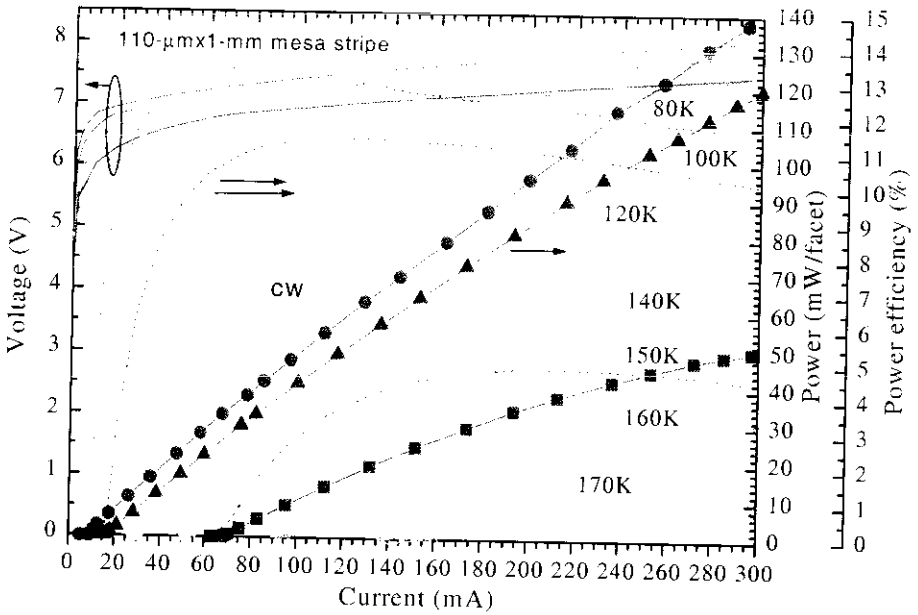


25 stage 150 μm x 1 mm mesa stripe

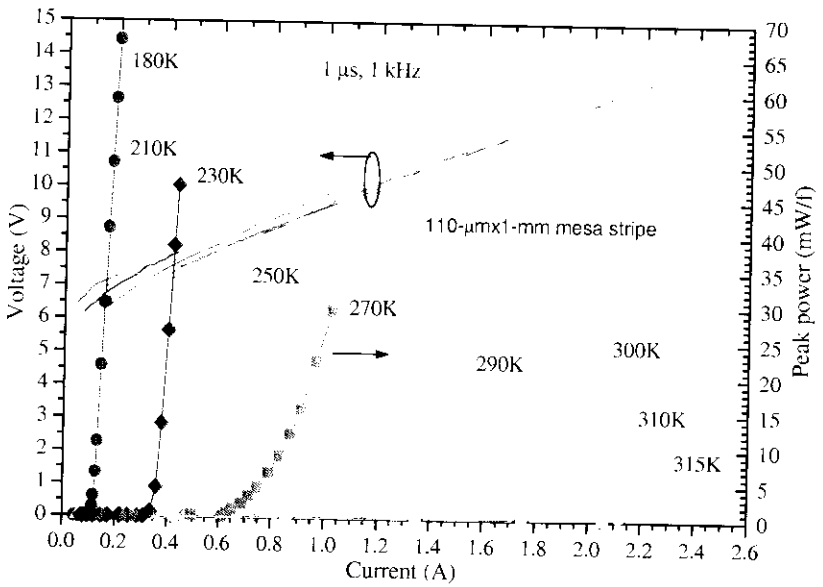


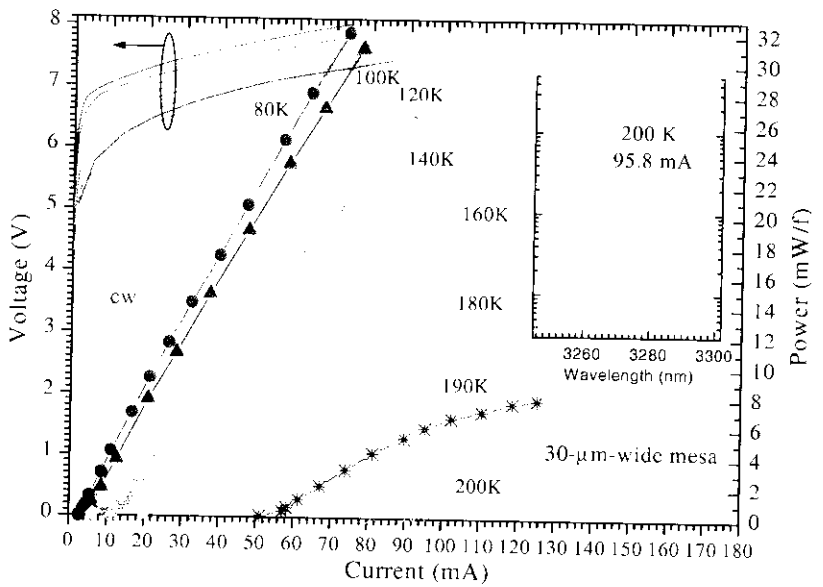
pulsed operation of a laser up to 325 K with λ=3.27 μm, the highest operating temperature among mid-IR III-V interband diode laser to date in literature

Characteristics of interband cascade lasers at ~3.3 μm



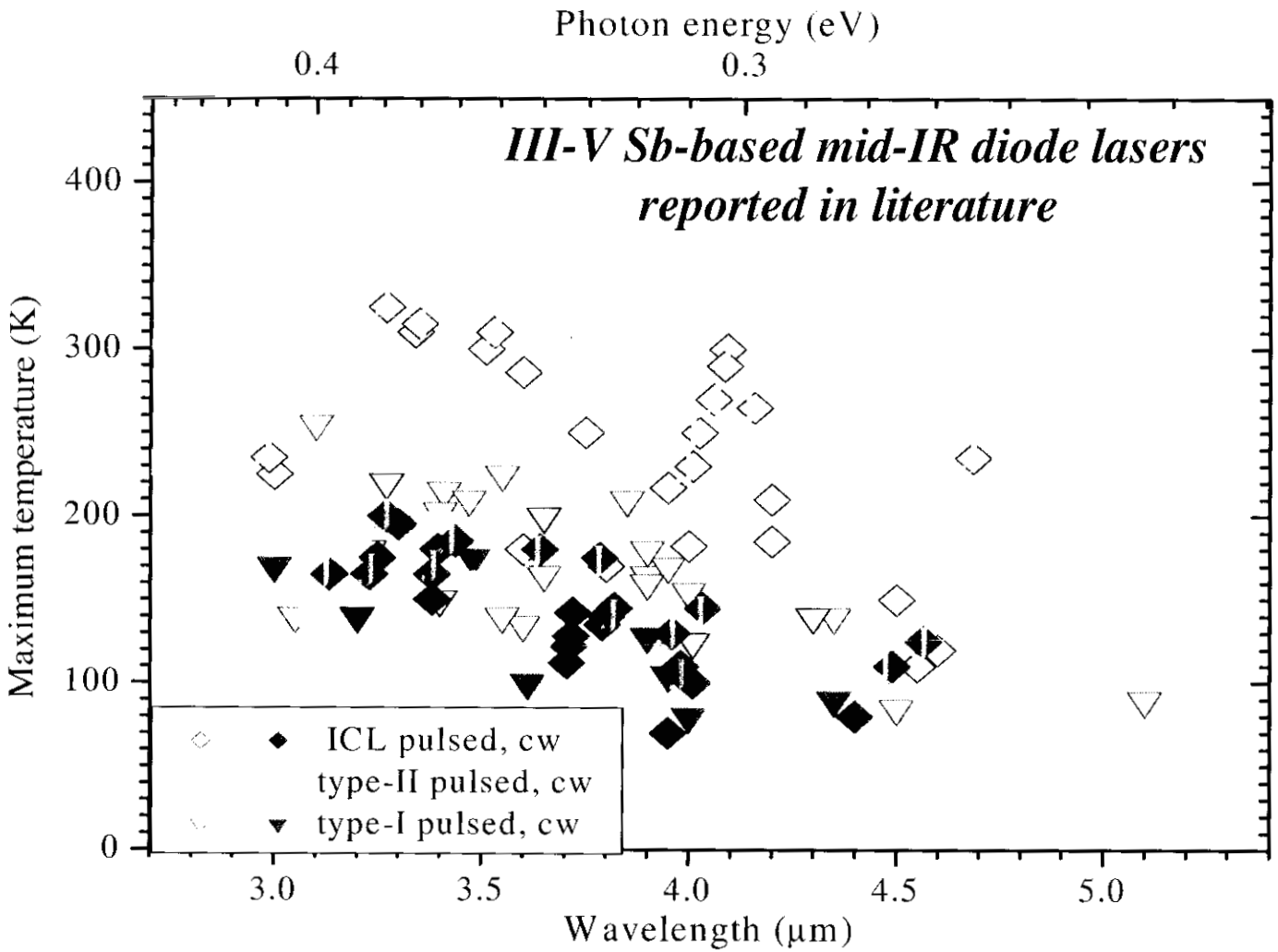
- threshold current density ~9 A/cm² at 80 K, the lowest for mid-IR lasers
- output power ~140 W/f (conservative), power η>13% (80 K)
- $T_{max,cw}$ ~ 175 K for 110-μm wide laser
- pulsed operation up to 315 K at ~3.4 μm
- Narrow-stripe (30-μm-wide) ⇒ reduced heating, $T_{max,cw}$ ~ 200 K in cw mode



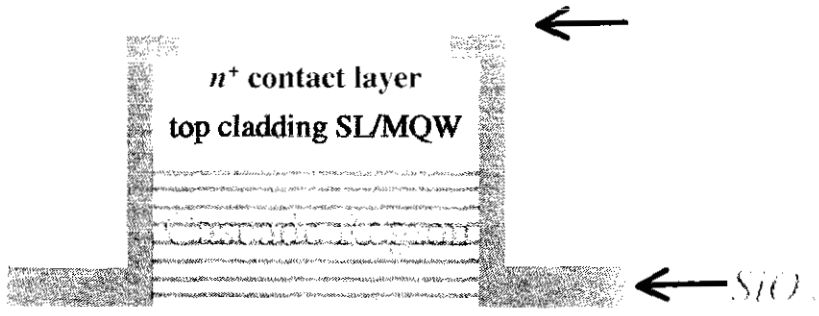


Current JPL Laser Status in terms of Max. *T*

(compared to open literature as of 9/2003)



Typical distributed feedback (DFB) IC laser structure



bottom cladding SL/MQW

GaSb buffer layer

GaSb substrate

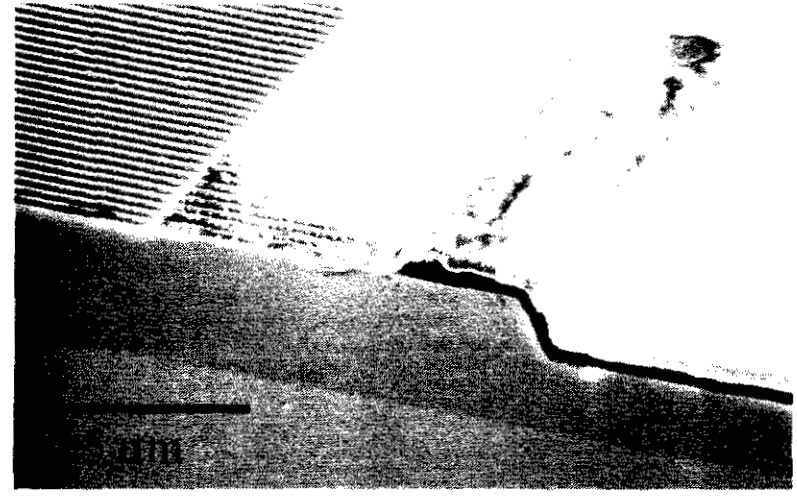
- Samples were typically processed into broad area lasers
- Laser bars were cleaved to form cavities (1-1.5 mm) with both facets left uncoated
- Laser bars were affixed with indium, epilayer side up, onto a copper heat sink.

Thin top-cladding InAs/AlSb SL

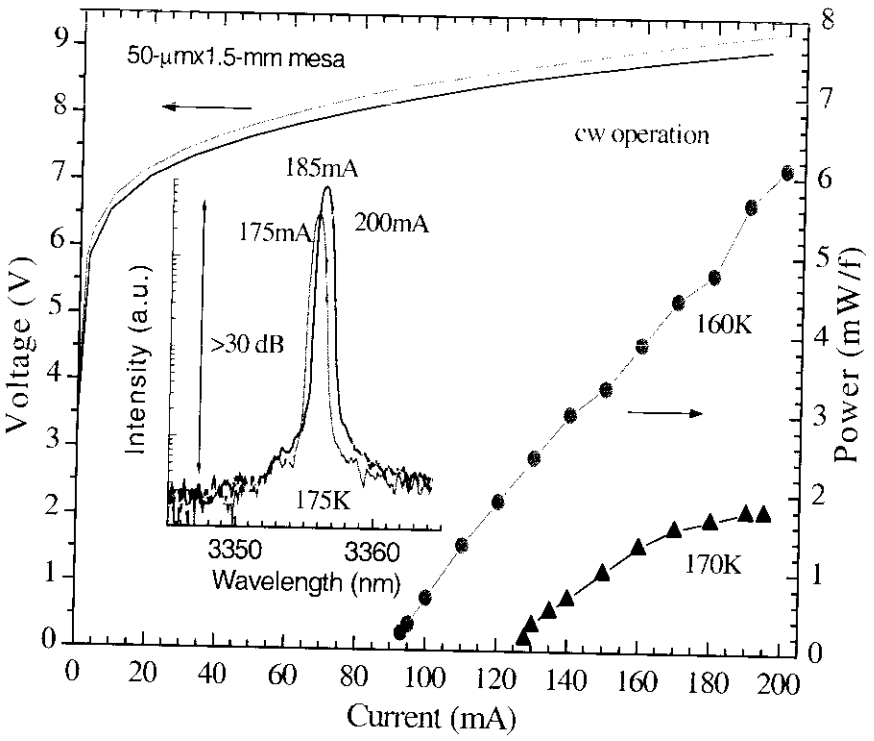
» Facilitate the integration of DFB gratings into the laser without the need of deep etching

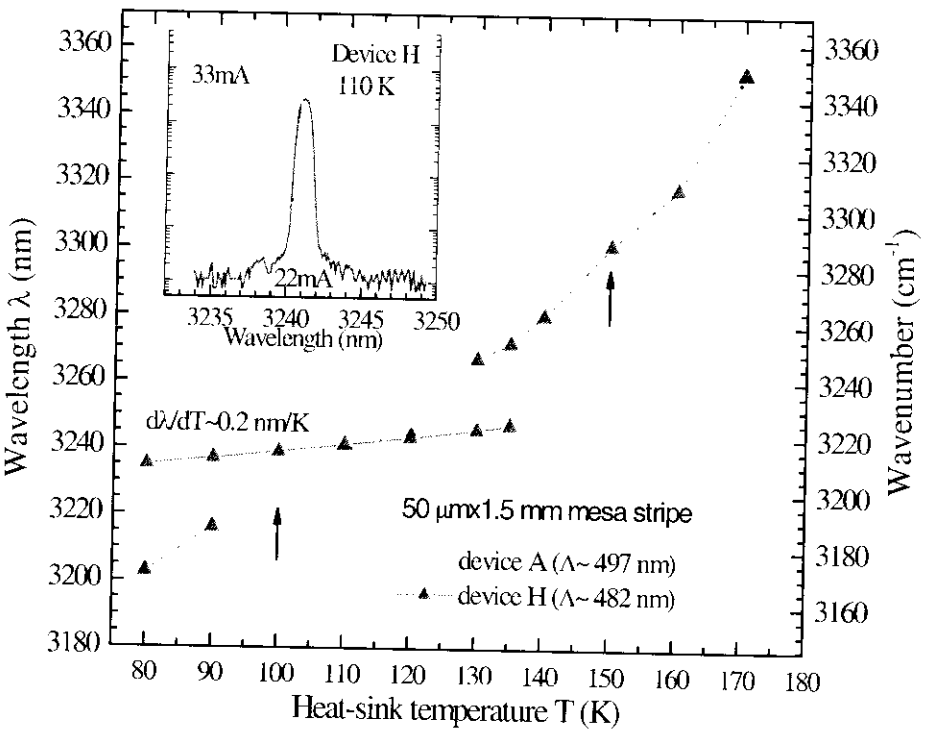
» Use SiO_2 layers for insulation and edge metal contacts to minimize the loss

» In-plane conductivity is much higher than the vertical one, leading to excellent lateral current injection



Distributed feedback (DFB) IC Lasers near 3.3 μm

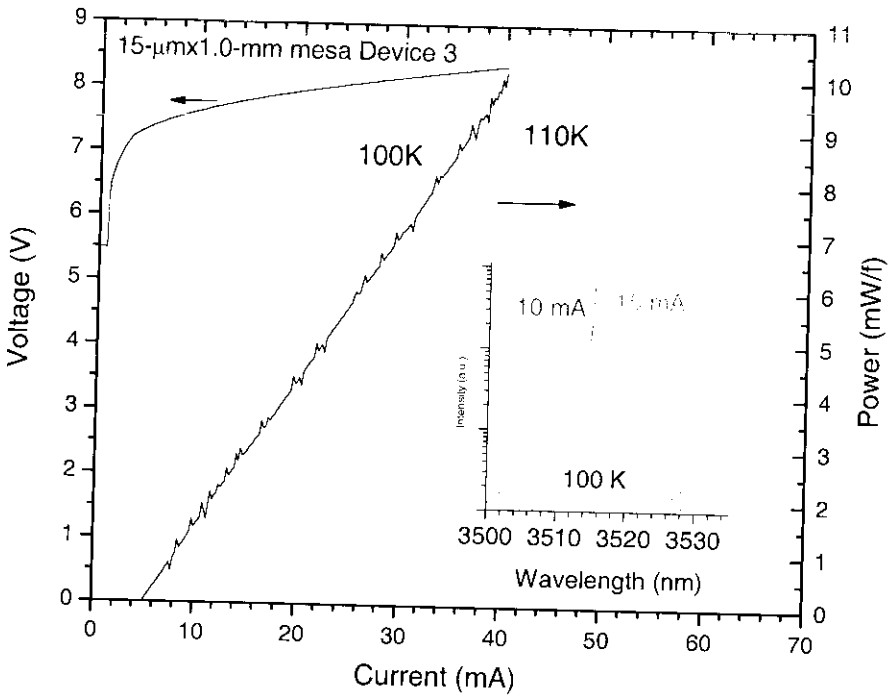


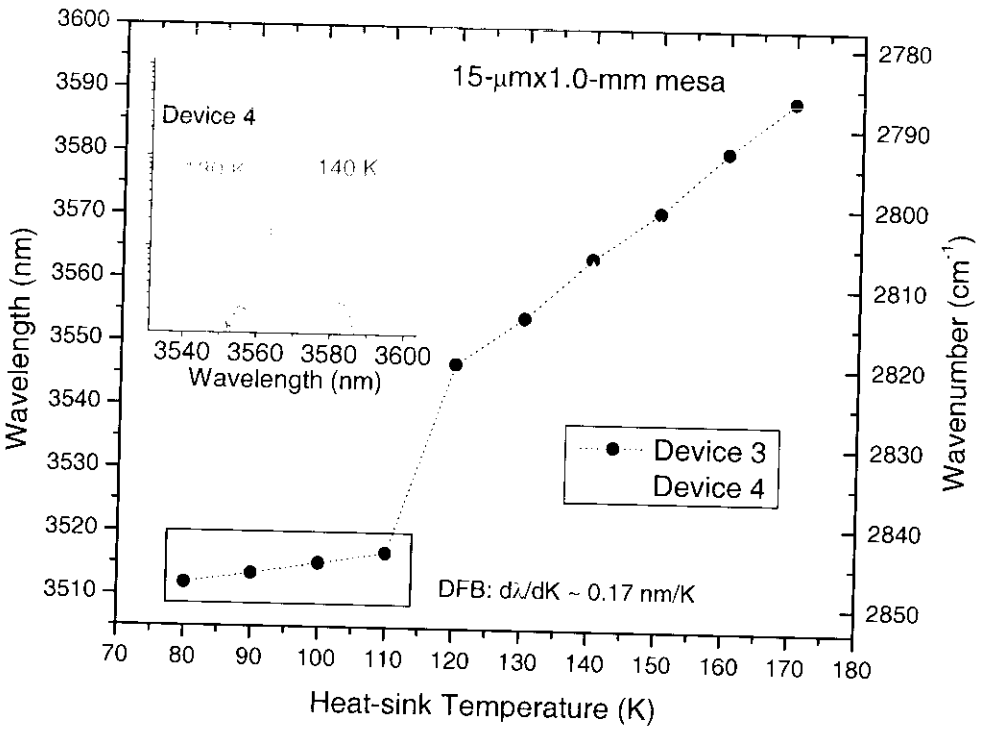


- Single-mode DFB lasers were observed at temperatures up to 175 K in cw mode
- wavelength can be tuned with current at a rate of ~0.05 nm/mA
- output power >1 mW, enough for gas sensing

- DFB mode is determined by grating period Λ
- temperature tuning coefficient ~0.2 nm/K
- both DFB and FB modes exist at certain temperatures and currents
- two degenerate DFB modes

Distributed feedback (DFB) IC Lasers near 3.5 μm





- Single-mode DFB lasers were observed near 3.51 μm
- wavelength can be tuned with current at a rate of ~0.03 nm/mA
- output power >1 mW, enough for gas sensing

- DFB mode is determined by grating period Λ
- temperature tuning coefficient ~0.2 nm/K
- both DFB and FB modes exist at certain temperatures and currents

Summary

- Significant progress has been made
  - Low threshold current density (e.g. 9 A/cm^2)
  - High temperature operation (325 K in pulsed, 200 K in cw)
  - Single-mode DFB lasers near 3.3 and 3.5 μm
- Issues under investigation
  - Relatively narrow tuning range of DFB IC lasers
  - High index substrate reduced photon leakage, which limits effective collection of output power and complicates mode selectivity
- The work was supported in part by
  - NASA Advanced Environmental Monitoring and Control Program
  - NASA Enabling Concepts and Technologies Program
  - JPL Internal Research and Technology Development Program