Type-II Interband Cascade Lasers: Review and Prospects

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Acknowledgments

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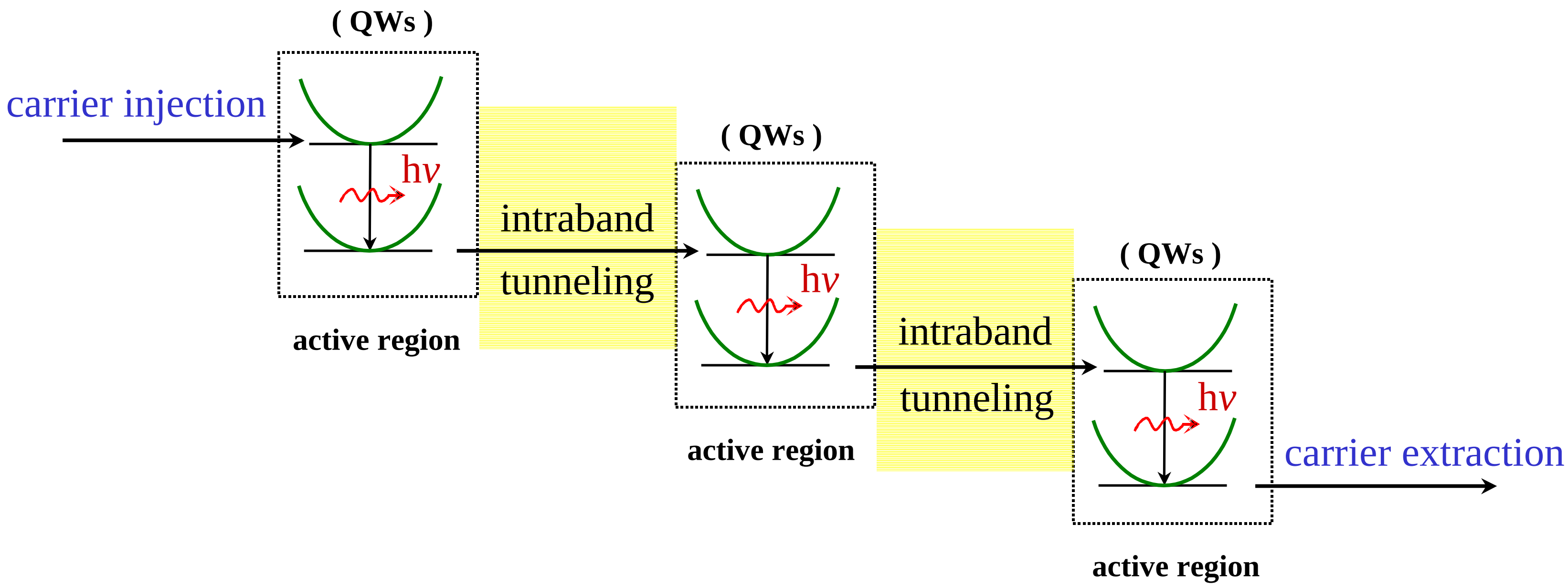
Outline

- Introduction
- Brief review of early investigations
- Progress and findings at Army Research Laboratory
- Current status
- Challenges and prospects/conclusions

Introduction
(what is the interband cascade laser)
a short development background

Intersubband Quantum Cascade Lasers



Cascade ⇒ quantum efficiency exceeding 100% and efficient use of bias voltage

⇒ high slope efficiency, large differential gain

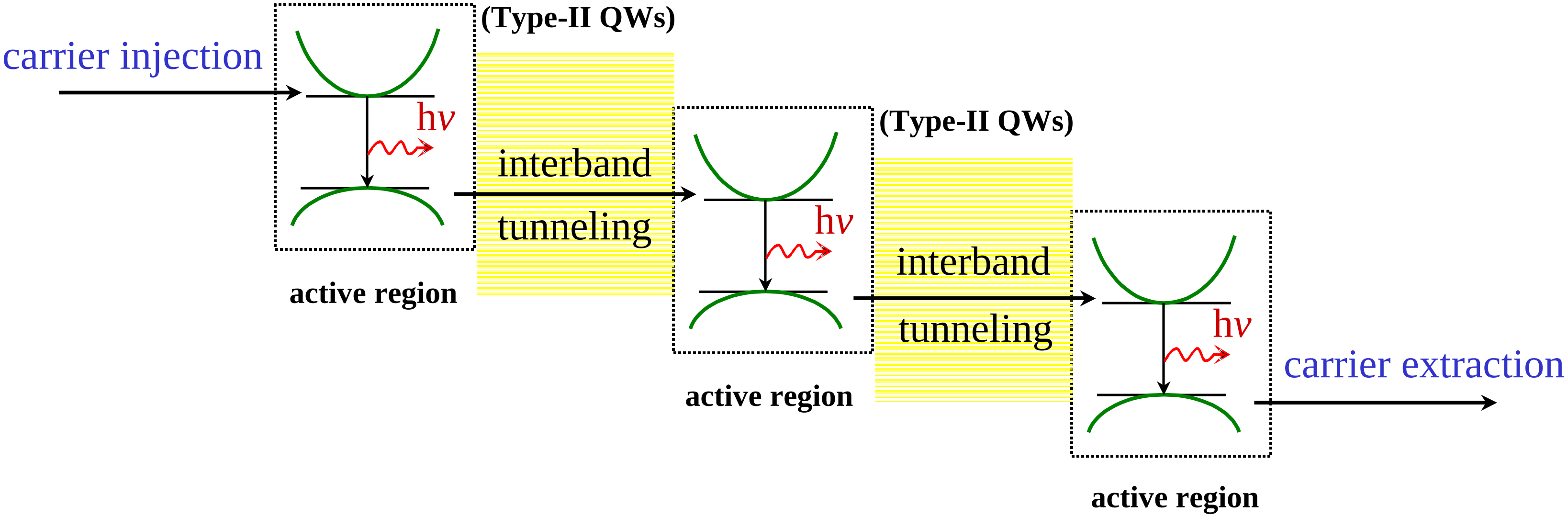
Wavelength tailoring is practically limited by the relevant band-offset

Fast phonon scattering ⇒ a relatively high threshold current density (typically >1 kA/cm^2)

Original concept [Kazarinov and Suris, Sov. Phys. Semicond. **5**, 707 (1971)]

First demonstration [Faist, *et al*, Science, **264**, 553 (1994)]

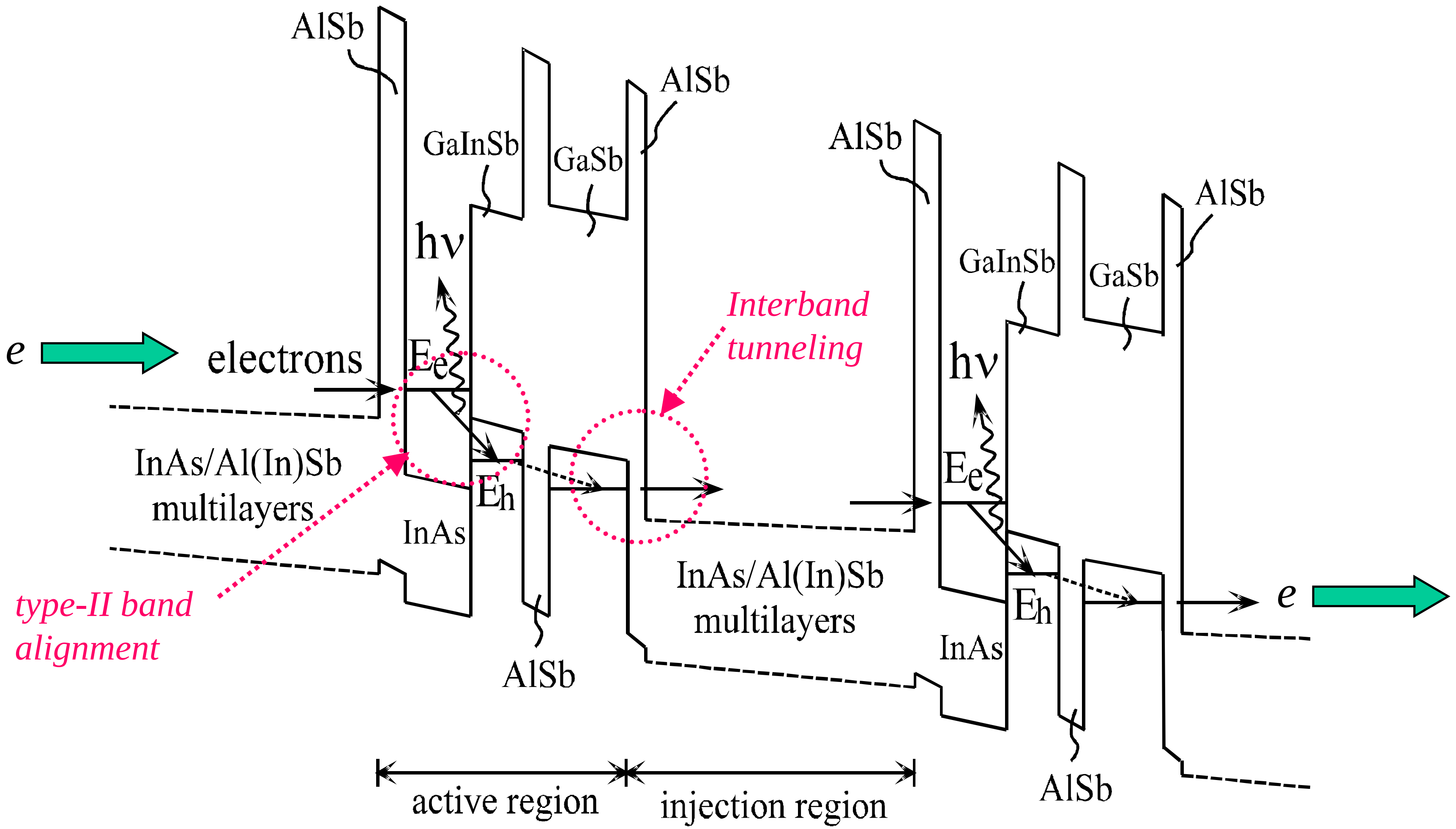
Type-II Interband Cascade Lasers



low threshold current, high efficiency, high output power

First proposed by Rui Q. Yang (then at U. Toronto, Canada) at ICSMM-7 (1994); Superlattices and Microstructures, **17**, 77 (1995).

Type-II Interband Cascade Design -- An Example

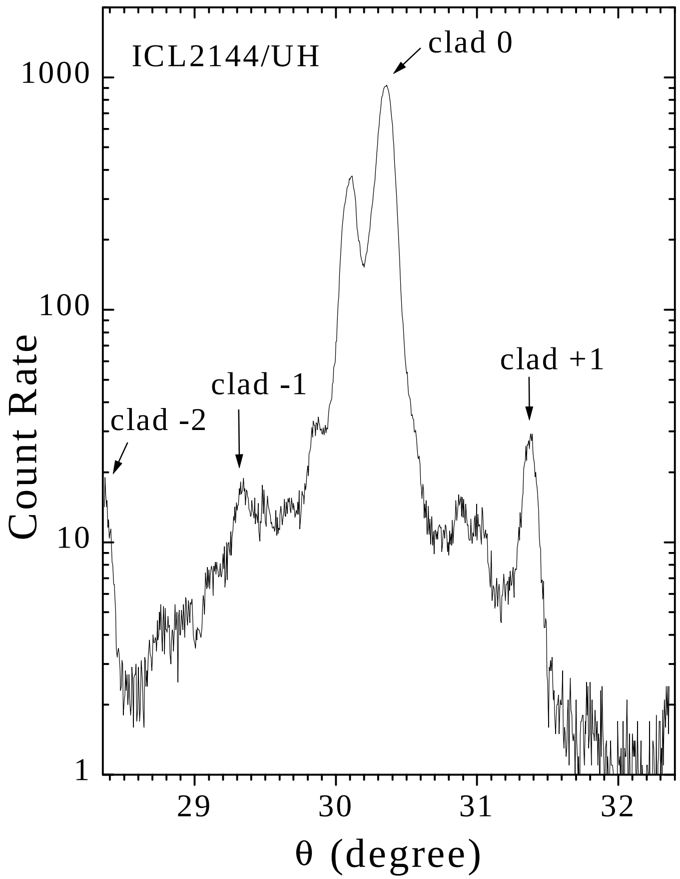


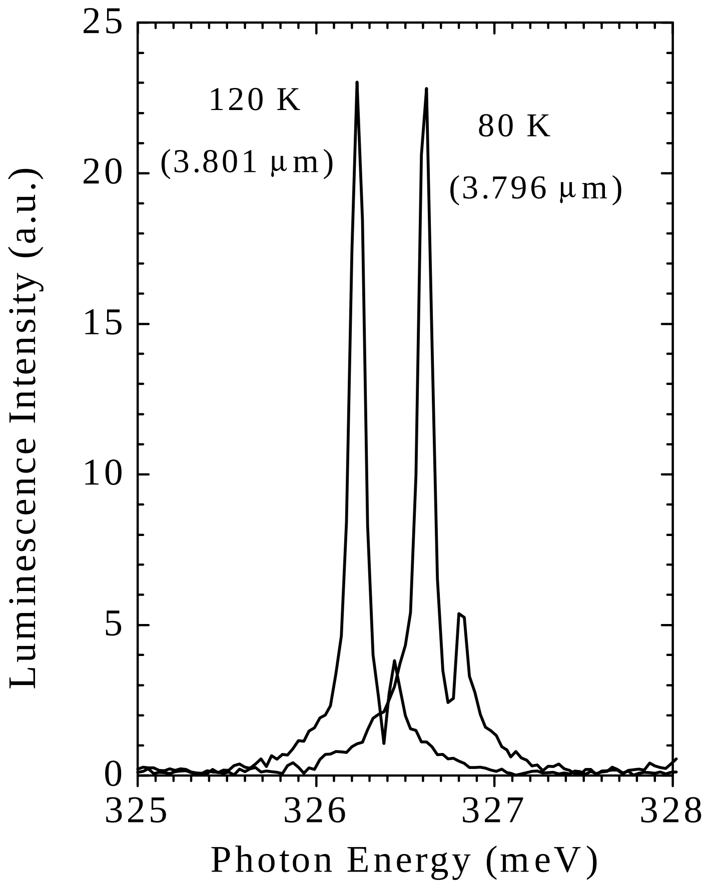
Synopsis of Interband Cascade Laser Development

1994	The concept of ICL was first proposed by Yang (U Toronto, Canada)
1995/96	Refined design, calculations suggested the feasibility of cw operation at room temperature with high output powers (Meyer, Vurgaftman, Yang, Ram-Mohan)
1996	Mid-IR electroluminescence and Stark effect (blue shift) observed in IC emitters (with collaborative efforts between UH, QET, NRC Canada, Sandia, Bell Labs)
1997	ICL was first demonstrated at a wavelength of ~3.8 µm by UH/Sandia 4-µm ICLs, DQE >200%, near quasi-cw operation (UH/QET) 3.5-µm ICLs with "W" active regions, pulsed operation up to 286 K (NRL/UH)
1998	Little new progress in ICLs
1999	ICLs (3.8– 4 µm) demonstrated at ARL with DQE > 600%, peak power ~ 6 W/facet, peak power efficiency ~10%, cw operation
2000	Low J_{th} (~44 A/cm^2), record-high power efficiency (>14% in cw >18% in pulsed)
2001	**……** high-performance potential of ICLs predicted by theory has yet to be realized

Brief review of early investigations

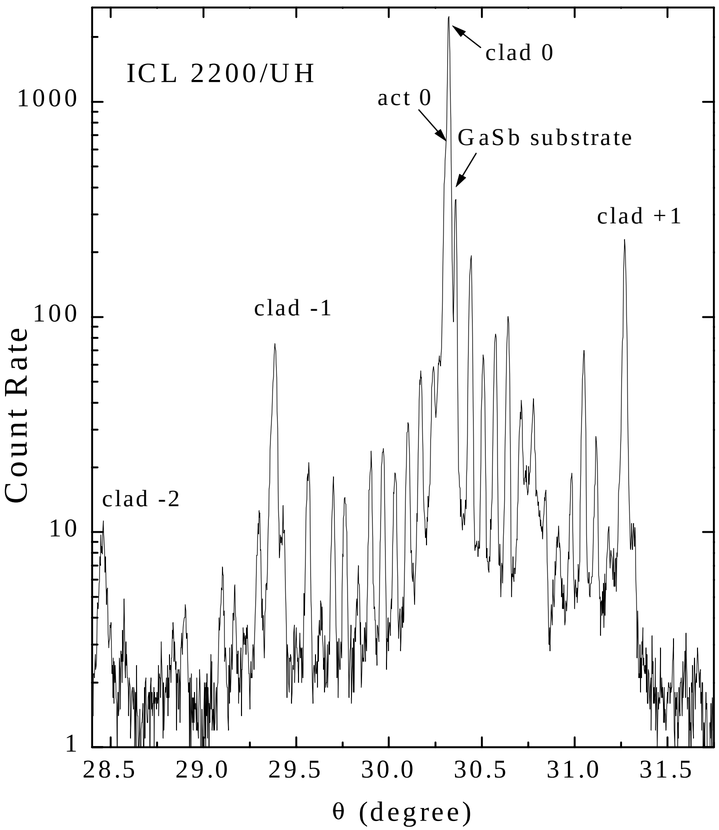
The First Demonstration of ICL

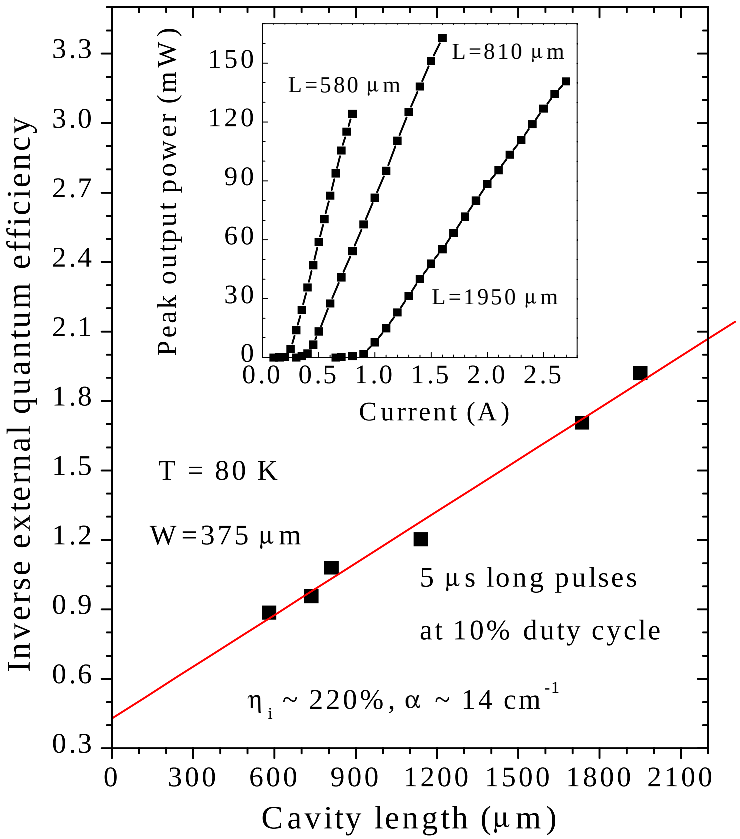




material quality is poor as shown by x-ray spectrum, but it lased up to 170 K with high threshold current densities (e.g. 4.17 kA/cm^2 at 80 K) [Electron. Lett. **33**, 598 (1997).]

Improvement of 4-μm ICLs with a DQE > 200%





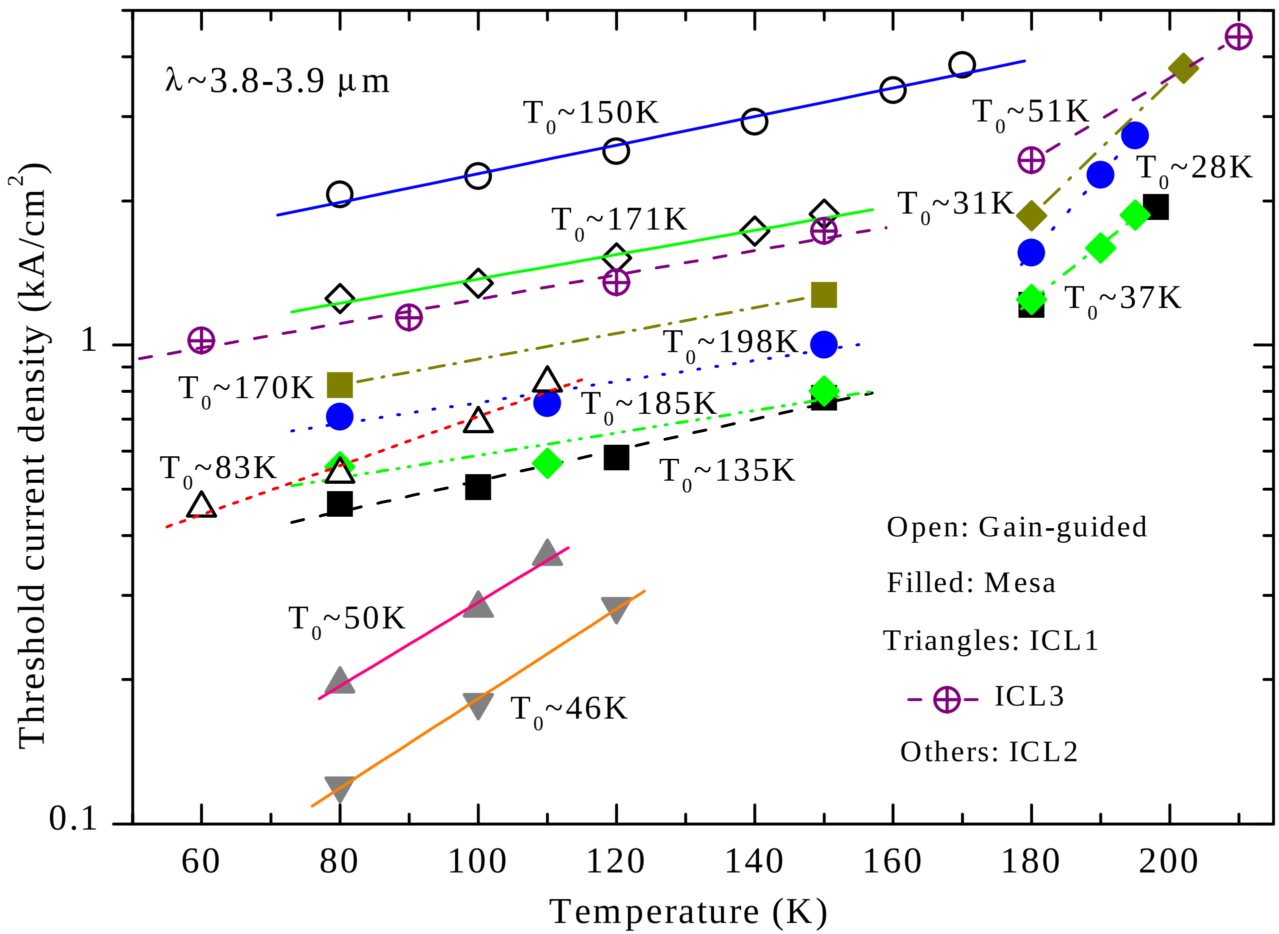
J_{th} ~110-130 A/cm^2 at 80 K, T_{max}~182 K, α~14 cm^{-1} (good material quality and device design)
DQE ~ 220% << 1000% (theoretical value of EDQE by assuming diminishing leakage)
⇒ a large potential for improvement [Appl. Phys. Lett. **71**, 2409 (1997); **72**, 2220 (1998).]

Issues Encountered During the Early Investigations

- Substantial variations in crystal growth conditions ⇒ poor reproducibility
- Material quality was not controlled well with various defects and interface roughness due to the intermixing of Sb and As ⇒ large leakage currents
- IC lasers, especially those with deep etched mesa structures, tended to be damaged at high injection level before saturation ⇒ limiting the output power and operating temperature
- W-active-region IC lasers (~3 and 3.5 μm), although operated at higher temperatures (up to 225 K and 286 K, respectively) possibly due to enhanced optical gain, could be operated only with short pulses (~100 ns) at low repetition rates (5-200 Hz).
- Long growth time (≥15 hours) with very high shutter moving frequencies ⇒ high rates of failure

Progress and Findings
at Army Research Laboratory

Threshold Current Density and Vendor-Source of GaSb Substrates



3 MBE growths at ARL
ICL1 (vendor A)
ICL2 (vendor B)
ICL3 (vendor B)

T_{max}=210 (ICL2)
T_{max}=217 (ICL3)

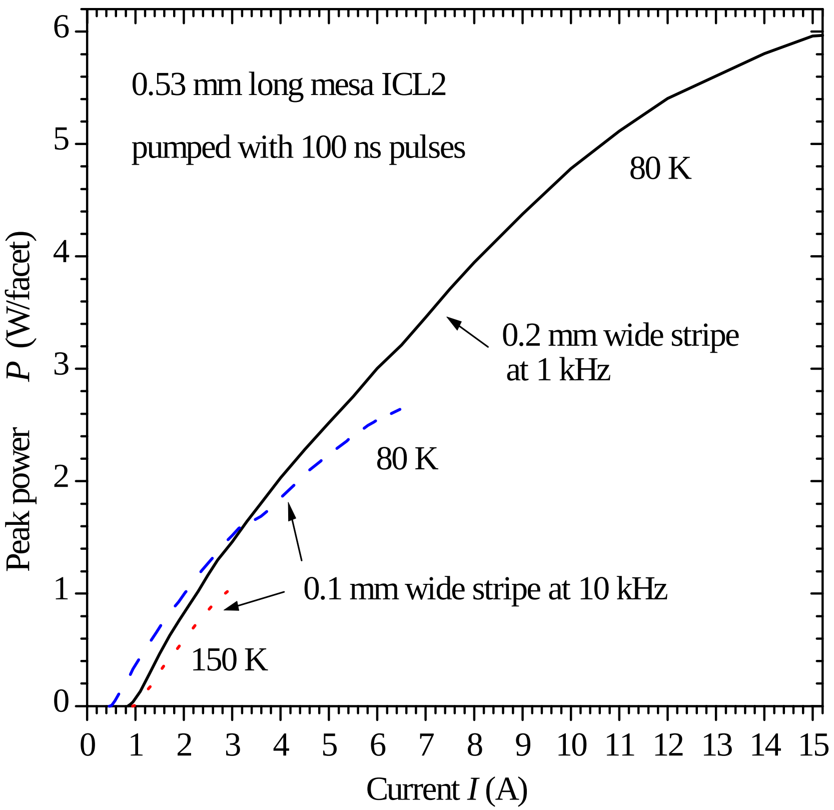
J_{th} varies significantly with device dimensions

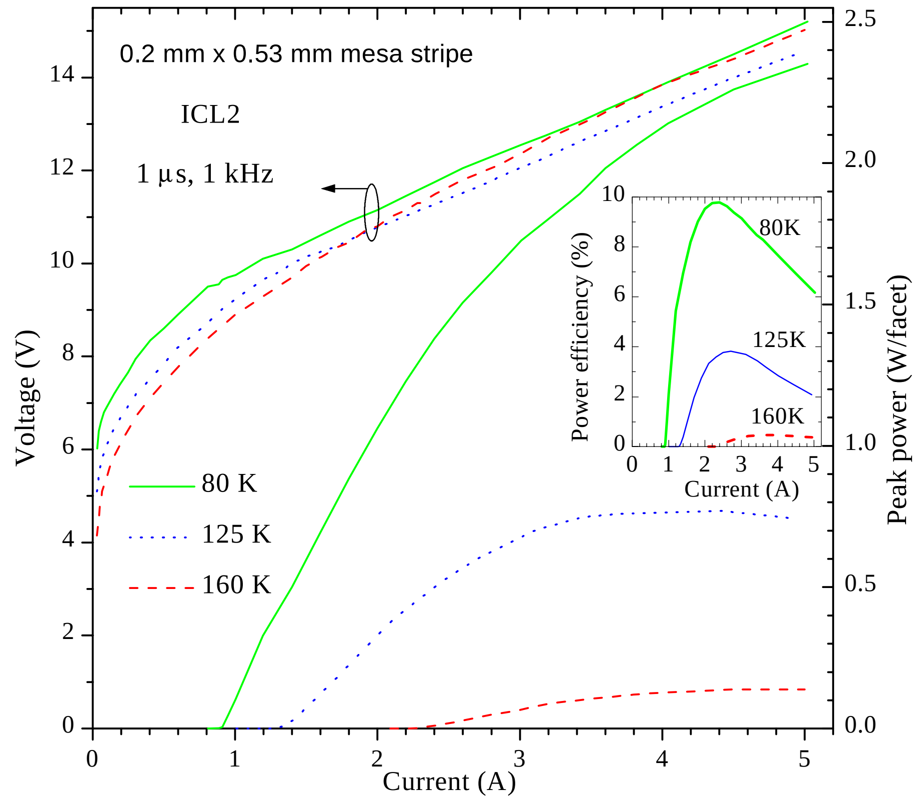
J_{th} is low for ICL1 (e.g. ~120A/cm^2 at 80 K)

J_{th} is high with large T_0 at T<180 K for ICL2 & ICL3

nominally same layer structure (23-stages) ⇒ λ~3.8-4 μm with good reproducibility
[Yang, *et al*., Physica E **7**, 69 (2000)]

High-power & Quantum Efficiency ICL2 Mounted on an Al-alloy-chip-carrier





peak power ~6W/facet

P>2.3 W/facet, η~10%, DEQE>600%

Devices can afford large current densities (>10 kA/cm^2)

Powers have been corrected for beam divergence losses using a collection efficiency of ~70%

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Heat Sinking

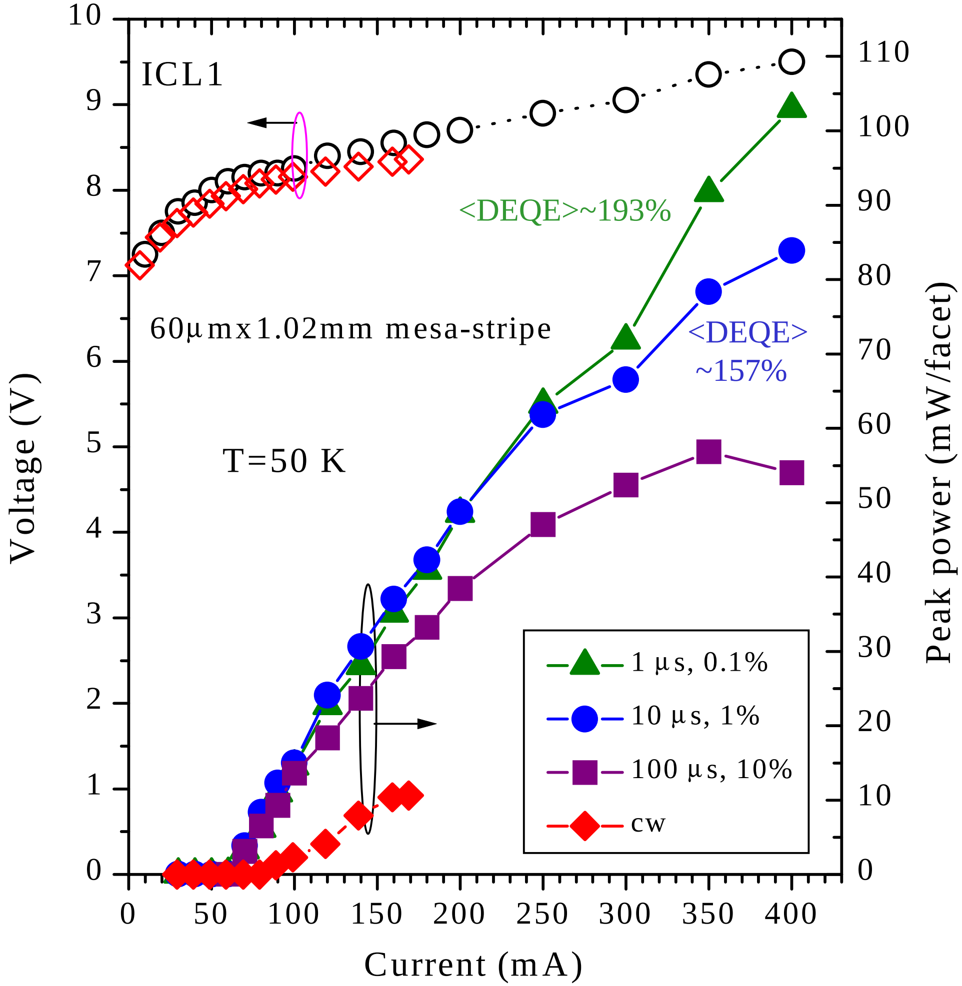
Sub-mount: chip carrier made of **Al-alloy**

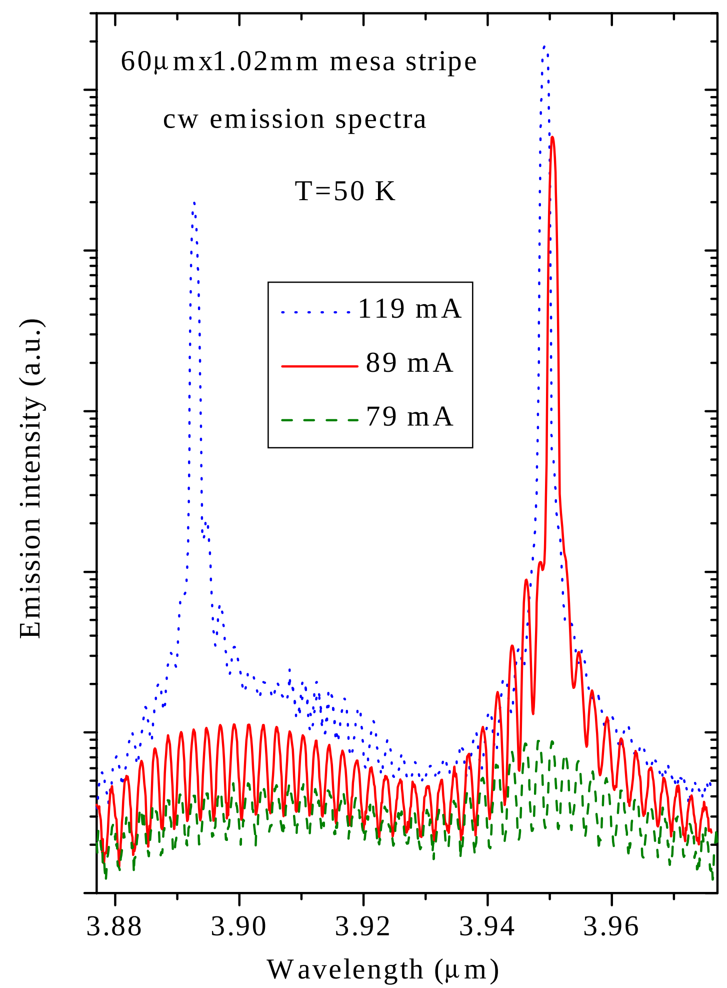
poor heat conductor, particularly at low temperatures

Use Cu instead of Al-alloy

(still epi-layer side up)

I-V-L characteristics with varying duty cycle & cw emission spectra of ICL1 on a thin Cu-sheet





T_{maxcw} ~ 70 K with epi-layer-side-up mounting

two peaks at a large current with a separation < linewidth of a gain spectrum

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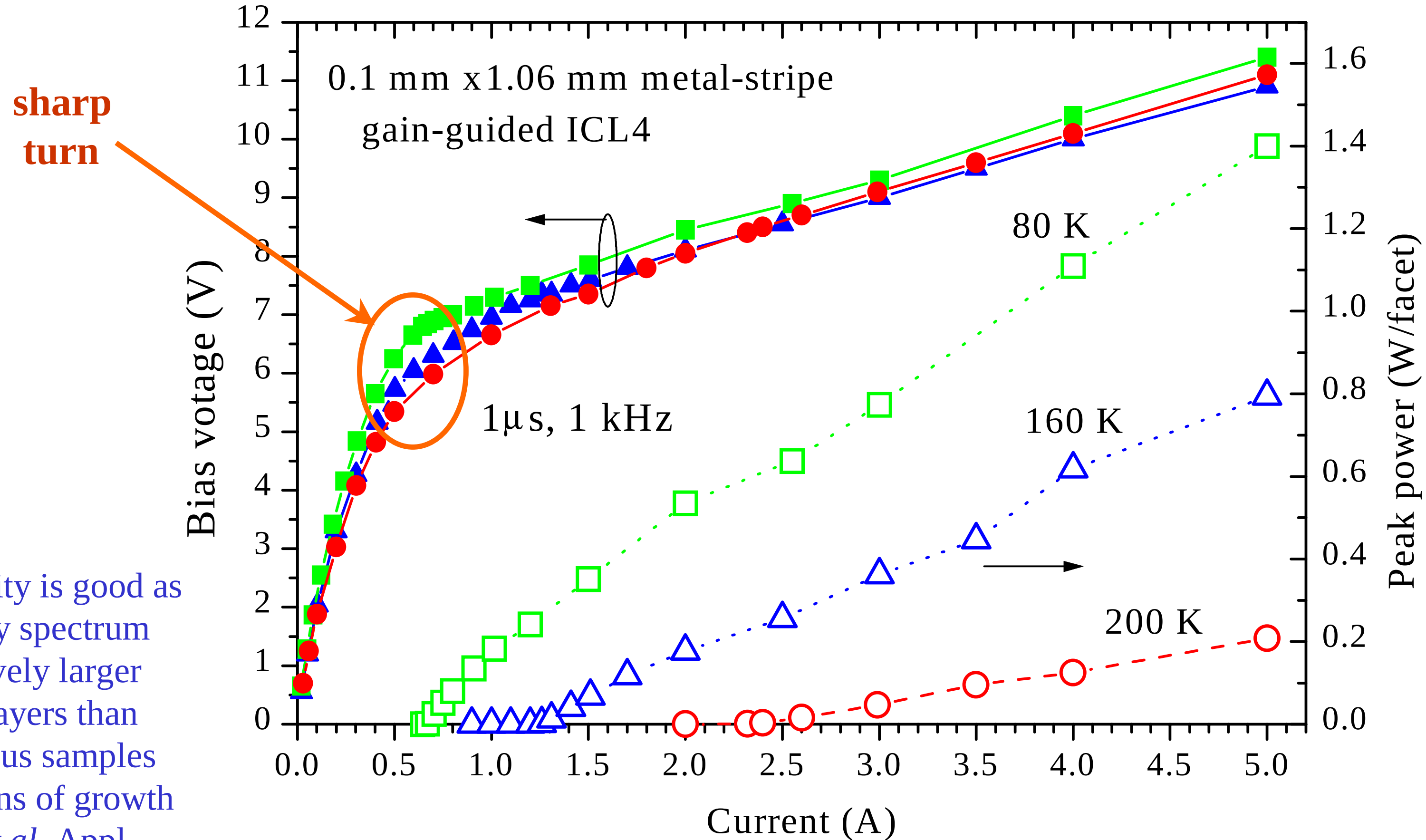
I-V-L Characteristics of a Gain-Guided ICL4 Device

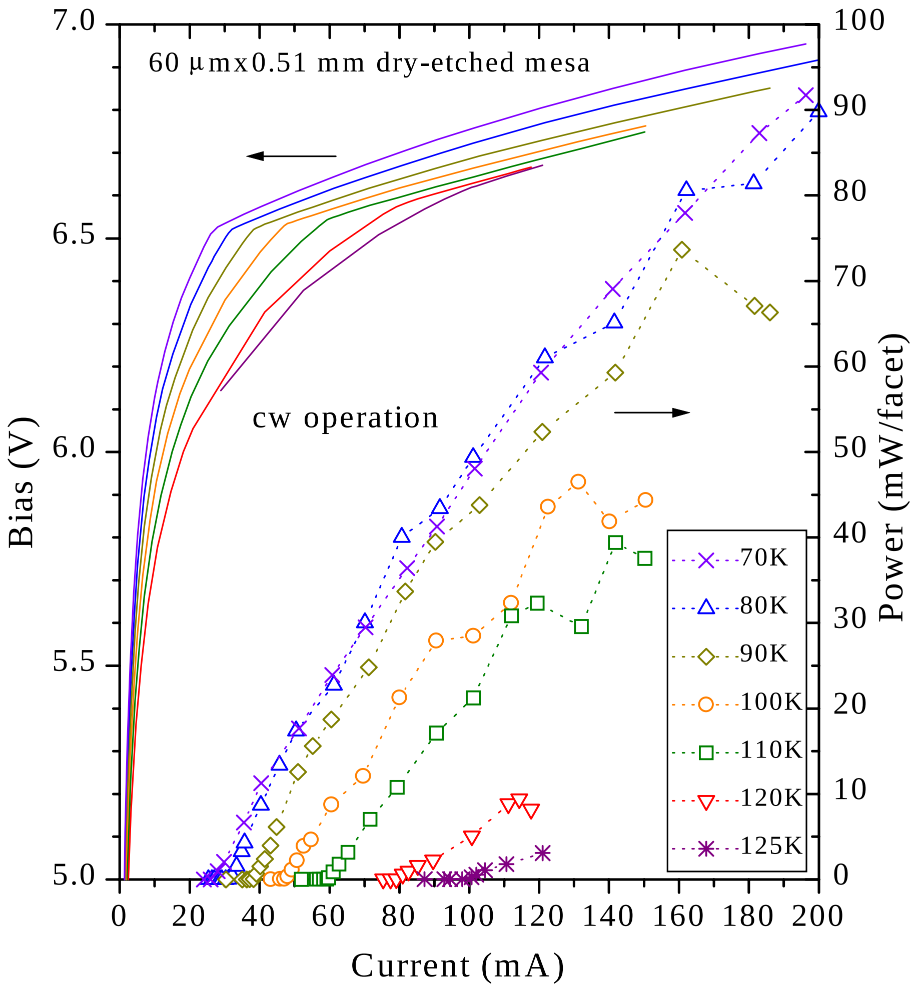
18-stages, on GaSb substrate (vendor A)

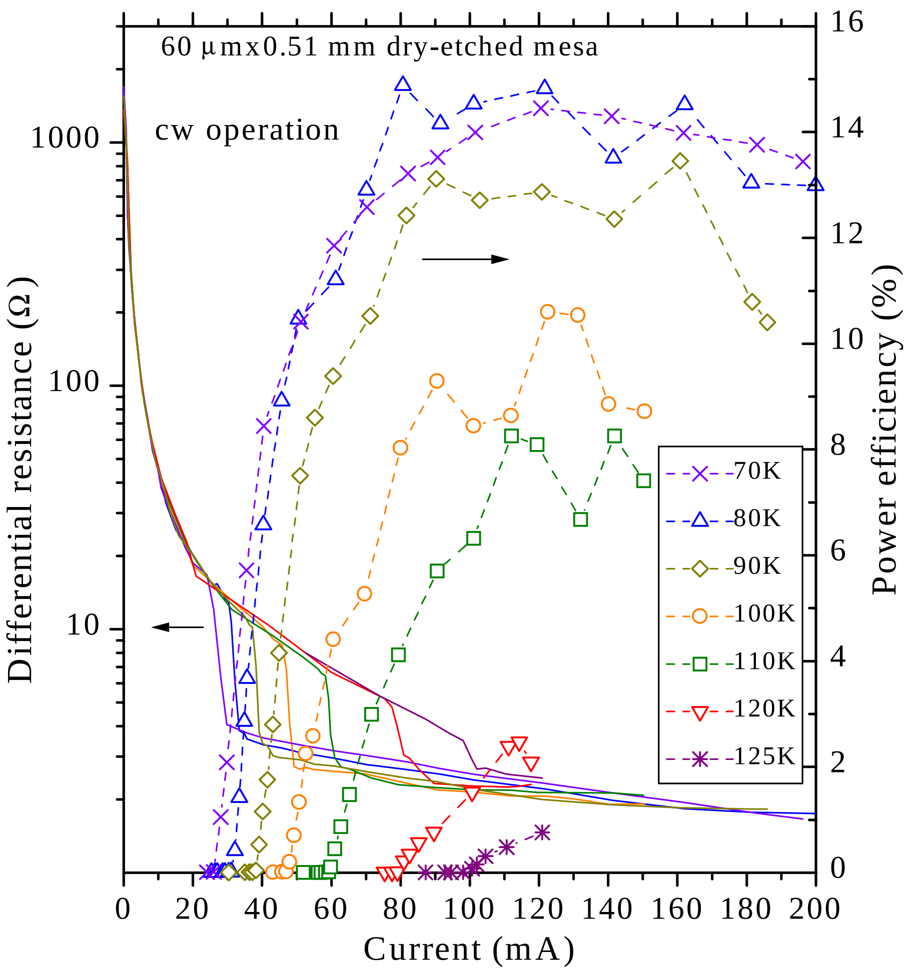


structural quality is good as shown by x-ray spectrum but with relatively larger strains in epi-layers than those in previous samples due to variations of growth rates [Bruno *et al*, Appl. Phys. Lett. **76**, 3167 (2000)]

At 80 K, threshold voltage V_{th}~6.8 V, peak power efficiency ~ 6%, peak power exceeding 4W/facet with large current pulses (15 A)

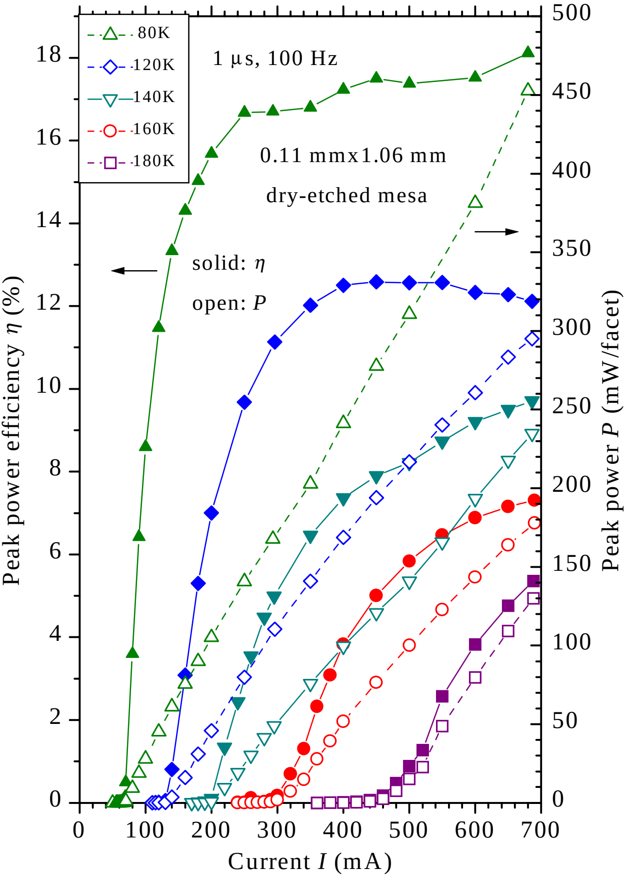
I-V-L and record-high power efficiencies from a 60-µm x0.51-mm dry-etched mesa ICL4 device





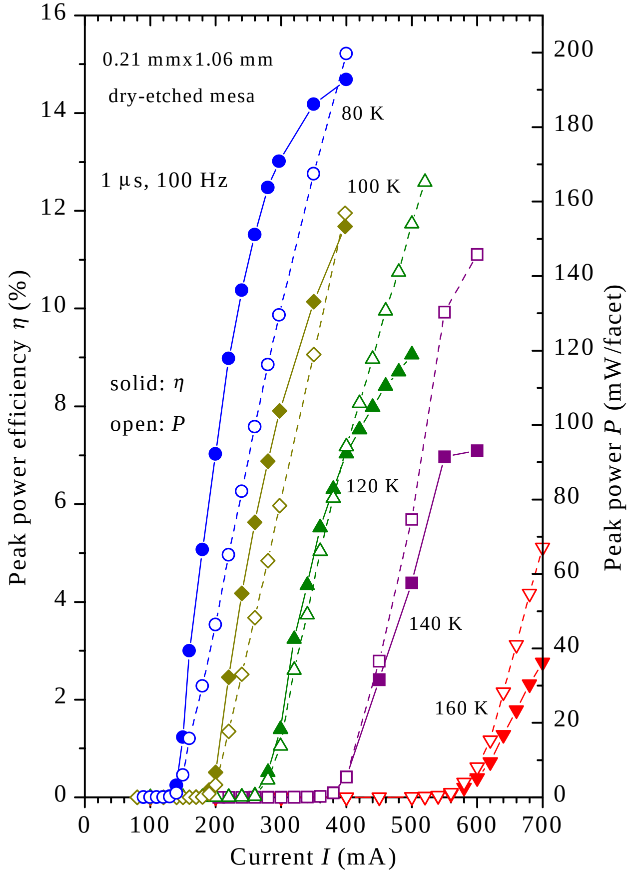
T_{maxcw}~128 K <DEQE> >300% at 70 & 80 K abrupt drop of resistance at threshold

Peak powers and efficiencies from several dry-etched mesa devices with different sizes



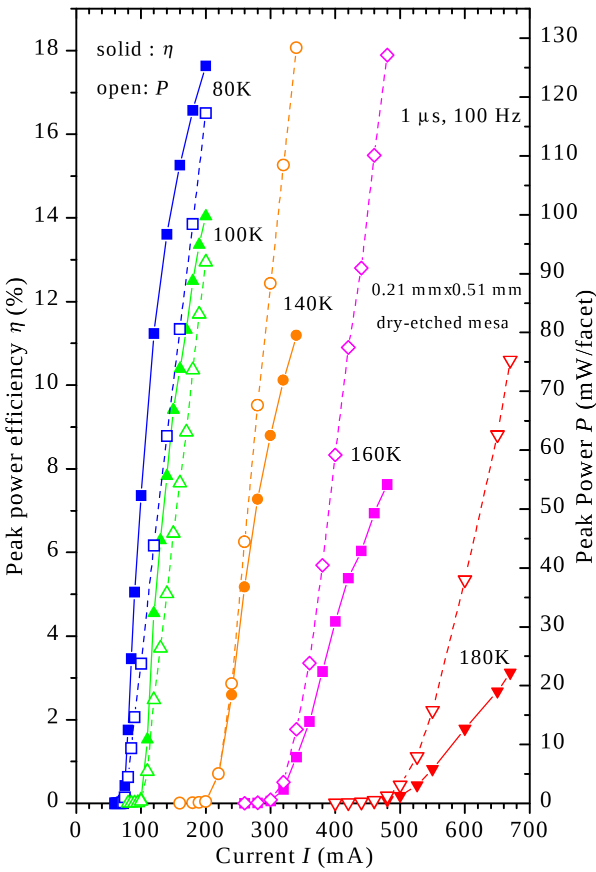
0.11 x 1.06 mm

<DEQE>~444% @ 80 K



0.21 x 1.06 mm

<DEQE>~473% @ 80 K



0.21 x 0.51 mm

<DEQE>~568% @ 80 K

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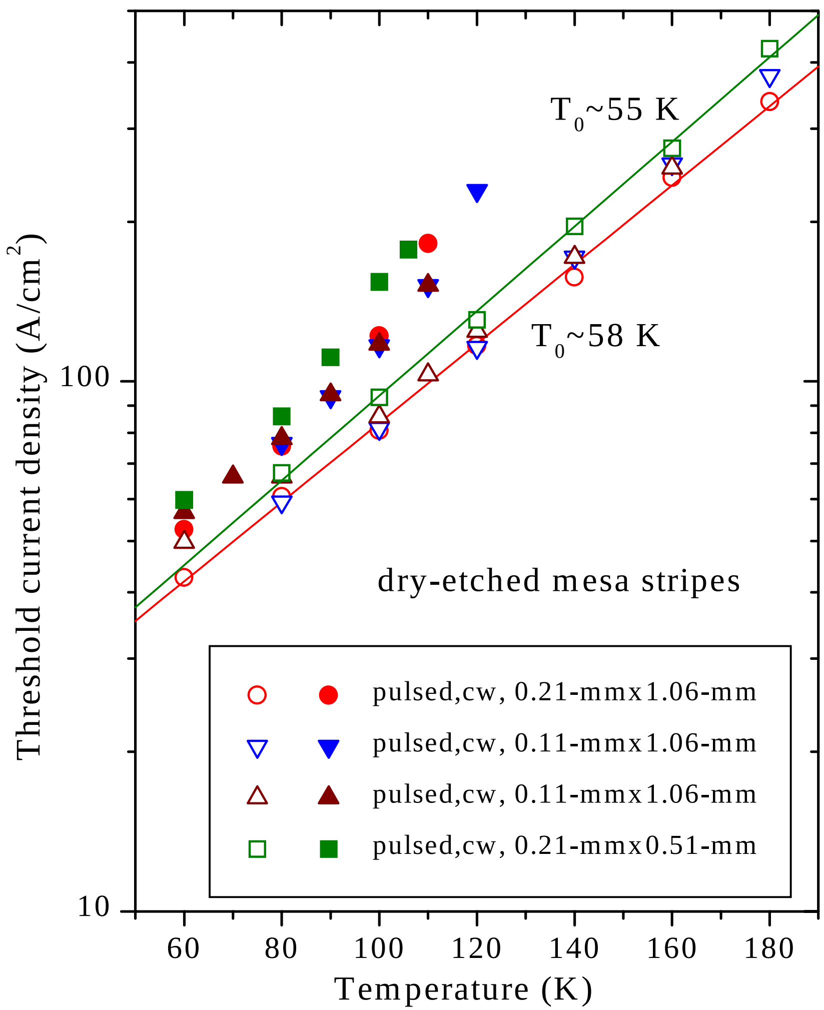
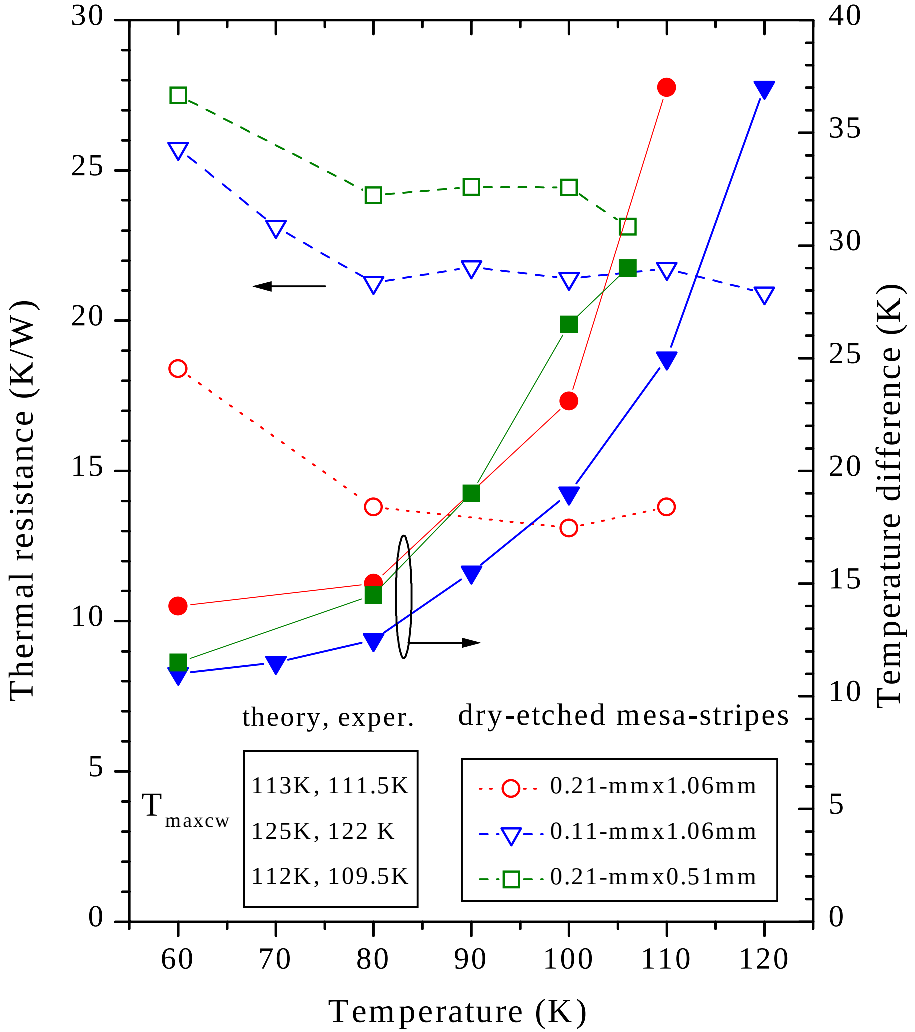
Thermal resistance of dry-etched mesa devices



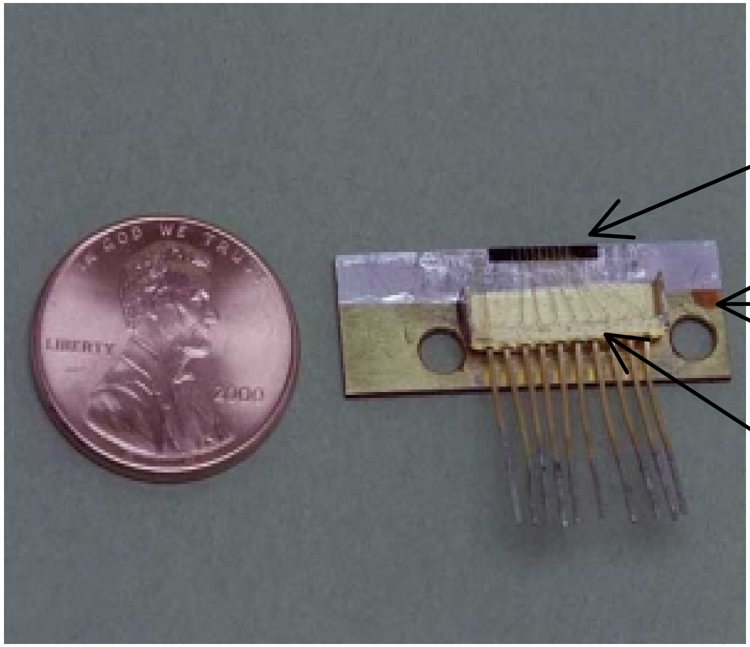


Reduce $R_{thermal}$ by a factor of 2-3 ⇒ T_{maxcw} up to ~160-185 K

Specific thermal resistance (a comparison)
scale photo of laser bar test setup

- narrow stripe intersubband QC lasers: ~2-2.4 K·cm^2/kW (epi-side-up),
  (Bell Lab) $T_{cw}\uparrow$ 175 K ~0.33-0.9 K·cm^2/kW (epi-side-down)
- broad-area type-II QW lasers: ≤2 K·cm^2/kW (epi-side-down, optical pumping),
  (NRL/Sarnoff) $T_{cw}\uparrow$ 290/195 K ~8-9.2 K·cm^2/kW (epi-side-down, diode)
- our present broad-area IC lasers: ~24-29 K·cm^2/kW (epi-side-up)

improvements in device fabrication and packaging can raise T_{maxcw} up & ⇒ higher cw power

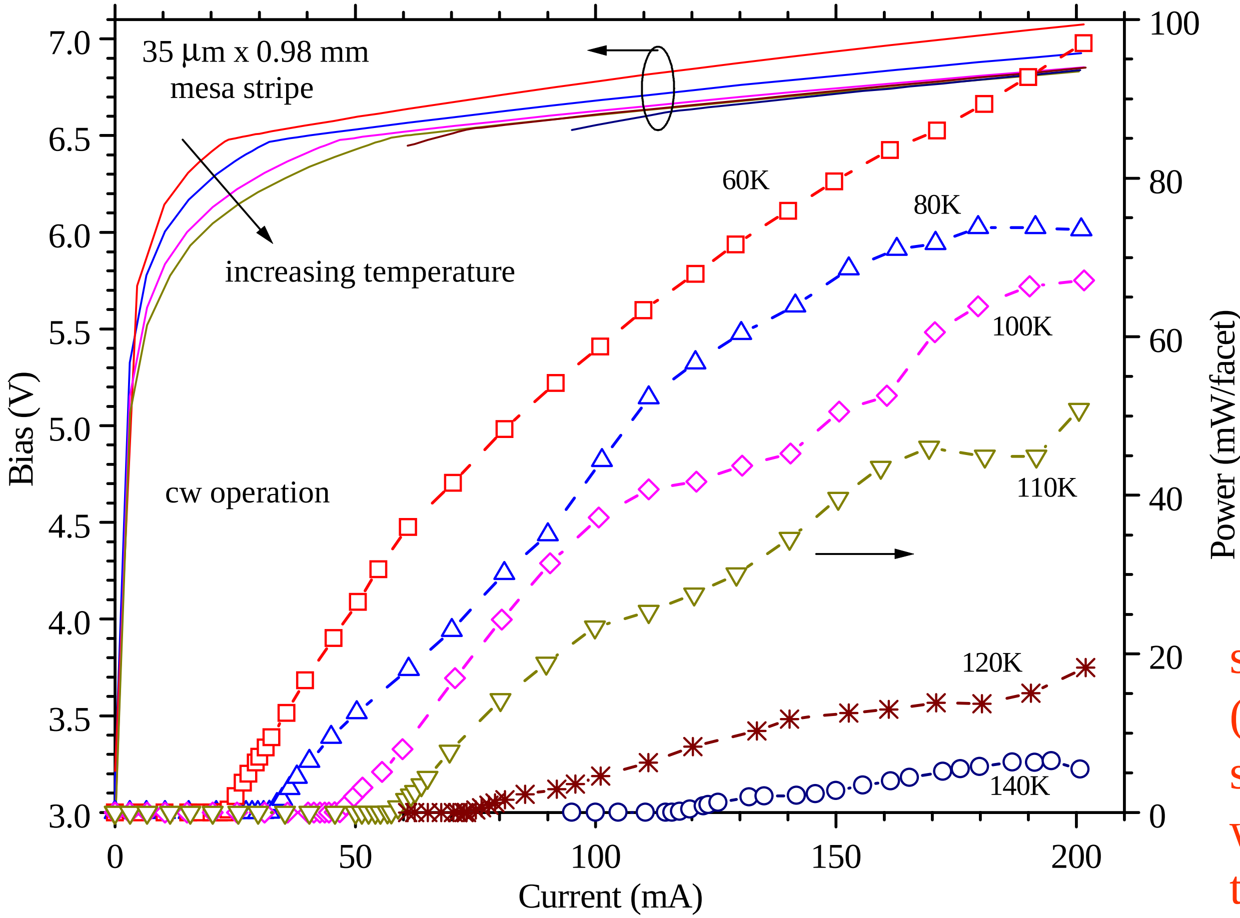


laser bar (~8 mm x 0.5-1 mm)

Cu heat sink

chip carrier

Enhanced Performance with Improved Device Fabrication



mesa was coated with SiO_2 layer

both facets were uncoated

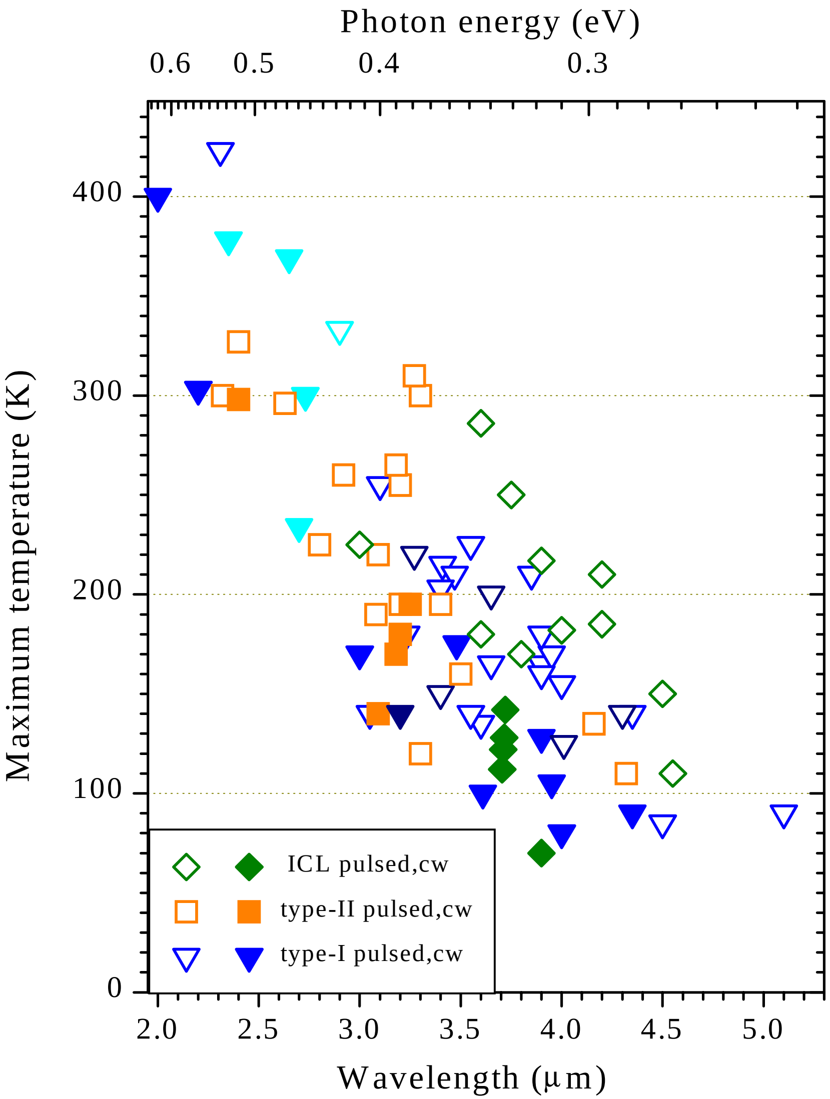
epi-layer-up mounting

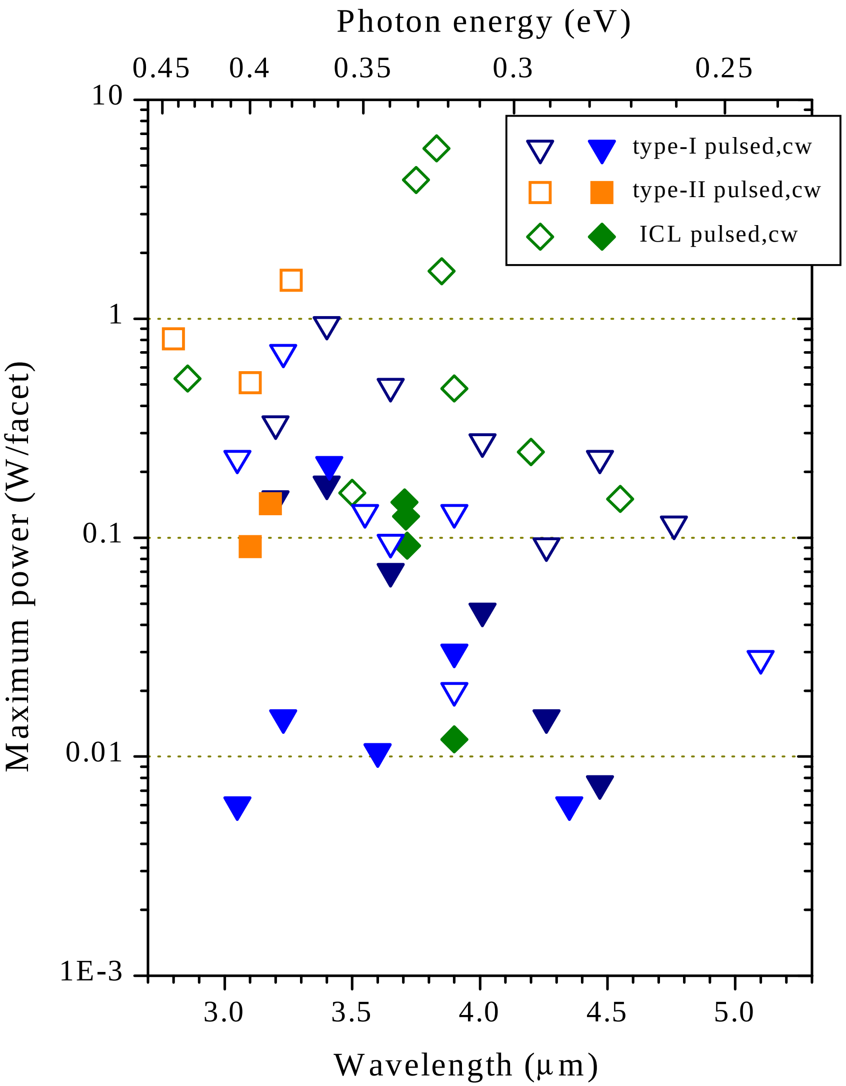
specific thermal resistance (~24-29 K•cm²/kW) is smaller than those for the wide-stripe ICLs, suggesting the reduction of heat accumulation in the device with improved fabrication.

T_{maxcw} = 142 K with a 35-µm-wide stripe
power efficiency reached 18% at 60 K

Current Status

III-V Sb-based Interband Diode Lasers





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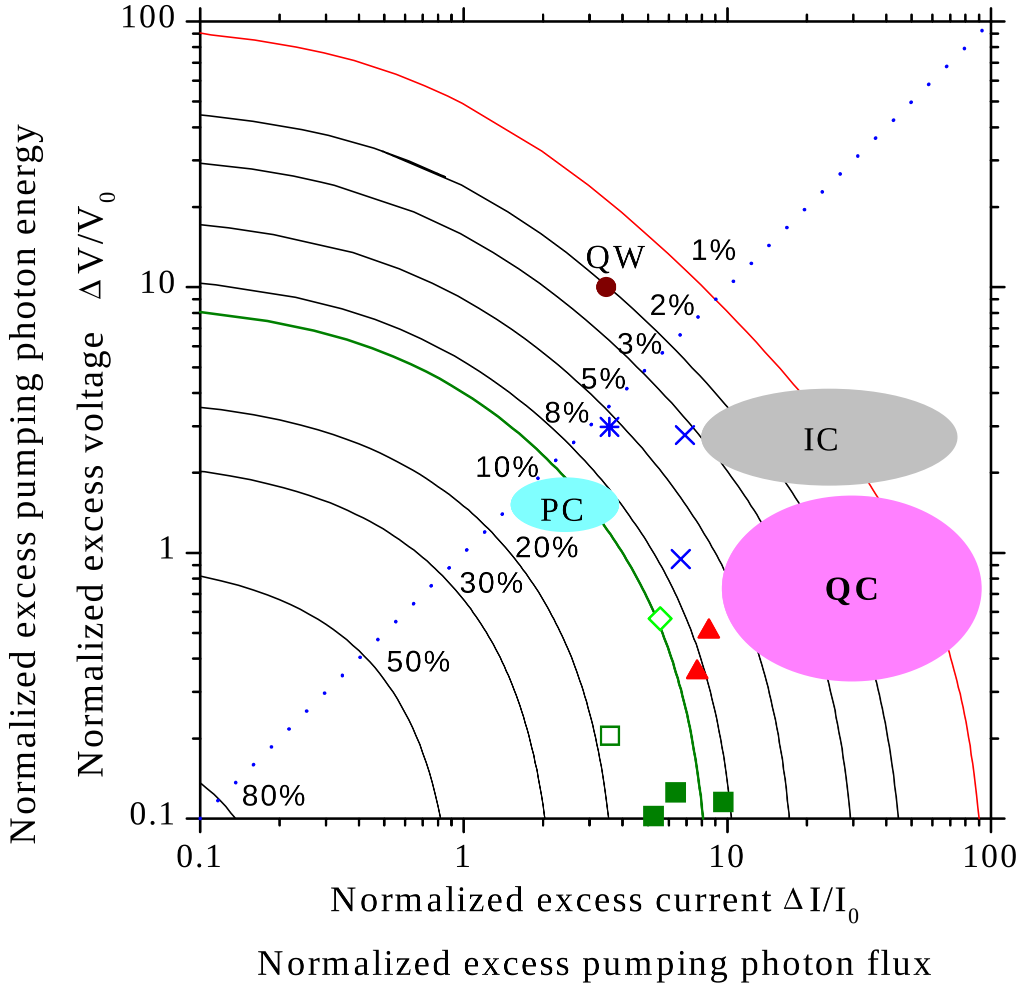
Power Efficiencies of Mid-IR Lasers

Contours of constant power efficiency



Notice that both axes are logarithmic

- ● 3.4-µm type-I QWL (cw 80 K)
- ▲ 5- & 8-µm-QCLs (cw 22K)
- × O-P. 3.7-µm type-I DHL(qcw 72 K)
- ✳ O-P. 3.9-µm type-II QWL (6-µs 69 K)
- ◇ 3.8-µm-ICL (pulsed 1-µs 80 K)
- ■ 3.7-µm-ICls (cw 80 K)
- □ 3.67-µm-ICL (pulsed 1-µs 80 K)

The shaded areas (QC, IC, PC) were estimates and speculations (made in 1997) for QC, IC, & projected optimized cascade lasers, respectively, at temperatures above 77 K.

$$V_0=N_c \cdot h\nu/e, \quad \Delta V=V-V_0$$

$$I_0=P_o/V_0= e\,P_o/(N_c \cdot h\nu), \quad \Delta I=I-I_0$$

present ICLs can meet the basic requirement for IRCM application if a diode array could be fabricated with improved device packaging and thermal management

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Challenges and Prospects/Conclusions

Challenging Issues and Lessons Learned

- Reduction of threshold current density

  defects ⇒ substrate quality, polishing, cleaning, MBE growth

  etched surfaces ⇒ leakage, recombination loss

  small-area ridge lasers ⇒ processing, passivation

- Improvement of device heat sinking and packaging

  using Cu (or better heat conductors such as diamond) instead of Al-alloy

  epilayer side down mounting (care needs to minimize mechanical stress)

  facet coating (for preventing oxidation and obtaining high output power)

- MBE growth and device design

  looking for optimum growth conditions

  varying design for better device performance

  adjusting design to accommodate systematic patterns of the growth

Prospects/Conclusions

- Considering limited investment, results are very encouraging:

  peak power ~ 6W/facet, DEQE > 600% in pulsed (23 stages)

  record-high power efficiency (>14% *in cw*, >18% *in pulsed*) *for mid-IR @ 80 K*

  cw P >100 mW/f, *DEQE* >300% (>500% *in pulsed*), *cw operation* ↑142 K

- Still in early stage and far from optimum

  present results not fully understood (i.e. spectra, temp. dependence of R_{thermal})

  threshold current density substantially larger than theoretical prediction

  many aspects can be improved, numerous variations in design

  significant progress (e.g. room temp. operation) is expected soon

- It is fun

  basic physics ⇆ quantum devices ⇆ various applications

  much less explored land with great opportunity and potential