Short Injector Regions for Improved Quantum Cascade Laser Performance

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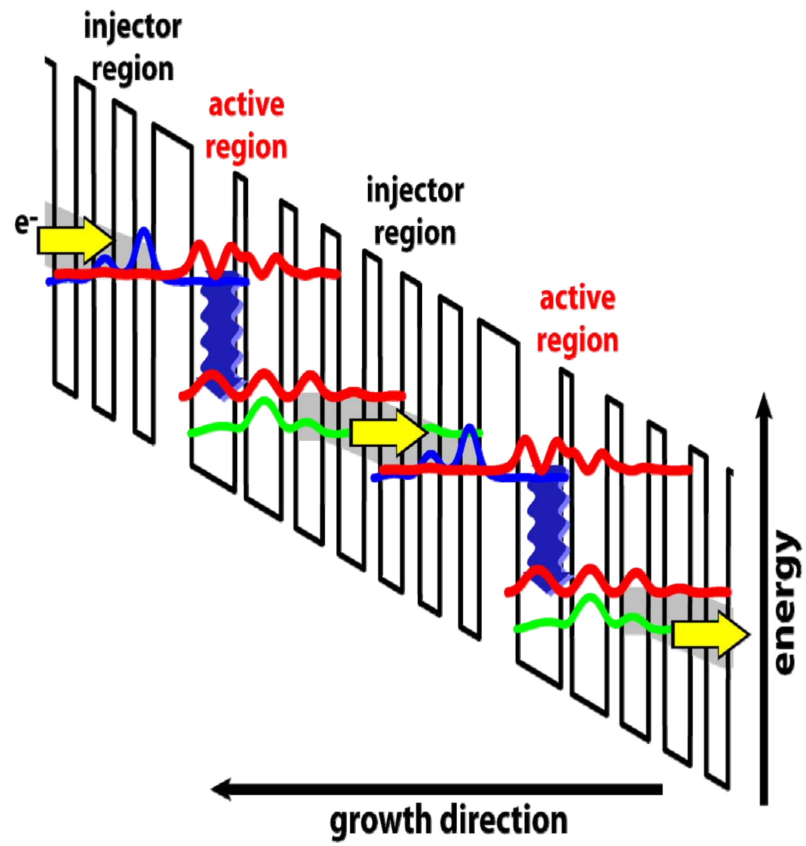
Outline

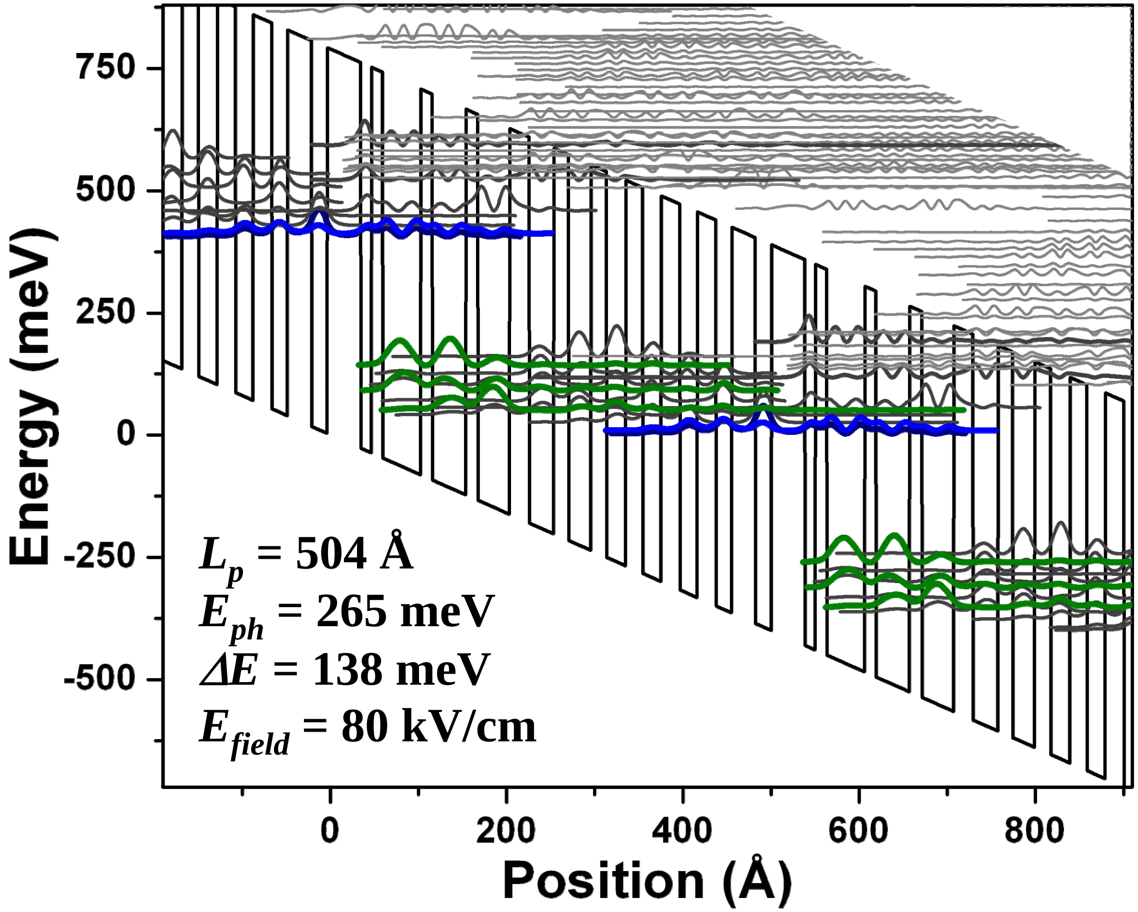
- Background and motivation
  - Conventional QC lasers
  - Minimizing injector length
  - Injectorless lasers
- Short injectors
  - 4 well injector
  - 3 well injector
  - 2 well injector
- Summary

Injector Regions
Why have them at all?

- efficiently inject electrons into the upper laser state
- isolate the upper laser state from the continuum
- allow electrons to 'relax' out of active region
- separate lower laser state from electron pool
- provide space over which electrons can gain energy relative to the band edge
- convenient space for doping



Conventional Short Wavelength Quantum Cascade Laser



λ = 4.6 µm

3 mm x 9.8 µm

J_{th} = 340 A/cm^2

Power = 4.0 W

η_{sl} = 3.6 W/A

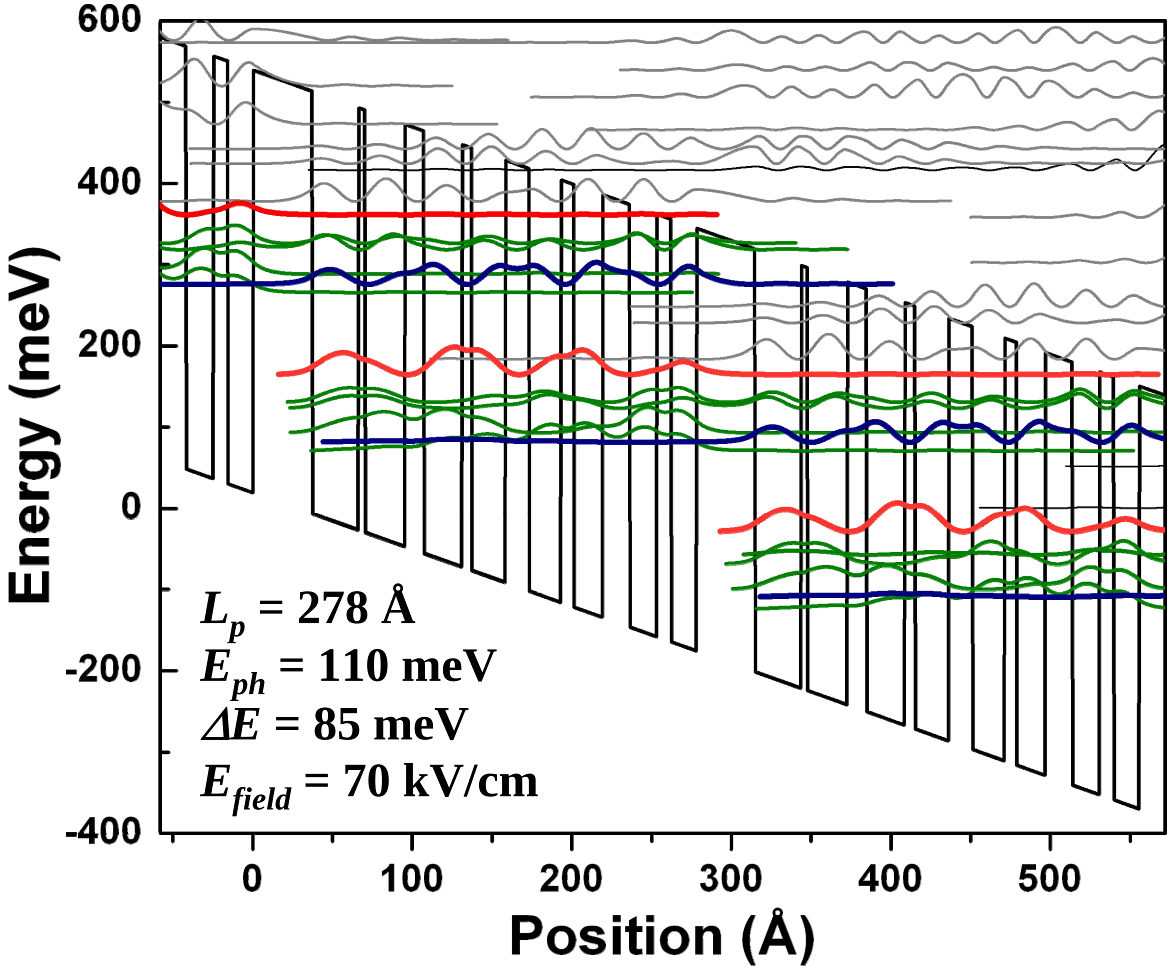
η_{wp} = 27%

T_0 = 143 K

A. Evans *et al.*, *Appl. Phys. Lett.* **91** 071101 (2007)

Y. Bai *et al.*, *Appl. Phys. Lett.* **92** 110105 (2008)

Injectorless QC Laser



Chirped superlattice design

λ **= 11.5 µm**

J_{th} **= 4.2 kA/cm²**

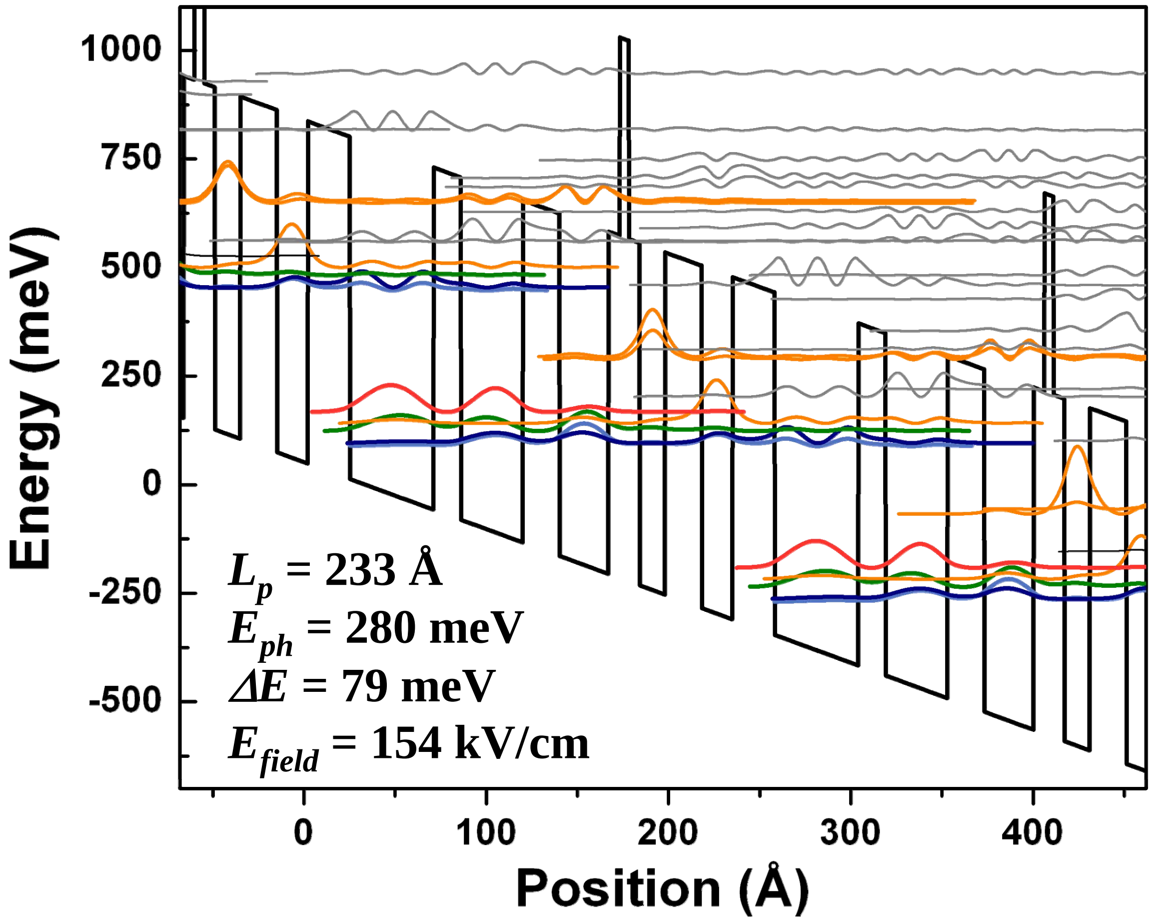
T_0 **= 48 K**

T_{max} **= 195 K**

η_{sl} **= 0.35 W/A**

M.C. Wanke *et al.*, *Appl. Phys. Lett.* **78** 3950 (2001)

Injectorless QC Laser



λ = 6 µm

J_{th} = 450 A/cm^2

T_0 = 140 K

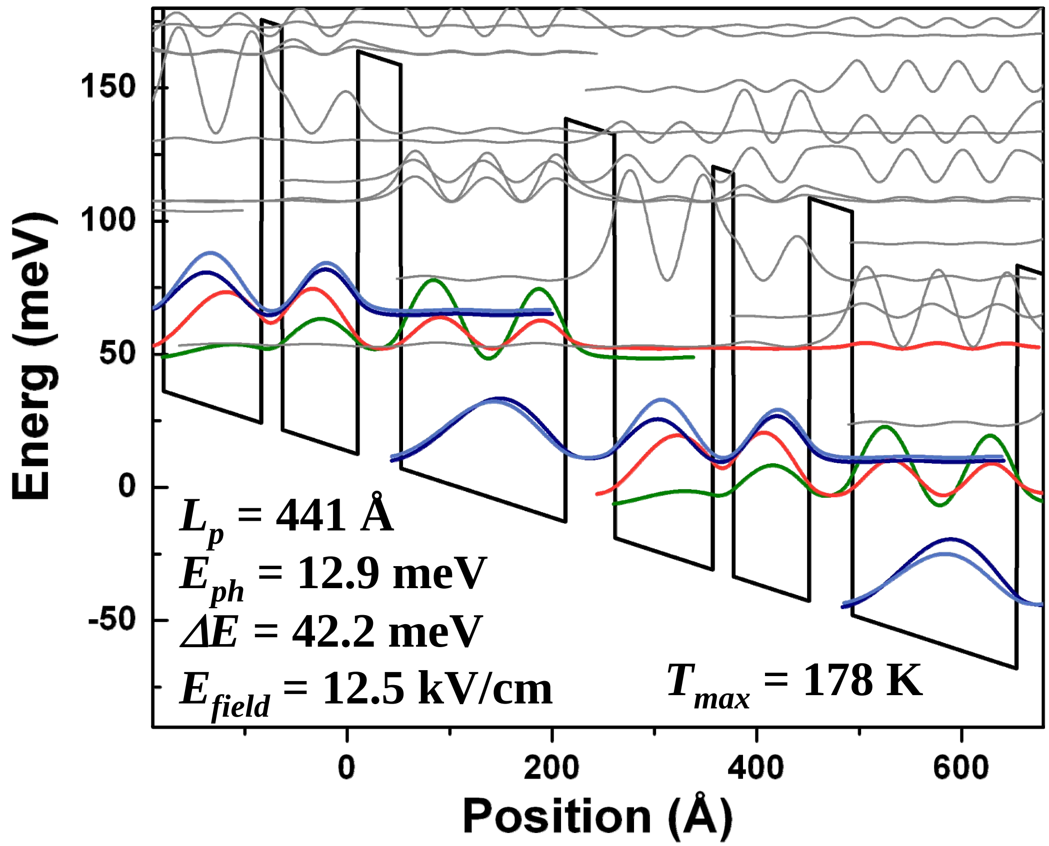
Power = 1.2 W

η_{wp} = 7%

A. Friedrich *et al.*, *Semicond. Sci. Technol.* **22** 218 (2007)

S. Katz *et al.*, IQCLSW

3 Well THz Laser



H. Luo *et al.*, *Appl. Phys. Lett.* **90** 041112 (2007)

M.A. Belkin *et al.*, *Opt. Express* **16** 3242 (2008)

Metrics of QCL Performance

Gain / Threshold

$$J_{th} = 2\gamma_{ul} \frac{\varepsilon_0 \lambda_0 n_{eff}}{4\pi q} \frac{\alpha_m + \alpha_w}{\tau_u (1 - \tau_l / \tau_{ul}) z_{ul}^2} \frac{d}{\Gamma} \frac{1}{N_p}$$

Power

$$P = N_p \eta_{tr} \frac{\hbar\omega}{q_0} \frac{\alpha_m}{\alpha_m + \alpha_w} (J - J_{th})$$

Efficiency

$$\eta_{wp} = \eta_{tr} \frac{1}{1 + \Delta_{inj} / (\hbar\omega)} \left[1 - \frac{\tau_{trans}}{\tau_{up}} \left(\frac{\alpha_m + \alpha_w}{n_s N_p g_c} + \frac{n_{therm}}{n_s} \right) \right]$$

$$\tau_{trans} = \tau_3 + \tau_2 + \tau_{inj}$$

Design Consequences of Shortened Injectors

- Increased field
  - $$E_{field} = \frac{Energy\ drop\ per\ QC\ period}{QC\ period\ length}$$
  - high fields may cause reliability problems
- Upper state confinement difficulty
  - may need larger band offset
  - may run into satellite valley problems
  - other parasitic states for electrons to tunnel into

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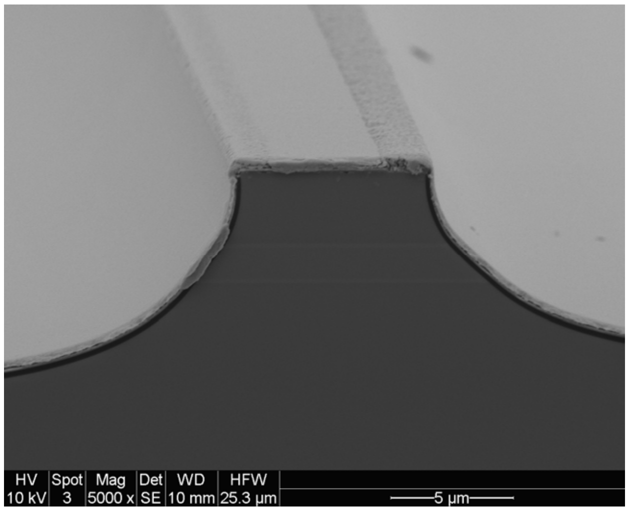
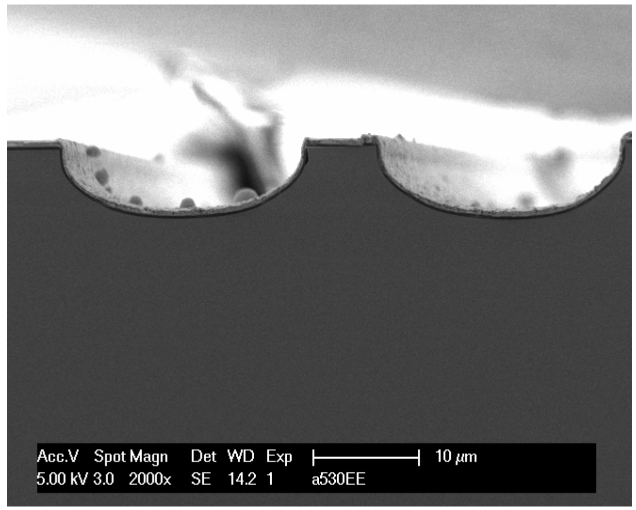
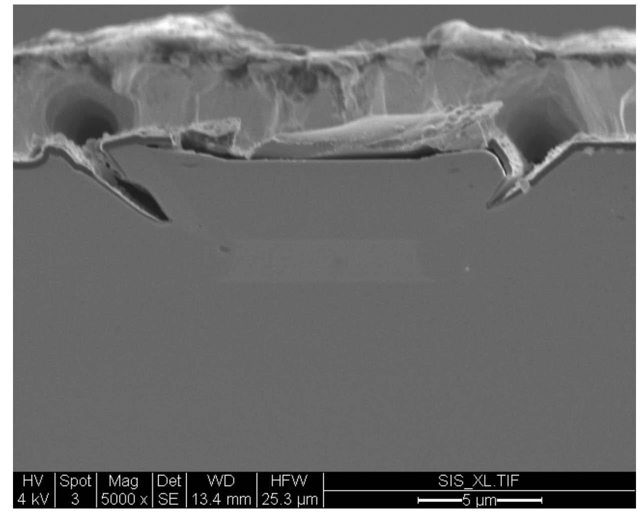
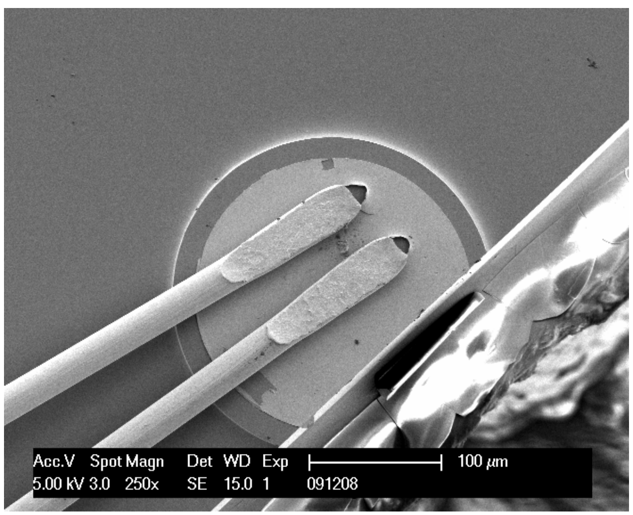
About the data



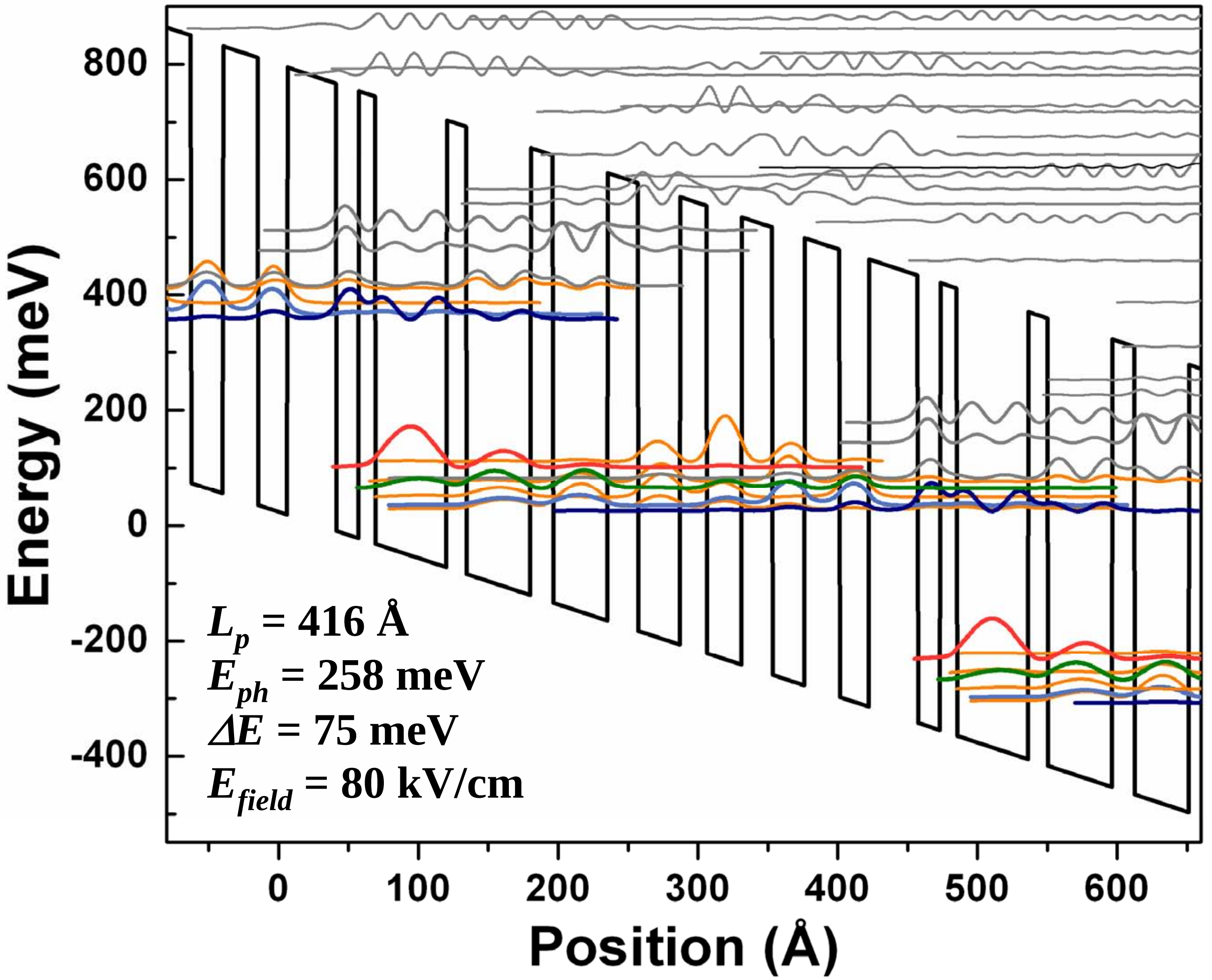






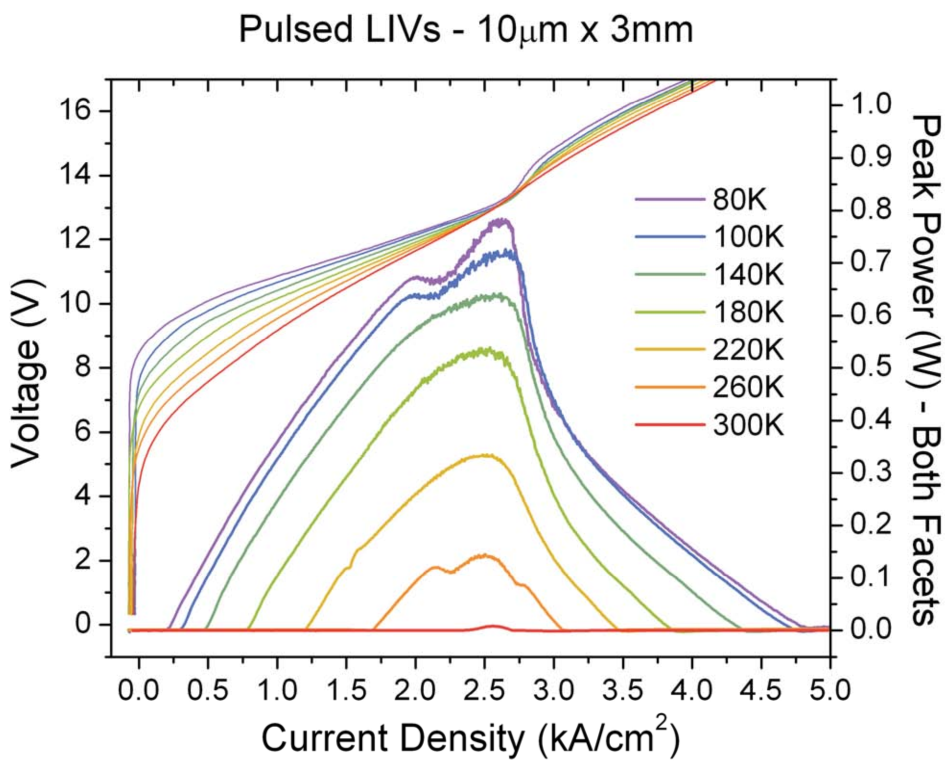
- Multiple processing methods
- Epi-up mounting
- Standard laser sizes: 2-3 mm x 7-10 µm
- Showing all pulsed data
- Power axes shown as total peak power

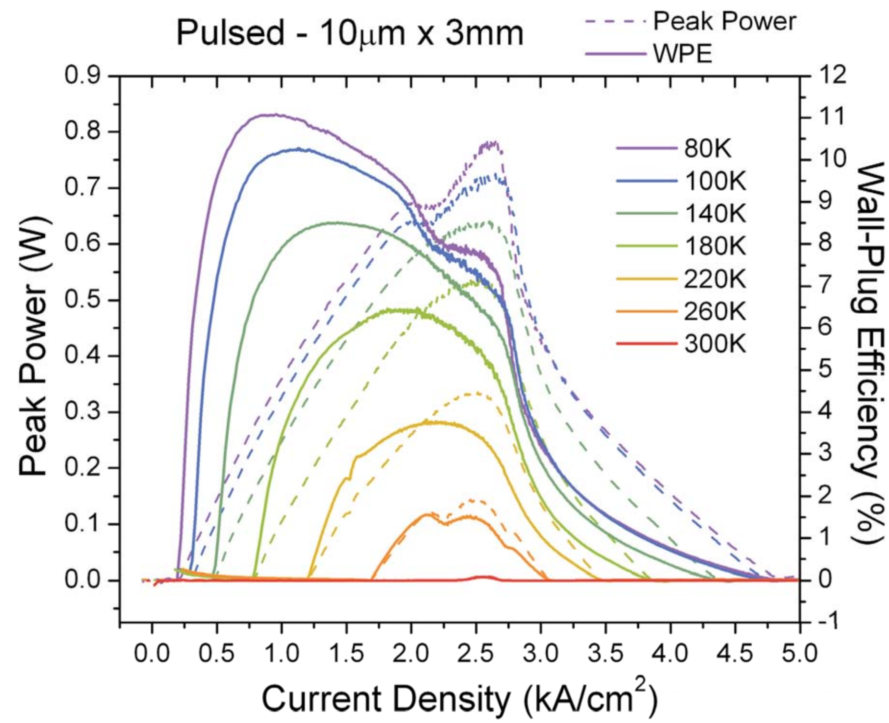
Four Injector Wells



4 injector wells

LIV Characterization



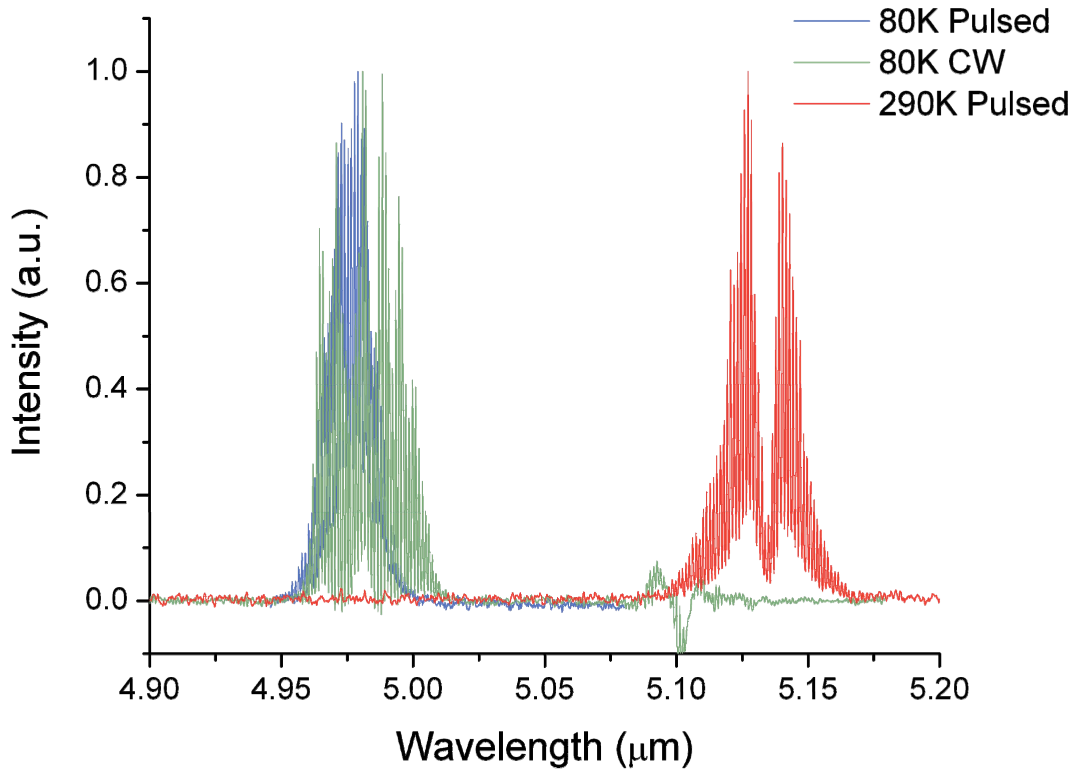


- J_{th} = 0.22 kA/cm² @ 80K
- E_{Δ} (@ 80K threshold) = 65 meV
- T_0 = 117 K

- Peak 80K Pulsed WPE > 11%

Spectral Characteristics

4 injector wells

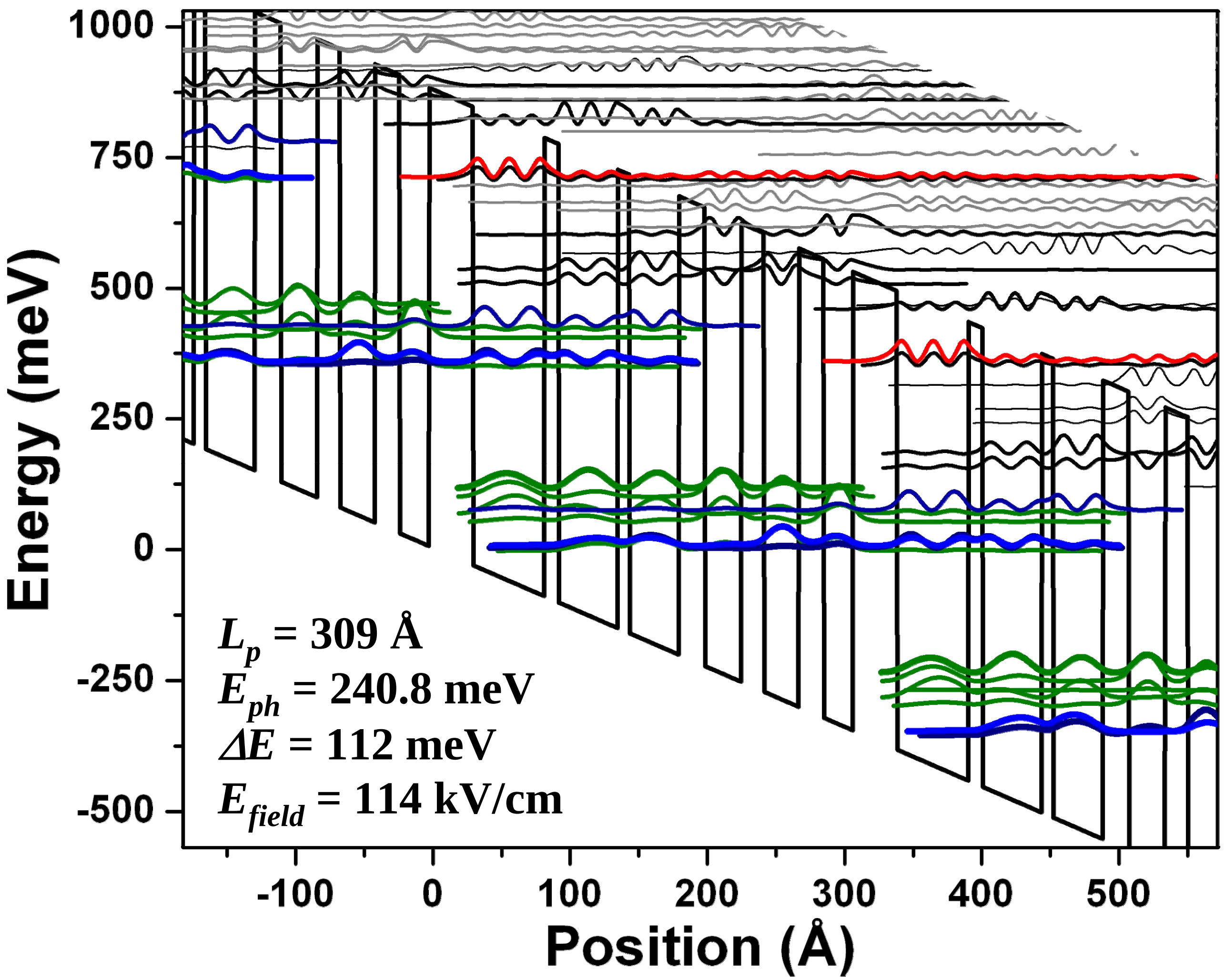


Poster

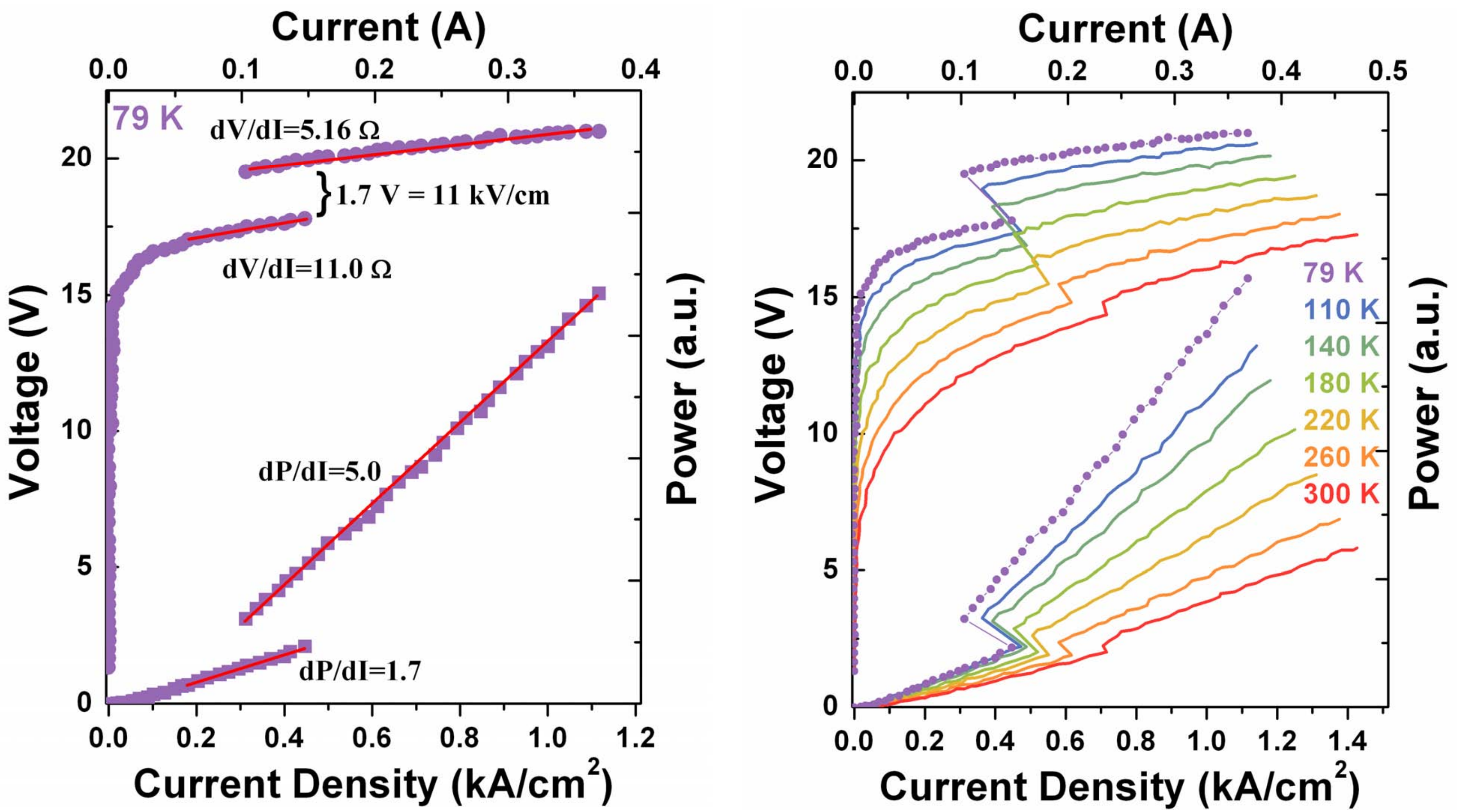
M.D. Escarra *et al.*,

"Improved Voltage Efficiency in Quantum Cascade Lasers"

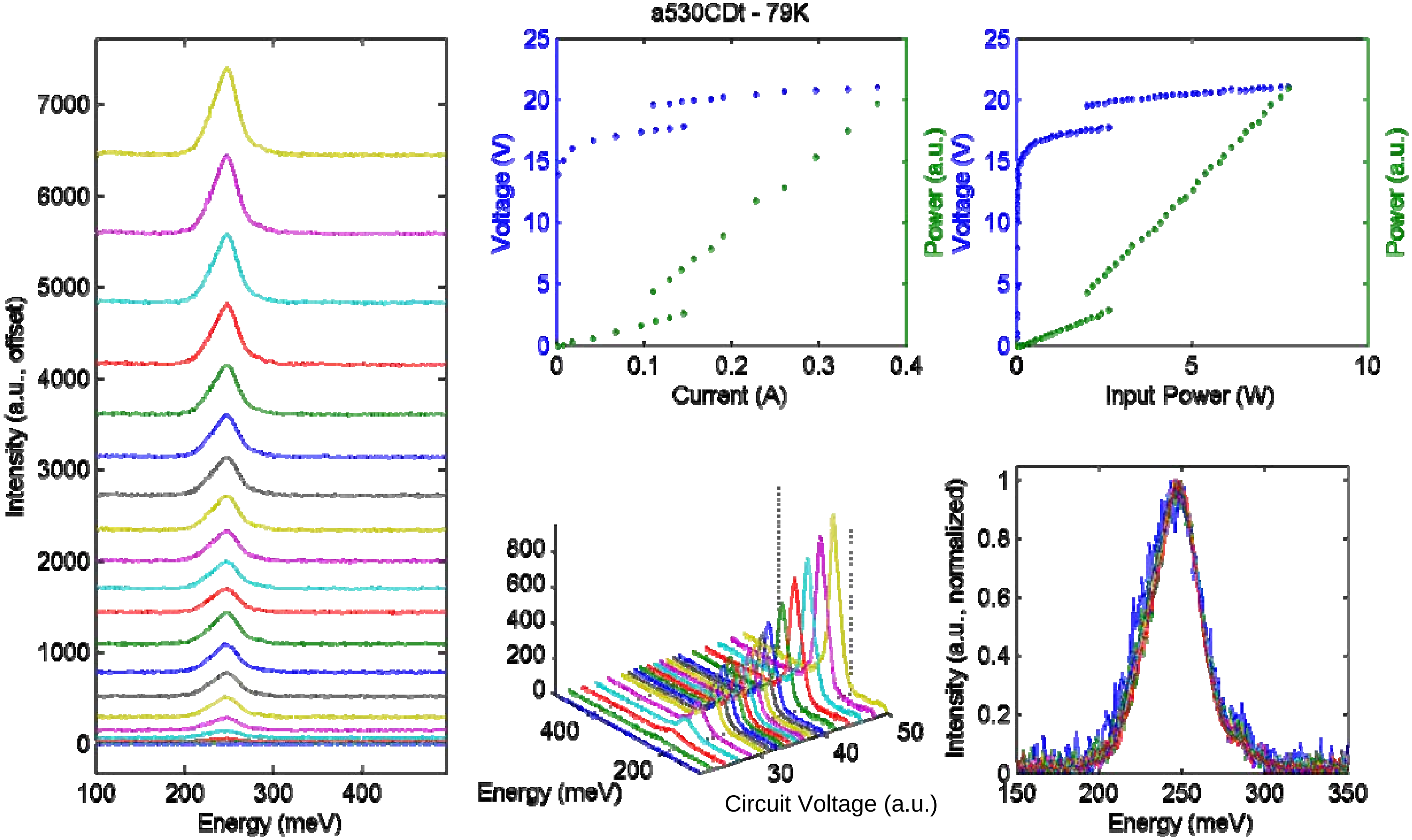
Three Injector Wells



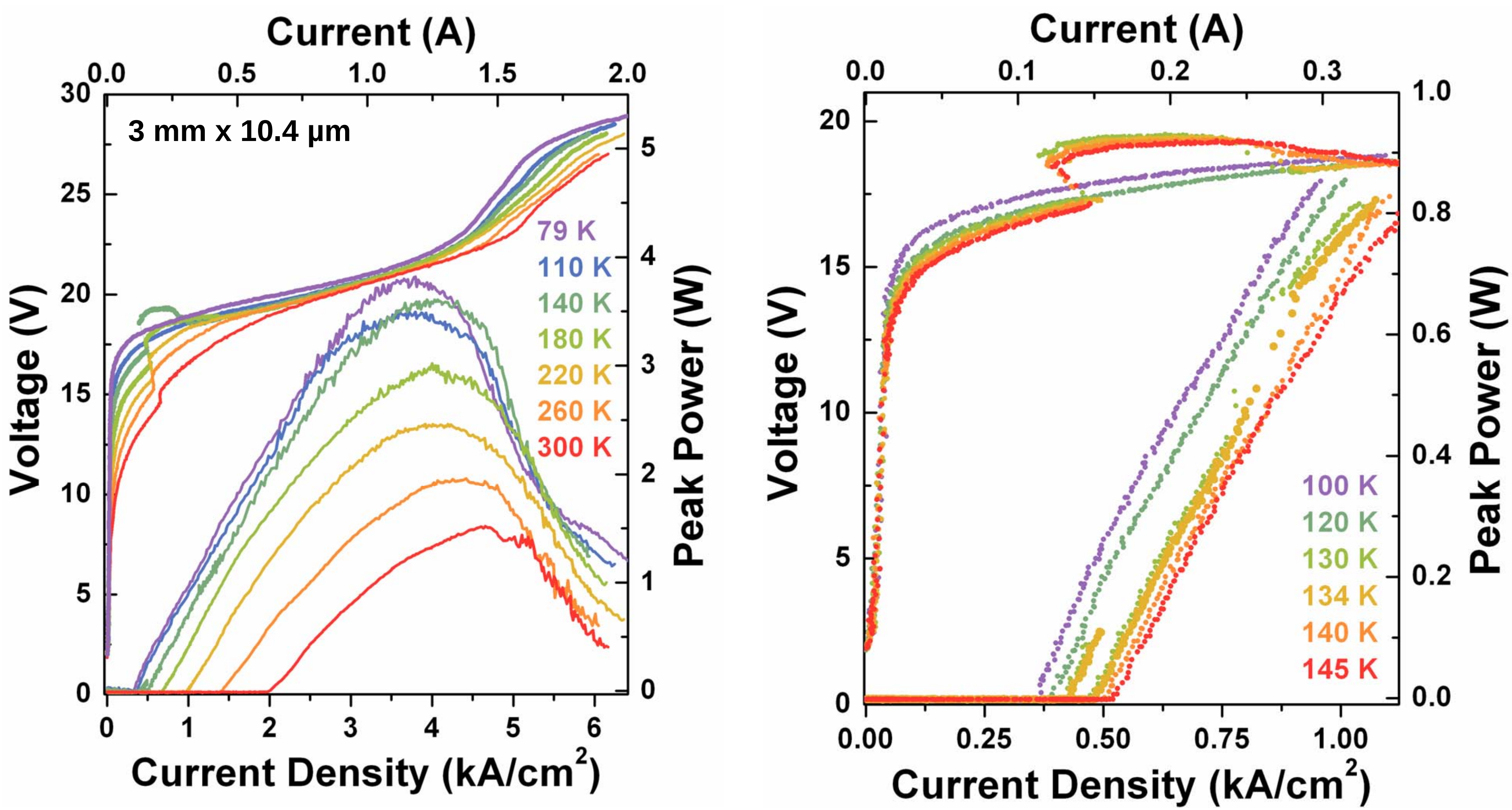
Electroluminescence LIV



Electroluminescence Spectra

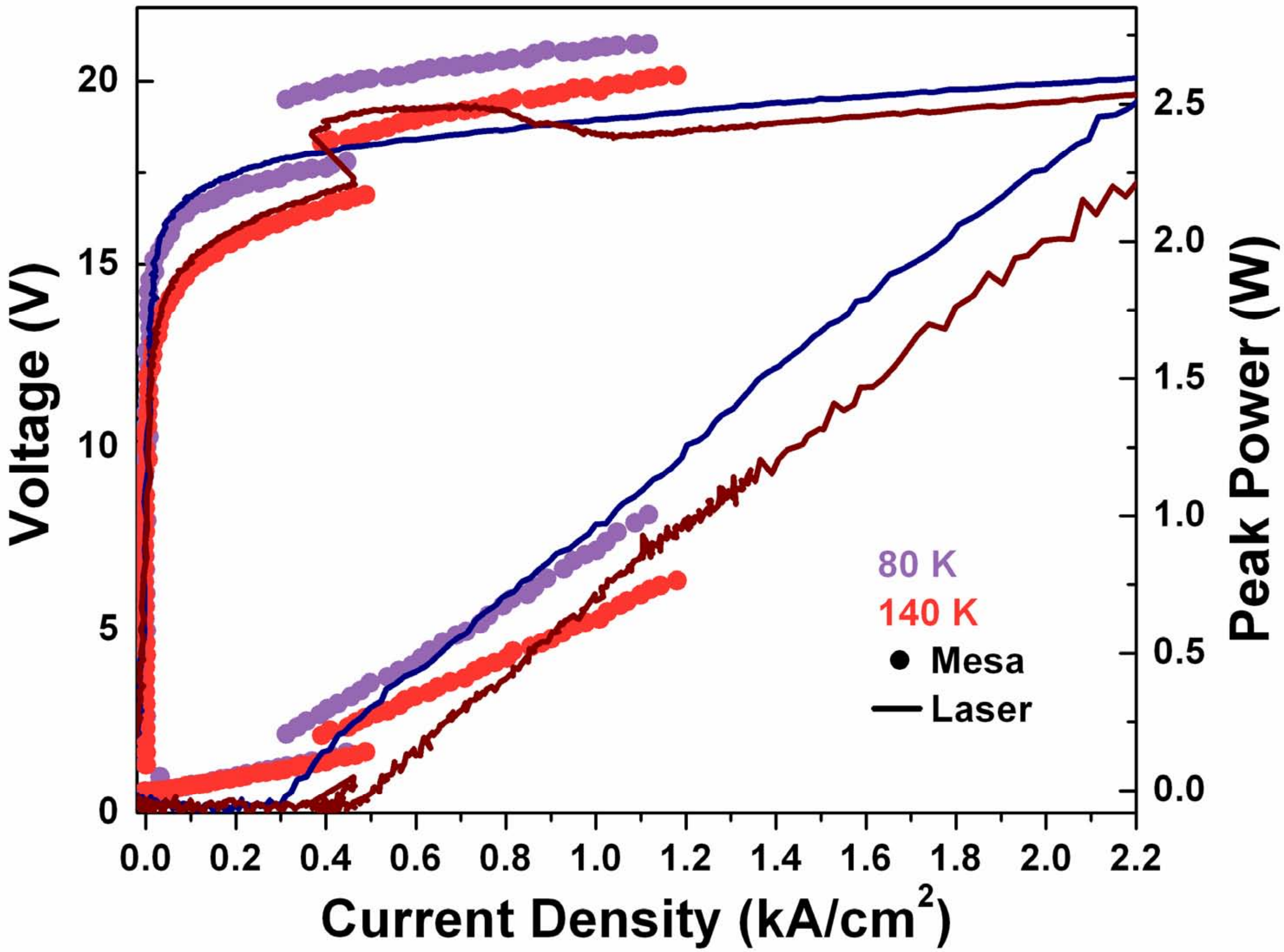


Light – Current – Voltage

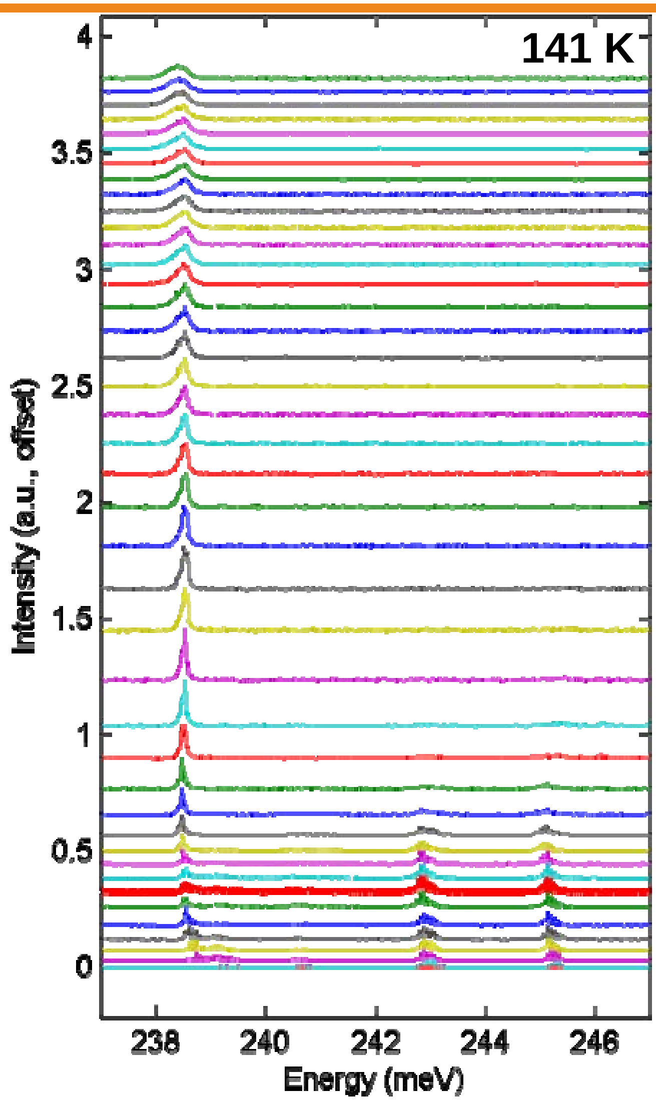


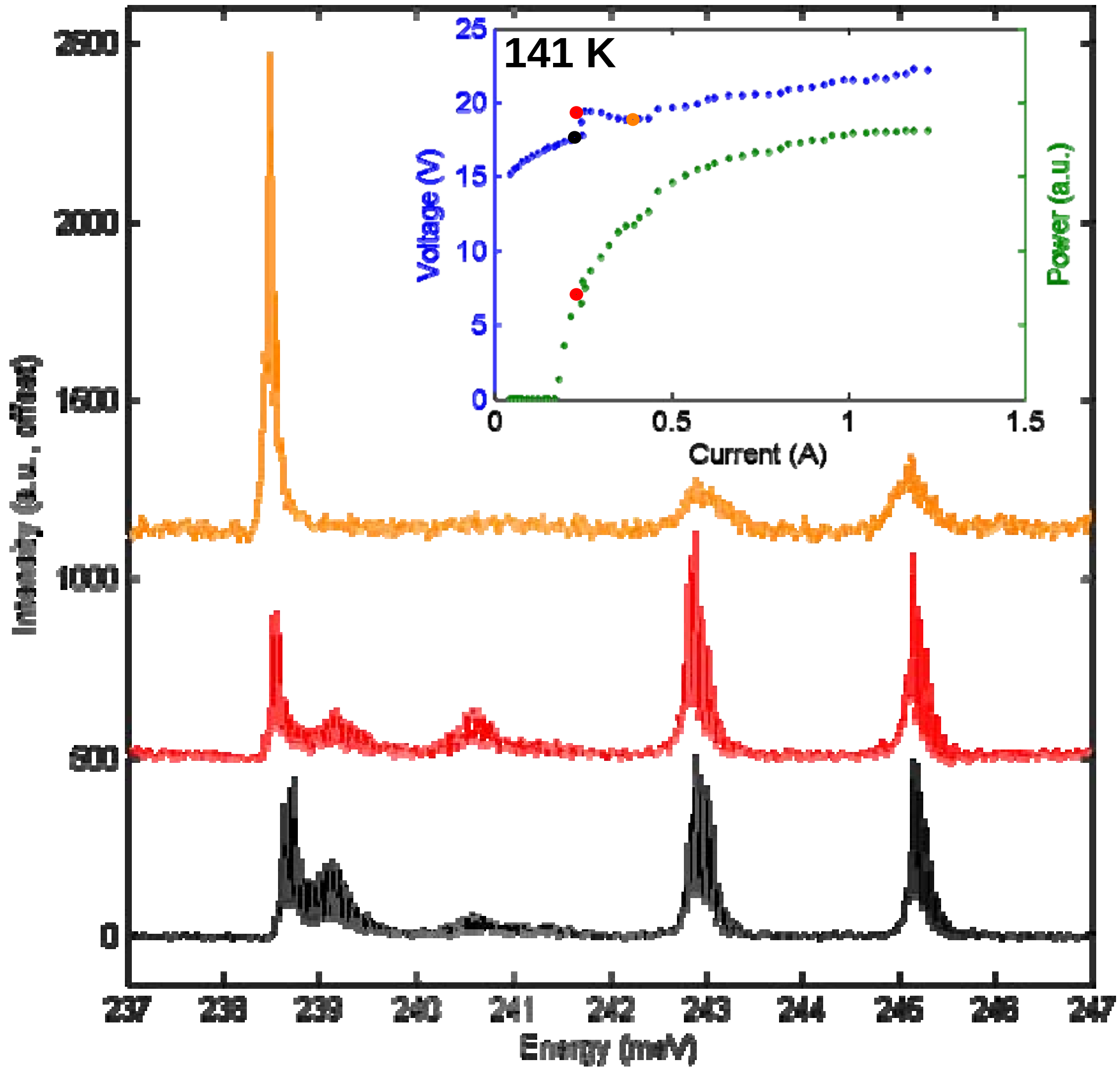
3 injector wells

Laser & Mesa Comparison



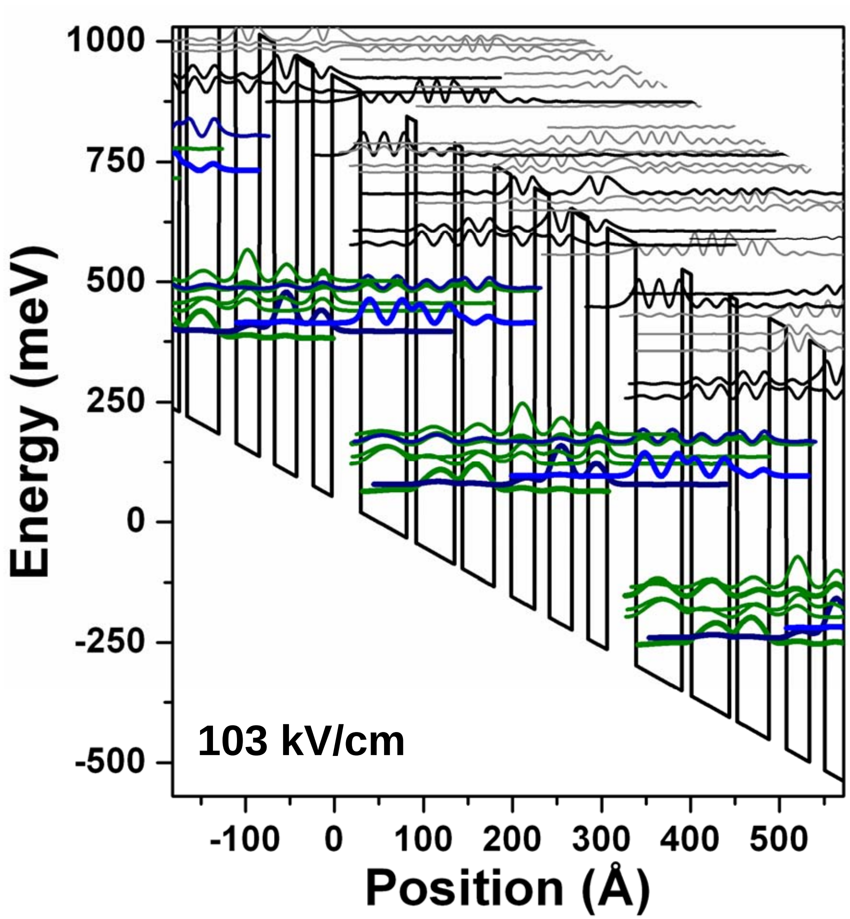
Spectra

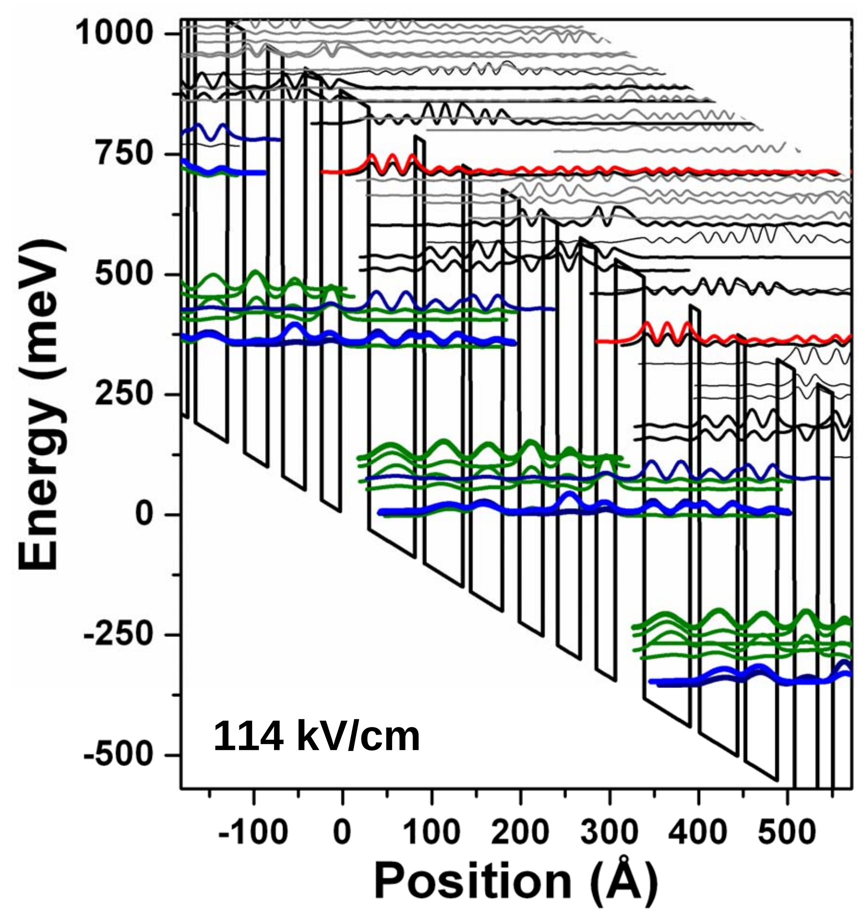

141 K
Intensity (a.u., offset)
Energy (meV)
0
0.5
1
1.5
2
2.5
3
3.5
4
238
240
242
244
246


141 K
Voltage (V)
Power (a.u.)
Current (A)
Intensity (a.u., offset)
Energy (meV)

3 injector wells

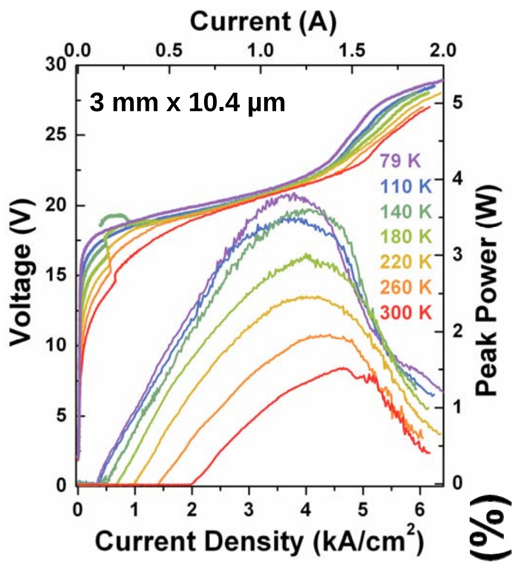
Band Diagrams

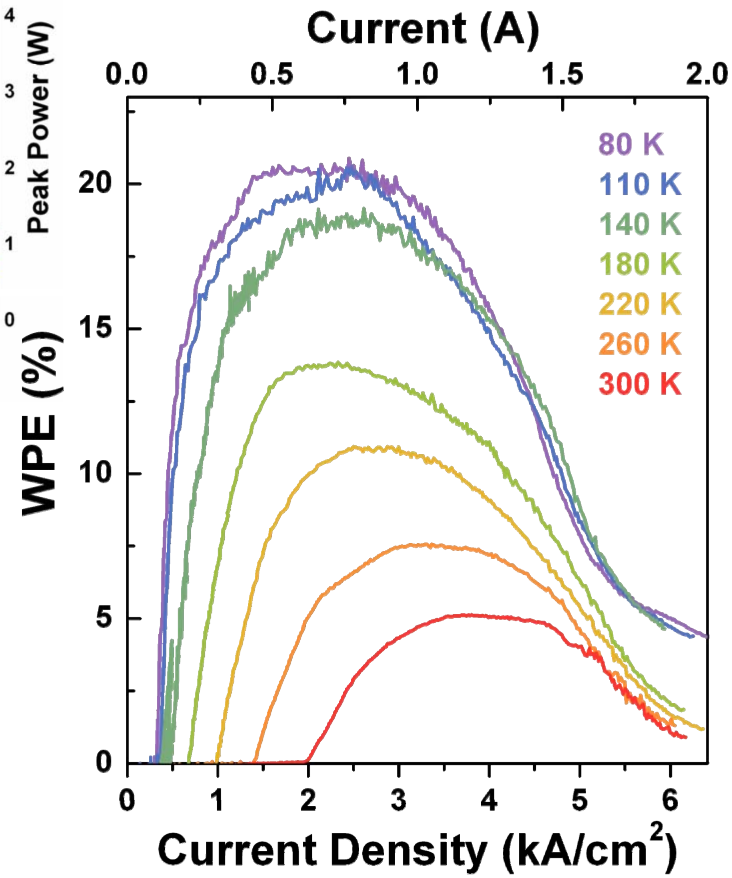


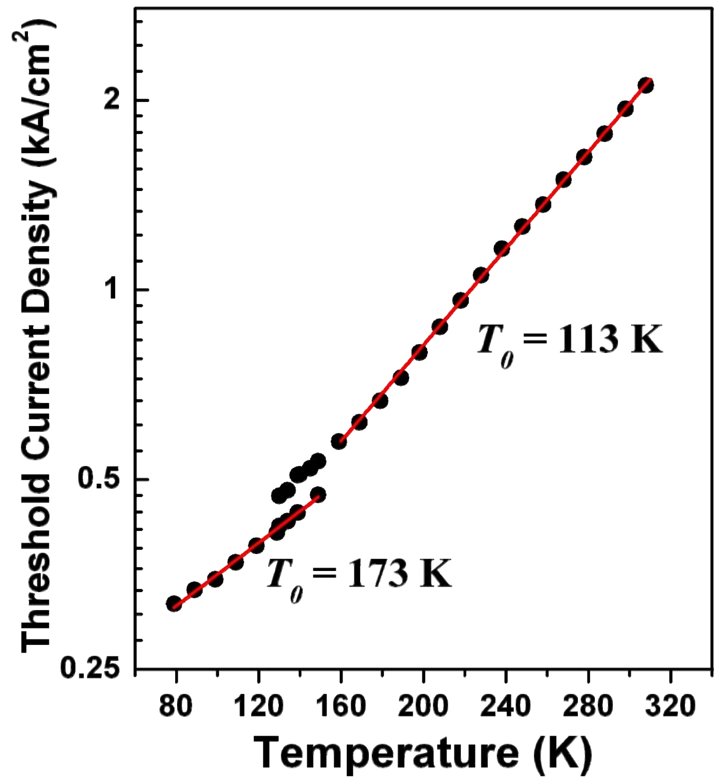


Light – Current – Voltage

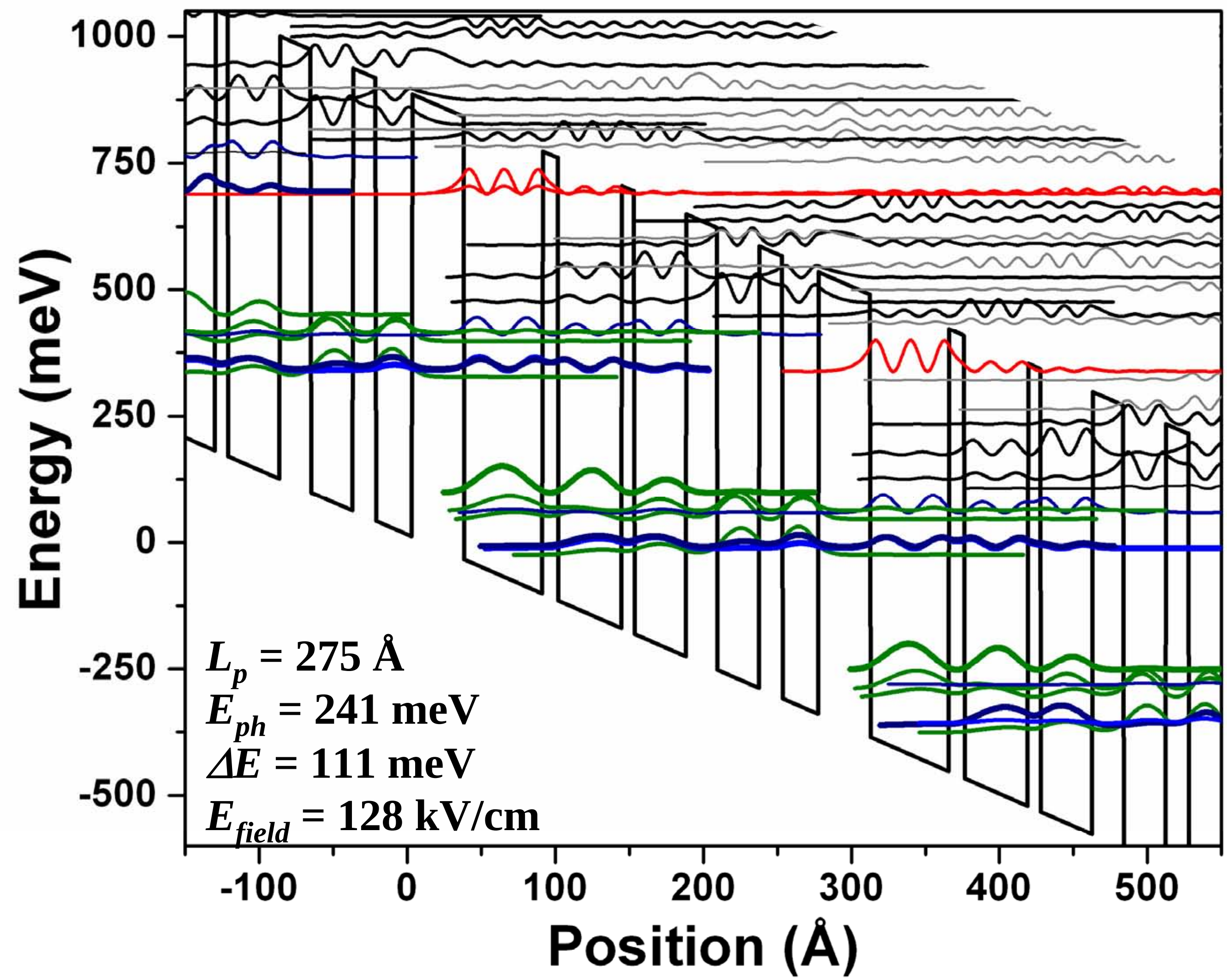
3 injector wells



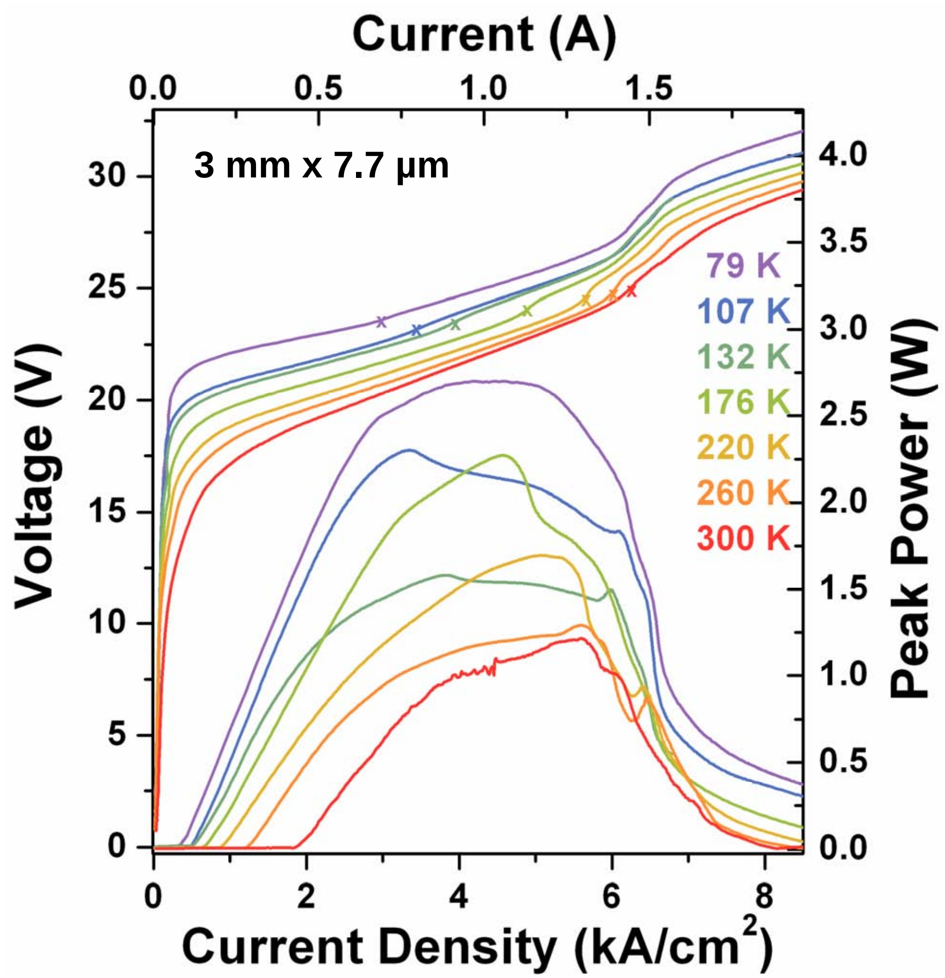


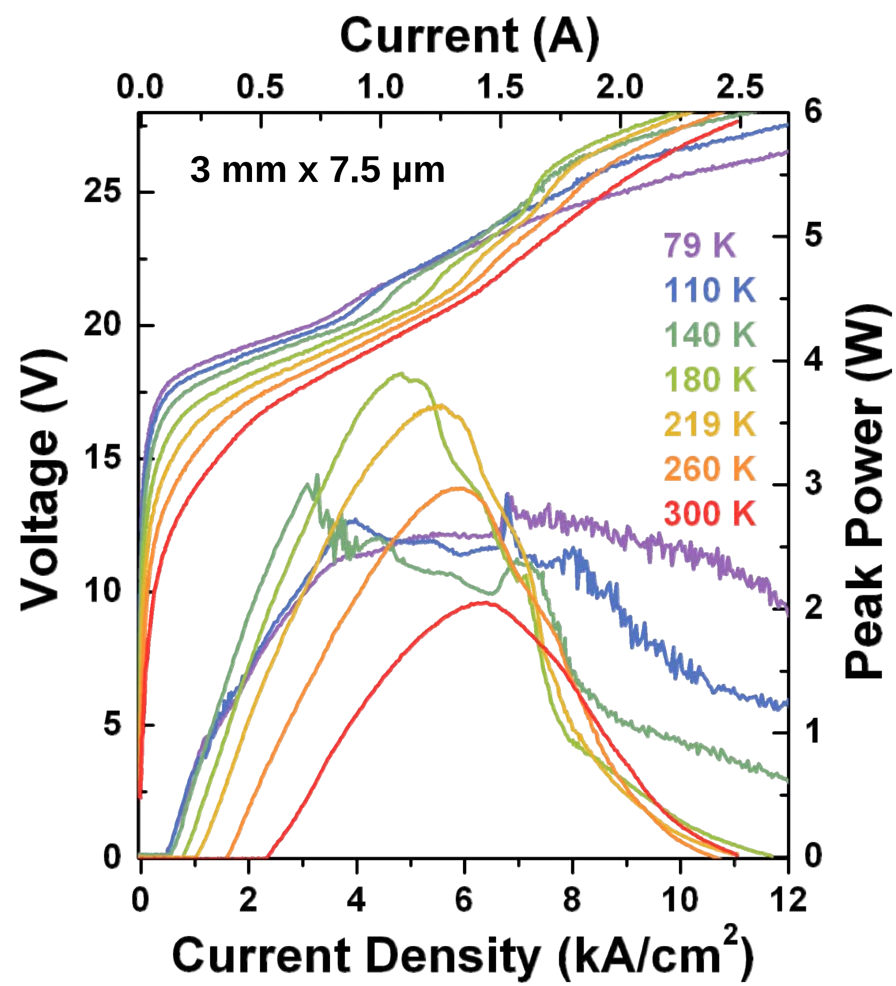


Two Injector Wells



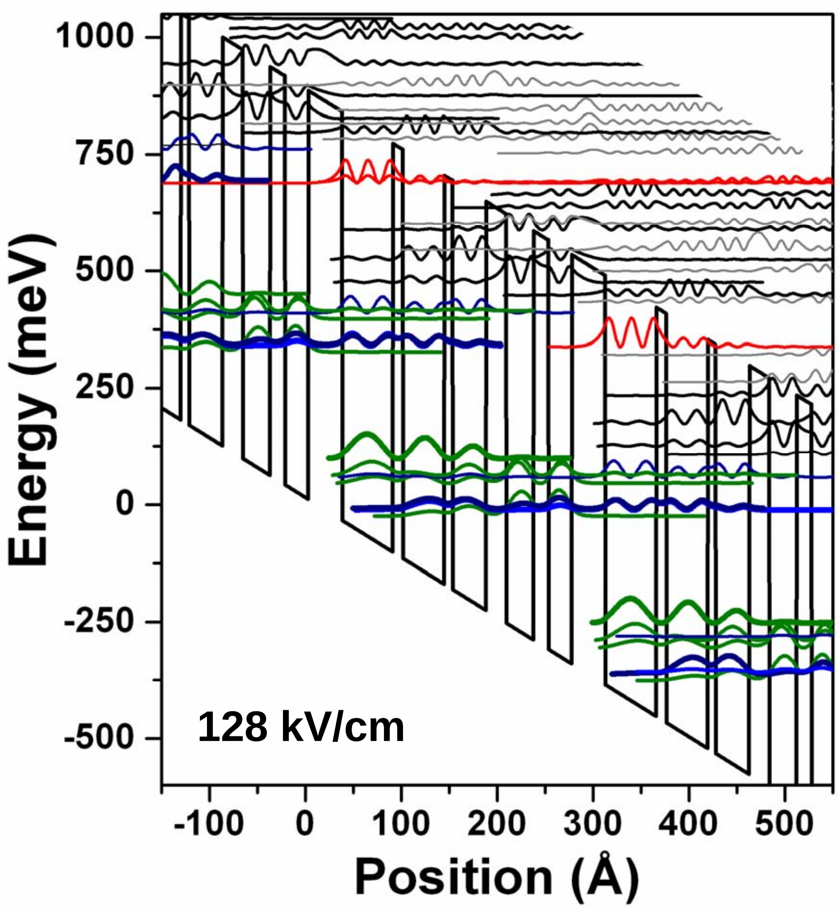
LIV

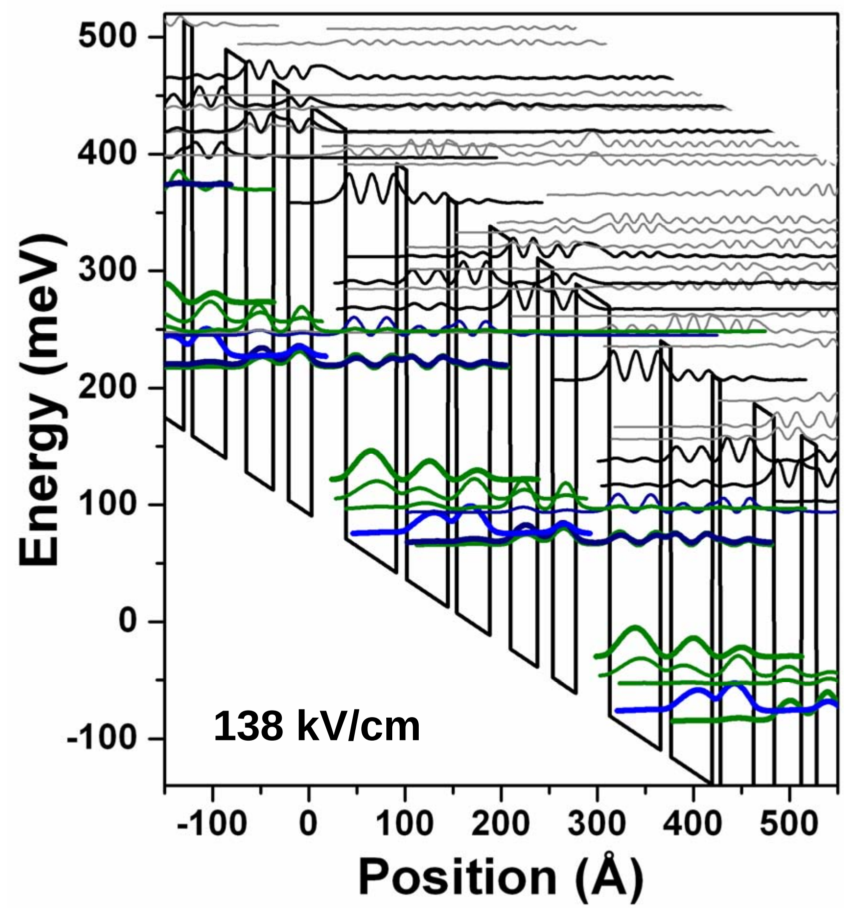

Current (A)
0.0
0.5
1.0
1.5
3 mm x 7.7 µm
Voltage (V)
Peak Power (W)
79 K
107 K
132 K
176 K
220 K
260 K
300 K
Current Density (kA/cm2)


Current (A)
0.0
0.5
1.0
1.5
2.0
2.5
3 mm x 7.5 µm
Voltage (V)
Peak Power (W)
79 K
110 K
140 K
180 K
219 K
260 K
300 K
Current Density (kA/cm2)

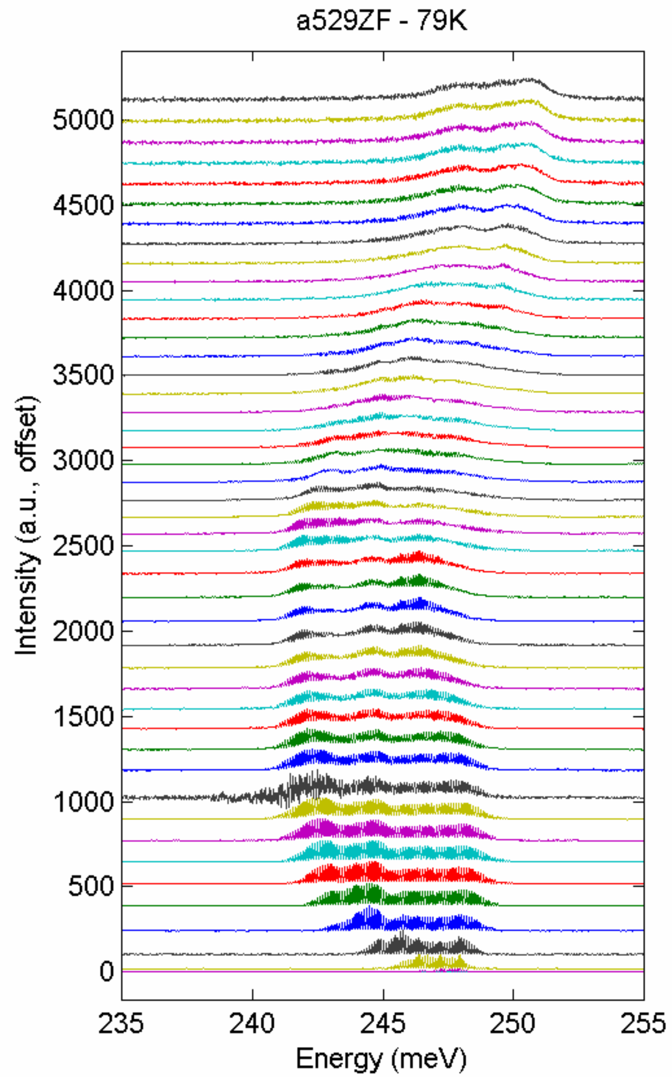
Band Diagrams

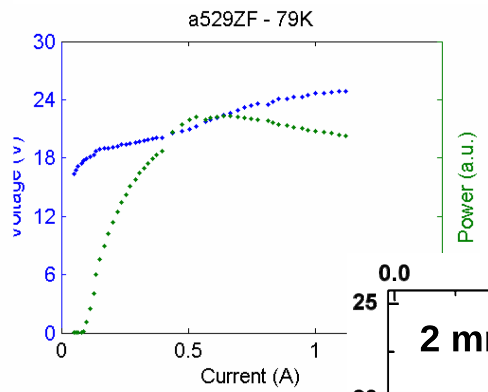
2 injector wells

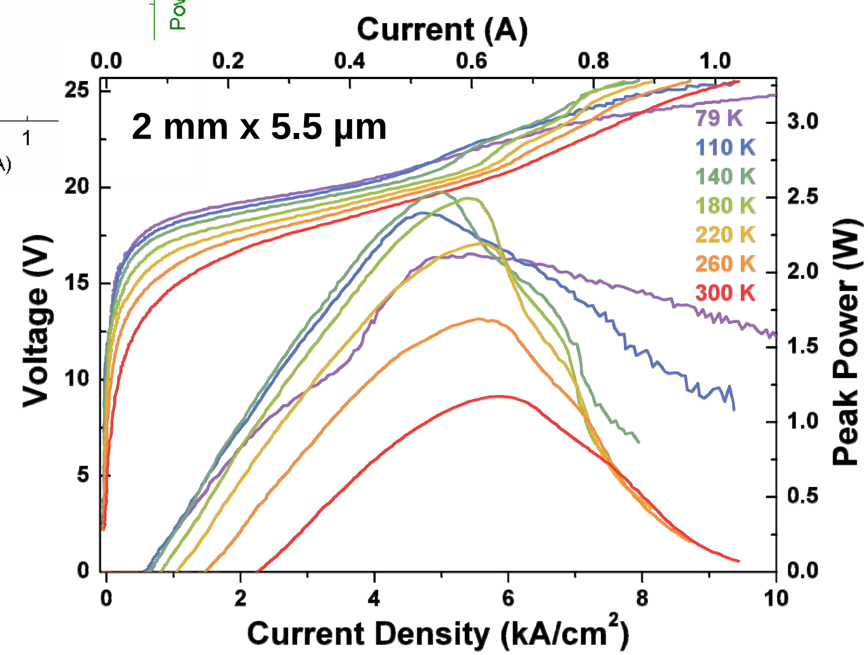




Spectra





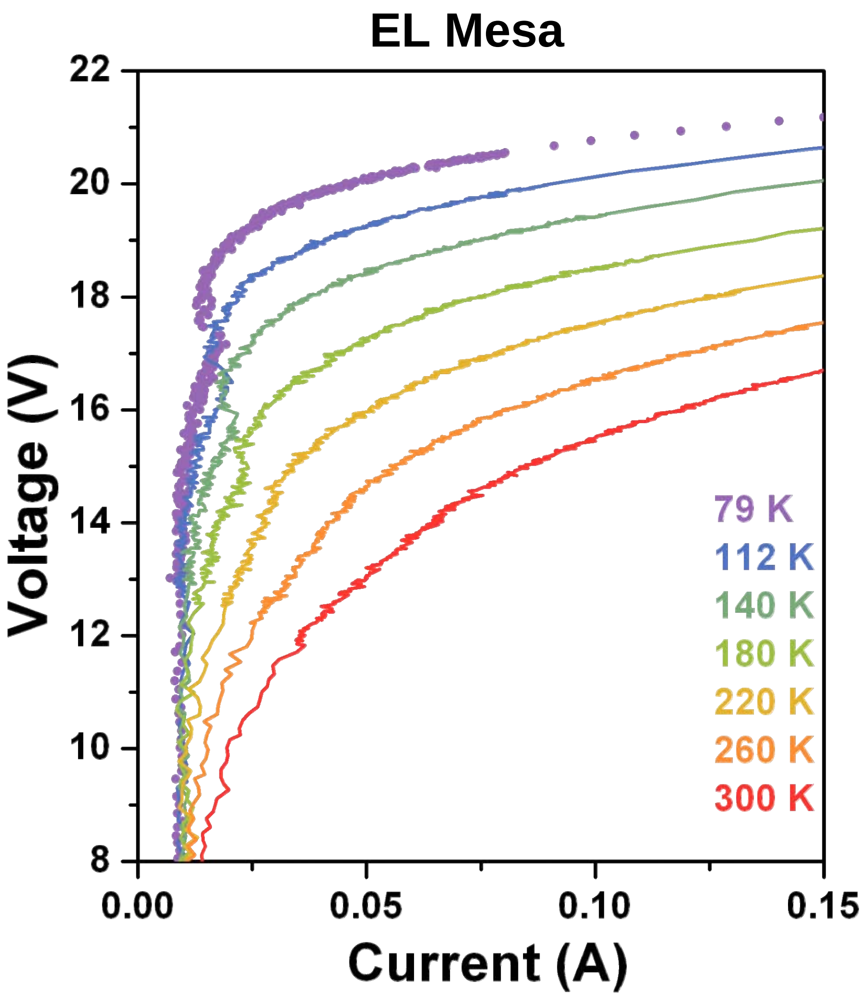


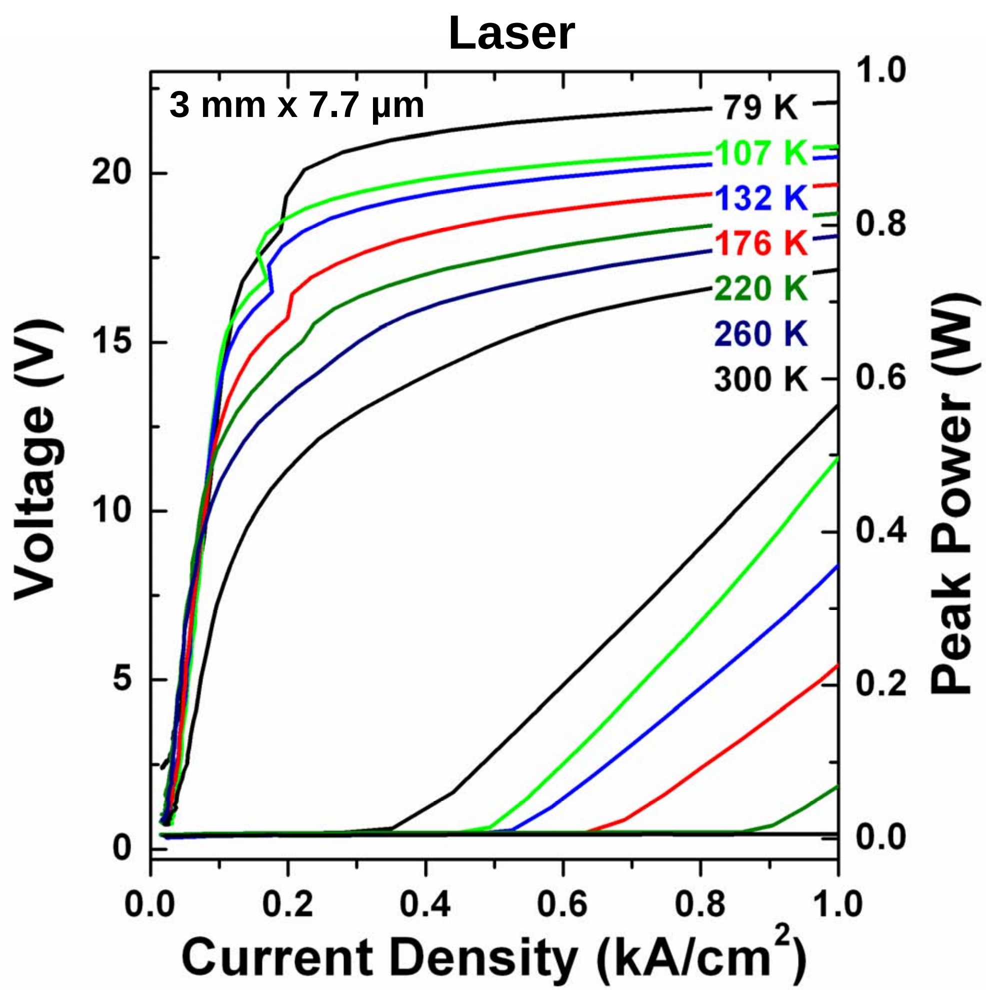
Poster

Y. Yao *et al.*,

"Voltage Tunability of Quantum Cascade Lasers"

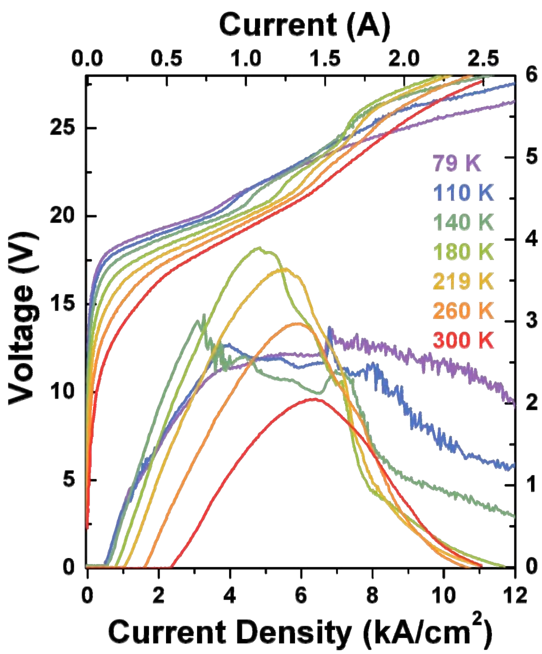
NDR

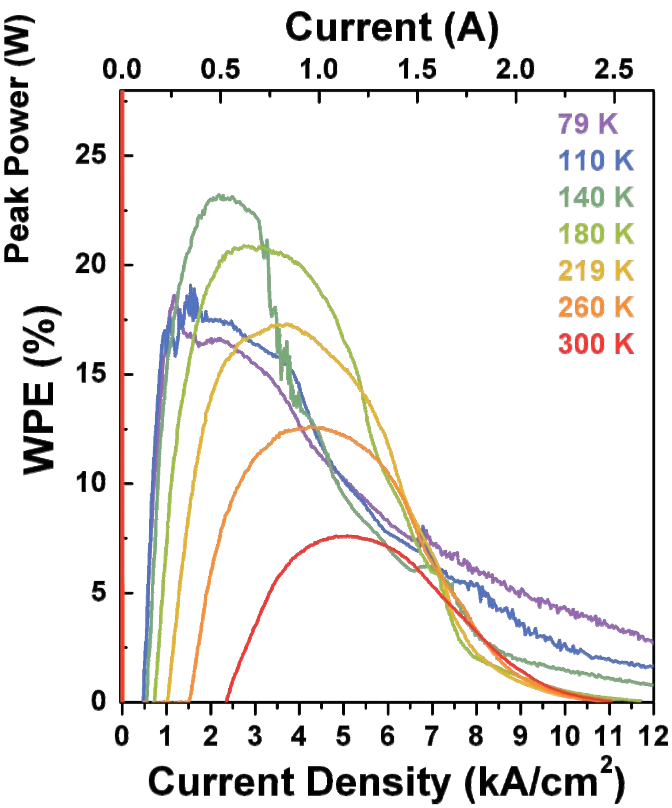

EL Mesa
Voltage (V)
Current (A)
79 K
112 K
140 K
180 K
220 K
260 K
300 K

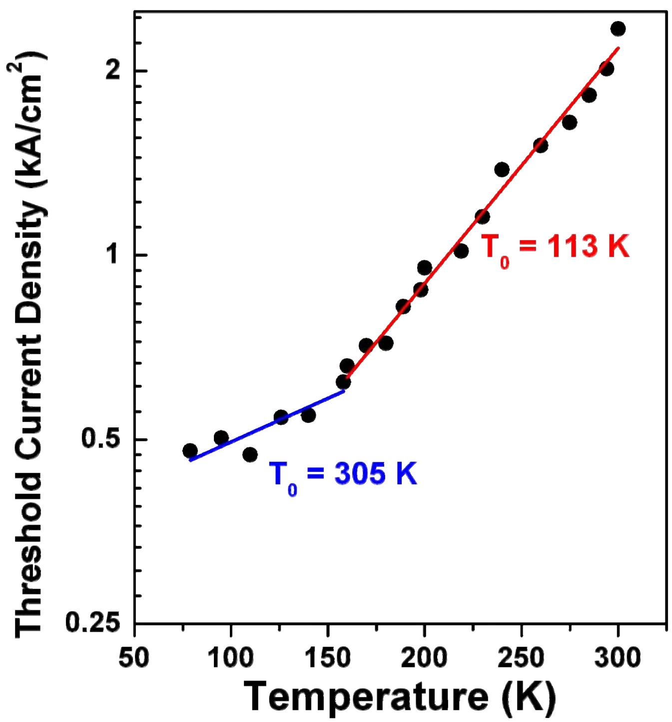

Laser
3 mm x 7.7 µm
Voltage (V)
Peak Power (W)
Current Density (kA/cm²)
79 K
107 K
132 K
176 K
220 K
260 K
300 K

2 injector wells

WPE & T_0







Data Summary

	4 well	3 well	2 well
N_p	30	50	50
L_p (Å)	416	309	275
E_{field} (kV/cm)	80	114	128
T_0 (K)	117	113	113
J_{th} (A/cm^2)	220	330	360
WPE (%)	11	21	23
η_{sl} (W/A)	1.5	4.4	5.0

Lessons Learned

- Short injectors as a strategy to higher performance QC lasers
- New design challenges
  - Parasitic current effects
  - Pulse stability
  - Injector/active region coupling