Inter-Valley Charge Transfer in Short-Wavelength InGaAs-AlAs Quantum-Cascade Lasers

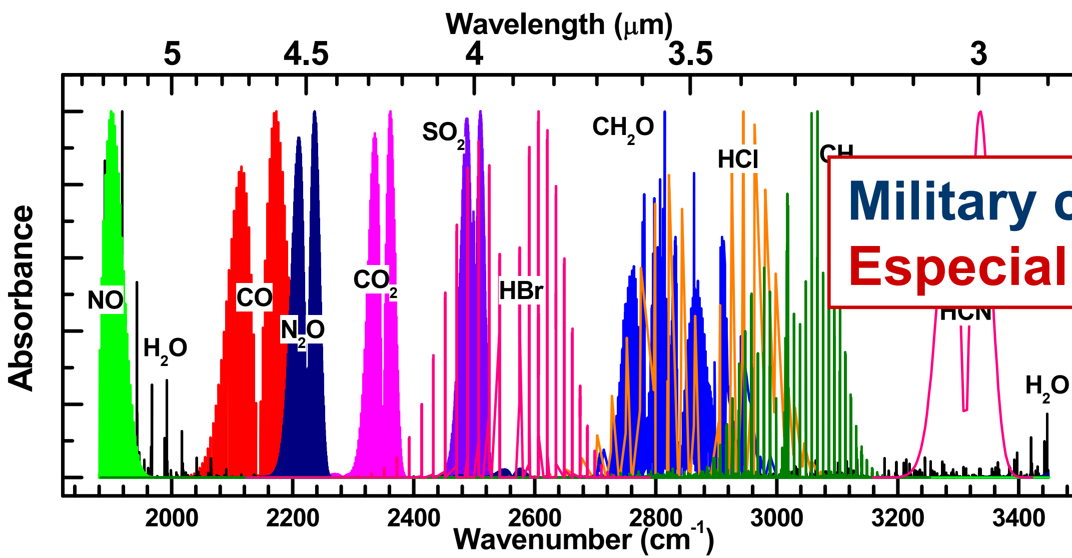
M.P. Semtsiv, M. Wienold, I. Bayrakli, S. Dressler, and W.T. Masselink

Humboldt-University, Berlin, Germany

“Short wavelength QCLs” emit in 1st atmospheric window, 3–5 µm.

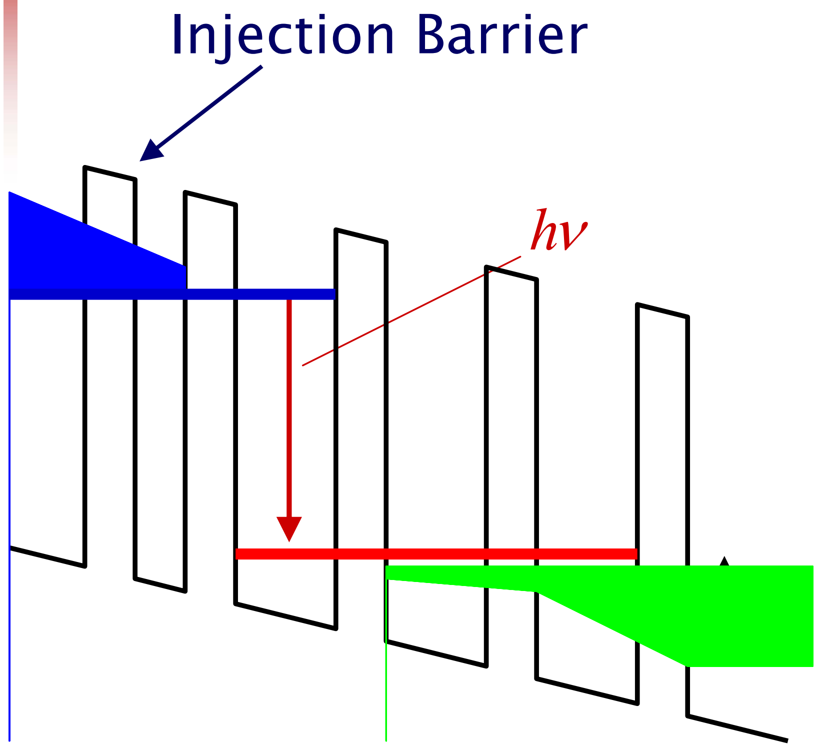
Gas detection:
- Environmental
- Medical diagnoses

Mid-IR imaging (medical)



Military countermeasures :
Especially 3.8–4.2 µm

Short wavelength emission requires a large ΔE_c.



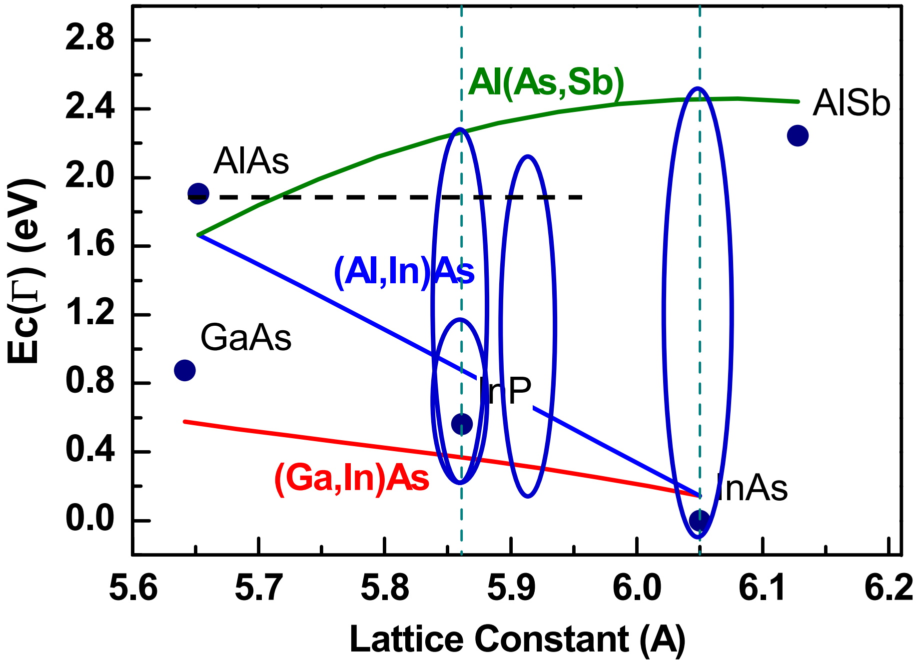
- Large ΔE_c for large $h\nu$
- High injection barrier to prevent thermal escape over top
- Minimize thermal backwash

For LIR QCLs,

$$h\nu \approx \frac{\Delta E_c}{2}$$

HUMBOLDT-UNIVERSITÄT ZU BERLIN

A large ΔE_c can be achieved in several direct-band-gap III-V heterosystems.



InAs-Al(As,Sb)
$\Delta E_c \approx 2.1$ eV

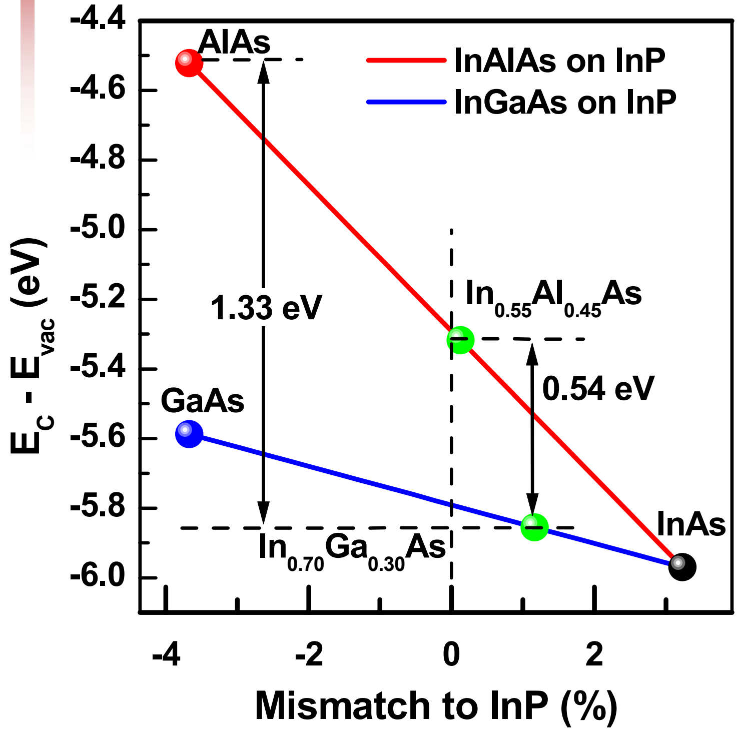
(Ga,In)As-Al(As,Sb)
$\Delta E_c \approx 1.6$ eV

(Ga,In)As-(Al,In)As
$\Delta E_c \approx 0.53$ eV

$\boxed{\textbf{(Ga,In)As-AlAs} \quad \Delta E_c \approx 1.3 \text{ eV}}$

Composite Barriers based on AlAs ⇒ independent control of energy and strain

Replace the AlAs with $In_{0.55}Al_{0.45}As$ + AlAs

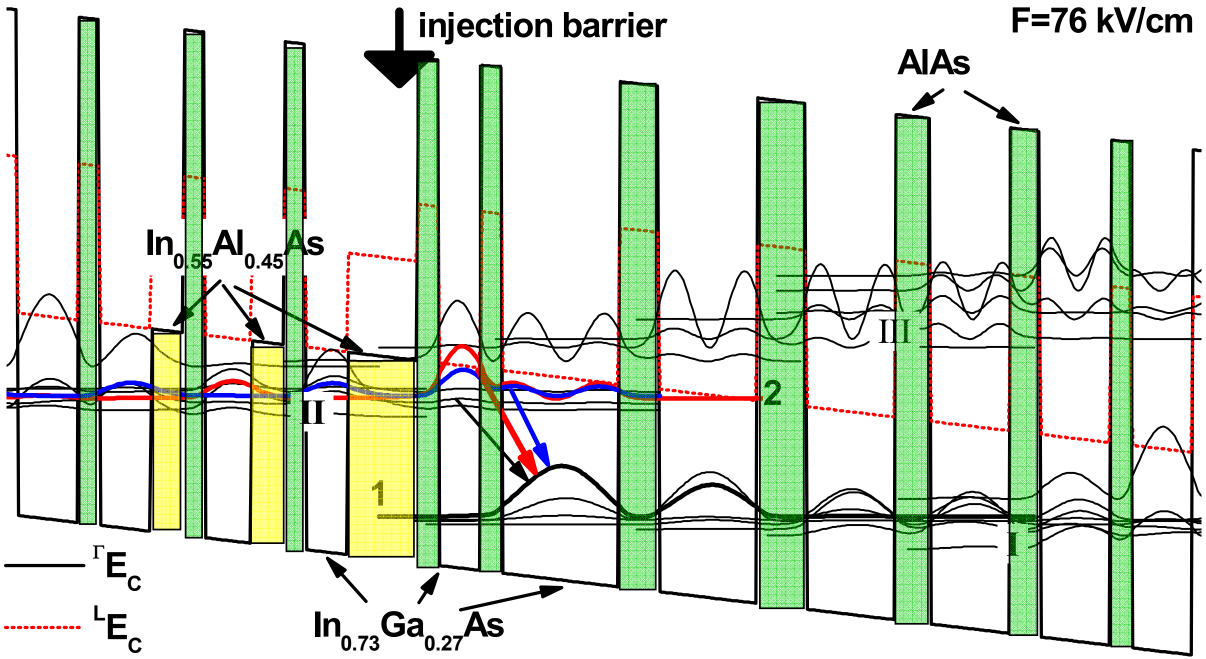


Addition of $In_{0.55}Al_{0.45}As$

- shrinks miniband
- partially compensates for thicker AlAs
- independent control of confinement and strain

Can also use AlAs with addition of Al(As,Sb).

Primary barrier material is AlAs

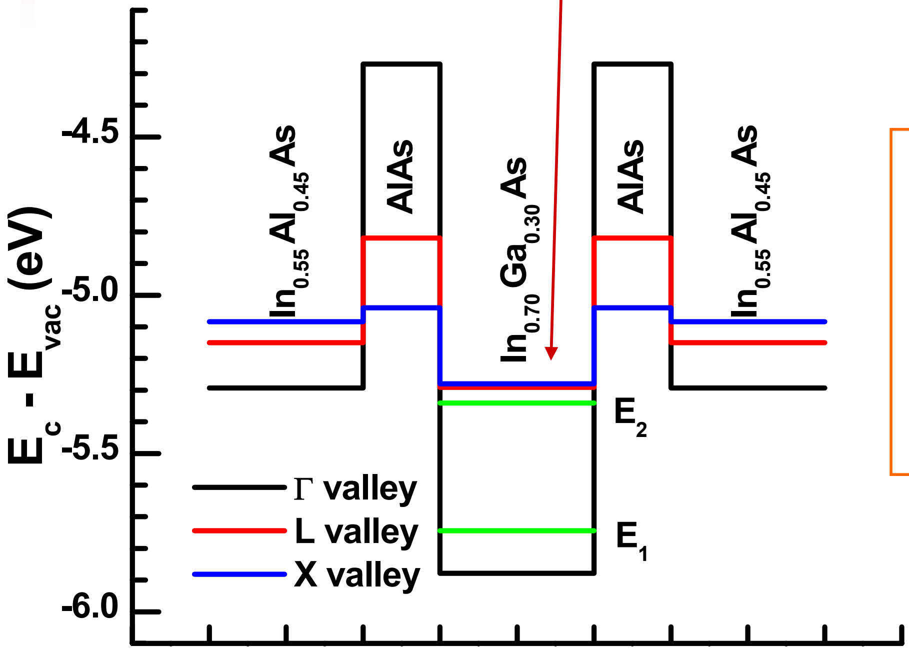


Modified "bound-to-bound" design

The emission wavelength is limited by the indirect valleys in the well, not by ΔE_c.

E_2 is limited by the indirect valleys in the InGaAs wells.

Max E_2-$E_1 \cong 0.37$ eV
(3.3 μm)

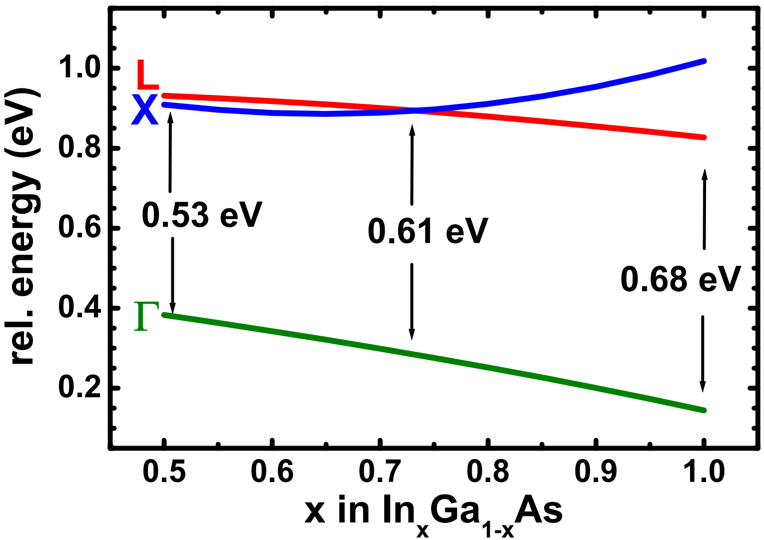


Question:
How far above the indirect valleys can the upper laser state be located?

Strategy #1: $In_xGa_{1-x}As$ with $x \approx 0.72$

(large indirect-Γ energy separation with moderate strain)

The indirect-Γ separation increases with In content. The maximum transition energy increases correspondingly.

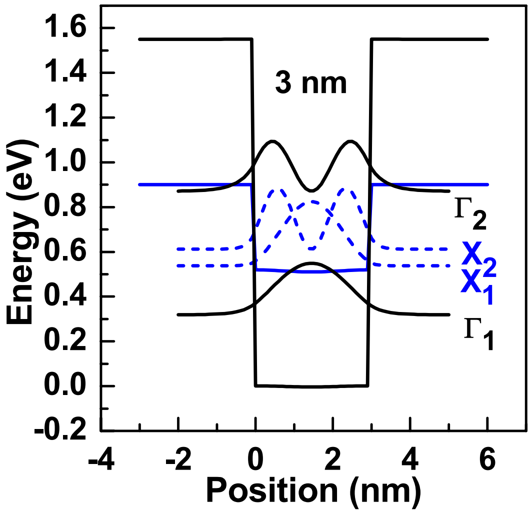


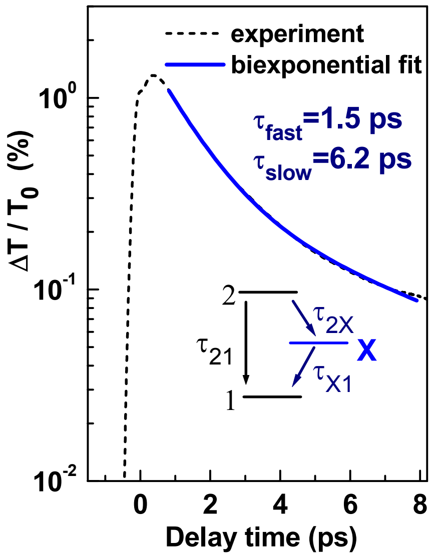
$$0.53\text{eV} \Rightarrow \lambda_{min} \approx 3.8\ \mu\text{m}$$
$$0.61\text{eV} \Rightarrow \lambda_{min} \approx 3.3\ \mu\text{m}$$
$$0.68\text{eV} \Rightarrow \lambda_{min} \approx 2.9\ \mu\text{m}$$

For relaxed InAs, $\lambda_{min} \approx 2.7\ \mu\text{m}$.

Strategy #2: Rely on poor coupling between Γ and X.

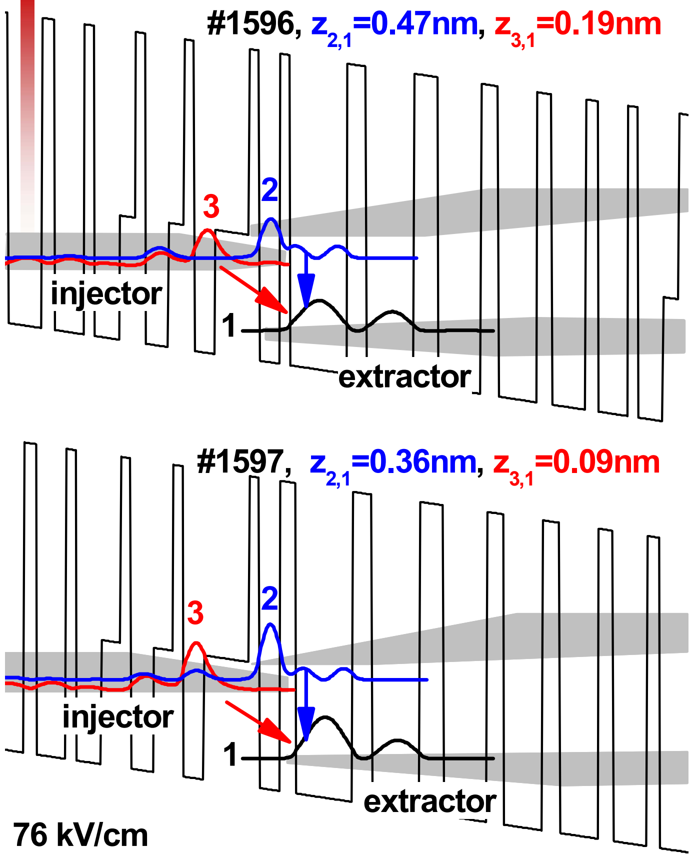
Relaxation from Γ_2 directly to Γ_1 is 4 times faster than via the X valleys.





(H. Schneider's Thursday Poster)

Strategy #3: Move the upper laser state away from the indirect valleys



"Diagonal" transitions can increase the emission energy through the Stark effect.

Thin injection barrier ⇒ lasing is 2→1 (vertical).

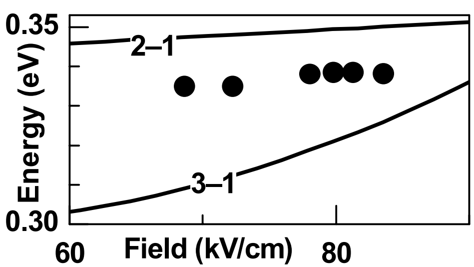
Thick injection barrier ⇒ lasing is 3→1 (diagonal).

Diagonal upper laser state less well coupled to indirect valleys in QW.

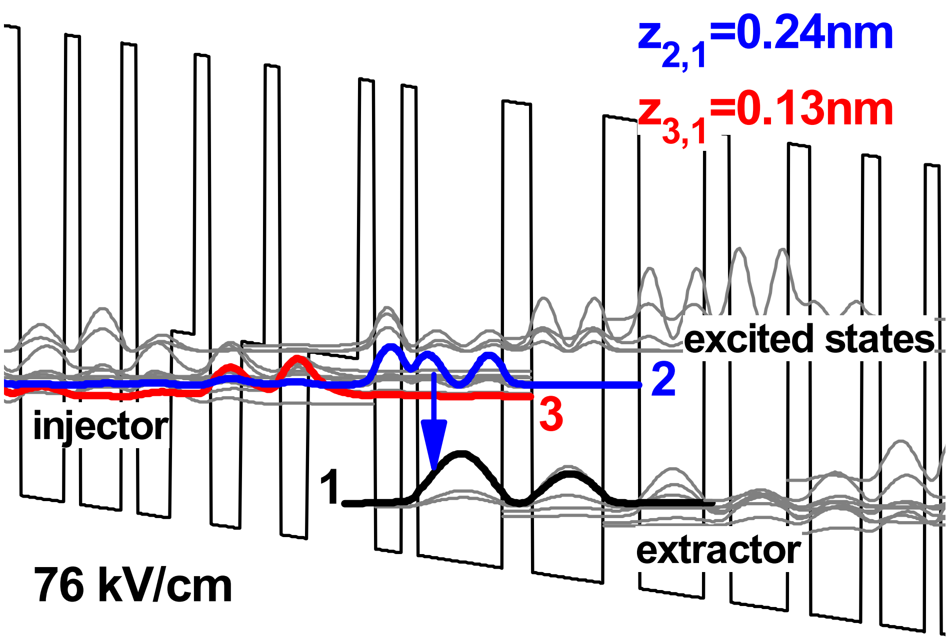
Strong coupling and vertical transitions makes the best lasers for moderate wavelength.

short wavelength:
77K: 3.6–3.8 μm
300K: 3.8–3.9 μm

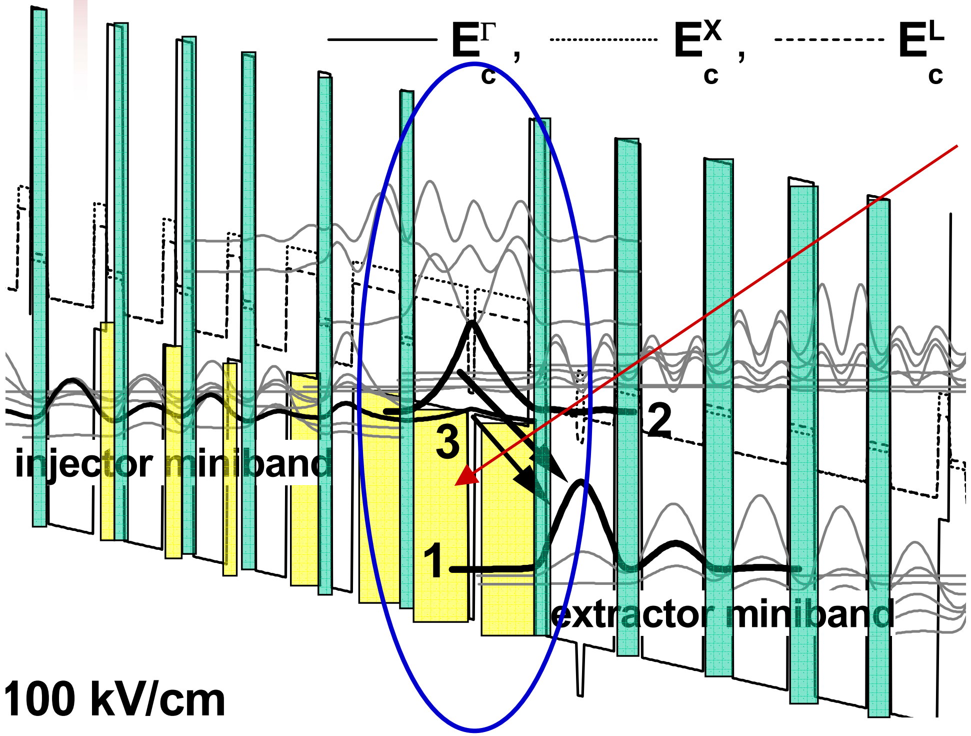
low thresholds:
77K: 0.6 kA/cm²
300K: 3.8 kA/cm²



The structure was designed for 3.6 μm based on the injection miniband lasing into state 1.



Strategy #4: Change well material for upper laser state

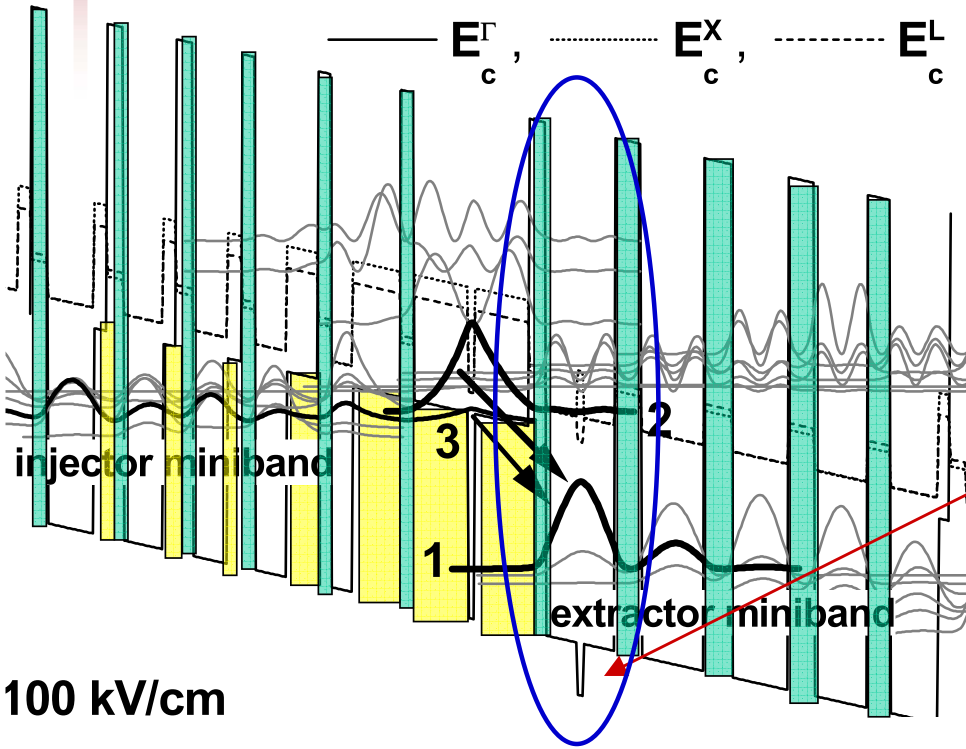


Upper laser states mostly located in AlInAs.

Upper laser states are high in energy and <u>not</u> well coupled to indirect valleys in lower QW.

Strategy #5: InAs insert in QW with lower laser state

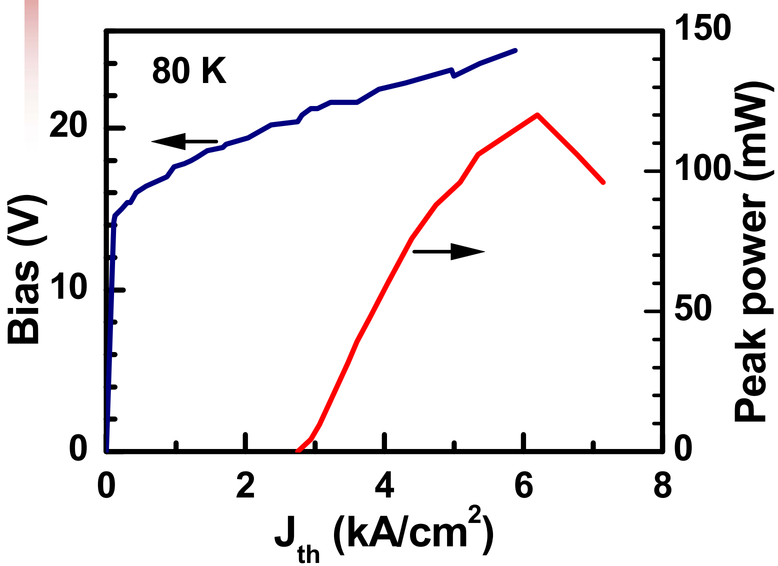
This design emits at 3.05 µm.

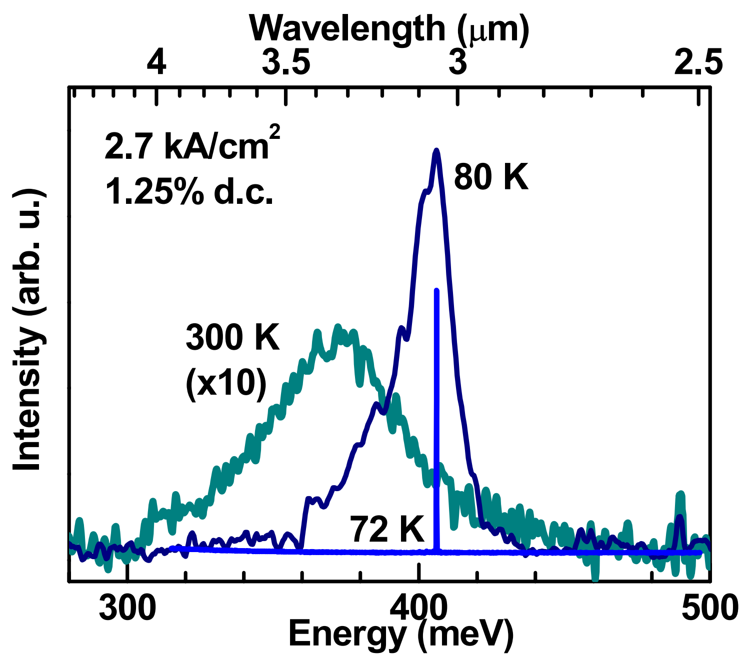


InAs insert lowers lower laser state, increasing the transition energy.

QW with lower laser state contains InAs insert.

The 3.05-µm QCL emits >100 mW power at 80K, but operates only up to 150K.

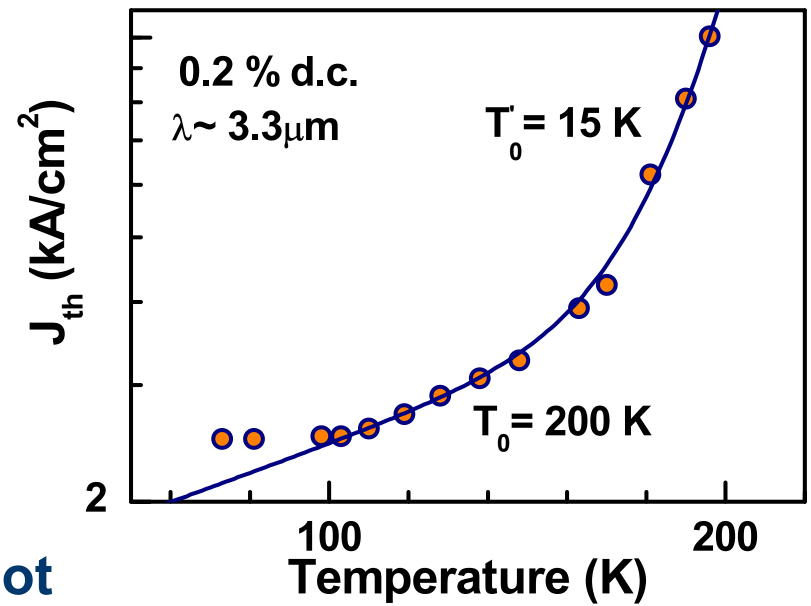




A similar design for 3.3 µm emits up to 600 mW and operates to 200K.

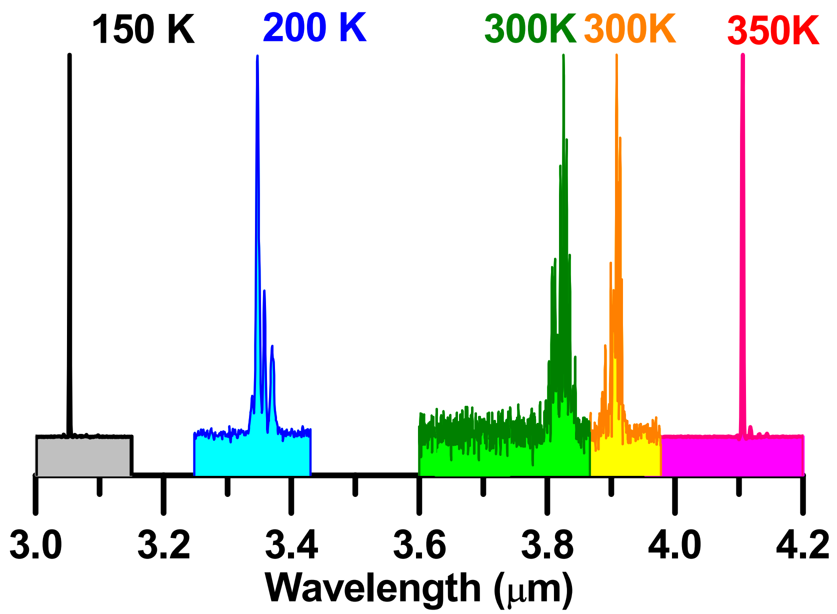
Short wavelength designs have difficulties at elevated temperatures.

Steep increase in J_{th} beginning at 150K is probably due to scattering into the indirect valleys.



The indirect valleys do not prevent lasing, but still have adverse effects.

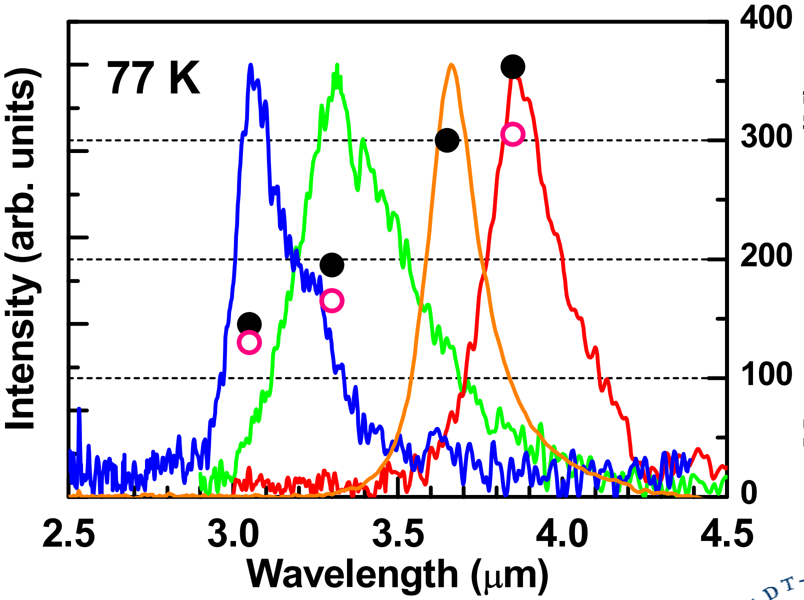
These design strategies allow QCL emission over the entire 1st atmospheric window.



QCL spectra taken at T_{max} for different designs.

Both the maximum temperature of operation and the onset of low T_0 decrease with emission wavelength.

The trend of steadily decreasing temperature for the onset of low T_0, despite many changes to the active region, implies that the culprit is the indirect valleys.



Extrapolating these results implies an ultimate limit of about 2.7 μm.

Summary

- For large enough ΔE_c , it is the indirect valleys of the well material that limit emission wave length.
- New design features to avoid emptying upper laser state into InGaAs indirect valleys – the upper laser state can be higher.
- QCLs to 3.6 µm: RT lasing, high efficiencies and T_0
- Record of 3.05 µm recently achieved
- QCLs limited by indirect valleys to about <3.0 µm (1st atmospheric window covered)