Gain Engineering with Additional Interface Roughness Scattering in Quantum Cascade Lasers

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MOTIVATION

In theory…

Interface roughness
- Roughness that occurs between the different layers within the band structure

Intersubband scattering
- Scattering of electrons caused by random reflection off the rough surface

Population inversion
- Concentration gradient generated by a low concentration of electrons in the lower laser state when compared to the higher laser state

Gain
- Quantity of amplification of light generated from the material

QUANTUM WELL DESIGN

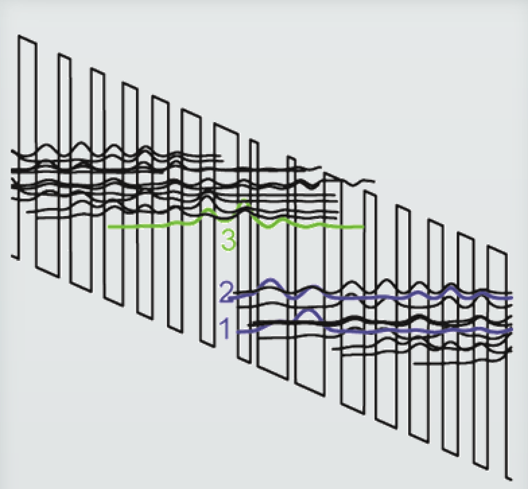


Fig. 1 Schematic for the baseline sample. This design lacks additional monolayer barriers within its band structure. This design is the control sample when calculating gain and slope efficiency.

Level/ transition	τ (ps)	$\propto \tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)$ (ps)	$\propto \frac{\tau_{eff}}{\tau_{eff}+\tau_2}$
3	0.39	0.22 Gain	0.48 Slope Efficiency
3→2	0.56		
2→1	0.25		

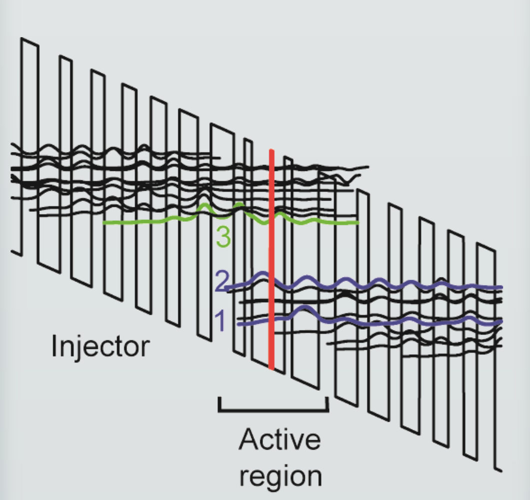


Fig. 2 Schematic for the low inversion sample. This design possesses an additional monolayer barrier within its band structure which primarily affects the upper laser state. **Notice the 40% decrease in gain when compared to the baseline.**

Level/ transition	τ (ps)	$\propto \tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)$ (ps)	$\propto \frac{\tau_{eff}}{\tau_{eff}+\tau_2}$
3	0.24	0.14 Gain	0.5 Slope Efficiency
3→2	0.33		
2→1	0.14		

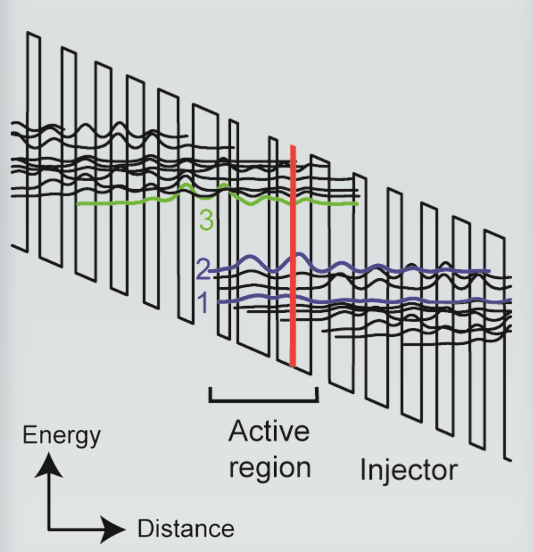


Fig. 3 Schematic for the fast depopulation sample. This design possesses an additional monolayer barrier within its band structure which primarily affects the lower laser state. **Notice the 60% increase in slope efficiency when compared to the baseline.**

Level/ transition	τ (ps)	$\propto \tau_3\left(1-\frac{\tau_2}{\tau_{32}}\right)$ (ps)	$\propto \frac{\tau_{eff}}{\tau_{eff}+\tau_2}$
3	0.33	0.28 Gain	0.78 Slope Efficiency
3→2	0.57		
2→1	0.09		

RESULTS/DATA ANALYSIS

Baseline | **Low Inversion** | **Fast Depopulation**

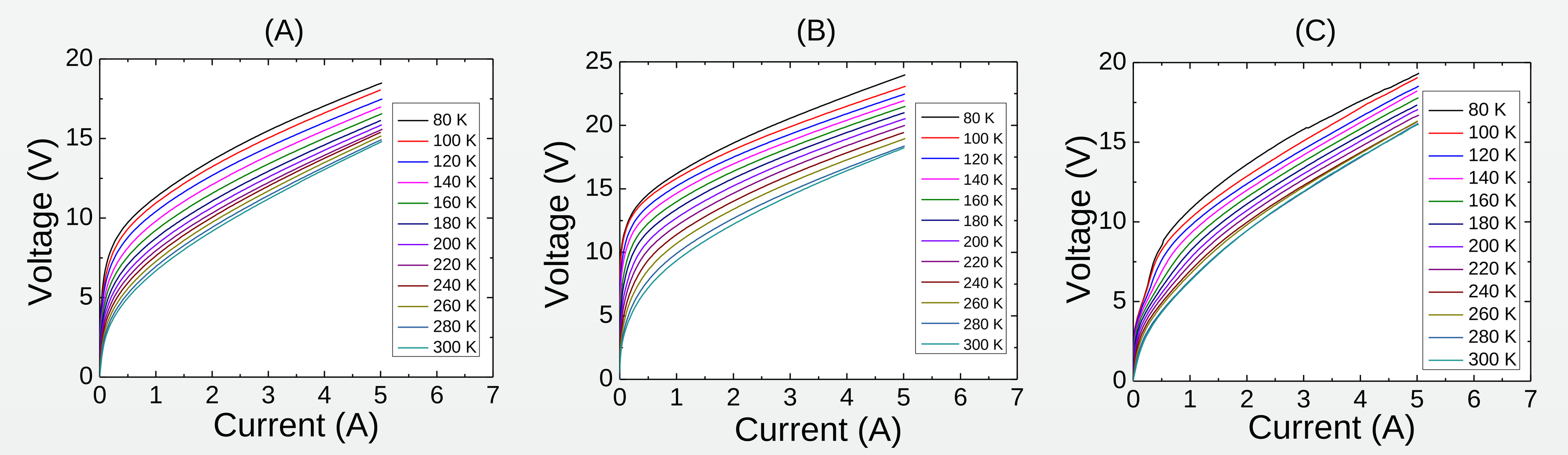


Fig. 4 Voltage versus current plot of various temperatures for the baseline sample (**A**), the low inversion sample (**B**), and the fast depopulation sample (**C**).

- Lines do not intersect throughout the entire temperature range for all samples
- Same conditions maintained for all measurements (eg. cryostat, resistors, cables)

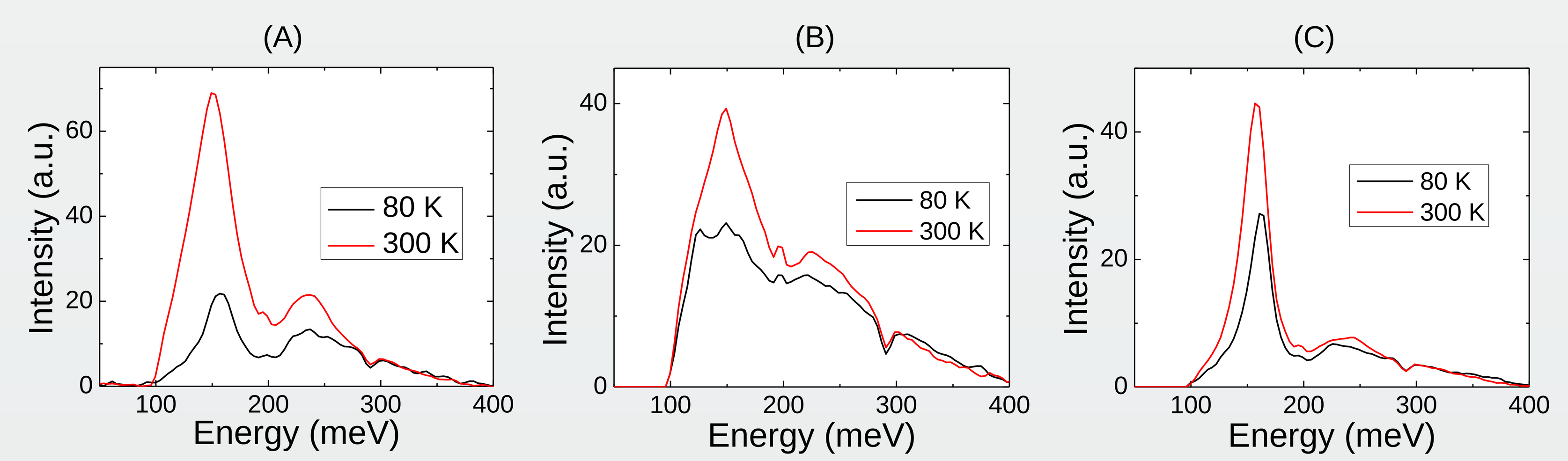


Fig. 5 Electroluminescence plot temperatures at 80 K and 300 K for the baseline sample (**A**), the low inversion sample (**B**), and the fast depopulation sample (**C**).

- Maintained same settings throughout the experiment (eg. sensitivity, cryostat, detector)

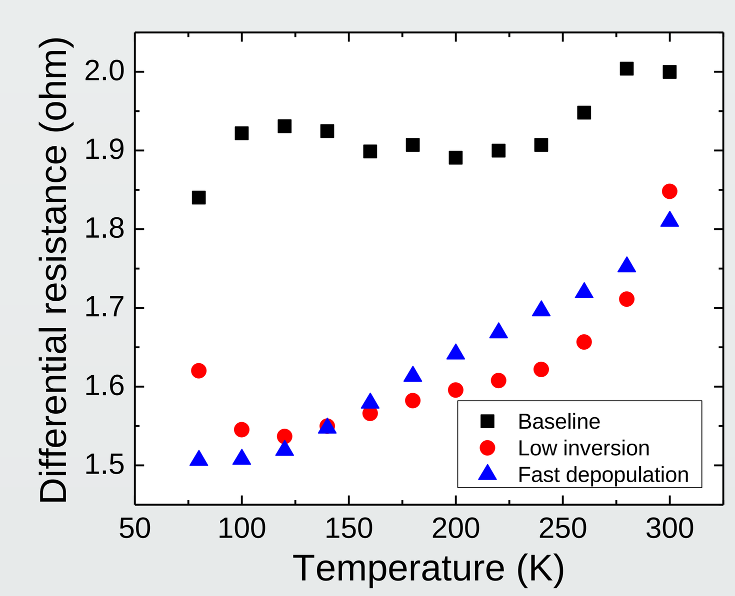


Fig. 6 Comparison of differential resistance with respect to temperature for the three samples. Differential resistance was derived from current versus voltage plots.

- **Differential resistance** is defined as $\frac{\Delta\, Voltage}{\Delta\, Current}$
- Differential resistance affects the speed at which carriers travel through the structure
- **Low differential resistance makes it easier to transport an electron**

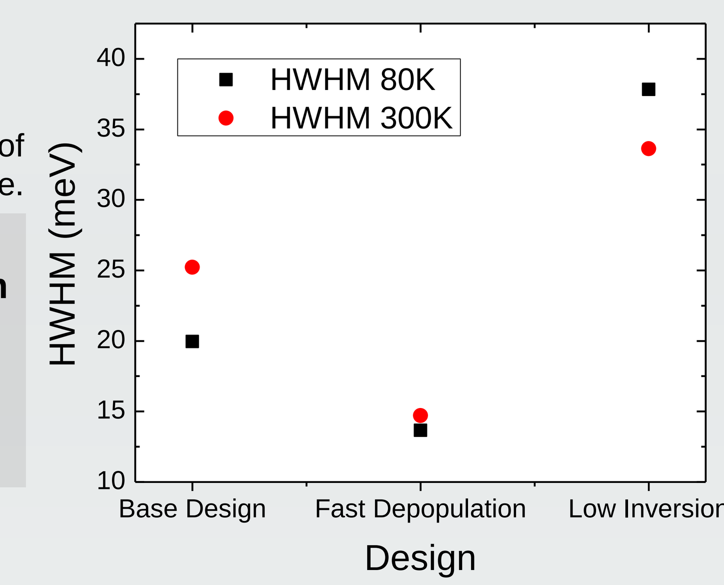


Fig. 7 Comparison of half width-half maximum (HWHM) of the peak intensity with respect to each sample.

- **Area under the peak intensity curve is directly correlated to light being passed from the device**
- Smaller HWHM suggests that, although the width of the peak intensity curve is small, its area is compensated by the height of the curve

CONCLUSIONS

To increase optical gain,

$$gain = (N_3 - N_2)\,\sigma(\nu)$$

Equation that relates gain to population inversion and transition cross section

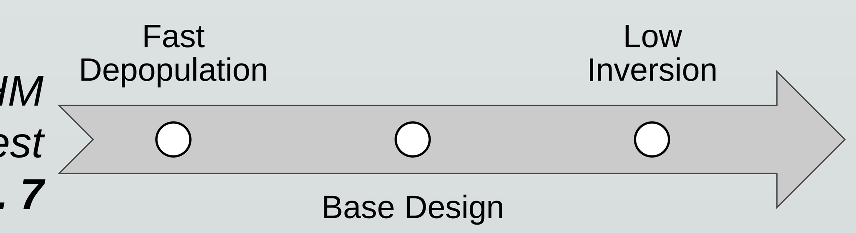
Increase Transition Cross Section

$$\sigma(\nu) = \frac{2\pi e^2 z_{32}^2}{\lambda_0 \epsilon_0 n} \times \frac{1}{\gamma_{32}}$$

$$transition\ cross\ section = const. \times \frac{1}{HWHM}$$

$$gain \propto \frac{1}{HWHM}$$

*Magnitude of HWHM from smallest to largest based on **Fig. 7***



Based on the results found, optical gain has been improved in the Fast Depopulation sample.

OR

Increase Population Inversion

**Lifetime of electron depopulation cannot be directly measured*

$$(N_3 - N_2) = R_{\tau_3}\left(1 - \frac{\tau_2}{\tau_{32}}\right)$$

$$population\ inversion = scattering\ time$$

$$gain \propto population\ inversion \propto scattering\ time$$

Observed optical gain increase → *Manipulated the magnitude of population inversion*

Based on these results, gain has been successfully engineered with the addition of rough interfaces.

FUTURE WORK

- ❑ Incorporate design into laser samples
- ❑ Experimentally test laser for gain and slope efficiency to determine viability of laser design

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