Thermally dependent gain of 1.3μm dilute nitride double quantum well lasers

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Presentation outline

Introduction

- Motivation

Experimental Method

- Device description
- Experimental system
- Extraction of gain - Cassidy's method
- Numerical estimation of experimental error

Results

- Net gain, cavity loss and modal gain
- Extract quasi-Fermi level separation
- T_0 (high/low temperature)
- Full width half maxima

Comparison with InP-based devices

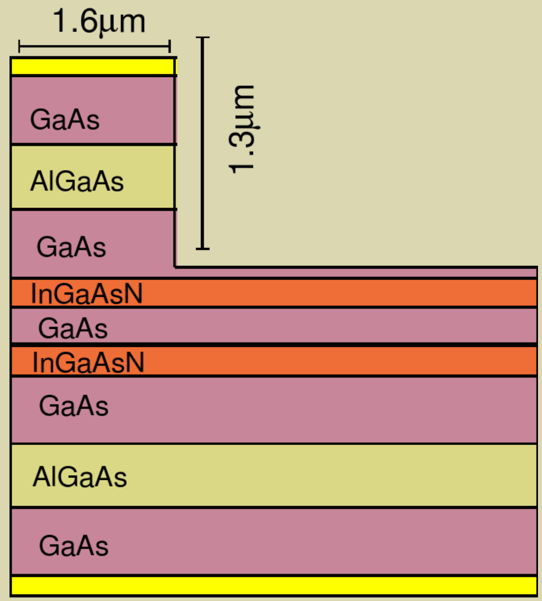
Device structure

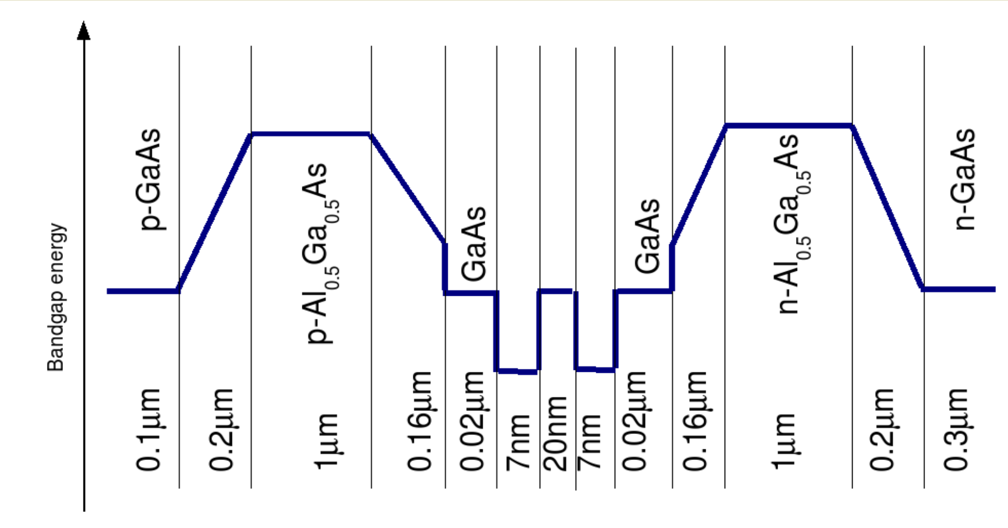
QW material: $Ga_{0.613}In_{0.387}NAs$ with 1.2% nitrogen

Number of QWs: 2

Ridge width: $W_r = 3.2\ \mu m$

Front facet output power: $P_{out} = 10 – 15$ mW





<u>Coated</u>

Front facet reflectivity: $R_f = 0.3$

Back facet reflectivity: $R_b = 0.7$

<u>Uncoated</u>

$R = 0.32$

Devices measured

Coated devices

- 250µm, 300µm, 500µm and 750µm

Uncoated devices

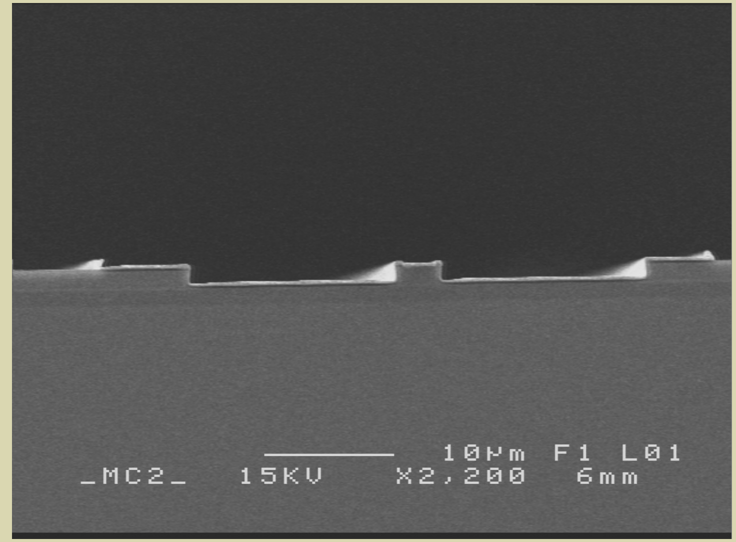
- 500µm, 1000µm, 2000µm

Measurements as a function of temperature

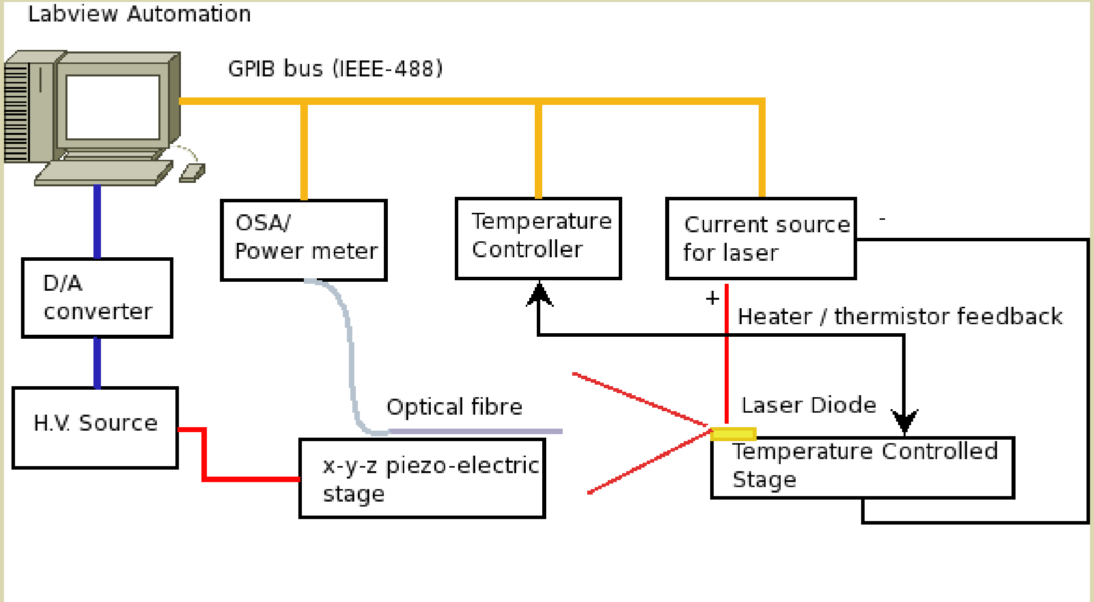
- 300K, 320K, 340K, 360K and 380K

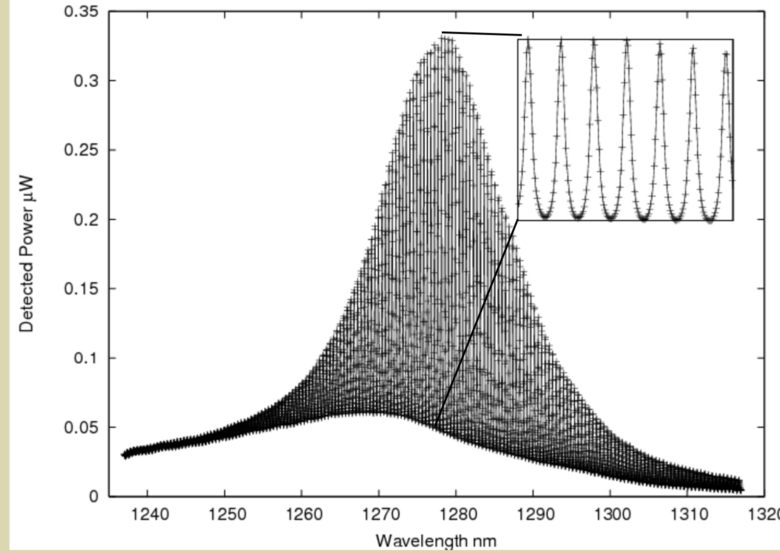
Measurements as a function of current

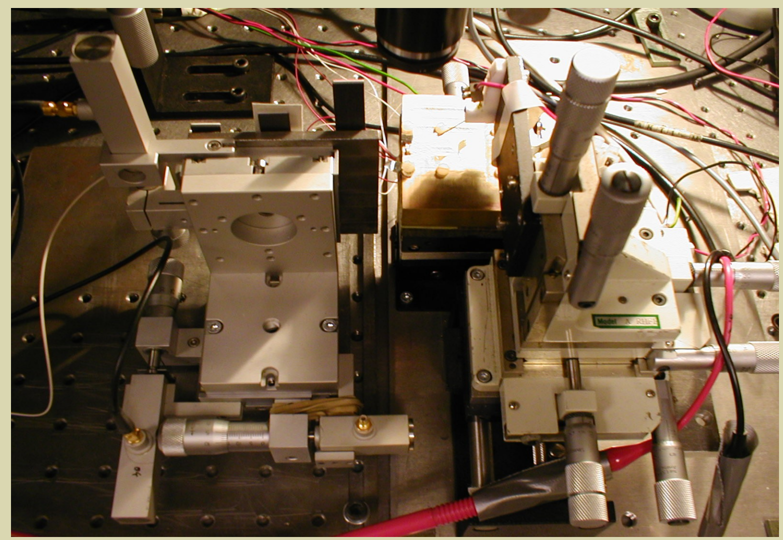
- 10 bias currents per temperature
- From far below threshold to slightly above



Experimental system







- ASE spectra measured from the front facet
- Fully automated system
- Optical fibre automatically aligned to laser
- Temperature range 25-110^{o}C
- Examined cavity integrity[1]

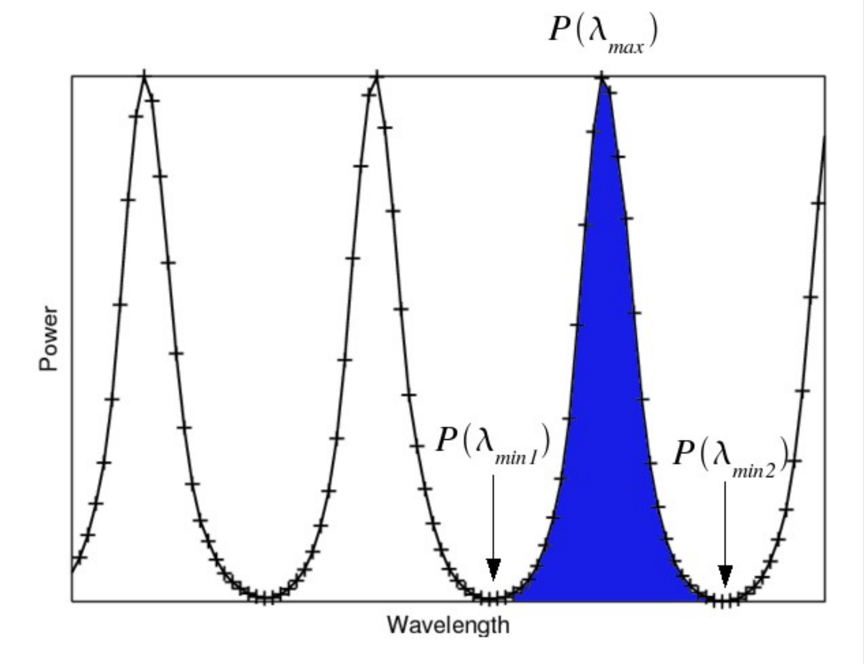
1) P.J. Bream, et.al. Appl. Phys. Lett. Vol. 86, 061104 (2005).

Extraction the gain using Cassidy's method

- Hakki-Paoli method $\gamma_i = \sqrt{\dfrac{P_{min1} + P_{min2}}{2P_{max}}}$

$$g_{net} = \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right) + \frac{1}{L}\ln\left(\frac{\gamma_i - 1}{\gamma_i + 1}\right)$$

- Cassidy's method
  - Calculated using mode sum
  - Better noise immunity by a factor of $\sqrt{N}$
  - Less sensitive to spectral resolution of measurement system

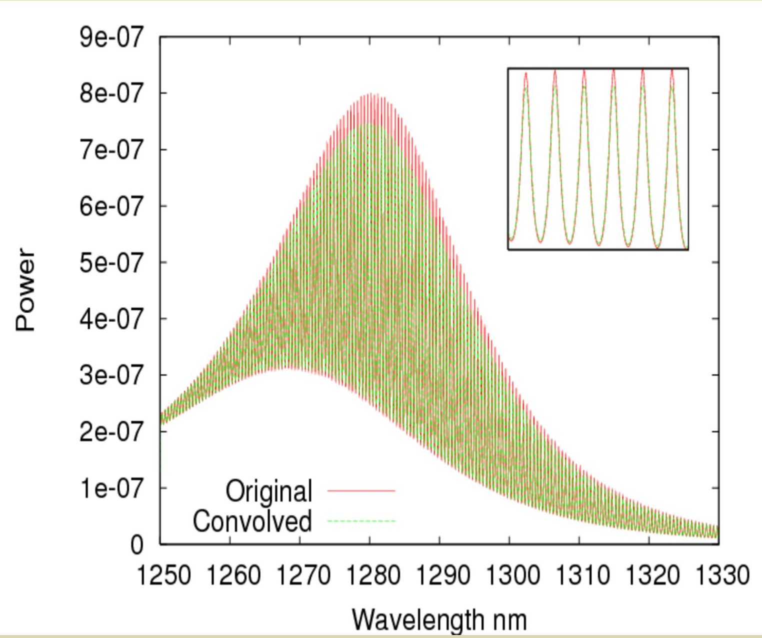


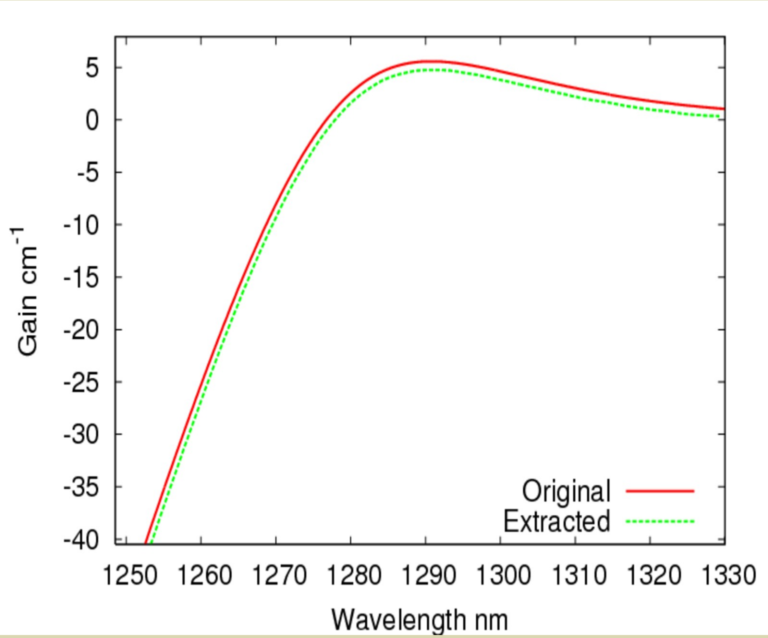
$$\gamma_i = \frac{\sum_{mode} P(\lambda)}{NP(\lambda_{min})}$$

N = sample points per mode
L = cavity length

Accuracy of the gain measurements

- Band structure calculated using 4x4 band **k**.**p** model for the valence band and band anti-crossing model for the conduction band
- The spontaneous and stimulated emission rates were calculated using Fermi's golden rule
- Fox-Li iteration scheme was used to model the cavity resonances
- Spectra convolved with an approximation of the instrument response
- Estimated errors
  - Worst case for modal gain 1.0cm^{-1}
  - Worst case net gain/loss 1.6cm^{-1}
  - Hakki-Paoli gave larger errors than Cassidy's method by ≈ 1cm^{-1}





Net gain spectra as a function of temperature

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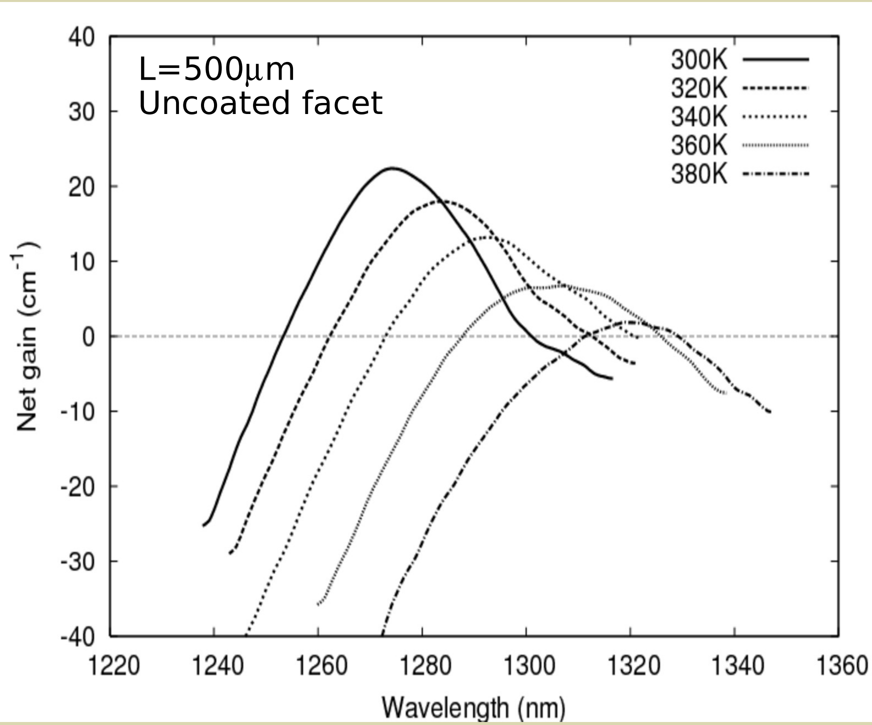


Variation of gain spectra at a constant current of 20mA with increasing temperature.

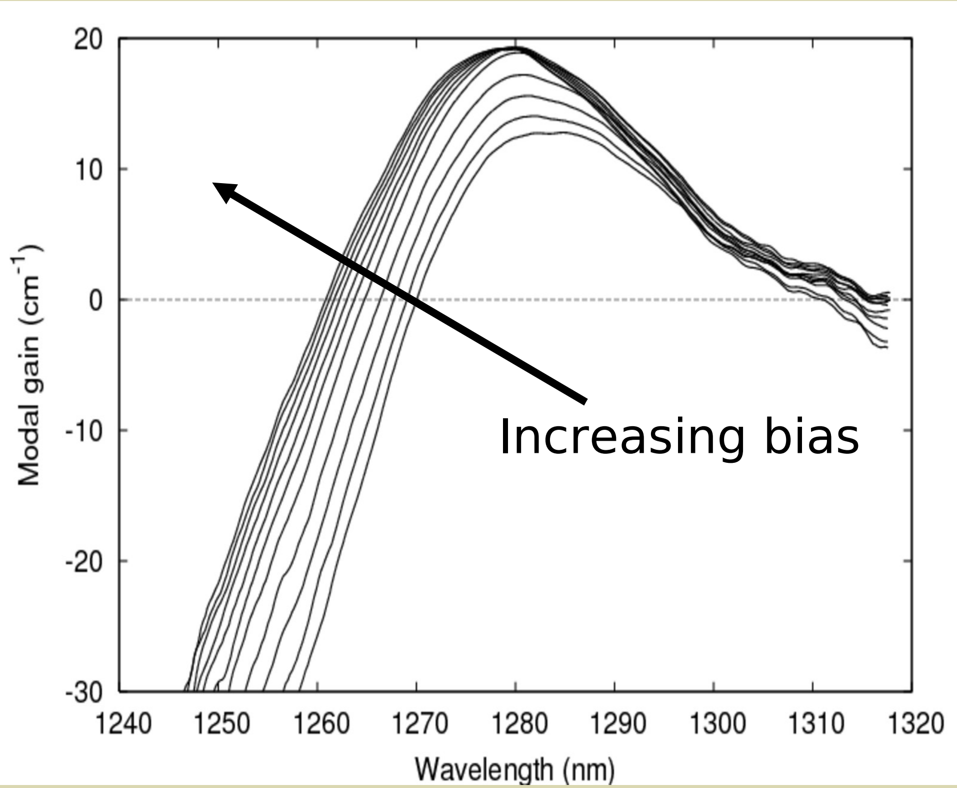
- Decrease of peak gain of 0.26 cm^{-1}/K
  - Comparable to InP-based devices 0.30 cm^{-1}/K
- The gain red shifts at a rate of 0.56nm/K
  - This is comparable to the 0.62nm/K for In-P based devices[1]
  - Mostly due to QW band gap shrinkage

This work $\Delta E_g / \Delta T_L \approx 0.47\, meV/K$

InP-based[1] $\Delta E_g / \Delta T_L \approx 0.57\, meV/K$

1) D. A. Ackerman IEEE J. Sel. Top. Q. Electron. , Vol. I , No. 2. 1995 p.250

Modal gain spectra as a function of bias - extraction of losses



1000µm uncoated device at 300K measured from 25-35mA

The difference between the low energy tail of the gain spectra and the zero point gives the cavity loss

For this work, we calculate

- A loss of 8± 1.6cm^{-1} (low)
- Loss *appears* to be temperature /carrier density independent

Typical InP-based devices

- Loss 7-20cm^{-1}
- Temperature/carrier density dependant

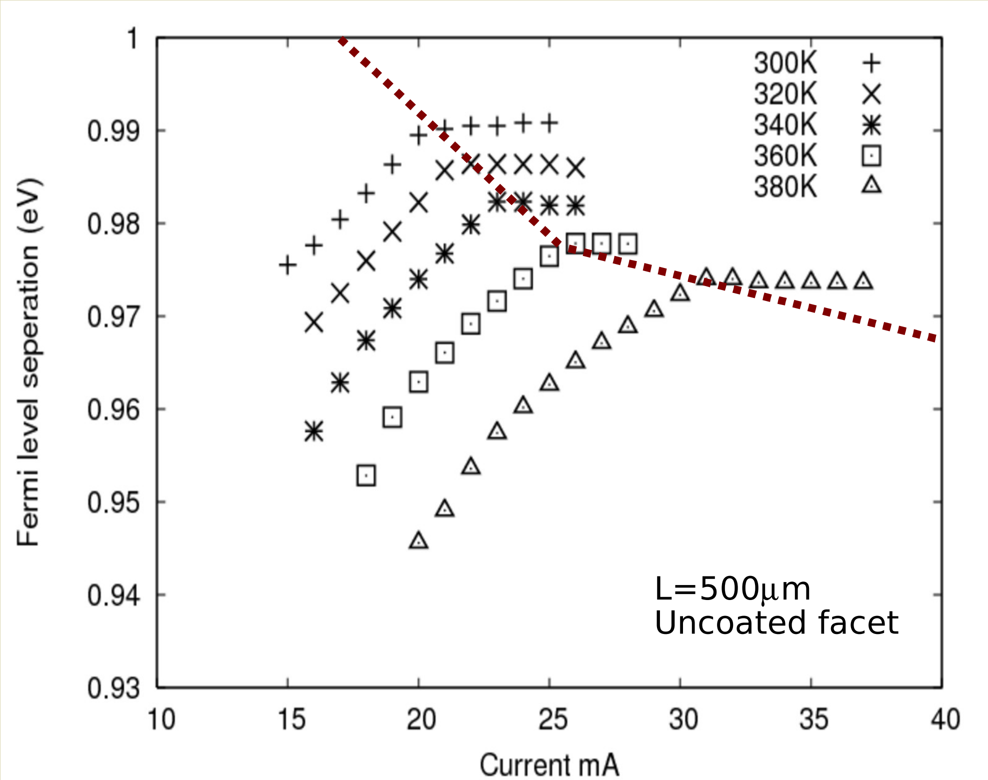
The peak gain blue shifts with increasing current at a rate of 1.17nm/mA

- band filling effects

Increase in FWHM of 2.4nm/mA

- band filling effects

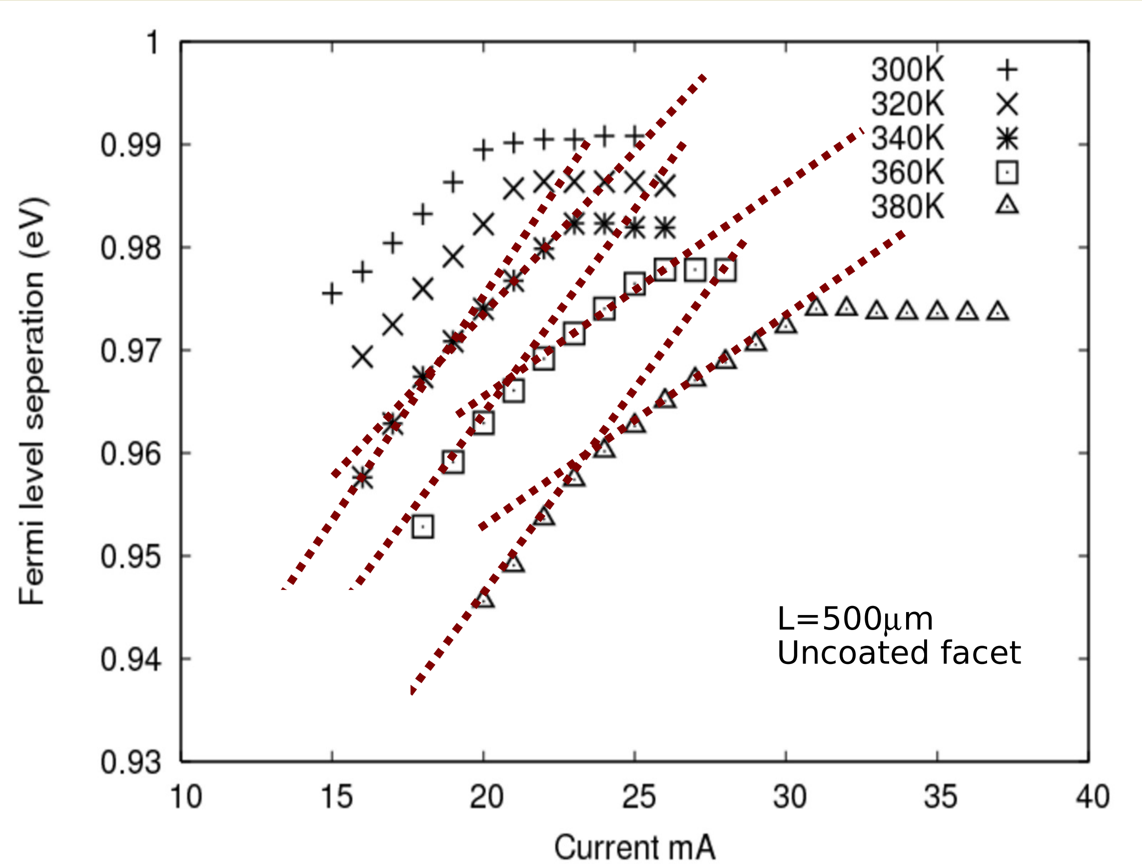
Quasi-Fermi level separation vs. Injection current



Extracted Quasi-Fermi level separation verses injection current.

- Shift of threshold with temperature
  - 300-360K
    - T_0=282K (High)
    - 0.10mA/K
  - 360-380K
    - T_0=113K (Still high)
    - 0.26mA/K
- Typical InP-based devices
  - T_0=70K
- Second characteristic temperatures not observed in longer cavities
- Function of carrier density and temperature
- Most probable cause
  - Thermionic emission of holes escaping from QW
  - Auger recombination

Quasi-Fermi level separation vs. Injection current



Extracted Quasi-Fermi level separation verses injection current.

- A kink can be seen in the curves at higher temperatures a
- Not observed in longer cavities
  - Simulations with our calibrated model suggest this is due to high rates of Auger recombination in the QW at high carrier densities
- Lower Fermi-level separation at higher temperatures is due to band gap shrinkage

Spread of FWHM with current and temperature

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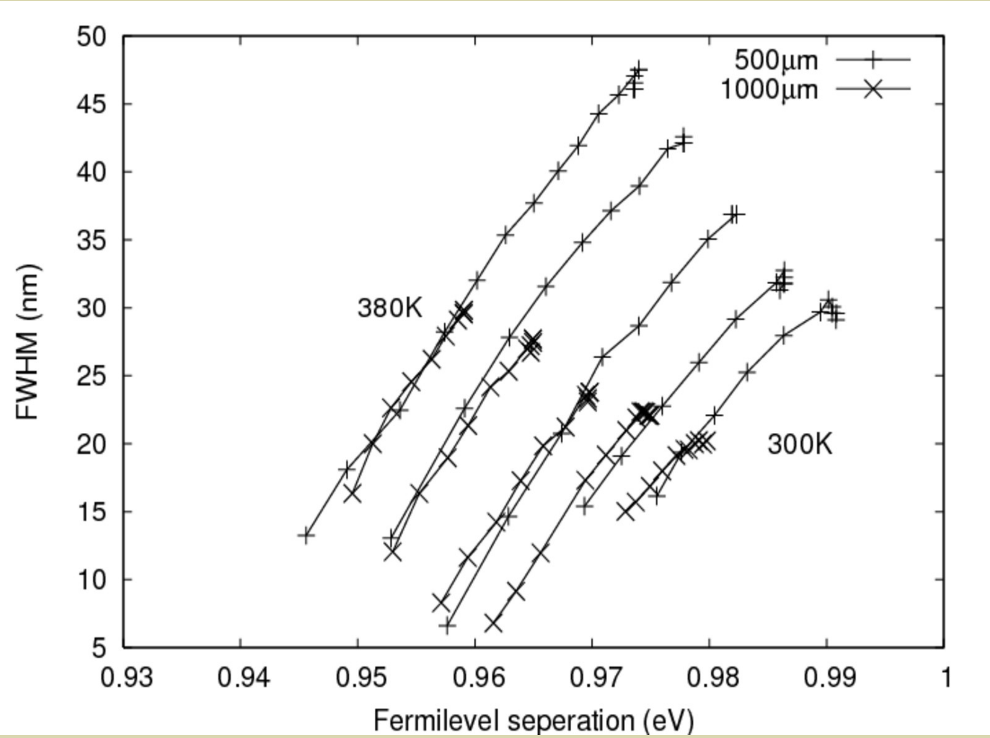


Spectral width of gain as a function of quasi-Fermi level separation and temperature

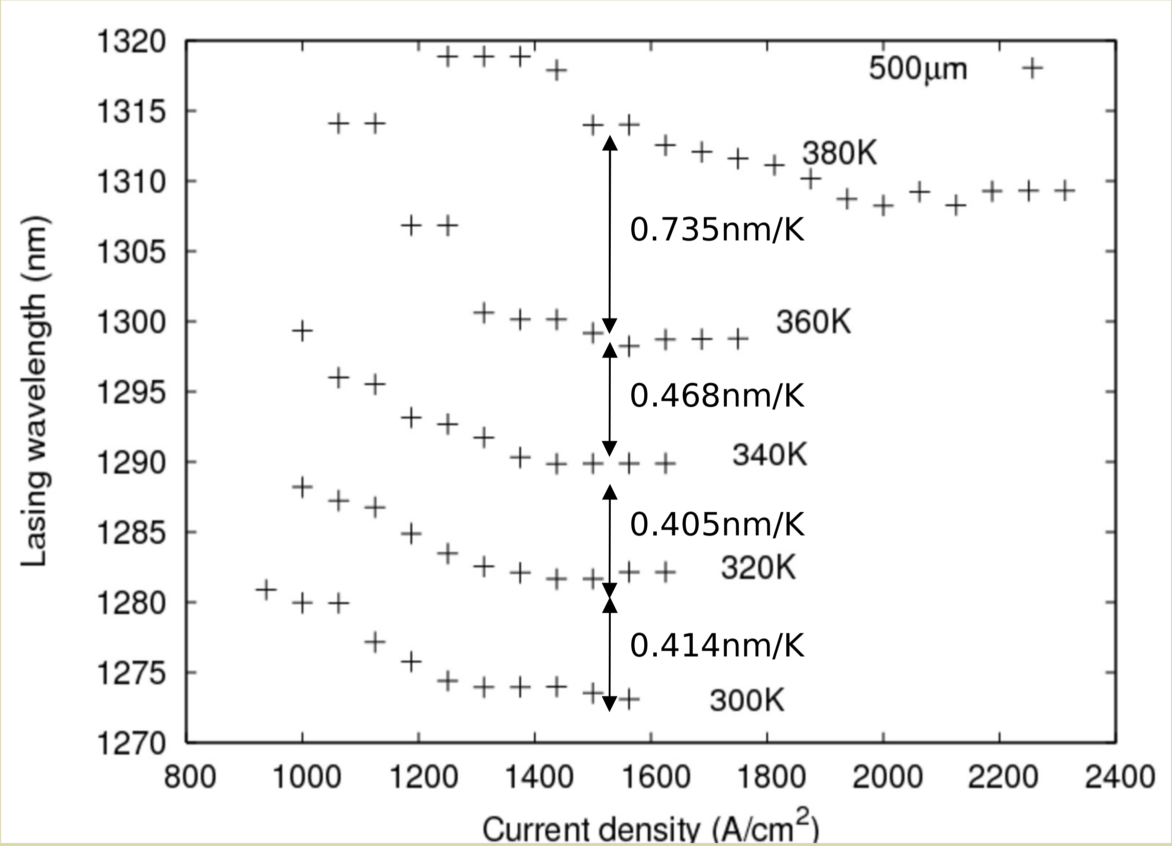
This work
- Maximum width of spectra 30-45nm
- Increase in the FWHM of the spectra of 0.35nm/K

InP-based materials[1]
- Maximum width of spectra 51-70nm
- 0.31nm/K

- Inhomogeneous pumping of larger number of QWs.

1) D. A. Ackerman IEEE J. Sel. Top. Q. Electron. , Vol. I , No. 2. 1995 p.250

Peak gain wavelength as a function of injection current density



Shift of peak gain with current density and temperature for all measured devices

- A red shift with increasing temperature can be observed
  - 300-340K dλ/dT=0.41nm/K
  - 340-380K dλ/dT=0.60nm/K
  - Average dλ/dT=0.51nm/K
- InP-based systems 0.3-0.5nm/K
- A blue shift with increasing current density can be observed
  - This work
    - 11pm/A/cm^2
  - InP-based
    - 13pm/A/cm^2

Conclusions

- A Low cavity loss of $8cm^{-1} \pm 1.6cm^{-1}$ has been determined
  - InP-based devices $7\text{-}20cm^{-1}$
- Comparatively small FWHM (30-45nm) - low number of QWs
  - InGaAsP QW (51-70nm)
- A small value of red shift with temperature 0.51nm/K has been observed
  - This is comparable to the 0.62nm/K for In-P based devices
- High T_0=113K-282K
  - InP-based devices T_0~70K
- Magnitude of gain decreases at 0.26 cm^{-1}/K
  - Compared to 0.30 cm^{-1}/K for InGaAsP
- At high current densities device behaviour changes (but still good).
  - Probably due to hole leakage current/Auger processes

Dilute nitrides are a clear competitor to 1.3µm InP-based devices