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Thermal performance investigation of DQW GaInNAs laser diodes

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NUSOD, Delaware – Sep. 24-27, 2007

Acknowledgements

We gratefully acknowledge the support of the European Commission through the FP6 IST project **FAST ACCESS** (IST-004772)

Presentation Outline

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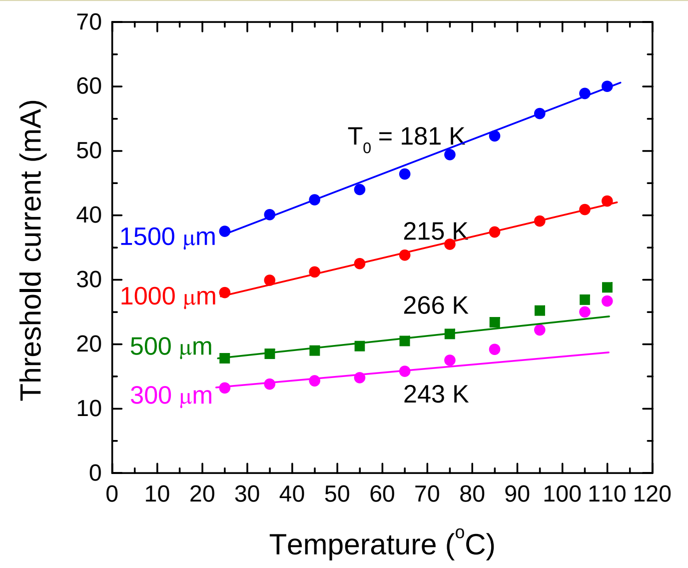
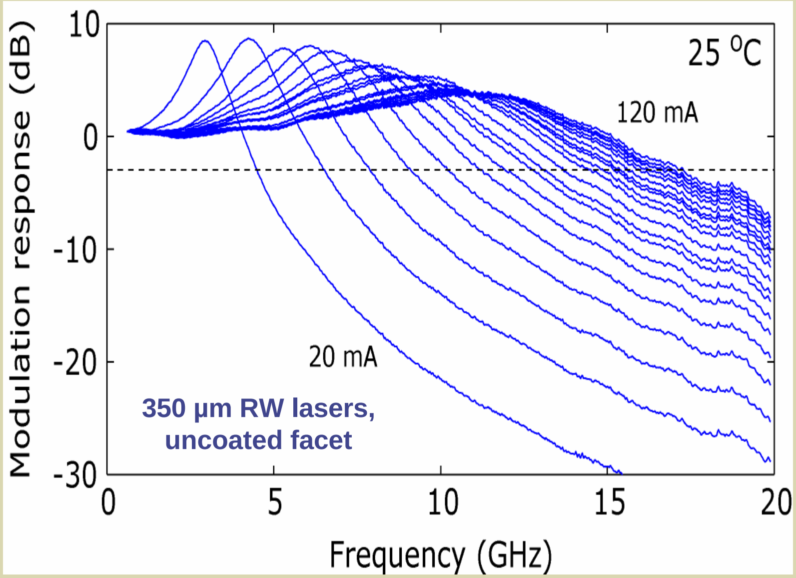
1. Introduction
2. Device structure
3. Calibration of gain data
4. Description of laser simulator
5. Calibration of operating characteristic
6. Cladding doping concentration investigation
7. Conclusion

Dilute Nitride Lasers



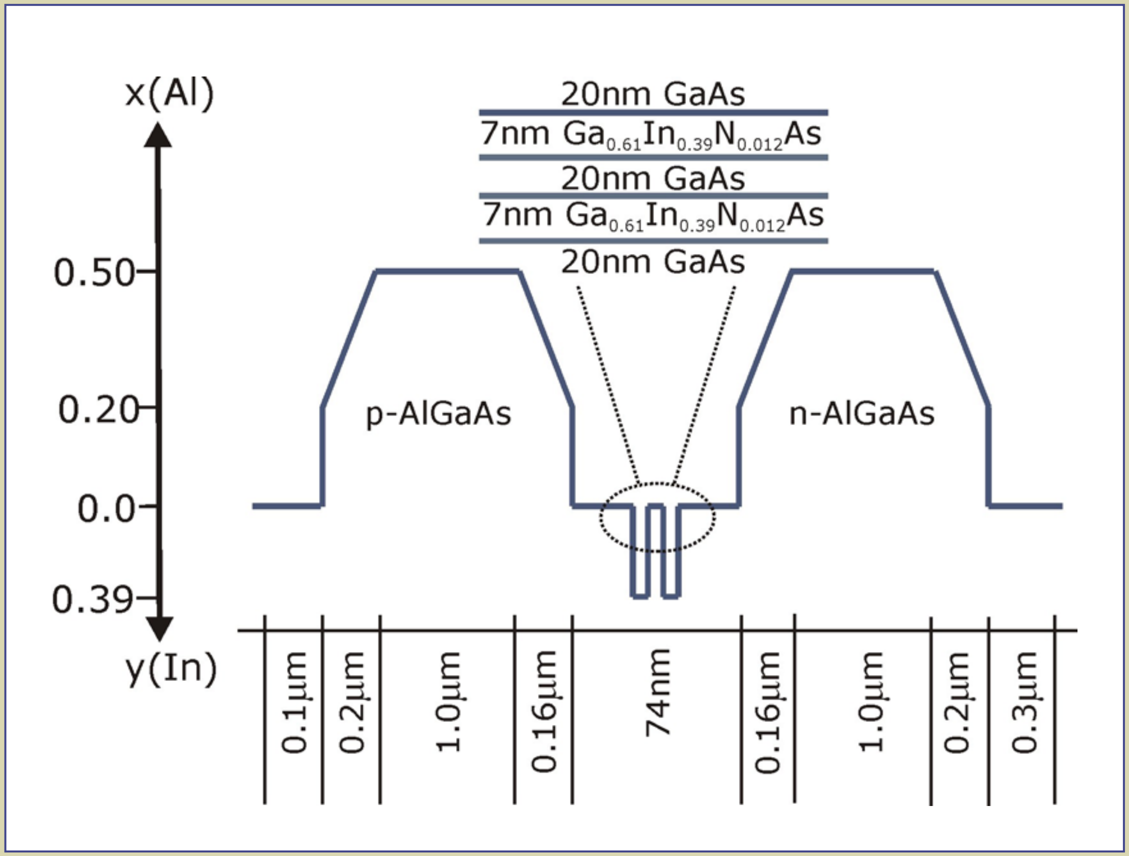


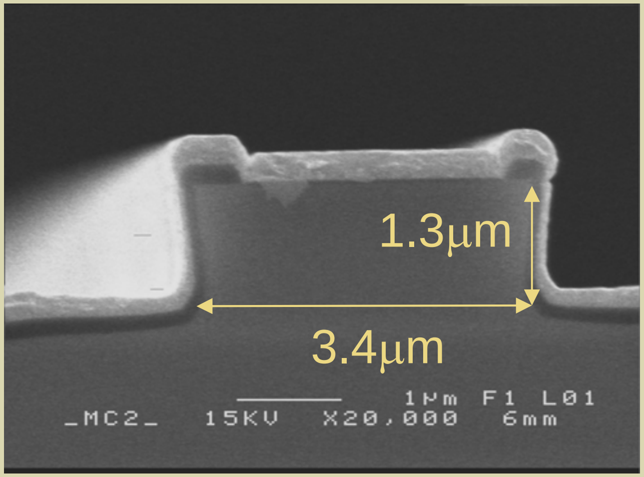
- Bandgap energy reduction – Longer wavelength
- Large conduction band offset – High T_o
- Low-cost alternative to InP lasers for access networks
- 17 GHz maximum modulation bandwidth
- Characteristic temperature, T_o = 181-266 K (20-70°C)

Reference: *Y.Q. Wei et al., Optics Express, Vol. 14, pp. 2753-2759, 2006*

Dilute Nitride Laser Structure

- 7nm $Ga_{0.61}In_{0.39}N_{0.012}As$/GaAs DQW grown by Chalmers University
- Ridge width of 3.4µm, and etch depth of ~1.3µm processed by Modulight Inc.

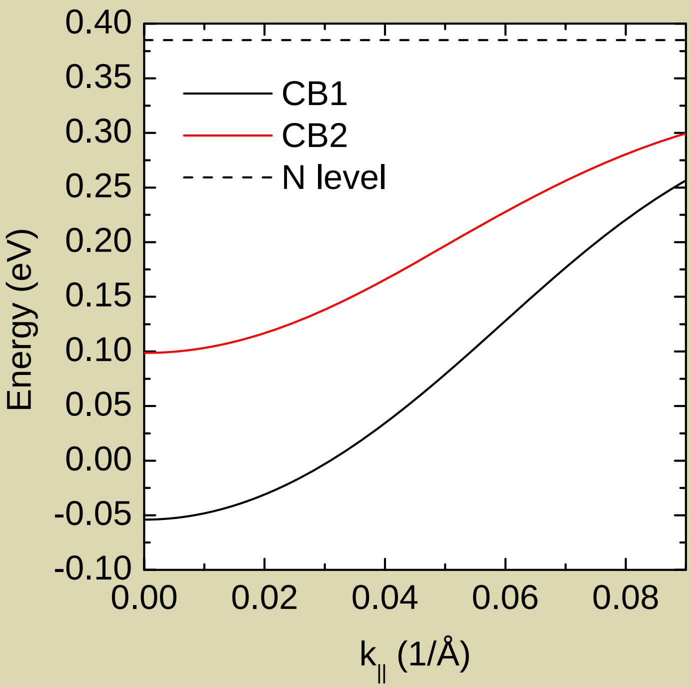




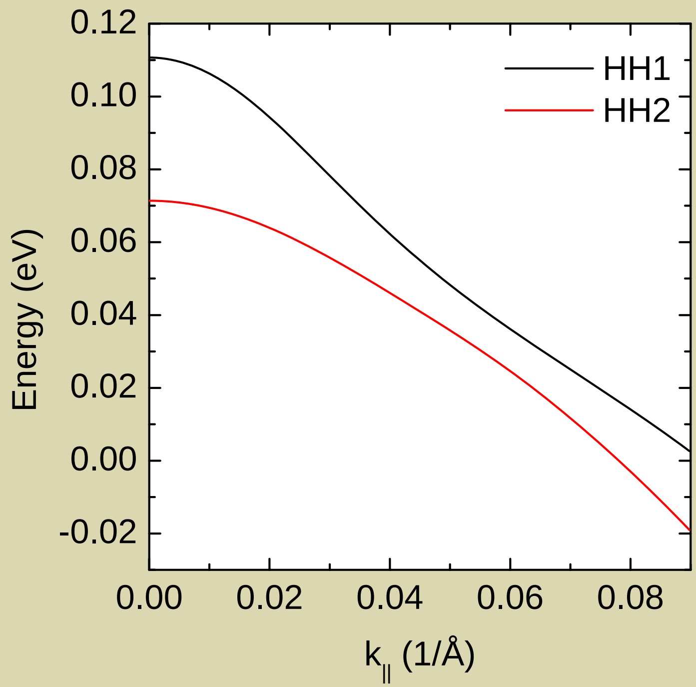
Reference: *Y.Q. Wei et al., Appl. Phys. Lett., Vol. 88, 051103, 2006.*

Bandstructure Calculation

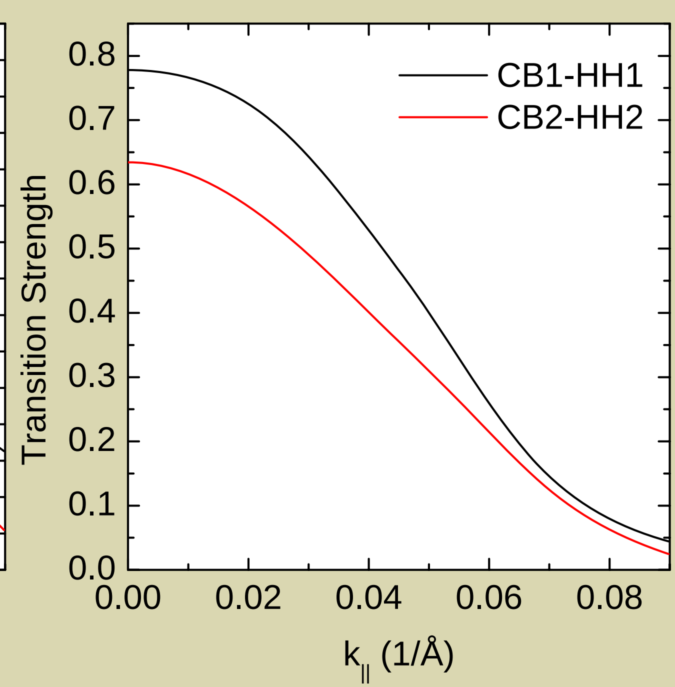
- BAC conduction band model
- Use 4x4 **k·p** valence band mixing model
- Material parameters from: Vurgaftman & Meyer, JAP **89**, 5815, 2001
- Band-offset ratio $\Delta E_c/\Delta E_g = 0.70$
- Nitrogen level relative to VBM of GaAs, E_N = 1.65 eV
- Adjusted interaction parameter, V_{MN} = $2.15\sqrt{x}$



Conduction band



Valence band



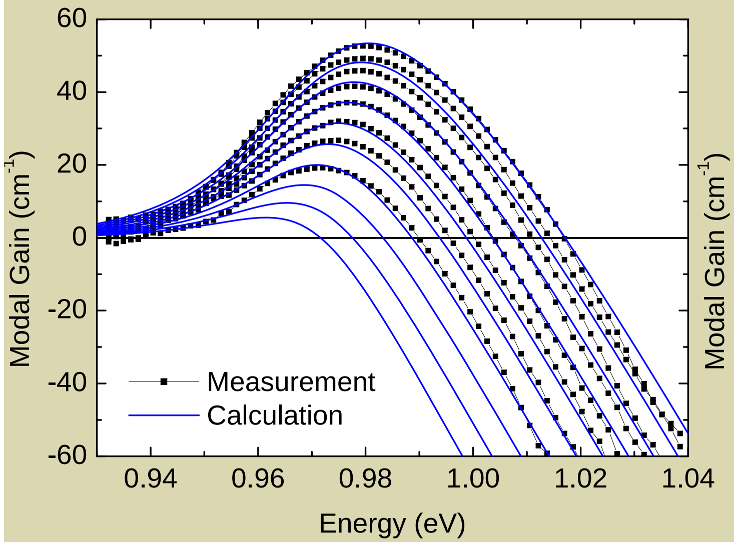
Transition strength

Calibration of Gain Spectra

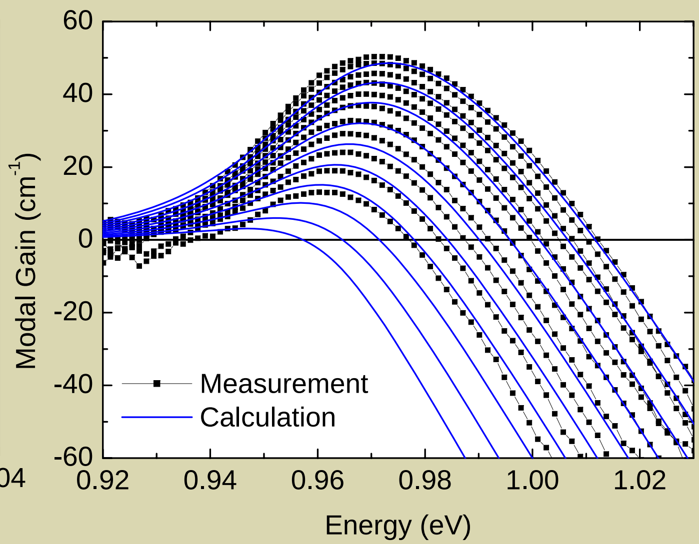
- Experimental gain measured using the segmented contact method
- Theoretical gain transformed from spontaneous emission spectra

$$g(E) = \frac{3\pi^2\hbar^3c^2}{2n^2E^2} R_{spon}(E)\left[1 - \exp\left(\frac{E - \Delta E_F}{kT}\right)\right]$$

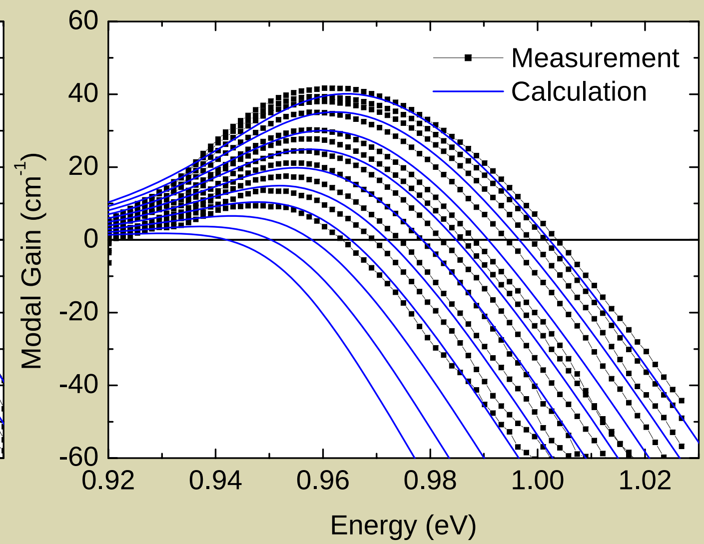
- Spontaneous emission spectra broadened using hyperbolic secant function
- Broadening lifetime: $\tau_{in} = (1.95\times10^{-13} - 4\times10^{-16}T)\cdot\left(n/10^{18}\right)^{-1/2}$ s



T=300K



T=325K



T=350K

Description of 2D Laser Simulator

- The model solves the following equations:

Poisson's Equation

$$\nabla\cdot(\varepsilon_r\varepsilon_0\nabla\phi)+q(p-n+N_D^+-N_A^-)=0$$

Continuity Equations

$$\frac{\partial n}{\partial t}=\frac{1}{q}\nabla\cdot\mathbf{J_n}-(R_{nr}+R_{spont}+R_{cap}^{n})$$

$$\frac{\partial p}{\partial t}=-\frac{1}{q}\nabla\cdot\mathbf{J_p}-(R_{nr}+R_{spont}+R_{cap}^{p})$$

$$\frac{\partial n_w}{\partial t}=\frac{1}{q}\frac{dJ_{nw}}{dx}-(R_{nr}^{qw}+R_{spont}^{qw}+R_{stim}^{qw}-R_{cap}^{n})$$

$$\frac{\partial p_w}{\partial t}=\frac{1}{q}\frac{dJ_{pw}}{dx}-(R_{nr}^{qw}+R_{spont}^{qw}+R_{stim}^{qw}-R_{cap}^{p})$$

Photon Rate Equations (m modes, 1 eqn. per mode)

$$\frac{dS_m}{dt}=v_g(G_m-\alpha)S_m+\beta r_{spont}^{qw}$$

- The equations are cast into matrix form and solved simultaneously using Newton's Method.

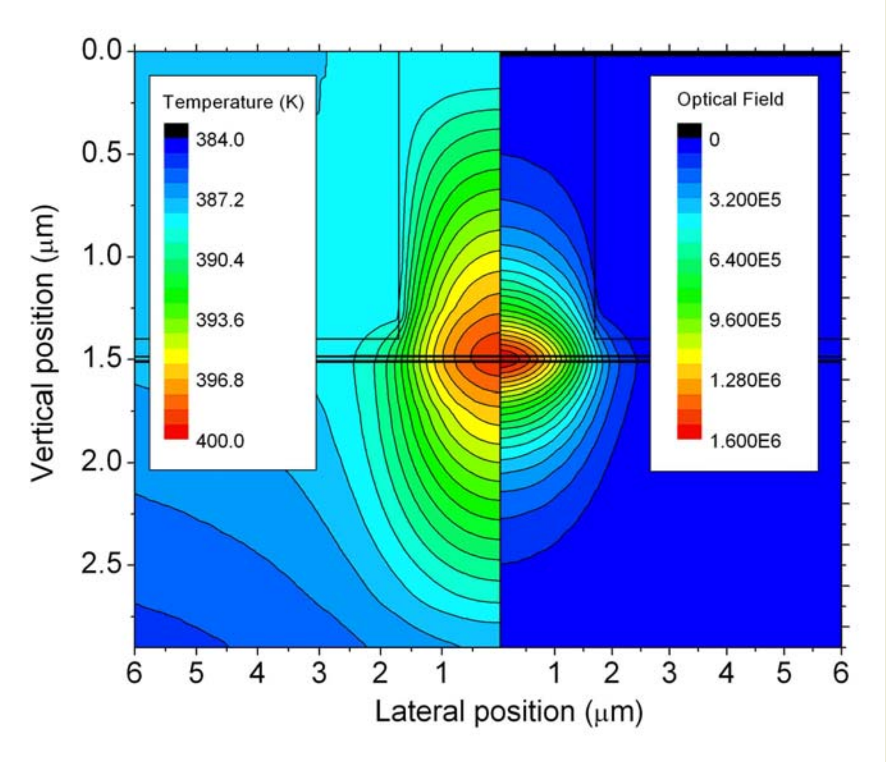
Description of Laser Simulator

Optical model

- Helmholtz's scalar 2D wave equation

$$\nabla^2\Phi + \left(k(x,y)^2 - \beta(\omega)^2\right)\Phi = 0$$

- Solved using Rayleigh quotient iteration method



Thermal model

- Lattice heat equation
- Heat sources:

  - Joule heat

$$H_{Joule} = \frac{\nabla E_c}{q}\cdot \mathbf{J}_n + \frac{\nabla E_v}{q}\cdot \mathbf{J}_p$$

  - Recombination heat

$$H_{Recomb} = R_{nr}\cdot E_{g,w}$$

  - Capture heat

$$H_{Cap} = R_{net}\cdot (E_g - E_{gw})$$

  - Absorption heat

$$H_{Abs} = \sum_m v_g \alpha \Phi S_m \hbar\omega$$

Calibration of Ridge Waveguide Laser

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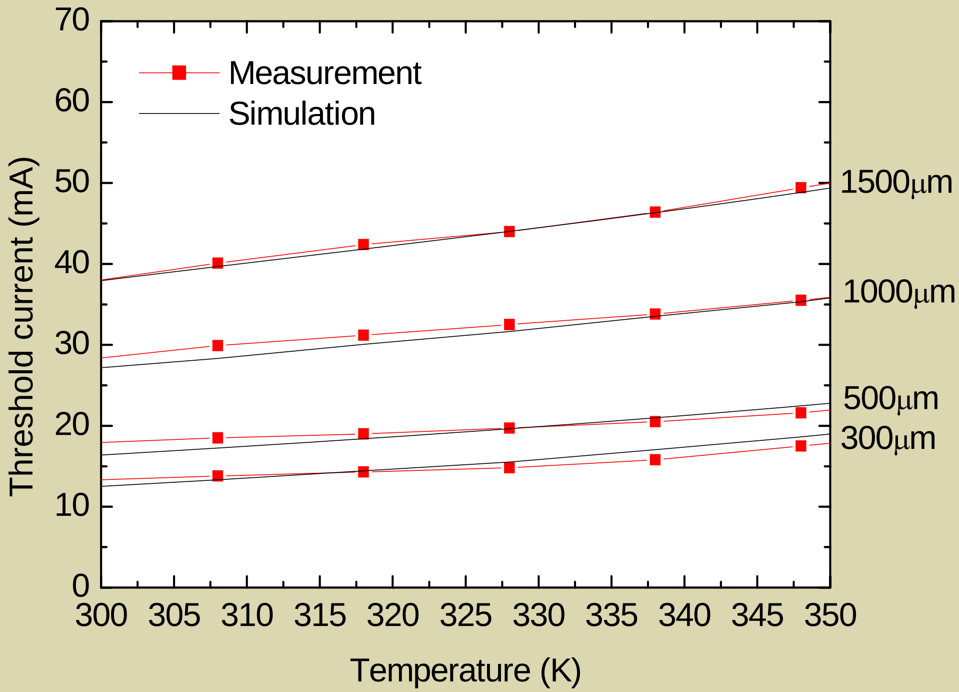
- Material parameters taken from the literature

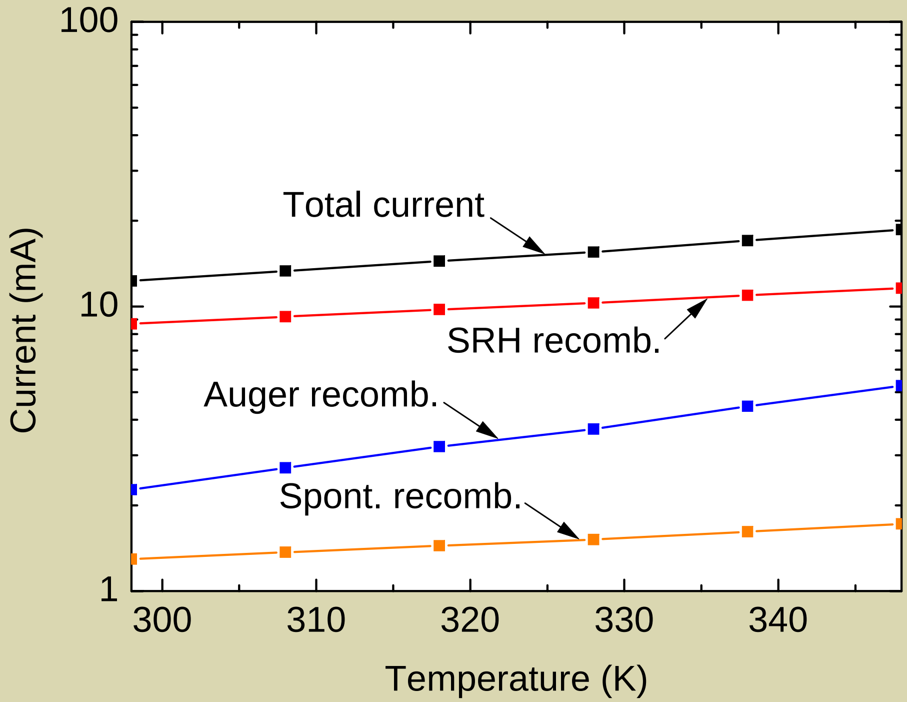
Layer	d (μm)	E_g (eV)	μ_n (cm^2/Vs)	μ_p (cm^2/Vs)	κ (W/mK)	n_r
p-GaAs	0.10	1.42248	1309	42.2	46	3.41741
p-$Al_{0.50}Ga_{0.50}As$ (cladding)	1.00	2.08076	196	77.7	10.77	3.15105
p-$Al_{0.50\text{-}0.20}Ga_{0.50\text{-}0.80}As$ (graded)	0.16	2.08076 - 1.72303	809 - 2875	181 - 253	10.77- 14.46	3.15105 - 3.30392
$Ga_{0.61}In_{0.39}N_{0.012}As$ (QW)	0.007	1.00797	500	483	5.08	3.60
GaAs (barrier & SCL)	0.020	1.42248	7800	490	46	3.41741
n-$Al_{0.20\text{-}0.50}Ga_{0.80\text{-}0.50}As$ (graded)	0.16	1.72303 - 2.08076	2875 - 809	253 - 181	14.46- 10.77	3.30392 - 3.15105
n-$Al_{0.50}Ga_{0.50}As$ (cladding)	1.00	2.08076	196	77.7	10.77	3.15105
n-GaAs	0.30	1.42248	1851	51	46	3.41741

- Bandgap energies from Vurgaftman & Meyer, JAP 89, 5815, 2001.
- Carrier mobilities and thermal conductivities from Joachim Piprek, *Semiconductor Optoelectronic Devices*, Academic Press, 2003 & Vassil Palankovski, *Analysis and Simulation of Heterostructure Devices*, Springer, 2004.
- Refractive indices from Afromowitz, Solid State Comm., 15, 59, 1974 and from Kitatani *et al.*, Jpn. J. Appl. Phys., 37, 753, 1998 for AlGaAs and GaInNAs respectively.

Calibration of Material Parameters

- A good fit of threshold current vs temperature for different cavity lengths was achieved:
  - $\sigma_{IVBA} \sim 2x10^{-16}\,cm^2 \rightarrow \alpha_i = 10\ cm^{-1}$
  - $C_{CHHS} = 1x10^{-28}\,cm^6 s^{-1}$
  - $\tau_n = \tau_p = 0.5ns$
- SRH recombination was found to dominate the threshold current.





Calibration of Ridge Waveguide Laser

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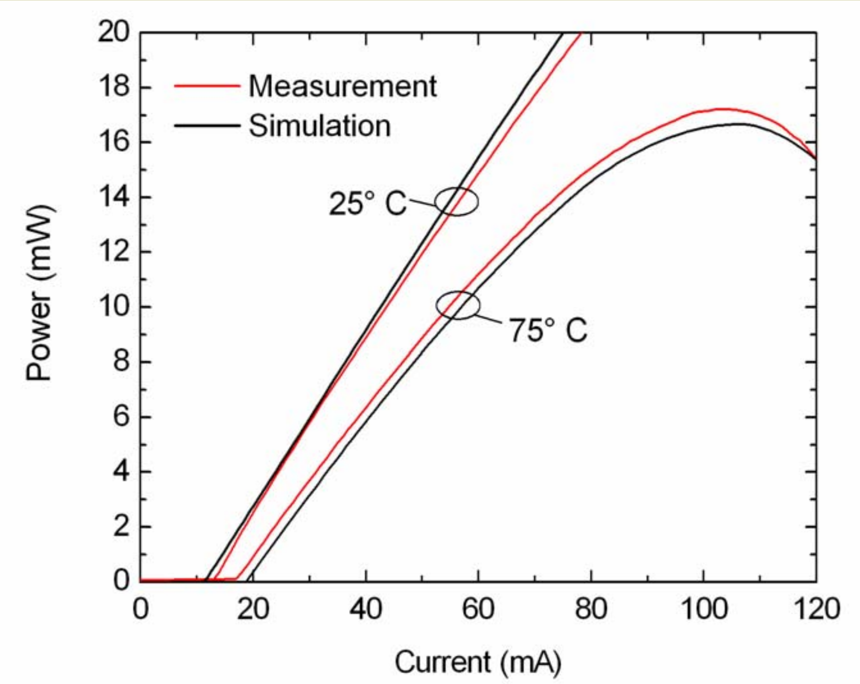
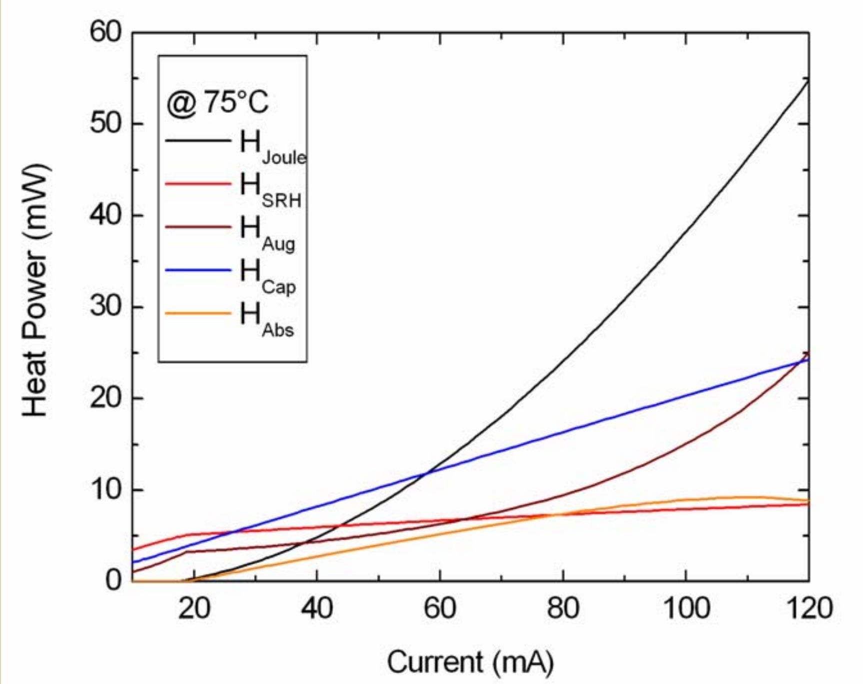
- 3.4 x 300 μm² RW laser
- To obtain agreement, Auger coefficient needs to be temperature dependent:

$$C_{HSH}(T) = C_0 \qquad T < 350\text{K}$$

$$C_{HSH}(T) = C_0\left[1 + \beta(T - T_0)^n\right] \qquad T > 350\text{K}$$

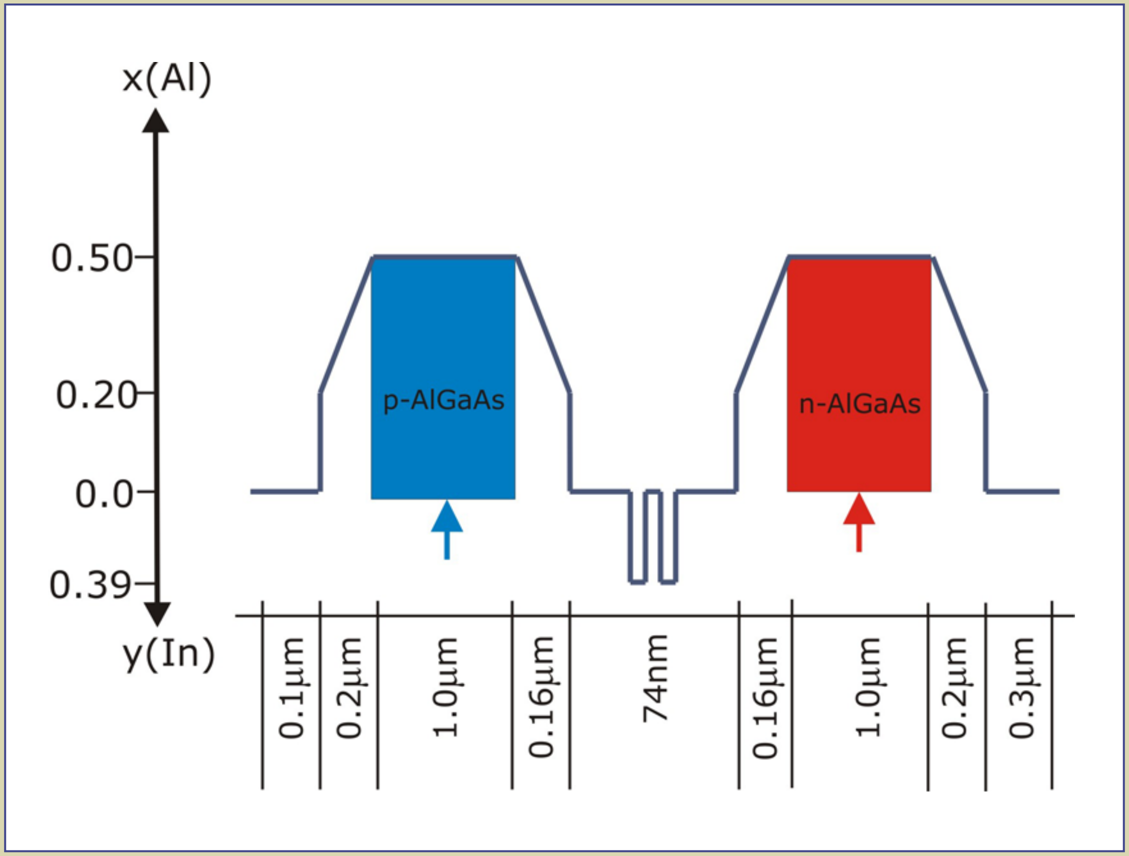
$C_0 = 1\text{x}10^{-28}$ cm^{6}s^{-1}, $\beta = 5\text{x}10^{-4}$, $n = 2.05$ and $T_0 = 350$ K





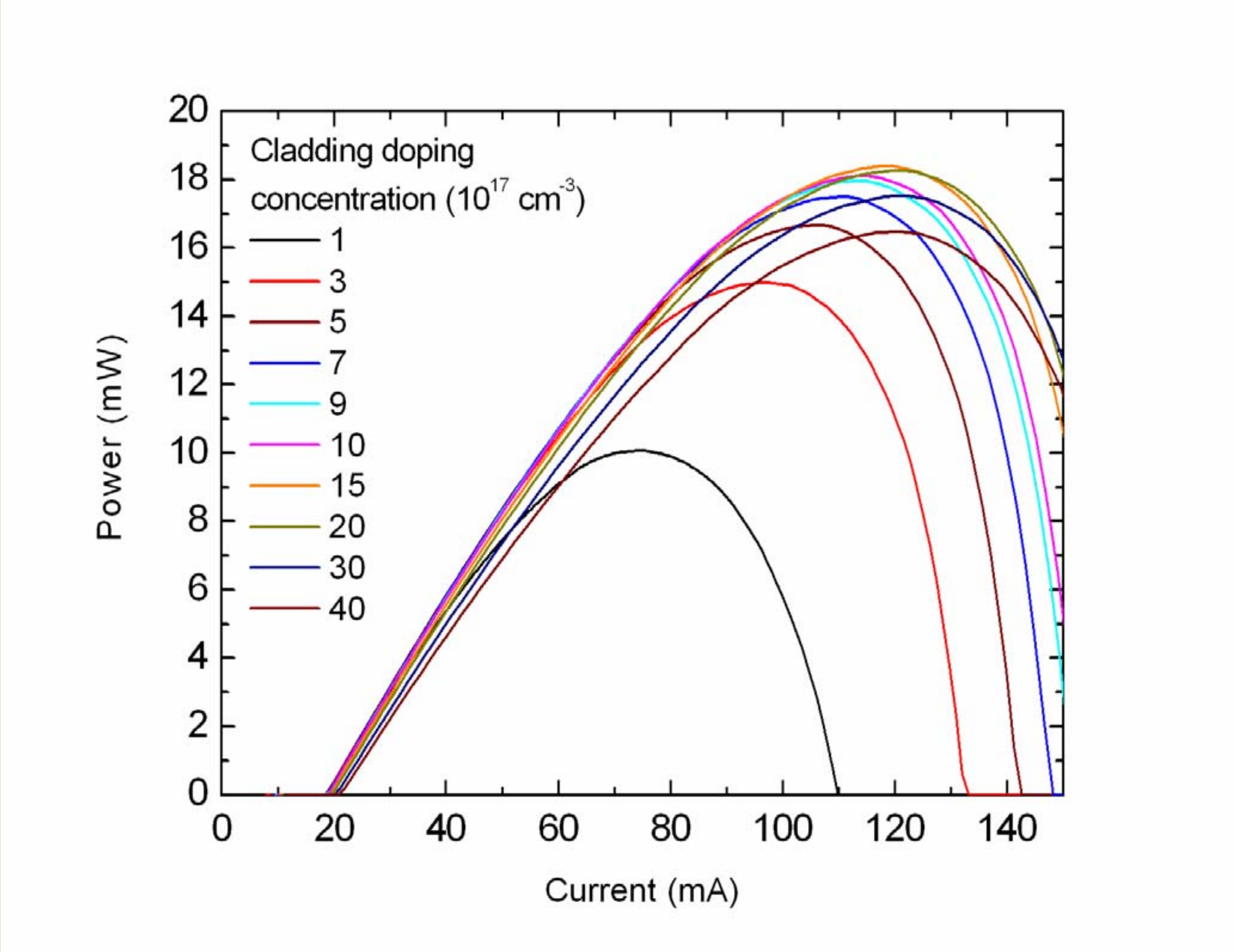
Cladding doping concentration study

- p-clad and n-clad doping concentration set equal and varied from 1×10^{17} to 4×10^{18} cm^{-3}
- original doping concentration = 5×10^{17} cm^{-3}



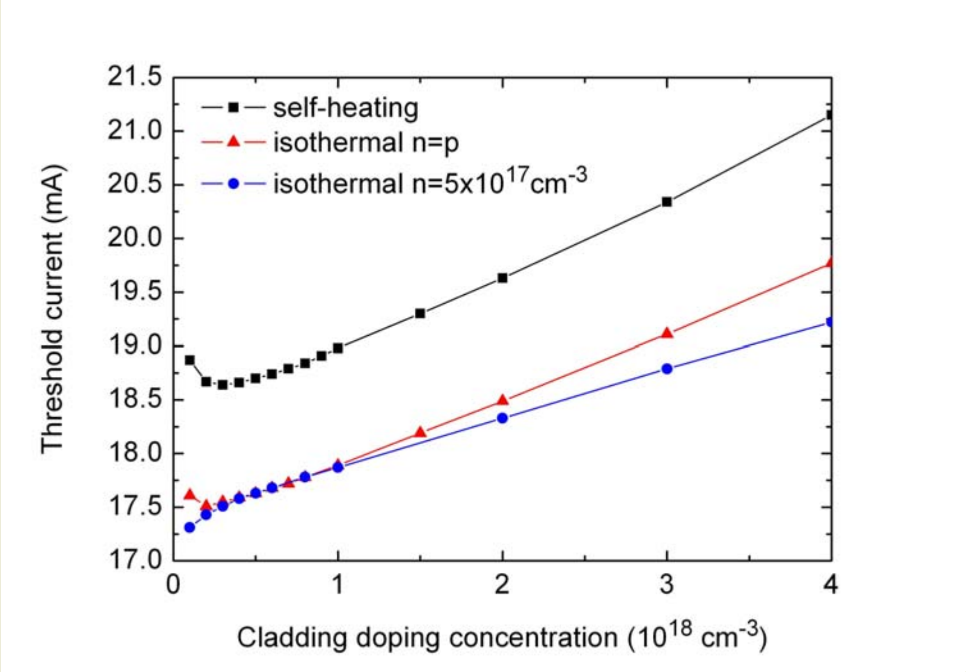
Cladding doping concentration study

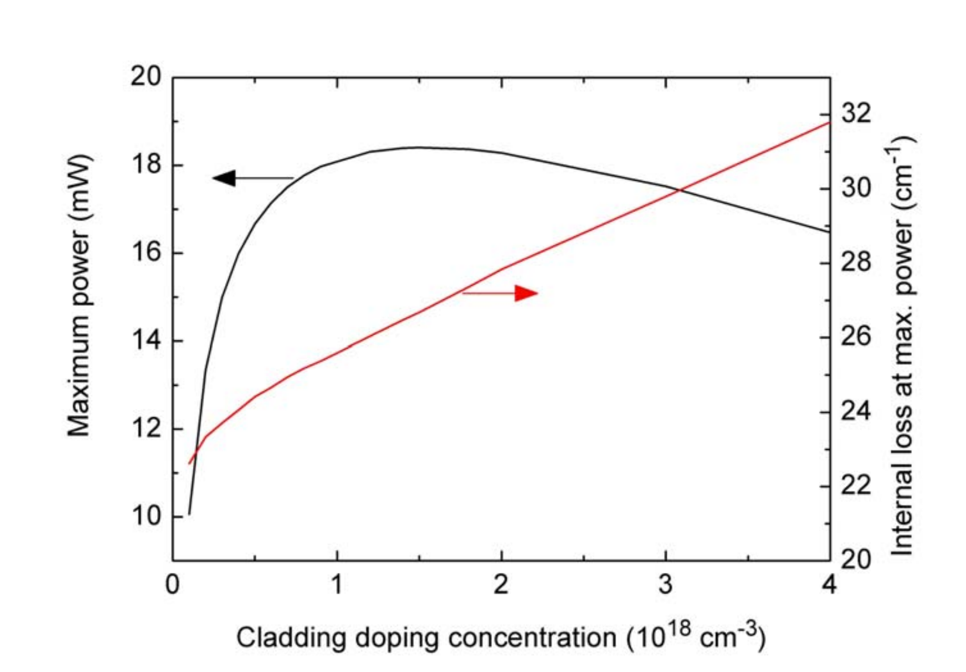
- L-I curves for different cladding doping concentration at 75°C.



Cladding doping concentration study

- Threshold current vs. cladding doping concentration
- Maximum output power vs. cladding doping concentration





- 0.3% improvement in threshold current at $3x10^{17}$ cm^{-3}
- 10% improvement in maximum output power at $1.5x10^{18}$ cm^{-3}

Conclusion

- Gain and spontaneous emission calculation calibrated to experimental data.
- Auger coefficient, SRH lifetime and absorption cross section fit to obtain agreement in threshold current vs. temperature and length.
- Self-heating model and temperature dependent Auger coefficient necessary to reproduce experimental L-I curves above threshold.
- An optimum doping concentration exists to reduce heat generation due to competition between Joule heating and FCA.
- A 10% improvement in maximum output power achieved using optimum cladding doping concentration.