SAND2019-12653C

Linewidth enhancement in quantum dot lasers

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Sandia National Laboratories

An illustration of device modeling:

What calculations are useful for device development

What are the requirements on the theory

International Symposium "Semiconductor Nanophotonics“
Collaborative Research Centre 787, Technische Universität Berlin, November 4th - 5th, 2019

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Why quantum dots

- Quantum wells have replaced bulk active regions for virtually all commercial applications
- Quantum-well laser technology (> 20 years old) is reaching fundamental performance limits
- Search for improvement at underlying physics level
- Quantum-dot laser is a strong candidate

Some history

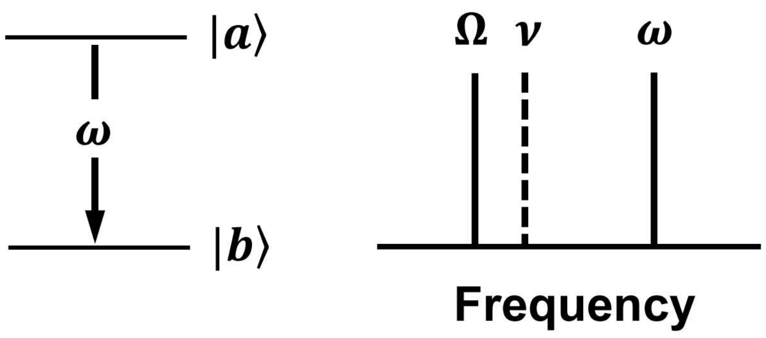
- Improvement via 1-d to 3-d quantum confinement (2-d to 0-d electron density of state) -- proposed 1982
- Demonstrated atomic-like laser emission – mid 1990
- Low threshold, high temperature, defect & optical-feedback tolerances, silicon integration – shown

Why linewidth enhancement factor

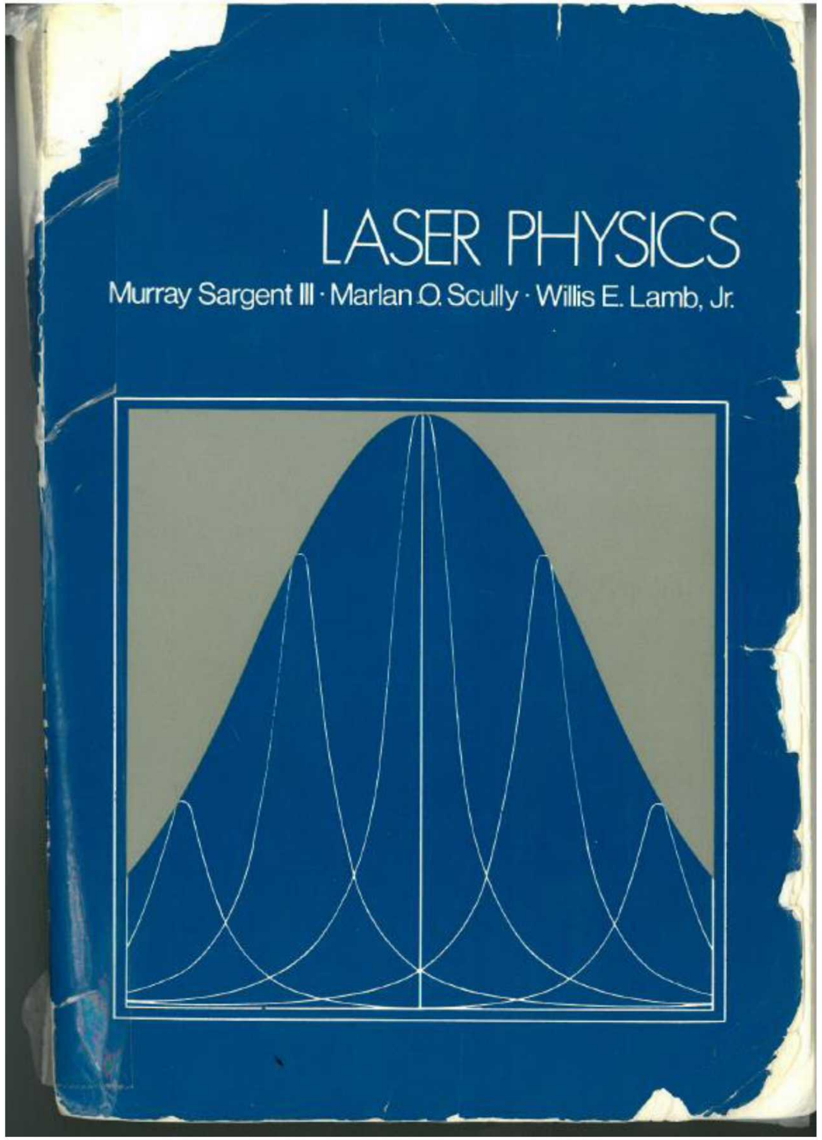
- Attention shifting to above-threshold properties
- Laser linewidth, chirp under high-speed modulation, optical feedback sensitivity
- Applications: datacom & telecom, chemical sensing, laser radar (LIDAR)

Laser theory

(e.g. Sargent, Scully and Lamb)



$$\overset{\text{Lasing frequency}}{\overset{\uparrow}{\nu}} = \underset{\underset{\text{Cavity resonance}}{\downarrow}}{\Omega} + \overbrace{\frac{(\omega - \Omega)}{\gamma^2 + (\omega - \Omega)^2}\underset{\underset{\text{Atomic resonance}}{\downarrow}}{[n_a(\omega) - n_b(\omega)]}}^{\text{Frequency pulling}}$$

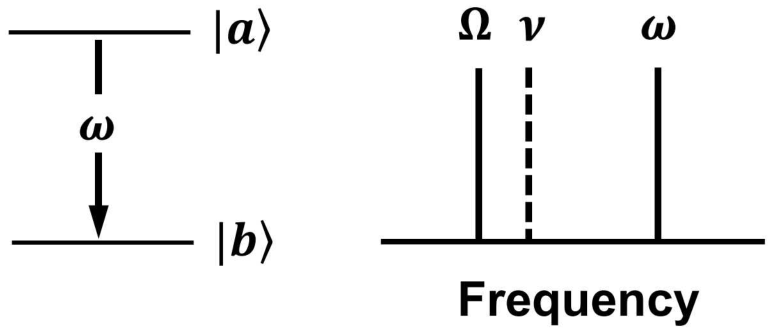


LASER PHYSICS

Murray Sargent III · Marlan O. Scully · Willis E. Lamb, Jr.

Laser theory

(e.g. Sargent, Scully and Lamb)



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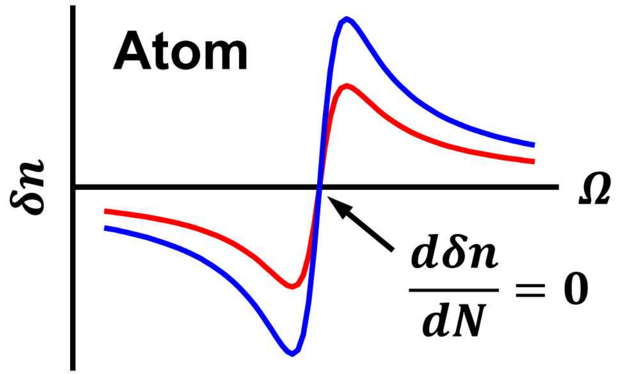
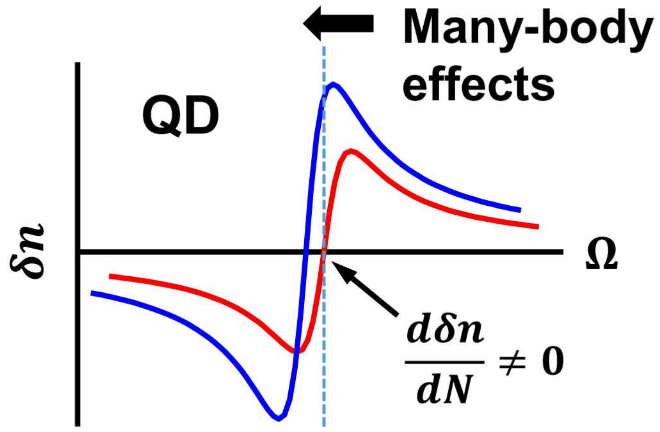
Refractive index

$$\nu = \frac{c}{\underset{\substack{\downarrow\\ \text{Carrier-induced refractive index change}}}{2L(n+\delta n)}} = \Omega\left(1-\frac{\delta n}{n}\right)$$





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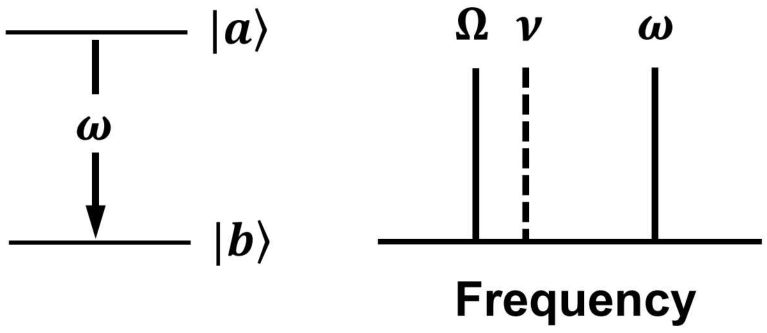

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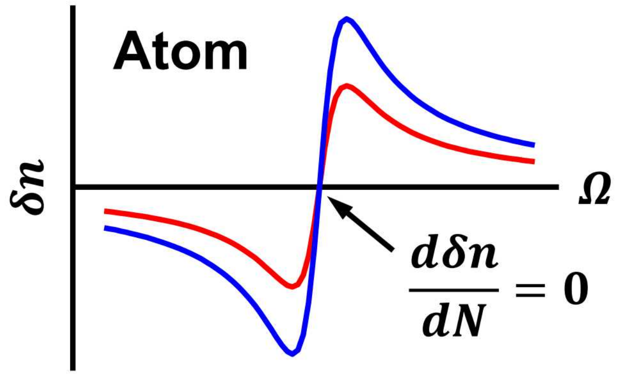
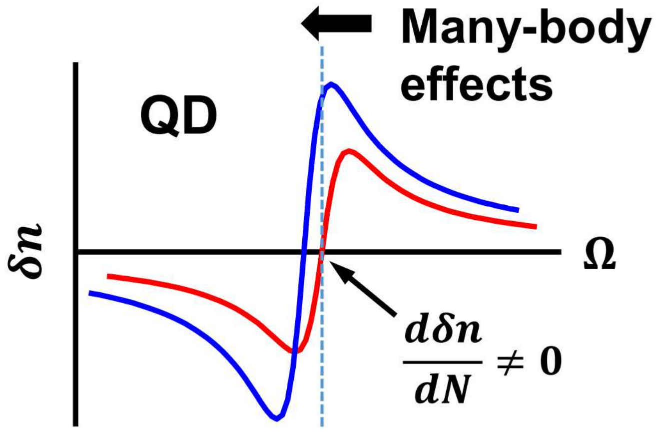




Linewidth enhancement factor

$$\alpha_H = -K\frac{d(\delta n)}{dN_e}\left(\frac{dg}{dN_e}\right)^{-1}$$

Laser linewidth

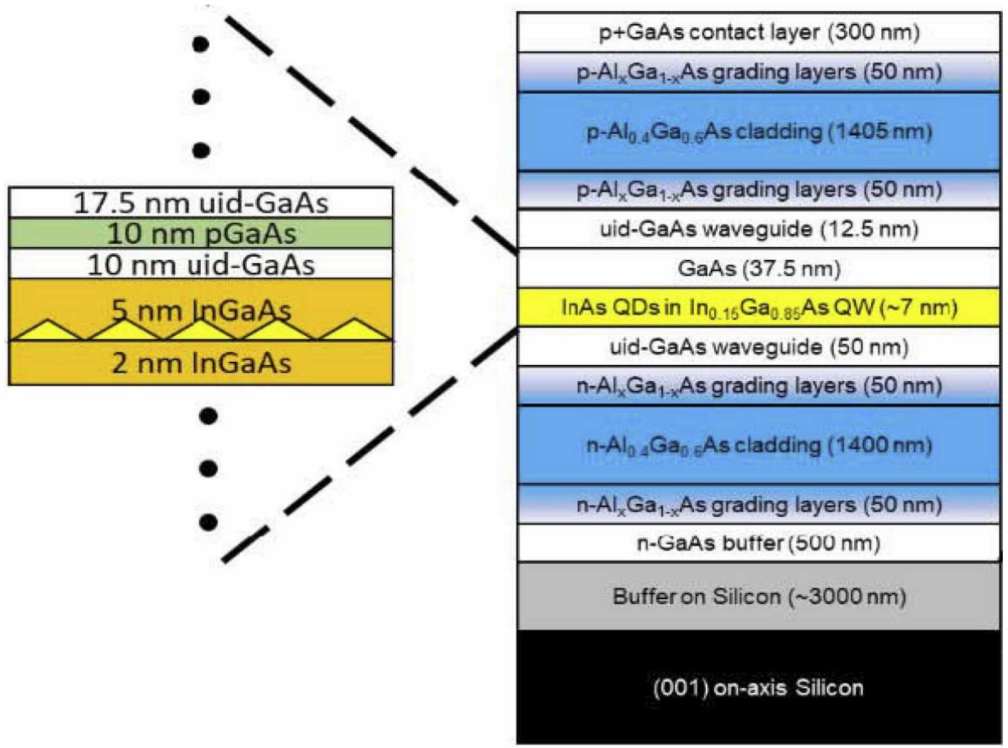
$$\Delta\nu = \Delta\nu'_{ST}\left(1+\alpha_H^2\right)$$

Feedback instability

$$f_{crit} = \xi\frac{1+\alpha_H^2}{\alpha_H^4}$$

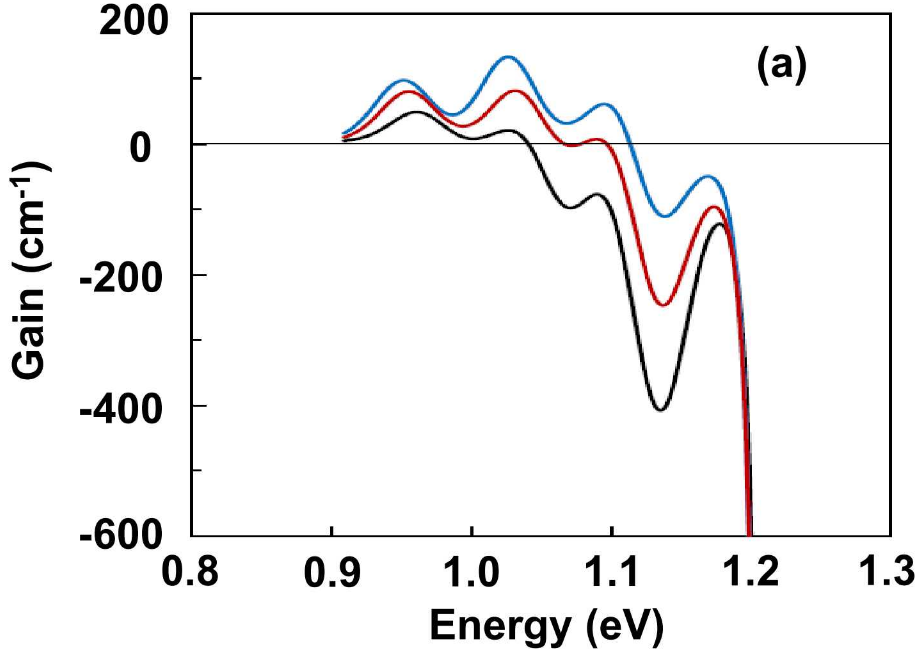
Chirp during high-speed operation

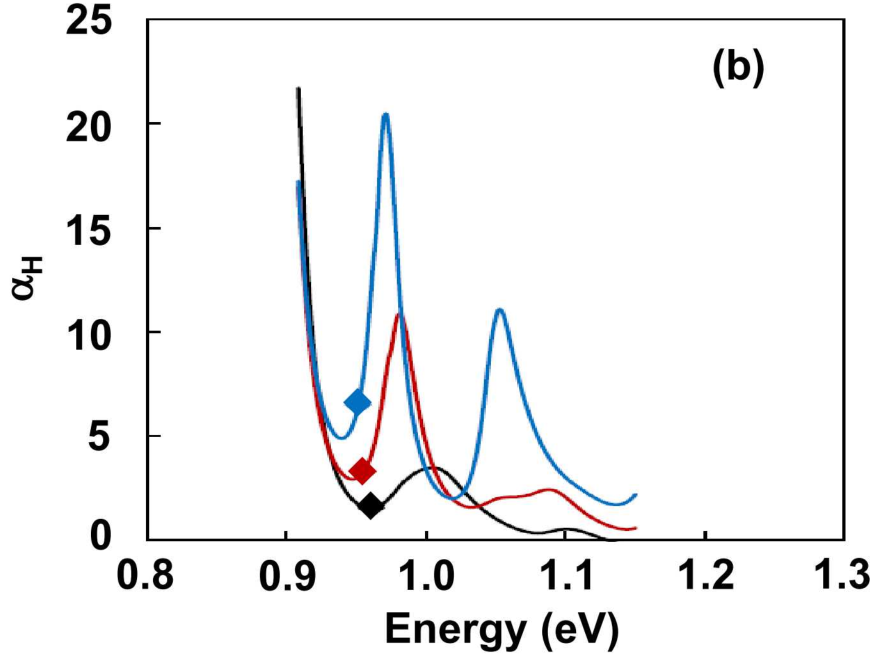
Typical gain and α_H for quantum dot laser

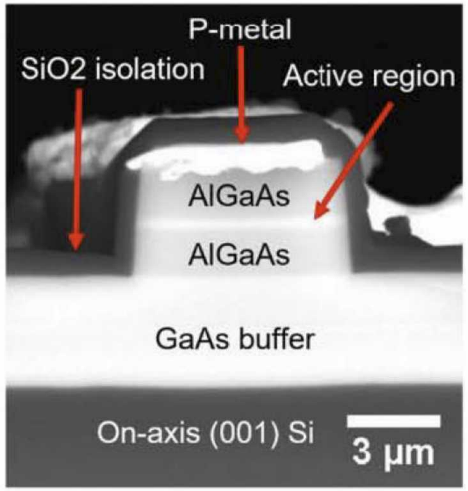


17.5 nm uid-GaAs
10 nm pGaAs
10 nm uid-GaAs
5 nm InGaAs
2 nm InGaAs

p+GaAs contact layer (300 nm)
p-$Al_xGa_{1-x}As$ grading layers (50 nm)
p-$Al_{0.4}Ga_{0.6}As$ cladding (1405 nm)
p-$Al_xGa_{1-x}As$ grading layers (50 nm)
uid-GaAs waveguide (12.5 nm)
GaAs (37.5 nm)
InAs QDs in $In_{0.15}Ga_{0.85}As$ QW (~7 nm)
uid-GaAs waveguide (50 nm)
n-$Al_xGa_{1-x}As$ grading layers (50 nm)
n-$Al_{0.4}Ga_{0.6}As$ cladding (1400 nm)
n-$Al_xGa_{1-x}As$ grading layers (50 nm)
n-GaAs buffer (500 nm)
Buffer on Silicon (~3000 nm)
(001) on-axis Silicon







8nm $In_{0.15}Ga_{0.85}As$ QW

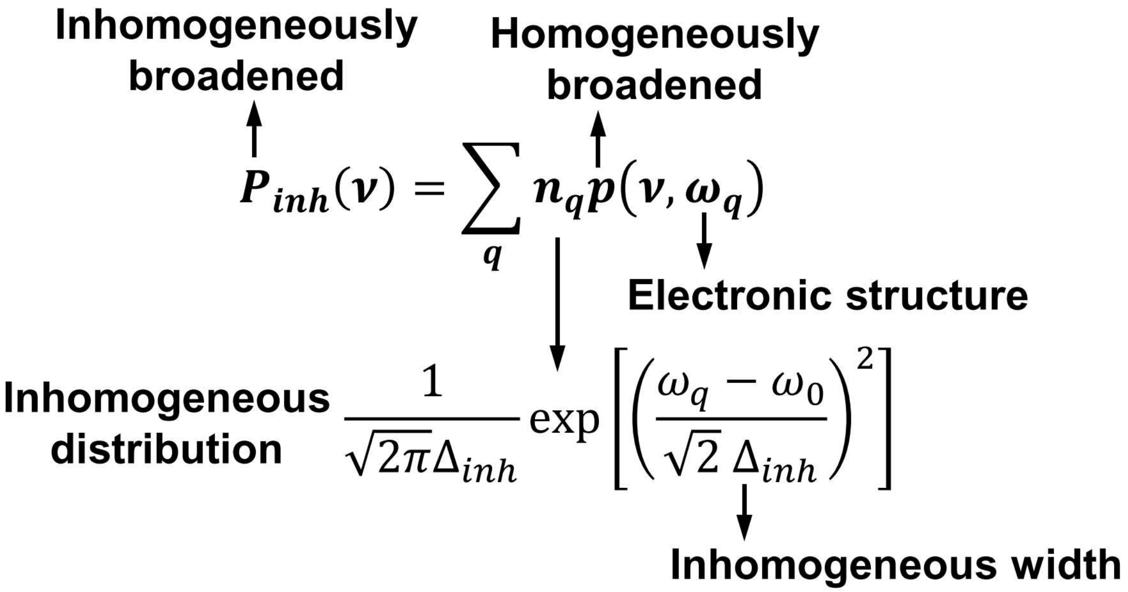
5 x 10^{10}cm^{-2} InAs QDs

GaAs barriers

Δ_{inh} = 20 meV → Δ_{sp} = 48 meV

Undoped, N_e = 3 x, 5 x, 7 x 10^{11} cm^{-2}

APL 107, 1171106 (2015)



Inhomogeneously broadened

Homogeneously broadened

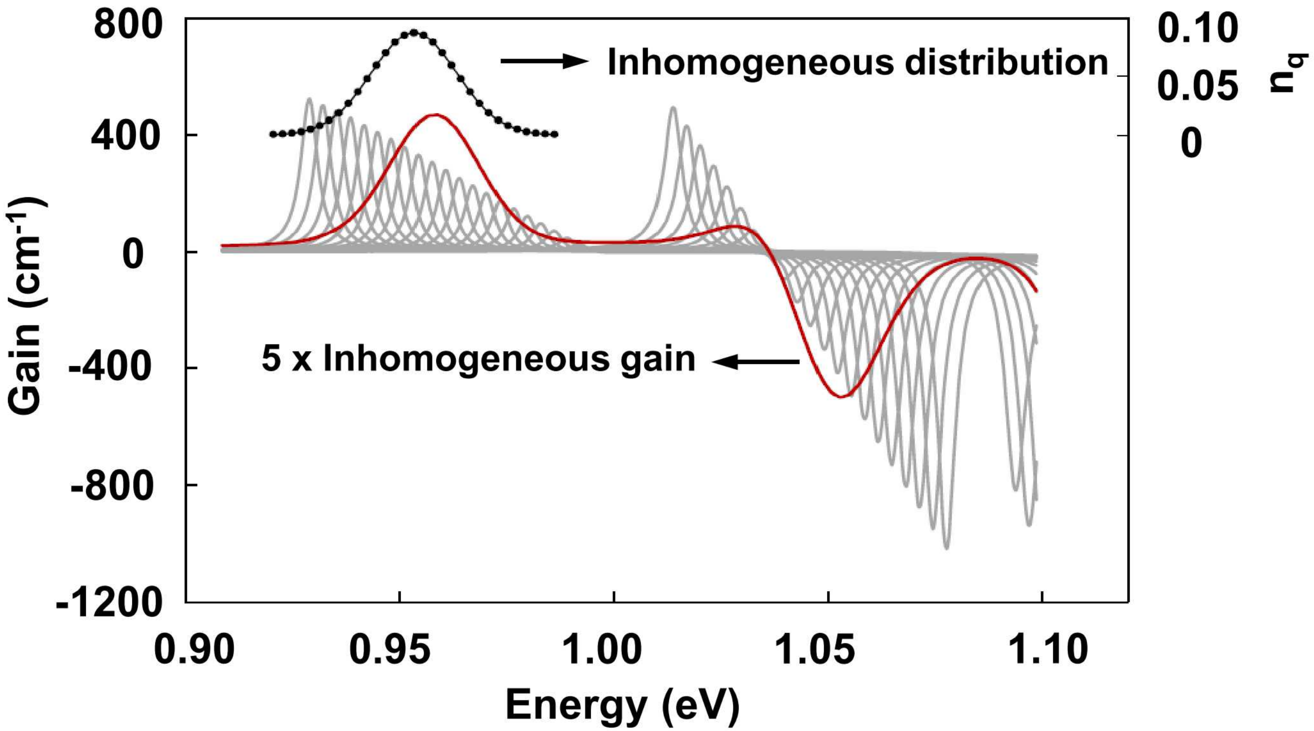
$$\boldsymbol{P_{inh}(\nu) = \sum_{q} n_q p(\nu, \omega_q)}$$

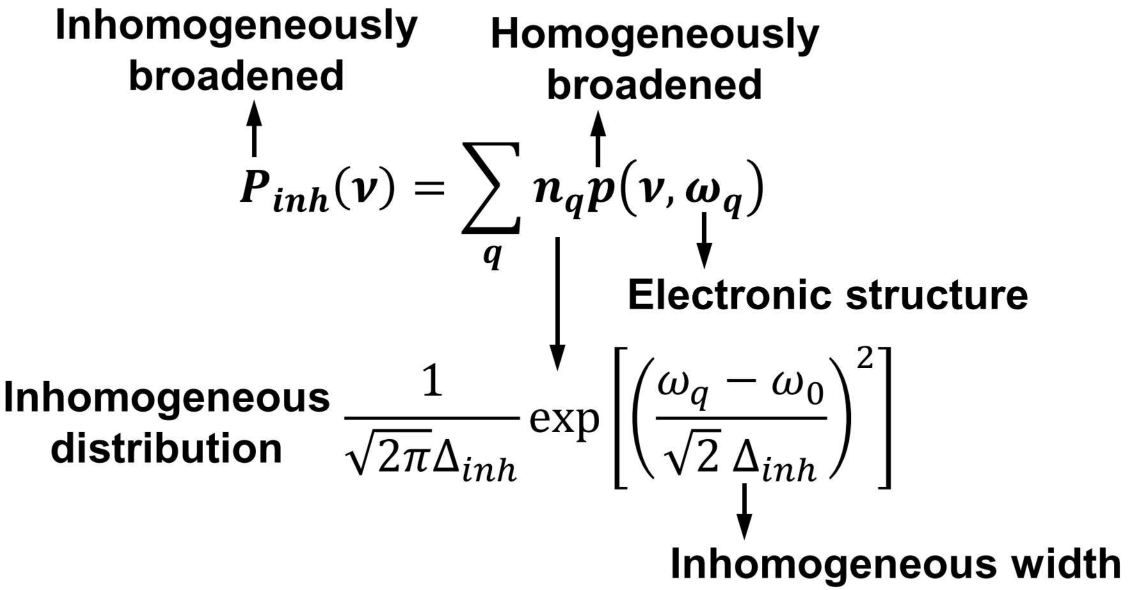
Electronic structure

Inhomogeneous distribution

$$\frac{1}{\sqrt{2\pi}\Delta_{inh}} \exp\left[\left(\frac{\omega_q - \omega_0}{\sqrt{2}\,\Delta_{inh}}\right)^2\right]$$

Inhomogeneous width





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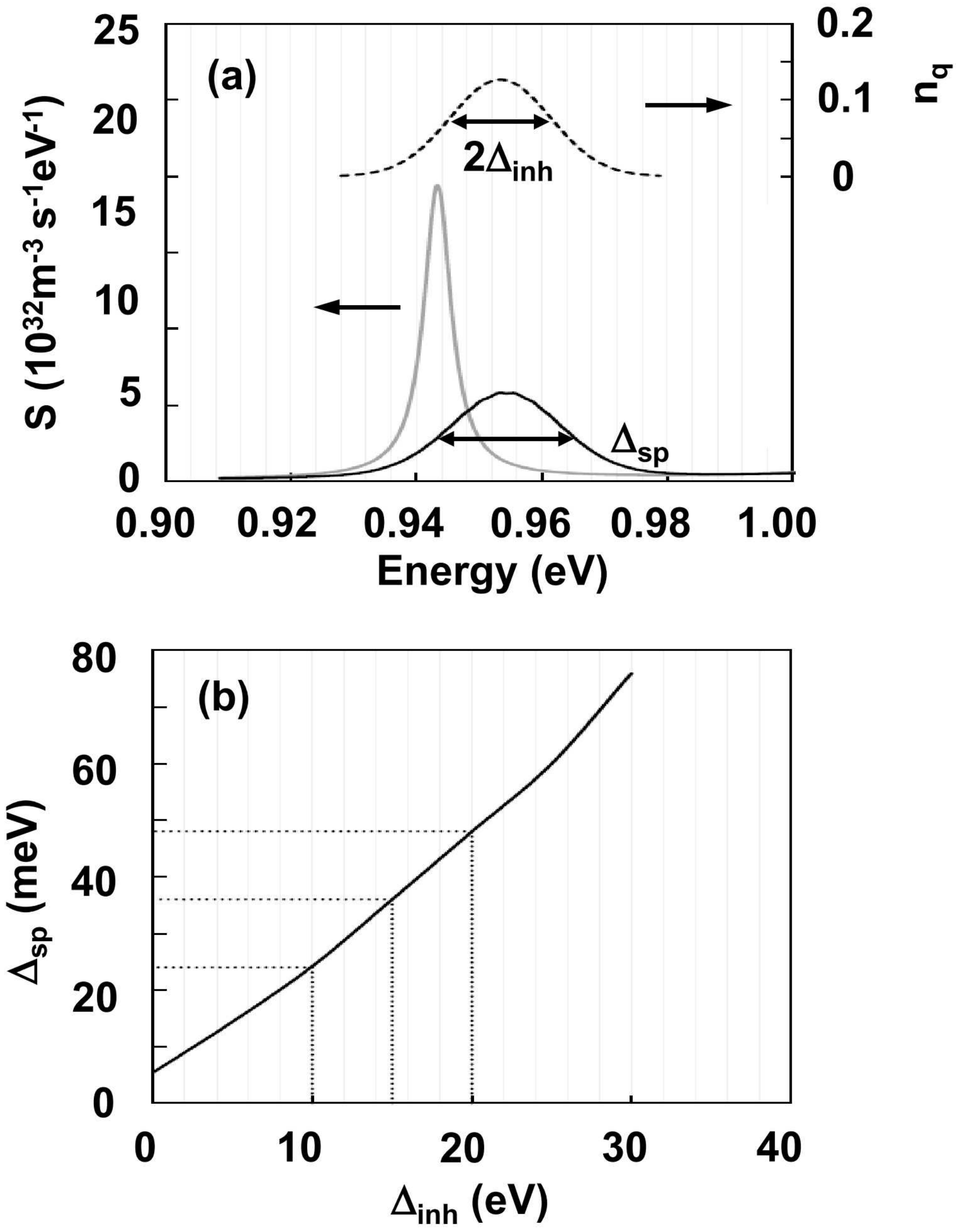
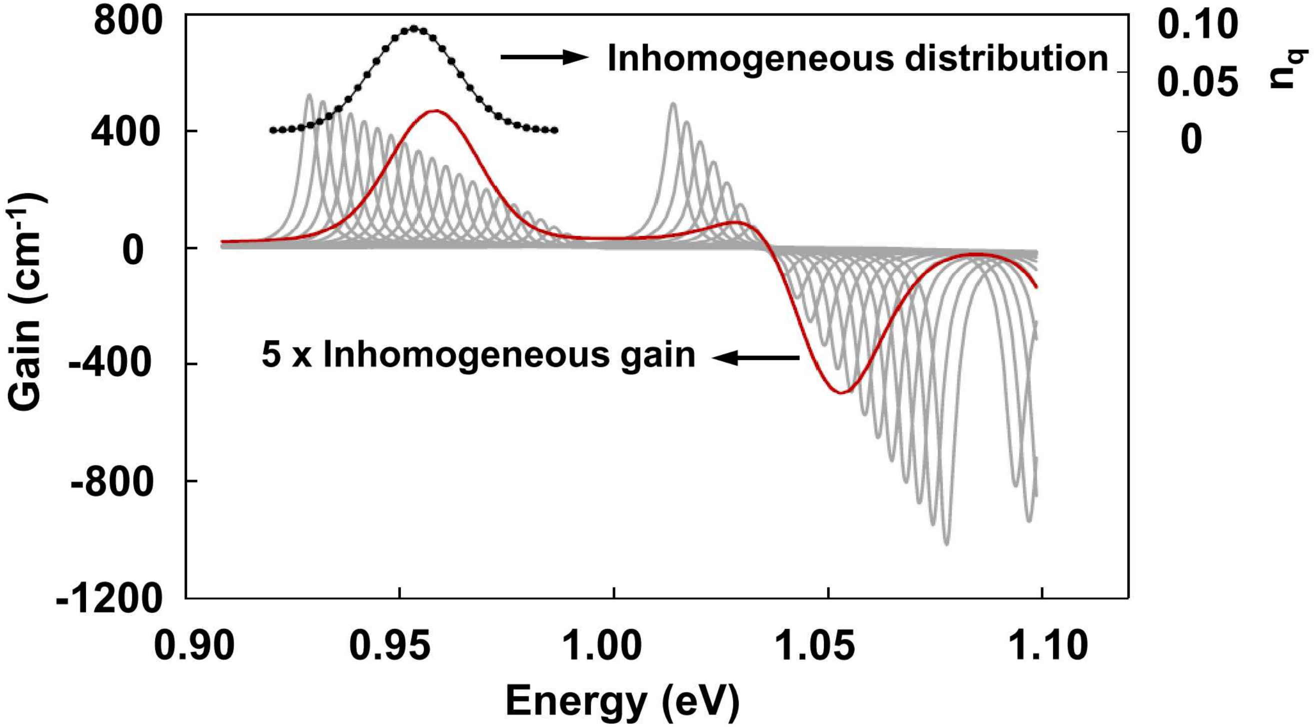
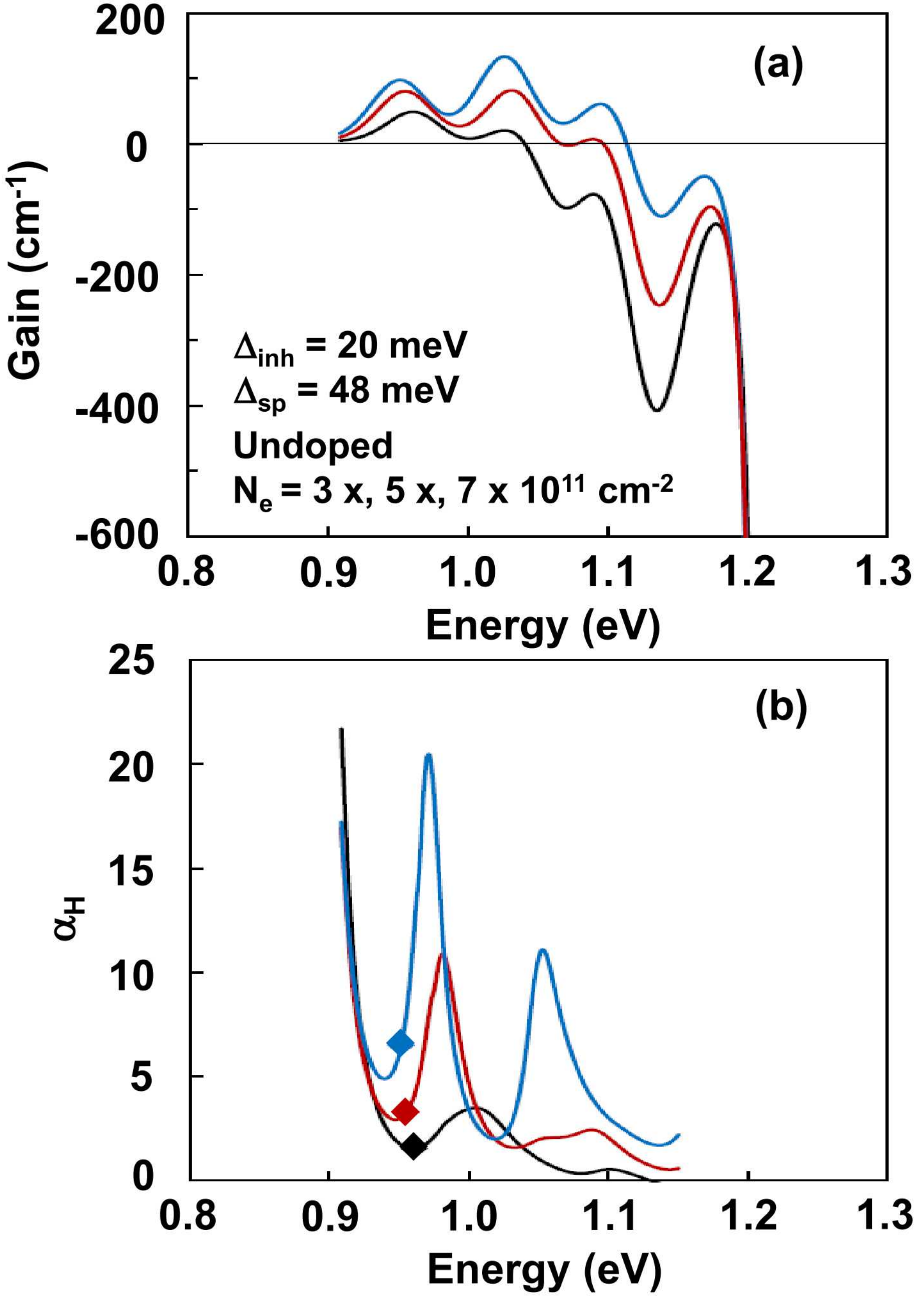
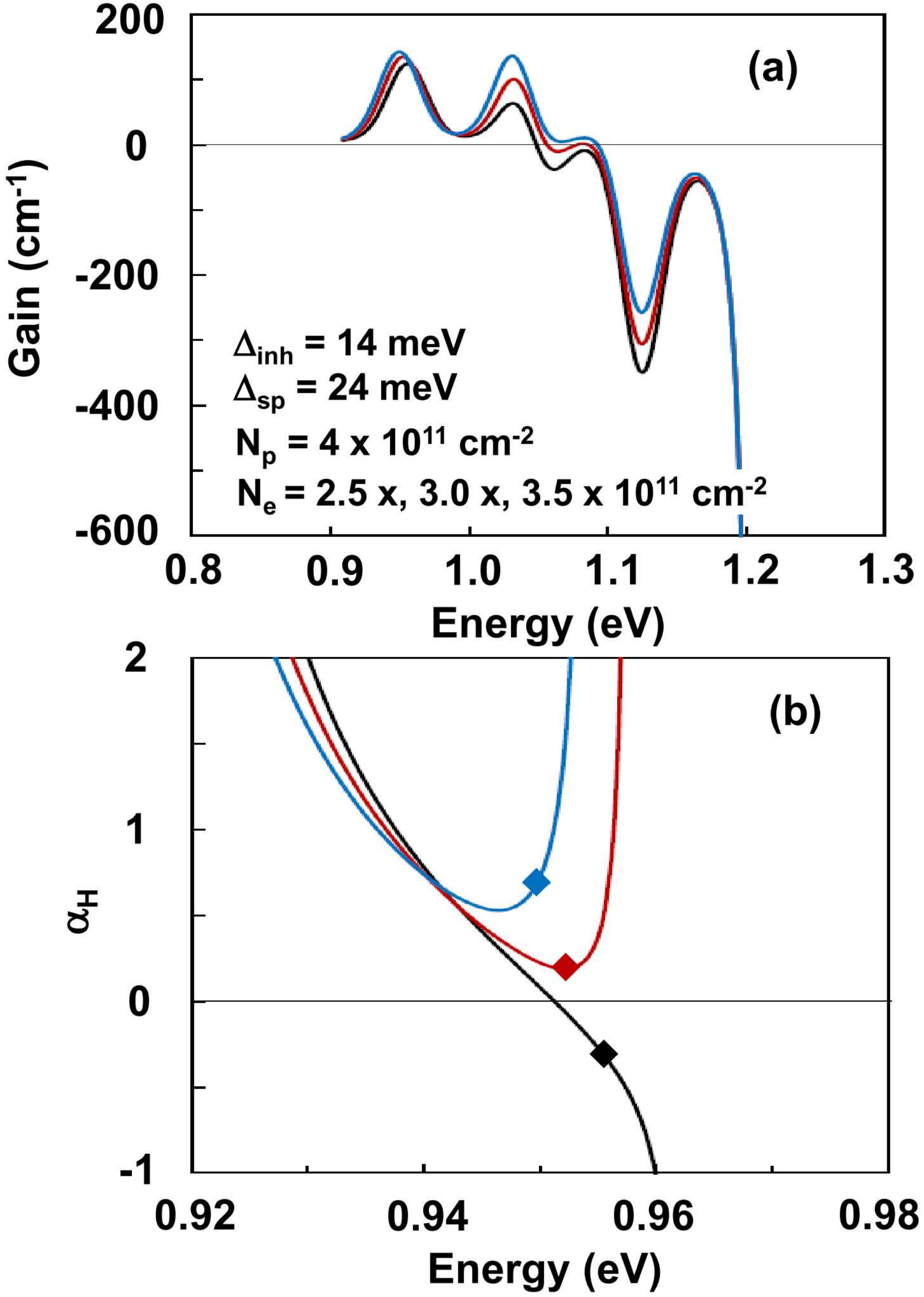




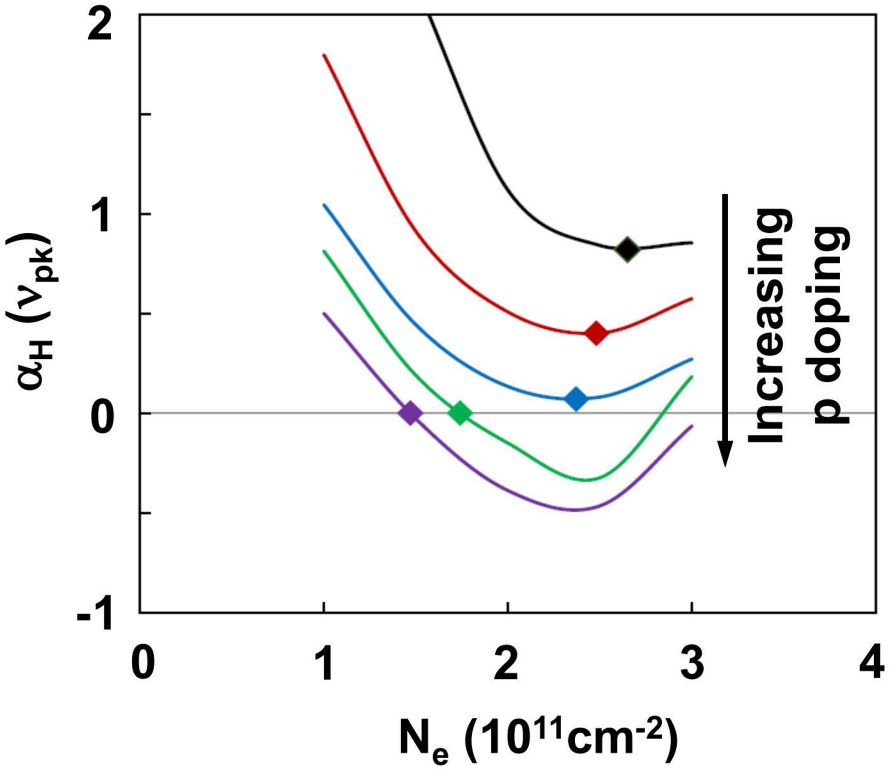
Gain and α_H spectra of quantum dot laser





Zhang, et al. APL 113, 061105 (2018)

Linewidth enhancement factor at gain peak for ground-state lasing

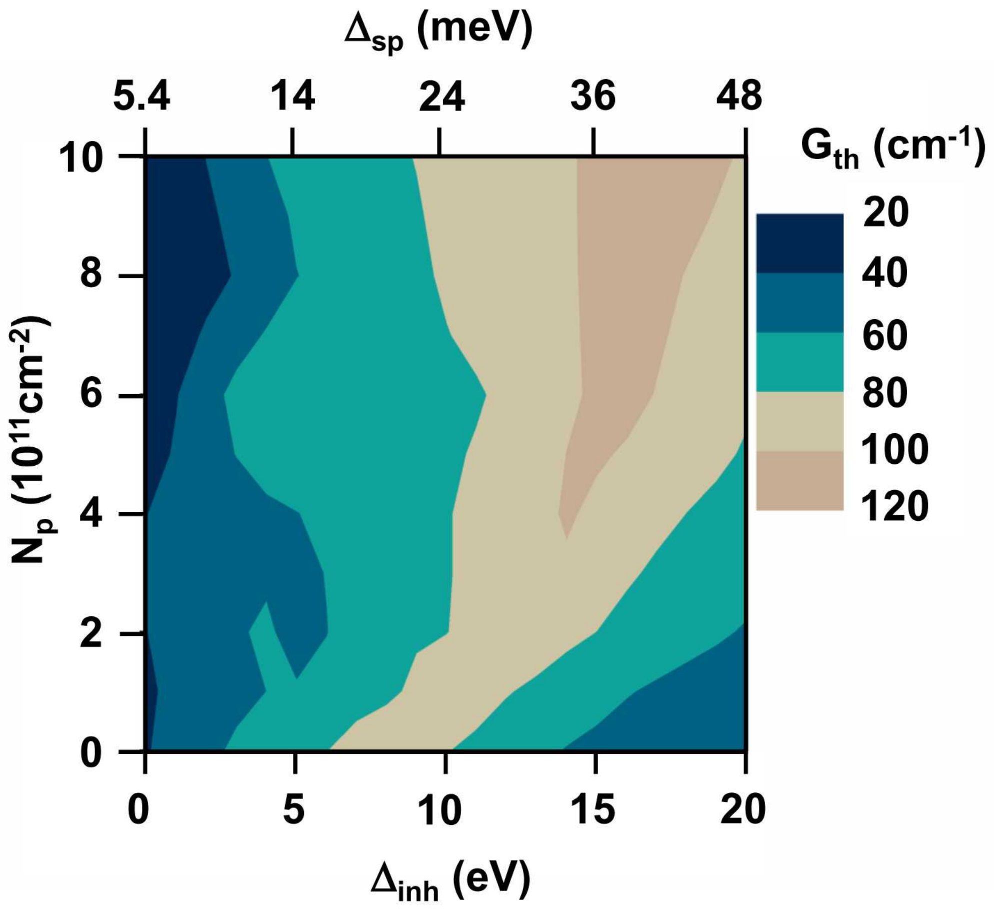


Δ_{inh} = 14 meV → Δ_{sp} = 24 meV

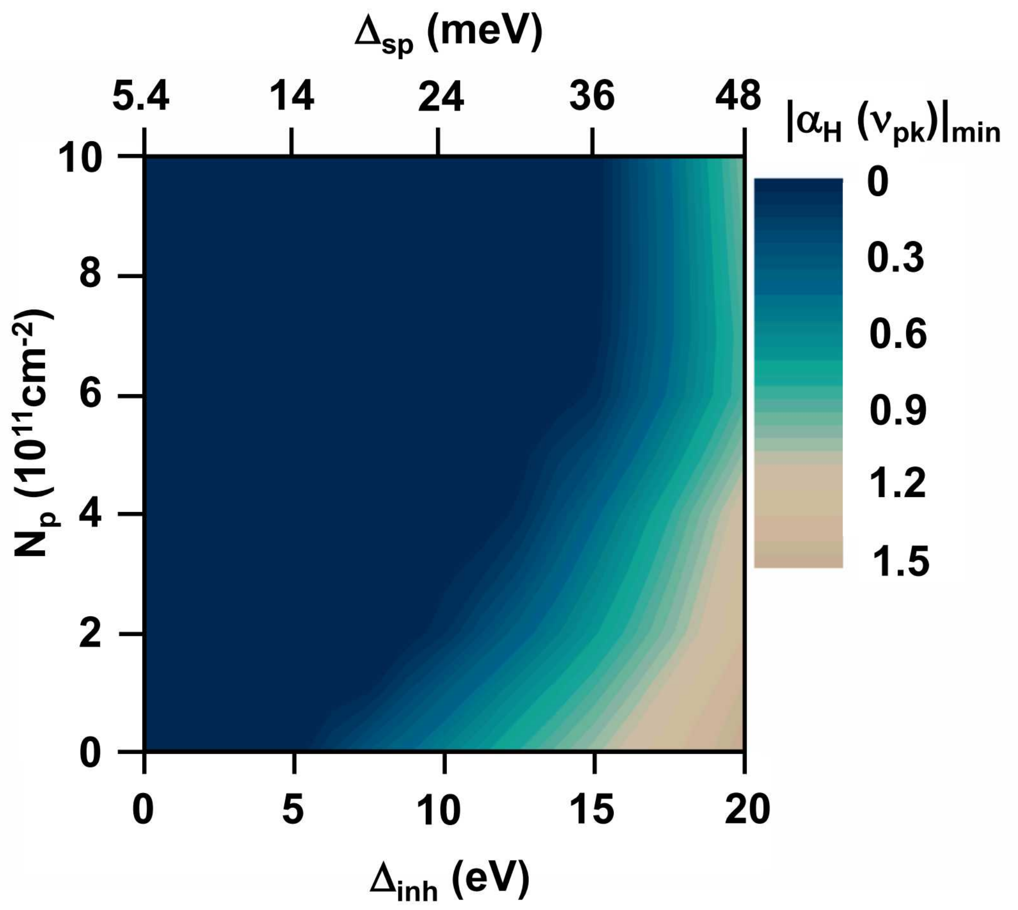
N_p = 0 x, 2 x, 4 x, 6 x, 8 x 10^{11} cm^{-2}

Designing QD lasers with minimum $\alpha_H(\nu_{pk})$

Combinations of $(\Delta_{inh}, N_p, G_{th})$ giving $|\alpha_H(\nu_{pk})|_{min}$

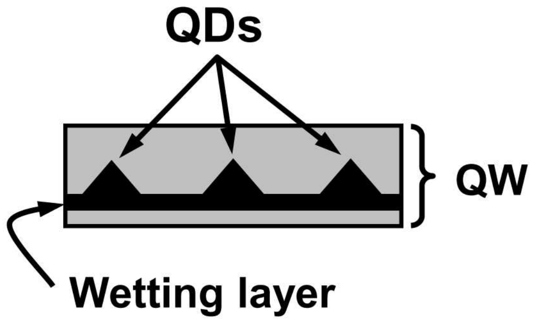


$|\alpha_H(\nu_{pk})|_{min}$ resulting from $(\Delta_{inh}, N_p, G_{th})$ combinations



QD laser theory

Semiclassical laser theory



$$\overset{\text{Carrier-induced refractive index}}{\overset{\uparrow}{[2K\delta n(\nu)}} + i\underset{\text{Intensity gain}}{\underset{\downarrow}{G(\nu)}}]\mathrm{E} = \frac{2\nu}{\varepsilon_0 n_B c h}\left[N_{QD}^{2d}\sum_n \wp_n \sum_q n_{n,q}^{inh} \underset{\text{QD polarization}}{\underset{\downarrow}{p_{n,q}(\nu)}} + \frac{1}{A}\sum_k \wp_k \underset{\text{QW polarization}}{\underset{\downarrow}{p_k(\nu)}}\right]$$

e-h polarization

$$\frac{dp_{n,q}}{dt} = i\left(\nu - \omega_{n,q}^{(0)}\right)p_{n,q} \overbrace{- i\frac{2\wp_n\mathcal{E}}{\hbar}\left(f_{n,q}^{e} + f_{n,q}^{h} - 1\right)}^{\text{Absorption and stimulated emission}}$$

Single-particle contributions

$$+\frac{i}{\hbar}\sum_k V_{n,k}\left(f_k^e + f_k^h\right)p_{n,q} + \frac{i}{\hbar}\sum_k V_{n,k}p_k$$

Exchange and excitonic effects

$$+ \underset{\text{Carrier-phonon scattering}}{\underset{\downarrow}{S_n^{c-p}}} + \underset{\text{Carrier-carrier scattering}}{\underset{\downarrow}{S_n^{c-c}}}$$

Dephasing and screening

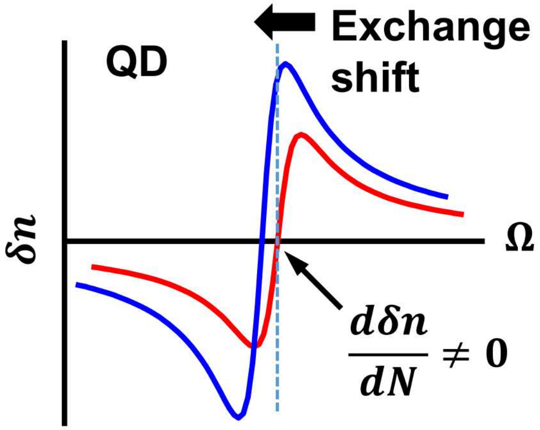
Many-body effects

Features of QD laser theory

① **QD/QW combination**

Renorminizations:

H.C. Schneider, et al.
PRB 64, 115315 (2001)
PRB 66, 41310(R) (2002)



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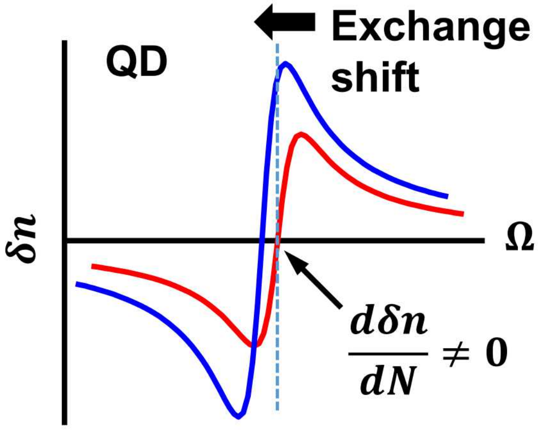
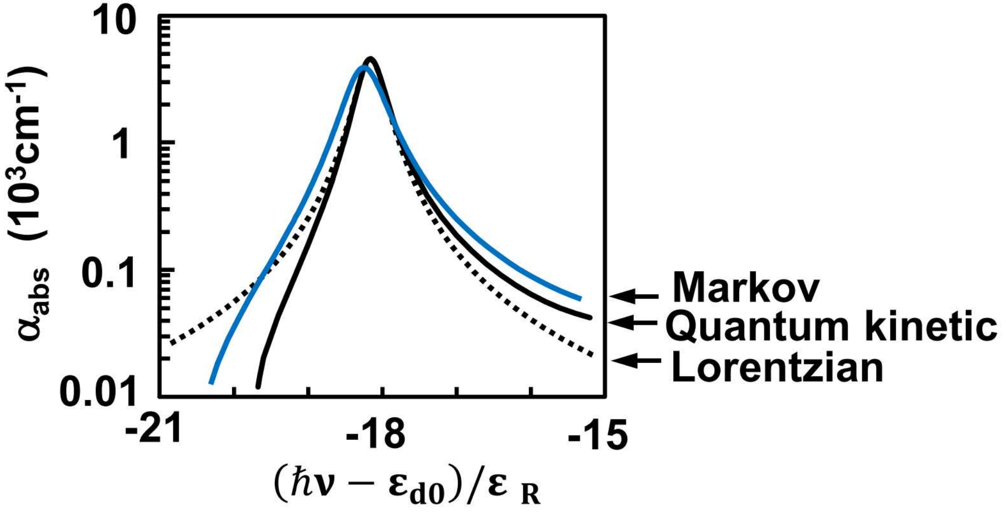


❷ Memory

H.C. Schneider, et al. PRB 70, 235308 (2004)



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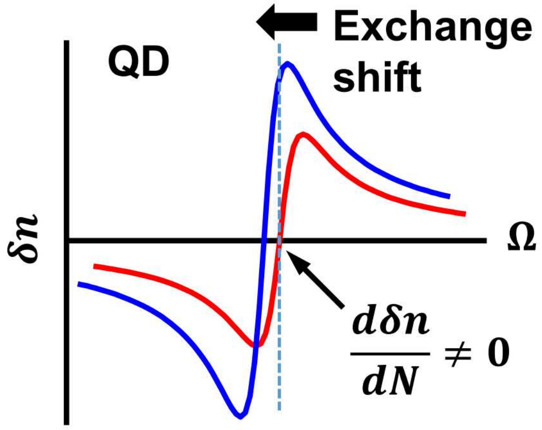

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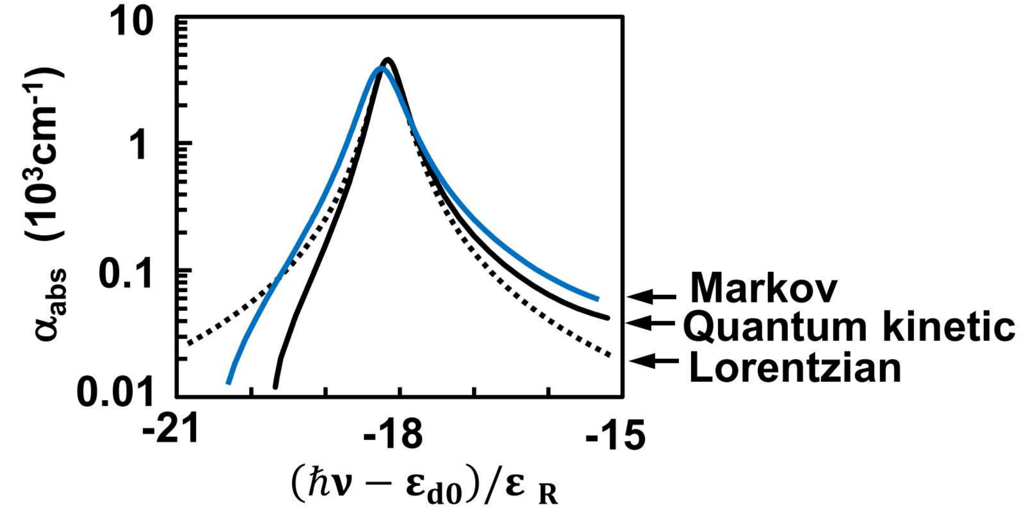
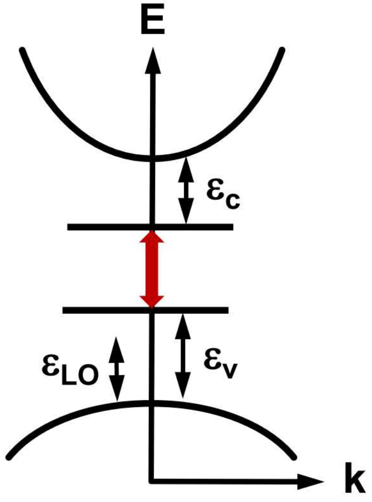
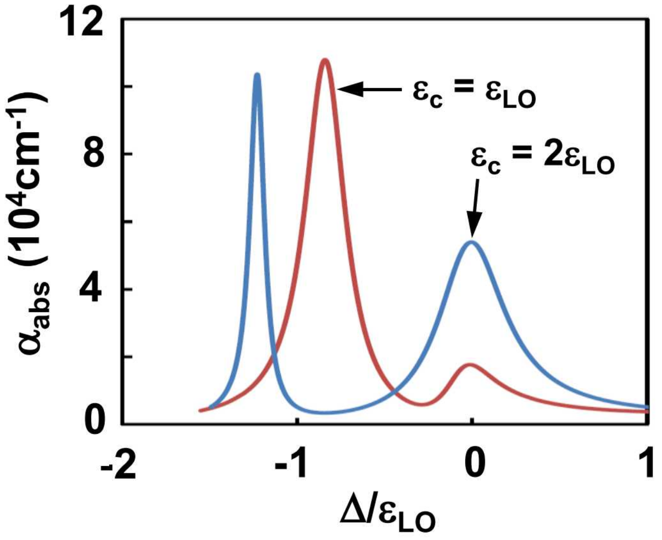
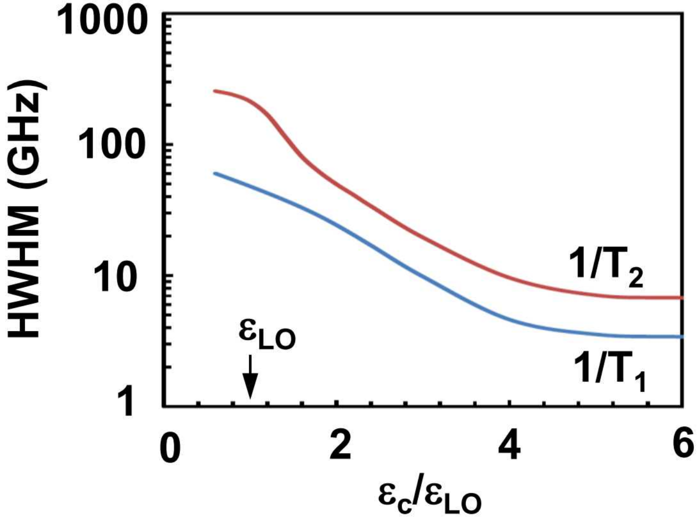


③ Scattering (beyond 2nd Born approx.)

J. Seebeck, et al. PRB 71, 125327 (2005)







No phonon bottleneck as predicted by H. Benisty, et al. PRB 44, 10945 (1991)

Summary

Calculations on devices a step from being ready for use in optoelectronics

Modeling devices versus modeling experimental results

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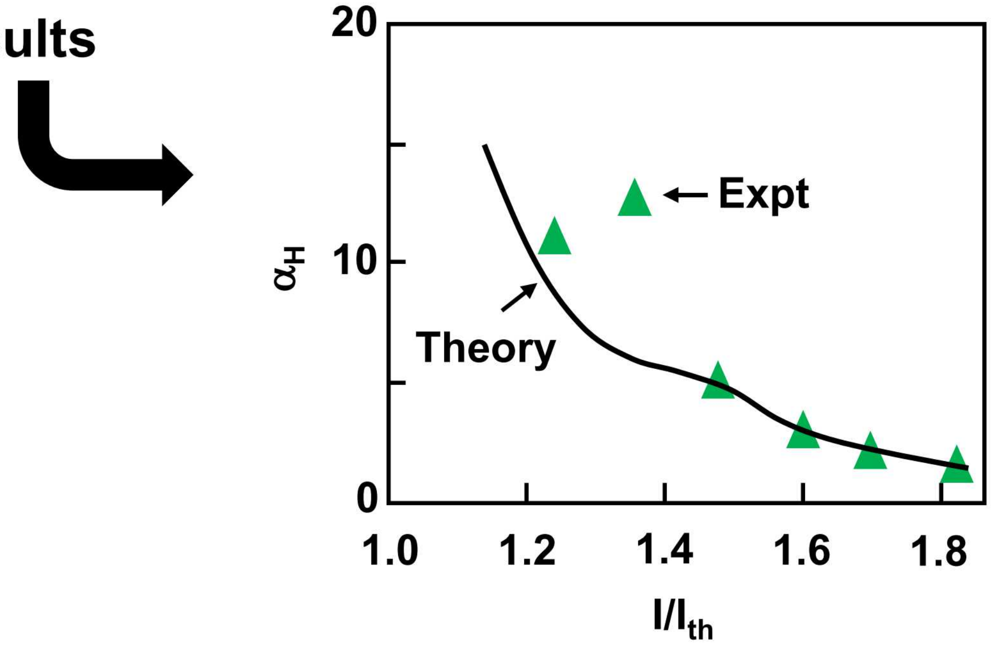

$In_{0.3}Ga_{0.7}As$ QD in GaAs QW

$N_{QD} = 5 \times 10^9 cm^{-2}$

$\Delta_{inh} = 30$ meV

S. Holzinger, et al. Opt. Exp. 26, 31363 (2018)

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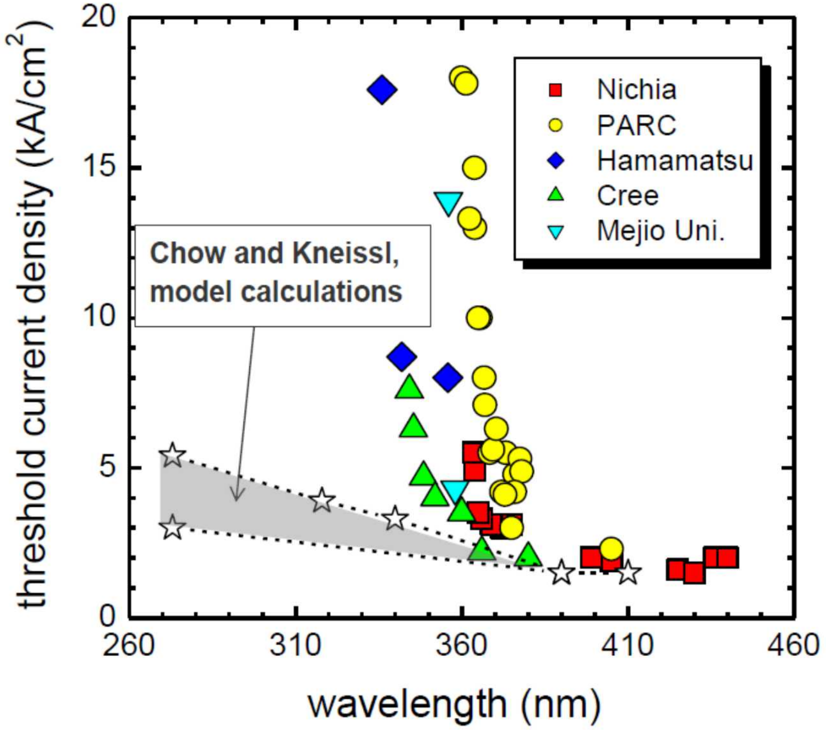
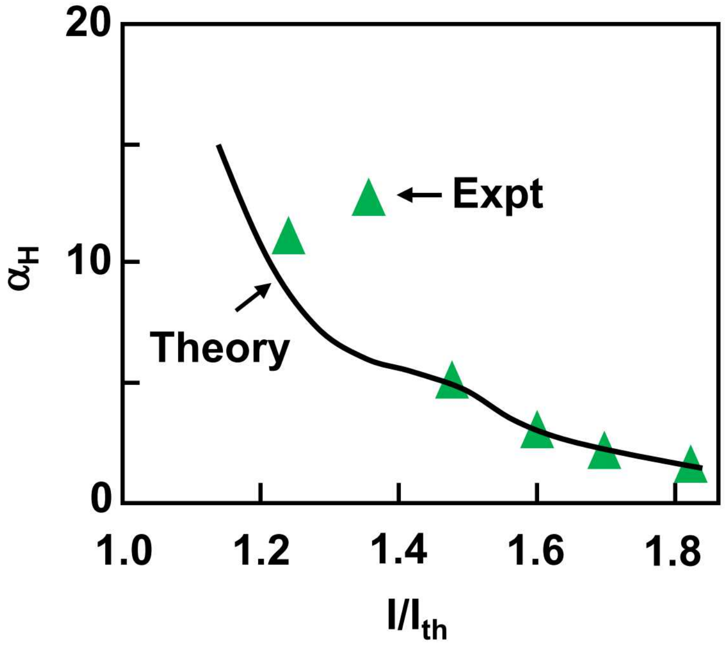
Zeeman laser
Multioscillator ring
laser gyro

Murray Sargent III (μsoft):
"Numerical experiments"



Chow and Kneissl, JAP 98, 114502 (2005)
Slide courtesy of Noble Johnson (PARC)

Funding: SFB 787



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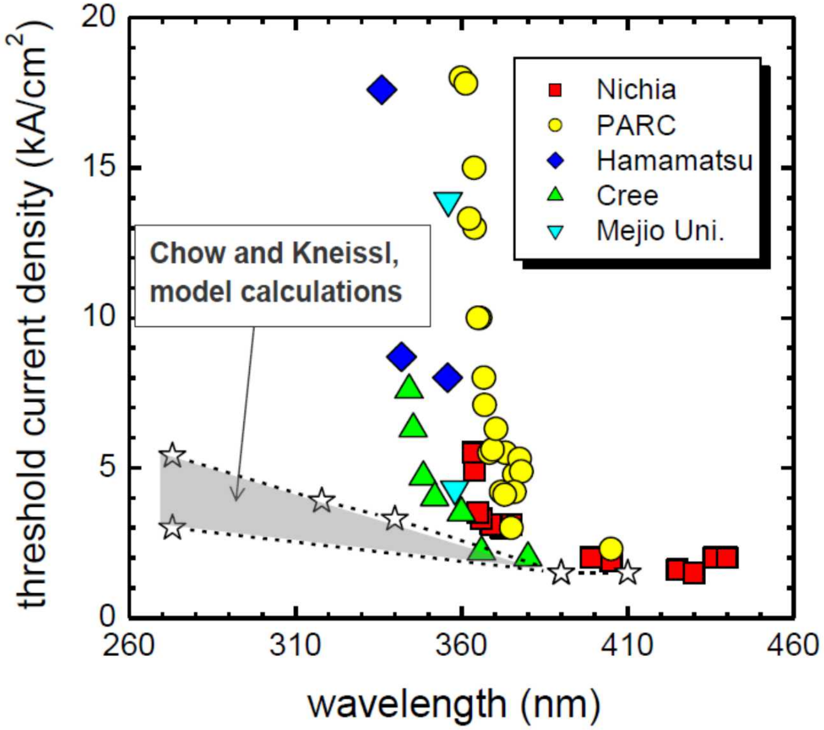
Z. Zhang, et al. 'Effects of modulation p-doping in InAs quantum dot lasers on silicon' APL 113, 061105 (2018)

Z. Zhang, et al. 'Linewidth enhancement factor in InAs/GaAs quantum dot lasers and its implication in isolator-free and narrow linewidth applications' IEEE J. Selected Topics in Quantum Electron. 25, 1900509 (2019)



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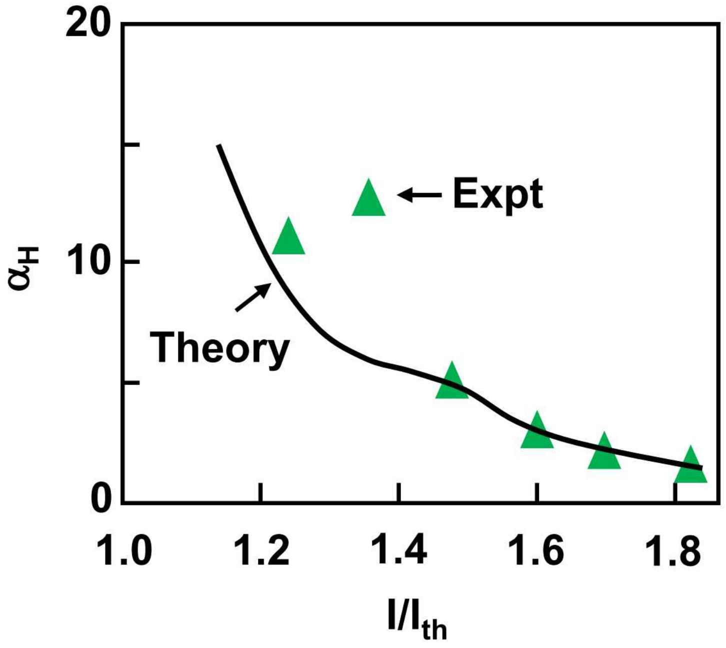

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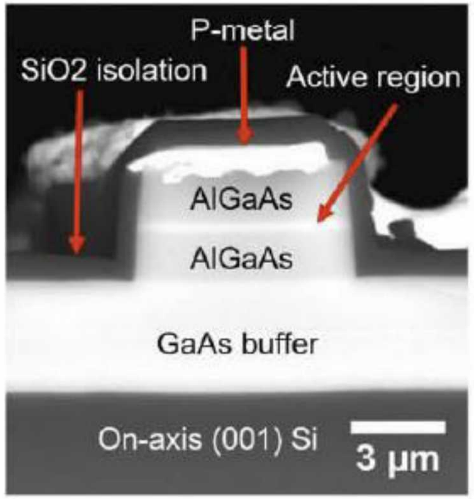
The real laser

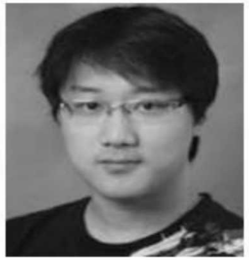


Quantum-dot gain


Justin Norman


Daehwan Jung


Robert Zhang

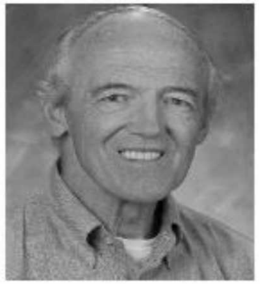

Shen Shang

Mode locking


Songtao Liu

Nanolasers


Yating Wan


Art Gossard


John Bowers

A review of high-performance quantum dot lasers on Silicon (IEEE JQE 55, 200511, 2019)

On the physics of semiconductor quantum dots for applications in lasers and quantum optics
Chow and Jahnke, Prog Quantum Electron 37, 109–184 (2013)

Quantum-optical influences in optoelectronics—An introduction
Chow and Reitzenstein, Applied Physics Reviews 5, 041302 (2018)