Gain-current relationships in quantum-dot and quantum-well lasers: Theory and experiment

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Motivation for experiment

Theoretical model

Results:

- **Sample characterization**
- **Prediction of eventual performance**
- **Quantum-dot/quantum-well comparison**

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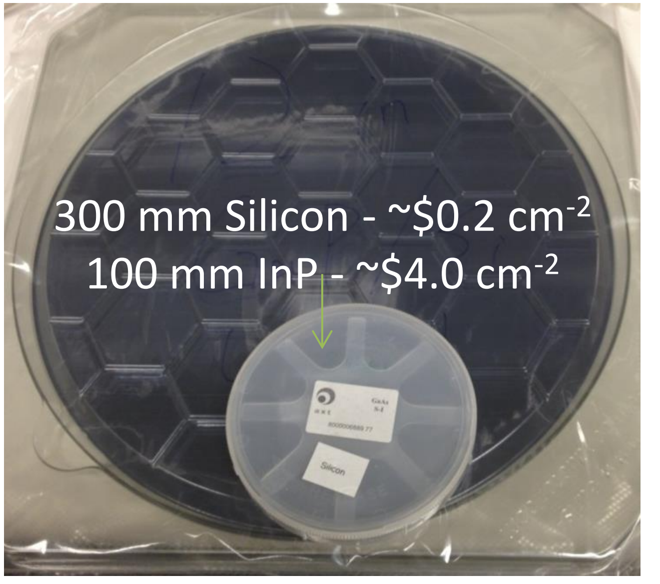
Quantum dot lasers for silicon photonics

Grow III-V lasers on larger and cheaper silicon substrates without sacrificing laser performance for <u>lower cost and higher throughput</u>

3-D confinement reduces carrier migration to dislocations

Quantum dot lasers have the lowest threshold current densities of all semiconductor lasers



(Courtesy of Dr. Jordan Lang, Yale)

To push the limits of device performance, it is critical to minimize nonradiative losses and inhomogeneous broadening

Bowers, John E., et al. "A Path to 300 mm Hybrid Silicon Photonic Integrated Circuits." OFC 2014

A. Y. Liu, A. C. Gossard, J. E. Bowers et. al, "Quantum dot lasers for silicon photonics [Invited]", Photonics Research, vol. 3, 2015

1991 – "Semiconductor Structure for Optoelectronic Components with Inclusions" (Jean Gerard & Claude Weisbuch), U.S. Patent No. 5,075,742

D. Bimberg, U. W. Pohl, "Quantum dots: promises and accomplishments." *Materials Today,* 2011.

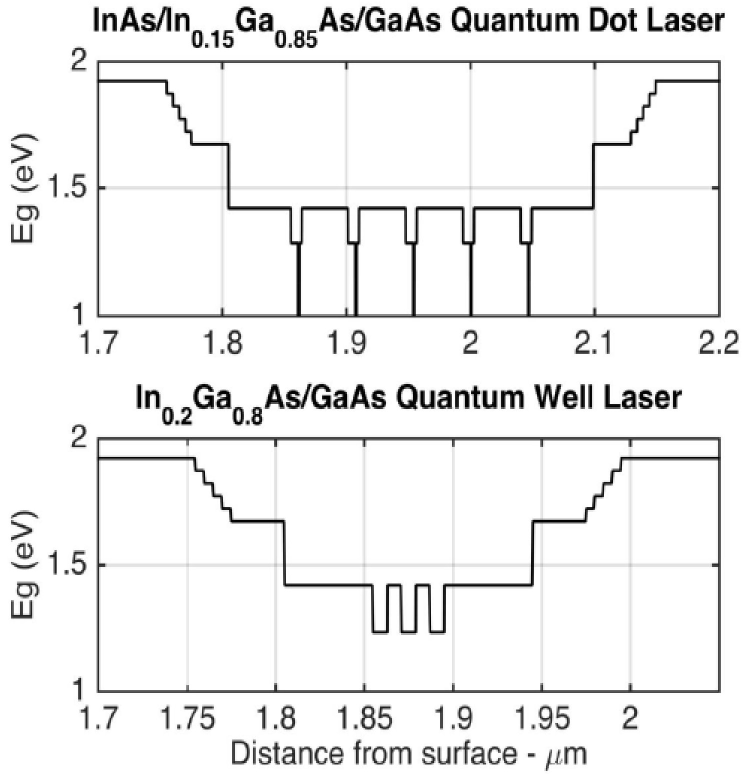
Experiment

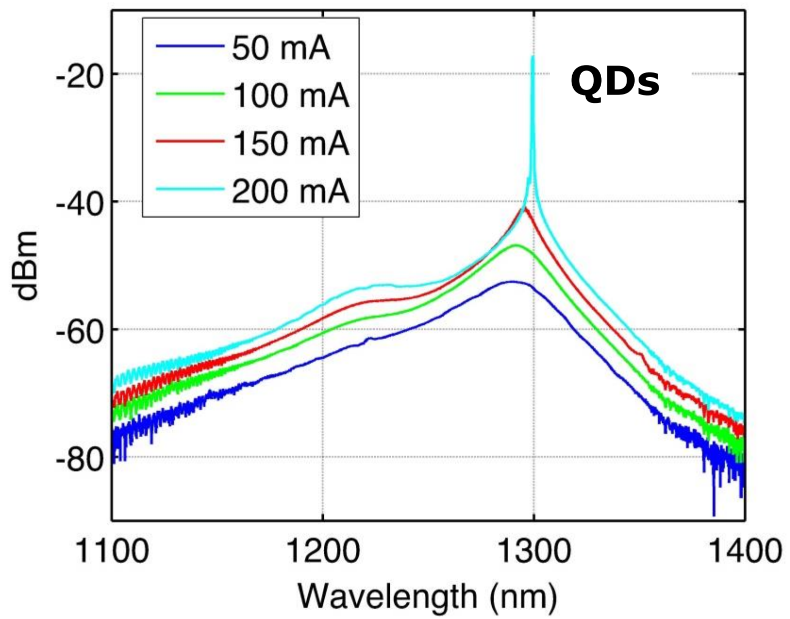
50 μms wide broad area lasers on GaAs

Measurements in pulsed mode, 5 μs pulse width, 1000 μs off time

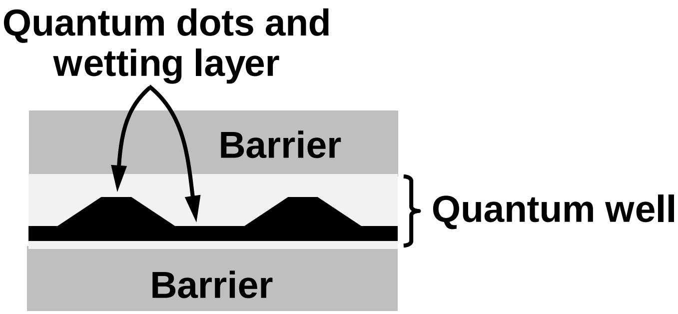
Assumptions:

- **Equal power output from both facets**
- **R=0.32**
- **Negligible cavity length dependent loss**

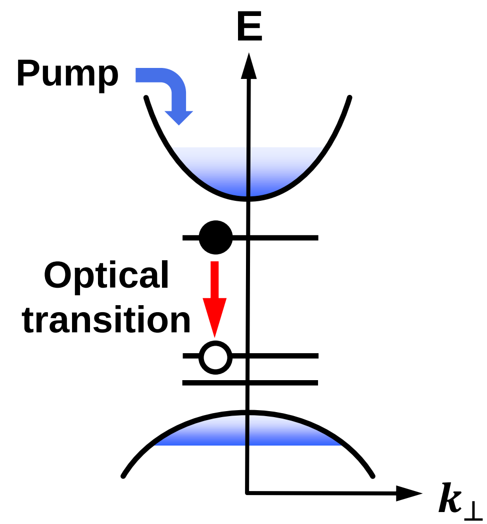




Approach (quantized electrons & classical optical field)



Electronic structure



$$H = \sum_\alpha \varepsilon^e_\alpha \, c^\dagger_\alpha c_\alpha + \sum_\beta \varepsilon^h_\beta \, b^\dagger_\beta b_\beta$$ **Single-particle**

$$- \sum_\alpha \left(g_\alpha b^\dagger_\alpha c^\dagger_\alpha + g^*_\alpha c_\alpha b_\alpha \right) E$$ **Light-carrier**

$$g_\alpha \leftarrow \wp W(R_{QD}) \sum\nolimits_n C_\alpha(R_n) V_\alpha(R_n)$$

$$+ \frac{1}{2} \sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta} \, c^\dagger_\alpha c^\dagger_\beta c_\eta c_\sigma + \frac{1}{2} \sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta} \, b^\dagger_\alpha b^\dagger_\beta b_\eta b_\sigma - \sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta} \, b^\dagger_\alpha c^\dagger_\beta c_\eta b_\sigma$$ **Carrier-carrier**

Matrix element of $\dfrac{e^2}{4\pi\varepsilon_b |r - r'|}$

$$+ \hbar \sum_{\alpha\beta q} G_q \left(c^\dagger_\alpha c_\beta + b^\dagger_\alpha b_\beta \right) \left(d_q + d^\dagger_q \right)$$ **Carrier-phonon**

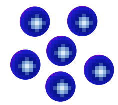
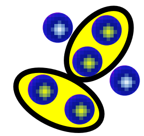
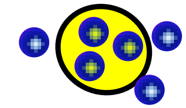
Heisenberg Picture $$\frac{\partial}{\partial t} A = -\frac{i}{\hbar} \, [A, H]$$

Populations and correlations

$\langle c_\alpha^\dagger c_\alpha \rangle, \langle b_\alpha^\dagger b_\alpha \rangle, \langle b_\alpha^\dagger c_\alpha^\dagger \rangle, \left\langle c_\alpha^\dagger c_\beta^\dagger c_\beta c_\alpha \right\rangle, \left\langle b_\alpha^\dagger b_\beta^\dagger c_\beta^\dagger b_\alpha \right\rangle, \ldots$

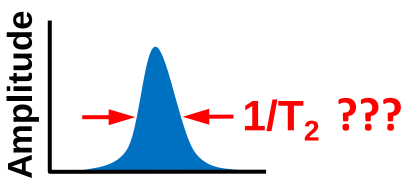
Cluster expansion

Single particles | Correlated pairs | Correlated 3-particle clusters

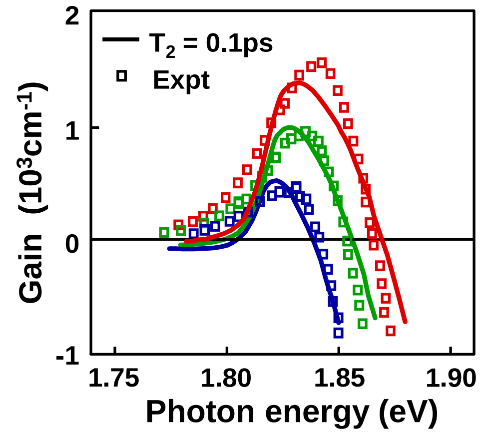
$\langle \hat{A} \rangle =$  +  +  + ...

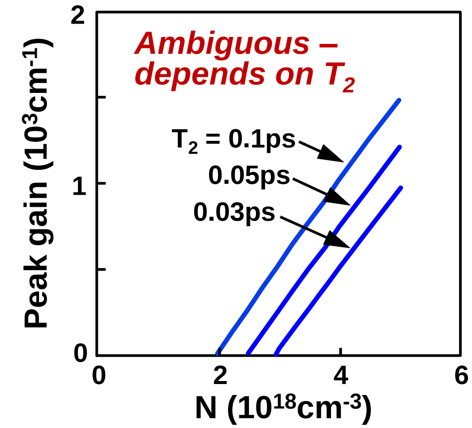
Singlet

$$G \propto \sum_{\alpha,\beta} \underset{\downarrow\ \text{Dipole matrix element}}{|\mu_{ij}|^2} \underbrace{L(\omega_{\alpha\beta} - \nu)}_{\text{Lineshape (collisions)}} \underbrace{(n_{e\alpha} + n_{h\alpha} - 1)}_{\text{Population inversion}}$$



6.8 nm $Ga_{0.41}In_{0.59}P$ / $(Al_{0.5}Ga_{0.5})_{0.51}In_{0.49}P$

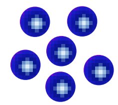




Populations and correlations $\langle c_\alpha^\dagger c_\alpha\rangle, \langle b_\alpha^\dagger b_\alpha\rangle, \langle b_\alpha^\dagger c_\alpha^\dagger\rangle, \left\langle c_\alpha^\dagger c_\beta^\dagger c_\beta c_\alpha\right\rangle, \left\langle b_\alpha^\dagger b_\beta^\dagger c_\beta^\dagger b_\alpha\right\rangle, \ldots$

Cluster expansion $\langle \hat{A}\rangle =$

Single particles



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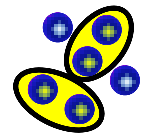
Correlated pairs



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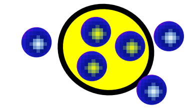
Correlated 3-particle clusters



\+ ...

Singlet

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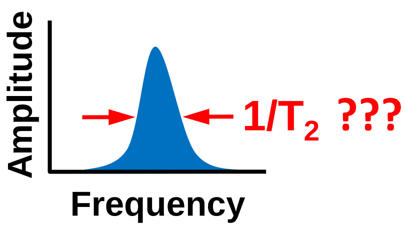

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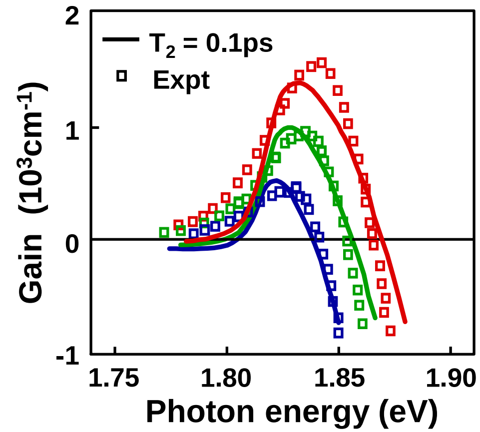
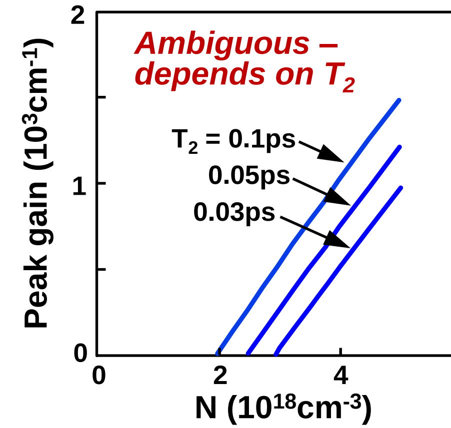


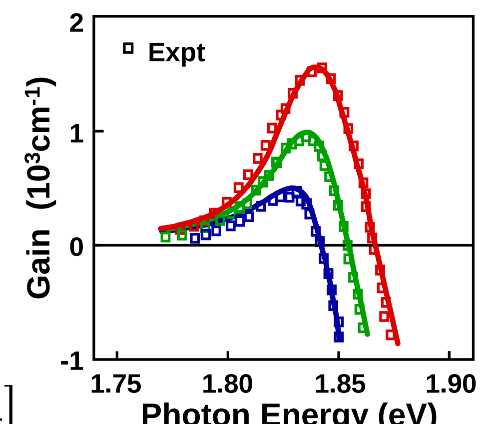


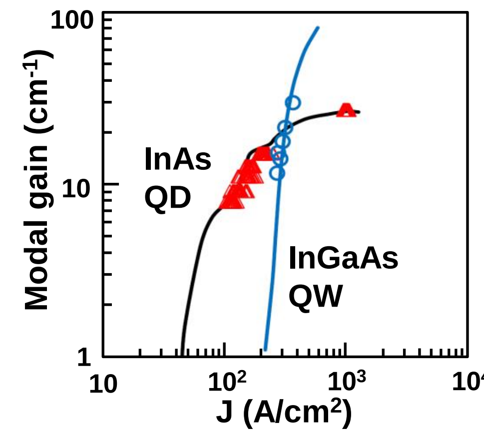
Doublet

$$\frac{dp_\alpha}{dt} = -i\omega_\alpha p_\alpha - i\Omega_\alpha(n_{e\alpha} + n_{h\alpha} - 1) + S_\alpha^{c-c} + S_\alpha^{c-p}$$

Collisions

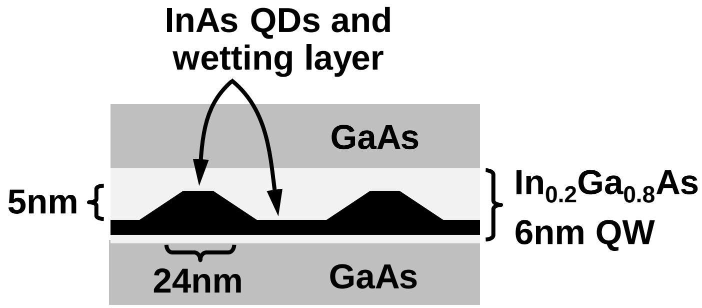
$$\overbrace{-p_\alpha \frac{2}{\hbar} \sum_{k'} \sum_{q} \sum_{\sigma} \sum_{\sigma'} \sum_{k} \xi_{\alpha k} \left[W_q^2 - \frac{\delta_{\sigma,\sigma'}}{2} W_q W_{|k'-q-k|} \right]}^{\text{Collisions}}$$
$$\times [\Delta - i\delta\varepsilon]^{-1}$$
$$\times \left[n_{|k'-q|,\sigma'}(1 - n_{k'\sigma'})(1 - n_{k\sigma}) + \left(1 - n_{|k'-q|\sigma'}\right) n_{k'\sigma'} n_{k\sigma} \right]$$





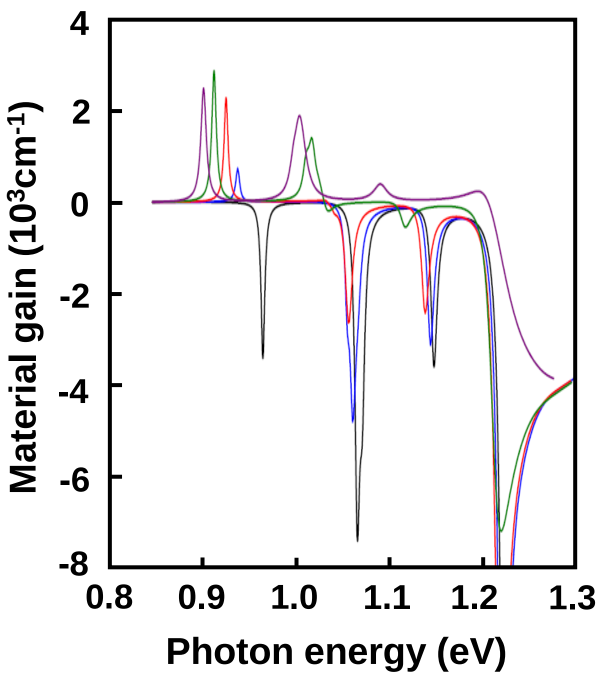
Overview: Chow & Jahnke, Progress in Quantum Electronics 37, 109 (2013)

Intrinsic versus inhomogeneously-broadened quantum dots



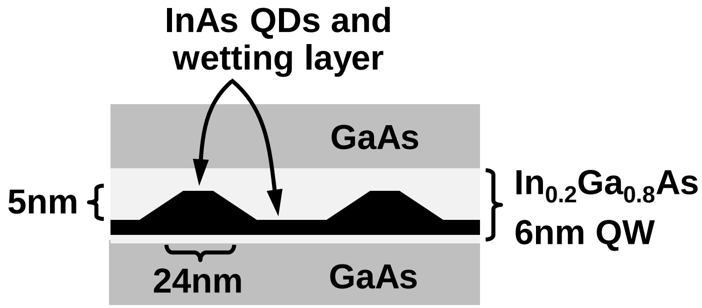
$N_{dot} = 5 \times 10^{10} cm^{-2}$

Intrinsic (Δ_{inh}=0)



T = 300K, N = 0.1x, 0.5x, 1x, 2x, 3 x $10^{12} cm^{-2}$

Intrinsic versus inhomogeneously-broadened quantum dots



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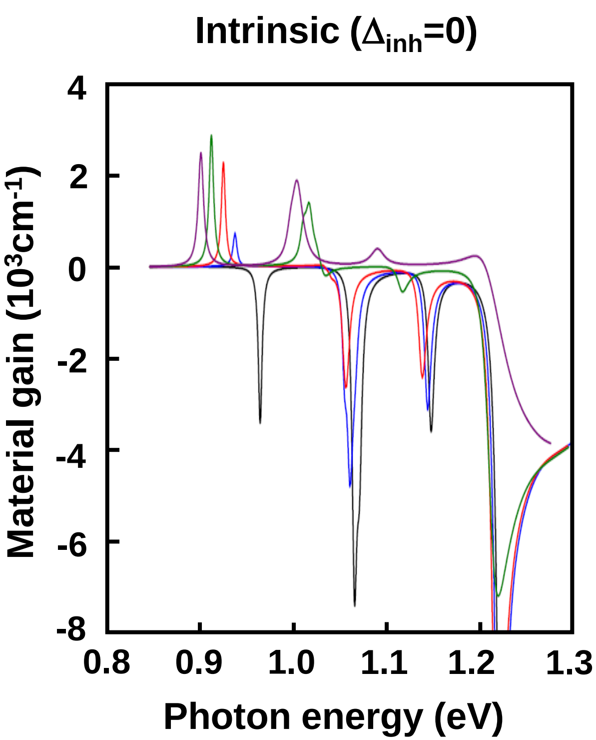
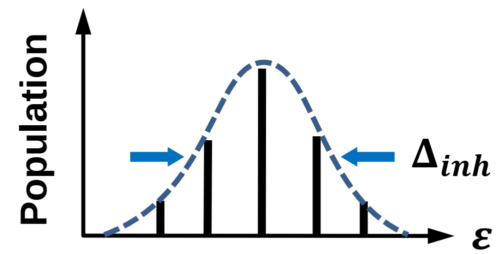
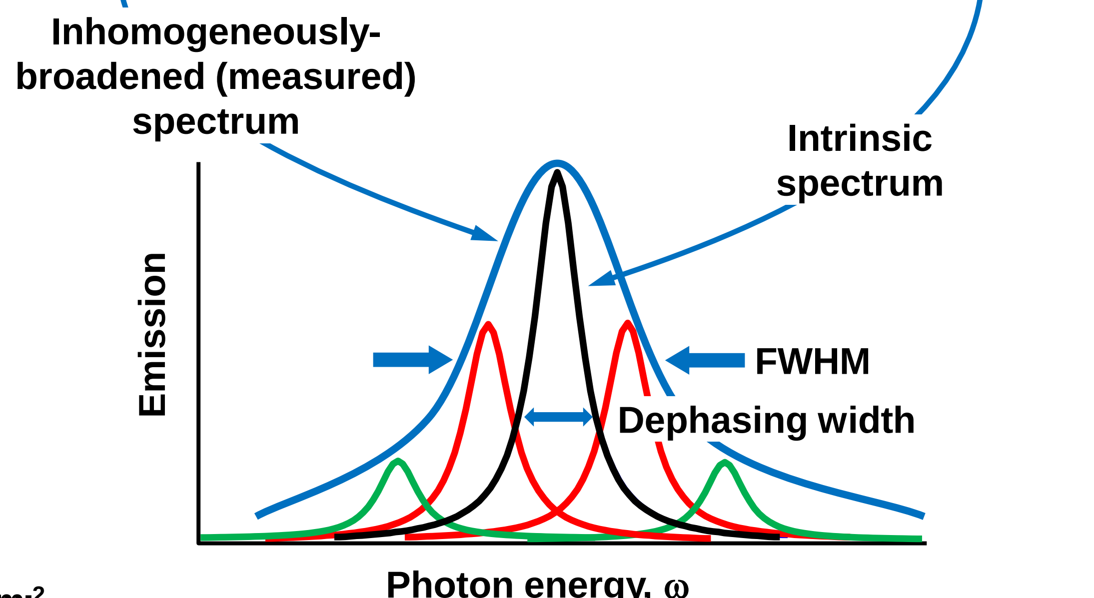


T = 300K, N = 0.1x, 0.5x, 1x, 2x, 3 x $10^{12} cm^{-2}$

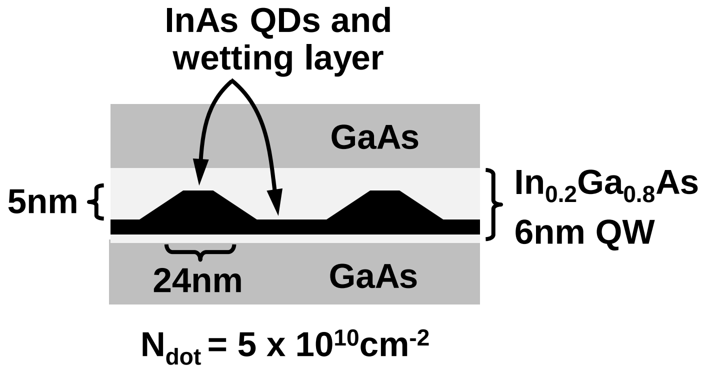
QD non-uniformity

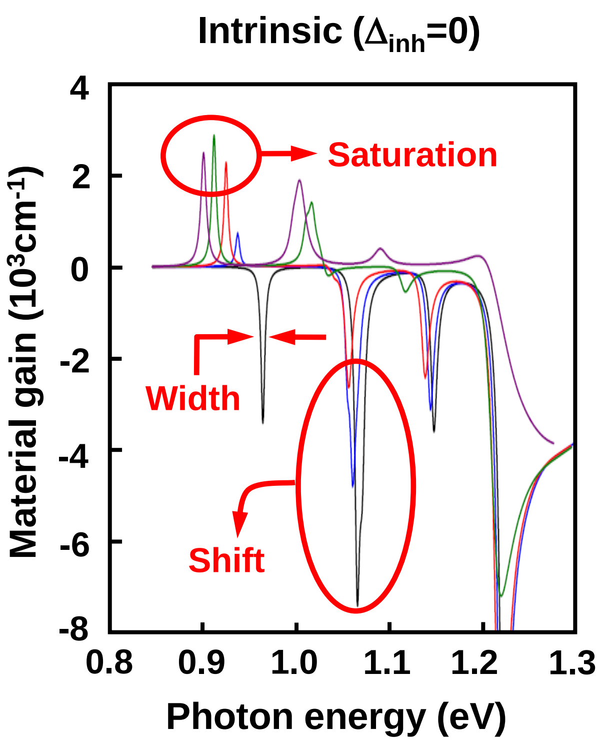


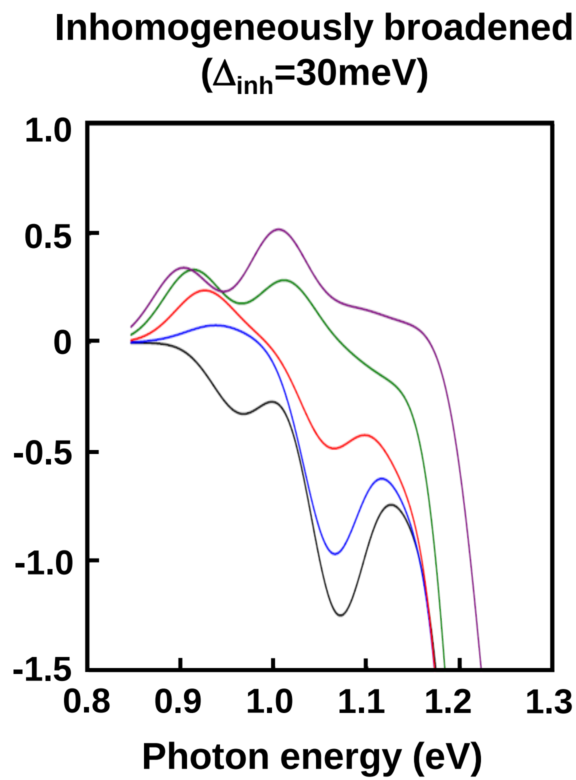
$$S_{inh}(\omega) = \int d\varepsilon \, \frac{1}{\sqrt{2\pi}\sigma_{inh}} e^{-(\varepsilon-\varepsilon_0)^2/\left(\sqrt{2}\,\Delta_{inh}\right)^2} S_{homog}(\omega,\varepsilon)$$



Intrinsic versus inhomogeneously-broadened quantum dots







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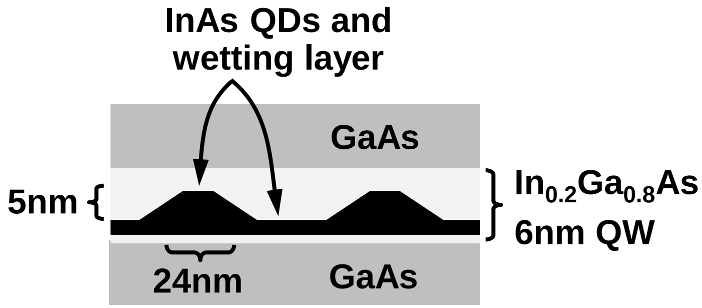
Intrinsic versus inhomogeneously-broadened quantum dots



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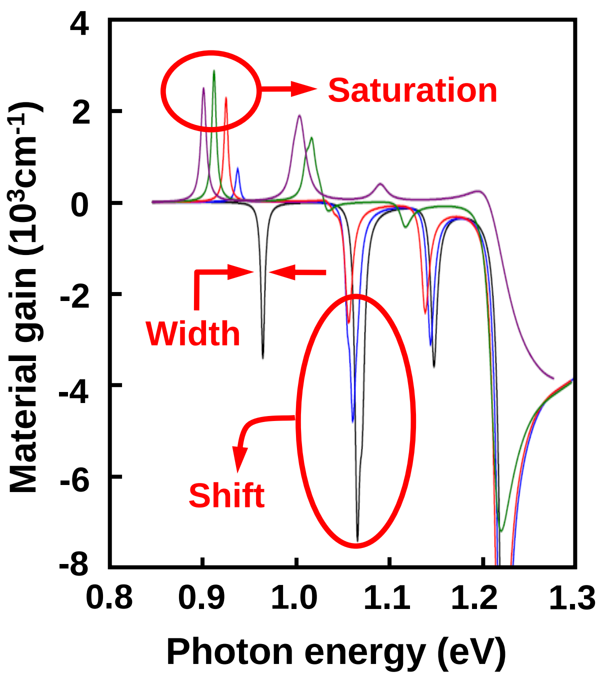
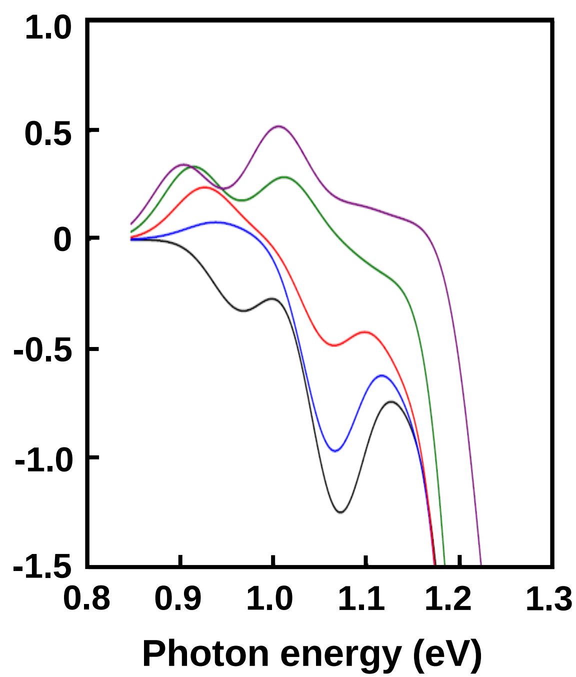
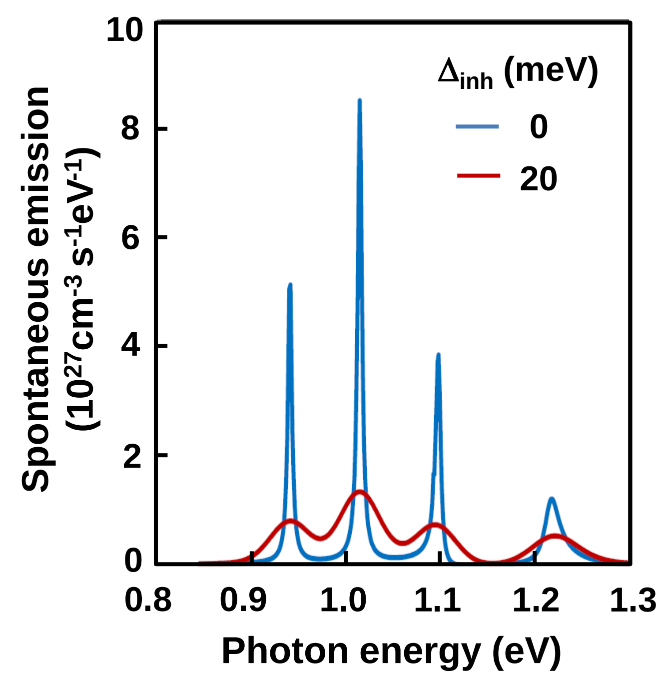


Inhomogeneously broadened (Δ_{inh}=30meV)



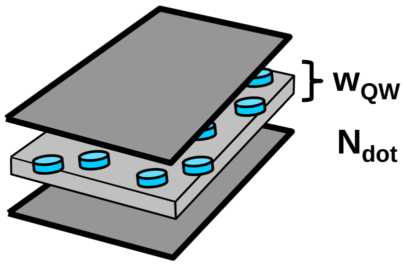
Spontaneous emission and effect of QD nonuniformity



T = 300K, N = 0.1x, 0.5x, 1x, 2x, 3 x $10^{12}cm^{-2}$

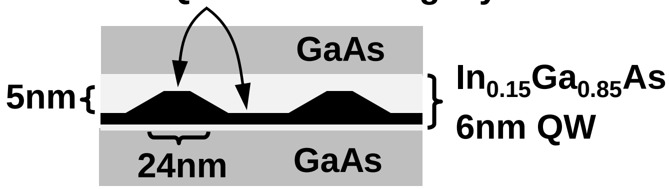
T = 300K, N = 4 x $10^{11}cm^{-2}$

Material gain



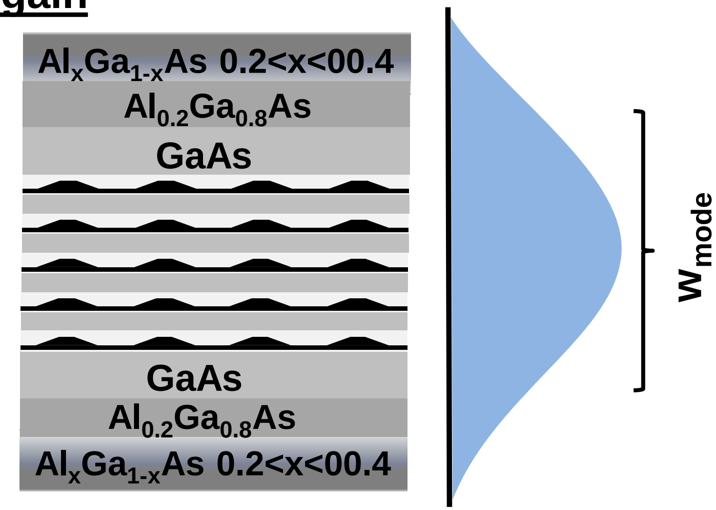
$N_{dot} = 5 \times 10^{10} cm^{-2}$

InAs QDs and wetting layer



Material gain is gain from $In_{0.15}Ga_{0.85}As$ QW embedding N_{dot} density of InAs QDs and wetting layer

Modal gain



From theory

$$G_{modal} = N_{QW} \frac{w_{QW}}{w_{mode}} G_{material} = 0.12 G_{material}$$

From solving Maxwell's equations for waveguide

From experiment

$$G_{modal,th} = \frac{1}{2L}[\alpha_{abs} - ln(R_1 R_2)]$$

Threshold current density

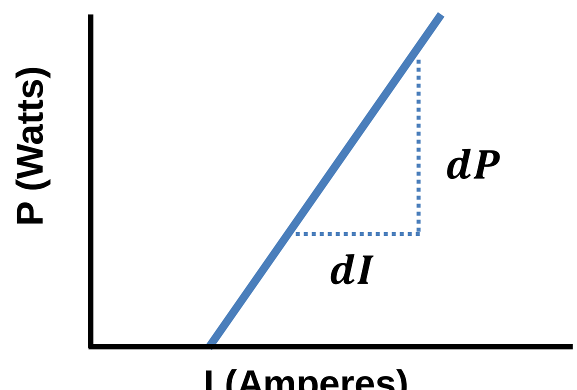
From gain calculation

$$J_{th} = \frac{1}{\eta_{inj}} (J_{sp} + AN_{th} + CN_{th}^3)$$

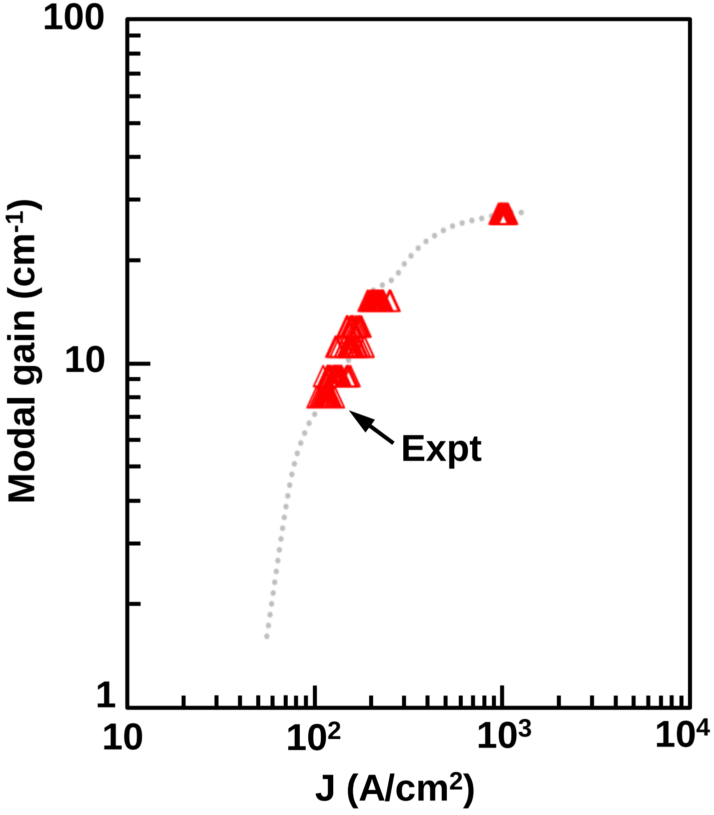
From experiment

Fitting parameters

$$\eta_{inj} = \frac{2e}{\hbar\nu} \frac{\Gamma G_{th}}{\Gamma G_{th} - \alpha_{abs}} \frac{dP}{dI}$$



Extraction of inhomogeneous broadening and nonradiative losses



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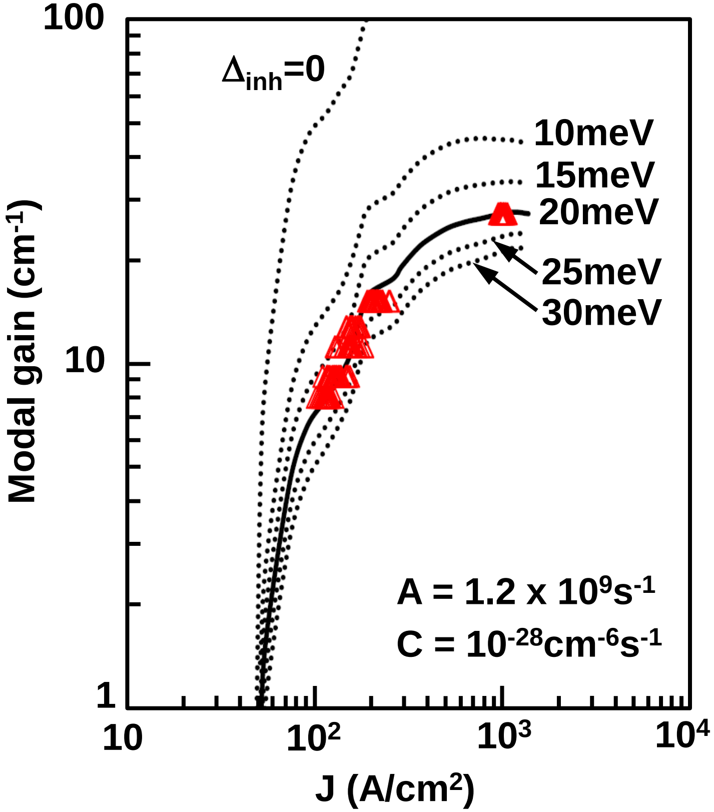

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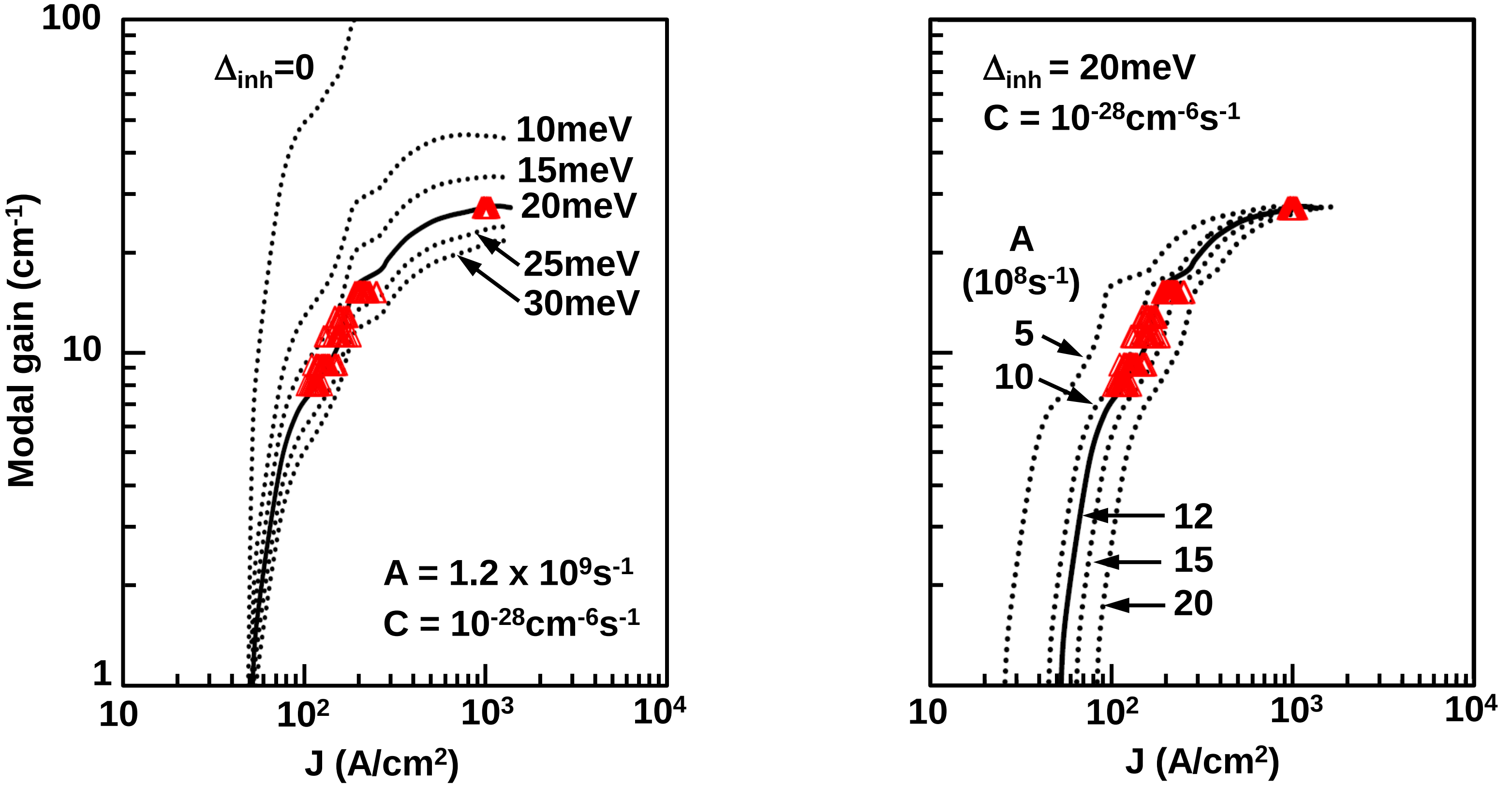
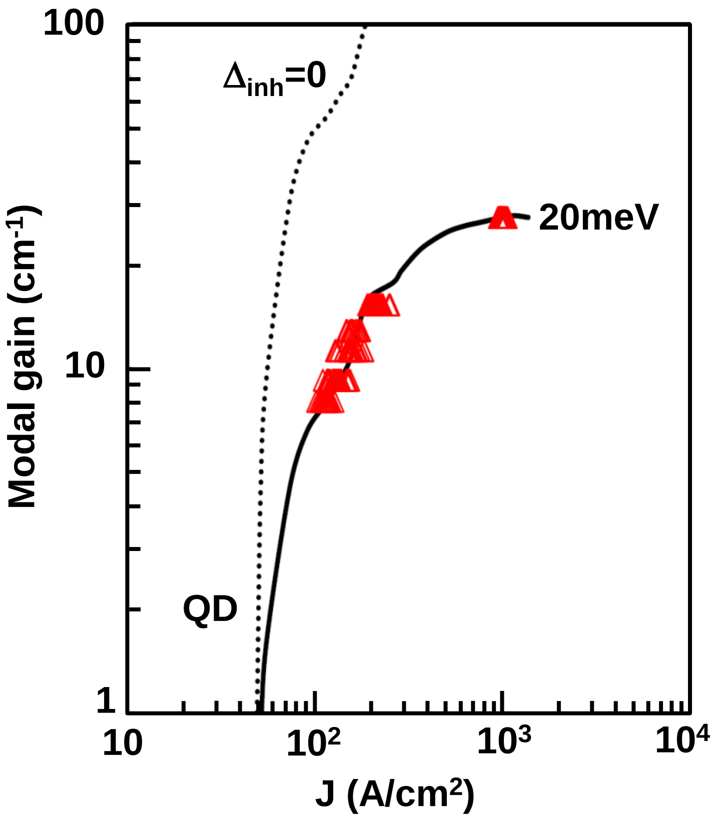
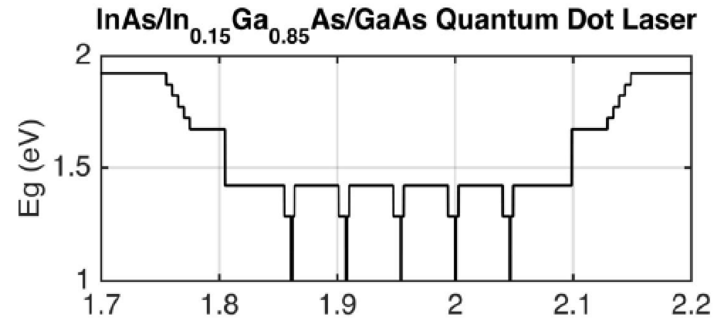


For more details on shape of QD G vs J curves see: M. Lorke, F. Jahnke and W. W. Chow, Appl. Phys. Lett. 90 051112, 2007

For details on the fitting process: Chow, Liu, Gossard and Bowers, ‘Extraction of inhomogeneous broadening and nonradiative losses in InAs quantum-dot lasers,’ (submitted APL)

Extraction of inhomogeneous broadening and nonradiative losses



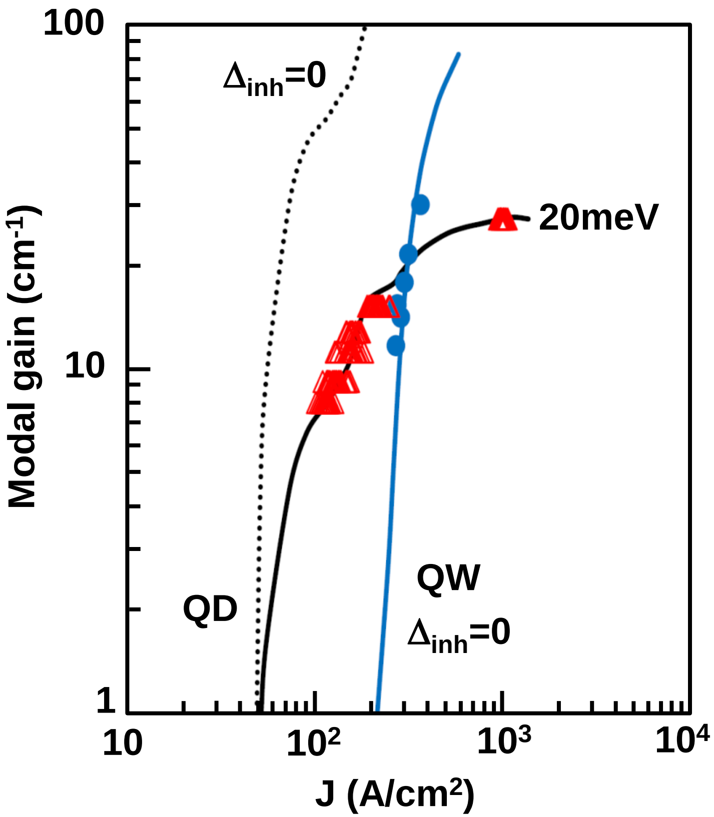


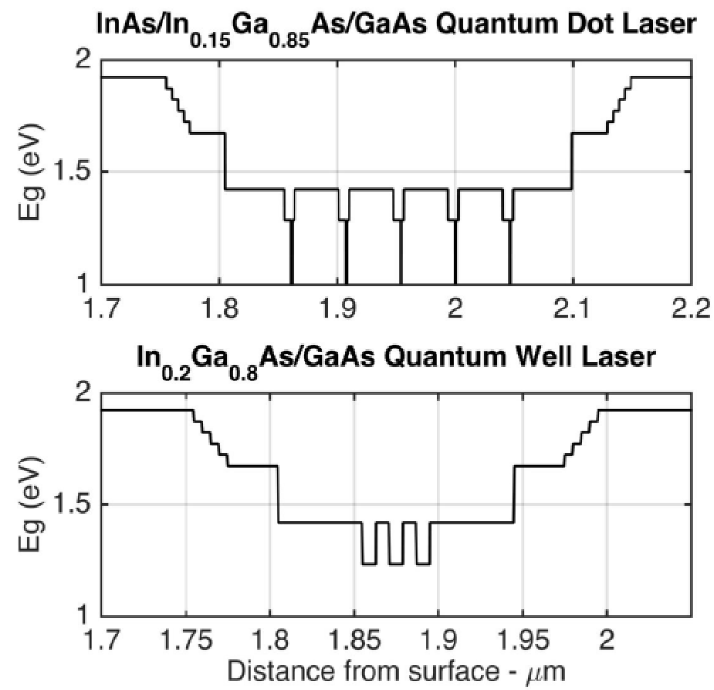
$C = 10^{-28} cm^{-6}s^{-1}$

$A = 1.2 \times 10^{9}s^{-1}$ (QD)

$\Gamma = 0.12$ (QD)

Comparison of QD vs QW





$C = 10^{-28}\,\text{cm}^{-6}\text{s}^{-1}$

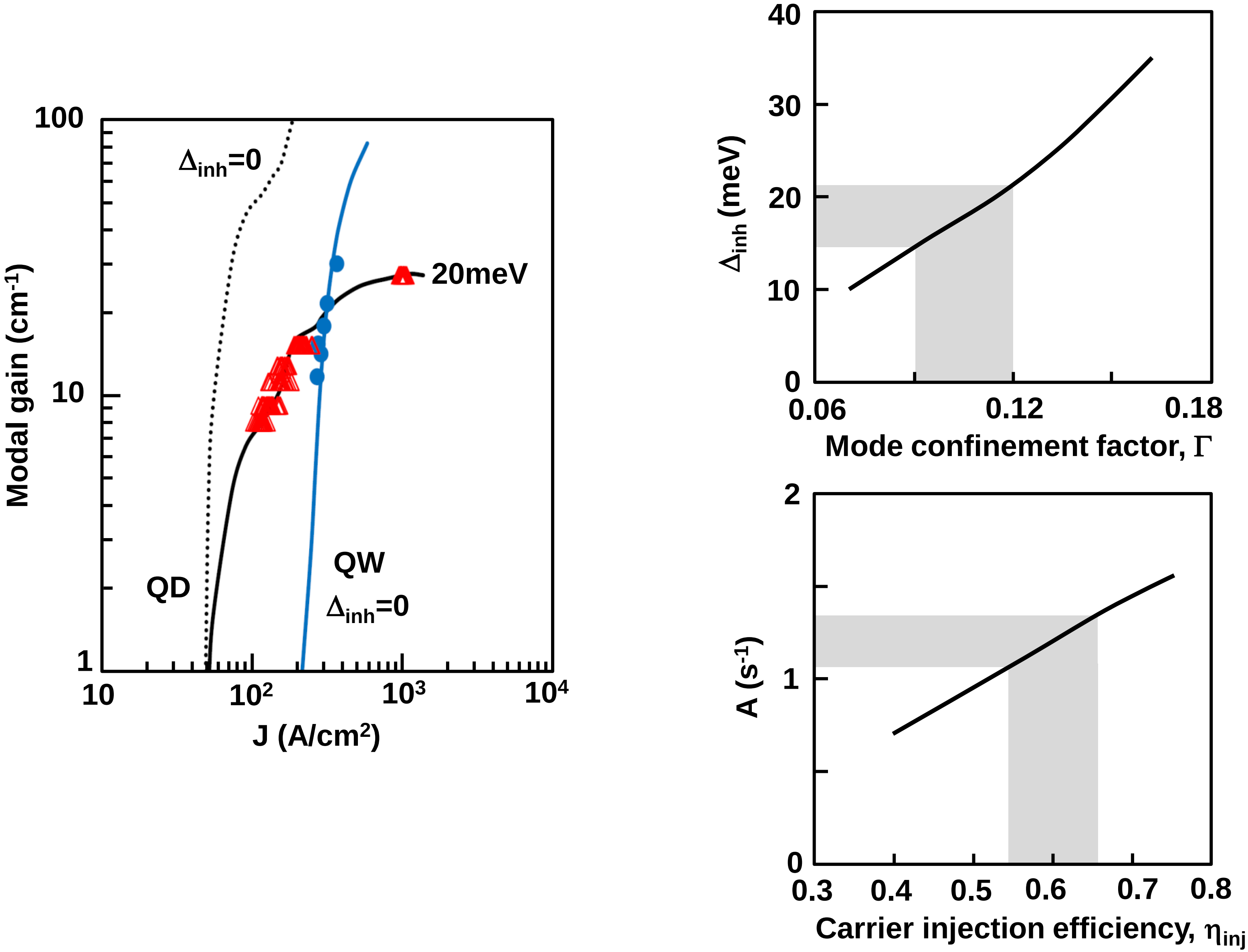
$A = 1.2 \times 10^{9}\,\text{s}^{-1}$ (QD)

$= 6.5 \times 10^{8}\,\text{s}^{-1}$ (QW)

$\Gamma = 0.12$ (QD)

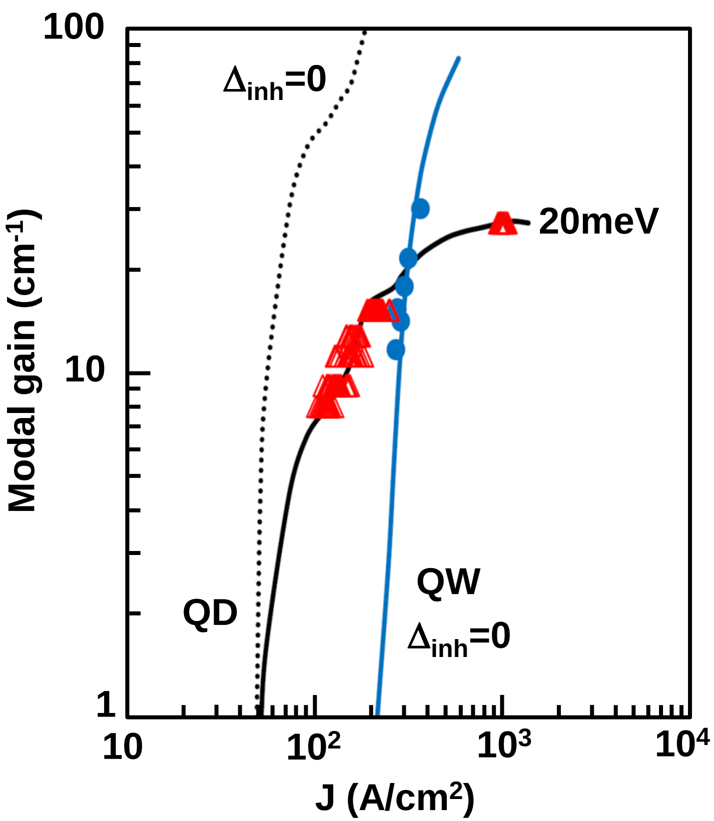
$= 0.054$ (QW)

Uncertainty in extracted parameters

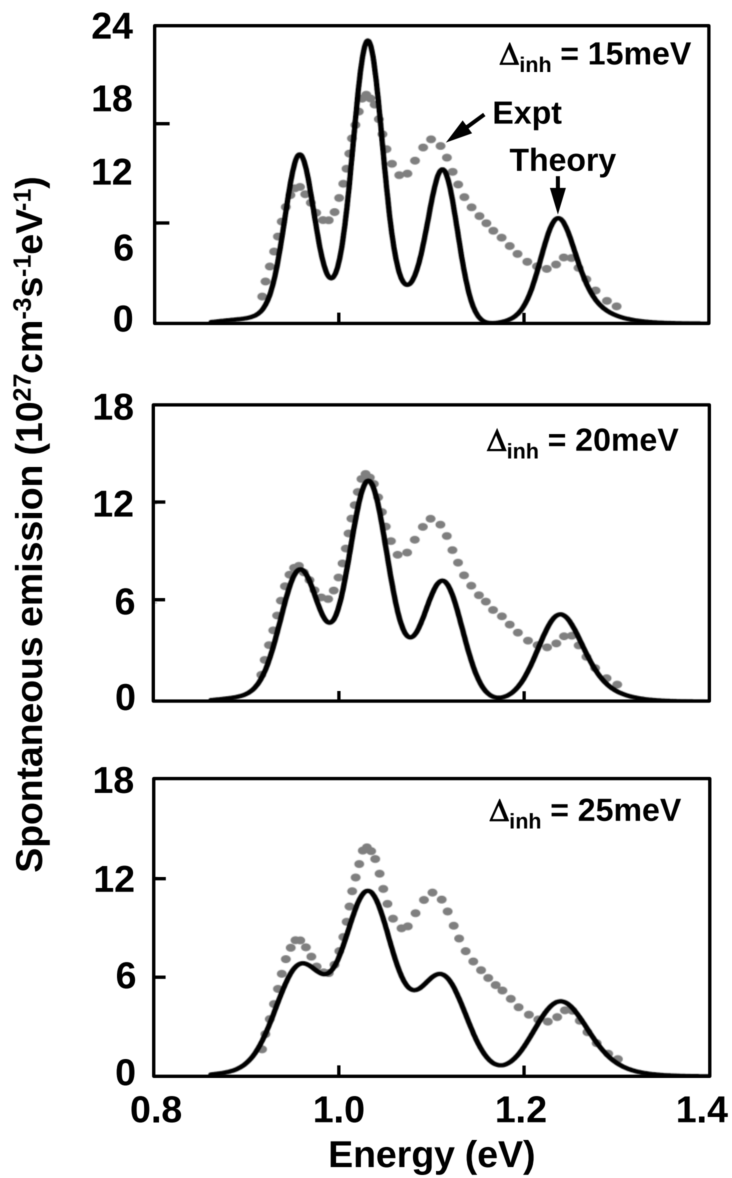


Uncertainty in extracted parameters

From Lasers



From spontaneous emission



Summary

Gain-current relationships in quantum-dot and quantum-well lasers: Theory and experiment

$\underbrace{\text{Weng Chow}}_{\text{Sandia National Labs}}$, $\underbrace{\text{Alan Liu, Art Gossard, John Bowers}}_{\text{University of California, Santa Barbara}}$ and $\underbrace{\text{Frank Jahnke}}_{\text{Bremen University}}$

$$G_{modal} = \frac{1}{2L}\left[\alpha_{abs} - ln(R_1 R_2)\right]$$ Experiment

$$= \langle \Gamma G_{material} \rangle_{\Delta_{inh}}$$ Theory

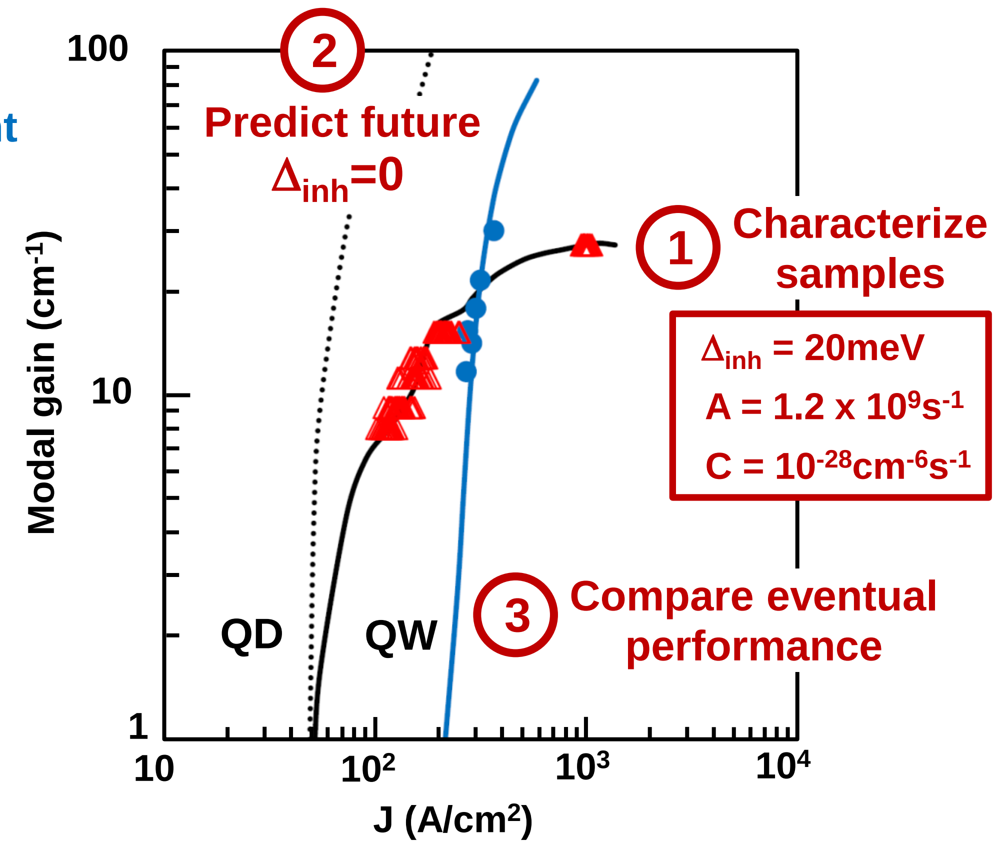
Microscopic calculation

Fitting parameters

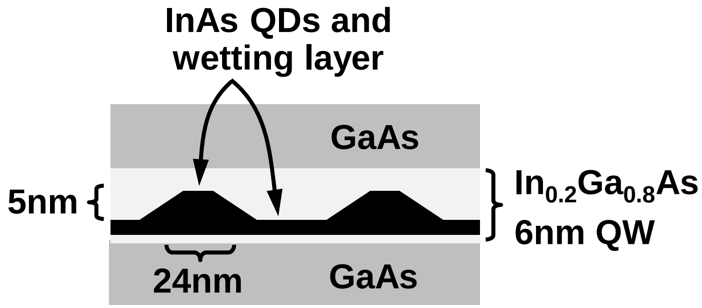
$$J = \frac{1}{\eta_{inj}}\left(J_{sp} + AN + CN^3\right)$$

Experiment

Microscopic calculation

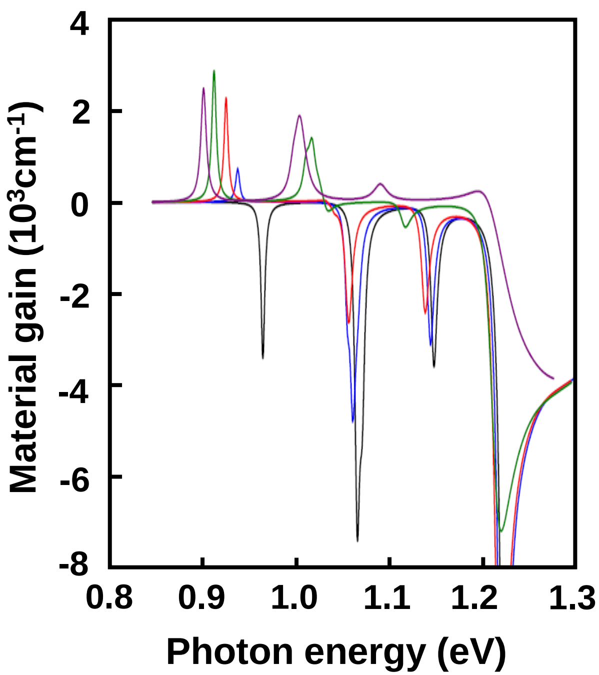


Intrinsic versus inhomogeneously-broadened quantum dots



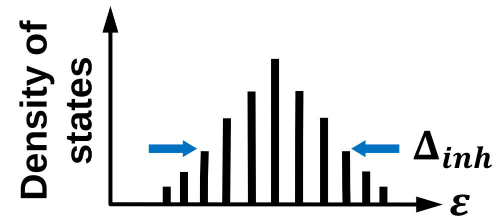
$N_{dot} = 5 \times 10^{10} cm^{-2}$

Intrinsic (Δ_{inh}=0)



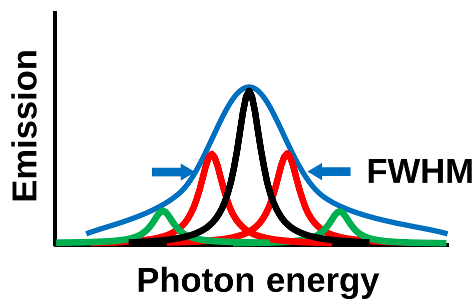
T = 300K, N = 0.1x, 0.5x, 1x, 2x, 3 x 10^{12}cm^{-2}

QD non-uniformity

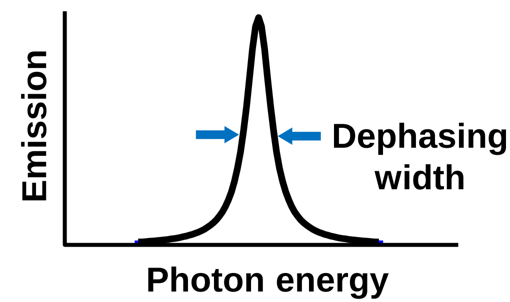


$$S_{inh}(\omega) = \int d\varepsilon \, \overbrace{\frac{1}{\sqrt{2\pi}\sigma_{inh}} e^{-(\varepsilon-\varepsilon_0)^2/(\sqrt{2}\,\Delta_{inh})^2}} \, S_{homog}(\omega,\varepsilon)$$

Inhomogeneously-broadened (measured) spectrum



Homogeneously-broadened (intrinsic) spectrum



$$S_{inh}(\omega) = \int d\varepsilon \, \frac{1}{\sqrt{2\pi}\sigma_{inh}} \, e^{-(\varepsilon-\varepsilon_0)^2/\left(\sqrt{2}\,\Delta_{inh}\right)^2} S_{homog}(\omega,\varepsilon)$$