Metastable Compound Semiconductors

Microscopic simulation of semiconductor lasers

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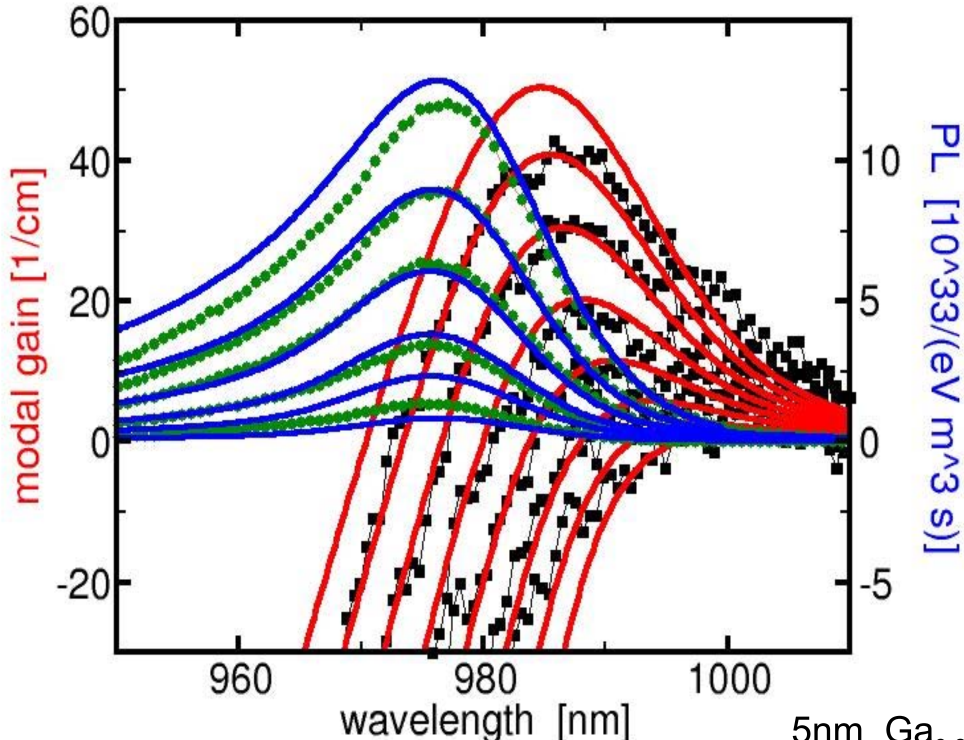
Gain/absorption and luminescence

Gain: Theory: 1.0, 1.125, 1.25, 1.375, 1.5, 1.625, 1.75, 1.875
Experiment: 6.0, 6.5, 7.0, 7.5, 8.3, 9.0 [mA]

PL: Theory: 0.17, 0.30, 0.40, 0.53, 0.68, 0.86 [10^{12} / cm^2]
Experiment: 12, 16, 18, 21, 24 [mW]



5nm $Ga_{0.8}In_{0.2}As/GaAs$ pin-MQW

Simple models: Fit to experimental data

- experimental input
- limited range of validity

Microscopic Theory: prediction

- Input = band structure parameters
- large range of validity

Hamiltonian

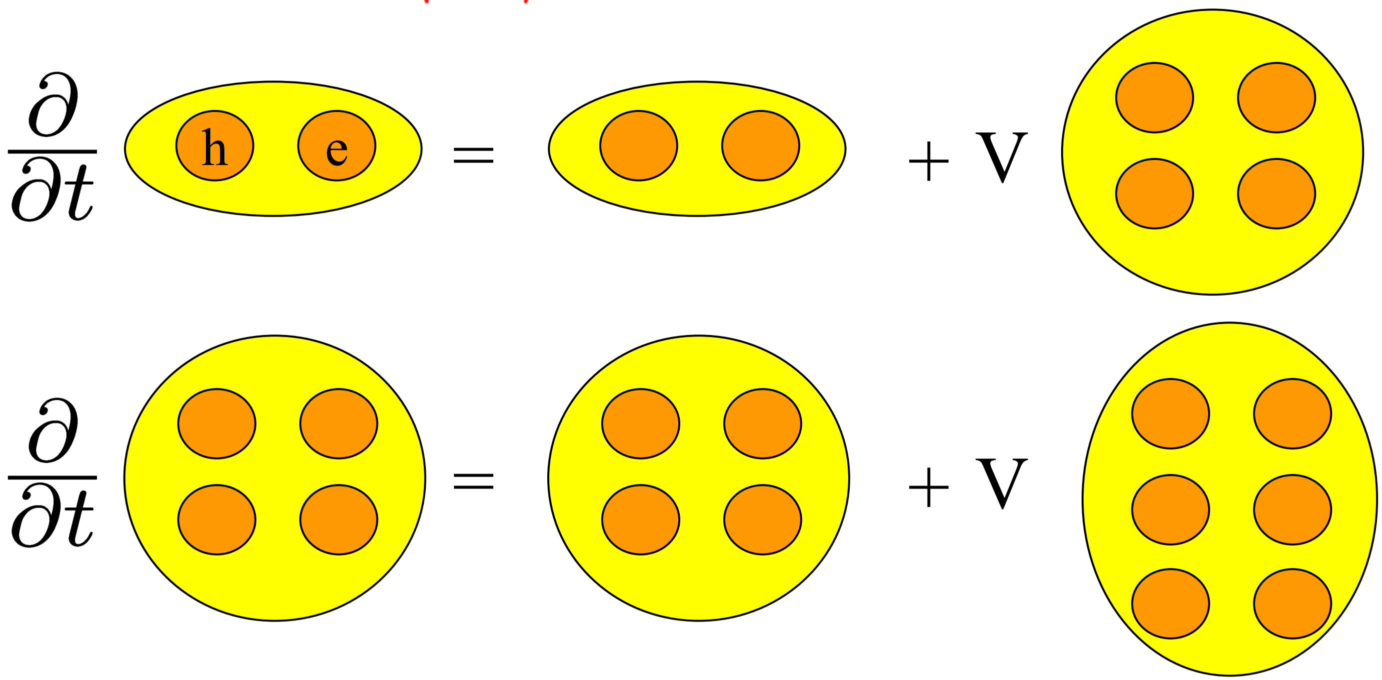
$$H = H_0 + H_{Coul} + H_{dip} + H_{phon}$$

H_0	single particle
H_{Coul}	Coulomb interaction between carriers
H_{dip}	dipole interaction with optical field
H_{phon}	carrier phonon interaction (LO phonons)

Equations of motion

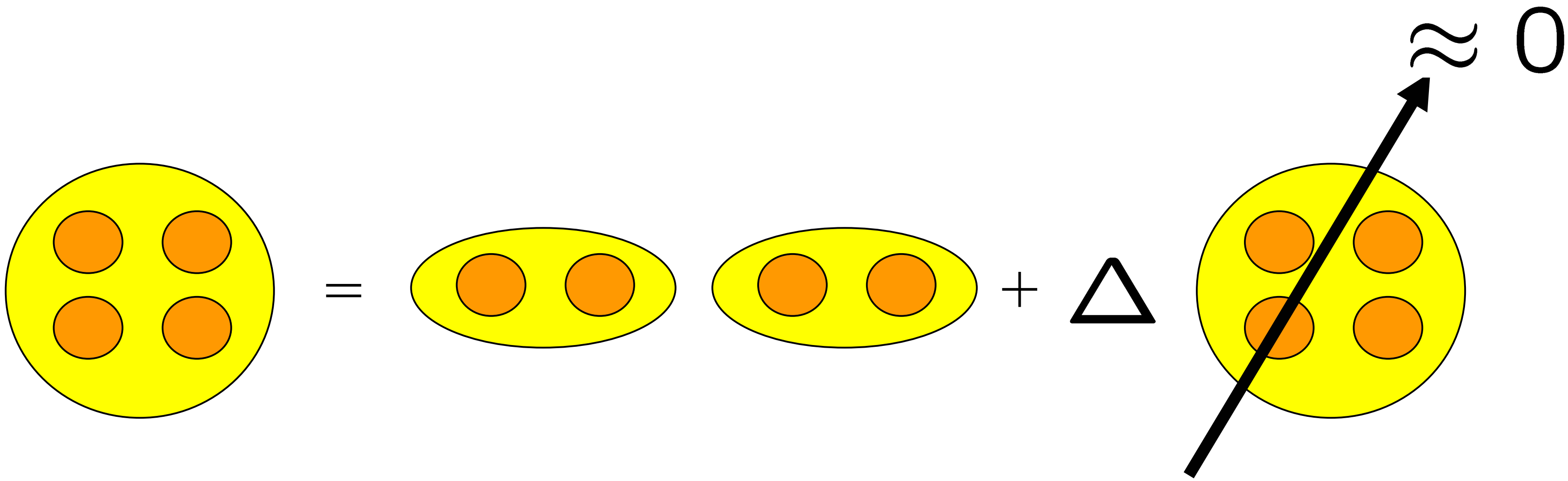
Heisenberg equation: $$i\hbar \frac{\partial}{\partial t} \mathcal{O} = [\, \mathcal{O}, \mathcal{H} \,]$$

Polarisation $p = \langle he \rangle$



- Infinite hierarchy of equations
- Requires controlled approximations

Hartree Fock approximation

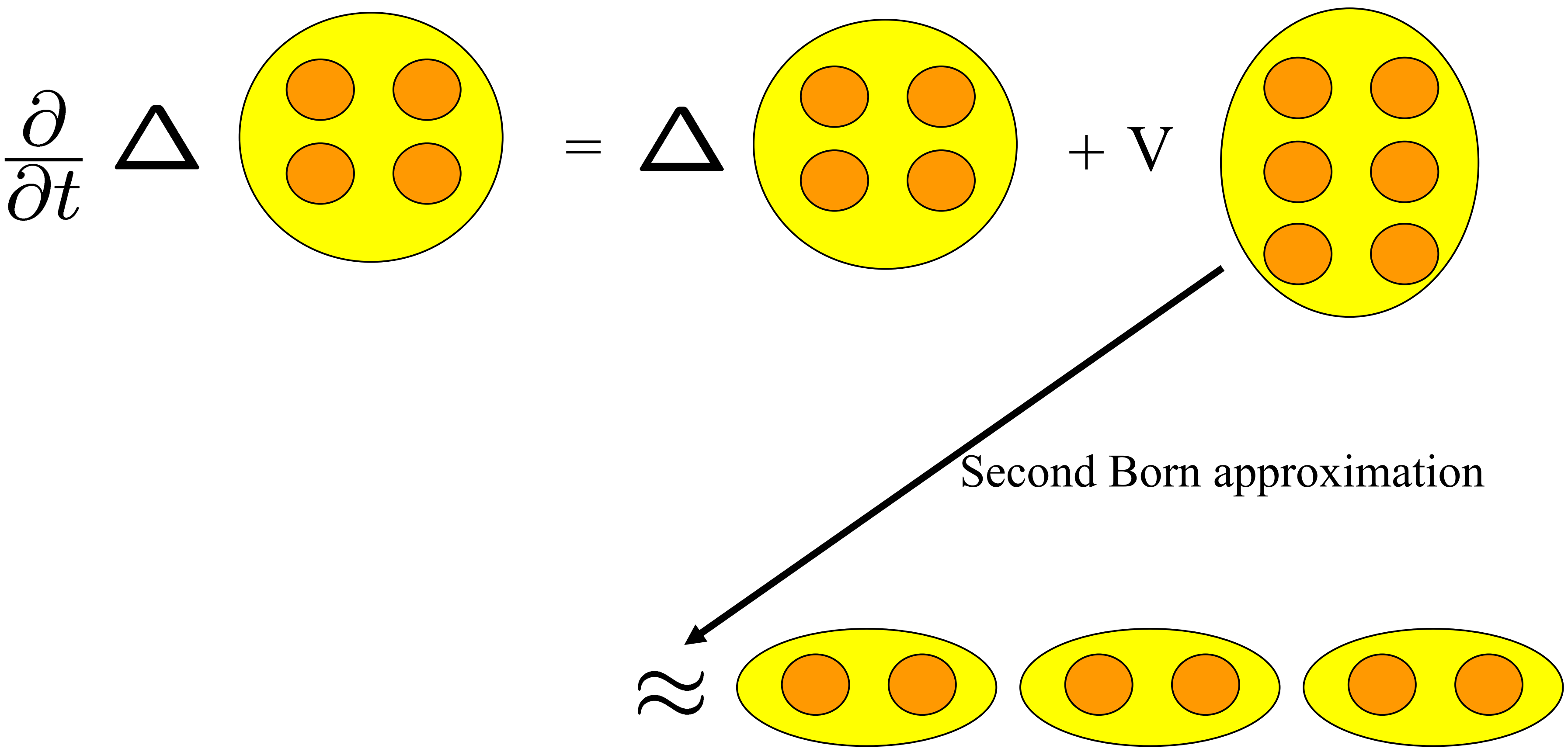


Δ-terms are called correlations. They contain dephasing and scattering.

Simplest approximation: dephasing time

$$\frac{\partial}{\partial t}P\Big|_{\text{corr}} = -\frac{P}{T_2}$$

Second Born approximation



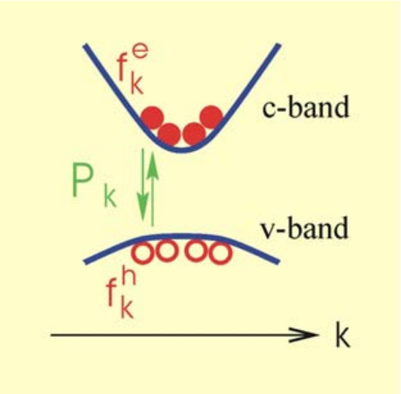
Terms upto second order in V!

Markov approximation: evaluate time integral by neglecting memory effects

Semiconductor Bloch equations

$$\left[i\hbar\frac{\partial}{\partial t} - \epsilon_k^e - \epsilon_k^h\right] P_k = \left[1 - f_k^e - f_k^h\right] \Omega_k + \frac{\partial}{\partial t} P_k|_{corr}$$

$$i\hbar\frac{\partial}{\partial t}\, f_k^a = -\Omega_k(t) P_k^* + \Omega_k^* P_k + \frac{\partial}{\partial t} f_k^a|_{corr}$$

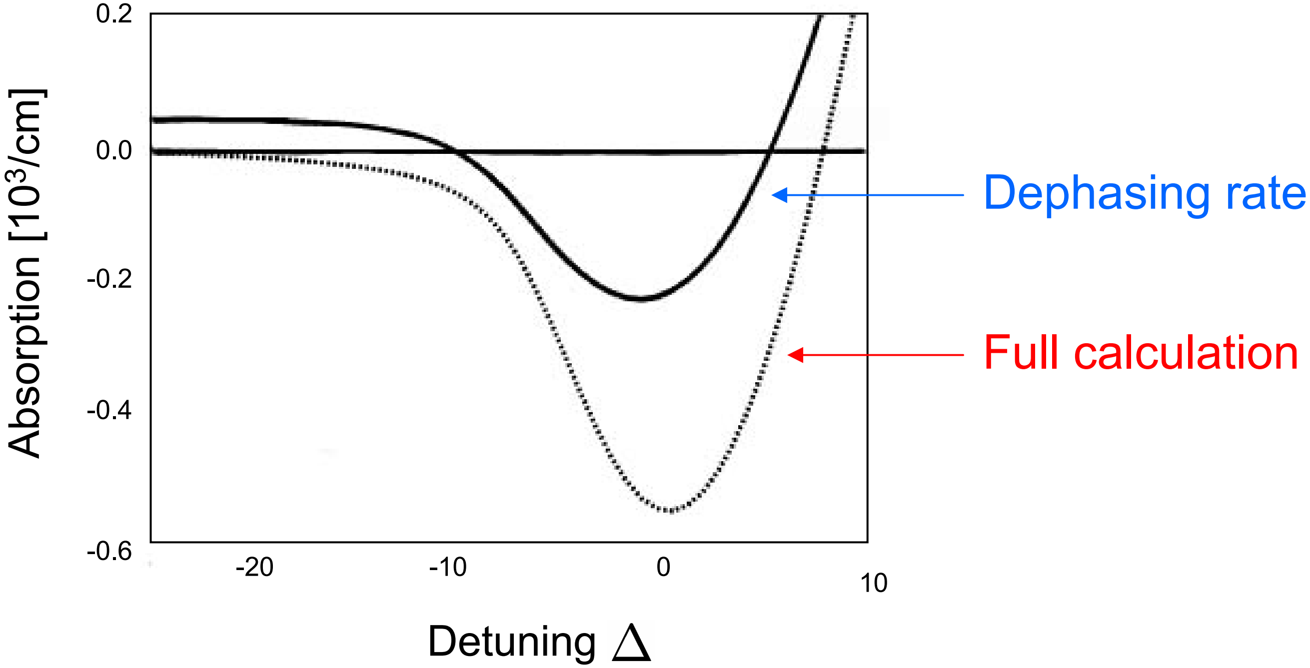


Field renormalisation $\Omega_k(t) = d_{cv}\ E^{QW}(t) + \sum_{k'} V_{k-k'}\ P_{k'}(t)$

Energy renormalisation $\epsilon_k^a(t) \ = \ \varepsilon_k^a - \sum_{k'} V_{k-k'}\ f_{k'}^a(t)$

- Nonlinearities: phase space filling, gap reduction, Coulomb enhancement
- Correlation contributions: scattering, dephasing, screening
- Band structure: 8-band (10-band) **k.p**-theory

Line shape



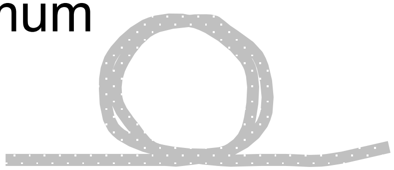
- $\Delta = (\hbar\omega - E_G)/E_B$
- Two-band model
- Dephasing rate → wrong lineshape and amplitude, absorption below bandgap

Dilute nitrides - GaInNAs

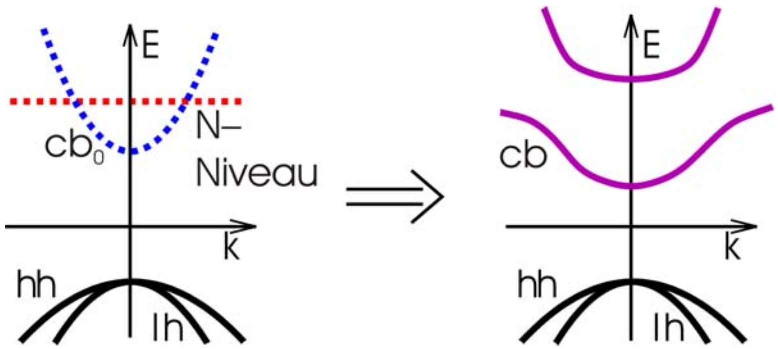
Technological interest:

GaAs-based laser enables AlAs/GaAs bragg reflector

Attenuation minimum of fibres around 1.55μm

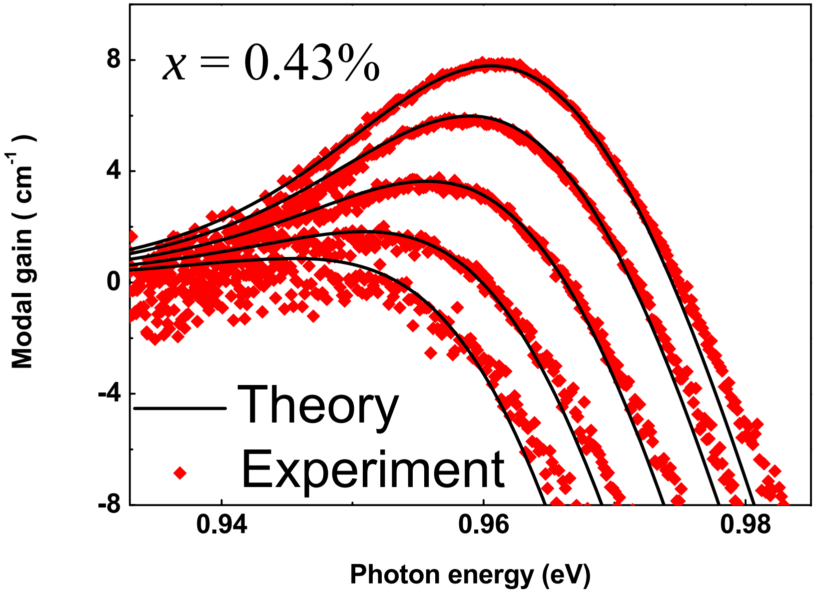


Physical interest: anticrossing of conduction & nitrogen band



GaInNAs Laser at 1.3μm ⇐ OK
But at 1.55μm: luminescence of experimental structures is orders of magnitude smaller, no amplification of light

Gain Modelling in $Ga_{0.6}In_{0.4}N_xAs_{1-x}/GaAs$



6nm $Ga_{0.6}In_{0.4}N_{0.0043}As_{0.9957}/GaAs$
N = 1.46, 1.4, 1.31, 1.21, 1.11 * 10^{12} cm^{-2}
exp. current 236, 221, 201, 180, 159 mA

- Excellent theory-experiment agreement

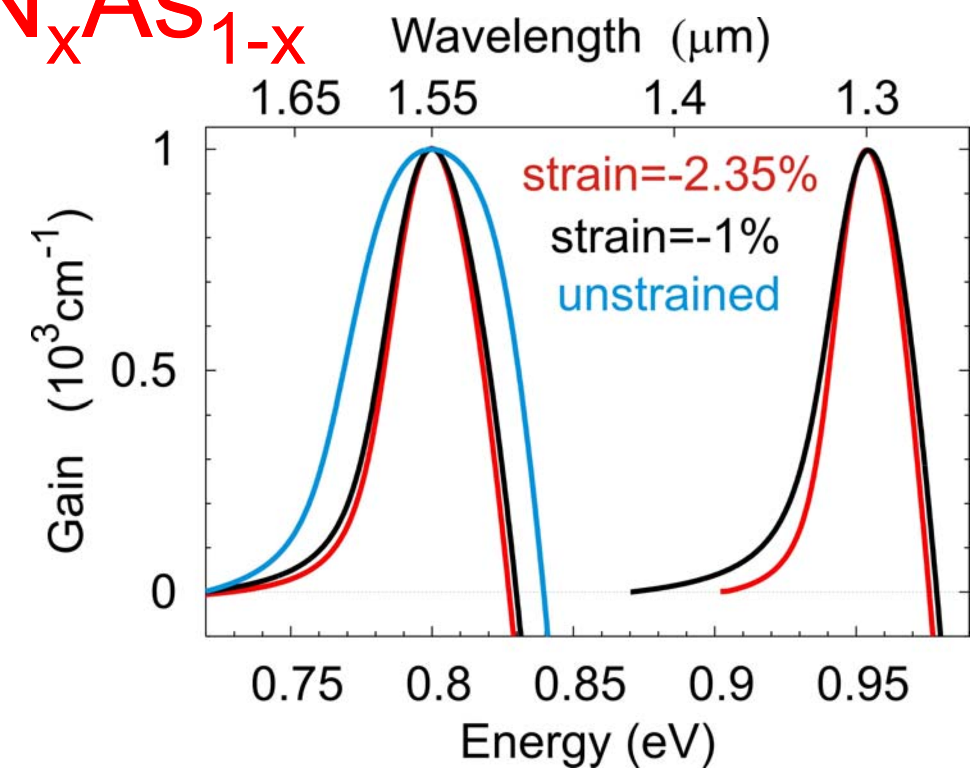
Exp.: L. Shterengas, G. Belenky, J.-Y. Yeh, L.J. Mawst, N. Tansu, see Thränhardt et al., Appl. Phys. Lett. **86**, 201117 (2005).

The search for 1.55µm

Quaternary $Ga_{1-y}In_yN_xAs_{1-x}$

⇒ Increase wavelength by

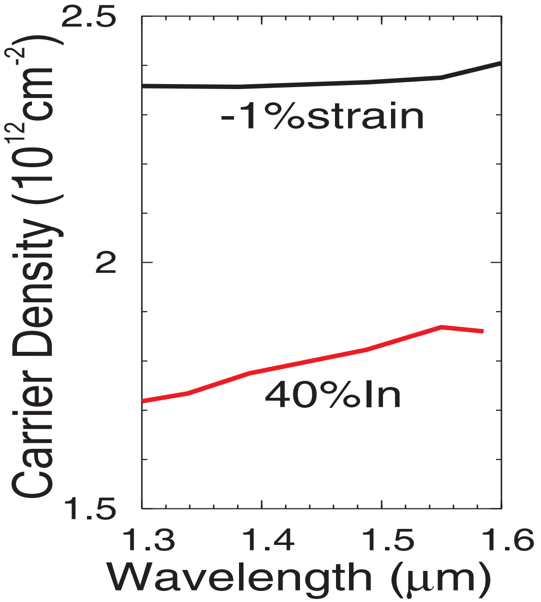
- More nitrogen (x↑)
- More indium (y↑)
- Or both ...

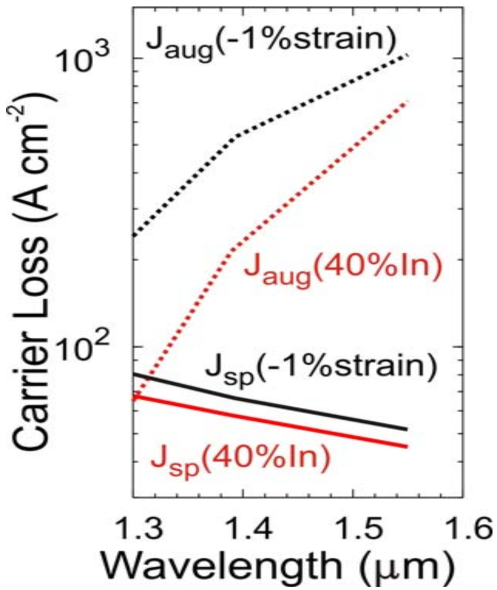


What is best?

GaInNAs Laser at 1.3µm ⇐ OK
But at 1.55µm: luminescence of experimental structures is orders of magnitude smaller, no amplification of light
- material characteristic or material quality ?

Losses

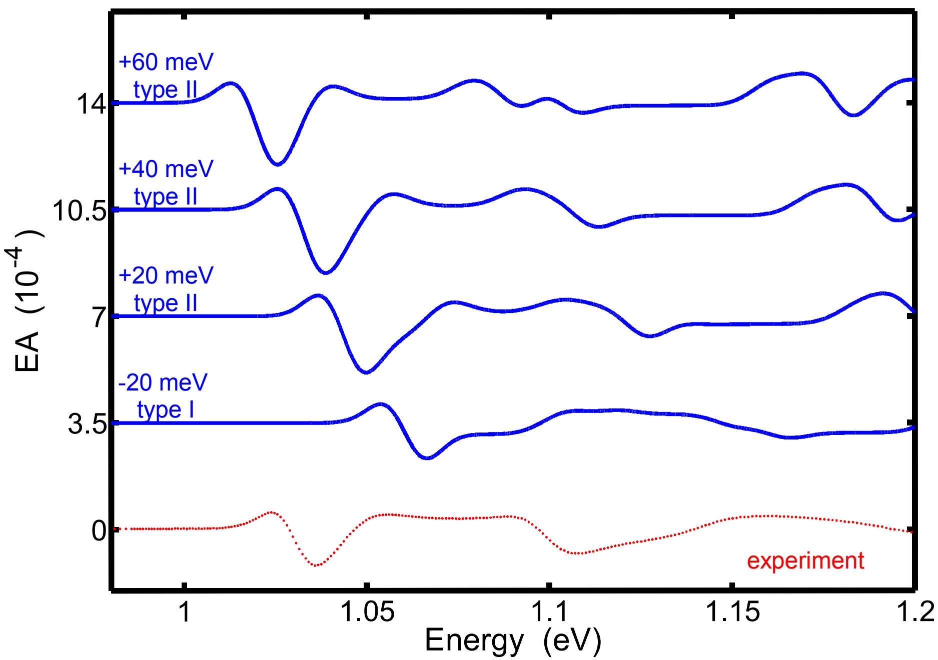




- Lasing at lower density in more highly strained structure
- Consequently lower radiative and Auger losses

GaAsSb – another GaAs-based telecommunication material

7nm $GaAs_{0.64}Sb_{0.36}$ QW, 6nm GaAs on both sides, $Al_{0.25}Ga_{0.75}As$ barriers



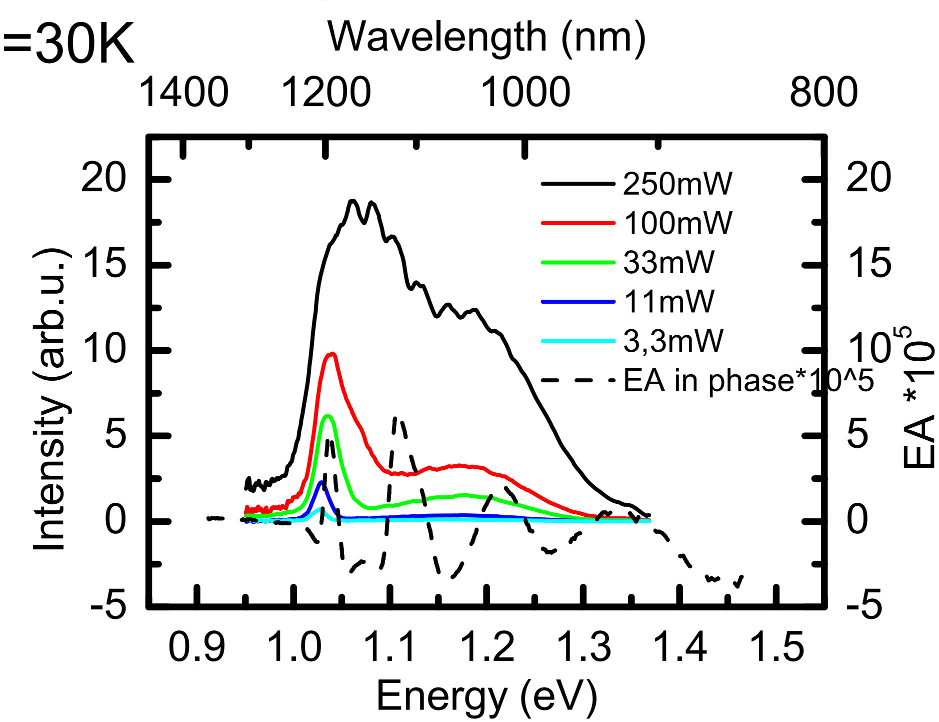
Experiment: G. Blume, P. J. Klar, G. Weiser

- Typ-II-Offset
- Elektroabsorption = Modulation of the electric field, measurement of the absorption change

Outlook: Spatially resolved PL

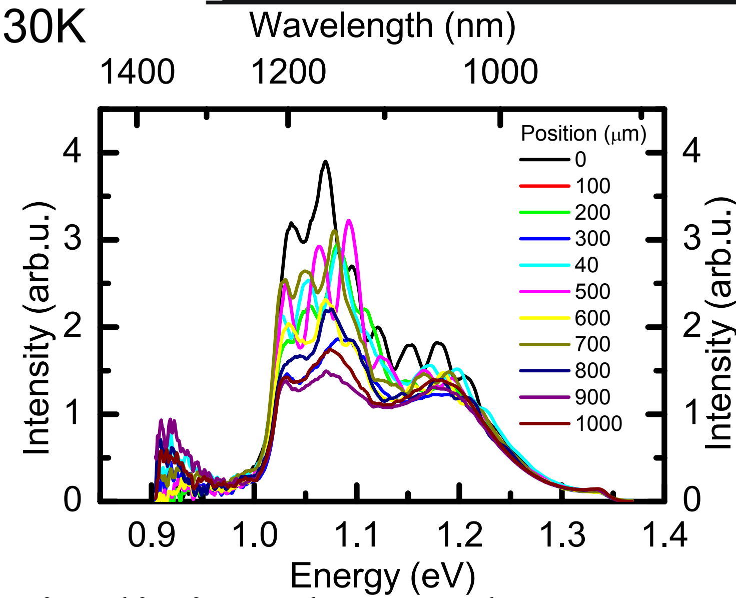
- "High spatial resolution" of 10µm x10µm
- Emission broadens with increasing carrier density
- Emission maxima = EA signals
- PL shows an almost periodic structure at high densities (solid black line)
- For comparison: Elektroabsorption (dashed)

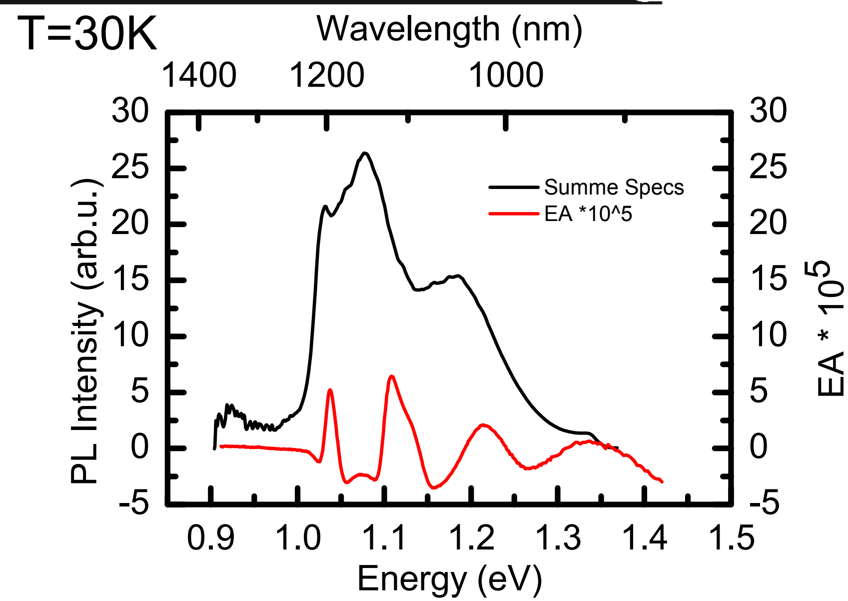
T=30K



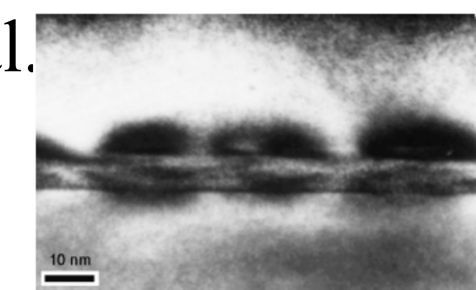
Experiment: S. Horst, S. Chatterjee, W. W. Rühle

Why is there a periodic structure in the PL signal?



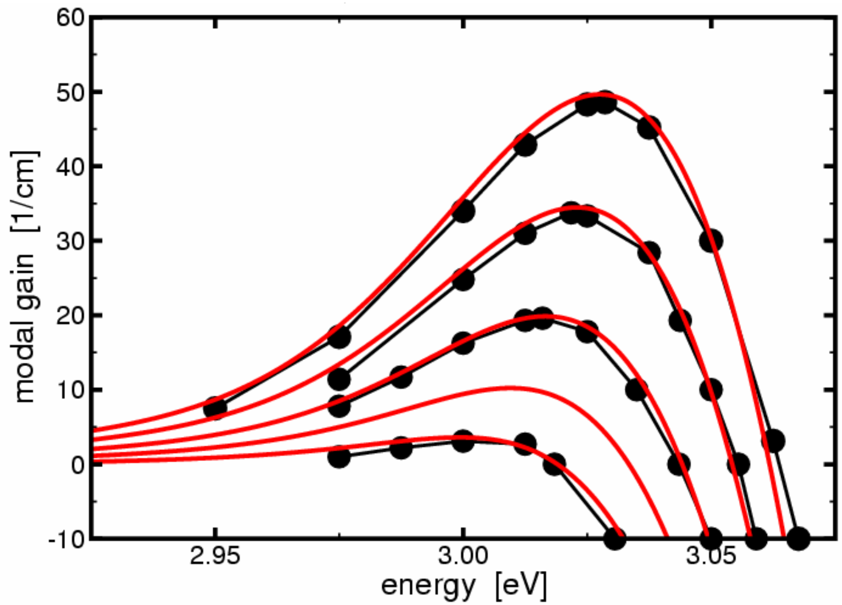


- Periodicity depends on position
- Addition of spectra shows main transitions according to EA
- Hypothesis: spatial confinement in in-plane direction
- Literature: “Dot substructure” (c.f. Braun et al. JAP **88**, 3004 (2000))



Experiment: S. Horst, S. Chatterjee, W. W. Rühle

„Blue“ gain



2 nm $In_{0.1}Ga_{0.9}N$ MQWs with 6nm GaN barrier layers

Good agreement between theory and experiment without the use of phenomenological parameters such as scattering rates.

Exp. Daten aus B. Witzigmann et al., Appl. Phys. Lett. 88, 021104 (2006).

Summary

- Microscopic theory consistently describes semiconductor lasers/semiconductor heterostructures, **predictive capability**
- Good agreement between theory and experiment for gain, linewidth enhancement factor, photomodulated reflection, time-resolved photoluminescence …
- 1.55 µm lasing in GaInNAs possible if good material quality can be achieved
- High strain preferable
- Other potential GaAs-based telecommunication material is GaAsSb
- Weak type II offset in GaAs
- Modeling of wide-gap materials equally possible