

Gain and Photoluminescence Dynamics in Semiconductor Lasers

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- Microscopic theory
- Gain and linewidth enhancement factor
- Radiative decay constants
- Carrier scattering times

Hamiltonian

$$\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_{\text{Coul}} + \mathbf{H}_{\text{dip}} + \mathbf{H}_{\text{phon}}$$

$\mathbf{H}_0$ single particle

$\mathbf{H}_{\text{Coul}}$ Coulomb interaction between carriers

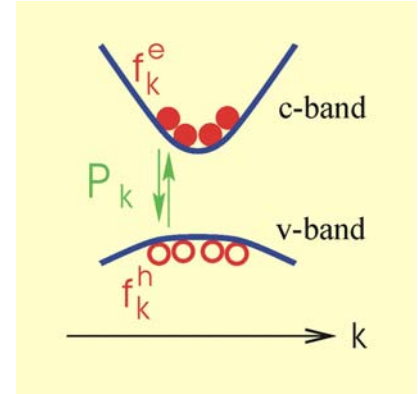
$\mathbf{H}_{\text{dip}}$ dipole interaction with optical field

$\mathbf{H}_{\text{phon}}$ carrier phonon interaction (LO phonons)

Semiconductor Bloch Equations

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

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

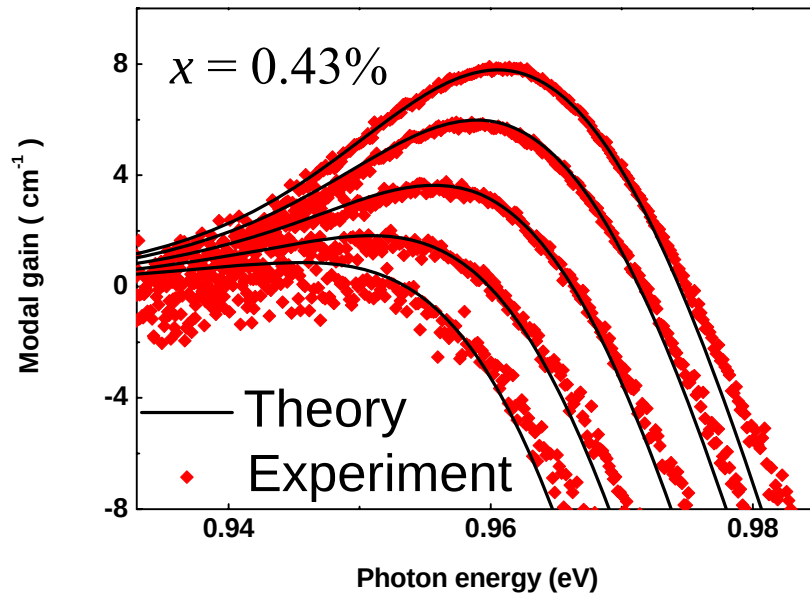


Field renormalization $\Omega_k(t) = d_{cv} E^{QW}(t) + \sum_{k'} V_{k-k'} P_{k'}(t)$

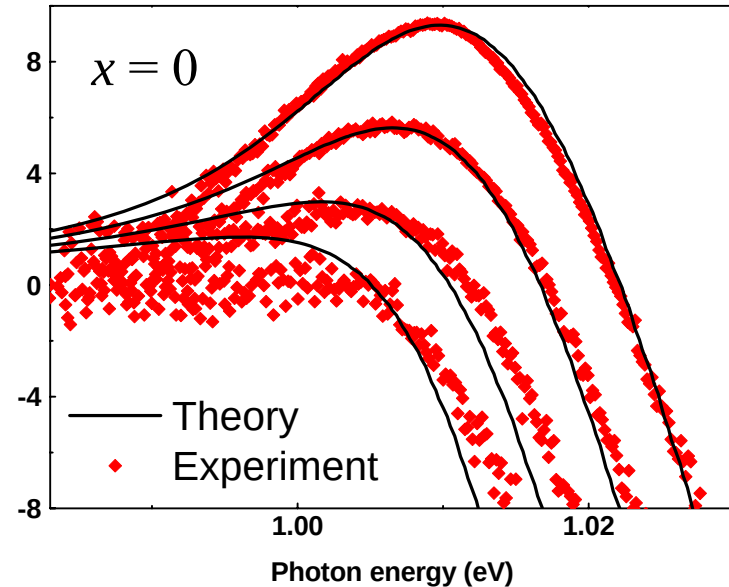
Energy renormalization $\epsilon_k^a(t) = \epsilon_k^a - \sum_{k'} V_{k-k'} f_{k'}^a(t)$

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

Gain Modelling in $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_x\text{As}_{1-x}/\text{GaAs}$



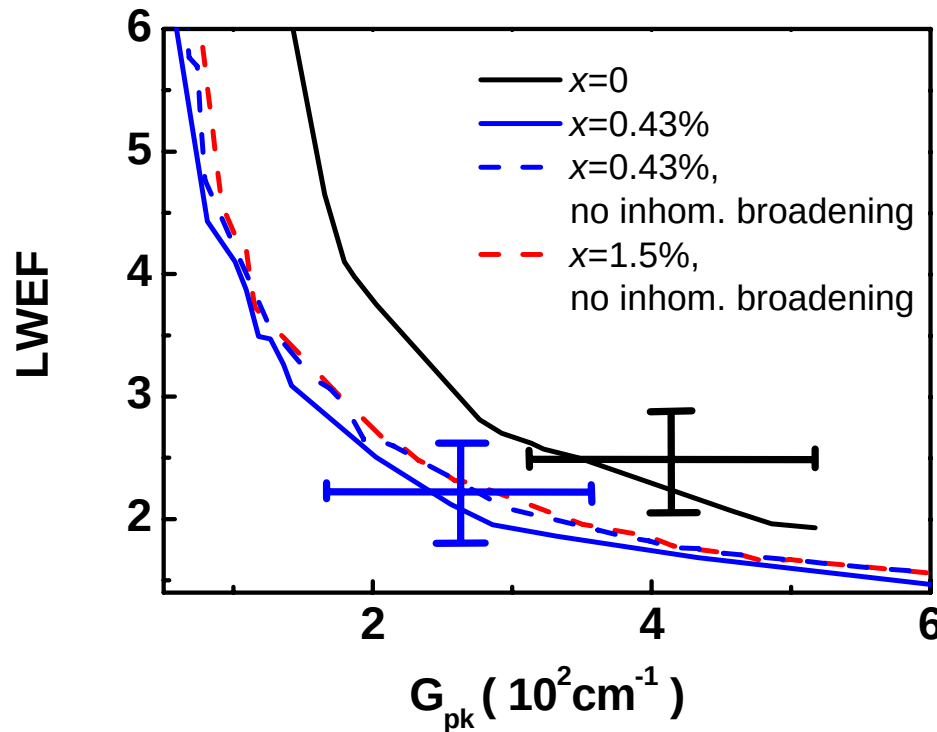
6nm $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_{0.0043}\text{As}_{0.9957}/\text{GaAs}$
 $N = 1.46, 1.4, 1.31, 1.21, 1.11 \times 10^{12} \text{ cm}^{-2}$
exp. current 236, 221, 201, 180, 159 mA



6nm $\text{Ga}_{0.58}\text{In}_{0.42}\text{As}/\text{GaAs}$
 $N = 1.01, 0.94, 0.85, 0.77 \times 10^{12} \text{ cm}^{-2}$
exp. current 102, 92, 80, 70 mA

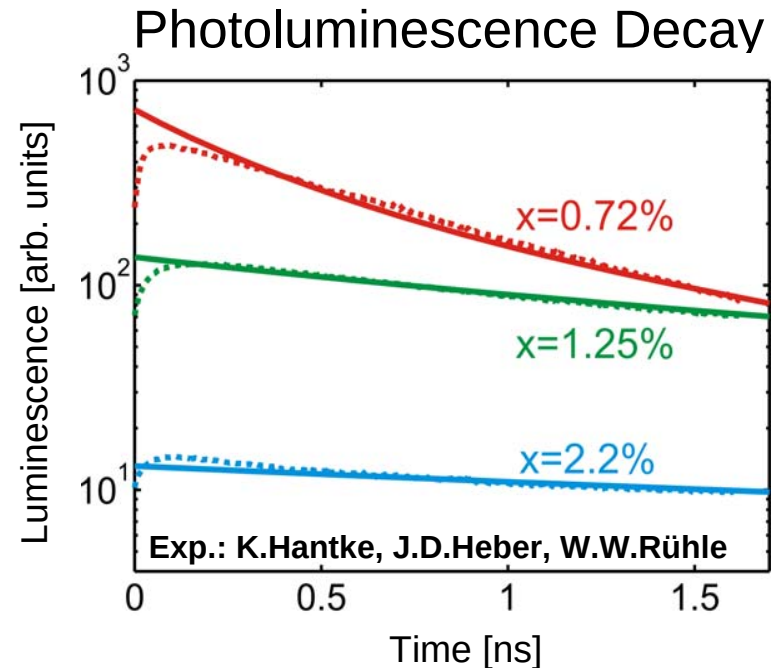
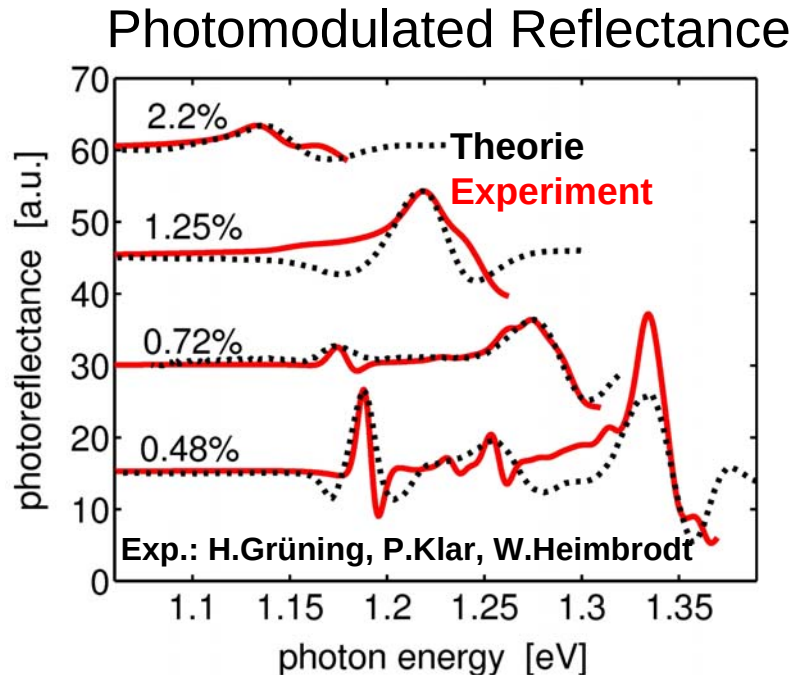
- Excellent theory-experiment agreement
- Higher threshold density in GaInNAs
- Higher carrier density required for similar peak gain in GaInNAs

Linewidth Enhancement Factor in $\text{Ga}_{0.6}\text{In}_{0.4}\text{N}_x\text{As}_{1-x}/\text{GaAs}$



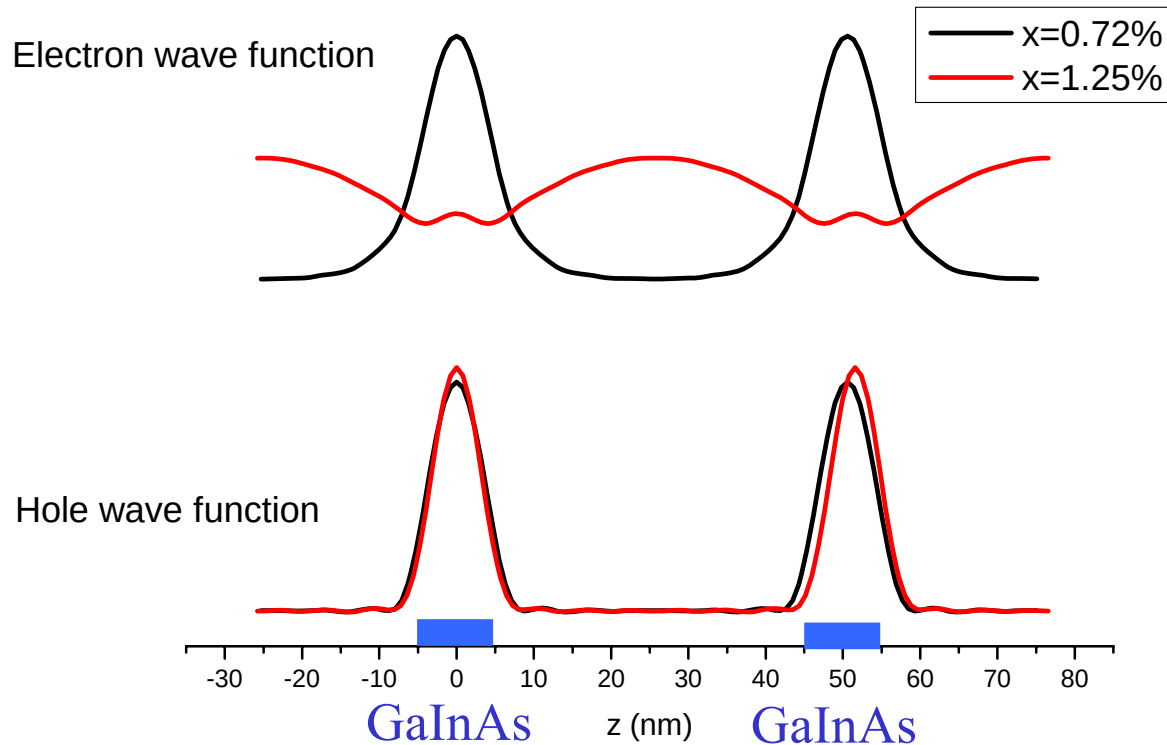
- Excellent theory-experiment agreement
- Decrease of LWEF by addition of nitrogen (GaInNAs vs GaInAs)
- Very slight increase of LWEF with further addition of nitrogen

Type I-Type II-Transition in $\text{Ga}_{0.77}\text{In}_{0.23}\text{As}/\text{GaN}_x\text{As}_{1-x}$ -Nanostructures



- Excellent theory-experiment agreement
- **Type I-Type II**-Transition with increasing nitrogen content
- Consistent set of bandstructure parameters
- Increasing nitrogen content x leads to change of (spatially) direct $\rightarrow$ indirect transition, slower radiative decay, see also poster tomorrow (WP2)

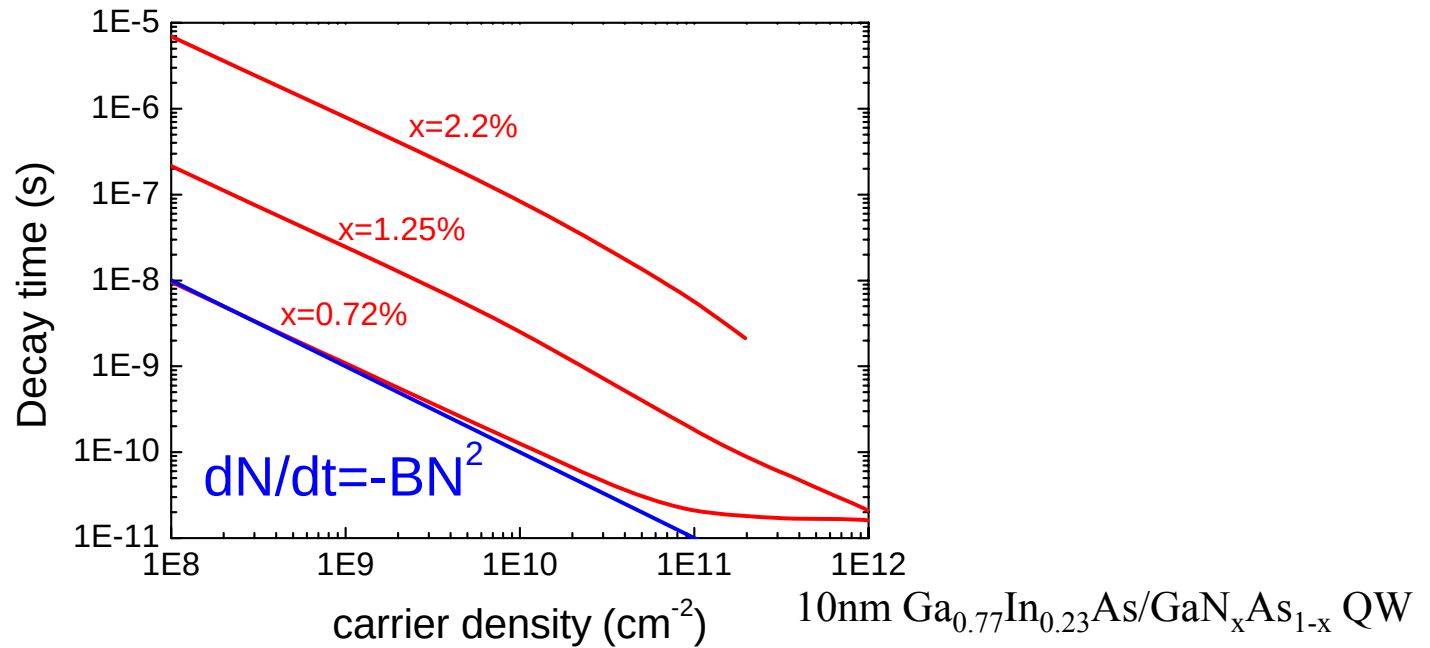
Type I – Type II



10 nm $\text{Ga}_{0.77}\text{In}_{0.23}\text{As}/\text{GaN}_x\text{As}_{1-x}$

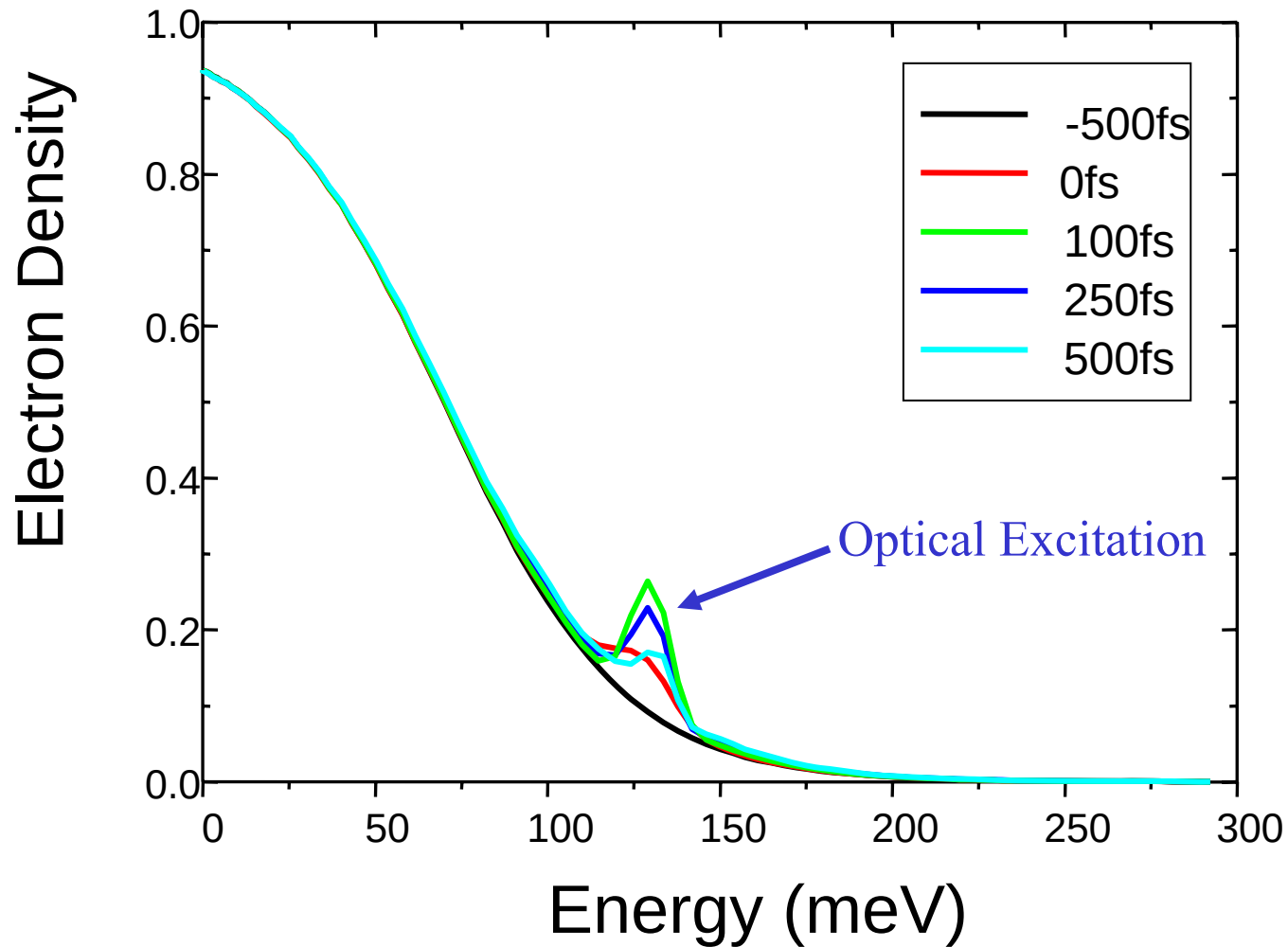
Transition spatially direct (Type I) => spatially indirect (Type II)

Radiative Decay Time



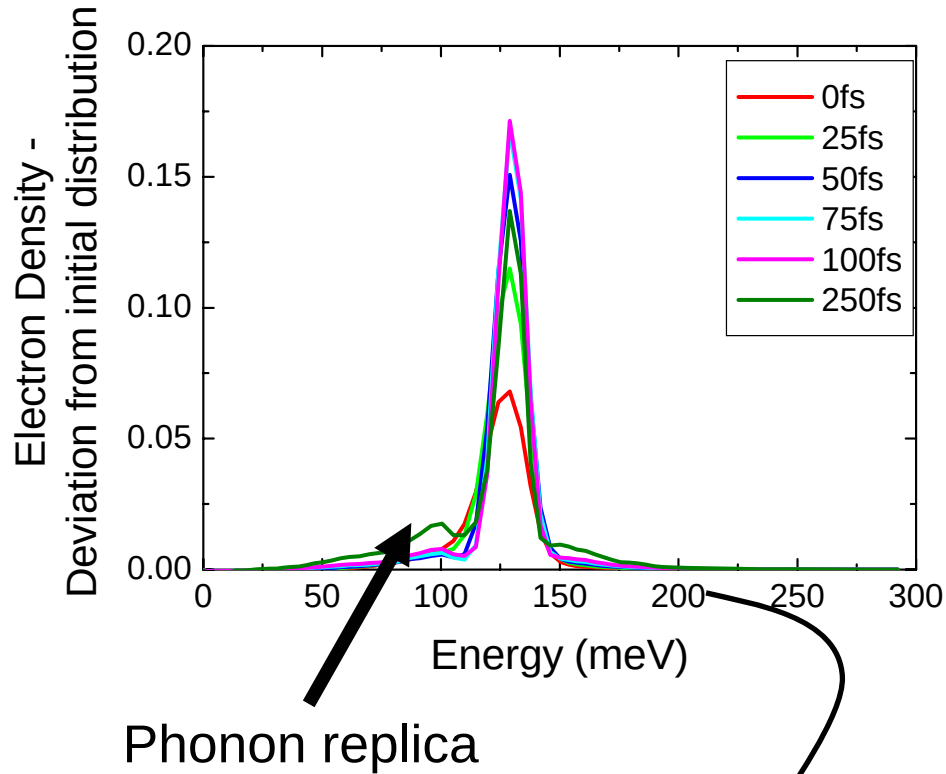
- B-coefficient good approximation for densities below lasing threshold
- Density-independence of τ in type I-sample for high densities due to change from Boltzmann-like to degenerate Fermi distribution
- Effect compensated in type II-sample due to Coulomb attraction between electrons and holes

Carrier Dynamics in Semiconductor Quantum Wells

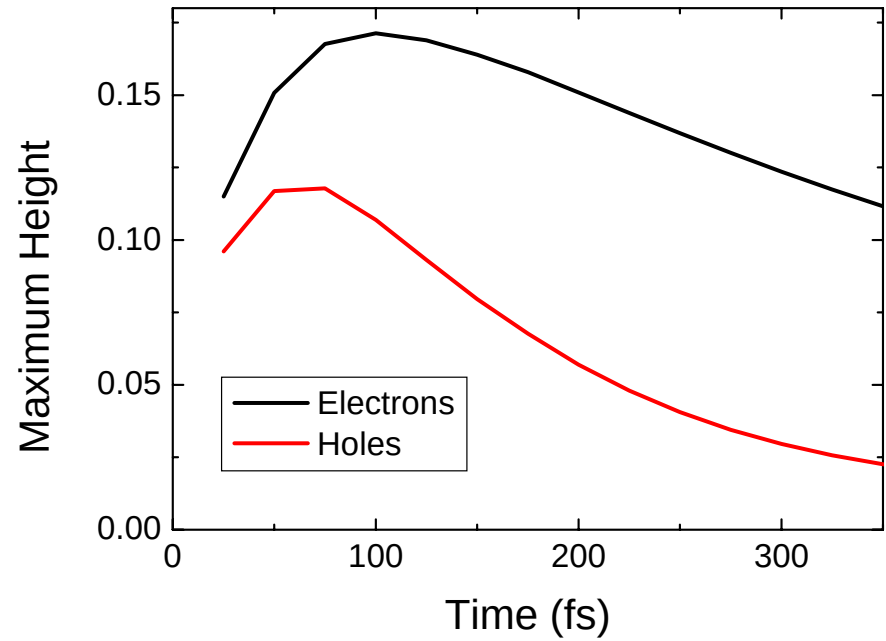


InGaAs-InP, Excitation by a 50fs pulse at 1.35eV at t=0

Extraction of Effective Relaxation Times

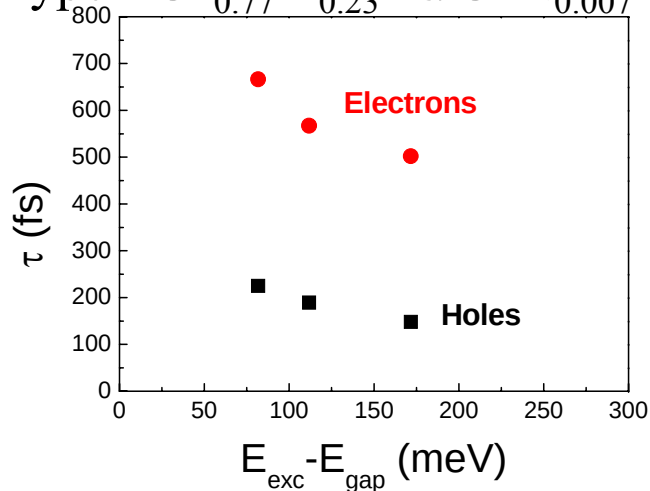


- Simple evaluation
- Exponential fits work well
- τ good measure for scattering strength

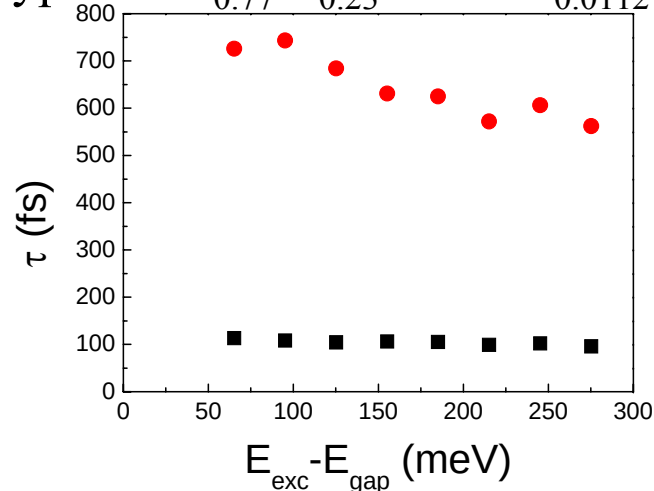


Typical Effective Electron-Hole Scattering Times

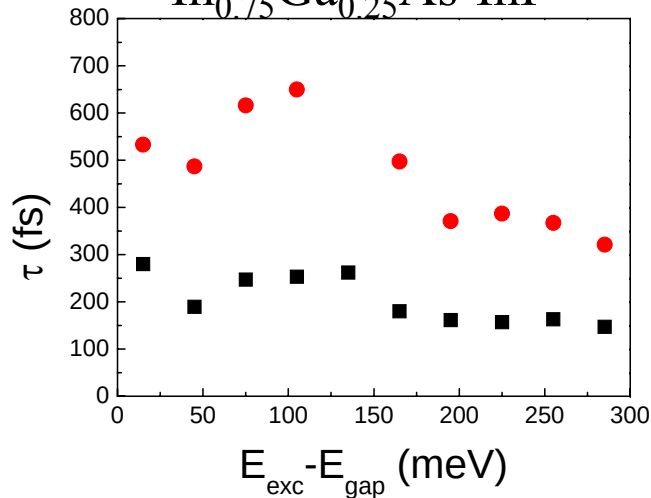
Type I $\text{Ga}_{0.77}\text{In}_{0.23}\text{As}/\text{GaN}_{0.007}\text{As}_{0.993}$



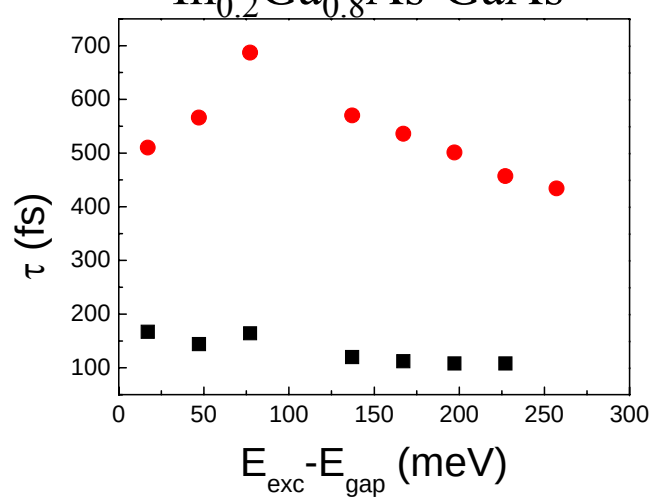
Type II $\text{Ga}_{0.77}\text{In}_{0.23}\text{As}/\text{GaN}_{0.0112}\text{As}_{0.988}$



$\text{In}_{0.75}\text{Ga}_{0.25}\text{As}-\text{InP}$

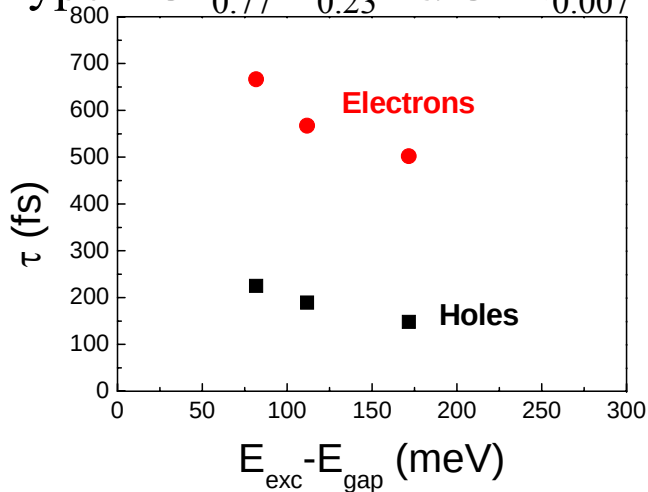


$\text{In}_{0.2}\text{Ga}_{0.8}\text{As}-\text{GaAs}$

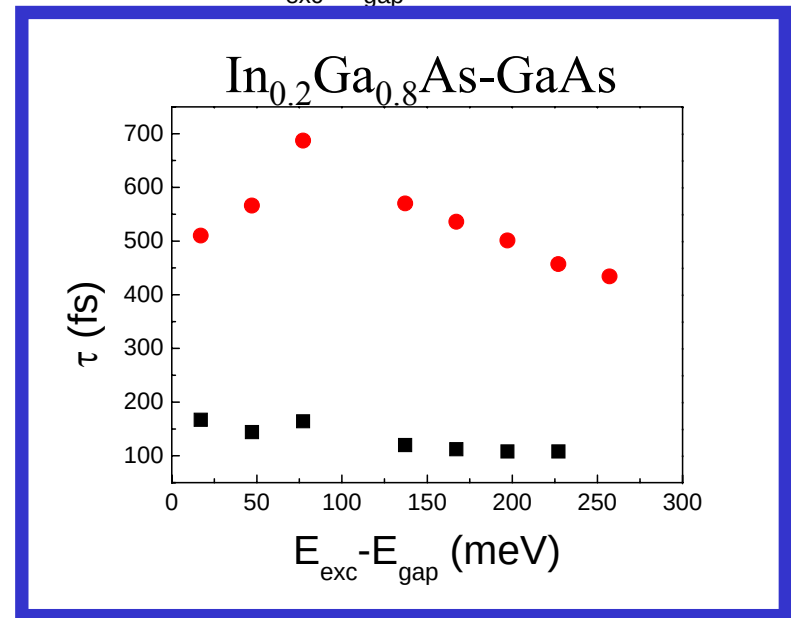
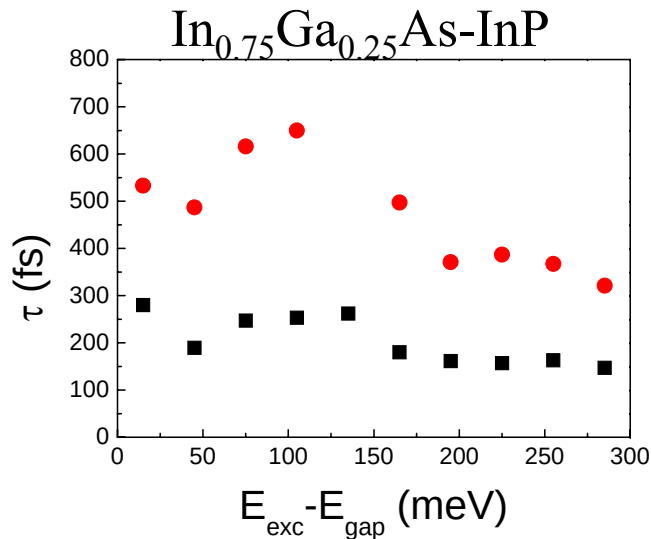
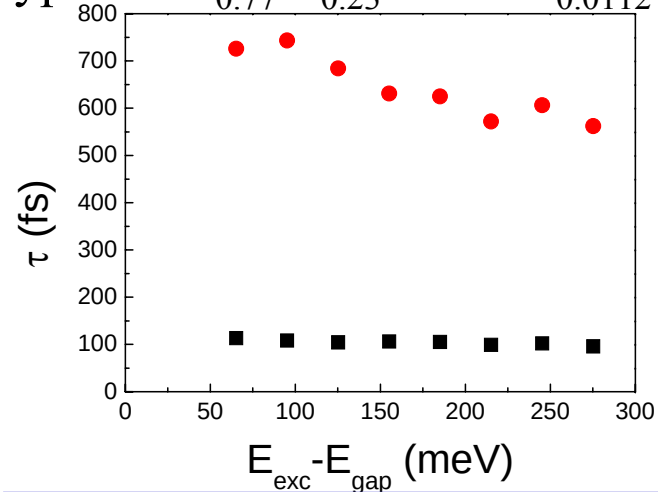


Typical Effective Electron-Hole Scattering Times

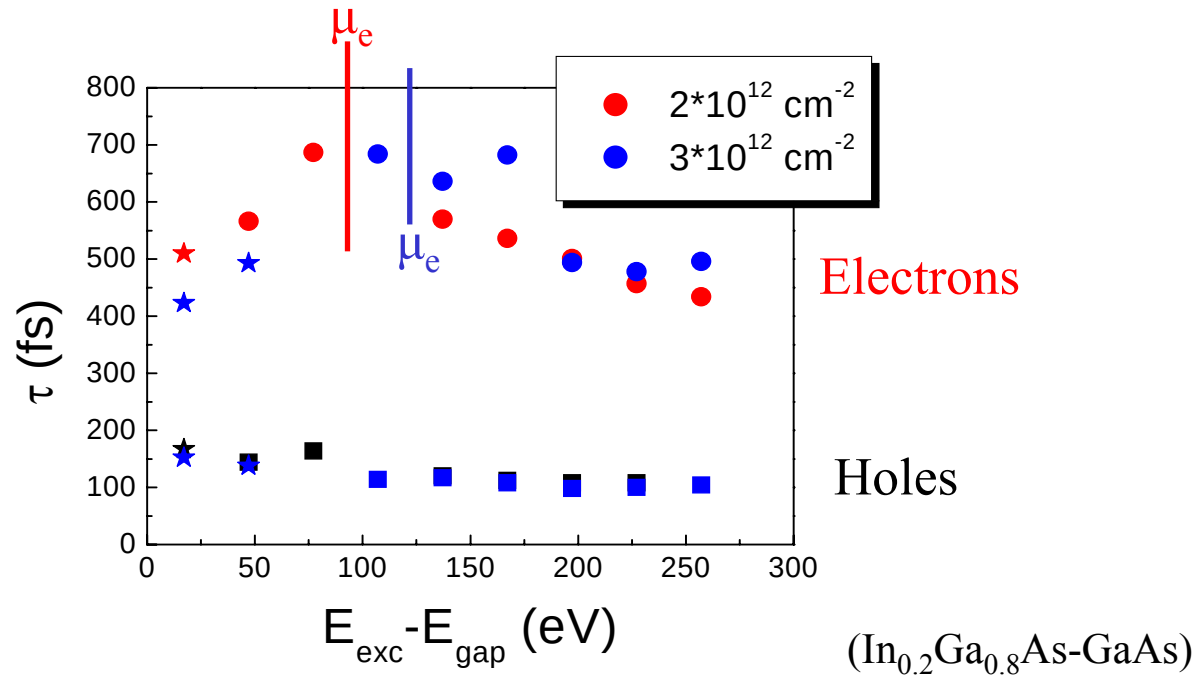
Type I $\text{Ga}_{0.77}\text{In}_{0.23}\text{As}/\text{GaN}_{0.007}\text{As}_{0.993}$



Type II $\text{Ga}_{0.77}\text{In}_{0.23}\text{As}/\text{GaN}_{0.0112}\text{As}_{0.988}$

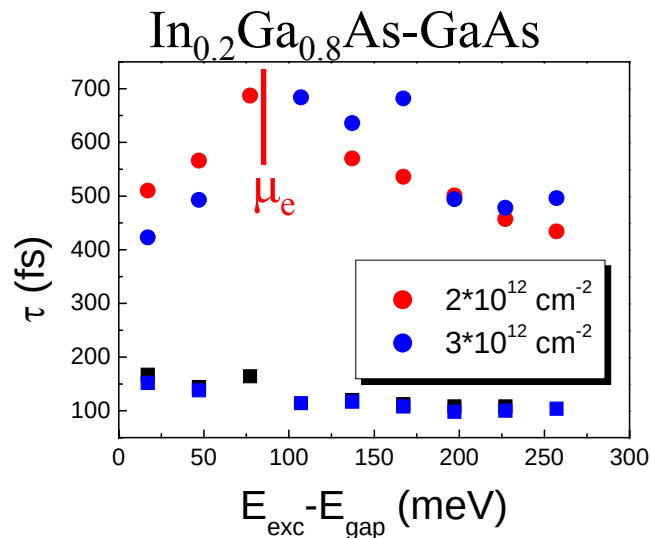
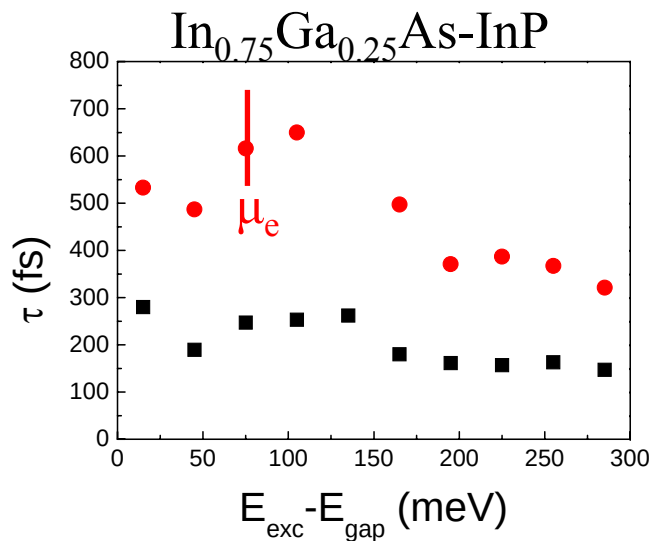
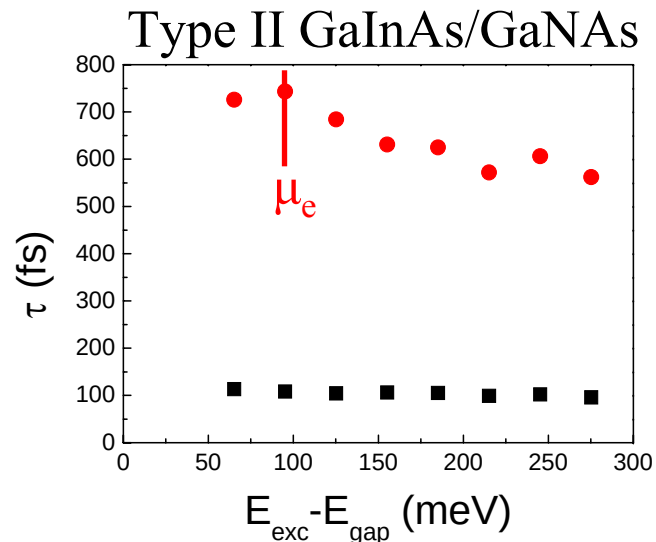
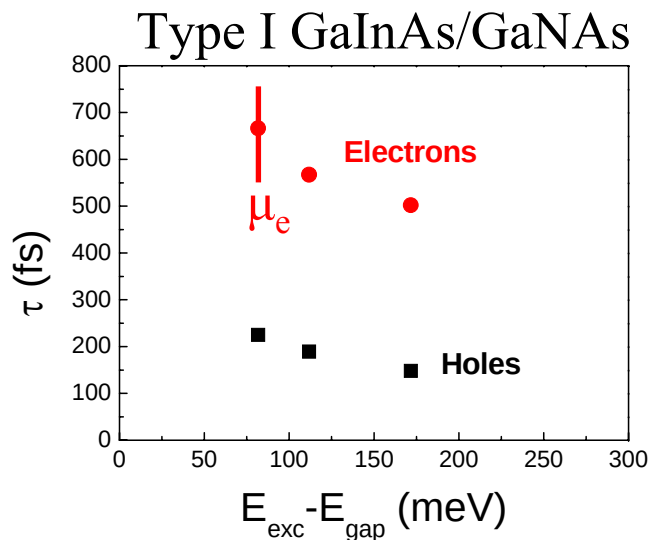


Carrier Scattering



- Hole scattering faster than electron scattering because of larger effective mass
- Comparable Times for hole burning (stars) and carrier excitation (circles/boxes)
- Slow scattering around chemical potential – scattering rate may decrease for increasing density
- No clear density dependence of scattering times

Typical Effective Electron-Hole Scattering Times



Conclusion/Outlook

- Microscopic theory shows excellent agreement with experiment (gain, LWEF, photomodulated reflectance, time-resolved photoluminescence)
- Large deviations from $dN/dt = -BN^2$ for lasing densities
- Optical pumping may cool carrier distribution
- Effective scattering rates may be extracted but depend on structural parameters, temperature and carrier density and distribution
- Scattering may become slower for increasing carrier density
- Scattering times may be used for parametric studies in simplified model, see A. Thränhardt et al., Appl.Phys.Lett. 85, 5526 (2004). => modelling of nonequilibrium gain