Energy Band Calculations for Dynamic Gain Models in Semiconductor Quantum Well Lasers

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Presentation Outline

- Fourier series representation of valence band asymmetries
- Carrier energy density of states
- Gain spectra
- Dynamic gain model

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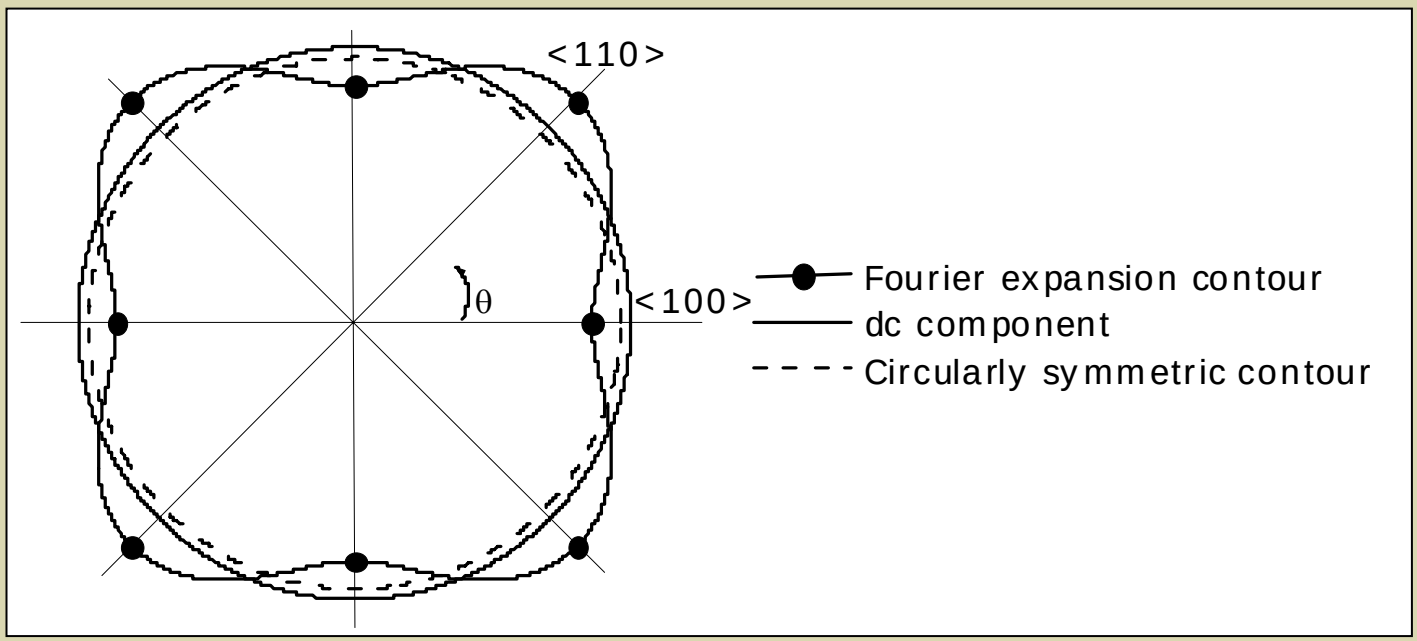
Quantum well valence band structure – Fourier expansion

- Decoupled 4-band ***k.p*** method for <100> and <110> crystal directions
- 1st order Fourier expansion fulfils symmetry and continuity requirements
- Numerically efficient

$$k(\theta) = \frac{k_{<110>} + k_{<100>}}{2} - \frac{k_{<110>} - k_{<100>}}{2}\cos(4\theta)$$



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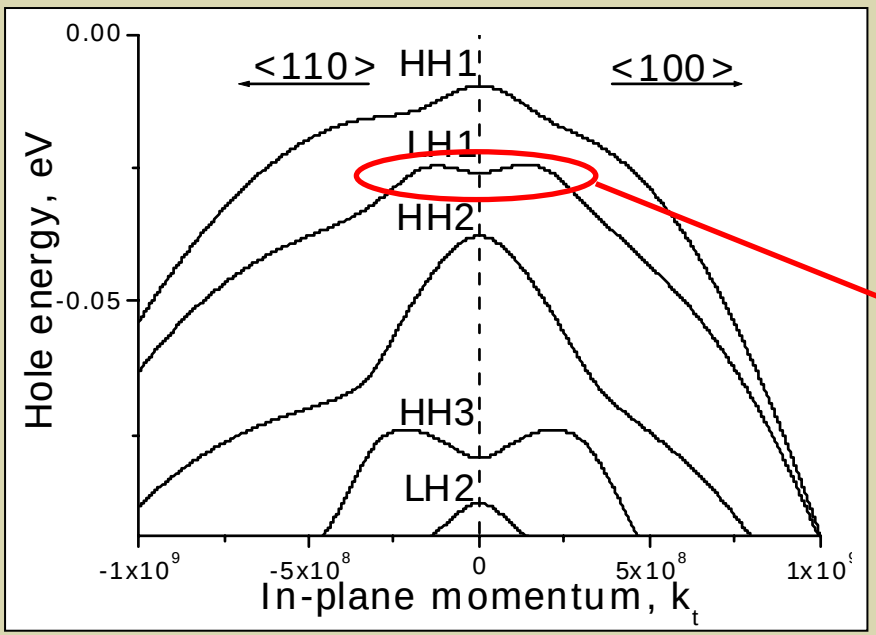
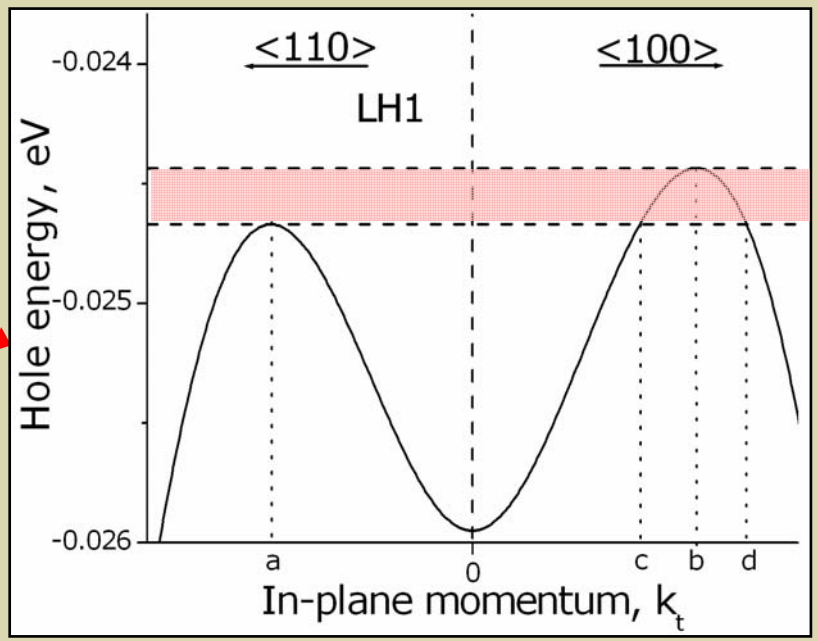
Quantum well valence band structure – local maxima

- Cannot use the Fourier expansion method in this region near local maxima
- 8nm $GaAs/Al_{0.2}Ga_{0.8}As$ QW





$$a \equiv k_{<110>}(E_{<110>max}); b \equiv k_{<100>}(E_{<100>max}); c \equiv k^{-}_{<100>}(E_{<110>max}); d \equiv k^{+}_{<100>}(E_{<110>max})$$

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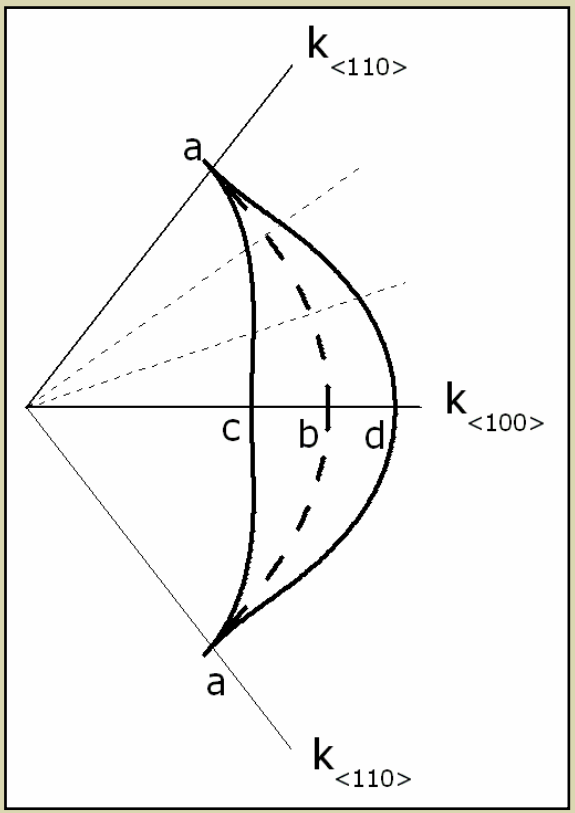
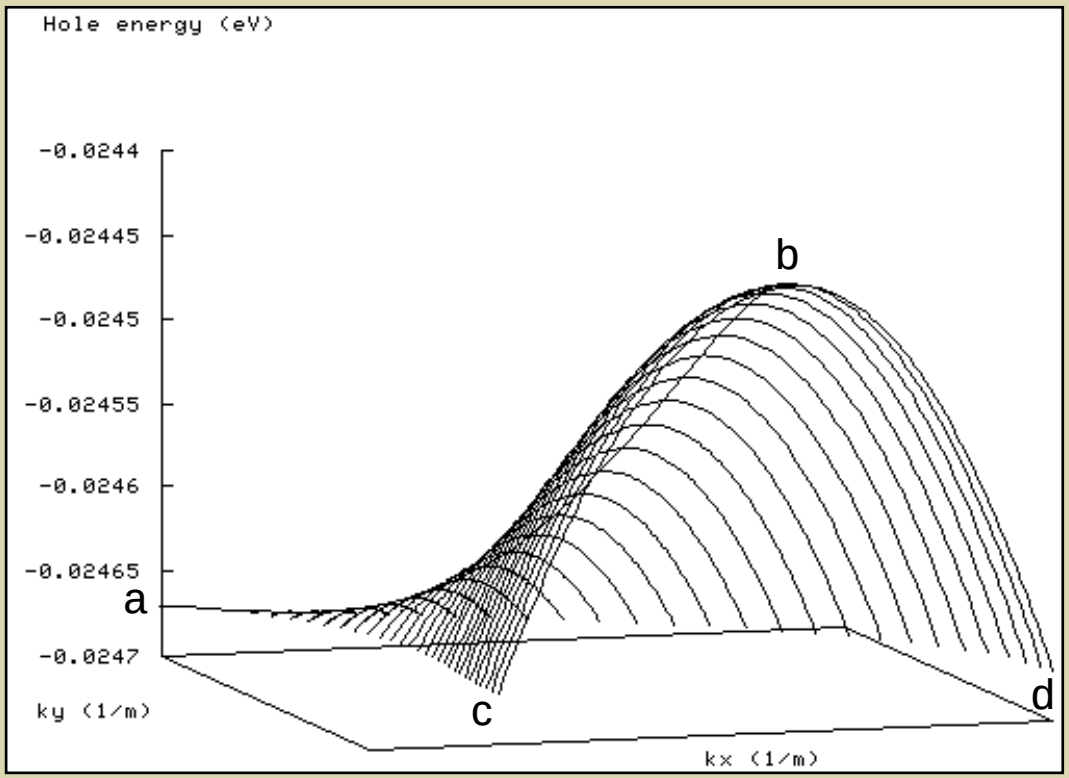
Quantum well valence band structure – local maxima

- Series of parabolic approximations made to describe energy contours near local valence band maxima





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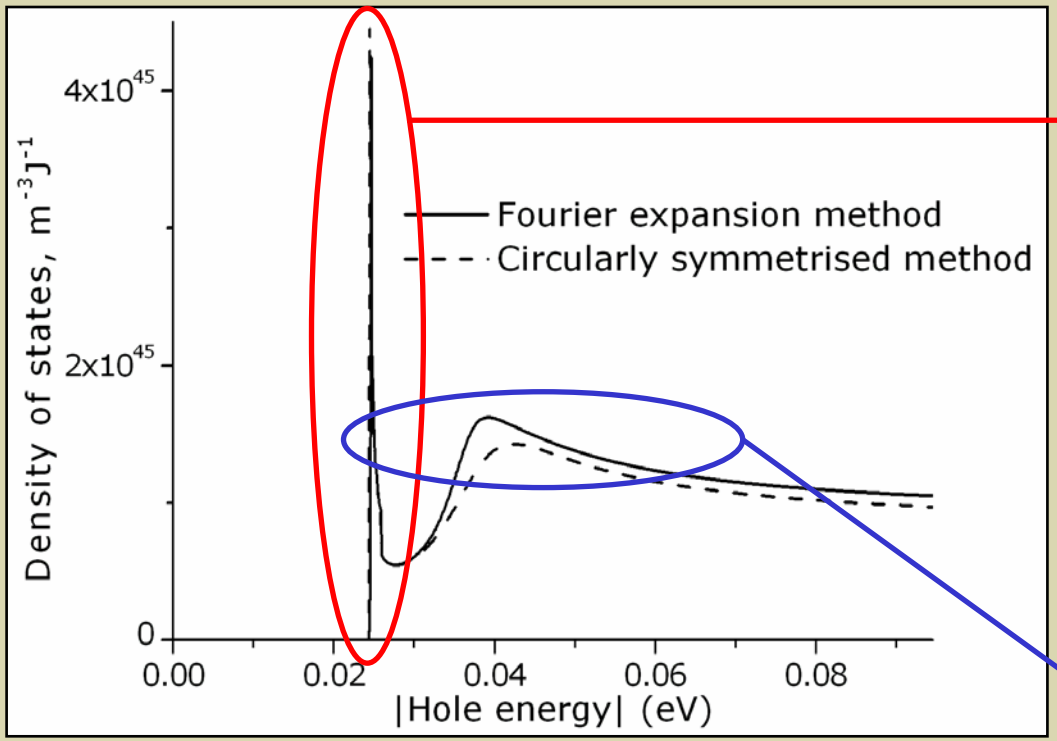
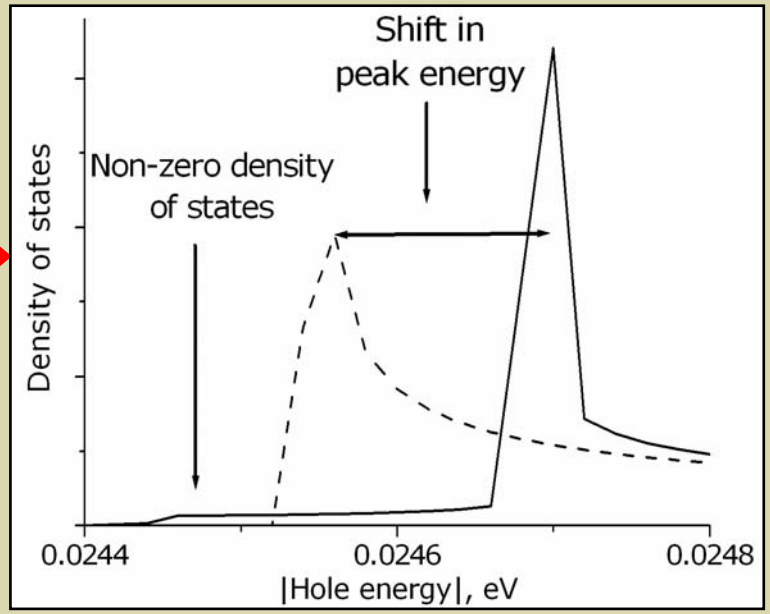
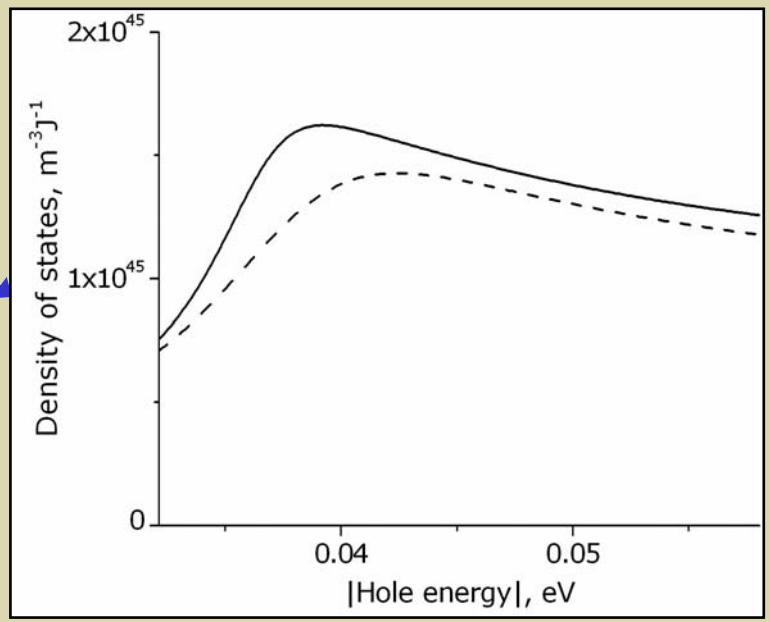
Subband energy density of states







- Non-zero density of states near local maxima
- Location of peak shifted
- Energy density of states up to 10% larger than for circularly symmetric method

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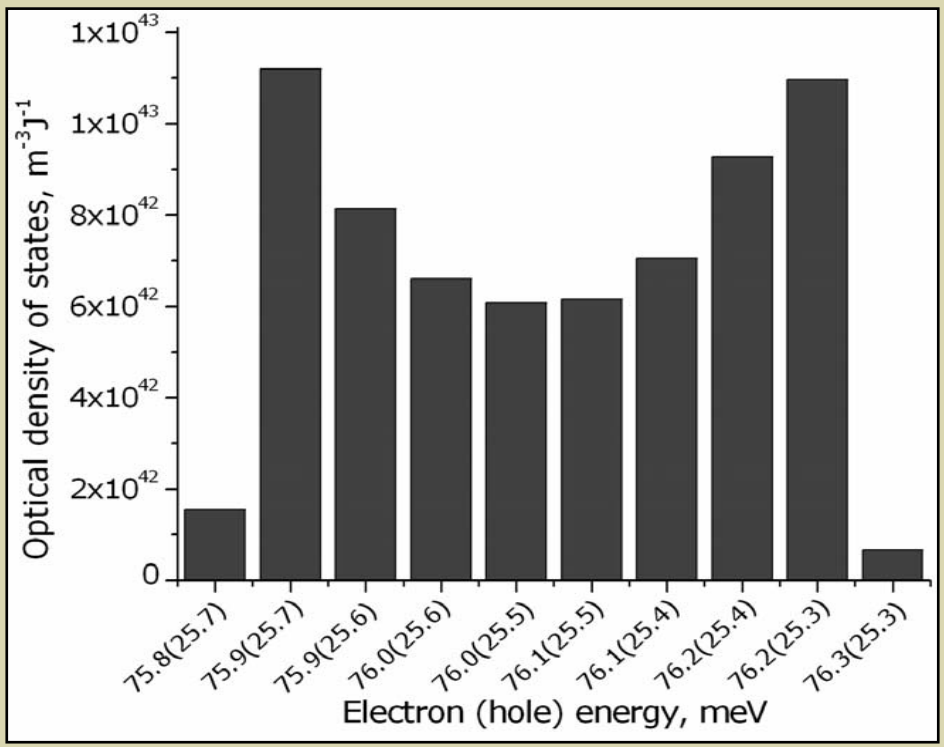
Optical energy density of states – carrier energy spread

8nm $In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW

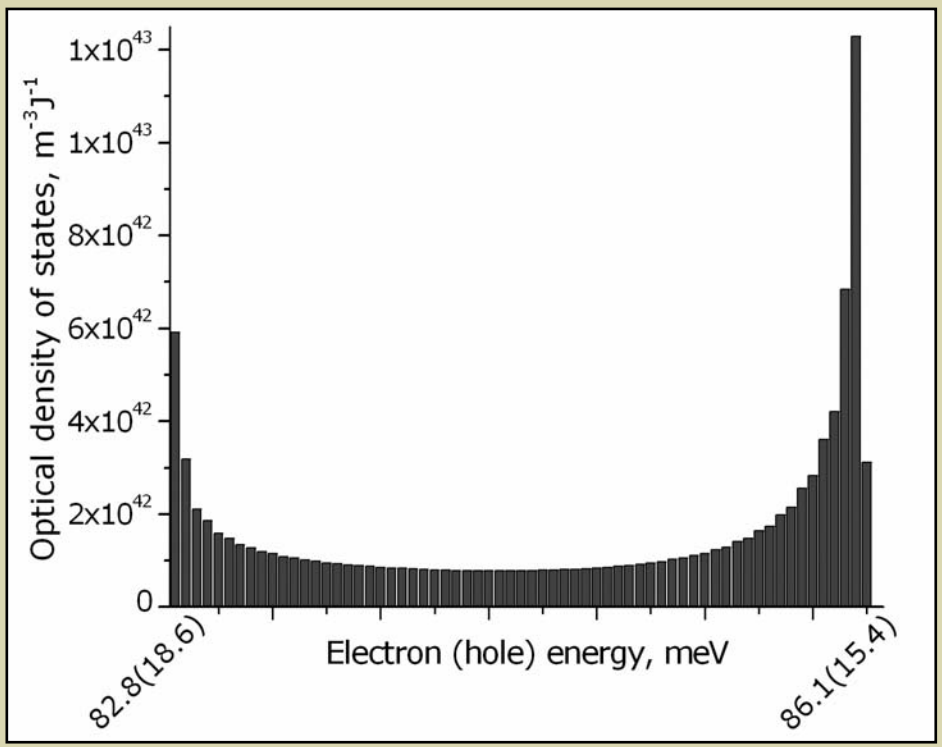
E_{photon} = 1.32eV



$$\Delta E_{carrier} \approx 0.5 meV$$

8nm $GaAs/Al_{0.2}Ga_{0.8}As$ QW

E_{photon} = 1.525eV



$$\Delta E_{carrier} \approx 3.3 meV$$

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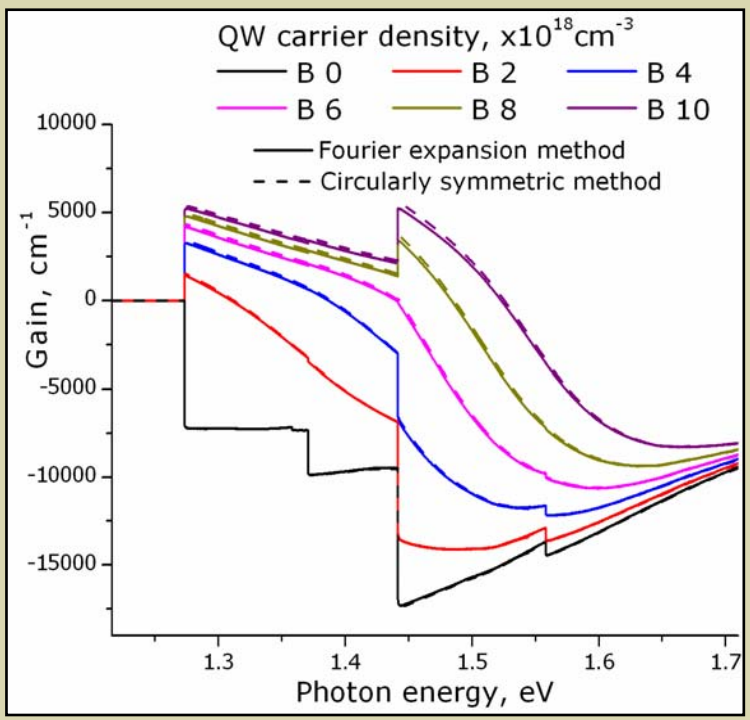
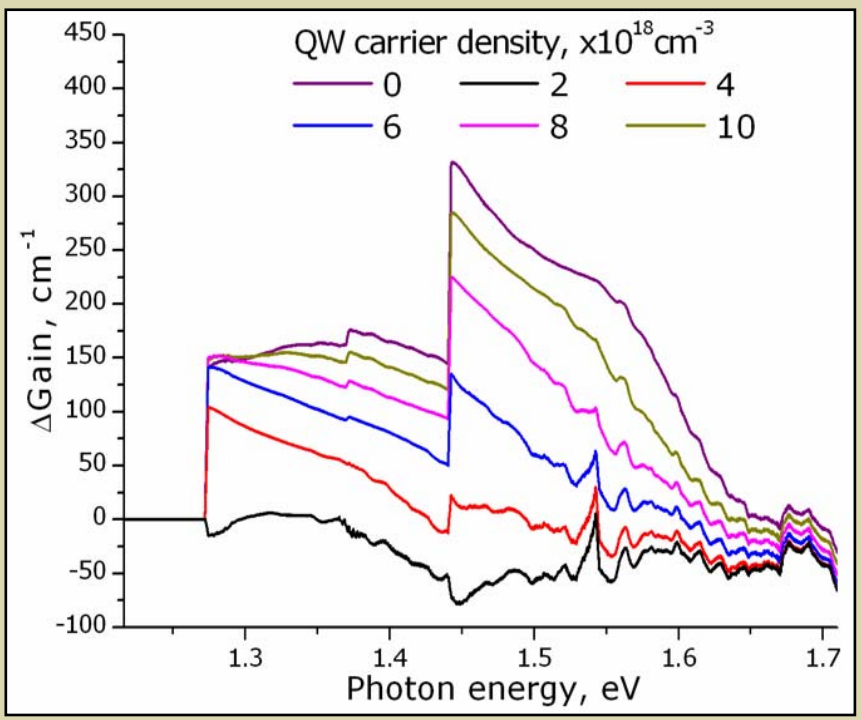
Gain / absorption

- Carrier energy spread affects matrix element and occupational probability
- Gain calculation requires sum over this range for each photon energy





$$g(E_{ph}) \propto \sum_{cb,vb} \int_{E_e} \int_{E_h} \left|M_T(E_e,E_h)\right|^2 \rho_{opt}(E_e,E_h)\left[f_c(E_e) - f_v(E_h)\right] dE_e dE_h$$

Dynamic QW gain model

- States at same energy assumed to have equal occupational probability
  - ultrafast momentum relaxation at given energy
  - implicitly assumed for relaxation rate approximation
  - allows $\int d^2\vec{k}$ to be replaced by $\int dE$
- Individual intrasubband, intersubband and interband relaxation processes treated separately
- Carrier-carrier scattering modelled using relaxation rate approximation
- Carrier-phonon scattering modelled using phonon emission/absorption
  - Carrier kinetic energy threshold for phonon emission
- Gain and spontaneous emission derived from band structure model
  - linewidth enhancement and bandgap renormalisation omitted for clarity

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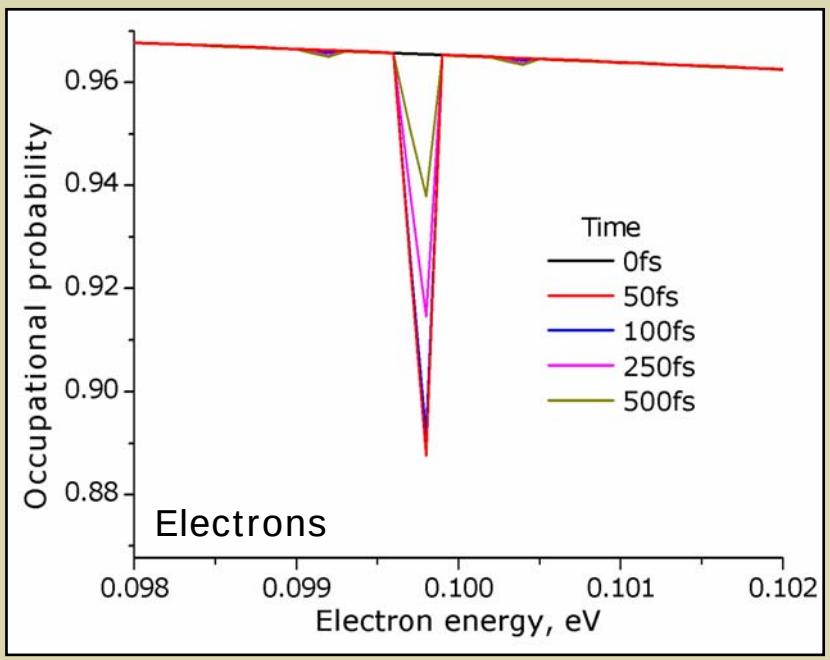
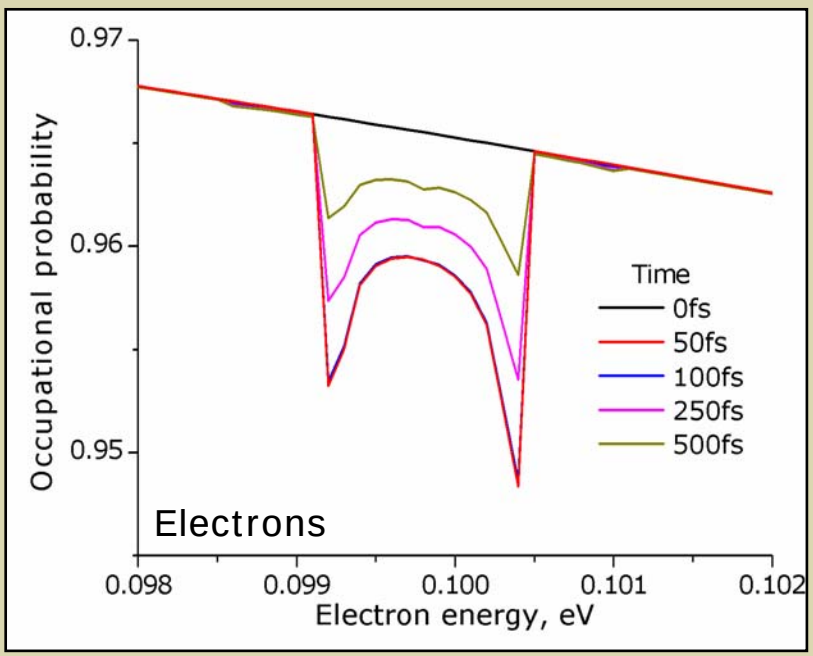
Dynamic QW gain model – spectral hole burning (case 1)

- 8nm $In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW
- thermal equilibrium carrier concentration of $2.5 \times 10^{18} cm^{-3}$ at $t=0^-$
- Excited by 15fs gaussian pulse, 1.35eV low energy source (25μJ average)

Spectral hole in electron occupational probability distribution



Circularly symmetric band structure method



Fourier expansion band structure method

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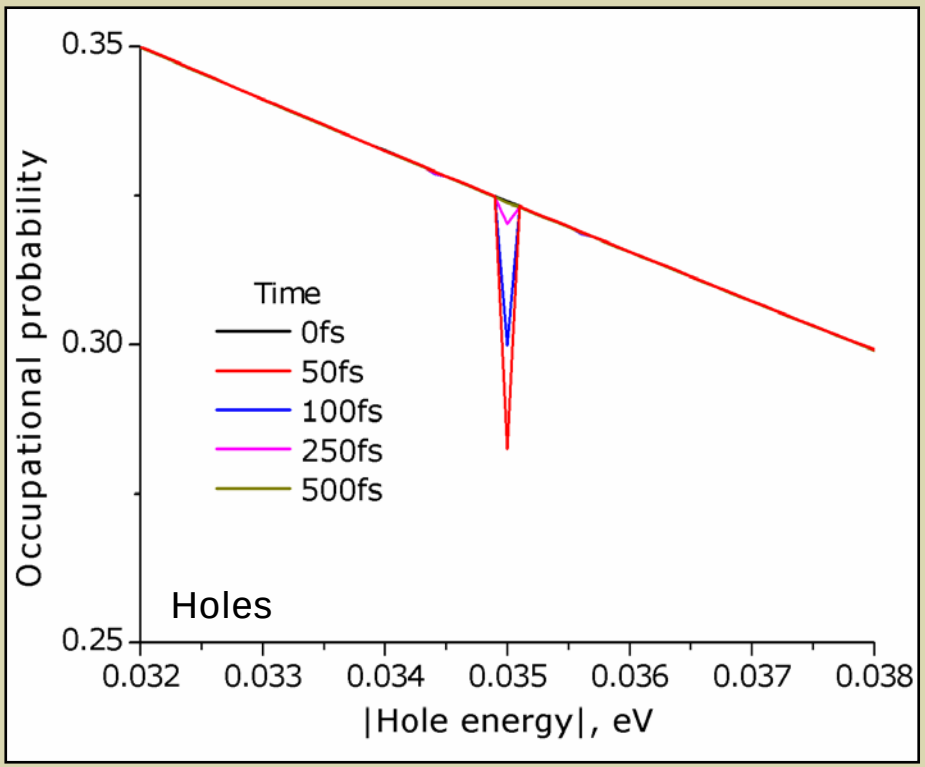
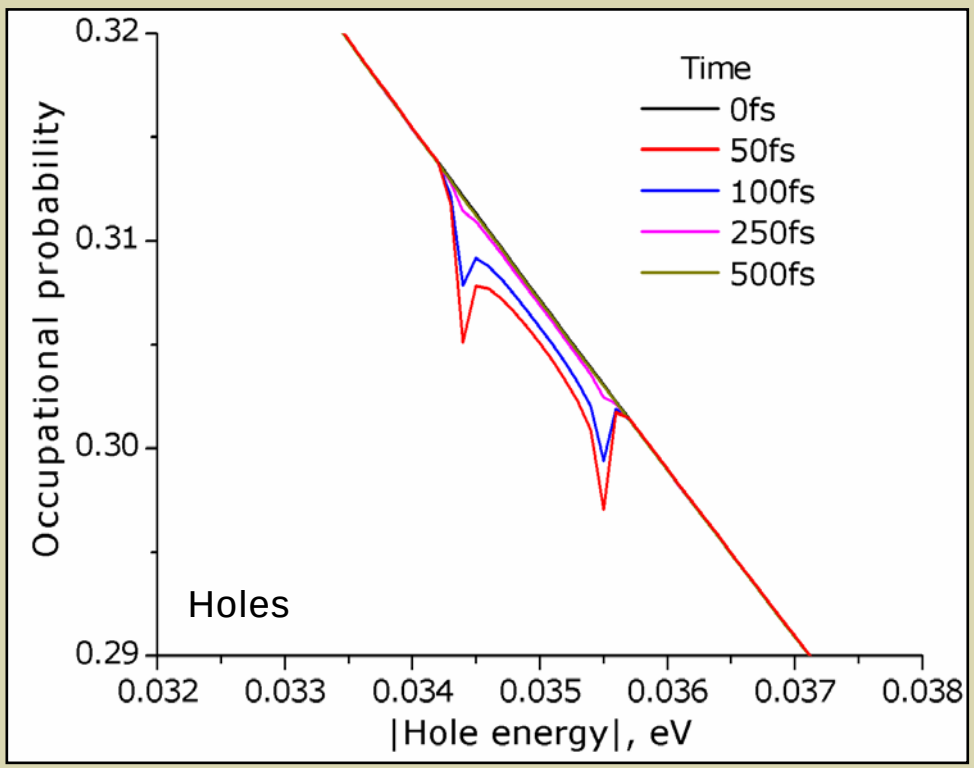
Dynamic QW gain model – spectral hole burning (case 1)

Spectral hole in hole occupational probability distribution



Circularly symmetric band structure method



Fourier expansion band structure method

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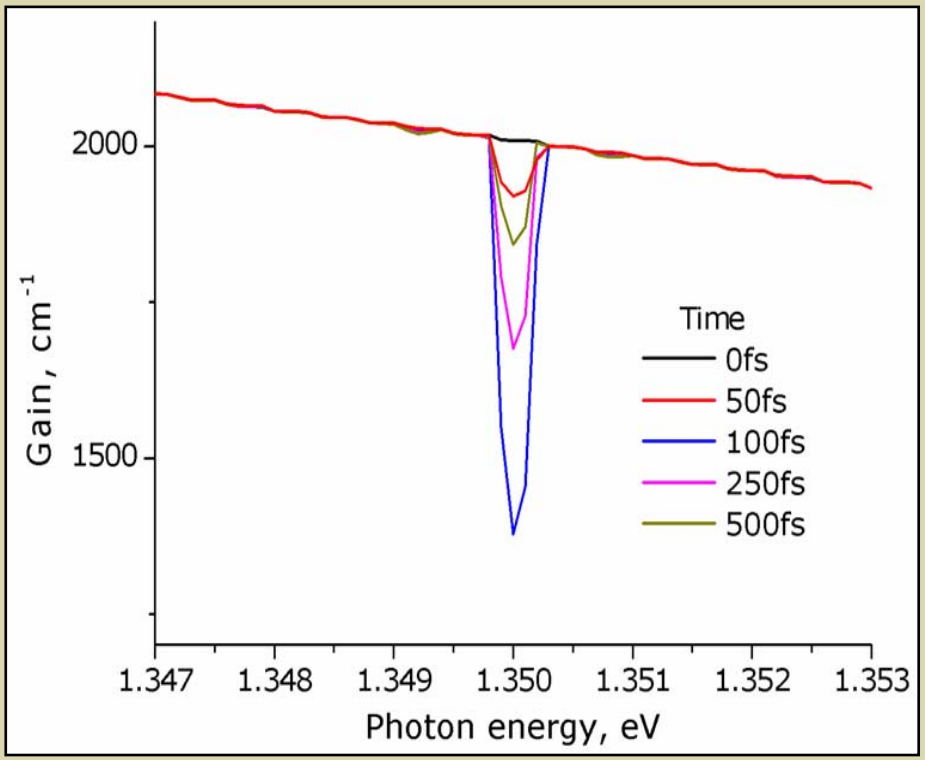
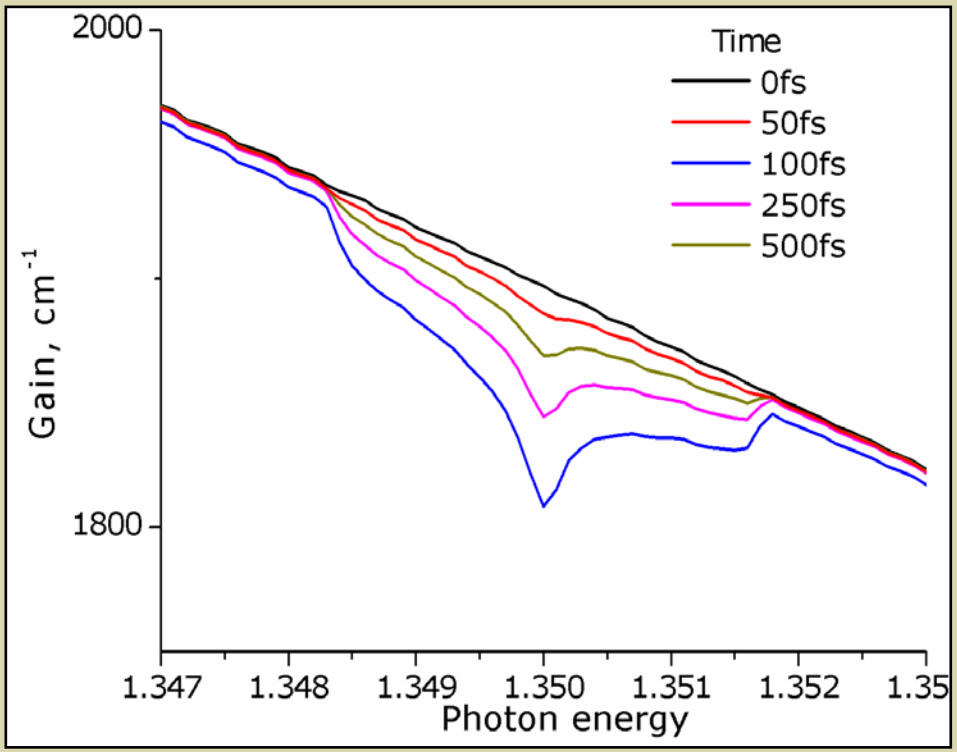
Dynamic QW gain model – spectral hole burning (case 1)

Spectral hole in gain spectrum



Circularly symmetric band structure method



Fourier expansion band structure method

- Affects linewidth enhancement

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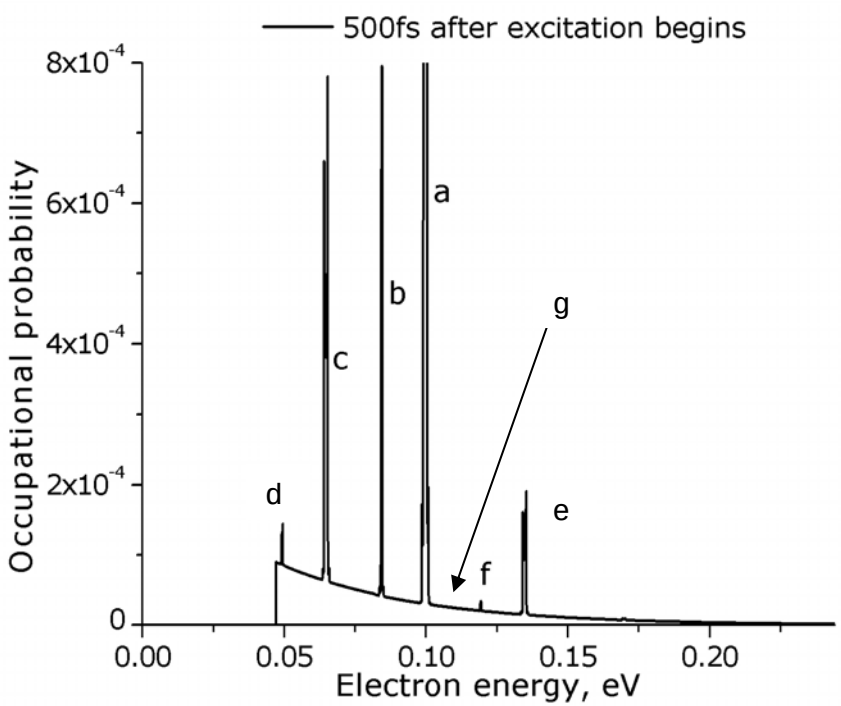
Dynamic QW gain model – optical pumping (case 2)

- 8nm $In_{0.2}Ga_{0.8}As/Al_{0.2}Ga_{0.8}As$ QW
- thermal equilibrium intrinsic carrier concentration at $t=0^-$
- 1MW/cm^2 CW pump (E_{ph}=1.35eV) introduced at $t=0^+$

Electron probability distribution – Fourier expansion band structure method



a – photon absorption from HH1 to CB1

b – photon absorption from HH2 to CB1

c,d – LO phonon emission replicas

e,f – LO phonon absorption replicas

g – electrons due to carrier-carrier scattering

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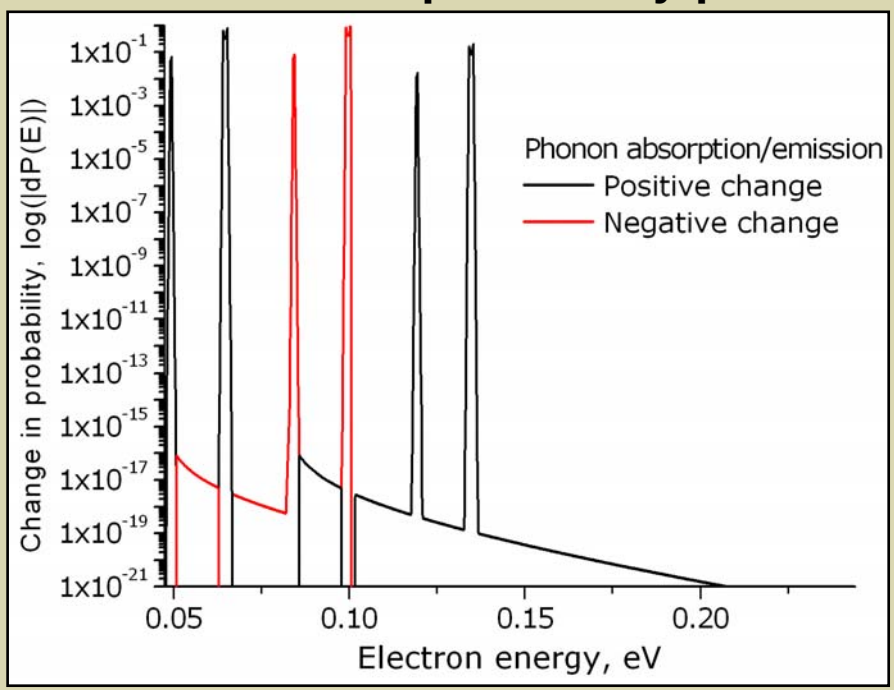
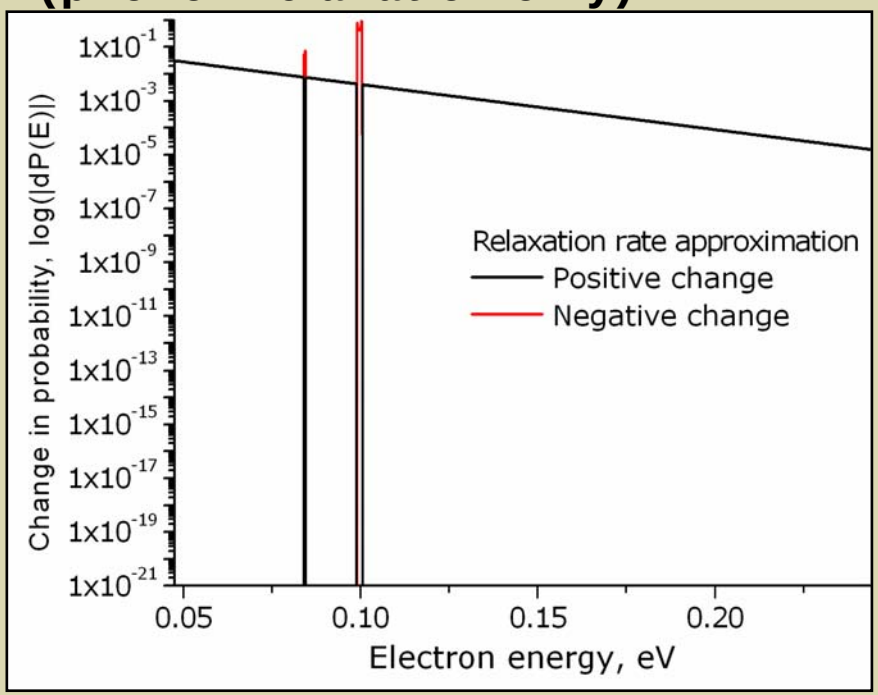
Dynamic QW gain model – phonon model

- Same QW and starting conditions
- Same optical pump but switched off after $\Delta t = 100$fs
- Fourier expansion band structure method

Electron probability perturbation (phonon relaxation only)



Phonon emission / absorption



Relaxation rate approximation

Summary

- Numerically efficient valence band model
  - Retains important asymmetrical features of full ***k.p*** model
  - Affects density of states and dynamic gain
- Dynamic gain model
  - Intrasubband, intersubband, interband processes separate
  - Carrier-phonon scattering modelled using emission/absorption

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IS THE RELAXATION RATE APPROXIMATION APPROPRIATE FOR CARRIER-CARRIER SCATTERING?

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