# *Many-Body, exciton and Inhomogeneous Broadening Effects In Device Simulation*

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# Many-body effects on gain

- Coulomb attraction between e-h pair enhances radiative recombination → enhanced optical gain and spontaneous emission.
- Band-gap reduction due to Coulomb-hole self energy and screened-exchange shift.
- Coulomb enhancement is more pronounced in wide band-gap materials, CdZnSe and GaN
- It has been reported that many body effects are important in prediction of laser characteristics.

# Exciton effects on absorption

- **Same coulomb attraction between e-h pair more pronounced in low carrier density/absorption when carrier screening effect is less.**
- **Results in excitonic peaks in absorption spectra.**
- **Many-body/exciton model critical for device simulation when active layer carrier density is low (such as EAM).**

# Inhomogeneous broadening tail states

- Fluctuation in quantum well thickness and composition, defects and impurities all contribute to inhomogeneous broadening of optical spectra.
- Manifests itself in an exponential tail in band gap.
- Results in reduced effective band gap and modification in gain/spontaneous emission spectra shape (more symmetrical)

# Physical Models

- Semiconductor Bloch equations with screened Hartree-Fork approximation
- First-order Pade approximation.
- Band-gap renormalization
  - Coulomb-hole self-energy $\Delta\varepsilon_{CH}$
  - Exchange energy $\Delta\varepsilon_{SX}$
- Optical gain enhancement

$$g(E) \propto \int g_0(E) \times CE\_factor(E) dE$$

Reference:

'Semiconductor Laser Fundamentals', by W.W. Chow and S.W. Koch

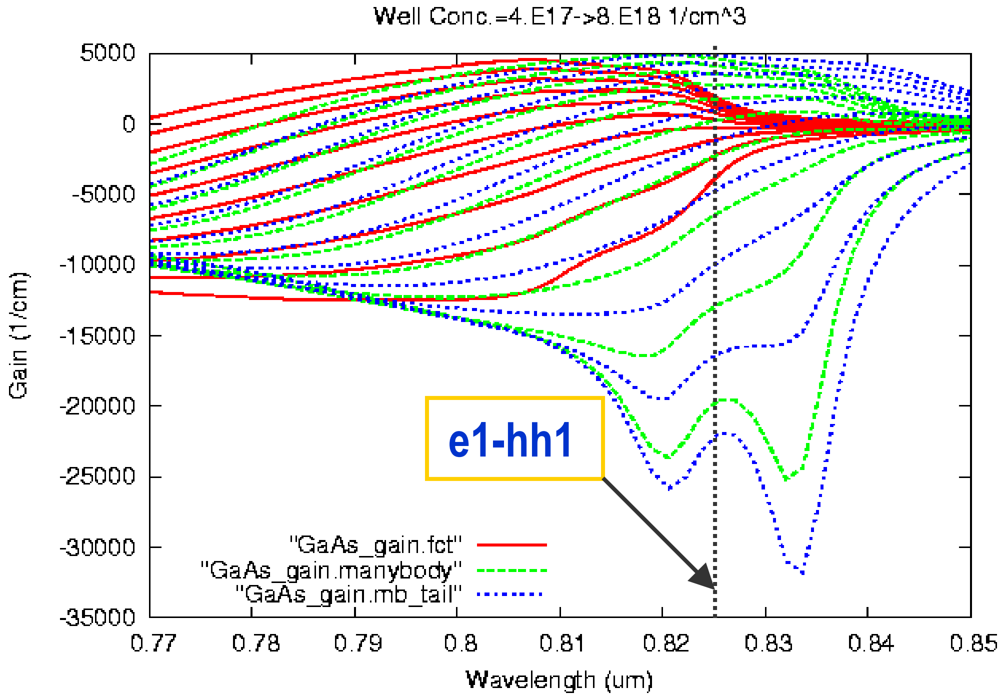
# GaAs / AlGaAs, Gain spectrum

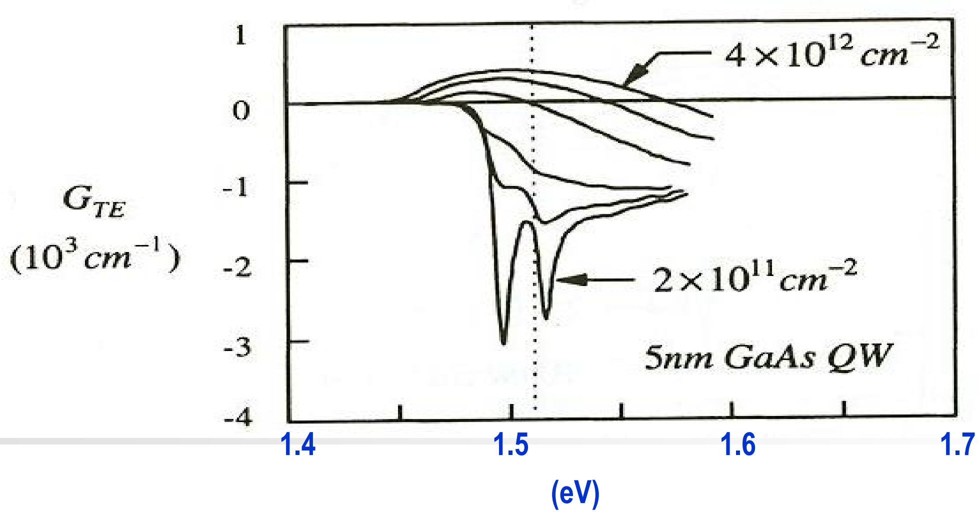
5nm GaAs/Al0.2Ga0.8A

Fct: free carrier theory

Manybody: Coulomb

mb_tail: Coulomb+tail states




'Semiconductor Laser Fundamentals', by W.W. Chow and S.W. Koch

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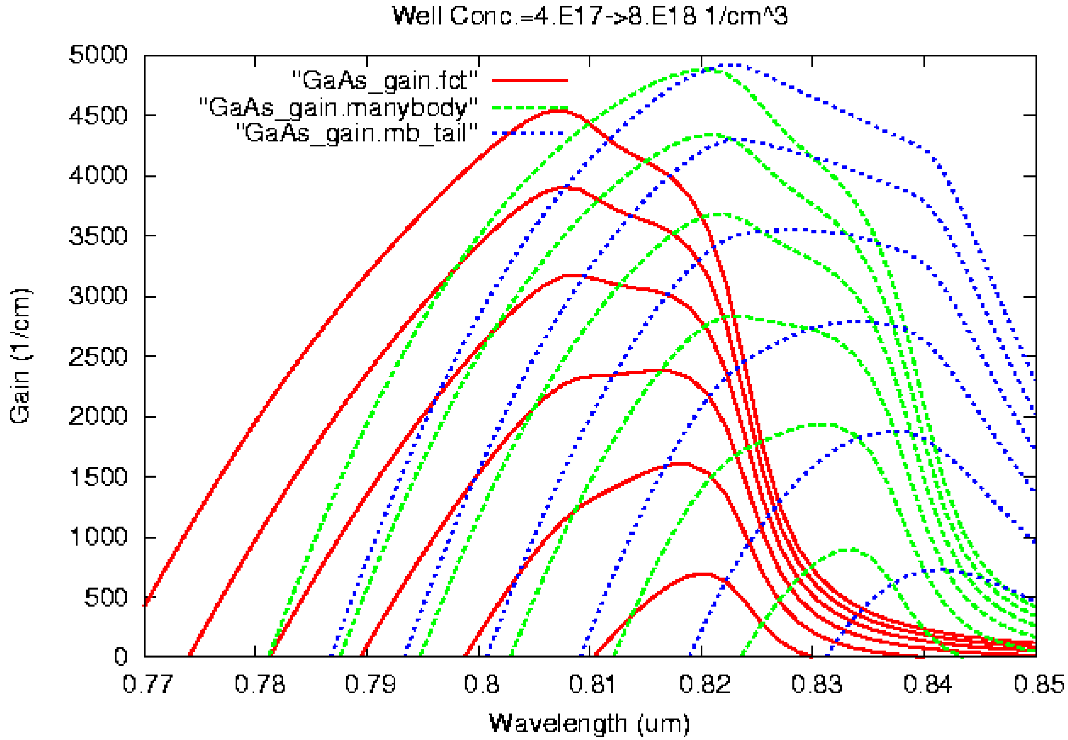
# Zoom in Positive Gain




**Coulomb enhancement (about 10%-20%) is not so strong for GaAs at high carrier density, but band-gap renormalization reduces the band-gap.**

**Many-body effects make big difference at low density gain spectra. The appearance of sharp exciton resonance is correctly predicted. 1s exciton binding energy is 18meV.**

**At high density inhomogeneous broadening shifts the gain peak to longer wave length.**

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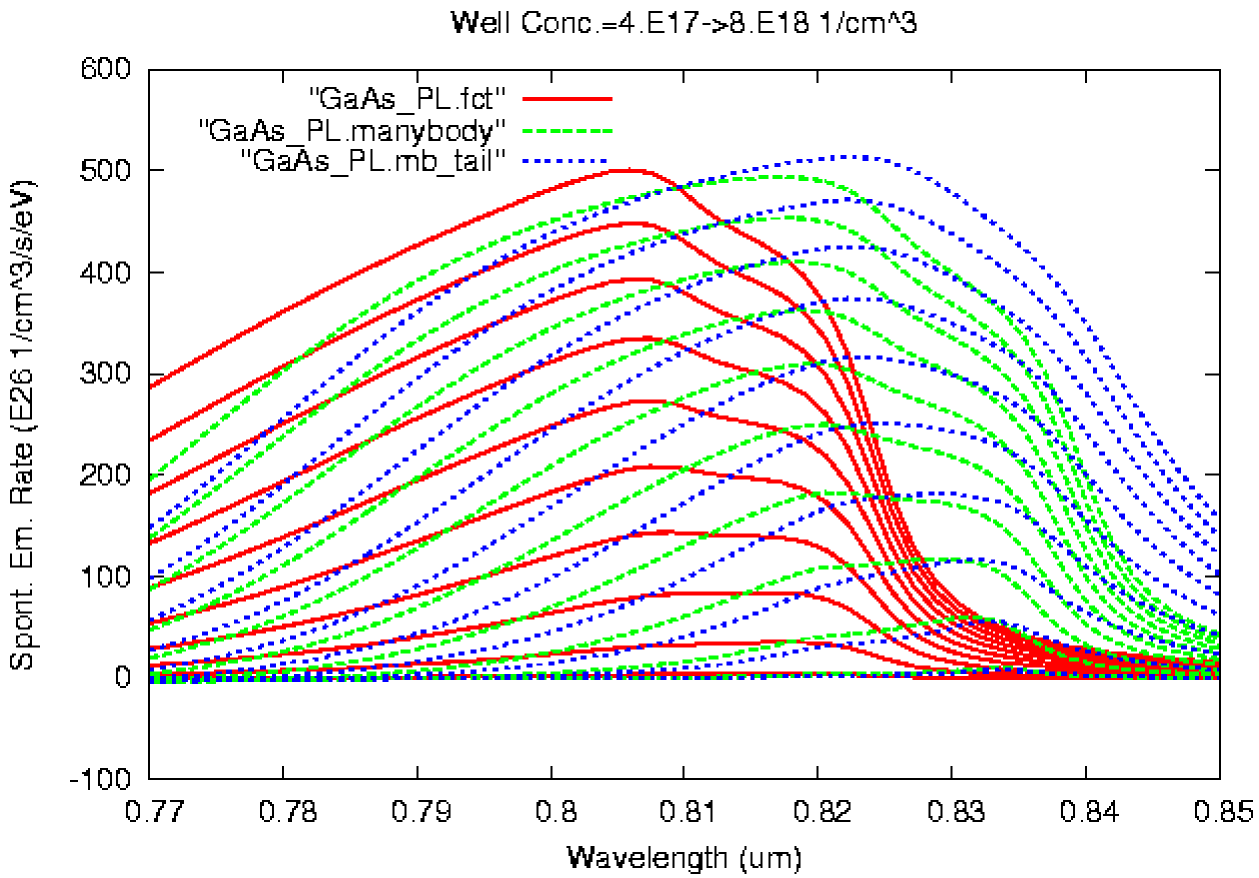
# Spontaneous emission

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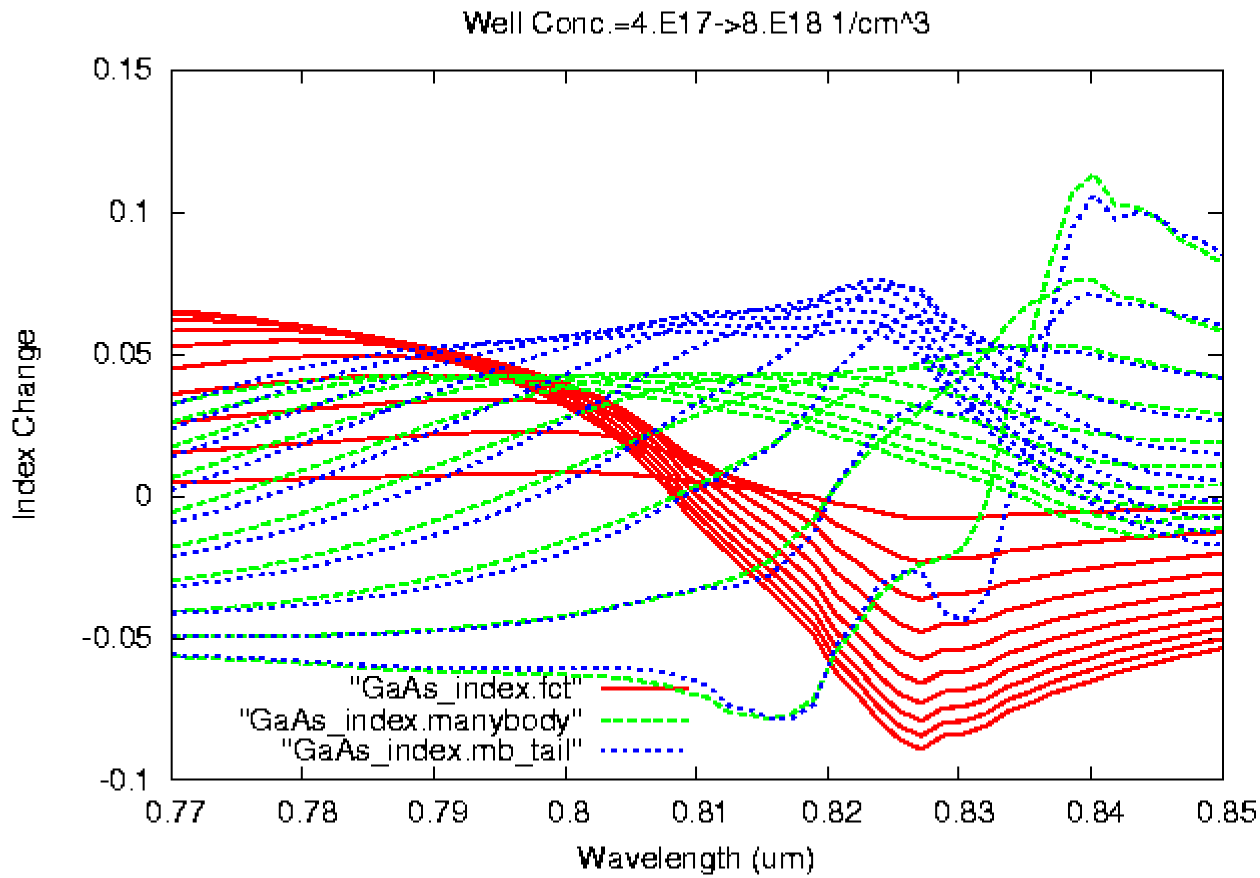
# Index change

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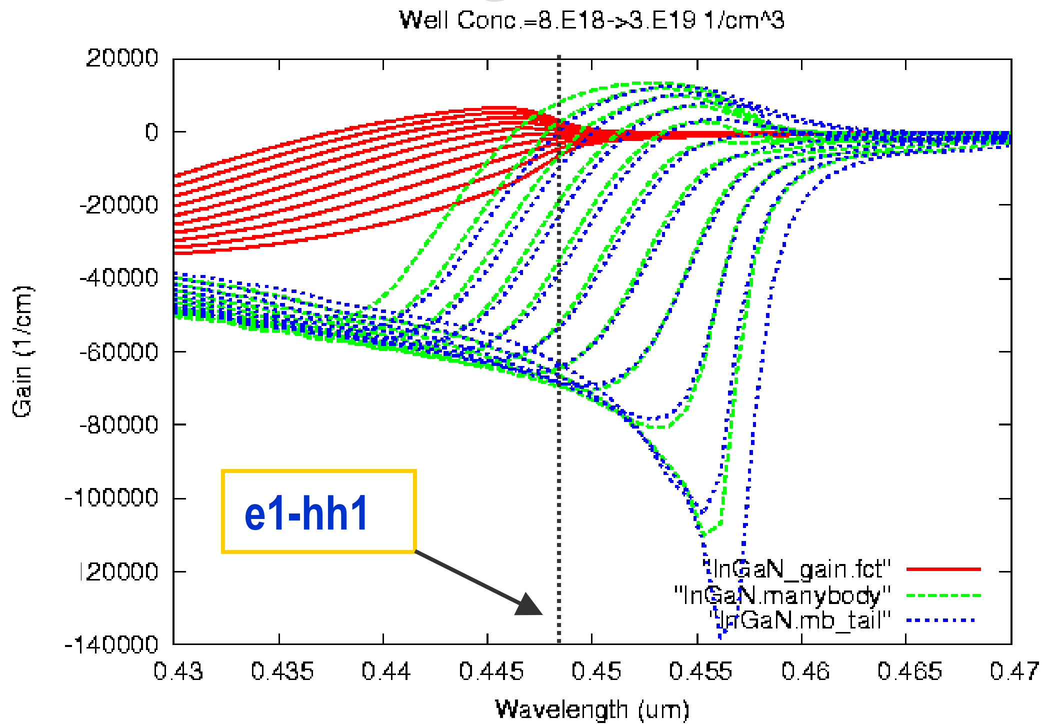
# InGaN / InGaN Quantum Well



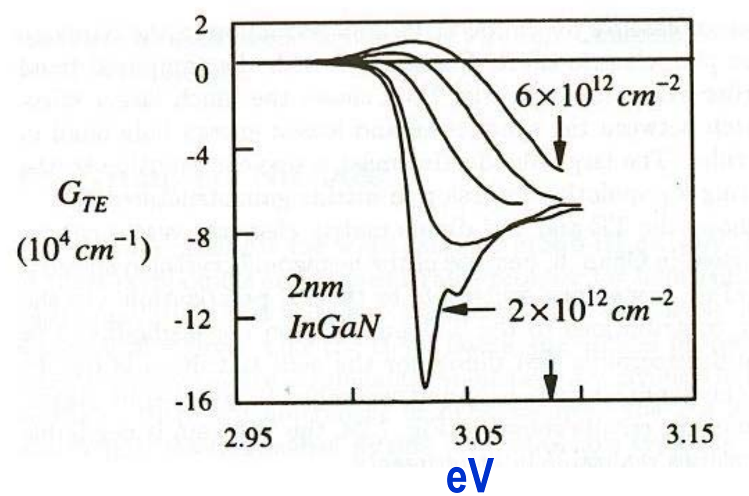

**2nm In0.2Ga0.8N/GaN**

**Fct: free carrier theory**

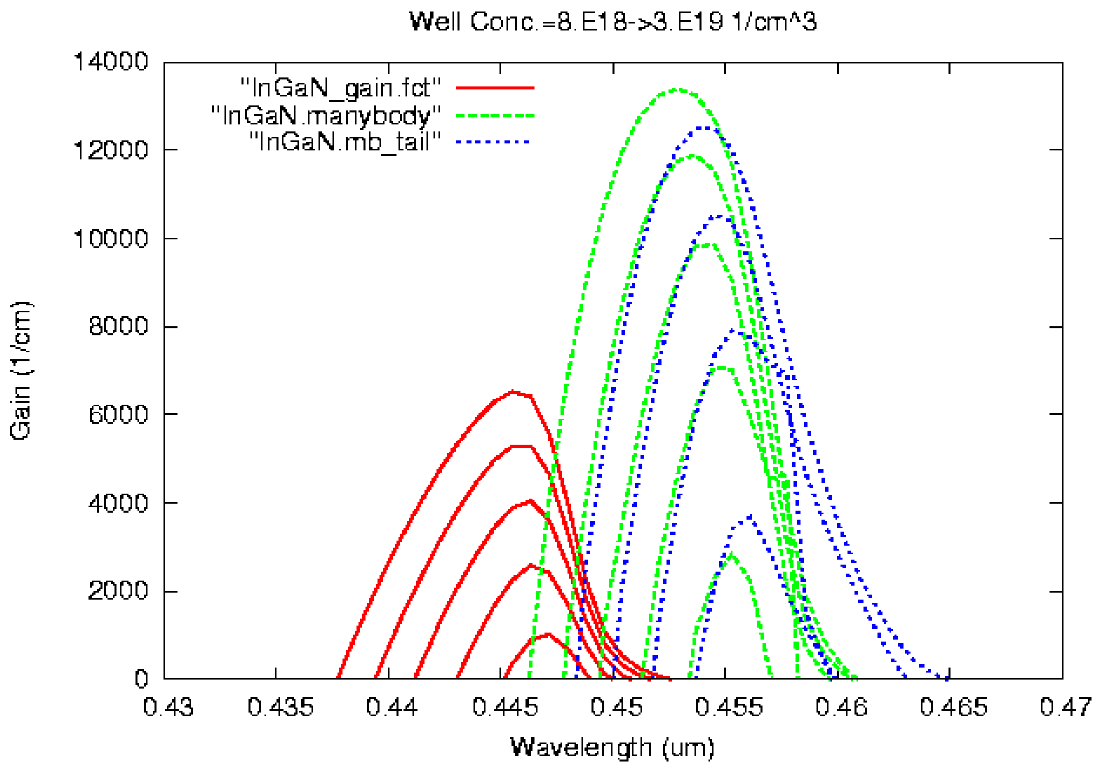
**Manybody: Coulomb**

**mb_tail: Coulomb+tail states**

**'Semiconductor Laser Fundamentals', by W.W. Chow and S.W. Koch**

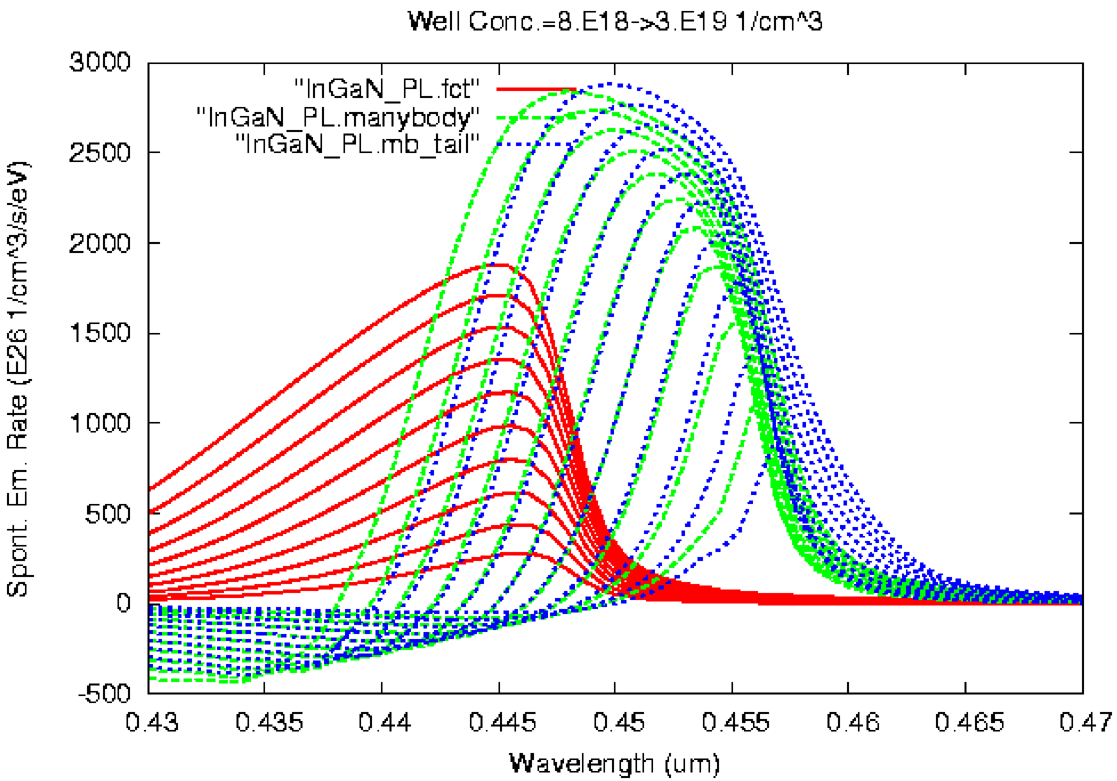


# Zoom in positive gain




**InGaN results show strong Coulomb enhancement (by a factor of 2) in the spectra and band-gap reduction. 1s exciton binding energy is about 46meV in good agreement with Chow's calculation.**

# Spontaneous emission




**Many-body simulation shows that spontaneous emission peak blue shifts with carrier density, not seen in free-carrier theory**

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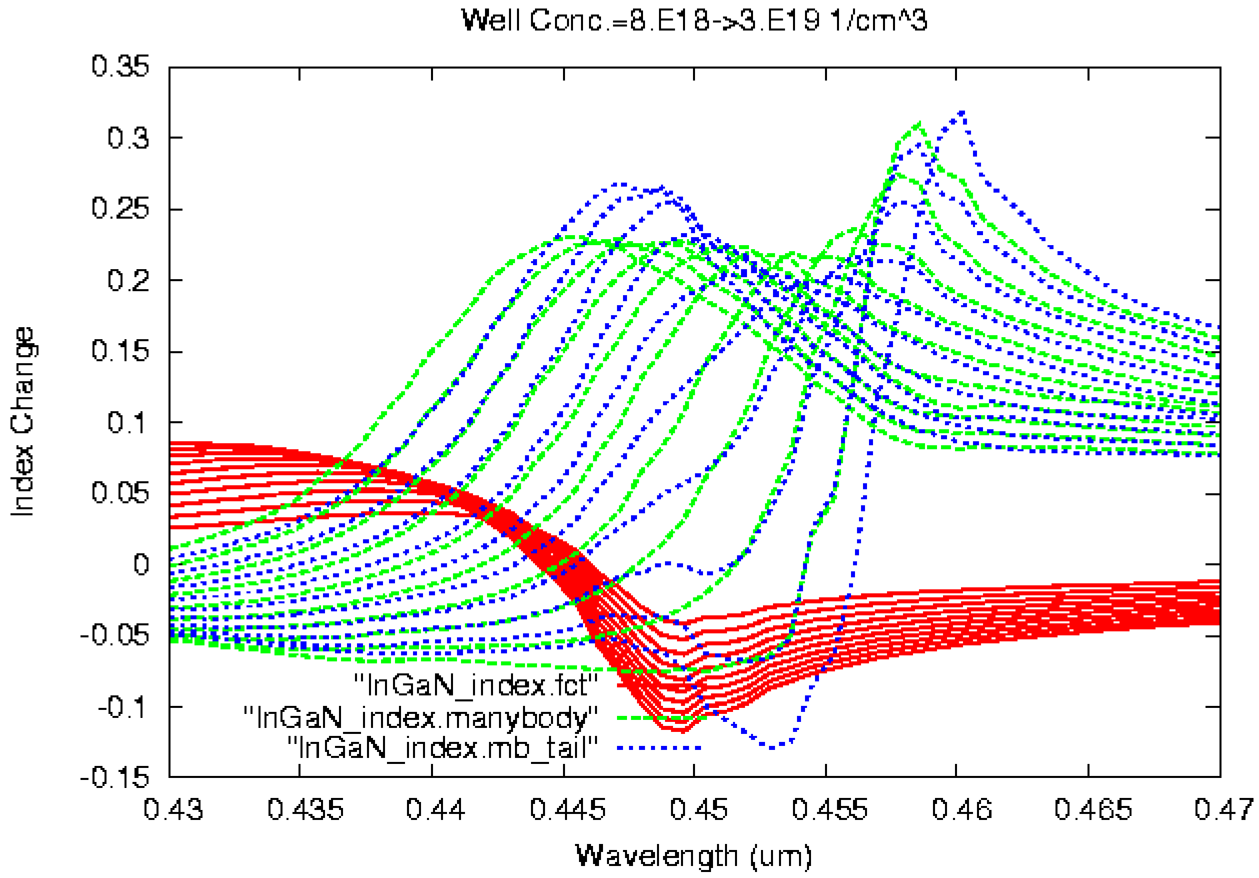
# Index change

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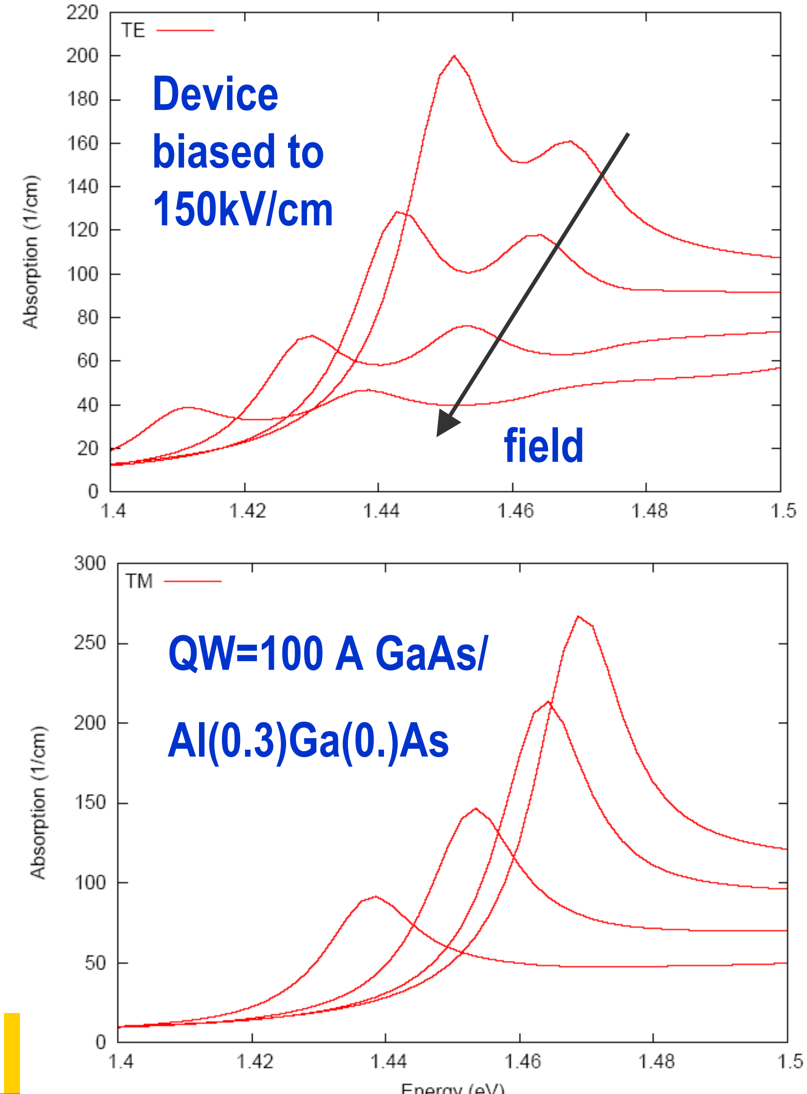
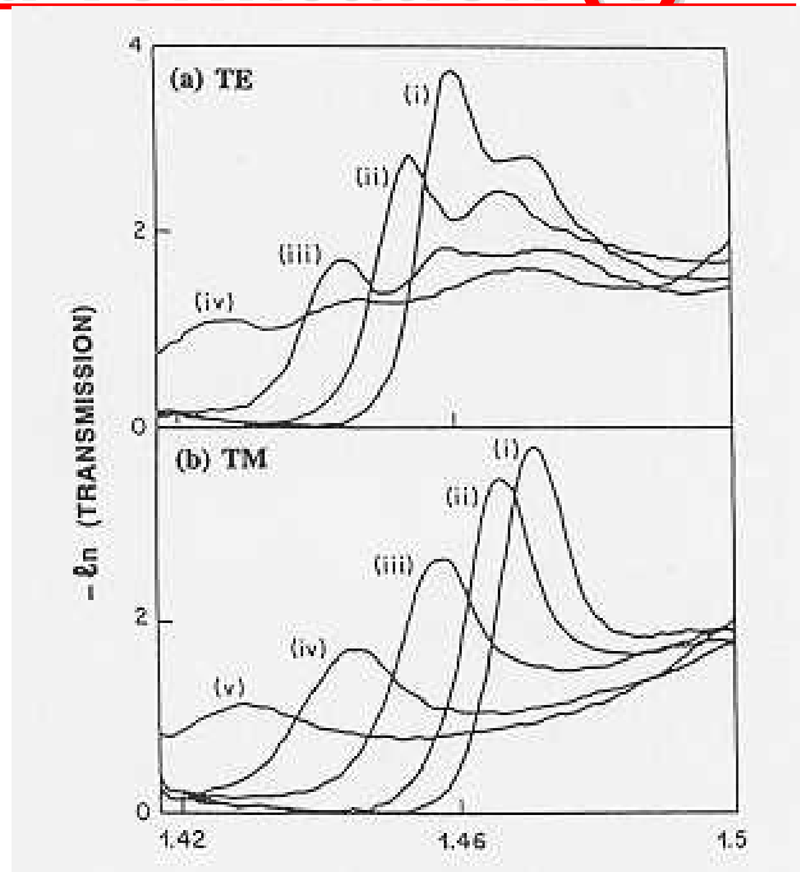
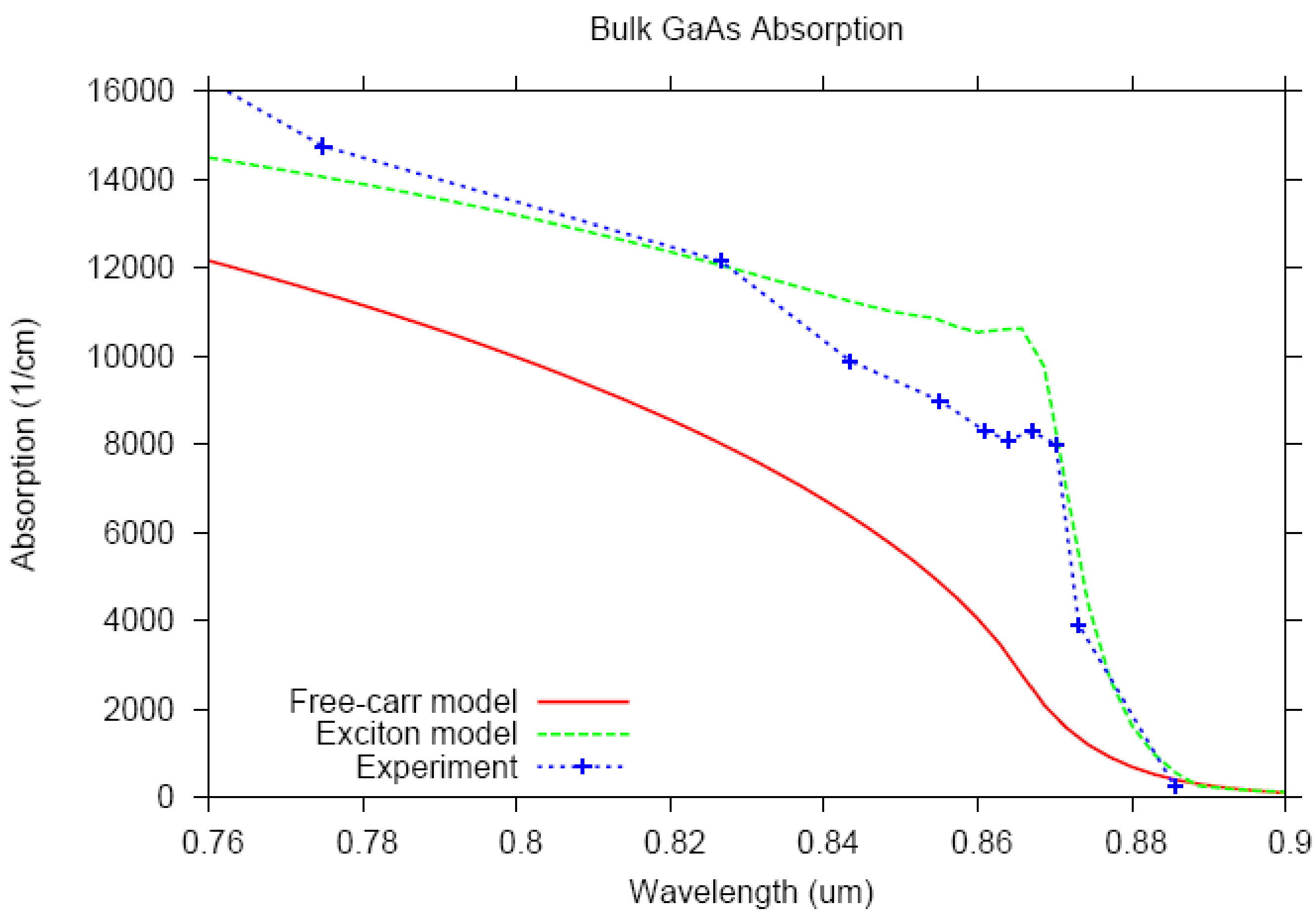
# Experimental verification (I)



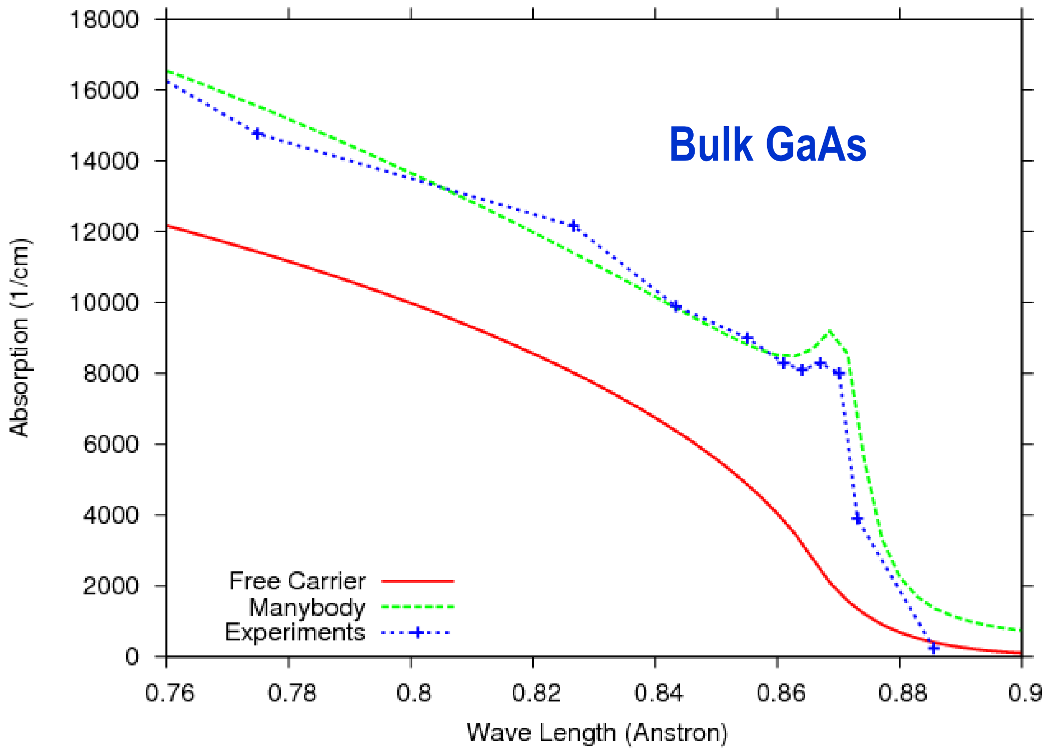

Experimental data from book of S.L Chuang, "Physics of optoelectronic devices," Wiley & Sons, 1995.

# Experimental verification (II)




**Experimental data from book of S.L Chuang, "Physics of optoelectronic devices," Wiley & Sons, 1995.**

# Experimental verification (III)




**Free-carrier theory underestimates absorption, especially near the band edge. Manybody Couloumb enhancement based on the pade approximation gives accurate results compared with experiments.**

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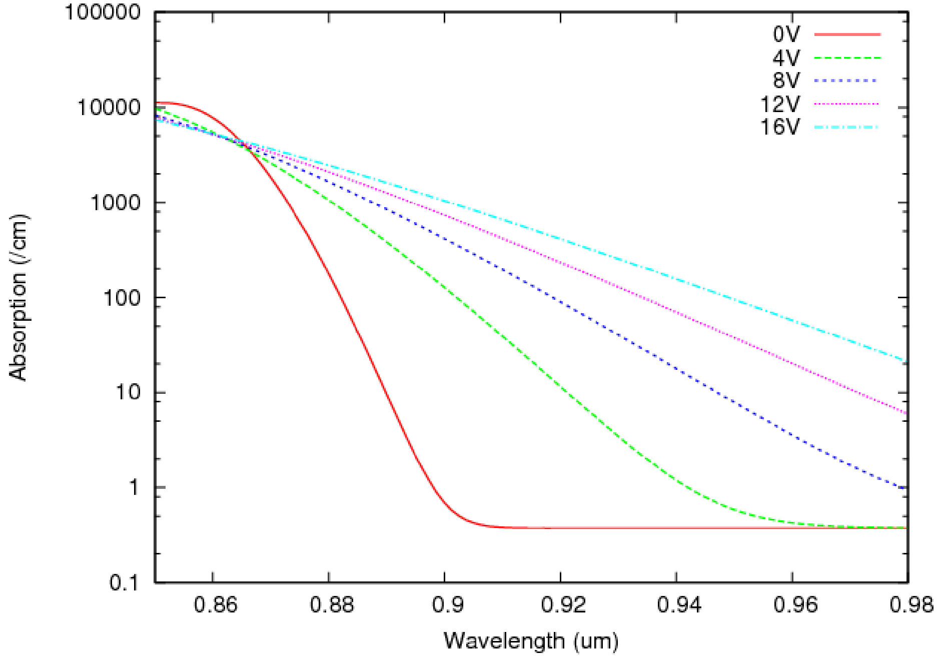
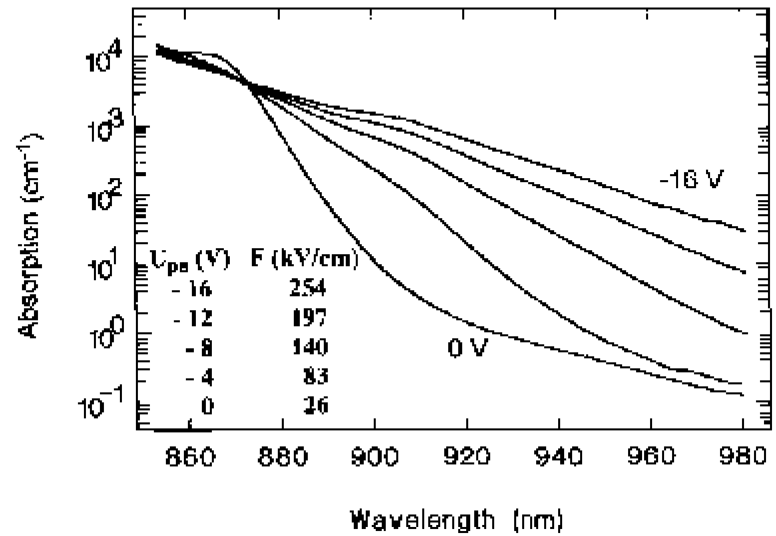
# Experimental (IV)




| $U_{pn}$ (V) | F (kV/cm) |
|---|---|
| - 16 | 254 |
| - 12 | 197 |
| - 8 | 140 |
| - 4 | 83 |
| 0 | 26 |

Fig. 1. Spectral dependence of the absorption coefficient $\alpha(\lambda)$ of the p–i–n DHS for a set of various voltages $U_{pn}$ which are shown together with the corresponding electric fields in the intrinsic region.

**Bulk GaAs/AlGaAs absorption α(V) is weighted by optical wave intensity. A dipole matrix enhancement factor from manybody calculations was used.**

# Recommendation / guidelines

- Scaling / damping parameters implemented so that MB effects can be freely suppressed to reduce to conventional free-carrier gain.
- Easy to recalibrate existing models by adjusting scaling / damping parameters.
- Slight increase in computational time may be tackled using precalculated gain tables from k.p + MB models.

# Summary

- Manybody (MB), exciton and inhomogenous broadening effects have been included in device simulators.
- Results agree with published theories and experimental data.
- Crosslight recommends new gain/absorption spectrum model to all users.