Optical Properties of Solids: Lecture 11

Stefan Zollner
New Mexico State University, Las Cruces, NM, USA
and Institute of Physics, CAS, Prague, CZR (Room 335)
zollner@nmsu.edu or zollner@fzu.cz

These lectures were supported by
- European Union, European Structural and Investment Funds (ESIF)
- Czech Ministry of Education, Youth, and Sports (MEYS), Project IOP Researchers Mobility – CZ.02.2.69/0.0/0.0/0008215

Thanks to Dr. Dejneka and his department at FZU.

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

http://ellipsometry.nmsu.edu

NSF: DMR-1505172

Optical Properties of Solids: Lecture 11

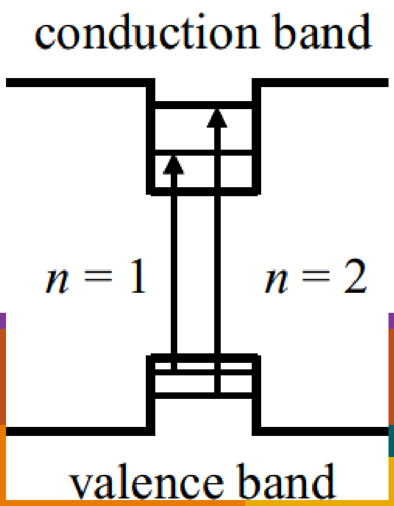
Emission of photons

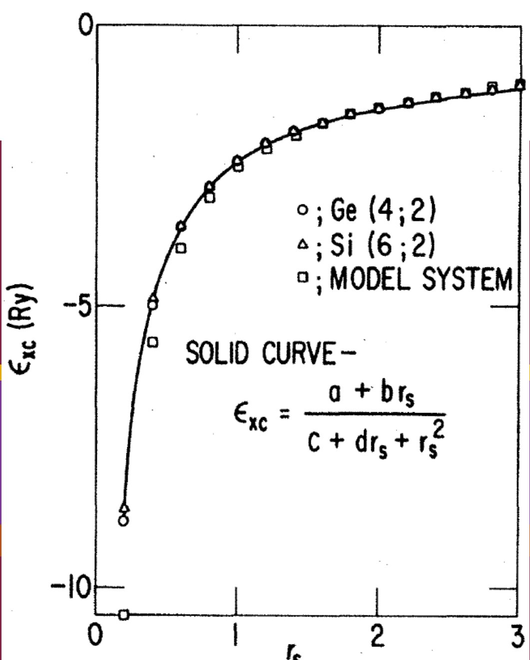
Photoluminescence

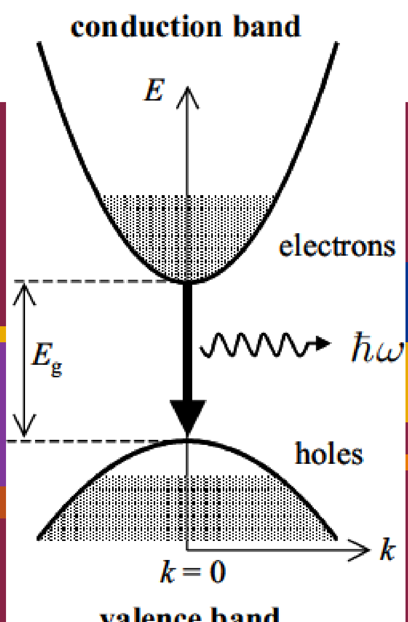
Electro-, cathodoluminescence

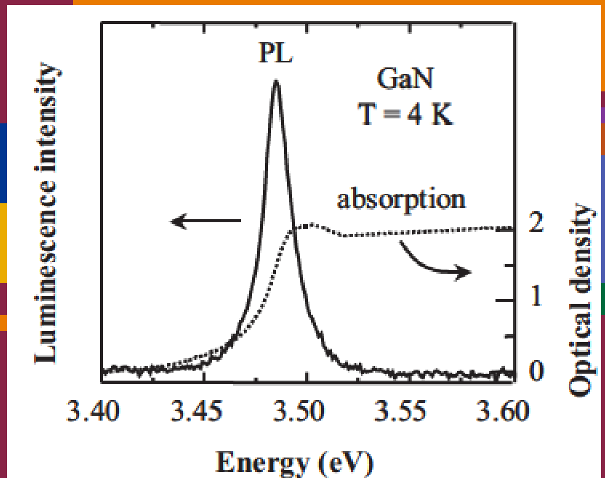
Quantum structures: wells, wires, dots

Absorption and emission of quantum wells









References: Band Structure and Optical Properties

Solid-State Theory and Semiconductor Band Structures:

- Mark Fox, Optical Properties of Solids (5+6)
- Ashcroft and Mermin, Solid-State Physics
- Yu and Cardona, Fundamentals of Semiconductors
- Dresselhaus/Dresselhaus/Cronin/Gomes, Solid State Properties
- Cohen and Chelikowsky, Electronic Structure and Optical Properties
- Klingshirn, Semiconductor Optics
- Grundmann, Physics of Semiconductors
- Ioffe Institute web site: NSM Archive
  http://www.ioffe.ru/SVA/NSM/Semicond/index.html

Outline

Photoluminescence

Electroluminescence, cathodoluminescence

Experimental techniques

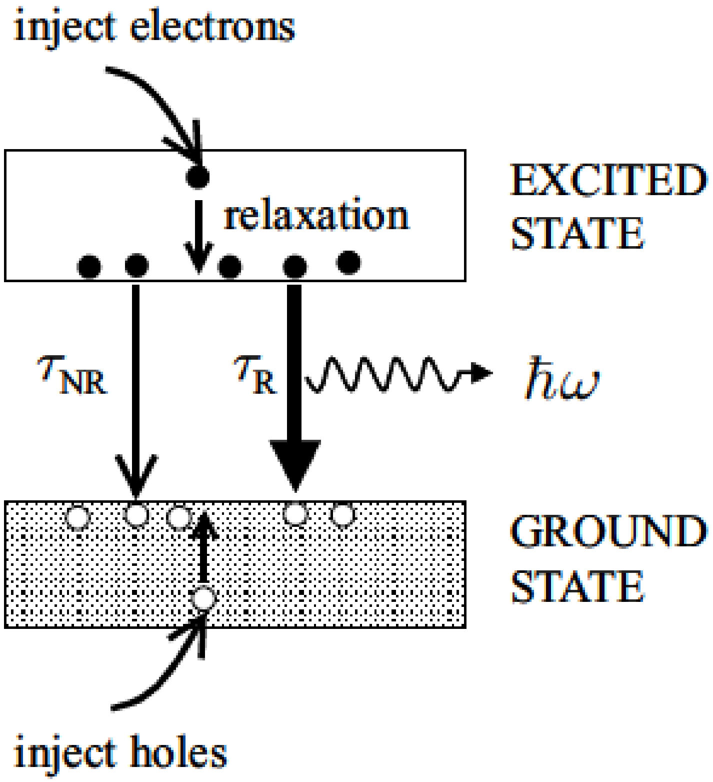
Hot carrier and high density effects

Quantum confinement and Heisenberg uncertainty principle

Growth of quantum structures

Electronic states, quantum well absorption and emission

Intersubband transitions



Light emission

- **Photoluminescence**
- **Electroluminescence**
- **Cathodoluminescence**
- **Etc**

PL Efficiency $\eta_R = \frac{1}{1 + {\tau_R}/{\tau_{NR}}}$

$$\left(\frac{dN}{dt}\right)_{\text{radiative}} = -AN$$

$$\left(\frac{dN}{dt}\right)_{\text{total}} = -N\left(\frac{1}{\tau_R} + \frac{1}{\tau_{NR}}\right)$$

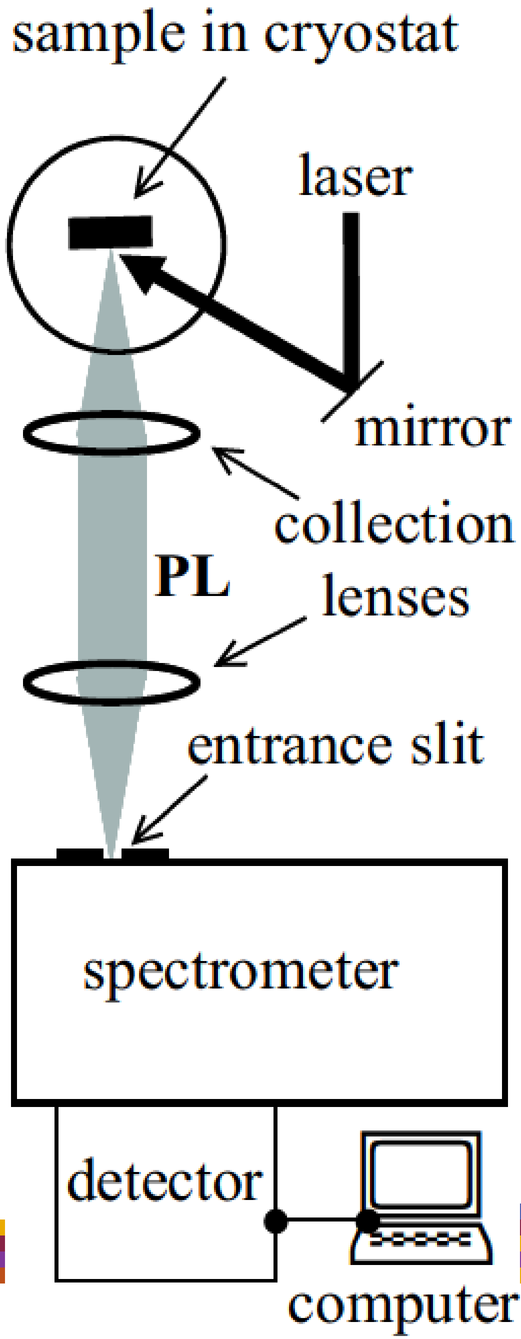
Einstein coefficient A
Radiative lifetime $\tau_R = A^{-1}$

Radiative and non-radiative recombination compete.

Spontaneous emission

Fox, Chapter 5

Photoluminescence experiments



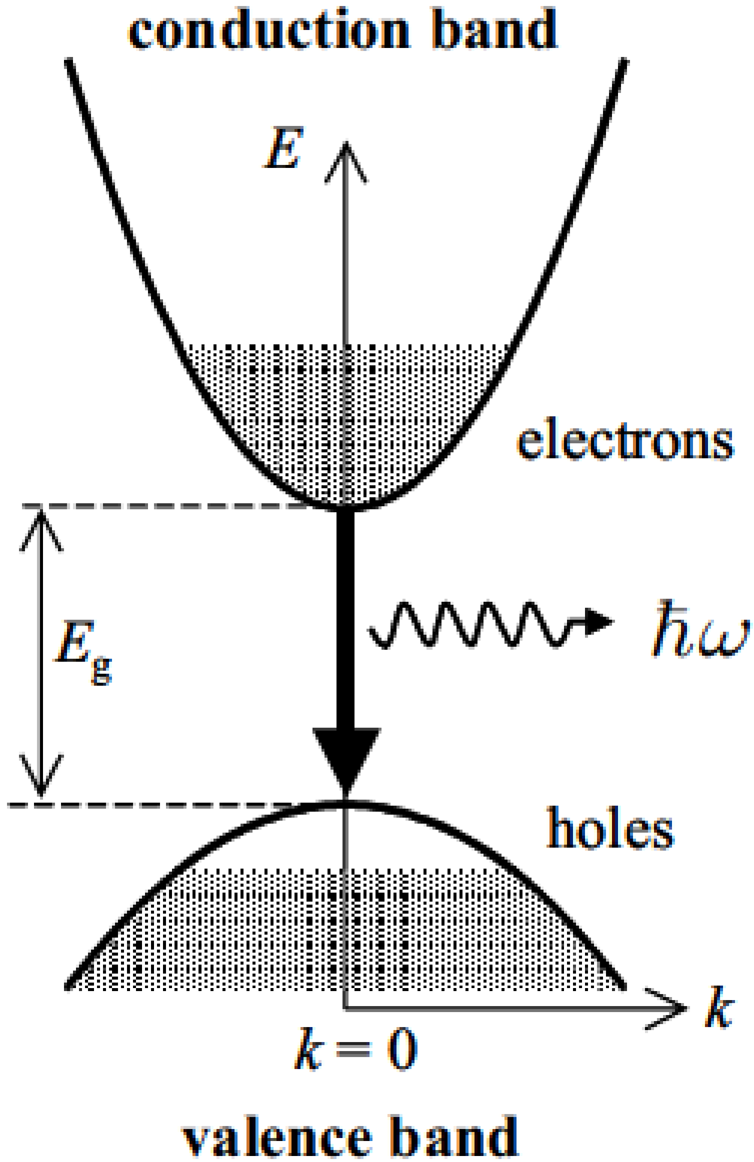
- •Laser excitation: IR to VIS to UV (a few mW)
- •CW or ultrafast (ns, ps, fs) lasers
- •Mirrors, windows, lenses optimized for incidence and emitted light.
- •Filters, apertures to reject unwanted light.
- •Polarization control (selection rules)

- •Grating or prism monochromator
- •CCD or photomultiplier detector
- •Software control for readout.

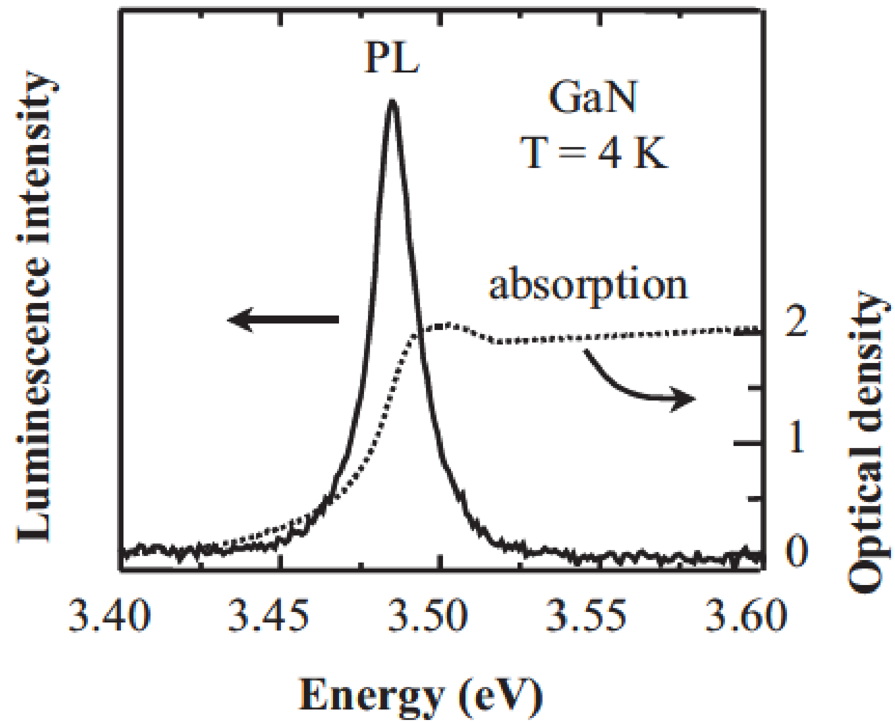
- •Cryostat from 1 to 1000 K.
- •Low count rates: Absolute darkness.

Fox, Chapter 5

Interband photoluminescence



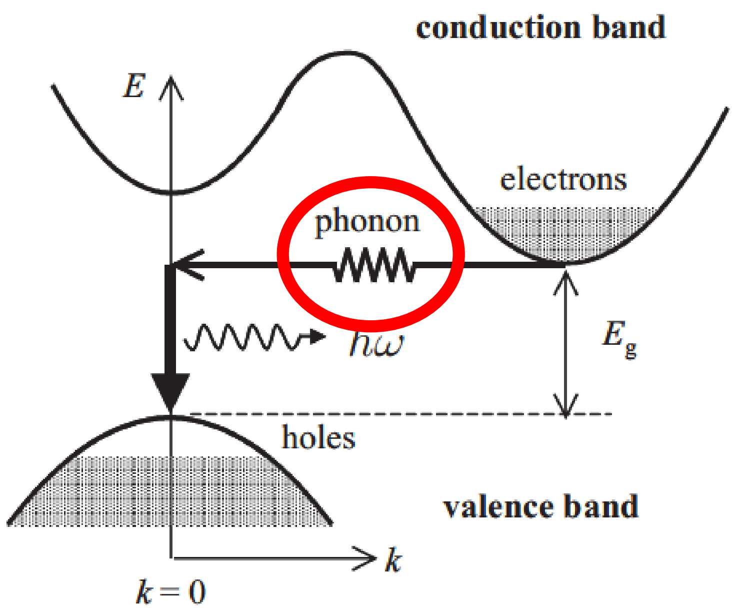
Direct semiconductor
Electron-hole recombination

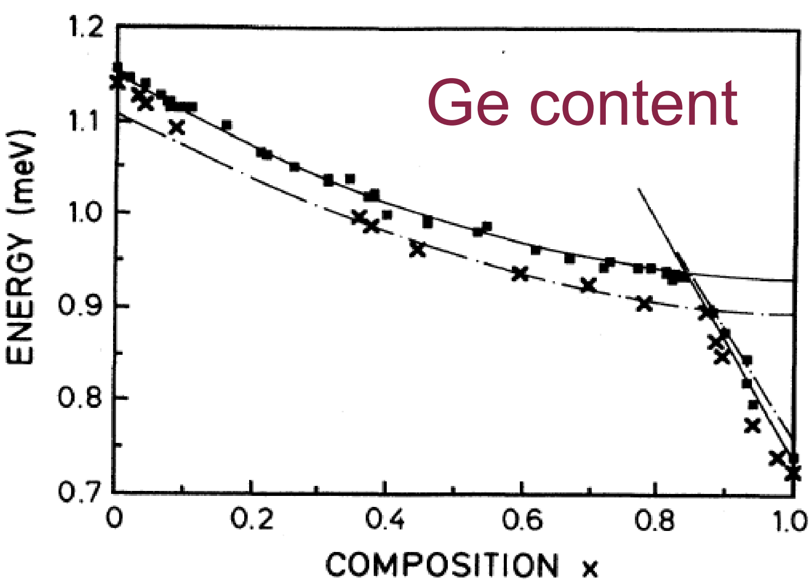


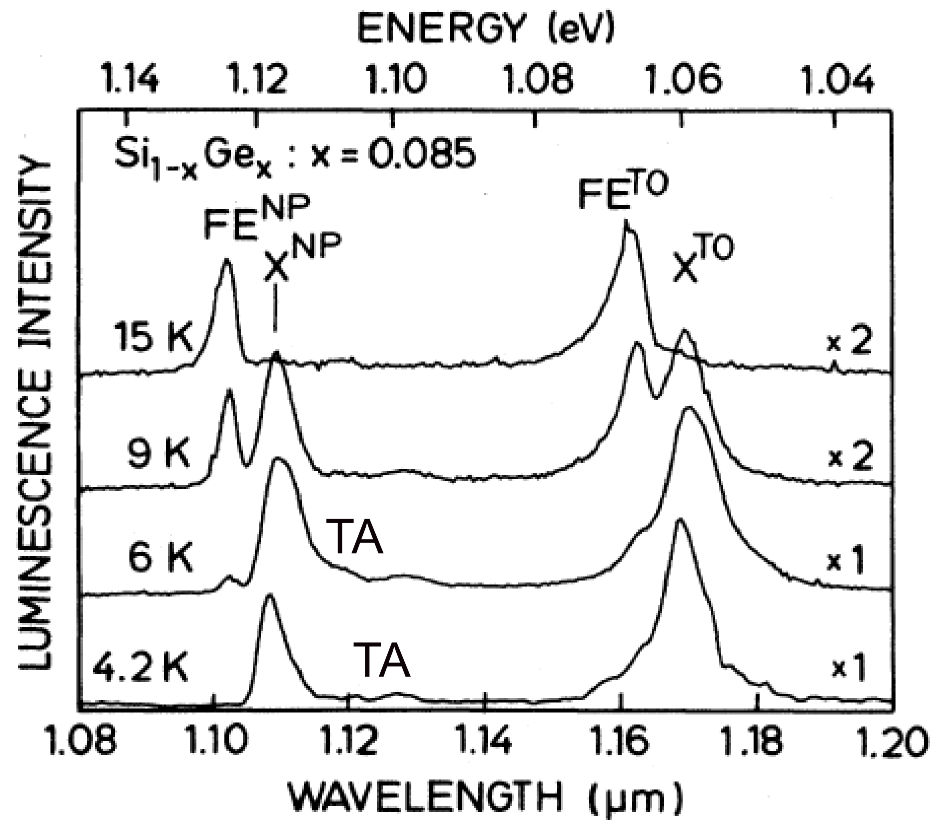
Shift between emission and absorption

Fox, Chapter 5

Indirect photoluminescence in Si-Ge alloys



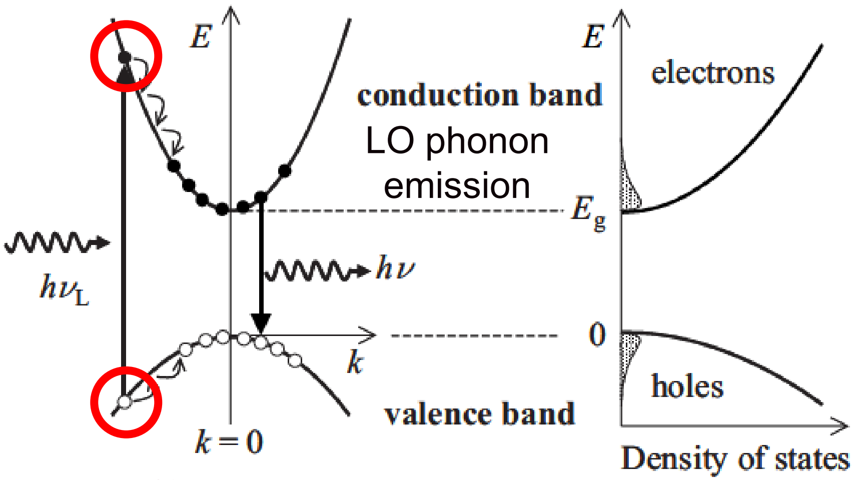


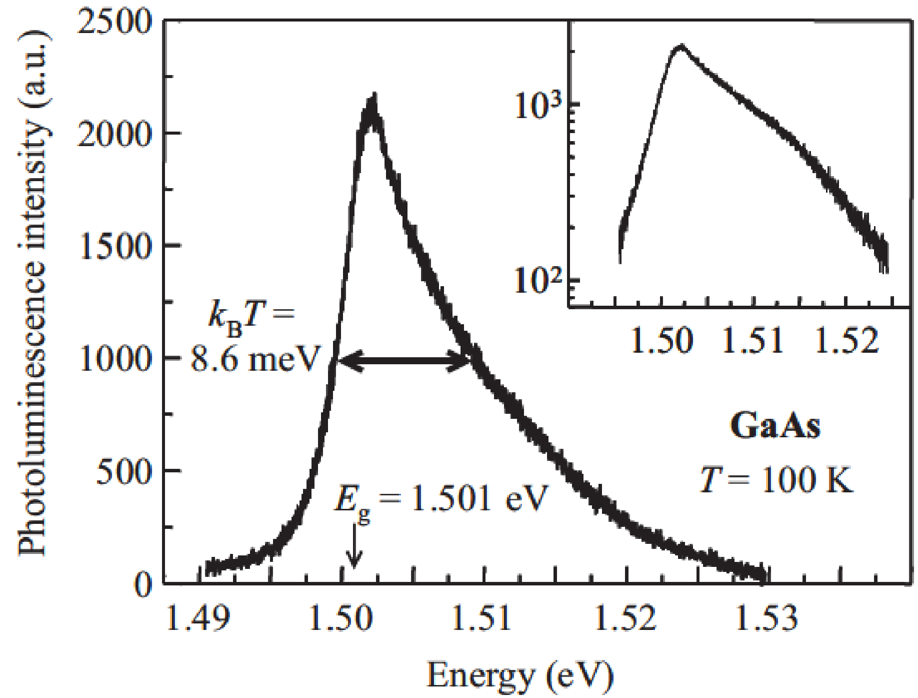


Free (FE) and bound exciton (X)
No-phonon lines and TA/TO replica

Fox, Chapter 5
Weber & Alonso, Phys. Rev. B **40**, 5683 (1989)

Relaxation and carrier temperature





$$N_e = \int_{E_g}^{\infty} g_c(E) f_e(E)\, dE$$

$$g_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{\frac{3}{2}} \sqrt{E - E_g}$$

$$N_e = \int_0^{\infty} \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{\frac{3}{2}} \sqrt{E}\left[\exp\left(\frac{E - E_F^c}{k_B T}\right) + 1\right]^{-1}$$

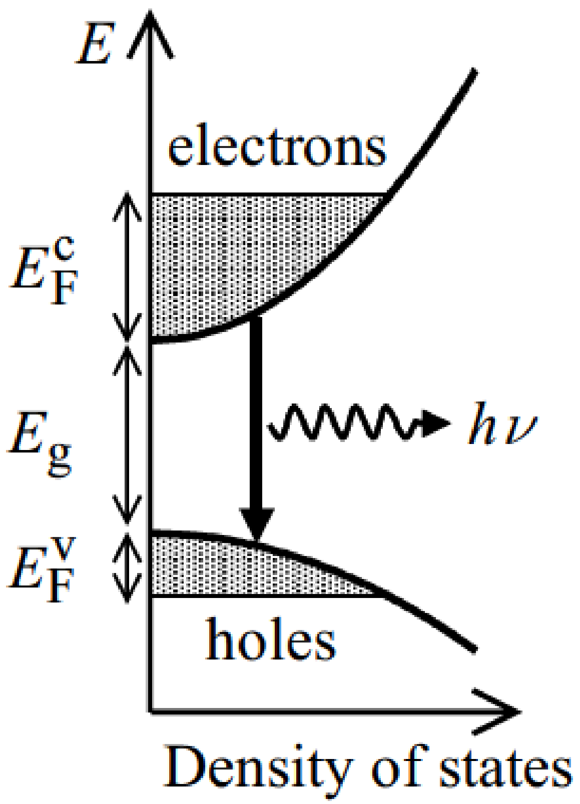
Similar expression for holes

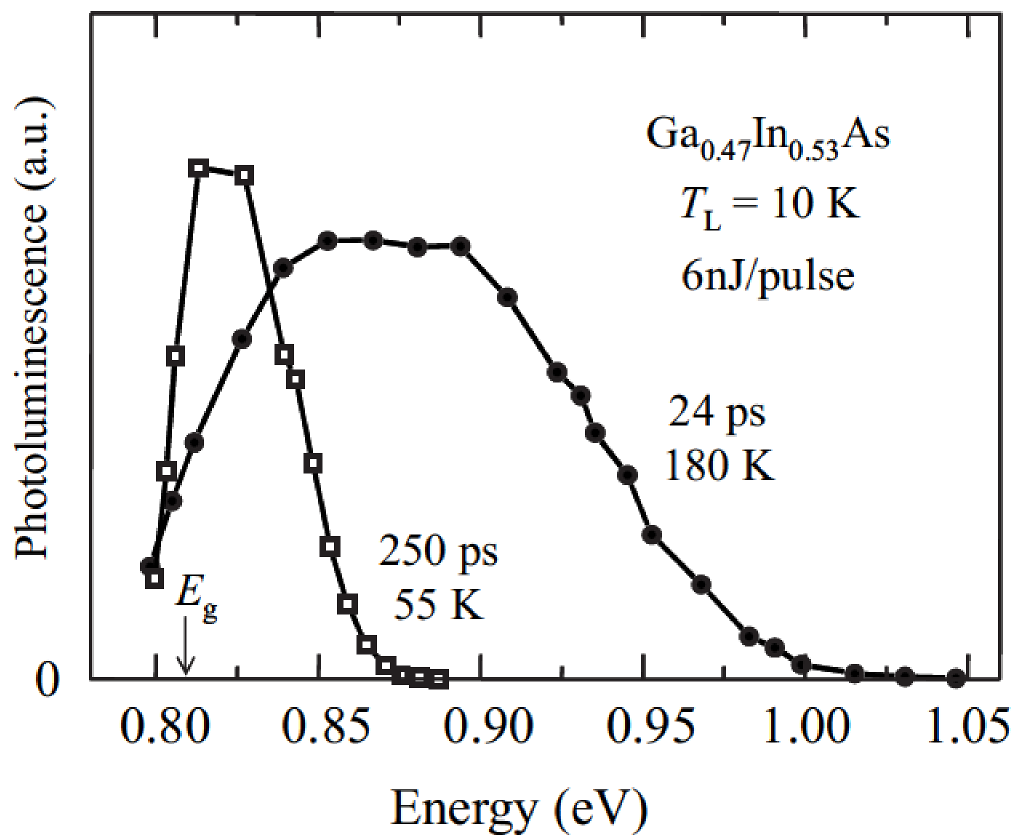
Low carrier density, high T:
Boltzmann statistics

$$I(E) = \sqrt{E - E_g}\,\exp\left(-\frac{E - E_g}{k_B T}\right)$$

Fox, Chapter 5

High carrier density: band filling





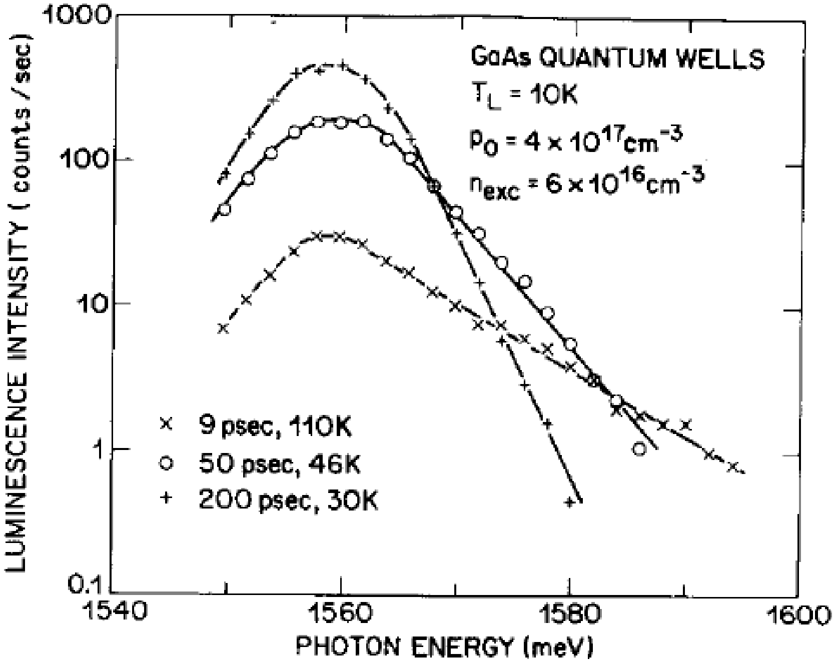
High carrier density, low T:
Quasi-Fermi levels for electrons and holes

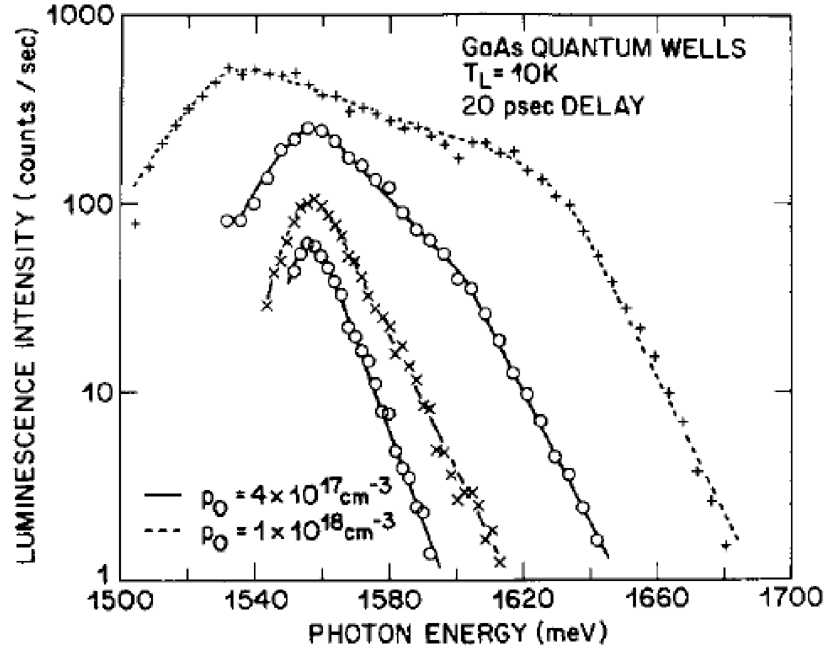
$$E_F^{c,v} = \frac{\hbar^2}{2m_{e,v}^*}\left(3\pi^2 N_{e,h}\right)^{\frac{2}{3}}$$

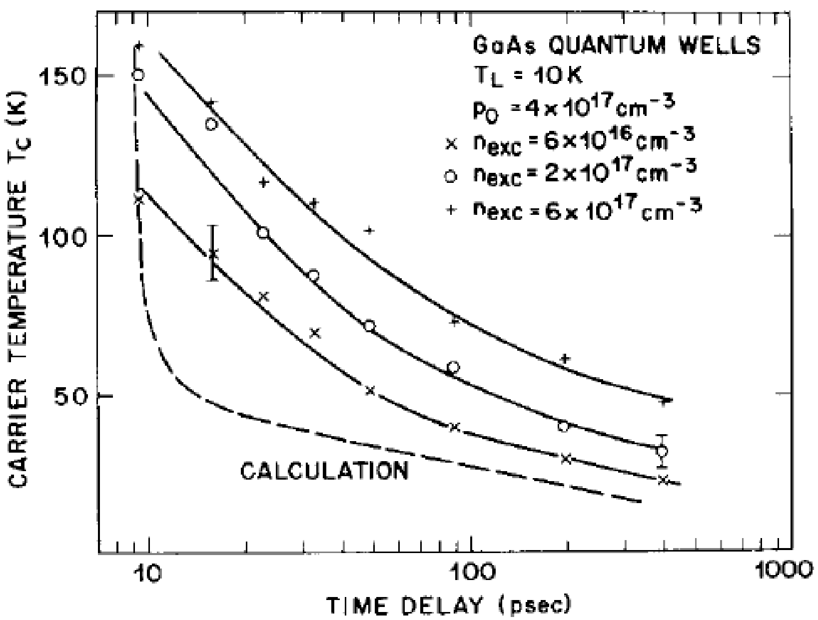
Fox, Chapter 5
S. Zollner, Diploma thesis (Stuttgart)

NM STATE

Carrier cooling and band filling in GaAs QW







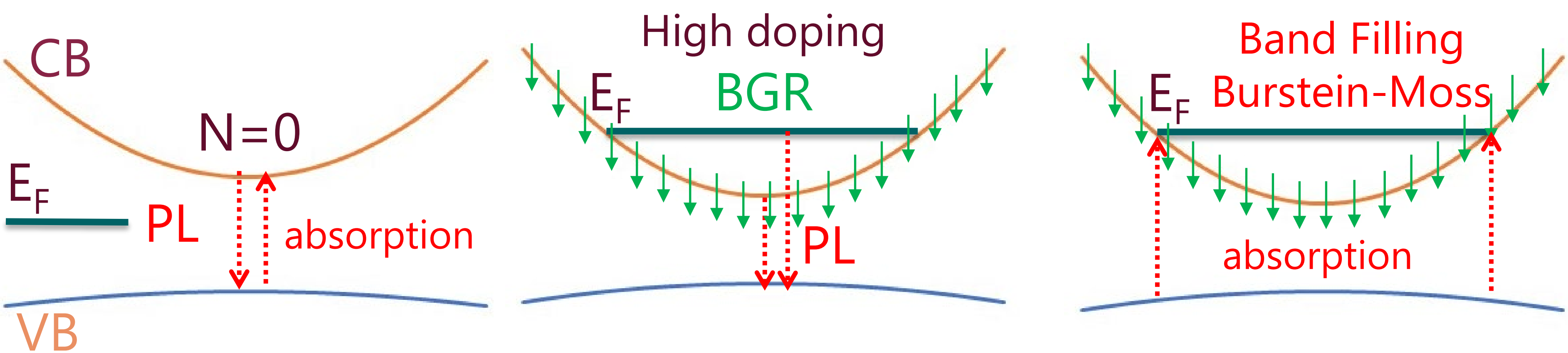
Carrier temperature versus time:

Carrier cooling much slower than expected due to nonequilibrium LO phonons.

Fox, Chapter 5
Kash & Shah, 1985

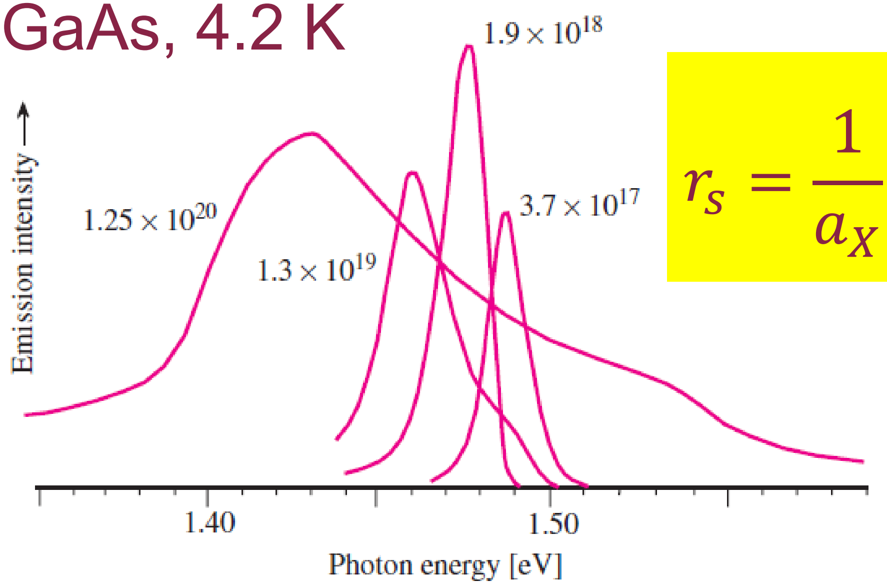
High carrier density: band filling

- **Band gap renormalization** (BGR)
  - Band gap is lowered at high carrier density **(redshift)**
  - Measurable with photoluminescence
- **Band filling** or **Pauli blocking**
  - Band filling affects absorption measurements **(blueshift)**
- **Burstein-Moss shift**
  - Absorption threshold affected by both BGR and band filling
- **Mott transition:** Individual excitons versus electron-hole liquid (EHL) at $r_s \sim 5$.

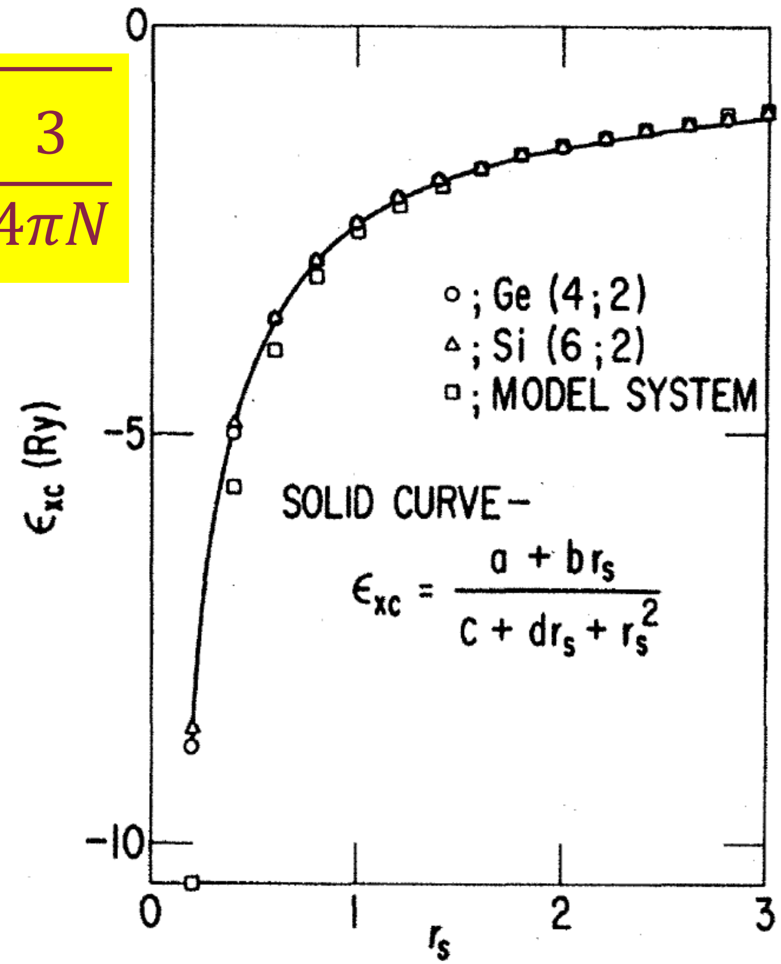


Band gap renormalization

GaAs, 4.2 K



$$r_s = \frac{1}{a_X}\sqrt[3]{\frac{3}{4\pi N}}$$

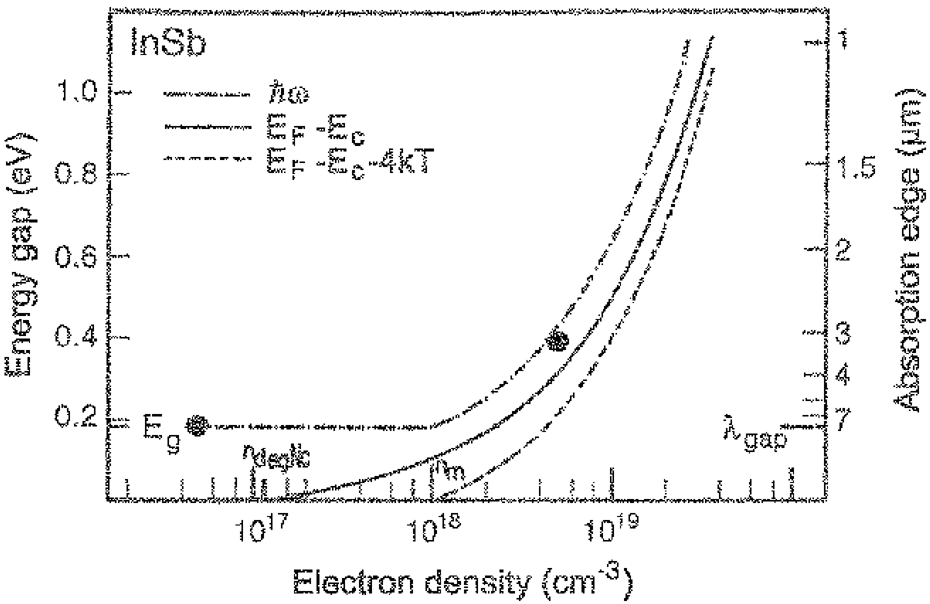


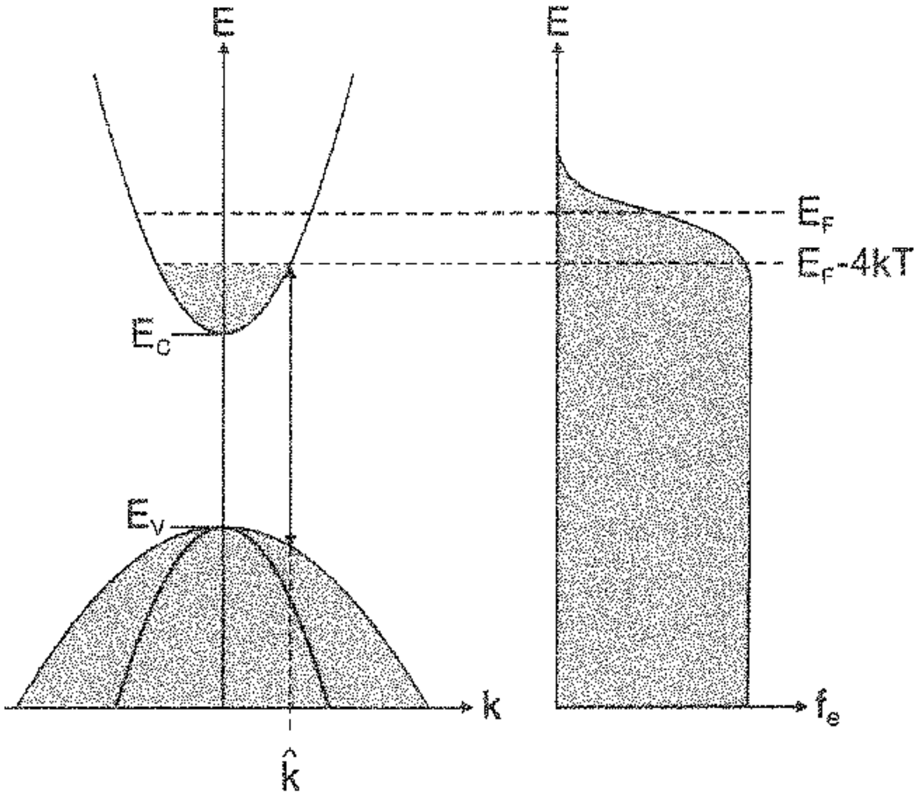
Band gap shrinks with increasing carrier concentration.

$$\Delta E_g(n,T) = -\frac{3.24 r_s^{-3/4}}{\left[1 + 0.0478 r_s^3 \mathcal{T}^2\right]^{1/4}}$$

Yu & Cardona
Vashista & Kalia, PRB **25**, 6492 (1982)
Zimmerman, PSSB **146**, 371 (1988)

Burstein-Moss shift: n-type InSb



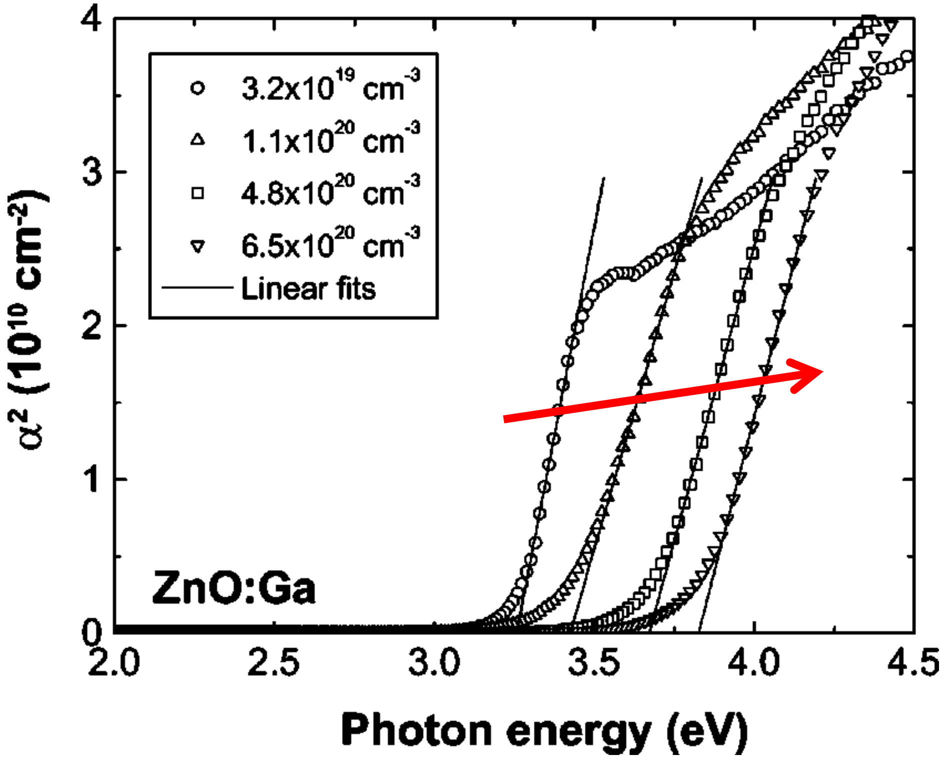


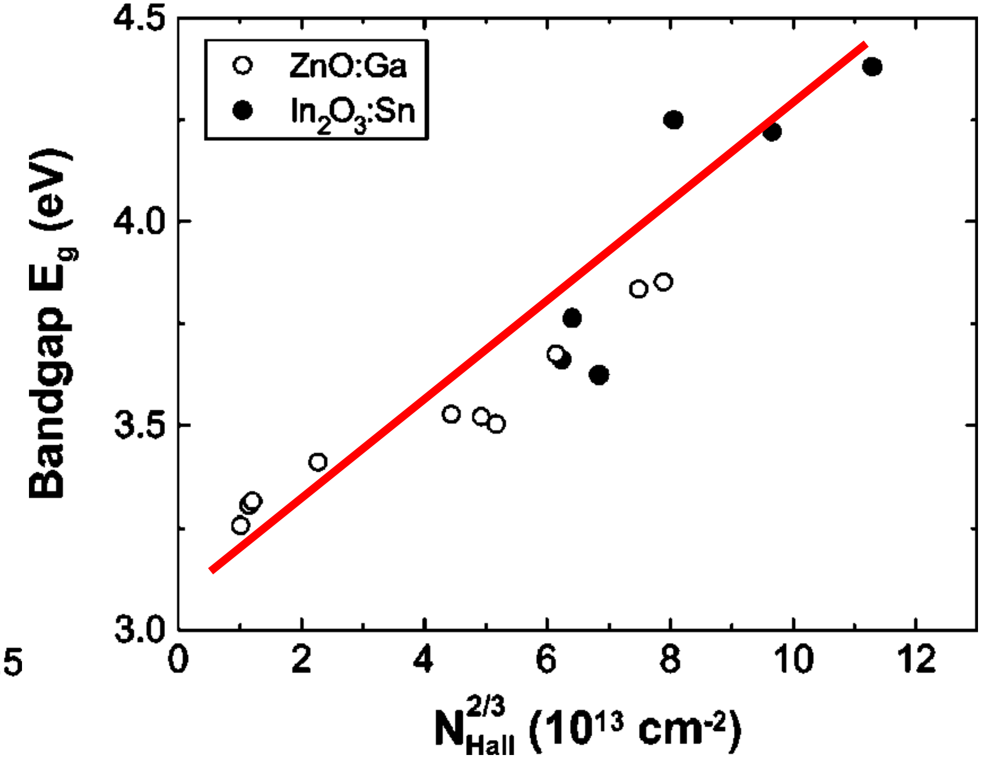
Absorption threshold (band gap) increases, because CB bottom is filled with electrons (Pauli blocking).

$$\Delta E = (E_F - 4kT - E_{CB})\left(1 + \frac{m_e}{m_h}\right) \approx \frac{h^2}{8m_r} n^{2/3}$$

E. Burstein, PR **93**, 632 (1954)
T.S. Moss, Proc. Phys. Soc. B **67**, 775 (1954)
M. Grundmann, Physics of Semiconductors

Burstein-Moss shift in ZnO and ITO



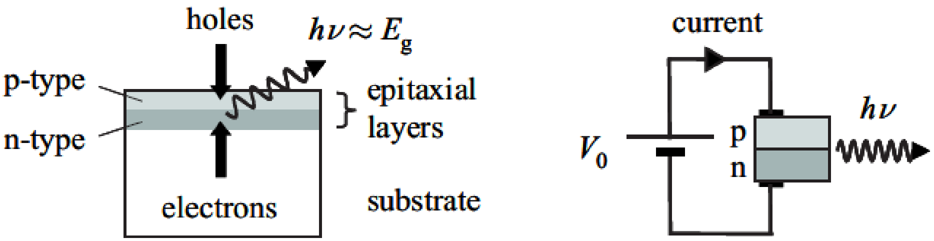


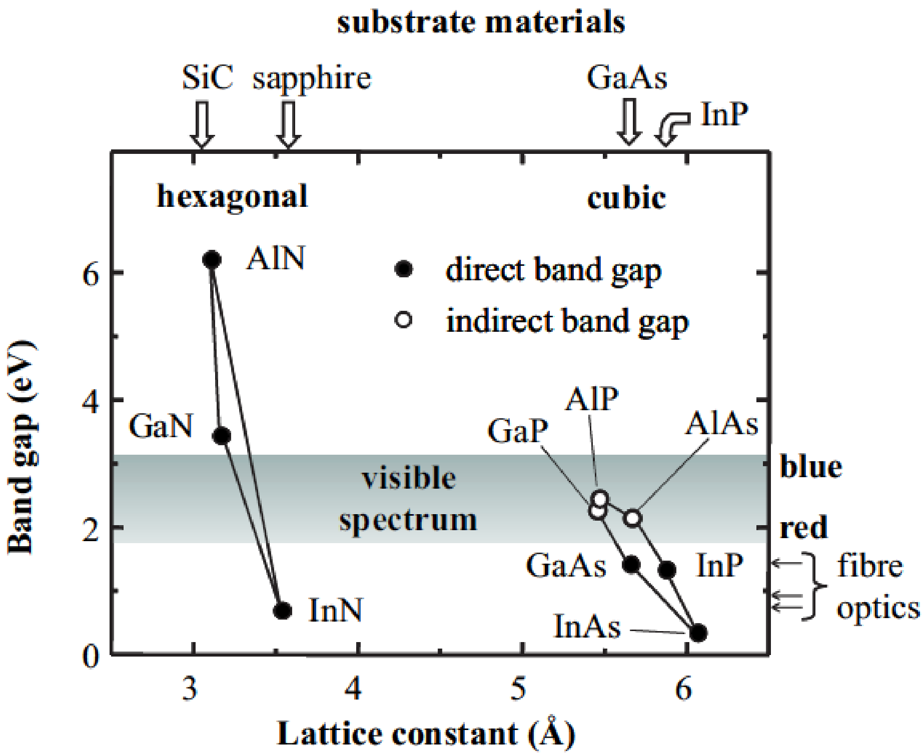
Band gap **increases** with increasing dopant concentration.
Band gap renormalization (decrease) PLUS band filling (increase).
Shift is proportional to $n^{2/3}$ (many-body effect).

Fujiwara, Phys. Rev. B **71**, 075109 (2005)

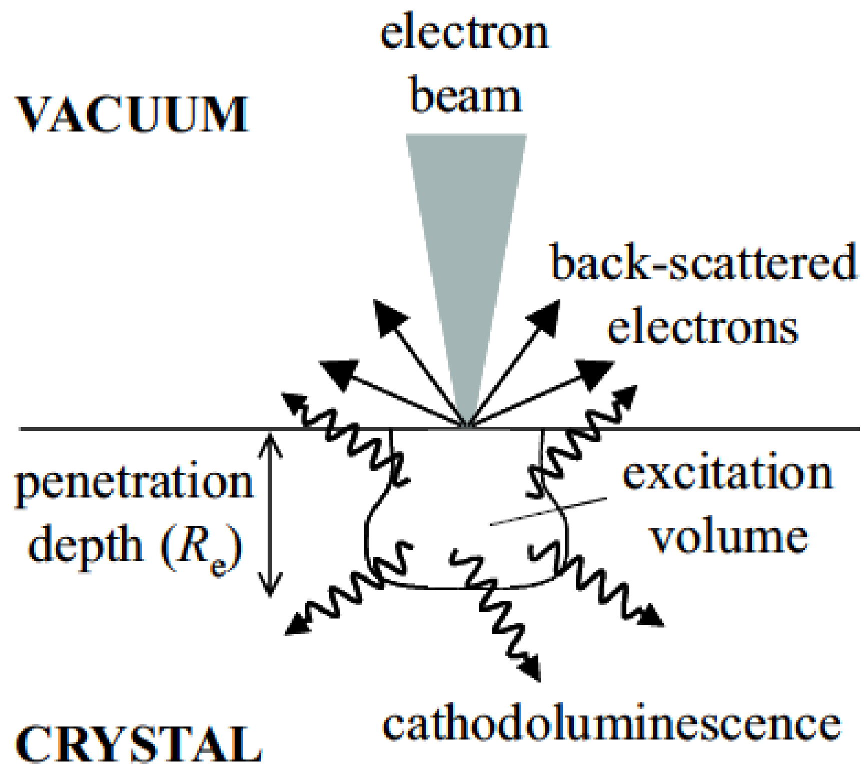
NM STATE

Electroluminescence





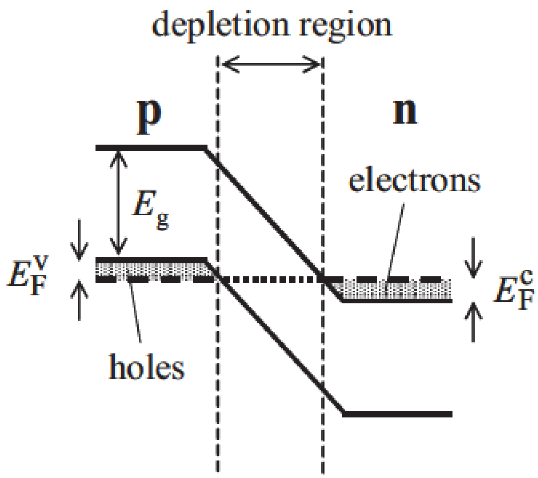
Cathodoluminescence



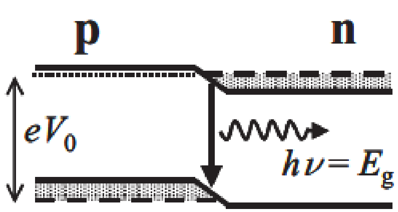
Defects (dislocations) in wide-gap materials: GaN or $SrTiO_3$.

Fox, Chapter 5

Semiconductor lasers

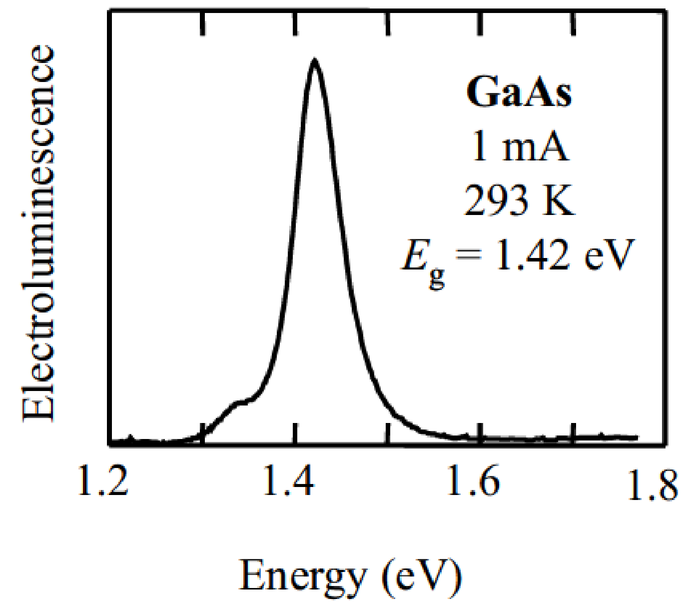


(a) $V_0 = 0$

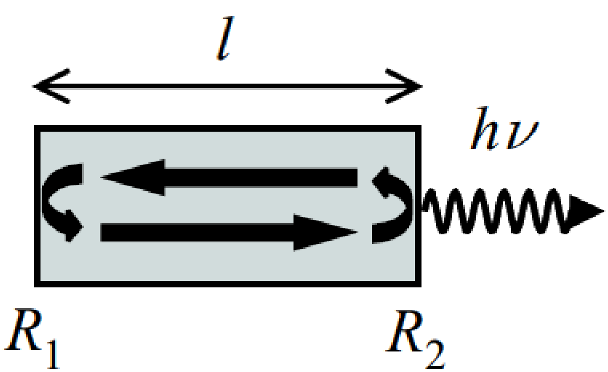


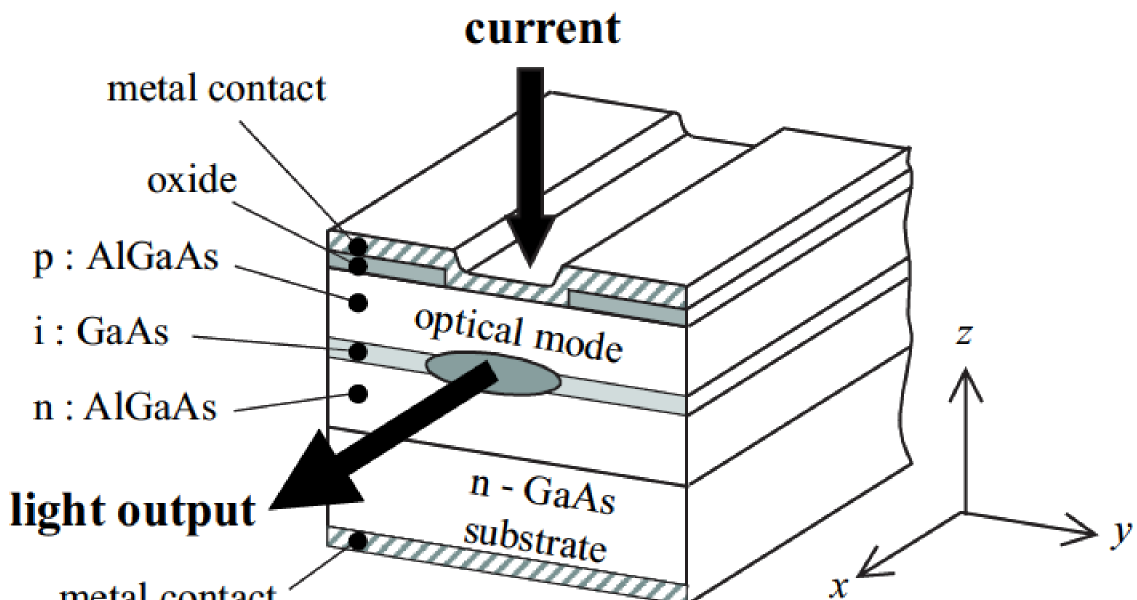
Applied voltage (flat bands)

(b) $V_0 \approx +E_g/e$



Fermi levels line up.



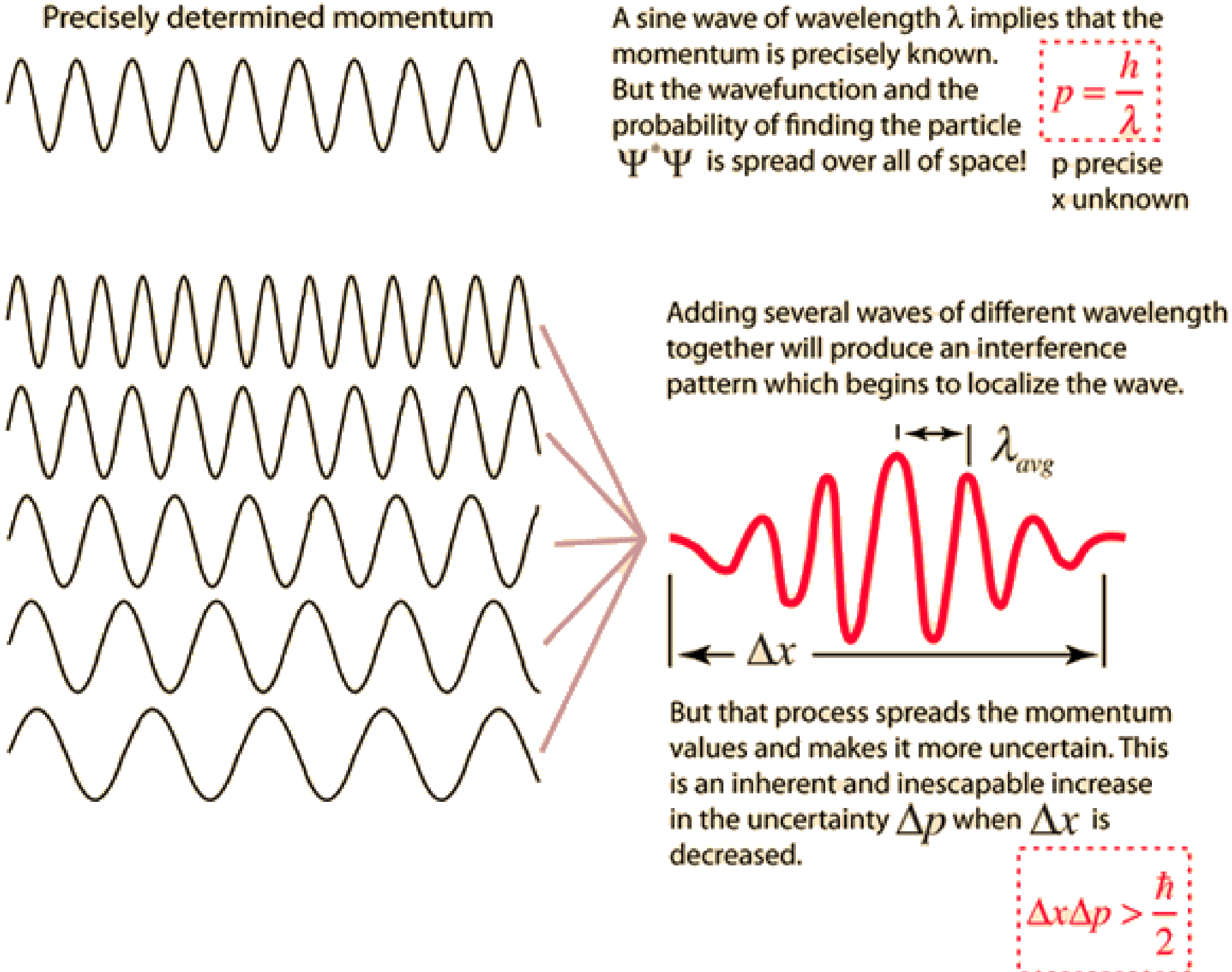


Fox, Chapter 5

Wave packet and momentum uncertainy

$\Delta p=0$
$\Delta x=\infty$

Wave packet



Heisenberg uncertainty and quantum confinement

Heisenberg uncertainty principle 1

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

Energy conservation can be violated for a short time.

Heisenberg uncertainty principle 2

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Momentum conservation can be violated in a nanostructure.

Quantum confinement energy:

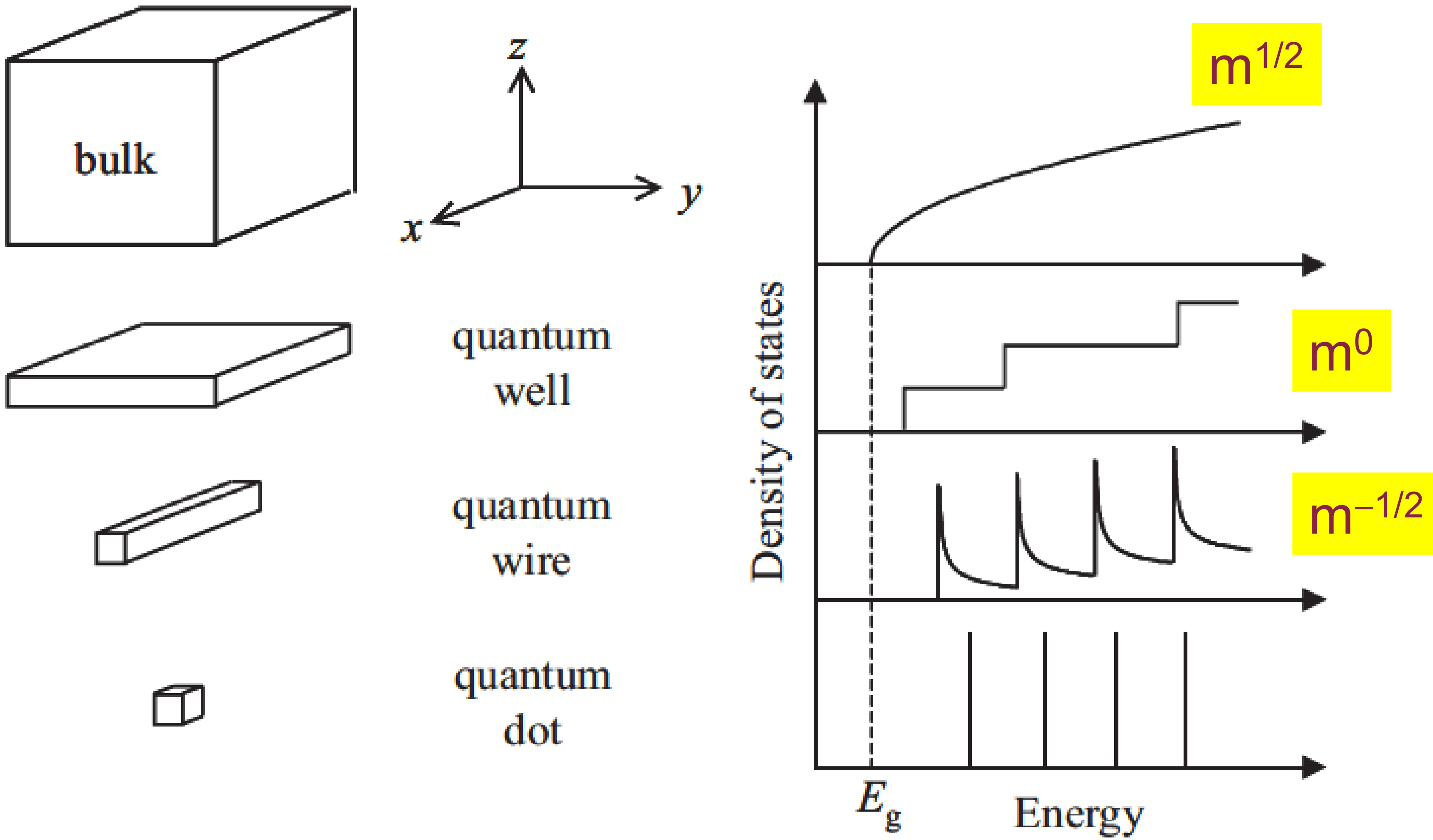
Momentum uncertainty leads to a kinetic energy.
Energies in a small particle are higher than in the bulk.

$$E_{\mathrm{confinement}} = \frac{(\Delta p)^2}{2m} > \frac{1}{2} k_B T$$

Quantum effects are important for small masses at low temperature.

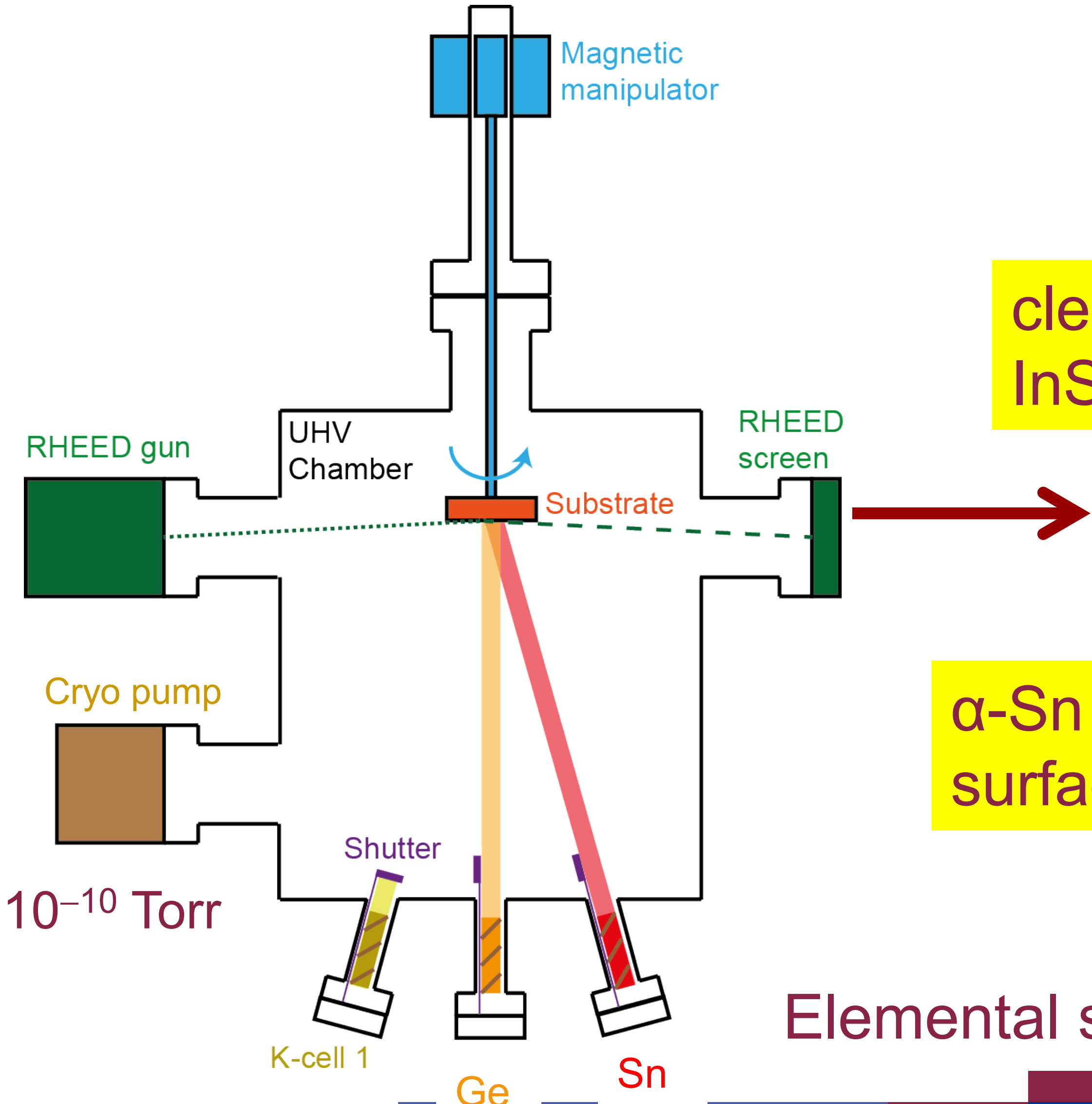
Fox, Chapter 6

Quantum structures and density of states

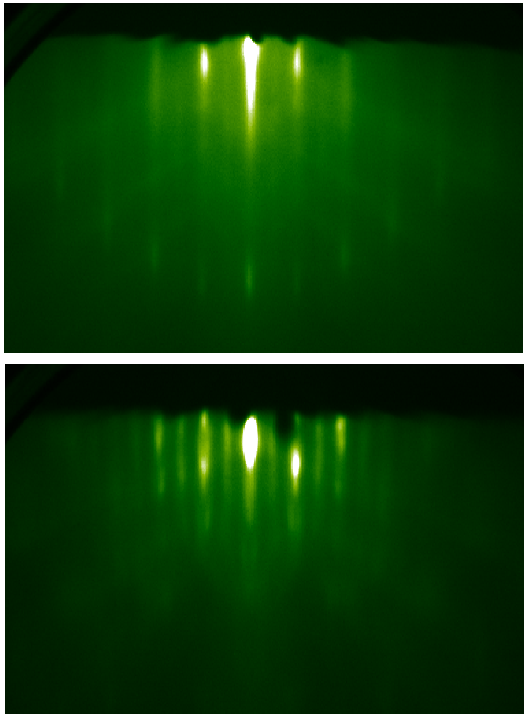


Fox, Chapter 6

Molecular beam epitaxy (Ge_xSn_{1-x} on InSb)



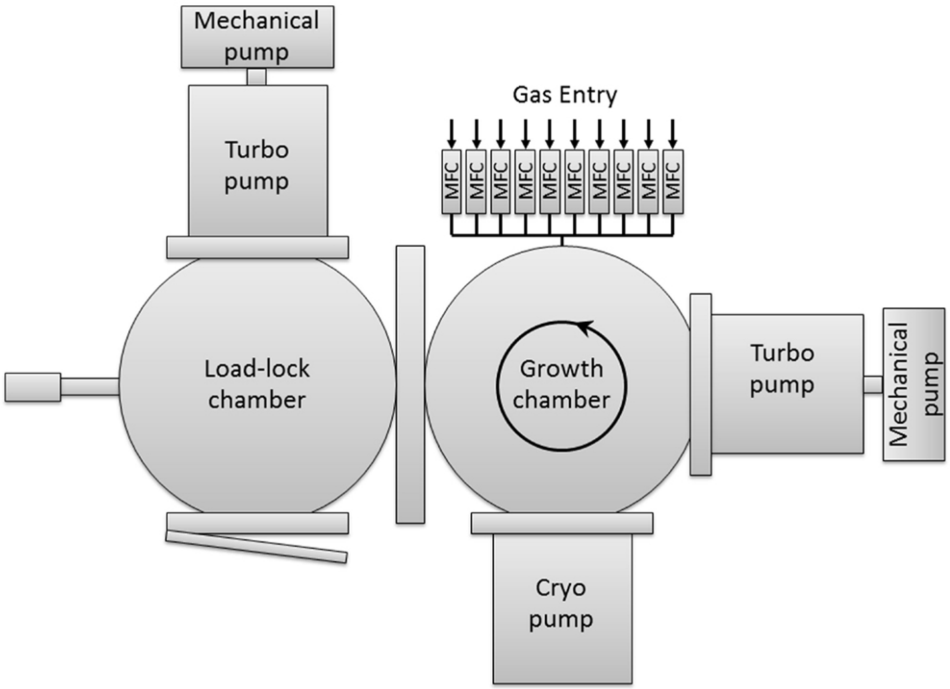
Elemental sources

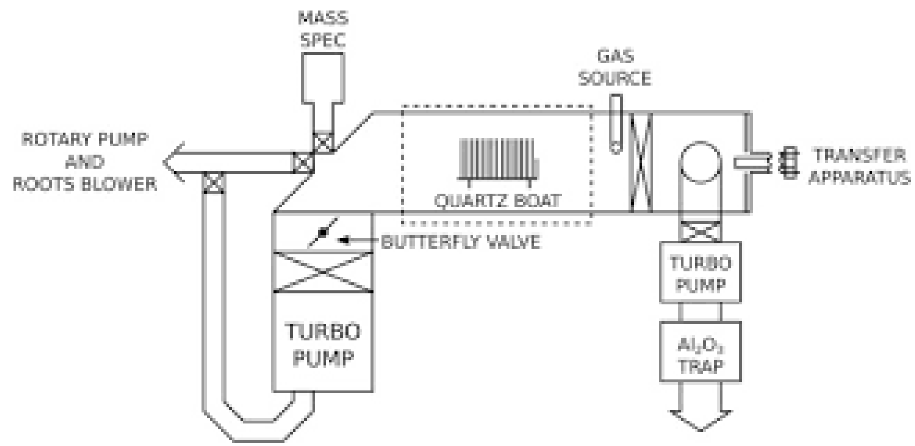


clean InSb

α-Sn film surface

Chemical Vapor Deposition (CVD, MOCVD, MOVPE)





Precursors plus inert carrier gas (usually H_2)

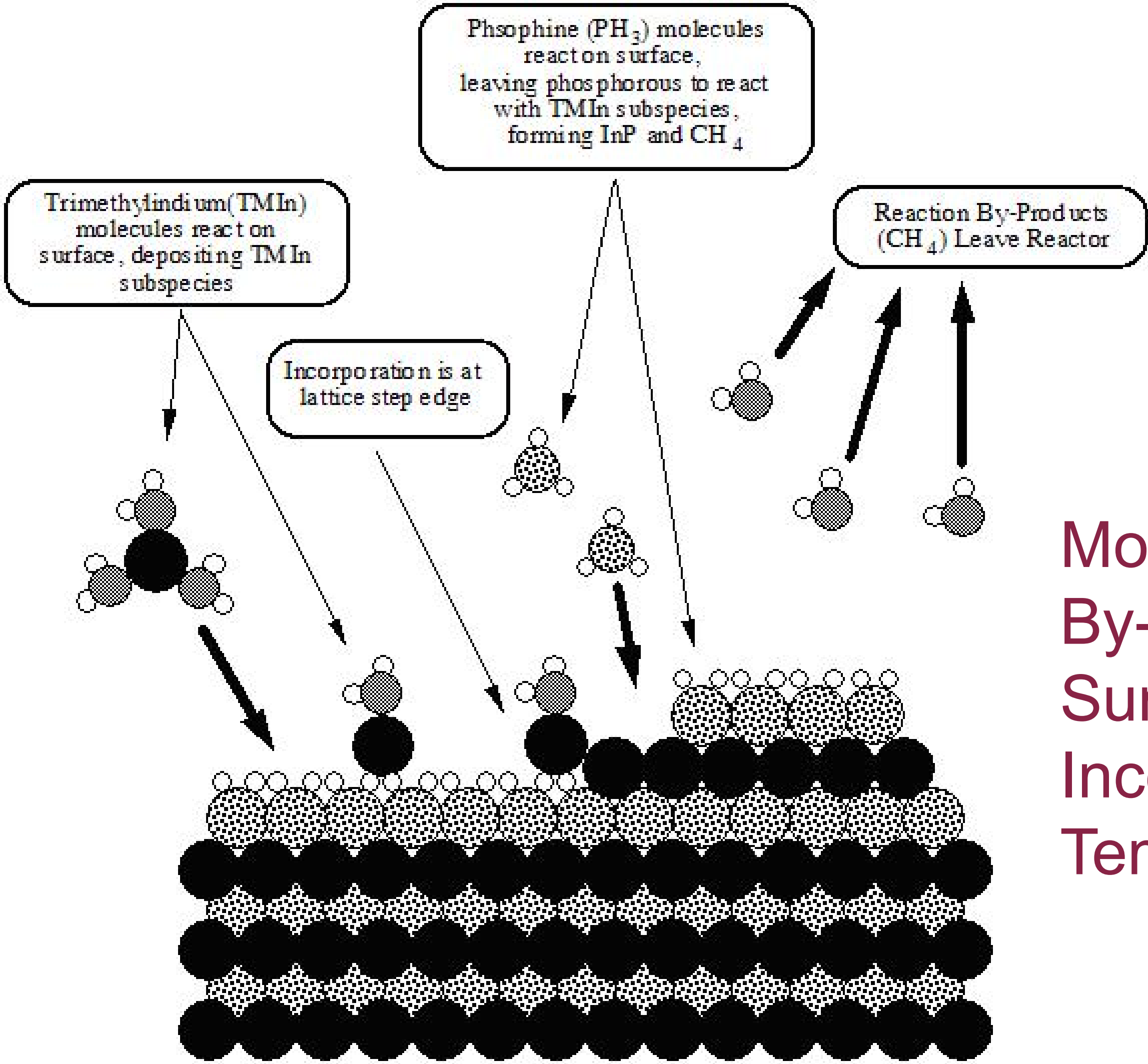
Precursors: SiH_4, GeH_4, AsH_3, PH_3, metalorganics (tri-methyl-Ga).

Explosive, toxic, flammable

No UHV. Extensive safety systems. Scrub exhausts.

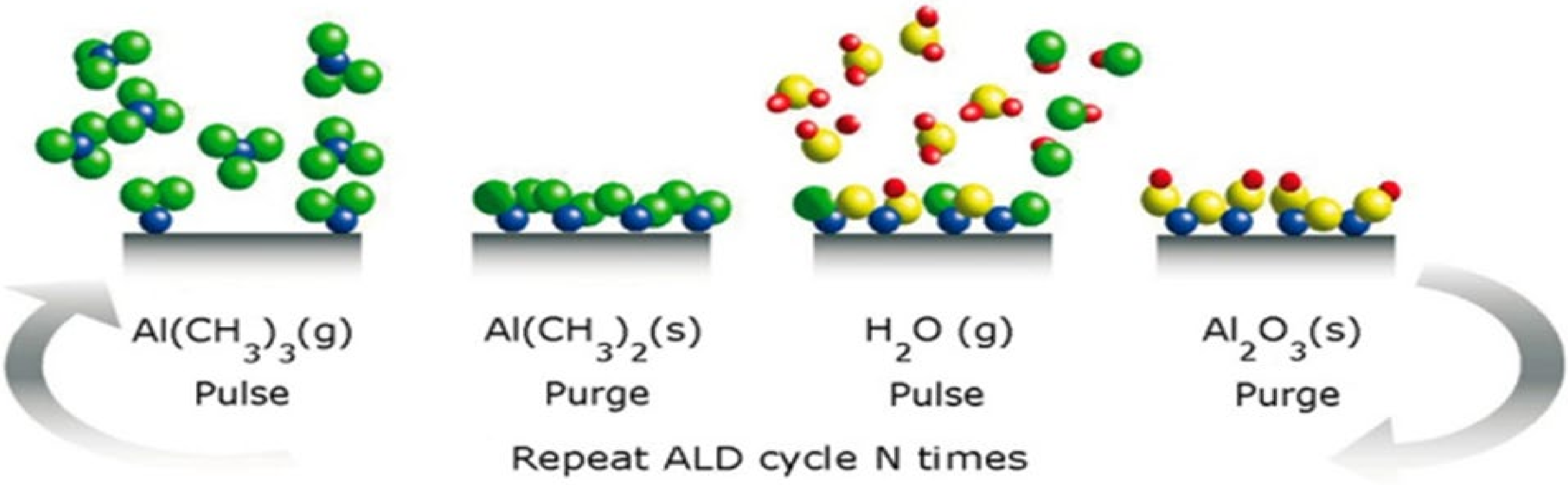
Higher throughput than MBE.

Principle of MOCVD growth (InP)



Molecule cracked at surface.
By-products pumped out.
Surface diffusion.
Incorporated at step edge.
Temperature controls growth.

Atomic layer deposition (ALD)



Self-limiting growth process: One half-layer at a time.
Sequential exposure to precursors.
Very good for oxides and nitrides (Al_2O_3, ZnO, HfO_2).
Low growth temperature.
Sometimes plasma- or photo-assisted.

Summary

- **Near-gap luminescence in excited semiconductors.**
- **Electroluminescence, cathodoluminescence.**
- **Experimental techniques**
- **Hot-carrier and band filling effects.**
- **Light-emitting diodes and semiconductor lasers.**
- **Quantum confinement, Heisenberg uncertainty principle**
- **Growth of quantum structures**
- *Electronic states, quantum well absorption and emission*
- *Intersubband transitions, quantum cascade lasers*

NM STATE