Optical Properties of Solids: Lecture 11

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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,
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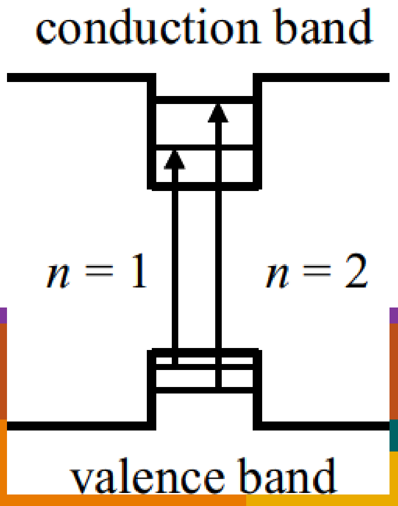
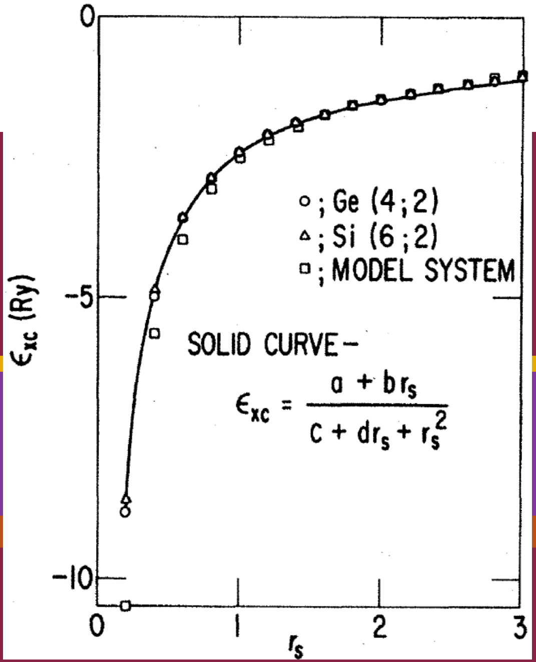
NSF: DMR-1505172

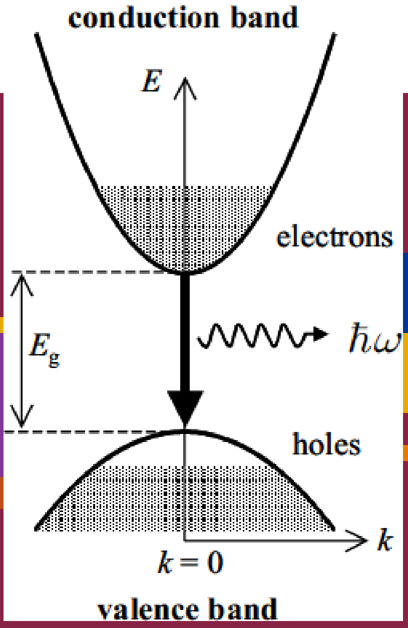
Optical Properties of Solids: Lecture 11

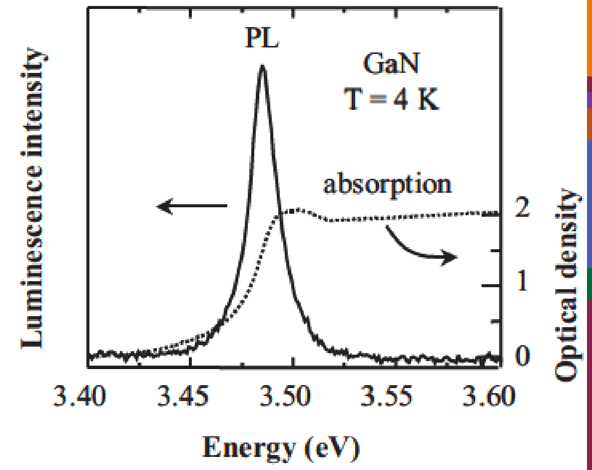
Emission of photons
Photoluminescence
Electro-, cathodoluminescence

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

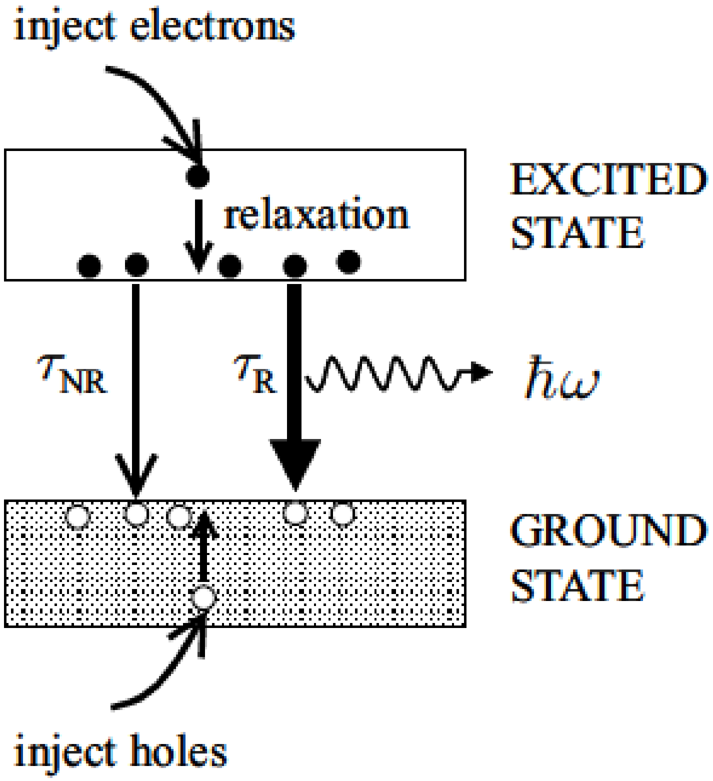
Quantum confinement and Heisenberg uncertainty principle

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

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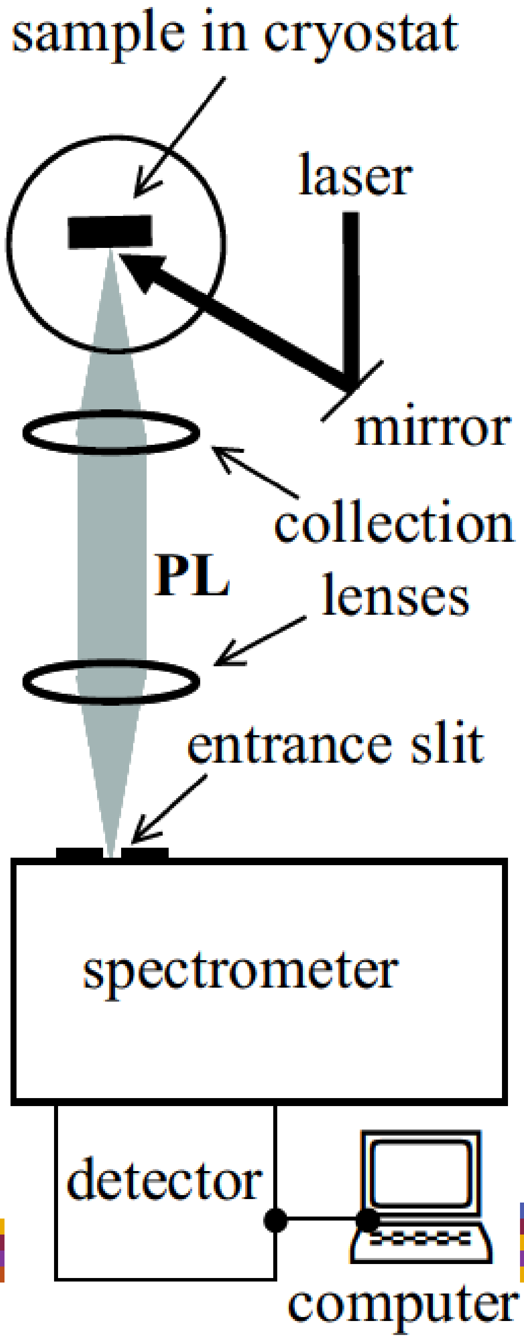
Photoluminescence experiments



- 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.

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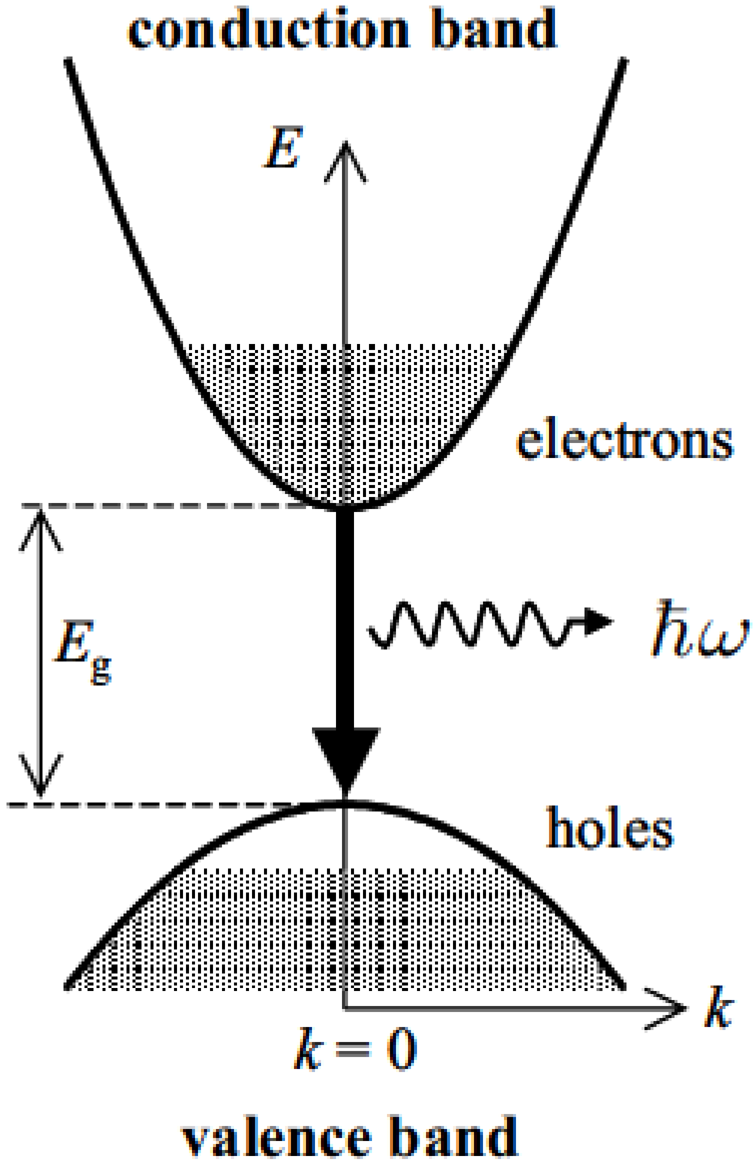
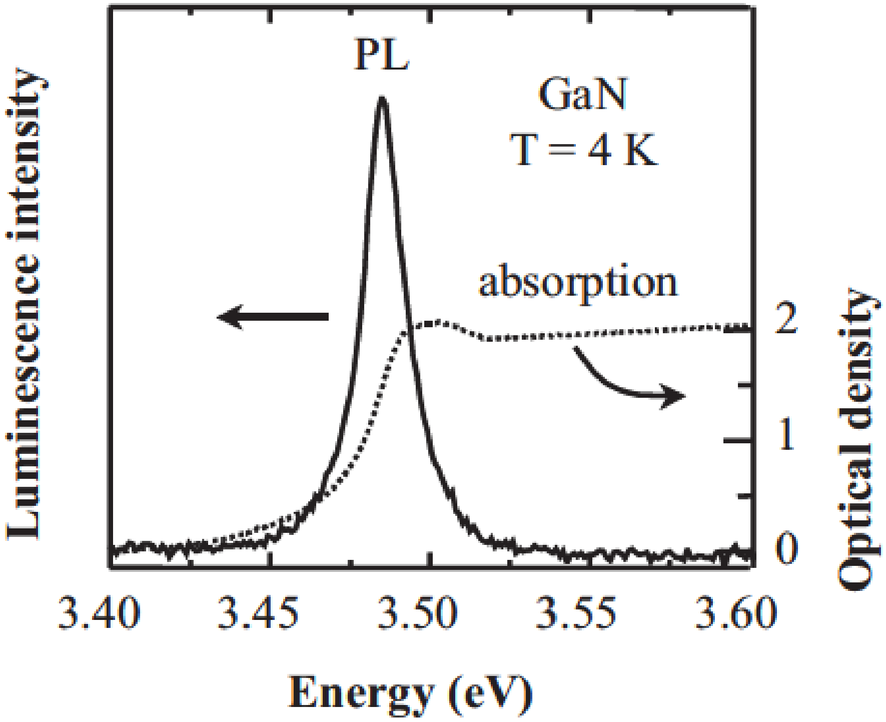
Interband photoluminescence



Direct semiconductor

Electron-hole recombination



Shift between emission and absorption

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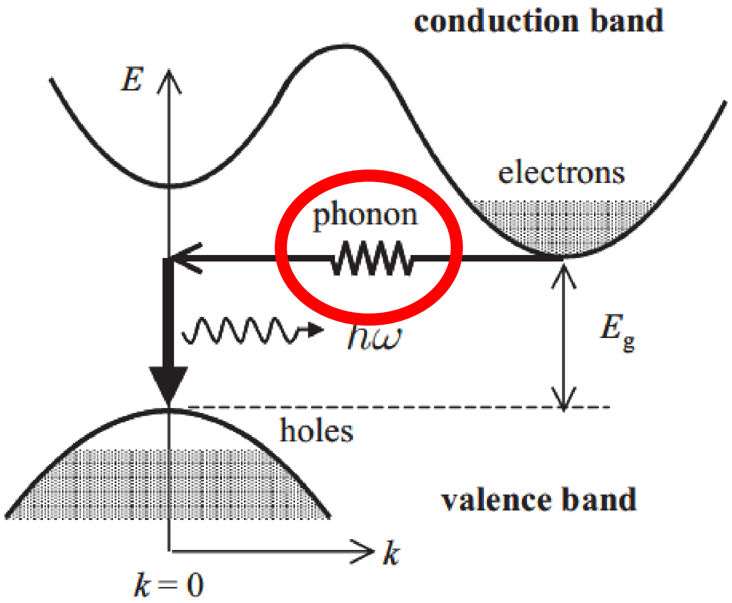
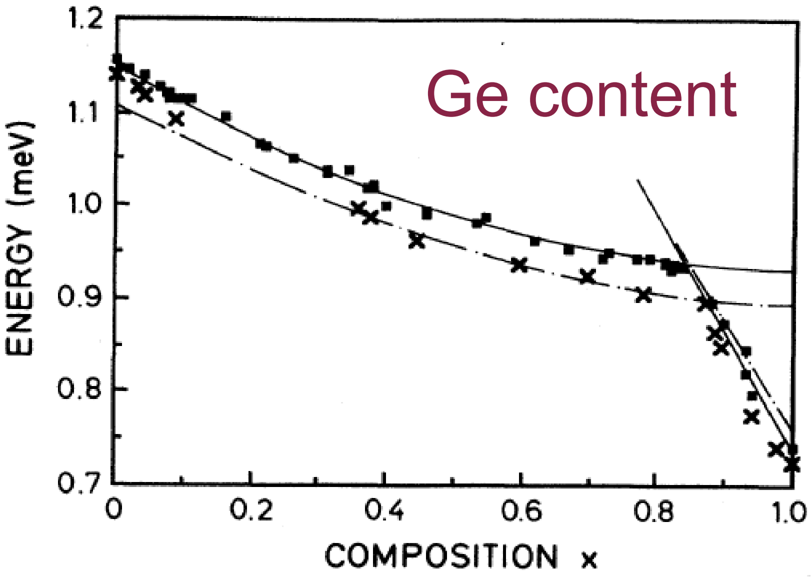
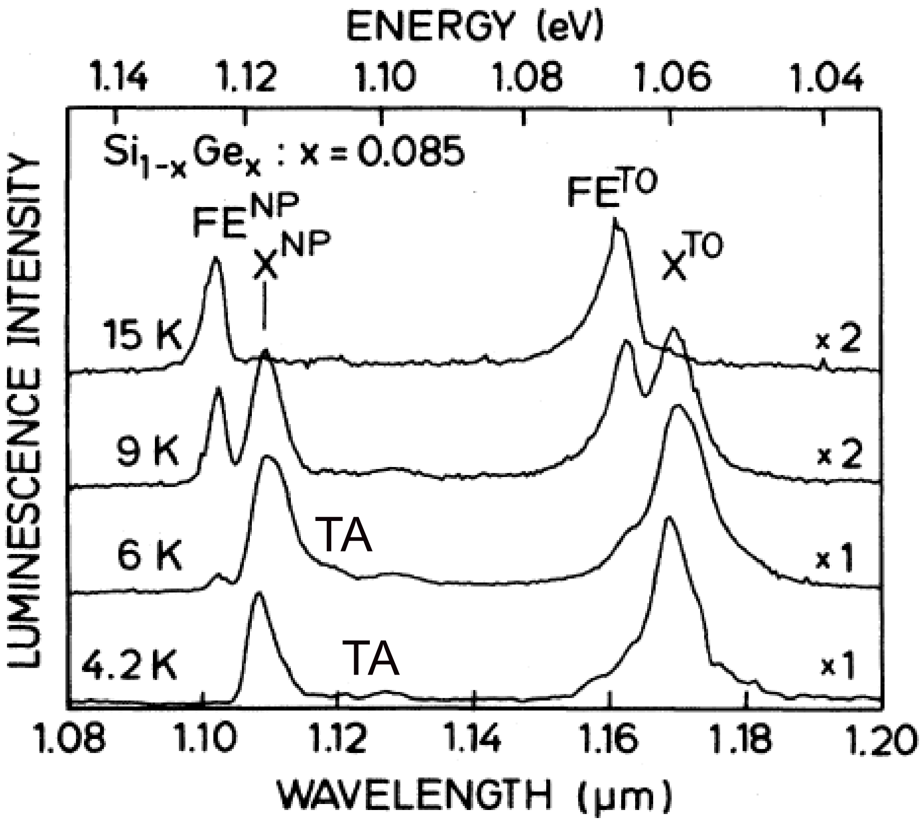
Indirect photoluminescence in Si-Ge alloys





Ge content



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

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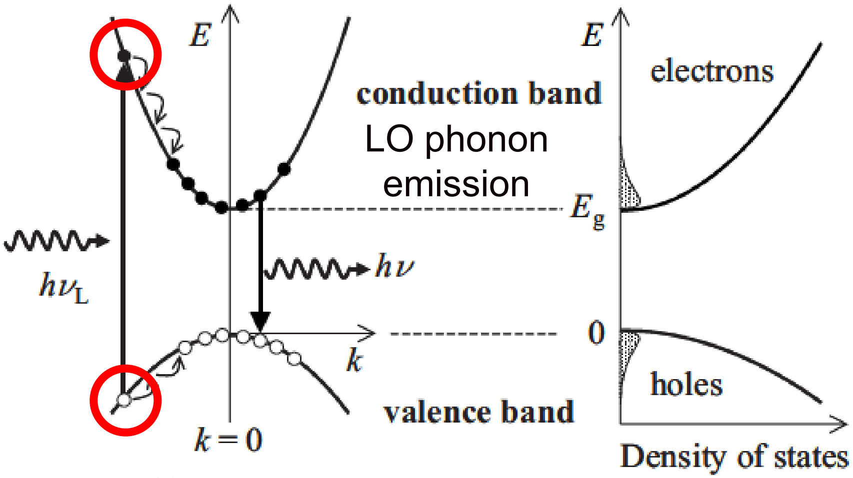
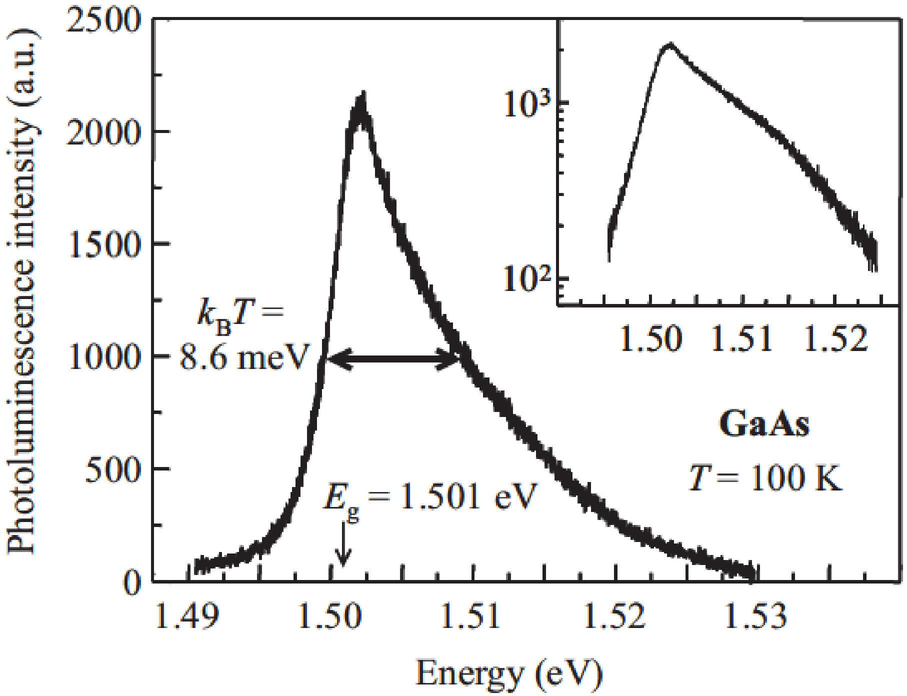
Weber & Alonso, Phys. Rev. B **40**, 5683 (1989)

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

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

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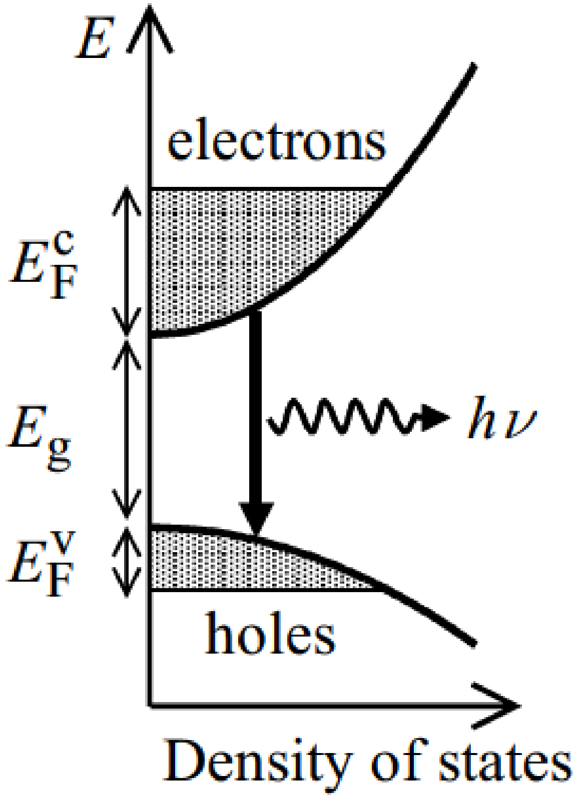
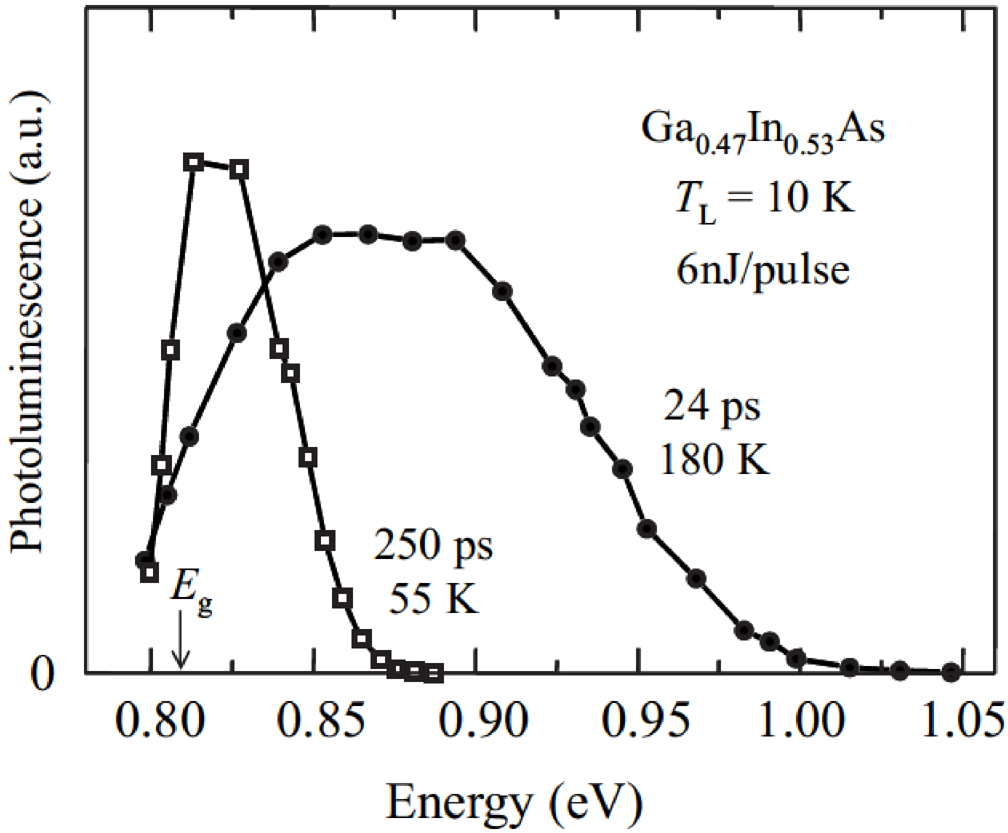
High carrier density: band filling



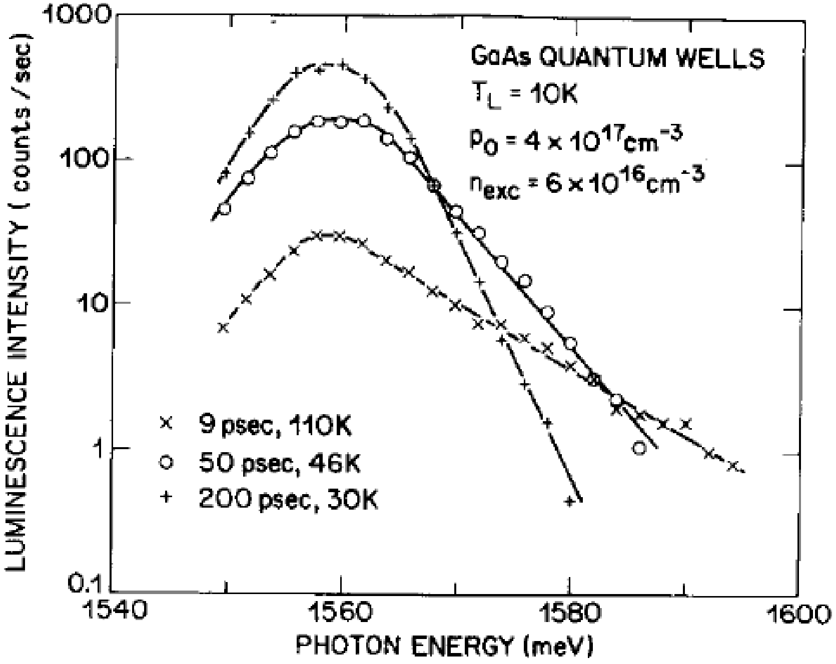


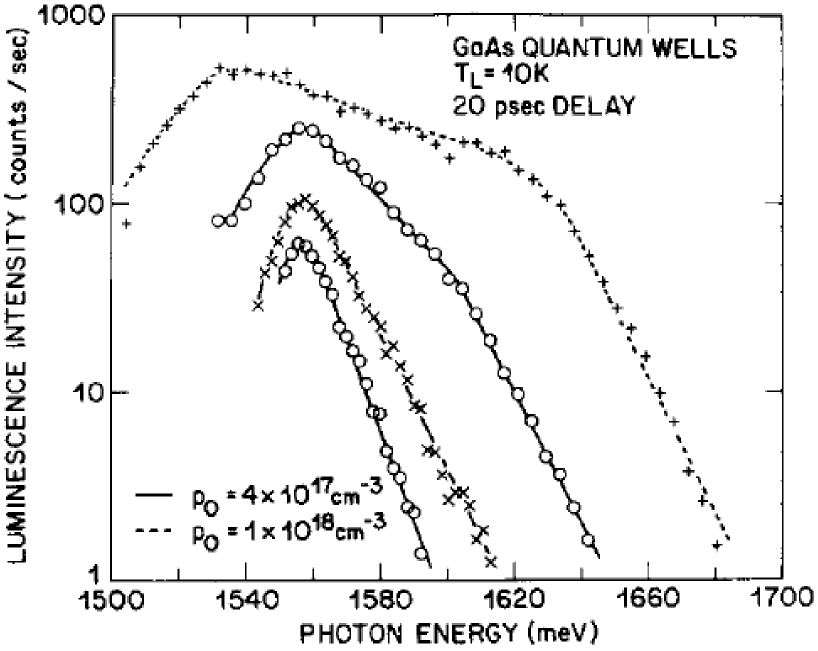
High carrier density, low T:
Quasi-Fermi levels for electrons and holes

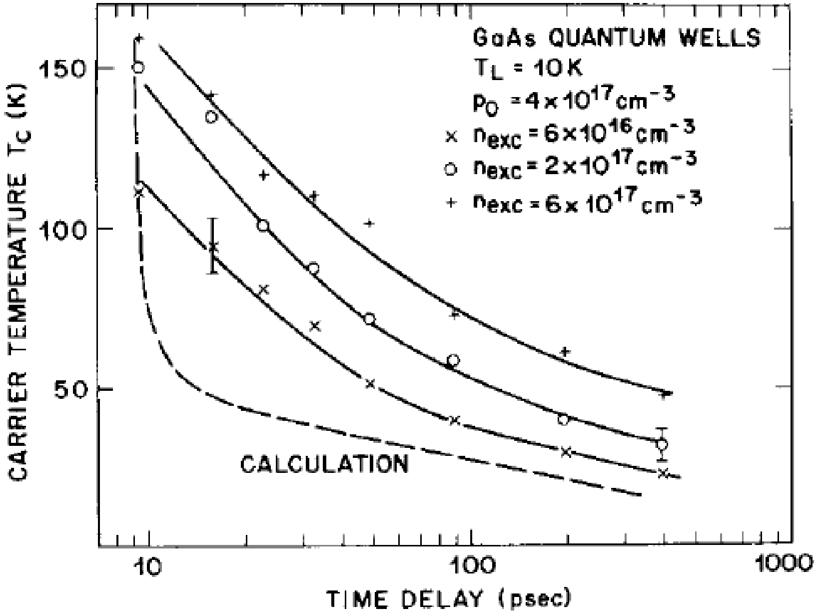
$$E_F^{c,v} = \frac{\hbar^2}{2m_{e,v}^*}\left(3\pi^2 N_{e,h}\right)^{\frac{2}{3}}$$

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

Carrier cooling and band filling in GaAs QW







Carrier temperature versus time:

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

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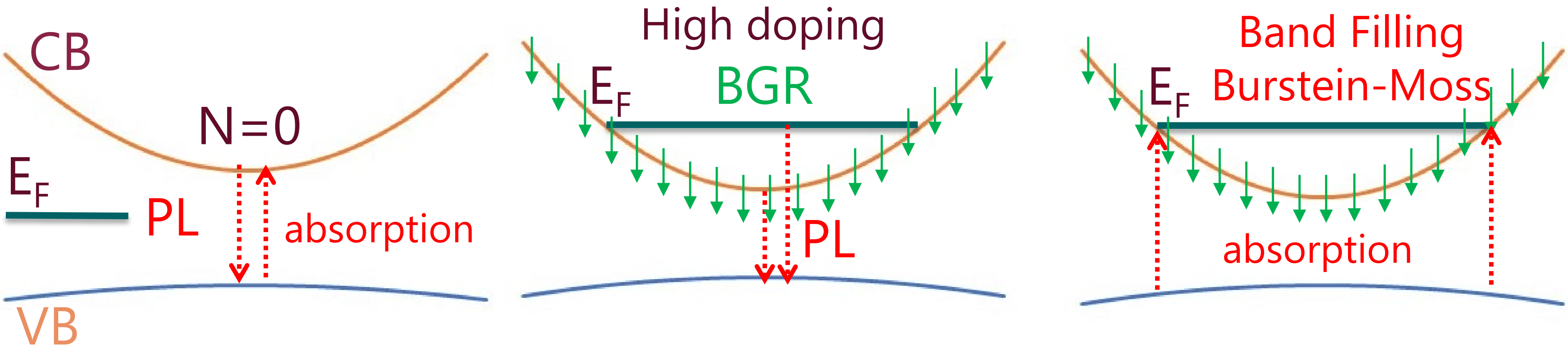
Kash & Shah, 1985

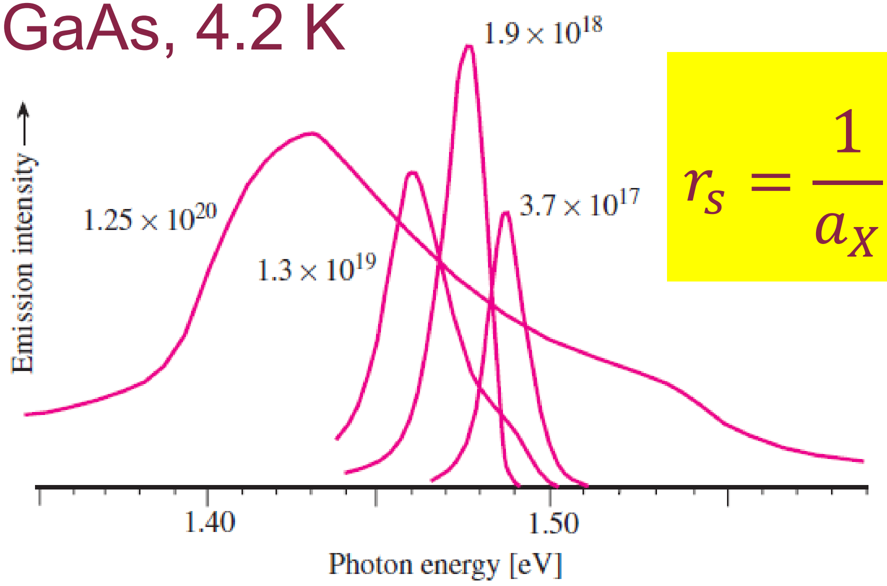
High carrier density: band filling

- **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 $r_s \sim 5$.

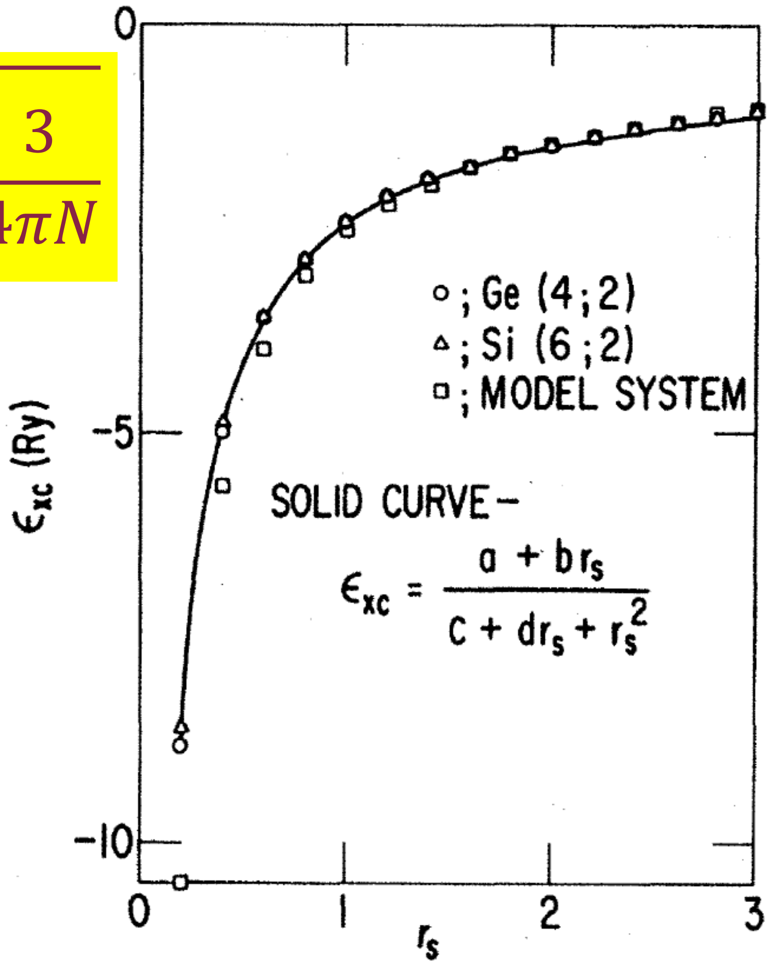


Band gap renormalization

GaAs, 4.2 K



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

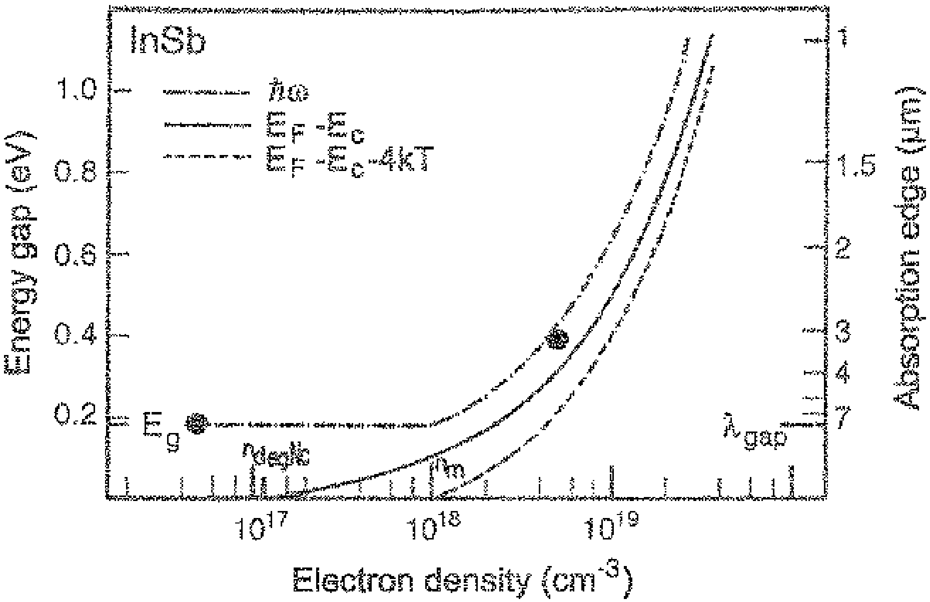


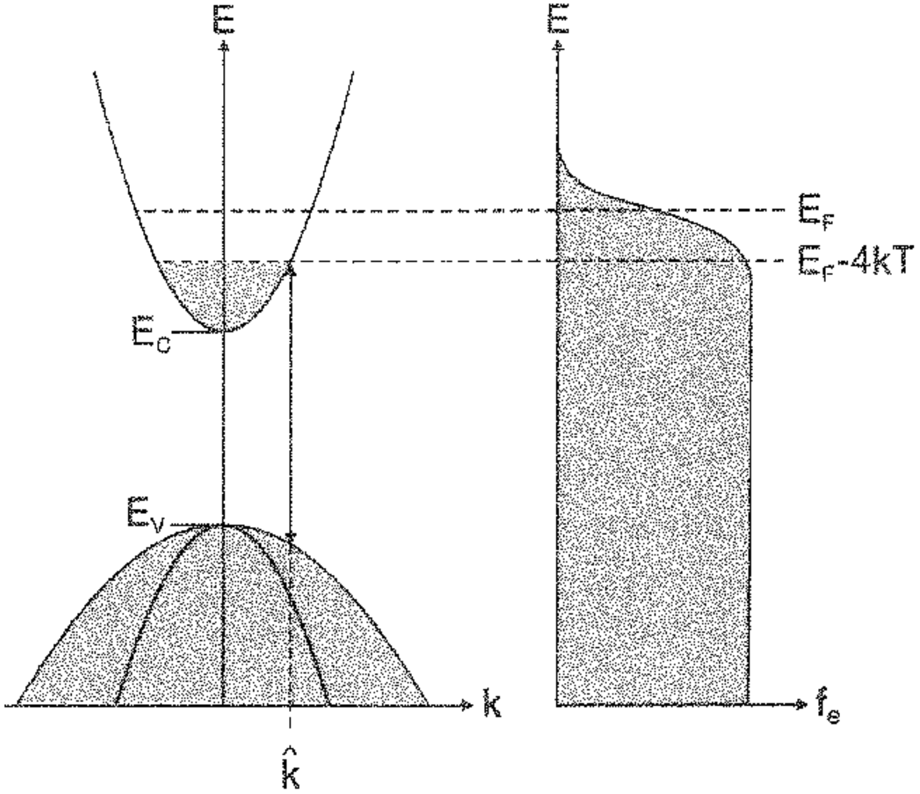
Band gap shrinks with increasing carrier concentration.

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

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

Burstein-Moss shift: n-type InSb



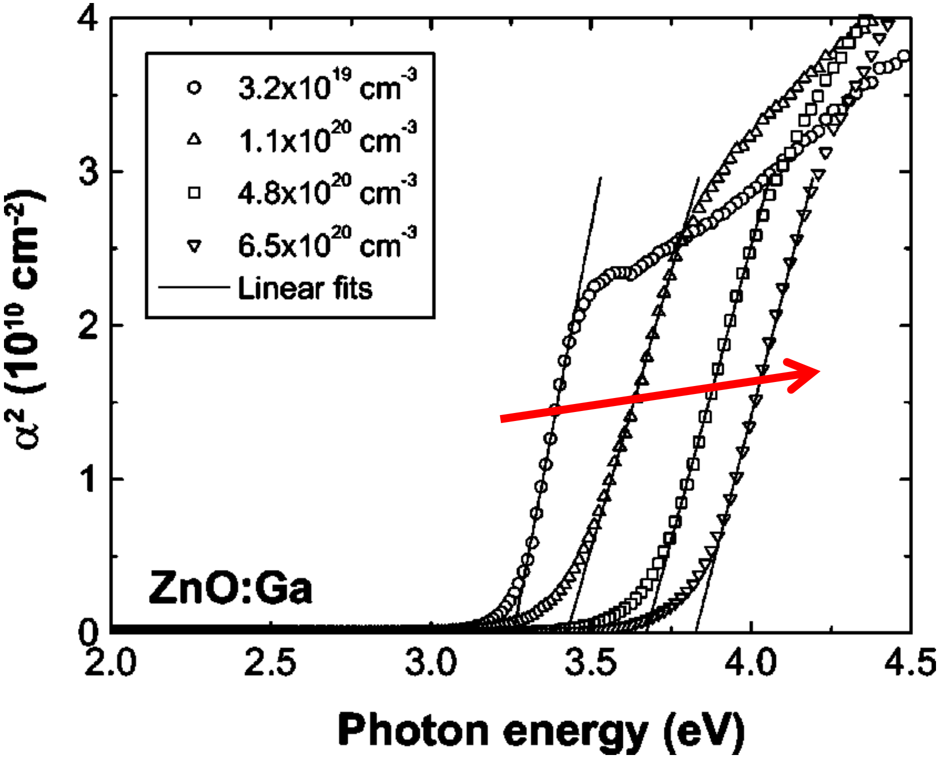


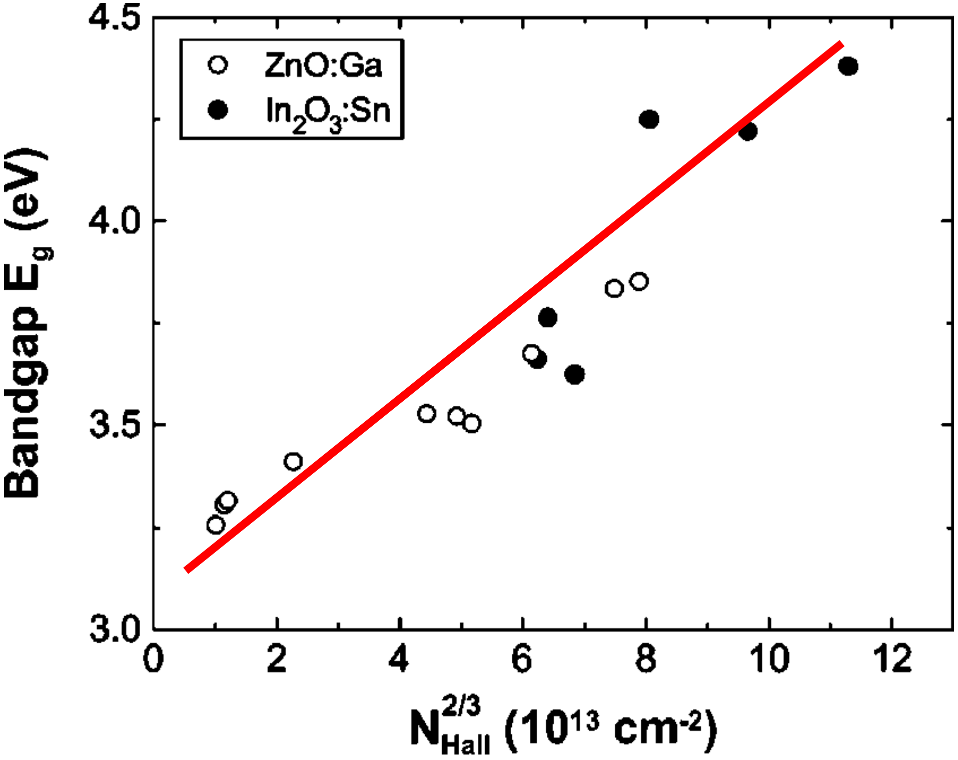
Absorption threshold (band gap) increases, because CB bottom is filled with electrons (Pauli blocking).

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

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





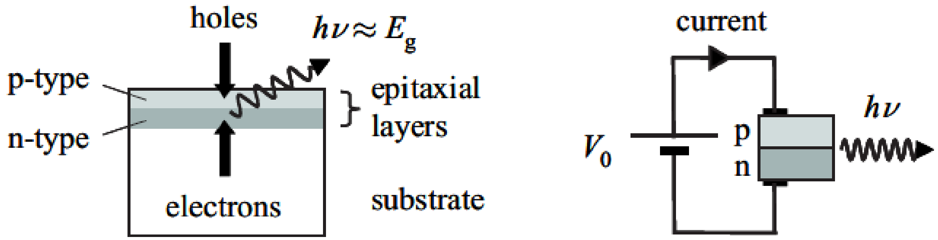
Band gap **increases** with increasing dopant concentration.

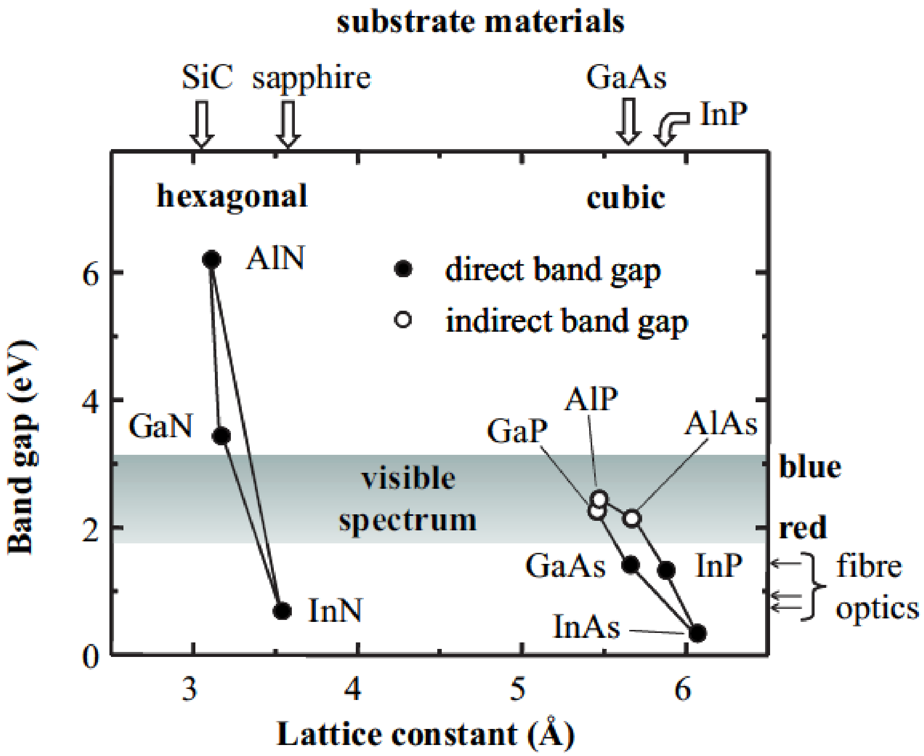
Band gap renormalization (decrease) PLUS band filling (increase).

Shift is proportional to $n^{2/3}$ (many-body effect).

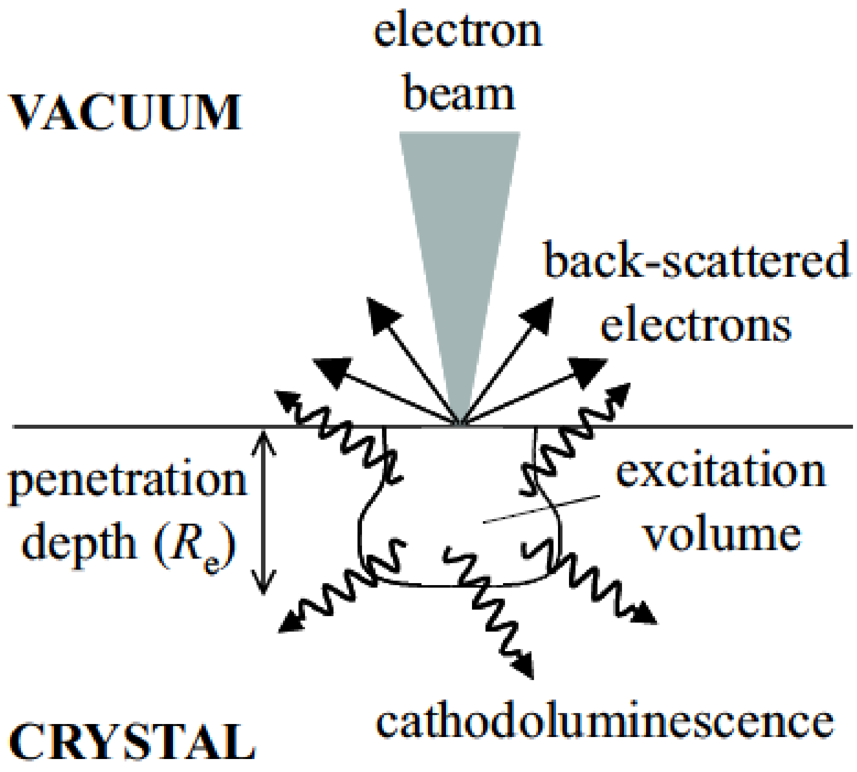
Fujiwara, Phys. Rev. B **71**, 075109 (2005)

Electroluminescence





Cathodoluminescence



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

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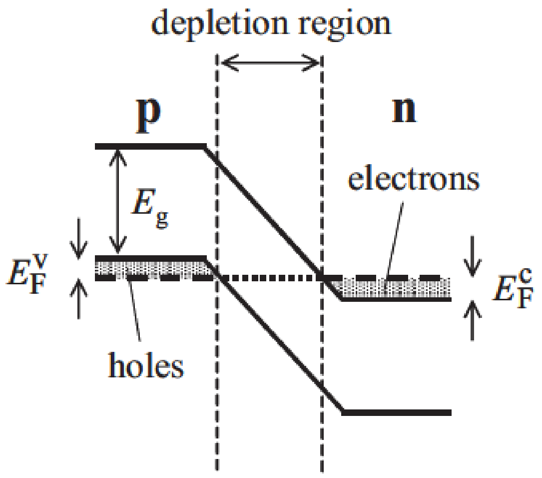
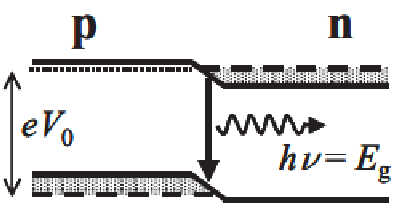
Semiconductor lasers

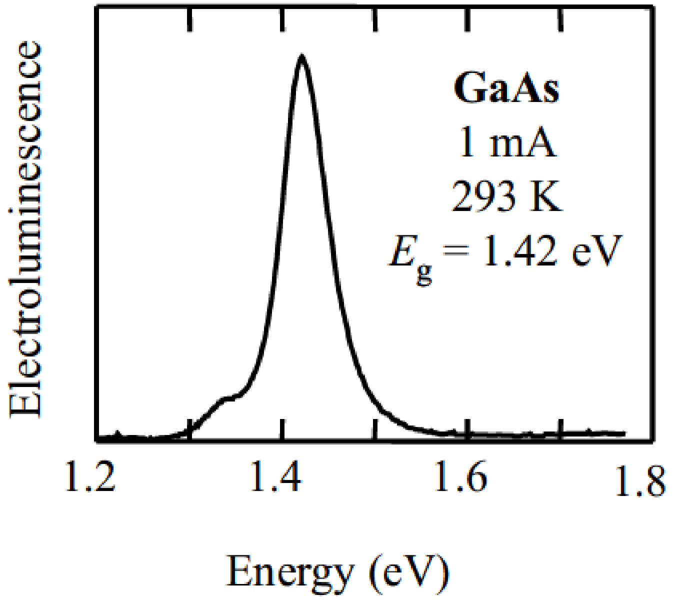


(a) $V_0 = 0$

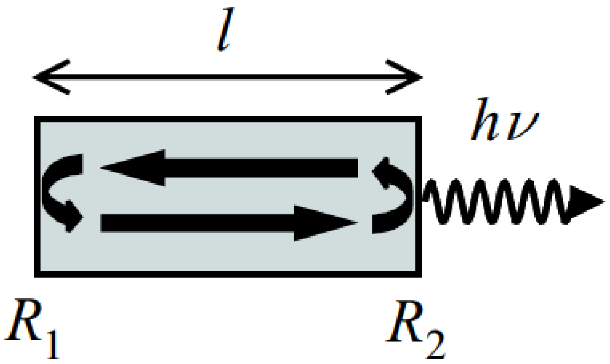


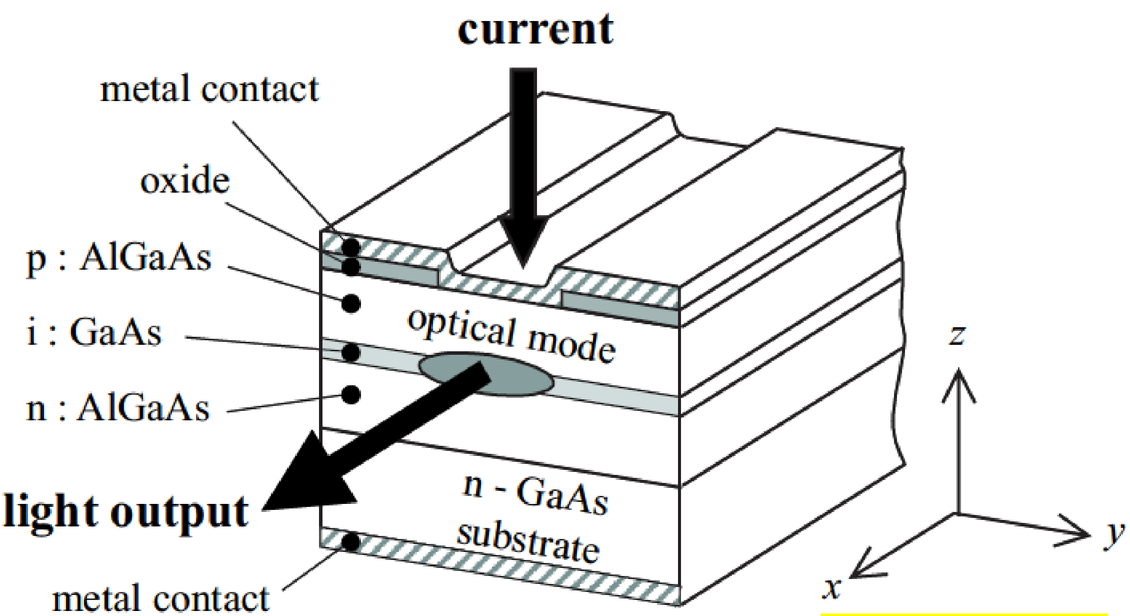
Applied voltage (flat bands)

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



Fermi levels line up.





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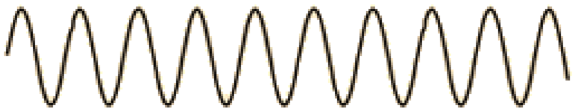
Wave packet and momentum uncertainy

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

Precisely determined momentum

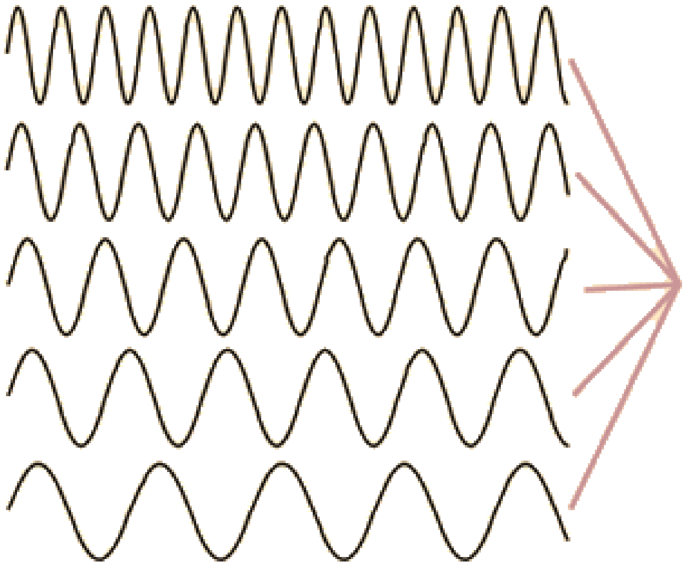


A sine wave of wavelength λ implies that the momentum is precisely known. But the wavefunction and the probability of finding the particle $\Psi^*\Psi$ is spread over all of space!

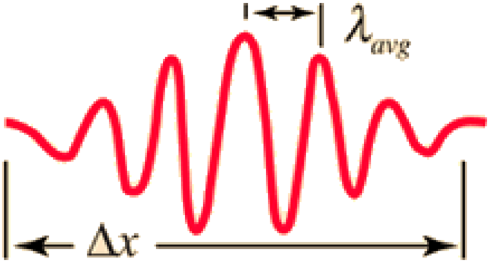
$$p = \frac{h}{\lambda}$$

p precise
x unknown

Wave packet



Adding several waves of different wavelength together will produce an interference pattern which begins to localize the wave.



But that process spreads the momentum values and makes it more uncertain. This is an inherent and inescapable increase in the uncertainty Δp when Δx is decreased.

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

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.

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

Quantum effects are important for small masses at low temperature.

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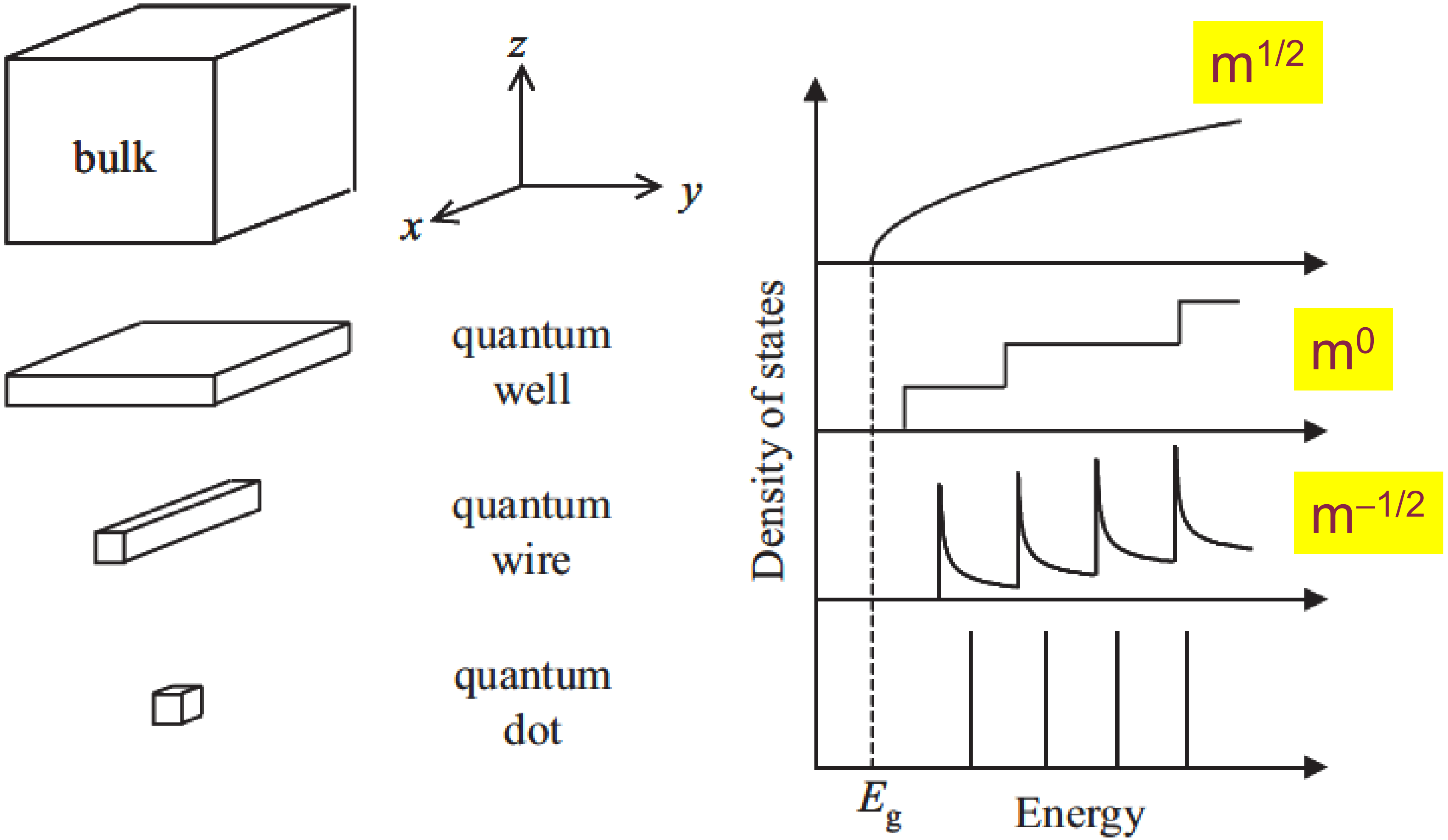
Quantum structures and density of states



$m^{1/2}$

m^0

$m^{-1/2}$

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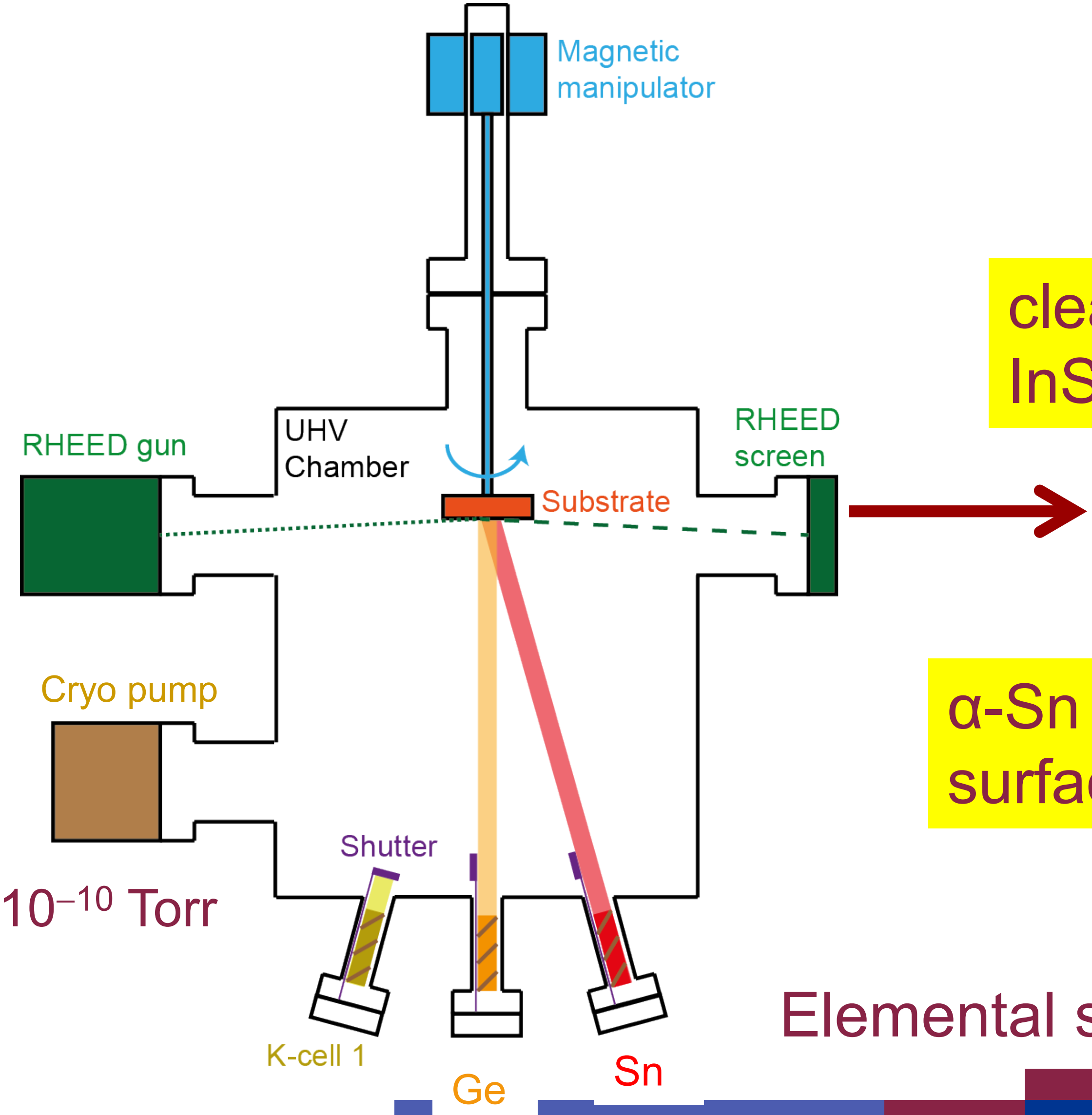
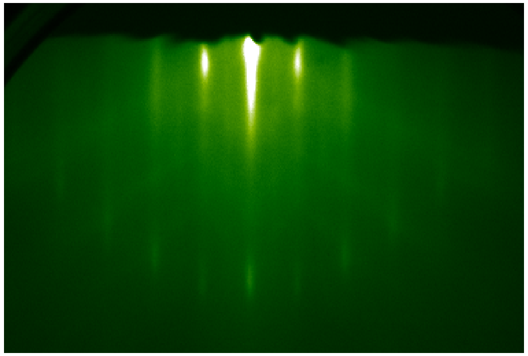
Molecular beam epitaxy (Ge_xSn_{1-x} on InSb)

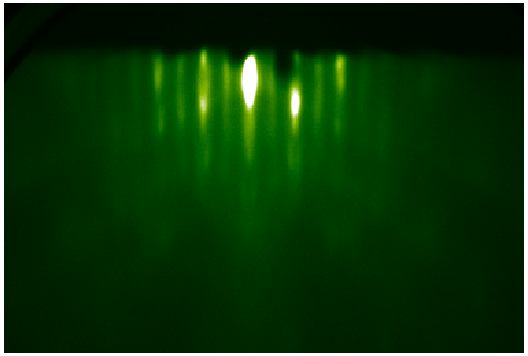


10^{-10} Torr

clean InSb

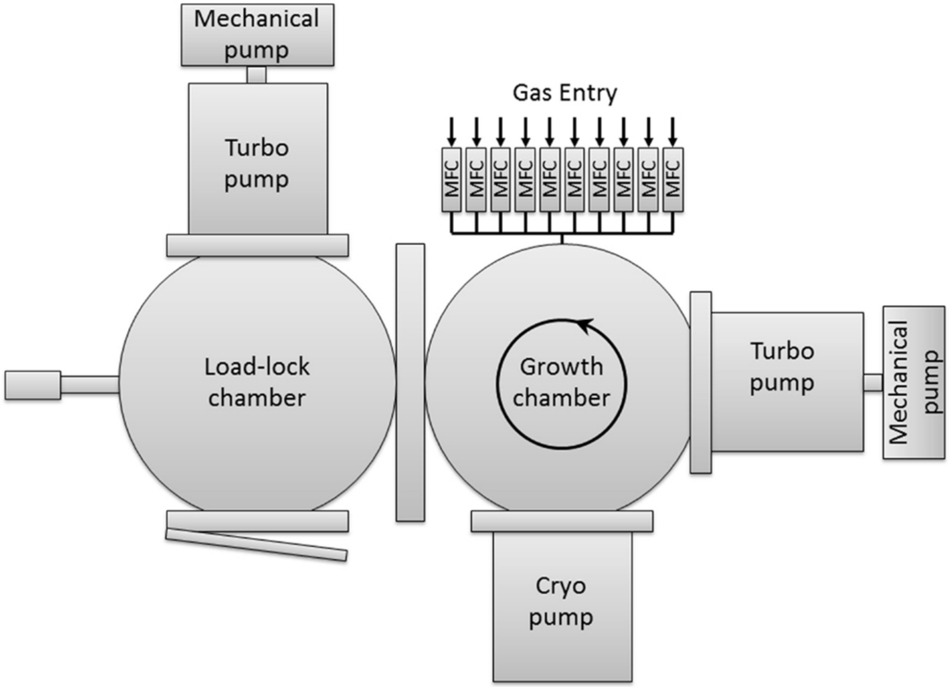


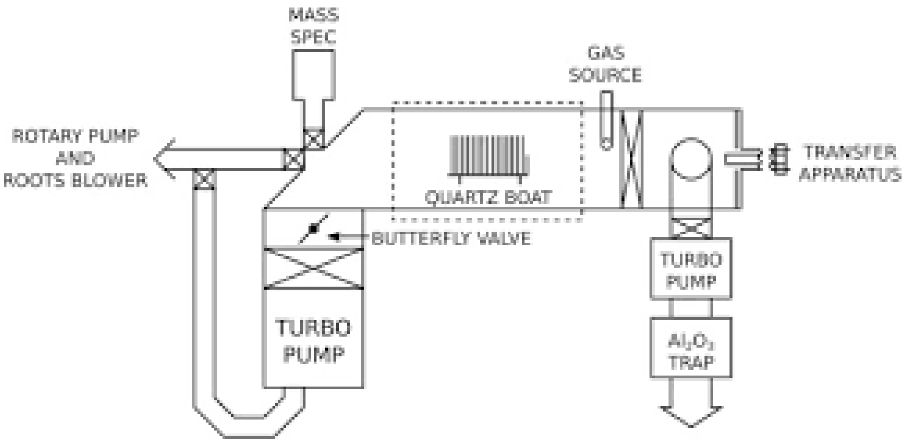
α-Sn film surface



Elemental sources

Chemical Vapor Deposition (CVD, MOCVD, MOVPE)





Precursors plus inert carrier gas (usually H_2)

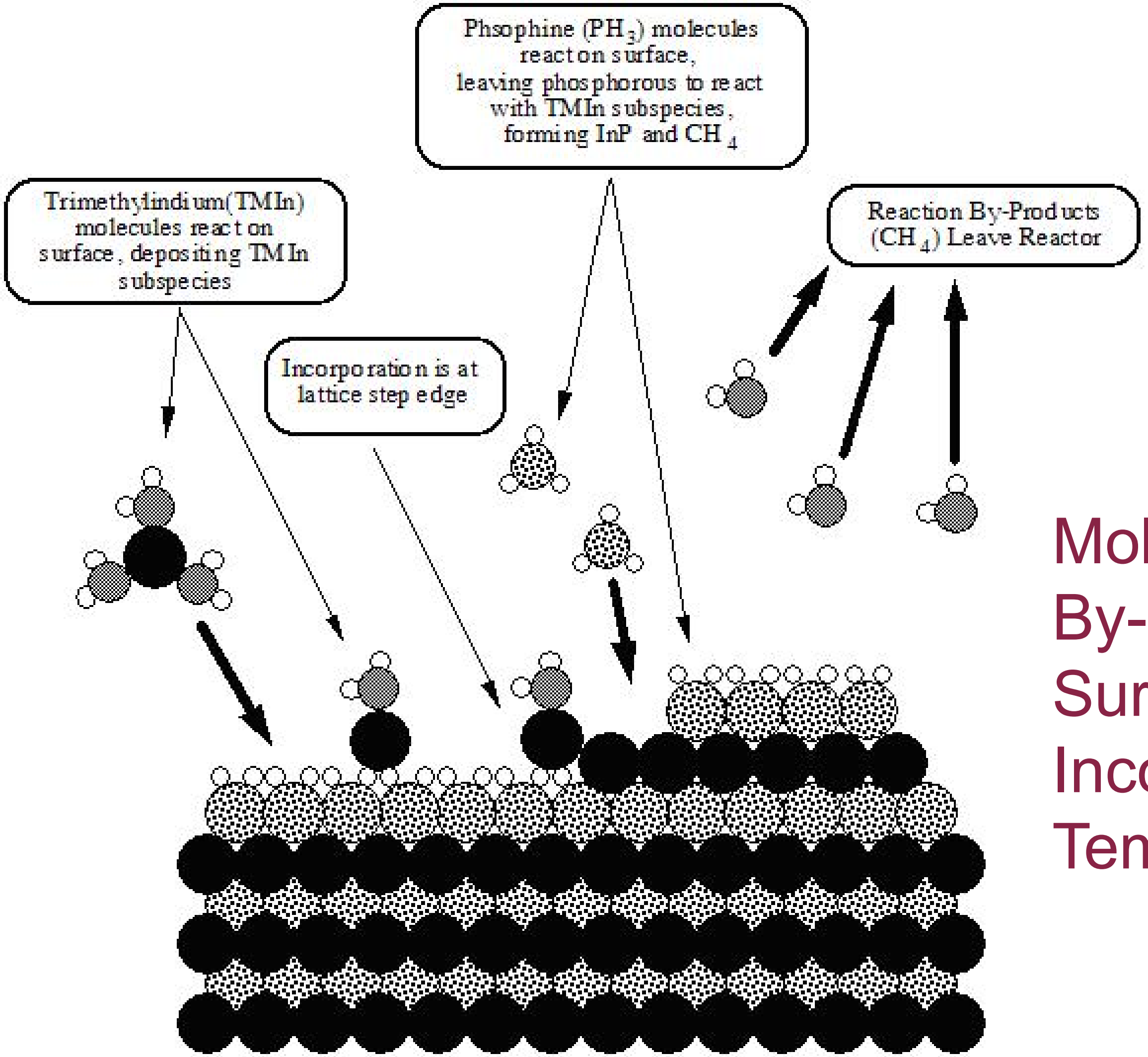
Precursors: SiH_4, GeH_4, AsH_3, PH_3, metalorganics (tri-methyl-Ga).

Explosive, toxic, flammable

No UHV. Extensive safety systems. Scrub exhausts.

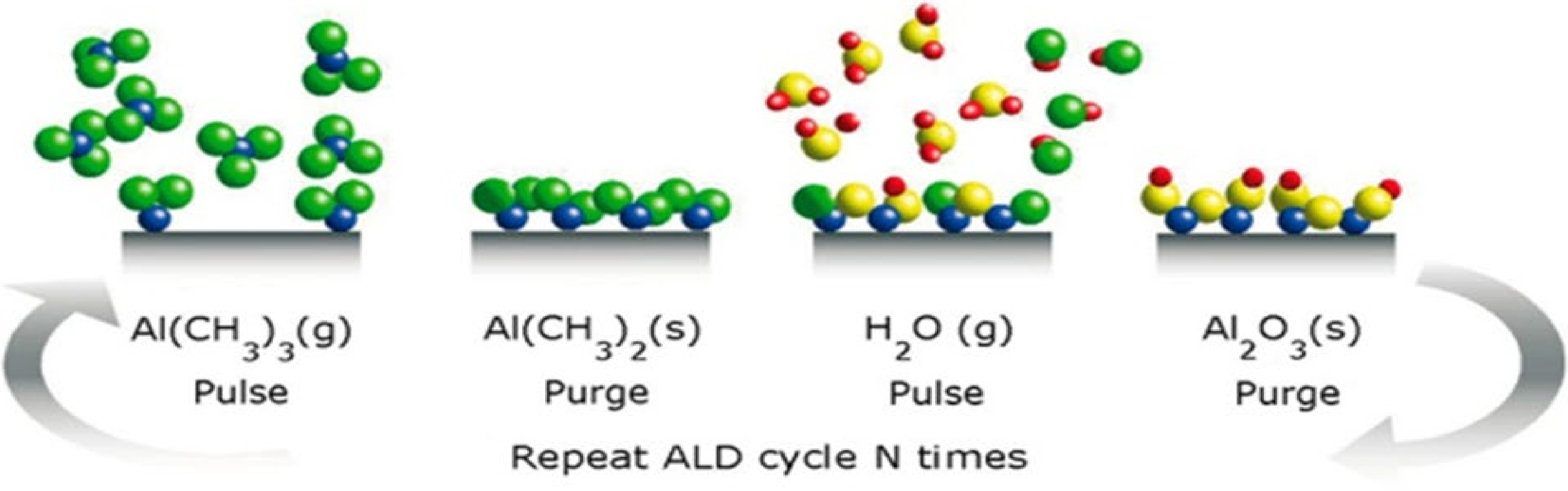
Higher throughput than MBE.

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*