Lecture 11 – Quantum Confinement

EECS 598-002 Winter 2006

Nanophotonics and Nano-scale Fabrication

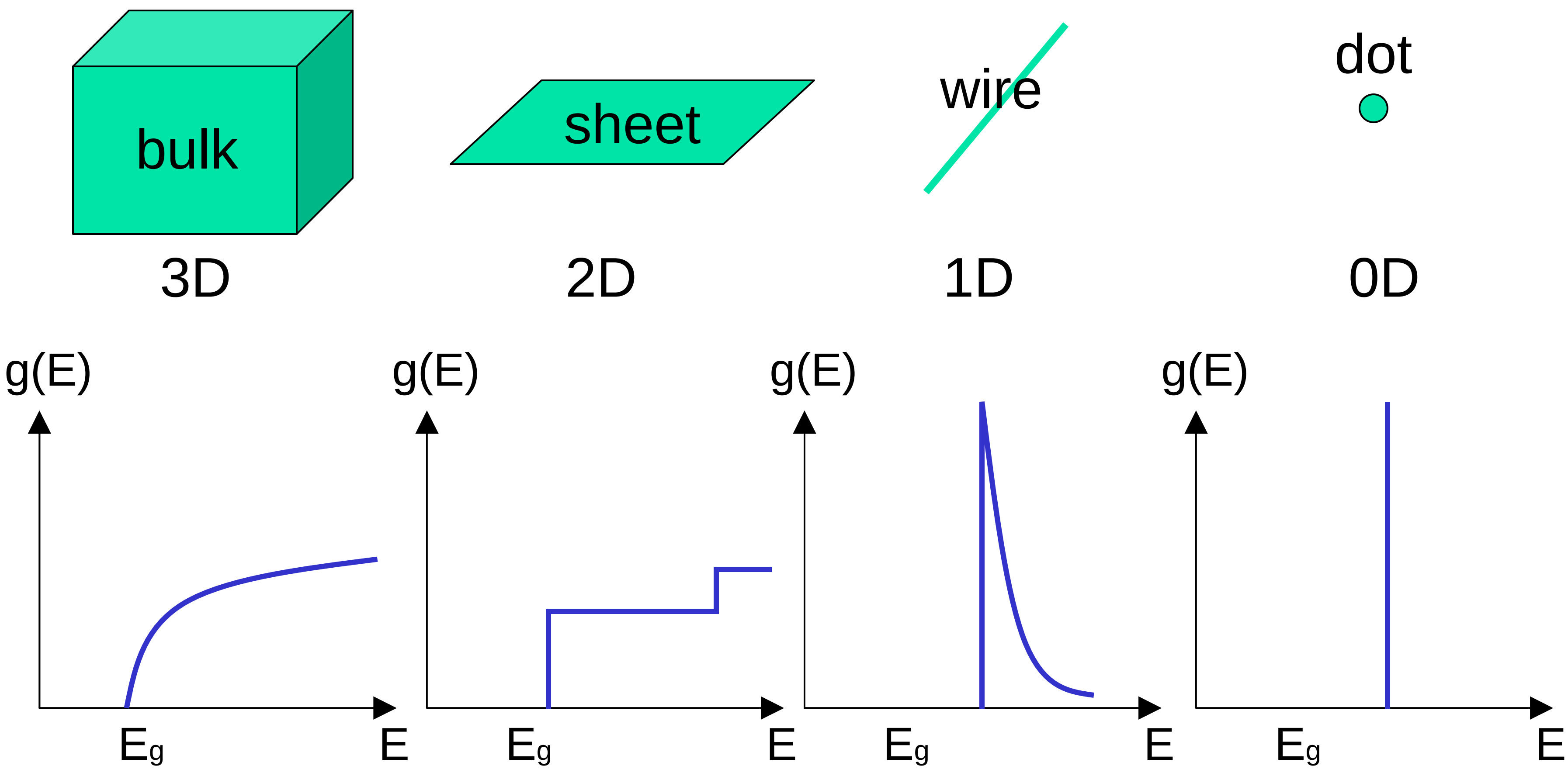
P.C.Ku

Schedule for the rest of the semester

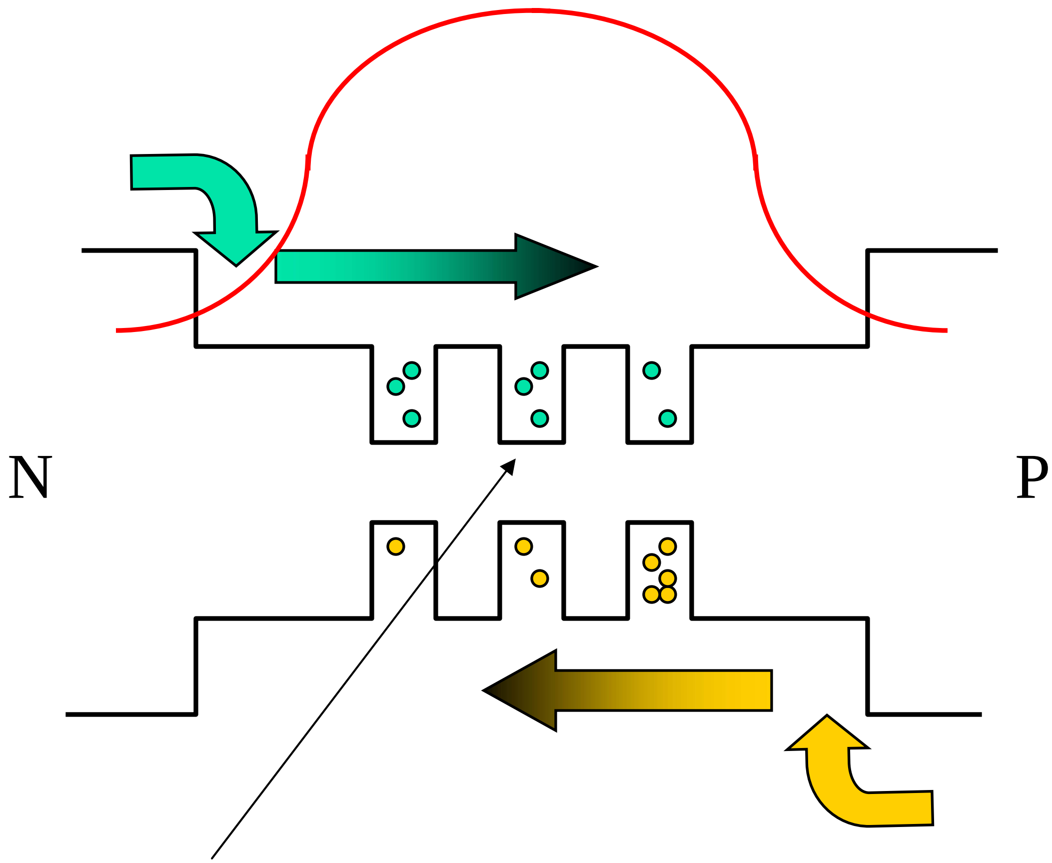
- Introduction to light-matter interaction (1/26):
  - How to determine $\varepsilon(r)$?
  - The relationship to basic excitations.
- Basic excitations and measurement of $\varepsilon(r)$. (1/31)
- Structure dependence of $\varepsilon(r)$ overview (2/2)
- Surface effects (2/7):
  - Surface EM wave
  - Surface polaritons
  - Size dependence
- Case studies (2/9 – 2/16):
  - **Quantum wells, wires, and dots**
  - Nanophotonics in microscopy
  - Nanophotonics in plasmonics
- Dispersion engineering (2/21 – 3/7):
  - Material dispersion
  - Waveguide dispersion (photonic crystals)

Quantum confinement review

g(E) = Density of states

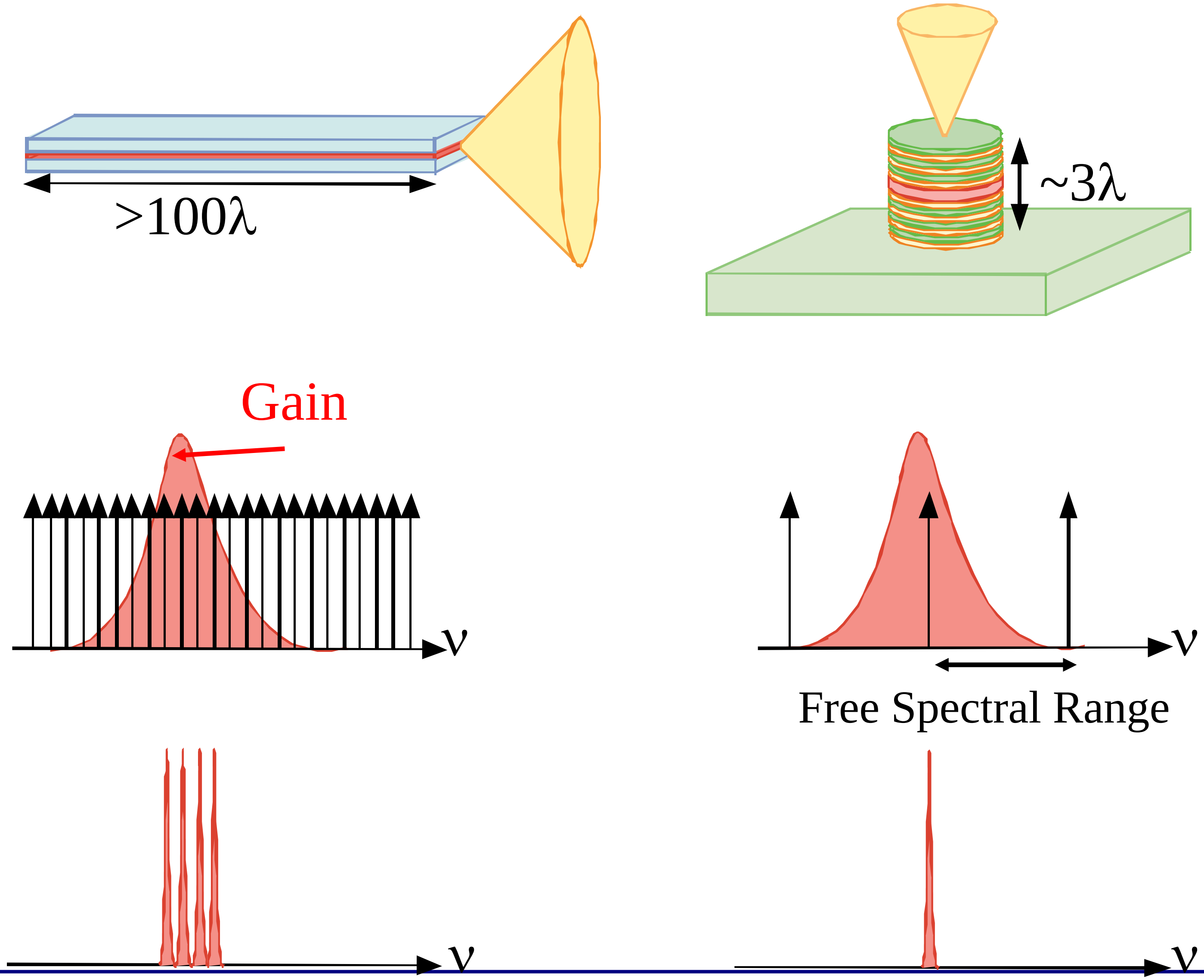


Quantum wells and double heterostructures

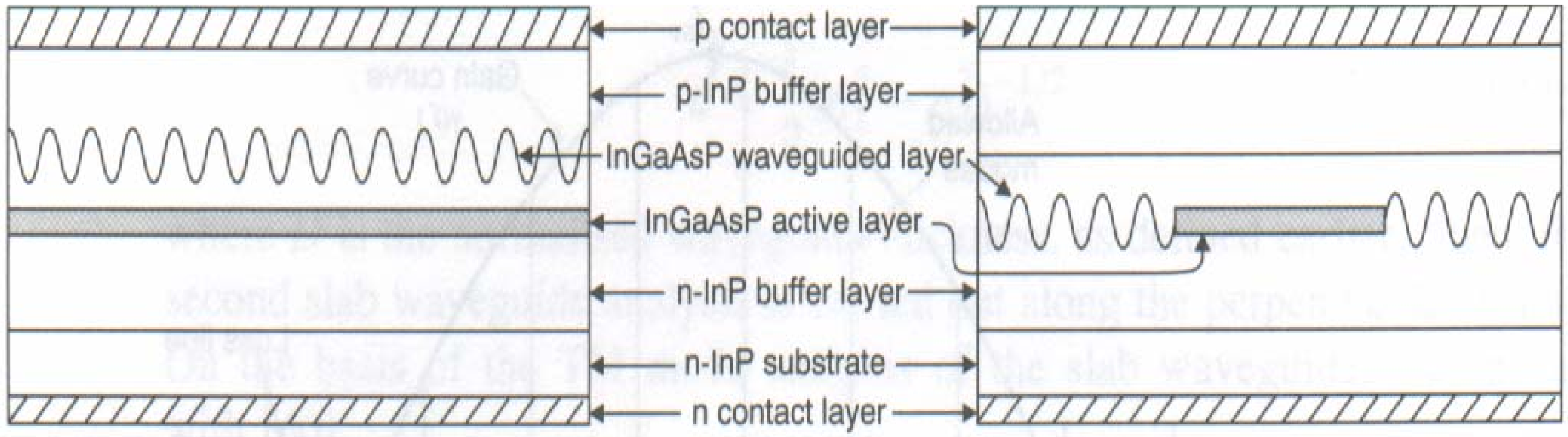


Recombination of electron and hole pairs generate radiation.

Quantum well lasers

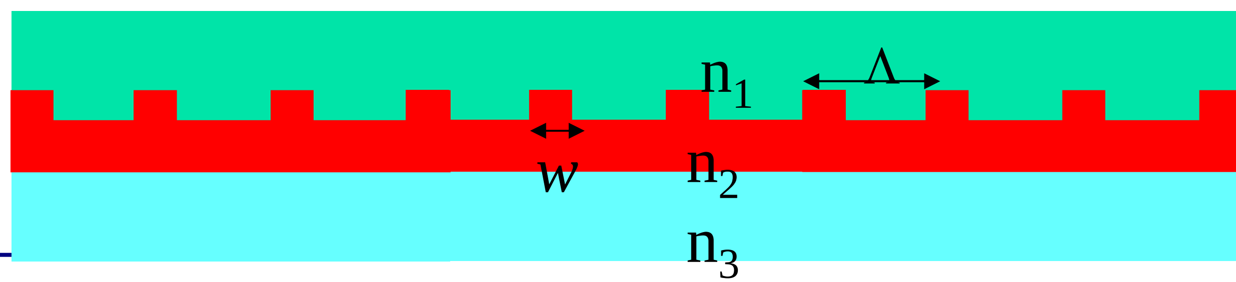


DFB v.s. DBR structures

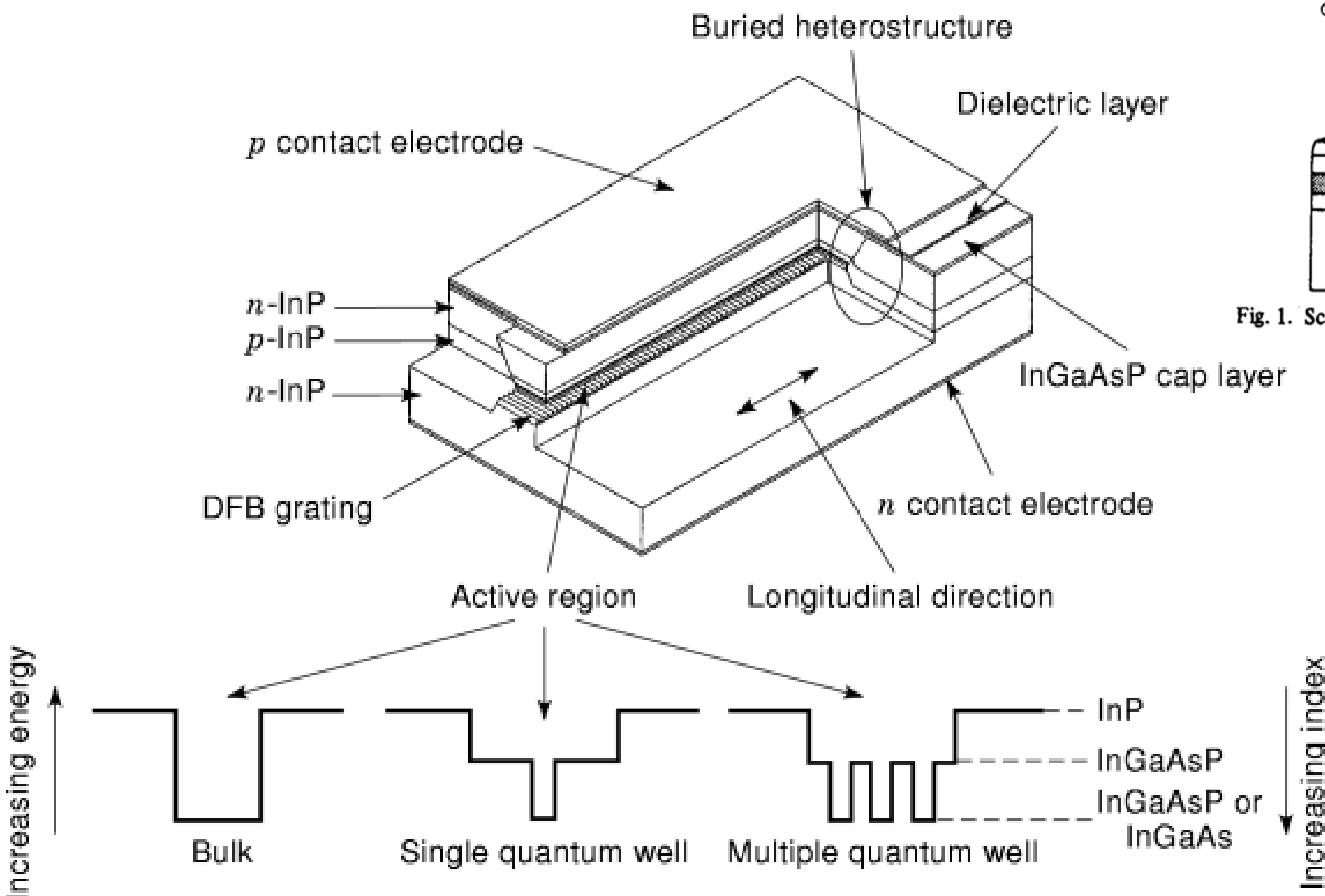


Distributed Feedback
DFB

Distributed Bragg Reflector
DBR



Cross section of DFB Lasers



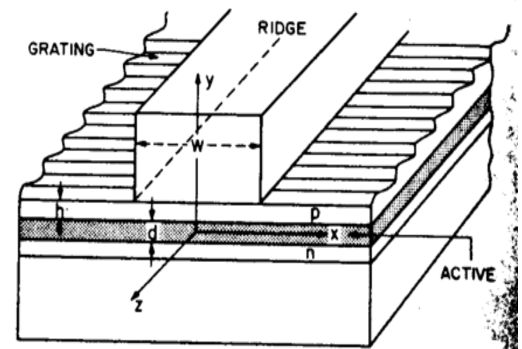
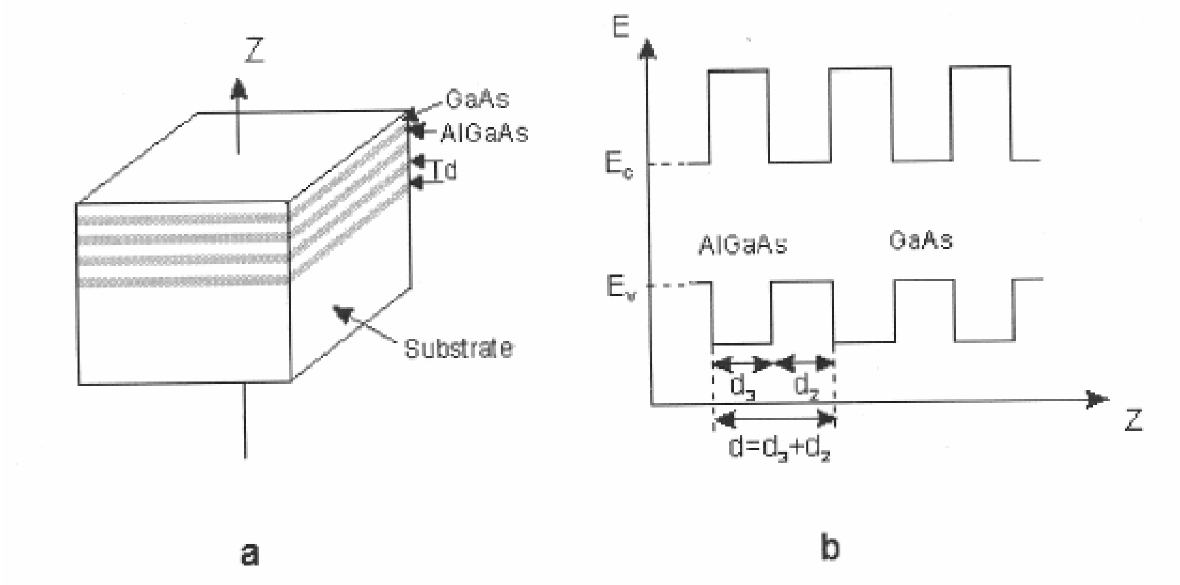
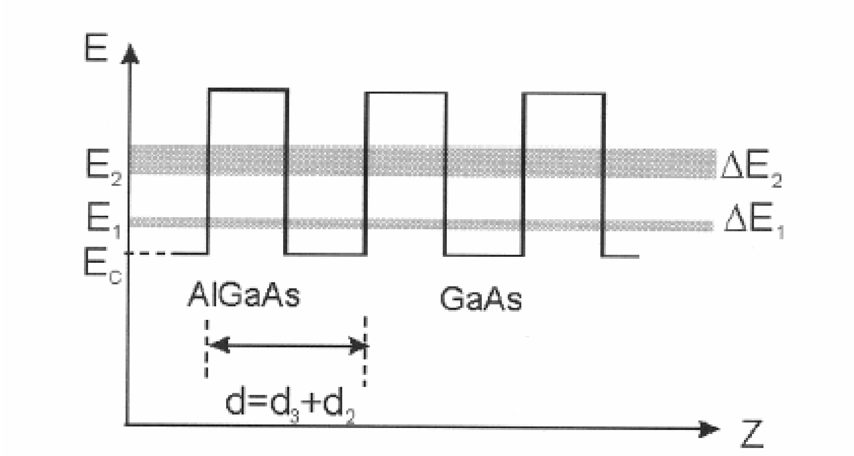


Fig. 1. Schematic view of a ridge-waveguide distributed feedb

Semiconductor superlattice

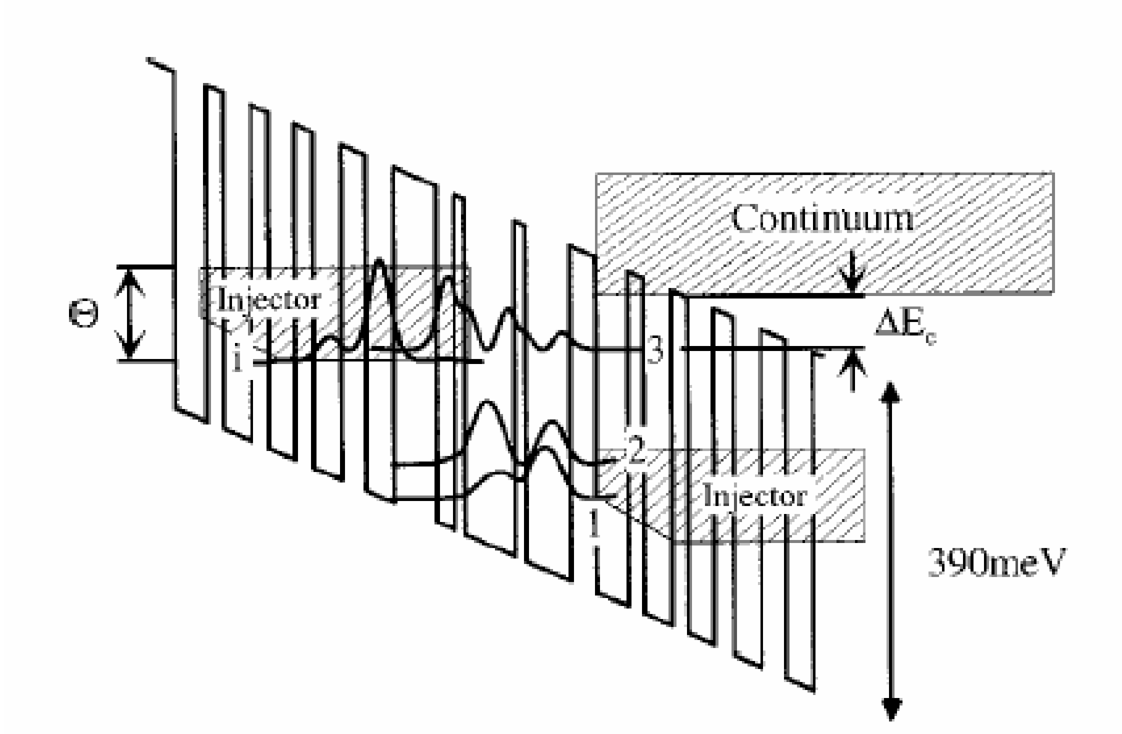




Ref: Prasad, chapter 4, figures 10 and 11.

Intersubband transition

- Intersubband transition can be used to generate or detect mid-infrared radiation (~ 10 μm).



Ref: H. Page et al., Appl. Phys. Lett., **78** (2001) 3529.

Quantum confined Stark effect (QCSE)

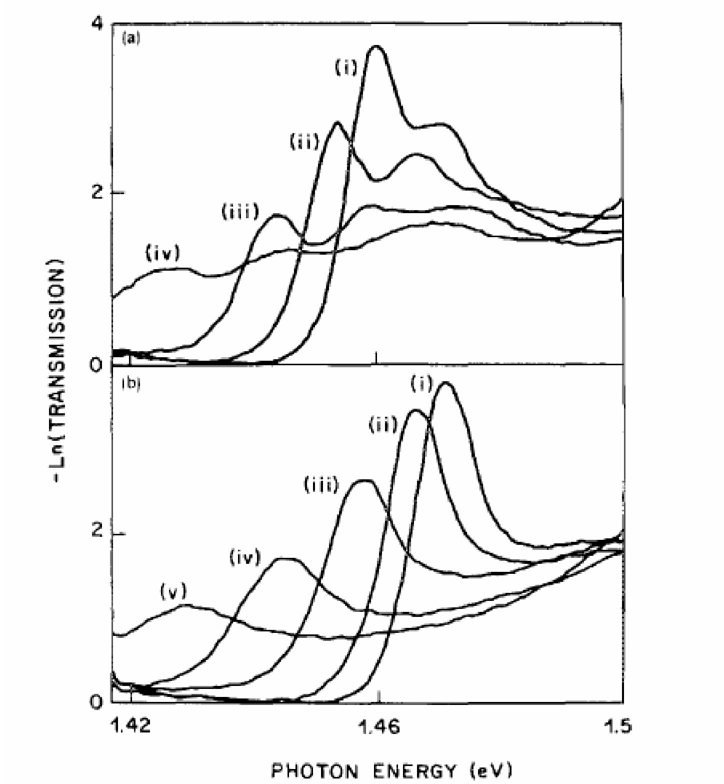
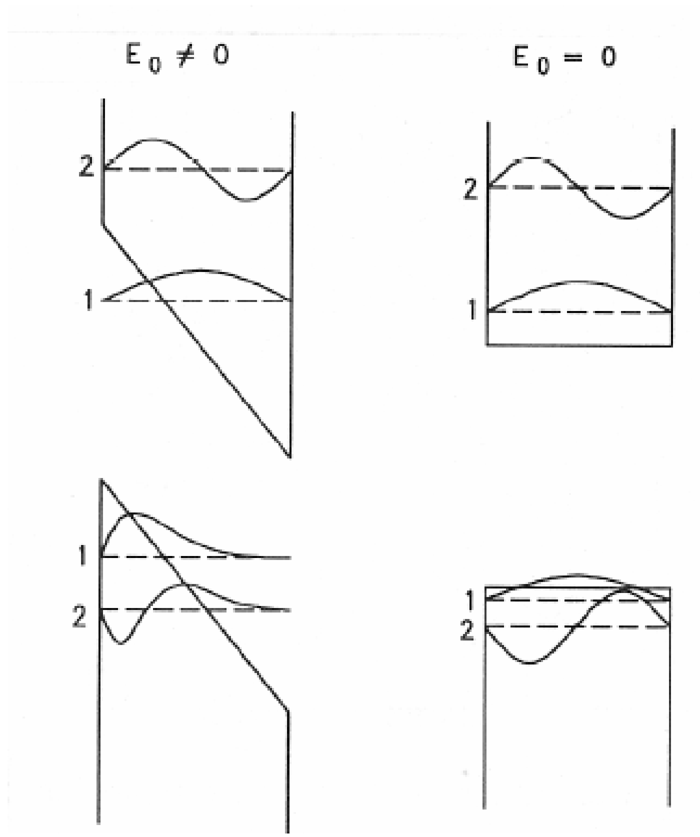
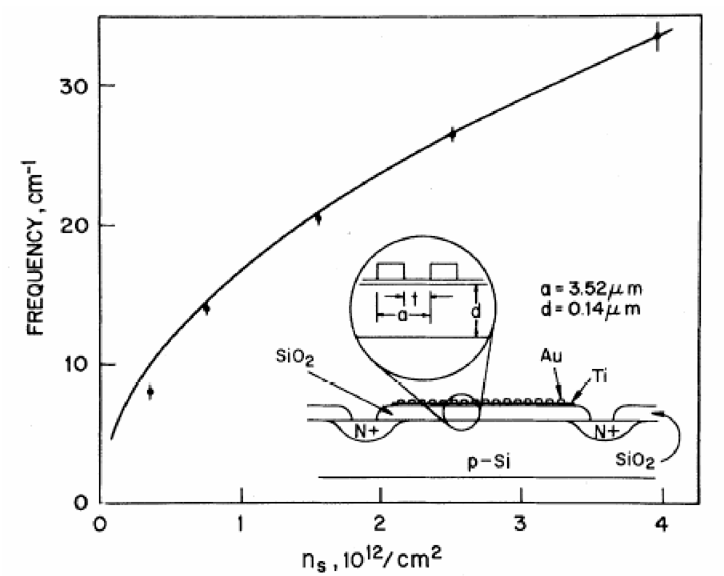


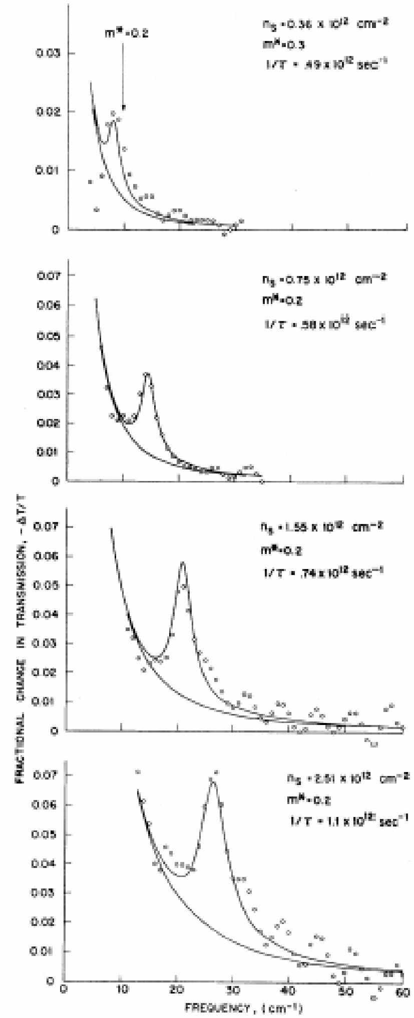
FIG. 2. Absorption spectra of a quantum well waveguide as a function of electric field applied perpendicular to the layers. (a) Incident polarization parallel to the plane of the layers for fields of (i) 1.6×10^4 V/cm, (ii) 10^5 V/cm, (iii) 1.3×10^5 V/cm, and (iv) 1.8×10^5 V/cm. (b) Incident polarization perpendicular to the plane of the layers for fields of (i) 1.6×10^4 V/cm, (ii) 10^5 V/cm, (iii) 1.4×10^5 V/cm, (iv) 1.8×10^5 V/cm, and (v) 2.2×10^5 V/cm. The fields were calculated from *C-V* measurements.



Ref: J. S. Weiner et al., Appl. Phys. Lett., **47** (1985) 1148.

2D plasmons realization





Ref: S. J. Allen et al., Phys. Rev. Lett., **38** (1977) 980.

Increase of quantum confinement in indirect semiconductors

- Confinement of electrons and holes in a small volume increase the possibly allowed Δk and therefore enhances the emission efficiency of an indirect semiconductor, e.g. silicon.

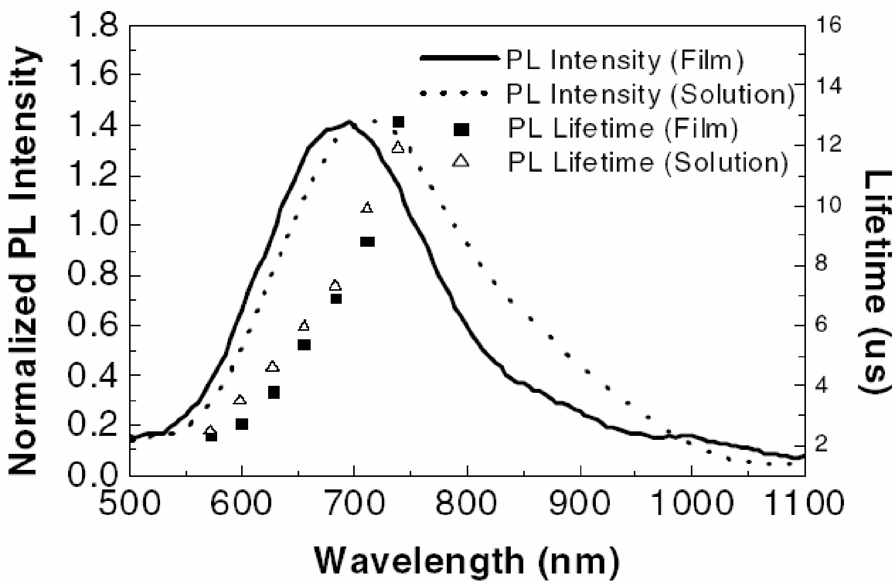


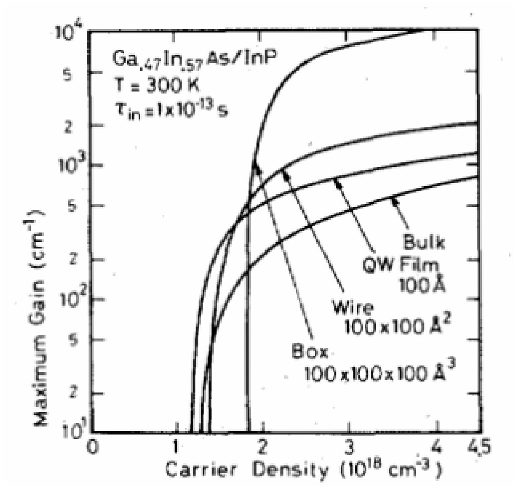
Figure 2. CW Emission and photoluminescence lifetime (400 nm excitation) of a silicon nanoparticle sample when embedded in PMMA and when dispersed in chloroform solution. The lifetimes were obtained using a single-exponential fit.

Ref: W. D. Kirkey et al., MRS Symp. **789** (2004) N15.30.1.

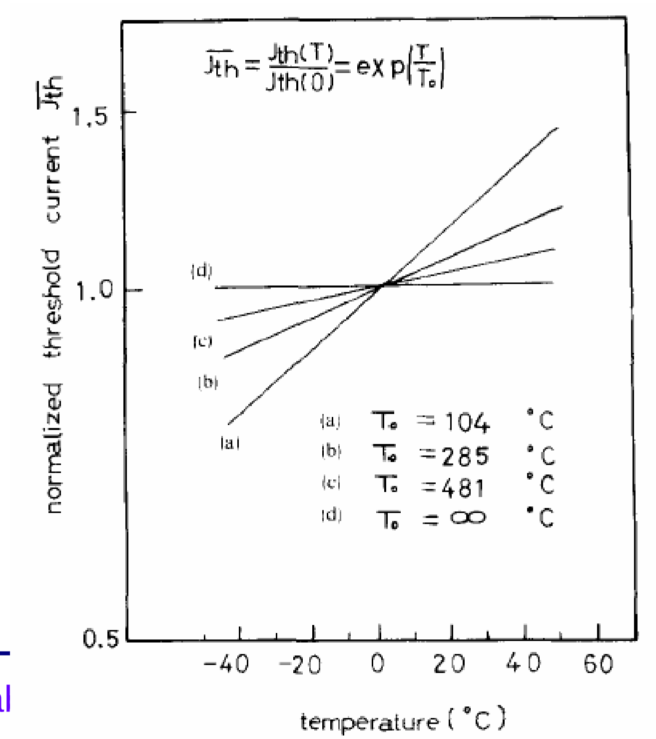
Quantum dot lasers

- Reduction of threshold current
- Reduction of temperature dependence → uncooled operation
- Increase in differential gain
- Smaller linewidth enhancement factor

} Better high-speed performance



M. Asada et al, J. Quantum Elec., **22** (1986) 1915.

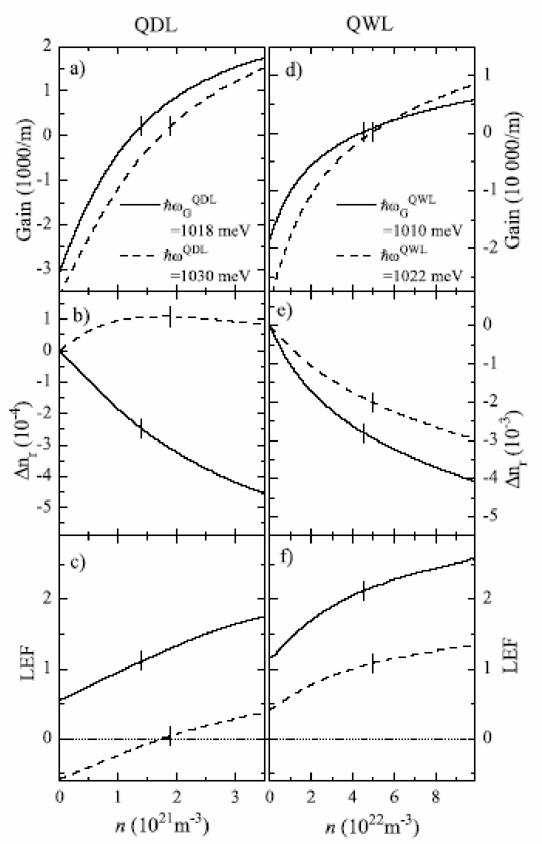


Y. Arakawa and H. Sakaki, Appl. Phys. Lett., **40** (1982) 939.

α – linewidth enhancement factor

- Change of carrier density (e.g. due to amplitude modulation) → change in absorption/gain → change in refractive index (via Kramers-Kronig relation)

$$\alpha \equiv \frac{\partial \operatorname{Re} \varepsilon / \partial N}{\partial \operatorname{Im} \varepsilon / \partial N}$$



Ref: J. Oksanen and J. Tulkki, J. Appl. Phys., **94** (2003) 1983.

Quantum optics in semiconductor QD's

- Rabi oscillation:

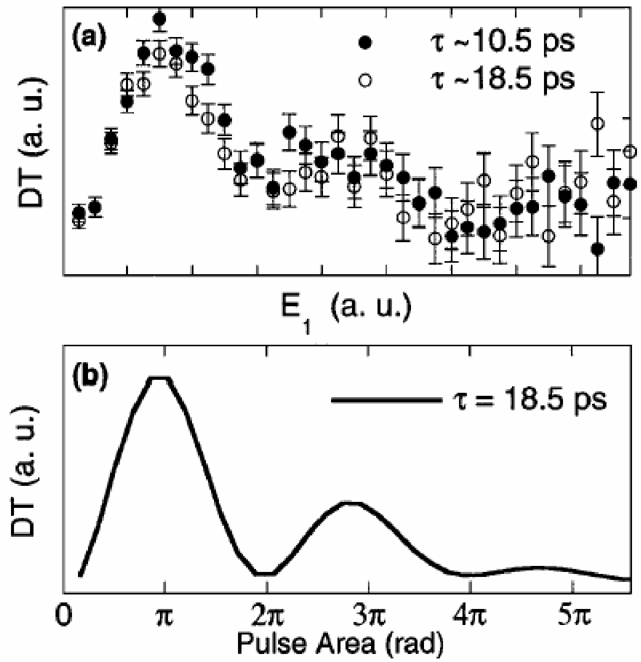
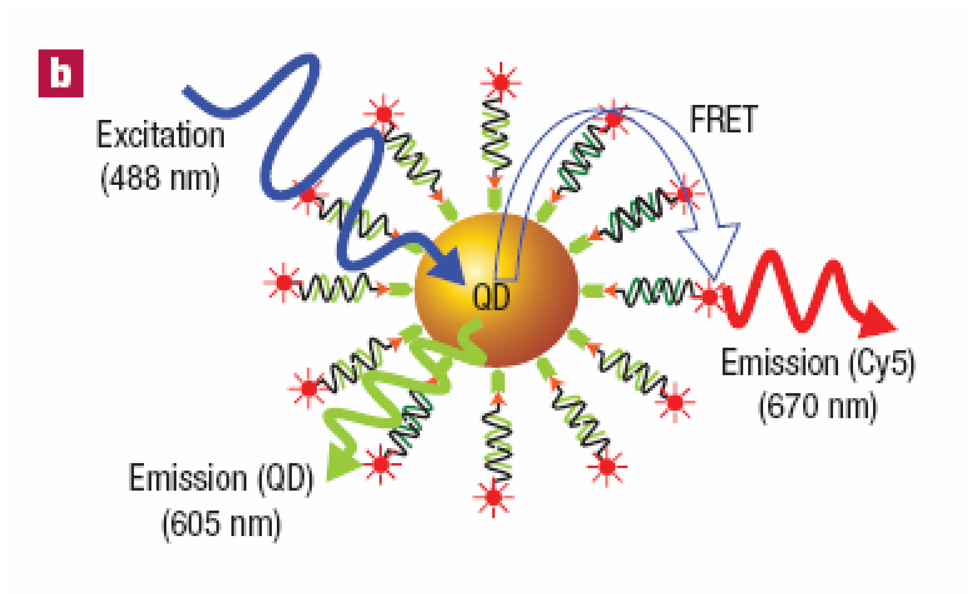


FIG. 3. (a) Measured DT vs pump field amplitude for $\tau = 10.5$ ps and $\tau = 18.5$ ps. Both data sets show behavior consistent with Rabi oscillations for the excitonic QD state under investigation. (b) Calculated DT for an 18.5 ps probe delay, including a continuum of delocalized excitons in the dynamics.

Ref: T. H. Stievater et al., Phys. Rev. Lett., **87** (2001) 133603.

Quantum dot biosensors



FRET = fluorescence energy transfer

Ref: C. Y. Zhang et al., Nature Mat., **4** (2005) 826.

Nonlinear optical properties in semiconductors

- Plasmon screening
- Exciton ionization

} Exciton signature reduction

- Bandfilling → blue shift
- Bandgap renormalization → red shift
- Thermal nonlinearities → red shift for most of materials