Lasing in Silicon

$$\text{InternalQuantumEfficiency } \eta_i = \frac{\tau_{\text{non-rad}}}{\tau_{\text{non-rad}} + \tau_{\text{rad}}}$$

For direct bandgap semiconductors, ς_i > 10 %
For silicon, ς_i is as low as 10^{-4} % to 10^{-5} %

Key factors that affect ς_i of Si nanocrystals[1]

1. Auger non radiative recombination
2. Quantum confined stark effect
3. Free Carrier Absorption

Lasing in Silicon is achieved using[1]:

- Microcavities
- Quantum confinement effect
- Porous Silicon
- Silicon quantum wires and quantum dots
- Si/SiO_2 quantum wells

"Once you reduce silicon to nanometer dimensions it is able to amplify light"- **Dr.Lorenzo Pavesi**, Associate Professor, Experimental physics, University of Trento, Italy[2].

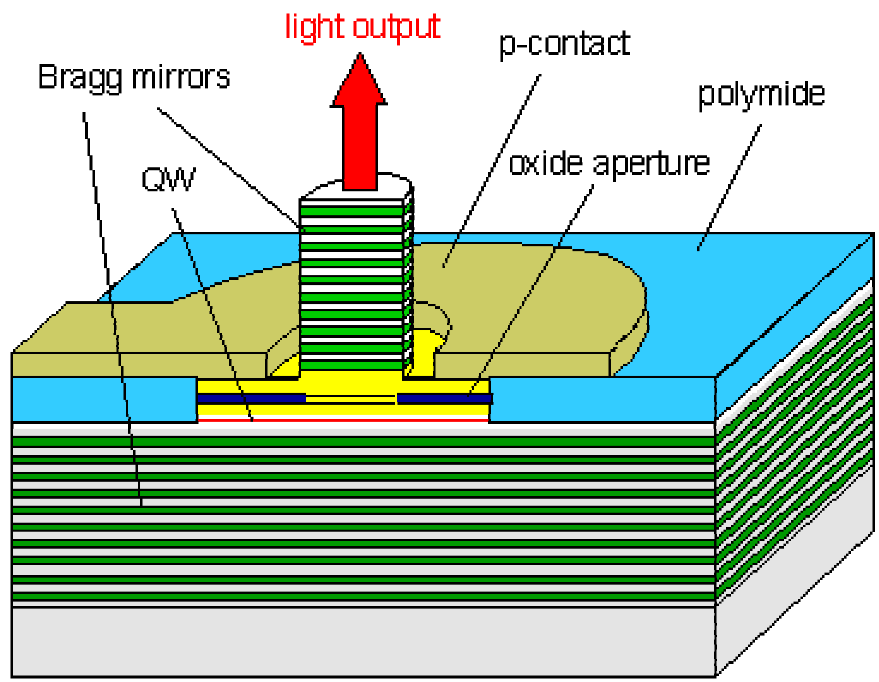
1. P.M Fauchet,S.Chan,H.A lopez and K.D Hirschman
Silicon light Emitters: preparation, properties,limitations and integration with microelectronic circuitry,edited by Loreno Pavesi, Kluwer Academic Press, 2000
2. http://www.trnmag.com/Stories/121300/Silicon_nanocrystals_glow_121300.html

Microcavity

1. When a semiconductor layer is placed in between an optical microcavity, Any slight change in the refractive index will induce a change in the reflectivity spectrum as well as in its photoluminescence spectrum[1].

2. The porous **silicon microcavity** was formed with a porous **silicon** active layer in the middle and sandwiched in between two multi-layered Bragg reflectors. Compared with a porous **silicon** single layer, the peak value of the emission intensity increased and the full width at half maximum value of the photoluminescence resonance noticeably narrowed when a **microcavity** structure was used [3].

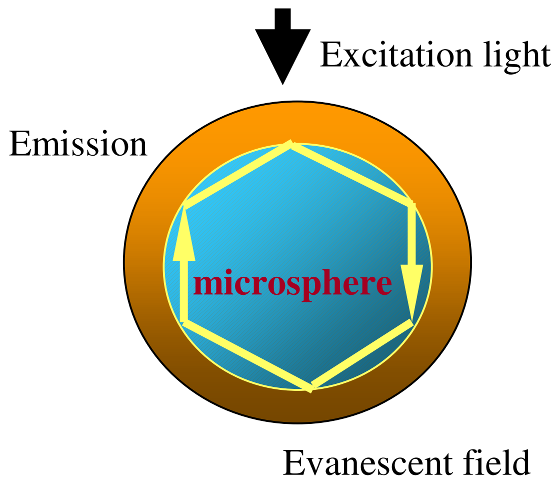
3. The luminescence from a microcavity resonator is highly directional, so the power efficiency is improved because the loss of optical power along unwanted directions is minimized 2.



Lateral Patterning made by lithography and dry etching[4]

1. http://www.ece.rochester.edu/users/schan/sensor.html
2. http://www.ece.rochester.edu/users/schan/electrical.html
3. Young-You Kim [a]; Jong-Hyun Jeon; Eun-Jun Ahn; Ki-Won Lee Photoluminescence resonance properties of a porous silicon microcavity Sae Mulli Volume 44, Issue 4, 2002, Pages 224-228
4. http://www.physik.uni-wuerzburg.de/TEP/Website/groups/opto/vcsel.htm

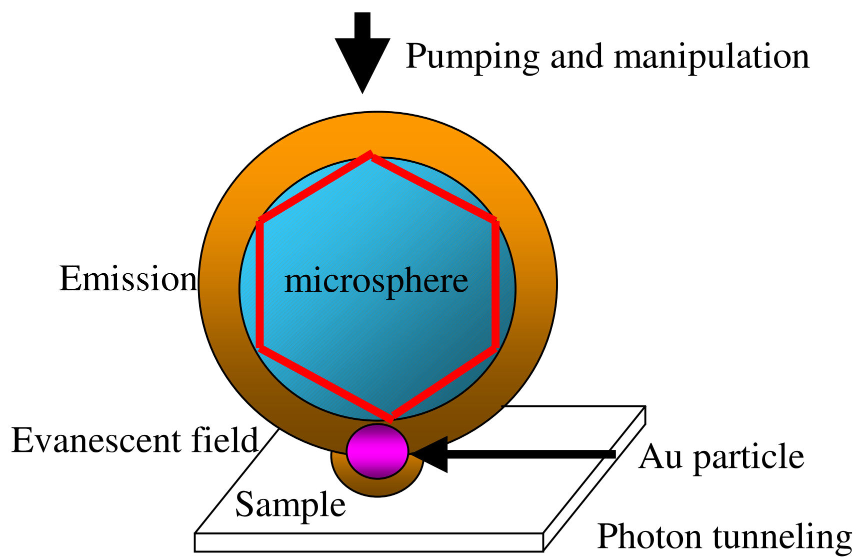
Microspherical Cavity



Under the resonance condition, light field inside the sphere will be enhanced and evanescent field will be generated just outside of the sphere. This is whispering gallery mode.

As the lights at resonance wavelengths were strongly confined near the surface, Q factor of the microspherical cavity reaches 10^4 - 10^8 so that laser oscillation can be induced within a dye-doped microsphere. The resonant field in the cavity penetrates just outside of the microsphere as evanescent field.

By attaching a nanometer-sized metallic particle to this lasing microsphere and manipulate it, the intense evanescent field will be modified and localized around the small particle. This part can work as the small light source.



Microsphere shown here is,
Rhodamine B doped PMMA microsphere (concentration = 10^{-3} mol/l, diameter = 24 micrometer).

http://optsys.es.hokudai.ac.jp/~fuji/res1_e.html

Porous Silicon

• Porous silicon is made by electrochemical etching bulk silicon wafer with aqueous hydrogen fluoride solution.

• The porosity of a sample is defined as the amount of air in the material after processing has finished, so a 45% porous sample would contain 45% air and 55% silicon.

• Light emission from porous silicon occurs mainly in the visible region of the electromagnetic spectrum.

• The emission has the unique property that the wavelength of the emitted light can be changed simply by increasing or decreasing the porosity of the material.

• For example, a highly porous sample (70-80% porosity) will emit green/blue light while a less porous sample (40%) will emit red light.

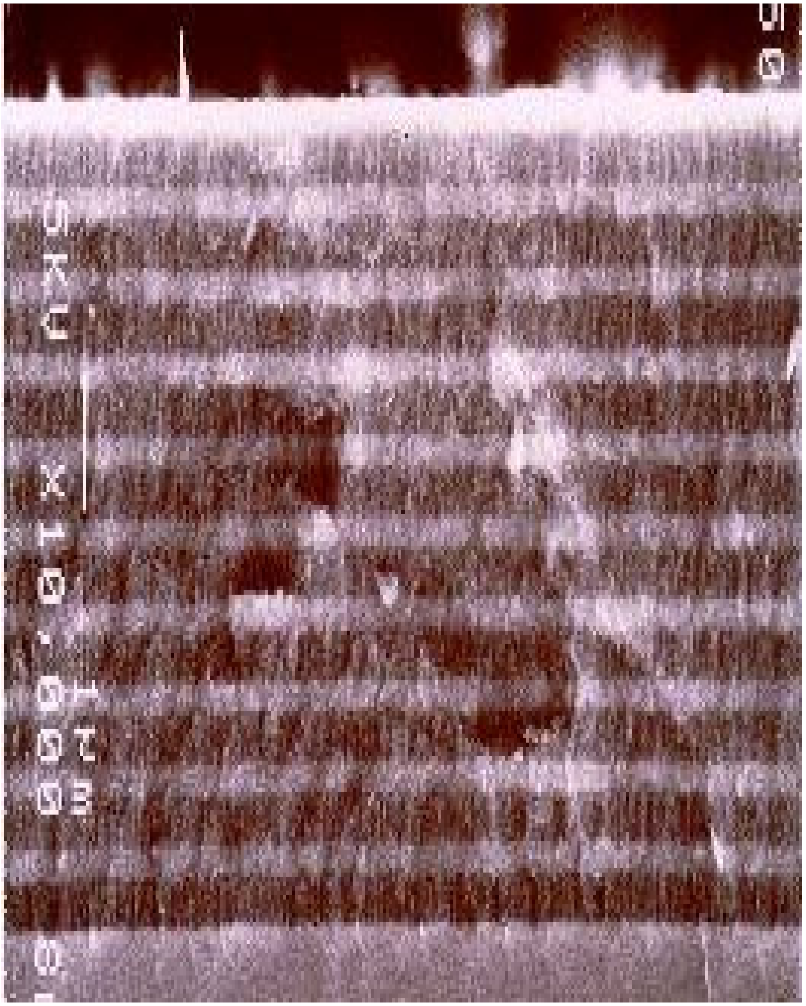
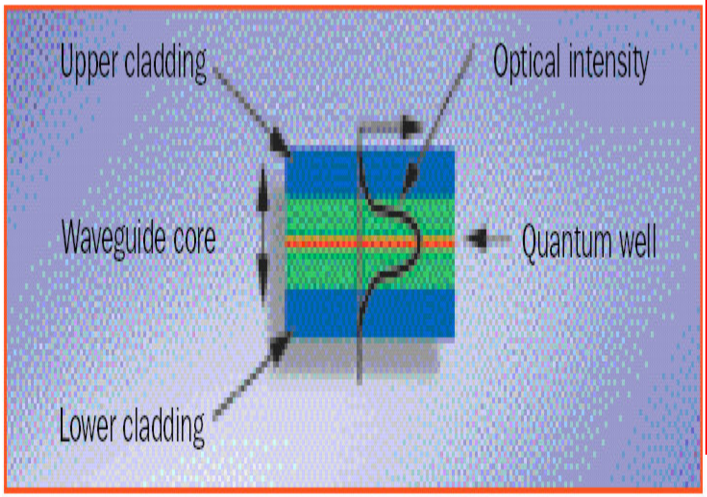


Fig: A porous silicon multilayer stack with a pitch of about half a micron, made by the electrochemical etching of a normal silicon wafer. The lighter layers are more porous than the darker layers. The stack is a very effective mirror, with a peak reflectivity of 95% at a wavelength of 950 nm.

http://www.bath.ac.uk/physics/groups/opto/old/research.htm

Cross-sectional TEM of a 4 nm Si quantum wire after stress-limited oxidation[1].



Quantum Wires and Quantum Dots

In a quantum wire the electron movement is confined in two out of three directions in space, i.e. it can only move along the wire. To drastically affect the properties of the material the diameter of the wire need to get close to 100 Å [1].

In a quantum dot the electron movement is confined in all three directions. The quantum dot can be looked upon as a man made atom, fabricated out of app. 1000 real atoms [2].

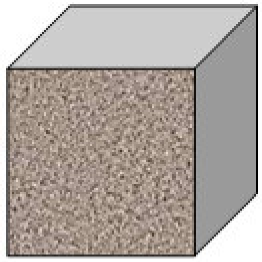
Quantum well

When an electric field is applied perpendicular to the surface of a quantum well, the optical absorption of the quantum well can be changed. This change in absorption is relatively large. In practice this means we can make small and efficient optical modulators using quantum wells[3].

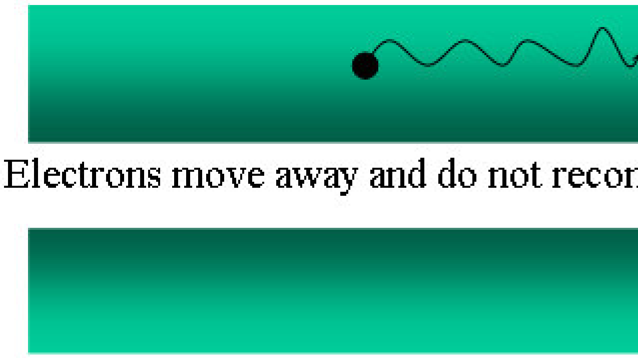
A QW is a very thin semiconductor layer,typically 10 nm, sandwiched between 'barriers' of larger bandgap. Because of the bandgap difference, electrons and holes are trapped in the QW. The small size of the well causes the electron and hole energy levels to become quantized, and so the bandgap energy of a QW is larger than that of an equivalent bulk layer[4].

1. http://buffy.eecs.berkeley.edu/IRO/Summary/99abstracts/jakub.2.html
2. http://www.ifm.liu.se/Matephys/AAnew/research/iii_v/easy0d1d.htm
3. http://www.bell-labs.com/project/oevlsi/tutorial/
4. John Marsh, A primer on quantum well intermixing-catalyst technology for photonic integrated circuits, Intense Photonics.

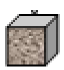
Bulk Si



1 cm



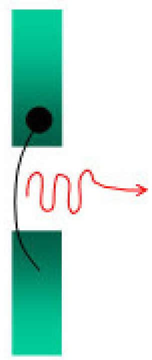
Si nc



100 atoms

1 nm

Electrons are confined and recombine



Light is generated

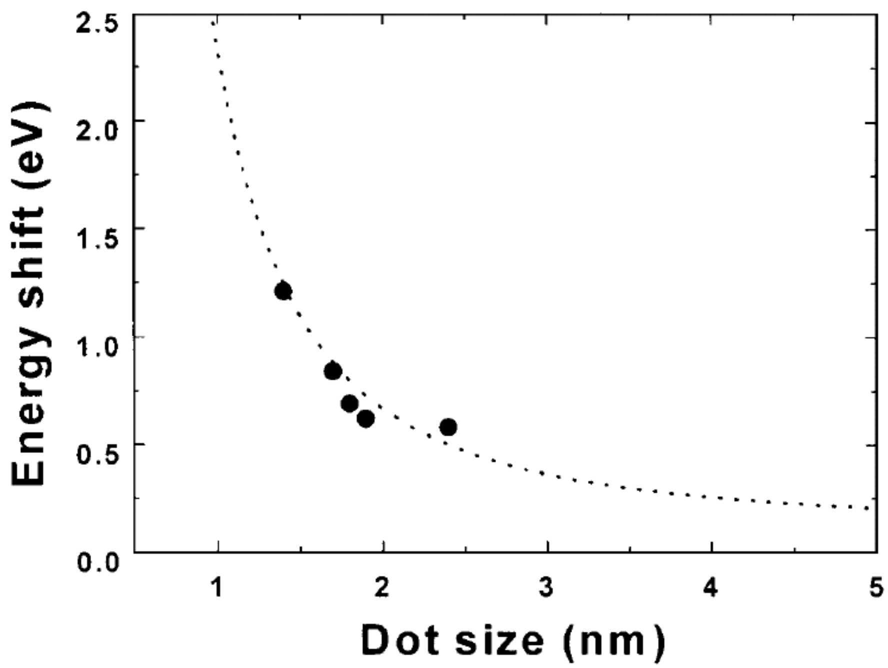
Quantum Confinement Effect

Quantum confinement effect enhances the electron-hole radiative recombination rate[1].

Band gap of *a*-Si QDs - from 2.0 to 2.76 eV [1]

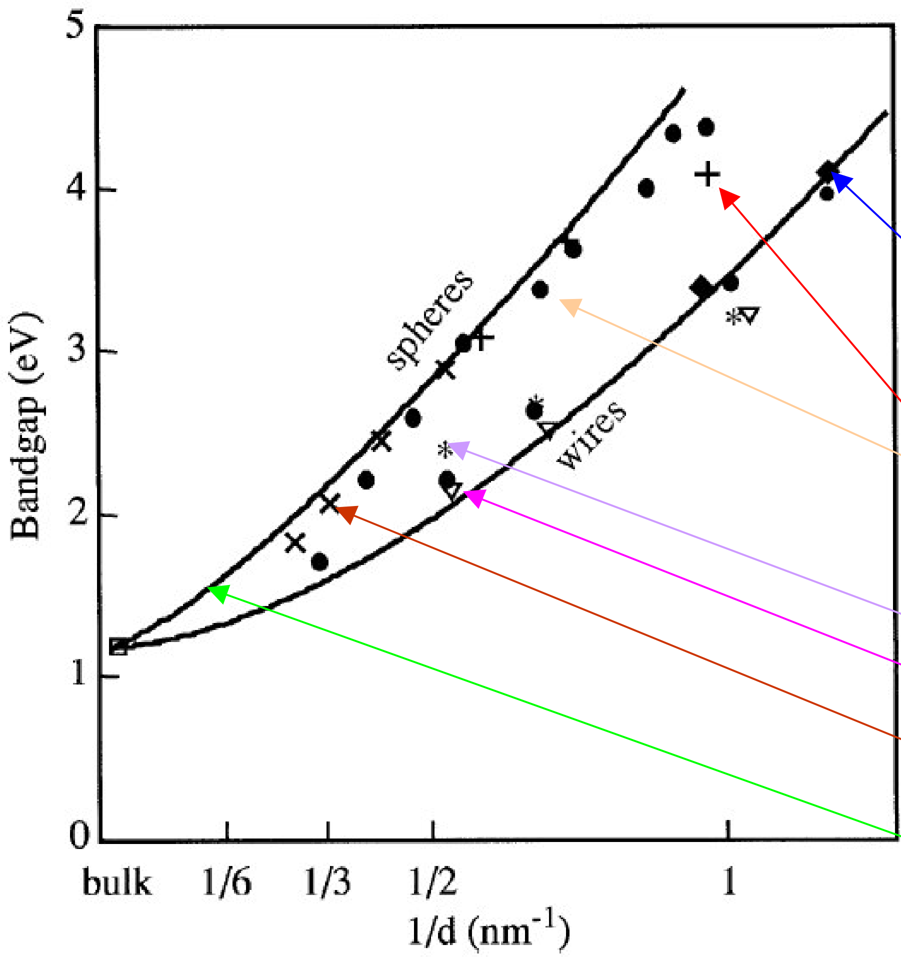
$$E(eV) = E_{bulk} + \frac{2.4}{a^2}$$

where E_{bulk} is the bulk *a*-Si band gap, *a* is the dot size



Nae-Man Park, Chel-Jong Choi, Tae-Yeon Seong, and Seong-Ju Park*,**Quantum Confinement in Amorphous Silicon Quantum Dots Embedded in Silicon Nitride,** *Department of Materials Science and Engineering and Center for Optoelectronic Materials Research, Kwangju Institute of Science and Technology, Kwangju, 500-712, Korea*

Energy Gap Vs Confinement Factor 1/d



$$d = a(0.75N\pi)^{\frac{1}{3}} \text{ for clusters}$$

$$d = a(0.5\frac{N}{\pi})^{\frac{1}{2}} \text{ for wires}$$

N is Number of Silicon atoms in the unit cell

a = 0.54 nm

By Mintmire

Ab initio Local Density Approximation (LDA)
By Delley et al

By Hirao et al

By Buda et al

By Read et al

Emprical PseudoPotential (EPS)

Emprical Tight Binding (ETB)

ETB, LDA have good fit

Optical band gap of Si nanoclusters,C.Delure,
Journal of Luminescence,80 1999 65-73

Recombination Rate Vs Band gap

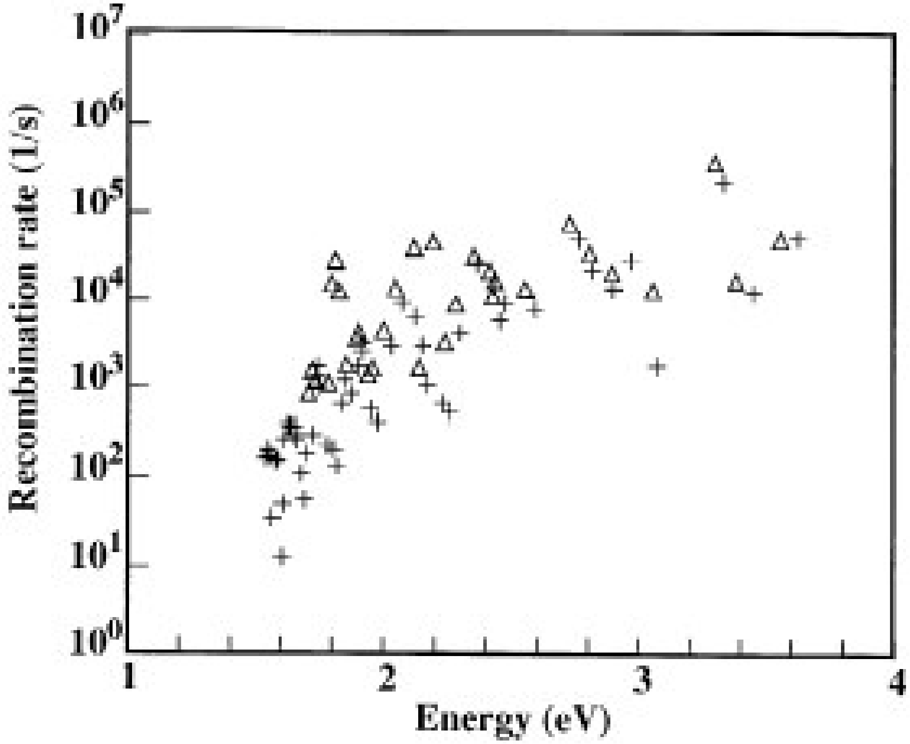


Fig. 7. Radiative recombination rate calculated for clusters of $Si_{0.8}Ge_{0.2}$ (triangles) and Si (crosses) with respect to their band gap.

Optical band gap of Si nanoclusters,C.Delure,
Journal of Luminescence,80 1999 65-73