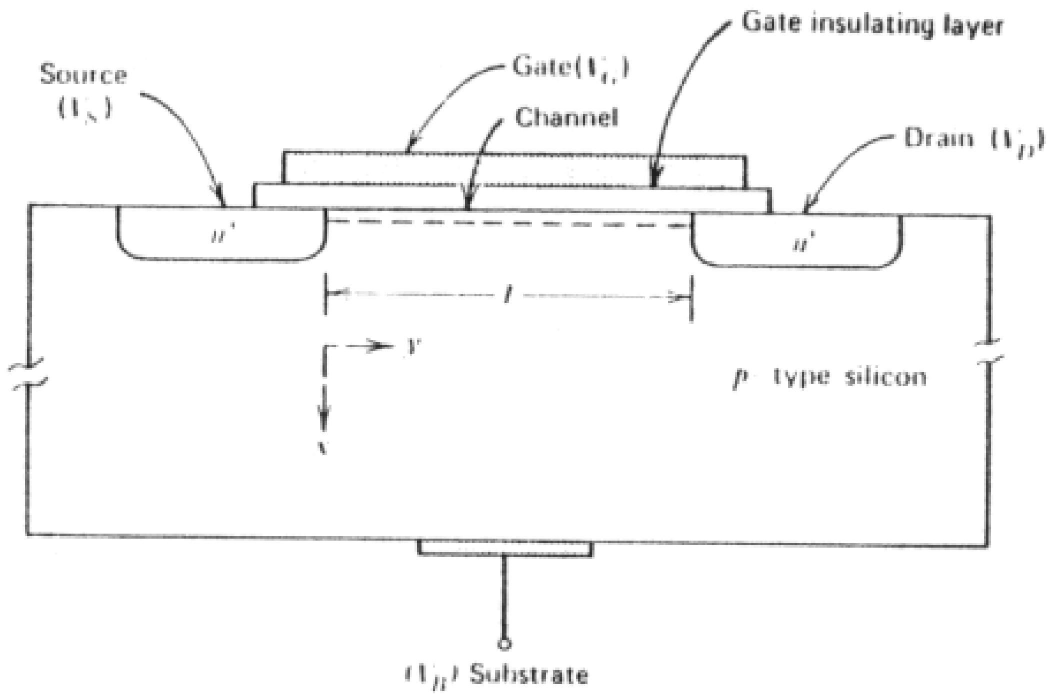
Efforts to reduce the size



Limitations to silicon MOSFET circuits.
New devices: Single electron transistors, resonant tunneling diodes.

Benefits of scaling

• Reducing the size of the transistors makes them faster and keeps the power consumption reasonable.

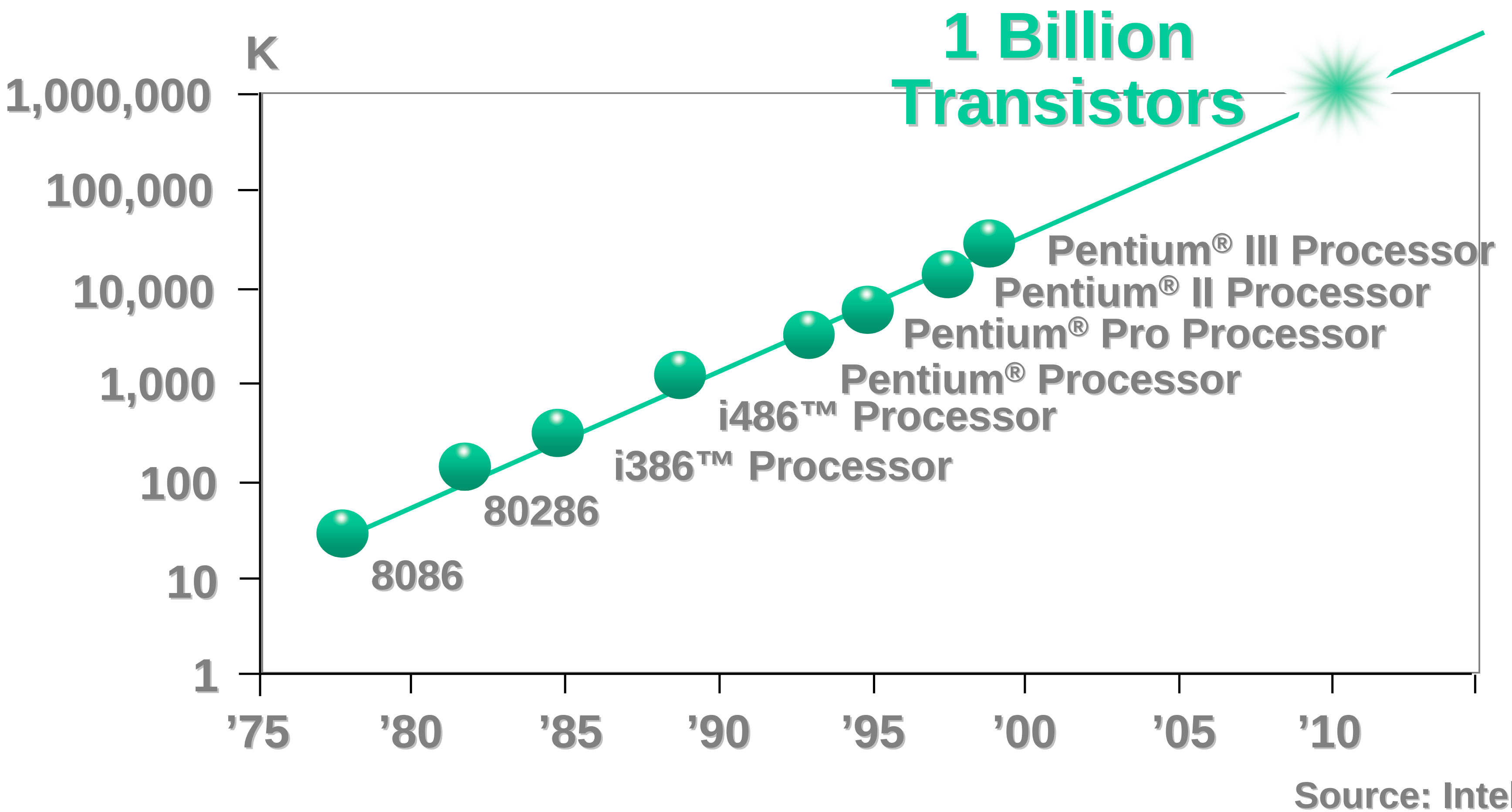
• Putting more transistors in a circuit enables more computation.

• Integrating several chips into one improves reliability.

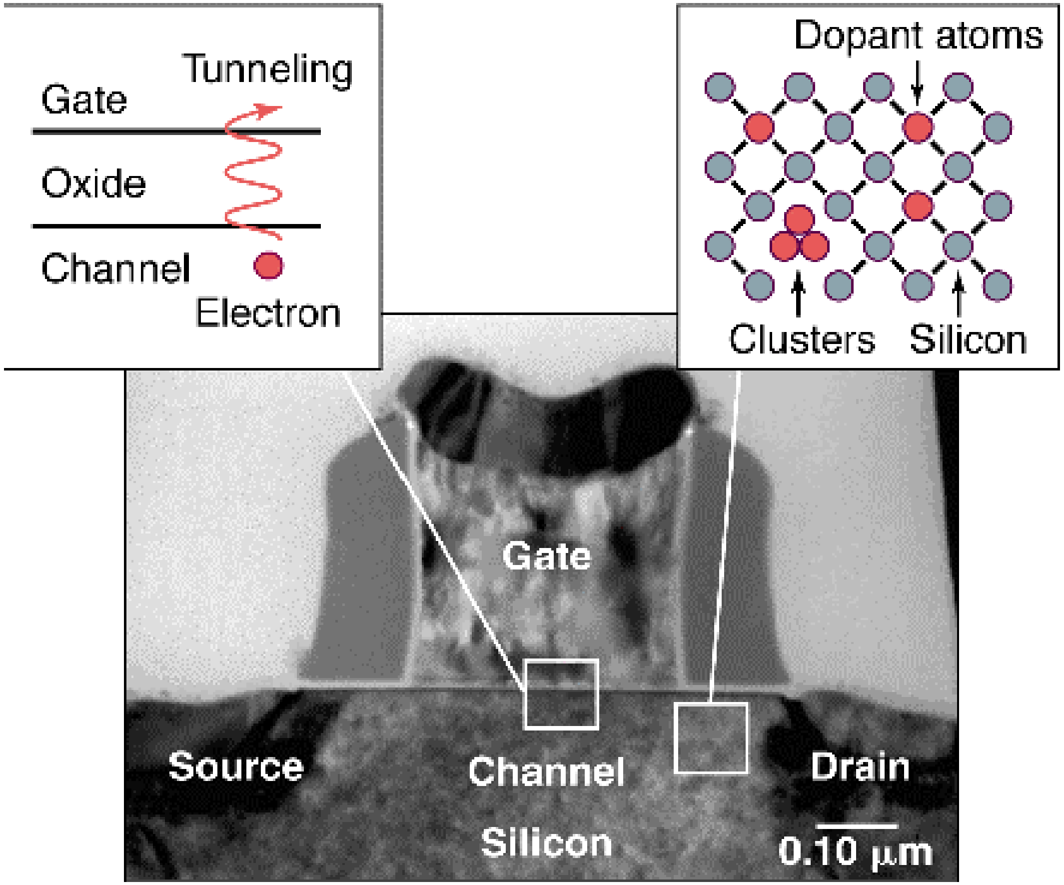
• Cost per transistor goes down.

How long will Moore's Law continue?

Billions of dollars will be spent to make sure that improvement of silicon chips stay on the curve predicted by Moore, but there are some serious obstacles that must be overcome.



Expected obstacles



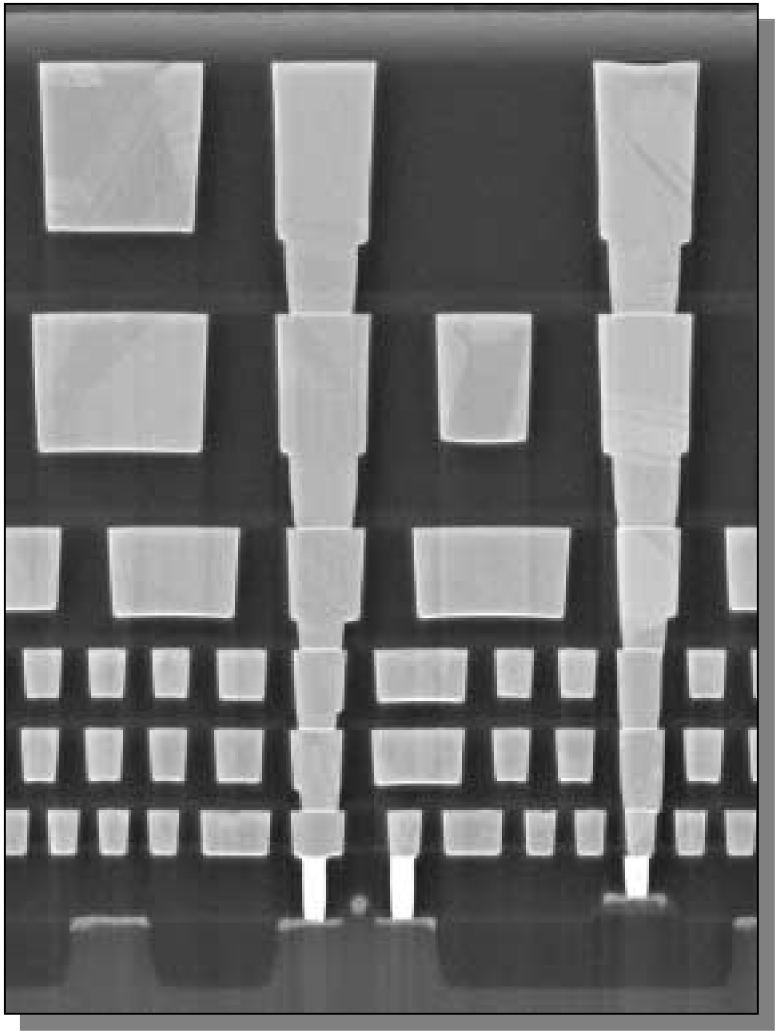
With very small channels, carriers could tunnel all the way across, even when there isn't supposed to be any current.

Paul Packan, *Science* **285** (1999) p. 2079.

Interconnects

The speed of circuits is starting to be limited by the RC time constant of the interconnects rather than the switching speed of the transistors. R is being reduced by using Cu instead of Al. C is being reduced by using a low-k dielectric, such as nanoporous silica, to insulate the wires from each other.

0.13μm Cu Interconnects



From Craig Barrett (Intel)

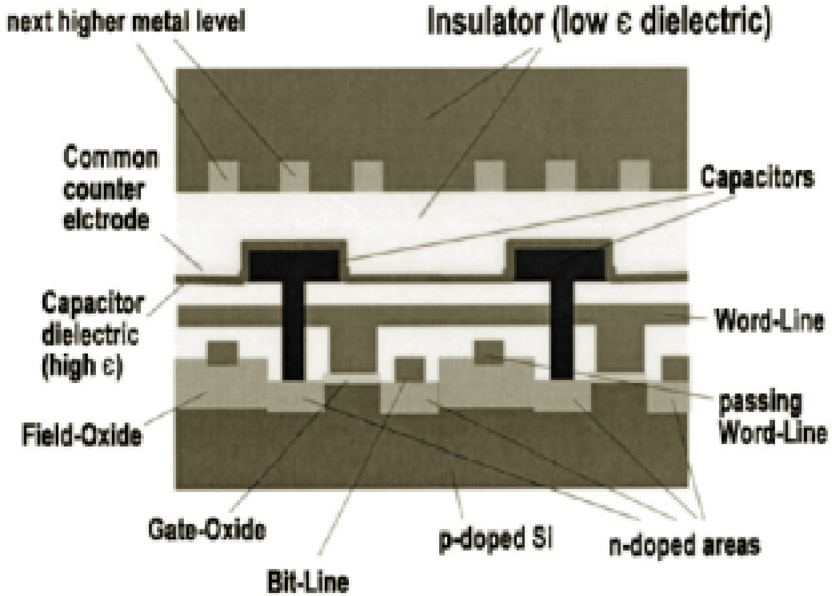


Fig. 1. Schematic representation of a DRAM-cell for storage of 1 bit.

Fig. 2. Interconnect array, three metallization levels [3].

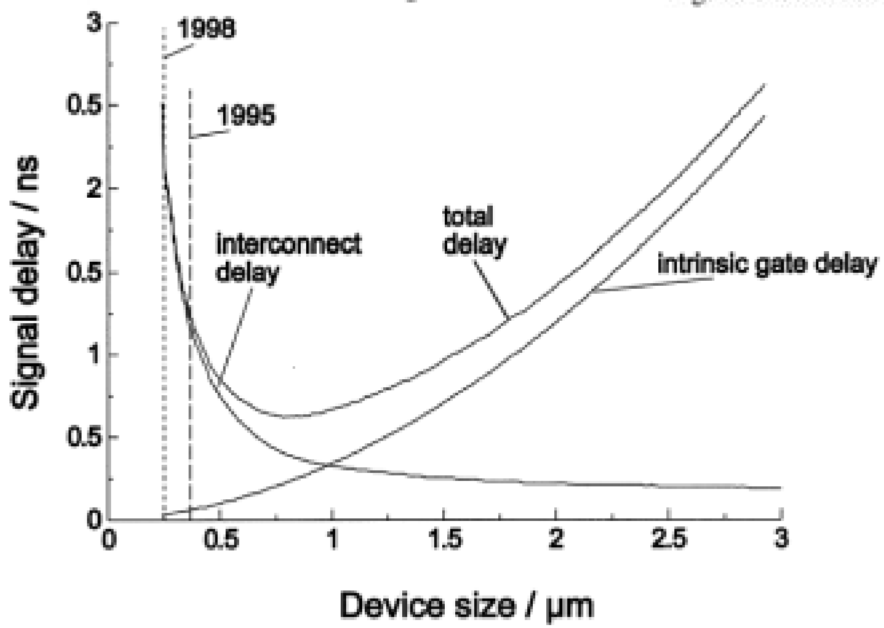


Fig. 3. Dependence of signal delay on device size [4,5].

Other obstacles

• The resolution of lithography must go below 100 nm.

• Heat must be dissipated.

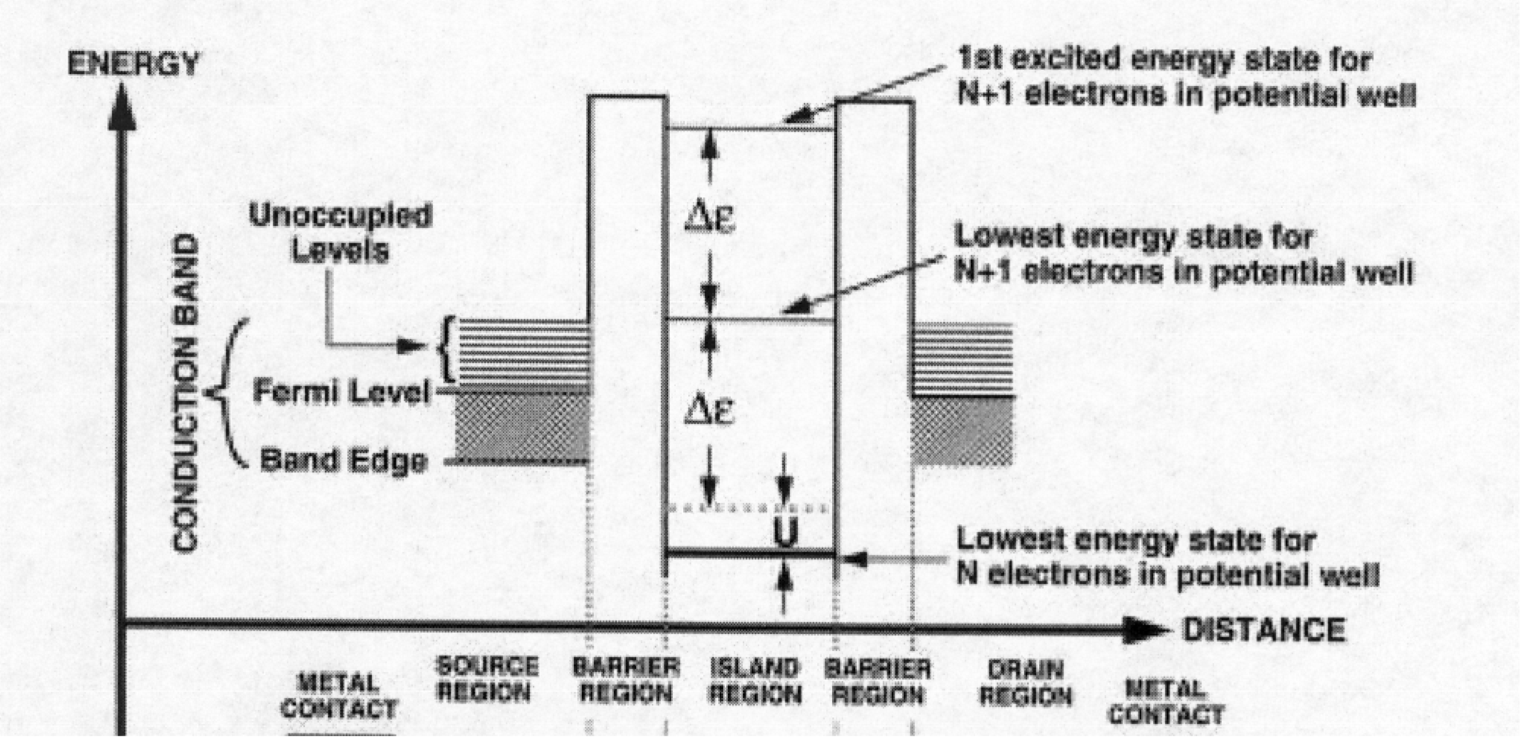
• Fabrication plants are costing billions of dollars.

As daunting as the problems are, it is expected that the silicon industry will find ways to solve them for at least 7 more years and maybe much longer.

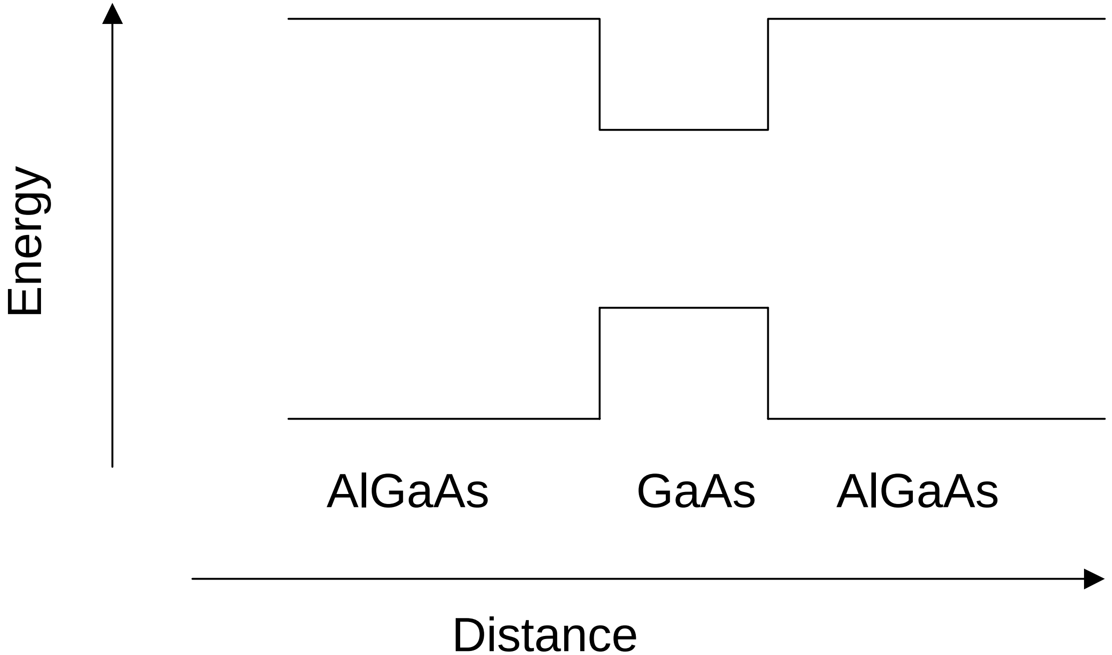
After ~2010: not how to push silicon (or germanium) technology forward, but how to make new devices with non-traditional fabrication techniques.

Nanoelectronics

Smaller devices will be made for all the reasons just given. When the devices become smaller than 100 nm in size, quantum mechanical effects such as energy quantization and tunneling will become important. These effects could be a problem, but they could be turned into an advantage.



Quantum wells (Electrons confined in one-dimension)



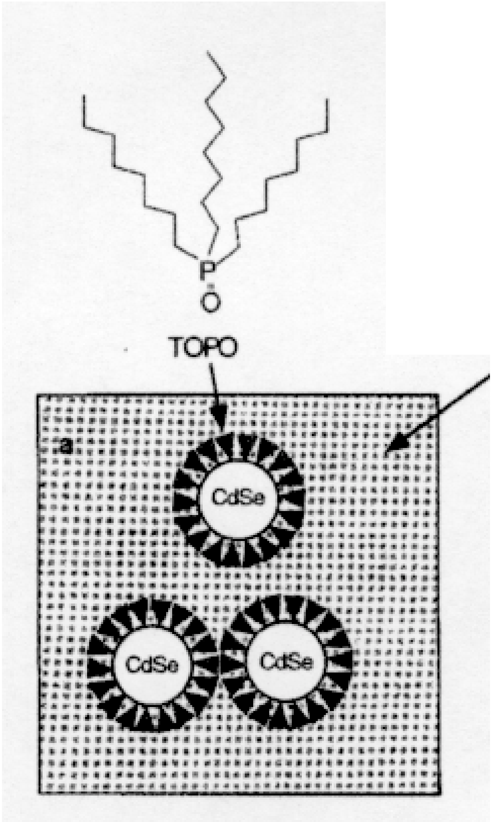
- Electrons are confined in one dimension and free in the other.

- A common method for making quantum wells is to use epitaxial methods to deposit alloys with varying composition onto a substrate.

Quantum dots (artificial atoms)

Electrons are confined in all three dimensions.

The energy levels are discreet, so these quantum dots are much like atoms.



Review Article

A.P. Alivisatos, "Semiconductor Clusters, Nanocrystals, and Quantum Dots," *Science* **271** (1996) p. 933.

Arrays of nanocrystals could be artificial crystals

Three things determine the electronic structure of a crystal

1. The energy levels of the atoms or lattice sites

2. The coupling between adjacent sites

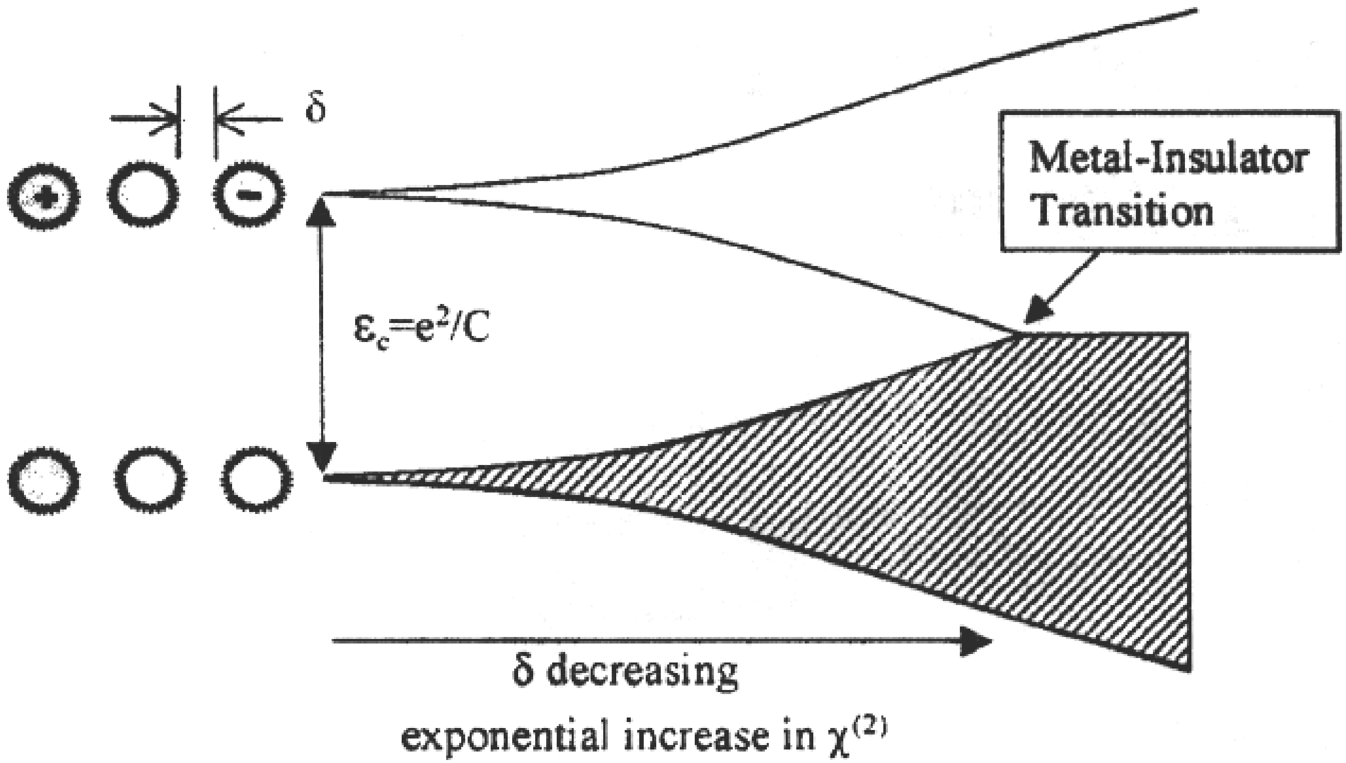
3. The symmetry of the solid.

A remarkably large number of materials with a wide range of properties can be made with the atoms in the periodic table.

New materials could be made if we could independently adjust each of the three parameters. One way to do this is to make arrays of nanocrystals, which can be thought of as artificial atoms.

James Heath et al., “Architectonic Quantum Dot Solids”, *Acc. Chem. Res.* **32** (1999) p. 415.

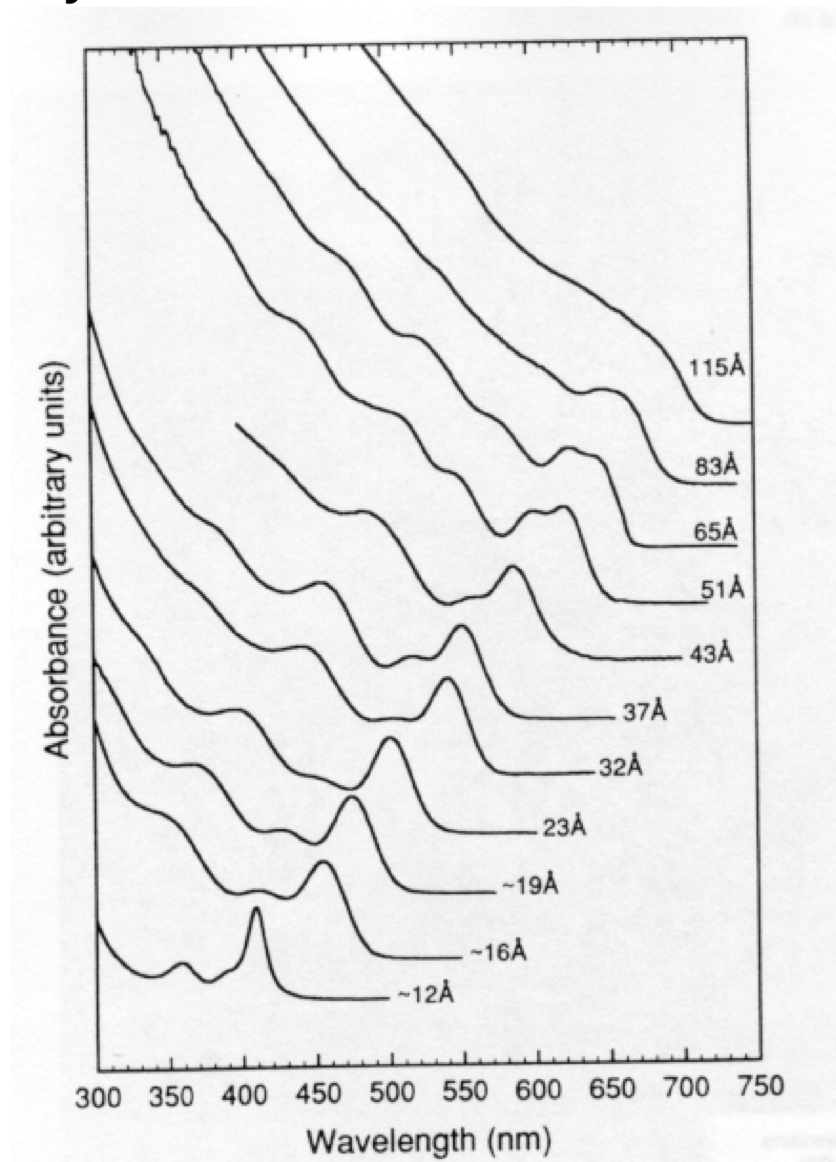
Tuning a crystal through a metal-insulator transition



James Heath et al., *Acc. Chem. Res.* **32** (1999) p. 415.

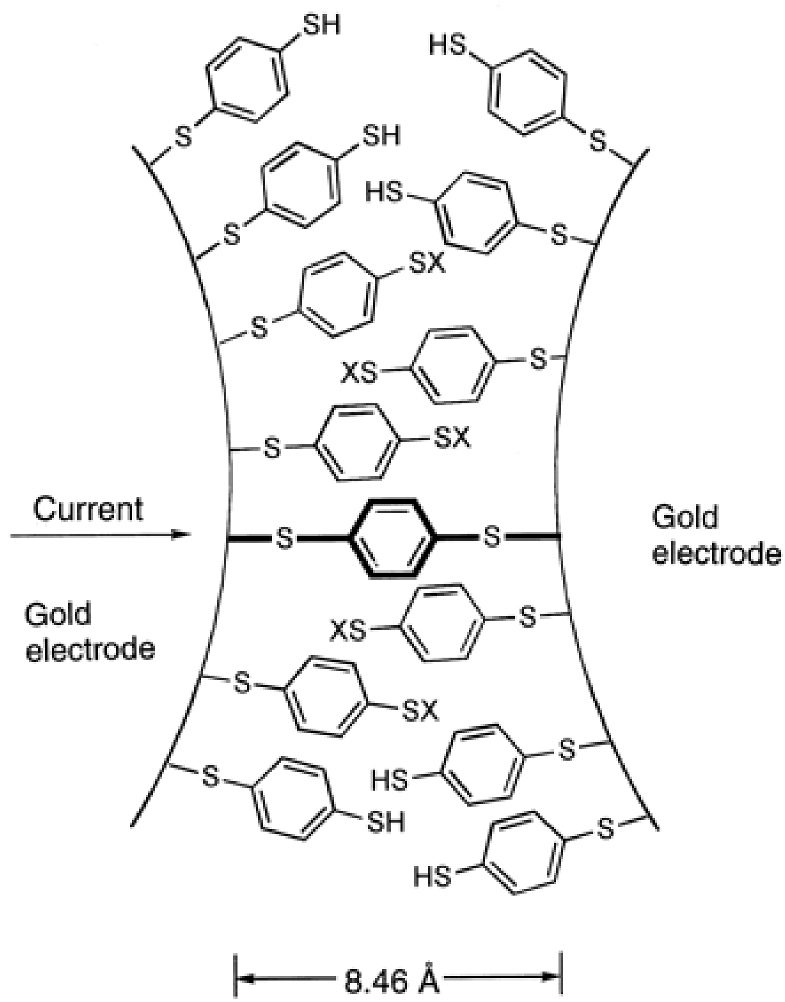
Nanocrystals

The absorption and emission spectra depend on the nanocrystal size.



M.G. Bawendi et al. *JACS* 115 (1993) 8706.

Molecular electronics



Mark Reed et al., *Science* **278** (1997) p. 252.