

Physics of semiconductors – selected topics

- 4h, 4cr, seminar type (to stimulate/induce for asking right questions)
- Style:
ask right questions → search → digestion → analytical thinking → useful knowledge → innovation
- Requirements:
 - Be present, actively participate in class and in labs
 - Perform computer simulation with given software package, may need simple programming with MATHLAB or others
 - Hand-on measurement experience in real laboratory settings
 - Be familiar with CUNY-wide semiconductor-related research labs
 - Submit 3 reports (ppt format) and present one of them

Topic #1

Semiconductor overview

2011-08-26

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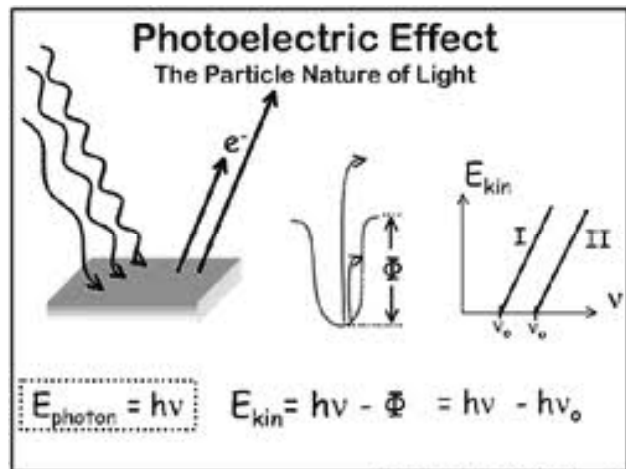
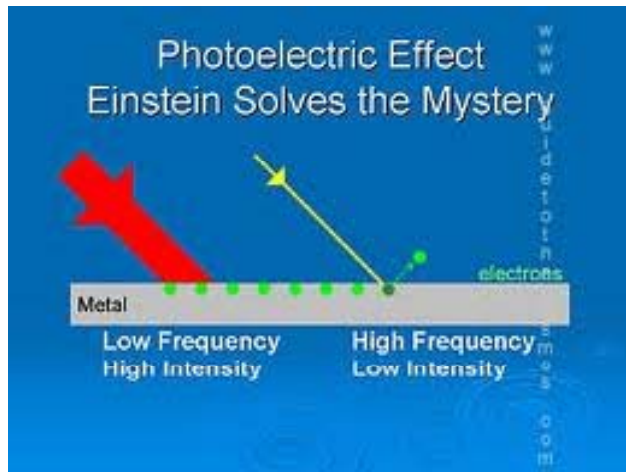
Contents

- **The dawn of semiconductors (1900 to 1947)**
- **Major semiconductor technology development stages**
- **Modern semiconductor device manufacture technologies**
- **The emerging nano era of semiconductors**
- Semiconductors in military/defense and aerospace (important, but not covered)

The dawn of semiconductors

- 1900 -1920: Quantum physics development
- Successful application of quantum physics to solid state → Solid State Physics → Band structure calculation methods (extended electronic states, band gaps, $E_g(T)$)
- 1939-1940: Discovery of a “crack” → junction concept → the name of semi-conduction → semiconductor
- Control of doping, localized, discrete electronic states
- Concept of hole (conduction)

Quantum physics

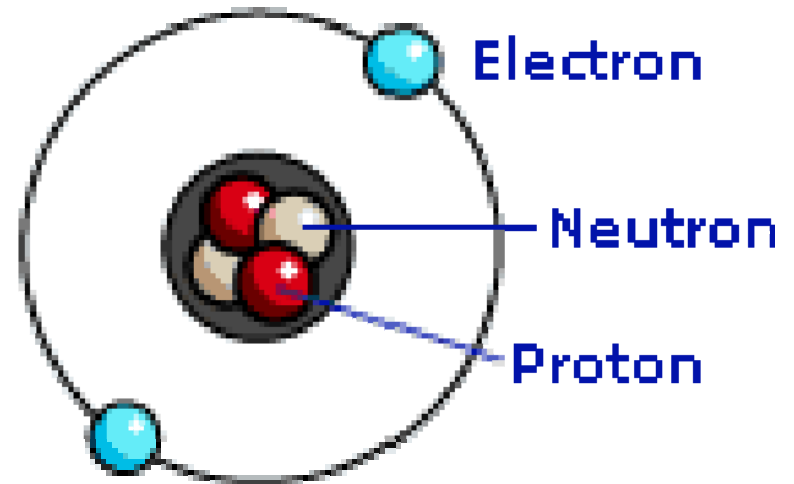
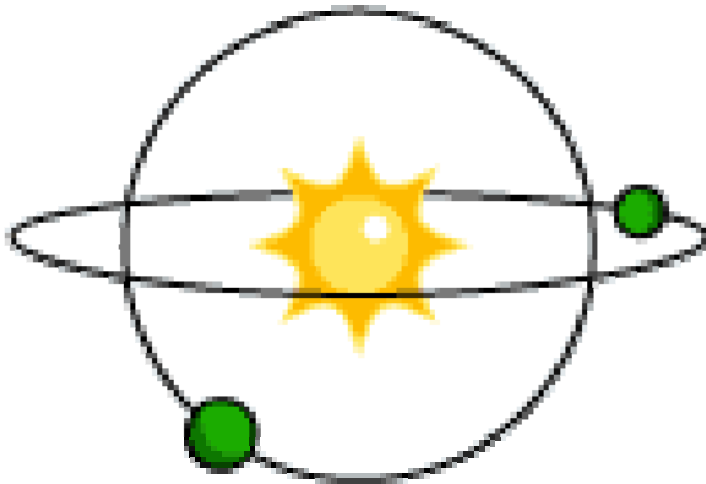


UC Berkeley's Digital Chem1A

Let's begin this journey into the world of semiconductors with a look at the history books. In the early 1900s, not much was known of the world at an atomic level, and even less so at the subatomic level. Physics, to a large extent, still calmly followed classical rules. But new discoveries like [Röntgen's](#) x-rays, Thomson's electron and [Rutherford's](#) discovery of the atomic nucleus made it clear that new rules were needed. Scientists like [Planck](#), [Einstein](#), [Bohr](#), [Pauli](#) and [Heisenberg](#), to name a few, all contributed to the development and understanding necessary for the creation of the new paradigm of quantum physics. The development of quantum physics also laid the ground for 'Solid State Physics' which is a discipline explaining the internal atomic structure and the electronic properties of the materials that we see in our everyday life such as metals, plastics, glass, etc.

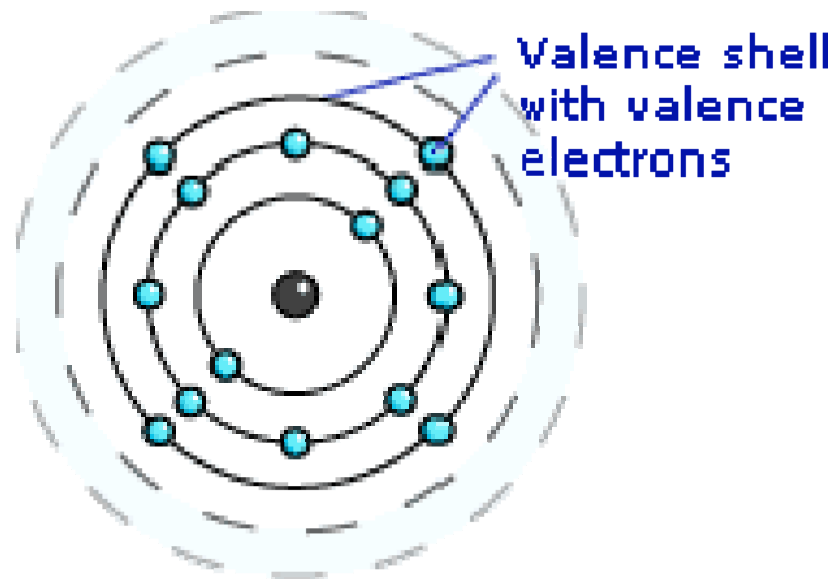
Basic atomic structure

Since all matter is made up of atoms we will begin with a somewhat simplified description of atomic structure. The atom consists of three major, extremely small, building blocks called protons, neutrons and electrons. Protons have a positive charge, while electrons are negatively charged and neutrons are neutral (no charge). Note that in reality, the size of the electron is much smaller than the size of the proton or the neutron.



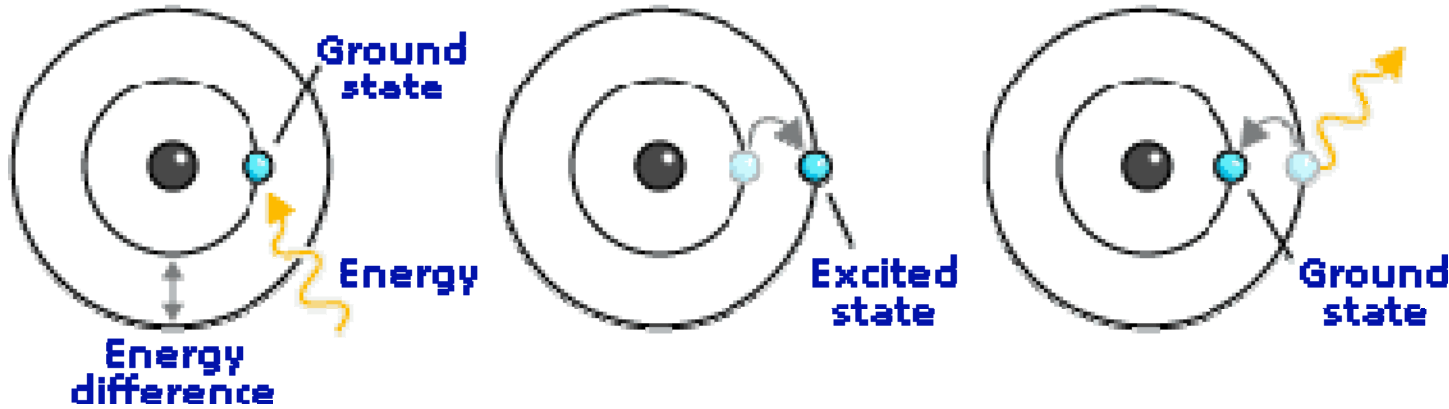
Shells and energy levels (Bohr model)

Each atom has a fixed number of electrons. Silicon, for instance, has fourteen of them. These electrons are divided into shells (orbits), depending on their energy. The closer the electrons are to the center of the atom, the lower their energy. This means that the electrons fill the shells of the atom from the bottom up. The highest shell in an atom *occupied with electrons* is called the valence shell. The electrons in the valence shell are called valence electrons. Note that the valence shell is not the outermost of all shells, it is just the outmost shell occupied with electrons. There are still empty shells outside it.



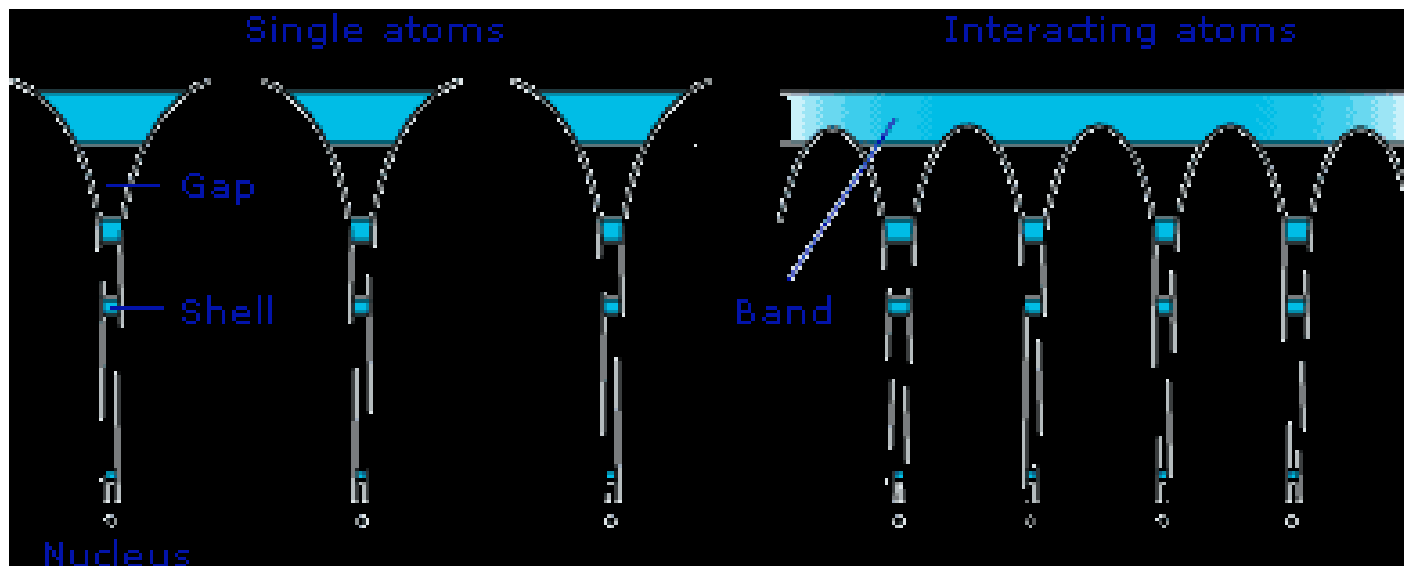
Shells and energy levels

We now have a model of an atom with a center and electrons orbiting around it at certain energy levels known as shells. The energy shells are separated by forbidden zones (energy differences). For an electron to bridge the energy difference and go from a low energy shell to a higher one, energy corresponding to the energy difference must be added. An electron that has absorbed energy and has jumped to a higher energy level is called an excited electron. But since the electron wants to have the lowest energy possible it quickly releases the added energy (for example by emitting light) and goes back to its original state, also known as its ground state.



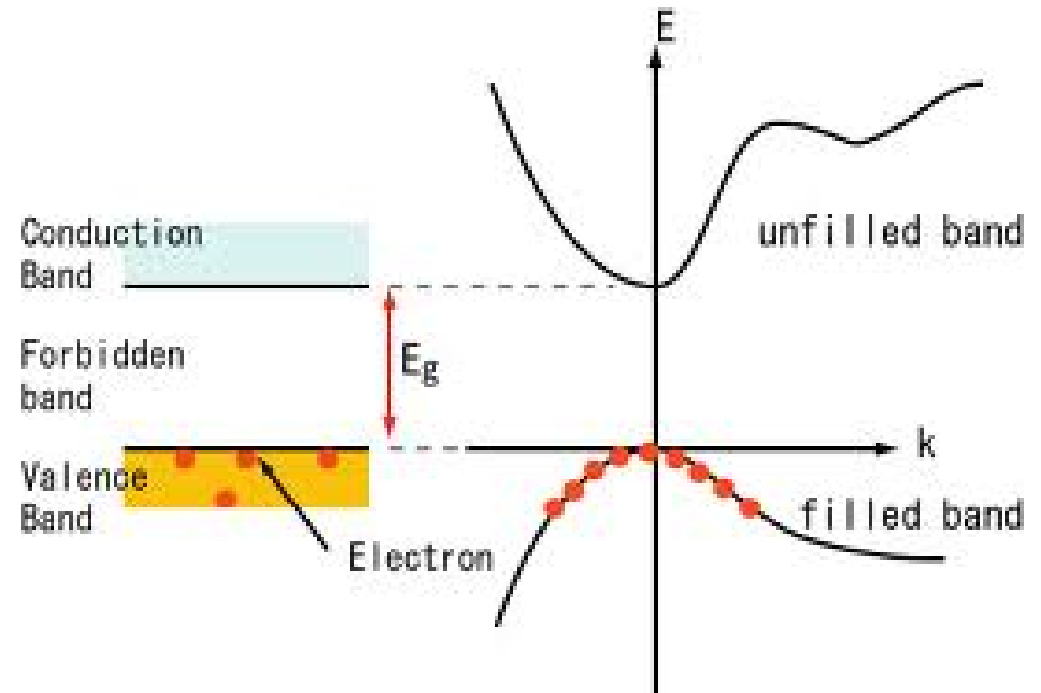
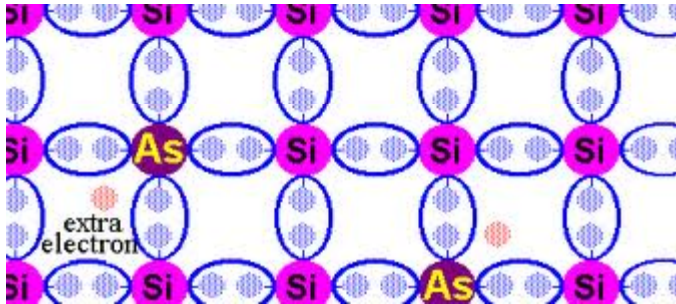
Solid state physics

If we look at the solid material of Silicon we will see that it is built from a huge number of Silicon atoms that are brought together. When the atoms interact with each other, the atomic shells of each atom interact with the atomic shells of neighboring atoms. On an energy scale, the overlapping energy shells of all the separate atoms form energy bands that are similar to the energy shells in the single atom. Between the bands no electrons are allowed. In a simplified way, it is almost as if the solid material is an enlargement of the single atom.

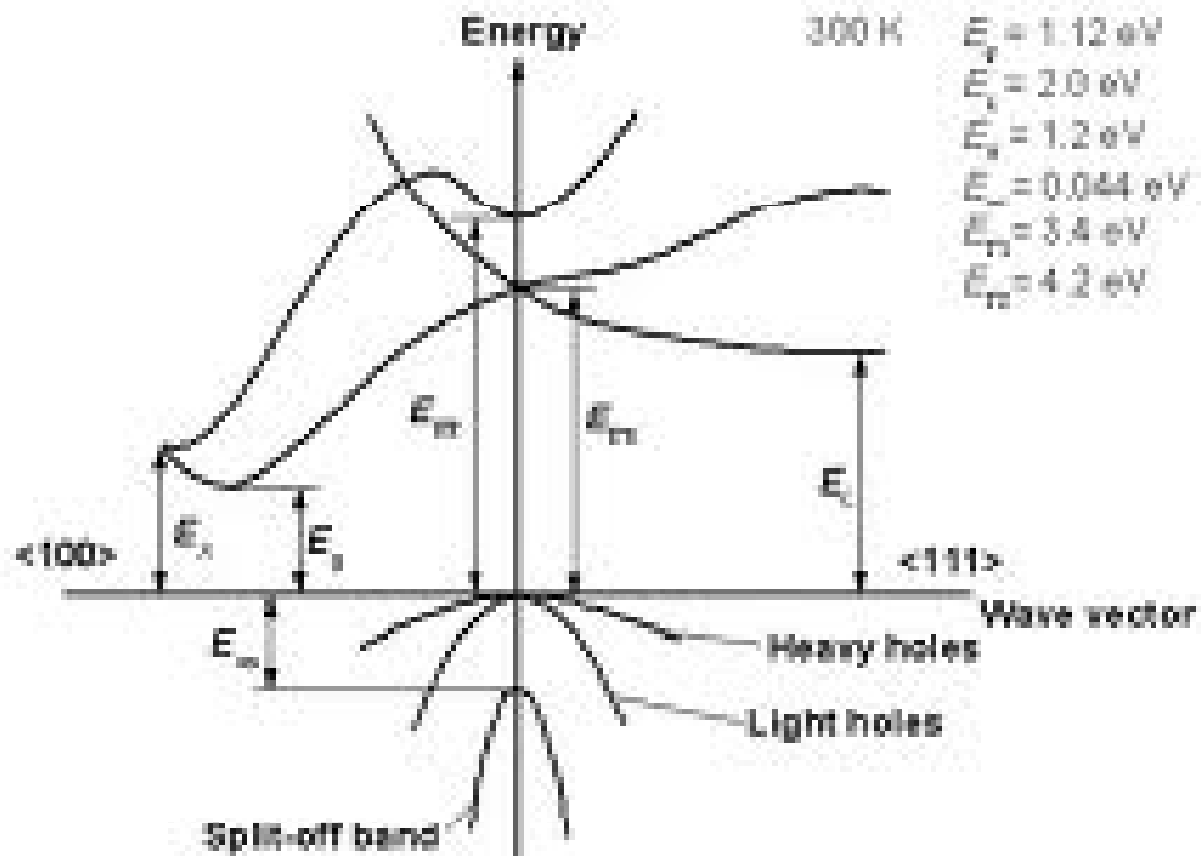


Energy gap

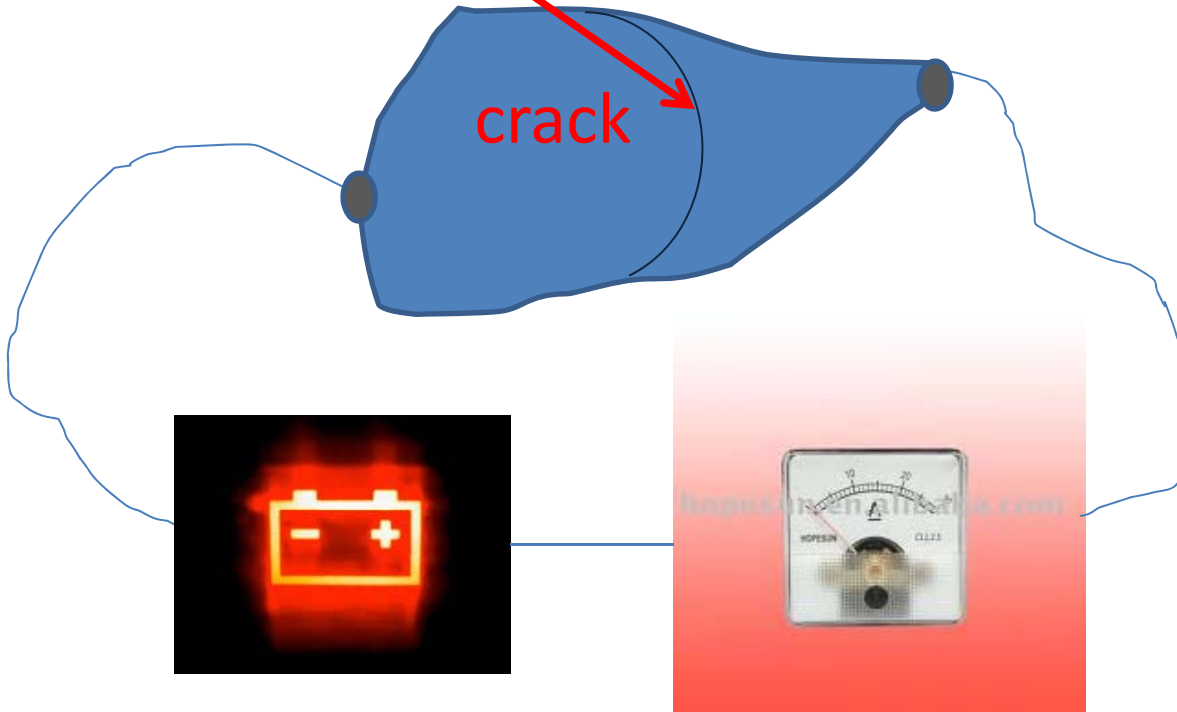
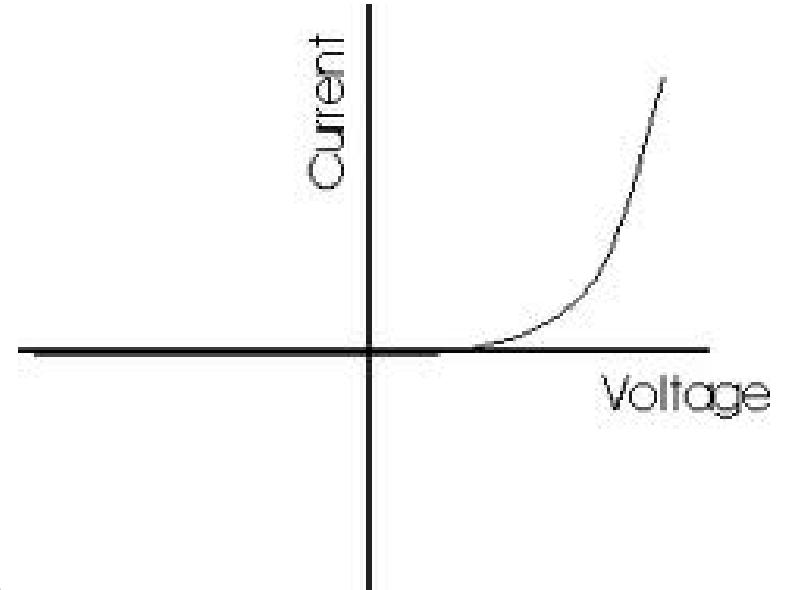
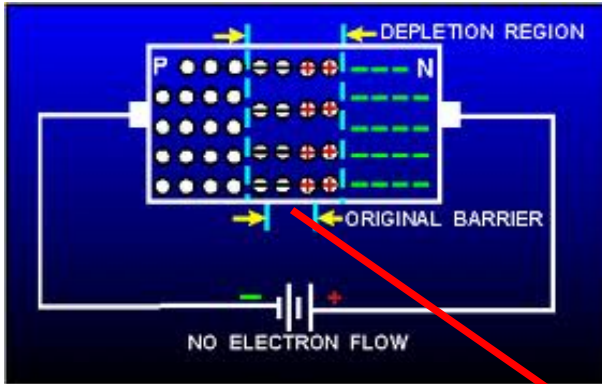
The highest energy band that is occupied by electrons in a material is called the **valence band**, just like in the single atom where the highest shell occupied by electrons is called the **valence shell**. The band with energy one step higher than the valence band is the **conduction band**. The energy gap between these two bands, where no electrons are allowed, is called the **band gap**.



Silicon band diagram

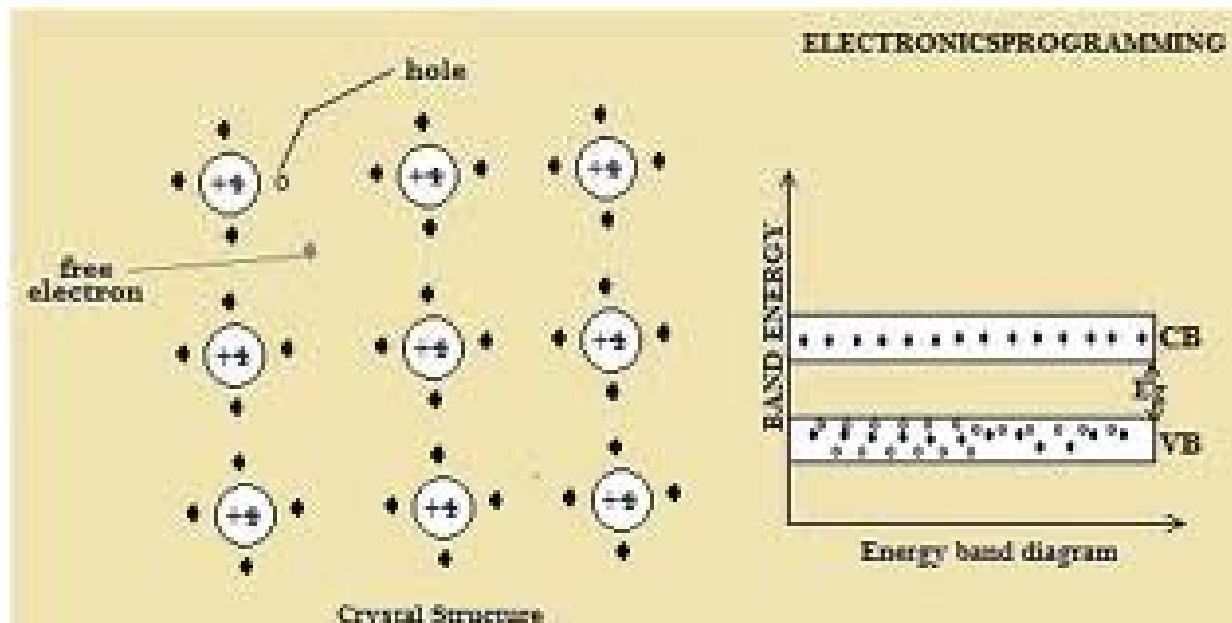


1939-1940: Brattain: Discovery of a crack in a Ge crystal



Electron-hole pairs

A very important feature of the semiconductor material is the electron-hole pair. To get a semiconductor to conduct a current, we must make an electron jump from an occupied to an unoccupied energy level. When it does this it leaves a hole (an empty state). This hole can be filled by another electron, which itself leaves a new hole. Therefore, we could say that both the hole and the electron contribute to the conductivity as they move around in the material. The hole is like a positive charge (lack of negative), the electron is negative.




Conduction in different type of materials

As mentioned earlier, the semiconductor has a conducting capacity somewhere between the conductor and the insulator. If we look closer at the materials we can see why they behave like this. Before we go on, note that contrary to what its name may suggest, the conduction band is not the only band where conduction of a current may occur. Conduction is equally possible in the valence band.

METALS


- Have very low resistivities ($\sim 10^{-6} \Omega\text{cm}$).
- Resistance is difficult to alter or tailor.

 because

Highest occupied energy band is partially filled with electrons.

SEMICONDUCTORS


Have resistivities that can be altered by up to 10 orders of magnitude by doping or external biases.

 because

Highest occupied energy band (valence band) is completely filled with electrons at low temperature. Next band (conduction band) is empty.

INSULATORS

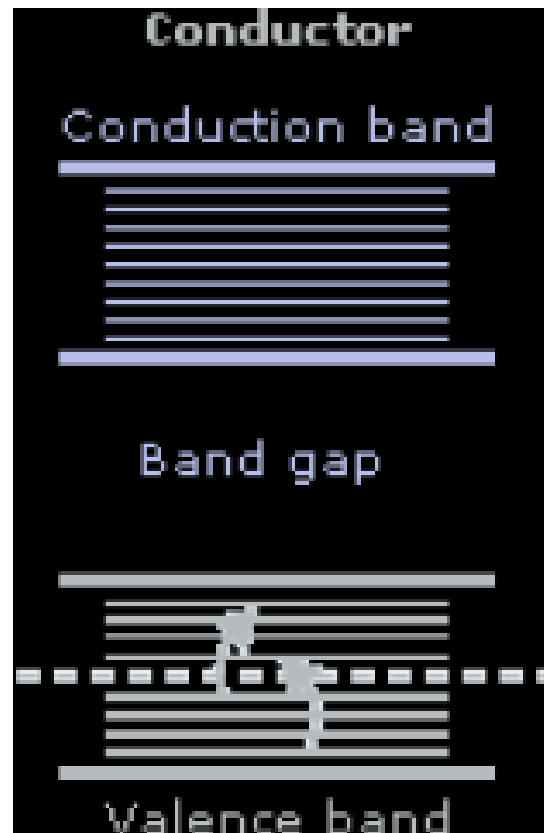
Have extremely high resistivities. It is difficult to alter the resistivity through doping or external fields

 because

High bandgap between valence band (filled) and conduction band (empty) is large ($\gtrsim 4 \text{ eV}$).

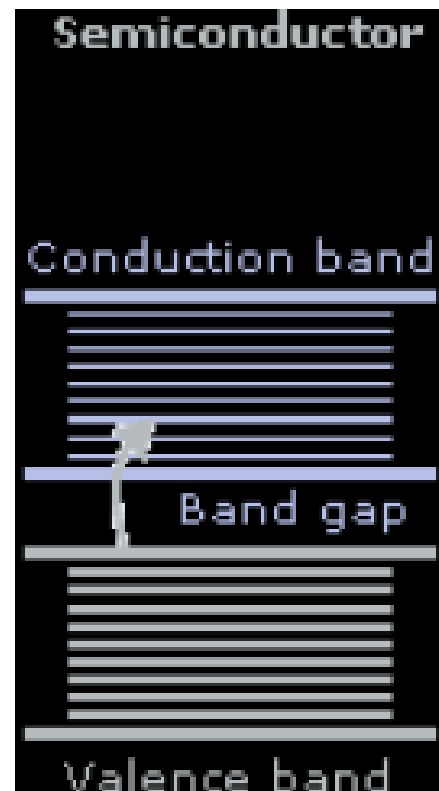
Conductor

In a good conductor like a metal, the highest energy band with electrons (valence band) is only partially filled. This means that the electrons can accelerate. In other words, they gain energy so that they can transfer to higher energy levels that are empty. Simply put, in a conductor there is plenty of room for the electrons to jump from an occupied state to an empty one.



Semiconductor

In a semiconductor, the distance between the valence band and the conduction band is fairly small. At a low temperature the semiconductor has a completely filled valence band. There are no empty energy positions available for the electrons to be accelerated in. Therefore, at low temperatures the semiconductor behaves like an insulator. At room temperature, the atoms in the semiconductor material vibrate enough so that a few electrons may escape from their positions in the valence band into unoccupied positions in the conduction band. The conduction at room temperature, however, is so small that no significant current can be said to pass.

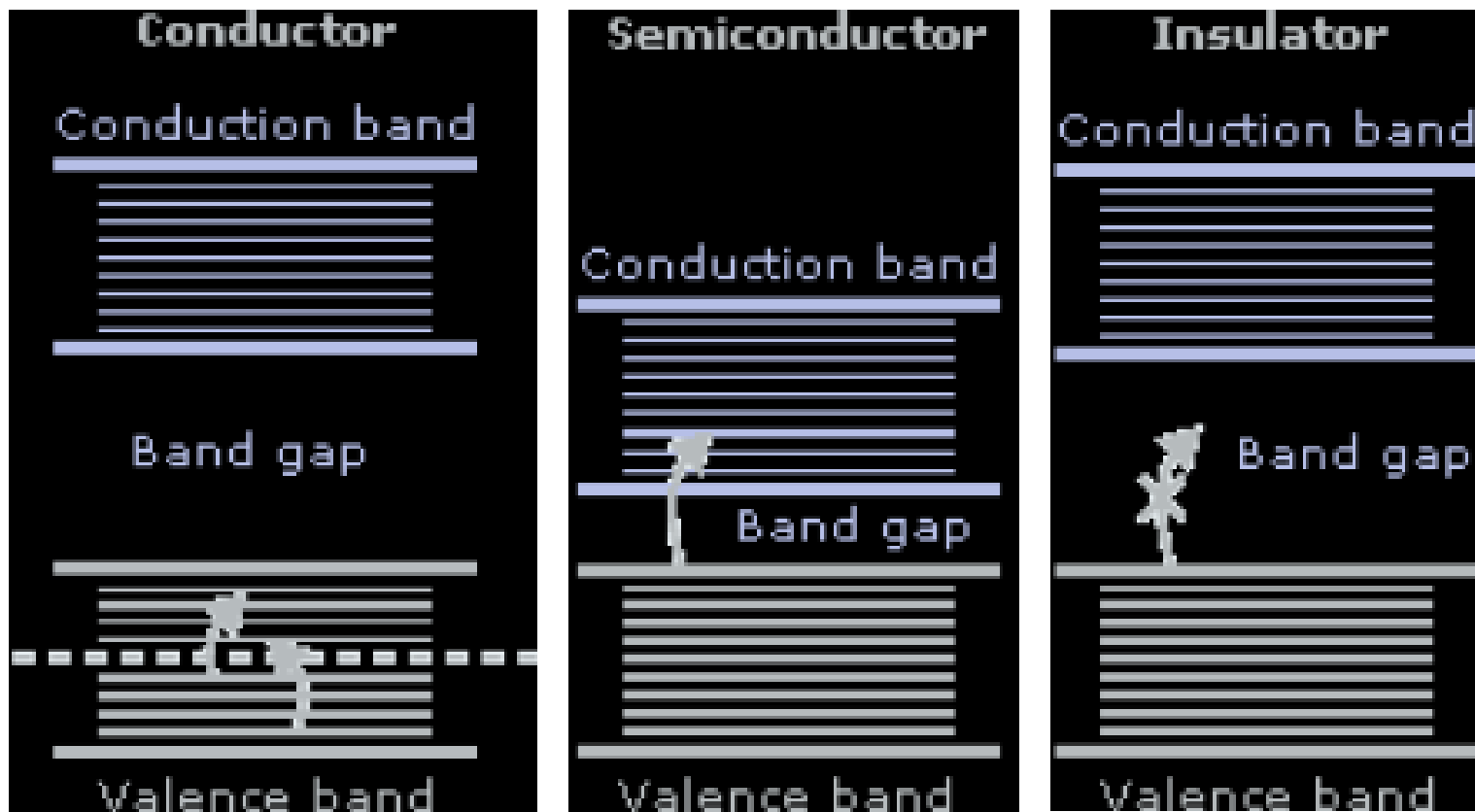


Insulator

In the insulator, the valence band is completely filled. Also, the band gap to cross between the valence and conduction band is very large. No electron will be able to make the jump to the conduction band at room temperature. Thus, there is no possibility for an insulator to conduct a current.

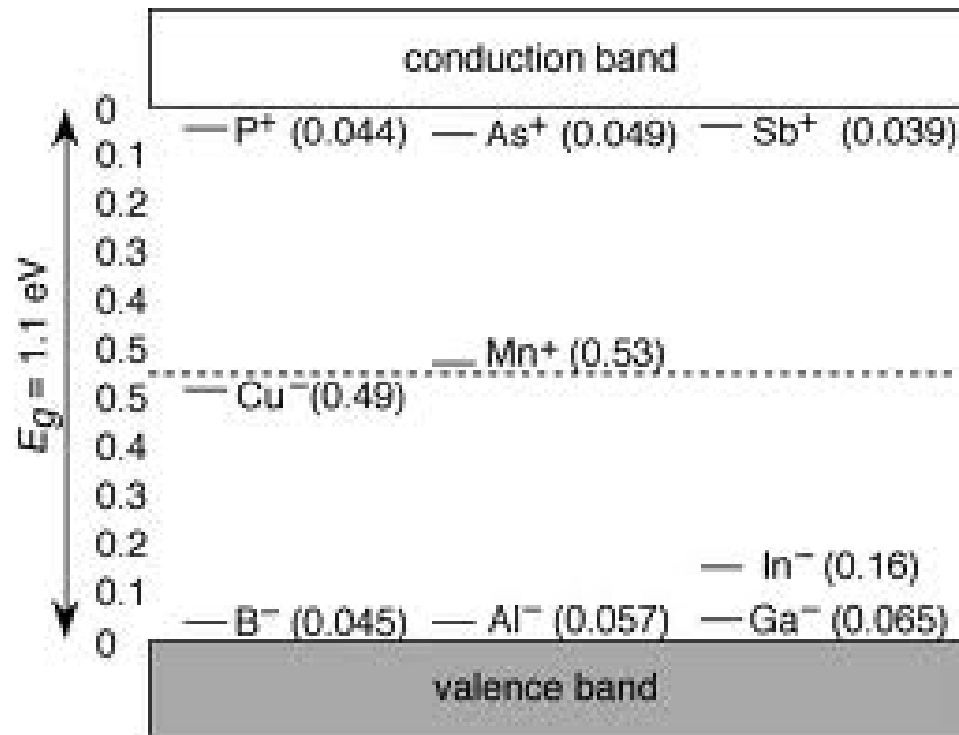


Metal, semiconductor, and insulator



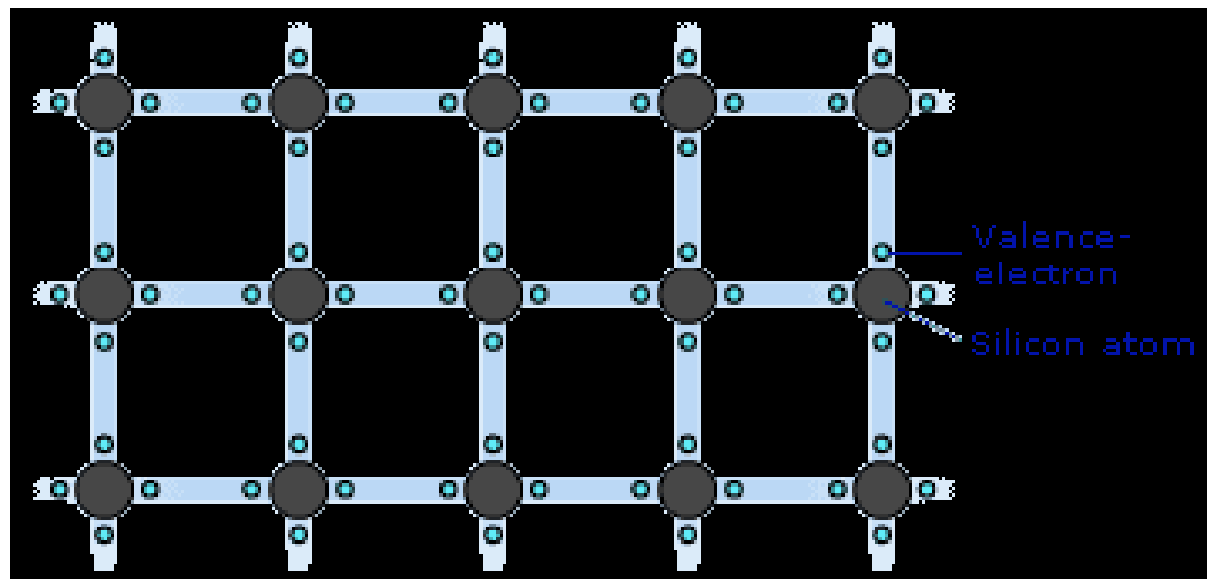
Doping

So, in the process of doping you add a tiny amount of atoms from another material to the pure semiconductor. By doing so, you can drastically increase its ability to conduct a current. There are two forms of doping, p and n . p stands for positive and n for negative. Finally, two words that are good to know: a pure non-doped semiconductor is called **intrinsic**, while a doped semiconductor material is called **extrinsic**.



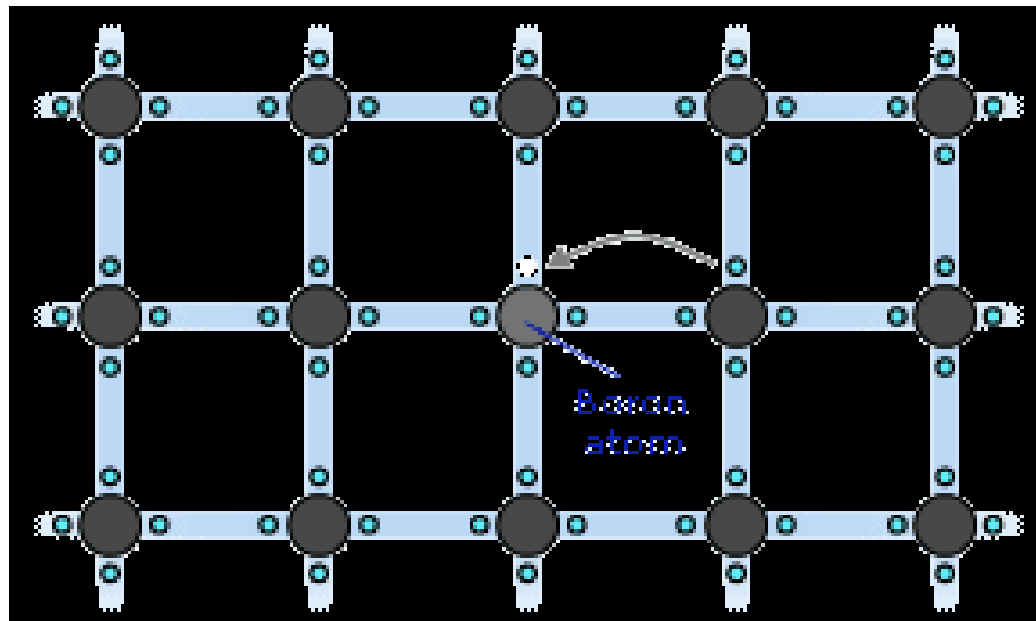
Without doping

Before we look at examples of doped semiconductors, let's look at how the silicon atoms in pure silicon interact to form the crystal structure of the material. In pure silicon, each atom has four valence electrons and these are shared with four neighboring silicon atoms to make four double bonds. Now each atom will have a completely filled valence shell of eight electrons. At low temperature this bond is very stable, completely filling the valence band and thus making conduction impossible. Here is a model of the structure of pure silicon:



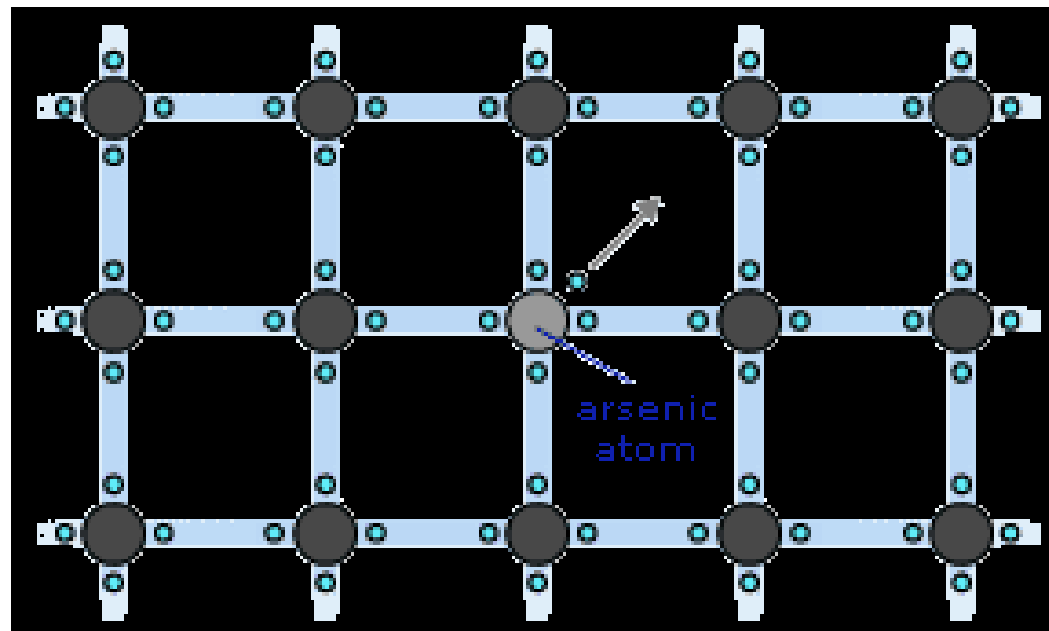
P-doping

p-doping is when you add atoms with less valence electrons to the semiconductor so that the material gets a shortage of electrons in the crystal bonds. This way positive holes that can transport current are formed. The materials that add holes are called acceptors because they accept electrons from the surrounding atoms. In a p-type semiconductor the major carrier of current are the holes, not the electrons.



N-doping

In the process of n-doping you add atoms with one extra valence electron to the pure semiconducting material. This creates a situation where there are extra electrons that are just loosely bound in the crystal. The amount of energy needed to get these electrons to jump to the conduction band so that a current may pass is very small. The materials that add electrons are called donors. This is simply because they donate electrons to the semiconductor. In the n-type semiconductor the major carrier of current is the negative electrons.



Major semiconductor technology development stages

- 1947, 1st point-contact transistor, Bell Labs
- 1952, single crystal Germanium (Ge)
- 1954, single crystal Silicon (Si)
- 1958, 1st Integrated Circuit (IC), TI
- Intel: Moor's Law (1960 → 2011)

Major stages

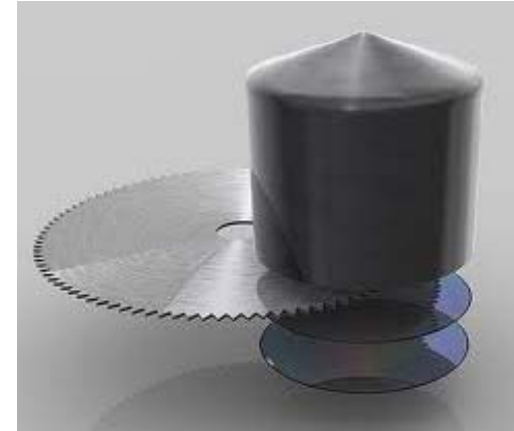


1st transistor, Bell Lab 1947

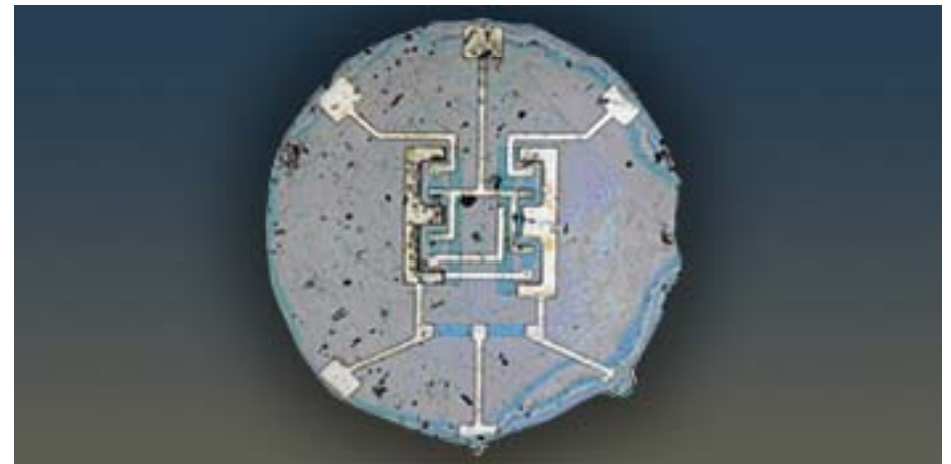
High quality Ge crystal

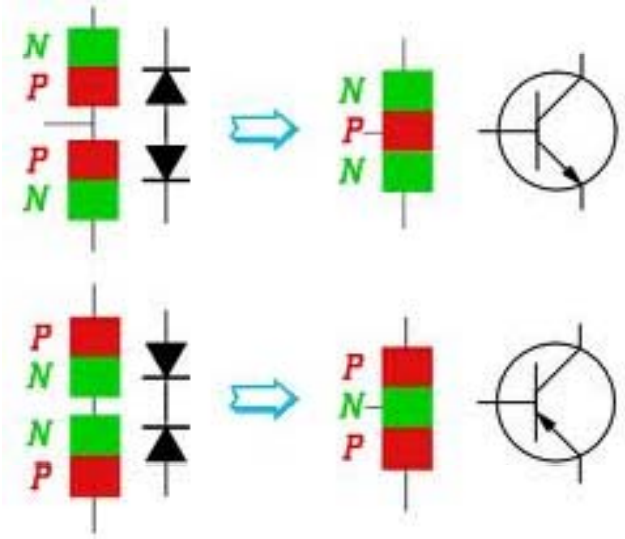
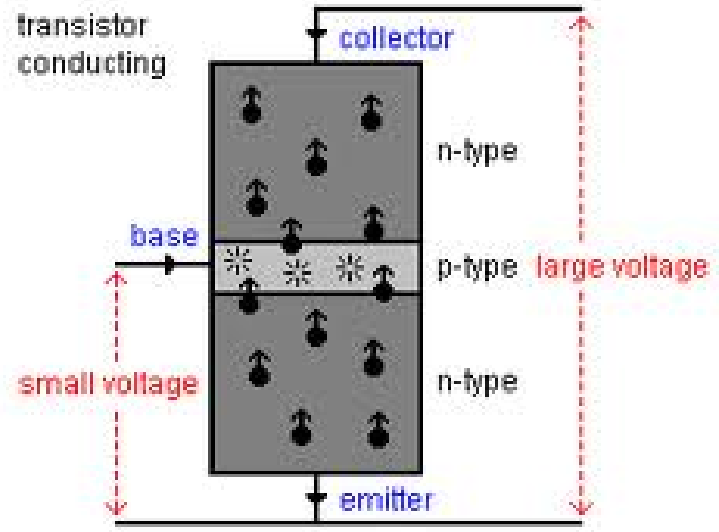
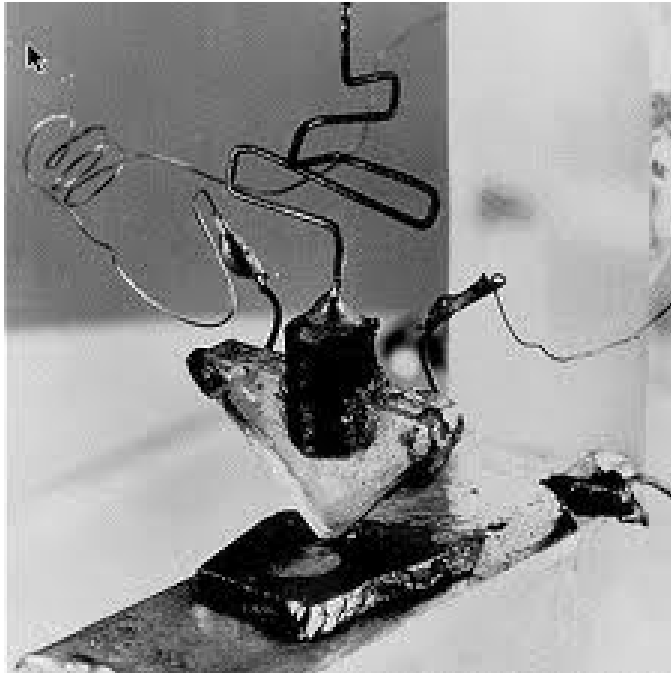


High quality silicon crystal



1st IC circuit



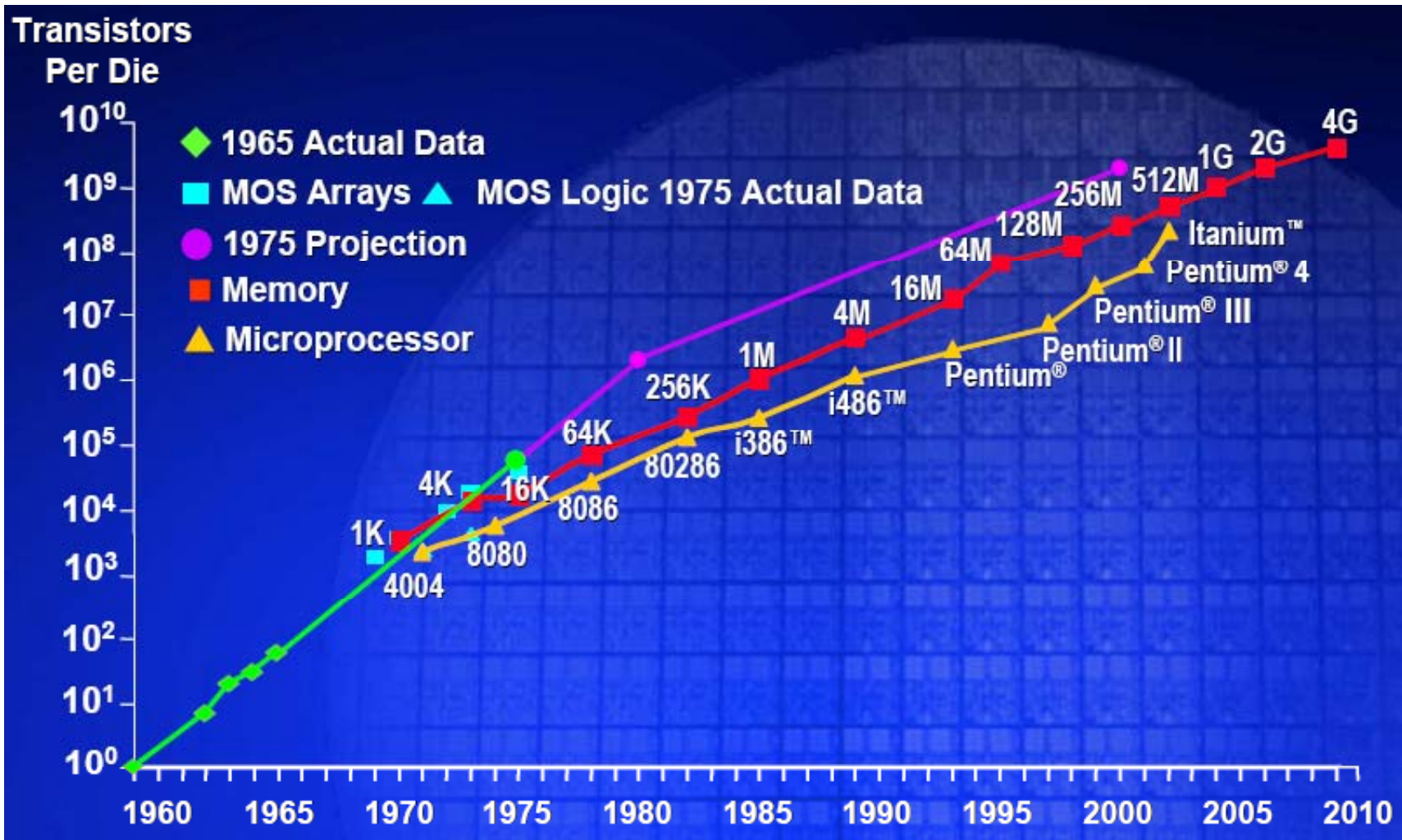


Inventors of 1st transistor

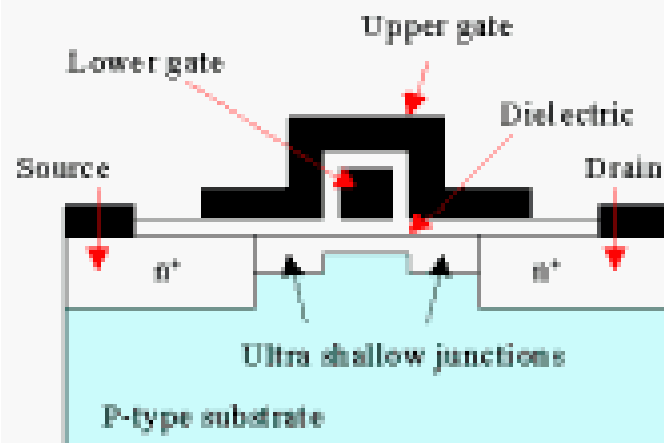


The new ways of looking at physics came in handy in 1947. Following in the footsteps of their predecessors, [William Shockley](#), [John Bardeen](#) and [Walter Brattain](#) made their breakthrough discovery of the transistor effect by constructing the first crude transistor. A vital part of this invention was the semiconductor and the theory behind it. In 1956 the trio got the Nobel Prize in Physics for:

Moor's Law



Smallest Known Transistor Made by NEC in 1997



0.014 micron lower gate width

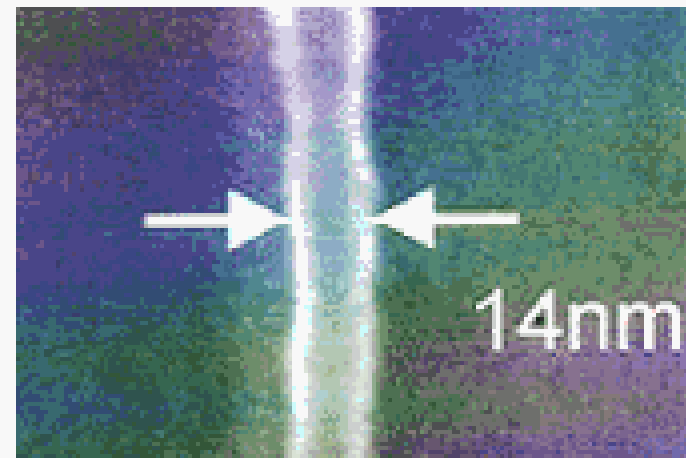


Photo courtesy: NEC Corporation

Major stage in terms of materials

- Ge, early development, not widely used
- Si, IC, solar cells, → main consumer electronics
- GaAs: LED, LD, RF amplifiers, → wireless applications
- InP, InGaAs: laser, modulators → optical communications
- GaN, UV lasers → storage, lighting

Materials for electronics

	ADVANTAGES	DISADVANTAGES
Silicon (Si):	The most important semiconductor system. MOSFETs, bipolar devices based on Si form over 90% of the electronic market.	Not as "fast" as other semiconductors. Not good for high power, high temperature operation. Cannot emit light, since it is an indirect gap material.
Silicon-Germanium (Si-Ge):	Can be grown on Si substrates and processed using Si technology. Bipolar devices have performance rivaling GaAs technology.	Strained system. Needs great care in crystal growth conditions.
GaAs; GaAs/AlGaAs:	High speed devices for digital/microwave applications. Performance is superior to silicon.	More expensive than Si technology.
InP; InGaAs/InP:	High speed performance is superior to GaAs based technology. Can be combined with longhaul optoelectronic communication technology.	Expensive.
GaN/AlGaN	High power/high temperature applications.	Not as reliable yet; high cost.
SiC:	High power/high temperature applications.	Reliability; cost.

Materials for optoelectronics – LED, LD

IMPORTANT MATERIAL SYSTEMS	COMMENTS
$\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$; $x = 0.47y$ for lattice match to InP $E_g = 1.35 - 0.72y + 0.12y^2$ eV	<ul style="list-style-type: none"> • Lattice matched to InP. • Wide range of emission energies can be accessed (~0.8 to 1.35 eV). • Material technology is quite advanced and can be exploited for communication applications.
AlGaAs $E_g = 1.43 + 1.25x$ eV; $x \leq 0.35$	<ul style="list-style-type: none"> • Lattice matched to GaAs. • Technology is quite advanced and can be used for LANs.
$\text{GaAs}_{1-x}\text{P}_x$	<ul style="list-style-type: none"> • Material becomes indirect at $x = 0.45$. • With N doping the LED can operate even if the material is indirect and green light emission ($\lambda = 0.55 \mu\text{m}$) can be achieved. • The versatile material can provide red ($\text{GaAs}_{0.6}\text{P}_{0.4}$); orange ($\text{GaAs}_{0.35}\text{P}_{0.65}:\text{N}$), and yellow ($\text{GaAs}_{0.15}\text{P}_{0.85}:\text{N}$) as well.
SiC, GaN, ZnS, ZnSe, AlInGaP —large gap materials which can emit blue light and beyond.	<ul style="list-style-type: none"> • Important materials for blue light emission (for displays, memories). • Technology for optical sources is not mature, but rapid progress is being made.

Materials for optoelectronics - detectors

InGaAs
(Tunable E_g)

- Excellent material for long haul communications (at 1.55 μm).
- Can be lattice matched to InP.

AlGaSb
(Tunable E_g)

- Excellent optical properties.
- Can be used for long haul communications.
- Suffers from poor substrate availability, since it has to be grown on GaSb, whose technology is not matured.

InGaAsP
(Tunable E_g)

- Suitable for both 1.55 μm and 1.3 μm applications for long haul applications.
- Can be lattice matched to InP substrates.

HgCdTe
(Tunable E_g)

- Excellent material for long wavelength applications in night vision and thermal imaging.
- Can be used for 1.55 μm and 1.3 μm , but the technology is not as advanced as the InP based technology.

Si
($E_g = 1.1 \text{ eV}$)

- Indirect material with small α near the bandedge.
- Has high β_{imp}/α_{imp} ratio and can be used in high performance avalanche photodiodes for local area network (LAN) applications.
- Not suitable for long haul communication at $\lambda = 1.55 \mu\text{m}$ or 1.3 μm .

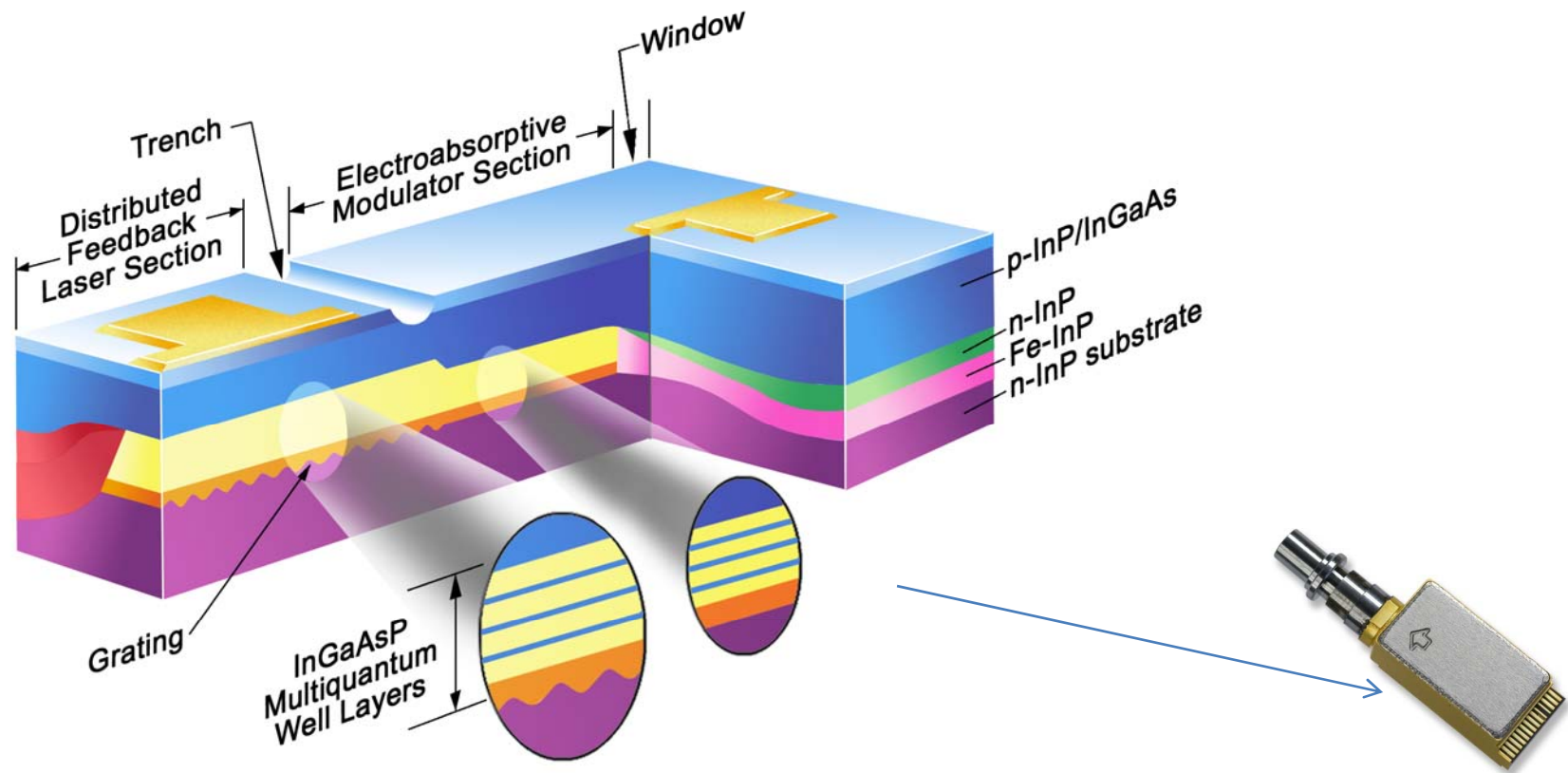
Ge
($E_g = 0.7 \text{ eV}$)

- Indirect material with small α near the bandedge.
- Has high β_{imp}/α_{imp} ratio and can be used for avalanche photodiodes for both local area and long distance communications.

GaAs
($E_g = 1.43 \text{ eV}$)

- Direct gap material.
- Not suitable for high quality avalanche detectors, since $\alpha_{imp} \approx \beta_{imp}$.
- Not suited for long distance or LAN applications.

10 Gb/s Electro-modulated laser (EML)

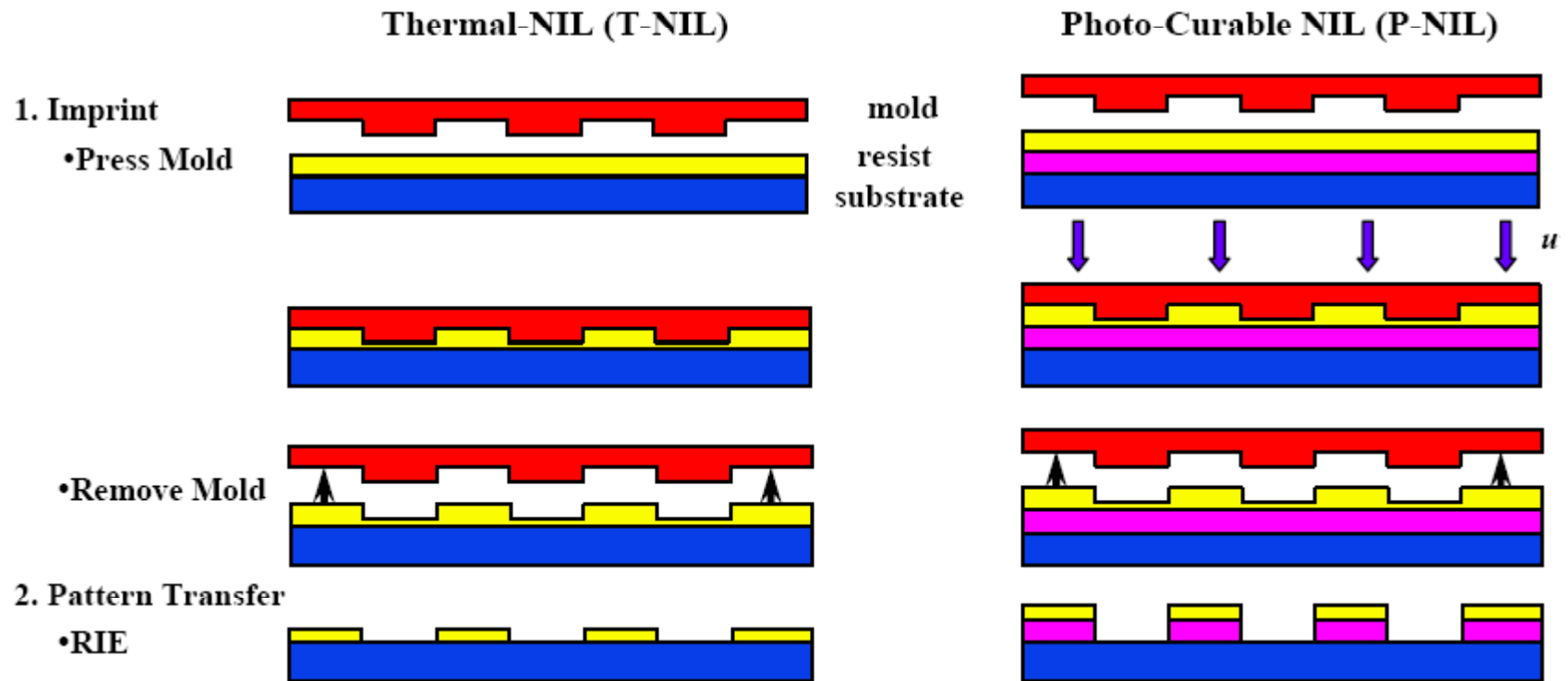


**Modern semiconductor
manufacturing technologies
(see additional file)**

The emerging era of nano semiconductors

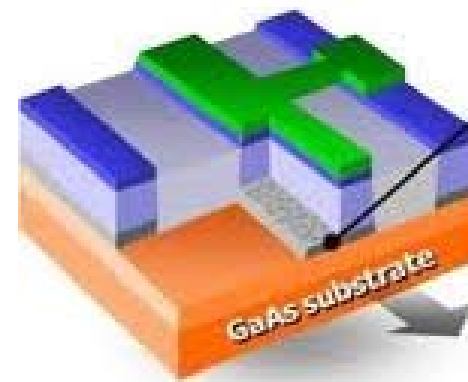
- Nano dots: CdSe, GaAs, InGaAs
- Nano sheet: carbon → Graphene
- Nano wires: ZnO, Si, SiGe
- Nanotubes: carbon

Nanofabrication -- Imprint technology

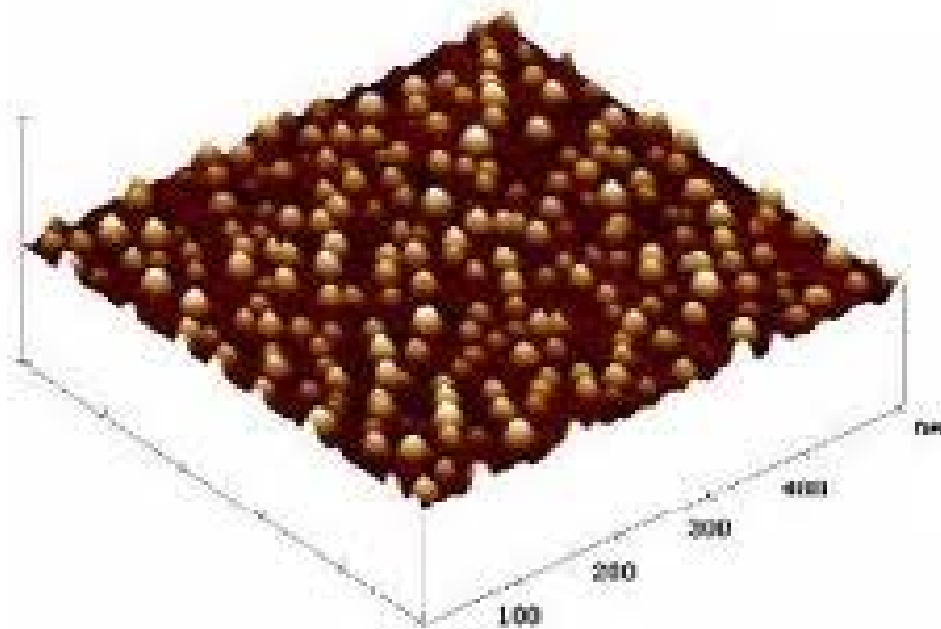
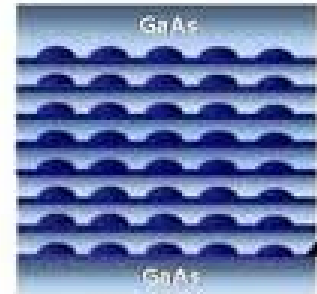


Source: Nanonex

Nano (quantum) dots

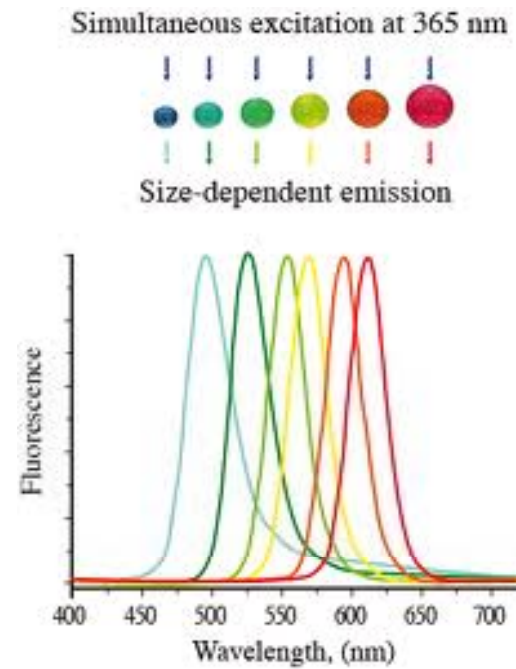
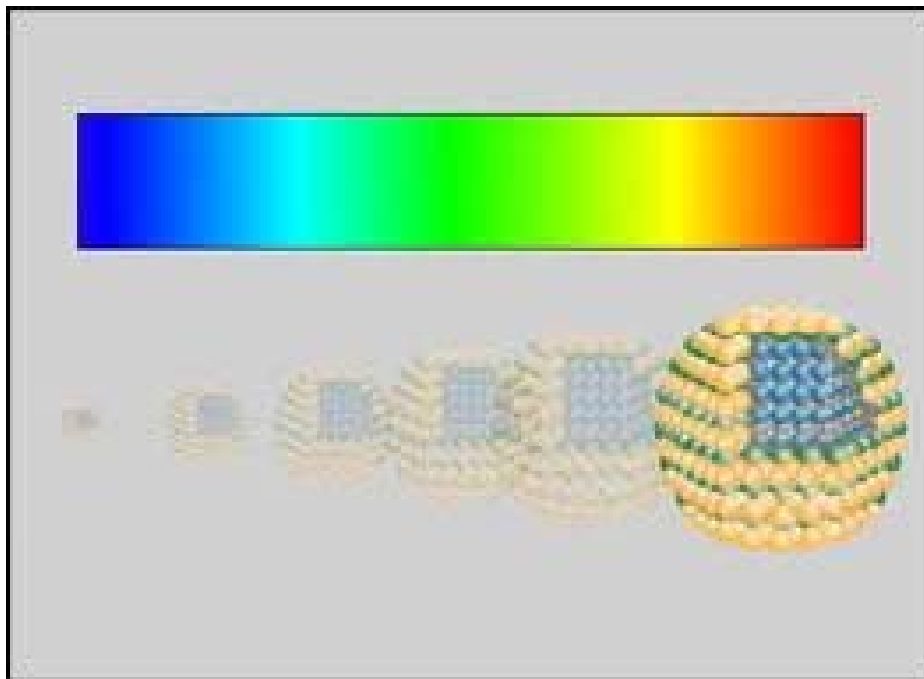


Quantum dot active layer



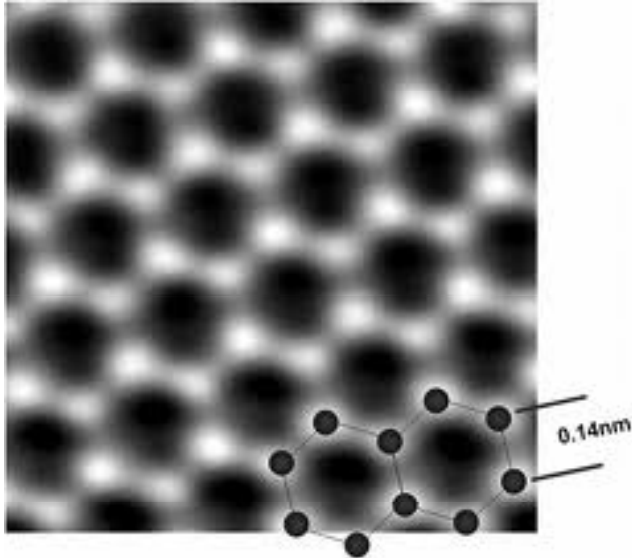
X 100,000 nm/div
Z 35,000 nm/div

Solution-based quantum dots

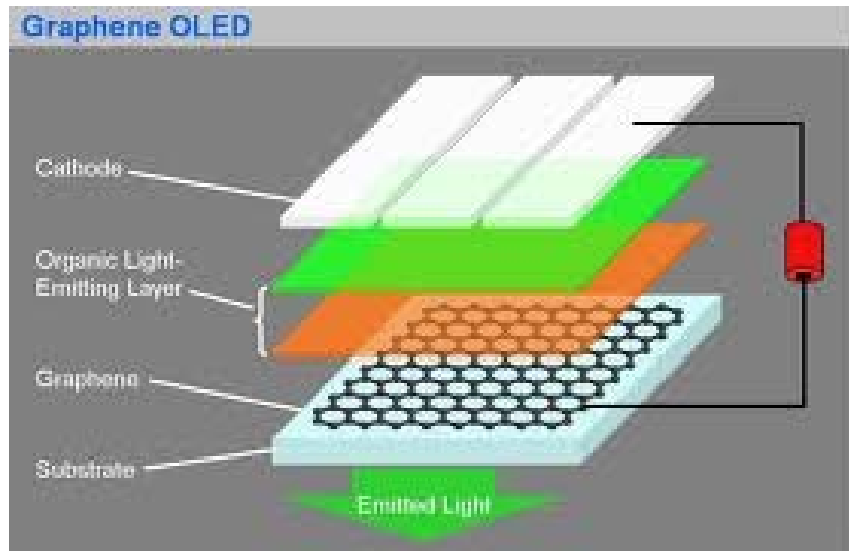
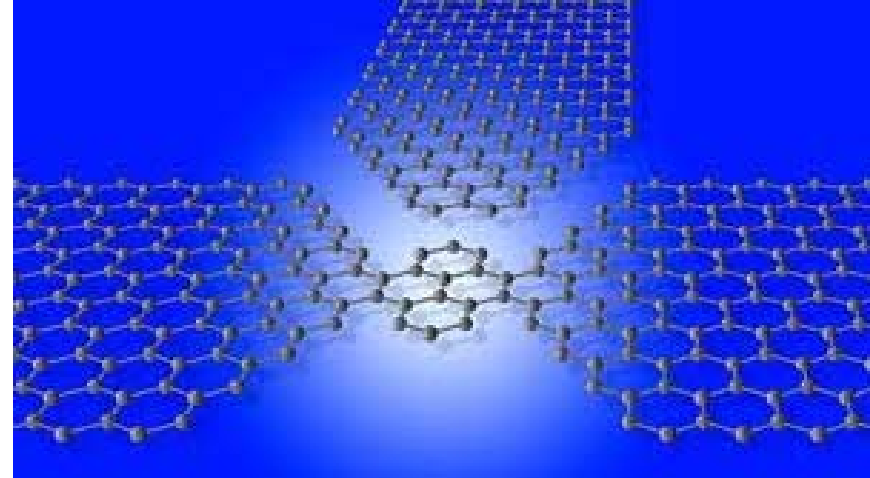


Graphene

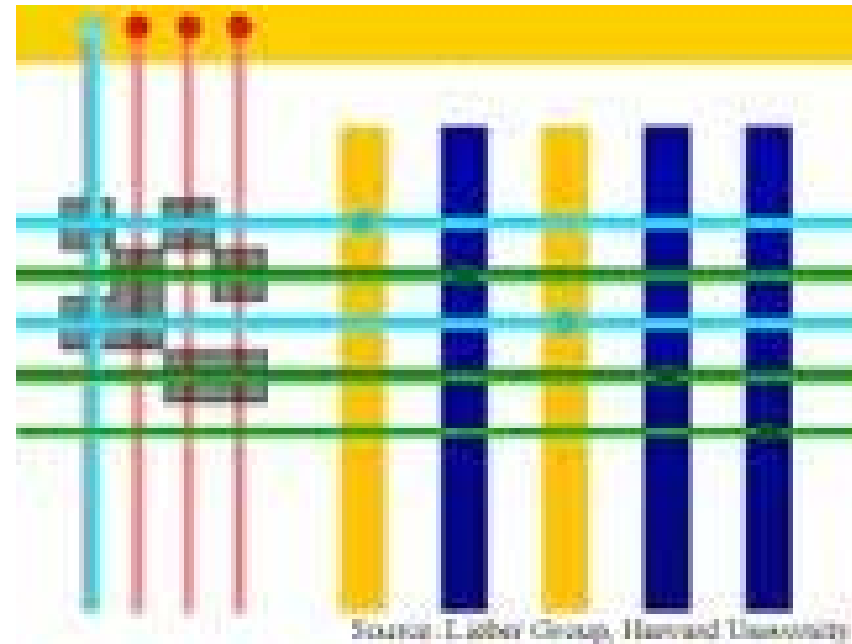
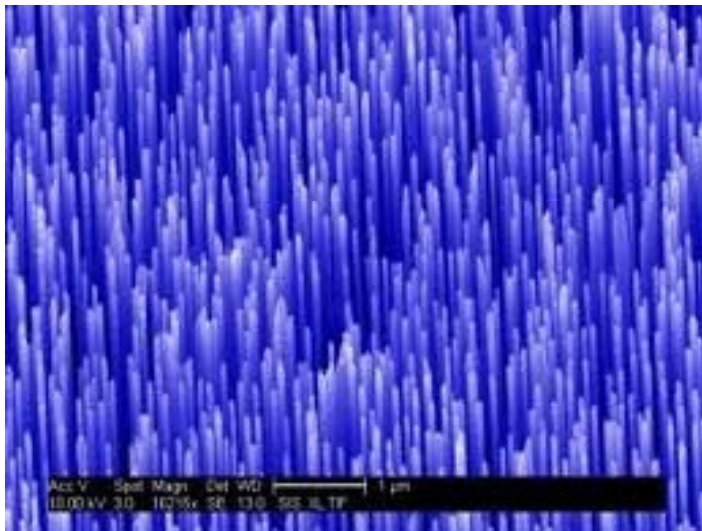
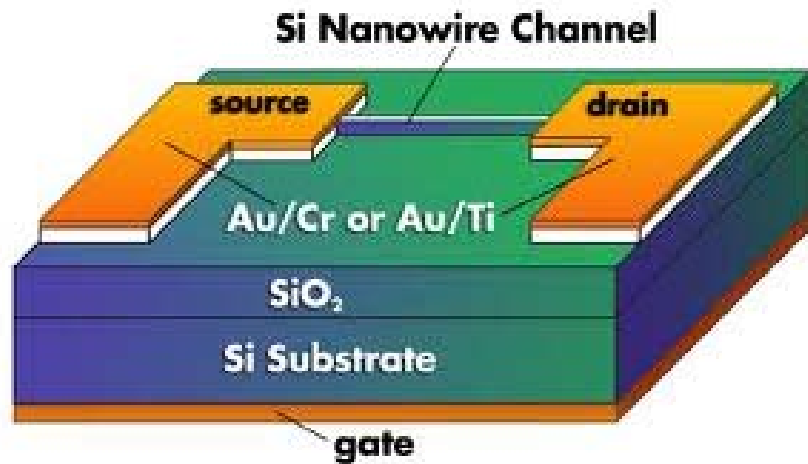
High resolution TEM



Transistor

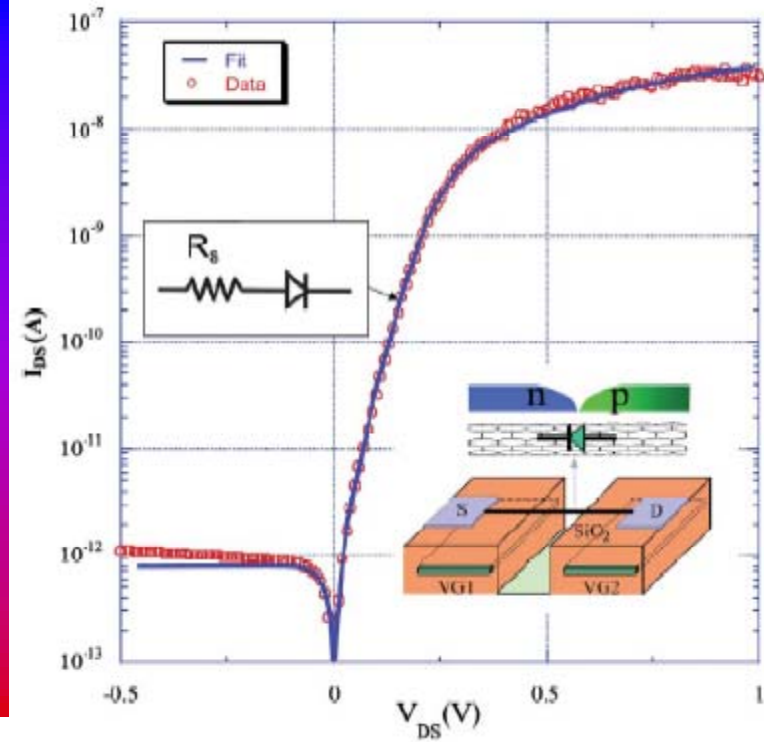
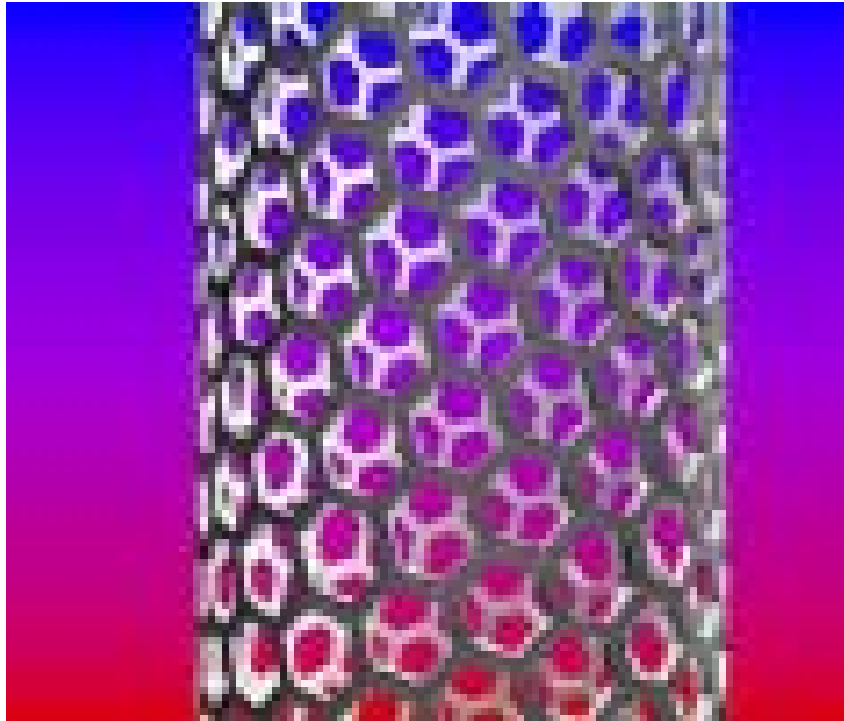


Nano (quantum) wires



This diagram shows a way to chemically connect an array of nanowires to much larger microchip wires.

Carbon Nanotubes



Source: APL 87, 073101 (2005)

Sensors



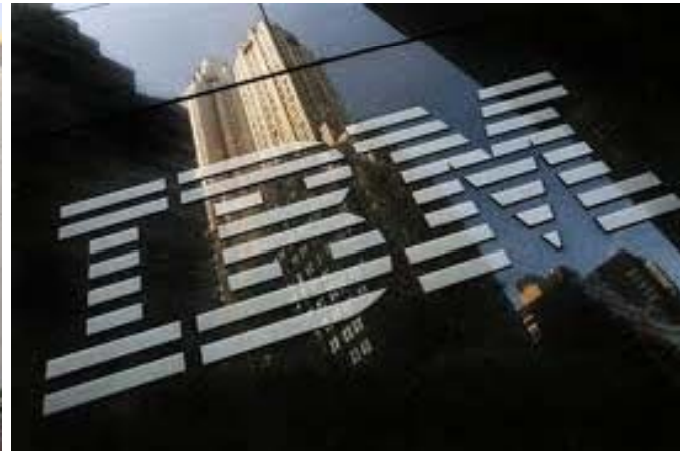
Semiconductor in-short

- Today, computers and computer chips are everywhere. The key to this technological revolution is the semiconductors. These are materials with the ability to conduct a current somewhere between good conductors (metals) and insulators. Semiconductors are very sensitive to impurities. By adding just small amounts of certain materials to them in a process known as "doping," we can greatly change their ability to conduct electricity.
- By combining differently doped areas of a semiconductor, we may guide the flow of current through its different parts. It is also possible to control the current using external control voltages, like in a transistor. Today, engineers are able to construct incredibly advanced structures, such as microprocessors, on tiny pieces of semiconductor material. In the early days of the semiconductor industry, the material germanium was most common. Today however, silicon has proven to be much more effective.

Semiconductor – the future

In a world where computers become faster and faster each year, semiconductor components, like chips and transistors, must be made smaller and smaller. This means that we will eventually reach a limit on how much faster and more effective the Silicon based technique can be made (in fact, devices operating with just a single electron have already been demonstrated). "What happens then?" you might ask yourself. Well we don't know for sure, but today's scientists are working hard to find new materials or to improve old ones. In the future, large molecules might do the work that transistors do today. This field is called Molecular Electronics. So hopefully (if you like information technology, that is) computers can continue to evolve for a long time to come.

Semiconductor companies to work for



Stion, San Jose/CA



Topic #2: Quantum mechanics

- Schrodinger wave equation
 - eigen states/wave-functions (Yariv 1D & HO, note-1998 Shum)
 - transmission/reflection (Yariv 1D)
 - 1st and 2nd order perturbation (Yariv)
 - exciton binding energy (note 2.2)
- Time-dependent Schrodinger equation (Yariv, 2000 VQP)
 - tunneling current (note: 1994 Jihad)
 - charge dynamics (2000 VQP)
 - transition rates (Yariv & 2000 Kai)
- Quantum superposition (2011 Wiki, 2011 V)
- Quantum correlation → Entanglement (2005 Kai)