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Semiconductors and Devices: EEE 6001

- Introduction: Why are semiconductors so important?
- Electrons in solids: conductors, insulators and semiconductors
- Energy bands & occupation: doping and the Fermi level
- The junction (or p-n) diode
- The Metal-oxide transistor
- Semiconductors as optical emitters and detectors
- Fibre optic systems
- Quantum mechanical view of Semiconductors
- Semiconductors in circuits

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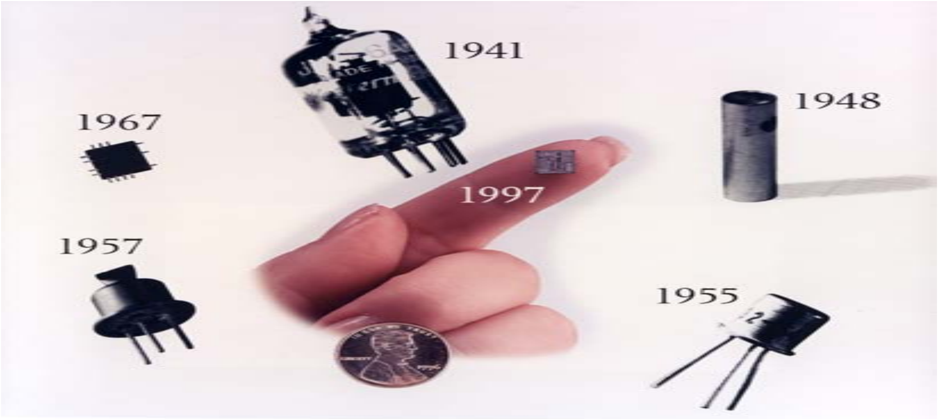
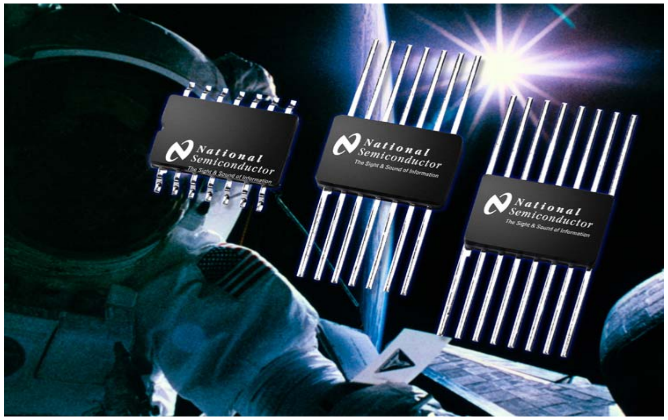
Semiconductors

John Bardeen, Walter Brattain and William Shockley developed the first transistor in December 1947,

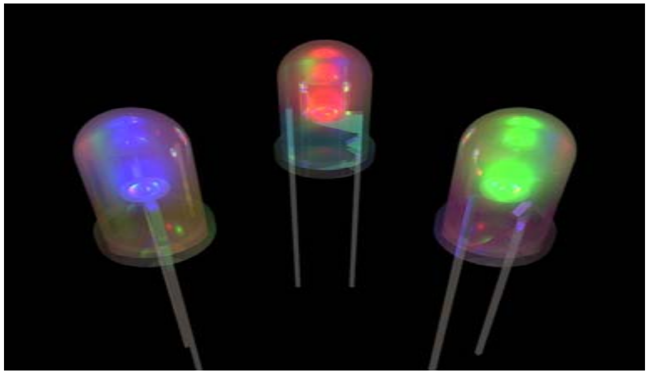


Over the subsequent 50 years semiconductors have revolutionised our world and become a 500 billion dollar business

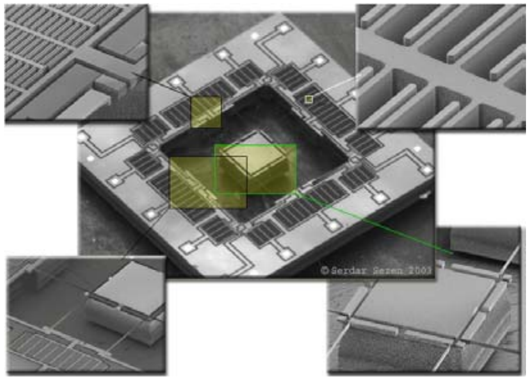
Semiconductors



Integrated Circuits



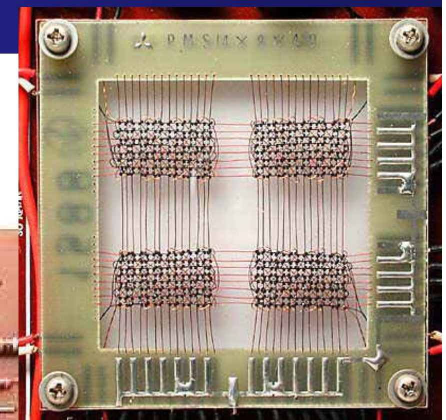
Optoelectronics



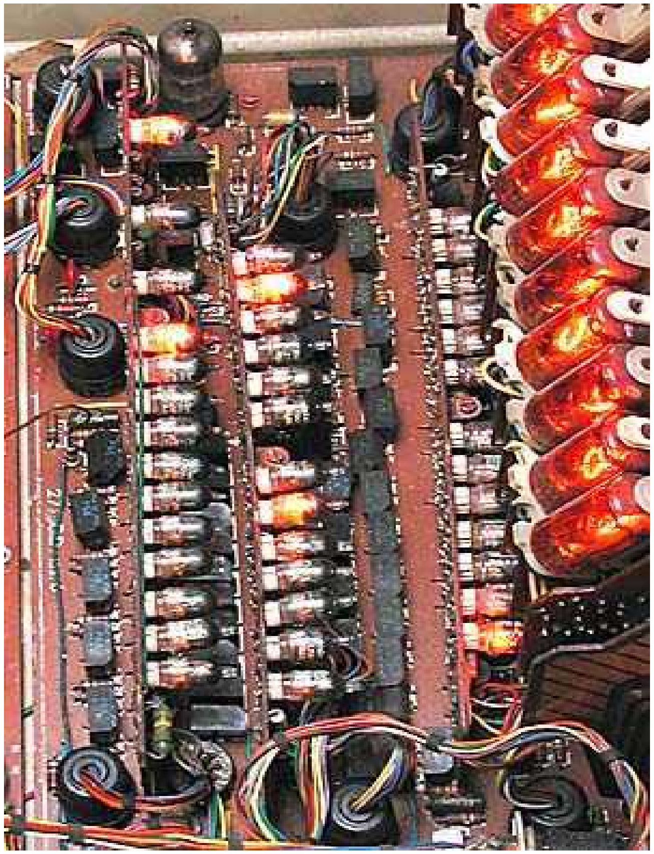
MEMS/ Sensors

RF Devices

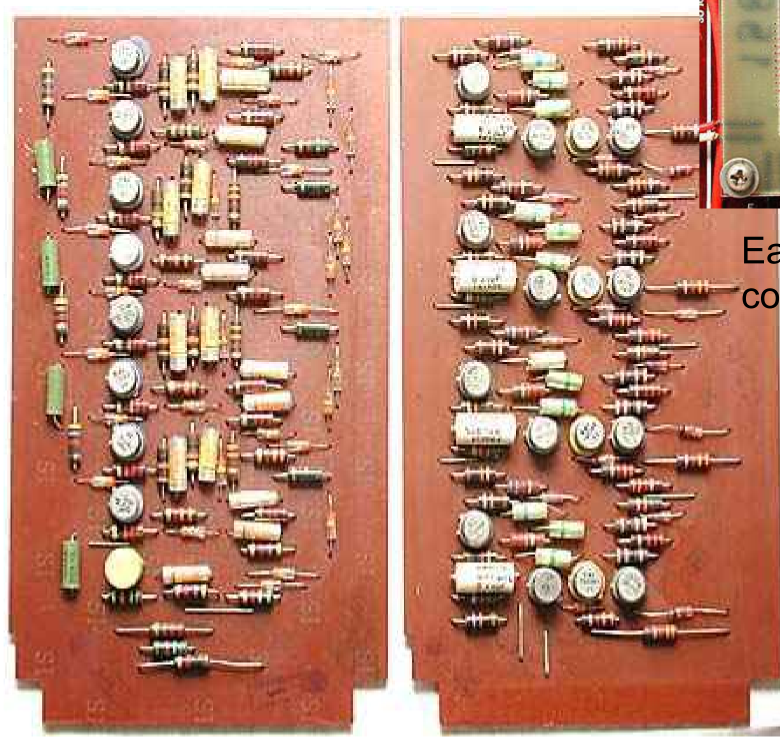
Historical Development



Early RAM! (magnetic core memory)

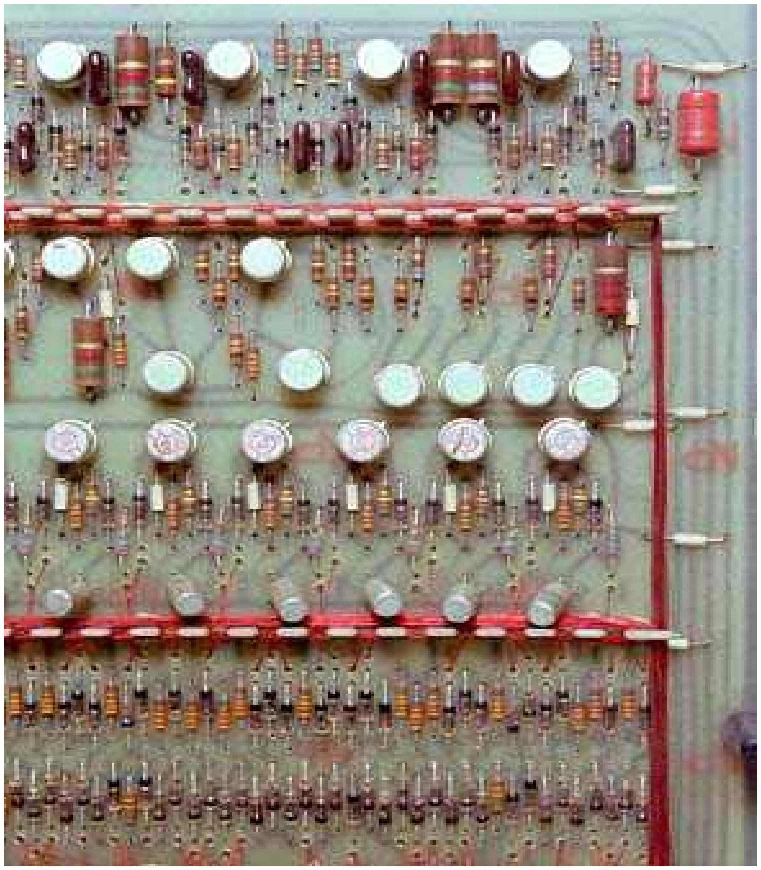


1950's Hardwire, Valves!



~ 1960 Hardwire, Transistors

Historical Development



~ Early 60's PCB, Transistors

Many individual components on PCB

- Semiconductor transistors and diodes
- Passives: Resistors, Capacitors,
  Inductors

All with individual packaging

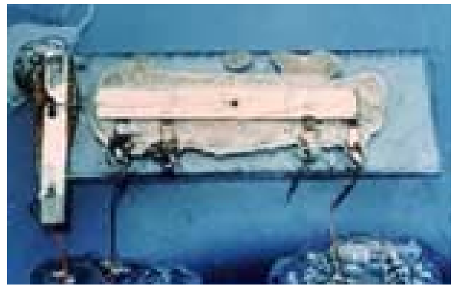
Large area, limited processing power, Slow!

Complex to assemble – Time consuming, costly

Not so reliable and expensive to repair

What about doing in all in Silicon?

Monolithic Integration: The IC



Kilby's Chip. Very crude!

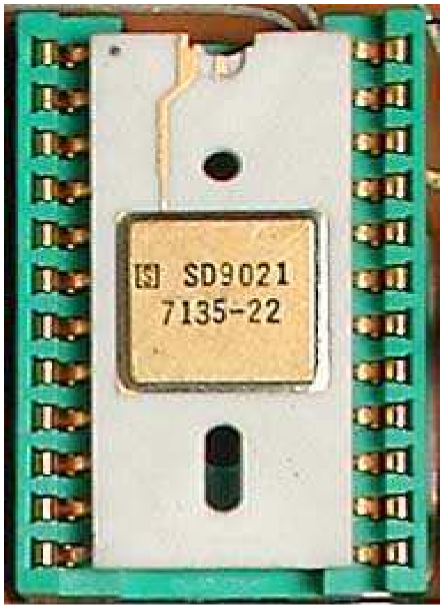
Jack Kilby (Texas Instruments, 1958)

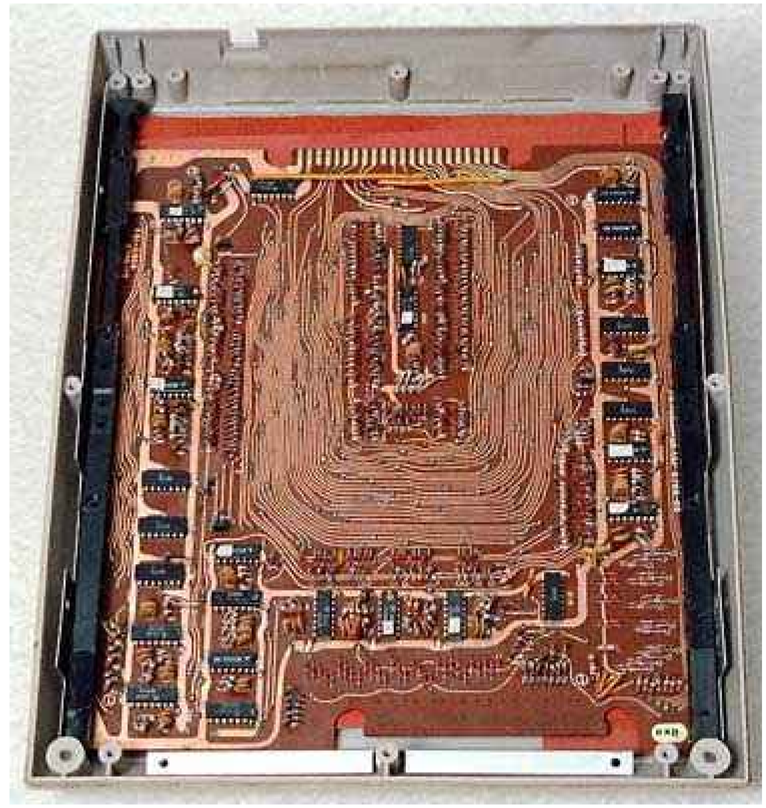
Big idea was to make all the components out of silicon

Robert Noyce (Rockwell, Intel,1959-

Developed the initial idea by depositing and etching metal to provide interconnects

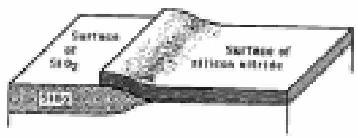
First commercial ICs (late 1960's)



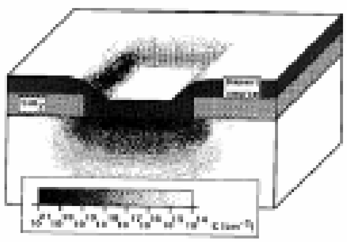


Less components, advanced PCB: Much greater complexity and speed at lower cost

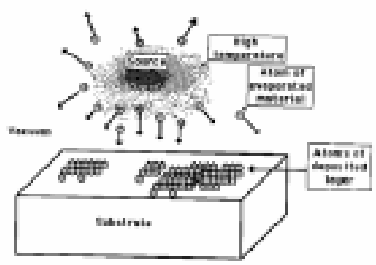
Silicon IC Manufacturing Steps



Growing silicon dioxide to serve as an insulator between layers deposited on the surface of the silicon wafer.



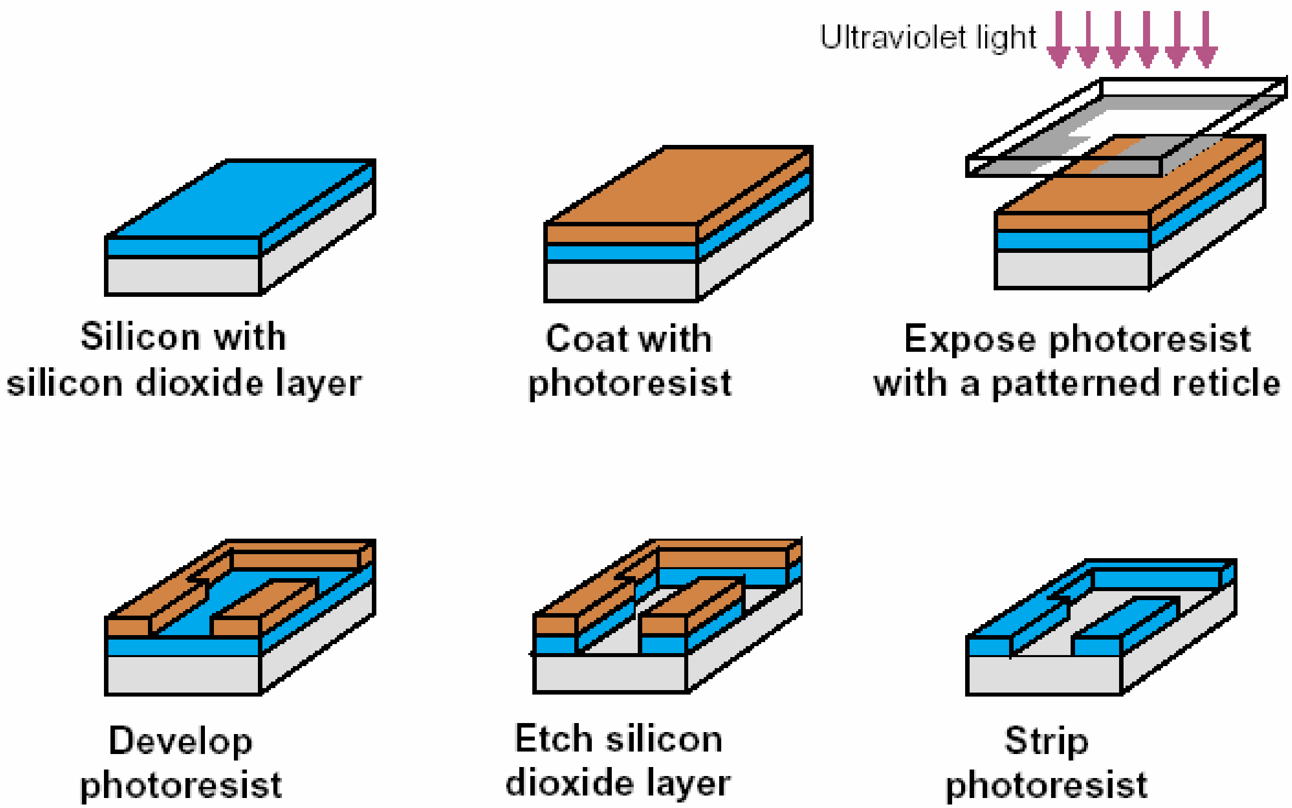
Doping the silicon substrate with acceptor and donor atoms to create p- and n-type diffusions that form isolating PN junctions and one plate of the MOS capacitor.



Depositing material on the wafer to create masks, wires and the other plate of the MOS capacitor.

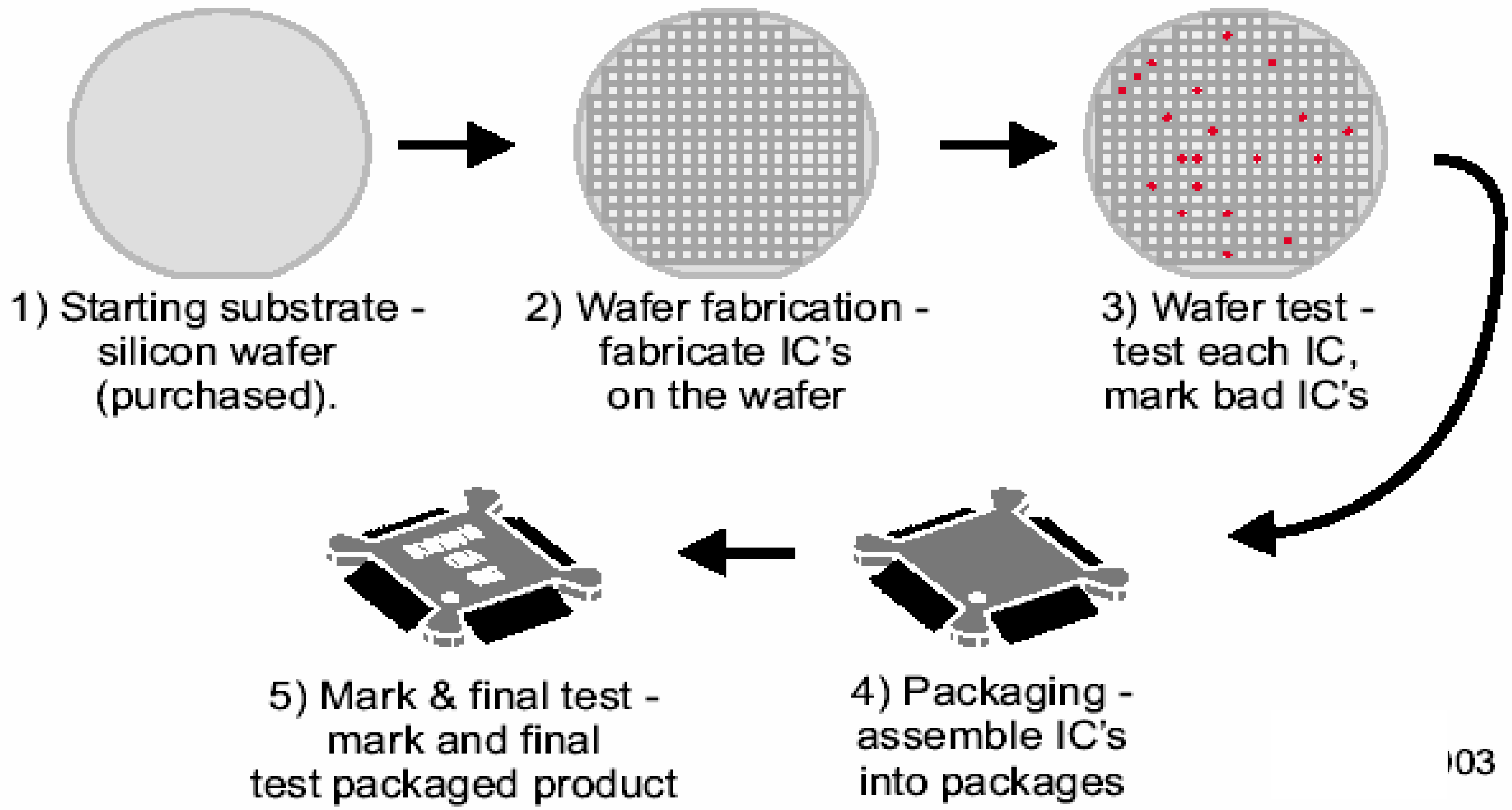
Etching deposited materials to create the appropriate geometric patterns.

Etch Process Steps

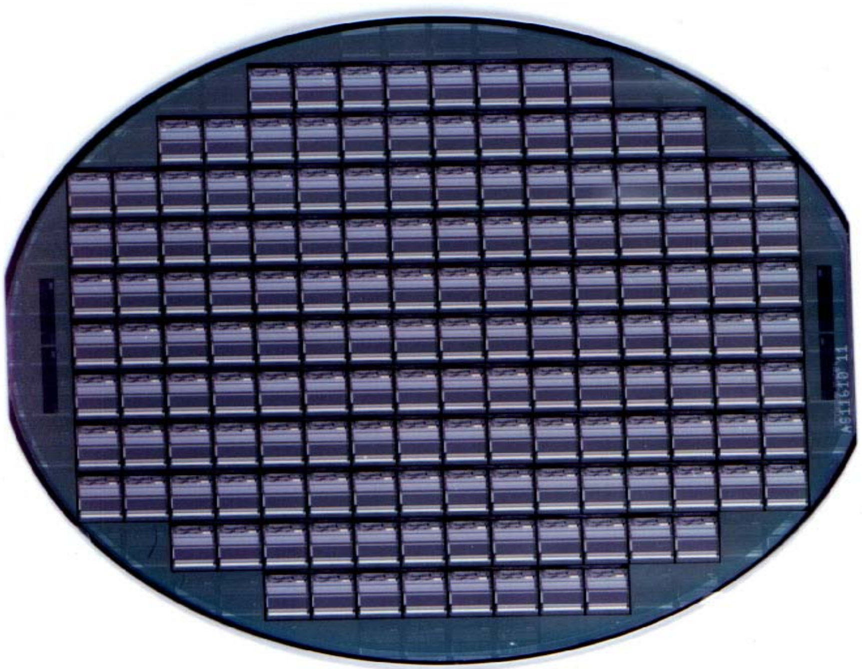


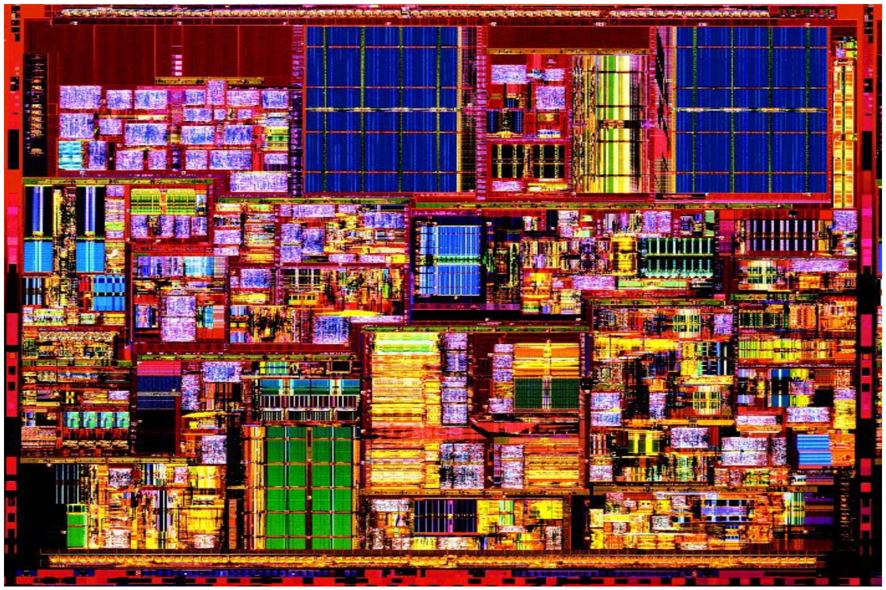
Photolithography and etch

IC Manufacturing Steps



IC Manufacturing Steps





Processed Silicon Wafer

Individual processed die (Pentium 4)

40 million transistors, 109 processed die per 12 inch wafer

Integrated Circuits

ICs are at the core of a modern digital system

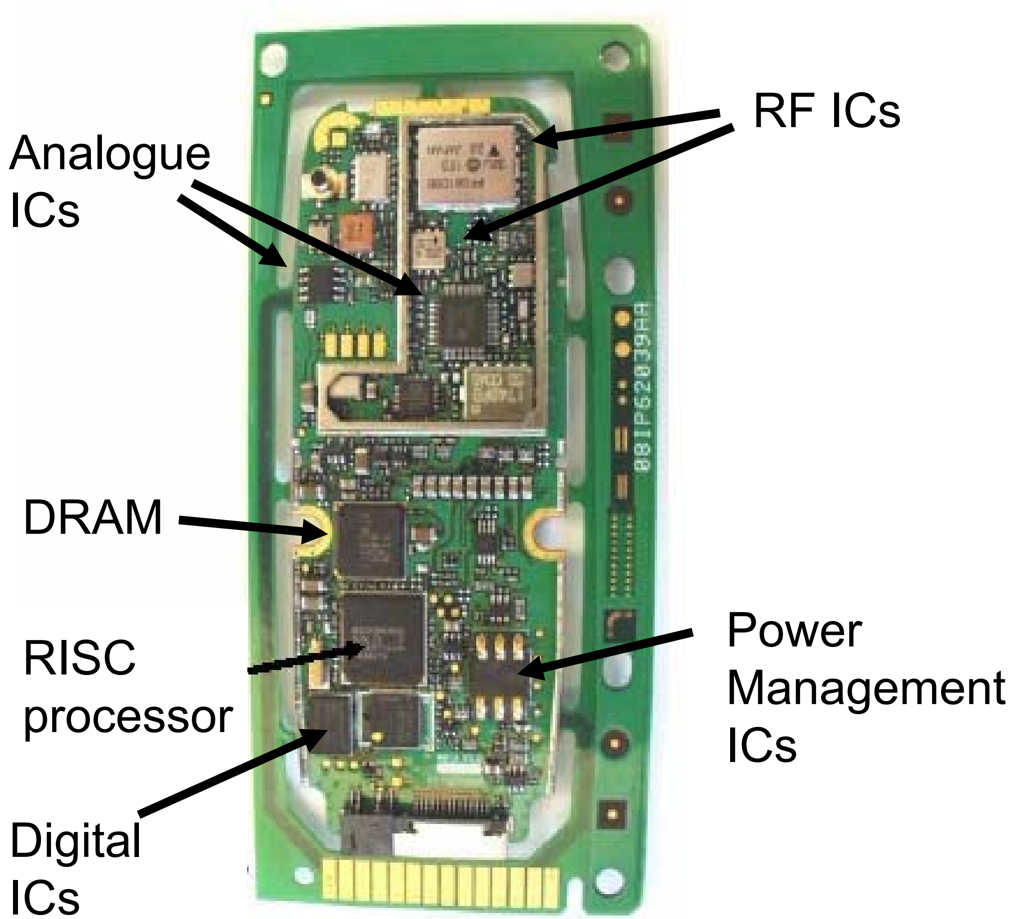
Many systems fit entirely on a single IC (SOC)

- A single (15mm) processor chip can hold 10^8 transistors
- A simple 32-bit CPU can be realised in an area of 1mm2

Modern Multi IC PCB (mobile phone)

Multifunction ICs enable:

- Small Form Factor
- High Performance
- Low Cost
- Low Power consumption
- High Reliability

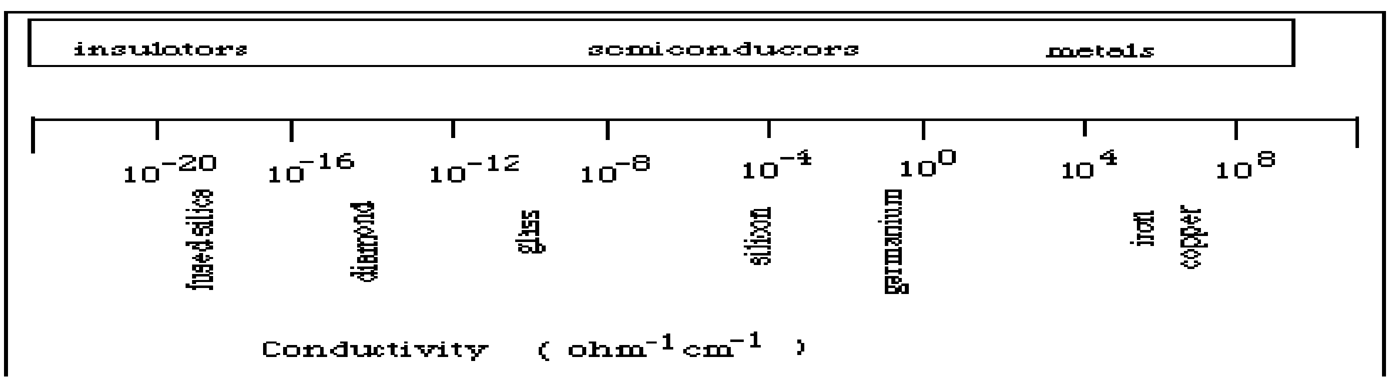


Electrons in Solids

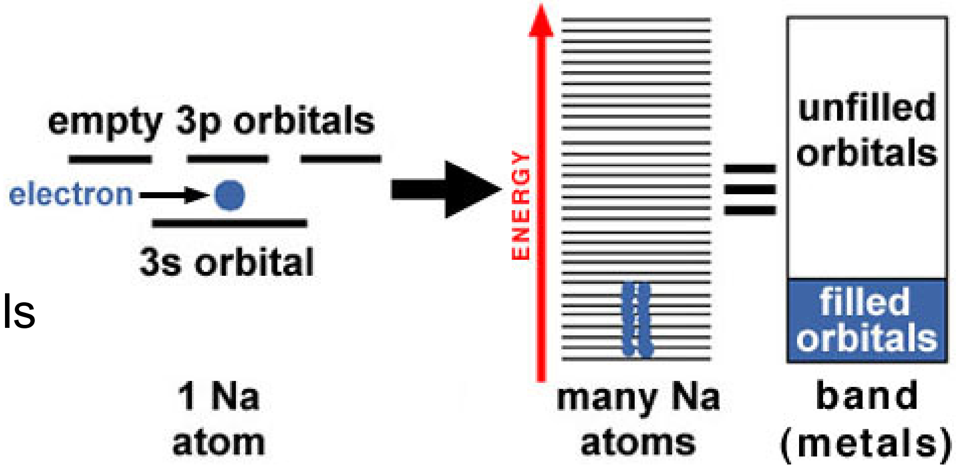
Metals are good conductors of electricity, of heat and are generally strong yet malleable materials: easy to form into various shapes eg: copper, aluminium, gold

Insulators are poor conductors of electricity and heat. They are often brittle and have high melting points. Examples include glasses & ceramics

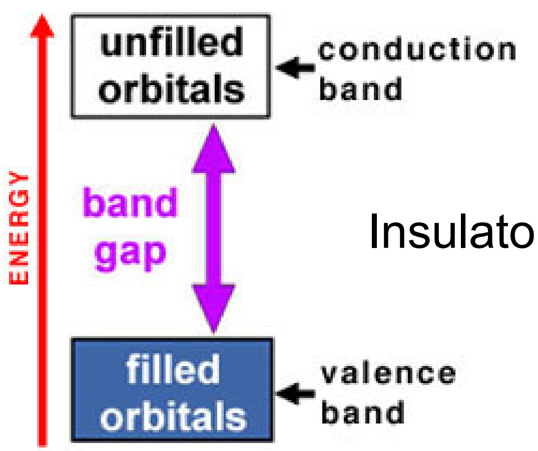
Semiconductors are somewhere in the middle. They can conduct, but their conduction is often controlled by impurities and effected by temperature. In many ways their physical properties can be viewed as 'semi-metallic' (poor metals).



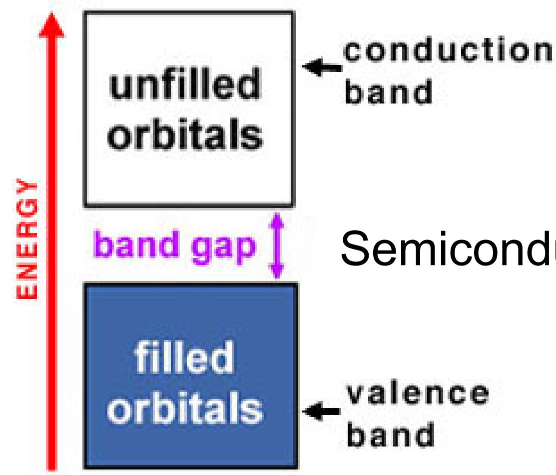
Electrons in Solids



Metals

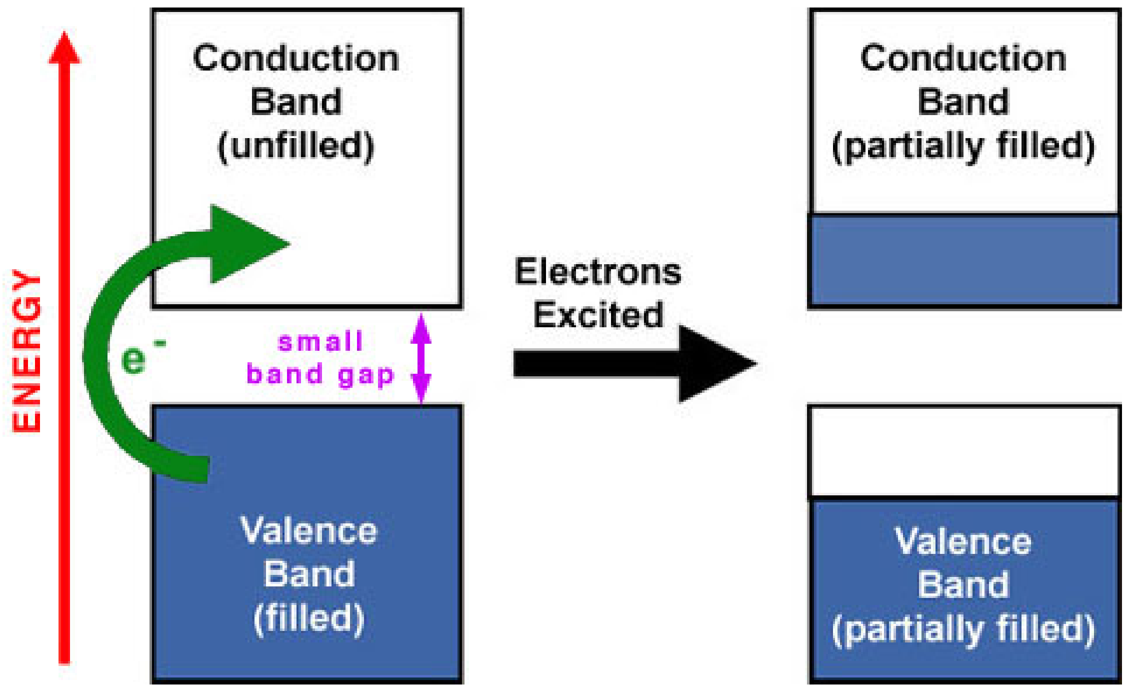


Insulators



Semiconductors

Electrons in solids



Conduction needs access to unfilled energy levels. In a semiconductor, the band gap is small enough that electrons can gain sufficient energy to move from the valence band to new orbitals in the conduction band. This leaves both bands partially filled, so the material can conduct electricity

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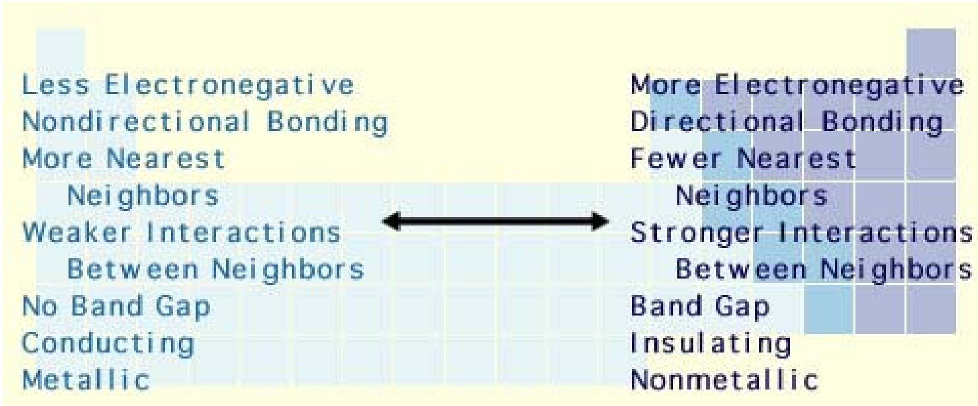
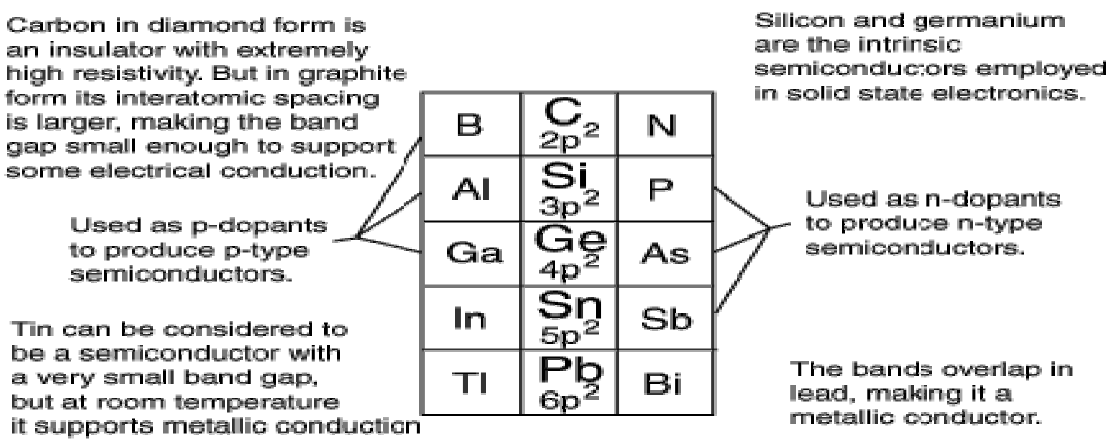
Electrons in Solids



The periodic table shows trends in bonding and conduction



Semiconductors come from one part of the periodic table

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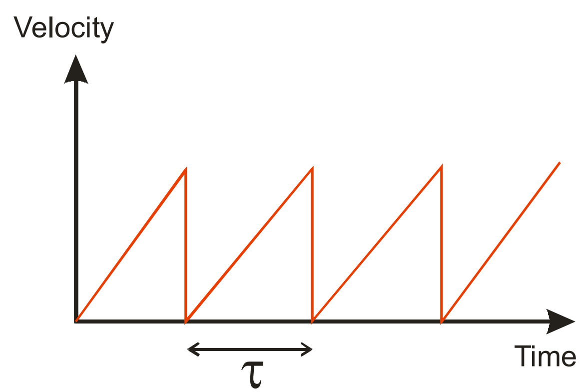
Electrons in Solids

Electron mobility in a semiconductor (μ)= = v/E
An electron in an electric field undergoes acceleration and then collides every τ seconds with phonons (lattice vibrations), defects, impurities etc. $\tau \sim 10^{-14}$sec



Force (F)= eE

*velocity (v)=accel x time. V= eE/m * t*

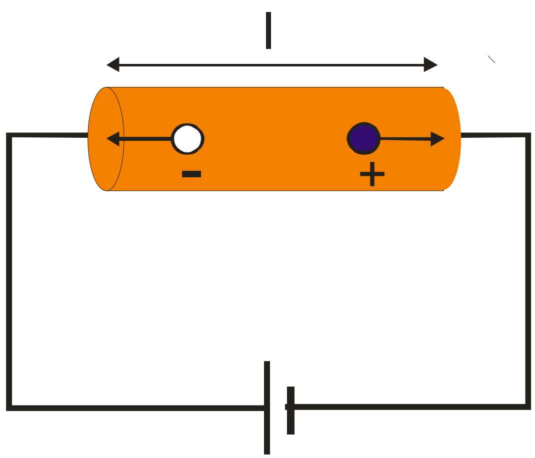
$$V_{Ave} = \frac{1}{2}(0 + eE\tau / m) = eE\tau / 2m$$

therefore

$$\mu = \frac{e\tau}{2m} \qquad Actually \rightarrow \mu = \frac{e\tau}{m}$$

See Allison (p72-74)

Intrinsic (pure) semiconductors have equal number of electrons and holes as when bonds are broken we have one electron and one hole created. Therefore; $n = p = n_i$



Field (E)= V/ l

Time (t)= l/ v

Since v=μ_eE, time (t)=l / μ_eE,

Similarly for holes

t =l / μ_hE

Electrons in Solids

$$Current(I) = charge/time$$

$$Charge = lA(n,p)e$$

$$I = \frac{lAne\mu_e E}{l} + \frac{lAnp\mu_p E}{l}$$

$$Current.density(J) = \frac{I}{A}$$

$$J = eE(n\mu_e + p\mu_h) = \sigma E$$

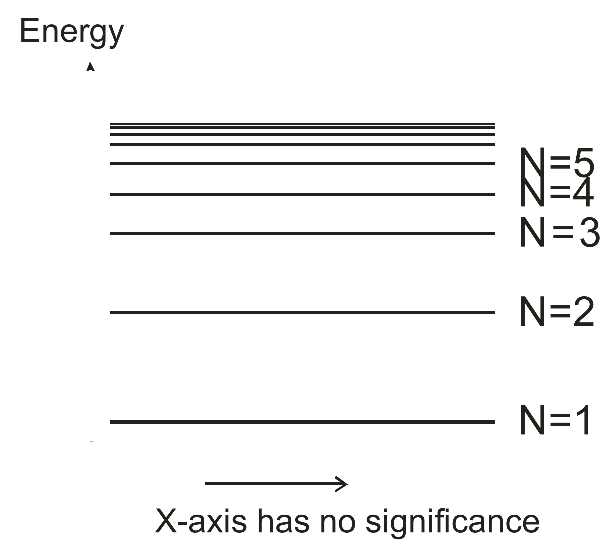
$$conductivity(\sigma) = e(n\mu_e + p\mu_h)$$

Energy Band Model for Electrons in Solids

Consider hydrogen atom as it has the simplest atomic structure
In 1913 Neils Bohr postulated that to explain discrete sharp lines in the radiation spectrum, the atom must consist of:
i) Fixed orbitals
ii) Quantised electron energy levels

$$E = -\frac{13.6\,eV}{n^2}$$

Where n are the principal quantum numbers: 1, 2, 3 etc



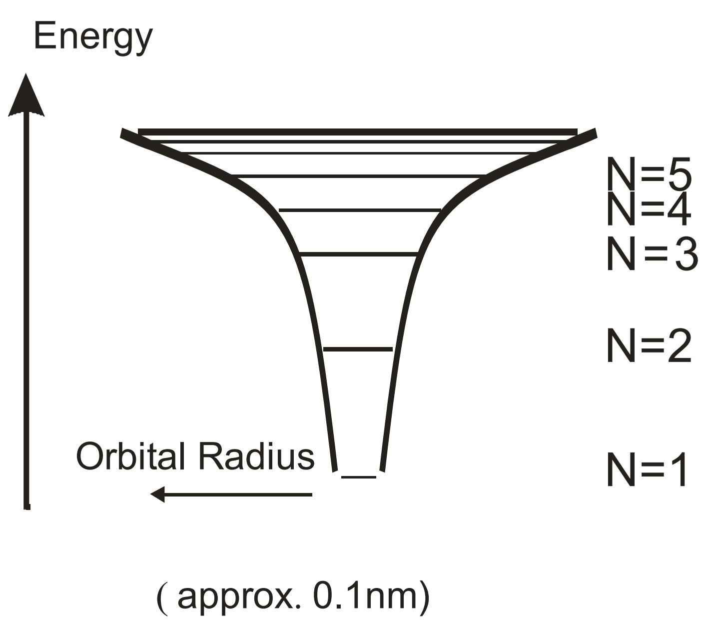
Electrons in Solids

Transitions between two levels result in emission of radiation of Energy E (=h. v), where h is Planks constant and v is the frequency.
Actual picture of energy levels is more complicated as there are **3** other quantum numbers: l (gives allowed angular momentum), m (magnetic quantum number -angle of spin axis with respect to a B field and s (spin, which is either +1/2 or -1/2 for an electron)

Electrons in solids also obey 2 other rules:

i) Usually occupy **lowest** available energy level

ii) Obey **Pauli Exclusion Principle** -only l electron is allowed in any particular quantum state, i.e. only 1 electron with particular (n,l,m & s values)



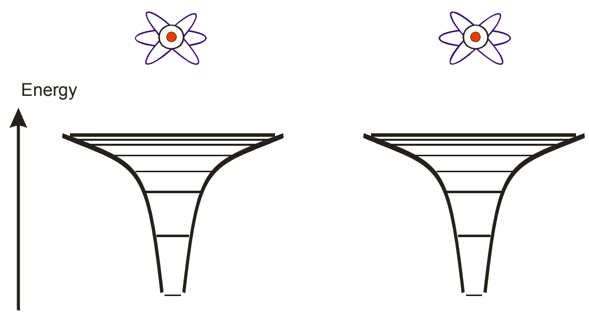
2 electrons cannot exist at the same place with the same energy

Higher quantum numbers mean larger radius

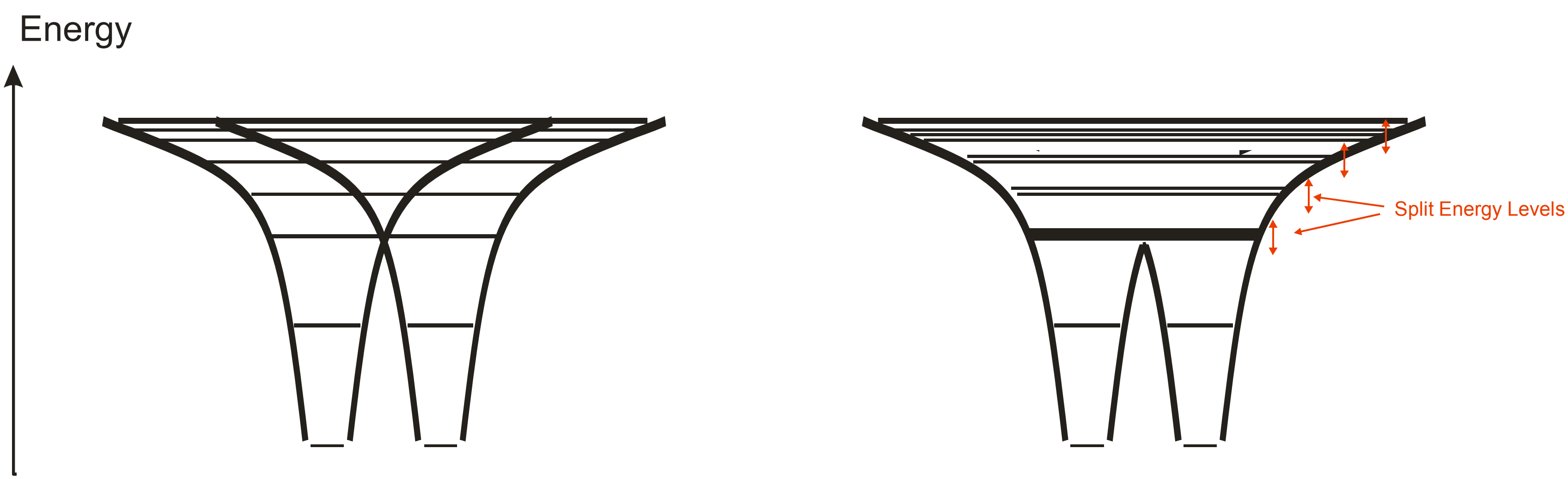
Potential binds electrons to the nucleus, but electrons in higher quantum number states are progressively more weakly bound

Electrons in Solids

When atoms are far apart -as in a gas without any interaction, there is no overlap of orbitals, so electrons **can** have the same energy levels.

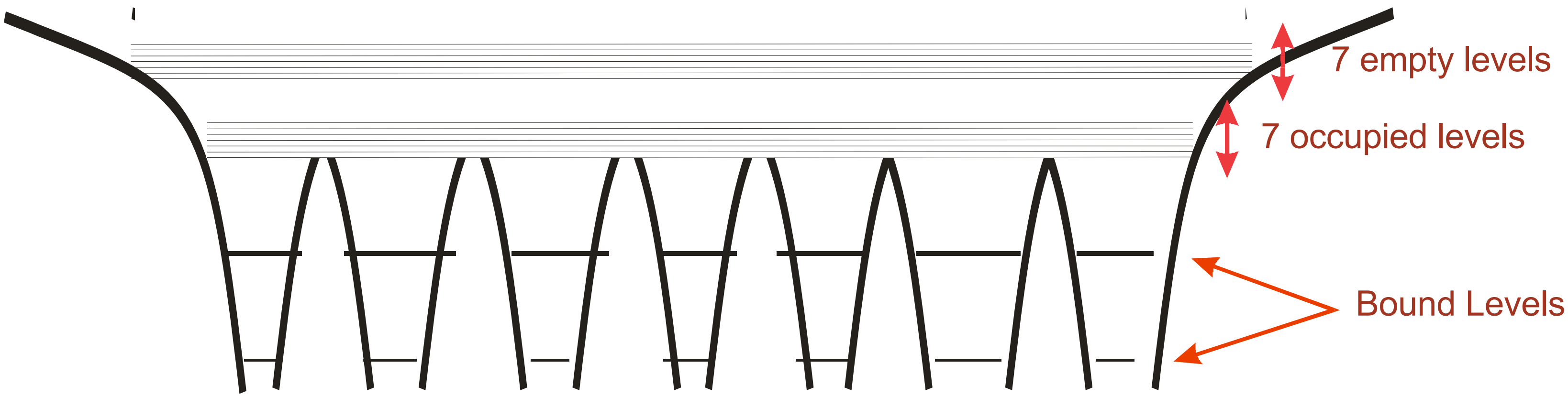


But as soon as atoms are brought together in a solid, outer electron orbitals overlap, so their corresponding energy levels change slightly ('split') to avoid contravening the Pauli exclusion principle. These electrons are not bound to the nucleus and become 'free'.



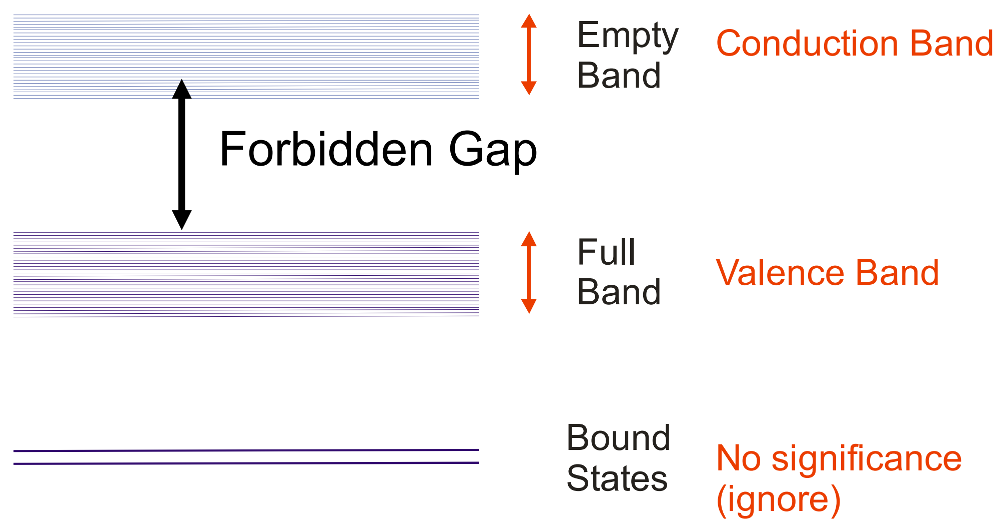
Electrons in Solids

7 atom solid



As **7** atoms interact to form the 'solid', outer overlapping electron levels each split 7 ways, so as to obey Pauli's exclusion principle
End up with a BAND of empty levels, a BAND of allowed levels

Energy levels in a band are 10^{-22}eV apart: quasi continuous



Electrons in Solids

Conduction in a band

i) There must be free electrons, i.e. no conduction in an empty C.B

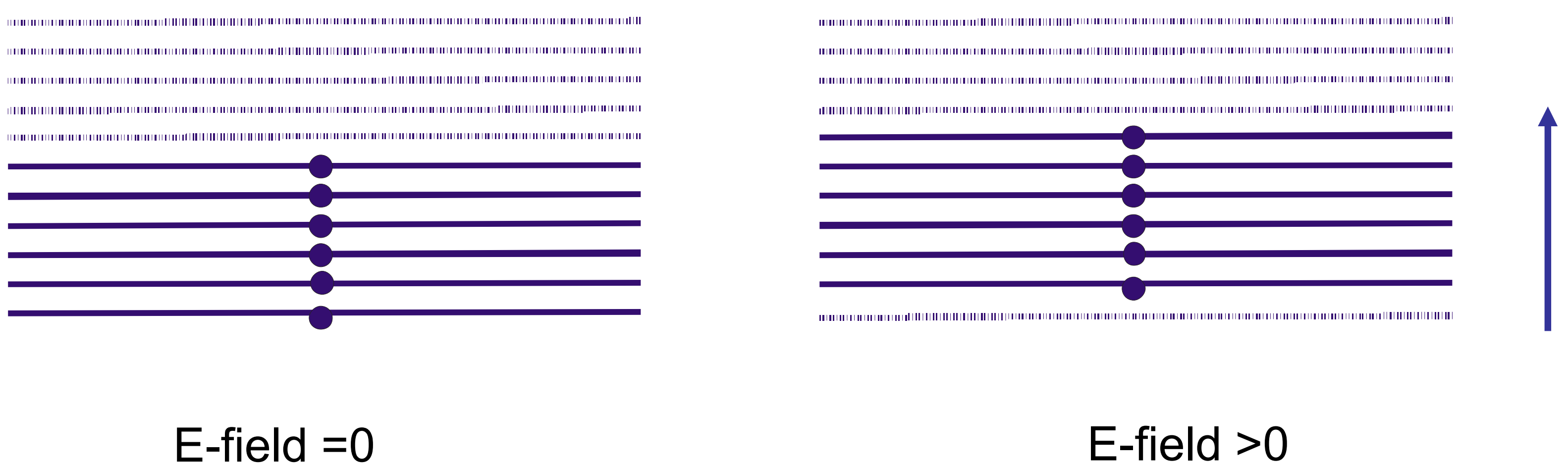
ii) There needs to be a band of states. If carriers gain energy there must be a higher empty level available, otherwise Paulis's exclusion principle violated.

Consequences:

(a) an empty C.B. cannot support conduction

(b) a completely full band cant support conduction either

Band must be partially filled!



If electric field is applied, electrons gain energy and can move into higher energy empty states

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Electrons in Solids

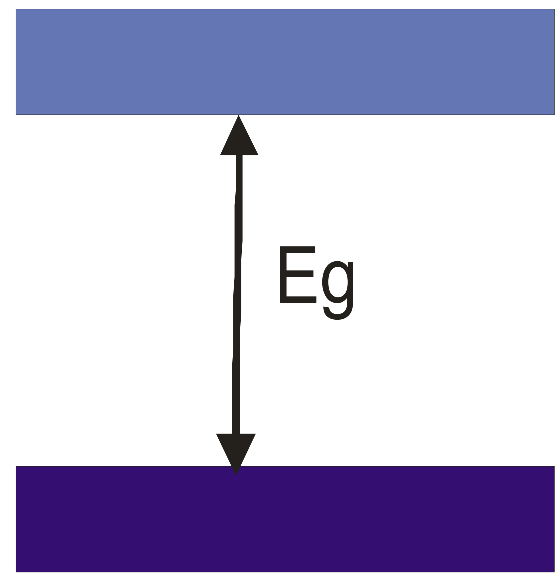
Insulators

Have a filled VB and a conduction band separated by a large energy gap (typically 5-20eV)

Only is electrons can acquire and energy E_g can they move into the CB.

Thermal energy = kT~ 0.025eV at 300K so probability is small

No (or very poor) conduction.



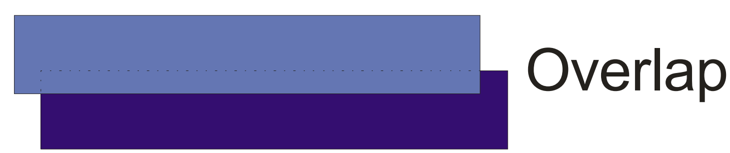
Metals

There electronic structure has a distinguishing feature.

Outer empty band overlaps the inner full band

As a result, you have a composite band and an ideal situation for conduction.

There is no energy gap. Electrons are free to move in an electric field to higher energy levels



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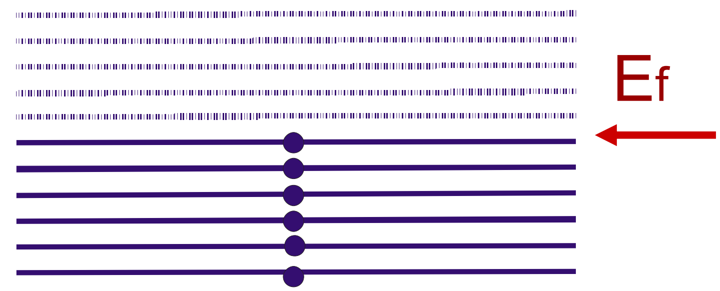
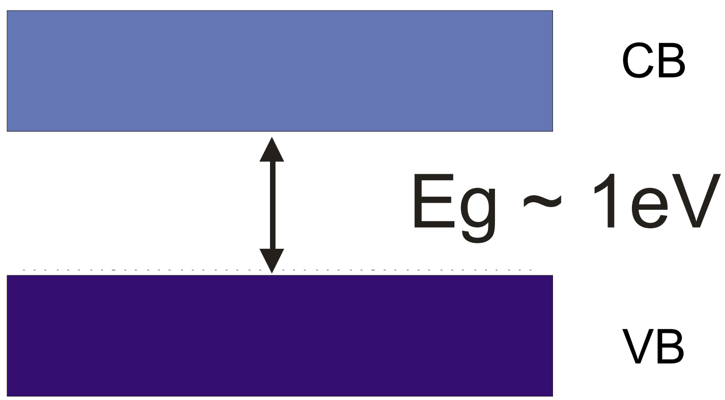
Electrons in Solids

We can define a fill level, known as the **FERMI LEVEL**

At OK, levels above the Fermi level are empty, levels below are full

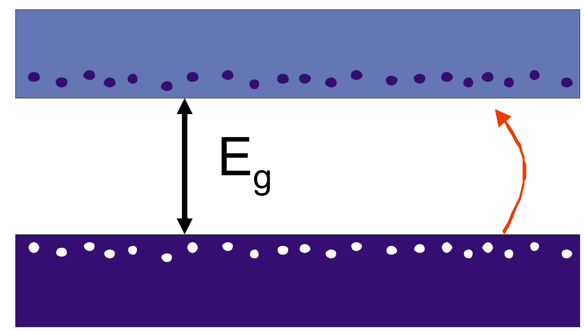


In a **Semiconductor** the energy gap (Eg) ~ 1eV
At low temperature electrons cannot reach the CB: INSULATOR
Thermal energy = kT~ 0.025eV at 300K
So Eg> kT, but there is a now finite possibility of some electrons in the CB



Electrons in Solids

Energy gap is sufficiently small that electrons can be promoted to the conduction band.



Each electron promoted to the CB leaves behind one vacant level (hole) in the VB. Conduction in semiconductors is due to:

(i) electrons moving in the part filled CB
(ii) electrons in the VB moving into levels vacated by electrons elevated into the CB. Easier to view as the movement of holes

In an intrinsic semiconductor:

number of electrons = n (m-3) = number of holes = p (m-3)
= n_i *(intrinsic concentration)*