

Semi Conductor Intelligence

Atoms are the building blocks of all matter be it gold water diamond or coal. There are 118 different types of atoms that occur in nature known as the elements. Each kind of atom is distinguished chemically by a different number of electrons ranging from 1 to 118. For charge neutrality the number of protons with unit positive charge in the nucleus must equal the number of unit negative charge electrons in orbit around the nucleus. The planetary atom. The hydrogen atom has 1 proton and 1 electron – no neutrons. Deuterium contains additionally 1 neutron while tritium contains 2 neutrons 1 proton and 1 electron. Neutrons and protons are called nucleons.

Orbitals available to accommodate electrons are the s p d f and g orbitals of increasing energy and they also define a keen electromagnetic space. Carbon has the electronic structure denoted by $1s^2 2s^2 2p^2$. The integer prefix denotes the (increasing) energy of the orbital while s stands for the spectral term ‘sharp’ and it is a spherical orbital. P denotes the spectral term ‘principal’ and a dumbbell like shape while the integer exponent numbers the electrons as 2, in each level. To complete the 2 shell would require 4 extra electrons to acquire the electronic configuration of ‘Neon’ $1s^2 2s^2 2p^6$. Neon has a particular stability, by virtue of its electronic configuration. Thus we say that Carbon has a valence of 4. Silicon is also a group 4 element with the electronic configuration $1s^2 2s^2 2p^6 3s^2 3p^2$. While carbon can be an excellent conductor as in graphene which is single sheet graphite, diamond is an insulator and silicon is a semi conductor.

It is in compounding a solid by imploding a gas that we move from an atomic orbital (ao) description of the isolated atoms to a linear combination of atomic orbitals (lcao) constituting the solid. The outer electrons of each atom combine to form bands and this is described below. It is not simply a matter of ‘adding’ the atomic orbitals but involves the use of the Schrodinger equation which we are soon to derive. Sometimes a fullband will overlap with an empty band giving electrons at the top of the full band room to move and allowing for conduction of electricity as in a metal. Maybe there will be a band gap of forbidden energies when the provision of heat will excite the topmost collection of electrons in the full band into the conduction band as in a semiconductor allowing conduction. Maybe the band gap will be much larger making excitation unreachable and forbidding conduction as in an insulator.

An intriguing question is why the 1s electron of hydrogen doesn’t fall into the nucleus? After all there is coulombic attraction between the negative electron and positive nucleus. Well it was way back in 1905 when one Albert Einstein won the Nobel prize for his explanation of the photo electric effect. The world of science was faced with a wave particle duality and a mass energy equivalence in fundamentals. On the atomic scale the electron shows its wave nature. As the degree of electron (box) confinement goes up so the energy of the electron goes up. Energy that overcomes the coulombic attraction. See the treatment of the electron in a box below.

Throw a stone into a still pool to see circular waves from the impulse. Now these waves can be described by an identity like equation elsewhere described as the fundamental wave

equation:
$$\frac{d^2 \Phi}{dx^2} = \frac{1}{v^2} \frac{d^2 \Phi}{dt^2} \dots\dots\dots(1)$$

v=velocity Φ =displacement

In order to separate variables

$$\text{Let } \Phi(x, t) = \Psi \sin(2\pi f t) \dots \dots \dots (2) \quad f = \text{frequency} :: \Psi = f(x)$$

Now we now proceed to find $\frac{d^2 \Phi}{dx^2}$ and $\frac{(d^2 \Phi)}{dt^2}$ to substitute into (1)

$$\text{So} \quad \frac{d\Phi}{dx} = \frac{d\Psi}{dx} \sin 2\pi f t$$

$$\text{and} \quad \frac{d^2 \Phi}{dx^2} = \frac{d^2 \Psi}{dx^2} \sin 2\pi f t$$

$$\text{For} \quad \frac{d\Psi}{dt} = \Psi \frac{d \sin 2\pi f t}{dt}$$

$$\text{Let } a = 2\pi f t \quad \text{which implies} \quad \frac{da}{dt} = 2\pi f$$

$$\text{and} \quad \frac{d \sin a}{dt} = \frac{d \sin a}{da} \frac{da}{dt} = 2\pi f \cos a = 2\pi f \cos 2\pi f t$$

$$\text{therefore} \quad \frac{d\Psi}{dt} = \Psi 2\pi f \cos 2\pi f t$$

$$\text{and} \quad \frac{d^2 \Psi}{dt^2} = -4\pi^2 f^2 \Psi \sin 2\pi f t$$

Substituting in (1)

$$\frac{d^2 \Psi}{dx^2} \sin 2\pi f t = \frac{-4\pi^2 f^2}{v^2} \Psi \sin 2\pi f t \quad \text{since } \lambda = \frac{v}{f}$$

$$\frac{d^2 \Psi}{dx^2} = \frac{-4 \pi^2}{\lambda^2} \Psi \quad \dots\dots\dots(3)$$

Now the kinetic energy of the electron equals $\frac{1}{2} mv^2 = p^2/2m$ given $p=mv$ De Broglie remains famous for introducing that all mass has a wavelength $\lambda=h/p$ and substituting in (3) we have:

$$\frac{d^2 \Psi}{dx^2} = \frac{-4 \pi^2 p^2}{h^2} \Psi \quad \dots\dots\dots(4)$$

then using $E=KE + PE = \frac{1}{2} mv^2 + V = p^2/2m + V$
 thus $p^2 = (E-V) 2m$ and substituting in (4) we have

$$\frac{d^2 \Psi}{dx^2} = \frac{-8 \pi^2 m (E - V) \Psi}{h^2}$$

and this is the much celebrated Schrodinger equation in 1 D.

The value of this equation is that its solution yields information about the value an electron can have for Ψ and E . Ψ^2 is the value for the probability of finding an electron at position x and different values for Ψ impose different geometric constraints when describing the geometrical shapes of Orbitals. The information given about E is also useful when one tries to calculate how the system behaves electrically whether in an organic chemical reaction or as an electronic component

For an electron trapped in a box where $V=0$ and outside the box $V=\infty$ the Schrodinger equation becomes

$$\frac{d^2 \Psi}{dx^2} = \frac{-8 \pi^2 m E \Psi}{h^2} \quad \dots\dots\dots(6)$$

a general solution is $\Psi = A \sin(Bx+C)$ (7)

Boundary conditions simplify matters considerably. Firstly the wave function must be continuous. Since the electron has zero probability of being found outside the box because $V = \infty$ then $\Psi_x = 0$ at $x=0$ and the same goes for $x=a$ where a is the x coordinate of the extent of (width) of the box. The first condition substituted in (7) yields $A \sin C = 0$ which then makes $C = 0$. the situation at the co-ordinate $x = a$ makes $A \sin(Ba) = 0$ which means $B = n_x \pi / a$ or $\Psi = A \sin Bx$ (8)

Since $\int_0^{\infty} \Psi^2 dx = 1$ Since the electron must be somewhere

we find $A = \sqrt{\frac{2}{a}}$ and substituting this value into (8) we get

$$\Psi = \sqrt{\frac{2}{a}} \sin \frac{n\pi x}{a}$$

$$\frac{d\Psi}{dx} = A \frac{n\pi}{a} \cos \frac{n\pi x}{a} \quad \text{and} \quad \frac{d^2\Psi}{dx^2} = -A \frac{n^2\pi^2}{a^2} \sin \frac{n\pi x}{a}$$

from eq (6) we have

$$\frac{d^2\Psi}{dx^2} = \frac{-8\pi^2 m E \Psi}{h^2} \quad \text{and so equating the rhs's we have}$$

$$\frac{-8\pi^2 m E \Psi}{h^2} = \frac{-n^2\pi^2}{a^2} \Psi \quad \text{which reduces to}$$

$$\frac{8mE}{h^2} = \frac{n^2}{a^2} \quad \text{which implies that} \quad E = \frac{n^2 h^2}{8ma^2}$$

then we make the substitution for $\hbar = \frac{h}{2\pi}$ and $k = n \frac{\pi}{a}$

$$\text{and write} \quad E = \frac{k^2 \hbar^2}{2m}$$

It can be seen from these equations that as the degree of confinement, as contained in the variable a , goes down, so the Energy increases. Also when one or even a few atoms are involved and they are being confined the energy levels are discrete and discontinuous. A fact we are going to use in the Quantum dot transistor described at the end of this chapter. When we consider a big crystal there are bands of continuous energy. In semiconductors the valence band is separated from the conduction band by a range of forbidden energy values. The band gap. Note that in the above expression E is a smoothly parabolic function of k .

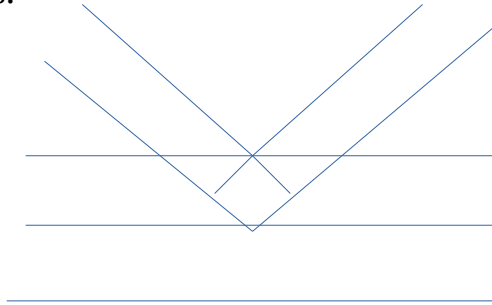
We are now going to discuss the Band theory where the smoothly parabolic nature of E vs k is distorted to forbid certain energies that now constitute a band gap.

An ideal crystal is constructed by the infinite repetition of identical groups of atoms. A group is called the basis. The set of mathematical points to which the basis is attached is called the lattice. The lattice in 3D may be defined by 3 translation vectors a_1 , a_2 and a_3 such that the arrangement of atoms in the crystal looks the same when viewed from the point r as when viewed from every point r' translated by an integral multiples of

the a 's. $r' = r + u_1a_1 + u_2a_2 + u_3a_3 \dots\dots(1)$ where the u 's are arbitrary integers. The set of points r' defined by (1) for all u defines the lattice.

Diffraction

The phenomenon of diffraction is also an analytical procedure using photons neutrons or electrons and detecting at what angles the reflection of a beam takes place. These angles are characteristic of the particular crystal that absorb and reflect the beam of 'radiation'. Consider a regular lattice and the planes that are formed between the rows.



Say that the beams radiation strikes the crystal at the angle θ and the distance between planes = d . Then the path difference between the 2 rays of the beam (from its source to the point of detection) is equal to $2d\sin \theta$. When this difference is equal to an integral number of (beam) wavelengths constructive interference occurs and there will be an observable reflection.. The distance d should be no less than half the wavelength of the beam. This is Bragg's Law of diffraction.

In a crystal the electrons are considered to be a wave and they have a wavelength.

This wavelength is related to the energy in $E = \frac{\hbar^2 k^2}{2m}$ $k = \frac{2\pi}{\lambda}$. When the

Bragg diffraction law is satisfied such that the path length difference is half a wavelength there is interference which sets up a standing wave eliminating that wave from the picture and the corresponding energies are 'forbidden'. The transmission of the (electro) wave is impossible due to Bragg diffraction. Thus the E vs k picture suffers distortion and there is a band of forbidden energies.

In metals semi-conductors and insulators the electrons are accommodated in a valence band. The valence band consists of multifold energy levels spaced infinitesimally apart and each level can accommodate 2 electrons of opposite spin. No 2 electrons can have the same 4 quantum numbers. These quantum numbers designate the energy, shape of orbital, orientation and spin. Then there is a band gap of forbidden energies before we get to the conduction band. Maybe as is the case with some metals the conduction band which is empty overlaps with the valence band. Now some of the low lying states in the conduction band can accommodate electrons which become available for conduction and chemistry. If the conduction band is only partly full and there is no overlap then the topmost electrons are free to move and can take part in conduction and chemistry. Even if there is band gap before the conduction band, at room

temperature an electron can gain enough energy to get into the conduction band and be available for chemistry and conduction as a semi-conductor would. Now when an electron migrates to the conduction band it leaves behind a positive hole which will conduct (positive) current subject to an electric potential difference. In principle and in preview an intrinsic semi conductor like silicon, Si, from group 4 with a valency of 4 can be 'doped' with a trivalent substance to the point where this now constitutes a P type semiconductor P for positive as are holes. Adding a pentavalent substance from group 5 would make the Si N type, N for negative when the 5'th electron becomes free to wander about in the crystal and conduct subject to the imposition of an electrical potential difference. We will write more about extrinsic semi-conductors bit later and now turn our attention to how we can calculate the fraction of energy states $f(E)$ occupied by an electron in a semi-conductor. The Fermi – Dirac distribution.

According to the Boltzman distribution the probability of a state E being occupied $f(E)$ is proportional to $\exp(-E/kT)$. According to the Pauli exclusion principle no occupied state can contain electrons with the same quantum numbers. So we can say then that any given state can be either empty or occupied by 1 electron. The probability that the state be empty = $P(0)$ while the probability of the state E being occupied by 1 electron = $P(1)$. The total probability $P(0) + P(1) = 1$.

So substituting for $P(0)$ and $P(1)$ we have

$$\frac{1}{Z} e^{-\frac{E(0)}{kT}} + \frac{1}{Z} e^{-\frac{E(1)}{kT}} = 1 \quad Z \text{ is a constant of proportionality}$$

So $Z = e^{-\frac{E(0)}{kT}} + e^{-\frac{E(1)}{kT}}$

Next we say that $f(E) = P(1) = \frac{1}{Z} e^{-\frac{E(1)}{kT}}$ is the fraction of states occupied by 1

electron at the energy level E. Substituting for Z and multiplying by $\frac{e^{-\frac{E(1)}{kT}}}{e^{-\frac{E(1)}{kT}}} = 1$ we

have :-

$$f(E) = \frac{e^{-\frac{E(1)}{kT}}}{e^{-\frac{E(0)}{kT}} + e^{-\frac{E(1)}{kT}}} * \frac{e^{\frac{E(1)}{kT}}}{e^{\frac{E(1)}{kT}}} = \frac{1}{e^{-\frac{E(0)}{kT}} * e^{\frac{E(1)}{kT}} + 1} \dots\dots\dots(A) \quad \text{Now}$$

consider that the total E = kinetic E + potential E

then $KE = E_T - \text{potential } E$

We set potential E to equal Fermi Energy thus $E(1)=E_T-E_F$. We use this below...
from eq A above we have

$$f(E) = \frac{1}{e^{\frac{(E(1)-E(0))}{kT}} + 1} \quad \text{and since } E(0)=0 \text{ and } E(1)=E_T - E_F$$

$$f(E) = \frac{1}{e^{\frac{(E_T - E_F)}{kT}} + 1} \quad \text{The Fermi-Dirac Distribution}$$

Just like to write a bit now about the Fermi energy and the Potential energy. The Fermi energy is the chemical potential of the electron. That electron available out of the full ensemble of electrons for chemistry. An electron buried deep in the ensemble is not available for chemistry and has no chemical potential. While the topmost electron has got chemical potential due also to its possible mobility not being buried in the ensemble.

Lets examine this Fermi Dirac Distribution.

At $E > E_F$ in the limit T goes to zero $f(E)$ goes to zero.

At $E < E_F$ in the limit T goes to zero $f(E)$ goes to one.

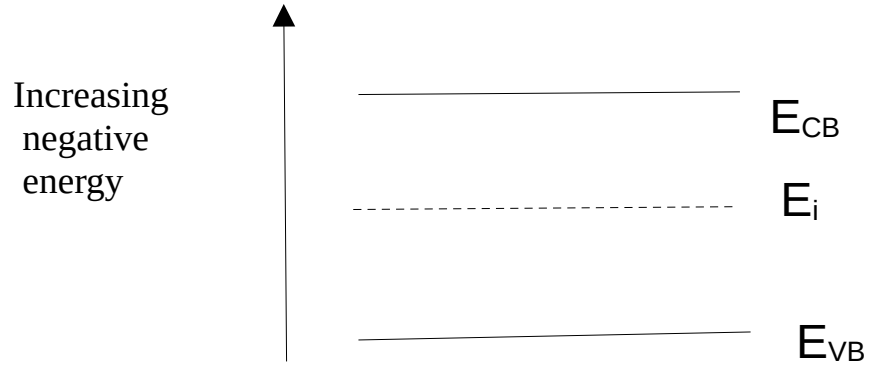
At $E = E_F$ $f(E) = 0.5$ ($E = E_T$)

$f(E)$ is the probability of an electron occupying a state of energy E . The Fermi energy level does not necessarily correspond to an actual energy level. It is a precisely defined thermodynamic quantity. It evenly separates the filled and unfilled states since at $E = E_F$ $f(E) = 0.5$.

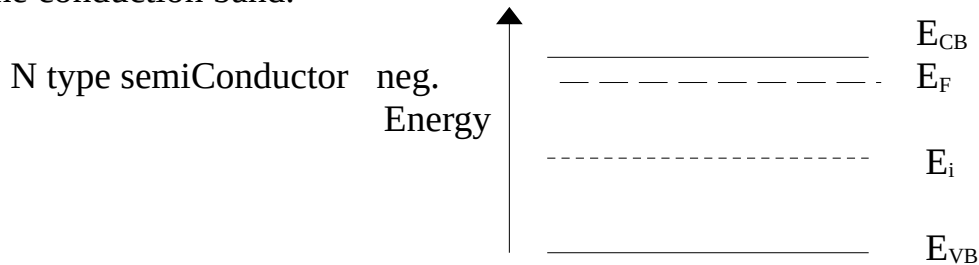
Intrinsic and Extrinsic Semi-Conductors.

Silicon crystallises out of the Big Bang as an Intrinsic Semi-Conductor-with a band gap. It is a group 4 element and to complete the stable octet of outer electrons it must bond with 4 of its immediate neighbours each of which contributes and reciprocally receives one electron. Thus all of the Silicon now has a stable octet of electrons in 4 covalent bonds. If the crystal absorbs energy be it light or heat then it can happen that an electron breaks free of a bond and finds its way into the conduction band leaving behind a positive hole.

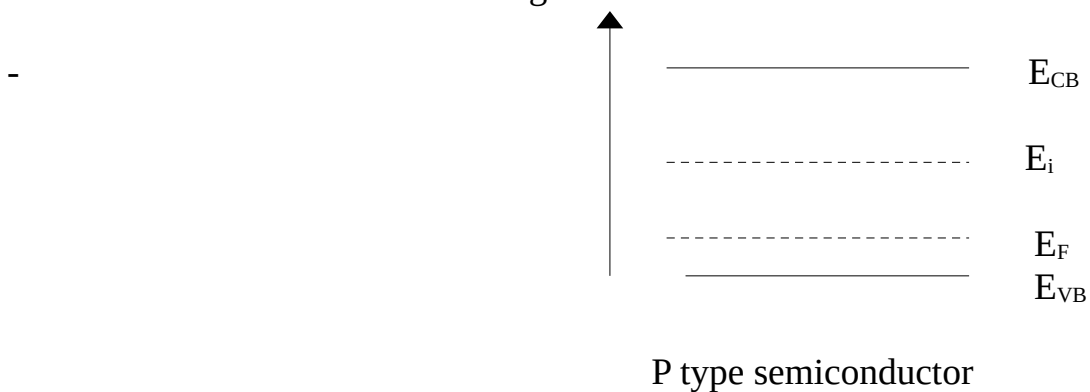
The probability of finding an electron in the conduction band is equal to the probability of finding a hole in the valence band. Thus the Fermi energy is in the middle of the band gap and is denoted as E_i .



If a pentavalent ion like Arsenic is melted into the Si at a level of 0.1ppm then what happens is that 4 bonds are made ,leaving 1 electron loose to wander about in the doped crystal .The probability of finding an electron in the conduction band is now greater than finding a hole in the valence band and the fermi level then lies close to the conduction band.

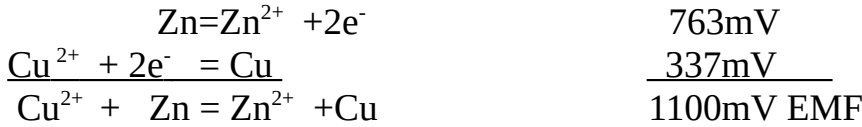


If a trivalent dopant like Aluminium is used 3 bonds are made leaving a hole now where the 4'th bond should be.This hole can – succesively - be filled with an electron to produce a new hole and now this is a material that conducts with holes.Positive current from a P type material . Since the probability of finding a hole in the valence band is greater than the probability of finding an electron in the conduction band, E_F is now closer to the valence band edge.



Below is a discussion of EMF using the concept of Fermi Energy
 It has been known for sometime that if 2 different metals say copppper Cu full of electrons till $4s^1$ and zinc Zn full up to $4s^2$ make electrical contact a potential difference V will be established between them.See ‘Contact Potential Difference’ in

the dictionary of science. The mod E_F Zn will be greater than the mod E_F Cu and on contact a small amount of (electron) charge will migrate from the Zn to the Cu to establish a field and a potential that will oppose further migration. Now the mod E_F Zn will decrease and the mod E_F Cu will move up till they are equal and thus in 'thermal' equilibrium. These two half reactions can be combined as in:-

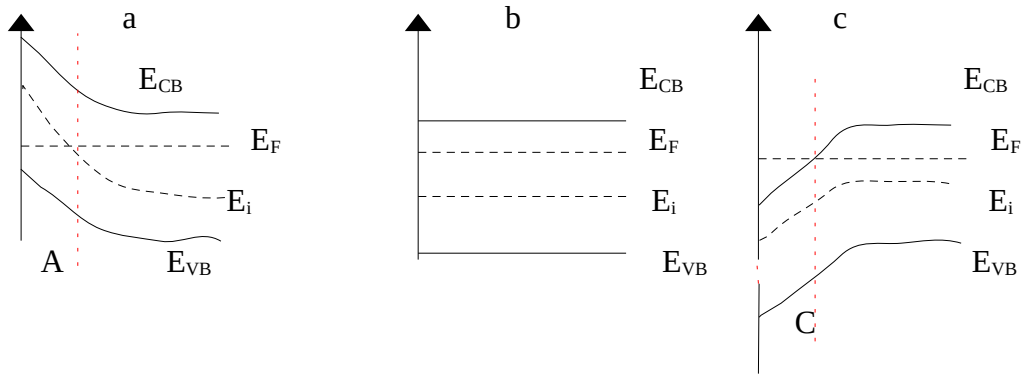


This set of reactions were used by the Indians at Rio Tinto to win copper from the river using cheaper zinc.

The Fermi level is related logarithmically to the concentration of charge carrier by

$$n = n_i e^{-\frac{(E_F - E_i)}{kT}} \qquad p = p_i e^{-\frac{(E_F - E_i)}{kT}}$$

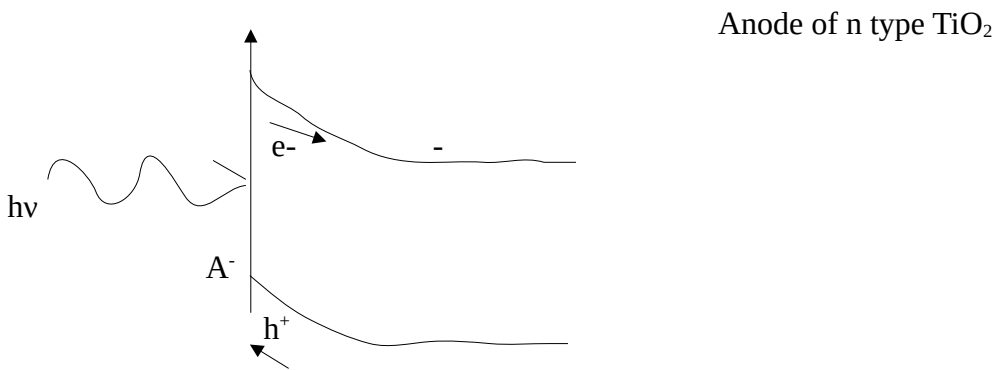
Consider the band bending of n Si at the surface when the n Si is polarised by a negative potential as in a going to positive as in c through the flat band potential as in b .



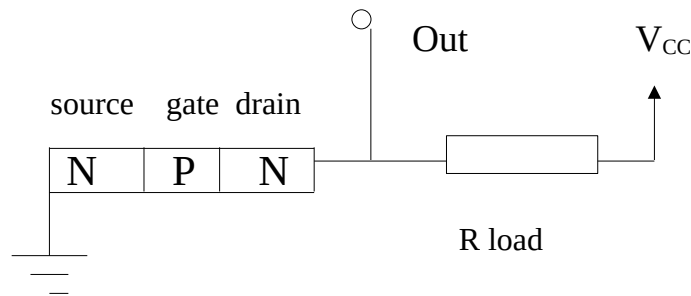
The ordinate is increasing negative energy and the abscissa is from left to right , surface into the bulk crystal. In region A $E_F > E_i$ so n is diminished to expose fixed positive dopant. In region C $E_F < E_i$ thus negative charges accumulate in the region C. Also in this region the conduction band edge is below the Fermi level so the semi conductor surface exhibits metal like conductivity. We will discuss this a bit later when we talk about the MOSFET. The flat band potential does not have to coincide with Zero charge. If you consider that every surface atom has one missing bond and therefore a bit of a charge then it will take an opposite charge to neutralise this effect to bring about a flat band. The point of Zero charge will still see some band bending.

The surface charge must have a counter charge in the semi-conductor (sc) surface to maintain charge neutrality. In a sc the space charge is 1000 x's deeper than in a metal., where the whole counter charge lies at the surface. In a sc the bands bend over a considerable width creating an electric field that extends some way into the bulk. This electric field can separate light induced e^-h^+ (electron-hole) pairs which can be created at the surface. If an e^-h^+ pair is created at the surface of a

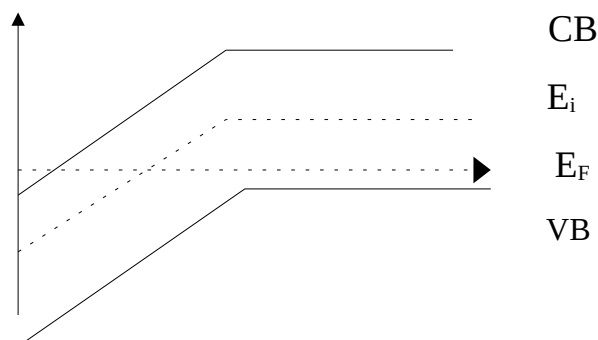
metal they recombine immediately. Consider n type TiO_2 as an anode electrode polarised negative by the adsorption of anions A^- ,



On illumination an $e-h^+$ pair is produced. The e^- goes with the ‘downhill’ potential field into the circuit and the h^+ ‘floats’ into the surface to oxidise A^- to A . Note the ‘intelligence’ in the n TiO_2 sc surface in separating the $e-h^+$ pair by the effective action of the field. Consider the action of the n channel Metal Oxide Semiconductor field effect transistor (Mofset). In the MOSFET



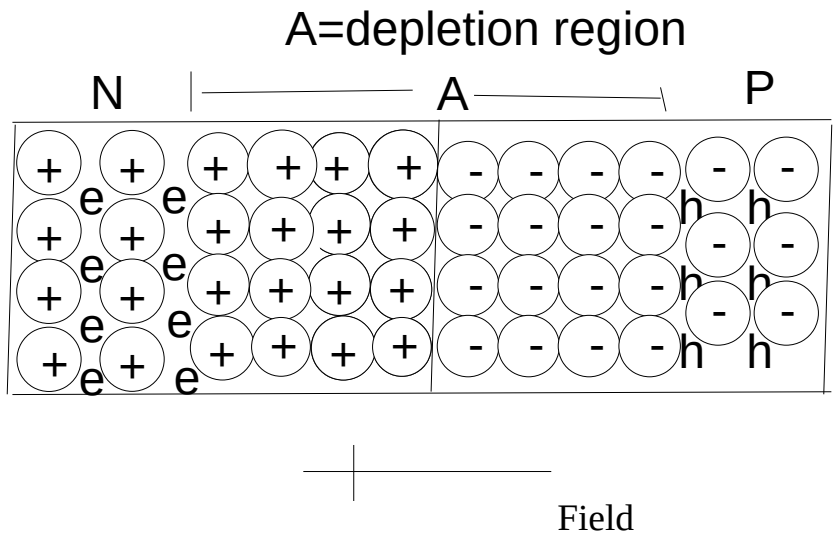
which has 3 terminals a gate a source and a drain a positive potential at the gate turns the Mosfet on and it draws minimal current from the gate while larger currents will move between the source and the drain. Lets look at how the P type gate band bending works subjected to a positive potential.



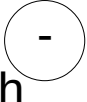



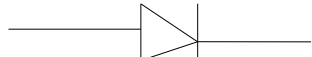
Remember $n = n_i e^{\frac{-(E_F - E_i)}{kT}}$ then in the bulk of the (gate) P layer which is insulated with a thin layer of SiO₂ $E_F - E_i > 0$ so p carriers dominate. Moving to the surface $E_F - E_i < 0$ so n carriers dominate which makes for metal like properties and conduction of positive current can occur.

The gate draws minimal current while the Source Drain current is a lot more.

This brings us now to the simplest semiconductor device called a Diode.



-  e donor atom
-  Donated an e
-  h donor atom
-  Donated a hole

The symbol used to represent the diode is :- 

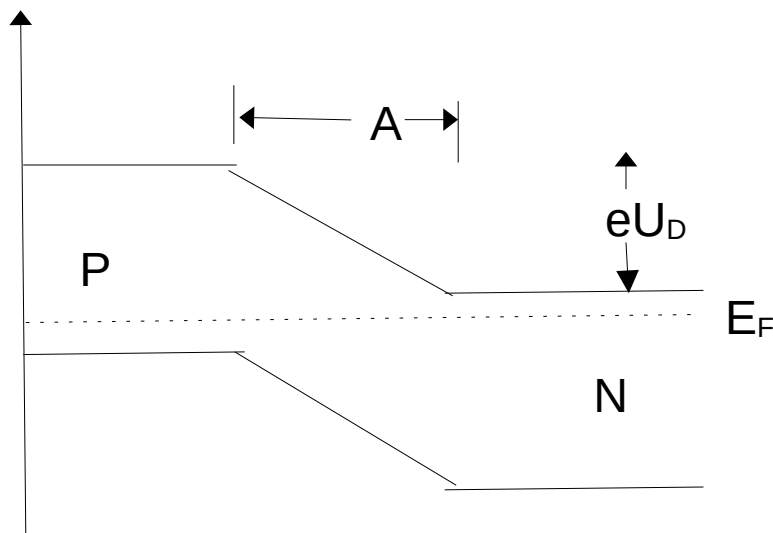
The arrow head pointing in the direction of positive current

The diode has some intelligence in that it acts as a rectifier. If we pass an ac signal (about ground) to the diode only the positive part of the signal will go through if the signal is applied to the P region known as the anode. If the signal is applied to the cathode or N region only the negative part will go through. This rectification is a

most useful property especially when making a power supply. The diode is a P-N (anode-cathode) junction grown in a continuous way.

Initially because there is a density gradient for electrons and holes across the junction, holes will diffuse from the P region into the N region. They will combine with electrons to produce zero charge. Electrons will diffuse from the N region into the P region and combine with holes. This leaves the area of the junction deplete of electrons and holes which are the charge characters and an electric field develops. This field builds up till it stops the diffusion. Since the region of the junction is deplete of mobile charges it is called the depletion region.

Consider the energy levels for a P-N junction. Band bending occurs because the E_F must be equal throughout



If N_d and N_a are the number of donors and acceptors and n and p are the intrinsic carriers then :-

$$U_D = \frac{kT}{e} \ln \frac{(N_D N_a)}{np} \text{ Volts}$$

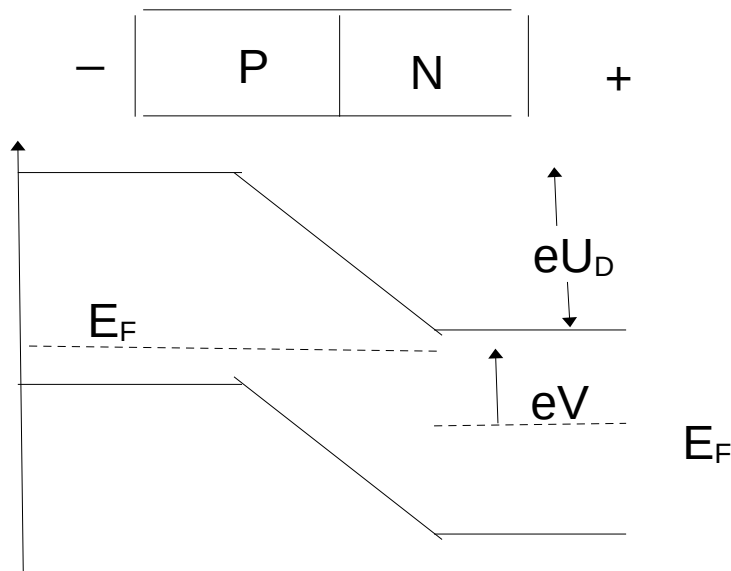
then $e U_D$ now an energy is illustrated above.

We have enough now to understand how dry photo Voltaic cells work. If sunlight shines on a junction of a diode this would provide enough energy to create e-h+ carriers in the junction when holes will be swept by the field into the P (anode) side and electrons into the N (cathode) side. This can provide current to do useful work like charging a battery.

Let us now examine how a diode responds to a forward and a reverse bias.

In the reverse biased situation the positive pole (of a battery say) is connected to the N side and the negative pole to the P side. The negative P side ‘sucks’ holes out of the P side while the positive N side ‘sucks’ out electrons. This increases the width of the depletion zone. This process cannot continue indefinitely since in order to have a steady flow of holes out of the P side, holes must be supplied by the N side where there are very few holes. A few holes will be generated thermally and the resulting current is called the reverse saturation current I_{CO} . Similarly the current due to the thermal generation of electrons in the N side also has the value I_{CO} , and the resulting current is $2I_{CO}$. This I_{CO} will increase with temperature and it is independent of voltage being limited by a slow thermal carrier generation rate.

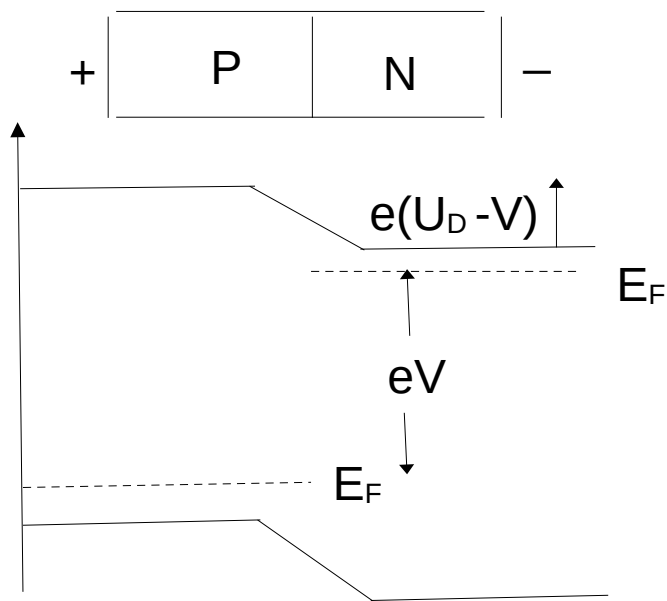
The mechanism of conduction in the reverse bias situation may be described with the aid of a diagram of the electron energy across the diode shown below:-



(remember the ordinate or vertical axis is as increasing negative energy)

With the applied reverse bias the height in the barrier for the conduction of electrons from the N side to the P side has been increased by eV . That same increase applies to the conduction of holes from the P side to the N side too. There is then virtually no current on reverse bias, only $2I_{CO}$ as discussed above.

For forward bias we have the electron energy band structure as depicted below.....

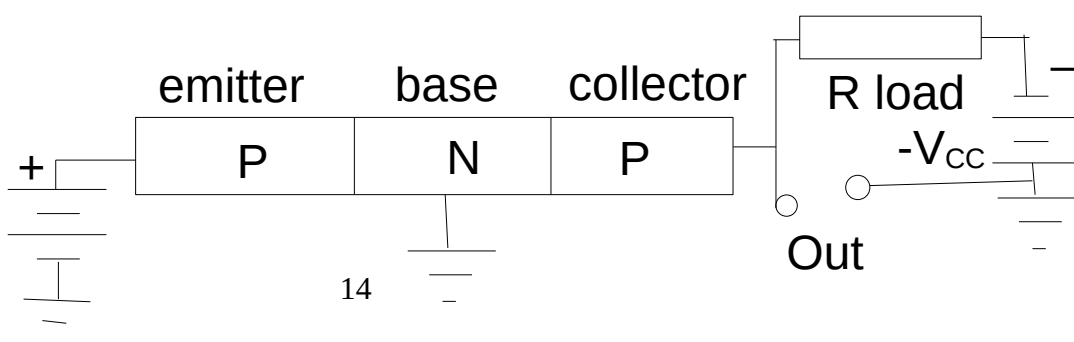


As can be seen the barrier for conduction of electrons from N to P has been reduced from eU_D to $e(U_D - V)$ where V is the applied voltage. Hence electrons readily cross from N to P as do holes from P to N. The resultant current is the sum of these 2 currents.

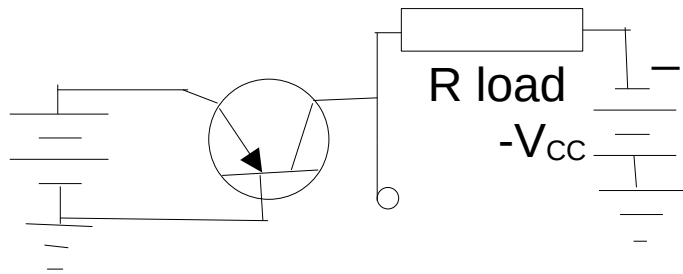
In some types of diode with the right composition, the injected minority carrier say an electron injected from N to P (now in P an electron is a minority carrier. In P holes are the majority carrier) will recombine with a hole in P and light will be produced – the light emitting diode or led.

The Transistor.

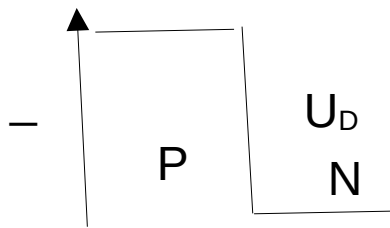
The transistor is made by growing continuous pnp or npn junctions. With bias the PNP transistor in the common base (earth is common to input and output) configuration is as follows



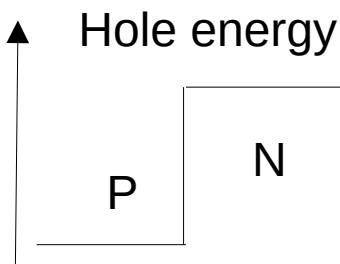
formally symbolized as follows



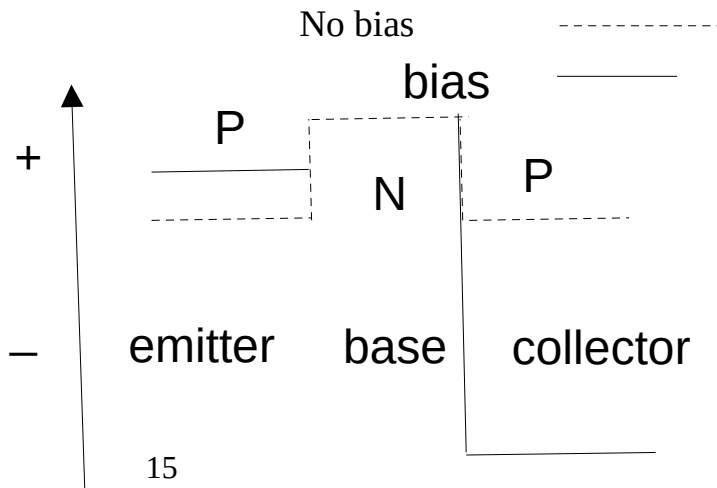
In the diode U_D is an important parameter



By symmetry for holes the picture is



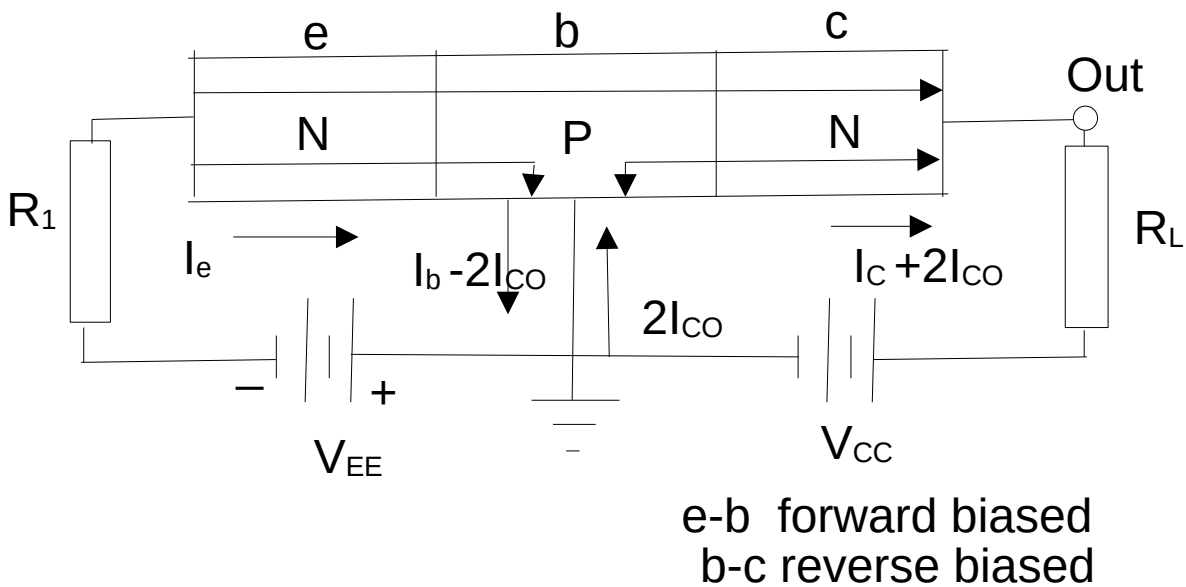
and now we can discuss the transistor above its positive current including a reverse biased collector base junction.



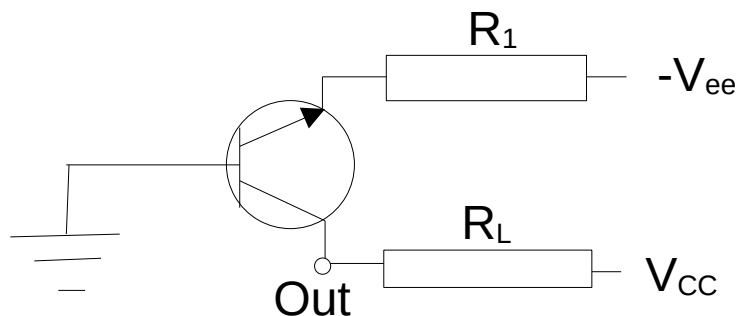
The hole energy profile with bias as described above.

In the case for the forward biased 'diode' holes are readily injected from P into the base. If the base is made thin enough so that these holes don't get eliminated in recombination some 98% get through to the collector by virtue of the reverse biased junction. This reverse bias acts to attract the holes through to the collector..Down the steep curve of negative potential picking up energy all of the way..Alas a sign of amplification.! Now for some that may be a satisfactory explanation of how a transistor works but we are going to take it further.

Indeed a common base configuration does produce a power and voltage gain but no current gain.To get current gain we need to change to a common emitter arrangement. In order to take a closer look let's examine the electrodynamics of the NPN transistor. First the common base configuration where thing look like the sketch below.



All the arrows pertain to electron current.This is compactly symbolized by



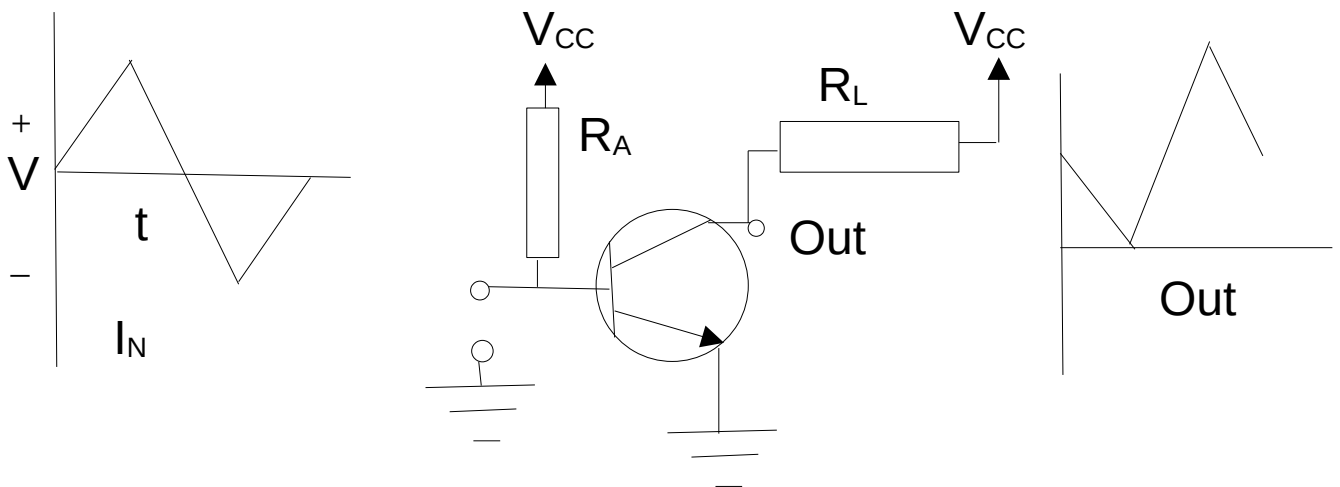
Input current = V_{ee} / R_1 and some large fraction α of the input current survives to reach the collector.

$$I_C = \alpha I_E + 2 I_{CO} = \alpha I_E \text{ assuming } I_{CO} = 0$$

I_b is that little bit of current that did not make it to the collector

$$I_b = (1-\alpha) I_E$$

and current gain $A_i = I_C / I_E = \alpha$. Typically $\alpha = 0.98$ so there is no current gain here. For current gain we need to go to the common emitter configuration.



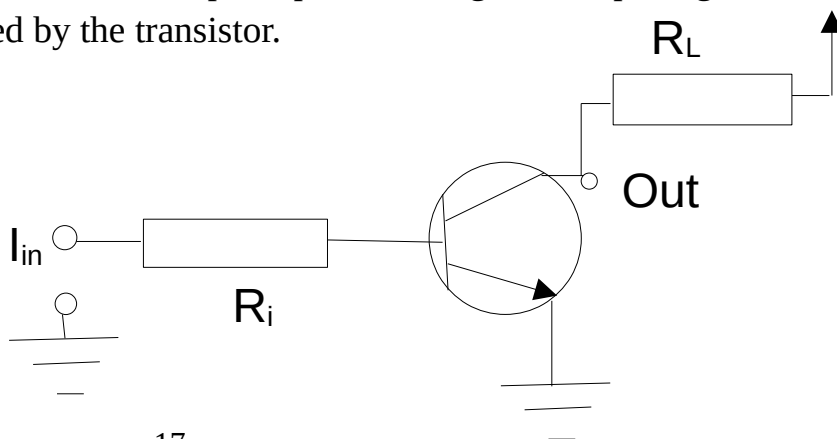
So we still have an NPN transistor a forward biased e-b junction and a reverse biased collector junction. The emitter is now at earth and I_b is the input current.

If we assume that $I_{CO} = 0$ then $I_C = \alpha I_E$ and $I_B = (1-\alpha) I_E$

$$\text{then current gain} = I_C / I_B = \alpha / (1 - \alpha) = \beta$$

for $\alpha = 0.98$ $\beta = 49$ solid current gain!!

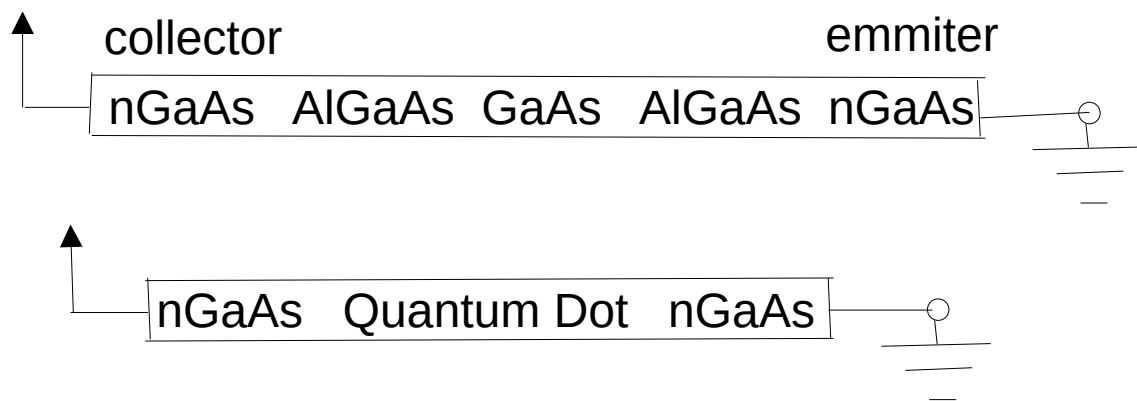
This resistor R_A is used to pull up the about ground input signal to be above ground. It is inverted by the transistor.



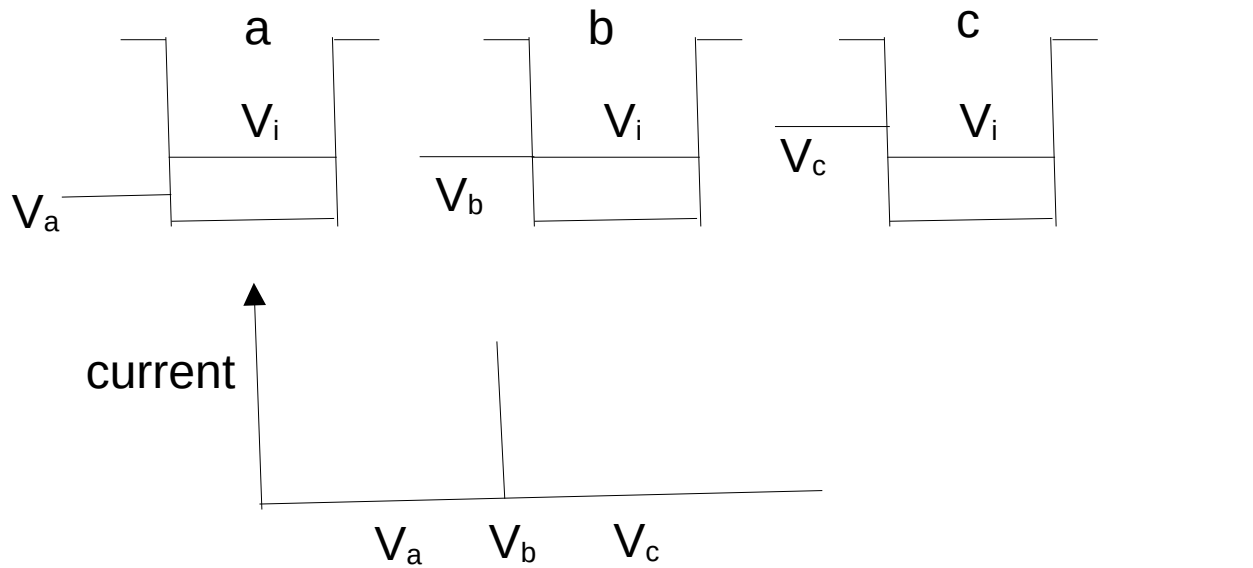
When V_{in} is low then I_{in} would be low and the transistor would be off and V_{OUT} would be high. With $V_{in} = 3\text{ V}$ say, the transistor switches on, there is b-e current which is collected by the reverse biased collector and the output goes to ground. So because of the b-e current some of which is 'collected' there is effectively a short circuit between the emitter and the collector. If the signal were not pulled up by R_A then the negative parts of the input signal would switch the transistor off because the b- e would no longer be in forward bias.

Let's then move to more modern times when the Quantum Dot Tunneling Transistor was invented. See "The Quantum Effect Device – Tomorrows Transistor ?" by R Bates in Scientific American March 1988.

AlGaAs has a higher band gap than GaAs and the Fermi level for electrons in GaAs lies well below the conduction band of AlGaAs. Electrons cannot escape from the GaAs if a continuous AlGaAs/GaAs/AlGaAs junction were to be made. Now these confined or trapped electrons can be compared to being confined in a box and have strictly quantized energy levels. Just like the electron in a box model that we studied at the beginning of this chapter. There we considered that the potential outside the box was infinite. Here we examine the case for a finite potential well which make tunneling possible.



Electrons cannot enter the Quantum Dot unless the emitter level matches the energy level in the QD. The Fermi level of the electrons in the emitter can be raised wrt the rest of the structure by a positive voltage at the collector when the emitter is now negative of the collector. When the emitter voltage matches the level of that state within the QD tunneling will be possible.



Here V_a , V_b and V_c are 3 values of emitter voltage showing tunneling when there is a voltage match. If there were 3 values of energy in the QD then by varying $V_{\text{collector}}$ we would get three peaks in the response. Here we have shown only 1 value of energy in the QD.

If the QD were to be made of PbSe then light energy can be used to promote an electron to the PbSe conduction band. Because the levels in the dot are discrete and singular unlike in a band where the levels are multifold and continuous phonon relaxation of 'hot' (wrt the band edge) electrons is impossible within the dot. The energy levels within the dot are separated by energies that the phonon cannot realize. There is no phonon pathway in the dot for relaxation.

X Y Zhu succeeded experimentally to trap hot electrons inside a PbSe dot and his experiment is described in Science V328 ::18 June 2010 . This result has serious implications for Solar energy photovoltaics.