Digital Integrated Circuits

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Lecture-1

Semiconductors

So welcome to this course on high speed integrated digital circuits so in this course we shall be discussing the entire domain of digital circuits. In order to understand or appreciate the working of these digital circuits it is very important to have a basic understanding of semiconductor devices, how this device works and also how these devices are modeled.

We shall start this course with a brief recapitulation, I say recapitulation because I expect that all of you must have gone through some course on semiconductor devices may be at undergraduate level or more recently. We shall start with a brief recapitulation of the main points which one must remember or recall in order to understand the working of these integrated circuits. Now going into the topic.

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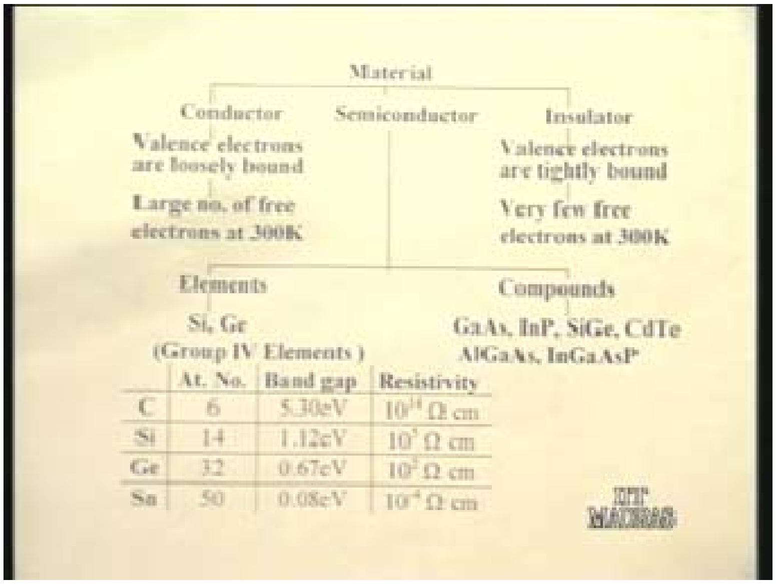

Material

Conductor
Valence electrons are loosely bound
Large no. of free electrons at 300K

Semiconductor

Insulator
Valence electrons are tightly bound
Very few free electrons at 300K

Elements
Si, Ge
(Group IV Elements)

Compounds
GaAs, InP, SiGe, CdTe
AlGaAs, InGaAsP

	At. No.	Band gap	Resistivity
C	6	5.30eV	$10^{14}\ \Omega$ cm
Si	14	1.12eV	$10^{5}\ \Omega$ cm
Ge	32	0.67eV	$10^{2}\ \Omega$ cm
Sn	50	0.08eV	$10^{-4}\ \Omega$ cm

Any material can be classified in terms of its electrical properties as a conductor, insulator or a semiconductor. Now what is it that makes a material conductor or another material insulator? You know that any solid has got a large number of electrons but all of them cannot participate in electrical conduction, only the valence electrons or the electrons in the outer shell can but they are bound or they participate in a bond but when they are bound they cannot again participate in electrical conduction. They cannot

move freely so in order to participate in electrical conduction the bonds must be broken and the electrons must become free.
So in a conductor the valence electrons are loosely bound that is the bonds are very weak and they can be very easily broken with the result that at room temperature there are large number of free electrons which can participate in electrical conduction whereas in an insulator the bonds are very strong. It is difficult to break and there are very few electrons which can participate in electrical conduction so that makes it an insulator. In fact we generally represent that what is called an energy band diagram, we must be familiar with that where you have what is called conduction band and you have a valence band.

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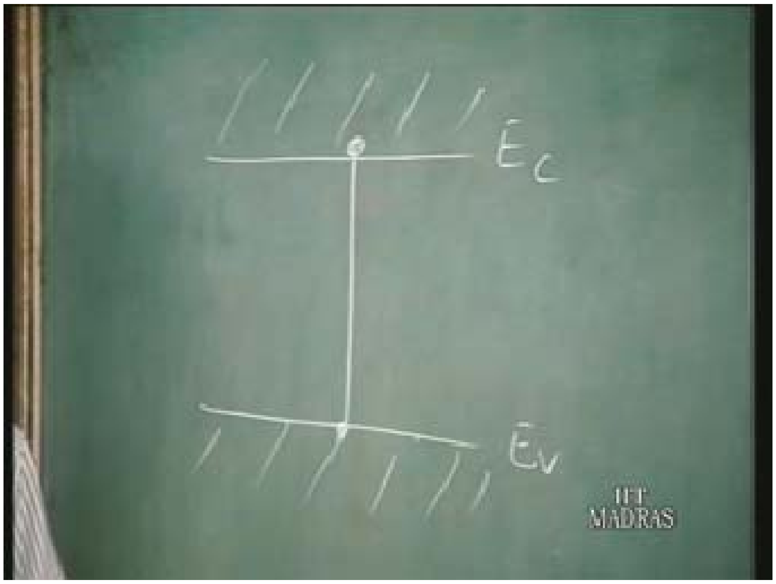

So normally at zero degree Kelvin say for example all valence electrons will be in the valence band and when they get sufficient energy and electron they move to the conduction band and when it moves to the conduction band it is free to conduct. So basically it is same as breaking a bond and this is what we call as band gap which is nothing but the energy required to break a bond. So in an insulator the band gap is large which means that actually it requires more energy to break a bond. So fewer bonds are broken and there are few electrons which can conduct whereas in a conductor, the band gap is very small or even the conduction band and valence band overlap so you have large number of electrons which can conduct.

So you have the two extremes the conductor, insulator and in between you have the semiconductor where the band gap is not very large but neither it is very small. So in between about one electron volt or one to two electron volts usually or even less than one electron volts in many cases. So a semiconductor can be elements, usually the group four elements like silicon or germanium or you also have the compounds semiconductors which is you have 3, 5 gallium arsenide that is gallium belonging to group 3 arsenic. Then you have the 4, 4 that is the silicon germanium, you also have silicon carbide which is very popular in our days specially for power devices.

Cadmium Telluride which is 2 6 then you have the ternaries that is the three materials aluminum, gallium, arsenide or indium, gallium, arsenide or phosphide. They are quaternaries so you have wide range of semiconductor materials but in this course we shall be mostly concentrating on this element semiconductor especially silicon and interesting thing is if you look at group 4 elements carbon, silicon, germanium, tin.

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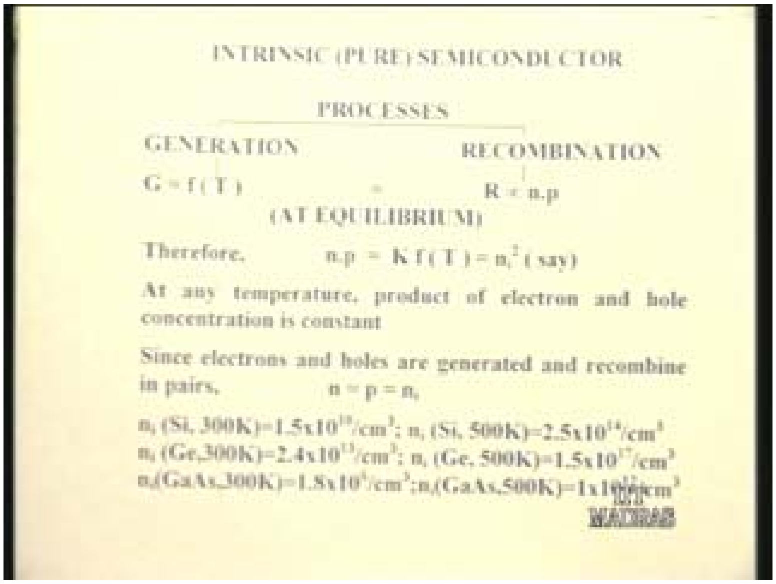

INTRINSIC (PURE) SEMICONDUCTOR

PROCESSES

GENERATION RECOMBINATION

$G = f(T)$ = $R = n.p$

(AT EQUILIBRIUM)

Therefore, $n.p = K f(T) = n_i^2$ (say)

At any temperature, product of electron and hole concentration is constant

Since electrons and holes are generated and recombine in pairs, $n = p = n_i$

n_i (Si, 300K)=1.5×10^{10}/cm^3; n_i (Si, 500K)=2.5×10^{14}/cm^3

n_i (Ge,300K)=2.4×10^{13}/cm^3; n_i (Ge, 500K)=1.5×10^{17}/cm^3

n_i(GaAs,300K)=1.8×10^{6}/cm^3;n_i(GaAs,500K)=1x10[illegible]/cm^3

If you see the increasing atomic numbers that is the size of the atoms are increasing and as the size of the atoms is increasing the band gap is reducing that is the electrons if you have smaller atoms the electrons are more tightly bound. So it requires more energy to break them up. So for example carbon has a very high band gap so it is an insulator, its resistivity is 10 to the power 14 ohm centimeter whereas if you go down the silicon the next bigger atom has the smaller band gap, germanium has even smaller band gap and tin which is also a group 4 is a conductor so because it is very large atom the electrons are loosely bound so it is easy to break the atom.

So you can see in this you have both insulators and conductors. So now let us concentrate on semiconductors because that is what we are going to talk about in this course because that is what the devices are made of. In a semiconductor there are two types of carriers you have the electrons and the holes. The electrons are of course negatively charged as you know and what is a hole? When an electron from the valence band goes into the conduction band it leaves the vacancy here and this vacancy can also conduct, when there is a vacancy an electron from the neighboring side can move and so the hole moves in the opposite direction. So it behaves like a positively charged carriers so we have electrons and holes in semiconductors and in an intrinsic pure semiconductor there are two types of processes taking place.

One is generation of carriers that is electrons constantly moving from valence band to the conduction band or the bonds being broken because of the thermal energy that's called the generation of carriers which is taking place and at the same time we have the recombination that is a electron which is already in the conduction band can move down to the valence band and recombine. So you have generation of carriers and loss of carriers by recombination and under equilibrium the generation must be equal to recombination to have a constant number of carriers. So this generation is a function of temperature and the recombination is proportional to the product of the electron concentration which is given by n here and the hole concentration which is given by p.

Now if you equate these two you get n into p is again a function of temperature, k is a constant, f is a function of temperature. Let us call that n_i square so which implies that at any temperature the product of electron and hole pairs, hole concentration is a constant. Now since electrons and holes are generated as well as they recombine in pairs so the electron concentration must be equal to the hole concentration. Now here if you put n is equal to p, we have n is equal to p is equal to n_i that n_i is called the intrinsic carrier concentration. That is the carrier concentration of an intrinsic material at a particular temperature. Now this n_i depends on the material as well as the temperature.

For example here we have here for silicon at room temperature it is 1.5 into 10 to the power 10 but if you go to 500 k it increases by 4 orders of magnitude whereas if you take germanium which has a lower band gap, so you will more carriers generated because there is more generation. So it is at room temperature itself we have 10 to the power 13 per centimeter cube and of course at higher temperature you have again about 4 orders magnitude higher whereas in gallium arsenide which is a very high band gap 1.42 electron volt compared to 1.1 in silicon. It is 10 to the power 6 centimeter cube only, you see that it depends on the material as well as the temperature.

Now that is of intrinsic or pure semiconductor but why is a semiconductor such an interesting material. The reason is that a semiconductor can be doped or you can introduce impurities and with that you can change the conductivity of the material through several orders of magnitude by introducing known amount of impurities. That is what makes a semiconductor such an interesting material. So you have what is called the extrinsic or the doped semiconductors. Now these semiconductors can be n type or p type. Now that depends on the type of impurities you are introducing.

If you introduce, for example a impurity of the group 5, well which has 5 electrons after shell you have a extra shell which is very loosely bound and can be easily released and become free for conduction. So that becomes n type, n stands for negative, electrons are negative charged carriers whereas if you introduce a group three atom which has got one electron less in the outer shell, there is a vacancy and which gives rise to a extra hole because electrons can easily move into that and create a vacancy in some other place. So that becomes a p type semiconductor, p stands for positive you know holes are positive charged carriers. So if you introduce for example $n_{D.}$’s the donors, so this group 5 elements are called donor impurities because it can donate an electron whereas group 3 elements are called acceptor impurities because it can accept an electron.

So in the majority carrier concentration, so in an n type material the donor concentration if it is 10 to the power 16 say per centimeter cube, you have electron concentration which is the majority carrier around 10 to the power 16 because almost all the donor atoms, the fifth electrons becomes free whereas the minority concentration, the hole concentration because the hole concentration and the product of the hole concentration and the electron concentration is a constant is equal to $n_{i.}$ square.

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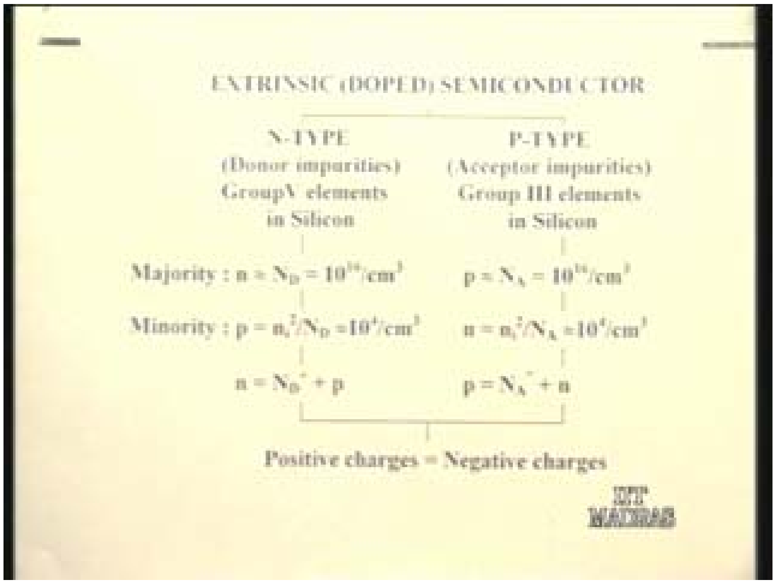

EXTRINSIC (DOPED) SEMICONDUCTOR

N-TYPE
(Donor impurities)
GroupV elements
in Silicon

P-TYPE
(Acceptor impurities)
Group III elements
in Silicon

Majority : $n = N_D = 10^{16}/cm^3$

$p = N_A = 10^{16}/cm^3$

Minority : $p = n_i^2/N_D = 10^4/cm^3$

$n = n_i^2/N_A = 10^4/cm^3$

$n = N_D^+ + p$

$p = N_A^- + n$

Positive charges = Negative charges

So you have the hole concentration which is minority carrier $n_{i.}$ square by $n_{D.}$ is just the order of 10 to the power 4. You see the difference in magnitude, one is in a n type semiconductor electrons are majority carriers and holes are minority carriers whereas in a p type semiconductor again if you have doped, acceptor doping concentration is about 10 to the power 16 per centimeter cube, electron concentration will be just 10 to the power 4 per centimeter cube again because p into n is equal to $n_{i.}$ square. So we have a large order of magnitude difference but exactly if you look at it you see that the material itself has to be charged free, there is no extra charges to be introduced.

So the number of positive charges must be equal to the number of negative charges. So the electron concentration, so in a n type semiconductor the negative charges are the electrons, the positive charges are the ionized donors that is where the donors donor atoms the free electron goes and it becomes positively ionized, so positively ionized donors plus holes. So n is equal to n_D + p of course when you add 10 to the power 4 by 10 to the power 16 it gives you 10 to the power 16 itself.

Similarly for p type, p is equal to n_A + n so this gives you the concentration of the electrons and holes in a extrinsic semiconductor. Now this is the concentration in an extrinsic semiconductor what we have studied is what is called a thermal equilibrium that is the forces in place of the thermal energy which is creating the holes and electrons generally.

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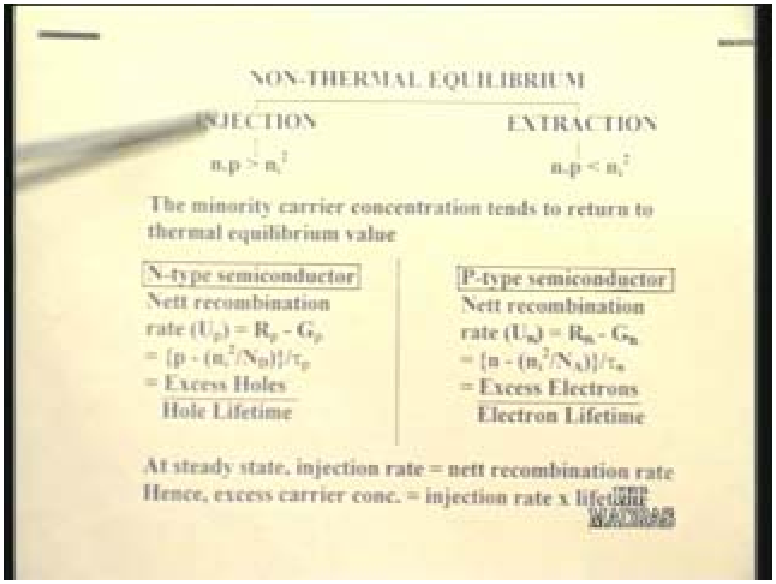

NON-THERMAL EQUILIBRIUM

INJECTION

$n.p > n_i^2$

EXTRACTION

$n.p < n_i^2$

The minority carrier concentration tends to return to thermal equilibrium value

N-type semiconductor

Nett recombination rate $(U_p) = R_p - G_p$

$= \{p - (n_i^2/N_D)\}/\tau_p$

$= \frac{\text{Excess Holes}}{\text{Hole Lifetime}}$

P-type semiconductor

Nett recombination rate $(U_n) = R_n - G_n$

$= \{n - (n_i^2/N_A)\}/\tau_n$

$= \frac{\text{Excess Electrons}}{\text{Electron Lifetime}}$

At steady state, injection rate = nett recombination rate

Hence, excess carrier conc. = injection rate x lifetime

Now if you have some other forces for example if you shine light on the semiconductor there is going to be extra generation or you have electrons or holes carriers flowing in from some other region of the semiconductor. For example in a p n junction so you have another equilibrium which is a non-thermal equilibrium, it's not a thermal equilibrium but that equilibrium is dictated by other forces also so in which case n p is equal to n_i square is no longer valid. If you have injection of carriers that is carriers flowing in or you have generation due to some other materials which is also called injection, you have n p product will be greater than n_i squared whereas if your extraction of carriers removing of carriers so you have n p product will be less than n_i square.

About these cases the minority carrier concentration in fact will tend to return to the thermal equilibrium value and you have excess generation or recombination. So for example if you have injection the net recombination rate, that is if the net recombination rate that is the difference of the recombination rate with the generation rate which is again determined by thermal values that is thermal generation is equal to n_i square by n_D is the thermal equilibrium value what you expect under thermal equilibrium. So p is the actual minority carrier concentration which is more than n_i square by n_D. So the net recombination rate is given by the excess holes by the hole life time.

So this lifetime is actually another parameter of a semiconductor material that is the average time before which the carriers recombine. So the net recombination rate is going to be equal to the excess holes in the n type semiconductor and a p type semiconductor the net recombination rate is given by the excess electrons divided by the electron lifetime. Now as you see here when we talk of recombination we are only referring to the minority carriers and in the n type we are talking of excess holes and a p type semiconductor we are talking of excess electrons. That is because the majority carrier concentration is so large compared to the minority carrier concentration.
There is hardly any difference, it doesn't make any difference to the concentration whereas the minority carrier concentration actually changes a lot and so we always refer to in terms of the minority carrier concentration. Although it is true that the electrons can only recombine with the holes so the rate of recombination of electrons is same as the recombination of holes but we always refer in terms of the minority carriers. So in the steady state again the net recombination rate must be equal to the injection rate for the carrier concentration to be constant. So if you introduce it here, the injection rate is equal to excess holes by whole lifetime. So here hence the excess carrier concentration which you have is given by the injection rate into lifetime.

So in a semiconductor if you have excess carriers the amount of excess carriers is equal to the injection rate that is the rate at which the carriers are flowing in or being generated into lifetime. So this is an important relationship or in other words you can also say the injection rate is equal to excess carrier concentration by lifetime. So if you know the excess carrier concentration and the lifetime you can find out the injection rate in fact that is how we also calculate the current flowing into a p n junction for example.

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CURRENT IN SEMICONDUCTORS

DRIFT
(Electric field driven)

$J_p = Q_p v = qp\mu_p E$
$J_n = -Q_n v = qn\mu_n E$

DIFFUSION
(Carrier conc. gradient driven)

$J_p = -qD_p(dp/dx)$
$J_n = qD_n(dn/dx)$

Mobility (μ_n, μ_p) and Diffusion Coefficient (D_n, D_p) are functions of:
a) Impurity Concentration
b) Temperature
c) Electric field for $E > 10^3$ V/cm

Electron current : $J_n = qn\mu_n E + qD_n(dn/dx)$
Hole current : $J_p = qp\mu_p E - qD_p(dp/dx)$

Einstein relation:
$(D_n/\mu_n) = (D_p/\mu_p) = (kT/q) = V_t \approx 26$mV at 300K

Current in semiconductors. Current is a rate of flow of charge. In a semiconductor there are two mechanisms of current flow. There are two reasons for current flow, one is called the drift current. This is the driving force is a electric field so if you have an electric field carriers can flow under the influence of electric field that is called drift current. You have diffusion current where the current flow is due to a concentration gradient so if there is a concentration gradient of carriers, carriers will flow from a region of higher concentration to a lower concentration. So for the holes it is given by the charge into the velocity of the carriers and the velocity is proportional to the electric field and the proportionality constant is called mobility.

Similarly for electrons and for diffusion current the current is proportional to the concentration gradient and again the proportionality constant is called the diffusion coefficient, diffusion constant and these mobility and diffusion coefficients are functions of the impurity concentration in the semiconductor as well as temperature and also the electric field. In fact mobility and diffusion constants are constants for low electric fields and as you go for higher electric fields it reduces.

So the total electron current is the sum of these components the drift and diffusion components and the total hole current is again the sum of the drift and diffusion component. Of course the negative sign is actually is regard to the direction of the current flow. So in fact the mobility and diffusion coefficients are related through the Einstein relation that is the hole diffusion coefficient divided by the hole mobility is equal to the electron diffusion coefficient divided by the electron mobility is equal to the whole diffusion coefficient divided by the hole mobility and is equal to the, what is called the thermal voltage that is k t by 2 which is around 26 milli volts at room temperature.

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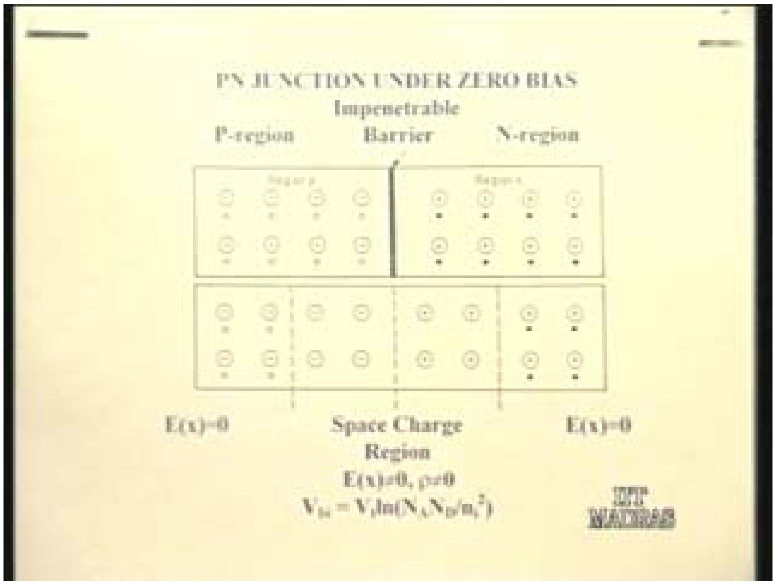

PN JUNCTION UNDER ZERO BIAS

Space Charge Region

$E(x)\neq 0, \rho\neq 0$

$V_{bi} = V_t \ln(N_A N_D/n_i^2)$

Now we have been talking about semiconductors in general. So now let us come to a semiconductor device. The simplest semiconductor device is the p n junction where you have a p type semiconductor and an n type semiconductor and you have a junction. Now suppose there is some barrier here this is how it will look this is the p region where you have the holes and the acceptor atoms are shown separately whereas on the n side you have the electrons and the donor atoms which are shown separately.

Now suppose you remove this barrier now, what happens? The holes will move under a concentration gradient. That is from a region of higher concentration to a region of lower concentration that is from the p side to the n side and electrons will move from the n side to the p side.

So when the holes move it leaves behind the uncovered acceptor ions which gives rise to a negative charge on this side and when the electrons move from n region to the p region it leaves behind the uncovered donor ions which creates a positive charge on the p side. So this separation of charge gives rise to an electric field inside the semiconductor across the junction and also what is called a built in potential. Now as this electrons and holes diffuse, this electric field which is created actually opposes the diffusion process. So as more and more electrons diffuse, the electric field goes on increasing and finally another equilibrium is established when there is effectively there is no further diffusion taking place. So in that equilibrium you have what is called a built in potential across this junction and this built in potential is given by this relationship.

It is proportional to the thermal voltage, it also depends on the doping concentration and also the intrinsic carrier concentration. Now of course it also depends on n_i square which means that for example if you have material with higher band gap n_i is going to be less which means the built in potential is going to be more. So if you have gallium arsenide you have a higher built in potential compared to silicon and germanium the built in potential is going to be less. So you have in fact after this at equilibrium you have the semiconductor basically three regions, one is what is called the p-bulk which behaves like a bulk semiconductor. You have a space charge region where you have the space charges uncovered charges and you have the n bulk region.

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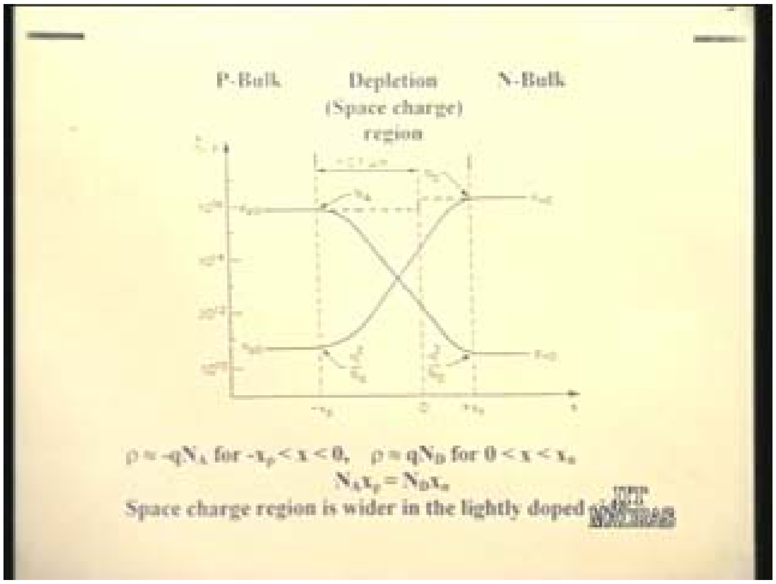

$\rho = -qN_A$ for $-x_p < x < 0$, $\rho = qN_D$ for $0 < x < x_n$

$N_A x_p = N_D x_n$

Space charge region is wider in the lightly doped

This slide actually shows the carrier concentration inside the space charge region. So it is not in fact the space charge region is totally devoid of carriers. So in the p bulk this is actually for germanium so the carrier concentrations so in the p bulk the majority carrier concentration is given by the acceptor impurity concentration and this is n_{i} square by n_{A} and this side it is n_{D} and this is n_{i} square by n_{D}.

Here it is the electron, the hole concentration falls gradually to this across this space charge region but the total charge in the space charge region whereas in the bulk it is charge free, the total charge is zero because the acceptor concentration is equal to the number of holes. So it almost cancels out, the total charge is zero whereas here the acceptor ion concentration is much larger than the mobile carrier concentrations. So the carrier concentration in the space charge region on the p side is equal to minus q N_{A} which is equal to the acceptor ion concentration whereas on the n side it is equal to q N_{D} and also another important thing to notice that the total charges again the total charge in the system must be zero because we are not generating charges anywhere. So the charges on this side of the space charge that is the p side must be equal to the n side so N_{A} X_{p} that is the area under this region must be equal to the area under that. So N_{A} X_{p} is equal to N_{D} x_{n}. So which means that the space charge region is going to be wider on the lightly doped side. So if you have a region which the p n junction the acceptor ion concentration is much larger than the donor ion concentration on the n side, so the space charge region is going to be predominantly on the lightly doped side that is on the n side.

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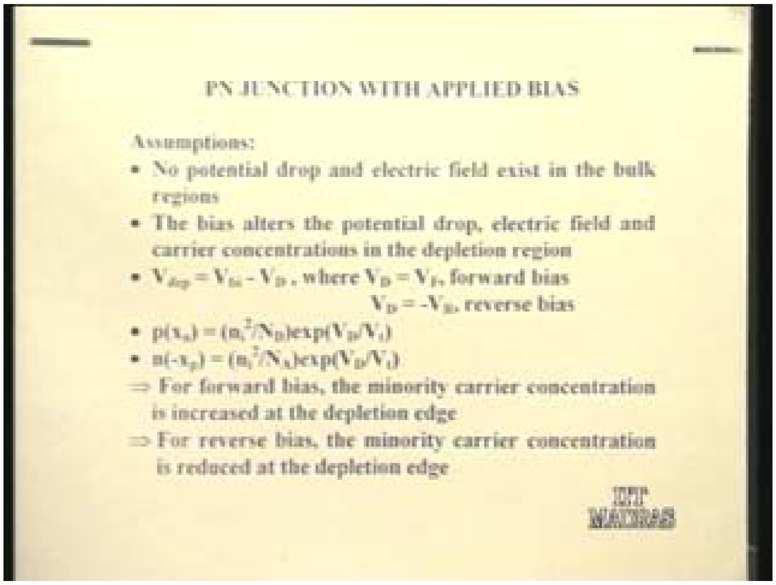

PN JUNCTION WITH APPLIED BIAS

Assumptions:

- No potential drop and electric field exist in the bulk regions
- The bias alters the potential drop, electric field and carrier concentrations in the depletion region
- $V_{dep} = V_{bi} - V_D$, where $V_D = V_F$, forward bias
  $V_D = -V_R$, reverse bias
- $p(x_n) = (n_i^2/N_D)\exp(V_D/V_t)$
- $n(-x_p) = (n_i^2/N_A)\exp(V_D/V_t)$

⇒ For forward bias, the minority carrier concentration is increased at the depletion edge

⇒ For reverse bias, the minority carrier concentration is reduced at the depletion edge

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Basically again you have three regions which we have discussed, you have the p bulk, you have the space charge region and you have the n bulk and you can look at it as bulk regions as regions of higher conductivity because there are more number of carriers whereas the space charge region is a region of lower conductivity high resistance region. So you have three regions lower conductivity, higher conductivity and again lower conductivity. Now if you apply a voltage say we have three resistances low resistance, high resistance, low resistance where is the voltage going to be dropped? Across the higher resistance.

Similarly when you apply an external voltage it is going to be dropped across the space charge region. So that is the assumption we make. So when we talk of a p n junction with an applied bias, when you apply an external bias the voltage is dropped across the space charge region and no potential and electric field exist in the bulk regions. So in the bulk nothing happens but the bias alters the potential drop, electric field and carrier concentrations in the depletion region or the space charge region. So the voltage in the depletion region is given by the built in potential minus V.D. where V.D. which is, if it is a forward bias when the p side is made positive with respect to the n side we call that forward bias and if it is other way round it is called reverse bias. So this is how it is.

If you apply a forward bias, the voltage across the depletion region is going to reduce and if you are going to apply a reverse bias, the voltage across the depletion region is going to increase and then this is some other relation we are not going to derive actually but one can derive it. That is we have seen in the previous slide that the carrier concentration at the edge of the depletion region is equal to the thermal equilibrium value but it is no longer going to be so when you have an applied bias. The whole concentration at the edge of the depletion region on the n side which is given by x.n. is given by the thermal equilibrium value exponential v.D. by v.t. and also similarly the electron concentration which is the minority carrier concentration. The edge of depletion on the p side is given by n.i. square by N.A .which is the thermal equilibrium value to exponential v.D. by v.t..

So v.D. is positive for forward bias and negative for reverse bias so the minority carrier concentration actually goes up is increased at the depletion edge and for forward bias and for reverse bias the minority carrier concentration gets reduced so at the depletion edge the carrier concentrations are modified because what happens is basically when you apply a reverse bias you are applying a extra field, you are applying a extra voltage or electric field is increased in the built in potential and you are actually aiding the field which is preventing diffusion. So that there is no diffusion whereas in the forward bias you are reducing the field which is sort of preventing this diffusion mechanism so there is no diffusion so carriers are flowing into more and more diffusion will take place. So actually this gives us the pictorial view of what is going to happen.

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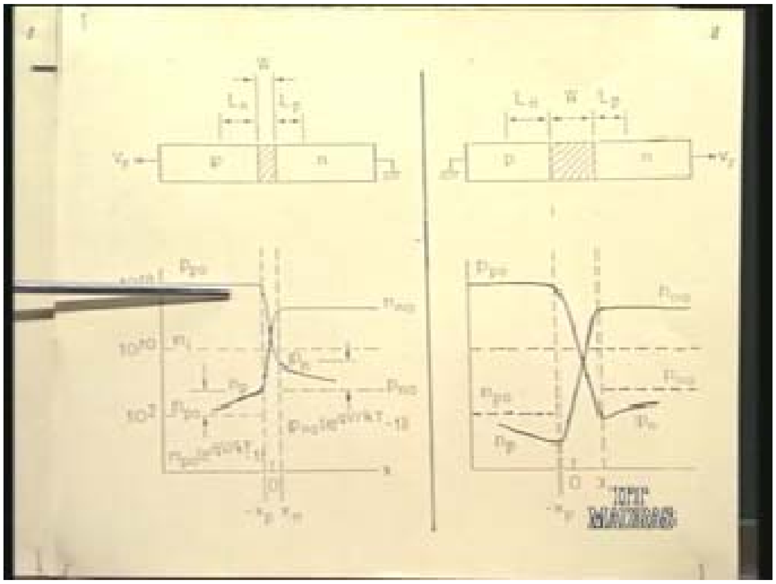

So if you apply a forward bias the space charge region the thickness is reduced because the voltage across the depletion region is reduced and so more and more diffusion takes place and the carrier concentration at this edge goes up, you see that this is the thermal equilibrium value but at this edge the hole concentration is more than the thermal equilibrium value whereas on this side also this has gone up because the field which was preventing this diffusion mechanism is reduced whereas here if you apply reverse bias, this field actually prevents the holes from this end, from the p side to the n side. So and also in fact this field is going to aid the flow of any minority carriers in the inside that is holes in the n side, from the n side to the p side.

In fact at the depletion region edge here the minority carrier concentration is reduced, here also you see it is reduced. So this is the carrier concentration profiles on the p side and the n side as well as in the space charge regions. So this is the difference as you see on the edges on the depletion region so this is very important so now the next thing is we have an increase here in the concentration whereas here we have a reduction. Now the next important thing for us to find out is what is the nature of variation of the minority carriers in the semiconductor. For example in the n side how is the hole concentration going to change. In order to do that what we have to do is we have to solve what is known as the continuity equation.

The continuity actually says that the change of carrier concentration in given volume is equal to the difference of the current flowing in and current flowing out of that volume and also the generation recombination. In fact so in a steady state that if there is no change in the carrier concentration, in the steady state means that there is no change in the carrier concentration. Then if you have a volume of semiconductor, now the current flowing in, this is the current flowing out, the net recombination in this semiconductor is going to be the difference of the current flowing in and current flowing out.

So that is what the continuity equation so we have to solve this continuity equation in this semiconductor region given the boundary conditions. The boundary condition is that at this edge we know we have already stated that this depends on n_{i} square by n_{D} in this case into exponential v_{D} by v_{t}, v_{D} is the applied voltage. On the other hand the other x boundary condition is that the minority carrier concentration at this edge, at the contact is equal to the thermal equilibrium value. There is no excess concentration this is because the recombination rates are very high or lifetimes are very low at the surface. So you have the carrier concentration at this edge of the semiconductor or the contact is equal to the thermal equilibrium value.

So once you solve this continuity equation, under this constraint, so in the n bulk assuming the electric field is equal to zero. Solution of continuous equation gives an relation this is p prime for x greater than x_{p} is equal to p prime x_{n} that is the carrier concentration edge of the depletion region and you get a relation like this. It gets quite complicated but we shall see how it looks like, so where p prime is actually the excess hole concentration and L_{p} is another parameter which is called the diffusion length. Diffusion length is actually the average distance traveled by a diffusing carrier before it recombines. So the electrons or holes which are diffusing length, how much length it travels before it recombines. So for holes if you assume, it is around 30 microns, if you assume diffusion coefficient 9 centimeter square second in lifetime is one microsecond, for electrons diffusion length is around 50 microns, there is a mistake here it is diffusion D_{n} is I think 25 centimeter square per second, lifetime is one micro second.

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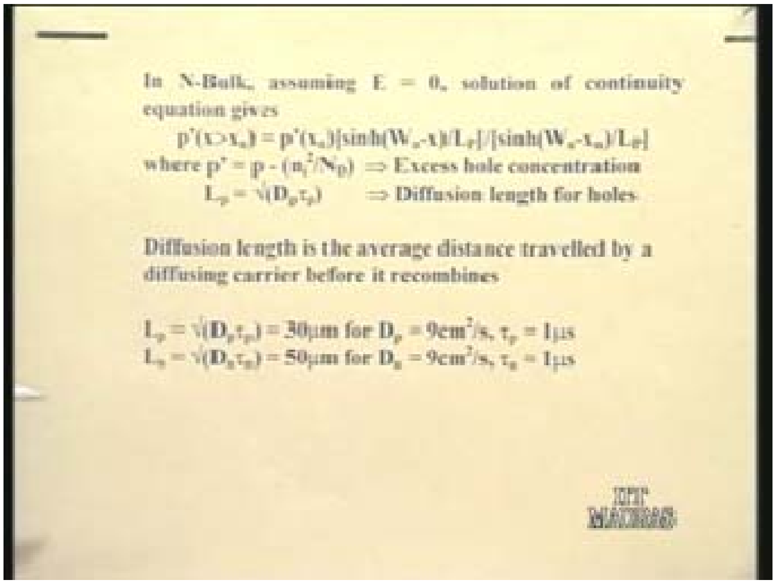

In N-Bulk, assuming E = 0, solution of continuity equation gives

$$p'(x>x_n) = p'(x_n)[\sinh(W_n-x)/L_p]/[\sinh(W_n-x_n)/L_p]$$

where $p' = p - (n_i^2/N_D)$ ⇒ Excess hole concentration

$L_p = \sqrt{(D_p\tau_p)}$ ⇒ Diffusion length for holes

Diffusion length is the average distance travelled by a diffusing carrier before it recombines

$L_p = \sqrt{(D_p\tau_p)} = 30\mu m$ for $D_p = 9cm^2/s$, $\tau_p = 1\mu s$

$L_n = \sqrt{(D_n\tau_n)} = 50\mu m$ for $D_n = 9cm^2/s$, $\tau_n = 1\mu s$

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So this is a diffusion length so it is in terms of you get a solution in terms of the diffusion length. So we get a solution like this.

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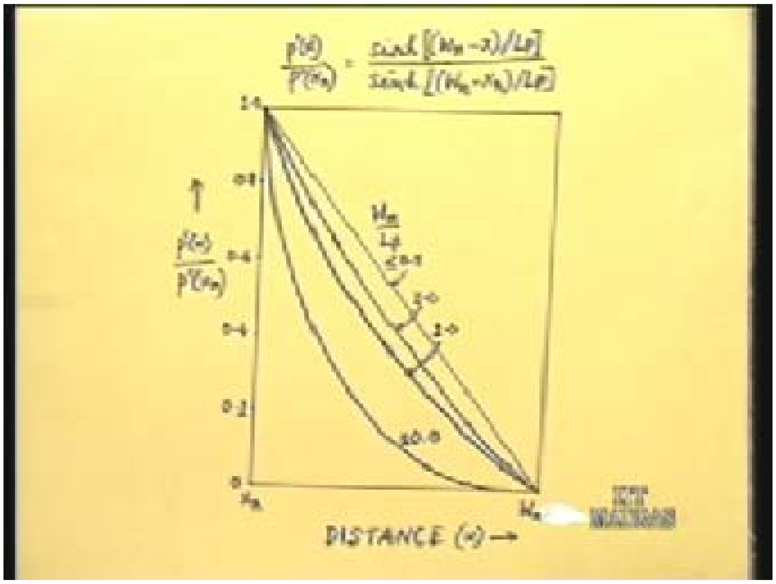

If you look at this relation which we have got for the carrier concentration we have plotted it here. Now it is related to w_n which is the actual length of the n type semiconductor and the diffusion length. If the length of the semiconductor is much smaller than the diffusion length which is w_n by L_p then the solution you see its almost like a straight line that the carrier concentration varies almost like a straight line whereas if on the other hand if it is w_n by L_p is 10 that is the length of the semiconductor is 10 times the diffusion length. It varies almost exponentially so these are the two extremes. On one hand if the semiconductor length is quite small, the carrier concentration varies almost like a straight line whereas if the semiconductor length is much larger compared to the diffusion length it behaves like it falls exponentially.

Now what does it mean, why does the carrier concentration behave as a straight line, when the semiconductor length is quite small? If you look at it this way that straight line means what is the current? Here of course in the bulk we assume that the electric field is zero so the current is totally a diffusion current and the current is proportional to the concentration gradient. Now if you have a straight line what is the concentration? The concentration gradient is a constant throughout which means that you have a constant current flowing and again if you think of the continuity equation which says that the net recombination rate is the difference of the currents, if you take any small region here, the concentration so basically it means that there is hardly any recombination because the current is a constant. If you take any region, the current flowing in is equal to the current flowing out so there is hardly any recombination which is to be expected because the length of the semiconductor is much less compared to the diffusion length.

Diffusion length is the average distance traveled before it recombines but here the length of the semiconductor is much less. On the other extreme if you take this as an exponential decay, so the current is also if you have an exponential decay of carriers, what is the nature of current? It is also exponential because gradient of the exponential is also an exponential. So the current changes continuously so it means that there is going to be lot of recombination which is to be expected because this region of the semiconductor is very much larger than the diffusion length. So there is going to be lot of recombination in fact you see that the carrier concentration goes to zero here. What does it mean? That means all the carriers which started of which means the carriers which started of from this end almost all of them have recombined before it reached the other end.

so all the carriers have recombined so you see that depending on whether the length of the semiconductor is large or small compared to the diffusion length, you have two different types of carrier concentrations. So one is a straight line and the other is exponential. Now this diode where you have a straight line concentration gradient, a small diode is called a short base diode whereas the one with an exponential decay of carriers is called the long base diode and so a short base diode will have a constant current in the semiconductor. So this gives the hole current, is going to be constant in the semiconductor this region n type semiconductor whereas in exponential decay it means the current varies exponentially in this part of the semiconductor.

So what we shall do in the next class is we shall take up these two types of semiconductors, these two types of diodes which are short base and a long base diode and we shall try to derive. We shall not derive basically, we again say that this is basically a recollection so we are going to recollect the relations for current relations for short base diode as well as for a long base diode. Then we shall look into another important aspects which in relation to the integrated circuits the capacitance of a p n junction. The stored charges in the p n junction which gives rise to delays as well as the transient what happens to a p n junction under transient conditions. That is if you apply step voltages to a semiconductor, how does it have p n junction, how does it react and the delays associated with this.