

so in the previous lecture i talked about doping in semiconductors through which we control the conductivity before going further let me recap what we did in the previous lecture

so the first thing was that the conduction properties of these semiconductors that can be precisely controlled this is very very important and that is why we do all kinds of doping and that is why semiconductors become

so important because we can control the conductivity not only the value of conductivity of the material as such but in the material itself in different regions we can have different conductivity profile that makes it immensely useful then we talked about how we and what elements we dope

so if you are talking of silicon or germanium this is our model semiconductor that i am using for giving all these physics of it you have varieties of semiconductors

so in silicon or germanium if you dope a pentavalent impurity such as phosphorus or arsenic that will make it n type we call it n type negative type and that makes conduction electron concentration much higher than the hole concentration and these are called n type semiconductors n stands for negative y negative the charge carriers the majority charge carriers are electrons conduction electrons and they have negative charge therefore they are called n type doped semiconductors ok then we talked of the impurity levels if you have doped these pentavalent impurities in silicon then you get impurity levels which are slightly below the conduction band what slightly few tens of milli electrons volts i will talk more about it in this particular lecture about this impurity levels and then these levels are occupied by those extra electrons which are brought by the impurity atoms and they fill these levels and then from here the electrons jump to conduction band and that is how you get n e much much larger than n h then at any finite temperature due to thermal energies large of number of them go to the conduction band and that increases any intrinsic concentration remember intrinsic when you do not dope any impurity the material is called intrinsic and there n e and n h are equal and the value the number itself depends on the temperature

so at room temperature it is of the order of 10^{10} per centimeter cube but if you do a ppm type doping parts per million type doping then this concentration could be around 10^{16} per centimeter cube and that is how you increase the conductivity now the electron concentration increases but then the recombination of electron hole pairs also increases and that reduces the whole concentration and for any kind of any level of doping n e into n h that remains constant this is independent of doping of doping and if you dope a trivalent impurity such as boron or aluminium that will make whole concentrations much higher than the conduction electron concentration because the impurity is coming with one electron less and therefore in that covalent bonding only three of the electrons which are there with the impurity atom they take part and the fourth bond is broken and this bond is between the impurity atom and neighboring silicon atom and that creates a again some levels impurity levels and these levels are occupied by electrons from the valence band and that is how holes are created and holes are equivalent to the positive charge carriers and that is why these are called p type positive type positive type p type semiconductors when you dope this trivalent impurities in silicon or germanium you get this p type semiconductor where the whole concentration is much much larger than the electron concentration the impurity levels are created here in p type semiconductors impurity levels are created slightly above the valence band and are vacant right because p types semiconductor you are doping impurities with less number of outer electrons and therefore all those broken

bonds are there but they are at a slightly higher energy if an electron has to occupy it it needs some energy few tens of milli electron volts of energy and that is easy to get from thermal interactions and that is why the valence electrons jump to these levels and you get more holes in this valence band ok

so valence electrons can jump to these impurity levels making holes in the valence band and that increases n_h once again by putting these impurities this whole concentration can be made much much larger say for ppm type of doping it will be around 10^{16} per centimeter cube whereas intrinsic concentration is around 10^{10} per centimeter cube all right here also once the whole concentration increases the probability of some hole going and of combining recombining with a conduction electron becomes larger and

so the number of electrons further go down but that product any into n_h that remains independent of doping levels and is n_i^2 what is n_i n_i is the concentration of conduction electron or holes when no doping is done

so n_e is equal to n_h is equal to n_i no doping that n_i into n_i zero doping so that remains same n_e into n_h is n_i^2 this is very very important though conduction electron concentration or whole concentration changes due to doping the average charge density remains zero in the material ok we are calling it n type or p type negative type or positive type but that does not mean that you have positive or negative charge density

so you should very clearly understand the difference between charge carrier density and charge density charge carriers are positive or char carriers are negative but the density of that means how many electrons conduction electrons are there or how many holes are there per unit volume

so that is charge carrier density when we are doping we are playing with this charge carrier density we are increasing one or the other but the charge density still remains zero if you take a somewhat reasonable volume in that volume the total charge will remain zero because if you are bringing a say pentavalent impurity also known as donor impurity for silicon you are also bringing the nucleus with one more proton you are bringing one more electron but also one more proton

so overall there is no charge density in general when you dope

so this is important that charge carrier density is not 0 or can be increased or decreased in doped semiconductors but the charge density itself remains zero on the average

so this is a an important aspect then we talked of what happens if we apply an electric field in such a material if we connect it to a battery what will happen how the current will go and then we said that the electrons and the holes both will contribute to this electric conduction they start moving systematically in influence of that electric field and that can create current and that current is coming from the electrons and also coming from the holes

so we say that i is i_h plus i_e the two currents are proportional to the concentration of the charge carriers but there are other things also i mentioned in the last lecture that there are some other things which control this current

so today i will be talking more on this current how this current is generated when we apply electric field across the semiconductor and also i will be talking of this impurity levels which are created and then i will be talking about a very very important device which is at the heart of all semiconductor electronics and which is known as pn junction ok

so let us recall how electric field drives a current in a normal metallic conductor if you have a wire suppose you have a wire with some cross sectional area a and you connect it to a battery or something create an electric field in this and that electric field is let us say in this direction left to right what happens you have conduction electrons in a metal and these conduction electrons

ah they move here and there in random directions with random velocities but once this electric field is there a systematic velocity is imposed on that random motion which we call drift velocity right which we call drift velocity and this drift velocity v_d is proportional to the electric field and what is this proportionality constant that also you know how to calculate if you take a very rough model between two successive collisions if the time is collision time is let us say τ average collision time then during this time the electron moves and it will have an acceleration which is force divided by mass and therefore the velocity acquired will be $e \tau E / m$ and then this τ

so this drift velocity which is of this order this is a very very rough calculation

so this is of this order some constant multiplied by this

so this drift velocity is small $e \tau E / m$

so this is the proportionality constant and this also has a name this is known as mobility and its written as μ

so if you have this wire and in this wire you have these electrons conduction electrons and let us say the density of conduction electrons density means number density of conduction electrons is n i am still talking of a metallic conductor and then the drift velocity is v_d the drift velocity of electrons will be opposite to the direction of the electric field because the electrons have negative charges but the magnitude is v_d

so how do you write the current suppose you have a cross section here at certain time think of a length of let us say a length of $v_d \Delta t$ suppose this is that length and you draw another cross section here okay and now consider all these electrons which are here they are all moving with the drift velocity at certain time t and what happens to these electrons in this time interval Δt this Δt each electron will drift through a distance $v_d \Delta t$ into Δt and therefore the electron which is here at time t will reach here at time $t + \Delta t$ and hence in this Δt all these electrons will cross this cross section

so what is the charge crossing the charge crossing will be in time Δt the charge crossing the cross section which cross section this cross section here the charge crossing will be number density number of electrons per unit volume times the volume that will be $n v_d \Delta t$

so this is the total number of electrons which are present in this volume at any given time t and these charges cross in time Δt

so the charge crossing is this multiplied by e and hence the current will be charge crossing per unit time that will be $n v_d \Delta t e / \Delta t$ and the current density j which is i / A is $n e v_d$ and that is $n e \mu E$

so this relation is an important relation this j the current density is equal to what is that $n e \mu E$ it is $n e$ and then μE this is known as conductivity and generally written as σ and this relation j equal to σE this is known as ohm's law it has a direct relation with the ohm's law that you study V is equal to $i R$ or i is equal to V / R R is the resistance it is directly it comes from here only

so that is ohm's law

so this is how the current density is created

so the current now depends on our conductivity now depends on the number of charge carrier which is this and also this mobility and this mobility μ as we have done here this mobility μ is $e \tau / m$ and hence $e \tau / m$ divided by mass this is the mobility now in semiconductors this mass of electron has to be replaced by something else is not a free space it is a periodic potential that these electrons are seeing in crystal in crystal in solids where the positive

ions are all arranged in a periodic fashion and they are creating a periodic potential and the electron is moving in that

so this crystal will alter this characteristics of motion

so if some force is applied how much will be the corresponding motion generated

so mass is coming from there f equal to $m a$ but if it is a periodic potential an electron has to move into that

so this periodic potential can help in motion or can hinder the motion and therefore we define something called effective mass to take care of that

so this mass here is written with a star a steric and this is known as effective mass and very interestingly if you look at the numbers for silicon and if you are considering conductivity this effective mass of electron m_e^* is something like $0.2 m_e$.

$2 m_e$ naught m_e

so this is the electron mass m_e is the electron mass and this is the effective mass

so effective mass has decreased that means this solid this crystal is helping in motion

so that effective mass has to be used here and

so the current is proportional to this concentration charge carrier concentration and also to this mobility and this mobility will depend on this effective mass similar thing for whole similar things for holes and hence you have j is equal to number of electrons and mobility of electrons this will be that electron part and $n_h \mu_h$ this will be that whole part and then multiplied by e into e

so this is how the current density will appear

so this finally gives you i equal to i_e plus i_h now let me talk little bit of impurity levels as we said in n type in n type semiconductors impurity levels are created slightly below the conduction band

so you have valence band you have conduction band and then the impurity levels are created here and if the doping concentrations are low ppm variety then these impurity levels are sharp its not spread like a valence band or conduction band why these impurities are not interacting with each other if the concentration levels are low then one impurity and the other impurity are far apart and therefore these levels are not getting mixed up they are not getting broadened and you have sharp impurity level and these are the levels of electrons which are that extra electron which are brought by the impurity atom

so in this crystal if you have silicon silicon silicon silicon silicon silicon and then you have a phosphorus here and the electrons four electrons are engaged in the bonding and the fifth one is somewhere here and which is still bound to this but with a very weak binding

so that is how these levels are created these levels correspond to that now you can make a simple model for calculation of this energy and that is known as hydrogenic model or hydrogenic energy levels because the impurity that has been brought has one extra z that proton number is one extra and of course when atom comes then everything is neutral

so all those electrons are there

so that fifth electron which is not taking part in that covalent bonding sp^3 hybridization that will see the impurity atom as an ion or a particle of charge plus e right because one extra electron we are talking

so the remaining part will have plus e charge and then this remaining plus e charge and this extra electron this you can try to model as proton electron hydrogen atom energy levels

so if you take this conduction band minimum as your energy 0 then this is the energy needed for this electron to go from this bound weakly bound state to the

conduction band where it can go anywhere in the silicon crystal
so you can do a calculation for hydrogen atom you know for hydrogen atom you know the ionization energy that is 13.

6 e v

so if you give 13.

6 e v energy to the electron then it can leave that nucleus and go similar modeling you can do here you have that impurity atom and this impurity atom has some charges and this fifth electron is outside and this has a charge plus e so you can try doing this uh modeling

so how that 13.

6 e v comes if you look at the expression that is given by some mass of the electron times electronic charge to the power four then sum four pi epsilon naught square and n square h cross square n is one

so this gives me the energy

so if you model this impurity extra fifth electron as moving in this field of this plus one charge of the that impurity atom that we have brought plus one charge but then that motion is in silicon crystal

so two modifications are needed

so if i model that silicon silicon silicon silicon crystal and then you have some impurity somewhere this is the impurity at plus e charge and then the electron is somewhere here which is going around let us say this impurity charge and if you do this same modeling the two modifications will be one is mass you have to write as m star effective mass of this electron in this silicon crystal and the other thing is this epsilon naught and this epsilon naught has to be replaced by epsilon which is the dielectric constant and times epsilon naught so this epsilon naught is dielectric constant times epsilon naught and dielectric constant of silicon is somewhere around twelve

so if you do these two modifications mass is reduced remember the effective mass of electron in silicon crystal is smaller than the free space charge of course this is for specific limited purpose some other purposes this effective mass can be different we are talking of motion

so conductivity in that kind of situations this effective mass is small then this epsilon naught has to be changed to k times epsilon naught this is in denominator

so both these effects will reduce this energy from 13.

6 e v and when you do that that turns out to be just few tens of milli electron volts

so that is how this impurity level that we were talking this impurity level they are generated at few ah say 10 20 type millivolts milli electron volts of energy which is comparable to k into t boltzmann constant into absolute temperature and that is why it is very easy for these electrons to go and populate this conduction levels when it goes what happens to this impurity atom it remains ionized it becomes ionized and that plus charge at the site of that impurity atom will be there but then remember you have electrons all over and those electrons are moving in the entire crystal

so if you are not right at one atom and you are looking at a certain volume the charge density is still zero

so now let me talk of a very very important device as i mentioned in the beginning all semi conductor electronics revolved around that and at least the physics the physics is contained in this particular device if i understand this device physics of this device i understand all devices and that is known as p n junction p n junction as the name indicates you have p type semiconductor and n type semiconductor and they are meeting at some cross section making a junction so you do not bring two semiconductors and put them in contact to make this p n

junctions not like that you take a single semiconductor material a wafer and then you diffuse impurity to make it of one type either p type or n type suppose i have this material and then from one side i am making it uh making some impurity go into it and make this entire thing as this whole thing as let us say p type

so we are putting this p type impurities or they are also known as remember acceptor acceptor acceptor impurities

so by putting these acceptor impurities if you are working with silicon by putting trivalent impurities you make this whole thing as p type and once you have done that now you have a material and this material is p type and then you diffuse let us say n type ah impurity from here that donor impurities now you put donor impurities in this material the concentration levels are higher

so wherever these impurities are going its making the whole thing n type right so if this diffusion is going up to this place then you have p type here and n type here this is n type and that is p type and then this one is the junction this one is the junction this is the pn junction this is the junction part

so this is how a pn junction is prepared is made of course you need metallic contacts if you want to use this as a circuit element from outside you have to you have to connect it to the outside world batteries and other things and all those

so you have metallic contact

so you do have metallic contacts at the end you you may have a metallic contact on this side you may have a metallic contact on this side and that is how this junction is made

so let me talk of this portion you have this n type portion then you have a junction here and then you have this p type

so let me draw another diagram in which i am drawing this that particular part and in this particular part is the whole thing and you have your metallic contact somewhere here you have metallic contact somewhere here and schematically this is all schematic drawings that i am making suppose this is that junction point this is a junction layer this is that junction layer it is this layer it is this layer and i am only showing this part i am only showing this part

so in that part you have a junction out here and one side is p side

so you will have lot many holes here you will have lot many holes here because you have put those acceptor impurities which have created energy levels quantum states slightly above the valence band and then those valence band electrons have gone to those impurity levels creating lot many holes and some electrons are still there some electrons are still there remember n_e into n_h is equal to n_i square

so these holes are the majority carriers on this side electrons are the minority carriers on this side

so this is your p side and the other part is inside in which you have a large number of electrons because you have doped those donor impurities and they have created energy levels slightly below the conduction band and these electrons from these impurity levels go to the conduction band and therefore the concentration of this conduction electron becomes very very high and you also have some holes here some holes here

so that is also there and on this side electrons are the majority carrier and holes are the minority carrier whereas opposite on this side electrons are minority carriers and holes are majority carriers but this is a an absolutely unstable situation why because you have large concentration gradient the concentrations of hole on this side is very large and all of sudden if this is the picture all of sudden the concentration of holes falls drastically similarly

on the other side on this side on this side electron concentration is very high and when you look at across the junction on the other side the electron concentration is very very low and you know this is not an equilibrium situation you cannot have in your room half the room where you have a wonderful aroma and you have all saints and room freshener and everything and the next half of the room is just devoid of all those things if you have a concentration gradient there will be a flow from higher concentration to lower concentration which we call diffusion that is how you put your incense in one corner of the room and the entire room gets that particular smell or that particular aroma that particular flavor

so because of this concentration gradient the electrons and holes they will diffuse diffusion will take place its it has its own equations and all that but essentially across the junctions what will happen systematically systematically because of these this concentration gradients electron will flow from right to left in this diagram and holes will flow from left to right in this diagram electrons and holes are making random motion that is fine but if there is a systematic motion of electrons what will happen if electrons go from one side to the other side then wherever they are going they are creating negative charges charge density whereas places from where they are going they will be left with positive charges and similar story with the holes also holes are equivalent to positive charges

so if the holes are going from left to right that means the positive charges are going from left to right what is happening in the actual crystal when i say that holes are going from left to right what is happening in the actual crystal if you think of that and you should keep thinking in terms of those actual crystal also

so that you do not lose sight of the physical phenomena

so if there is a hole somewhere here and if this hole has moved if there is a hole somewhere here and this hole has moved here what does that mean that means the broken bond which was here now the broken bond is here this electron has gone this electron from the bond has gone and filled this

so its essentially it is a electron flow but equivalently we say it is a whole flow and then we treat this hole as a positive charge

so if the holes are diffusing from left to right systematical motion then you will have positive charge because of that positive charge is getting accumulated on the right side and correspondingly negative charge will come here

so both ways the first thing is both ways because of this diffusion you will have charge density

so this is very very important phenomena that across the junction in this region now the charge density is appearing charge density is no more zero and what kind of charge is appearing which side on this side on this side negative charge is appearing negative charge is appearing and on this side positive charge is appearing

so this is one thing that is new in a doped semiconductor the charge carriers were there but the charge density was zero but if you are able to make a p n junction one side p ah other side n then you will have charge density which is also non zero

so that is one thing

so in this material you have a junction somewhere and then you have a region somewhere let us say this is a region up to here this is region up to here in which you have rho charge density this is p side and this is n sides electrons are going

so rho is negative negative charge density negative charge density and on this side you have positive charge density

so that is the first thing to be understood why this limited region only why did i say that up to here only you have charges and up to here only you have charges why not in the entire thing that is because this diffusion is not a continuous process as the charge density is created it also creates an electric field it also creates an electric field if you have a positive charge on the right side and negative charge on the left side what will happen it will create an electric field from right to left

so you will have an electric field in this direction and what will this electric field do if you have this electric field and electrons are trying to diffuse from right to left what will happen this electric field will oppose that the force on this electron because of the electric field will be from left to right and similarly if hole wants to diffuse from left to right if hole wants to go here this electric field will oppose that

so there is a balance an equilibrium situation where you have certain charge distribution up to some distances on the two sides electric field is as is now sufficient

so that this electric field is causing the diffusion to reduce significantly and you do not have these charges systematic charges going much beyond the this junction point

so that is one thing another important thing is if these electrons are going and let us say if you have this you have this and then this is the region i say and this is p type this is n type this side is n type and this side is p type and then i say that the electrons are going from here to here and you have large now you had large number of holes here and then the electrons are going from this side to that side what will these electrons do these electrons will recombine with these holes and therefore the electron hole pair will get annihilated the pair will not be there electrons will fill up those holes this conduction electrons will now go into the bonding electrons and these electrons and these holes they both will disappear from the scene similarly if the holes are diffusing from left to right if the holes are going from left to right and you have large number of electrons here in the n side

so these holes will go there and recombine with the electron what does that mean that means the bond on the right side is broken and that is how we say that the hole has diffused and that electron from that broken bond will go to left and then it will fill the hole

so the hole has diffused but then you have conduction electrons and these conduction electrons will fill that newly created hole on the right side

so what will happen these electrons and these holes they will all recombine in this region and in this region the carrier density the charge carrier density will become zero

so in this junction region across the junction up to some length what you have is you have charge density very very important you have charge density which is not zero but you have charge carrier density which is zero when i started this lecture i emphasized that although you are making the semiconductor p type although you are making the semiconductor n type although number of conduction electrons is much much larger than the number of holes or number of holes is much much larger than number of conduction electrons the charge density in the entire material remains 0 on the average

so charge carrier densities are increased decrease they are there but the charge density is 0 now what i am telling is opposite in this region in this region the charge density is not zero this charge density is not zero but the charge carrier density is zero there are no electrons here no holes here because they have all recombined

so this region is known as depletion region this is known as depletion depleted

this region is depleted of charge carriers there are no charge carriers as such so this is the kind of situation that you do have a region

so called depletion region you have a junction and then on both sides of the junction you have these a region which is known as depletion region this whole thing is p type up to junction remember even though you do not have charges charge carriers it is p type and the right side is n type because the impurity atoms are very much there the impurity atoms are very much there

so it is p type up to the junction n type up to the junction and this part is known as depletion region what i am drawing you have seen you are seeing that what i have drawing is this separation i have drawn smaller and this separation i have drawn larger call it x_1 and call it x_2 and that was to emphasize that yes it is possible to have unequal widths on the two sides of this junction why this is because that will depend on the concentration of holes and concentration of these conduction electrons and that will depend on my doping characteristics how much is this impurity concentration here acceptor impurity concentration and how much is that donor impurity concentration there of that we are controlling and therefore it is possible to have let us say less density of conduction electron on this side to start with and more concentration of let us say holes on this side this is possible we can do that and therefore if holes and electrons have to neutralize each other and here the density is much larger and here the density is much smaller and remember one electron will neutralize one whole

so you will have smaller width on this side and larger width on that side

so that width will depend on this n_a and n_d larger the doping level smaller will be the width in this depletion region

so this is how the depletion region acts you do not have charge carriers you do have charge densities and the two sides you can have different widths the total width that is width of this called width of the depletion region that depends on many things especially the doping levels especially the doping levels

so width of this depletion region that depends on n_a n_d and then the electric field that is created i told that finally in equilibrium you have an electric field and therefore you have a potential drop potential difference between the two sides that is known as potential barrier that is known as potential barrier

so that potential barrier height v the doping level n_a n_d the width of the depletion region on the two sides x_1 x_2 and the total width these are all related to each other

so in our next lecture we will explore this relation what is the relation between the depletion width the barrier height and these doping levels you