we talked about the basics of conduction metals and insulators semiconductors

so let me recap what i did in the previous lecture

so first thing is for an isolated atom the possible energies of quantum states are discrete

so that is one thing that if you have an atom the possible energies that electrons can have they are discrete like this

so you have this one s two s two p two s and

so on

so these are different energy levels and in these you have quantum states and each quantum state can have only one electron the second part is for a gas or vapor of that material the same energies are available for one atom you have certain energy levels and if you have a gas of that particular material where

so many atoms are there the energy levels remain the same the electrons can occupy only those energy levels and

so this diagram this diagram remains the same now the electrons fill the orbital from lowest energy states from here onwards like this first the electrons will fill this one then it will fill this one and

so on one per quantum state poly exclusion principle the last non empty level may be completely or partially filled then we talked about making of solids when atoms come closer and make solid then all this energy levels they get changed

so as the atoms are brought closer to form the solid crystalline state these outer electrons also start interacting through bonding you know the electrons ah bond the atoms neighboring atoms

so those interactions will change the energy levels and therefore the energies are split in almost continuous energy bands

so what was the discrete energy levels now becomes ah energy bands

so the energies are split its no more a sharp energy level you have some quantum states go up some quantum states go down and

so it becomes a band then the lower energy levels like 1 s 2 s they are populated by the inner electrons and the inner electrons they are not much affected because of this bonding and interactions they do not take part in bonding

so those energy levels are still sharp quite sharp but then the outer ones they spread more the outer ones the they spread much more and the bands are wide then the highest completely filled energy band the highest completely filled energy band is called valence band this is important now and the next higher band which is not completely filled it may be completely empty or it may be partially filled

so that next higher band is called conduction band

so these things we talked now what happens in good conductors in good conductors the conduction band is partially filled like here the conduction band is par the red one is denoting filled and the blue one is denoting empty

so the valence band is completely filled and the conduction band is partially filled only this much is filled and this is empty

so in conductors good conductors the conduction band is partially filled there are enough electrons in the conduction band and enough empty states in the conduction band even at very low temperatures

so that is a good conductor if you apply an electric field then these electrons which are in the conduction band they can take up those small energies and go to quantum states which are available all right in insulators what happens in insulators the conduction band is completely empty this conduction band is completely empty and the energy gap between the valence band and conduction band is large this energy gap we write it e g is large large means what say 3 ev 4 ev 6 cv like that now at normal temperatures like room temperature or so no electrons populate the quantum states in conduction band

so this is the structure and it at low temperatures this valence band is completely filled the conduction band is completely empty as the temperature is increased thermal energy of the order of kt is now available but then the gap is

so large that these valence electrons cannot cross over that and therefore even at normal temperatures room temperature or slightly above also it is completely empty and no conduction takes place that is why they are insulators ok in semiconductors the valence band is completely filled the conduction band is completely empty just like insulators the only difference is this gap this gap is a low say less than 3ev or

so typically thumb rule for silicon it is one point one two e v

so although its still very high as compared to that k into capital t which is ah some point zero two six electron volts at room temperature three hundred kelvin but still its not that high

so some of the electrons at say room temperature some of these electrons in valence band get sufficient energy from thermal interactions and they cross over the gap and occupy quantum states in the conduction band

so some of these electrons in the balance band they jump over and they occupy quantum states in the conduction band and if that happens in the valence band one quantum state is made available its it becomes empty

so other electrons in the valence band can go over there fill that gap and create a new vacant state somewhere else

so that is how we have this

so called holes or vacant states

so these are the things that we discussed in the previous lecture

so all this discussion was in terms of rectangles that i drew and called that energy levels and conduction band and valence band electron going from the valence band to the conduction band on all that but what is the actual physical picture where is the electron its not in my diagram where the electron

so let us connect this energy level diagram to the actual silicon crystal or semiconductor crystal and see how the two things are related to each other

so if i talk in terms of silicon it is it has diamond crystal structure

so each silicon is bonded to four neighboring silicon atoms through that sp3 hybridized covalent bonding

so we we will show it here in a two dimensional ah diagram although it is a three dimensional thing it is a tetrahedral kind of structure but let us say each silicon atom is bonded to four different silicon atoms

so this is all bonds it contains two electrons one electron being shared by this silicon another electron is shared by this silicon and these two make a bond between these two similarly the bonds are here here here

so the four outer electrons those sp3 electrons they are consumed in making these bonds similar thing happens with this with this with this this this whole crystal is there now what is a conduction electron and what happens when i say that an electron has gone from the valence band to conduction band what is the meaning in this diagram all these electrons which are shown here in this bonds people also show it like two lines like this because two electrons are involved in the bond

so this is also one way of showing and you also know this is also like methane you just draw one line and say that its a its a bond covalent bond

so these all these electrons which are there two electrons here two electrons here two electrons here two electrons here and

so on all these are in valence band if i draw this diagram here i call this as valence band and this as conduction band all these electrons correspond to electrons somewhere here in this valence band everywhere everywhere all the bonded electrons are represented as electrons in the valence band now suppose because of those thermal energies and interactions some electron gets extra energy one of these two electrons let us say it gets extra energy and then this bond is broken suppose this bond is broken all right

so this bond is broken and the two electrons are there one electron is still there and other electron is broken

so let us take this diagram

so suppose this is broken

so there is no electron out here

so only one electron where has that electron gone after getting the energy it has gone somewhere this is a silicon this is a silicon ion ion and that electron has gone somewhere it is not forming is not part of this covalent bond here and therefore it can move in the crystal it can move somewhere else you have another silicon atoms other silicon atoms they are all bonded they are all bonded like that and this can go anywhere here here here here i will say that after receiving that extra energy the bond is broken and this electron has gone to the conduction band this electron is now a here in this conduction band it has occupied a quantum state which is available at these energies which is much more than this

so through that thermal interaction it received the energy goes from here to here that means it goes from here to here or here means it is going anywhere and this bond is broken now if bond is broken there is a quantum state available at this energy which any electron can occupy

so we say that in this valence band a hole is created a hole is created a vacant quantum state is created and this vacant quantum state can be occupied by any electron this electron may come from the available conduction band electrons also

so maybe in the whole crystal you have an electron free electron here conduction electron here may be a conduction electron here maybe a conduction electron here and

so on

so this conduction electron can also come and fill this quantum state in our diagram what we will say there was an electron here and this electron went and filled this hole

so whole electron pairs can be created by the thermal energies and whole electron pairs can be destroyed because of this thermal energies some where it is gaining energy somewhere it is losing energy and this

so you have this creation of whole electron pair and you also have destruction or recombination going on and given a particular temperature given a particular temperature there will be some equilibrium number how many quantum states in the conduction band are filled and how many quantum states here are empty

so that number number of electron hole pair that will stabilize somewhere although both ways the process is going on new whole electron pair are being created and they are recombining but on the average finally you have a particular number of whole electron pair for a particular temperature for room temperature i will give you some data at room temperature which is around say 300 kelvin ah silicon have has 5 into 10 to the power 22 atoms per centimeter cube the density number density how many atoms per centimeter cube and then the electron hole pair at this temperature that number is 1.
5 into 10 to the power 10 per centimeter cube

so you can see the fraction per centimeter cube these many atoms are there these many atoms are there and how many are broken broken bonds about 10 to the power 10

so that is the kind of ratio you expect at room temperature it is a factor of

10 to the power say 12 or
so and that is understandable your k into t k into t boltzmann constant times the temperature at room temperature is 0.
026 ev and that band gap is one two e v still much larger
so the probability is small but even this small probability is very large because uh it has created these many charge carriers all these electrons are now available for conduction all these holes are now available for conduction
so these many pairs these many conduction charge carriers for conduction are made available even if the probability is very small and if you want to compare with a normal conductor say copper the copper atomic density is 8.
4 into 10 power 22 atoms per centimeter cube ok and each copper atom remember each quarter atom will contribute to electrons in the conduction band
so that number will be of this order
so the conductivity of copper is much much larger than the conductivity of silicon but nevertheless if you look for compare with insulator it is quite large
so that is how the silicon or any semiconductor will give rise to conduction now these uh now these uh semiconductors pure semiconductors are called intrinsic semiconductors these are called intrinsic semiconductor by the way in the previous lecture i showed you an experiment and i showed that if a semiconducting material is heated temperature is increased the conductivity increases opposite to what happens with the normal metallic conductors right and now you can understand why it is
so if you increase the temperature then this kt will increase band gap remains the same that energy gap remains the same
so if kt increases thermal energies increases then there is a more probability larger probability of electrons going from valence band to conduction band or those bonds being broken and electrons made free for conduction
so that probability will increase that number will increase the charge carriers will increase and that is why the conductivity of a semiconductor increases as you increase the temperature in metals that will not happen in metals the valence bands are all full and conduction band will have a fixed number of like copper conduction electrons will be fixed if you increase the temperature this number is not going to increase
so ah there is another mechanism where temp if you increase the temperature then those scattering from different sites ionic sites will increase drift velocity will decrease and the conductivity will decrease that phenomena is also there in the semiconductors but then the number of charge carriers increases
so much that that scattering those things are all becomes less important and the conductivity increases ok
so we have this intrinsic semiconductor that means all the semiconducting properties is not because of any outside controls it is its own a pure material and in that case number of ah electrons which electrons conduction electrons and number of holes that will be equal you can call it n i i for intrinsic in the previous lecture i also told that semiconductors are
so important
so powerful because we have the control to tune the conductivity why one should use a low conductivity material in in any kind of transmission electric currents because we have controls we can change the conductivity according to our requirement which we cannot do with the copper copper wires or copper structures how that is by putting some foreign of some impurity atoms we are calling it impurity although we like that impurity most of the time people say that impurity is something which is which has to be avoided one should be pure and all that but here we put some impurity atoms in the in this structure and that

is called extrinsic extrinsic semiconductor or doped semiconductor what is this doping and what is this doped semiconductor you have that structure that crystal structure all bonded atoms all bonded atoms covalent bonding everywhere and this is all silicon silicon silicon silicon now silicon remember it is z is equal to fourteen and the last one is s p s s2 p2 of course it is all hybridized in covalent bonding now if you take an element from the next column of the periodic table where it is the last one is s two p three like phosphorus for example or arsenic you have s two p three five outer electrons

so if i have a silicon and then ah using some whatever process i diffuse some amount of this phosphorous or arsenic into this silicon crystal and if my process is is good nicely formulated and well implemented then these phosphorus atoms will go and sit at the site of silicons some of the silicons will be replaced by this phosphorus or arsenic

so what happens if say all this is silicon and this particular thing is let us say our phosphorus

so all this is silicon all this is silicon all this is silicon but here i am bringing that pentavalent material that a particular atom is sitting here it is a neutral atom it has as many protons as as the number of electrons and then this neutral atoms comes here there are five outer electrons those five electrons where will they go in this particular crystal structure in this particular crystal structure that the silicon has four of these electrons will be part of this bonding four of these electrons will be part of this bonding where is the fifth one the fifth one will not be at this energy level it will be at a higher energy level

so it is bonded to this but then the energies are much higher energies are much higher is going on a larger orbit or

so and then the bonding is very weak the bonding is is very weak bonding of this particular electron to this is quite weak calculations can be made and this bonding turns out to be say few tens of mevs say 50 mev right

so like that

so this particular extra fifth electron for this the energy which is there it is much larger than this valence bond energy

so if i again go to my valence energy diagram we have this valence band here we have this conduction band here all these bonding electrons they have energies which are lying here in this energy band in this width in this range but this one has a very high energy how high it is close to this conduction band somewhere here

so these new energy levels are created new energy levels here just below the this conduction band and this gap is small it is in milli electron volt say 50 mev this gap is small

so that means you give 50 mev and this electron will be detached from this parent atom

so if that happens what will happen this will go to the conduction band

so the electron is already here in these quantum states these electrons electrons like this you of course you do not put one phosphorous atom ah even if it is ppm one part per million

so per ten to the power six there is one and then remember per centimeter cube you have ten to the power twenty two

so there are many such

so all these electrons which are there they are in these levels these are impurity levels or donor levels

so they are created here but then 50 mev is a small energy

so from thermal interactions easily this gap can be crossed and all these electrons will move most of them will move into the conduction band moves into the conduction band means it becomes free to move anywhere in this crystal going from this atom to that atom that attempt that atom and

so on

so that is how you will get this

so now what happens from the usual electron hole production and recombination you had some number of holes here and some number of electrons here which was n e and n h on top of that on top of that all these electrons are now made available

so in the conduction band now you have many many more electrons than this this number of holes here for each hole you do have an electron there but these impurity levels they are giving us many many more electrons in the connection band

so n e number of conduction electrons is much much larger than number of holes because of this impurities and there is yet another phenomena this number of electron hole pairs that i was talking that depends on the temperature that's an equilibrium state new holes electrons are being produced and they are the electron hole pairs are destroyed because of recombinations and the some equilibrium thing is happening the probability of this creation and probability of this recombination they become same at certain level now if there are too many electrons here the probability of electron going into this hole recombining this hole becomes very large ok in intrinsic case you had few much fewer number of conduction electrons

so an electron going and filling that vacancy that probability was less if you think in terms of the crystal in the actual crystal yes if there is a bond broken here and there are some free electrons available those free electrons can come here and fill this gap if there are many many free electrons available around then the probability of someone coming here and filling that gap will definitely increase

so the recombination rate of filling these vacancies will increase and therefore the number of holes will further go down in the intrinsic case we had this number of holes some number of holes but when we are putting impurities pentavalent impurities we are increasing the number of electrons fine at the same time the number of holes is decreasing because of this recombination increased rate of recombination and

so if i say that if i compare with this intrinsic one let us say let us put some symbol here

so if i compare with this in this case n e is larger than n i that is understandable and also this n h this is right no need of that dash n i is there and this nh is but nh is smaller than ni that is important that is interesting not only that the number of electrons has increased the number of holes has decreased because of the increased recombination and then one can do some mathematics some theory and turns out that this n e into n h that turns out to be n square very interesting n i square very interesting n e is increasing n h is decreasing but the product remains same

so if it is if there is no doping that product is ni into ni and if there is doping still the product remains the same

so that is very very interesting ok one can do some numerical on that ok

so numerical problem suppose you have a pure silicon no doping and at room temperature the total number of atoms per unit volume is per unit volume is 5 into 10 power 28 per meter cube per meter cube previously i had talked in terms of per centimeter cube and that is why it has gone to 10 power 28 and not 10 power 22 and then at this temperature let us say the hole density and the electron density they are equal intrinsic density and that is let us say 1. 5 into 10 power 16 per meter cube now we put a pentavalent impurity arsenic let us say arsenic 1 ppm what is ppm ppm means parts per million that means 1 in 10 to the power 6

so whatever is the number of atoms per unit volume one part in 10 to the power 6 is replaced by this arsenic now the problem is to find after this doping how much is this electron density conduction electron density n e and how much is the whole density nh

so that's the problem i have copied this data on the bold and let us solve it there

so how do i solve this problem the number of extra electrons conduction electrons that we have created through those impurity levels that will be one per impurity atom okay one atom pentavalent five electrons four go in bonding one is extra that is that goes to the impurity level and from there it goes to the conduction level

so that ah n e number of uh these electrons which are created due to this doping that will be one ppm that means if you have five into ten to power twenty eight atoms ah one by 10 to the power 6 of that that is 5 into 10 to the power 22 these many new conduction electrons are being injected then there are conduction electrons from the intrinsic processes but that number is small that number is 10 to the power 16 very small as compared to this this is very small

so the actual number is this plus this but is

so small that you can take that any is just equal to this and then any into n h number of electrons into number of holes that should remain the same that is independent of doping

so this is your n i square and n i square you can take it from here it is 2. 25 and into 10 to the power 32 of course the unit will be also squared and all that but anyway thats i am talking of now in these units

so what is an h nh number of holes will be equal to this two five into ten to the power thirty two and divided by n e and n e is five into ten power twenty two

so work out how much is this how much is this this is 0. 45 into 10 to the power 10 or 4. 5 into 10 to the power 9 per meter cube okay

so the number of holes has decreased originally this was the number of holes it has decreased from there now in these type of extrinsic semiconductors the number of electrons conduction electrons is much larger than the number of holes and therefore they are called n type semiconductors

so these when you dope these things and n e becomes much much larger than n h then you call it n type semiconductors you have a the other variety where you do not go into that pentavalent things you go for trivalent things like boron or aluminium or gallium they have three electrons in the outer shell s two p

so if i make a semiconductor take a silicon and then do all that thermal processing diffuser or whatever is prescribed and diffuse some of these trivalent impurities in that what will happen

so once again if i go for the structure i have silicon here i have silicon here everywhere i have silicon and they are all bonded to the neighbors and somewhere here we have a tribal let us say boron

so this is all silicon it is important that during this doping process we do not destroy the crystal structure that crystal structure should remain the same

so that you still have all the covalent bonding and on those things

so you have all these things here all the bondings are there two electrons per covalent bond but here boron comes with three electrons only

so it can participate in three covalent bonds the fourth covalent bond it cannot participate and therefore this particular one one of the bone one of the states will be empty so you have a two electrons here two quantum states but because this it does not have four electrons it only has three electrons it has come with three electrons and therefore you have a hole here you have a vacant state here this bond is broken

so a hole is created but this hole the energy of this hole is different if if there is a hole created here if there is a hole created here silicon silicon bond if that is broken and the hole created here that is the different energies if an electron comes and sits here makes a bond electron comes and sits here makes a bond these energies are different because the nucleus is different this nucleus is different this nucleus is different

so new quantum states are available new quantum states are available in this energy range somewhere near that but not exactly in the original valence band these new energies are slightly above the valence band

so if i have a diagram if this is your valence band if this is the conduction band you have all these quantum states here at these energies at these energies you have all quantum states available and these correspond to the usual covalent bonds between silicon silicon but a bond between boron and silicon that will have energy which will be slightly higher than this and it will be somewhere here it will be somewhere here

so the quantum states are created new energy levels are created let me use some other color

so these quantum states are created these are now impurity level or acceptor level y acceptor this quantum state has a larger energy than this quantum state ok this quantum state has an energy which is shown here slightly above the valence band whereas this s i s i this these quantum states are having energies which is here in this valence band slightly higher if an electron wants to break from here and fill this vacant state the energy is slightly more some energy is required how much once again that small energy is few tens of milli electron volts say 50 mev or

so and that can easily come from thermal interactions

so in that case

so any of these things can break from here get some thermal energy and fill this state and

so the electrons can come from these levels one of these levels here these are here are those level silicon silicon silicon silicon silicon silicon

so from here it can come to here that means somewhere here it can break and it can occupy this quantum state

so we say that electrons can go to these states these states and holes can be created here

so as many atoms you are duping each atom is creating a quantum state in in this impurity level and since this is small very easily electrons from this valence band are going and sitting here and therefore the holes are created in valence band ok

so in this case the number of holes will be larger than number of electrons when i say electrons remember its conduction electrons and holes are in that valence band the same story once again if you have a too many holes and few electrons coming from that intrinsic processes

so and their corresponding holes are there but then those holes are much smaller in number

so the number is dominated by the impurities

so if there are too many holes and you have few electrons then the probability of one electron going and filling some hole will increase if you have a same number of of holes then there is some probability but a too many holes

so electron can either fill that or fill that or fill that or fill that the probability will increase many fold what will happen that creation remains the same the destruction becomes larger and therefore this number will reduce further

so the same story the whole number will increase the electron number will decrease and that product any nh will remain at that ni square now since here the holes are in a larger number than electrons we call them p type semiconductors these are called p type semiconductors and now you know where is that control of conductivity that control is in doping how much i am doping and whether i am doping it uniformly across that silicon crystal or i am i am creating a gradient density gradient of that doped material how i am monitoring that that will give me the handle to change the conductivity at will how much conductivity i need if i need conductivity in this portion more conductivity in this portion less conductivity i can do that if i need more holes here less electrons there i can do that in the same crystal in the same wafer i can diffuse ah phosphorus from one side i can diffuse boron from other side with different concentrations or phosphorus with different concentration i can play with it and i can have a great control on conductivity profile and that is how these things become very very important

so now let me talk of conduction by holes and by electrons

so let us say we have a valence band and in this valence band we have certain holes certain holes certain quantum states are empty and then we have a conduction band in which certain quantum states are occupied it could be n type semiconductor or p type semiconductor

so there are some conduction electrons available and some these holes are available and in the crystal if you think once again the same diagram like this covalent bonding everywhere and some of the bonds are broken some of the bonds are broken

so you can also do that let us say this bro

so at some places you have holes at some places you have electrons in general if you do not apply any electric field you do not connect it to battery nothing in general these conduction electrons which are free to move almost free to move in this crystal they will be going from here to there there to there randomly sometimes combining with the hole sometimes moving at some other site and

so on similarly when the electrons go somewhere and fill that hole if valence electrons can also do that valence electrons can break a bond here and go some hole is created here then it this bond can be broken this electron can go here sometimes from this side from sometimes from that side you can picture it as the electrons are moving in random directions and the holes are also moving in random directions the conduction electrons they go from one atom to other atom and then when the valence electrons they also change sides if there is some hole here some empty quantum state here the electron neighboring electron can come and fill that

so the hole has moved from one side to the other side holes are also moving randomly in this crystal and then you connect it to a battery and you apply an electric field in this material in certain directions

so you apply an electric field in certain direction

so the elect this electric field will exert forces on all the electrons and if possible if it is possible for the electrons to take up that energy and go somewhere else they will respond otherwise they will not

so if the electrons are there and this is this electric field is there that the movement of electron will be according to that electric field opposite to the direction of electric field

so on the top on top of that random motion ah systematic drift velocity will be induced what happens to the holes the valance electrons will also feel the pinch of this electric field but in the neighborhood if there are no vacant states they will just stay there they will not respond to the electric field but if in the vicinity there is some broken bond and the electric field is there to push the electron in proper direction in that direction of the hole remember the force is opposite because of negative charge

so if the electric field is there to push the electron in a certain direction and in that direction only in the neighborhood some broken bond is there this valence electron will be prompted to go there and fill that

so because of the electric field the holes will also move in in the preferred directions and the electrons will also conduction electrons will also move in the proper preferred directions because of this field and therefore you have a conduction you have a current because of the electrons and also because of the holes

so the total current in that material will be because of these conduction electrons and because of these holes of course the two are not equal you do not think that number one the number of electrons can be very large as compared to number of holes or number of holes can be very large as compared to number of conduction electrons and therefore these two need not be equal and not only that the mobility if an electric field is applied how much current it will generate

so that is also different for electrons and for holes and therefore the two need not be equal in any case even in for even for intrinsic semiconductors nevertheless you have conduction because of the holes that means you have conduction because of the bonded electrons it is a new feature in metals that does not happen if you have free electrons if you have conduction electrons fine ah the metals in metals you have those and therefore conduction in semiconductors you have conduction because of these conduction electrons and also because of the valence electrons which are bonded they are only changing atoms from this bond to the neighboring broken bond and

so on

so both of these contribute to the conduction in semiconductors

so let me summarize what we did in this lecture essentially we try to connect the diagrams that i make conduction band and valence band these diagrams we make and what do these diagrams mean in terms of the actual crystal that was the first part and we said that in semiconductors here atoms and these atoms are bonded the outer electrons of the atoms take part in this covalent bonding and then all these electrons which are used in these bondings these electrons will have energies which will be in this valence band these quantum states here correspond to the bonding electrons whereas if some bond is broken and the electron goes somewhere else in the crystal which is weakly bound to some atom that electron will have energy which will be in the conduction band then we talked of how electrons jump from valence band to the conduction band

so if you have a electron which is sitting here in this valence band and then we say that it goes to the conduction band what do we mean by that

so the meaning of that is some bond is broken some bond two electrons are here in this bond

so this is broken and one electron gets freed from this bond and then it can go somewhere else weakly bound can change atom from one atom to other atom and therefore can move in the entire crystal and then we say that the electron has gone from this bonding to this free state not free state but nearly free state and here we say that a hole is created when this electron goes from here to here we say that a hole is created this particular quantum state which contained electron is now vacant okay then we talked about intrinsic semiconductor when you have not doped anything that is known as intrinsic semiconductor and in that case n e and n h what is this this is number density of conduction electron and this is number density of those vacant states or holes all per centimeter cube or per meter cube whatever you take and then you have n e equal to n h which we write in i now the most important part you can do doping most important part because this is the doping which gives us control on conductivity

so you can dope certain elements which can create more holes than electrons or which can create more electrons than holes

so if you dope pentavalent impurities like arsenic or phosphorus in silicon then you get what we call n e is much much greater than n h okay then we this very important part to understand about this doping that you do not have charge density right when you put this a pentavalent impurity and you have you have many more electrons than holes do not think that the material gets negatively charged these type of semiconductors are called n type semiconductor and y n type n type because of this n stands for negative and what is negative the charge carrier the majority charge carrier that is negative that is negative these are electrons and that is why it is called n type semiconductor but the charge density is still zero you have charged carriers but not charge densities because you only dope neutral atoms you only dope neutral atom what happens if i apply an electric field if i have the semiconductor electrons are there holes are there right one may be larger one may be smaller or they may be equal if i connect it to a battery if i apply an electric field what happens this electric field as usual tries to drive electrons in one direction and holds in another direction

so because of both you have current

so the current is because of the electron movement and because of the whole movement

so this is what we did in this lecture and from here we will take about devices the p n junctions and other things in the next lecture you