Semiconductor Devices and Circuits
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Lecture – 11
Carrier Concentration

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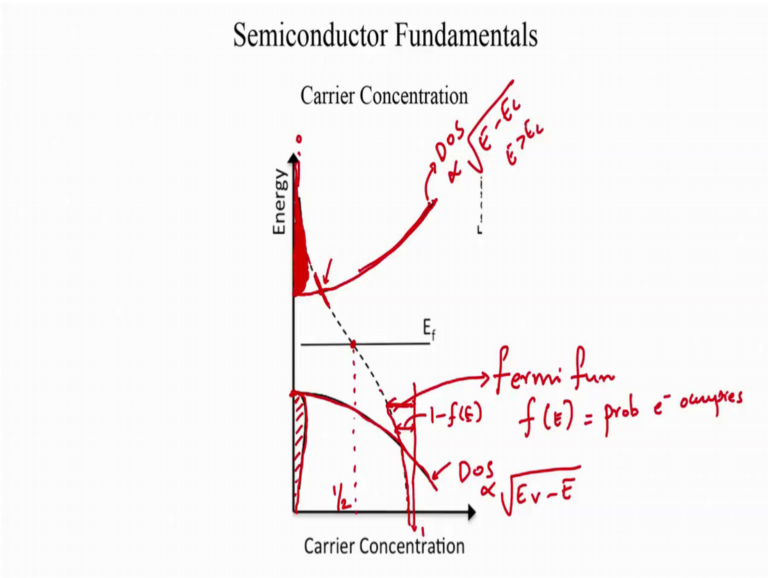

So, now, let us sort of visualize this ok. So, let us say this is my fermi level Ef and this dotted line that you see ok, so, this dotted line is your fermi function. So, this is my fermi function that is f of E.

Now, at E equal to Ef, it takes a value of half and below this it starts to approach the value of 1 and above that it starts to approach the value of 0. So, that is your fermi function. So, that is the probability that an electron occupies the energy level. This line here, this solid line here, which I mark in red, is the density of states. So, that is the density of states in the conduction band, which varies as the square root of E minus Ec and this is the density of states in the valence band, which varies as the square root of E v minus E ok.

So, these are the number of states available and that is the probability that these states are occupied and the product of these two essentially gives you the electron count in the conduction band and the whole count in the valence band. So, the product is given by this region, which I am shading here. So, you see that the density of states is large and right at this point the density of states is 0, the fermi level, the fermi f of E is not 0, but at 0 times some non zero value, which is essentially 0. So, you have 0 electrons here, but as we just, as we just move away from this point as E goes greater than Ec square root of E minus Ec is no longer 0.

So, you do have some density of state and you have the maximum possible fermi level, fermi f of E value the maximum possible value of f of E, sorry not the fermi level, the maximum possible value of f of E and therefore, the product begins to take a significantly large number and therefore, you will find that the electron count increases, but then as you move further up the density of states goes up, but the probability of occupancy comes down and therefore, the electron count starts to fall off.

So, you find that the electron distribution and energy above the conduction band edge looks like what is shown in this shaded region here. Similarly, if you look at the whole population or the whole count in the valence band edge, you have the same story here. You have the density of states being 0 and 1 minus f of E, which is basically, this gap being non zero ok. So, we are interested in this number.

Now and therefore, the number of holes right at this edge is 0, but then as we start heading lower below Ev; Ev minus E increases, but at the same time the fermi level starts approaching 1, which means this value, which is basically 1 minus f of E begins to decrease and you find that the probability keeps getting down, which, which allows the number of holes or the whole distribution in energy to take a shape as shown in this shaded region here ok. So, that is a graphical visualization of how the electrons and holes are distributed in energy all right.

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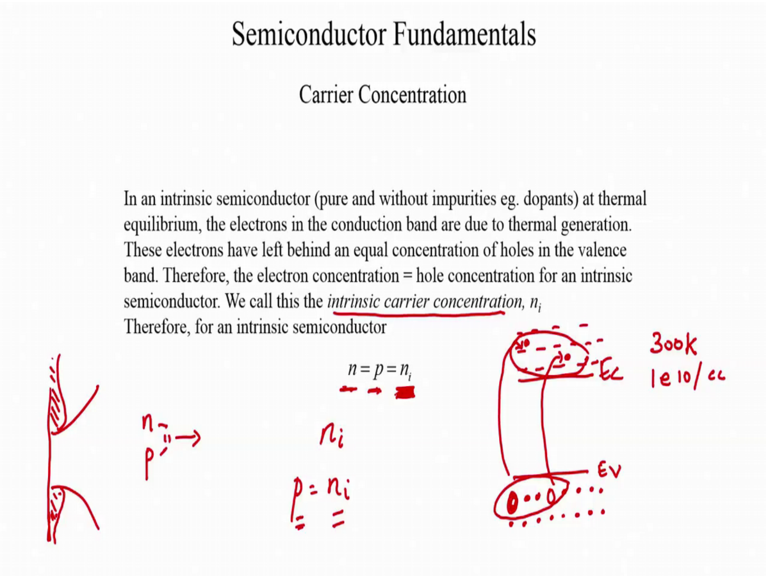

So, now, let us start making some definitions. Now, let us say I have a pure semiconductor and what I mean by pure is it is not, there are no impurities present inside the semiconductor and I am bringing this concept up in the context or something which I am going to talk about very soon, which is something called as doping. So, in a pure semiconductor, you have your valence band, you have your conduction band and you initially had a T equal to 0, you had all the electrons being bound by all the atoms of the semiconductor lattice.

I know you had all the valence electrons all located in the valence band, the conduction band was largely, it was completely empty at T equal to 0. Now, as we started increasing the temperature ok, the electrons gained some thermal energy and some of these electrons were promoted to the conduction band. So, you started having holes or vacancies being left behind in the valence band and electrons being promoted to the conduction band. So, this was as we started increasing temperature.

Now, in the case of intrinsic silicon at 300 Kelvin, you will find a count, if you look at the number of electrons per unit volume, sitting in the conduction band, it would be about say 1 e 10 per cc all right. So, so this is what happens as you start increasing temperature, which means that the number of electrons present in the conduction band, must be equal to the number of holes present in the valence band, because it is these, these holes are the consequence of the electron getting promoted to the conduction band.

So, if you were to measure, if you were to take it carry count of the number of electrons in the conduction band and the number of holes in the, in the valence band. These two are equal ok, one is led to the other and that concentration has got a special term for an intrinsic or a pure semiconductor and that is something called as the intrinsic carrier concentration and we will always denote it by the symbol ni ok.

So, both when I say the number of holes is equal to ni. It means that the holes have the hole concentration has matched their intrinsic carrier concentration, which is semiconductors like as though it would have been in a pure state and all this is a conditions, which is known as thermal equilibrium which is I have not thrown light on the semiconductor. You have not applied any voltage, you just have the semiconductor sitting in dark sitting at a temperature at some temperature T and as a consequence of the temperature you applied.

You have a certain statistical count or you have a certain population of free electrons and holes and that population is called as the intrinsic carrier concentration, which is ni ok. Now, if you go back to what we looked at what it implies is that, if you have a density of states and you have a certain f of E the product of your density of states and f of E integrated over your band edges that is this count matches the number of electrons. So, the whole count matches the electron count and we, we always talk in terms of concentration.

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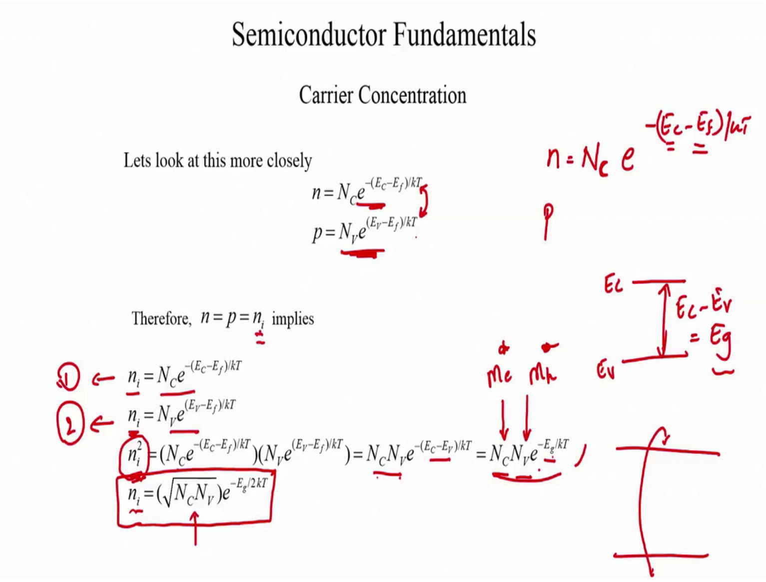

So, n is the number of electrons per unit volume p is the number of holes per unit volume ni is the intrinsic carrier concentration per unit volume ok. So, now we can sort of bring in some of the concepts we learned earlier. So, we earlier found that n is equal to the effective density of states in the conduction band into e to the power minus Ec minus Ef by k T where Ef is the fermi level right and Ec is the conduction band edge

Similarly, p was equal to and v into e to the power e v minus Ef by k T where nv is the effective density of states in the valence band. Now, in an intrinsic semiconductor n is equal to p is equal to ni ok. So, which is the intrinsic carrier concentration, this means that I should be able to equate these two terms ok. So, what happens? So, n is equal to ni ok. So, ni is essentially that term that p is also equal to ni.

So, p is equal to. So, ni is also equal to that term there and if I take a product of these two equations. Let us say this is equation 1 and this is equation 2 and if I multiply these two equations, I get ni square on the left side and I get Nc Nv into e to the power E c minus E v minus of Ec minus E v. So, because you have the Ef term will cancel off and you have Nc Nv e to the power minus Ec minus Eb by k T. So, that is Ec that is E V and this is Ec minus E V which is nothing, but your energy gap.

Therefore, ni square turns out to be Nc into Nv into e to the power minus Eg by k T. Now, what is Nc? Nc is a constant right, it only depends upon some universal constants and the effective mass of the electron and v is also a constant, it depends upon several universal constants and the effective mass of the whole, Eg is again at a given temperature, eg is a fixed parameter right. You have the energy gap.

So, which means to say that, this ni square seems to be very much a constant as long as you do not vary Nc Nv and Eg, you cannot vary ni square and this is a very powerful relation, because it tells you a method to count at a given temperature, if I want to know what is the intrinsic carrier concentration, it is essentially the square root of N c N v into e to the power minus Eg by 2 k T.

So, as the energy gap increases the ni decreases and that is very intuitive, because as the energy gap decreases, I need a higher temperature for me to promote my electron from the valence band to the conduction band and therefore, my intrinsic carrier concentration decreases. So, this is a very powerful relation. It is a very helpful, a very useful relation.

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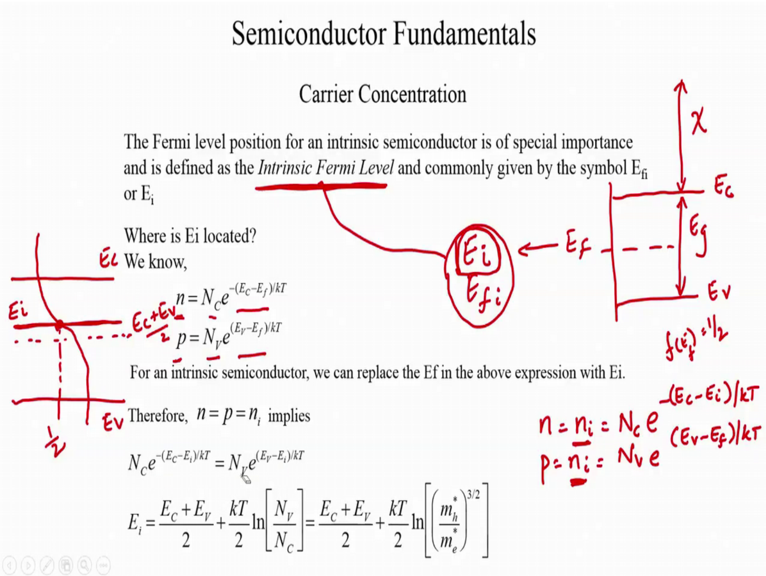

So, let us play around with this a little bit more v. So, now, let us say we have our intrinsic semiconductor. Now, when we discuss the fermi level, we really did not locate it ok, we just sort of vaguely, drew it somewhere, between Ec and E v, we did not really locate it accurately. So, what is the accurate location of the fermi level? So, we know Ec, we know Ev, because in a semiconductor Ec is defined by the electron affinity ok.

So, there is a certain electron affinity and that defines, my Ec and then I have my energy gap and therefore, I know Ev with regards to Ec ok, but where is this fermi level located, because the fermi level location is important, because that is where f of E is going to take a value of half f of E is equal to Ef is equal to half.

So, what is the location of the fermi level? So, once again let us get back to these equations, we know that n that is the number of electrons in the conduction band is Nc e to the power minus Ec minus Ef by k T p is Nv e to the power Ev minus ef by k T and for an intrinsic semiconductor what we do is we took that fermi level a special name ok.

So, we want to know where is the Ef for this intrinsic semiconductor we give it a special name and we call it the intrinsic fermi level ok. So, E i or sometimes you know its Ef i is also used this Ei or Efi is something called as the intrinsic fermi level and we are trying to identify, it is location, which is basically, the fermi level location in a pure semiconductor. So, for a pure for an intrinsic semiconductor I can replace this Ef by E i.

So, Ef we will keep it as a more general fermi level, variable and E i, we will use it especially only to indicate the fermi level of intrinsic semiconductors. So, then in that case your n for a pure semiconductor, you will find n is equal to n i, which is Nc e to the power minus Ec minus E i by k T ok. I am just replacing the variable Ef with the variable E i, because E i has got a special status, it is the fermi level, location for a pure semiconductor and p is also equal to n i, which is Nv e to the power E v minus Ef by k T.

So, that is your p and since both these have the same value, there or both equal to ni, you can equate the number of electrons with the number of holes with that being the intrinsic fermi level and just by, by solving this equation, you will find that E i is equal to Ec plus Eb by 2 plus k T by 2 ln of Nv by Nc. So, what is Ec plus Ev by 2, it is the location exactly at the mid gap ok.

So, that is my energy gap, if I were to take a location here, it is Ec plus E v by 2 and what this is saying is that you reach mid gap and you offset it by this quantity that is kT by 2 ln of Nv by Nc, if you were to offset yourself from the mid gap by this amount of energy, you will find the location of the intrinsic fermi level. So, to draw this more cleanly, the intrinsic fermi level is not generally located right at mid gap, it is slightly offset from mid gap.

So, let us say this is E c that is E v, let us say that is perfect mid gap Ec plus E v by 2. Now, if this quantity Nv by Nc is a positive, is, is a say Nv is greater than Nc. So, which means that this quantity is a positive number then my Ei e location, my fermi level is actually located there. So, that is my intrinsic fermi level position, which means that my f of E ok.

The probability of occupancy will take a value of half at that location and that energy. So, what; so, when does this term become equal to 0, because if this term had to become equal to 0, then is then the fermi level, the intrinsic fermi level is located exactly at mid gap. This term will become 0, if N v is equal to Nc, because then you have the logarithm of 1, which is 0.

So, when does Nv become equal to Nc, if you look at the expressions for Nv and Nc, you will find that you have most of the terms to be constant or most of the terms of universal constants, except for the effective mass of the holes and the effective mass of the electrons. So, if the effective mass of the holes matches the effective mass of electrons then you will find that the intrinsic fermi level lies exactly at mid gap.

Otherwise, it is going to be offset by this number and in fact, you could take this 3 by 2 and probably locate it outside the logarithm. So, you can call that 3 by 4 ok. So, that is your expression for the location of the intrinsic fermi level ok.

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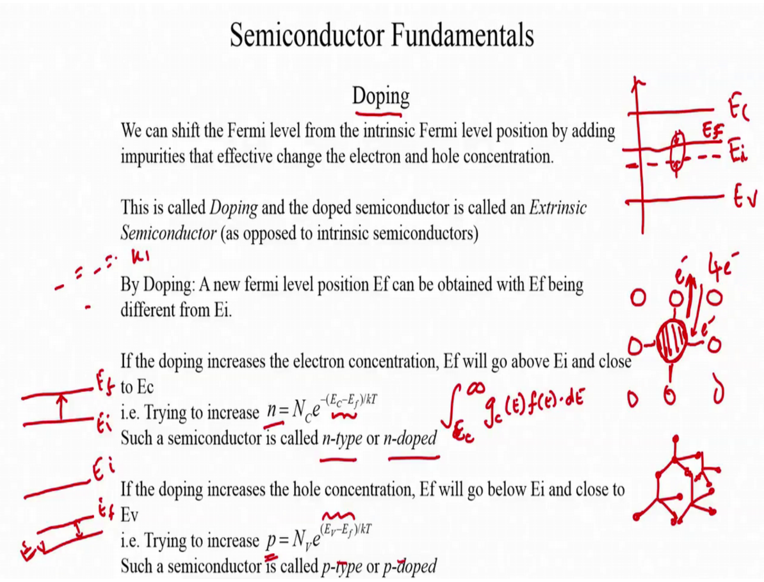

So, now, we are going to approach a different topic and we are going to call this as something called as doping and I will explain what doping means.

Now, we know the location of the intrinsic fermi levels. So, you know this is Ev, you know that is Ec and I know my intrinsic fermi level location that is E i, that is the fermi level in a pure semiconductor. Now, I could. So, the pure semiconductor implies I have my silicon lattice right it is a yeah. So, if you are going to talk about silicon, you have your silicon lattice, which each silicon atom being bonded to four other silicon atoms ok.

If you were to look at it, in the tetrahedral lattice formation it is essentially this, it is got four neighbours and these have got four neighbours and so on, the lattice continues that way. So, if I were to now, create a defect, I get rid of the silicon atom and I bring in some other species. The silicon has got four electrons in the valence shell; I can bring in some other species that sort of forces itself to bind and accommodate itself into this lattice but in order to do.

So, it could change the electron or hole population it could either give away an electron or take away an electron. So, let us say you are going to add an impurity into the lattice, you are purposefully adding a measured impurity concentration into the lattice and if this is all done at a suitably high temperature, which means if it is, if the temperature is not 0 kelvin. These impurities could get ionized and they could contribute or change the electron and hole population in the semiconductor.

So, if the electron and hole population changes the fermi level location in this doped or impure semiconductor will shift away from Ei ok. So, this is E i it is got a special relevance ok. So, it is an imaginary fermi level to remember, because that is what your pure semiconductor look like. We will draw it with a dotted line. Now, if you take another, if you take the same semiconductor and you dope it, you are going to create impurities and you could the fermi level, could take up a new position and we will now, call it Ef ok.

It is no longer Ei and E i is just this dotted imaginary line, which is no longer valid for this new semiconductor, but it gives you a reference as to how much of impurity you have added to the semiconductor. So, you could actually artificially move the fermi level location about by adding impurities, in the semiconductor and this concept of adding impurities to the semiconductor, in order to relocate the fermi level is called as doping.

Now, why will the fermi level relocate? Firstly, because your n is equal to Nc e to the power minus a in, in, let us say in an intrinsic semiconductor, in a pure semiconductor. It was Ec minus E i by k T. So, that was your n which is equal to ni. Now, I have changed n, now, I made n to be different from n i ok. So, let us say I made n to be greater than ni. I cannot have this exponent, have the same value here.

So, now my Ef, it will have a different value for Ef, which is going to be smaller as compared to Ec minus Ef. So, in general, so, we will get back to the general expression, which we derived, which we looked at earlier by you know sort of integrating the from 0 to from our Ec to infinite when we integrated the density of states into f of E into DE we obtained this expression and this expression had the fermi level term in it.

And for an intrinsic case, this fermi level was the special intrinsic fermi level, but in general we will retain this symbol Ef and increasing n will relocate Ef in order to decrease, this term decreasing n will relocate Ef to increase this term, because it is E to the power minus a larger number to in order to reduce n. So, if a semiconductor is doped. So, as to increase the electron count, you will find that this term has to decrease or the fermi level will move above will move away and above, the intrinsic fermi level and this semiconductor is called as an n type or an n doped semiconductor.

The doping or the impurity was added to increase the electron count. On the other hand if the doping or a dopant is added to increase the whole population then it is called a p type or a p doped semiconductor.

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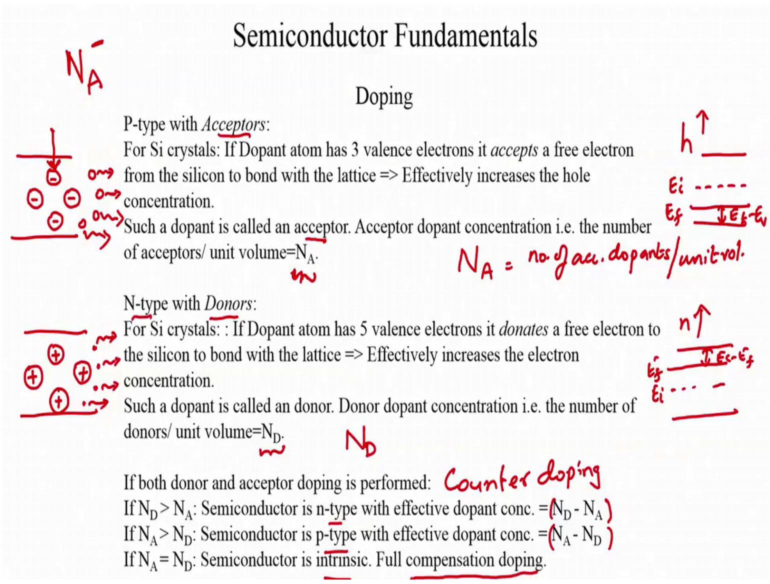

Sorry, if the dopant is added to increase the whole population. It is called a P type or a P doped semiconductor, where your Eb minus Ef. So, this term has to increase or decrease in order to accommodate that.

So, you will find that if you are trying to increase the whole population Ef will have to move below E i in order to, in order to, get closer to the valence band edge. So, that is E v ok. So, now, how do we; so, let us just talk about more technical terms. So, you have two kinds of doping ok. So, you have p type doping, where you are trying to increase the whole population and relocate the fermi level. So, this is the intrinsic fermi level, you are going to relocate the fermi level to some location here.

So, that to; so, as to bring down, this value of Ef minus Ev and this kind of doping was called as p doping and it is done with something called as acceptors. So, what the concept here is that you have your silicon lattice. So, let us say, we will just draw these 5 atoms and initially each silicon atom was bonded to 4 other silicon atoms.

So, it had a valence it had 4 valence electrons and now, if I were to remove the silicon atom and bring in an impurity, which has got only three electrons ok. It is this impurity has got three electrons and it is going to participate in bonding. So, it is going to bond with 3 of the silicon atoms, but in order to bond with the fourth. It is going to take away an electron a free electron, from the lattice and it is going to bond with the 4 silicon atom.

So, it is going to complete, it is bonding by taking electrons away from the existing electron population and it is going to essentially leave behind a hole. So, therefore, in some sense, it is improved the hole to electron ratio. It has increased the hole count with respect to the electrons and therefore, this dopant, which accepted the electron is called as an acceptor like dopant and this kind of dopant is called a p type doping.

Now, you can depending on the concentration of dopants. I have added, I can change the hole and electron population of accordingly, and therefore, it is useful to define a concentration for your acceptor ions and we typically denoted by the symbol NA. So, capital NA is the number of acceptor dopants added to the intrinsic semiconductor per unit volume. So, it is, it is always per unit volume ok. Now, similarly we can add something called as donor dopants in order to create a n type semiconductor, which is you have a silicon lattice, where the silicon atoms are all bonded to 4 other silicon atoms.

And now, I am going to bring in another species or different an impurity, which has got 5 electrons in the valence shell. So, we are going to bring in an impurity, which is got 5 electrons, which means it is going to use up 4 electrons to bond itself, to accommodate itself into the lattice, but it is got this fifth electron that is free and if it is ionized, this fifth electron is free to move about in the lattice.

So, this is essentially increased the electron population. So, this kind of doping, which increases the electron population is called an n type doping and it is done with donor dopants, because this dopant donated an electron as opposed to accepting an electron, it is called as a donor dopants and what this does is, it essentially moves the fermi level above Ei in order to decrease the Ec minus Ef gap and increase the electron concentration.

And once again, it is useful to define a concentration for the donors and we do it with the symbol N D, which is the number of donor dopants per unit volume ok. So, what does doping actually mean. So, it means that you have added and ion ok. So, if this dopant is ionized, what you have essentially done is you took a neutral species as a neutral.

Let us say you are trying to do n type doping, you have taken a neutral species, which is an atom, which had 5 electrons in the valence shell and several other electrons in the inner shells and it had some positive charge in the nuclei and you implanted it as a defect inside your silicon lattice and since one of the electrons could not be used for bonding. So, these four were used for bonding.

But this electron could not be used and at a significantly high temperature, this electron got away and became a free electron in the silicon lattice. This is free, which means that this species now is essentially positively charged, because the charge in the nucleus is knob not balanced by the electron charge cloud. So, it is fixed, because it is now, bonded itself to the silicon lattice, it is not a moving charge. This positive charge is now fixed.

But it; so, it is a fixed ion, which has got positive charge and it is left behind, free moving electron, it has got a negative charged, negative charge. So, essentially by doping the silicon atom n type, we have maintained charge neutrality, for the entire system, which is the silicon is charged neutral, the dopant plus this, this ionized dopant plus this extra electron balances itself out in terms of charge and the entire species charge neutral. It is not only a charge to the silicon atom ok, it is charge neutral.

All we have done is added an entity, which was charged neutral and ionized it, which means we have pulled an electron away and left behind a fixed in mobile positive charge. So, that is what has happened, when we doped it n time. Similarly, when we doped it p type, we have not changed the charge, we have not disturbed the charge neutrality of the silicon.

So, we took her neutral species which had three electrons and an equivalent balancing negative or positive charge inside positive charge is the nucleus and we added this into the silicon lattice and this species now gained an electron, it accepted an electron in order to bond with the silicon lattice and by accepting electron, it became an effectively negatively charged ion, because now the positive charge in the nucleus does not balance the excess negative charge on the shell.

So, it became a negatively charged ion which is an immobile ion, but it left behind a positively charged mobile species called the hole ok. So, the hole is free to move about in the silicon lattice and you have an ionized species here which is got a negative charge and is fixed. So, essentially what you are doing, my doping is for p type doping we are creating fixed negative charges immobile negative ions in the silicon lattice.

And mobile holes added to the silicon lattice these are mobile and in the case of n type doping we are creating fixed immobile positive charges and mobile electrons for the silicon lattice. So, essentially the entire system is charge neutral. Now if all the dopants were all ionized, if everything that we added were all ionized what is the concentration of this fixed negative charge, these negative ions in the case of p type doping.

It is an NA, because we added any acceptor like dopants per unit volume all these NA dopants were ionized and all of them gained a negative charge. So, you have NA fixed negative charges per unit volume sitting in your p doped silicon. On the other hand, your donors we added ND donors per unit volume. All of them got ionized and they all became positive ionized species and we have ND positively charged immobile species located per unit volume in the silicon.

So, that is the situation when we dope it and clearly, we are affecting the electron and hole concentration, which means we are affecting the fermi level location. Now it is possible to counter dope a silicon so you add not only NA or ND we add both positive and negative or we add both acceptor and donor dopants. So, this is something called as counter doping now if we add both ND and NA, but your ND turns out to be greater than NA, then it is equivalent to you doping the semiconductor n type with an effective dopant concentration of ND minus NA, it is like as though we have added this many donor atoms

On the other hand, if NA is greater than ND the semiconductor will behave like a p type with an effective dopant concentration of NA minus ND. Now it is possible to balance NA and ND and make the semiconductor pure, like as though it is intrinsic, and this is something called as complete compensation. So, we have completely compensated any dopant with the counter. So, these things are quite useful, and it would become clearer when we do a problem session that we will solve some problems, you know just to calculate and get comfortable with the calculations.