Semiconductor Device Modelling and Simulation

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Lecture - 15
Semiconductor Statics (Contd.,)

Hello, welcome to lecture number 15 we have already discussed about the density of states and the probability of filling those states using Fermi Dirac distribution function.

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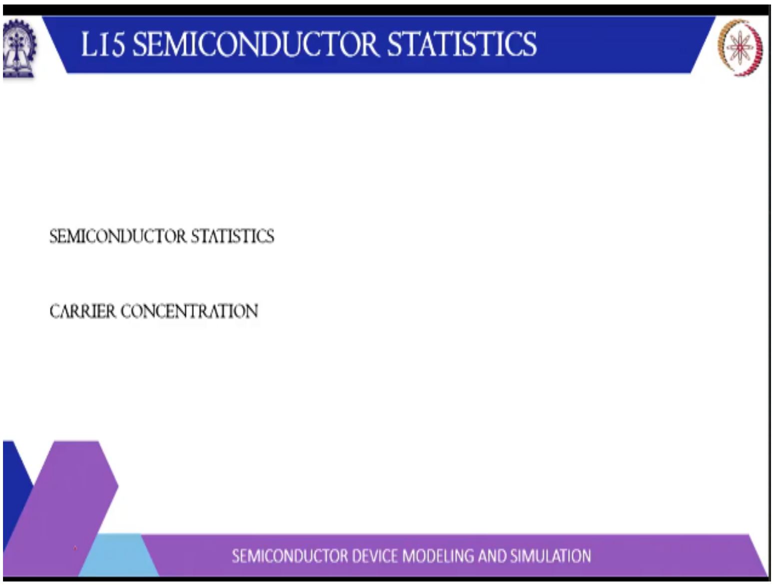

L15 SEMICONDUCTOR STATISTICS

SEMICONDUCTOR STATISTICS

CARRIER CONCENTRATION

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

Now, today, we will learn how to calculate the carrier concentration, if we know these 2 concepts.

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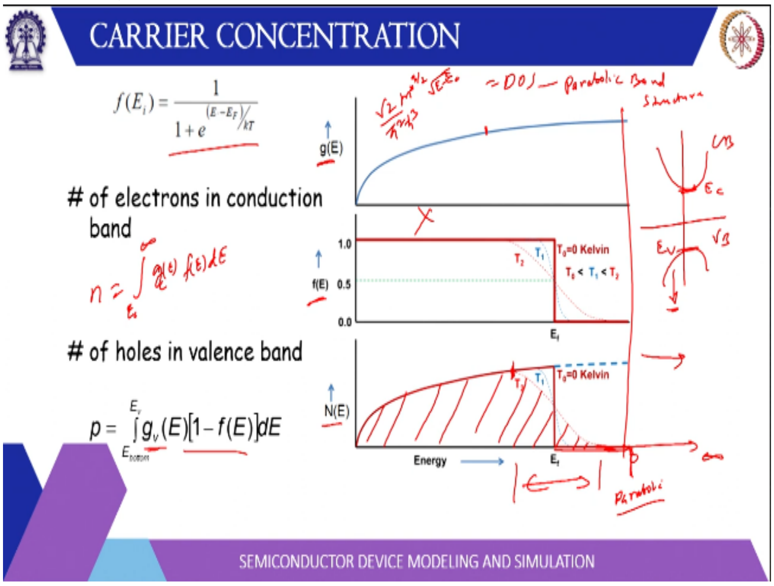

CARRIER CONCENTRATION

$$f(E_i) = \frac{1}{1+e^{(E-E_F)/kT}}$$

\# of electrons in conduction band

$$n = \int_{E_c}^{\infty} g(E)\, f(E)\, dE$$

\# of holes in valence band

$$p = \int_{E_{bottom}}^{E_v} g_v(E)[1-f(E)]dE$$

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

Let us plot the density of a state so for 3d you know the density of a state is the root 2 by pi square h bar cube m effective to the power 3 by 2 the square root of E – E C. So, this is the curve for density of states this is DOS then second curve is the Fermi Dirac distribution function which is given by 1 over 1 + exponential E – E F by kT. And this solid red curve is for 0 Kelvin. So, where f is strictly 1 for energy less than E F and it is a strictly 0 for energy more than E F. And if you increase the temperature, this transition becomes more sloppy.

And when you multiply these 2 functions g times f, so up to a certain point, it follows a same function as g and then of course, it gets multiplied by a factor which is less than 1. So, it goes to basically 0 at certain energy level. And so this is a density of state multiply the probability. So, this tells you the density of electrons basically and if you integrate it over energy this is 42 you will get the number of electrons. So, integral of this will be number of electrons so n will be integral.

If you recall the band structure, this is let us say conduction band, this is let us say valence band this energy level is E C. This energy level is E V. So, for conduction band, we have to integrate from E C onwards. So, this is integral from E C to infinity, then g for the conduction band as a function of energy that is g E times fE, dE. So, that will tell you the electron concertation for the whole concertation it is g for holes that is g V that is basically same only difference this mass is replaced by the hole effective mass times.

In valence band we have to find the absence of electron, so, probability of not finding electron which is 1 - f times dE and limit service from E V to minus infinity. So, whatever is the bottom 2 E V. Now, here somebody may ask in reality the band structures are not parabolic, but this expression for DOS assumed a parabolic band structure so, how can we use this expression?

The reason is if you look at the product of g and f it is start to reduce from certain near E F and it goes to certain to 0 after certain energy above V F that means this is in the vicinity of E F only. So, that means, you do not have to go to infinity energy, but certain energy after E F the probability will go to 0 basically. So, that means if up to this point, if the band is parabolic then you do not have to worry about beyond this point whether the band is parabolic or not. So, therefore we can use it for most of the semiconductors and in most of the situations.

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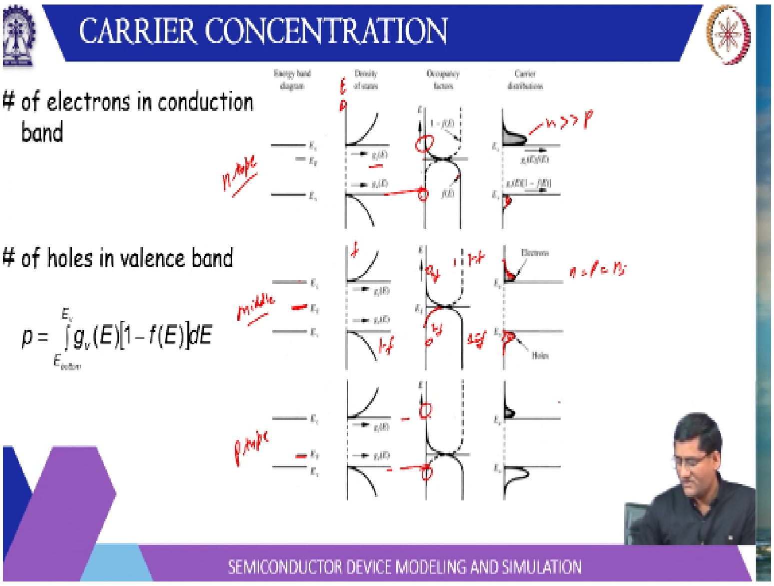

CARRIER CONCENTRATION

# of electrons in conduction band

# of holes in valence band

$$p = \int_{E_{bottom}}^{E_v} g_v(E)[1-f(E)]dE$$

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

So, here we can see 4 different bands and for different scenario let us see Fermi level is in the middle of the valence band and the conduction band so middle one, we are Fermi level is in the middle so that is the probability f is 1 below this and 0 f here. So, this is f 1 – f will opposite so, 1 - f will be 1 here and 0 f. So, you have to multiply by f for conduction band so, they said 2 multiplied by the f for the valence when it has to be multiplied by 1 - f. So, this is 1 - f and this is f.

So, when you multiply by f, it goes to a small number it reduces, so, what happens, it peaks somewhere and then it decreases. So, look for a valence band 1 - f is decreases like this. So, this peaks here and then decreases. So, the area under this curve will tell you the number of electrons and holes. The Fermi level is roughly in the middle of intrinsic semiconductor and these areas are roughly equal and for intrinsic semiconductor number of electrons f equal to number of electrons we call it n i intrinsic carrier concentration.

This is how it will basically look in case of n type the Fermi level is close to the conduction band. So, if you look at the Fermi distribution function it will have larger magnitude here and if you look at 1 - f it will have a smaller magnitude here because you see the distance from the Fermi level. So, this electron concentration will be more in fact much larger than the hole concentration and that you can see pictorially you can in fact plot these curves in MATLAB.

So, this is your y axis which is energy then this is the x axis where you have the g and f which you can easily plot and multiply and see these curves. So, looking for p type semiconductor, the Fermi level is close to the valence band. So, your 1 - f will be large compared to f which will be quite small. So, now, here n is this area is much smaller than the hole concentration.

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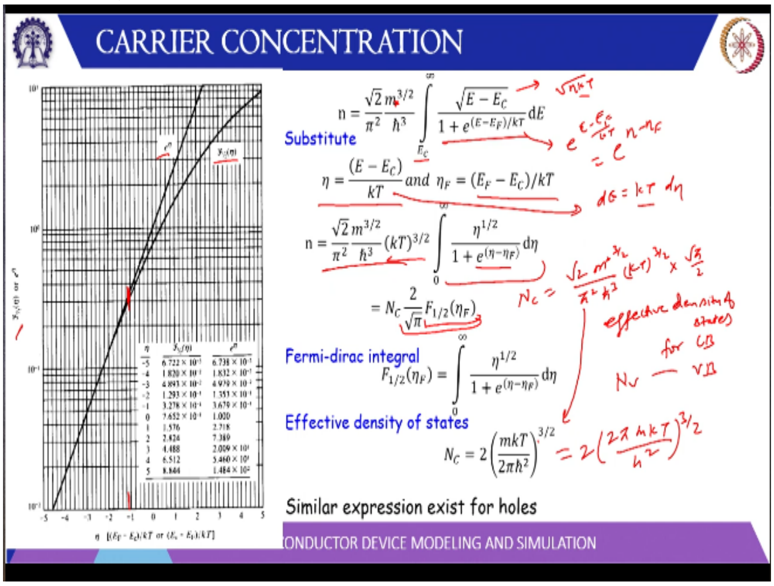

CARRIER CONCENTRATION

$$n = \frac{\sqrt{2}\, m^{3/2}}{\pi^2\, \hbar^3} \int_{E_C}^{\infty} \frac{\sqrt{E - E_C}}{1 + e^{(E-E_F)/kT}}\, dE$$

Substitute

$$\eta = \frac{(E - E_C)}{kT} \text{ and } \eta_F = (E_F - E_C)/kT$$

$$n = \frac{\sqrt{2}\, m^{3/2}}{\pi^2\, \hbar^3} (kT)^{3/2} \int_0^{\infty} \frac{\eta^{1/2}}{1 + e^{(\eta-\eta_F)}}\, d\eta$$

$$= N_C \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_F)$$

Fermi-dirac integral

$$F_{1/2}(\eta_F) = \int_0^{\infty} \frac{\eta^{1/2}}{1 + e^{(\eta-\eta_F)}}\, d\eta$$

Effective density of states

$$N_C = 2\left(\frac{mkT}{2\pi\hbar^2}\right)^{3/2} = 2\left(\frac{2\pi mkT}{h^2}\right)^{3/2}$$

Similar expression exist for holes

η	$\mathcal{F}_{1/2}(\eta)$	e^{η}
-5	6.722 × 10⁻³	6.738 × 10⁻³
-4	1.820 × 10⁻²	1.832 × 10⁻²
-3	4.893 × 10⁻²	4.979 × 10⁻²
-2	1.293 × 10⁻¹	1.353 × 10⁻¹
-1	3.278 × 10⁻¹	3.679 × 10⁻¹
0	7.652 × 10⁻¹	1.000
1	1.576	2.718
2	2.824	7.389
3	4.488	2.009 × 10¹
4	6.512	5.460 × 10¹
5	8.844	1.484 × 10²

We can use the expression for density of a state which is root 2 m to the power 3 by 2 this is effective mass m star times root E – E C dE square h bar cube this is multiplied by the Fermi Dirac distribution function. So, let us do this for electron. So, the integral has to be from E C to infinity. Now, here to make it look simple, we can make 1 substitution we can substitute eta = E – E C by kT and eta F = E F – E C by kT. So, this exponential E - E F by kT can be written as e to the power eta - eta F.

So, easy will cancel out it will be E – E F by kT. So, this is exponential e to the power eta – eta F and of course, numerator is square root of eta. And from this you can also find out dE = kT times d eta. So, kT will come here and square root of E – E C will also be root of eta kT. So, these 2 kT will add up and become k 2 to the power 3 by 2. So, this is a factor times 1 integral. Now, because this integral comes out to around root pi by 2 times exponential for certain a special case, so, what we are doing? We are taking out these factors.

So, your N C will become basically this factor root 2 m star to the power 3 by 2 divided by pi square h bar cube here all the m are effective mass so, you go to replace m with m star times kT to the power 3 by 2 times now, we have taken this 2 by root pi factorial, so, square root pi by 2, so, that will be N C and N C is basically called effective density of states for conduction band similarly you can calculate N V that will be for the valence band.

And this integral F half is called Fermi Dirac integral that is square root of eta by 1 + exponential eta - eta times d eta and if you simplify this expression, you get 2 times mkT by 2 pi h bar square to the power 3 by 2, it is some tests that is also written as 2 times 2 pi mkT by x square to the power 3 by 2. So, both the expression are same because h bar is x by 2 pi. Similar expression and exist for the holes.

This picture is taken from a textbook SMG where this Fermi-Dirac integral is compared with e to the power eta and you can notice here for eta less than -1 this the value it roughly approximate e to the power eta I think there is a correction some of the factor of root pi by 2.

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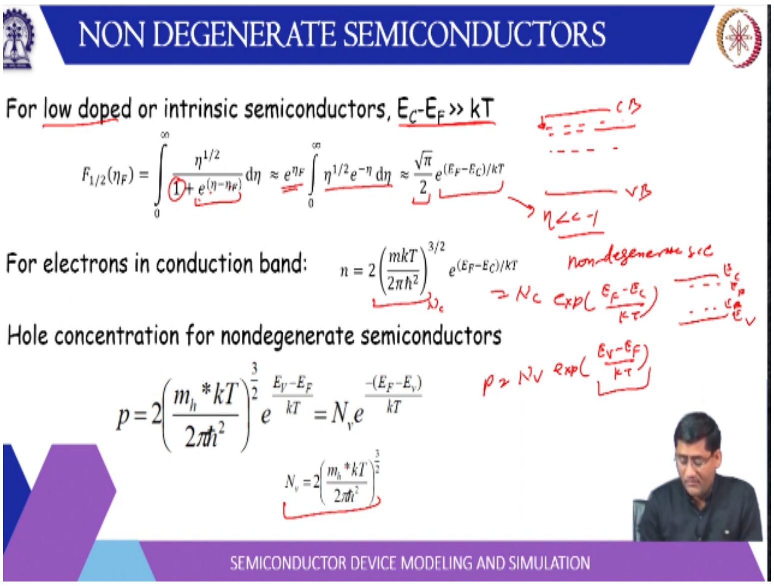

NON DEGENERATE SEMICONDUCTORS

For low doped or intrinsic semiconductors, $E_C - E_F \gg kT$

$$F_{1/2}(\eta_F) = \int_0^\infty \frac{\eta^{1/2}}{1 + e^{(\eta-\eta_F)}} d\eta \approx e^{\eta_F} \int_0^\infty \eta^{1/2} e^{-\eta} d\eta \approx \frac{\sqrt{\pi}}{2} e^{(E_F - E_C)/kT}$$

$\eta << -1$

For electrons in conduction band: $n = 2\underbrace{\left(\frac{mkT}{2\pi\hbar^2}\right)^{3/2}}_{N_c} e^{(E_F-E_C)/kT}$ $= N_c \exp\left(\frac{E_F - E_c}{kT}\right)$

non-degenerate s/c

Hole concentration for nondegenerate semiconductors

$$p = 2\left(\frac{m_h^* kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} e^{\frac{E_V - E_F}{kT}} = N_v e^{\frac{-(E_F - E_v)}{kT}}$$

$p = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$

$$N_v = 2\left(\frac{m_h^* kT}{2\pi\hbar^2}\right)^{\frac{3}{2}}$$

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

Now, when the doping is less that means Fermi level is well within the band gap. So, what is happening here, let us say this is your semiconductor. So, this is the conduction band is the valence band for NDSC Fermi level is here as you can see is a doping, n type doping, this Fermi level goes up as long as this doping is small, it is well within the band gap. So, if it is filling the band gap then you can compare it if is E F – E C. So E F is below E C. So this is a negative number. So, E C – E F is much larger than kT.

So that means E F – E C is much smaller than you know it is basically few typical guideline is less than 3 kT. So, this parameter integral simplifies to you can this is large number you can ignore one. So it because basically goes to the numerator, so e to the power - eta times e to the power eta F. So e to the power eta F you can take out and e to the power - eta square root of eta d eta that will come around to be root pi by 2 times e to the power eta F and eta F is E F – E C by kT.

The approximation of Fermi Dirac integral for E C – E F is more than kT that means it is less than few kT. So eta means it is much less than -1. So, this is 2 time eta F is much less than -1. So, in fact you can see F here when eta is less than 1 it is already quite good approximation. And then for low doped or intrinsic semiconductor also called non degenerate semiconductor where Fermi level is value below the conduction band at (()) (13:10).

Then of course, you can write the expression n is equal to this factor which is N C times exponential E F – E C by kT, now, this is basically Fermi Dirac integral root pi by 2. So, this is taken care of just by this multiplication 2 by 2 pi they will cancel out. So we can write easily that n = N C exponential E F – E C by kT. Similarly, we can get the expression for holes. So your p will be N V exponential E V – E F by kT.

Now you notice a sign here in case of electron it is E F – E C. So this is E C and E F is somewhere here. So this term is basically negative. Similar in case of valence band E V is here and E F is somewhere here. So it has to be E V – E F. So, this term is negative and false and N V is also as an expression 2 times m effective mass for the holes times kT by 2 pi h bar square to the power 3 by 2.

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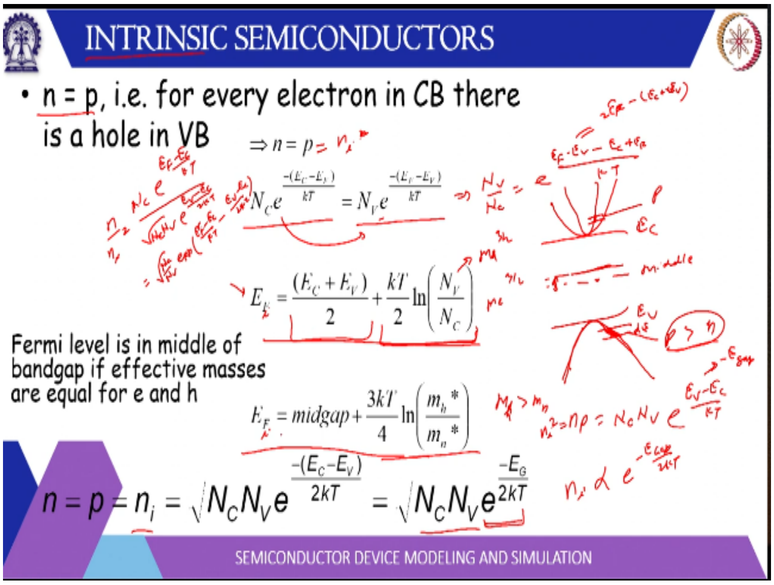

INTRINSIC SEMICONDUCTORS

- n = p, i.e. for every electron in CB there is a hole in VB

$$\Rightarrow n = p$$

$$N_C e^{\frac{-(E_C-E_F)}{kT}} = N_V e^{\frac{-(E_F-E_V)}{kT}}$$

$$E_F = \frac{(E_C+E_V)}{2} + \frac{kT}{2}\ln\left(\frac{N_V}{N_C}\right)$$

Fermi level is in middle of bandgap if effective masses are equal for e and h

$$E_F = midgap + \frac{3kT}{4}\ln\left(\frac{m_h^*}{m_n^*}\right)$$

$$n = p = n_i = \sqrt{N_C N_V}\, e^{\frac{-(E_C-E_V)}{2kT}} = \sqrt{N_C N_V}\, e^{\frac{-E_G}{2kT}}$$

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

For intrinsic semiconductor n = p this we call intrinsic semiconductor n i so we can add the expression is N C exponential E F – E C by kT which is equal to N V times exponential E F – E V by kT. And if you rearrange it, you take to one side. So this becomes N V by N C to here an exponential take the side so exponential E F - EV – E C + E F by kT. So, then if you take the log, so log of N C by N V this value 2 E F – E C + E V by kT. So, E F is basically kT log N V by N C + E C E V and divided by 2.

So, this is expression for the Fermi level, we call it intrinsic Fermi level. Now, you notice here E C + E V by 2, this is the conduction band or E C the valence band E V. So, E C + E V by 2 is basically just in the middle. But this intrinsic Fermi level is not exactly in the middle, it is slightly shifted, shifted how much amount kT by 2 log of N V by N C. So N V N C basically if you see here these are the number of states in the valence band.

Then this is the N C is the number of states in the conduction band and N C and N V they are proportional to m to the power 3 by 2. So, if you replace this m valence band that is m hole and this is m electron power 3 by 2, power 3 by 2. So, if you take 3 by 2 out, so it was 3 by 4 kT log of m hole by m electron. So, this is slightly shifted. Now you notice here if m h is more than m n that means hell hole is heavy compared to electron then the Fermi level will be slightly above this value.

And if electron mass is more, it will be slightly below you can understand like this. If let us say hole is heavy, then this will be more flat. So, the curvature will be less and if electron is light, then its curvature will be more now, you see here for a given energy this curvature and for the same dE this curvature which will have more number of states here it is more vertical. So, it will have less number of state and this is more slanted it will have more number of states. So for given dE hole has hole number of states.

So, if formula is just in the middle, then probability same here, let us say probabilities p here probabilities p here same probability, but number of a state is more. So hole will actually be more than the electron. So, this formula has to be slightly above so that the probability is reduced in proportion to the number of states in the valence band. So that is why for heavy holes and lighter electrons, the Fermi level is slightly shifted upwards there in the middle of the bandgap. So, this is the concept for intrinsic Fermi level and we call it EFI.

Now, you can also recall that we have discussed that n p = n i square that is a law of mass action. So, if you multiply these 2 expression n p what do you get? N C times N V exponential E F – E C + E V – E F. So what you get? E V – E C by kT and which is basically negative band gap and this product is n i square. So, n i square is N C and N V exponential E

V – E C which is minus of bandgap E Gap by kT. So, if you take the square root, so n i is equal to root N C and N V exponential – E G by 2 kT.

So, this we have discussed while discussing the bandgap that in case of semiconductor, the intrinsic carrier concentration is proportional to e to the power - E Gap by 2 kT. So, based on this discussion, we can use a better form of n i apart from this N C and N V because N C N V some value has to be given n i you can it is easily given for the given semiconductor and they are tabulated. So in terms of n i also you can write this expression for n and p.

So if you divide this n by n i what you will get? N C exponential E F – E C by kT divided by the square root of N C and N V exponential E V – E C by 2 kT for this way n by n i and then if you rearrange you will get some expression root of N C by N V exponential E F – E C by kT – E V – E C by 2 kT and you can again substitute with this expression for E F from here this expression exponential E F will be this thing.

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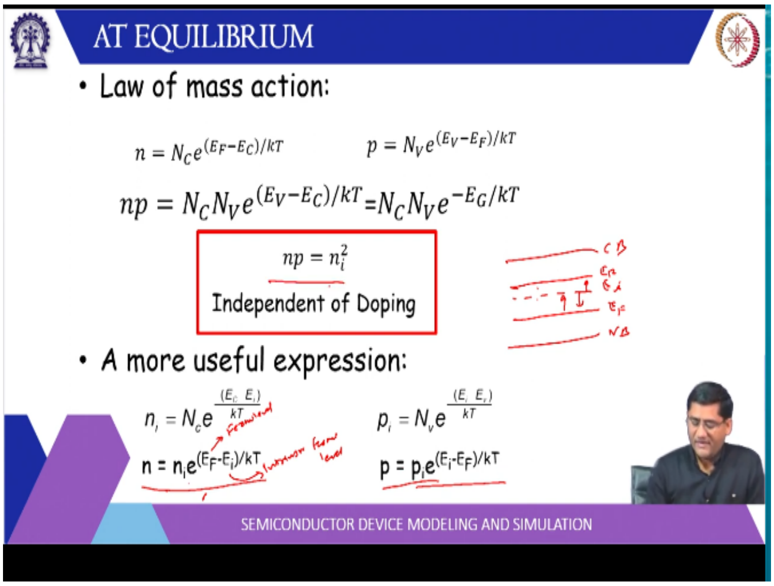

AT EQUILIBRIUM

- Law of mass action:

$n = N_C e^{(E_F - E_C)/kT}$ $p = N_V e^{(E_V - E_F)/kT}$

$np = N_C N_V e^{(E_V - E_C)/kT} = N_C N_V e^{-E_G/kT}$

$np = n_i^2$

Independent of Doping

- A more useful expression:

$n_i = N_c e^{\frac{(E_i - E_c)}{kT}}$ $p_i = N_v e^{\frac{(E_v - E_i)}{kT}}$

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

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

So, that expression you can write is n = n i exponential E F – E i by kT where E i is the intrinsic Fermi level. So, E F is the Fermi level for doped semiconductor E i is the intrinsic Fermi level so, in a for hole you can add p = p i exponential E i – E F by kT. So, it is something like this, let us say this is a conduction band, this is the valence band and this is the intrinsic Fermi level and here is Fermi which is here.

So, now, you can see from here and is E F – E i by kT so, this is negative and p is E i – E F by kT is positive. So, hole concentration is more if the Fermi level is somewhere here, then E

F – E i by Kt is positive, so electron concentration is more and E i – E F is negative. So, the hole concentration is less and the product is n p will be n i n p which is n i square. So, this explanation np = n i square is independent of doping, this law of mass action.

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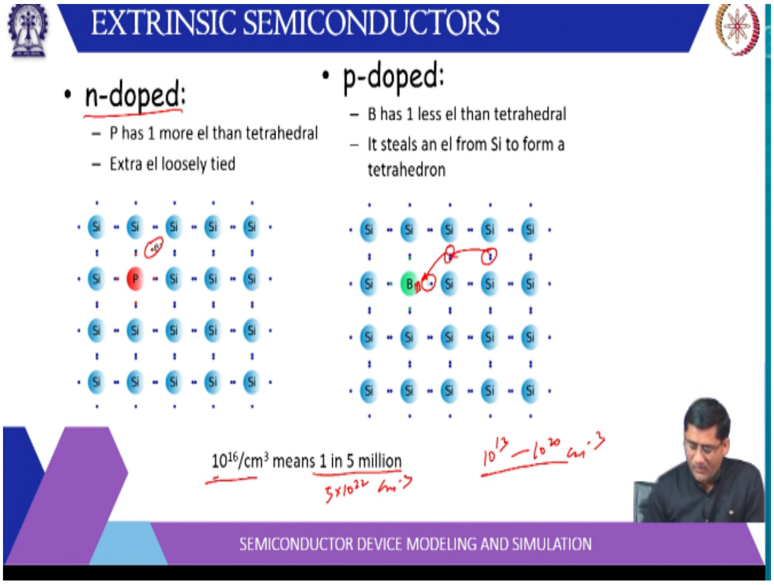

EXTRINSIC SEMICONDUCTORS

- n-doped:
  - P has 1 more el than tetrahedral
  - Extra el loosely tied
- p-doped:
  - B has 1 less el than tetrahedral
  - It steals an el from Si to form a tetrahedron

$10^{16}/cm^3$ means 1 in 5 million

$5\times10^{22}\ cm^{-3}$

$10^{13} - 10^{20}\ cm^{-3}$

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

Just a recap of the doping so, we have already discussed the domain that n doping if for n doping, we insert electron with from go 5 for silicon lattice and this has 1 extra electron which is 3 and loosely bound for p doping we use group 3 impurity which has 1 lack of electron and this lack of electron can move around by getting some electron from nearby. So, electron comes here hole moves here electron comes here hole moves here. So, that way this hole is moving for p type semiconductor.

And if you consider that doping, let us say doping range is typically starting from 10 is to power 13 to 10 is to power 20 this is range per cubic centimetre. So, what 10 is power 16 doping number of atoms is some 5 into 10 is to power 22 per cubic centimetre. So that means, the dope and is basically 10 is to power 16 5 into 10 is to power 22. So, that is around 1 in 5 million. So, that for says 10 is to power 16 doping, there is 1 dope and atom for 5 million host atoms.

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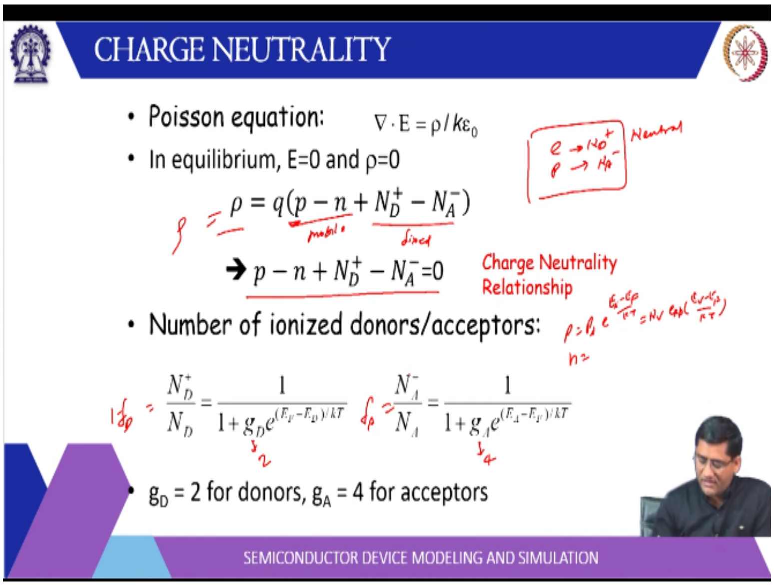

CHARGE NEUTRALITY

- Poisson equation: $\nabla \cdot E = \rho / k\varepsilon_0$
- In equilibrium, E=0 and ρ=0

$$\rho = q(\underbrace{p - n}_{mobile} + \underbrace{N_D^+ - N_A^-}_{fixed})$$

$$\rightarrow p - n + N_D^+ - N_A^- = 0$$

Charge Neutrality Relationship

$e \rightarrow N_D^+$
$p \rightarrow N_A^-$
Neutral

- Number of ionized donors/acceptors:

$p = p_i e^{\frac{E_i - E_F}{kT}} = N_V \exp(\frac{E_V - E_F}{kT})$
$n =$

$$1 - f_D = \frac{N_D^+}{N_D} = \frac{1}{1 + \underset{2}{g_D} e^{(E_F - E_D)/kT}} \quad f_A = \frac{N_A^-}{N_A} = \frac{1}{1 + \underset{4}{g_A} e^{(E_A - E_F)/kT}}$$

- g_D = 2 for donors, g_A = 4 for acceptors

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

Now, in a typical semiconductor we have to consider that charge neutrality because the semiconductor is charge neutral. So, when electrons are more, it does not mean there is a net negative charge because there are corresponding to those electrons there are positive charge ions. Similarly when holes are worth, it does not mean that semiconductor is positively charged because corresponding to those holes, there are negative ions, acceptor ions.

So, if there is electron here, there has to be some positive ion for holes, there has to be some negative ions. So, which will take the electron and for electron they will give the electron. So, the charge utility requires the total charge rho which is q times for negative ions which are holes. These are mobiles basically so, these are the mobile charges, p holes minus electrons then there are fixed charges these are ions basically. So, donor ions minus acceptor ion that is a no net charge.

And if there is no other source for inserting these carriers this total charge has to be 0. So, you can take yourself p - n + N D + - N A - has to be 0. So, given the situation we know the expression p = p i exponential E i - E F by kT or it is N V exponential E V – E F by kT. Similarly, for n we have n i exponentially E i – E F by kT and which is also equal to N C exponential E F – E C by kT for the ions impurities.

Again you can use this Fermi Dirac distribution concept here is N D + by N. So, this is 1 - f for donor N A - by N this is f acceptor and this g D is we calculate 2 and g D calculated to be 4 in the last class. So, we can substitute all these 4 expression into this equation.

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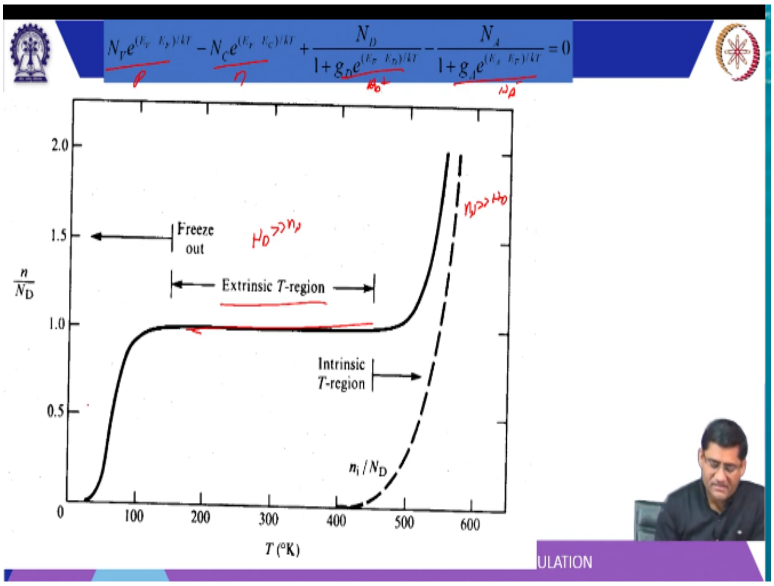

$$\underbrace{N_V e^{(E_V-E_F)/kT}}_{p} - \underbrace{N_C e^{(E_F-E_C)/kT}}_{n} + \underbrace{\frac{N_D}{1+g_D e^{(E_F-E_D)/kT}}}_{N_D^+} - \underbrace{\frac{N_A}{1+g_A e^{(E_A-E_F)/kT}}}_{N_A^-} = 0$$

So, this is our overall equation, this is basically holes this is number of electrons, these are the donors N D + and this is N A - and total should be 0. And from this equation, we can plot this curve, this we have already discussed that for high temperature a semiconductor becomes intrinsic or middle temperature where the semiconductor is intrinsic. So, that doping is much larger than n i for intrinsic n i is much larger than the doping and freeze out the temperature is too small to excite the carriers.

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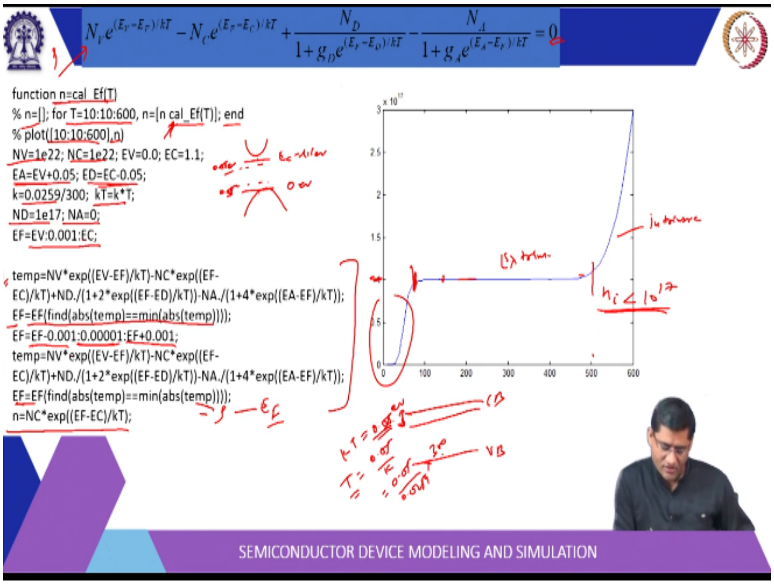

$$N_V e^{(E_V-E_F)/kT} - N_C e^{(E_F-E_C)/kT} + \frac{N_D}{1+g_D e^{(E_F-E_D)/kT}} - \frac{N_A}{1+g_A e^{(E_A-E_F)/kT}} = 0$$

```
function n=cal_Ef(T)
% n=[]; for T=10:10:600, n=[n cal_Ef(T)]; end
% plot([10:10:600],n)
NV=1e22; NC=1e22; EV=0.0; EC=1.1;
EA=EV+0.05; ED=EC-0.05;
k=0.0259/300; kT=k*T;
ND=1e17; NA=0;
EF=EV:0.001:EC;

temp=NV*exp((EV-EF)/kT)-NC*exp((EF-
EC)/kT)+ND./(1+2*exp((EF-ED)/kT))-NA./(1+4*exp((EA-EF)/kT));
EF=EF(find(abs(temp)==min(abs(temp))));
EF=EF-0.001:0.00001:EF+0.001;
temp=NV*exp((EV-EF)/kT)-NC*exp((EF-
EC)/kT)+ND./(1+2*exp((EF-ED)/kT))-NA./(1+4*exp((EA-EF)/kT));
EF=EF(find(abs(temp)==min(abs(temp))));
n=NC*exp((EF-EC)/kT);
```

So, you can write a simple MATLAB code here I have done simple calculation, what I have done here there is a function called calculate Fermi level as a function of temperature. So, and this code can be run using temperature = 10 to 600 kelvin and for each calculation update end so, you start with n blank. So, for t = 10 it will calculate t f and put here again t = 20 again calculate and so on end it then of course, you can plot for these temperatures electron concentration n these temperatures electron concentration n. So, we are calculating n for these different temperatures basically.

Now, these are the constant NV is that effective density of estates for holes NC is effective density of states for electron and we can take this valence band difference to be 0 electron volt and EC is 1.1 electron volt acceptor energy level is taken somewhere here EV + 0.05 electron volt and donor energy level check an EC – 0.05 electron volt. So, these values you can change basically and absorb the variation then kT is 0.0259 electron volt. So, k is written is 0.0259 divided by 300 and kT is k times T and T is 300 kelvin different somewhere.

Then ND is the donor concentration which is 10 is 17 and we have assumed as acceptor concentration is 0 that E F is basically changed from EV to EC in the state of 0.01. And what is done here this expression given here the rho is calculated through temp. So, for all these values of EF from EV to EC in the steps of 0.101 is calculated and we know that the case for which this temp is minimum that means, this charge has to be 0 the neutrality condition has to be satisfied that should be the point closer to EF.

So, we find out the coordinate for which this rho is minimum and again use that EF in the vicinity of the EF and further refine it, this is actually a crude way of doing things you can use Newton method and so on to find out but this one is simple example to illustrate the point. So, again it is basically expanded from around this EF calculated for greater resolution 0.00001 and then again found the index corresponding to this we are rho is minimum which is 10 and using this EF.

So, what we have done here we have calculated the EF for which rho is very close to 0 and using this EF we have calculated the electron concentration and that is returned to end and it is it is written by calculate EF because you see here n is the output. So, when you write cal Ef it is basically putting the end here so, it is the ranging for different temperatures. And then when you plot this n versus temperature you get this kind of curve.

Now, you can vary it for different accepted doping donor doping and so on you can vary this acceptor energy level donor energy level and see how it varies basically if you see here because 10 was 17 is the doping. So, this is the doping level. So, as long as the n i is less than this 10 was 17 so, up to this point n i is less than 10 was 17. So, we can say this material is extrinsic and beyond this temperature now, n i is more than the doping level. So, it becomes intrinsic and of course, here you see that it is due to the free out.

Because temperature is so low that you see here the valence band is the conduction band this energy is 0.05 electron volt. So, if you equate it to kT you will get some T = 0.05 by k. So you can calculate k is 0.05 divided by 0.0259 divided by 300 so, it basically roughly half of it. So, slightly less than 100 somewhere so, you see there you observe this effect. So when this temperature is smaller than this gap 0.025 which is equal to if you get it to kT so that will be around 150.

So 150 somewhere here, so maybe roughly half of that 75. So, if the energy is half of this 0.5 that is 0.025 electron volt you will observe this carrier freeze out defect.

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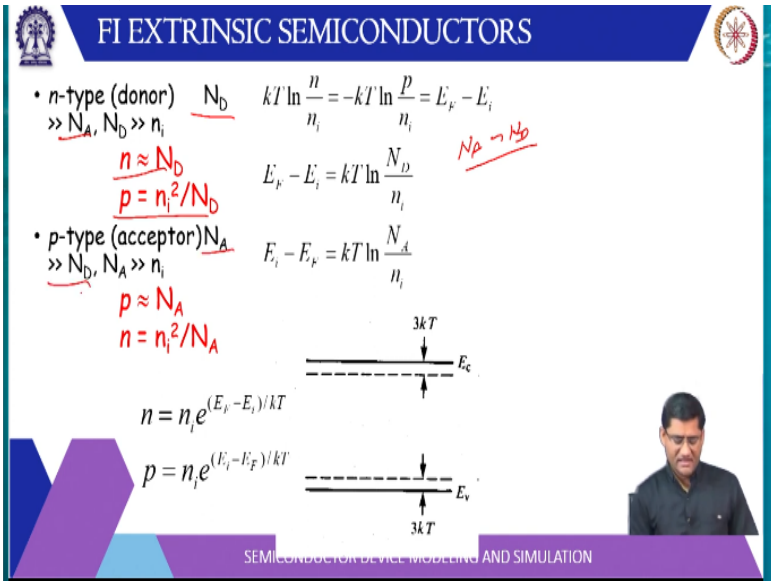

FI EXTRINSIC SEMICONDUCTORS

- n-type (donor) N_D $\gg N_A$, $N_D \gg n_i$
  - $n \approx N_D$
  - $p = n_i^2/N_D$
- p-type (acceptor) N_A $\gg N_D$, $N_A \gg n_i$
  - $p \approx N_A$
  - $n = n_i^2/N_A$

$$kT\ln\frac{n}{n_i} = -kT\ln\frac{p}{n_i} = E_F - E_i$$

$N_A \to N_D$

$$E_F - E_i = kT\ln\frac{N_D}{n_i}$$

$$E_i - E_F = kT\ln\frac{N_A}{n_i}$$

$$n = n_i e^{(E_F - E_i)/kT}$$

$$p = n_i e^{(E_i - E_F)/kT}$$

And then this is another way to look at the band diagram. So, for dopant let us say n type donor N D you can say that you know if there are acceptor concentration or N D is much larger than N A then you can say that number of electron is equal to N D and using mass x and you can say that p = n i square by N D when N A and N D are comparable then you have to be more careful and you have to use this charge equality equation to calculate electron and hole concentration.

And of course, when it is concentration p donor accepted time so, n is much less than N D then of course hole concentration is N A and electron concentration n i square by N A.

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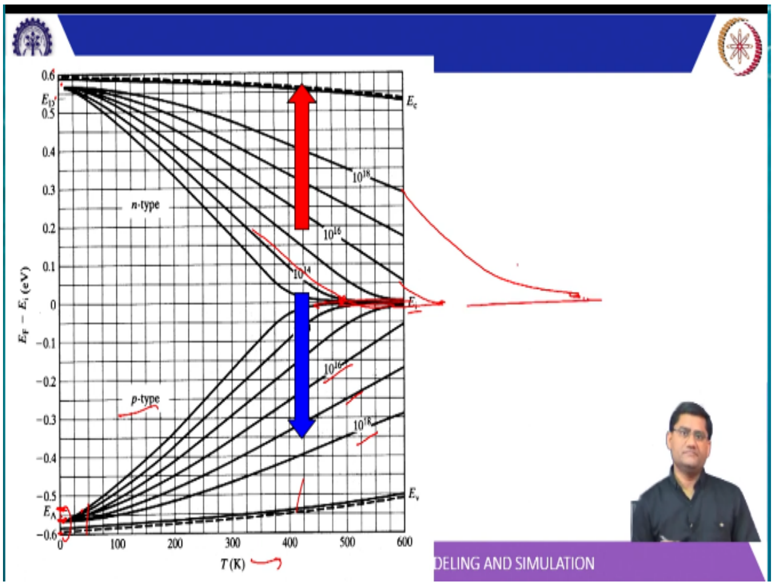

And here this is a picture again from the textbook it shows if you increase the temperature what happened to the Fermi level. So, for p type Fermi level somewhere here. So, at 0 kelvin it is in the middle of E A and the valence band why because E A is empty and this is acceptor. So, it takes electron but the temperature is so small that electron cannot come from valence band to this level. So, this is empty this is full so, this is Fermi level is somewhere here between E A and E V.

And then of course as you increase the temperature they can easily go so around 50 this has already crossed E A and as will increase temperature it goes to E i so it becomes intrinsic here. So, you see and these are the different colours for different doping. So 10 are18 doping 10 are 17 doping 10 are 16 doping and so on. So, as you increase the doping, you get these different curves and similar case for the electrons. So, for 0 kelvin, the Fermi level is somewhere between the conduction band and the donor energy level.

As you increase the temperature, this Fermi level will close to the E i, if the doping is more it will go to E A at high temperature if doping is less it go to E A at lower temperature, because at this temperature E i is more than 10 are 14 at this temperature E i is more than 10 are 16 at this temperature E i is more than 10 is for 18 and so on.

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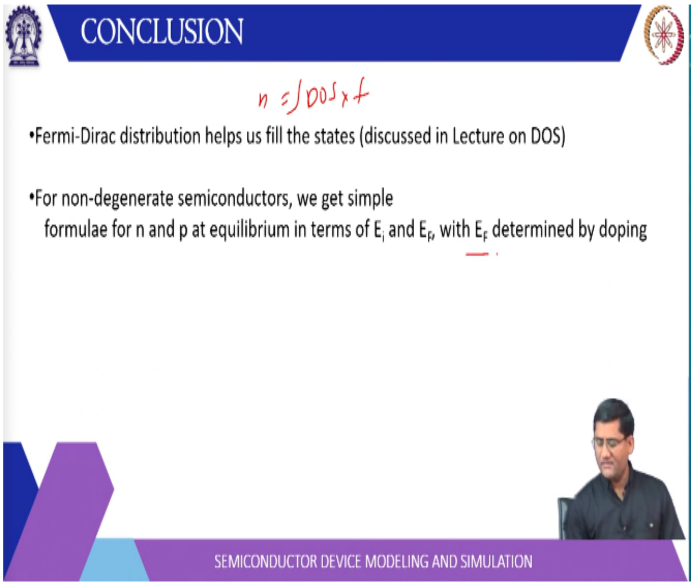

CONCLUSION

$n = \int DOS \times f$

- Fermi-Dirac distribution helps us fill the states (discussed in Lecture on DOS)
- For non-degenerate semiconductors, we get simple formulae for n and p at equilibrium in terms of E_i and E_F, with E_F determined by doping

SEMICONDUCTOR DEVICE MODELING AND SIMULATION

So, in last lecture in the current lecture, we have discussed the Fermi Dirac distribution, which helps us to fill the state. So, DOS times the Fermi-Dirac distribution tells you the number of carriers. So, for nondegenerate semiconductor where the; Fermi level is at least 3 kT away from the bandage inside the bandgap. We got simplified expression for n and p in terms of E i and E F and E F is determined by the doping using the charge neutrality condition. Thank you very much.