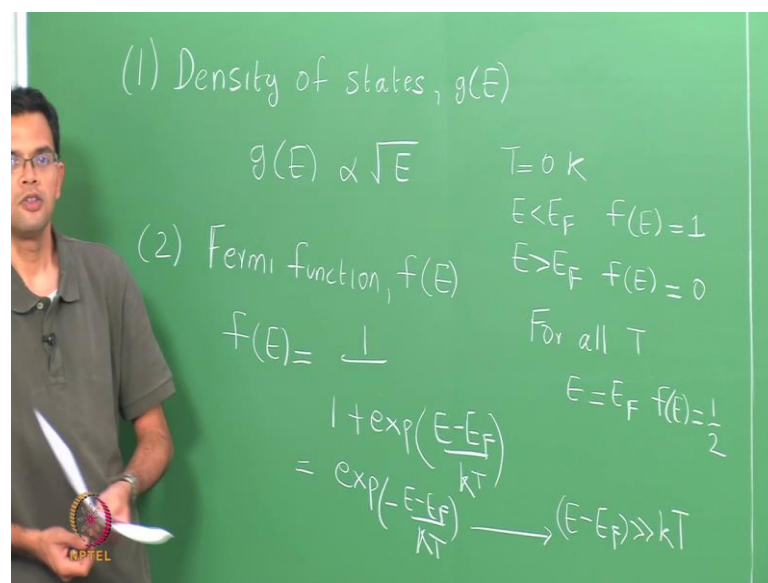


Electronic Materials, Devices and Fabrication
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Lecture - 5
Intrinsic Semiconductor

Let us start with the brief review of the last class; in last class we looked at 2 important concepts.

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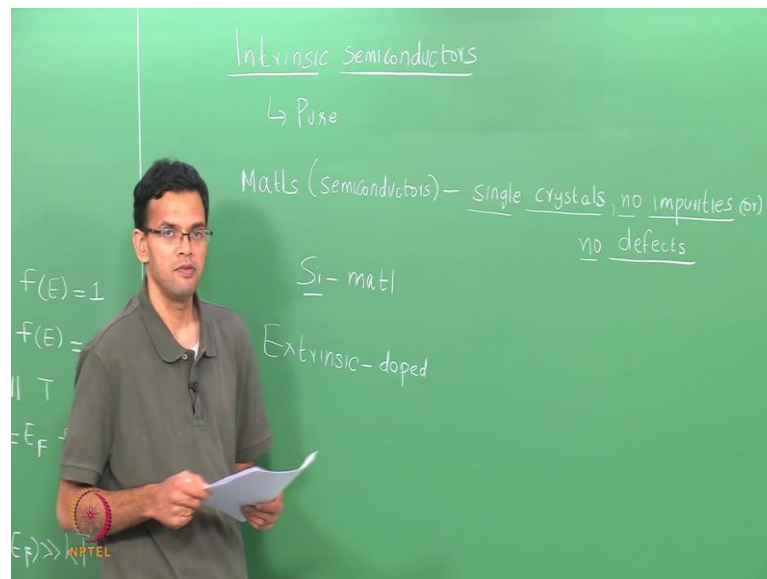


The first one is called the density of states we denoted this as g of E density of states refers to the number of available states for electrons to occupied. We looked at a simple model where we had a solid as a uniform 3 dimensional box with no potential. In such a case, we found that the density of states is directly proportional to a square root of the energy. So, thus the energy goes up the total number of available states for the electrons to occupy also go up.

We also looked at another concept we called the Fermi function. We denoted this by F of E the Fermi function tells you, the probability of occupation of an energy state by an electron. F of E found is 1 over 1 plus exponential E minus E_F over kT . We saw that a temperature equal to 0 Kelvin, if E is less than E_F F of E is 1 , which means all the levels below Fermi energy are occupied at E greater than E_F F of e is 0 , which mean above the Fermi energy all the levels are unoccupied.

We saw that all temperatures at energy E equal to E_F of E is half, when the energy is much higher than kT we can approximate the Fermi function by Boltzmann function. So, this becomes exponential minus E minus E_F over kT . Which is the Boltzmann function and this is true, so this what we looked at last class. We will use these concepts of density of states and Fermi function in order to calculate the electron whole concentration in semiconductors and first we will start with intrinsic semiconductors.

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We will start with intrinsic semiconductors another name for this is Pure semiconductors. We will use the concepts of the density states and Fermi function to calculate the carrier concentration that is the electron whole concentration we will also use we will also, define concepts of electron mobility and conductivity. Once we are done this for the intrinsic semiconductors, we will move on to extrinsic semiconductors.

So, what are intrinsic semiconductors? So, these are materials I will just say semiconductors in the bracket. That are single crystal and have no impurities or defects. We will say later, why it is important that there should be no impurities or defects. Most of what we do, we will reference using silicon as the material because; silicon is the dominant material in today's microelectronic industry.

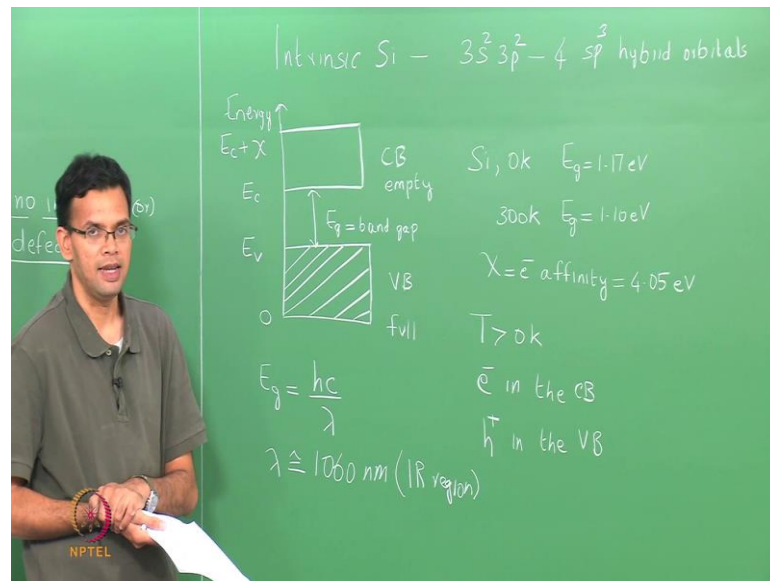
But all the concepts that we develop can be equally applied to other semiconductors and later, when we look at examples we will also looks at other materials to compare and contrast with silicon. But for the most part we will deal with silicon. As oppose to

intrinsic I mentioned earlier that you also have extrinsic semiconductors these are doped semiconductors.

If you look in terms of applications extrinsic semiconductors are almost always used. Intrinsic semiconductors do find some applications, but not whole a lot; mostly intrinsic semiconductors are used as optical senses in the cases photoluminescence experiment or as senses for x-rays in electron microscopes. So, these are senses which are called Energy Dispersive x-ray analysis.

Usually in those cases, either intrinsic silicon or germanium is used cool to around liquid nitrogen temperatures, but for applications extrinsic semiconductors are preferred. We will start with intrinsic first and once we develop these concepts we will go on to use them to understand extrinsic semiconductors. So, let us start with intrinsic semiconductors.

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As we saw earlier the electronic configuration of the outer shell of silicon is $3s^2 3p^2$ there are total of 4 electrons the s and p orbitals hybridized to give you 4 sp^3 hybrid orbitals. And we later saw, that these orbitals when they form a solid give you a valance band which is completely and a conduction which is completely empty.

In show that band diagram here; you have a valence band that is completely full, you have conductional band that is empty. You why axis here refers to energy usually the

energy is referenced with respect to the bottom of the valence band. So, the bottom of the valence band is given 0 eV denotes the top of the valence band and E_c denotes the bottom of the conduction band.

The difference between the top of the valence band and the bottom of the conduction band is, the band gap we call E_g . In the case at silicon at 0 Kelvin, E_g has the value of around 1.17 electron Volts at room temperature E_g is slightly lower around 1.10 electron Volts. The top of the conduction band usually denoted as $E_c + \chi$ where, χ is the electron affinity for silicon χ has value for 4.05 electron Volts.

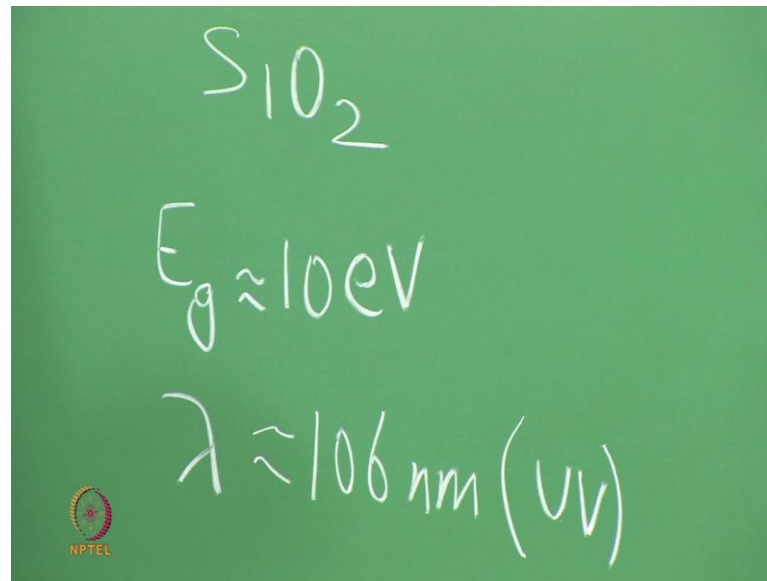
So, at 0 Kelvin you have a valence band that is completely full and a conduction band that is completely empty. At any temperature above 0 Kelvin we saw earlier, you have thermal excitation of electrons so that, the electrons from the valence band can move to the conduction band and leaving behind holes. So, any temperature greater than 0 Kelvin you will have electrons in conduction band and holes which is the absence of electrons in the valence band.

We also saw, that apart from thermal excitation; we can also use light in order to excite carriers across the band gap. If E_g is the band gap of material the wave length of light that is required in order to excite carriers is nothing but hc/λ we can do this calculation for silicon were, we find that λ is approximately 1000 nanometers and this lies in the IR region.

As long as we shine light with a wave length that is less than 1000 nanometers which means, the energy will be higher than the band gap; you can always excite carriers from the valence band to the conduction band. So, this explains why silicon is opaque because visible light has a wave length less than 1000 nanometers.

The visible range is from 400 to 800 nanometers which means, silicon will be able to absorb the visible light and produce electrons in holes. Similarly, SiO_2 which is glass has a band gap of approximately 10 electron holes.

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So, if you have SiO_2 has a band gap approximately 10 electron holes which means, the wave length that is required to excite electrons from the valance band to the conduction band this approximately 106 nanometers. So, 10 times less than that of silicon this lies in the uv region again explains why glass is transparent.

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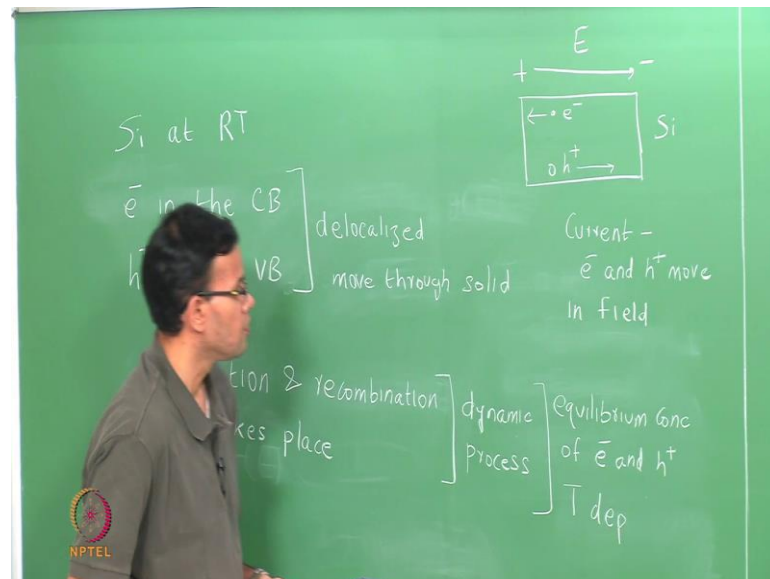
Si at RT
 \bar{e} in the CB
 h^+ in the VB
delocalized
move through solid
Formation & recombination takes place
dynamic process
equilibrium conc of \bar{e} and h^+
T dep

So, coming back to silicon here is the picture we have at room temperature. we have electrons in the conduction band we have holes in valance band and these electrons and holes are set to be delocalized that is they can move through the solid. The process of

formation of the electrons and holes is a dynamic process. That is electrons and holes are constantly being formed at the same time electron also, fall back to the valance band and recombine with the holes so that, they are also getting illuminated.

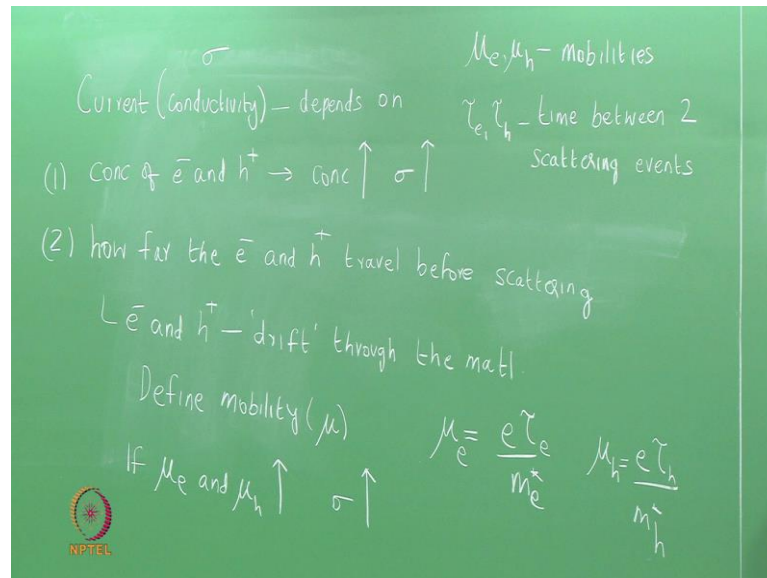
So, the formation and recombination takes place so that, we can say this is dynamic process. So, we have an equilibrium concentration of electrons and holes and this concentration depends upon the temperature. And say we have an equilibrium concentration of electrons and holes and this temperature dependent. When we apply an electric field this electrons and holes can essentially moved.

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So, we will just show the schematically a solid of silicon you have electrons, you have holes you apply in electric field E is the electric field electrons will go in the direction opposite to the field, holes will go in the direction of the field and finally, you will have current. The current is because, the electron moves in the conduction and the holes move in the valance band. What are the factors on which the current depends on?

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Let us, look that next current or of you want to think about it conductivity in case of an intrinsic semiconductor depends upon 2 factors: the first 1 is the concentration of electrons in holes that are available. So, more the electrons in holes there are higher is the conductivity. Concentration of electrons and holes we can denote the conductivity by the symbol sigma and I will just say as concentration increases your sigma will also increase.

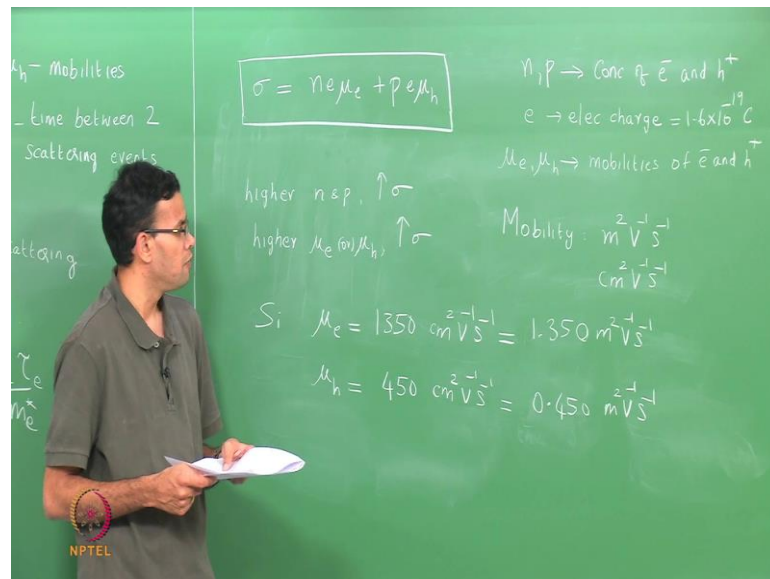
The next factor on which the conductivity depends on is, how far these electrons in holes can travel before that get scattered by lattice. So, remember you have electrons that are moving in the conduction band and you holes that are moving in the valance band. But these are moving through a solid of silicon atoms we are looking at intrinsic silicon. And all these atoms are vibrating which means, this electron and holes can interact with atoms and get scattered.

In the case of a semi conductor, these electrons and holes are set to drift to the material. To understand this we define the quantity that we call the mobility. Mobility is denoted by the single mu and the expression for mu, we are looking at electrons we can say mu e is nothing but tau e over me star you can write a similar expression for holes mu h. So, mu e depends upon a factor tau e and the effective mass of the electron mu h on a factor tau h and the effective mass of the holes.

So, μ_e and μ_h are the mobilities the factors τ_e and τ_h refers to the time between 2 scattering events. So, if τ_e and τ_h are large which means time between 2 scattering events is large. So, the electrons can travel a large distance before scattering. In such a case, if these 2 are large your mobilities are also large and hence the conductivity is also higher.

So, we can say if μ_e and μ_h increases and they would increase if the scattering is less the conductivity increases. So, we saw that the conductivity depends on 2 terms: one is the concentration, the other is the mobility. We can put this together to write an equation for the conductivity.

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So, if the sigma is the conductivity sigma is nothing but $ne\mu_e + pe\mu_h$ now this is a very important equation which relates the conductivity to the electron concentration and the mobility. And this equation is true whether, you have an intrinsic semiconductors or an extrinsic semiconductor. The n and p refers to the concentration of electrons in holes, which is the first factor that we saw earlier e is the electric charge which is 1.6 times 1 to the minus 19 Coulombs.

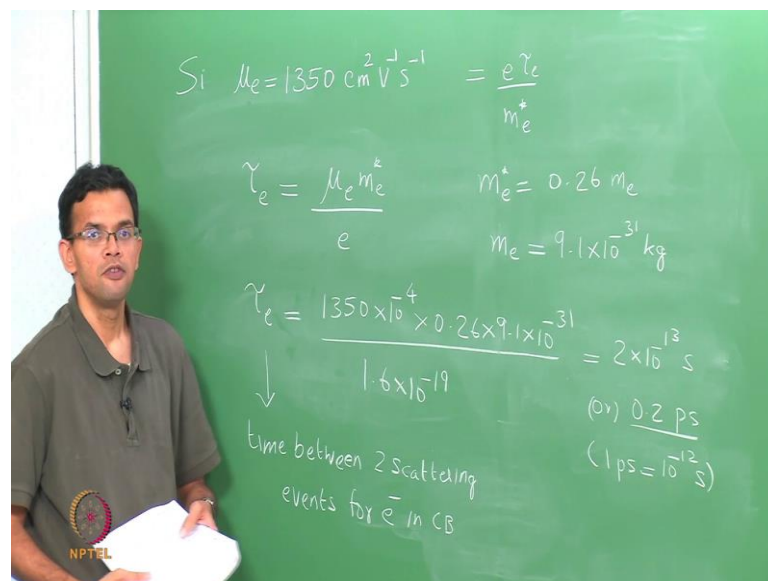
So, that is the constant and μ_e and μ_h are the mobilities of electrons and holes. So, if you look at this expression higher the concentration so higher n and p mobility is higher. Similarly, higher the conductivity is higher similarly higher μ_e or μ_h the conductivity is higher. The typical units for mobility are meter square holds per second

units for mobility can either, use meter square per volt per second you will also find that some books give values in centimeter square volts per second.

So, let us take look at the mobility values for silicon we have silicon μ_e which is the mobility of the electron in the conduction band is around 1350 centimeter square volt per second if you want to convert this to si unit you just divide by 10 to the 4. So, this is 1.350 μ_h which refers to the mobility of the holes in the valance band slightly smaller. So, around 450 centimeter square volts per second or can divide this by 10 to the 4.

The top 1 should be 1.350 just rewrite that. So, these are the unit or these are the values of conductivity in the case of silicon for both electrons and holes. We define mobility the ability of the electron to move through the material before being scattered. We also, saw that the mobility depends upon the scattering time we will use this to do some calculations for the scattering time. So, consider the case of silicon and we will only talk about the electrons can use the similar calculation for the holes.

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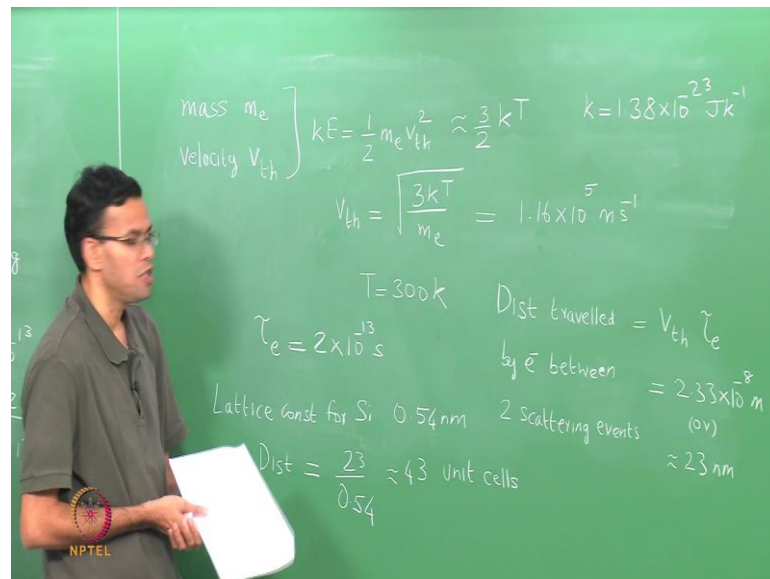


Consider the case of silicon when μ_e is 1350 we also, said earlier μ is related to this scattering time the expression was $e \tau_e$ over m_e^* . Just rearranging the terms, gives you τ_e , so all I did take this term here and then bring e down. In the case silicon m_e^* is around 0.26 m_e , where m_e is the mass of electron and m_e has a value.

So, we can substitute the number here to get the value tau e. So, 1350 and multiply by 10 to the minus 4 convert to SI units if you do the math's tau e works out to be 2 10 times to the minus 13 seconds or 0.2 Pico seconds and 1 Pico seconds is 10 to the minus 12 seconds. So, this time 0.2 Pico seconds represents the time between 2 scattering events for an electron and silicon that is moving through the conduction band.

So, tau e refers to the time between 2 scattering events and since we are talking about the electron is for the electrons in the conduction band. We will also, like to calculate the distance the electron travel between these 2 scattering events or the distance the electron travels in the time 0.2 Pico seconds.

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If you look at on electron with a mass given by m_e and velocity that is given by V_{th} then the kinetic energy is nothing but $\frac{1}{2} m_e v^2$, since the kinetic energy of electron. In case of most solid you can say that the kinetic energy is approximately equal to the thermal energy. So, this is approximately equal to $\frac{3}{2} kT$, where k is the Boltzmann constant k has the value 1.38×10^{-23} Joules per Kelvin.

Equating this expression we can find a value for $V_{thermal}$ or the velocity of the electron which is nothing but square root of $\frac{3kT}{m_e}$ can again, plug in all the numbers we are doing this calculation at room temperature. So, temperature is 300 Kelvin if you do this $v_{thermal}$ works out to be 1.16×10^5 meters per second.

So, we calculated thermal to be 1×10^5 meters per second earlier we saw the time between the 2 scattering events was 2×10^{-13} seconds or 0.2 Pico seconds. So, the distance travel by the electron between 2 scattering events is nothing but $V_{thermal} \times \tau$ which if you do the math is around 2.33×10^8 meters or approximately 23 nanometers.

To put this into perspective you can say that, the lattice constant for silicon is 0.357 nanometers. So, the distance travels in terms of the lattice constant is $23 / 0.357$, which if you see approximately 64 unit cells. So, the time between 2 scattering events is really small. So, the time is of the order of Pico seconds, but because your electrons are such a high velocity.

The velocity is around 10^5 meter per second we find that the electron actually travel a substantial distance. So, it travels nearly 64 unit cells before is under goes another collision and the scattering. Mobility is usually a function of temperature it is also, can be a taut of as a material property as long as you do not add any impurities.

Later when we look at extrinsic semi conductors, you will find that increasing the concentration of the dopens decreases the mobility. You can compare the mobility of silicon with some other semiconductors to see the values.

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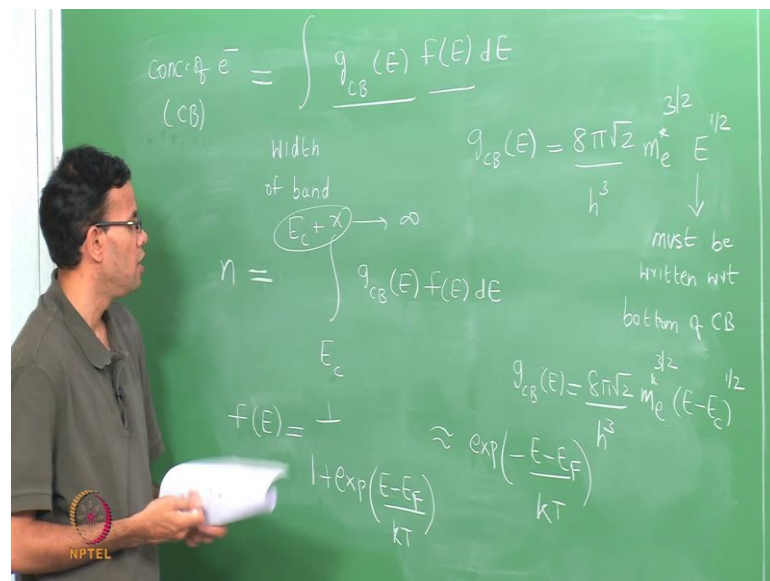
The image shows a green chalkboard with handwritten equations. At the top, the conductivity formula $\sigma = n_e \mu_e + p_e \mu_h$ is enclosed in a white box. Below it, three lines list electron mobility values for different materials: $\mu_e = 1350 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for Si, $\mu_e = 3900 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for Ge, and $\mu_e = 8500 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for GaAs. An NPTEL logo is visible in the bottom left corner of the chalkboard.

$$\sigma = n_e \mu_e + p_e \mu_h$$
$$\mu_e = 1350 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \quad \text{Si}$$
$$\mu_e = 3900 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \quad \text{Ge}$$
$$\mu_e = 8500 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \quad \text{GaAs}$$

I will leave the expression of sigma up here we saw that the I will leave the expression of sigma up here we saw that the mobility of electron in silicon was around 1350 centimeter square per volt per second this is for silicon. If you had germanium, germanium has slightly higher mobility mu e is 3900 that is the value for germanium gallium arsenide is even higher. So, if you want to improve the conductivity of material and you are ask to choose materials in order to have higher conductivity just based upon the mobility value the choice would be gallium arsenide

Because, gallium arsenide has a highest value 8500 which is nearly 6 times or 7 times higher than that of silicon. But if you look at the expression for sigma it not only depends upon mobility it also, depends upon on the concentration of electron and holes. So, the next we do is to calculate the electron and holes calculation has a function of temperature. So, in last class we looked at the concept of the density of states.

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And the Fermi energy putting those 2 concepts together, you can say that the concentration of electrons in the conduction band is nothing but the integral over the entire width of the band of the density of states in the conduction band I call that g CB of times F of E dE.

To put this into words, if you want to find the number of electrons in the conduction band at any given temperature it is going to depend on the number of states that are available

in the conduction band which is g_{CB} of E the density of states and probability that those states are occupied by the electron, which is F of E .

If you look at a conduction band the width of the conduction band we saw earlier goes from E_c to $E_c + \chi$ where, χ is the electron affinity goes from E_c to $E_c + \chi$ g_{CB} which is the density of states times the Fermi energy dE . Now, we want to calculate the density of states and silicon is real crystal, but we can make use of the assumption of a solid with a uniform potential, which we did earlier for a solid with a uniform potential.

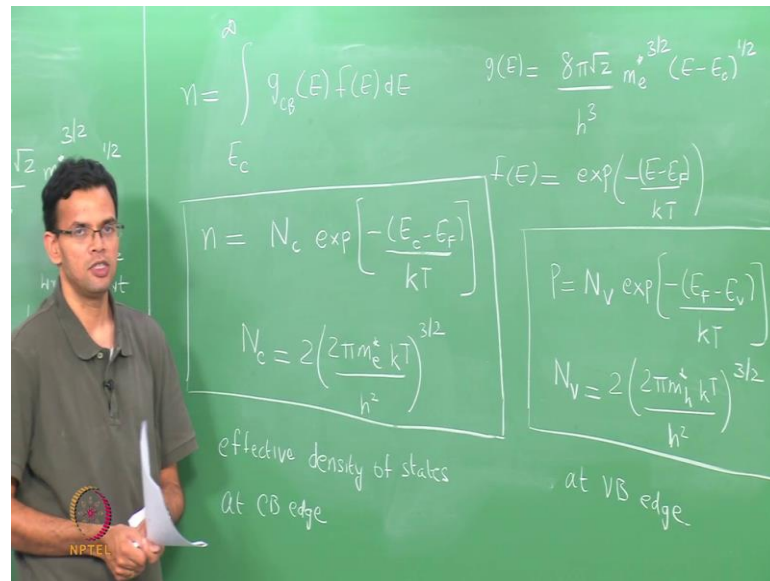
The density of states E is given by $8 \pi^2 \sqrt{2} m_e^{3/2} E^{1/2}$, which is the effective mass of the electron in conduction band times E to the half. So, this expression we saw earlier for a solid with a uniform potential a 3d solid and we will use that expression to find the density of states of electrons in the conduction band of silicon. So, we are looking at only the conduction band E here must be written with respect to the bottom of the conduction band.

So, we will modify this expression g_{CB} and write it as $8 \pi^2 \sqrt{2} m_e^{3/2} (E - E_c)^{1/2}$ and instead of E we will write it as $E - E_c$ the whole half. So, you are writing the energy with respect to the bottom of conduction band F of E is $1 / (1 + \exp((E - E_F) / kT))$. Usually in the case of silicon and you will actually showed it explicitly later on $E - E_F$ will be of the order of the electron holes.

Or a point greater than 0.5 electron holes kT is usually of the order of milli electron holes. So, we can approximate the Fermi function as a Boltzmann function and write this exponential minus $E - E_F$ over kT , so this expression approximate to this 1. In the case of the silicon semiconductor our limits where, the width of the band that goes from E_c to $E_c + \chi$ for ease of integration we can replace the $E_c + \chi$ term with infinity this also true.

Because, we find that most of the electrons are located very close to the bottom of the conduction band. So, we can take the top of the conduction band to be infinity and we would not lose much in the model. So, we replace $E_c + \chi$ with infinity let me, and then rewrite this expression again.

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If you rewrite this n which is the number of electron in the conduction band goes from the base of the conduction band E_c up to infinity the density of state times to Fermi function dE , where the density of state is given by this expression m_e^* whole power 3 over 2 E minus E_c whole power half and F of E we will use Boltzmann approximation and write it an exponential e minus E_F over kT .

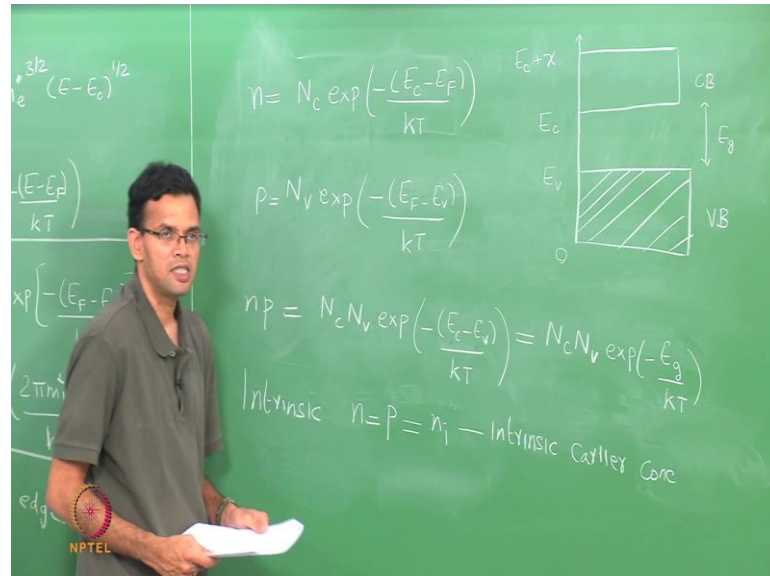
We can substitute this 2 in this expression and do the integration I will not show the integration explicitly, but write down the final result. When we do this we get n is equal to N_c , which is a constant at a given temperature times exponential minus E_c minus E_F over kT N_c is nothing but 2 times 2 pi m_e^* kT over h^2 whole power over 2. This part N_c is called the affective density of states at the conduction band edge.

So, n depends upon the effective density of states at the conduction band edge times and exponential function, what do we derivation we did for electrons we can equally do for the holes in the valence band I would not do the derivation for holes, but I will just write down the expression. For holes P which is the concentration of holes in valance band is N_v which is a constant times exponential minus E_F minus E_v over kT N_v is 2 2 pi m_h^* kT over h^2 whole power 3 over 2.

This is the affective density of the state at the valance band edge. So, we have 2 expressions: 1 for electrons and 1 for holes. These expressions 1 for electrons and 1 for

holes give you the concentration of electrons in the conduction band and holes in the valance band for a given semiconductor as function of temperature.

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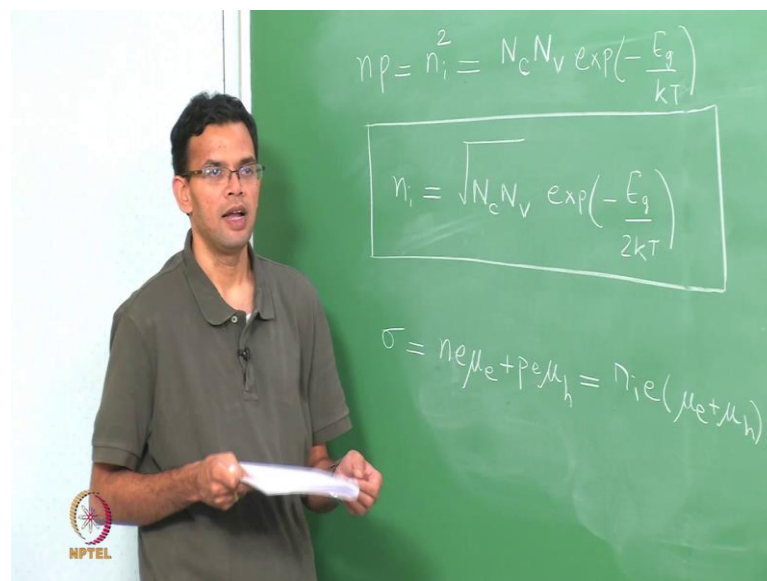
Let me, just rewrite those 2 expression n this Nc exponential in P is Nv exponential minus EF minus Ev over kT. We can mark the position of Ec and Ev in the band diagram. So, if you draw this you have a valance band the base of the valance band is set as 0, the top of valance band is Ev then you have conduction band the base of the conduction band is Ec the top of the conduction band is Ec plus kai.

The difference between the valance band and the conduction band is the band gap. So, here your expression is long as we know all these values Nc Nv Ec Ev we can calculate the concentration of electrons in holes. If you look at this expressions the Fermi energy term EF is in there, but I am not marked where the Fermi energies. So, if you do not know where EF is you only able to calculate n and p.

So, let us go ahead and eliminate EF by multiplying n and p together. If you do that n p will be Nc Nv exponential minus Ec minus Ev over kT all have done is multiply this 2 together. Ec minus Ev if you see from this band diagram this whole thing is Ec this is Ev. So, Ec minus Ev is nothing but the band gap, so this I can replace Nc Nv exponential minus Eg over kT.

In the case of an intrinsic semiconductor your electrons are created because, they are excited from the valance band and to the conduction band. And whenever, an electron is created a hole is also created. So, in the case of intrinsic semiconductors n which is the concentration of the electrons is equal to P , which is a concentration of holes. And this is usually denoted as n_i , n_i is called the intrinsic carrier concentration. So, for an intrinsic semiconductor n equal to P equal to n_i .

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So, if you make use of the fact n is equal to p then we can rewrite the expression np is nothing but n_i square which is the square of intrinsic carrier concentration that is equal to $N_c N_v$ exponential minus E_g over kT . And then taking square root you get n_i a square root of $N_c N_v$ exponential minus E_g over $2 kT$.

This is expression for the carrier concentration, so the concentration of electrons in holes in an intrinsic semiconductor as a function of temperature. We saw that the conductivity equation $ne \mu_e + pe \mu_h$, in the case of an intrinsic semiconductor n is equal to p is equal to n_i . So, we can take this term outside, so its $n_i e \mu_e$ over μ_h .

So, the conductivity depends on the some of mobilities of both the electron and the hole in the case of an intrinsic semiconductor. So, this is where we will stop for today in the next class we will start by calculating these values for the intrinsic carrier concentration and the conductivity for silicon. Then, we look at how changing the materials will these values then we will proceed from there.