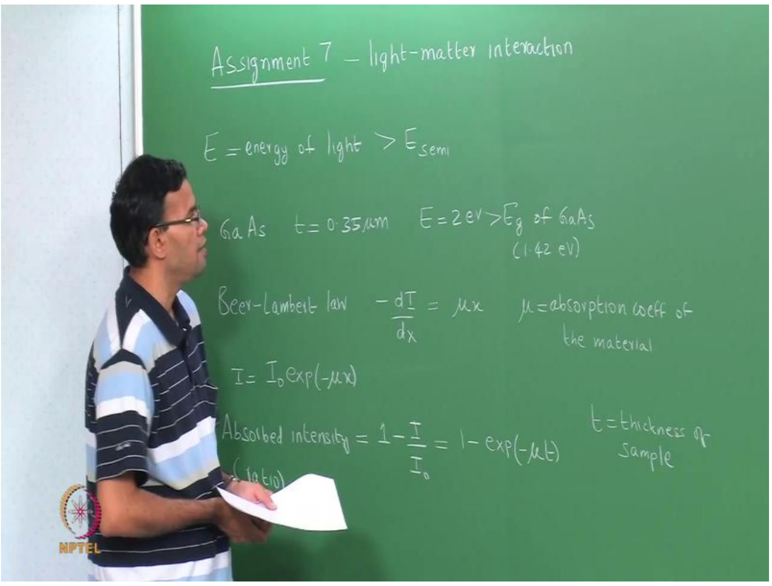
Fundamentals of electronic materials, devices and fabrication
Dr. S. Parasuraman
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Assignment - 7
Optical Properties

In today's assignment, we are going to look at the interaction of light with matter.

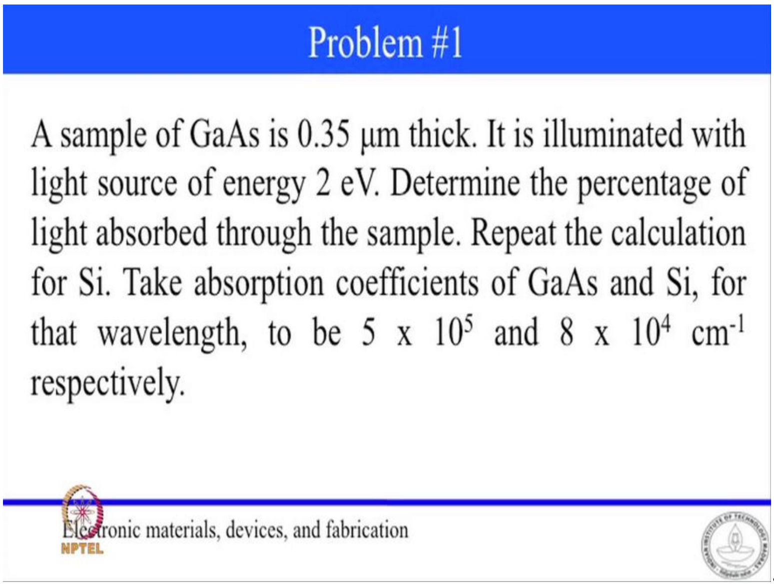
(Refer Slide Time: 00:23)



This is assignment 7, going to look at light-matter interaction. So, during the course of the lecture we first studied how generally lights interact with semiconductor materials, we then looked at some specific examples and applications of this. We looked at LED's, Photo diodes, LASERs, solar cells and so on. In this assignment, we will focus on the general interaction and in the next one we will take a problems related to the specific devices which I just mentioned. So, we talked about light interacting with matter the basic thing we said was said that the energy of the light E must be greater than some interaction energy within the semiconductor. So, In most cases this interaction is essentially the band gap of the material, so that when the energy of the light is greater than the band gap, electrons are excited from the valence to the conduction band.

You could also have situations where there are defect states or trap states located within the band gap. So, these could be located either close to the valence band or to the conduction band and again the interaction of light with the semiconductor causes carriers to excite from either the valence band to the trap state or from a trap state to the conduction band. That is why E semi cannot only refer to the band gap of the material, but could also refer to the energy for a defect state and a band gap. So, with this brief introduction let me go through the problems, as we go through the problems we will again related to the concepts that we dealt with in the lectures.

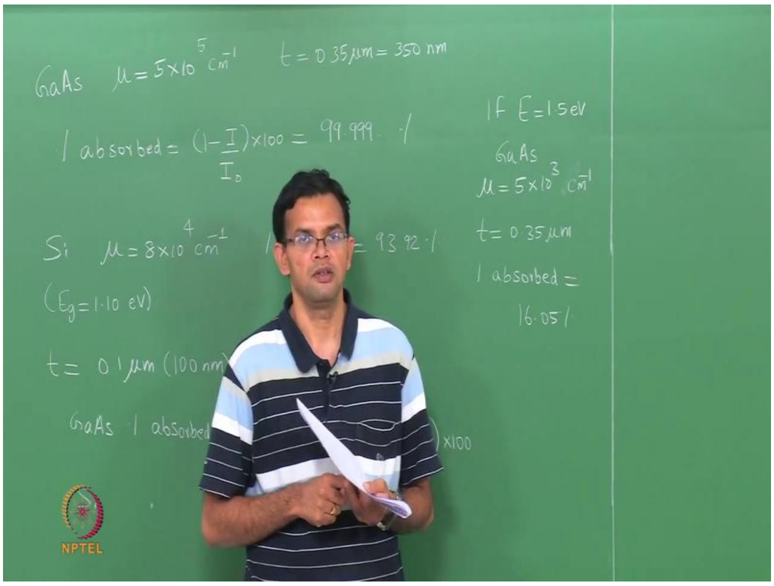
(Refer Slide Time: 02:52)



Problem 1: We have a sample of gallium arsenide which is 0.35 μm thick. It is illuminated with the light source and the energy is given. So, energy E is 2 electron volts this is greater than the band gap of a gallium arsenide, so E_g of gallium arsenide which is 1.42 electron volts. Determine the percentage of light observed through the sample and we want to repeat the same calculation for silicon. So, when we look at light absorption through a material we basically go back to the Beer-Lambert law. The Beer-Lambert law says, that the change in intensity over a small distance dx and there is a negative sign because the intensity actually it goes down, is directly proportional to x and the proportionality constant is called μ. μ here, is the absorption coefficient of the material, this intern depends upon the wavelength of the light that is shining through this. We can integrate this and basically put the boundary conditions which give us I is equal to $I_o \exp(-\mu x)$.

So, I here represents the transmitter intensity so if you want to find the absorbed intensity, and if you want to find it as a ratio it is nothing but 1 - I/I_o. This is essentially a ratio which we can convert to a percentage, which is 1-exp(-μ). In this particular case, we have been given the thickness of the sample so t here refers to the thickness. We can basically use this expression to calculate the value for gallium arsenide.

(Refer Slide Time: 06:05)



So, for gallium arsenide, the absorption coefficient mu is given, so μ is 5 x 10^5 cm^{-1}. So, from this we can calculate the percentage absorbed, which is just $\left(1 - \frac{I}{I_o}\right) * 100$ and here we substitute all the values, this works out to be 99.999 and there are few more trailing 9's, which means when you shine light of 2 electron volts on a sample of gallium arsenide that is only 0.35 μm thick, so 0.35 is just 350 nm. It is only 350 nm and all most all the light is absorbed. So, that gallium arsenide is essentially opaque to this radiation.

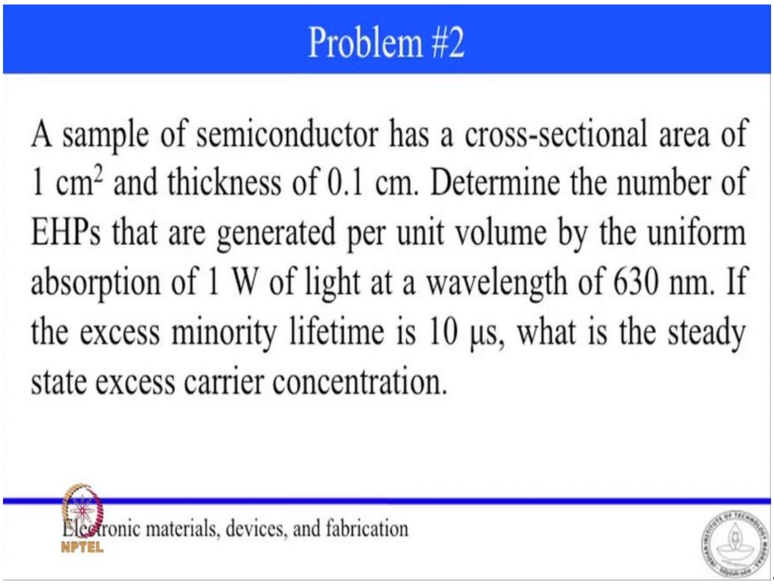
We can do the same calculation for silicon. The value of μ is 8 x 10^4 cm. So, silicon actually has a lower band gap than gallium arsenide. So, E_g of silicon is 1.10 electron volts at room temperature, so even though it has a lower E_g the value of the absorption coefficient at 2 electron volts is slightly lower than that of gallium arsenide. And, this is basically related to how the density of states is distributed in the valence and the conduction band. So, Taking this value of mu we can calculate the percentage absorbed, can again plug in the numbers and this is 93.92 %, so it is still a high number but nearly 7 % of the light guess through while the rest is absorbed. So, we can actually go beyond and do some more calculations just to get a feel of this value. Instead of 0.35 μm, I now reduced my thickness to 0.1 μm, this is approximately 100 nm my energy is still 2 electron volts, so that I can use the same values for the absorption coefficient. If you do that for gallium arsenide the percentage absorbed is 1 times 100, which is $1-\exp(-\mu t)\times 100$ and this is 99.3.

So, when we reduce the thickness further, so we actually take it down where on 3 times you go from 350 nm to 100 nm, still we get a really high percentage of light that is absorbed. For silicon, on the other hand the percentage absorbed for 100 nm is only 55 percent, so only half the light is absorbed and the other half gets transmitted. Another variable we can introduce is to change the wavelength or the energy of the light. If you take energy to be 1.5 electron volts, so instead of shining light of 2 electron volts you shine light of only 1.5 electron volts. For gallium arsenide, μ is lower so it is 5×10^3 cm^{-1} sorry, 5×10^3 cm^{-1}. This is still above the band gap, but it is very close to the band gap so that the numbers of available states are small, so correspondingly the absorption coefficient is also small.

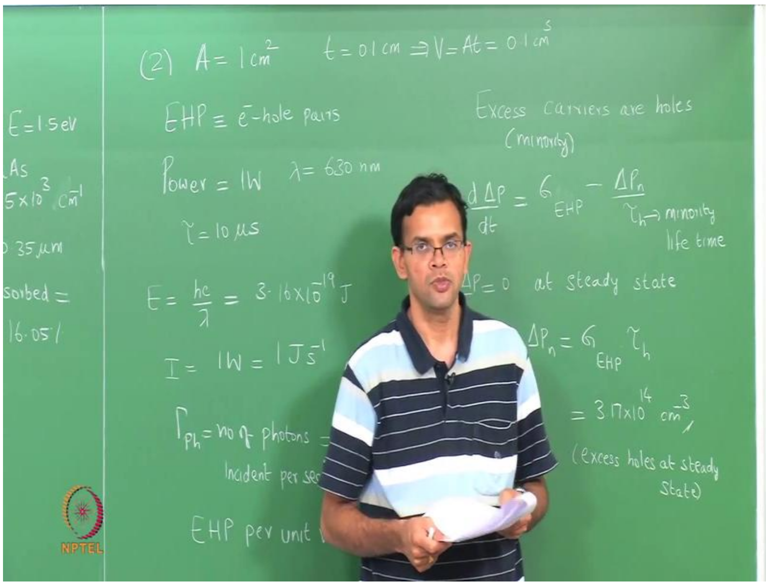
Now, if you have a thickness of 0.35 μm, so the same 350 nm the percentage absorbed using the same formula is only 16.05 so nearly 84 % of the light is transmitted while the rest is absorbed. So, the absorption coefficient mu place a really key role in determining the thickness of the sample that you need in order to either get light to completely pass through or light to be absorbed. If you are trying to build a transparent semiconductor with gallium arsenide, we find that if you have light of energy greater than 1.5 electron volts and this is already in the visible region, we find that most of light essentially gets absorbed and only of small percentage of light gets transmitted. So, the value of mu and the corresponding at different wavelengths, something that plays a very important role in determining the type of material you would choose and also the thickness of the material.

So, let us now go to problem 2.

(Refer Slide Time: 12:42)



(Refer Slide Time: 12:47)



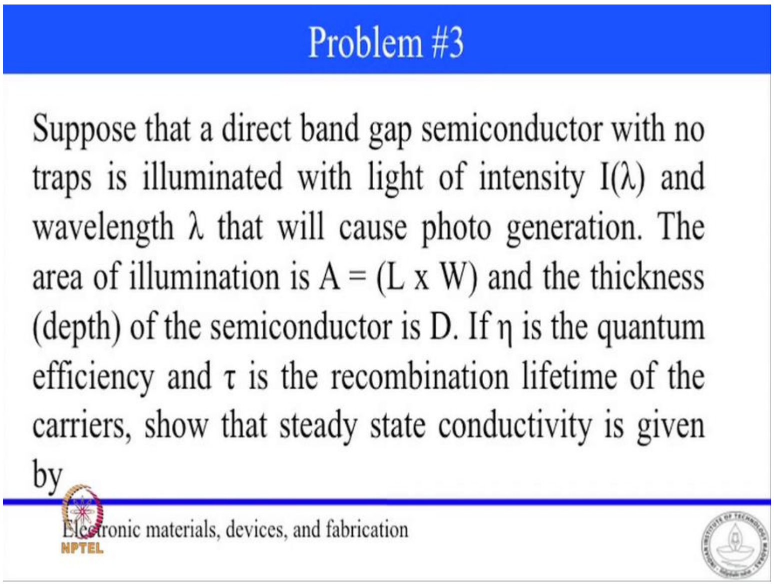
In problem 2, we have a sample of a semiconductor, the cross-sectional area A is 1 cm^2 and the thickness is 0.1 cm. So, We want to find out the number of electron hole pairs, so EHP is nothing but electron hole pairs. So, we want to find the number of electron hole pairs that are generated per unit volume when you absorbed light of 1 watt, so the power is 1 watt and the wavelength λ is 630 nm. In this particular case the band gap of the semiconductor is not given, but we are going to take it such that the light has sufficient energy to excite electrons across the band gap so that we can get electron hole pairs. If the x is minority life time is 10 microseconds, so the minority life time τ is 10 microseconds.

We are also asked to calculate the steady state excess carrier concentration. So, we look at the first part of the problem. We have light of wavelength 630 nm. So, the first thing is to calculate the energy, energy is nothing but $\frac{hc}{\lambda}$, this works out to be 3.16×10^{-19} joules. So, We also know the intensity of the length, so I is 1 watt which is $1\ Js^{-1}$. So, we can calculate the total number of photons, this is the number of photons that are incident per second, this is equal to I divided by the energy. So, $\frac{I}{(\frac{hc}{\lambda})}$. So we can plug in the numbers, this works out to be 3.17×10^{18} photons per second. So, We also want to calculate the electron hole pairs per unit volume. So volume is nothing but A times t, so 0.1 cm^3. So, This we can divide by the volume, we also say that each photon gives rise to 1 electron hole pair. So this means there is a quantum efficiency of 100%, usually that is not the case the quantum efficiency would be lower than 100 in which case you will have to multiply by the appropriate fraction.

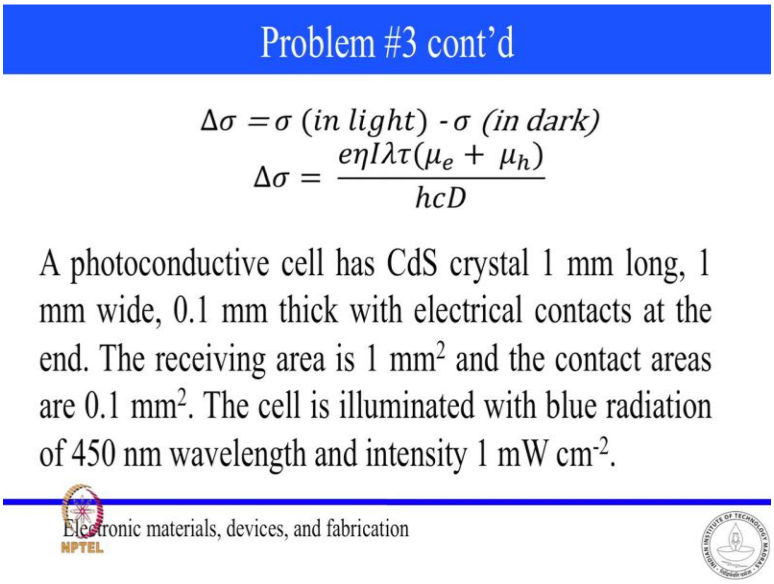
But for this particular problem we will take the quantum efficiency to be 100%, so of this is a number of photons that are incident these will give rise to an equal number of electron hole pairs. So, The number of electron hole pairs per unit volume is nothing but $3.17 \times 10^{19}\ cm^{-3}\ S^{-1}$, so you just dividing the number of photons by the volume. In the next part, we are asked to calculate the steady state excess carrier concentration. So, We do not know if this material is a p type or an n type semiconductor. So, just for simplicity I will take it to be an n type, so that the excess carriers or holes. You can do the same thing by assuming the material to be a p type, so that the excess minorities carriers are electrons, but it will not affect the final results. These are the excess minorities carriers. So when we have light illuminating on a sample, it is possible to right an equation for the excess carriers this differential equation just says $\frac{d\Delta P}{dt}$, so ΔP represents the excess minority carriers that are created. This is equal to the number of electron hole pairs that are generated $\frac{-\Delta P}{\tau_h}$, where τ_h is the minority life time.

When we basically have steady state, ΔP is 0, so $\frac{d\Delta P}{dt}$ is 0 at steady state. Which implies the steady state excess carrier concentration is nothing, but the number of electron hole pairs that are generated times the life time of the minority carriers. This we can again substitute, we know the life time is given to be 10 microseconds, the number of carriers per unit volume is something we just calculated, so this is equal $3.17 \text{ x } 10^{14}$ cm^3. So, These are the excess holes at steady state. So, let us now go to problem 3.

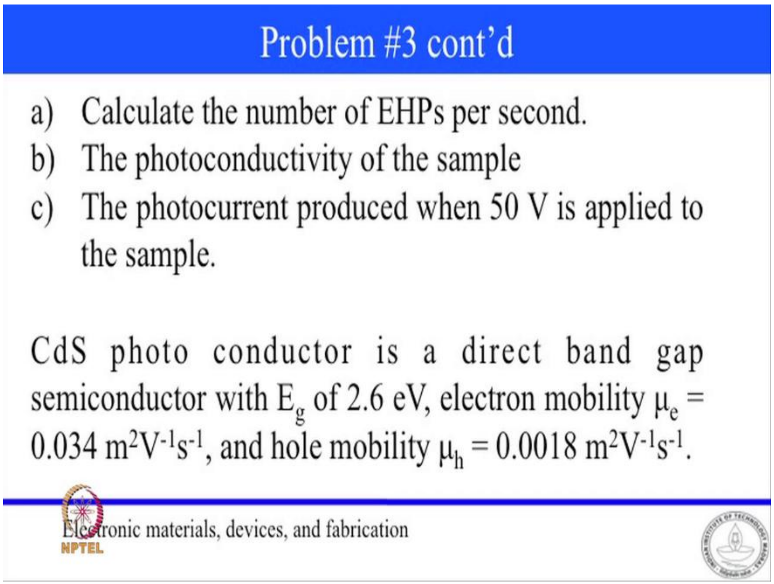
(Refer Slide Time: 20:16)



(Refer Slide Time: 20:22)



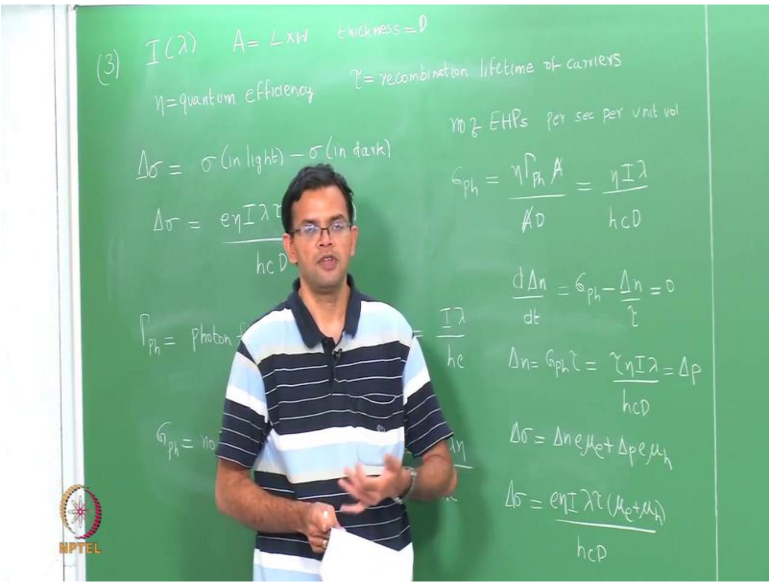
(Refer Slide Time: 20:27)



(Refer Slide Time: 20:33)

So, Problem 3: we have a direct band gap semiconductor with no trap states. So, we do not have any defects or traps that are located within the bad gap. This is important because, trap states can usefully trap the carriers and these have a longer lifetime then the electrons and holes in the band. This will again change the carrier life time and that will again affect properties like the conductivity and also the quantum efficiency. So, we have a direct band gap semiconductor, it is illuminated with light of intensity.

(Refer Slide Time: 21:22)

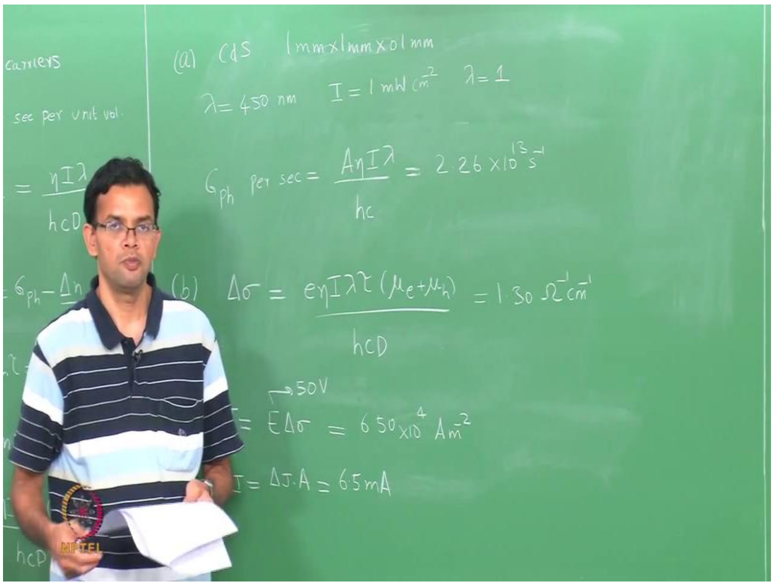


So, $I(\lambda)$, in this case I is essentially a function of the wavelength, this causes photo generation. Once again we are saying that the wavelength λ or the energy of the light is greater than the band gap, so that we have electron hole pairs that are created the area of the illumination is given. So, A is length times W and the thickness of the semiconductor is D. If η is the quantum efficiency, quantum efficiency defines how many electron hole pairs, how many photons are converted to electron hole pairs. In the last problem, we assume the quantum efficiency to be 1, so that every photon gets converted to an electron hole pair. If you take the quantum efficiency to be 0.5 or 50 percent, if you have 2 photons coming in only 1 of them will get converted to an electron hole pair.

The quantum efficiency is given and tau is the recombination life time of the carriers. So when we shine light in the material we generate excess electrons in holes, these electrons in holes can basically take part in conduction so that there is a change in conductivity when we expose light. This is essentially called Photo conductivity and the difference in conductivity delta sigma is defined as sigma in the presence of light minus sigma in the absence of light, typically there is a dark state and we have to show that delta sigma is equal to $\frac{e\eta I\lambda\tau(\mu_e+\mu_h)}{hcD}$. In some ways problem 3 is similar to problem 2 except that we are using symbols instead of numbers, and in the last part of problem 3 we will actually plug in some numbers to get this expression. So, Once again the first thing we need to do is to calculate the number of photons or the photon plugs that is incident on the sample. So, Γ_{ph} is your photon flux, this is given by I is the intensity divided by $\frac{hc}{\lambda}$ which is the energy. So, this is the intensity and then this is the energy.

This is $\frac{I\lambda}{hc}$. We define quantum efficiency as the number of electron hole pairs that are generated for a certain photon flux. So, G_{ph} which is the number of electron hole pairs generated is nothing, but η which is the quantum efficiency times γ_{Ph}. So, this is $\frac{I\lambda\eta}{hc}$. So, In this particular problem, the intensity is given per second, so intensity is given per unit area. So, to calculate the volume change or to calculate the number of the electron hole pairs that are generated per unit volume, you basically need to multiply by the area and also divide by the volume. The number of electron hole pairs per second per unit volume, so again I am going to use the same symbol G_{ph}, but now this is per unit volume is nothing but $\eta\frac{\gamma_{ph}A}{Volume}$. A gets canceled, we can plug in the value of γ_{Ph}, so this is nothing but $\frac{\eta I\lambda}{hcD}$. Again, we have a steady state situation, so we can right the continuity equation. So, if we take the excess carriers to be electrons then $\frac{d\Delta n}{dt}$ is nothing but $\frac{G_{ph}-\Delta n}{\tau}$ and it is steady state this change is equal to 0, so Δn is $G_{ph} \times \tau$. You can substitute that expression, so it is $\frac{\tau\eta I\lambda}{hcD}$. This is the excess electrons that are generated, this must be the same as the extra holes because electron hole pairs are generated so every time in a electron is generated a hole is also generated. So, the change in conductivity $\Delta\sigma$ is nothing but $\Delta n_e \mu_e + \Delta P\mu_h$, these 2 terms are the same and equal to this. So, this you could take it out and when you rewrite you get the final expression $\Delta\sigma$ is $\frac{e\eta I\lambda\tau(\mu_e+\mu_h)}{hcD}$. So, In some ways is very similar to the previous problem except that instead of putting numbers, you have divide a more general expression that takes into a account the life time of the carriers and also the excess carriers that are generated. Now, we tried to put some numerical values to this.

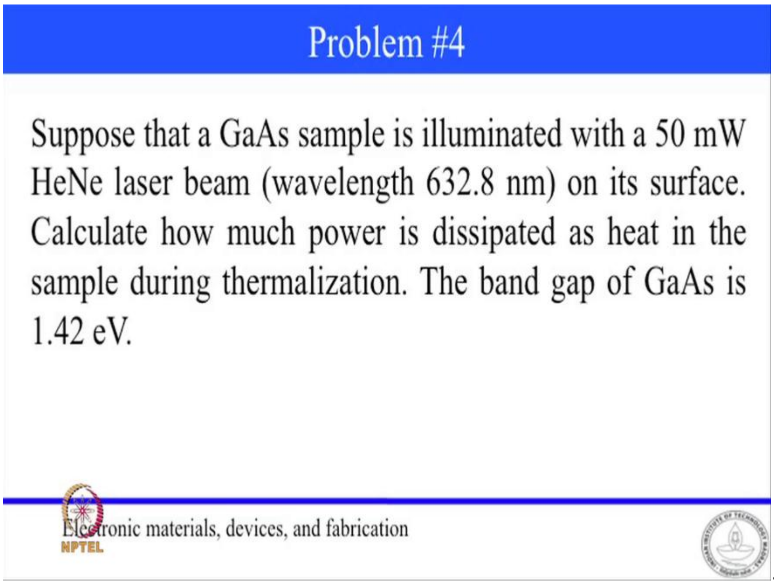
(Refer Slide Time: 29:28)



So, Now, we say that the material we have is cadmium sulfide with dimensions are essentially given, so 1 millimeter by 1 millimeter by 0.1 millimeter. The wavelength of the light is given, so lambda is 450 nm and intensity per unit area is 1 milli watt per centimeter square. We need to calculate the number of electron hole pairs per second. The quantum efficiency lambda is equal to 1. It is a same application of the formula. So, number of electron hole pairs G_{ph} per second is nothing but $\frac{A\eta I\lambda}{hc}$. A is the cross-sectional area, you can substitute all the values. So, this gives you 2.26×10^{13} S^{-1}, if you divide this by the volume you can get the number of electron hole pairs per unit volume.

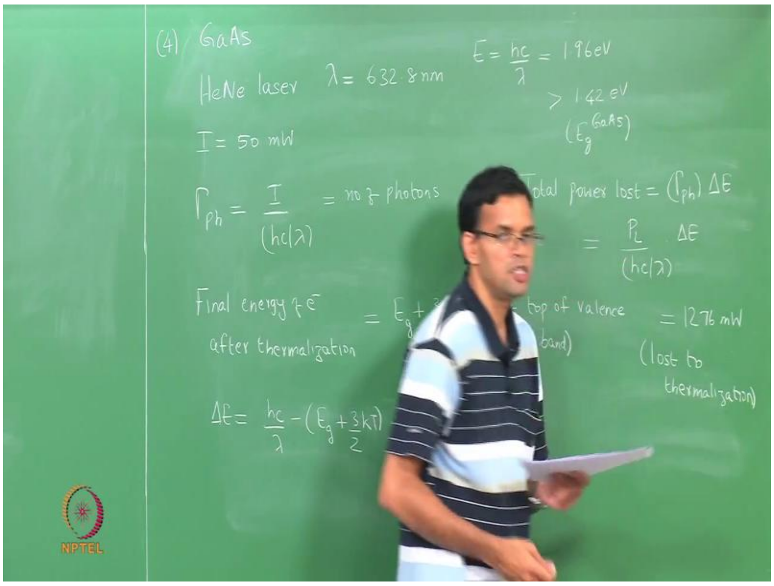
In part-b, we need to calculate the photo conductivity, so delta sigma is essentially $\frac{e\eta I\lambda\tau(\mu_e+\mu_h)}{hcD}$. So, this is the expression that we derived, all the values are essentially known μ_e and μ_h are also given. $\Delta\sigma$ works out to be 1.30 ω^{-1} cm^{-1}. In part-c, we need to calculate the photo current ΔJ when you apply a potential of 50 volts. ΔJ is nothing but $e\Delta\sigma$, so e is 50 volts. So, we can calculate ΔJ, this works out to be 6.50×10^4 amp m^{-2}. To calculate the current, so delta I is nothing but delta J times the cross-sectional area A, this is 6.5 milli amperes. So, let us now go to problem 4.

(Refer Slide Time: 32:39)



.

(Refer Slide Time: 32:44)



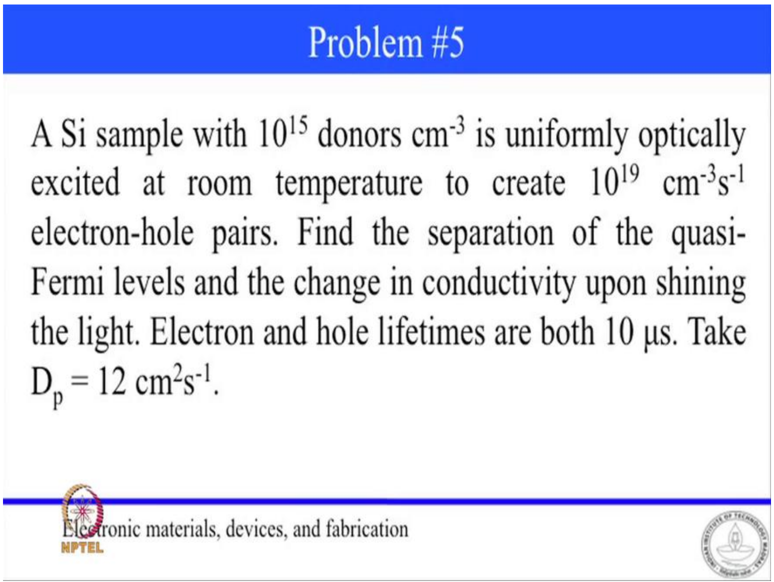
Problem 4: you have a gallium arsenide sample is illuminated with a helium neon laser beam. So, you have a helium neon laser, the wavelength of the laser light is 632.8 nm and the intensity is 50 milli watts. We want to calculate how much power is dissipated as heat in the sample due to thermalization. Once again we can calculate the energy, energy $E = \frac{hc}{\lambda}$ is 1.96 electron volts, so this is greater than E_g of gallium arsenide which is 1.42 electron volts. So, what happens is that the excess energy of the photons basically gets translated into excess energy of the electrons in holes, this excess energy is lost as heat to the surrounding material and this is essentially your thermalization process.

To calculate the energy lost or the power lost to thermalization we worse need to calculate the number of photons, this is again $\frac{I}{hc/\lambda}$ which gives you the number of photons. So, excess energy which is the electrons and holes possess are essentially lost to the lattice and when the energy is lost the electron comes close to the conduction band edge or the hole goes close to the valence band edge. There is always a certain thermal energy which the electron will possess, so the final energy of the electron after thermalization is nothing but E_g which is the band gap $+3/2kT$. This is with respect to the top of the valence band. So, that the top of the valence band is taken as 0. The energy of the electron after losing the access energy to the lattice is just $E_g + \frac{3}{2}kT$.

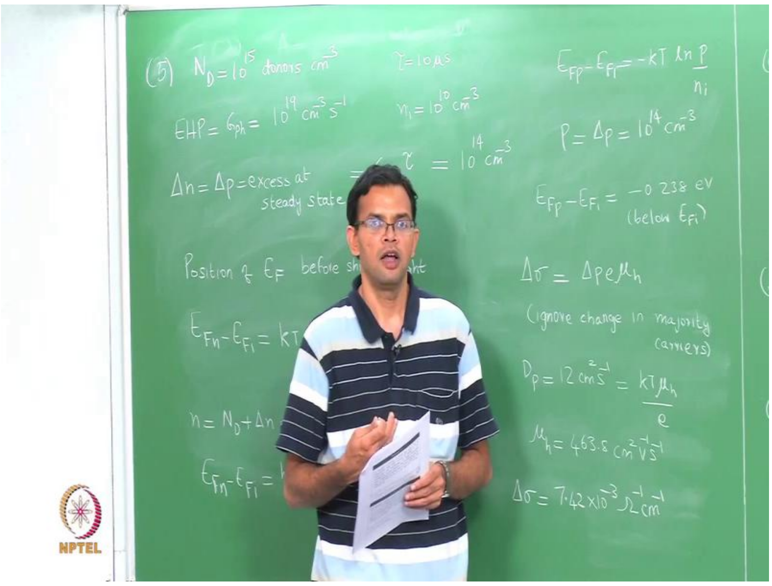
So, This is the initial energy of the electron, this is the final energy. So, the total energy lost delta E is nothing but $\frac{hc}{\lambda} - E_g + \frac{3}{2}$, this energy lost. If you do the numbers is 0.503 electron volts. So, this energy is lost by every electron that is generated which is equal to the total number of photons that are incident. So, The total power that is lost is nothing but γ_{Ph} ΔE which is nothing but the incident power $\frac{P_L}{hc/\lambda}\Delta E$. This is nothing but the ratio of the incident power to the final energy or the energy that is lost which depends upon the band gap. So, all these values are known P_L is 50 milli watts, So, if you substitute this works out to be 12.76 milli watts lost to thermalization. If you increased our energy of the incident right, so instead of helium neon with 1.96 electron volts, if you have a higher energy light the value of ΔE will be higher which means more amount of power will be essentially lost to thermalization.

So, This is important when we decide what kind of incident radiation we want in order to generate your electron hole pairs, so if there is a large miss match between the incident energy and the band gap of the material most of the heat will essentially be lost as thermalization. If you are trying to operate this in a form of a device this heat lost can basically increase the temperature of the device and cause the device to be more in efficient. Let us now go to the last problem.

(Refer Slide Time: 38:30)



(Refer Slide Time: 38:33)



Problem 5: You have a silicon sample with 10^{15} donors, so N_D is 10^{15} donors cm^{-3} is illuminated with light to create 10^{19} electron hole pairs. So, 10^{19} $cm^{-3}s^{-1}$.We need to find the separation of the quasi Fermi levels talk about it in a minute and the change in conductivity upon shining the light. So, These are the number of electron hole pairs that are generated. So, we need to calculate the excess carriers at steady state. This we have seen before is nothing but G_{ph} x τ, the value of τ is also given, so τ is 10 microseconds. So, that this is equal to 10^{14} cm^{-3}. N_D is 10^{15} this is silicon, so n_i is 10^{10}. So, Before shining light we can basically calculate the position of the Fermi level. So, we can calculate position of E_F before shining light, this is nothing but an n type semiconductor so that, $E_{Fn} - E_{Fi} = kT \ln \frac{N_D}{n_i}$this works out to be 0.298 electron volts and this is will be above E_{Fi}.

So, we now shine light and the light generates excess electrons in holes. So, your new electron concentration n is nothing but $N_D + \Delta n$ which works out to be $1.1 \text{ x } 10^{15}$ cm^{-3}. So, If you have an excess concentration of electrons, this will again cause a slight shift in the Fermi level. This is your quasi Fermi level, so the new $E_{Fn} - E_{Fi} = kT \ln \frac{N_D}{n_i}$, where the value of n is now 1.1. So, this gives you 0.3004. The shift is very small because the increase is not that much, but there is still a small shift in the Fermi level. You can also do a similar calculation for the holes. $E_{Fp} - E_{Fi} = kT \ln \frac{P}{n_i}$, where P is ΔP which is the excess carriers that are generated which is equal to 10^{14} cm^{-3}. If you do this $E_{Fp} - E_{Fi}$ is

- 0.238 electron volts, this is basically below E_{Fi}.

When we shine light on to the material, we generate excess electrons in holes, we can define a quasi Fermi level for these excess electrons and holes, and we just did calculation taking the n separately and taking the p separately. These do not reflect the real Fermi levels in the material because these are excess that are generated during illumination, but we can treat them as n and p type semiconductors and get an idea of where the Fermi level will be located. And now, we want to calculate the excess conductivity delta sigma, so we find that there is only a small increase in the electron concentration, but there is drastic increase in the whole concentration. So, The change in conductivity will be more or less driven by this excess whole concentration. So, delta sigma is nothing but $\Delta P e \mu_h$, so we ignore the change in minority carriers and only look. So, the ignore change in the majority carriers and only look in the minority carriers. μ_h is not known, but we do know the value of D_P. D_P is 12 cm^2 s^{-1} and this is nothing but $\frac{kT\mu_h}{E}$ k T mu h over E, so from this we can calculate the value for μ_h. μ_h works out to be 463.8 centimeter square per volt per second.

So, This we can substitute here and you can calculate the change in conductivity and this is driven by the excess holes 7.42×10^{-3} ω^{-1} cm^{-1}. So, we can treat a semiconductor which has a non equilibrium concentration of electrons and holes as essentially an n and the p-type separately, and then we can basically calculate the increase in conductivity and this increase in conductivity is mainly due to the increase in the minority carrier concentration.