Electronic Materials, Devices and Fabrication

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Module - 01
Assignment - 07
Optical Properties

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

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So, this is assignment 7, going to look at light matter interaction. So, during the course of the lecture, we first studied how generally lights interacts with semiconductor materials, within looked at in specific examples in applications of this. So, we looked at LED's, photodiodes, lasers, solar cells and so on. So, in this assignment, we will focus on the general interaction and in the next one, we will take a problem related to the specific devices, which a just mentioned.

So, we talked about light interacting with matter, the basic thing we said was at the energy of the light E must be grater then 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 the excited from the valence to the conduction band. We could also have situations where there are defect states or traps states, located within the band gap. So, these could be located either close the valence band or to the conduction band and the again the interaction of the light the semiconductor, causes carriers to exited from either the valence band and to the trap state or from the trap state to the conduction band. So, that is why E semi can not 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, this brief introduction, let me go the problems, as we go through the problems we will again related to the concepts that we delta within the lectures.

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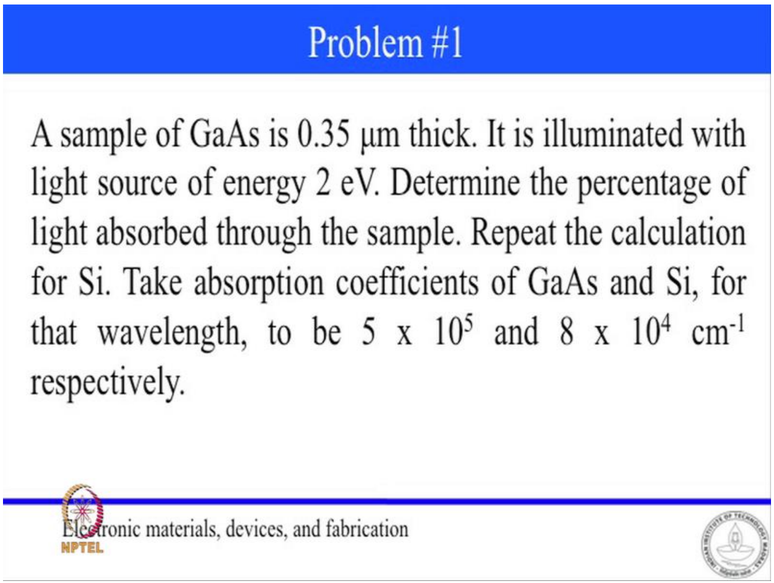

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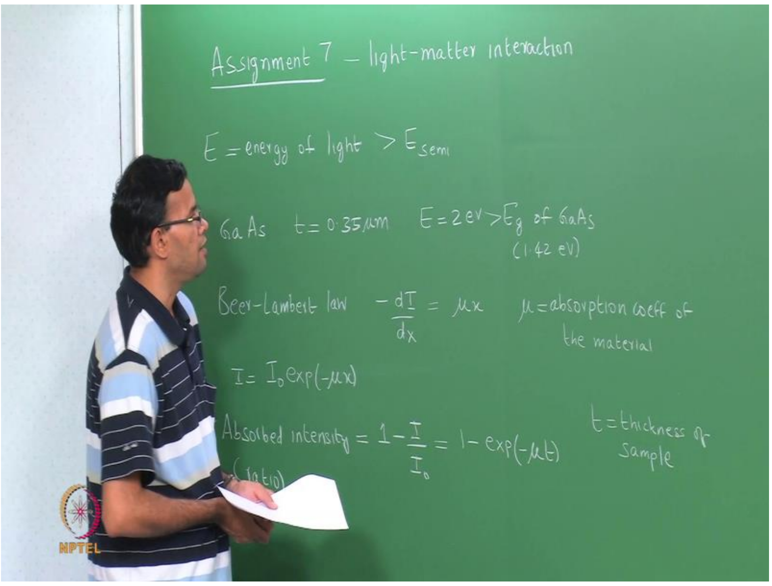

Problem 1. So, we have a sample of gallium arsenide which is 0.35 micro meters thick, it is illuminated with the light source and the energy is given. So, energy E is 2 electron volts. This is greater than the band gap of gallium arsenide, so E g of gallium arsenide, which is 1.42 electron volts. Determine the percentage of light, absorb through the sample and we want to repeat the calculation for silicon. So, when we look at light of the absorption through a material, we basically go back to the Beer Lambert law.

The Beer Lambert law's says that, the change in intensity over a small distance d x and there is negative sign because, the intensity actually goes down, is directly proportional to x and the proportionality constant is call mu. mu 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 gives us I is equal to I not exponential minus mu x. So, I here represent the transmitter intensity. So, if we want find the absorb intensity and if you want to find it as the ration, it is nothing, but 1 minus I over I not.

So, this is essentially a ratio, which we can convert to a percentage so which is 1 minus exponential minus mu. In this particular case, we have been given the thickness of the sample. So, t here refers to the thickness. So, we can basically use this expression to calculate the value for gallium arsenide.

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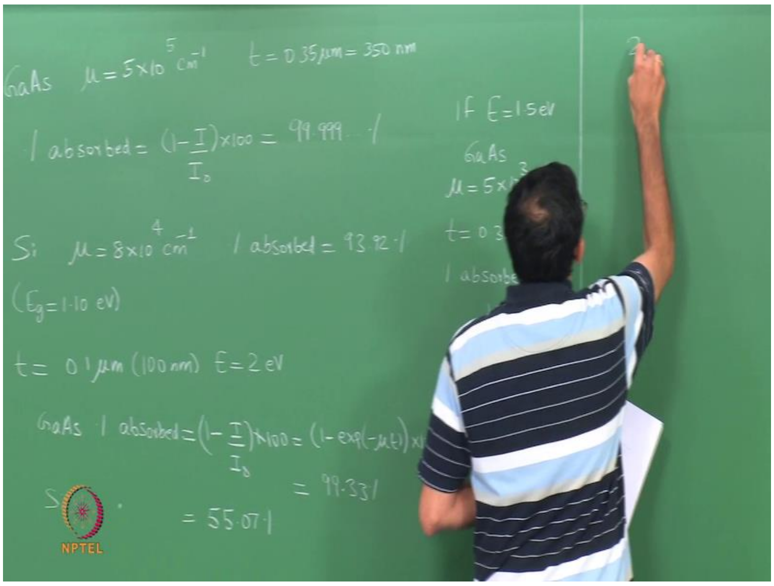

So, for gallium arsenide, the absorption coefficient mu is given. So, mu is 5 times 10 to the 5 per centimeter inverse. So, from this, we can calculate the percentage absorb which is just 1 minus I over I not times 100 and here we substitute all the values this works out to be 99.999 and there are few more trailing 9s which means, when you shine the light of 2 electron volts on a sample of gallium arsenide, there is only 0.35 micro meters thick. So, 0.35 is just; 350 nanometer. So, it is only 350 nanometers and almost; all the light absorbed so that, gallium arsenide is essentially opaque to this radiation.

We can do the same calculation for silicon the value of mu its 8 time 10 to the 4 per centimeter. So, silicon actually has lower band gap then gallium, gallium arsenide. So, E g of silicon is 1.10 electron volts at room temperature. So, even though it has lower E g, the value of the absorption coefficient a 2 electron volts is slightly lower than that of gallium arsenide and this basically related to how the density of the states is distributed in the valence and the conduction band. So, taking this value of mu, we can calculate the percent absorbed; can again plug in the numbers. This is 93.92percent. So, it is still a high number, but nearly 7 percent of the light gets through, well the reset is the absorbed.

So, we can actually go beyond and do some more calculations just to get a feel of this value. So, instead of 0.35 micrometers, I know reduce my thickness to 0.1 micro meters. This is approximately 100 nanometers. 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 percent absorb is 1 times 100, this is 1 minus exponential minus mu t times 100 and this is ninety 99.3. So, when we reduce the thickness further, so we actually take it down, were on 3 times, you go from 350 nanometers to 100 nanometers, still we get a really high percentage of light that is absorbed.

So, for silicon on the other hand, the percent absorbed for 100 nanometers is only 55 percent. So, only the half the light absorbed and the other half gets transmitter and other variable we can introduce, is to change the wave length of the energy of the light.

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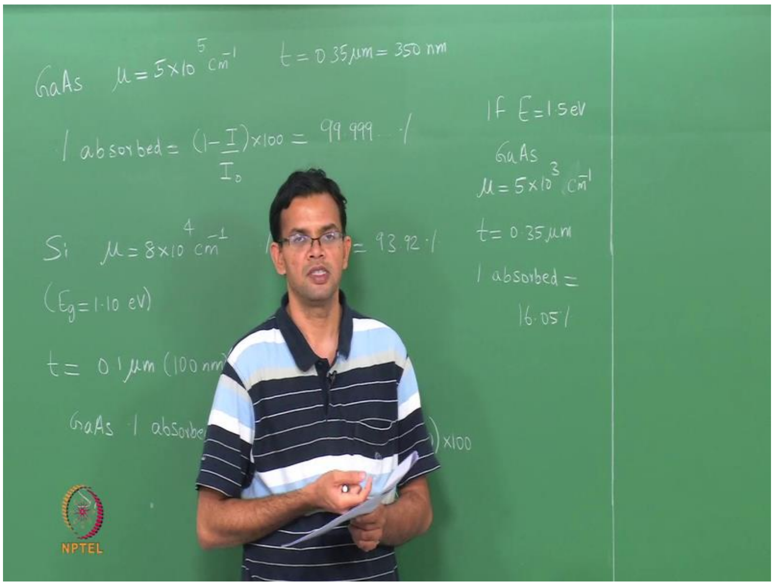

So, if you take energy to be 1.5 electron volts. So, instead of shining light of 2 electron volts, we shine light of only 1.5 electron volts. For gallium arsenide mu is lower, so its 5 times 10 to the 3 for centimeter, 5 time 10 to the 3 per centimeter. So, this is still above the band gap, but it is 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 micro meters, so the same 350 nanometers, the percentage absorbed fusing the same formula is only 16.05. So, nearly 84 percent of the light is transmitter, 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 get completely pass through or light to be absorbed. So, if we 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 the light essentially gets absorbed and only a small percentage of light get transmitted.

So, the value of mu and the corresponding at different wavelengths, something the place of very important role in determining the type of material you choose and also thickness of the material. So, let us now go to problem 2.

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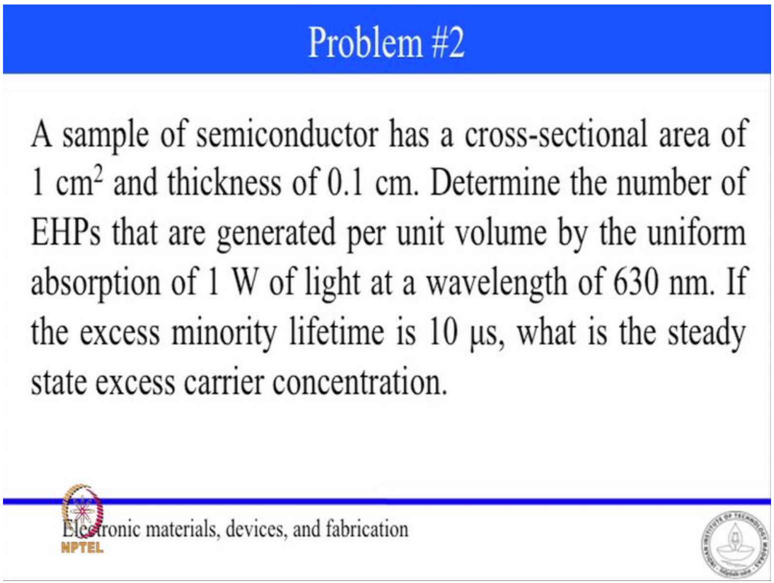

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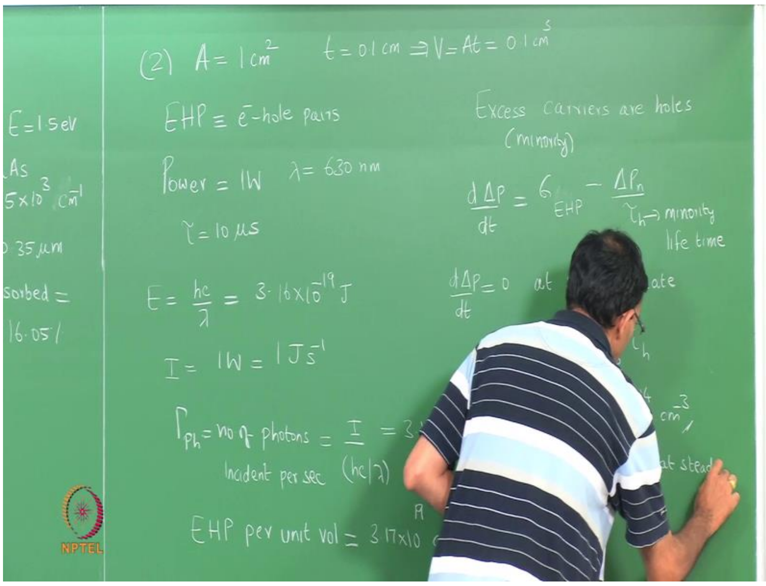

In problem 2, we have a sample of semiconductor, the cross sectional area A is 1 centimeter square and the thickness is 0.1 centimeters. So, you want to find out the number of electron hole pairs. So, EHP is nothing, but electron hole pairs. So, we want to find the number of electron hole pairs that at generated per unit volume, when you absorb light of 1 what. So, the power is 1 what and the wavelength lambda is 630 nanometers. In this particular case, the band gap of the semiconductor is not given, but we are going to take it, that is, that the light has sufficient energy to exit electrons across the band gap, so that, we can get electron hole pairs.

If, the x is minority lifetime is 10 micro seconds. So, the minority lifetime this 10 micro seconds. We are also calculate the study state excess carrier concentration. So, we look at the first part of the problem. So, we have light of wavelength 630 nanometers. So, the first thing is to calculate the energy. Energy is nothing, but h c over lambda, in this works out to be 3.16 times 10 to the minus 19 joules. So, we also know the intensity of the light. So, I is 1 watt which is 1 joule per second. So, we can calculate the total number of photons. So, this is the numbers of photons that add incident per second. This is equal to I divided by the energy. So, I divided by head see over lambda. So, we can plug in the numbers this works out to be 3.17 times 10 to the 18 photons per second.

So, we also want to calculate the electron hole pairs for unit volume. So, volume is nothing but A times t, so, 0.1 centimeter q. 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 quantum efficiency of 100 percent, usually that is not the case, the efficiency would be lower than hundred 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 percent. So, 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 10s to the 19 per centimeter cube per seconds. We just are dividing the number of photons by the volume. So, in the next part, we are asked to calculate study state excess carrier concentration. So, we do not know 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. We can do this same thing by assuming material to be a p type so that, the excess minority carriers are electrons, but it will not affect the final result.

So, these are the excess minority carriers. So, when we have light illuminating on a sample, it is possible to write an equation for the excess carriers. This differential equation just as d delta p over d t, so it delta p represents the excess minority carriers there are created this is equal to the number of electron whole piers that are generated, minus delta p n over h were h is the minority lifetime. So, when we basically have study state, delta p is 0. So d delta p over dt 0 at study state, which implies; the study state excess carrier concentration is nothing, but the number of electron hole pairs that as generated, times lifetime of the minority carriers.

So, this we can again substitute, we know the lifetime is given to be 10 micro seconds; the number of carriers per unit volume is something which is calculated.

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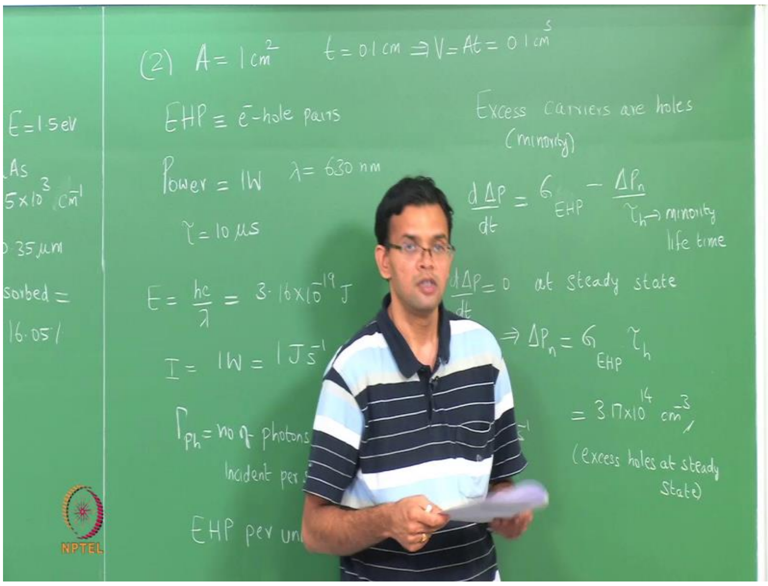

So, this is equal 3.17 times 10 to the 14 per centimeter q. So, these are the excess holes at study state. So, let us now go to problem 3.

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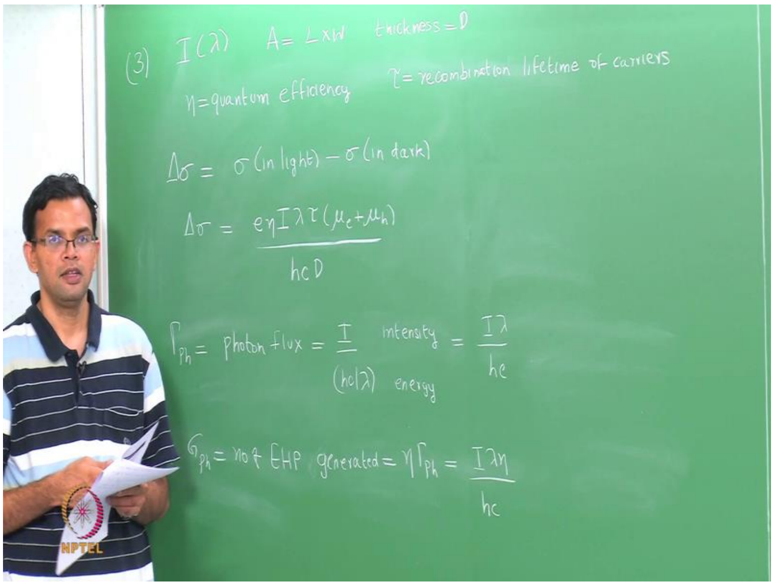

So, problem 3, we have a direct band gap semiconductor with no trap states. So, we do not have any defects or traps that are located within the band gap. So, this is important because, traps state can usually trap the carriers and these have longer lifetime then the electrons and the holes in the band. This will again change the carrier lifetime 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, so I of lambda. So, in this case I is a essentially of the function of the wavelength. This causes photo generation.

So, once again we are saying that the wavelength lambda 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 the eta is the quantum efficiency, quantum efficiency defines how many electron hole pairs are, how many photons are converted to electron hole pairs. In the last problem, we assume the quantum efficiency p to be 1 so that, every photon gets converted to a electron hole pair. It take the quantum efficiency to be 0.5 or 50 percent, if we have 2 photons coming in, only 1 of them will get converted to an electron hole pair.

The quantum efficiency is given and is the re combination of lifetime of the carriers. So, when we shine light in a 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 call photo conductivity and that difference in conductivity delta sigma is defined as sigma in the presence of light, minus sigma in the absence of light typically that is a dark state. And we have to show that, delta sigma is equal to e eta I lambda mu e plus mu h over h c d.

So, 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 gain first thing we need to do is to calculate the number of photons or the photon fluxes that is incidents on the samples. So, 5 ph is photon flux, this is given by I is the intensity divided by h c over by lambda, which is the energy. So, this is the intensity and then this is the energy. So, this is I lambda over h c.

So, we define quantum efficiency, as the number of the electron whole pairs that are generated for a certain photon flux. So, it G ph which is the number of electron whole pairs generated nothing, but eta which is the quantum efficiency times gamma p h, so this I lambda eta over h c. So, in this particular problem, the intensity is given per second. So, intensity is given per unit area. So, it calculate volume change or to calculate the number of electron hole pairs there are generated for unit volume, we basically need to multiply by the area and also divide by the volume.

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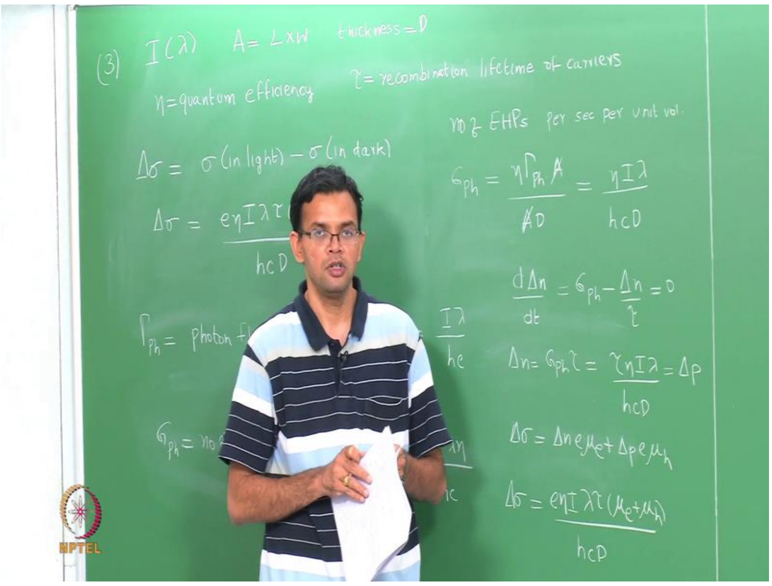

So, the number of electron hole pairs per second per unit volume. So, again I am going to use the same symbol G p h, but now this for unit volume is nothing, but eta cans gamma p h times A divide by the volumes. So, A can get cancelled, we can plug in the value of gamma p h. So, this is nothing, but eta I lambda over h c d. So, again we have a steady state situation. So, we can write the continuity equation.

So, if we take the excess carriers to be electrons, then b delta n over d t is nothing, but G p h minus delta n over. And at steady state, this change is equal to 0. So, delta n is G p h times, we can substitute that expression. So, it is tau eta I lambda over h c D. So, this is the excess electrons there are generated, this must be the same as the extra holes because, electron hole pairs are generated. So, every time in electron is generated holes is also generated.

So, the change in conductivity delta sigma is nothing, but delta n e mu e plus delta p e mu h. These 2 terms are the same an equal to this. So, this you could take it out and when you re write, you get the final expression delta sigma is e eta I lambda u e has mu h divided by h c D. So, in some ways is very similar to the previous problem, excepted that instead of putting numbers, we have divide a more general expression that takes into account, the lifetime of the carriers and also the excess carriers there are generated.

So, now, we try to put some numerical values to this. So, now we say that, the material we have cadmium supplied.

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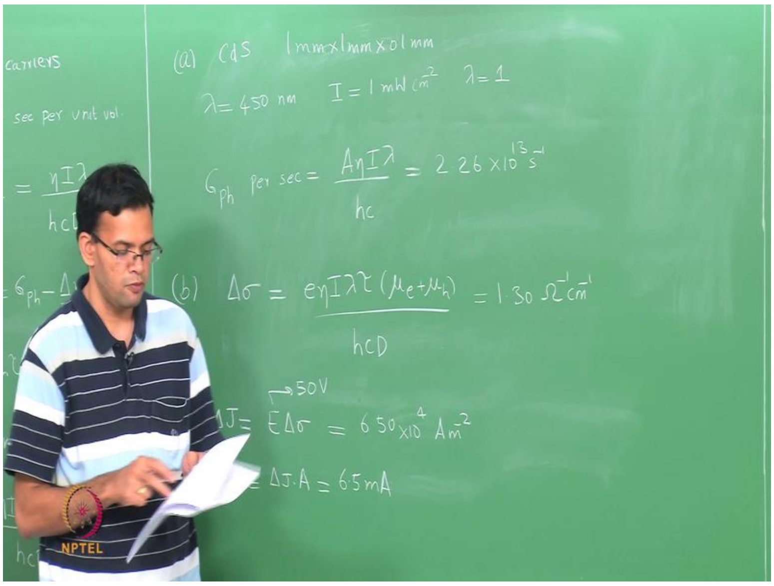

The dimensions are essentially given, so 1 millimeter by 1 millimeter by 0.1 millimeter. The wavelength of the light is given. So, lambda this 450 nanometers and intensity for unit area is 1 milli watt per centimeters square. So, we need to calculate the number of electron hole pair per second. The quantum efficiency lambda is equal to 1. So, it is a same application of the formula. So, number of electron hole pairs G p h per second is nothing, but a eta I lambda over head c, A is the cross sectional area, can substitute all the values. So, this gives you 2.26 times 10 to the 13 per second. If we divide by this the volume, you can get the number by the electron hole pairs for unit volume.

In part b, we need to calculate the photo conductivity. So, delta sigma is essentially e eta I lambda tau mu e plus mu h divide by h c and D. So, this is the expression that we derived. All the values are essentially known, mu e and mu h are also given. So, delta sigma works out to be 1.30 inverse centimeter inverse. In part c, we need to calculate the photo current delta j and you apply a potential of 50 volts. So, delta j is nothing, but e times delta sigma. So, e is 50 volts. So, we can calculate delta j this works out to be 6.50 times 10 to the 4 amperes per meter square. We calculate the current, so delta I is nothing, but delta j times the cross sectional area. This is 6.5 milli amperes.

So, let us now go to problem 4.

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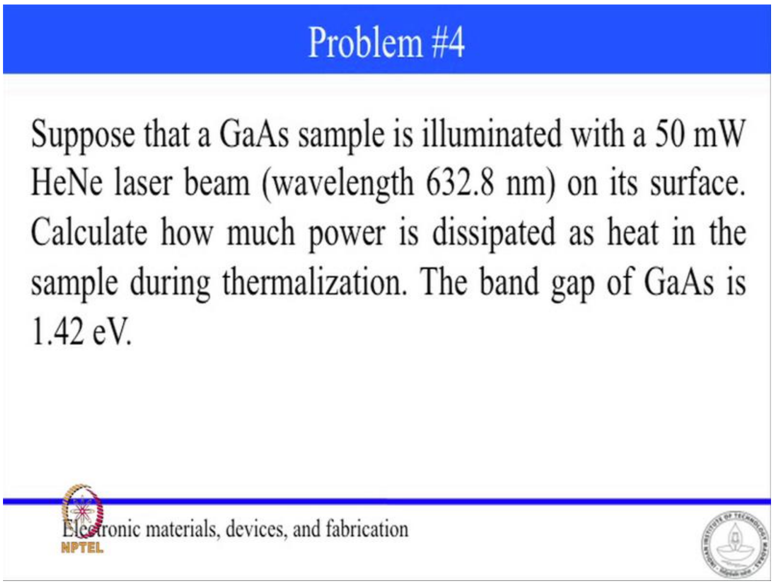

So, problem.

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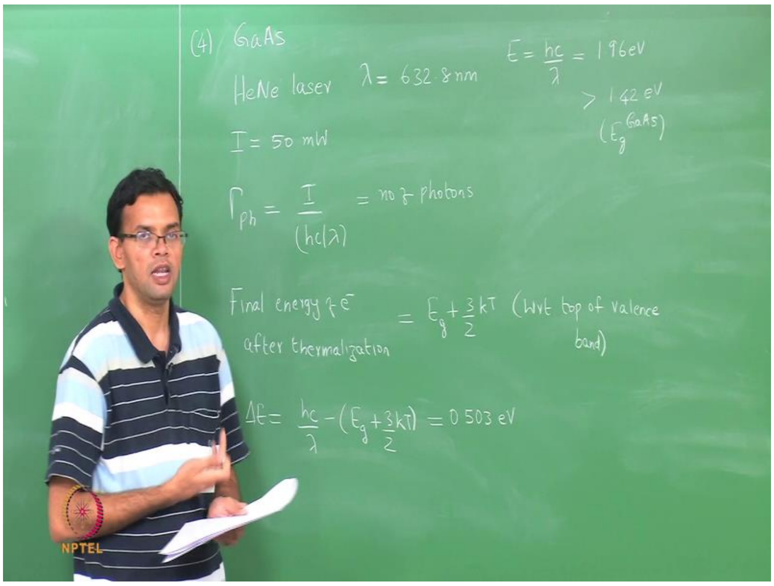

So, problem 4, we have gallium arsenide sample is illuminated with the helium neon laser b. So, you have a helium neon laser. The wavelength of laser light is 632.8 nanometers and the intensity is 50 mill watts. We want to calculate how much power is dissipated as heat in the sample due to thermalisation. So, once again, we can calculate the energy. Energy E equal to head c over 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 in to excess energy of the electrons in holes. This excess energy is lost has heat to the surrounding material and this is essentially a thermalisation process. So, it calculate the energy lost of the power lost thermalisation, we worst need to calculate the number of photons this is again I over h c over lambda, which gives you the number of photons. So, excess energy which is the electrons and holes posses are essentially lost to the lattice and when the energy is lost, the electrons come close to the conduction band edge or the hole goes close to the valence band edge. Here is a always a certain thermal energy which the electron will posses.

So, the final energy of the electron after thermalisation is nothing, but E g which is the band gap plus 3 over 2 k T this is with respect to the top of the valence band so that, the top of the valence band is taken as 0. So the energy of electron, after losing the excess energy to the lattice is just E g plus 3 half k T. So, this is the initial energy of the electron this is the final energy. So, the total energy lost delta E is nothing, but h c over lambda minus E g plus 3 halves k T. This energy lost we do the numbers is 0.503 electron volts. So, this energy is lost by electron that is generated, which is equal to the total number photons that are incident.

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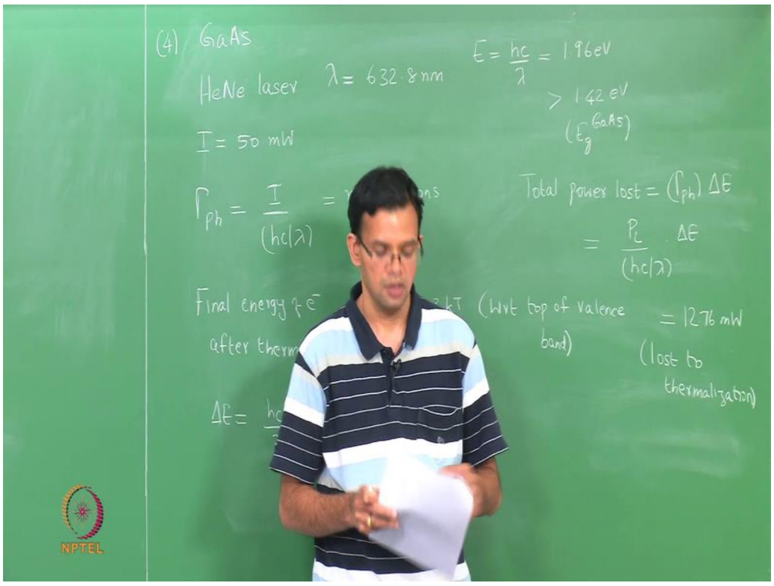

So, that the total power that is lost is nothing, but gamma p h times delta E which nothing, but the incident power p l divided by h c over lambda times delta E. So, this is nothing, but the ration of the incident power to the final energy of the energy that is lost, which depends upon the band gap. So, all these values are known; p l is 50 milli watts. So, if you substitute this works out to be 12.76 mili watt lost to thermalisation.

If you increase the energy of the incident right, so instead helium neon with 1.96 electrons volts, we have a higher energy light. The value of delta E will be higher, which means more amount of power will be essentially lost to thermalisation. So, this is important, when we decide what kind of incident radiation we want in order to generative electron hole pairs. So, if there is large mismatch between the incident energy and the band gap of the material, most of the heat will essentially will be lost thermalisation. If we trying to operate this in the form of device, this heat lost in basically increase the temperature of the device and cause the device to be more inefficient.

Let us now go to the last problem.

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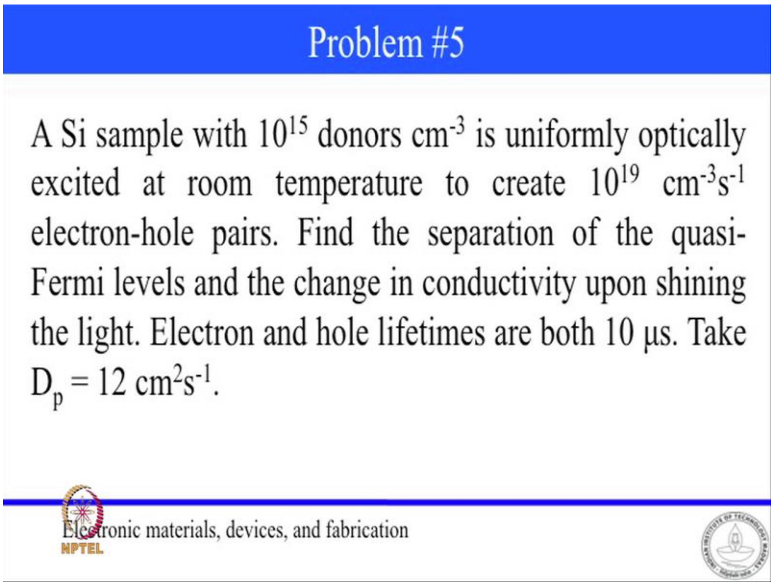

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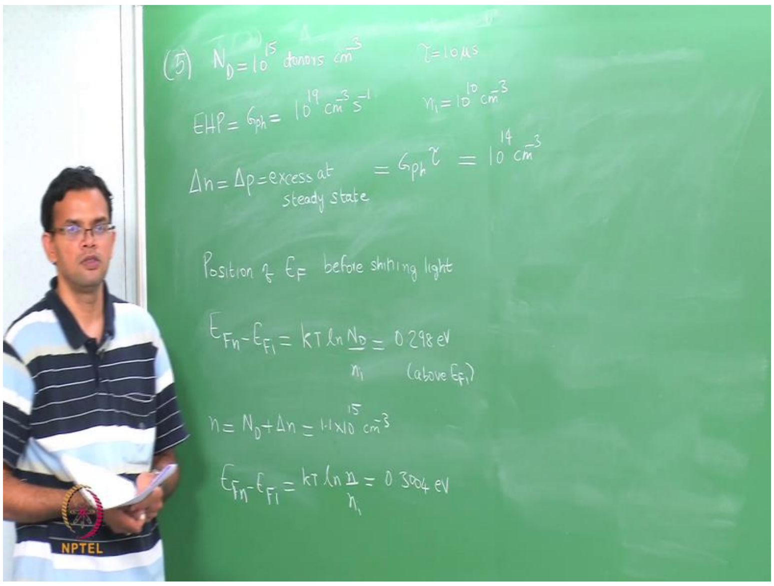

Problem 5: you have a silicon sample with 10 to the 15 donors. So, N D is 10 to the 15 donors per centimeter q is illuminated with light to create 10 to the 19 electron hole pairs. So, 10 to the 10 per centimeter cube per second. So, we need to find separation of the quiz firmy levels, talk about it in the minute and the change in conductivity upon shining the light. So, these are number of electron hole pairs there are generated. So, we need to calculate the excess carriers at study state. This we have seen before is nothing, but G p h times tau. The value of also given, so is 10 micro seconds so that, this is equal to 10 to the 14 per centimeter cube. So, N D is to 10 to the 15, this is silicon. So, n i is 10 to the 10.

So, before shining light, we can basically calculate the position of firmy level. So, we can calculate position of E F before shining light. So, this is nothing, but an n type semiconductor. So, that E f N minus E F I is k T lon of N D over n i. This works out to be 0.298 electron volts and this will be above p f I. So, we now shine light and the light generates excess electrons and holes. So, you new electron concentration n is nothing, but N D plus delta n which works out to be 1.1 times 10 to the 15 per centimeter cube.

So, we have excess concentration of electrons, is will again cause a slight shift the firmy level. This your quazi firmy level. So, the new E F N minus E f I is k T lon n over n i were the value of n is now 1.1. So, this gives you 0.3004. The shift is very small because, increase is not that much, but there is still a small shift in the firmy level.

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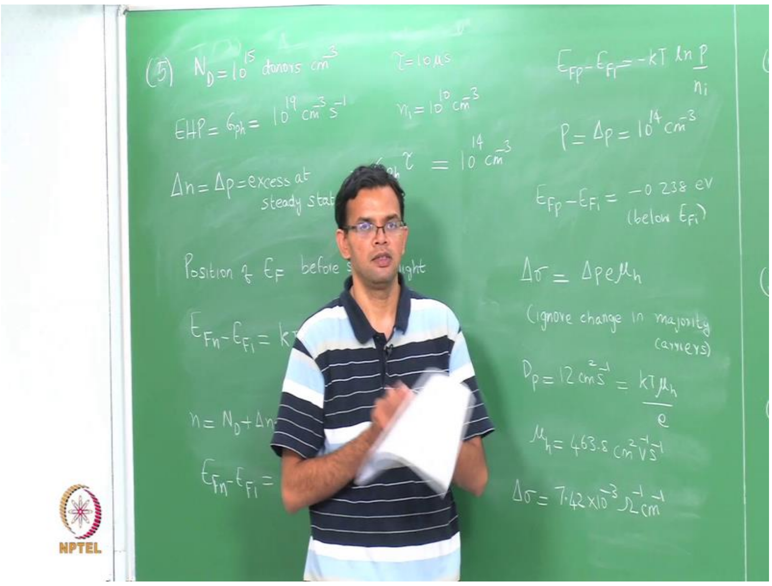

We can also do a similar calculation for the holes E F P minus E F I is minus k T lon of P over n i at P is delta P which excess carrier then there are generated. This is equal 10 to the 14 per centimeter cube. So, if you do this E F P minus E F I is minus 0.238 electron volts, this is basically below E F I. So, when we shine light on to the material, we generate excess electrons in the holes, we can define a quazi firmy level for this excess electrons and holes and we just take the calculation, taking the n separately and the taking the p separately. These in not reflect the real firmy level in the material because, these are excess that are generated during elimination, when we can treat them as n an p type semiconductors, in get an idea of where the firmy level will be located.

We now want to calculate the excess conductivity delta sigma. So, you find that, there is only a small increase in the electron concentration, but there is a drastic increase in the hole concentration. For the change in conductivity, we do more all as driven by this excess hole concentration. So, delta sigma is nothing, but delta P E mu h. So, we ignore the change in minority carriers an only look. So, ignore the change in the majority carriers an only look in the minority carriers. So, mu h is not known, but we do know the value of D P, D P is 12 centimeter square per second and this is nothing, but k T mu h over E.

So, from this we can calculate the value for mu h, mu 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 times 10 to the minus 3 on inverse centimeter. So, we can treat a semiconductor, which has non equilibrium concentration of electrons and holes has essentially and n and the p type separately. And then, we can basically calculate the increase in conductivity and this in increase in conductivity is mainly; due to the increase in the minority carrier concentration.