Introduction to Semiconductor Devices
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Lecture - 11.1
Optical Absorption and Bandgap

Hello, everyone. Let us get started. So, in the last 10 weeks of the course, we have looked at the electronic devices. We have understood how to analyze their properties in sufficient depth I believe. So, now, in the last 2 weeks of this course, we would like to focus on optoelectronic devices. Why are we interested in them? Well, it turns out that the optoelectronic or the photonic devices are very important part of the current technology.

We see you know, solar cells, LEDs, you know lasers all of these are optoelectronic devices. And, we can apply the concepts that we have learned so far to understand how these devices work. So, because of this critical importance of this technology, we would like to discuss it now. And to start with, we will have to understand optical absorption.

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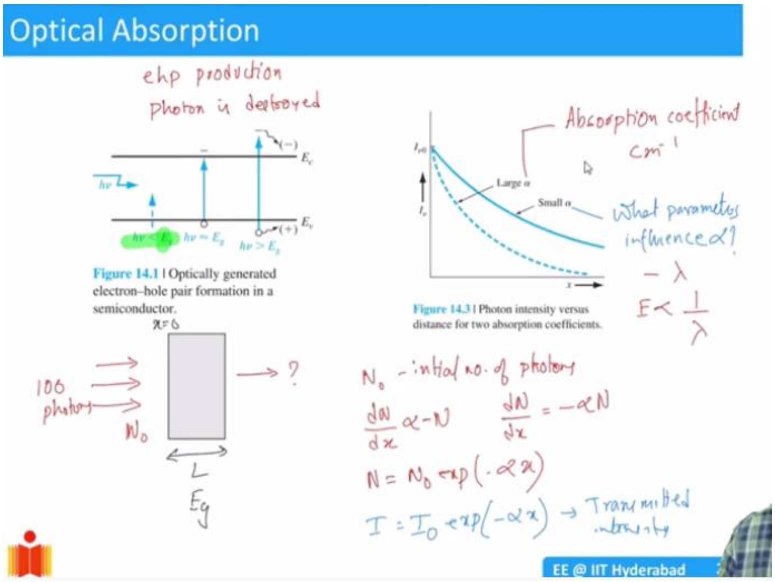

Optical Absorption

ehp production
photon is destroyed

Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

Absorption coefficient
cm^{-1}

What parameters influence α?
– λ
$E \propto \frac{1}{\lambda}$

Figure 14.3 | Photon intensity versus distance for two absorption coefficients.

N_0 - initial no. of photons

$\frac{dN}{dx} \propto -N$ $\quad$ $\frac{dN}{dx} = -\alpha N$

$N = N_0 \exp(-\alpha x)$

$I = I_0 \exp(-\alpha x)$ → Transmitted intensity

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So, we have briefly mentioned it, you know, multiple times in this course already. So, let us say you have a semiconductor and then we shine light on it. What happens? We said that let us say the semiconductor has a bandgap of in this case let us say Eg. If the energy of the photon is less than Eg, the photon does not have sufficient amount of energy to excite an electron hole pair. We talked about it already.

So, now, if the photon has energy equal to Eg or greater than Eg, what would happen? Well, it will take an electron out of the conduction band and put it in the valence band. What does it mean physically? Well, when the electron is in a valence band, we are saying that the electron is bonded to the, you know silicon atoms. It is part of the covalent bond. Now, when a photon hits the material, the covalent bond is broken with the photon has sufficient energy.

When the proton has sufficient energy, the covalent bond is broken. And then, the electron moves into the conduction band meaning with that it can move freely move about in the lattice. So, essentially, electron hole pair is produced. What happens to the photon? The first effect is you have electron hole pair production. And, what happened to the photon? Well, photon is annihilited. Photon is destroyed or annihilited.

There is no more a photon. The energy of the photon, photon is essentially energy packet. So, the energy is consumed by the, you know during the process of breaking the bond and there is no more a photon. So, the photon is destroyed. So, how do we quantify this you know? So, let us say if I take a piece of semiconductor, and I shine, let us say 100 photons on that. 100 photons is a very small number.

But, let us say I managed to shine 100 photons on this semiconductor. And let us say the thickness of the semiconductor is L or T, whatever L. If the thickness is L and we know the bandgap, of course, Eg something is there, so, how many photons will come out of this? That is a problem we want to understand. So, to analyze this, well, the number of photons that comes out is the photons that are remaining.

Some of them are getting absorbed. And the absorption will lead to reduction in the number of photons. So, let us say I have 100 photons incident on the left side now. Let us call it maybe x equal to 0 here. x equal to 0. There will be 100 photons. But, the moment, let us say they go you know let us say L by 2 distance, midway through. There might be only 50 of photons. 50 of them are got they got absorbed.

So, basically, what we are interested in is, let us say if your initial number is N or N_o let us say. If the initial number of photons is N_o, how much you know initial number of photons how many photons are surviving at a distance x? So, what we are interested in is dN by dx the change in the number of photons as a function of distance. Well, obviously, the change is going to be proportional to the number of photons at a particular distance.

So, this will be proportional to N. So, therefore, what we do is we say that dN and well the number of photons reduces. So, there should be a minus N here. It should be proportional to minus of N. So, as the number of photons is larger, the greater number of photons will be reduced. So, dN by dx, we will introduce a constant of proportionality and say that we call it α. So, dN by dx is equal to α times N.

$$\frac{dN}{dx} \propto -N \qquad \frac{dN}{dx} = -\alpha N$$

So, if you solve this, it turns out that this will be N equal to N naught exponential minus α x.

$$N = N_o \exp\,(-\alpha x)$$

Sometimes, we can also instead of talking in terms of number of photons we can also talk in terms of intensities. The optical intensity that gets transmitted is essentially equal to I naught exponential minus α x, same thing

$$I = I_o \exp\,(-\alpha x)$$

. So, this is I can call it transmitted intensity. Now, we can plot this and that is what is shown here, but, 2 different values of α.

And this α, we will call it as absorption coefficient. Let us all call it as absorption coefficient. And its units, generally we will refer to them in terms of centimeter inverse per centimeter inverse, per centimeter rather. So, if you have a larger absorption coefficient that means the number of photons will decay faster. The intensity will fall faster. That is what is shown here, larger α.

And, if you have a smaller α, the absorption coefficient is small that the photons will continue to go forward. So, now, based on our knowledge of semiconductor devices, is α fixed quantity for a material? Or, what are the parameters that affect α? So, think about it. So, what parameters influence α? Well, we know that, if the wavelength, it is definitely a wavelength dependent quantity.

Because, we know that wavelength if it is larger than you know if the wavelength is smaller than Eg that is energy is larger than Eg, then it will be absorbed. If the wavelength is longer, so, you know that energy is inversely proportional to λ. So, if the wavelength is longer, the energy of the photon is smaller than the Eg, let us say. And then, it will be transmitted. So, α is going to be dependent on λ. That is one critical parameter.

So, well, I mean, in the sense, it is depends in the bandgap indirectly that we can say that it is dependent on λ. So, of course, there is also other things like, you know there is some variations in terms of temperatures and other parameters and even the smoothness of your surface. So, but we will not get into it. Those are like secondary effects. So, this is how you will calculate optical absorption. Why is this important to us?

Well, it is important because it helps us understand many things that we see around us. Like for example, I am wearing glasses now. So, why are these glasses transparent? You might ask. So, the reason they are transparent is we know that the bandgap of silicon dioxide.

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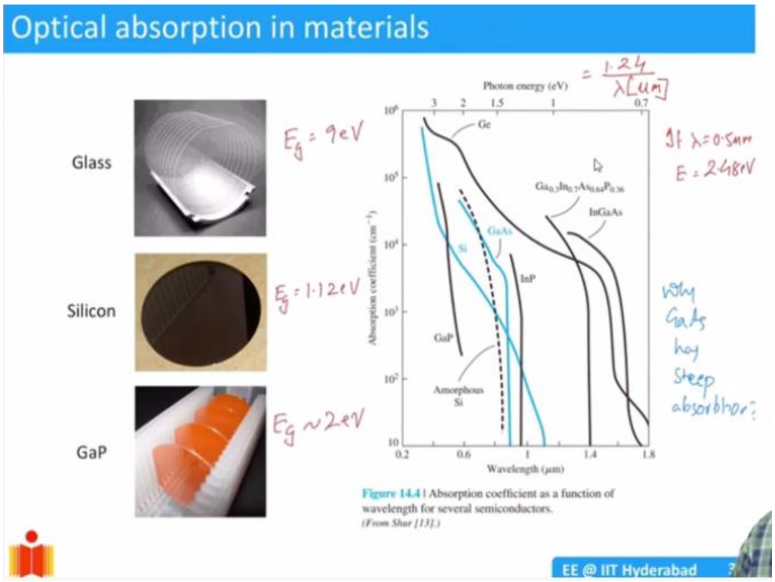

Optical absorption in materials

Glass

$E_g = 9eV$

Silicon

$E_g = 1.12eV$

GaP

$E_g \sim 2eV$

$= \frac{1.24}{\lambda[um]}$

If $\lambda = 0.5um$

$E = 2.48eV$

why GaAs hay steep absorbtion?

Figure 14.4 | Absorption coefficient as a function of wavelength for several semiconductors.
(From Shur [13].)

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Glass is essentially silicon dioxide. And, bandgap of silicon dioxide is Eg is about nine 9 eV. And one of the easy ways to calculate you know the photon energy is basically let us say I have a photon of let us say 500 nanometers. 500 nanometers means it is equal to 0.5 microns. So, what is the energy of that photon? That energy of photon will be given by if λ equal to 0.5 microns, energy will be 1.24 divided by 0.5.

You know we have to write λ in microns. And, this will be 2.48 eV. So, I if I have a visible like this is green light, λ is λ equal to 500 nanometers essentially green light. So, when it you shine, when you shine green light on a piece of glass, it is its energy is the photon energy is smaller than the bandgap. So, it gets transmitted. So, you can actually look, analyze and understand that you know, the visible range of variation is from 300 to 700 nanometers.

So, if you shine any of these photons on piece of glass, they get transmitted. That is why glass is transparent. The same analysis can be used to understand why silicon is not transparent. This is a image of silicon I have taken from the web. And, we know that silicon’s bandgap is 1.12 eV. What happens if I shine a visible light photon on it? Visible light let us take the center one, 500 nanometers. So, it is 2.48 eV energy of the photon.

And, if you shine 2.48 eV, photon on a silicon piece, then it definitely will get absorbed. And that is why if you put a piece of silicon between you and a light source, light will not pass through it. And, that is why we see that it is more transparent. And, we also have some interesting materials like you know gallium arsenide, gallium phosphide. Here, I have taken another image. This is a wafer of gallium phosphide.

And gallium phosphide, I think has a band gap of about 2 eV about I do not remember the exact number but Eg should be about 2 eV. So, what that means is the red photons are transmitted. So, if you this is, let us look at this figure and that will help you understand this. So, on the x axis of this figure, we are having wavelength 0.2 to 1.8 microns. On the top, for the same corresponding wavelengths, we have the energy calculated.

So, simply, we can calculate it by 1.24 by λ. So, we have this energy is given. So, if the energy is 2 eV, so, in this scale, if the λ you know if the energy of the photon is anywhere here, it will get transmitted. Only for the photons, which have energy greater than this, will get absorbed in the gallium phosphide. So, that is what is happening. So, the red photons you know because generally 700 nanometers 600 nanometers are red region of the spectrum.

If you go to violet, it will be you know, blue you know, blue region of the spectrum we say. So, the red region of the spectrum is getting transmitted. That is why it looks reddish yellow. This is gallium phosphide. So, you clearly can understand that the bandgap influences the transmission properties of a material. And this picture here on the right is showing you the absorption coefficient for various semiconductors.

So, you notice some trends here, which is, all the materials have low absorption at long wavelengths, all of these materials shown here. And it is been the familiar once plus, which is silicon. Silicon is shown in blue here. So, absorption is increasing. And this is a logarithmic scale, remember. So, if you go to lower wavelengths than the bandgap you know, so, bandgap, I am using in terms of you know wavelength or energy.

I can use you know equivalently. So, if your wavelength is lower than the bandgap, then it is getting absorbed. Equivalently, if the photon energy is greater than the bandgap, it is getting absorbed. Similarly, you can look at gallium arsenide. Gallium arsenide has a very steep increase in the absorption and then continues to increase further to lower wavelengths. So, what is the difference? Why gallium arsenide has a steep absorption?

Why Ga gallium arsenide has steep absorption? And its wavelength just you know below bandgap, it simply absorbs very fast. Why? If you look, if you notice a few other compounds like indium phosphide also has a very steep absorption. I will talk about this other things in the next few lectures. We will get back. But, if you look at germanium, germanium has a more gradual change in the bandgap.

Of course, germanium’s bandgap is only 0.8 eV, roughly around 0.8 eV. So, that is why it starts absorbing even at longer wavelengths. So, this is all the trend is. So, the reason this happens is something to do with the direct and indirect nature of a bandgap.

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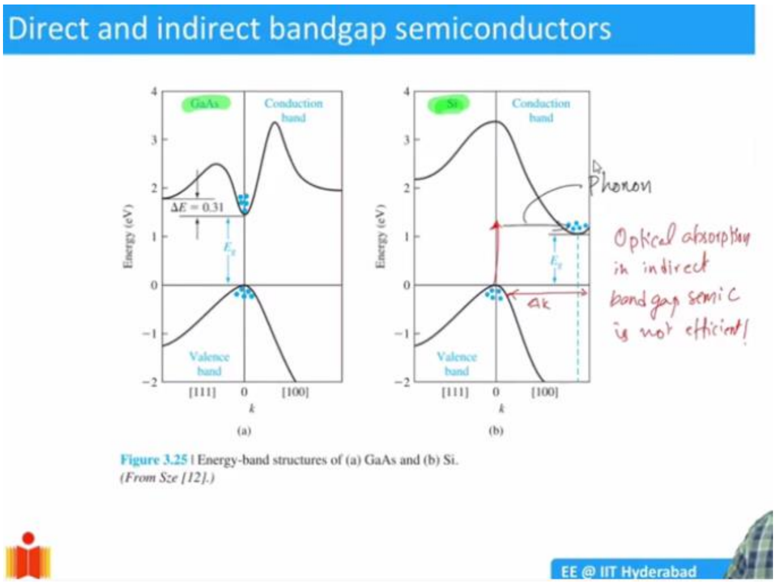

Direct and indirect bandgap semiconductors

Optical absorption in indirect bandgap semic is not efficient!

Figure 3.25 | Energy-band structures of (a) GaAs and (b) Si.
(From Sze [12].)

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I mentioned this in the beginning of the course. Wherein, we talked about the E-k diagrams and how to analyze, how we get E-k diagrams. And we mentioned that if the peak of the valence band is coinciding with the bottom of the conduction band, we call it a direct bandgap semiconductor. And that is what we have here, gallium arsenide which is a direct bandgap semiconductor.

Whereas, if you look at silicon, if you look at the E-k diagram, it turns out that the peak in the valence band is not coinciding with the bottom of the conduction band. There is a difference in k because of which silicon this is called as an indirect bandgap semiconductor. And generally, indirect bandgap semiconductors are not efficient absorbers of light. Because of, because you essentially need an additional phonon to get, you know because this k is there.

There is a difference in k. This is I would say, Δk you can call it, the difference in energy. And we already saw that the photon has very, you know it has good amount of energy, but it has negligible momentum. So, a photon can only make a transition happen from here to here. It cannot make a transition happen from here to here. So, for this, you need a phonon which will assist the transition. And it is a second order process.

And because of which the optical absorption in indirect bandgap semiconductors is not efficient. It does not mean that they are useless. They are still useful, but the absorption efficiency is less whereas in a direct bandgap semiconductor, it is very efficient. There is no momentum requirement. Only energy conservation is required. And because of which they are very efficient in absorbing the photons.

So, that is why you look at it, there is a very steep increase in the absorption above bandgap in a direct bandgap semiconductor material. Whereas, in indirect bandgap, we have more you know for more if you have higher and higher energy you need more phonons to help the absorption process. And eventually, it increases. But, it is not. It is a gradual process gradual increase. This is one key difference between direct and indirect bandgap semiconductors.

Let us try to you know this is mainly what I wanted to talk about optical absorption. Let us try to solve a couple of problems so that you get confident about it.

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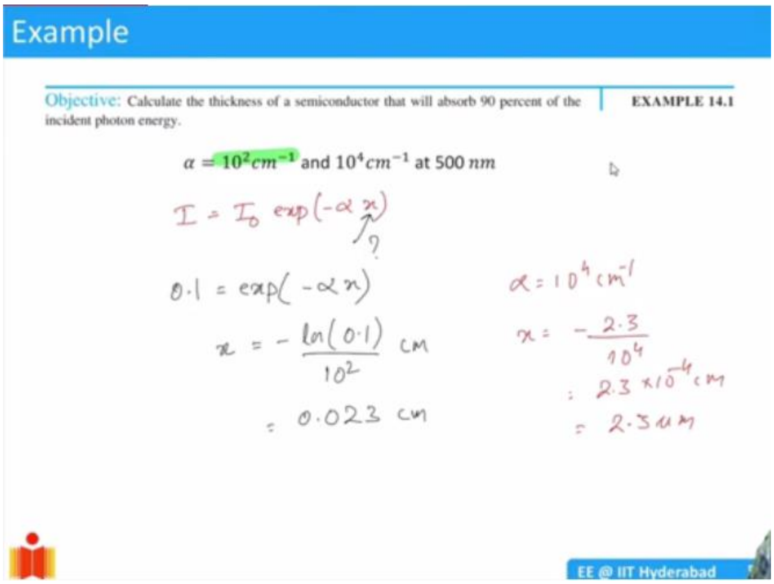

Example

Objective: Calculate the thickness of a semiconductor that will absorb 90 percent of the incident photon energy.

EXAMPLE 14.1

$\alpha = 10^2 cm^{-1}$ and $10^4 cm^{-1}$ at 500 nm

$I = I_0 \exp(-\alpha \overset{?}{x})$

$0.1 = \exp(-\alpha x)$

$x = -\frac{\ln(0.1)}{10^2}$ cm

$= 0.023$ cm

$\alpha = 10^4 cm^{-1}$

$x = -\frac{2.3}{10^4}$

$= 2.3 \times 10^{-4}$ cm

$= 2.3 \mu m$

So, this is an example from the textbook. So, you are given, calculate the thickness of a semiconductor that will absorb 90% of the incident photon energy whether you talk of incident photon energy or incident intensity or number of photons all of them are equivalent. So, when will it absorb 90% of the photon energy? Well, we know that law is basically I equal to I naught exponential minus α x.

$$I = I_o \exp(-\alpha x)$$

So, if the, let us say initial photon energy is you know 1, so, it has to lose 90% of the energy. What is the thickness? We want to find this thickness. What is this thickness? So, let us say the remaining energy is basically going to be 0.1. So, 0.1 equal to exponential minus α x. So, I need to use some α. So, this number is given I just copy pasted. Let us say, it is 10 power 2 per centimeter inverse at 500 nanometers. Just as an example.

If you do that quickly you can calculate this. So, the length or x in this case is going to be ln of 0.1 divided by α in centimeters.

$$x = \frac{-\ln{(0.1)}}{10^2} cm$$

So, α is rather 10 power 2 here. This is going to be centimeters. x in centimeters. So, this is going to be ln of 0.1. I think is minus 2.3. So, this will be going to 2.3 minus minus will cancel out. 2.3 divided by 10 square. So, that is going to be 0.023 centimeters. This is the thickness.

So, in other words, this is well 0.023 centimeters, 0.2 millimeters. So, what happens if the absorption coefficient is larger? If in case, α is like 10 power 4, this is a case two basically α equal to 10 power 4 per centimeter in per centimeter, then x is going to be minus 2.3 divided by 10 power 4. So, that is going to be 2.3 into 10 power minus 4 centimeters. So, that is equal to 2.3 micrometers. So, this is going to be the distance.

So, we just need if absorption coefficient is strong, you just need 2.3 micrometers of thickness to absorb 90% of the energy. So, you saw these pictures here. For example, these wafers are not transmitting. You know silicon wafer is not transmitting whereas glass is transmitting. But of course, we assume that all of them have similar thicknesses, which is in this case a few millimeters.

Now, silicon might be 500 micrometers. This might be a couple of millimeters, wafer in gallium phosphide. And typically glass also has, you know, say 500 to 750 microns. So, they are reasonably in thick material and that is why you see that either there is complete absorption or just transmission. If you make you know, glass which is, let us say metres of thick, then probably you will start seeing some absorption.

Just because the thickness is large you know absorption α is less per glass. But, the thickness is large. If the thickness is large, there can be some absorption. So, this is how you can calculate the different absorption coefficients for you know when light incident on a semiconductor. Now, let us do one more problem.

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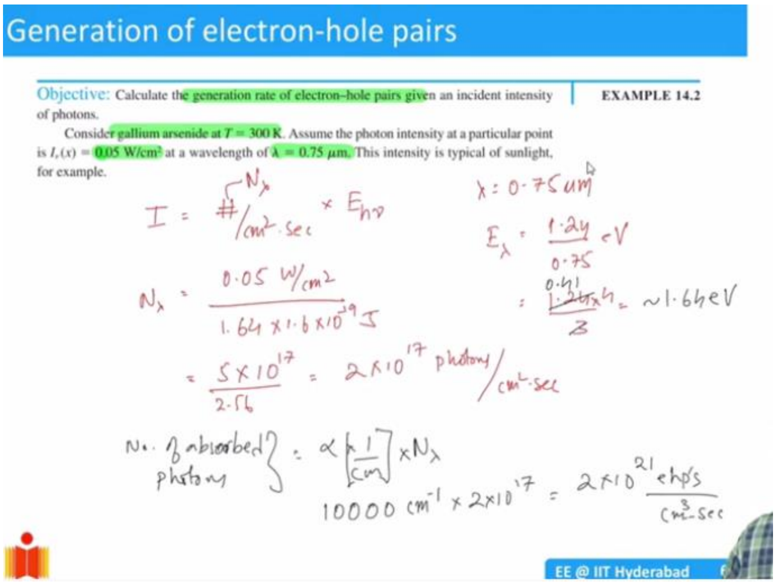

Generation of electron-hole pairs

Objective: Calculate the generation rate of electron–hole pairs given an incident intensity of photons. **EXAMPLE 14.2**

Consider gallium arsenide at $T = 300$ K. Assume the photon intensity at a particular point is $I_\nu(x) = 0.05$ W/cm² at a wavelength of $\lambda = 0.75\ \mu$m. This intensity is typical of sunlight, for example.

$I = \frac{\overset{N_\lambda}{\#}}{cm^2 \cdot sec} \times E_{h\nu}$

$\lambda : 0.75\ um$

$E_\lambda = \frac{1.24}{0.75}\ eV$

$= \frac{\overset{0.41}{\cancel{1.24}} \times 4}{\cancel{3}} = \sim 1.64\ eV$

$N_\lambda = \frac{0.05\ W/cm^2}{1.64 \times 1.6 \times 10^{-19}\ J}$

$= \frac{5 \times 10^{17}}{2.56} = 2 \times 10^{17}\ \text{photons}/cm^2\text{-}sec$

No. of absorbed photons $\Big\} = \alpha \left[\frac{1}{cm}\right] \times N_\lambda$

$10000\ cm^{-1} \times 2 \times 10^{17} = 2 \times 10^{21}\ \frac{ehp's}{cm^3\text{-}sec}$

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And this is about generation of electron hole pairs. So, we said that when the photon is absorbed, it gives rise to electron hole pairs. So, what is the rate at which you can generate these electron hole pairs? So, calculate the generation rate of electron hole pairs given some incident intensity. So, this is you know we are asked to calculate for gallium arsenide at room temperature.

And photon incident intensity incident at a particular point is 0.05 watt per centimeter square. Λ is this at this wavelength. So, the intensity is typical of sunlight. Well, this intensity is typical of sunlight. So, how many electron hole pairs are produced? Well, to calculate that we need to realize that what is intensity? Intensity is essentially number of photons per centimeter square times the energy of the photon.

So, the intensity of the photon is simply number of photons I will just put it as hash. Number of photons per centimeter square per second into E of h nu I will say or h nu of the photon, energy of the photon.

$$I = \frac{\#}{cm^2 .sec} \times E_{h\gamma}$$

This is going to give you energy per second will give you the power per centimeter square will give you sorry energy power and intensity. So, what is this number of photon? I can call it maybe you know N λ. That is even better.

So, we are given, we need to calculate, what is the energy of the photon? How much is the energy of the photon of you know λ equal to 0.75 micrometers? So, energy of this photon E λ is going to be 1.24 divided by 0.75 microns. In this expression, I have to always put the denominator in micrometers not in nanometers or millimeter, only in micrometers. Then, it works because this comes from $\frac{hc}{\lambda}$

You can calculate and see that it turn out to be this. This is going to be eV. So, this will be 1.24 divided 0.75 is going to be 3 by 4 3 into 4, 3. So, this will be 0.41 something. So, this will be something like approximately 1.64 eV something like that. Let us say this is 1.64 eV. This is the energy. So, how many photons? Well, to calculate that, we have to go back and substitute here.

Number of photons in Nλ is going to be intensity which is 0.05 watts per centimeter square. Like this I will write it deliberately, divided by energy of the photon is 1.64 eV. And, by the way, this is eV. So, this has to be always multiplied by 1.6 into 10 power minus 19 to get joules. So, this will give you the number of photons. So, if you calculate this, I mean you will calculate it.

I guess it will turn out to be some number you know 10 power 15 into 10 power 17 some number it will be. Because this is 10 power minus 19 it will go up, so, 10 power 19. And then, let us approximate it 10 power 19. So, this will be 5 into 10 power 17 divided by 1.6 into 1.6 2.56. That is roughly going to be 2 into 10 power 17 photons per centimeter square per second.

This is the rate at which the photons are incident. Now, but, you are not asked number of photons you are asked, how many electron hole pairs are generated? So, how do you calculate the number of electron hole pairs? Well, to calculate that, you have to look at the absorbed you know number of absorbed photons. So, this will be number of absorbed protons is going to be α times the incident you know number.

At particular point, the absorption coefficient will give you how many photons are getting absorbed. So, the α is basically per centimeter inverse into 1 over you know centimeter. This is the units into N λ you do. And this is what gallium arsenide and 0.75 microns. Let me just go back. Gallium arsenide, 0.75 microns say 0.75 somewhere here. Just generally a gallium arsenide bandgap is 870 nanometers.

So, 750 is just kept above this bandgap. So, there is a very steep increase. So, we can take the absorption coefficient of this guy, gallium arsenide. Let us take it to be 10,000 centimeter inverse. That is a typical number because it is above bandgap. We can roughly take that, into 2 into 10 power 17. So, if you calculate this, what are you going to get? Well, 10 power 21, 2 into 10 power 21 ehps per centimeter cube per second.

So, this is the rate at which you are generating the electron hole pairs. Sorry, this is the rate. Yes, of course, you know, this is just the, generation rate is going to also depend on the τ you know the minority carrier lifetime. So, this is just the number of photons absorbed. But, then, there is also going to be influence of the steady state concentration of photons is going to be dependent on the τ.

Because we saw that when we analyze the non-equilibrium statistics of semiconductors, we saw that once you have this electron hole pairs produced some of them are going to get recombined. So, there will be an equilibrium concentration in steady state. That is going to be this number times τ. τ is typically 10 power minus 6 or something. So, I would say, in steady state, there will be about 10 power 15 electron hole pairs in the semiconductor.

So, you can analyze these things. So, this is basically about optical absorption. So, given an optic absorption coefficient for a particular material at a particular wavelength, you can estimate, how many photons are absorbed? And, how many electron hole pairs are generated? By the way, when we calculate the number of electron hole pairs generated, we assume that all the photons are getting converted to electron hole pairs. That does not happen.

There is a certain efficiency. Sometimes you are given the efficiency, so you have to just scale it by that number. Let us say the efficiency is 90% you know. Then, you scale it by 90% and get the final number. Right now, in this calculation, I assume that all of the photons are getting absorbed. And, they resulting in electron hole pairs. That is a iffy condition. That does not happen in like real life. So, this is about optical absorption.

So, I will stop this video here. So, once we understand this now, in the next video, I will talk about solar cells, which is a very important semiconductor device nowadays. I will see you there. Thank you so much for your attention, have a great day, bye.