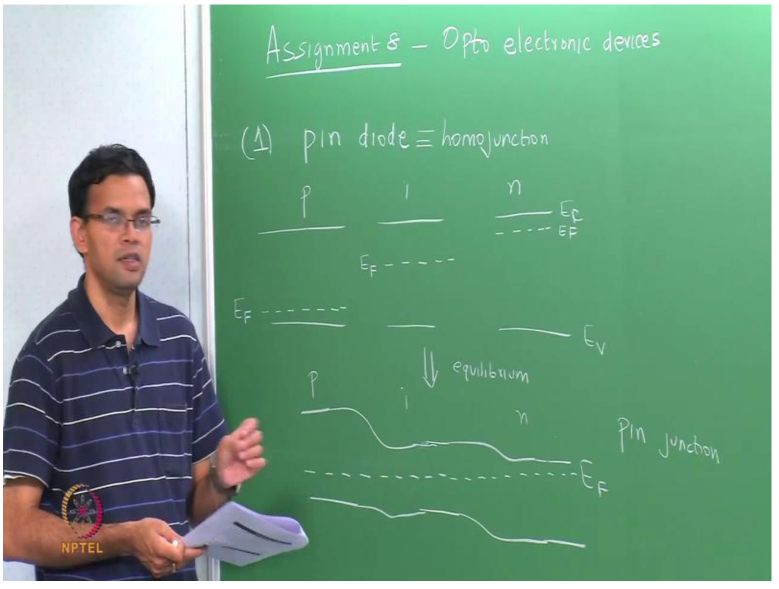
# Fundamentals of electronic materials, devices and fabrication

**Dr. S. Parasuraman**
**Department of Metallurgical and Materials Engineering**
**Indian Institute of Technology, Madras**

## Assignment – 8
## Optoelectronic devices

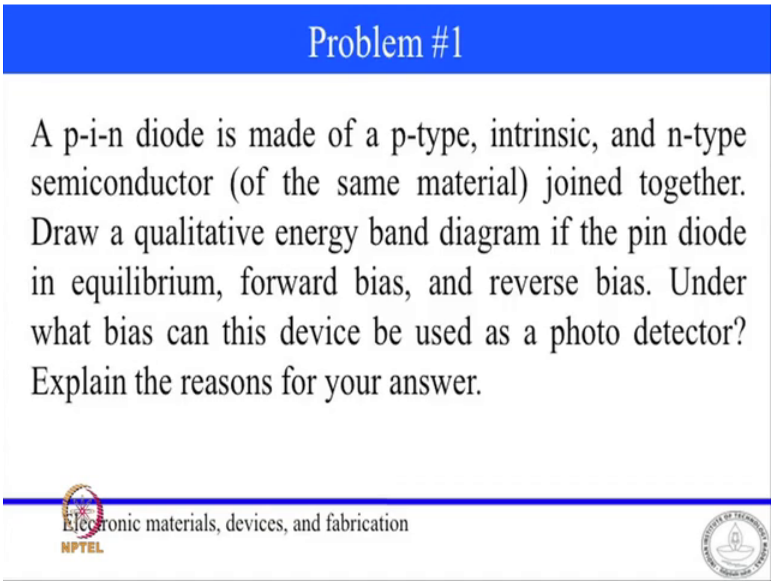
In today's assignment, we are going to look at optoelectronic devices.

(Refer Slide Time: 00:23)




So, this is assignment 8. In assignment 7, we looked at problems dealing with general interaction of light with semiconductors. Today, we are going to look specifically at some problems leading to devices. So, in the classes we looked at photo detectors, solar cells, LEDs and lasers. We did a bit of solar cell trying to calculate the current-voltage characteristics. So, some of the assignment problems here will mostly deal with solar cells. We will also a bit at photoconductors and also a problem on LED. We would not be focusing on lasers, because the way the laser works is very similar to how an LED works except that you have a population inversion that is created, and you have an incoming photon that stimulates the emission.

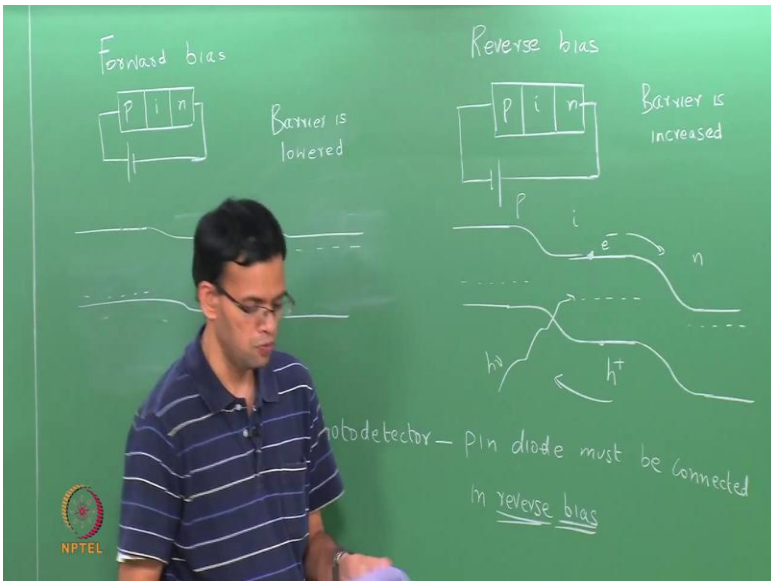
(Refer Slide Time: 01:40)




So, let us go to problem number 1. In problem 1, we have a pin diode. So, you have a p-type intrinsic and an n-type. So, we asked to draw a qualitative energy band diagram both in equilibrium forward and reverse bias. So, we have a pin diode. So, we have essentially two interfaces; one between the p type and the intrinsic material, the other between the intrinsic and the n type. For simplicity, we will just take this to be a homo junction, so all the three materials are the same; the only difference is in the doping concentration and the type. So, I will start with the p, i and n. So, we can draw the energy band diagram for all three of this. So, the material is the same. So, the valence band and the conduction band are essentially located at the same point. In the case of a p type material, the Fermi level is close to the valence band for an intrinsic, it is close to the middle, and for an n type $E_F$ is close to the conduction band.

So, when we have this in equilibrium we know that the Fermi levels must line up. So, in equilibrium, I have the Fermi levels line up. Far away from the interface your materials will behaves as the same. So, this is p-type, this is intrinsic, and this is n-type and are making sure that the band gaps are approximately the same, and then we can join all three. So, essentially this is your pin junction in equilibrium; there are 2 contact potentials are developed one between the p and the intrinsic region, and one between the intrinsic and the n -type region. So, we can again draw this in both forward and reverse biased. In the case of a forward bias the p is connected to positive and n is connected to negative, so that carriers are injected into the device and the barriers are lower. In reverse bias, it is the other way round; p is connected to negative n is connected to positive, so that the barriers actually increase. So, lets me draw that next.

(Refer Slide Time: 05:17)

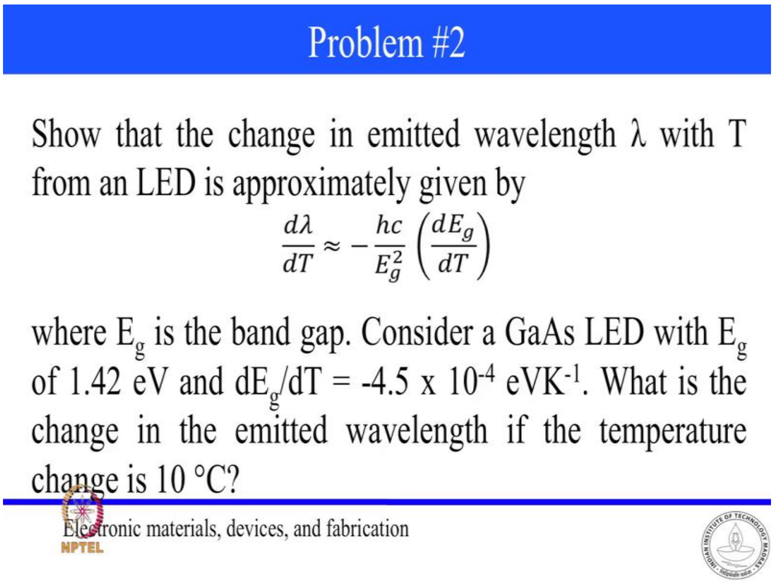



So, in the case of a forward bias, p is connected to positive and n is connected to negative. So, on this side, I have a p-type semiconductor at the center, I have an intrinsic and here I have an n-type. We should draw this slightly more clearly. So, the important point is that in the case of a forward bias, the barrier is lower, so that you can have a current going through the device. Now, you have a reverse bias, so p is connected to negative and n is connected to positive. So, here the barrier is actually increased, so that now it is become more difficult for the current to flow through it.

So, the last part of the question asked for use as a photo detector, do we use the pin junction in forward or reverse bias. So, if you look at the working of a photo detector, a photo detector is one where light falls on to your material, so on to your device and essentially this creates electron and holes which are detected as a current, and the intensity or the value of the current is directly proportional to the intensity of the light. So for this to happen, we essentially want the current through the device to be very small, because if there is a background current that will essentially act as noise to the current that is generated by light shining on the material. So, this happens when the pin junction is essentially connected in reverse bias, so that electrons and holes that are typically created in the intrinsic region gets separated.

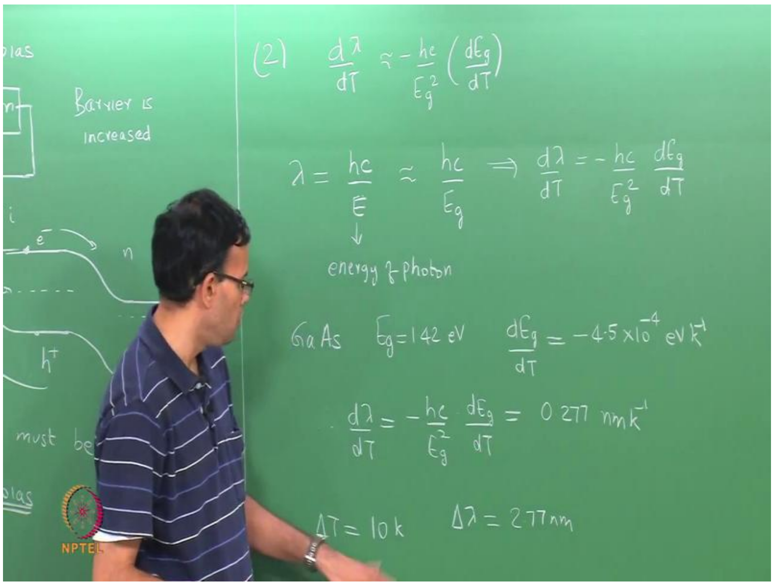
So, if I have a p i and a n and I have light shining on to the material electron is generated here, a hole is generated here. These electrons move to the n-side and the holes moves to the p-side, because of reverse bias and this gets detected as a current. The current once again is proportional to the number of electrons and holes that are generated, which is directly proportional to the intensity of the light that is falling. So, for use as a photo detector, the p i n junction or the p i n diode must be connected in reverse bias.

(Refer Slide Time: 10:21)




So, let us now go to problem 2. So, problem 2, essentially deals with an LED. LED is your light emitting diode that based upon the fact that you inject electrons and holes into your material a typical diode is nothing but a p-n junction these electrons and holes recombine and basically give you light. The wavelength of the light depends upon the band gap of the material. So, by tuning the band gap of the material by adding different dopants can essentially tune the light output.

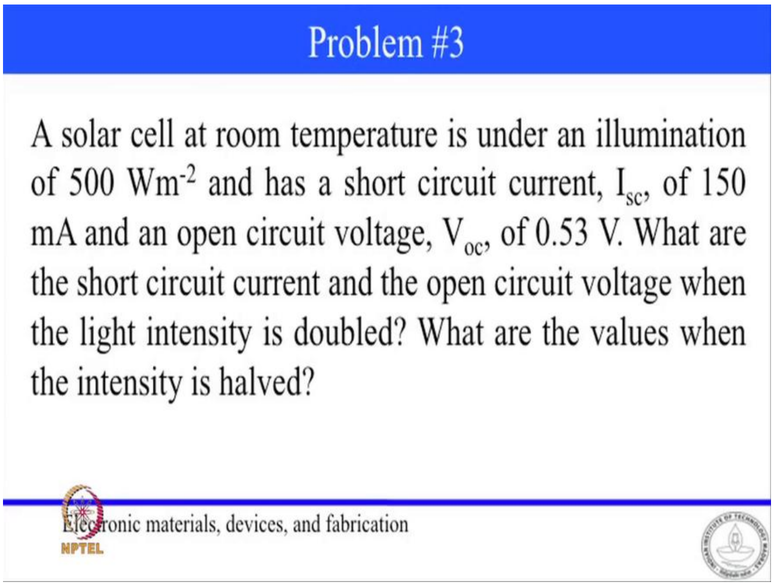
(Refer Slide Time: 11:14)




So, in this particular case, we asked to show that the change in the emitter wavelength lambda, so $\frac{d\lambda}{dT}$. So, the change in wavelength with respect to temperature is approximately given to be $\frac{-hc}{E_g}\sqrt{\frac{dE_g}{dT}}$ . And then, we are asked to do the calculations for a gallium arsenide system, where the band gap is given and also the temperature variation is given. So, the first part can actually be very easily shown. So, I just describe the working of an LED, and said that the wavelength of the light is approximately equal to the band depends upon the band gap of the material. So, $\lambda$ which is the wavelength of the light is equal to $\frac{hc}{E}$, where E is the energy of the photon. This in turn depends upon the energy of the electron and hole that are involved in recombination. This electron and hole is usually very close to the valence band h and the conduction band h, so that this can be written approximately as $\frac{hc}{E_g}$. So, usually the electron or the hole is not located exactly at the band h, but there is some thermal energy is typically of the order of kT, but we can ignore the thermal energy and say that lambda is approximately $\frac{hc}{E_g}$.

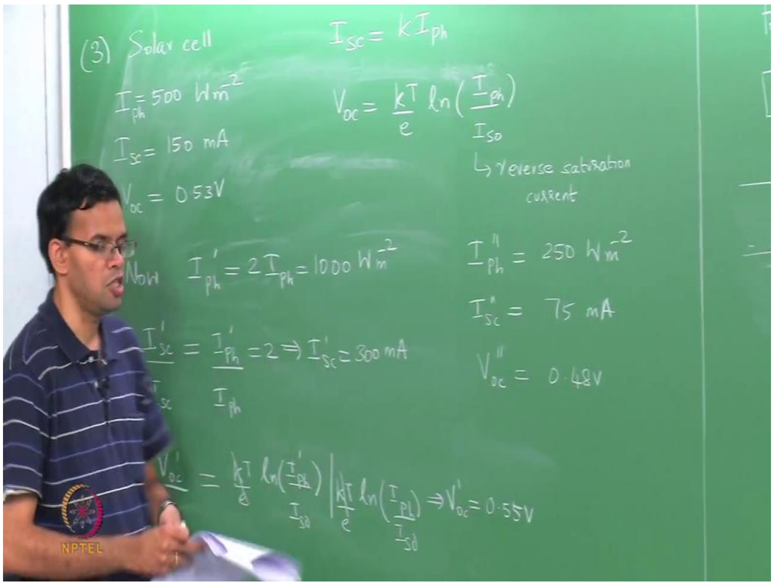
If you look at this expression h and c are essentially constants the only variable is $E_g$. So, if we differentiate this we get $\frac{d\lambda}{dT}$ is nothing but $\frac{-hc}{E_g^2}$ since you are differentiating $\frac{1}{E_g}$ $x$ $\frac{dE_g}{dT}$. So, we are asked to do this calculation for gallium arsenide. Gallium arsenide has an $E_g$ of 1.42 electrons volts. This typically lies in the infrared region and the value of $\frac{dE_g}{dT}$ is also given 4.5 x $10^{-4}$ ev $K^{-1}$. So, we can calculate the change in wavelength with respect to temperature. So, $\frac{d\lambda}{dT}\frac{hc^2}{E_g}\frac{dE_g}{dT}$. So, we can substitute all the values and this gives you a value 0.277 nanometer per Kelvin. So, if you look at it $\frac{dE_g}{dT}$ with respect to temperature is negative which means the band gap essentially decreases with rise in temperature; corresponding to a decrease in band gap, the wavelength will increase because λ is inversely proportional to energy. So, dλ with respect to temperature is a positive quantity. So, the question also says your Δt is nothing but 10 degrees, so in Kelvin, it is a same 10 Kelvin. So, the corresponding change in the wavelength delta lambda is nothing but 2.77 nanometers. So, all we are doing is substituting ΔT here and then just multiplying.

(Refer Slide Time: 15:35)




So, let us now go to problem 3.

(Refer Slide Time: 15:40)



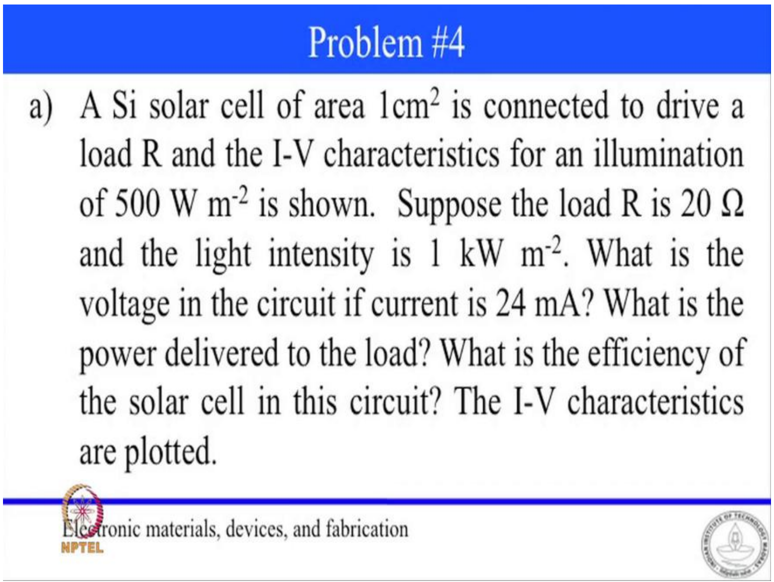

So, problem-3, relates to a solar cell. So, we have a solar cell at room temperature and it is under illumination. So, the intensity of the light is given; so I is 500 watts per meter square. The short circuit current is also given, so $I_{sc}$, $I_{sc}$ is 150 milliamps, and also the open circuit voltage $V_{oc}$ is 0.53 volts. So, the question asked; what is the short circuit current? And also, the open circuit voltage when we double the value of the illumination. So, illumination goes from 500 to 1000 watt or 1 kilo watt $m^{-2}$. Similarly, what are the values when the illumination is essentially half? So, the short circuit current is essentially the current when there is voltage is equal to 0, and $I_{sc}$ is proportional to the intensity of the light that is falling where typically it is equal to some constant times $I_{ph}$.

So, $I_{ph}$ if we write the subscript here $I_{ph}$ is nothing but the intensity of the photons that is falling on to your solar cell. So, $I_{sc}$ is essentially some constant k times $I_{ph}$. $V_{oc}$ which is your open circuit voltage, so this is the voltage when the current through the system is essentially 0 is equal to $\ln \frac{I_{ph}}{I_{so}}$, where $I_{so}$ is your reverse saturation current. So, this depends upon the material of the solar cell and also the kind of the dopants the concentration of the dopants, the width of the depletion regions and so on. So, we have simple expressions that relate both $I_{sc}$ and $V_{oc}$. So, the short circuit current, and the open circuit voltage to your incident photon radiation. So, when you change the radiation intensity, you can basically calculate the change in these values.

So, now, the new value of $I_{ph}$ is double. So, let me write this as $I'_{so}$. So, it is 2 times the original value is 1000 watts m$^{-2}$. So, the new short circuit current, so $I_{sc}^{new}$, so I am going to write it $\frac{I'_{sc}}{I_{sc}}$ is nothing but $I'_{so}$, $I_{ph}$ which is equal to 2. Therefore, the new short circuit current is essentially the double of the original short circuit current, so this is nothing but 300 milli amperes. Similarly, I can write the value of $V_{oc}$. So, $\frac{V'_{oc}}{V_{oc}}$ again you are taking the ratio of these two quantities $\frac{kT}{e}\frac{I'_{sc}}{I_{so}}\frac{I_{ph}}{I_{so}}$. So, $\frac{kT}{e}$ will essentially cancel, this we can simplify because the values of $I'_{ph}$ , $I_{ph}$ are known; $I_{so}$ is not known, but we can calculate $I_{so}$ by knowing the open circuit voltage when the current intensity is 500 watts per meter square.

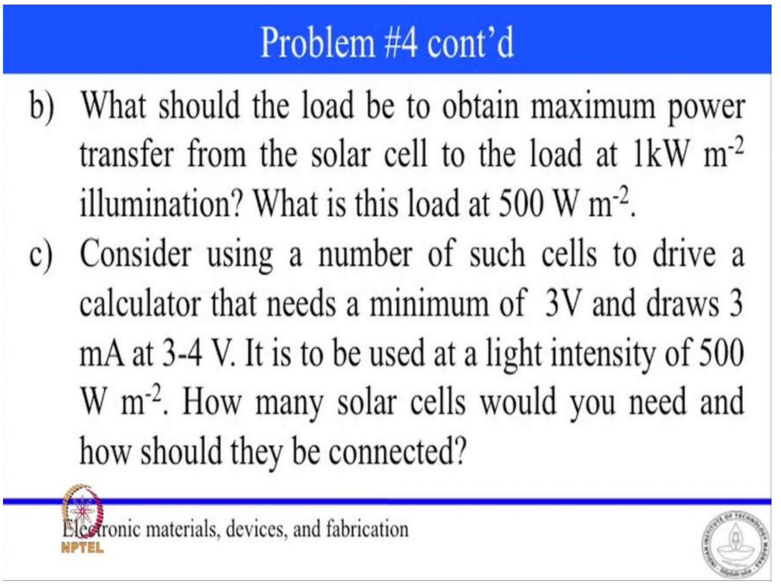
So, from this, we can calculate the value of $V_{oc}$. So, $V'_{oc}$ is essentially 0.55 volts. So, we now have a situation where instead of doubling the photon intensity reducing it by half. So, $I_{ph}$ is nothing but 250 watts m$^{-2}$. So, you have reduced it by half. So, the new short circuit current $I''_{sc}$ will also be half. So, this will be 75 milliamps and the new $V_{oc}$. So, let me write this is double prime is 0.48 volts. So, this we can get by following the same procedure where instead of having it as thousand, we now have it as 250.

(Refer Slide Time: 22:20)

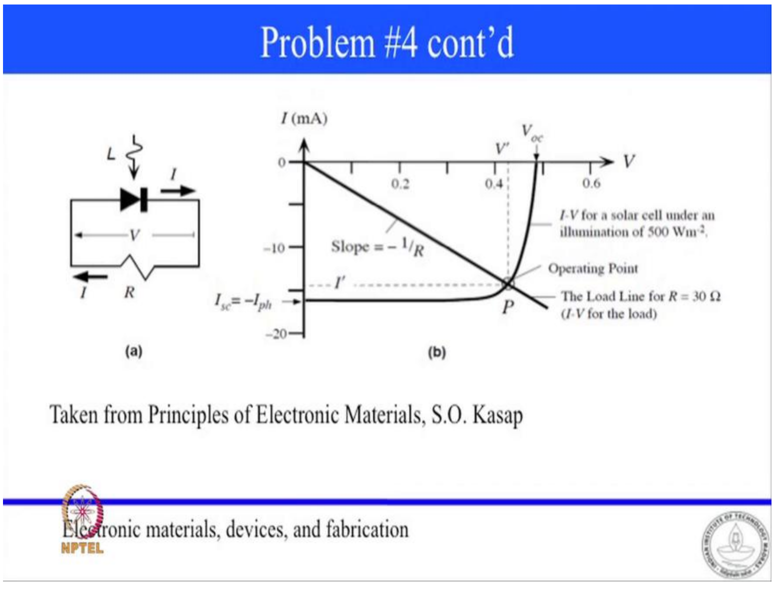



So, let me go to problem 4.

(Refer Slide Time: 22:24)

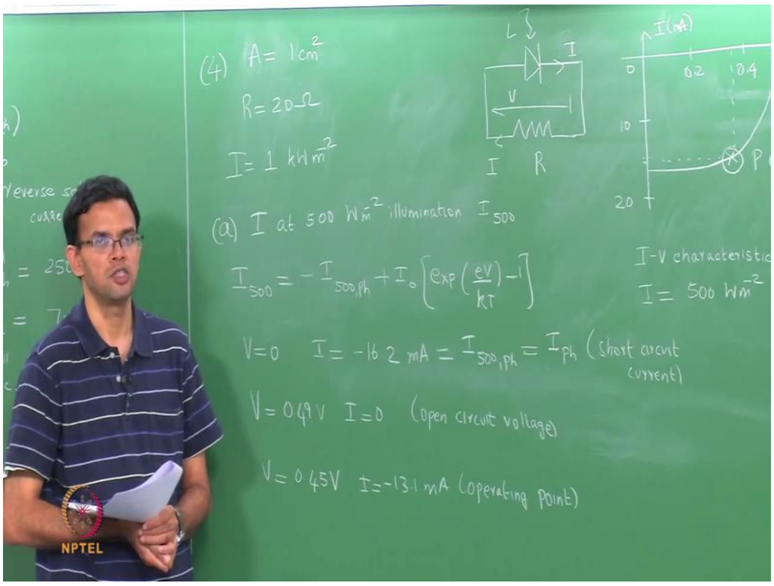



(Refer Slide Time: 22:27)




Problem 4 is also related to a solar cell.

(Refer Slide Time: 22:56)



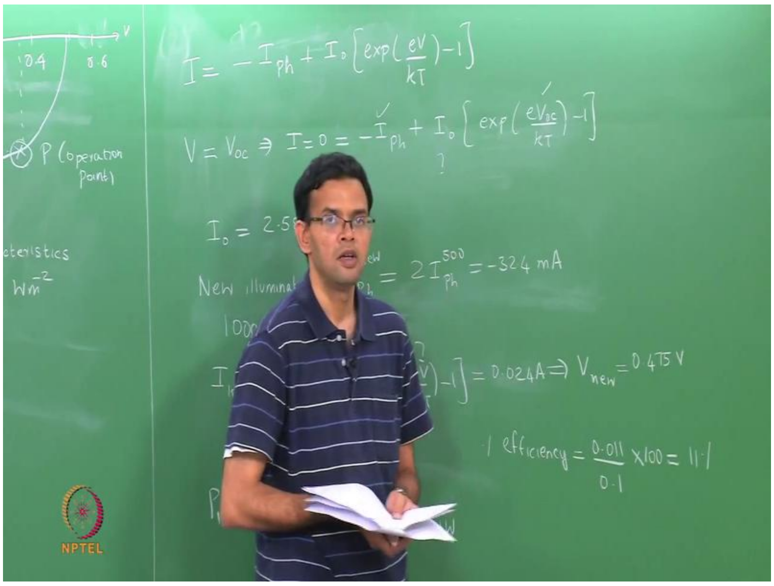

So, we have a solar cell of area A is given, and is connected to drive a load R of 20 Ω. So, R is essentially 20 Ω. So, we can actually draw how the solar cell connection looks. So, this is given as part of the question. So, you have the solar cell essentially connected to a resistor. So, R is the resistor. So, light falls on the solar cell. So, you have some light I which drives a current I. So, this in turn generates a voltage V that opposes in built voltage in the solar cell. So, the intensity of the light is given so that is 1 kilo watt per meter square. And we want to calculate the voltage in the circuit when the intensity is 1 kilo watt per meter square. The corresponding value of current for that is given. So, in the question along with how the solar cell is connected, we are also given it is I-V characteristics.

So, let me plot this; this I-V characteristic is for 500 watts per meter square. So, we have current-I that is in milliamps, and we have voltage-V. So, this is 0, you have 10, you have 20, this is 0.2, 0.4, let me just extend this a bit and you have 0.6. So, the I-V characteristics, so this is I-V characteristics of the solar cell. So, this is drawn when the illumination is 500 watts per meter square. So, we are asked to calculate the current for particular voltage or the voltage for a particular current when the illumination is now changed to 100 watts per meter square.

So, we can go to the problem. So, let us go to part A. So, when a solar cell is essentially driving an external resistor R, there is some current that is flowing through. So, this current at 500 watts per meter square illumination, I am going to call this as $I_{500}$. So, $I_{500}$ is given by the intensity of the light plus a voltage due to the potential barrier that is created by the resistor, this is given as $I_o \exp\left(\frac{eV}{kT} - 1\right)$. So, this is a general expression that relates the current at a particular intensity to both the open circuit current, the short circuit current and also the voltage when you have some external load R sitting on the system. So, from the graph, we can essentially marks the values of these various points. So, when V is equal to 0, this is your short circuit voltage, the corresponding current I is minus 16.2 milliamps. This is nothing but $I_{500}$, $I_{ph}$ and just for simplicity I will write this as $I_{ph}$. So, this is the short circuit current.

You can also calculate or you can also look at the open circuit voltage, so that when the current is 0, the voltage is exactly 0.49 volts. This is the open circuit voltage. The question also says that the device at 500 milliamps or 500 watts per meter square illumination is essentially operating at point P; in for this, we can calculate the current and the voltage. So, V is 0.45 volts, and the corresponding current I is -13.1 milliamps. So, this represents the operating point for the circuit. So, we now have to use these to calculate the values when your solar cell is illuminated with 1 kilo watt per meter square.

(Refer Slide Time: 30:04)

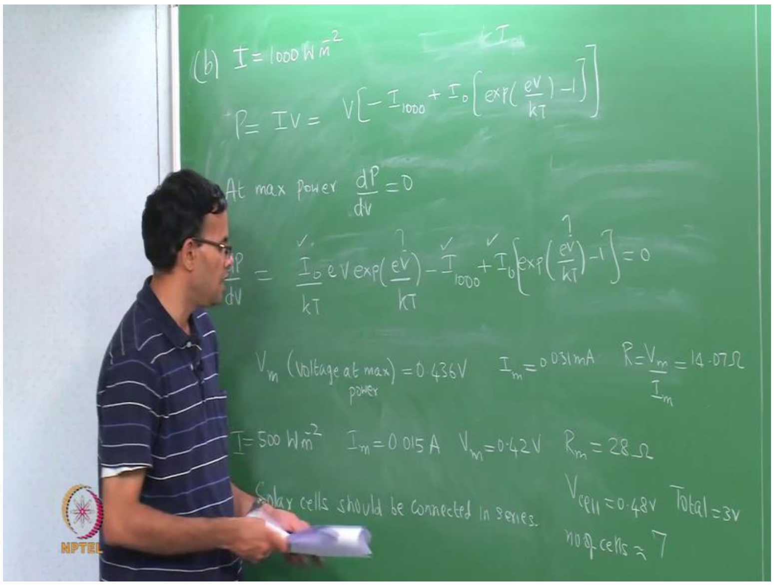



So, once again let me write the expression. So, I is equal to minus $I_{ph}$ + $I_o$ $\exp\left(\frac{eV}{kT} - 1\right)$. So, $I_o$ we do not know, but $I_{ph}$ we know. So, when voltage V is equal to $V_{oc}$, which implies current is equal to 0; this is $-I_{ph}$ + $I_o$ $\exp\left(\frac{eV_{oc}}{kT} - 1\right)$. So, in this, $I_{ph}$ is known, $V_{oc}$ is known, the only unknown is essentially $I_o$. So, we can make the substitutions and $I_o$ is calculated to be $2.58 \times 10^{-11}$ amp. So, this represents the reverse saturation current in the system. So, now the new illumination $I_{new}$; so let me call it $I_{ph}^{new}$. So, new illumination is 1000 watts per meter square.

So, in the previous problem, we saw that when the illumination is doubled the short circuit current is essentially doubled. So, $I_{ph}^{new}$ is $2 \times I_{ph}$ at 500. So, this is -32.4 milliamps. So, the corresponding current is also given. So, $I_{1000}$ is nothing but $I_{ph}^{new} + I_o \exp\left(\frac{eV}{kT} - 1\right)$. So, this current is given and this is equal to 0.024 amperes. So, $I_{ph}^{new}$, we have just calculated; I naught is something we calculated from the data for 500 watts per meter square. So, this is known, this is known, the only unknown is the new operating voltage. So, we can make the substitutions, so that the new voltage $V_{new}$ is equal to 0.475 volts.

We can also calculate the power in this system. So, power is nothing but $V'$ times the current. So, the current is $I_{1000}$, this is equal to 0.011 watts. We are also asked to calculate the efficiency of the system. So, the input radiation is 1000 watts. So, P in is 1000 watts per meter square, and the area of the solar cell is 1 centimeter square, so that is $10^{-4}$ $m^{-2}$. So, this gives you 0.1 watt. So, 0.1 watt is the input power, the output power in the form of electrical current is 0.011 watt. So, the efficiency in terms of percentage is 0.011 divided by 0.1 x 100, that is equal to 11 percent.

(Refer Slide Time: 35:12)



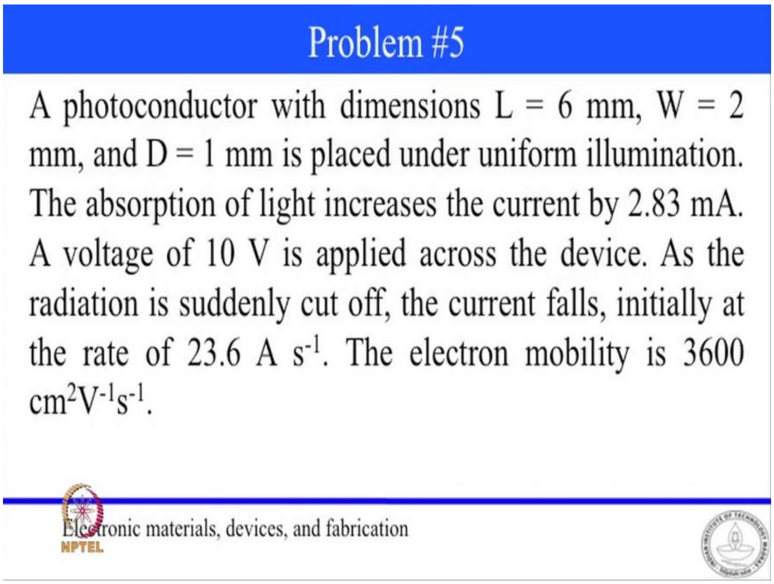
So, let us now go to part-b. So, in part b, we are asked to calculate the load, so to have a maximum power transfer from the solar cell to the load. So, once again the illumination I is 1 kilo watt per meter square or 1000 watts per meter square. So, in problem a, we essentially looked at the load for a given value of current and voltage. We now have to find out the load at which, the power transfer is essentially maximum. So, power P is nothing but I x V, which can be written as V x $-I_{1000}$, so we have $I_{1000} + I_o \exp\left(\frac{eV}{kT} - 1\right)$. So, this is the expression for the power. If you look at it, everything here is a constant except for the voltage, so to have maximum power; so at maximum power $\frac{dP}{dV}$ must be essentially 0. So, we can differentiate this expression for P. So, $\frac{dP}{dV}$ and that is given by $I_o\left(\frac{kT}{eV}\right) exp\left(\frac{eV}{kT}\right) - I_{1000} + I_0 \exp\left(\frac{eV}{kT} - 1\right)$, this is equal to 0.

So, this you can get by essentially treating this as the differential of 2 functions. So, you differentiate one, keeping the other constant; then you differentiate the other, keeping the first one constant. This is now equated to 0 for maximum power. So, in this case, $I_o$ is known, $I_{1000}$ is known, this is the short circuit current at thousand which is 2 times the short circuit at 500, and we just calculated it. So, the only unknown is essentially the voltage.

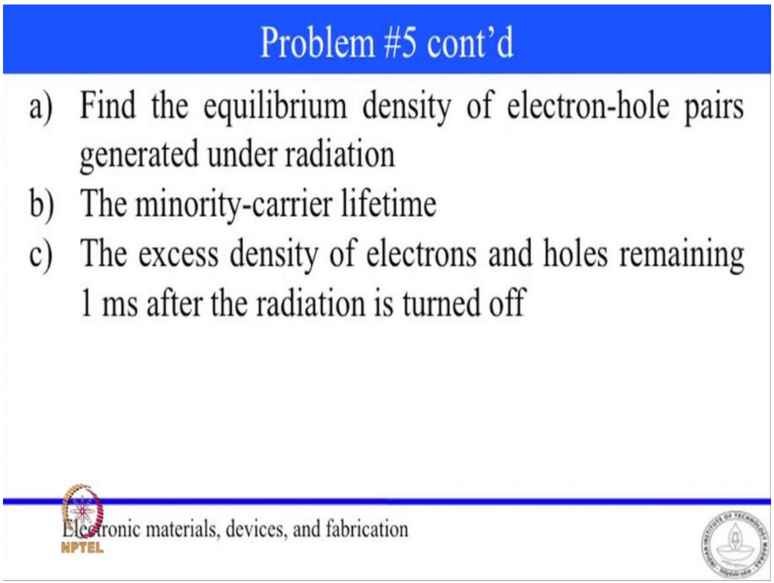
So, if you solve this, this gives the voltage $V_m$ which is the voltage at maximum power, and this is equal to 0.436 volts. The corresponding current $I_m$ is 0.031 milliamps, and the resistor R is $\frac{V_m}{I_m}$ which is 14.07 ohms. So, this is essentially the load at which, the power is maximum. We can also do this for the illumination at 500 watts per meter square. So, if I is 500 watts per meter square, we can repeat this, I will just write the answer; $I_m$ is 0.015 amps, $V_m$ is 0.42 volts and the load $R_m$ is essentially 28 ohms.

So, the last part of the question part-c. So, we need to connect solar cells in order to drive a calculator. The calculator is to be used at a light intensity of 500 watts per meter square. So, when we have solar cells each having a particular voltage and they should essentially be connected in order to give the voltage of three volts, these solar cells should be connected in series. So, the solar cells should be connected in series. So, if you look at the initial operating condition that was specified in part-a, the voltage for each solar cell is 0.48 volts. So, voltage per cell is 0.48 volts. We basically want a total voltage of 3 volts. So, the number of cells is essentially 3 divided by 0.48 and you round off to the highest integer, so this gives you 7. So, we need 7 solar cells all connected in series to basically supply enough voltage to run a calculator.

(Refer Slide Time: 41:16)

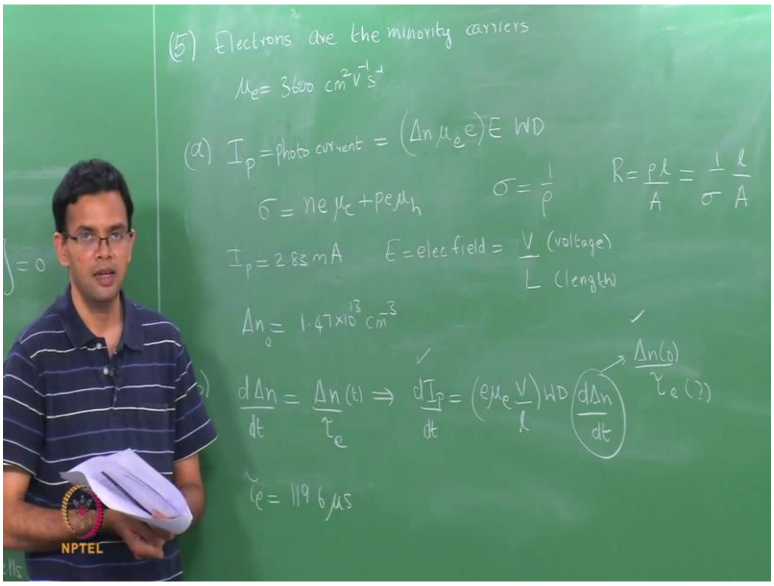



(Refer Slide Time: 41:19)




Let us now go to the last problem. So, problem 5 is related to a photoconductor. So, we saw some variation of this problem in a previous assignment - assignment 7. So, you have a photoconductor that is placed under uniform illumination. It says the absorption of light basically causes an increase in current, the increases is given when you have a particular voltage then the radiation is cut off, so that the access carriers start to recombine and when that happens the carrier concentration drops, and the current also drops.

(Refer Slide Time: 42:16)



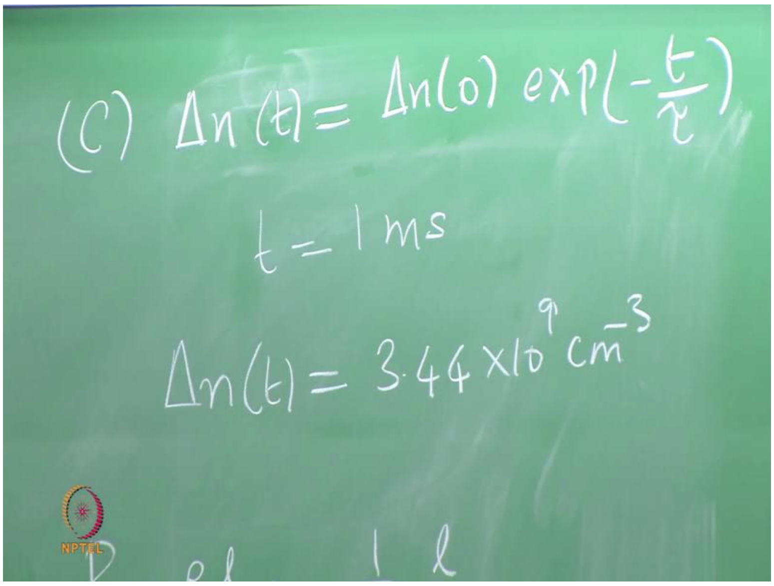

So, in this particular case, we are going to take electrons to be the minority carriers. So, the increase in current is always due to the increase in the minority carriers. This is especially true when we have week illumination, where we assume that the illumination intensity is smaller compared to the concentration of the majority carriers. So, electrons are the minority carriers, and we have also given the electron mobility, so $\mu_e$ to be 3600 centimeter square per volt per second. So, the first part of the question, we need to calculate the equilibrium density of the electron hole pairs generated under radiation.

So, we can write an expression for that. So, the current I which is your photocurrent is due to the excess electrons that are created. So, this is equal to $\Delta n$ which is the excess electrons times the mobility times the electric charge e of the electron times an electric field E that is applied across the material, and since it is the current we have to multiply by the area. So, this expression is got from the original expression for conductivity; conductivity is $n_e\ \mu_e + p\ e\ \mu_h$; conductivity sigma is related to the resistivity as $1/\rho$, and r is nothing but $\rho l/A$. So, this is $l/\sigma$, $l/A$. So, this is the expression for the current due to the increase in the electron concentration.

In this particular case, $I_p$ is given. So, this value is 2.83 milliamps; the electron mobility is given, so this should actually be $\mu_e$. So, electron mobility is given. The dimensions of the device are given. E is the electric field, which is nothing but the voltage V/L. So, the only unknown in this expression is Δn. So, Δn is 1.47 x $10^{13}$ $cm^{-3}$. So, this is the excess electron hole pair concentration that is created when light is shining.

Part-b, we want to calculate the minority carrier lifetime. So, when the light is switched off, the concentration of the minority carriers essentially decrease. And this is given by the value at a particular time t divided by the minority carrier lifetime $\tau$. So, since we are dealing electrons, I will call this $\tau_e$. So, you can write this in terms of current, and if you do this $\frac{dI_p}{dt}$ is nothing but $(e\mu_e \frac{V}{l})WD(\frac{d\Delta n}{dt})$; $\frac{d\Delta n}{dt}$ is nothing but Δn at time 0 divided by $\tau_e$. So, Δn at time 0 is nothing but what we calculated in part-a, $\frac{dI_p}{dt}$ which is the rate at which the current falls is given in the question this value is 23.6 ampere per second. So, this is known, this is known, the only unknown is $\tau_e$. So, $\tau_e$ is essentially 119.6 microseconds.

(Refer Slide Time: 47:51)




Part-c, we want to calculate the excess density of electrons and holes 1 milliseconds after the radiation if turn off. So, part-c, we want to calculate Δn 1 millisecond later. So, Δn at time t is nothing but Δn a time t equal to 0 exp($-t/\tau_e$). So, t is 1 millisecond, Δn at time t equal to 0 is what we calculated in part-a, which is the excess equilibrium concentration tau is what we calculated in part-b. So, Δn is nothing but 3.44 x $10^9$ $cm^3$.

Once again, we are assuming a condition of weak illumination, so that any change in conductivity is driven by the minority carriers. So, that in this particular case, the change in concentration of the majority carriers which are holes is not significant enough to affect the conductivity.