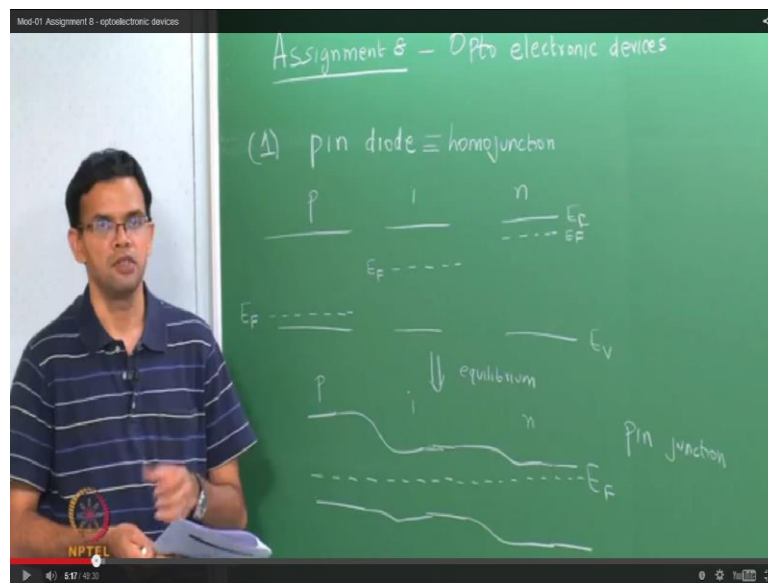


Electronic Materials, Devices and Fabrication
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Lecture – 27
Assignment 8 - Optoelectronic Devices

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In today's assignment we are going to look at optoelectronic devices. So, this is assignment eight. In assignment seven we look at problems dealing with general interaction of light semiconductors. Today we are going to look specifically at some problems leading to devices. So, in the classes we look 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 look a bit at photo conductors 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. So, let us go to problem number one.

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Problem #1

A p-i-n diode is made of a p-type, intrinsic, and n-type semiconductor (of the same material) joined together. Draw a qualitative energy band diagram if the pin diode in equilibrium, forward bias, and reverse bias. Under what bias can this device be used as a photo detector? Explain the reasons for your answer.

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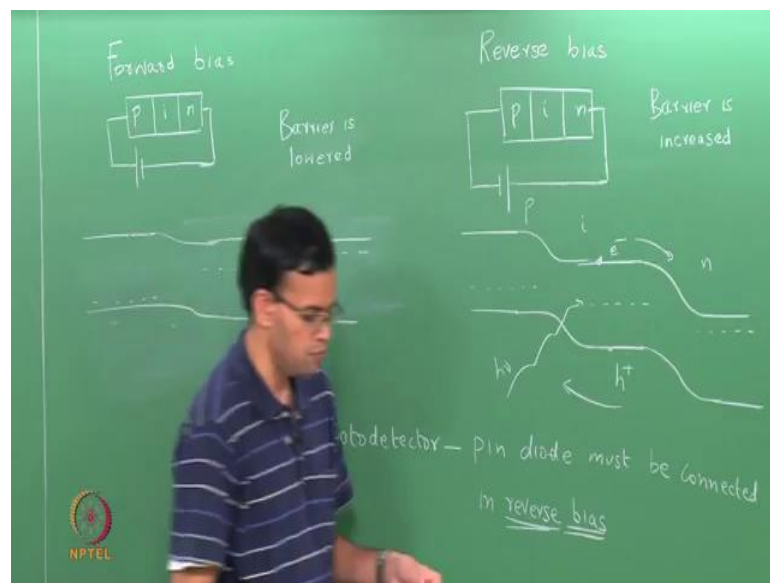
In problem one, we have a p i n diode. So, you have a p type intrinsic and an n type. So, we ask to draw a qualitative energy band diagram both in equilibrium forward and reverse bias. So, we have a p i n diode so we have essentially two interfaces one between the p type and the intrinsic material the 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 material will behaves as the same. So, this is p type, this is intrinsic, and this is n type.

We making sure that the band gaps are approximately the same and then we can join all three. So, essentially this is your p i n junction in equilibrium. There are two contact potential 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 bias. 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, let me draw that next.

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So, in the case of a forward bias, p is connected to positive and n is connected to negative. So, in this side I have a p type semiconductor. At the center, I have an intrinsic and here I have an n type. We should be always slightly more clearly. So, important point is that in the case of forward bias the barrier is lower, so that you can have 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 p i n junction in forward or reverse bias. So, if we look at the working of a photo detector, a photo detector is one where light falls on to a material. So, on to a 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 p i n junction is essentially connected in reverse bias. So, that electrons and holes that are typically created in the intrinsic region get separated.

So, if I have a p i and n and I have the light shining on to the material. Electron is generated here, a hole is generated here. These electrons move to the end side and the holes move 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 on the p i n diode must be connected in reverse bias. So, let us now go to problem 2.

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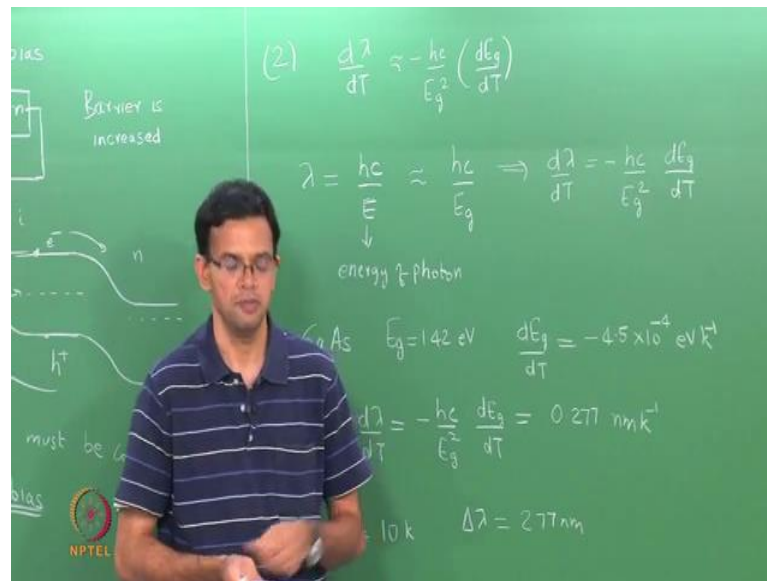
Problem #2

Show that the change in emitted wavelength λ with T from an LED is approximately given by

$$\frac{d\lambda}{dT} \approx -\frac{hc}{E_g^2} \left(\frac{dE_g}{dT} \right)$$

where E_g is the band gap. Consider a GaAs LED with E_g of 1.42 eV and $dE_g/dT = -4.5 \times 10^{-4} \text{ eVK}^{-1}$. What is the change in the emitted wavelength if the temperature change is 10 °C?

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So, problem 2 essentially deals with led. Led is a light emitting diode, that based upon the fact that you inject the electrons and holes in your material. A typical diode is nothing but a p n junction, these electrons and holes recombine and basically give you light. The wave length 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. So, in this particular case we ask to show the change in emitted wavelength lambda. So, d lambda over dT so the change in wavelength with respect to temperature is approximately given to be minus hc over E g square dEg over dT and then we are ask to do the calculation 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 described 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 hc over 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 edge and the conduction band edge. So, that this can be written approximately as hc divided by Eg. So, usually the electron or the hole is not located exactly at the band edge, but there is some thermal energy is typically

of the order of kT , but we can ignore the thermal energy and say that λ is approximately 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 $d\lambda/dT$ is nothing but $-hc/E_g^2$ since you are differentiating $1/E_g$ times dE_g/dT . So, we are asked to do this calculation for gallium arsenide. Gallium arsenide has an E_g of 1.42 electron volts. This typically lies in the infrared region and the value of dE_g/dT is also given 4.5×10^{-4} electron volts per Kelvin. So, we can calculate the change in wavelength with respect to temperature so $d\lambda/dT = hc^2/E_g^3 \times dE_g/dT$ so we can substitute all the values and this gives you a value 0.277 nanometer per Kelvin.

So, if you look at 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 $d\lambda/dT$ with respect to temperature is a positive quantity. So, the question also says your ΔT is nothing but 10 degrees, so in Kelvin is the 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 multiply. So, let us now go to problem three.

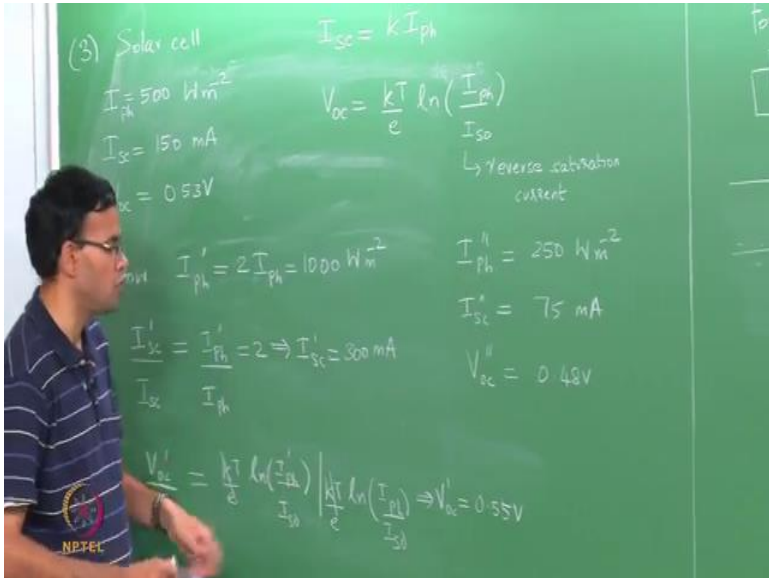
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Problem #3

A solar cell at room temperature is under an illumination of 500 Wm^{-2} and has a short circuit current, I_{sc} , of 150 mA and an open circuit voltage, V_{oc} , of 0.53 V. What are the short circuit current and the open circuit voltage when the light intensity is doubled? What are the values when the intensity is halved?


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(3) Solar cell

$$I_{sc} = k I_{ph}$$

$$V_{oc} = \frac{kT}{e} \ln\left(\frac{I_{ph}}{I_{s0}}\right)$$

$I_{ph} = 500 \text{ Wm}^{-2}$
 $I_{sc} = 150 \text{ mA}$
 $V_{oc} = 0.53 \text{ V}$

$I_{ph}' = 2 I_{ph} = 1000 \text{ Wm}^{-2}$
 $I_{sc}' = \frac{I_{sc}}{I_{ph}} = 2 \Rightarrow I_{sc}' = 300 \text{ mA}$

$I_{ph}'' = 250 \text{ Wm}^{-2}$
 $I_{sc}'' = 75 \text{ mA}$
 $V_{oc}'' = 0.48 \text{ V}$

$V_{oc}' = \frac{kT}{e} \ln\left(\frac{I_{ph}'}{I_{s0}}\right) = \frac{kT}{e} \ln\left(\frac{I_{ph}}{I_{s0}}\right) + \frac{kT}{e} \ln(2) \Rightarrow V_{oc}' = 0.55 \text{ V}$

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} is 150 amps and also the open circuit voltage V_{oc} is 0.53 volts. So, the question asked what is the short circuit current also the open circuit voltage when we double the value of the illumination? So,

illumination goes in 500 to 1000 watts or one kilo watt per meter square. 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 there is falling were typically it is equal to some constant times I_{ph} . So, I_{ph} if you write the substitute substrate the subscript here I_{ph} was nothing but the intensity of the photons that is falling on to a solar cell. So, I_{sc} essentially some constant k times I_{ph} V_{oc} which is the open circuit voltage. So, this is the voltage when the current through this system is essentially 0 is equal to kT over e \ln of I_{ph} by I_{s} not where I_{s} not is a reverse saturation cut. 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 depletion regions and so on. So, we have simple expressions were relate both I_{sc} and V_{oc} to the short circuit current and the open circuit voltage to your incident photon radiation. So, when we change the radiation intensity we can basically calculate the change in these values. So, now the new value of I_{ph} is double so it is 2.

So, let me write this as I_{ph} prime. This is two times the original value 1000 watts per meter square. So, the new short circuit current so I_{sc} new so I am going to write it I_{sc} prime divide by the original I_{sc} is nothing but I_{ph} prime by I_{ph} so 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 milliamps similarly, i can write the value of V_{oc} so.

V_{oc} prime by V_{oc} again you are taking the ratio of these two quantities kT over e , \ln of I_{ph} prime by I_{s} not I_{ph} by I_{s} not. So, kT over e will essentially cancel, this we can simplify because the values of the I_{ph} prime I_{ph} are known, I_{s} is not known but, we can calculate I_{s} not by knowing the open circuit voltage when the current intensity is 500 watts per meter square. So, from this we can e s t we can calculate the value of V_{oc} . So, V_{oc} prime 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 per meter square. We have reduced it by half, so

the new short circuit current I_{sc} double prime 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 we following the same procedure were instead having it has 1000 and now have it as 250. So, let me now go to problem 4.

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Problem #4

a) A Si solar cell of area 1cm^2 is connected to drive a load R and the I-V characteristics for an illumination of 500 W m^{-2} is shown. Suppose the load R is $20\ \Omega$ and the light intensity is 1 kW m^{-2} . What is the voltage in the circuit if current is 24 mA ? What is the power delivered to the load? What is the efficiency of the solar cell in this circuit? The I-V characteristics are plotted.



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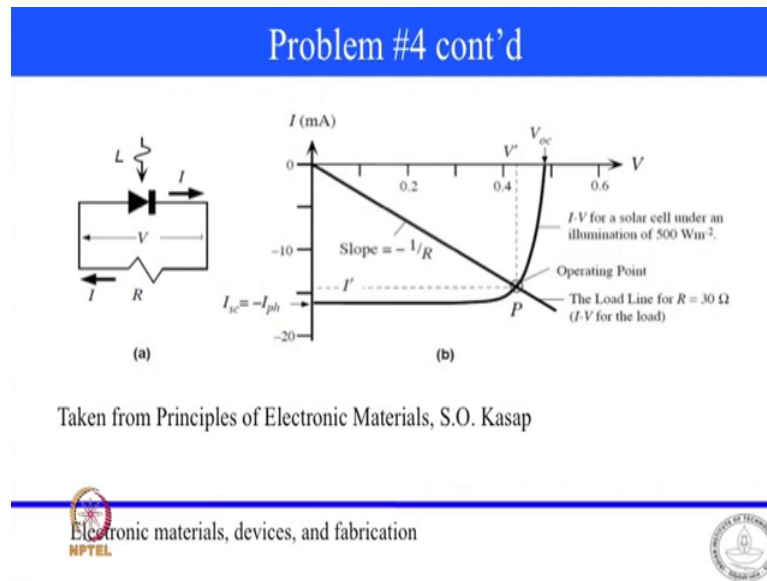
Problem #4 cont'd

b) What should the load be to obtain maximum power transfer from the solar cell to the load at 1 kW m^{-2} illumination? What is this load at 500 W m^{-2} .

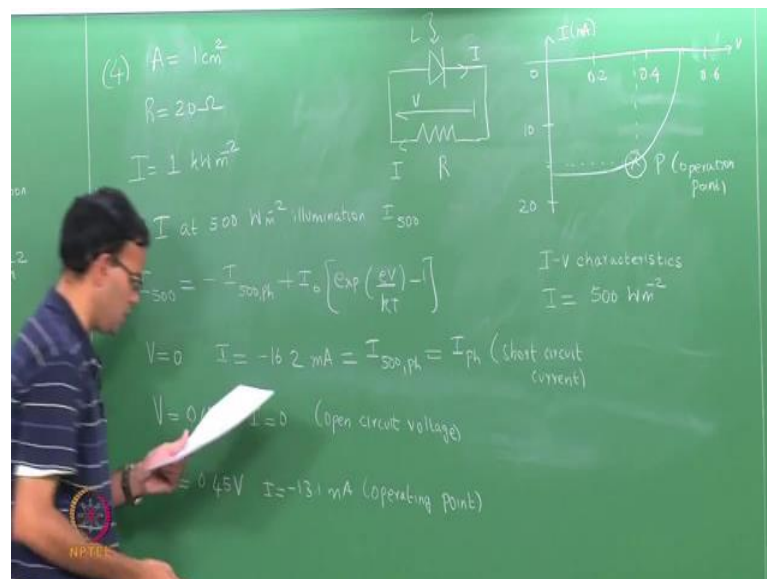
c) Consider using a number of such cells to drive a calculator that needs a minimum of 3 V and draws 3 mA at $3\text{--}4\text{ V}$. It is to be used at a light intensity of 500 W m^{-2} . How many solar cells would you need and how should they be connected?

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Problem 4 is also related to a solar cell, so we have a solar cell of area A is given and is connected to drive a load R of 20 ohms. So, R is essentially 20 ohms. 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 cells 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 intern

generate a voltage V , that opposes the in-built voltage in the solar cell. So, the intensity of the light 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 its $i-v$ characteristics. So, let me plot this, this $I-V$ characteristics is for 500 watts per meters square. So, we have current I that is in milliamps, we have voltage V . This is 0, you have 10, you have 20 this 0.2 you have 0.4 let me just extend this a bit and you have 0.6. So, the $I-V$ characteristics so this is a $I-V$ 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 a particular voltage or the voltage for a particular current when the illumination is now changed to 1000 watts per meter square. So, we can go to the problem.

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 intensity of the light plus a voltage due to the potential barrier that is created by the resistor. This is given as I not exponential eV over kT minus 1. 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 mark the values of these various points. So, when V is equal to 0 this is a short circuit voltage the corresponding current I is minus 16.2 milliamps. This is nothing but I_{500} comma 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 and for this; we can calculate the current and the voltage. So, V is 0.45 volts and the corresponding current I is minus 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.

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Handwritten mathematical derivation on a green chalkboard:

$$I_0 = 2.58 \times 10^{-11} \text{ A}$$

New illumination $I_{ph}^{new} = 2 I_{ph}^{500} = -32.4 \text{ mA}$

$$1000 \text{ W m}^{-2}$$

$$I_{1000} = I_{ph}^{new} + I_0 \left[\exp\left(\frac{eV}{kT}\right) - 1 \right] = 0.024 \text{ A} \Rightarrow V_{new} = 0.475 \text{ V}$$

$$P = V I_{1000} = 0.011 \text{ W}$$

$$P_{in} = (1000 \text{ W m}^{-2}) (10^{-4} \text{ m}^2) = 0.1 \text{ W}$$

$$\text{efficiency} = \frac{0.011}{0.1} \times 100 = 11\%$$

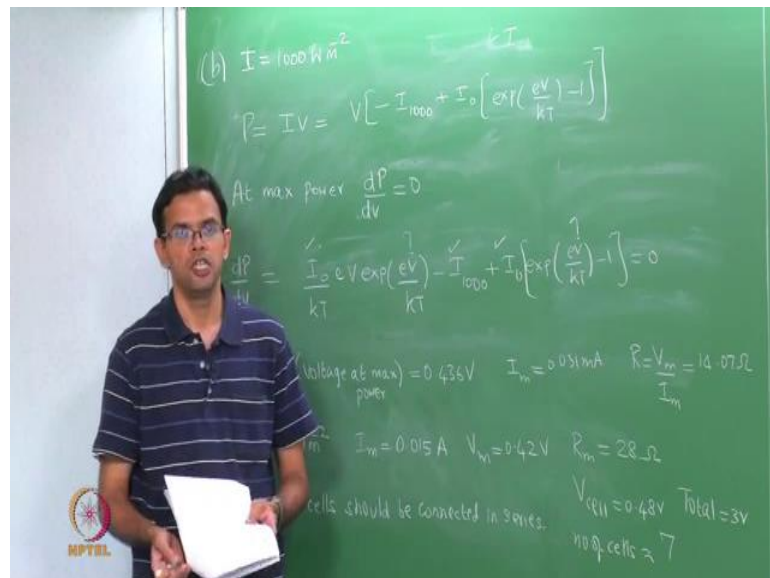
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So, once again let me write the expression. So, I is equal to minus I_{ph} plus I_0 exponential eV over kT minus 1. So, I_0 we do not know, but I_{ph} we know. So, when voltage V is equal to V_{oc} implies current is equal to 0. This is minus I_{ph} plus I_0 exponential eV_{oc} over kT minus 1. So, in this I_{ph} is known, V_{oc} is known, the only unknown is essentially I_0 . So, we can make the substitutions and I_0 is calculated to be 2.58 times 10^{-11} amperes. So, this represents the reverse saturation current in this system. So, now the new illumination I_{ph}^{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}^{500} so this is minus 32.4 milliamps. So, the corresponding current is also given, so I of 1000 is nothing but I_{ph}^{new} plus I_0 exponential eV over kT minus 1. So, this current is given and this is equal to 0.024 amps. So, I_{ph}^{new} we have just calculated, I_0 something we calculated from the data for 500 watts per meter square so this is known, this is known.

We only unknown is the new operating voltage. So, we can make the substitution 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 prime 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 watt so P in is 1000 watts per meter square. And the area of the solar cell is 1centimeter square. So, that is 10^{-4} meter square. 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 times 100 that is equal to 11 percent. So, let us now go to part b.

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So, in part b we are asked to calculate the load. So, to have 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 for 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 times V which can be return as V times minus I of a 1000. So, we have I 1000 plus I not exponential eV over kT minus 1.

So, this is the expression for the power we look at it everything here is a constant except

for the voltage. So, it have maximum power so at maximum power dP over dV must be essentially 0. So, we can differentiate this expression for P . So, dP over dV that is given by $I_{sc} - \frac{I_0}{I_{sc}} \left(\frac{V}{kT} + 1 \right) \exp\left(\frac{eV}{kT}\right) - I_0 \exp\left(\frac{eV}{kT}\right)$ this is equal to zero. So, this you can get by essentially treating this as a differential of 2 functions so we 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_{sc} is known, I_0 is known this is the short circuit current at 1000. Which is two 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 V_m over I_m which is 14.07. 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, I_{sc} 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 3 volts. These solar cells should be connected in series. So, the solar cells should be connected in series. So, if we 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 seven solar cells all connected in series to basically supply in a voltage to run a calculator.

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Problem #5



A photoconductor with dimensions $L = 6 \text{ mm}$, $W = 2 \text{ mm}$, and $D = 1 \text{ mm}$ is placed under uniform illumination. The absorption of light increases the current by 2.83 mA . A voltage of 10 V is applied across the device. As the radiation is suddenly cut off, the current falls, initially at the rate of 23.6 A s^{-1} . The electron mobility is $3600 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$.

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Problem #5 cont'd

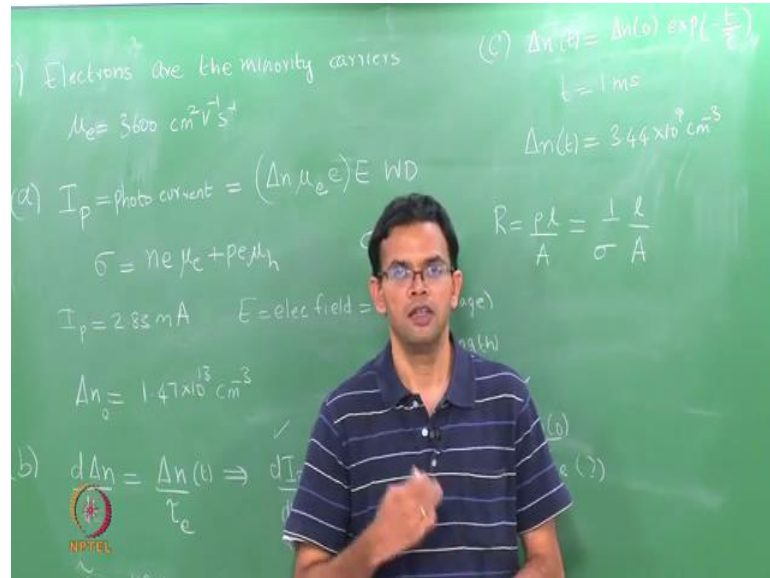
- a) Find the equilibrium density of electron-hole pairs generated under radiation
- b) The minority-carrier lifetime
- c) The excess density of electrons and holes remaining 1 ms after the radiation is turned off

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Let us now go to the last problem, so problem 5 is related to photo conductor. So, we saw some variation of this problem in previous assignment, assignment seven. So, you have a photo conductor that is placed under uniform illumination. It says the absorption of light basically causes an increase in current. The increase is given when you have a particular voltage. Then the radiation is cut off, so that the excess carrier start to

recombine and when that happens in the carrier concentration drops and the current also drops.

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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 weak 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 μ_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 photo current is due to the excess electrons that are created. So, this is equal to Δn 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 $n e \mu_e$ plus $p e \mu_h$, conductivity σ is related to the resistivity as 1 over ρ and R is nothing but ρl over A . So, this is 1 over σl over 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 μ_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 divided by the length L . So, the only unknown in this expression is Δn . So, Δn is 1.47×10^{13} per centimeter cube. 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 life time. So, when the light is switched off the concentration of the minority carriers essentially decreased and this is given by value either particular time t divided by the minority carrier lifetime τ . So, since we are dealing with electrons, I will call this τ_e . So, you can write this in terms of current and if we do this dI_p over dt is nothing but $e \mu_e v$ over l times Wd $d\Delta n$ over dt d $d\Delta n$ over dt is nothing but Δn at time 0 divided by τ . So, Δn at time 0 is nothing but what we calculated in part a dI_p over dt which is the rate at which the current falls which given in the question. This value is 23.6 ampier for second so this is known, this is known the only unknown is τ_e so τ_e is essentially 119.6 micro seconds. Part c we want to calculate the excess density of electrons in holes 1 mini second after the radiation is turn off.

So, part c you want to calculate Δn 1 millisecond later so Δn at time t is nothing but Δn at time t equal to 0 exponential minus t over τ . So, t is one millisecond Δn at time t equal to 0 is what we calculated in part a, so is the excess equilibrium concentration τ is what we calculated in part b. So, Δn is nothing is but 3.44 times 10^9 centimeter cube. Once again we 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.