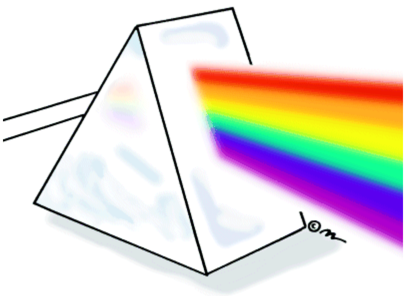
EP118 Optics

TOPIC 11
OPTOELECTRONIC DEVICES



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Content

11.1 Introduction

- Optoelectronics is the branch of physics that deals with the interaction of light with electronic devices, or the production of light from such devices.
- Optoelectronic devices are
  - electrical-to-optical or optical-to-electrical transducers (converters).
- Optoelectronics is based on the *quantum mechanical* effects of light on *semiconducting* materials.

Common Light sources:
- LED
- Laser
- LCD
- ...

Common Light Detectors:
- Photodiodes
- Phototransistors
- Photoresistors (LDR)
- Photomultiplier Tube (PMT)
- Charge coupled device (CCD)
- Optocouplers
- ...

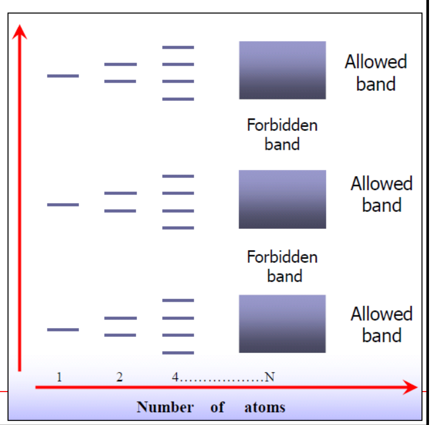
In this chapter, we'll see some of above

11.2 Semiconductors (very basic level)

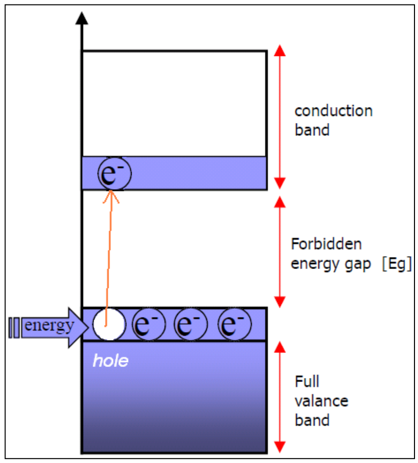
- Materials can be categorized into
  conductors,
  insulators or
  semiconductors (S/C)
  by their ability to conduct electricity (Conductivity σ).
- $\sigma_{metals} \sim 10^{10}/\Omega.cm < \sigma_{S/C} < \sigma_{insulator} \sim 10^{-22}/\Omega.cm$

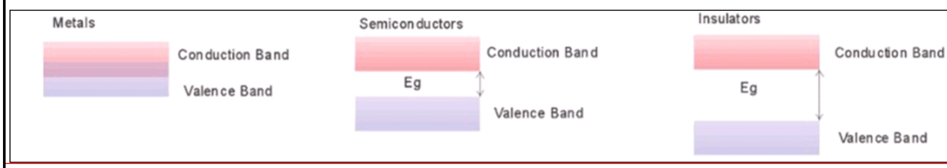
BAND STRUCTURE

- The electrons surrounding a nucleus have certain well-defined energy-levels.
- Electrons don't like to have the same energy in the same potential system.
- Hence the band structure of solid take place.



- Assume some kind of energy is provided to the electron (valence electron) sitting at the top of the valance band.
- This electron contributes to the conductivity and this electron is called as a conduction electron.
- When enough energy is supplied to the e- at the top of the valance band, e- can make a transition to the bottom of the conduction band.
- This electron leaves behind a missing electron state called hole.
- Hole behaves as a positive charge carrier.

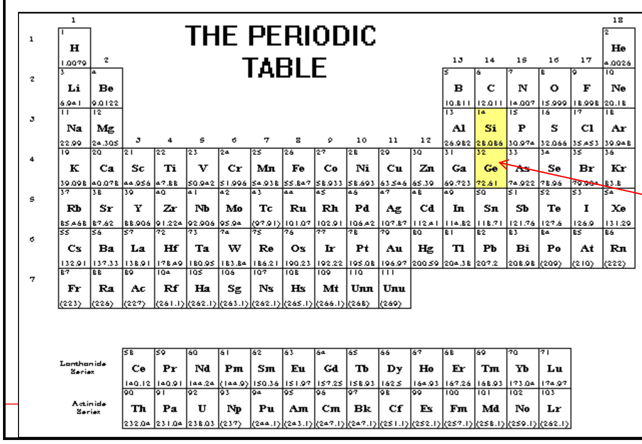




Elemental semiconductors are semiconductors where each atom is of the same type. *Examples are Ge, Si*.

Adding impurity atoms from 3A or 5A elements (about 1 in 10^6) to the pure S/C (Si) crystal makes S/C a good conductor.

Compound semiconductors are made of two or more elements. *Common examples are GaAs or CdS*.



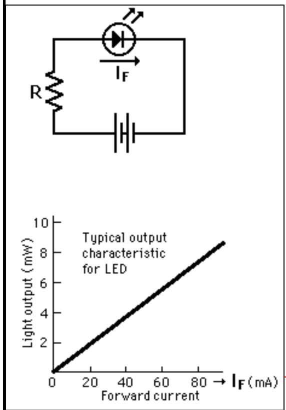
Example 4A S/C Elements

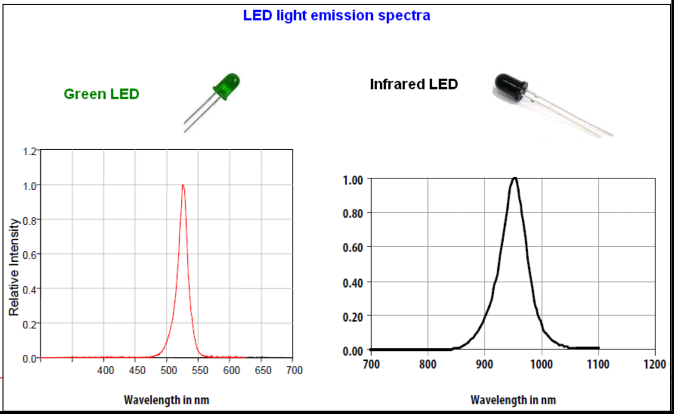
You will see the details at EP311 Physics of Semiconductor Devices

11.3 LED

- A light-emitting diode (LED) is a semiconductor light source.
- Circuit Symbol: 

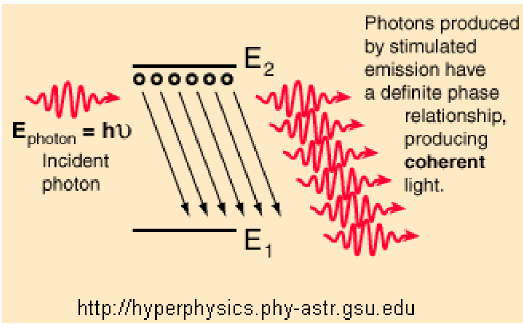
- A LED can produce the visible, ultraviolet and infrared wavelengths, with very high brightness.





11.3 Laser

- "Laser" stands for
Light **A**mplification by **S**timulated **E**mission of **R**adiation
- A laser is a device that emits light through a process of optical amplification based on the stimulated emission of photons.
- A Laser is coherent, monochromatic and collimated light.
- A Laser light can be
* *visible*
* *infrared*
* *ultraviolet*
* *X-ray*



- Laser is highly collimated --> beam divergence ~ mrad (milli-radians)
- Properties of an example laser pointer (GLP-III-594)

Specifications	
Wavelength	593.5 ±1 nm
Output Power	5 – 20 mW
Transverse Mode	TEM_{00}
Operating Mode	CW
Beam Divergence (full angle)	< 1.5 mrad
Beam Diameter (at the aperature)	~ 1.5 mm
Power Supply	1 x 18650 Li-Ion battery (included)
Expected Lifetime	5000 hours
Max. continuous ON time	**30s**
Warranty period	6 months

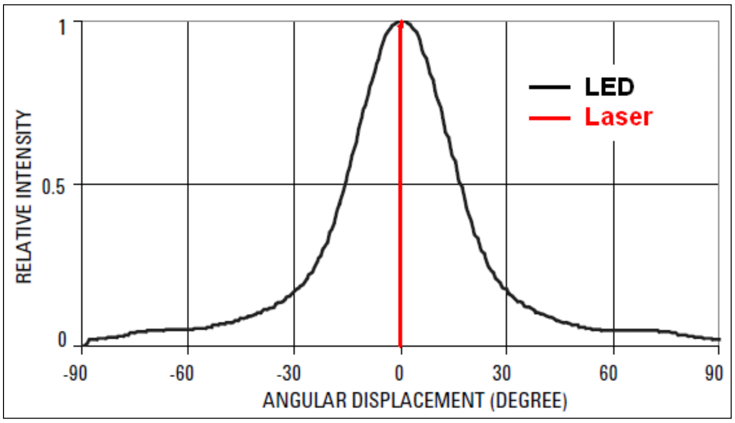
EXAMLPE 1

Consider laser pointer whose aperture diameter is D = 1.5 mm and beam divergence is $\Delta\theta$ = 1.5 mrad (=0.086°). What is the diameter of the laser spot on a screen at a distance L = 100 m away from the pointer?

SOLUTION

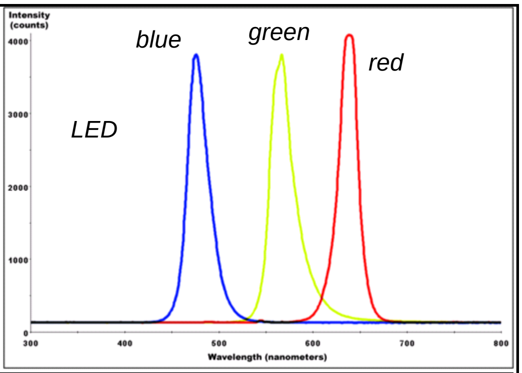
LED vs Laser

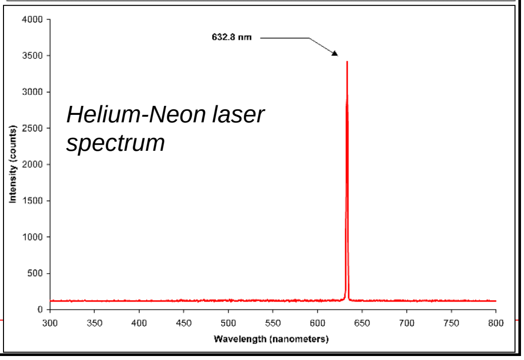
- Comparison of Beam Divergence of LED and Laser



LED vs Laser

- Spectral width of the laser is 10,000 times narrower than the spectral width of a light-emitting diode.





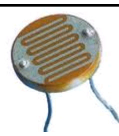
Laser Radiation

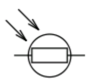
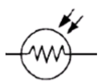
- Lasers can cause damage in biological tissues, both to the eye and to the skin.
- *Unprotected Human Eye is extremely sensitive to laser radiation and can be permanently damaged from direct or reflected beams.*
- High power lasers can also burn the skin.

Wavelength Division	Wavelength (nm)	The main injury parts of eyes
UV laser	180-400	Cornea, lens
Visible Laser	400-700	Retina, choroid
Near-infrared laser	700-1400	Retina, choroid, lens
Far-infrared laser	1400-106	Cornea

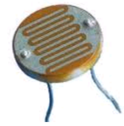
- There are some government regulations that define classes of laser according to the risks associated with them.

11.5 Photo-resistor (LDR)



- A photoresistor or Light Dependent Resistor (LDR) is a resistor whose resistance decreases with increasing incident light intensity. It can also be referred to as a **photoconductor**.
- Circuit symbol:  or 
- A LDR is made of a high resistance *semiconductor*.
  - If light falling on the device is of high enough frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the *conduction band*.
  - The resulting free electron (and its hole partner) conduct electricity, thereby lowering resistance.
- LDR come in many different types. Inexpensive cadmium sulfide (CdS) cells can be found in many consumer items such as *camera light meters* and *street lights*.

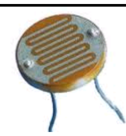
Some Properties of LDR (Extracted from http://www.sunrom.com/files/3190-datasheet.pdf)



- *Typical Characteristics*

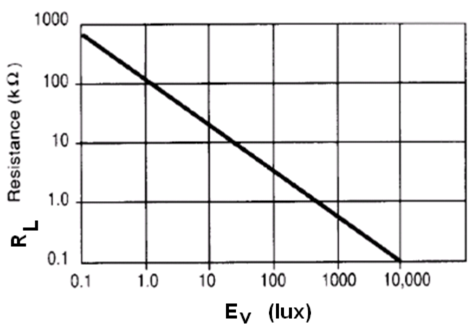
Parameter	Conditions	Min	Typ	Max	Unit
Cell resistance	1000 LUX 10 LUX	- -	400 9	- -	Ohm K Ohm
Dark Resistance	-	-	1	-	M Ohm
Dark Capacitance	-	-	3.5	-	pF
Rise Time	1000 LUX 10 LUX	- -	2.8 18	- -	ms ms
Fall Time	1000 LUX 10 LUX	- -	48 120	- -	ms ms
Voltage AC/DC Peak		-	-	320	V max
Current		-	-	75	mA max
Power Dissipation				100	mW max
Operating Temperature		-60	-	+75	Deg. C

(Extracted from http://www.sunrom.com/files/3190-datasheet.pdf)



- *Sensitivity*
  The sensitivity of a LDR is the relationship between the light falling on the device and the resulting output signal (resistance).

RESISTANCE AS FUNCTION OF ILLUMINATION

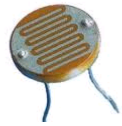


Equation of line is

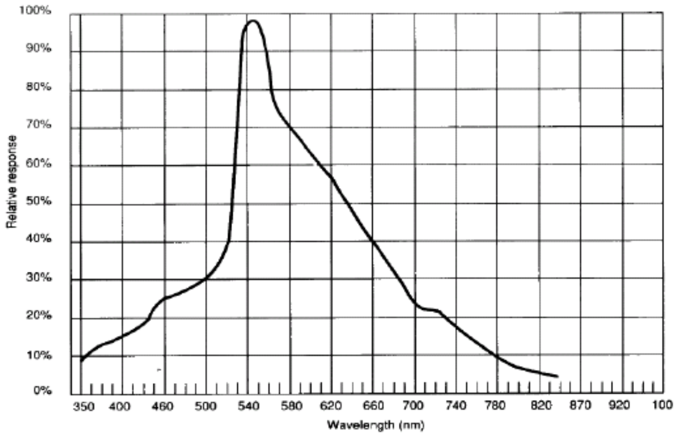
$$\log(R_L) \approx 2 - 0.75\log(E_v)$$

LDR resistance in kΩ — **illuminance in lux**

(Extracted from http://www.sunrom.com/files/3190-datasheet.pdf)



- *Spectral Response*
  Like the human eye, the relative response of a LDR cell is dependent on the wavelength (color) of the incident light. Each photoconductor material type has its own unique spectral response curve.



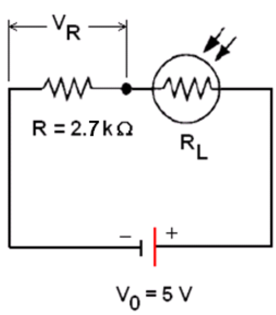
a simple lux-meter

EXAMPLE 2

One can setup the following simple circuit to measure the illuminace (E_v) by measuring the potential across the resistor R. Assume that the LDR resistance (R_L) in kΩ is related to E_v in lux as follows:

$$\log(R_L) = -0.75\log(E_v) + 2$$

Calculate E_v if V_R = 2 V and R = 2.7 kΩ.



SOLUTION

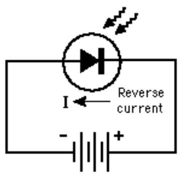
11.6 Photo-diode

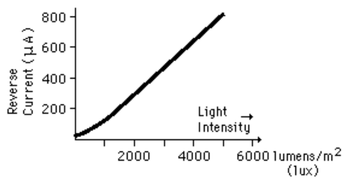
- A photodiode is capable of converting light into either current or voltage, depending upon the mode of operation.
- Circuit symbol: 

- A traditional *solar cell* is just a large area photodiode.
- When a photon of sufficient energy strikes the diode, it excites an electron, thereby creating a free electron and a (positively charged electron hole). Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced.
- Materials commonly used to produce photodiodes are:
  Silicon (Si)
  Germanium (Ge)
  Indium Gallium Arsenide (InGaAr)

Sayfa 19

- When light falls on the photodiode, a reverse current flows which is proportional to the illuminance.

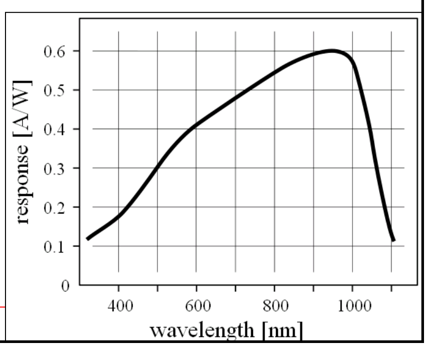




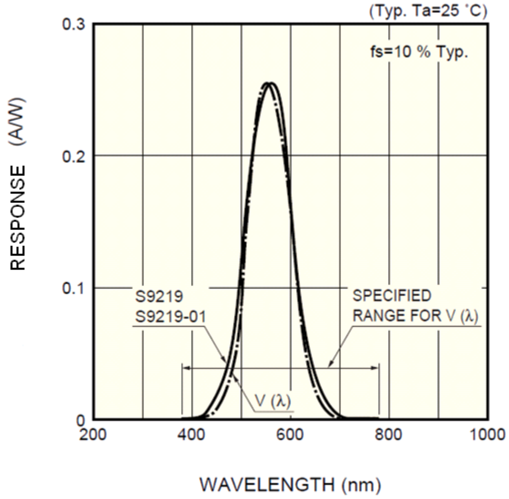
- Responsivity of a an electronic device is measure of the electrical output per optical input.

  SI Unit: Ampere/Watt

Response of a silicon photo diode vs wavelength of the incident light



- An example Si photodiode (S9219 series) whose spectral response is like *human eye*!



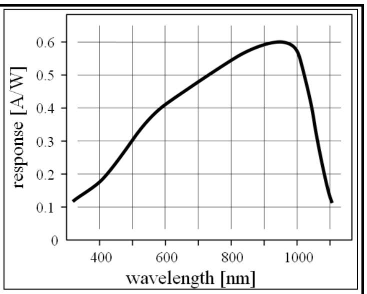
See: http://www.datasheetdir.com/S9219+download

EXAMPLE 3

Responsivity of a Si photodiode is shown in figure. What current does the photodiode produce if it is illuminated

(a) by a 10 mW laser whose wavelength is 600 nm?

(b) by a light (of wavelength 600 nm) whose luminous flux on the diode is 10 lm?



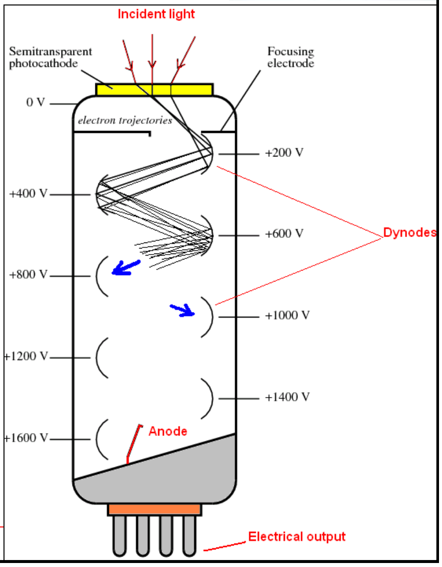
SOLUTION

11.7 Photo-multiplier Tube (PMT)

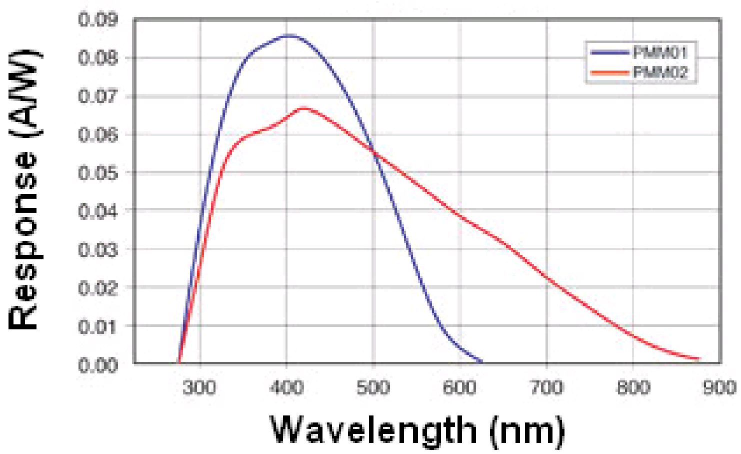
- PMT is a light detector that are useful in low intensity applications. Due to high internal gain, PMTs are very sensitive detectors.

- PMTs consist of a photocathode and a series of dynodes in an evacuated glass enclosure.

1. *Photons that strikes the photocathode which emits electrons.*
2. *The electrons are accelerated towards a series of additional electrodes called dynodes where cascading electrons are generated.*
3. *This cascading effect creates 10^5 to 10^7 "new" electrons for each photon hitting the first cathode.*
4. *This amplified signal is finally collected at the anode where it can be measured as electrical current.*



Spectral response of two different PMTs



- Typical Characteristics of a PMT

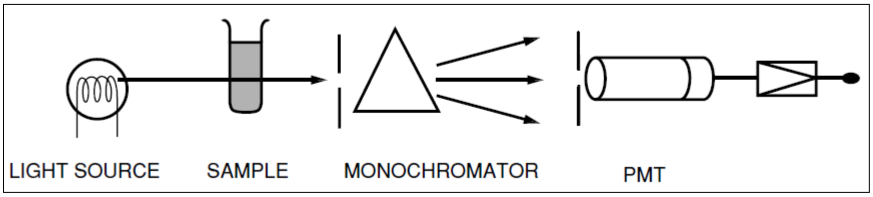
Dimensions (mm)	50.8x13x53.2
Input Current (mA)	7
Input Voltage (V)	± 11.5 to ± 15.5
Control Voltage (V)	+0.25, +0.9, +1.0
Radiant Sensitivity - Anode	4.2×10^5 A/W
Radiant Sensitivity - Cathode (mA/W)	105
Peak Response Wavelength (nm)	450
Spectral Response (nm)	185-900
Sensitivity Adjustment	$1:10^4$
Output Signal	10
Ripple (mV)	0.5
Active Area (mm)	3.7x13.0
Dark Current I_d (nA)	2/10
Settling Time (seconds)	10
Rise Time (ns)	1.4
Operating Temperature (°C)	+5 to +50
Storage Temperature (°C)	-20 to +50
Weight (g)	110

NT66-272

Current Output Type PMT Module

Price: $1295

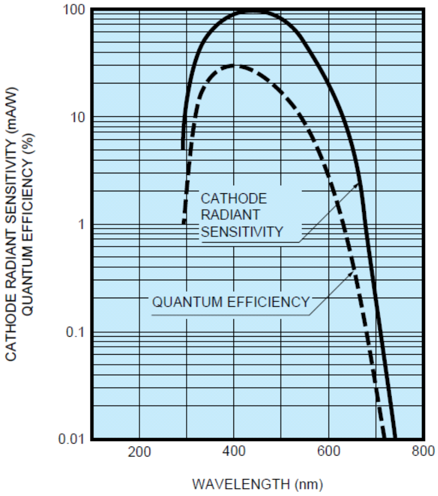
An example application used in absorption spectroscopy.



- Quantum Efficiency (QE)

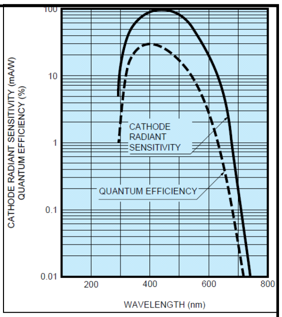
QE is a quantity defined for a photosensitive device (such as PMT, CCD, etc) as the percentage of photons hitting the photoreactive surface that will produce an electron–hole pair.

Figure shows a typical Spectral Response and QE of a PMT



EXAMPLE 4

Spectral Response and QE of a PMT is shown in figure.
It is illuminated by a 10 mW laser of wavelength 600 nm.
(a) What current does PMT produce?
(b) How many of the photons generated in one second by the source will be converted into electrons in the PMT?



SOLUTION

From figure the output current response of the PMT is 20 mA/W and QE = 3% at λ=600 nm.

(a) The current produced by the PMT is:

$$i = (0.02\ \text{A/W})(10.0\times10^{-3}\ \text{W}) = 2.0\times10^{-4}\ \text{A} = 0.2\ \text{mA}$$

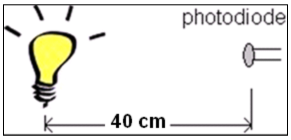
(b) Number of photons generated by the laser and electrons converted in PMT:

$$N_{ph} = \frac{W}{E_{ph}} = \frac{W}{hc/\lambda} = \frac{10\times10^{-3}\,\text{W}}{(6.6\times10^{-34}\,\text{J.s})(3\times10^{8}\,\text{m/s})/600\times10^{-9}\,\text{m}} = 3\times10^{16}\ \frac{\text{photons}}{\text{s}}$$

$$N_{elec} = N_{ph}(QE) = (3\times10^{16}\ \frac{\text{photons}}{\text{s}})(0.03\frac{\text{electrons}}{\text{photons}}) = 9\times10^{14}\ \frac{\text{electrons}}{\text{s}}$$

11.8 Exercises

1. What is the sensitivity and responsivity of an optoelectronic device?
2. Explain how the circuit in EXAMPLE 2 can be used to measure irradiance of a light source?
3. In EXAMPLE 2, assume that the diameter of the LDR is 0.5 cm and it is illuminated by a monochromatic light whose wavelength is 580 nm.
   (a) Calculate the luminous flux in lumens on the surface of the LDR.
   (b) Calculate the radiant flux in Watts on the surface of LDR.
4. In EXAMPLE 3, assume that the photodiode has a diameter of 0.5 cm and is illuminated only by a bulb radiating monochromatic light in all directions. The radiant power of the bulb is 100 W and the distance between the bulb and photodiode is 40 cm as shown in figure. If the photocurrent measured by the diode is 2 mA, calculate the wavelength of the light radiated from the bulb. (*Ans: λ~750 nm*)



5. A PMT is illuminated by a monochromatic light source whose wavelength is 400 nm. The luminous flux on the tube surface is 20 lm. Calculate current that can be produced by the PMT if its response is like PMM01 given in page 24.

11.9 References

1. http://en.wikipedia.org/wiki/Optoelectronics
2. http://en.wikipedia.org/wiki/LED
3. http://en.wikipedia.org/wiki/Laser
4. http://en.wikipedia.org/wiki/Laser_safety
5. http://en.wikipedia.org/wiki/Light_Dependent_Resistor
6. http://en.wikipedia.org/wiki/Photodiode
7. http://en.wikipedia.org/wiki/Photomultiplier
8. http://en.wikipedia.org/wiki/Quantum_efficiency
9. http://www.sunrom.com/files/3190-datasheet.pdf
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13. http://www.datasheetcatalog.com
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