EP118 Optics

TOPIC 11
OPTOELECTRONIC
DEVICES

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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 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 $\sigma$).
- $\sigma_{\text{metals}} \sim 10^{10}/\Omega\cdot\text{cm} < \sigma_{\text{S/C}} < \sigma_{\text{insulator}} \sim 10^{-22}/\Omega\cdot\text{cm}$

**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 valence 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 valence 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.
11.3 LED

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

- Circuit Symbol: ![Circuit Symbol](image)

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

11.3 Laser

- "Laser" stands for Light Amplification by Stimulated Emission of Radiation

- 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

[Diagram of Laser Light Emission]

http://hyperphysics.phy-astr.gsu.edu
- Laser is highly collimated $\Rightarrow$ beam divergence $\sim \text{mrad}$ (milli-radians)
- Properties of an example laser pointer (GLP-III-594)

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$593.5 \pm 1$ nm</td>
</tr>
<tr>
<td>Output Power</td>
<td>$5 - 20$ mW</td>
</tr>
<tr>
<td>Transverse Mode</td>
<td>$\text{TEM}_{00}$</td>
</tr>
<tr>
<td>Operating Mode</td>
<td>CW</td>
</tr>
<tr>
<td>Beam Divergence (full angle)</td>
<td>$&lt; 1.5$ mrad</td>
</tr>
<tr>
<td>Beam Diameter (at the aperture)</td>
<td>$\sim 1.5$ mm</td>
</tr>
<tr>
<td>Power Supply</td>
<td>1 x 18650 Li-Ion battery (included)</td>
</tr>
<tr>
<td>Expected Lifetime</td>
<td>5000 hours</td>
</tr>
<tr>
<td><strong>Max. continuous ON time</strong></td>
<td><strong>30s</strong></td>
</tr>
<tr>
<td>Warranty period</td>
<td>6 months</td>
</tr>
</tbody>
</table>

**EXAMPLE 1**
Consider laser pointer whose aperture diameter is $D = 1.5$ mm and beam divergence is $\Delta \theta = 1.5$ mrad ($=0.086^\circ$). 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

![Graph showing beam divergence comparison between LED and Laser](image)

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

![Spectral comparison between LED and Helium-Neon laser](image)
**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.

<table>
<thead>
<tr>
<th>Wavelength Division</th>
<th>Wavelength (nm)</th>
<th>The main injury parts of eyes</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV laser</td>
<td>180-400</td>
<td>Cornea, lens</td>
</tr>
<tr>
<td>Visible Laser</td>
<td>400-700</td>
<td>Retina, choroid</td>
</tr>
<tr>
<td>Near-infrared laser</td>
<td>700-1400</td>
<td>Retina, choroid, lens</td>
</tr>
<tr>
<td>Far-infrared laser</td>
<td>1400-106</td>
<td>Cornea</td>
</tr>
</tbody>
</table>

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

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**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: ![Circuit symbol](image)

- 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*.

- **Typical Characteristics**

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

Equation of line is

\[
\log(R_L) \approx 2 - 0.75\log(E_v)
\]

Sensitivity

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

![Spectral Response Graph]

**EXAMPLE 2**

One can setup the following simple circuit to measure the illuminance \( E_v \) 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 \( V_R = 2 \text{ V} \) and \( R = 2.7 \text{ kΩ} \).

**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: \[\text{anode} \quad \text{cathode}\]

- 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)

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

- Responsivity of an electronic device is a measure of the electrical output per optical input.
  
  SI Unit: Ampere/Watt
An example Si photodiode (S9219 series) whose spectral response is like human eye!

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

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**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 $10^6$ 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.
• Typical Characteristics of a PMT

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm)</td>
<td>50.8x13.5x53.2</td>
</tr>
<tr>
<td>Input Current (mA)</td>
<td>7</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>± 11.5 to ± 15.5</td>
</tr>
<tr>
<td>Control Voltage (V)</td>
<td>+0.25, +0.9, +1.0</td>
</tr>
<tr>
<td>Radiant Sensitivity - Anode</td>
<td>4.2x10^3 A/W</td>
</tr>
<tr>
<td>Radiant Sensitivity - Cathode (mA/W)</td>
<td>105</td>
</tr>
<tr>
<td>Peak Response Wavelength (nm)</td>
<td>450</td>
</tr>
<tr>
<td>Spectral Response (nm)</td>
<td>185-900</td>
</tr>
<tr>
<td>Sensitivity Adjustment</td>
<td>1.10^4</td>
</tr>
<tr>
<td>Output Signal</td>
<td>10</td>
</tr>
<tr>
<td>Ripple (mV)</td>
<td>0.5</td>
</tr>
<tr>
<td>Active Area (mm)</td>
<td>3.7x13.0</td>
</tr>
<tr>
<td>Dark Current Ig (nA)</td>
<td>2/10</td>
</tr>
<tr>
<td>Settling Time (seconds)</td>
<td>10</td>
</tr>
<tr>
<td>Rise Time (ns)</td>
<td>1.4</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td>+5 to +50</td>
</tr>
<tr>
<td>Storage Temperature (°C)</td>
<td>-20 to +50</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>110</td>
</tr>
</tbody>
</table>

**NT66-272**

**Current Output Type PMT Module**

**Price**: $1295

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An example application used in absorption spectroscopy.

![Diagram of absorption spectroscopy setup]

- **Light Source**
- **Sample**
- **Monochromator**
- **PMT**
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:
\[ i = (0.02 \text{ A/W})(10.0 \times 10^{-3} \text{ W}) = 2.0 \times 10^{-4} \text{ A} = 0.2 \text{ mA} \]

(b) Number of photons generated by the laser and electrons converted in PMT:
\[ N_{ph} = \frac{W}{E_{ph}} = \frac{W}{hc/\lambda} = \frac{10 \times 10^{-3} \text{ W}}{(6.6 \times 10^{-34} \text{ J.s})(3 \times 10^8 \text{ m/s})/600 \times 10^{-9} \text{ m}} = 3 \times 10^{16} \text{ photons/s} \]
\[ N_{elec} = N_{ph} \cdot (QE) = (3 \times 10^{16} \text{ photons/s})(0.03 \text{ electrons/photon}) = 9 \times 10^{14} \text{ electrons/s} \]
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: $\lambda \approx 750$ 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

10. http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/optelcon.html
12. http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/lascon.html