Chapter 4
OPTICAL DETECTORS

(Reference: Optical Electronics in Modern Communications, A. Yariv, Oxford, 1977, Ch. 11.)

Photomultiplier Tube (PMT)
• Highly sensitive detector for light from near infrared → ultraviolet
• Can detect as little as $10^{-19}$ Watt!

![Diagram of Photomultiplier Tube]

Voltage divider chain to bias dynodes

- $R$ chosen to have ~100V drop per dynode
- Photocathode $C$: absorbs photon $\rightarrow$ ejects electron
  - work function $\phi$ is the minimum energy needed to eject an electron
  - the photon energy must exceed the work function $h\nu > \phi$ to get photoelectrons

Dynodes D1-D8: Secondary electron emission. Electron from cathode accelerated by ~100 eV. Impact into dynode surface causes ejection of multiple electrons, $\delta \approx 5$.

For $N$ dynodes, the total gain is then $\delta^N$.

Photocathode quantum efficiency: $QE \equiv$ probability a photon will eject one electron

$0 \leq QE \leq 1$

Typical photocathode response

![ QE vs. Wavelength ]

Sensitivity:
Chapter 4: DETECTORS

For 10 dynodes, $\delta = 5$, $G = 5^{10} \approx 10^7$.

Take 2eV photons (620 nm), 1 picoW = $10^{-12}$W = $10^{-12}$J/s

With $QE = 30\%$, Anode current is

Phototube dark current: 1) random thermal excitation of electrons from photocathode
2) cosmic rays, ambient radioactivity

- Thermal excitation rate is proportional to $e^{\Phi}$, where $\Phi$ represents the cathode work function
  - so lower work function $\rightarrow$ IR sensitivity, but larger dark current

- For room temperature, typical cathode dark current, $I_{cd}$, is $\approx 10^4$ electrons/sec. Anode dark current is then

- Dark current sets a lower limit to phototube sensitivity to low light levels. To distinguish a light signal above the background dark current, the photoelectric cathode current must exceed the dark current. If $I_{cd}$ is $\approx 10^4$e/sec, then the sensitivity to light can be $\sim 3 \times 10^4$ photons/sec (assuming $QE = 30\%$). $3 \times 10^4$ red photons/s $\approx 10^{-14}$ W!

- Dark current can be reduced by cooling. Using thermoelectric cooling $T = -40^\circ C$ is easily obtained. Assume a work function of $\Phi = 1.5$ eV

\[
\frac{I_{cd}(260K)}{I_{cd}(300K)} = e^{-1.5/0.0225} = e^{-1.5(44.4 - 38.5)} = e^{-8.8} \approx 1.4 \times 10^{-4}
\]

Dark current is reduced by this amount! $\rightarrow$ down to $\sim 1$ e/sec. Minimum detectable power become $< 10^{-18}$ W!

Photon counting: PMT is so sensitive, we are really counting photons. Often, PMT circuits are specifically optimized to do this.
Photon counting system:

PMT output pulse

- How big is the PMT output pulse from one photon? For $G \sim 10^7$, we get $10^7$ electrons $\approx 10^{-12} \text{C}$. For $\tau_p = 10^{-8} \text{sec}$, $I_{apk} \sim 10^{-4} \text{A}$. For $R = 50\Omega$, $V_p \sim 5 \text{mV}$.

- Discriminator eliminates electrical noise in $< 1\text{mV}$ range. $V_p$ has a variation due to statistical nature of gain process. Discriminator also eliminates this.

*Shot noise:* Photon arrival is always statistical. Generally it follows Poisson statistics. Then if the photon arrival rate is $N \text{ph/sec}$, and we count for 1 sec, we get $N$ on average. The standard deviation will be found to be $\sqrt{N}$. This means we have noise.

Shot noise is universal for light detection. Even if photons are not explicitly counted, the shot noise is a fundamental limit. It is most significant at low light levels, though, due to $\sqrt{N}$ dependence.

*Johnson noise:* Random thermal noise in any resistor, $R$
Chapter 4: DETECTORS

\[ I_{RMS} = \sqrt{\frac{4kT}{R}} B \]

\[ V_{RMS} = \sqrt{4kTRB} \]

Equivalent model of noise as either current or voltage source.

Channel Electron Multiplier (Channeltron)

Single monolithic device functions as a PMT:

1. Photon hits funnel portion
2. Electrons are accelerated into the bent tube by bias field
3. Secondary electron emission gives gain at each electron collision with wall
4. Must be operated in vacuum
5. Typical gain ~ 10^4
6. More compact and rugged than PMT

Microchannel plate MCP – array of channeltrons

Glass tube bent around curve. One end open as a funnel shape. Coating acts as photocathode and secondary electron emitter. Also, coating has high, but not infinite electrical resistance.

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- each channel is a miniature channeltron
- gain ~10^3

Dual Plate MCP Detector

Gain ~10^6  HV ~1-2KV
MCP Image Intensifier

- Electrons accelerated out of back of MCP into phosphor
- Phosphor QE ~50% photons/electrons

Image intensification → Night vision goggles

Semiconductor Photodetectors
- Semiconductor band structure

- Optical absorption across the bandgap

If $h \nu > E_G$, an electron and hole (pair) is created after photon absorption.

In a suitable structure, the electron and the hole can contribute to an electric current through the device.
Chapter 4: DETECTORS

- p-n Junction

\[ N = N_D - N_A \]

\[ N_D \]

\[ -N_A \]

\[ z \]

\[ \rho \]

\[ -l_p \]

\[ l_n \]

\[ \varepsilon \]

\[ z \]

- Depletion approximation: Assumes carriers diffuse across junction and create regions that are totally devoid of free carriers

\[ \rho \]

\[ -l_p \]

\[ l_n \]

\[ \varepsilon \]

\[ z \]
Chapter 4: DETECTORS

- Reverse bias

Under reverse bias, no current flows because the barrier to diffusion increases. Under forward bias, barrier to diffusion is reduced.

Photodiode

Reverse bias condition: electron and hole created in the depletion region follow the electric field and separate.

The electric field exists only inside the depletion region. So the light absorption must also occur there to create current.

Construction

- Photodiodes can be used at longer wavelength than photomultiplier – \( E_G < \Phi \)
- Typically fast response time < 10 nsec
• Compact, inexpensive

p-i-n photodiode

$\varepsilon$-field in the i-layer

constant $\varepsilon$-field in the i-layer
Solar cells


silicon p-n junction diode:

\[ I = I_0 \left( \frac{V}{V_{th}} \right)^n \]

Solar radiation -
AM 1.5 - on a clear day, the typical maximum solar irradiance is $\sim 1\text{ kW/m}^2$ or $100\text{ mW/cm}^2$, which translates to $\sim 4.4\times 10^{17}\text{ photons/cm}^2\text{-sec}$. In principle, when absorbed, this photon flux could produce a ‘generation current’ of

$$I = N \times A$$

where $N$ is the number of photons absorbed per second, and $A$ is the area that is exposed to light. For the entire solar spectrum, this corresponds to about $70\text{ mA/cm}^2$. The band gap for crystalline silicon is $1.1\text{ eV}$, so only the part of the spectrum shown above that is shaded in black can be absorbed. Thus, for silicon, the maximum generation current is about $44\text{ mA/cm}^2$.

**Direct vs. indirect gap**
Some semiconductors are good absorbers, and absorb all above-bandgap light in a layer of a few microns thick. These are called direct-bandgap semiconductors. In others, called indirect-gap semiconductors, which include crystalline silicon, the absorption process is weaker. In this case, a phonon (a quantum of the lattice vibration) is necessary to conserve momentum in the light absorption process. In silicon, a layer several hundred microns thick is required.

Solar cell structure

The top contact structure typically consists of widely spaced thin metal strips to allow the light to pass through, with a larger bus bar connecting them all to extract the current. An anti-reflection coating on top of the cell can be used to minimize reflection loss from the top surface.
The light generation current in the diode is in the reverse direction, so we can write to total current as the difference between the two:

The I-V characteristic now looks like this:

Maximum power point
No power is generated under open or short circuit. The maximum power $P_{\text{max}}$ is produced by the device at a point on the characteristic where the product $IV$ is maximized. The position of the maximum power point represents the largest area of the rectangle shown in the figure below. The ‘fill factor’, FF is commonly defined by:
The efficiency of a solar cell, $\eta$, is defined as $P_{\text{max}}$ produced by the cell under standard test conditions, divided by the power of the radiation incident. Usually, the standard conditions are: irradiance of 100 mW/cm$^2$, standard reference AM1.5 spectrum and temperature of 25°C.

**Some common solar cell types**

High quality crystalline silicon and gallium arsenide solar cells can achieve efficiencies approaching 25%, but are relatively expensive because the cost of growing and processing large single-crystal wafers is high. The p-i-n structure is used for silicon cells in order to get an active light absorbing layer that is over 100 microns thick.

Thin-film solar cells can be much cheaper, but are not as efficient (10-15%). A very common material for thin-film cells is amorphous silicon. Silicon is a four-fold coordinated atom that is normally tetrahedrally bonded to four neighboring silicon atoms. In crystalline silicon this tetrahedral structure is continued over a large range, forming a well-ordered lattice (crystal). In amorphous silicon this long range order is not present and the atoms form a continuous random network. Not all the atoms within amorphous silicon are four-fold coordinated. Due to the disordered nature of the material some atoms have a dangling bond. These dangling bonds are defects in the continuous random network, which cause undesired (electrical) behaviour. The material can be passivated by hydrogen, which bonds to the dangling bonds and neutralises this defect. Hydrogen passivated amorphous silicon has a sufficiently low amount of defects to be used within devices. Amorphous silicon can be deposited over large areas using chemical vapor deposition methods.

Amorphous silicon (a-Si) becomes a direct-gap semiconductor with a band gap of about 1.75 eV. Absorption is higher in a-Si compared to crystal silicon (c-Si), but p-i-n structures are generally still used. The transport properties of a-Si are inferior to c-Si and so many carriers can recombine before they reach the contacts, reducing the efficiency of the cell.
Chapter 4: DETECTORS

Solar cell efficiency progress

![Graph showing solar cell efficiency progress over time.](image)

**Brief discussion of global solar energy**

Total average global power consumption in 1990: 12 TW. Projected to grow to 28 TW by 2050.

1.2x10^5 TW of solar energy potential globally

Generating 2x10^1 TW with 10% efficient solar farms requires 2x10^2/1.2x10^5 = 0.16% of Globe = 8x10^11 m^2 (i.e., 8.8 % of U.S.A)

Generating 1.2x10^1 TW (1998 Global Primary Power) requires 1.2x10^2/1.2x10^5= 0.10% of Globe = 5x10^11 m^2 (i.e., 5.5% of U.S.A.)

U.S. Land Area: 9.1x10^12 m^2 (incl. Alaska)

Average solar irradiance: 200 W/m^2

2000 U.S. Primary Power Consumption: =3.3 TW

1999 U.S. Electricity Consumption = 0.4 TW

Hence:

3.3x10^12 W/(2x10^2 W/m^2 x 10% Efficiency) = 1.6x10^11 m^2
Requires $1.6 \times 10^{11} \ m^2 / 9.1 \times 10^{12} \ m^2 = 1.7\%$ of Land

$7 \times 10^7$ detached single family homes in U.S.

$\sim 2000$ sq ft/roof = 44 ft x 44 ft = 13 m x 13 m = 180 m$^2$/home

= $1.2 \times 10^{10} \ m^2$ total roof area

Hence can (only) supply 0.25 TW, or $\sim 1/10$th of 2000 U.S. Primary Energy Consumption

6 boxes at 3.3 TW each
Charge coupled device (CCD)

The basic CCD is composed of a linear array of MOS capacitors. It functions as an analog memory and shift register. The operation is indicated in the diagram below:

In the fashion indicated, charge is transferred down the line. In the modern CCD image sensor, there is one such CCD transfer line for each column of the array. During the image exposure, one phase in each column is biased in deep depletion. Light passes through the gate electrodes, which are made thin enough so that most of the light creates electron-hole pairs in the substrate, which are then collected under the gates. To read out the array, each column is clocked down by one. At the bottom, there is one extra CCD line oriented in the horizontal direction. The columns deposit their charge in this horizontal array, which then clocks out to a charge sensitive amplifier and then off-chip. In turn, the array is read out one line at a time in this fashion.

Spatial Light Modulator (SLM)

Electro-optic devices that can modulate certain properties of an optical wavefront: amplitude, intensity, phase, or polarization
Liquid Crystal Display – Liquid Crystal Light Valve

By using two polarizers, twisted nematic liquid crystal and applied electric field, modulation of light intensity can be achieved.

<table>
<thead>
<tr>
<th>Advantage of LCD</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) size and weight</td>
<td>a) viewing angle</td>
</tr>
<tr>
<td>b) low power consumption</td>
<td>b) high cost</td>
</tr>
<tr>
<td>c) color performance</td>
<td>c) low temperature operation</td>
</tr>
<tr>
<td>d) low cost due to mass production</td>
<td></td>
</tr>
</tbody>
</table>

Liquid Crystal

- crystals \( \longrightarrow \) liquid \( \longrightarrow \) vapor
- Liquid Crystal

nematic Liquid Crystal

- orientation

semectic LC

- orientation layers

cholesteric LC

Properties of LC

Dielectric anisotropy

- \( \varepsilon_\perp \)
- \( \Delta \varepsilon = \varepsilon_\perp - \varepsilon_\parallel > 0 \)

Optical anisotropy (birefringence)

- extraordinary \( (n_e) \)
- ordinary \( (n_o) \)
- \( \Delta n = n_e - n_o > 0 \)
Twisted nematic Liquid Crystal (90° rotation)

[Diagram showing twisted nematic LCD with polarizers and voltage applied]

Super twisted nematic Liquid Crystal (180 - 270° rotation)

[Diagram showing super twisted nematic LCD with polarization change]

Electro-optic response of a TN LC cell

[Graph showing voltage vs. relative transmittance]

- contrast ratio = $\frac{T_{\text{max}}}{T_{\text{min}}}$
- grayscale achieved with intermediate value of $V$.

For normally-white case.

→ Normally-black is a mirror image of normally white.
Example:

Electro-optic response: Effect of twist

Non-linearity increases as increasing twist (STN > TN).

- steep electro-optic response is needed for high-contrast passive-matrix displays ⇒ NO CROSSTALK—advantage of using STN-LC.

**Pixel** — Smallest resolvable spatial information element

- May be subdivided to achieve color or gray scales
- Active area can be less than pixel area (~30%).

You can calculate the pixel size for a given display type and size.

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGA</td>
<td>640 x 200(V)</td>
</tr>
<tr>
<td>VGA</td>
<td>640 x 480(V)</td>
</tr>
<tr>
<td>SVGA</td>
<td>800 x 600(V)</td>
</tr>
<tr>
<td>XGA</td>
<td>1024 x 768(V)</td>
</tr>
<tr>
<td>SXGA</td>
<td>1280 x 1024(V)</td>
</tr>
<tr>
<td>VXGA</td>
<td>1600 x 1280(V)</td>
</tr>
</tbody>
</table>

Pixel arrangement for color displays

**Triad**          **Stripe**          **Quad**

⇒ human eyes pick up green more
Matrix Addressing Mode

Passive Matrix

Example: Earlier laptop display, PDAs

- stripes of conductor on opposing glass plates
- pixels defined by intersection of electrodes

- Non-linearity requirement for PM LCD
  - want to have high non-linearity to reduce cross-talk

- Discrimination ratio (D): $D = \frac{L}{L_0}$, where $L = \text{luminance (transmitted)}$

- Pixel Contrast Ratio (PCR): $\text{PCR} = \frac{L_0}{L}$, where $M = \text{number of display rows}$

-TN LCD: Low PCR and D
STN LCD: High PCR and D
Active Matrix

Example: Laptop display, desktop monitor

- array of pixel electrodes on one glass plate
- switch at each pixel for isolation—less crosstalk
- an active element is used as a switch to store charge on LC capacitor

- switching element = thin-film transistor (TFT)

\[ C_{LC}: \text{liquid crystal capacitance} \]
\[ C_S: \text{storage capacitance} \]