Photodetectors

- Convert light signals to a voltage or current.
- The *absorption* of photons creates electron hole pairs.
- Electrons in the CB and holes in the VB.
- A $p^+n$ type junction describes a heavily doped p-type material (acceptors) that is much greater than a lightly doped n-type material (donor) that it is embedded into.
- Illumination window with an annular electrode for photon passage.
- Anti-reflection coating ($Si_3N_4$) reduces reflections.
Photodetectors

- The $p^+$ side is on the order of less than a micron thick (formed by planar diffusion into n-type epitaxial layer).

- A space charge distribution occurs about the junction within the depletion layer.

- The depletion region extends predominantly into the lightly doped n region (up to 3 microns max)

(a) A schematic diagram of a reverse biased $pn$ junction photodiode. (b) Net space charge across the diode in the depletion region. $N_d$ and $N_a$ are the donor and acceptor concentrations in the $p$ and $n$ sides. (c). The field in the depletion region.

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Photodetectors

Short wavelengths (ex. UV) are absorbed at the surface, and longer wavelengths (IR) will penetrate into the depletion layer.

**What would be a fundamental criteria for a photodiode with a wide spectral response?**

Thin p-layer and thick n layer.

**What does thickness of depletion layer determine (along with reverse bias)?**

Diode capacitance.

**What does capacitance dictate?**

Response time.
Photodetectors

- Assume a reverse bias condition ($V_r$) applied to the device.

- The depletion layer presents a high resistance under this condition and a voltage of $V_r + V_0$ is developed across $W$. ($V_0$ is a built in voltage).

- An E field develops in the depletion region and can be determined by integration of the net space charge density $p_{net}$.

- The field is not uniform. It is maximum at the junction and tapers into the n region.

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(a) A schematic diagram of a reverse biased $pn$ junction photodiode. (b) Net space charge across the diode in the depletion region. $N_d$ and $N_a$ are the donor and acceptor concentrations in the $p$ and $n$ sides. (c). The field in the depletion region.

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Photodetectors

Regions outside the depletion region (neutral regions) hold majority carriers. These neutral regions can be considered resistive extensions of electrodes to the depletion region.

When a photon with an energy greater than bandgap ($E_g$) is incident, the photon is absorbed and generates a free EHP in the depletion layer.
Photodetectors

(a) An EHP is photogenerated at $x = l$. The electron and the hole drift in opposite directions with drift velocities $v_h$ and $v_e$. (b) The electron arrives at time $t_e = (L - l)/v_e$ and the hole arrives at time $t_h = l/v_h$. (c) As the electron and hole drift, each generates an external photocurrent shown as $i_e(t)$ and $i_h(t)$. (d) The total photocurrent is the sum of hole and electron photocurrents each lasting a duration $t_h$ and $t_e$ respectively.

- The E field separates the electron and hole and causes them to drift in opposite directions until they reach neutral regions.
- The drifting carriers generate a photocurrent in the external circuit developing an electrical signal.
- The photocurrent exists for a time frame equal to the time it takes for the electron and hole to cross the depletion layer and arrive at the neutral region.
- The magnitude of the photocurrent is dependant on the number of EHPs generated and the drift velocities of the carriers while moving across the depletion layer.

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Photodetectors

- Note: the absorption of photons occurs over a distance that is dependant on wavelength. Remembering that the distribution of the field is not uniform tells us that determining the time dependence of the photocurrent signal is difficult.

- The resultant photocurrent is a result of electron flow only and not hole migration.

- Integrating the hole current to calculate the Q charge will show that the total photogenerated electrons is $eN$ (electrons) and not $2eN$ (electrons and holes).
PIN Photodetectors

- Lower doping levels cause depletion region to become thicker which in turn reduces diode capacitance.

- PIN photodiode implements this concept by insertion of a thick, high Z low doped n-type layer (middle layer) between the p and n layers of the original model.

- The middle layer is called the *intrinsic layer* or I-layer.

- A moderate quantity of reverse bias can extend the depletion layer to the bottom of the I-layer.

**Result:**

1. Faster response time.
2. Improved (wider) spectral response.
A reverse biased pin photodiode is illuminated with a short wavelength photon that is absorbed very near the surface. The photogenerated electron has to diffuse to the depletion region where it is swept into the $i$-layer and drifted across.
Absorption coefficient ($\alpha$) vs. wavelength ($\lambda$) for various semiconductors (Data selectively collected and combined from various sources.)

Figure 5.3
Responsivity ($R$) vs. wavelength ($\lambda$) for an ideal photodiode with $\text{QE} = 100\%$ ($\eta = 1$) and for a typical commercial Si photodiode.

Drift velocity vs. electric field for holes and electrons in Si.

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Silicon Photodetectors -- Interdigitated Lateral Trench

Interdigitated electrodes are often used to increase the active region area while optimizing the electric fields in the carrier collection region. Electrode can either be p+/n+ or just metal.

Finger space = 3.3 µm  
Trench depth = 8 µm  
Finger size = 0.35 µm  
For λ=845 nm, BW=1.5 GHz, Responsivity = 0.47 A/W at 5V
Silicon Photodetectors -- Resonant-cavity-enhanced

Why? High Speed

Uses three pair of quarter wavelength SiO$_2$ and polysilicon at bottom (LPCVD). SiO$_2$ Side-wall to prevent defects at the edge of poly. Two pairs of ZnSe-MgF on top (evaporated).
Silicon Photodetectors -- Schottky Barrier

300,000 PtSi/p-Si Schottky barrier IR detector focal plane arrays have been developed and used on Air Force B-52
Silicon Photodetectors -- Schottky Barrier

- High dark current, has to operate at low temperature (40 ~ 80 K).
- Low quantum efficiency (QE).

\[ QE = C_1 \frac{(h \nu - q \phi_B)^2}{h \nu} = 1.24C_1 \lambda \left( \frac{1}{\lambda} - \frac{1}{\lambda_C} \right)^2 \]

High \( \lambda_C \) gives high QE. To expand the spectrum, need to decrease the barrier height.
(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.

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(a) A pictorial view of impact ionization processes releasing EHPs and the resulting avalanche multiplication. (b) Impact of an energetic conduction electron with crystal vibrations transfers the electron's kinetic energy to a valence electron and thereby excites it to the conduction band.

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(a) A Si APD structure without a guard ring. (b) A schematic illustration of the structure of a more practical Si APD

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(a) Energy band diagram for a SAM heterojunction APD where there is a valence band step $\Delta E_v$ from InGaAs to InP that slows hole entry into the InP layer.

(b) An interposing grading layer (InGaAsP) with an intermediate bandgap breaks $\Delta E_v$ and makes it easier for the hole to pass to the InP layer.

Simplified schematic diagram of a separate absorption and multiplication (SAM) APD using a heterostructure based on InGaAs-InP. $P$ and $N$ refer to $p$ and $n$-type wider-bandgap semiconductor.

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Simplified schematic diagram of a more practical mesa-etched SAGM layered APD.

Energy band diagram of a staircase superlattice APD (a) No bias. (b) With an applied bias.

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Photodetectors in High Energy Physics

• Calorimeters (measure energy and position)
  - Scintillation light detected by photodetector
  - Cherenkov light radiation
• Time-of-flight
  - Fast scintillators used to determine speed of particle
• Readout of electronics in large hermetic detectors
• Fiber backbone for local and wide area networks
  • First use for detection of $\alpha$ particles: Geiger & Marsden (1909) using ZnS (Ag)
A large area silicon PIN diode

Data from Hamamatsu Photonics

Note 8 to 10 decades of linear response
A large area silicon APD

Data from Hamamatsu Photonics

Note sensitivity to voltage and temperature
Solid State Photodetectors for HEP -- Issues

- Silicon is not cheaper per unit area than vacuum photodetectors (for areas greater than a few mm$^2$)

- Really large devices cannot be made

- Problem with damage from high neutron flux in hadron collider experiments (such as the LHC)

- Need low noise (i.e. expensive) pre-amplifiers

- Hard to do photon counting
Photodetectors – vacuum

- A *free* electron is liberated from a *photocathode* (photoelectric effect) into a vacuum under an electric field
  - The free electron is accelerated to a few hundred volts and hits a *dynode*
  - Low energy *secondary electrons* are liberated from the dynode (4 to 10 dependent on voltage and material of dynode)
  - Each secondary electron is accelerated and hits the next dynode
  - And so on …
- A typical tube used in HEP has 10 to 14 dynodes
- Thus a high gain is achieved (10^6 to 10^7)
- Large areas (hundreds of cm^2) are possible, but low QE compared to silicon devices
- Most PMT are very sensitive to magnetic fields
Typical dynode gain is about 5 and a typical PMT has 12 dynodes. Gain is therefore of order $12^5 \sim 250000$.

Data from Hamamatsu Photonics
See [http://www.hpk.co.jp/Eng/products/ETD/pmte/pmte.htm](http://www.hpk.co.jp/Eng/products/ETD/pmte/pmte.htm)
Photomultipliers

Effect of different windows

Total supply voltage

A typical 2” tube designed for high blue-green response

Data from Electron Tubes
See http://www.electron-tubes.co.uk/pmts/pmt_menu.html
Hybrid Photodetectors

- Generate free photoelectrons in a vacuum (like a photomultiplier tube)
- Accelerate photoelectrons to a high energy (10 to 20 kV)
- Use a silicon diode as an electron detector, with approximately 2500 eh-pairs for each 10 kV photoelectron

Note the incredible resolution of 1, 2, 3, … photons $<n> = 5.4$
Applications

- Calorimetry: conversion of particle energy into light by either scintillation or Cherenkov effect
Applications

- Cherenkov: when a charged particle travels in a dense medium faster than the speed of light in that medium then Cherenkov light is produced.

For a given medium, there is a minimum velocity below which no light is produced. Light is emitted in a cone around the particle trajectory, with a yield $\sim \lambda^{-2}$

Cone angle depends on speed and refractive index

$$\theta_c = \arccos\left(\frac{1}{n\beta}\right)$$
$$\approx \sqrt{2(1-1/n\beta)} \quad \text{for small critical angles e.g. in a gas}$$

Number of photons $N$ per unit length $x$ produced by a particle of charge $z$ is given by

$$\frac{d^2 N}{dx d\lambda} = \frac{2\pi az^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Note the dependence on $1/$wavelength$^2$. This implies good UV transparent materials and detectors with UV response.
Water Cherenkov

Pampa Amarilla in western Argentina

Application: Photodetectors for LIGO

- Material: InGaAs based family
- Pattern: Single element
- Diameter > 2 mm
- Frequency response: ~100 MHz
- Packaging: rf operable
- Cooling: Possible TEC
- Optical power: ~1 W
- Quantum efficiency target: 70%
Imaging Photodetectors & Biology Applications

Structure of the Human Eye

- **Cornea:** transparent
  - **Sclera:** opaque
- **Choroid**
  - contains blood vessels
  - heavily pigmented and reduce the amount of light entering the eye and backscatter within the eye
- At anterior, Ciliary body & iris diaphragm
- **Iris:** control the amount of light, 2~8mm
- **Lens:**
  - 60~70% water, 6% fat, and protein,
  - slightly yellow,
  - absorbs approximately 8% of the visible light spectrum
**Retina**

- Image is focused on retina
- Two classes of receptors: *cones* and *rods*

**Cones**

- 6~7 million
- Located primarily in the fovea
- Color sense
- One nerve for one cone: resolve fine detail
- Cone vision called photopic or bright-light vision

**Rods**

- 75~105 million
- Distributed over the retinal surface
- One nerve for several rods
- Sensitive to low levels of illumination
- Rod vision called scotopic or dim-light vision
- Blind spot
- Receptor distribution
- Fovea
  - Circular indentation of about 1.5mm in diameter
  - Density of cones is approximately 150,000 cones/mm²
  - 1.5mm x 1.5mm square → 337,000 cones
* Bright adaptation range is on the order of $10^{10}$
* Subjective brightness is a logarithmic function of the light intensity
* The range of photopic vision is about $10^6$
* The visual system cannot operate over the range simultaneously
* It is done by changes in its overall sensitivity

$\rightarrow$ **Bright adaptation**

**FIGURE 2.4**
Range of subjective brightness sensations showing a particular adaptation level.
Image Sensors

Figure 2.12
(a) Single imaging sensor.
(b) Line sensor.
(c) Array sensor.

Figure 2.13
Combining a single sensor with motion to

One image line out per increment of rotation and full linear displacement of sensor from left to right.

Figure 2.14
(a) Image acquisition using a linear sensor strip.
(b) Image acquisition using a circular sensor strip.
Image Sensors

**CCD vs. CMOS**

CCD (charge-coupled device) and CMOS (complimentary metal-oxide semiconductor)

A CCD is like a threedecker sandwich. The bottom layer contains the photosites. Above them is a layer of colored filters that determines which color each site records. Finally, the top layer contains microlenses that gather light. Courtesy of Fujifilm.
Image Sensors

**CCD vs. CMOS**

- In a CCD device, the charge is actually transported across the chip and read at one corner of the array. An analog-to-digital converter turns each pixel's value into a digital value.
- In most CMOS devices, there are several transistors at each pixel that amplify and move the charge using more traditional wires. The CMOS approach is more flexible because each pixel can be read individually.
- CCDs use a special manufacturing process to create the ability to transport charge across the chip without distortion. This process leads to very high-quality sensors in terms of fidelity and light sensitivity.
- CMOS chips, on the other hand, use traditional manufacturing processes to create the chip. CMOS sensors, traditionally, are more susceptible to noise.
- Because each pixel on a CMOS sensor has several transistors located next to it, the light sensitivity of a CMOS chip tends to be lower. Many of the photons hitting the chip hit the transistors instead of the photodiode.
Image Sensors


• Retina is a light sensitive neural network
• Diseases such as Retinitis Pigmentosa (RP) and Age-related Macular Degeneration (AMD) primarily affect the photoreceptors, are both presently incurable, and render 100,000s blind each year

Retinal Prosthesis – Epiretinal vs. Subretinal

- **Epiretinal**
  - Less disruptive to the retina.
  - More flexibility in component placement.
  - More complex stimulus algorithms required.

- **Subretinal**
  - In natural position of photoreceptors.
  - Disruptive to retina.
  - Devices relying on incident light for power cannot generate effective stimulus.
Retinal Prosthesis – State of the Art

• **Epiretinal and Subretinal** at Investigational Device Exemption Stage
• **Epiretinal** - encouraging results, but better technology required
• **Subretinal** – No direct evidence demonstrating functional electrical stimulation, but patients report subjective improvements in vision

![Optobionics ASR™](image1)

![Argus™ II](image2)
Artificial Silicon Retina (ASR)

The ASR contains about 3,500 microscopic solar cells that are able to convert light into electrical pulses, mimicking the function of cones and rods. To implant this device into the eye, surgeons make three tiny incisions no larger than the diameter of a needle in the white part of the eye. Through these incisions, the surgeons introduce a miniature cutting and vacuuming device that removes the gel in the middle of the eye and replaces it with saline. Next, a pinpoint opening is made in the retina through which they inject fluid to lift up a portion of the retina from the back of the eye, which creates a small pocket in the subretinal space for the device to fit in. The retina is then resealed over the ASR.

ARCC will give blind patients the ability to see 10 by 10 pixel images, and are developing a version of the chip that would allow 250 by 250 pixel array.
Retinal Prosthesis – MEMS component

- Flexible frame for attachment
- (polymer) frame
- Microelectronics
- Surface micromachined springs
- Posts for assembly and electrical interconnect
- Micromachined electrode array (silicon substrate)
- Electroplated or assembled electrodes
- Retina
- Electrodes
- Inner-eye electronics
- Flexible interconnect
- Tack
- Antenna

Diagram elements:
- Flexible frame
- Micromachined electrode array
- Electroplated or assembled electrodes
- Retina
- Antenna
- Inner-eye electronics
- Flexible interconnect
- Tack