Lecture 8
Optical Sensing
Q: What are we measuring?
A: Electromagnetic radiation labeled as Ultraviolet (UV), visible, or near, mid-, far-infrared (IR)

SI Units: Lumen (lm), Lux (lx=lm/m²), Candela (cd)
**Optical Sensors**

**Photoresistor**
- Sparkfun SEN-09088

**Photodiode**
- Fairchild QSD2030F

**Phototransistor**
- Honeywell SDP8406-003

**Thermopile**
- Amphenol ZTP-101T

**Infrared**
- Lumex SNR-40135

**CMOS Image Sensors**
- On Semiconductor KAC-06040
- Samsung S5K9A1
Applications of Optical Sensors

Proximity (Distance) Sensing

Smoke Detector
Applications of Optical Sensors

Controlling Gas valve with Thermopiles

Gas valve in Fireplace

Gas valve in Waterheater
Applications of Optical Sensors

Smartphone/tablet Camera

Military Night Vision Camera
Types of Optical Sensors

- Quantum Detectors
  - Photoresistor (Photocell)
  - Photodiode
  - Phototransistor

- Thermal Detectors
  - Thermopile

- Image Sensors
  - CMOS Image Sensor
Einstein discovered that when high energy photons interact with electrons, it is possible for the electrons to be ejected from the material.

Photoconductive Effect

Photon absorption and increase in conductivity

- Given small bandgap, incident photons can make the electrons jump into the conduction band.
- The resulting free electrons (and holes) increase conductance and hence lower resistivity of a material
Photoresistor (or Photocell or Photoconductor)

**Light Dependent Resistor (LDR)**
- Light-controlled variable resistor
- The resistance of a photoresistor *decreases* with *increasing light intensity*
- An active semiconductor layer (e.g. CdS) that is deposited on an insulating substrate
- The semiconductor is normally lightly doped
- Less light-sensitive than photodiodes and phototransistors
LDR Circuit Example

- When LDR is exposed to light, LDR resistance is low which makes the base voltage of $Q_1$ high enough for the collector current to sink.
- As a result LED turns on.

- When LDR is blocked, the resistance goes up (MΩ), and base voltage drops down and shuts off the transistor.
- As a result LED turns off.
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Photodiode

- p-type material is doped with boron (donor), n-type material is doped with acceptor atoms.
- When the light energy is greater than the band gap energy, the electrons move into the conduction band creating electron-hole pairs.
- In the depletion layer the electric field accelerates these electrons toward the n-layer and holes toward the p-layer.
- This results in a positive charge in the p-layer and a negative charge in the n-layer.
- If an external circuit is connected between the PN junction, electrons will flow away from n-layer, and holes will flow away from the p-layer.
Photodiode

Photodiode Operation

- Light-controlled current through a diode
- When exposed to light, electron-hole pairs are created
- Newly generated electron-hole pairs are swept away by the existing PN junction and current (also known as photo current) is created
- Must be reverse-biased so that the depletion region is larger

Avalanche Photodiode

Solar Cell Mode

Responsivity ($\lambda$) = Photocurrent/Incident Light Power

Photodiode Mode
Photodiode Model

- $I_{PD}$ = Photo Current, $I_D$ = Dark Current=Saturation Current=Leakage Current at zero bias, $C_j$=Junction Capacitance, $R_S$=Shunt Resistance of zero-biased PN junction
- **Photoconductive mode**: under reverse bias, the measured output current is linearly proportional to the input optical power
- **Photovoltaic mode**: under zero bias, the current is held constant vice is restricted and a voltage builds up, dark current is kept at a minimum

Ref: thorlabs.us
Reverse Bias (improve bandwidth and lower junction capacitance) or Zero Bias (minimum dark current)
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Photovoltaic Effect

Photon absorption and emission of electrons

If a high energy photon strikes an electron, the electron can escape into conduction band and creates holes and electrons (free charge carriers)
Phototransistor operation

- Large Base and Collector areas
- Active region operation
- Base is left open and is exposed to light
- Light causes hole electron pairs to be generated
- This occurs in the reverse biased base-collector junction (BCJ)
- The hole-electron pairs move under the electric field in the depletion region and provide the base current, causing electrons to be injected into the collector.
Phototransistor Example

- Detect light in near-infrared ($\lambda=700$ nm-$1100$nm)
  - CE: Current is amplified and $V_{out}$ is generated
  - CC: $V_{out}$ switches from Low to High state

- Both can be operated in Active or Switch mode

  - Active mode: phototransistor generates a response proportional to the light received

  - Switch mode: phototransistor will either be "off" (cut-off) or "on" (saturated) in response to the light.
Phototransistor Modes: CC Amplifier

Common-Collector (CC) Amplifier (object detection, encoder)

1) Low state to a high state when light is detected

2) **No light:** \( V_{out} = 0V \)

3) **Light:** base current \( I_B \) is generated, which is amplified by the collector, \( I_C \) is generated

   - with \( R_{on} \sim 0 \Omega \), \( V_{out} = \frac{R_E}{(R_E + R_{on})} V_{cc} \)

   \( V_{out} = V_{cc} \)

4) Mode is set by adjusting \( R_E \)

   - **Active Mode** (\( V_{out} \) proportional to light level):
     \( V_{cc} > R_E \times I_C \)
   - **Switch Mode**: \( V_{cc} < R_E \times I_C \)

where \( I_C = \text{max collector current for specific light level} \)

Phototransistor Modes: CE Amplifier

Common-Emitter (CE) Amplifier (compare two levels of light)

1) High state to a low state when light is detected

2) No light: $V_{out} = V_{CC}$

3) Light: base current $I_B$ is generated, which is amplified by the collector, $I_C$ is generated
   - with $R_{on} \approx 0 \, \Omega$, $V_{out} = \left( \frac{R_{on}}{R_{on} + R_{on}} \right) V_{cc}$
   - $V_{out} = 0V$

4) Mode is set by adjusting $R_C$
   - Active Mode ($V_{out}$ proportional to light level): $V_{cc} > R_C \times I_C$
   - Switch Mode: $V_{cc} < R_C \times I_C$
   - where $I_C = \text{max collector current for specific light level}$

Phototransistor Example Circuit

Optocoupler

- Source signal current passes through the input LED which emits an infra-red light whose intensity is proportional to the electrical signal.
- IR light generates current in the base and it is amplified at the collector.
- When the current flowing through the LED is interrupted (e.g. digital data), the IR light is cut off and the photo transistor cuts off.
- Optocouplers are used to switch transistors or other components as they provide electrical isolation between a lower voltage control signal and the higher voltage or current output signal.
- Examples: Microprocessor input/output switching (turn on/off motor, heater, lights), DC and AC power control.
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Thermopile Sensors

Thermopile Basics

- Thermopiles detect thermal radiation (heat)
- Thermopile is a chain of serially connected thermocouples*, typically 50–100 junctions.

a: thermopile with a reference temperature sensor attached, x and y are different materials

b: micromachined thermopile sensor (note the semiconductor reference temperature sensor on the silicon frame where the cold junctions are deposited)

c: sensor in a TO-5 package

*Thermocouples: https://www.picotech.com/library/application-note/thermocouple-application-note
Thermopile Sensors

Thermopile Operation

- IR light is absorbed by or emanated from the membrane and temperature of the membrane changes
- Since the membrane carries “hot” junctions, the temperature differential with respect to the “cold” junctions located on the frame generate thermoelectric voltage
- Membrane may be thermally coupled with a reference temperature sensor or attached to a thermostat having a precisely known temperature
- Example circuit: measured temp. is amplified and processed via DSP

Example Circuit (Melexis MLX90615)
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Image Sensor Basics

Charge Coupled Device (CCD)
(Tutorial: https://www.youtube.com/watch?v=Xkput-1xNYE)

- CCD chip is divided into pixels*
- Each pixel has a potential well that collects the electrons produced by the photoelectric effect.
- After the exposure (incoming photons), each pixel has collected a finite amount of electrons (and hence charge) proportional to the amount of light
- CCD is then read out by cycling the voltages applied to the chip in a process called “clocking.”
- Clocking causes the charge in one pixel to be transferred to an adjacent pixel

CMOS Image Sensor*

- Like CCDs, CMOS imagers have an array of photo diodes, one diode within each pixel.
- Unlike CCDs, each pixel in a CMOS imager has its own individual amplifier.
- Each pixel in a CMOS imager can be read directly on an x–y coordinate system.
- While a CCD pixel always transfers a charge, a CMOS pixel always detects a photon directly and converts it to a voltage.

* More in http://www.onsemi.com/pub_link/Collateral/KAC-06040-D.PDF
CMOS Image Sensor: An Example

On Semiconductor KAC-06040
- Resolution: 2832 (H) x 2128 (V), 6 megapixel
- Fabrication Technology: 4.7 μm 5T CMOS
- 200 MHz DDR at 400 Mbps data rate

More in http://www.onsemi.com/pub_link/Collateral/KAC-06040-D.PDF