EE3: Introduction to Electrical Engineering

Lecture 8: Photonic Devices

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Outline

- Basic physics
- Digital cameras
- Photodiodes
- LED
- Lasers
- Fiber optic systems

Transduction Principles

Devices that convert energy from photons to electrical energy and vice versa have a broad set of applications

The basic transduction principle used in semiconductor based devices is the photoelectric effect. This is manifested in emission of electrons caused by exposure to light.

The number emitted is proportional to the light intensity, with their kinetic energy proportional to the light frequency. Three different responses of materials are observed.

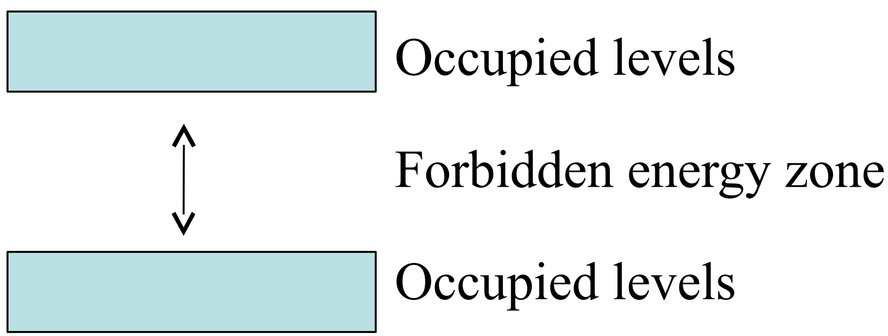
1. Photoemission: electrons are ejected from the surface of the solid (used in photodiodes)

2. Photoconductivity: conductivity changes in response to light (basis of IR, UV, and visible detectors/cameras)

3. Photovoltaic effect: absorption of radiation causes current to flow across junction of materials (solar cells)

Mind the Gap

A quantum effect that is important in these devices is the band-gap



The presence/size of gap depends on the choice of materials.

When photons of energy similar to that of the band gap arrive, they cause electron/hole pairs to form in the separated energy zones. The excess electrons/holes cause a change in conductivity.

When pairs recombine to a lower energy state, a photon is ejected (or if trapping occurs, energy is released as heat).

Digital Camera

Commercial products are based on the active pixel sensor

This exploits CMOS technology, and is very low cost

An array of sensors are placed in the focal plane of the camera; excess electrons are accumulated in a capacitor

The voltage indicates light intensity; when flush the capacitor, amplify the current, digitize, and get a gray scale value

To get color, four sensors are used for each pixel, with a colored lens over each:

RGRG	Variable shutter speed is required to compensate
GBGB	for different light conditions; a supplementary
RGRG	sensor for light intensity is used to automatically
GBGB	control the speed.

EFTS

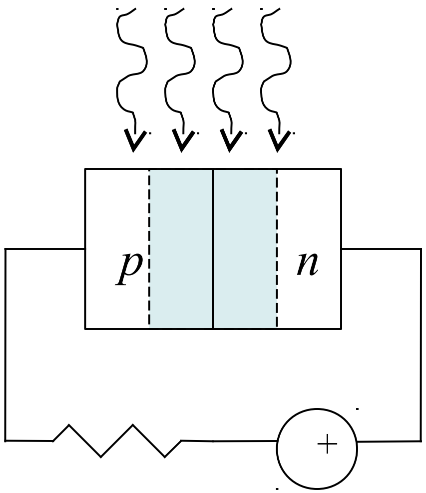
Conversion efficiency with digital cameras is 70% vs. roughly 2% for film. For the same light gathering power, how much smaller can the lens diameter be for a digital camera?

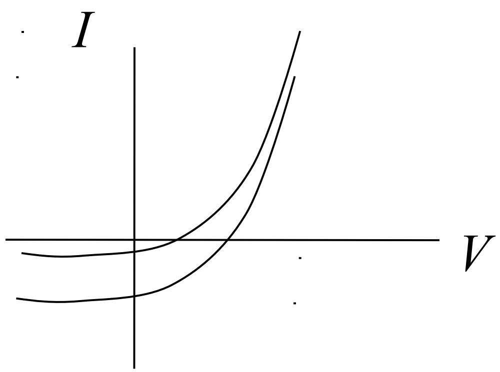
Solution: light gathering power is directly proportional to area.

$$Area = \pi r^2 \qquad \frac{r_{digital}^2}{r_{film}^2} = \frac{0.02}{0.70} \qquad \frac{r_{digital}}{r_{film}} = 0.17$$

Thus lenses can be less than 1/5 the diameter; in practice a slightly larger lens is used to enable good performance in low light conditions.

Photodiode

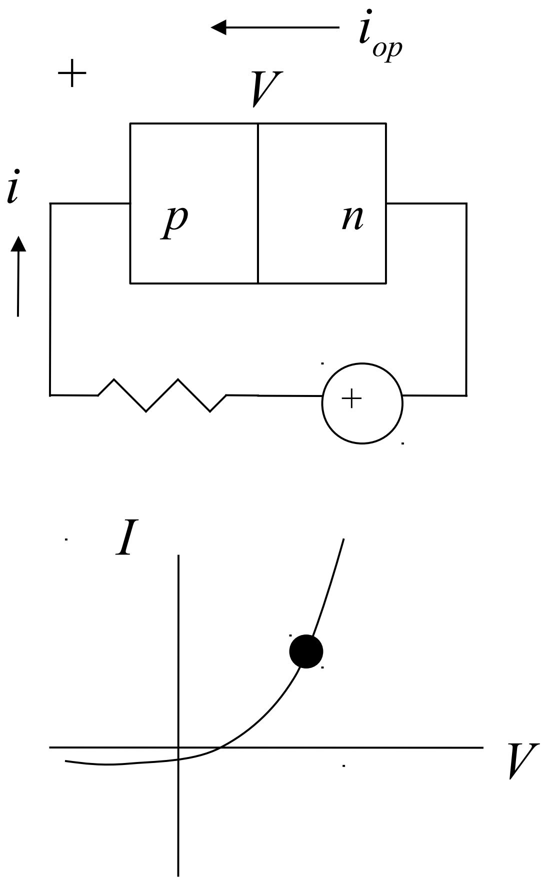




Light causes additional minority carriers that are swept through the junction

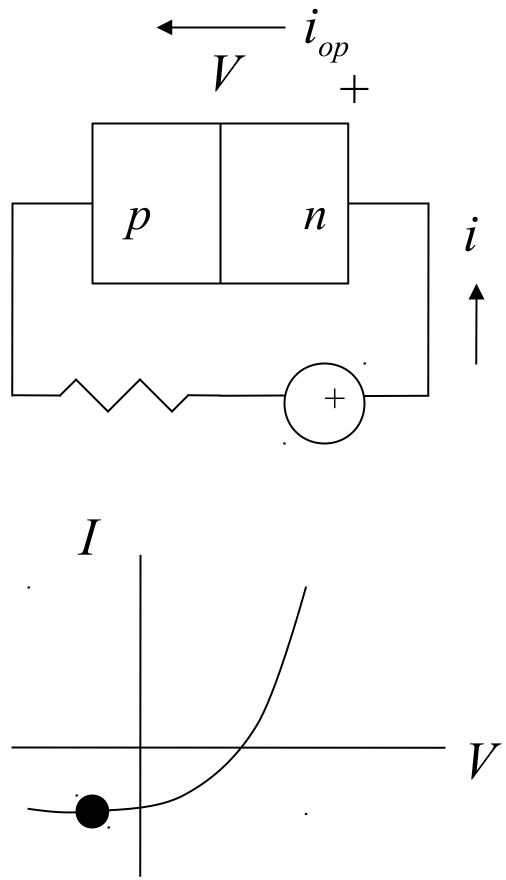
Because the current is opposite to that of the thermal drift, the device can be biased to operate in a variety of different modes (Recall: the direction of electric fields also affects hole/electron migration through a *p-n* junction).

Photodiodes Under Illumination



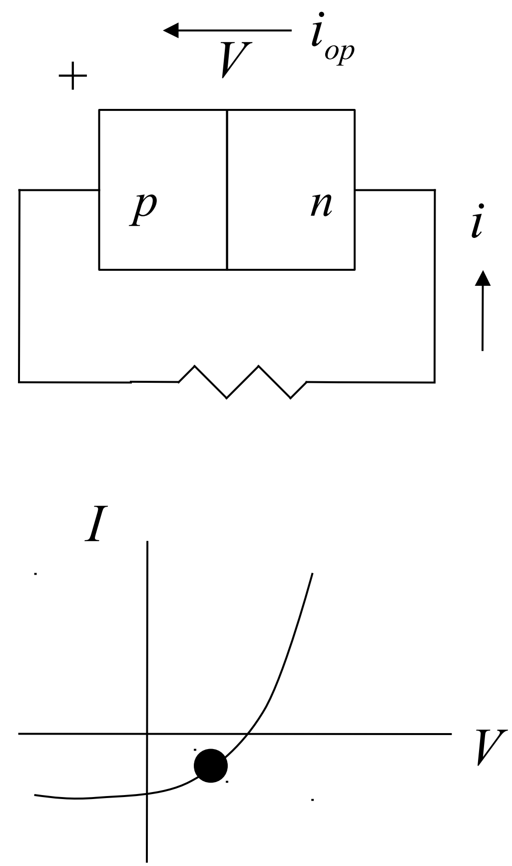
1st quadrant

LED



3rd quadrant

Photodetector



4th quadrant

Photocell

Photodiode Operation Notes

Three current components: diffusion, field induced, optically induced; the diffusion current goes from p to n, and the optical current from n to p. The optical current induced from external illumination is very small for the LED due to device design.

The voltage drop across the junction for the LED and photodetector in the direction of the current indicates that resistive losses outweigh any power generation. For the photodetector, current becomes independent of voltage, but linearly dependent on light intensity.

The voltage gain across the junction in the direction of the current for the solar cell indicates that the optically induced current is dominating so that power is delivered to the load.

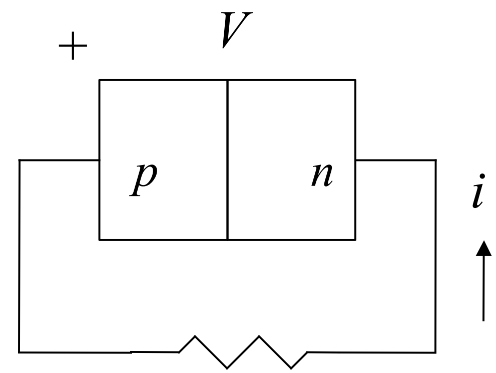
Photocells

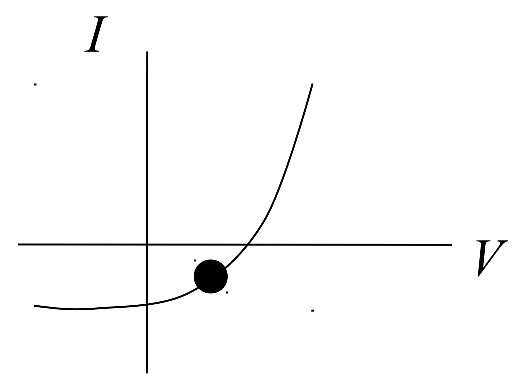
Sunlight density at full sun is up to 1 kW/m^2

Cells are designed with a large area of junction exposed.

The game is to achieve high conversion efficiency at low cost, and long device lifetime. In 1980 efficiency was 10%; it is now 35% at vastly decreased cost, but near the fundamental efficiency limits.

Multilayer devices based on polymers are now appearing with efficiency >10%; low cost commercial plastic cells will appear when efficiency is around 20%





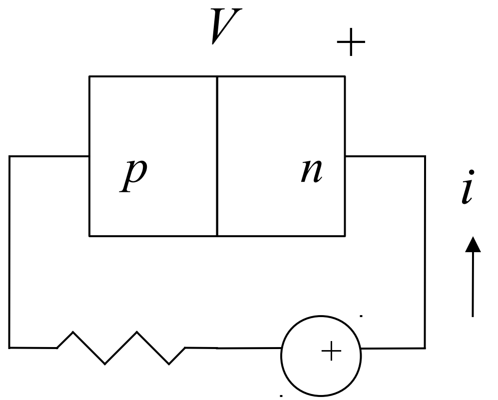
4th quadrant

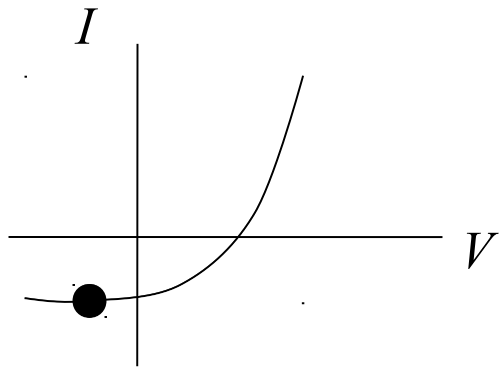
Photocell

Photodetector

The wavelength detected depends on the size of the band gap (IR, visible, UV all possible).

They can be operated in "avalanche" mode, where one photon triggers a flood of current. This is the typical device used as a detector in fiber optic communication.

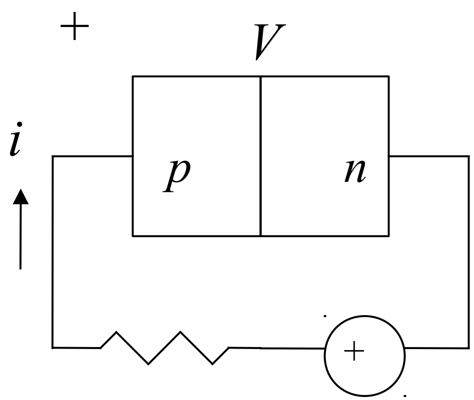


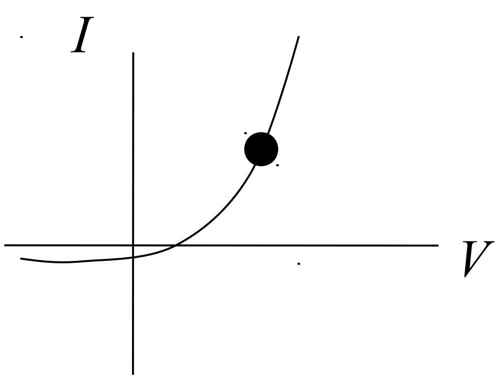


3rd quadrant

Photodetector

Light Emitting Diode





1st quadrant

LED

When the diode is forward biased, photons are emitted when recombination occurs.

The color depends on the size of the gap and whether direct or indirect recombination occurs

LEDs can now be designed with efficiencies that far exceed other light sources, providing significant energy savings.

Laser Diode

In LEDs, light is emitted from spontaneous recombination

In lasers, we suppress such events and instead use the presence of light to stimulate coherent emission (i.e., everything is in phase)

Stimulated emission: photon in laser cavity lowers energy barrier for another photon to be created in phase with it.

The basic elements are:
1) Population inversion—puts in excess carriers to limit spontaneous recombination
2) Mirrored assembly—photons are trapped in resonant cavity to build standing wave and stimulate emissions

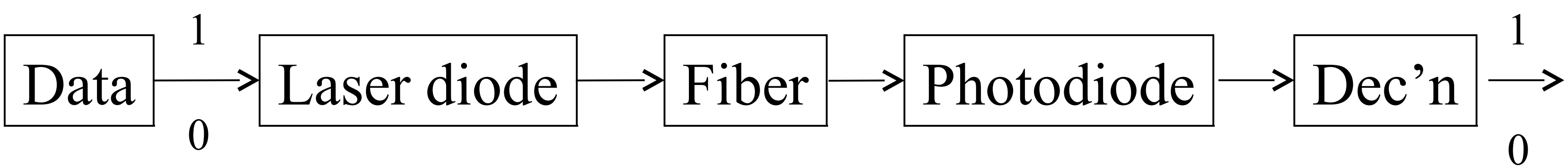
Laser Diode II

p-n junctions can be designed that support the population inversion. However, higher efficiency results from use of "heterojunctions," i.e., use of multiple layers (3 is typical).

Note that while the light emitted at any given moment of time is coherent, due to temperature variations over the duration of laser pulses the size of the cavity changes. Thus in reality the spectrum resembles narrowband noise.

Fiber Optic Communications

The basic system is depicted below.



Other components can include external modulators, optical switches, and devices to change frequencies. Almost all long-distance data/telephone traffic now uses fiber.

Glass fiber is now very low loss, so that few digital repeaters are needed even for crossing oceans.

Modulation is on/off signaling, with simple thresholding to make decisions

Fiber Optic Challenges

Bandwidths of many GHz are now possible with these systems.

The main challenge for higher speeds is optoelectronic conversion: having the electronics keep up

This is also the main barrier to optical computing; as of now, there is no known convenient optical replacement for RAM and other critical elements, and so hybrid electronic/optic systems are the present limit.

Single mode fiber is very thin, and considerable losses result in splicing it in without expensive assemblies; thus the “last mile” is typically coaxial cable which can also support multiple Gb/s rates using modern modulations.

EFTS

The earliest digital telecommunications were optical: bonfire relays, and later semaphore networks (France, Prussia). Why were free-space optics abandoned for terrestrial long-distance communications? Where might it be more practical?

The telegraph avoided all the trouble of line of sight and weather effects. Reliability is very important in communications.

Space is an obvious place to use free-space laser communication. But note that beams do not stay narrow forever—spread according to Huygen’s principle.

Summary

- Photonics relies upon results from quantum mechanics for basic device operation
  - Complete system typically also requires wave/optical ray approximation theory to explain lenses and guided transmission.
- Depending on *V-I* operating point, get very different behaviors from photodiodes
  - Similar idea to transistor models; view input/output relations
- Photonic devices have been improving at fast rates
  - Uses same types of fabrication technology as ICs
  - Large commercial applications: digital cameras, fiber optic systems, solar cells