The Diode

• The diode is a two terminal semiconductor device that allows current to flow in only one direction.
• It is constructed of a P and an N junction connected together.

Diode Operation

• No current flows because the holes and electrons are moving in the wrong direction.
• If you flip the battery around, the electrons are repelled by the negative terminal and the holes are repelled by the positive terminal allowing current to flow.
An ideal diode would block all current when reverse biased. From the graph we see that this is not the case.

A small current ($\approx 10\mu$Amps) will flow when reverse biased and if the reverse voltage is increased enough the junction breaks down and current will begin to flow (Avalanche and Zener Breakdown).

When forward biased, a small voltage is required to get the diode current flowing.

For a silicon diode this voltage is approximately 0.7V
For a germanium diode, this voltage is approximately 0.3V
Fig. 6.4: Schematic sketch of the $I$-$V$ characteristics of Ge, Si and GaAs $pn$ Junctions

**Figure 18.20** The current–voltage characteristics of a $p$–$n$ junction for forward and reverse biases. The phenomenon of breakdown is also shown.

**Figure 18.21**  
(a) Voltage versus time for the input to a $p$–$n$ rectifying junction.  
(b) Current versus time, showing rectification of voltage in (a) by a $p$–$n$ rectifying junction having the voltage–current characteristics shown in Figure 18.20.
Current flow through a reverse biased p-n junction

- Diode: tiny reverse current under reverse bias
- Illuminated solar cell: large reverse current under forward bias
- Base-collector junction: large reverse current under reverse bias

Reverse current:
A large reverse current requires a source of minority carriers
- light (solar cell) OR
- a nearby forward-biased junction (Bipolar Junction Transistor BJT)
What happens with the absorbed photons?

Part of it is re-emitted as light called **photoluminescence**.

**Luminescence** = emission of optical radiation as a result of an electronic excitation.

- **Photoluminescence**: optical excitation
- **Catholuminescence**: excitation by electron irradiation
- **Electroluminescence**: excitation by current

 ![Diagram](attachment:image.png)

Radiative transition: emission of photon

Non-radiative transition
Semiconductor Devices: Light-related

Three major methods for light to interact with a material:

**Absorption**: incoming photon creates electron-hole pair (solar cell).

**Spontaneous Emission**: electron-hole pair spontaneously decays to eject photon (LED).

**Stimulated Emission**: incoming photon stimulates electron-hole pair to decay and eject another photon, i.e. one photon in $\rightarrow$ two photons out (LASER).

\[
\frac{hc}{\lambda} = E_2 - E_1
\]
Light-emitting diode (LED)

Converts electrical input to light output: electron in $\rightarrow$ photon out

Device with spontaneous light emission as a result of injection of carriers across a $p$-$n$ junction

Light source with long life, low power, compact design.

Applications: traffic and car lights, large displays.
LEDs are **p-n junction** devices constructed of gallium arsenide (GaAs), gallium arsenide phosphide (GaAsP), or gallium phosphide (GaP). Silicon and germanium are not suitable because those junctions produce heat and no appreciable IR or visible light. The junction in an LED is **forward biased** and when electrons cross the junction from the *n*- to the *p*-type material, the electron-hole recombination process produces some photons in the IR or visible in a process called **electroluminescence**. An exposed semiconductor surface can then emit light.

When the applied forward voltage on the diode of the LED drives the **electrons and holes** into the active region between the *n-type* and *p-type* material, the energy can be converted into infrared or visible photons. This implies that the electron-hole pair drops into a more stable bound state, releasing energy on the order of electron volts by **emission** of a photon. The red extreme of the visible spectrum, 700 nm, requires an energy release of 1.77 eV to provide the **quantum energy** of the photon. At the other extreme, 400 nm in the violet, 3.1 eV is required.
**Solar Cell**
Converting light input to electrical output: photon in → electron out
(generated electrons are “swept away” by E field of p-n junction)
Renewable energy source!
If light (with $E > E_g$) generates free electrons and holes in the depleted region, the electric field makes these carriers move. The electrons generated by light move from the **p-side** to the **n-side**. The holes generated by light move from the **n-side** to the **p-side**.
Light is converted to electrical energy.
Solar cells are essentially semiconductor junctions under illumination.

A) Light generates electron-hole pairs on both sides of the junction, in the **n-type emitter** and in the **p-type base**.

B) The generated electrons (from the base) and holes (from the emitter) then diffuse to the junction.

C) A positive charge is built up at the base and a negative charge is built up at the emitter. Thus, an electric current is produced across the device.

D) Note how the electric currents of the electrons and holes reinforce each other since these particles carry opposite charges.

E) The p-n junction therefore separates the carriers with opposite charge, and transforms the generation current between the bands into an electric current across the p-n junction.
The Solar Cell

- Sun
- Front metal grid
- N-type region
- Pn junction
- Rear metal contact
- P-type region
- Electron current
- External circuit
Solar cell under illumination

\[ V = IR \]
Key point

In an operating diode:
- The voltage is in the forward direction
- The current is in the **forward** direction

In an operating solar cell:
- The voltage is in the forward direction
- The current is in the **reverse** direction
LASER

**LASER** = Light Amplification by **Stimulated** Emission of **Radiation**

- Laser creates **inverted population** of electrons in upper energy levels and then **stimulates them to all coherently decay** to lower energy levels.

- **Applications**: fiber optics, CD player, machining, medicine, etc.
  
  e.g. GaAs laser: 25% efficiency, 100 yr lifetime, mm size, IR to visible
Figure 22.14 For the semiconductor laser, schematic representations of the
stimulated recombination of excited electrons in the conduction band with holes
in the valence band that gives rise to a laser beam. (a) One excited electron
recombines with a hole; the energy associated with this recombination is emitted
as a photon of light. (b) The photon emitted in (a) stimulates the recombination
of another excited electron and hole resulting in the emission of another photon
of light. (c) The two photons emitted in (a) and (b), having the same wavelength
and being in phase with one another, are reflected by the fully reflecting mirror,
back into the laser semiconductor. In addition, new excited electrons and new
holes are generated by a current that passes through the semiconductor. (d) and
(e) In proceeding through the semiconductor, more excited electron-hole
recombinations are stimulated, which give rise to additional photons of light that
also become part of the monochromatic and coherent laser beam. (f) Some
portion of this laser beam escapes through the partially reflecting mirror at one
end of the semiconducting material. (Adapted from “Photonic Materials,” by
J. M. Rowell. Copyright © 1986 by Scientific American, Inc. All rights reserved.)
Properties:

Monochromatic (narrow range of wavelength)

Coherent (in phase)

Beam Divergence (almost collimated – all photons travel in the same direction)

High Irradiance (high irradiant power)
The transistor

The transistor was invented in 1947 by three American physicists at the Bell Telephone Laboratories, John Bardeen, Walter H. Brattain, and William B. Shockley. It proved to be a viable alternative to the vacuum tube, and by the late 1950s supplanted the latter in many applications.

“Transistor” is short for “Transfer Resistor” or modulation of the resistance between two terminal by applying an electrical signal to a third terminal.

Capable of two primary types of function:
(1) It amplifies an electrical signal.
(2) It serves as switching devices (on/off) in computers for the processing and storage of information.

There are two major types:
(A) Bipolar Junction Transistor (BJT)
(B) Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
BJT

It is composed of two p-n junctions arranged back-to-back in either the n-p-n or the p-n-p configuration.

**p-n-p:** A very thin n-type base region is sandwiched in between the p-type emitter and collector regions.

*Region emitter-base junction is forward bias (junction 1), whereas a reverse bias voltage is applied across the base-collector junction (junction 2).*

Since the emitter is **p-type** and **junction 1** is forward biased, large numbers of holes enter the base region. These injected holes are minority carriers in the **n-type** base and some will combine with the majority electrons.

If the **base is extremely narrow**, most of the **holes will be swept through the base without recombination**, then across **junction 2** and into the **p-type collector**.

The holes become part of the emitter-collector circuit. **A small increase in input voltage within the emitter-base circuit produces a large increase in current across junction 2.**

The large increase in collector current is also reflected by a large increase in voltage across the load resistor.
Figure 18.22
Figure 18.23  For a junction transistor \((p-n-p)\) type, the distributions and directions of electron and hole motion \((a)\) when no potential is applied and \((b)\) with appropriate bias for voltage amplification.
The BJT – Bipolar Junction Transistor

The Two Types of BJT Transistors:

- npn
- pnp

- Collector doping is usually $\sim 10^6$
- Base doping is slightly higher $\sim 10^7 – 10^8$
- Emitter doping is much higher $\sim 10^{15}$
The MOSFET

Metal-Oxide Semiconductor Field-Effect Transistor

**Figure 18.24**
Schematic cross-sectional view of a MOSFET transistor.
Depletion mode p-type

It consists of two small islands of p-type semiconductor, that are created within a substrate of n-type silicon.

The islands are joined by a narrow p-type channel.

Appropriate metal connections (source and drain) are made to these islands; an insulting layer of silicon dioxide is formed by the surface oxidation of the silicon. A final connector (gate) is then fashioned onto the surface of this insulating layer.

An electric field imposed on the gate varied the conductivity of the channel.

If the electric field is positive, it will drive charge carriers (holes) out of the channel, reducing the electrical conductivity. Thus a small change in the gate field will produce a large variation in current between the source and the drain.

Primary difference between BJT and MOSFET is that the gate current is small in comparison to the base current in the BJT.

*MOSFETS are used where the signal sources to be amplified can not sustain an appreciable current.*
MOS STRUCTURE AND OPERATION

Metal-Oxide-Semiconductor Structure

Terminals:
- Bulk - Used to make an ohmic contact to the substrate
- Gate - The gate voltage is applied in such a manner as to invert the doping of the material directly beneath the gate to form a channel between the source and drain.
- Source - Source of the carriers flowing in the channel
Figure 18.25  (a) Scanning electron micrograph showing a small region of a microprocessing chip (a 0.5-MB selected address device). The narrow, white regions are an aluminum top layer that serves as the wiring for this device. The gray regions are diffusion-layer doped silicon that have been coated with an interlayer dielectric. Approximately 2000×. (b) An optical photomicrograph showing a portion of a circuit that is used to test microprocessing chips. The narrow, light regions are aluminum connectors, and the white, square areas are test pads (semiconductor devices); test circuits (also composed of semiconductor devices) appear in the upper left-hand corner of the photograph. Approximately 50×. (Both photographs courtesy of Nick Gonzales of National Semiconductor Corporation, West Jordan, UT).