Optoelectronic devices

- Fundamentals of Photodiodes
- Light emitting devices
- Semiconductor LASERs
- Solar cells
- CCDs along with Nanoelectronic devices

Optoelectronic Devices

- Semiconductor devices that converts optical energy into electrical energy, and that converts electrical signals into optical signals are called optoelectronics.
- Devices that convert **optical energy into electrical energy** include **photodiodes and solar cells**. Two-terminal devices designed to respond to photon absorption are called **photodiodes**.
- Emitters of photons include incoherent sources such as light-emitting diodes (**LEDs**) and coherent sources in the form of **lasers** i.e. **convert electrical signals into optical signals.**
- These devices are used in broadband communications and data transmission over optical fibers.

- When a semiconductor is illuminated with light, the photons may be absorbed or they may propagate through the semiconductor, depending on the photon energy and on the bandgap energy E_g.
- If the photon energy E<Eg, the photons are not readily absorbed.
- If E>Eg, the photon can interact with a valence electron and elevate the electron into the conduction band. The valence band contains many electrons and the conduction band contains many empty states, so the probability of this interaction is high when E>Eg.
- This interaction creates an electron in the conduction band and a hole in the valence **band—an electron–hole pair.**

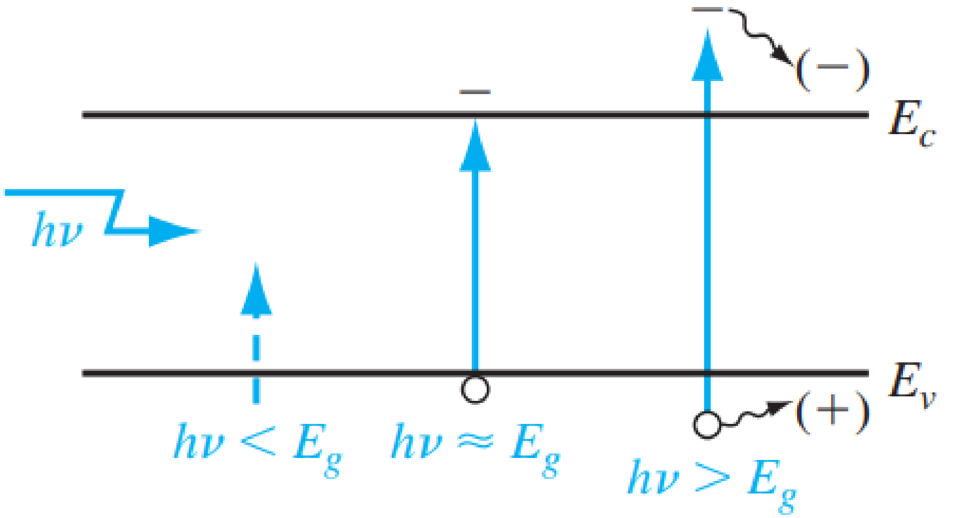


Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

Electron hole pair generation rate

We have shown that photons with energy greater than E_g can be absorbed in a semiconductor, thereby creating electron–hole pairs. The intensity $I_\nu(x)$ is in units of energy/cm^2-s and $\alpha I_\nu(x)$ is the rate at which energy is absorbed per unit volume. If we assume that one absorbed photon at an energy $h\nu$ creates one electron–hole pair, then the generation rate of electron–hole pairs is

$$g' = \frac{\alpha I_\nu(x)}{h\nu} \tag{14.6}$$

which is in units of #/cm^3-s. We may note that the ratio $I_\nu(x)/h\nu$ is the photon flux. If, on the average, one absorbed photon produces less than one electron–hole pair, then Equation (14.6) must be multiplied by an efficiency factor.

Photodetectors

- Photoconductor
- Photodiode
    - PIN photodiode
    - Avalanche photodiode
- Phototransistor

Photoconductor

If excess carriers are generated in the semiconductor, the conductivity becomes

$$\sigma = e[\mu_n(n_0 + \delta n) + \mu_p(p_0 + \delta p)] \tag{14.18}$$

The conductivity from Equation (14.18) can be rewritten as

$$\sigma = e(\mu_n n_0 + \mu_p p_0) + e(\delta p)(\mu_n + \mu_p) \tag{14.19}$$

The change in conductivity due to the optical excitation, known as the *photoconductivity*, is then

$$\Delta\sigma = e(\delta p)(\mu_n + \mu_p) \tag{14.20}$$

An electric field is induced in the semiconductor by the applied voltage, which produces a current. The current density can be written as

$$J = (J_0 + J_L) = (\sigma_0 + \Delta\sigma)\mathrm{E} \tag{14.21}$$

where J_0 is the current density in the semiconductor prior to optical excitation and J_L is the photocurrent density. The photocurrent density is $J_L = \Delta\sigma \cdot \mathrm{E}$. If the excess electrons and holes are generated uniformly throughout the semiconductor, then the photocurrent is given by

$$I_L = J_L \cdot A = \Delta\sigma \cdot A\mathrm{E} = eG_L\tau_p(\mu_n + \mu_p)A\mathrm{E} \tag{14.22}$$

where A is the cross-sectional area of the device. The photocurrent is directly proportional to the excess carrier generation rate, which in turn is proportional to the incident photon flux.

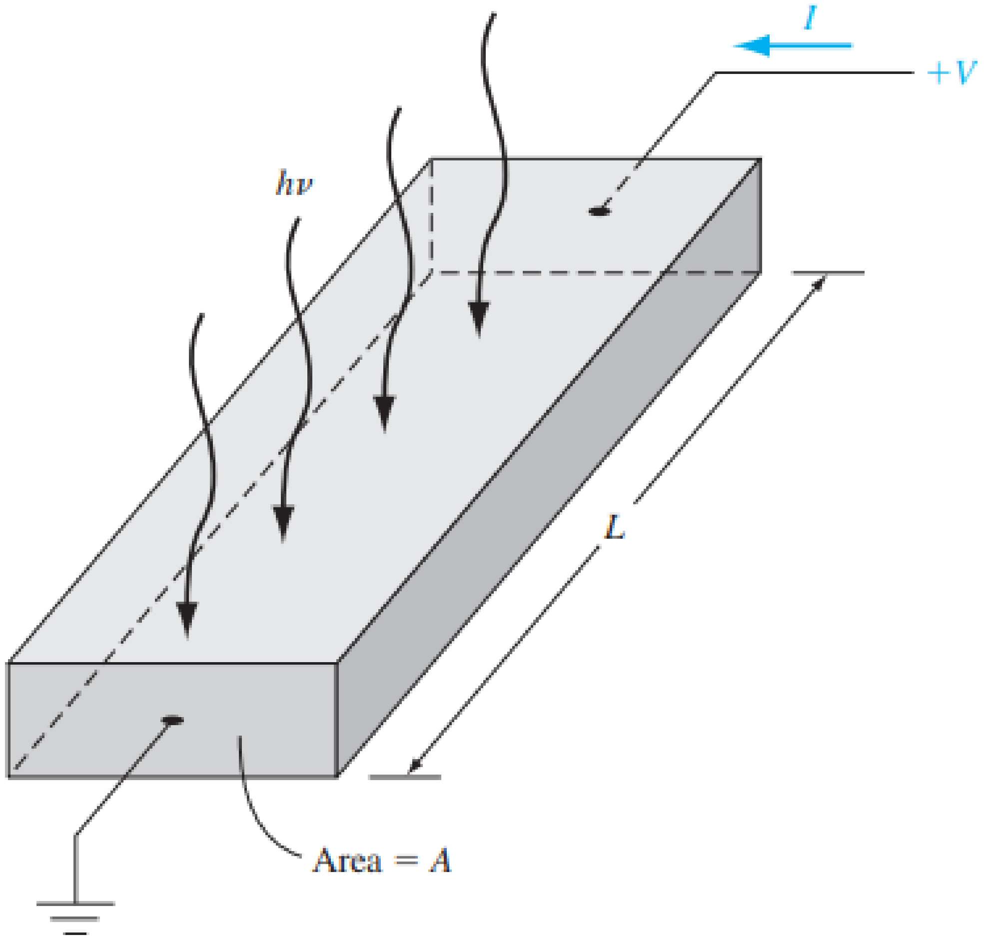


Figure 14.16 | A photoconductor.

Fundamentals of Photodiodes

- A photodiode is a pn junction diode operated with an applied reverse-biased voltage.
- It works on the principle of the **photoelectric effect.**
- If the energy of the falling photons (E) is greater than the energy gap (E_g) of the semiconductor material ($E>E_g$), electron-hole pairs are created near the depletion region of the diode.
- The direction of the electric field in the diode forces the electrons to move towards the n-side and consequently the holes move towards the p-side.

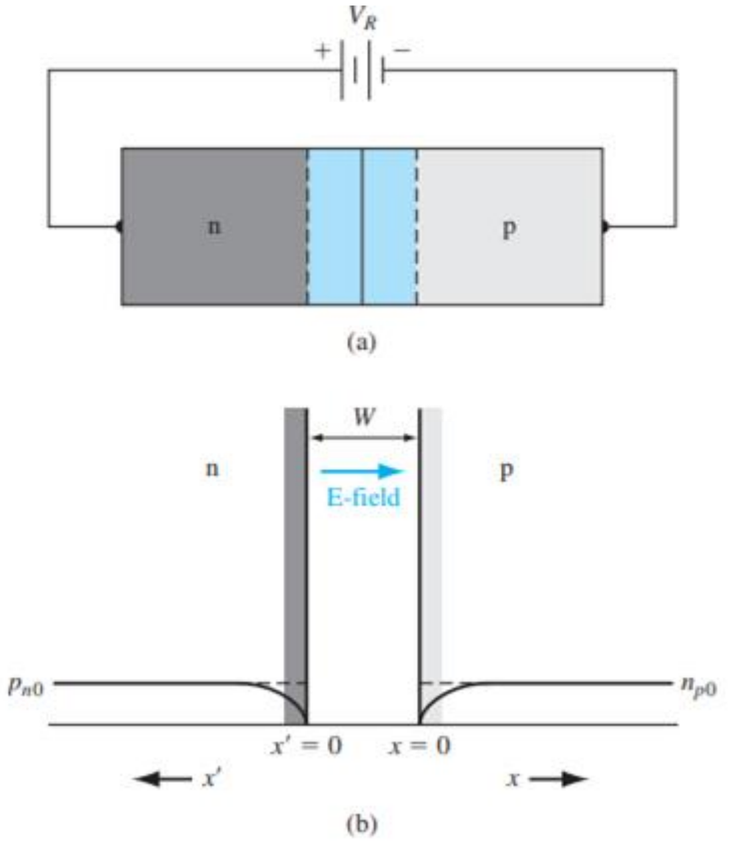
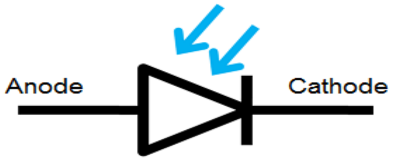


Figure 14.17 | (a) A reverse-biased pn junction. (b) Minority carrier concentration in the reverse-biased pn junction.

Types of Photodiode

- ➢PIN Photodiode
- ➢Avalanche Photodiode



Photodiode symbol

- An increase in the number of electrons on the n-side and holes on the p-side, a rise in the electromotive force is observed.
- When an external load is connected to the system, a current flow is observed through it.

Applications:

- Photodiodes are used in solar cell panels, logic circuits, the detection circuits.

PIN Photodiode

- To increase the photodetector sensitivity, the depletion region width should be made as large as possible. This can be achieved in a PIN photodiode.
- A p–i–n photodiode, also called PIN photodiode, is a photodiode with an intrinsic (i.e., undoped) region in between the n- and p-doped regions.

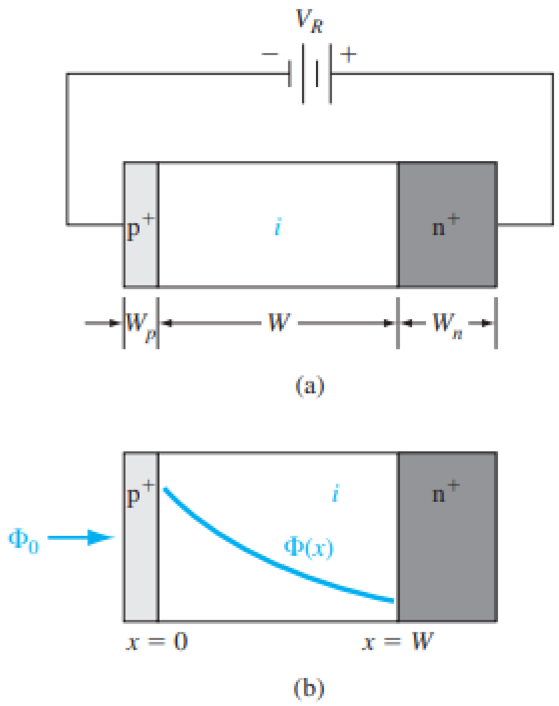


Figure 14.19 | (a) A reverse-biased PIN photodiode. (b) Geometry showing nonuniform photon absorption.

PIN Photodiode

- Most of the photons are absorbed in the intrinsic region, and carriers generated therein can efficiently contribute to the photocurrent.
- The photocurrent density generated in the intrinsic region can be found as

$$J_L = e\int_0^W G_L\,dx = e\int_0^W \Phi_0\alpha e^{-\alpha x}\,dx = e\Phi_0(1-e^{-\alpha W})$$

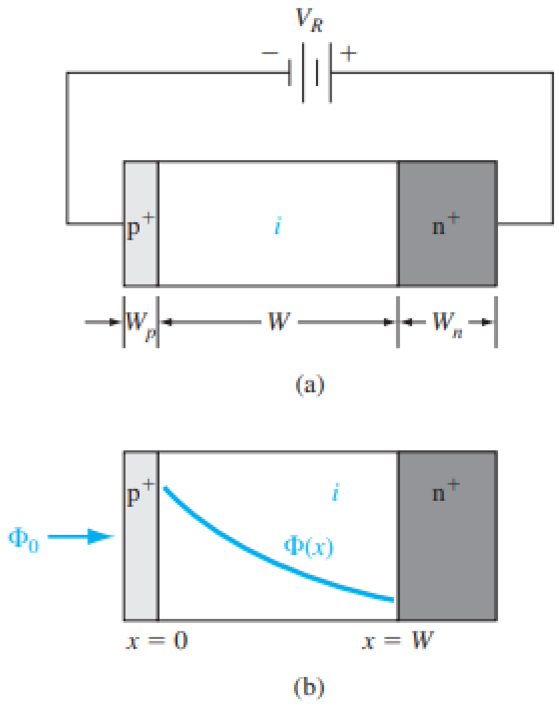


Figure 14.19 | (a) A reverse-biased PIN photodiode. (b) Geometry showing nonuniform photon absorption.

Calculate the photocurrent density in a PIN photodiode. Consider a silicon PIN diode with an intrinsic region width of W 20 m. Assume that the photon flux is 10^{17} cm^{2} –s^{-1} and the absorption coefficient is   10 ^{3} cm^{1} .

The generation rate of electron–hole pairs at the front edge of the intrinsic region is

$$G_{L1} = \alpha\Phi_0 = (10^3)(10^{17}) = 10^{20}\ \text{cm}^{-3}\text{-s}^{-1}$$

and the generation rate at the back edge of the intrinsic region is

$$G_{L2} = \alpha\Phi_0 e^{-\alpha W} = (10^3)(10^{17})\exp\left[-(10^3)(20 \times 10^{-4})\right]$$

$$= 0.135 \times 10^{20}\ \text{cm}^{-3}\text{-s}^{-1}$$

The generation rate is obviously not uniform throughout the intrinsic region. The photocurrent density is then

$$J_L = e\Phi_0(1 - e^{-\alpha W})$$

$$= (1.6 \times 10^{-19})(10^{17})\{1 - \exp\left[-(10^3)(20 \times 10^{-4})\right]\}$$

$$= 13.8\ \text{mA/cm}^2$$

Avalanche Photodiode

- The avalanche photodiode is similar to the pn or PIN photodiode except that the bias applied to the avalanche photodiode is sufficiently large to cause impact ionization
- This diode includes two heavily doped & two lightly doped regions.
- Electron–hole pairs are generated in the space charge region by photon absorption

- Avalanche breakdown occurs mainly once the photodiode is subjected to maximum reverse voltage.
- This voltage enhances the electric field beyond the depletion layer.
- When incident light penetrates the p^+ region then it gets absorbed within the extremely resistive p region then electron-hole pairs are generated.
- Charge carriers drift including their saturation velocity to the pn^+ region wherever a high electric field exists.
- When the velocity is highest, then charge carriers will collide through other atoms & produce new electron-hole pairs. A huge charge carrier’s pair will result in high photocurrent.

- If the saturation velocity is 10^7 cm/s in a depletion region that is 10m wide, then the transit time is $$\tau_t = \frac{10^7}{10 \times 10^{-4}} = 100 \text{ ps}$$

- The period of a modulation signal would be 2t, so that the frequency would be

$$f = \frac{1}{2\tau_t} = \frac{1}{200 \times 10^{-12}} = 5 \text{ GHz}$$

- If the avalanche photodiode current gain is 20, then the gain-bandwidth product is 100 GHz.
- The avalanche photodiode could respond to light waves modulated at micro wave frequencies.

Solar Cells

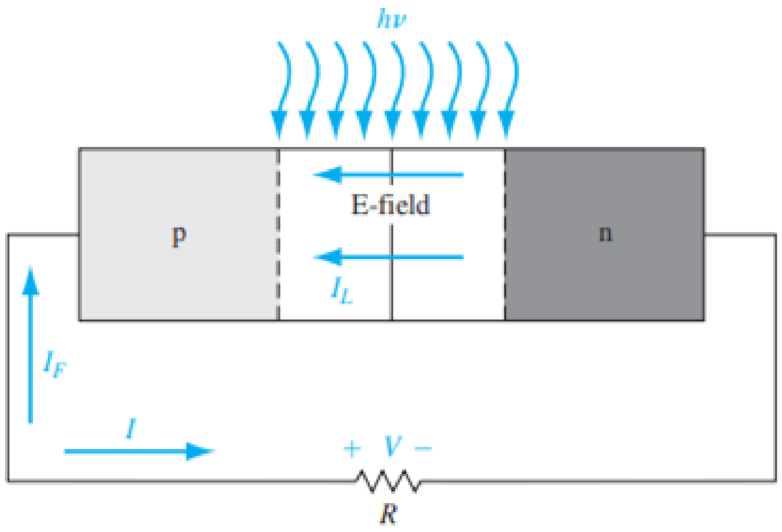
- A solar cell is a pn junction device with no voltage directly applied across the junction.
- The solar cell converts **photon power into electrical power** and delivers this power to a load.

Working principle:

- When light reaches the p-n junction, the light photons can easily enter in the junction, through very thin p-type layer.
- The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs.
- The incident light breaks the thermal equilibrium condition of the junction.
- The free electrons in the depletion region can quickly come to the n-type side of the junction.

The pn Junction Solar Cell

- Incident photon illumination can create electron–hole pairs in the space charge region that will be swept out producing the photocurrent I_L in the reverse-biased direction
- The photocurrent I_L produces a voltage drop across the resistive load which forward biases the pn junction. The forward-bias voltage produces a forward-bias current I_F
- The net pn junction current, in the reverse-biased direction, is



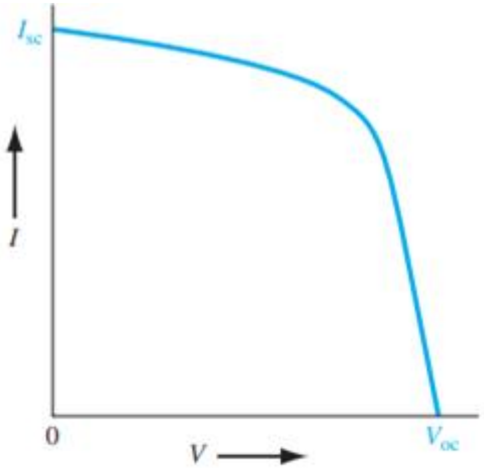


Figure 14.7 | *I–V* characteristics of a pn junction solar cell.

$$I = I_L - I_F = I_L - I_S\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

Two limiting cases of interest.

1. **short-circuit condition** occurs when R=0 so that V=0. The current in this case is referred to as the short-circuit current given as,

$$I = I_{sc} = I_L$$

2. The **open-circuit condition** and occurs when R → ∞.The net current is zero and the voltage produced is the open-circuit voltage.

$$I = 0 = I_L - I_S\left[\exp\left(\frac{eV_{oc}}{kT}\right) - 1\right]$$

The open circuit voltage can be given as,

$$V_{oc} = V_t \ln\left(1 + \frac{I_L}{I_S}\right)$$

The conversion efficiency of a solar cell is defined as the ratio of output electrical power to incident optical power. For the maximum power output, we can write

$$\eta = \frac{P_m}{P_{\text{in}}} \times 100\% = \frac{I_m V_m}{P_{\text{in}}} \times 100\% \tag{14.14}$$

The maximum possible current and the maximum possible voltage in the solar cell are I_{sc} and V_{oc}, respectively. The ratio $I_m V_m / I_{\text{sc}} V_{\text{oc}}$ is called the fill factor and is a measure of the realizable power from a solar cell. Typically, the fill factor is between 0.7 and 0.8.

The Heterojunction Solar Cell

- A heterojunction is formed between two semiconductors with different bandgap energies.
- Assume that photons are incident on the wide-bandgap material.
- Photons with energy less than E_{gN} will pass through the wide-bandgap material, which acts as an optical window, and photons with energies greater than E_{gp} will be absorbed in the narrow bandgap material.
- On the average, excess carriers created in the depletion region and within a diffusion length of the junction will be collected and will contribute to the photocurrent.

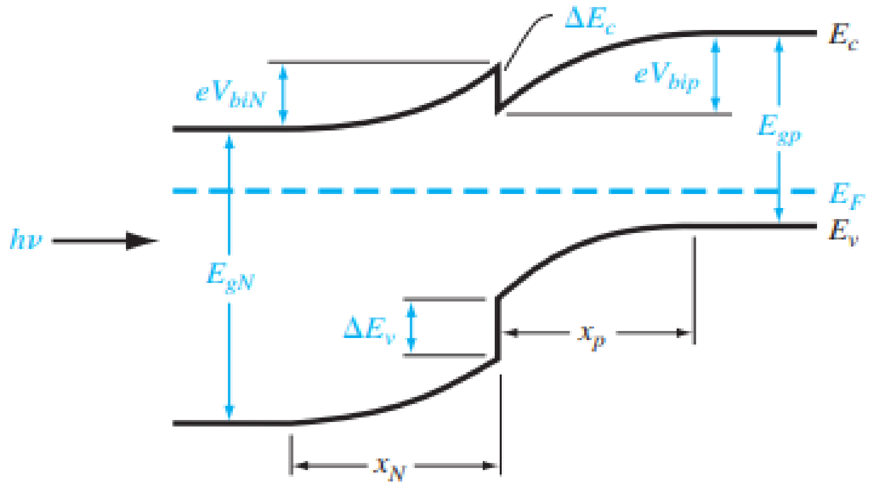


Figure 14.12 | The energy-band diagram of a pN heterojunction in thermal equilibrium.

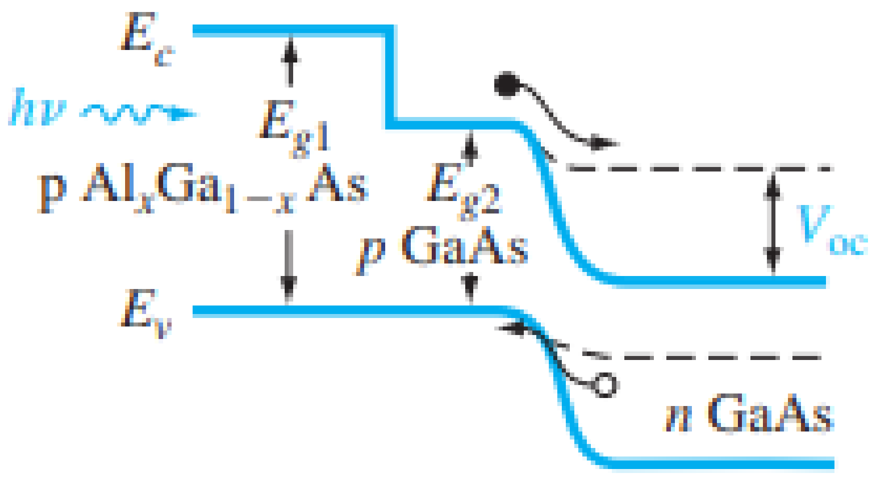


Figure 14.13 Variation of the heterojunction.

Amorphous Silicon Solar Cells

- Amorphous silicon solar cells provide the possibility of fabricating large area and relatively inexpensive solar cell systems.
- When silicon is deposited by CVD techniques at temperatures below 600 C, an amorphous fi lm is formed regardless of the type of substrate.

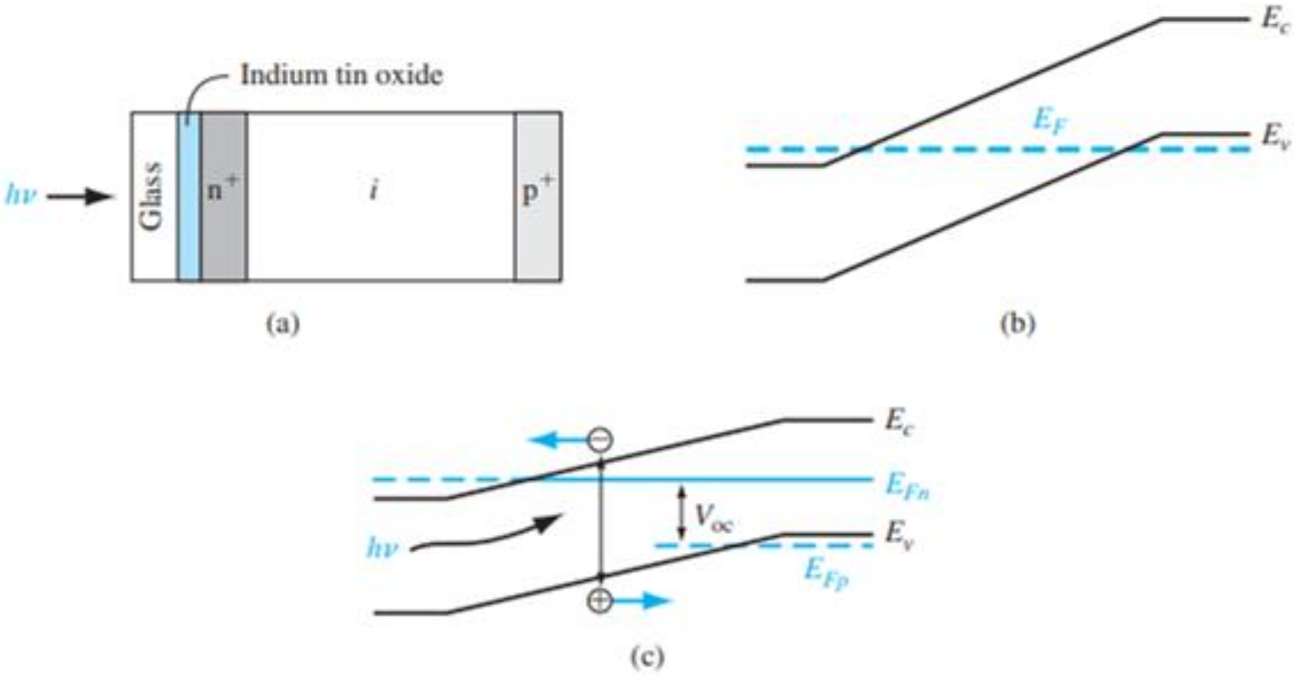
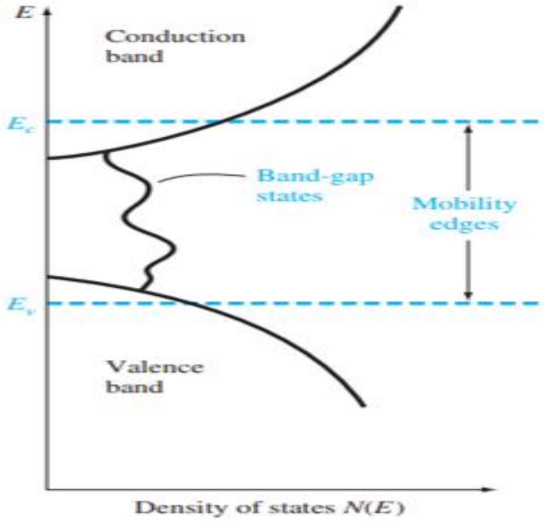


Figure 14.15 | The (a) cross section, (b) energy-band diagram at thermal equilibrium, and (c) energy-band diagram under photon illumination of an amorphous silicon PIN solar cell. *(From Yang [22].)*



Phototransistor

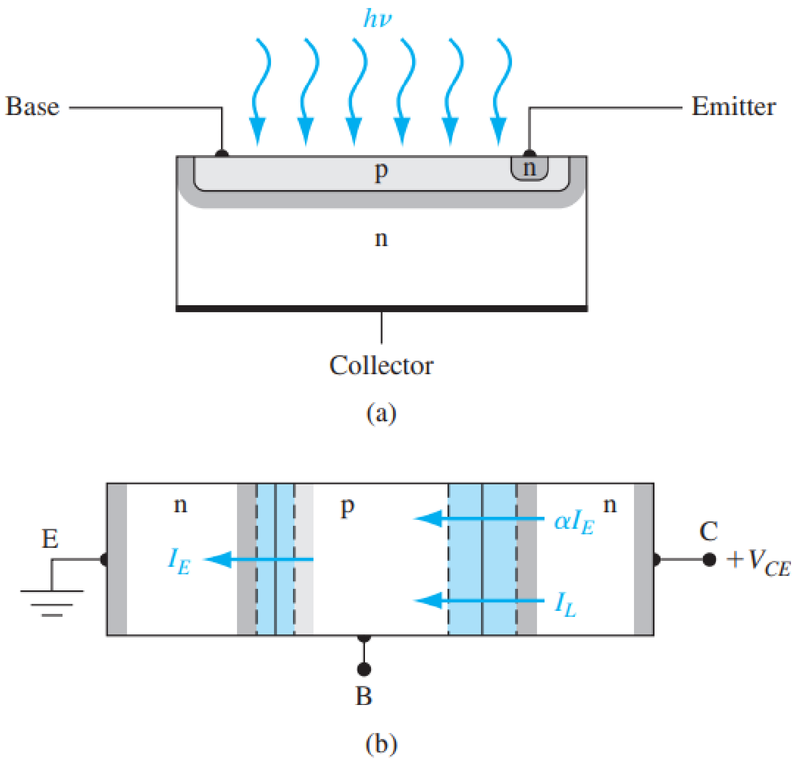


Figure 14.20 | (a) A bipolar phototransistor. (b) Block diagram of the open-base phototransistor.

into the p-type base, making the base positive with respect to the emitter. Since the B–E becomes forward-biased, electrons will be injected from the emitter back into the base, leading to the normal transistor action.

From Figure 14.20b, we see that

$$I_E = \alpha I_E + I_L \tag{14.44}$$

where I_L is the photon-generated current and α is the common base current gain. Since the base is an open circuit, we have $I_C = I_E$, so Equation (14.44) can be written as

$$I_C = \alpha I_C + I_L \tag{14.45}$$

Solving for I_C, we find

$$I_C = \frac{I_L}{1 - \alpha} \tag{14.46}$$

Relating α to β, the dc common emitter current gain, Equation (14.46) becomes

$$I_C = (1 + \beta)I_L \tag{14.47}$$

Equation (14.47) shows that the basic B–C photocurrent is multiplied by the factor $(1 + \beta)$. The phototransistor, then, amplifies the basic photocurrent.

Light Emitting Devices

- On passing a current through the diode, minority charge carriers and majority charge carriers recombine at the junction.

- Excess carriers are generated and then recombine resulting in the emission of photons in a forward biased pn junction, this inverse mechanism is called **injection electroluminescence**. This device is known as a Light Emitting Diode (LED).

- LED photon emission is due to a spontaneous transition of an electron from valence band to conduction band resulting in the fairly wide spectral output bandwidth. The wide wavelength bandwidth is between 30 and 40 nm.

Generation of Light:

Photons may be emitted if an electron and hole recombine by a direct band-to-band recombination process in a direct bandgap material.

The emission wavelength,

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g}\ \mu\text{m}$$

where E_g is the bandgap energy measured in electron-volts

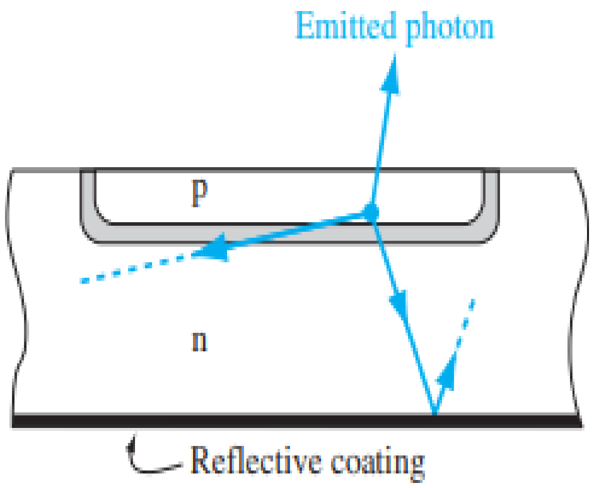


Figure 14.25 | Schematic of photon emission at the pn junction of an LED.

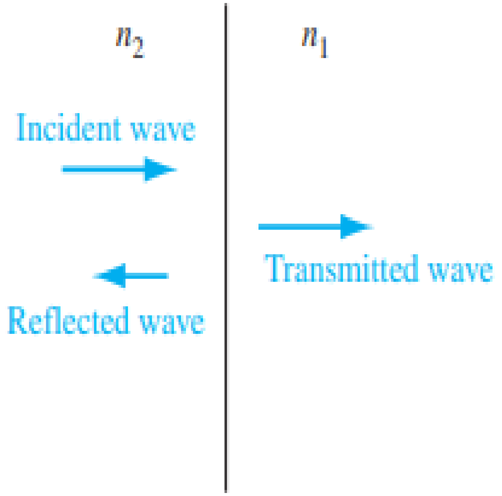


Figure 14.26 | Schematic of incident, reflected, and transmitted photons at a dielectric interface.

Internal Quantum Efficiency

- The internal quantum efficiency of an LED is the **fraction of diode current that produces luminescence.**
- The internal quantum efficiency is a function of the injection efficiency and a function of the percentage of radiative recombination events compared with the total number of recombination events.
- Once the electrons are injected into the p region, not all electrons will recombine radiatively.

- The radiative and non-radiative recombination rates can be defined as

$$R_{nr} = \frac{\delta n}{\tau_{nr}} \qquad R_r = \frac{\delta n}{\tau_r}$$

- The total recombination rate is

$$R = R_r + R_{nr} = \frac{\delta n}{\tau} = \frac{\delta n}{\tau_r} + \frac{\delta n}{\tau_{nr}}$$

Where τ is net excess carrier lifetime.

- The radiative efficiency is defined as the fraction of recombination that are radiative.

$$\eta = \frac{R_r}{R_r + R_{nr}} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} = \frac{\tau}{\tau_r}$$

- The internal quantum efficiency is now written as

$$\eta_i = \gamma\eta$$

External Quantum efficiency

- The **fraction of generated photons that are actually emitted** from the semiconductor.
- Once a photon has been produced in the semiconductor, there are three loss mechanisms the photon may encounter:

1. Photon absorption within the semiconductor
2. Fresnel loss
3. Critical angle loss

- The parameter n_2 is the index of refraction for the semiconductor and n_1 is the index of refraction for air.
- The reflection coefficient is

$$\Gamma = \left(\frac{\overline{n}_2 - \overline{n}_1}{\overline{n}_2 + \overline{n}_1} \right)^2$$

- This effect is called Fresnel loss.
- The reflection coefficient is the fraction of incident photons that are reflected back into the semiconductor.

Problems:

Calculate the reflection coefficient at a semiconductor–air interface. Consider the interface between a GaAs semiconductor and air.

The index of refraction for GaAs is $\bar{n}_2 = 3.8$ at a wavelength of $\lambda = 0.70\ \mu m$ and the index of refraction for air is $\bar{n}_1 = 1.0$. The reflection coefficient is

$$\Gamma = \left(\frac{\bar{n}_2 - \bar{n}_1}{\bar{n}_2 + \bar{n}_1}\right)^2 = \left(\frac{3.8 - 1.0}{3.8 + 1.0}\right)^2 = 0.34$$

Semiconductor LASER

- When a p-n junction diode is forward biased, the electrons from n – region and the holes from the p- region cross the junction and recombine with each other.
- During the recombination process, the light radiation (photons) is released from a certain specified direct band gap semiconductors like Ga-As.
- This light radiation is known as recombination radiation. The photon emitted during recombination stimulates other electrons and holes to recombine.
- As a result, stimulated emission takes place which produces laser.

Semiconductor LASER

- When an incident photon is absorbed and an electron is elevated from an energy state E1 to an energy state E2. This process is known as **induced absorption**.
- If the electron spontaneously makes the transition back to the lower energy level with a photon being emitted, we have a **spontaneous emission process.**
- IF the LED device structure and operating mode are modified, the device can operate in new mode in which bandwidth is very narrow and photon output is coherent. This is called laser diode.
- LASER diode relies on

  stimulated emission

  Population inversion

  Optical resonator cavity

Semiconductor LASER

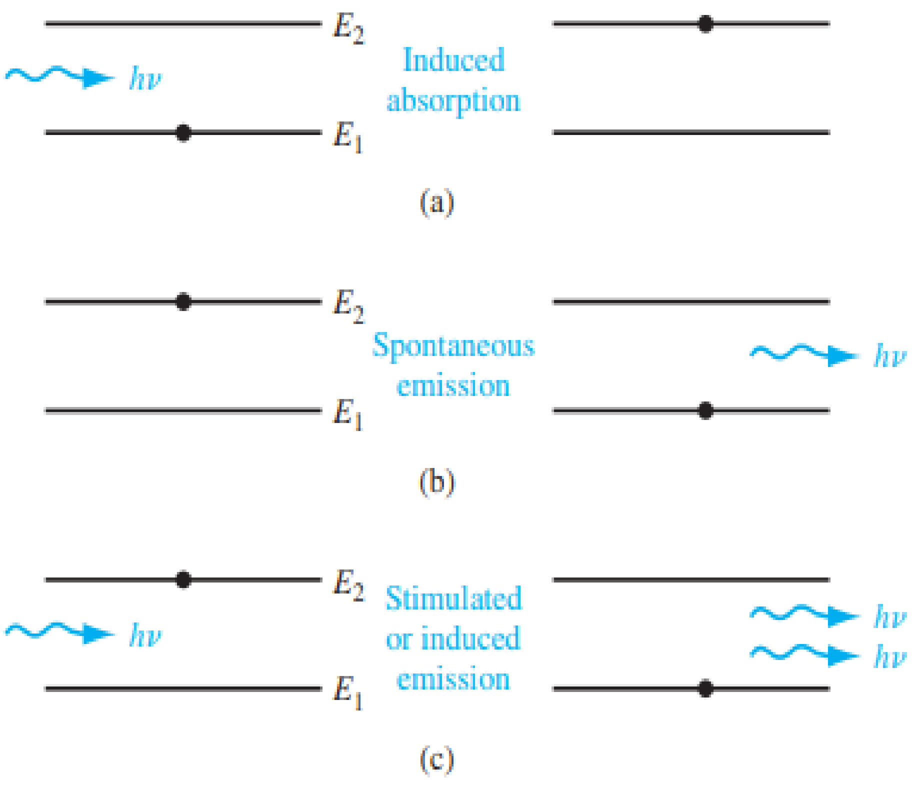


Figure 14.31 | Schematic diagram showing (a) induced absorption, (b) spontaneous emission, and (c) stimulated emission processes.

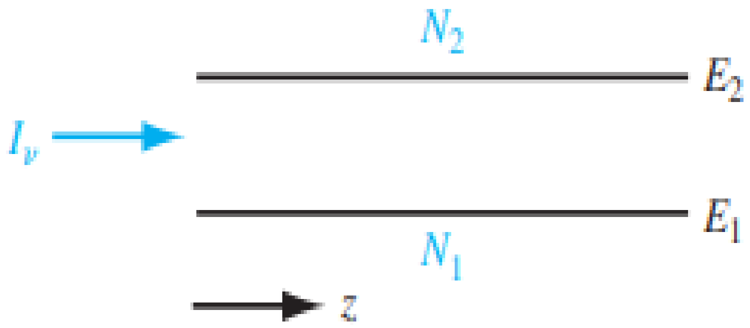


Figure 14.32 | Light propagating in z direction through a material with two energy levels.

Semiconductor LASER

- In thermal equilibrium, the electron distribution in a semiconductor is determined by the Fermi–Dirac statistics. If the Boltzmann approximation applies, it can be written as

$$\frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right]$$

N_1 and N_2 are the electron concentrations in the energy levels E_1 and E_2

- In order to achieve optical amplification or for lasing action to occur, we must have N_2 N_1; this is called population inversion.

Optical Cavity

- A resonant cavity consisting of two parallel mirrors is known as a Fabry–Perot resonator
- For resonance, the length of the cavity L must be an integral number of half wavelengths, or,

$$N\left(\frac{\lambda}{2}\right) = L$$

N is an integer. Since λ is small and L is relatively large, there can be many resonant modes in the cavity

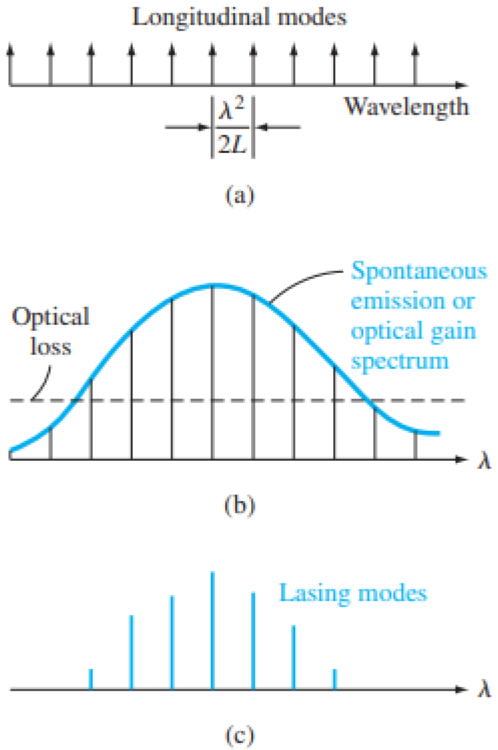


Figure 14.35 | Schematic diagram showing (a) resonant modes of a cavity with length *L*, (b) spontaneous emission curve, and (c) actual emission modes of a laser diode.
(After Yang [22].)

Threshold Current

- The photon absorption in the semiconductor material can be written as

$$I_\nu \propto e^{-\alpha(\nu)z}$$

α(v) is the absorption coefficient

- The optical gain is a function of the pn junction current, we can define a threshold current density as

$$J_{th} = \frac{1}{\beta}\left[\alpha + \frac{1}{2L}\ln\left(\frac{1}{\Gamma_1\Gamma_2}\right)\right]$$

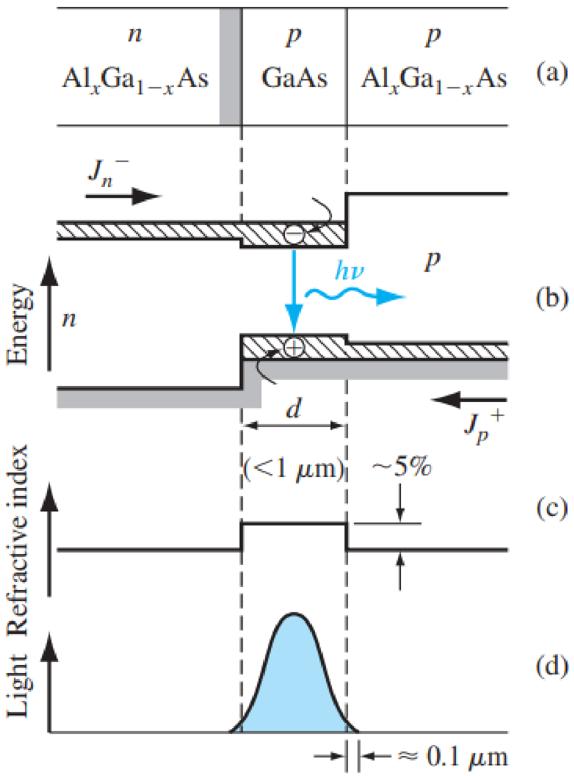


Figure 14.38 | (a) Basic double heterojunction structure. (b) Energy-band diagram under forward bias. (c) Refractive index change through the structure. (d) Confinement of light in the dielectric waveguide. *(From Yang [22].)*

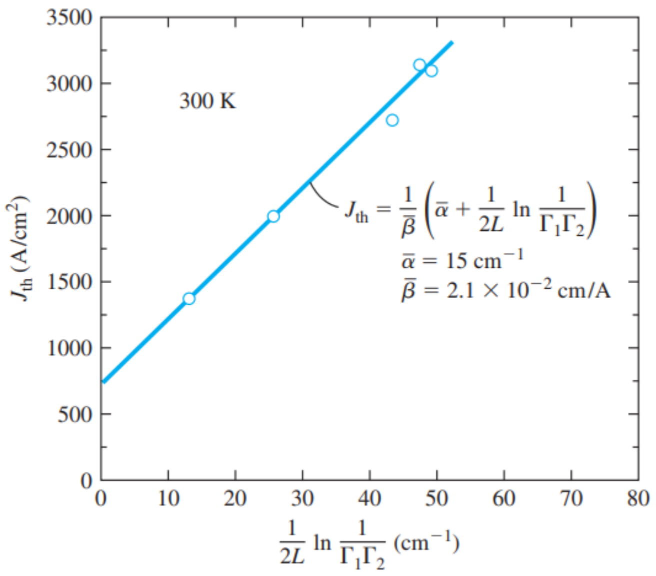


Figure 14.36 | Threshold current density of a laser diode as a function of Fabry-Perot cavity end losses. *(After Yang [22].)*

CHARGE-COUPLED DEVICE (CCD)

- The charge-couple device (CCD) can be used either as an image sensor or as a shift register.
- As a photodetector, it has also been called charge-coupled image sensor or charge-transfer image sensor
- As a signal shifter, it is also called a charge-transfer device.
- Applications : CCD are widely used in surveillance, hand-held and desktop computer video cameras, and document scanners.

CCD Image Sensor

- CCD image sensor have the gates that are semitransparent to let light pass through.
- Gates are made of materials like metal, polysilicon, and silicide
- The CCD can be illuminated from the back of the substrate to avoid light absorption by the gate
- The CCD photodetector is unique in that there is no external dc photocurrent during light exposure.
- The photogenerated carriers are integrated during light exposure, and the signal is stored in the form of a charge packet, to be transported and detected later.

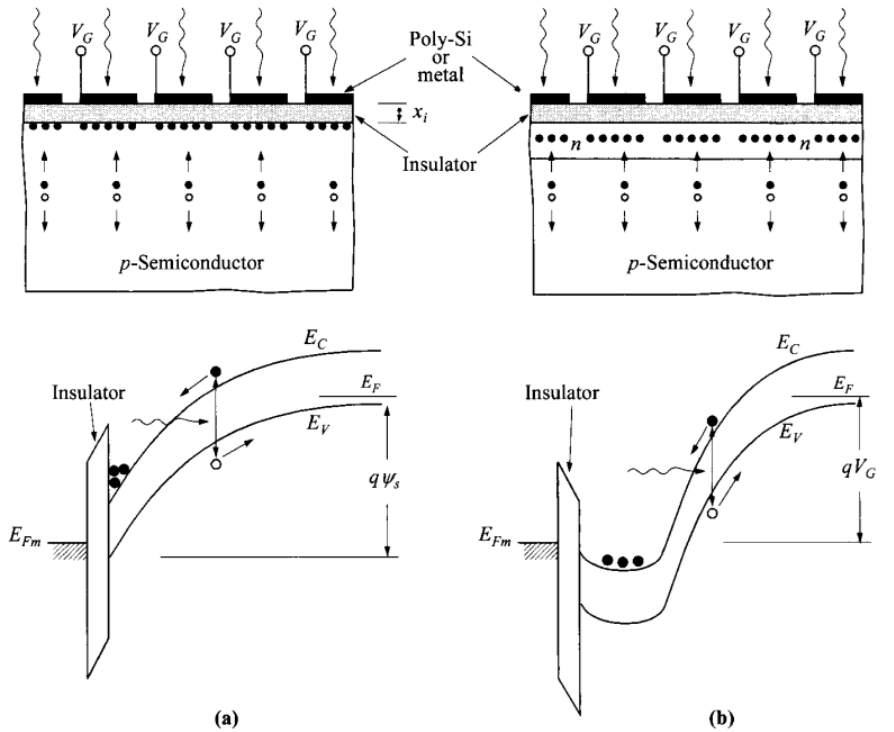


Fig. 23 Structures and energy-band diagrams of (a) surface-channel CCD and (b) buried-channel CCD. For *p*-type substrate, a positive gate bias is applied to drive the semiconductor into deep depletion under nonequilibrium condition.

Charge-Transfer Mechanisms

The three basic charge-transfer mechanisms are
(1) thermal diffusion,
(2) self-induced drift, and
(3) fringing-field effect

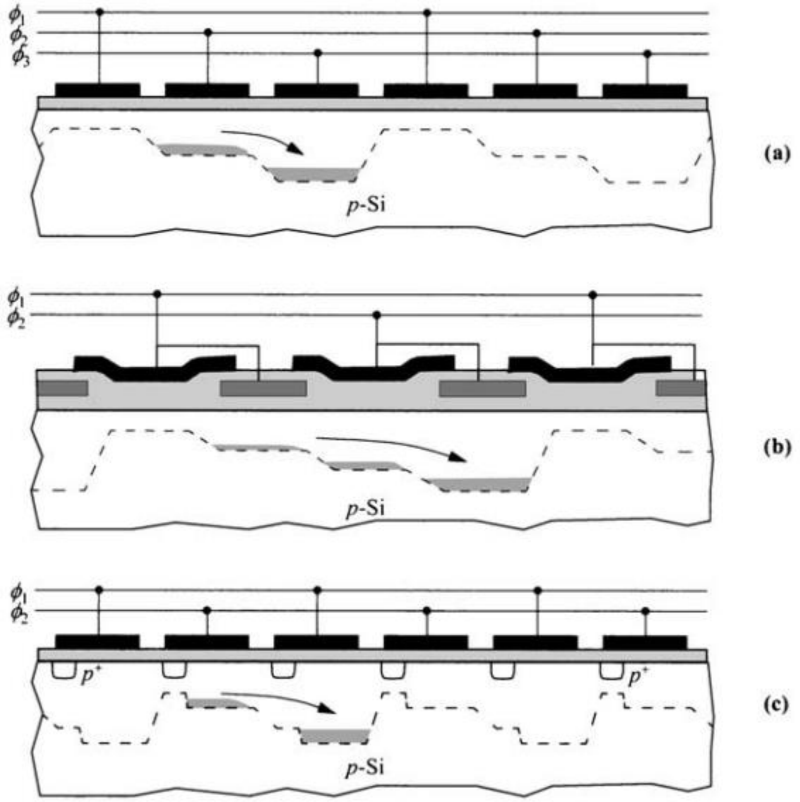


Fig. 28 CCD shift registers using (a) 3-phase single-level gate, (b) 2-phase with step oxides, (c) 2-phase with heavily doped pockets. Dashed lines indicate channel potential.

Nano electronic Devices

- Nanotechnology is sometimes defined as engineered objects in the length scale of 1–100 nm with novel, useful properties.
- This nanoscale regime, sometimes also known as the mesoscale, lies between the microscale (~microns) and atomic/molecular scale (~0.1 nm).
- When objects are shrunk from the macro to microscale and beyond, they don't just become smaller, but they also behave differently.

Types of Nanoelectronic Devices

1. Zero-dimensional quantum dot
2. One-dimensional semiconductor quantum wires
3. Two-dimensional Layered crystals
4. Spintronic Memory
5. Nanoelectronic Resistive Memory

1.Zero-dimensional quantum dot: Zero-dimensional quantum dot systems have singularities in the density of states, where N(E) varies as 1>E. These are sometimes called “artificial atoms.”

Applications: Biomedical applications such as drug delivery, live imaging, and medical diagnosis .

Example: LEDs and solid state lighting, displays and photovoltaics.

2.One-dimensional semiconductor quantum wires:

One-dimensional semiconductor quantum wires or nanowires are an attractive platform for making ultra-scaled MOSFET.

Example: Carbon nanotube, silver nanotube

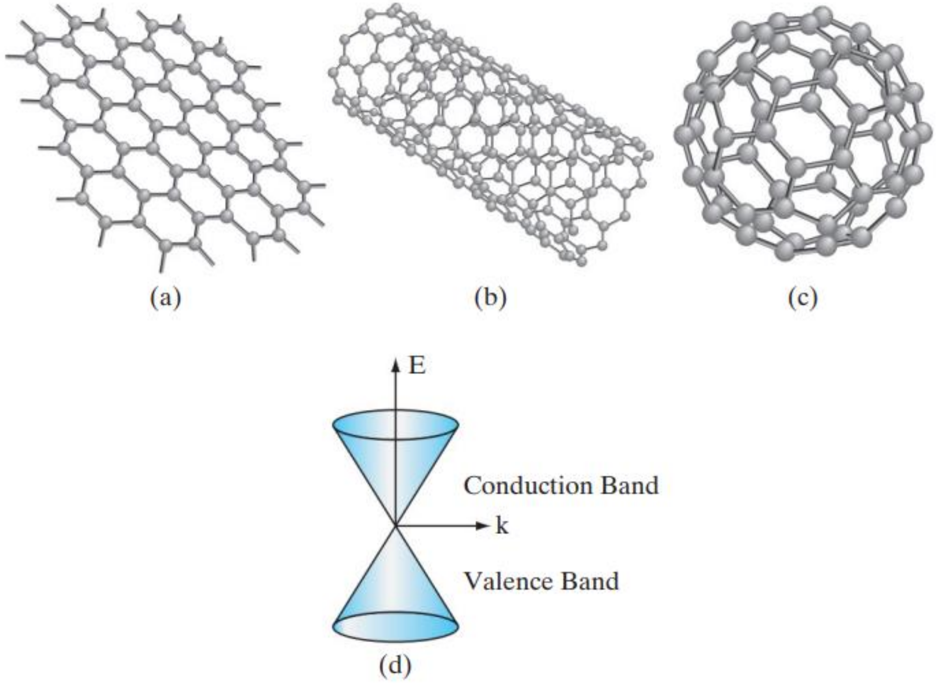
Applications:batteries, piezoelectric

3.Two-dimensional Layered crystals:

Two-dimensional (2D) layered structures are generally considered to be effective “energy converters” that can transform the mechanical energy acting on bulk material into relative motion between layers when the material is subjected to intense mechanical stimuli.

Example: hexagonal boron nitride (h-BN), transition metal dichalcogenides, transition metal oxides

Applications:. They are used in industries like optoelectronics, spintronics, sensors, thermoelectric, photoelectric, superconductors, energy storage, and topological insulator devices.



Nanostructures of carbon: (a) 2-D graphene; (b) 1-D nanotube; (c) 0-D buckyball (fullerene); (d) linear band structure of graphene showing Dirac cones.

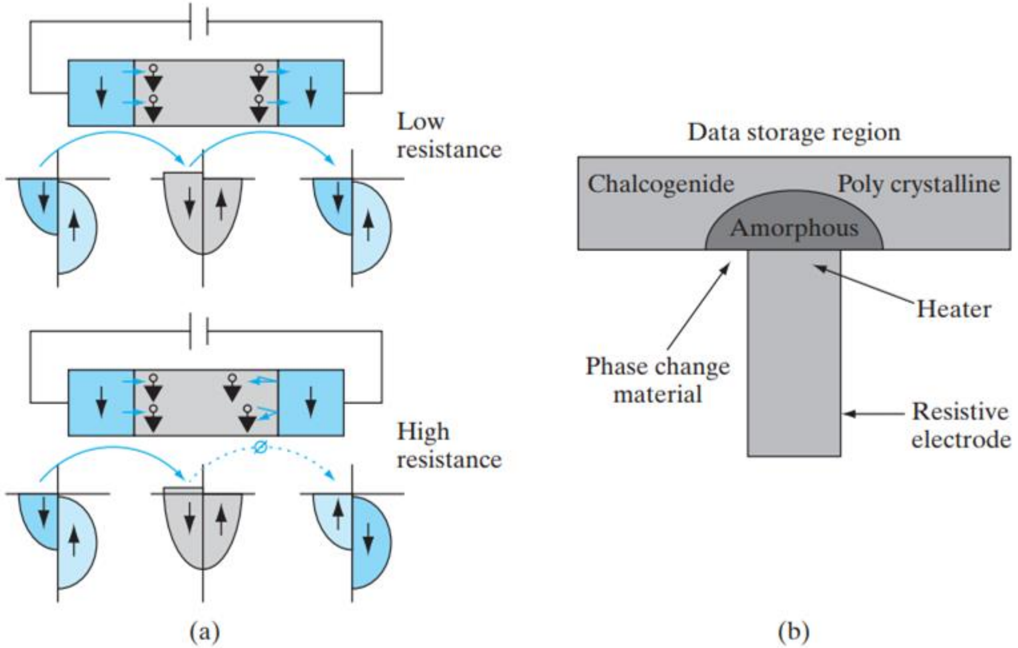


Figure 10–19
(a) Spin-based memory. Depending on whether the "free" magnet on the right is parallel (anti-parallel) to the "fixed" magnet on the left, we have a low (high) tunneling resistance corresponding to the two memory states. (b) Phase change memory whose resistance changes depending on the crystallinity of the chalcogenide.