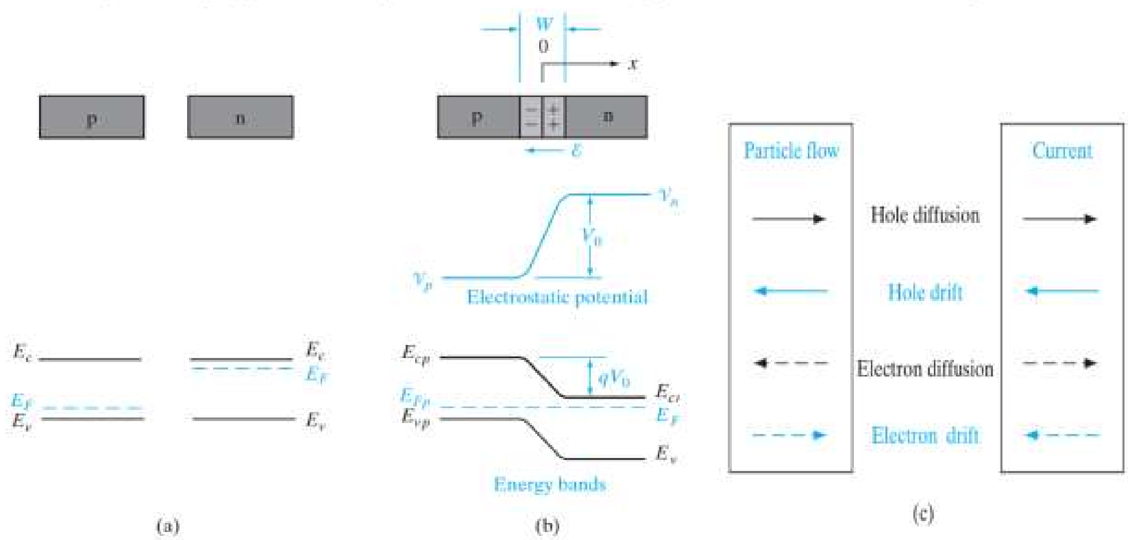
MODULE 2--PN- Junction Analysis-Biasing, Applications

- Forward and Reverse biased junctions- Qualitative description of Current flow at a junction, reverse bias, Reverse bias breakdown- Zener breakdown, avalanche breakdown,
- Rectifiers.
- Optoelectronic Devices Photodiodes: Current and Voltage in an Illuminated Junction,
- Solar Cells,
- Photodetectors.
- Light Emitting Diode: Light Emitting materials

Properties of an equilibrium p-n junction

neutral regions of p-type and n-type material and energy bands for the isolated regions



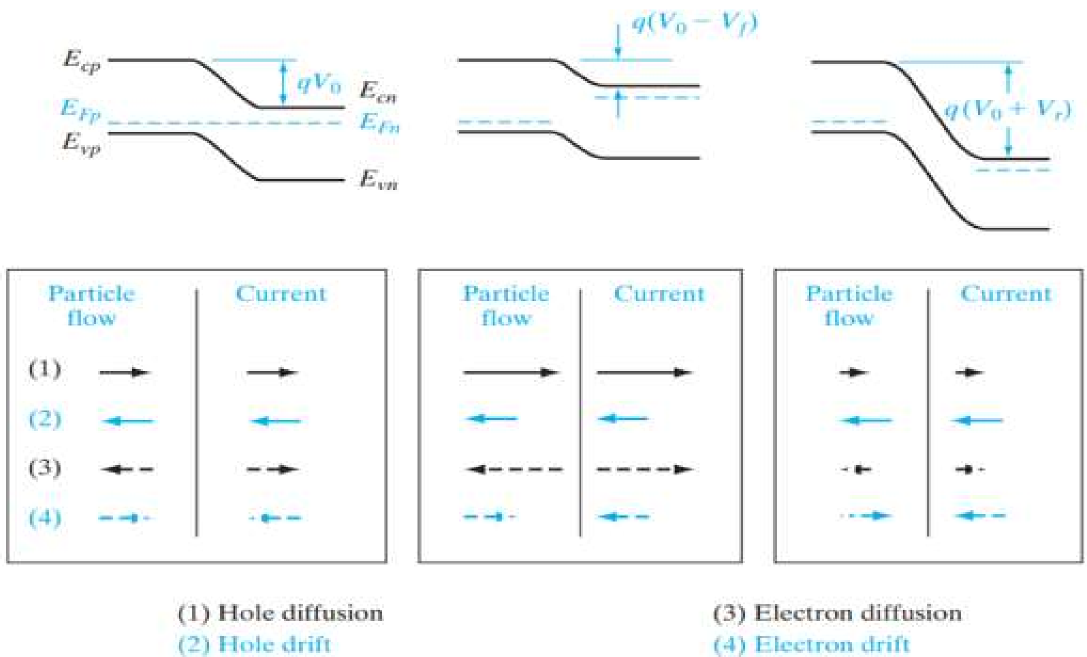
FIGURE

Fermi level is the highest energy stage occupied by electrons in a material at 0 degree kelvin.
In a p-n junction, at equilibrium the fermi levels align on both sides
This implies that energy has to be supplied to move an electron or a hole.
The potential profiles (and band edges) vary as the square of distance from the depletion edges.
Therefore, the shape of the band diagram in the depletion region is not linear, but consists of two parabolic curves that join smoothly

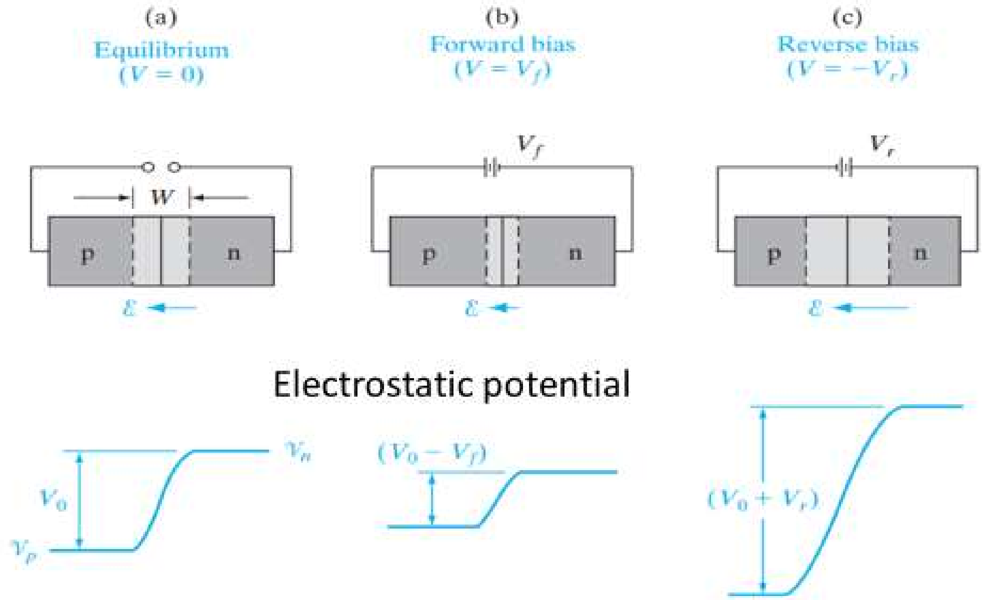
If the hole concentration just at the edge of the transition region on either side, pp and pn

$$V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n} \qquad \frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$$

Qualitative Description of Current Flow at a Junction can be done as belo



Effects of a bias at a p-n junction;



- The electrostatic potential during FB is lowered by (V0 - Vf) and it is increased by (V0 + Vr) in the reversed biased condition.
- The electric field decreases with forward bias as it opposes the contact potential and it increases with reverse bias as it aids the contact potential
- The width of transition region reduces in FB due to reduction in field and W increases in the RB condition
- The separation of the energy bands is a direct function of the electrostatic potential barrier at the junction.
- The height of the electron energy barrier is simply the electronic charge q times the height of the electrostatic potential barrier.
- Thus the bands are separated less [q(V0 - Vf)] under forward bias than at equilibrium, and more [q(V0 + Vr)] under reverse bias.

- Under forward bias, the Fermi level on the n side EFn is above EFp by the energy qVf ;
- for reverse bias, EFp is qVr joules higher than EFn.

Components of Current in a PN junction

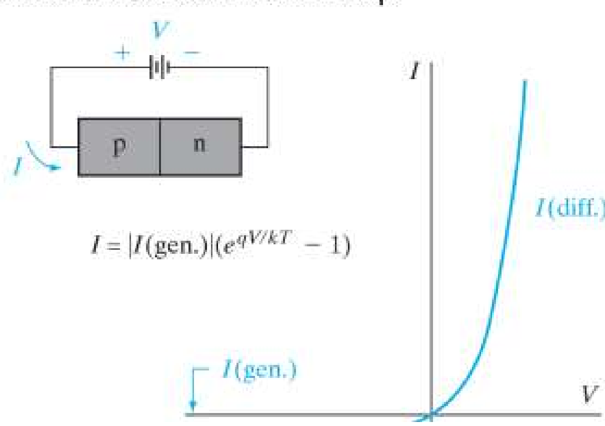
- Diffusion current is defined as the current due to migration of charge curriers from higher concentration region to lower concentration region and will be large under FB condition.
- The drift current is relatively insensitive to the height of the potential barrier and is proportional to the applied field.
- The current due to drift of generated carriers (EHP) across the junction is commonly called the generation current since its magnitude depends entirely on the rate of generation of EHPs.
- The total current crossing the junction is composed of the sum of the diffusion and drift components.

- The net current crossing the junction is zero at equilibrium, since the drift and diffusion components cancel for each type of carrier.

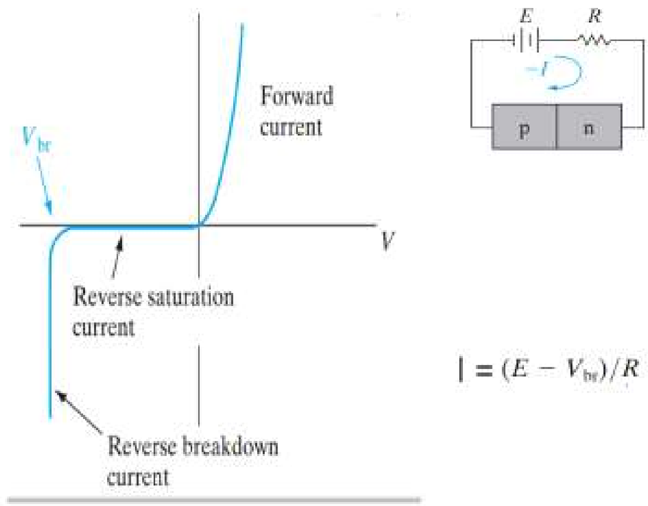
$$I = I(\text{diff.}) - |I(\text{gen.})| = 0 \text{ for } V = 0$$

- Under reverse bias, both diffusion components are negligible because of the large barrier at the junction, and the only current is the relatively small (and essentially voltage-independent) generation current from n to p.

I–V characteristic of a p-n junction.



- The series resistance R can be chosen to limit the current to a safe level
- The excessive reverse/forward current, overheats the device and may damage it as the maximum power rating is exceeded
- Breakdown diodes are designed to operate in the reverse breakdown regime of their characteristics.
- Reverse breakdown can occur by two mechanisms, each of which requires a critical electric field in the junction transition region.
- Zener effect, is operative at low voltages (up to a few volts reverse bias).
- If the breakdown occurs at higher voltages (from a few volts to thousands of volts), the mechanism is avalanche breakdown

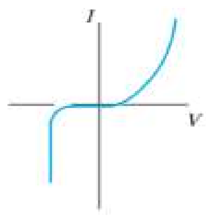


- In the diode Eq. , the applied voltage V can be positive or negative, V = Vf or V = -Vr.
- When V is positive and the exponential term is much greater than unity. The current thus increases exponentially with forward bias.
- When V is negative (reverse bias), the exponential term approaches zero and the current is –Io, which is in the current from n to p (negative) direction.
- This negative generation current is also called the reverse saturation current.

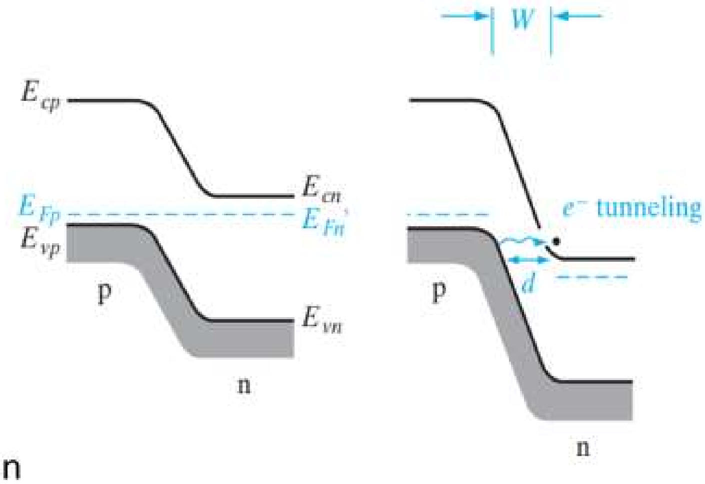
Reverse Breakdown in a PN junction

- As the reverse voltage is increased, at critical voltage (Vbr) the reverse current through the diode increases sharply, and relatively large currents can flow with little further increase in voltage.
- If the current is limited to a reasonable value by the external circuit, the p-n junction can be operated in reverse breakdown as safely as in the forward-bias.

Zener Breakdown



(c)



(a) (b)

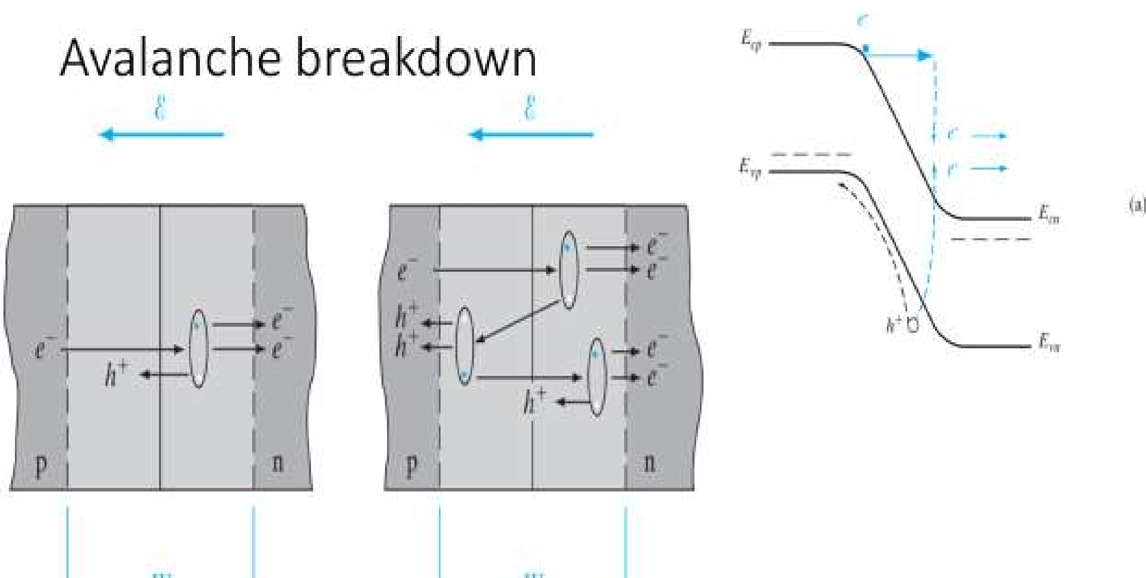
(a) heavily doped junction at equilibrium;
(b) reverse bias with electron tunneling from p to n;
(c) I–V characteristic

- When a heavily doped junction is reverse biased, the energy bands become crossed at relatively low voltages (i.e., the n-side conduction band appears opposite the p-side valence band).
- As Fig. indicates, the crossing of the bands aligns the large number of empty states in the n-side conduction band opposite the many filled states of the p-side valence band.
- If the barrier separating these two bands is narrow, Tunneling of electrons from the p-side valence band to the n-side conduction band constitutes a reverse current from n to p; this is the **Zener effect.**
- The basic requirements for tunneling current are a large number of electrons separated from a large number of empty states by a narrow barrier of finite height.
- Since the tunneling probability depends upon the width of the barrier (d), it is important that the metallurgical junction be sharp and the doping is high, so that the transition region W extends only a very short distance from each side of the junction.

- In the simple covalent bonding model, the Zener effect can be thought of as field ionization of the host atoms at the junction.
- The reverse bias of a heavily doped junction causes a large electric field of E= V/d within W;
- At a critical field strength, electrons in covalent bonds may be pulled out from the bonds by the field and accelerated to the n side of the junction.
- The electric field required for this type of ionization is on the order of 10 MV/cm.

Avalanche breakdown

- For lightly doped junctions, the breakdown mechanism involves the impact ionization of host atoms by energetic carriers.
- Normal lattice-scattering events can result in the creation of EHPs.
- if the electric field $\mathcal{E}$ in the transition region is large, an electron entering from the p side may be accelerated to high enough kinetic energy to cause an ionizing collision with the lattice.
- A single such interaction results in carrier multiplication;
- the original electron and the generated electron are both swept to the n side of the junction, and the generated hole is swept to the p side .



(a) band diagram of a p-n junction in reverse bias showing a (primary) electron gaining kinetic energy in the field of the depletion region, and creating a (secondary) electron–hole pair by impact ionization, the primary electron losing most of its kinetic energy in the process; (b) a single ionizing collision by an incoming electron in the depletion region of the junction; (c) primary, secondary, and tertiary collisions

- The degree of multiplication can become very high if carriers generated within the transition region also have ionizing collisions with the lattice creating more EHPs. This is an avalanche process, since each incoming carrier can initiate the creation of a large number of new carriers. The total no. of electrons ejected from n region due to collisions :

$$n_{\text{out}} = n_{\text{in}}(1 + P + P^2 + P^3 + \ \ldots\ )$$

Where P is the probability P of a carrier having an ionizing collision with the lattice, and the electron multiplication Mn is given by,

$$M_n = \frac{n_{\text{out}}}{n_{\text{in}}} = 1 + P + P^2 + P^3 + \cdots = \frac{1}{1 - P}$$

- As the probability of ionization P approaches unity, the carrier multiplication (and therefore the reverse current through the junction) increases without limit
- In general, the critical reverse voltage for breakdown increases with the band gap of the material, since more energy is required for an ionizing collision.
- Vbr decreases as the doping increases.

Carrier multiplication M in junctions near breakdown lead to an empirical relation (n value varies from 3-6 with the type of material)

$$M = \frac{1}{1 - (V/V_{\text{br}})^{\mathbf{n}}}$$

Sl no.	Parameter	Zener BD	Avalanche BD
1	Reason	Field ionization	Impact ionization
2	Reverse potential	Low	High
3	Transition Region width -W	Thin	Thick
4	Doping	High	Low
5	Electric field	High	Strong
6	Ionization due to	Electric field	Collision

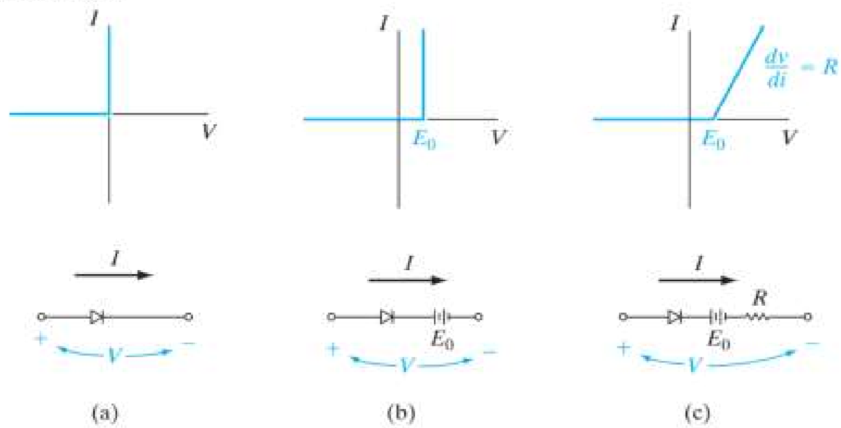
Rectifiers

- Piecewise-linear approximations of junction diode characteristics:

(a) the ideal diode;

(b) ideal diode with an offset voltage;

(c) ideal diode with an offset voltage and a resistance to account for slope in the forward characteristic.



- The unilateral nature of diodes is useful for many other circuit applications that require wave shaping.
- This involves alteration of a-c signals by passing only certain portions of the signal while blocking other portions.
- Junction diodes designed for use as rectifiers should have I–V characteristics as close as possible to that of the ideal diode.
- The reverse current and forward resistance should be negligible.
- The reverse breakdown voltage should be large and the offset voltage E0 in the forward direction should be small.
- A rectifier made with a wide band gap material can be operated at higher temperatures, because thermal excitation of EHPs is reduced by the increased band gap.
- Such temperature effects are critically important in rectifiers, which must carry large currents in the forward direction and are thereby subjected to appreciable heating.
- Si is generally preferred over Ge for power rectifiers because of its wider band gap, lower leakage current and higher breakdown voltage with better fabrication properties.
- The doping concentration on each side of the junction and geometry of the PN layers influences its operation.

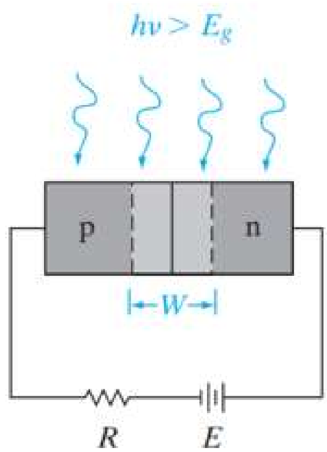
Optoelectronic Devices

- Devices that convert optical energy into electrical energy include photodiodes and solar cells.
- Emitters of photons include incoherent sources such as light- emitting diodes (LEDs) and coherent sources in the form of lasers.

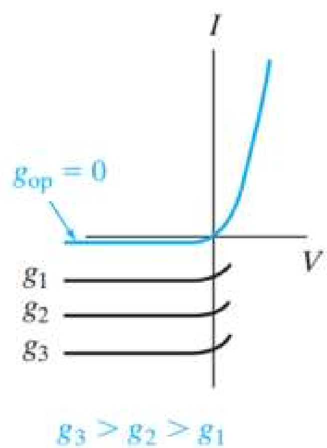
Photodiode

- Two-terminal devices designed to respond to photon absorption are called photodiodes.
- In a photodiode, If the junction is uniformly illuminated by photons with $h\nu > E_g$, more EHPs are generated, with a generation rate gop (EHP/cm3 - s).
- This results in a current due to the collection of optically generated carriers by the junction (Iop)
- Also, under reverse bias condition there exists a current due to minority carriers(and is referred as Ith) when there is no illumination and known as dark current.
- Thus with illumination the I– V curve is lowered by an amount proportional to the generation rate

Operation of a Photodiode



(a)



(c)

- Optical Generation rate (gop) --- (EHP/cm3 - s)
- Diffusion length of holes in the transition region on the n side --- Lp
- Diffusion length of electrons in the transition region on the p side --- Ln
- The number of holes created per second within a diffusion length } --- $AL_p g_{op}$
  of the transition region on the n side

- The electrons generated per second within diffusion length } --- $AL_n g_{op}$
  of the transition region on the p side

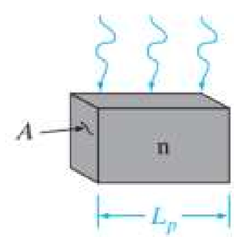
- Carriers generated within W --- AWg_{op}
- The resulting current due to the collection of these optically generated carriers by the junction $\boxed{I_{op} = qAg_{op}(L_p + L_n + W)}$

- Total reverse current with illumination

$$I = I_{th}(e^{qV/kT} - 1) - I_{op}$$

Where I_{th} is the thermally generated current /generation current/dark current

- Hole concentration in n side -- Pn
- Electron concentration in P side -- np
- Average life-time of hole in n-side -- τ_p
- Average life-time of electron in p-side -- -- τ_n



- Then $I_{th} = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)$

carrier lifetime is defined as the average **time** it takes for a minority **carrier** to recombine

- If the device is short circuited, I= - Iop
- When there is an open circuit across the device, I = 0 and the voltage V = Voc

$$V_{oc} = \frac{kT}{q}\ln[I_{op}/I_{th} + 1]$$

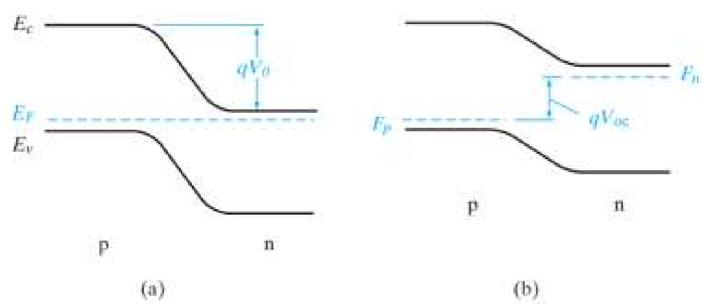
- For a symmetrical junction, pn = np and $\tau_p = \tau_n$: we rewrite Eq. in terms of the thermal generation rate $p_n/\tau_n = g_{th}$

(represents the equilibrium thermal generation– recombination rate) and the optical generation rate gop. Neglecting generation within W:

$$V_{oc} \simeq \frac{kT}{q}\ln\frac{g_{op}}{g_{th}} \quad \text{for } g_{op} \gg g_{th}$$

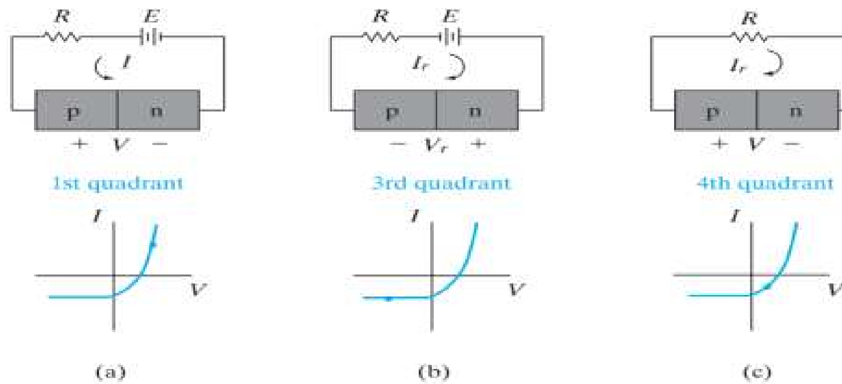
The appearance of a forward voltage across an illuminated junction is known as the photovoltaic effect.

Effects of illumination on the open circuit voltage of a junction: (a) junction at equilibrium; (b) appearance of a voltage Voc with illumination.



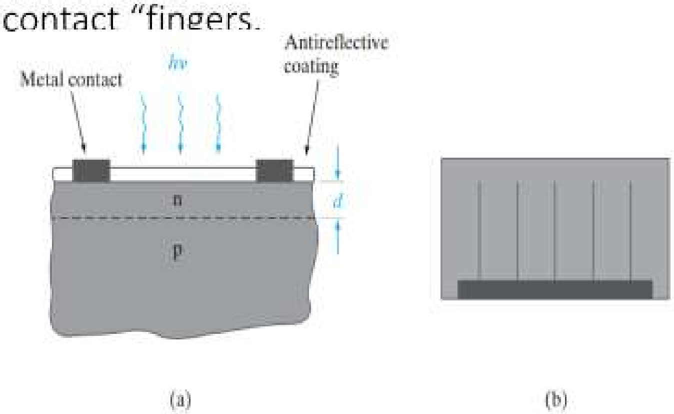
- As the minority carrier concentration is increased by optical generation of EHPs,
- the lifetime τ_n: becomes shorter, and pn , τ_n: becomes larger
- Therefore, Voc cannot increase indefinitely with increased generation rate; and limited by contact potential

Operation of an illuminated junction in the various quadrants of its I–V



- If power is to be extracted from the device, the fourth quadrant is used(solar cell);
- In applications as a photodetector we usually reverse bias the junction and operate it in the third quadrant.

Configuration of a solar cell (Photovoltaic cell):
(a) enlarged view of the planar junction;
(b) top view, showing metal contact "fingers.



It is important that the series resistance of the device be very small so that power is not lost to heat due to ohmic losses in the device itself. To prevent this effect, the contact can be distributed over the n surface by providing small contact fingers as in Fig. These narrow contacts serve to reduce the series resistance without interfering appreciably with the incoming light.

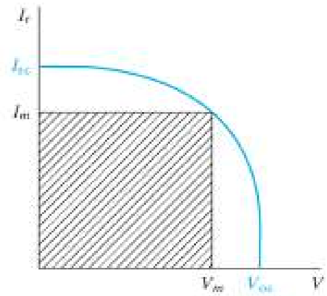
solar cell design

- In the device shown, the junction depth d must be less than Lp in the n material to allow holes generated near the surface to diffuse to the junction before they recombine;
- The thickness of the p region must be such that electrons generated in this region can diffuse to the junction before recombination takes place.
- This requirement implies a proper match between the electron diffusion length Ln, the thickness of the p region, and the mean optical penetration.
- It is desirable to have a large contact potential V0 to obtain a large photo voltage,
- Heavy doping is preferred;
- Long lifetimes are desirable though it is reduced by doping. Equivalent circuit for a photodiode…

Solar cell

- Large area junction located near the surface of the device.
- The planar junction is formed by diffusion or ion implantation,
- The surface is coated with appropriate materials to reduce reflection and to decrease surface recombination.
- Operate device in the 4th quadrant where the device generates energy to the circuit…
- The voltage is restricted to values less than the contact potential, In Si ~ 1V.
- Current generated is ~ 10-100 mA for 1cm2 illuminated area.
- Solar cell arrays are used to increase the power level.

I–V characteristics of an illuminated solar cell (The maximum power rectangle is shaded)



Pmax = (f.f.) IscVoc

The ratio ImVm/IscVoc is called the fill factor, and is a figure of merit for solar cell design.

Solar cells can supply power for the electronic equipment aboard a satellite over a long period, which is a distinct advantage over batteries. The array of junctions can be distributed over the surface of the satellite or can be contained in solar cell "paddles" attached to the main body of the satellite

Photodetectors

- When the photodiode is operated in the third quadrant of its I– V characteristic,
- the current is essentially independent of voltage but is proportional to the optical generation rate.
- Such a device provides a useful means of measuring illumination levels or of converting time-varying optical signals into electrical signals.
- For example, if the photodiode is to respond to a series of light pulses 1 ns apart, the photo generated minority carriers must diffuse to the junction and be swept across to the other side in a time much less than 1 ns.
- The carrier diffusion step in this process is time consuming and should be eliminated if possible.
- Therefore, it is desirable that the width of the depletion region W be large enough so that most of the photons are absorbed within W rather than in the neutral p and n regions.
- When an EHP is created in the depletion region, the electric field sweeps the electron to the n side and the hole to the p side.
- Since this carrier drift occurs in a very short time, the response of the photodiode can be quite fast. When the carriers are generated primarily within the depletion layer W, the detector is called a depletion layer photodiode.
- Obviously, it is desirable to dope at least