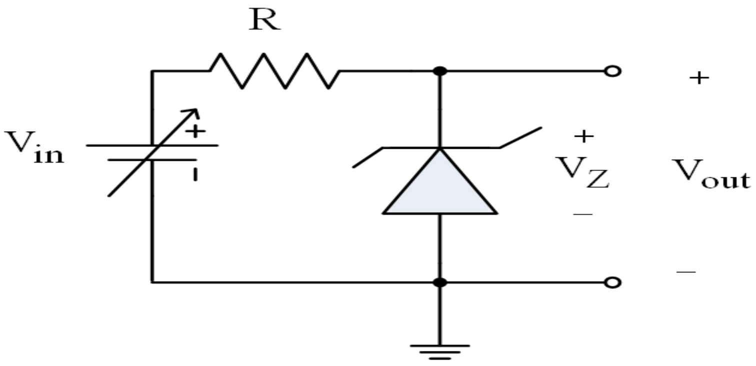
CLASS 13 & 14

Zener regulator and limiter, Special diodes : varactor diode, LED, photodiode, tunnel diode, LASER, Schottky diode

Output voltage regulation with variable input voltage



$I_{ZK} = 4$ mA

$I_{ZM} = 40$ mA

$R = 1$ kΩ

$V_Z = 10$ V

Determine the permissible range of V_{in} to fulfill the specifications.

$V_{out} = V_Z$

$-V_{in} + I_ZR + V_Z = 0$

$V_{in} = I_ZR + V_Z$

If $I_Z = I_{ZK} = 4$ mA, $V_{in} = (4\text{ m})(1\text{ k}) + 10 = 14$ V

If $I_Z = I_{ZM} = 40$ mA , $V_{in} = (40\text{ m})(1\text{ k}) + 10 = 50$ V

The permissible range of V_{in} is $14\text{ V} \le V_{in} \le 50$ V.

Output voltage regulation with variable load

Determine the allowed range of R_L.

I_T is fixed since V_{in} and V_{out} are fixed as $V_{out} = V_Z$ and R is also fixed.

$I_T = I_L + I_Z$

If I_L increases, I_Z decreases.

$I_T = (V_{in} – V_Z)/R$

If $I_L = I_{L(min)}$, $I_Z = I_{Z(max)}$

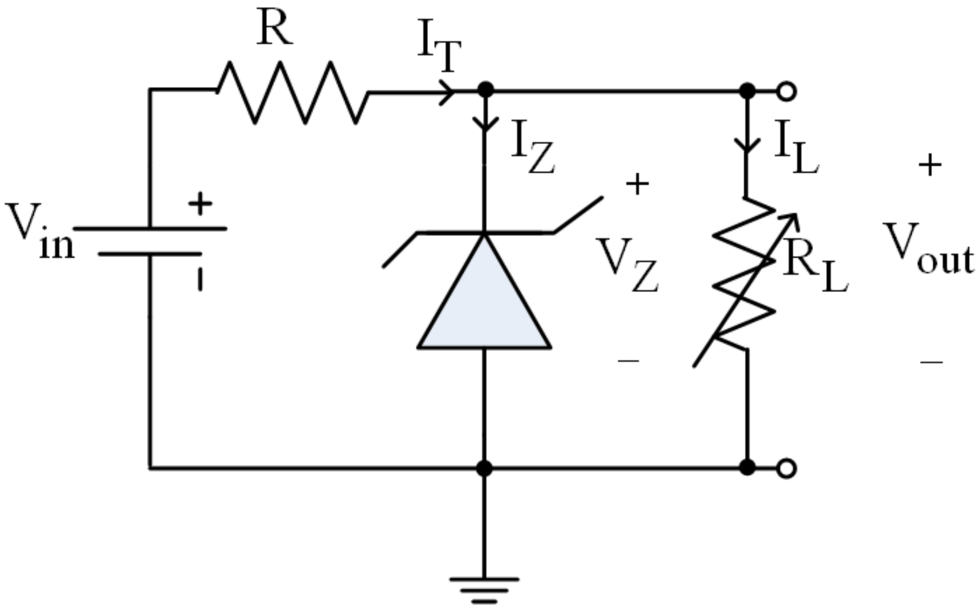
If $I_L = I_{L(max)}$, $I_Z = I_{Z(min)}$

$R_{L(min)} = V_Z / I_{L(max)}$

$R_{L(max)} = V_Z / I_{L(min)}$

Range of allowed R_L is:

$R_{L(min)} \leq R_L \leq R_{L(max)}$.



Determine the allowed range of R_L if

I_{ZK} = 3 mA, I_{ZM} = 90 mA, R = 470 Ω,

V_Z = 12 V and V_{in} = 24 V.

$I_T = (V_{in} - V_Z)/R = (24 - 12)/470 = 25.5$ mA

$I_T = I_L + I_Z$

If $I_Z = I_{Z(max)}$ = 90 mA, this value is larger than I_T, which is an impossible condition. Hence, $I_Z \neq$ 90 mA. To determine the practical $I_{Z(max)}$, $I_{L(min)}$ has to be determined. The minimum that I_L can be is 0 A.

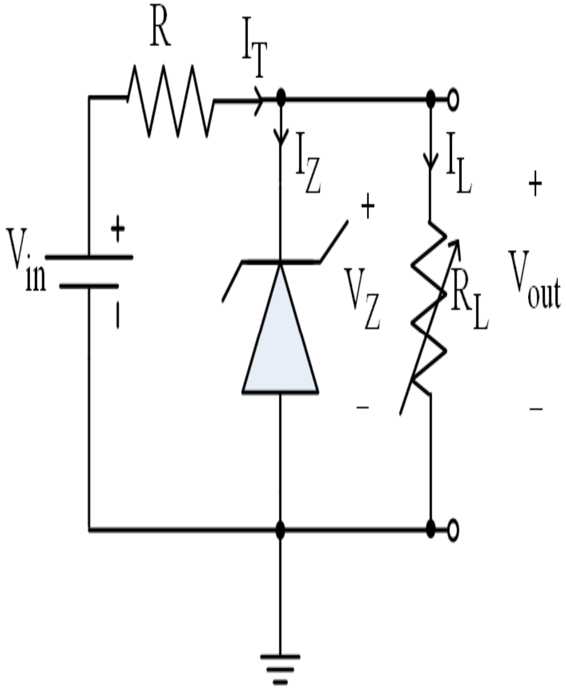
When $I_{L(min)}$ = 0 A, $I_T = I_{Z(max)}$ = 25.5 mA. Since $R_{L(max)} = V_Z / I_{L(min)}$, $R_{L(max)}$ is an o/c.

$I_{Z(min)}$ = 3 mA, thus $I_{L(max)}$ = 25.5 m – 3 m = 22.5 mA

$R_{L(min)} = V_Z / I_{L(max)}$ = 12 / 22.5 m = 533 Ω.

Therefore, the range of allowed R_L is:

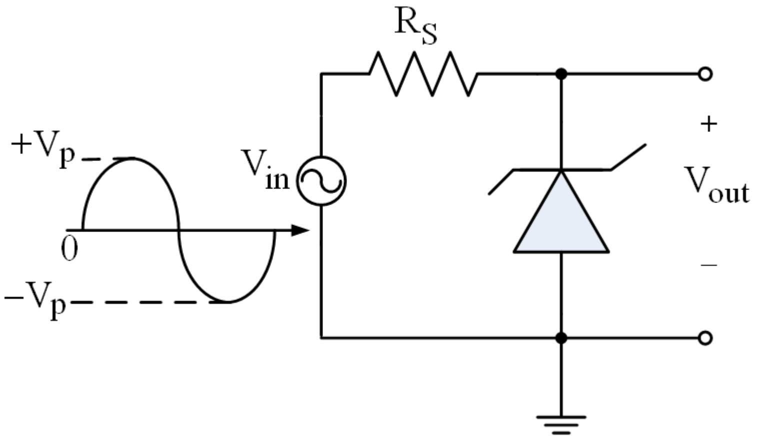
533 Ω ≤ R_L ≤ ∞.



Conclusion on voltage regulation by the zener diode:

- V_{in} and R_L are chosen so that the zener diode will operate in the breakdown region. This is the region where the zener diode is a constant voltage device.
- The breakdown region is used in this operation as the large change in the current that flows through the diode will only result in a very small change in the zener voltage. Thus, the diode will regulate the load voltage at one fix value although there is a large variation in the load current (i.e. variation in load resistance) or the supply voltage.

The zener limiter

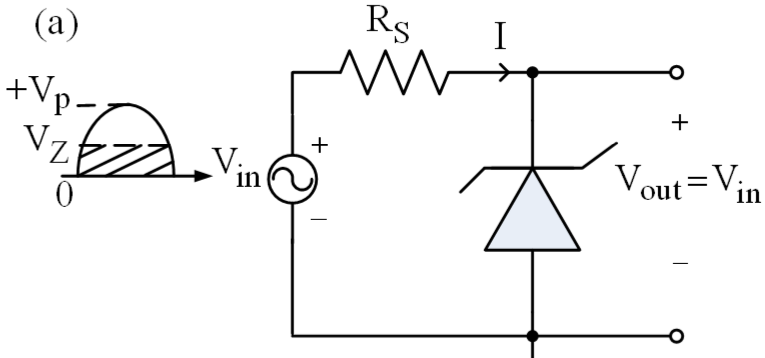


During the +ve half cycle, I is flowing from the cathode to the anode. The zener diode is rb.

(a) If I < I_{ZK} , I ≈ 0 A. The zener diode is represented by an o/c. Hence,

$V_{out} = V_{in}$.

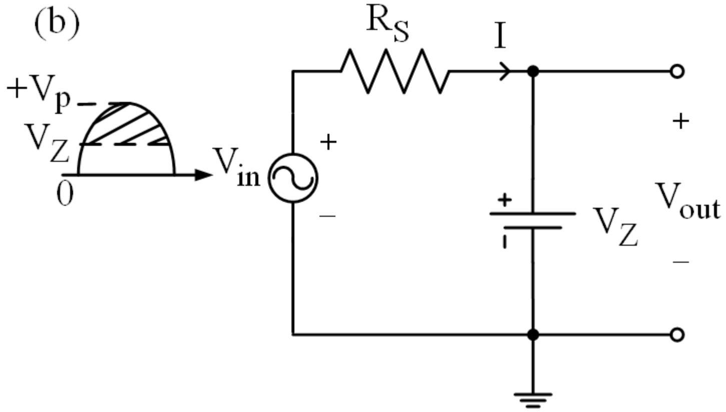
(a)



(b) If I > I_{ZK} , the zener diode will regulate at V_Z. Hence,

$V_{out} = V_Z$

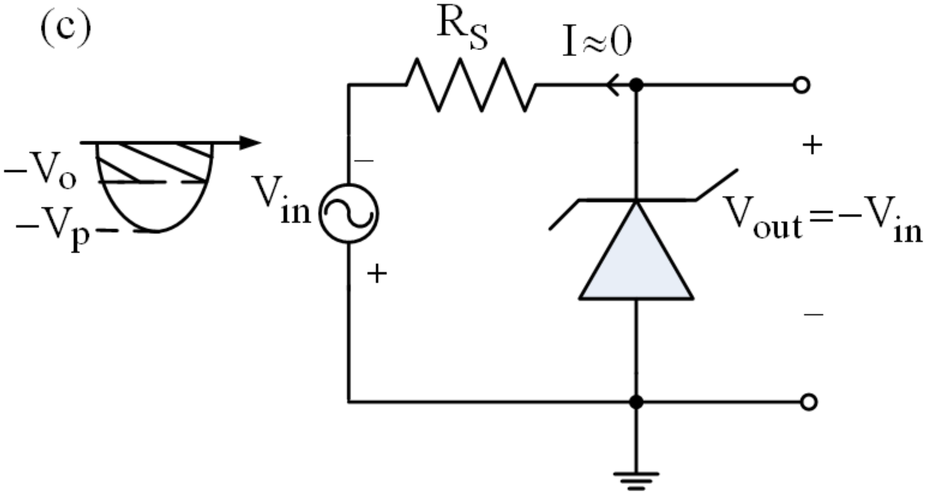
(b)

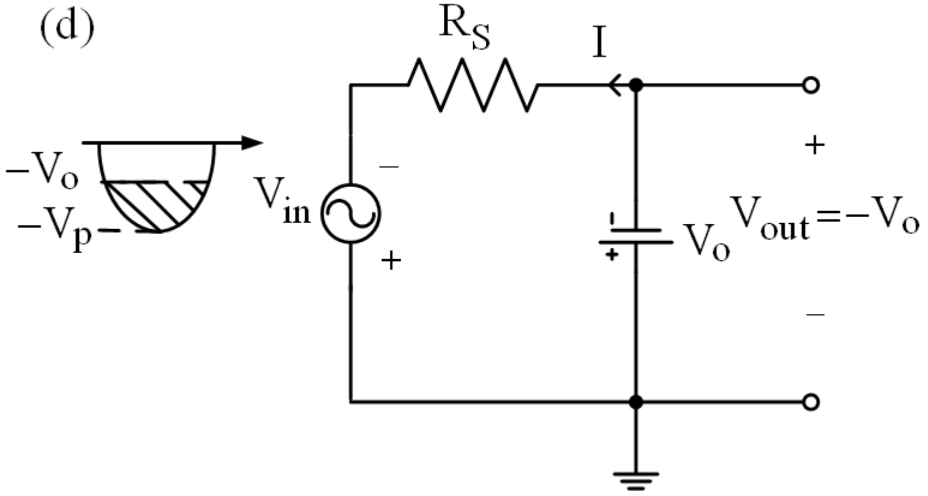


(c) During the –ve half cycle, diode is fb if V_{in} is more –ve than the $-V_o$. If V_{in} is more +ve than the $-V_o$, the diode is still OFF and I ≈ 0 A. Hence,

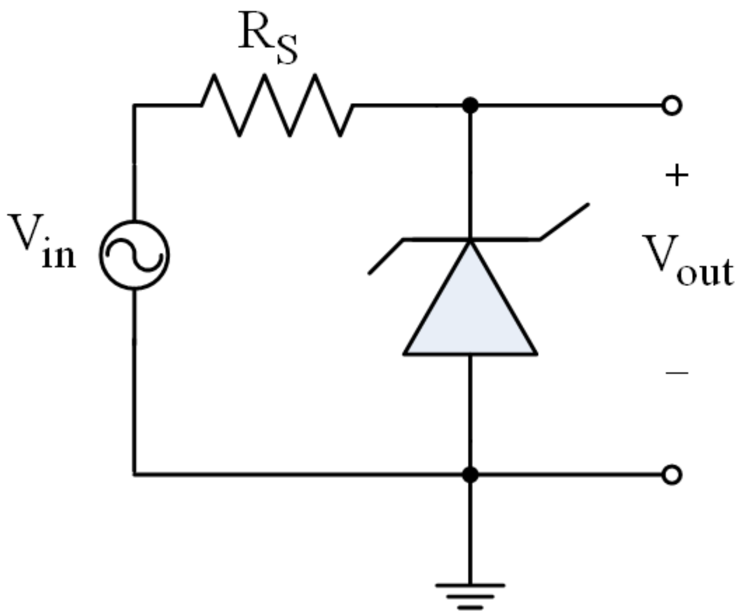
$V_{out} = V_{in}$.

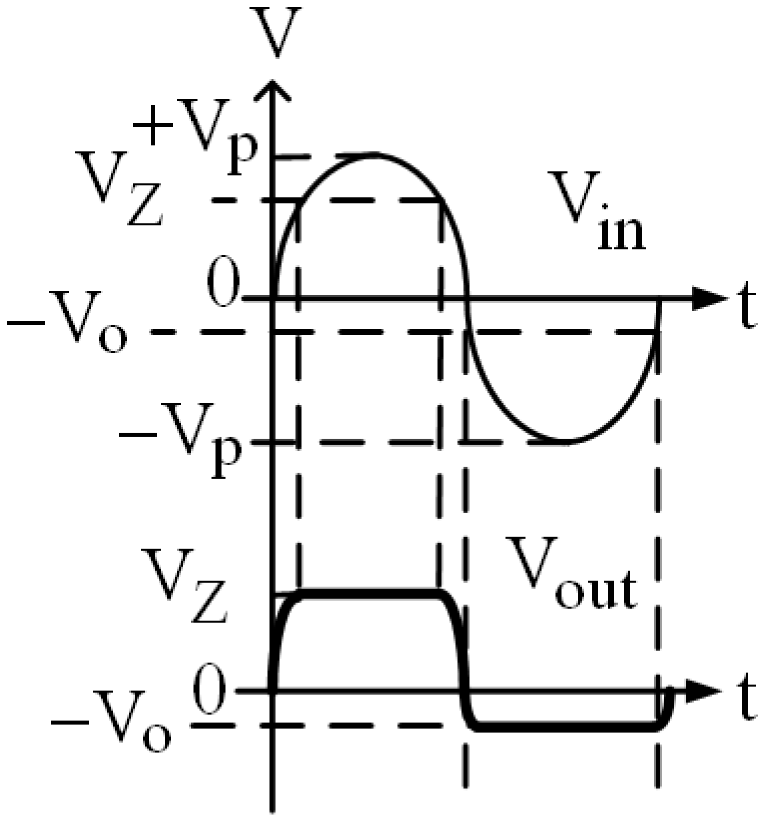
(d) If $_{in}$ is more –ve than the $-V_o$, diode is fb and the voltage across the diode is $-V_o$. Hence, $V_{out} = -V_o$.

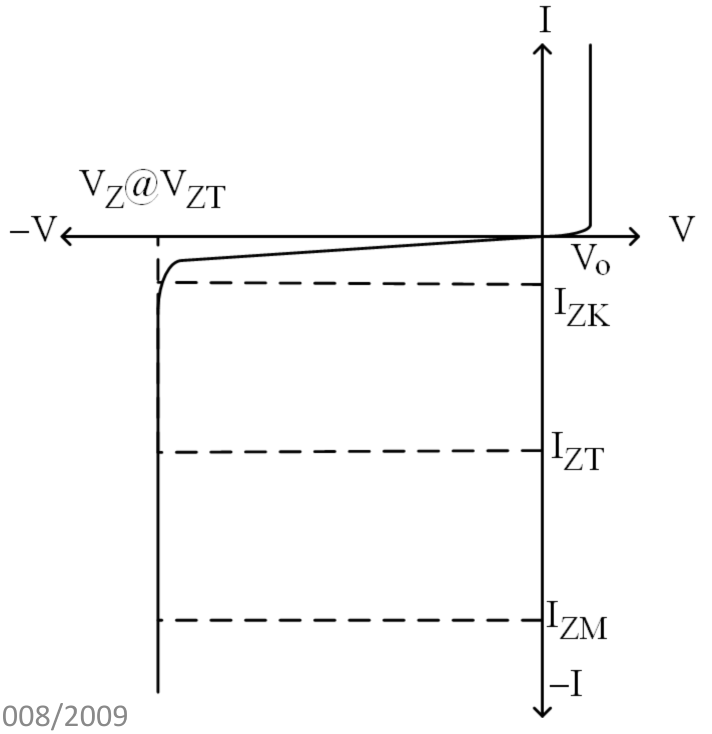




Overall performance:

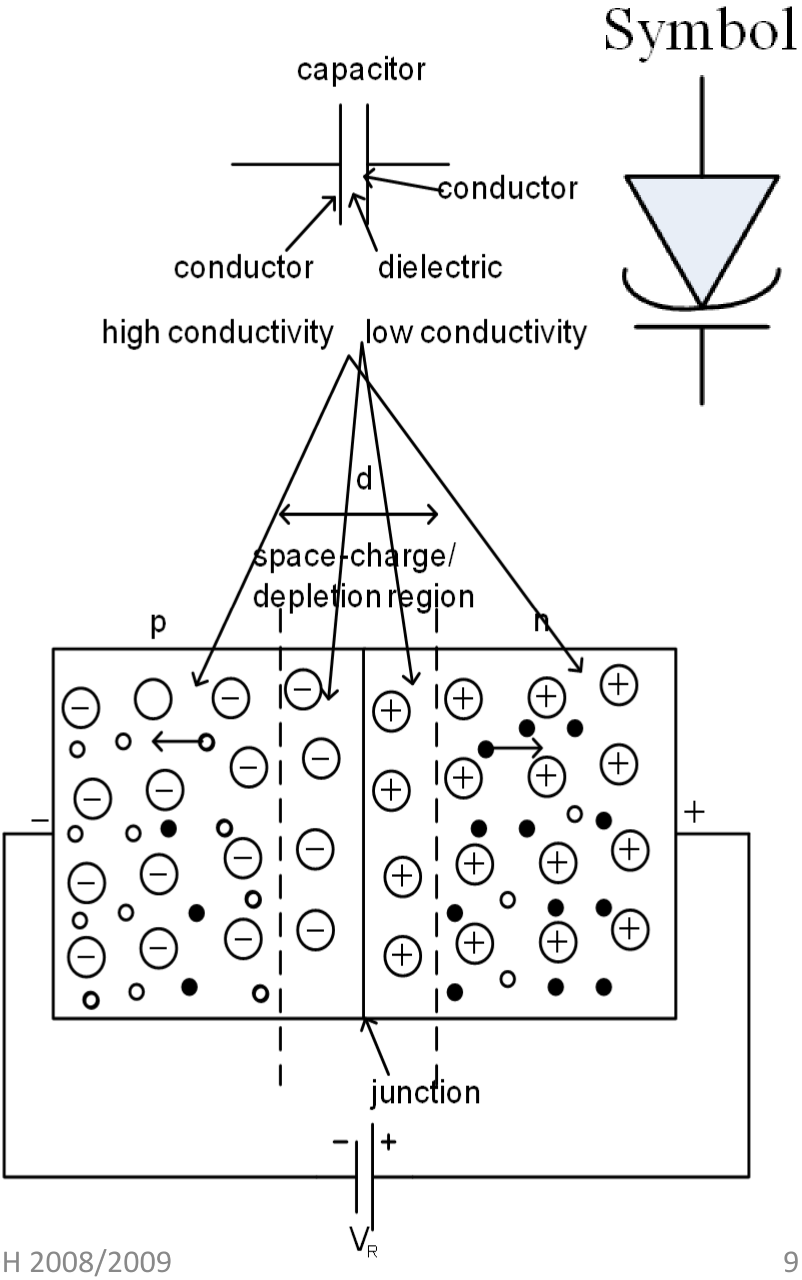






SPECIAL DIODES – (1) VARACTOR DIODE

- **Varactor is a variable capacitor.**
- **Varactor operates when it is rb.**
- **In the depletion region, conductivity is ↓ due to the depletion of majority carriers. The p and n have high conductivity due to the majority carriers. In a capacitor, the plets are conductors and dielectric is an insulator. Hence, a rb diode is similar to a capacitor.**
- **C = Aε/d where A=cross-section are, ε=dielectric constant and d=distance between 2 plates.**
- **V_R ↑, depletion region width ↑, d ↑, C ↓.**
- **Capacitance can be varied by changing the V_R.**



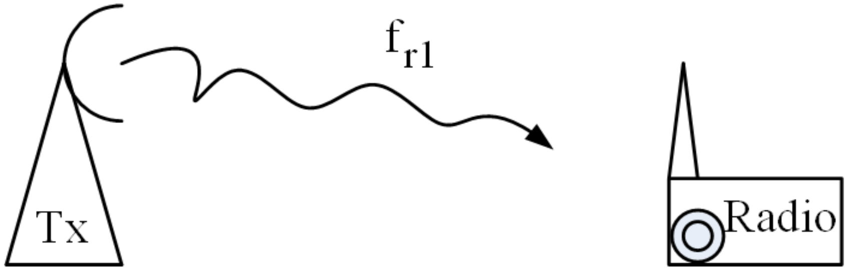
Application:

In a tuning circuit (such as the one in a radio), the voltage is varied and this changes the capacitance of the varactor diode.

Resonance frequency,

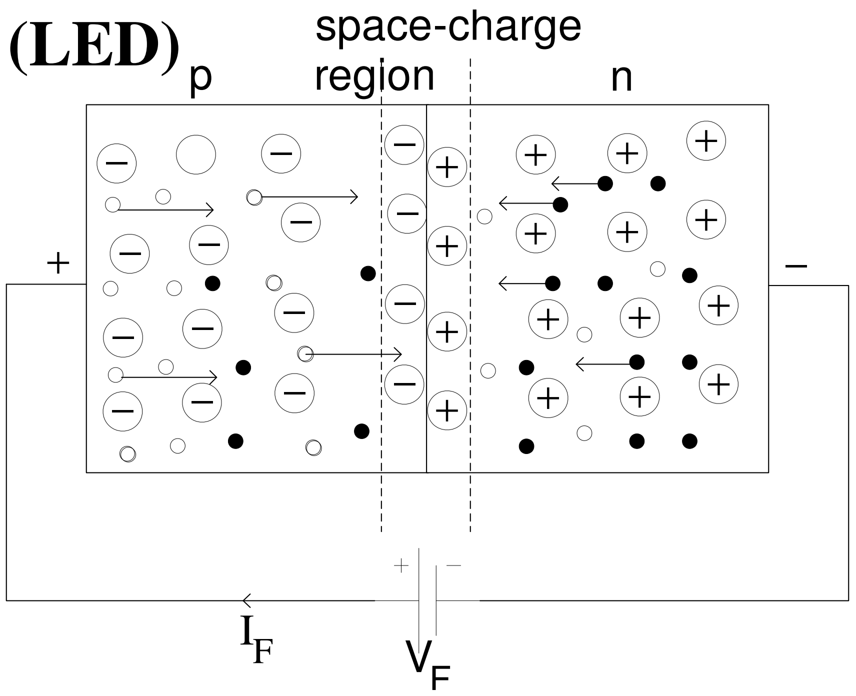
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

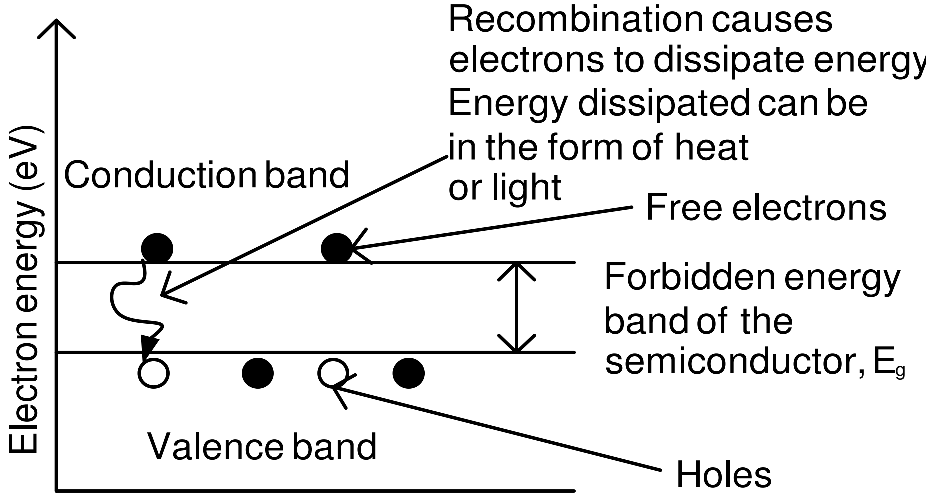
By changing the capacitance, the frequency is tuned towards the frequency of the desired channel, f_{r1}.



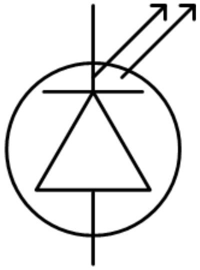
2. LIGHT EMITTING DIODE (LED)

- **In a fb diode, majority carriers cross the junction. When free electrons from n enter p, recombinations occur.**
- **In Si and Ge, the dissipated energy is in the form of heat.**
- **LEDs are made of GaAs, GaAsP and GaP which emit light when the electrons dissipate energy.**
- **Different dopant produces different light wavelength. Hence, the colour of the emitted light will be different.**





Symbol



Semiconductor material	Dopant	Light colour
Gallium Arsenide (GaAs)	Zinc, Si	Infra-red (cannot be seen by the human eyes)
Gallium Arsenide Phosphide (GaAsP)	Nitrogen	Orange, yellow and red
Gallium Phosphide (GaP)	Nitrogen (light doping) Nitrogen (heavy doping) Zn, O	Green Yellow Red

$V\uparrow I_F\uparrow$ emitted light ↑

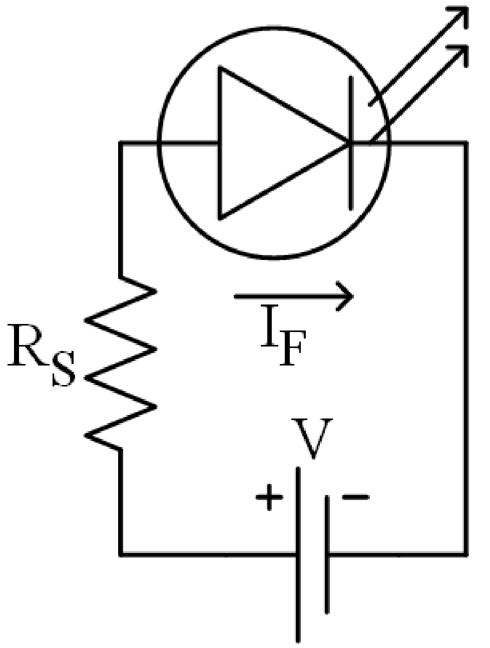
Applications

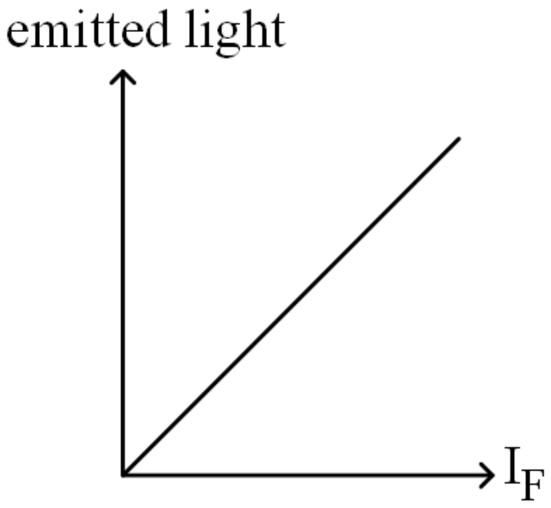
1. **LED with visible light.**

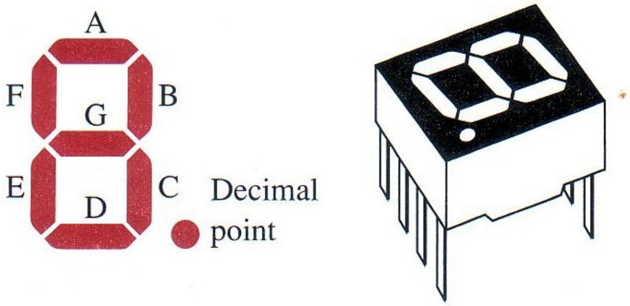
   Indicator lamps and readout displays. The most common is 7-segment display.

2. **LED with invisible light (infra-red).**

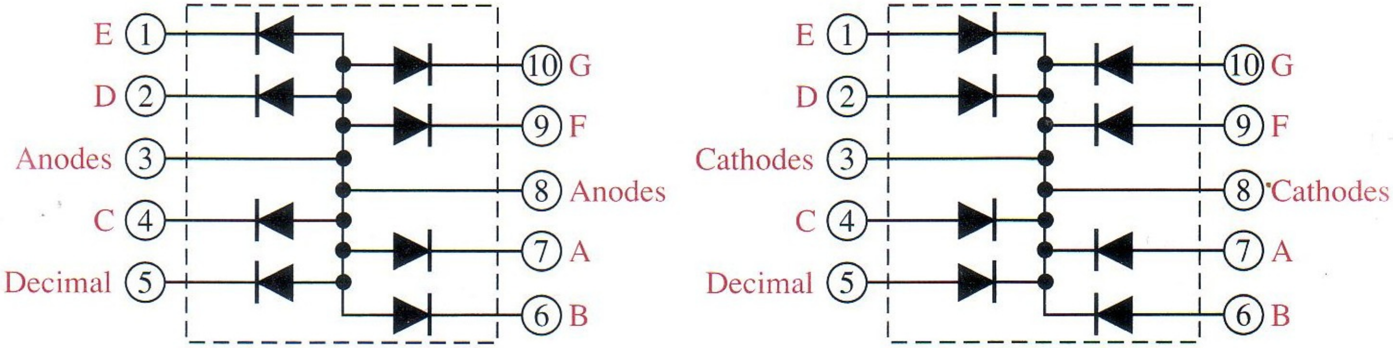
   Optical coupling applications, often in dealing with fiber optics.







(a) LED segment arrangement and typical device



(b) Common anode

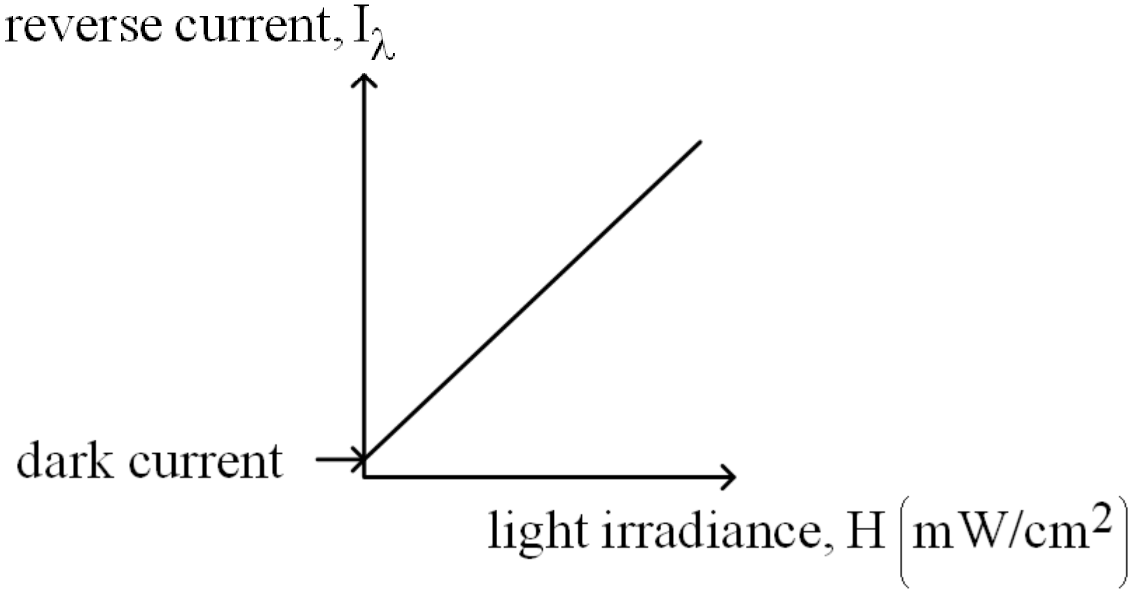
(c) Common cathode

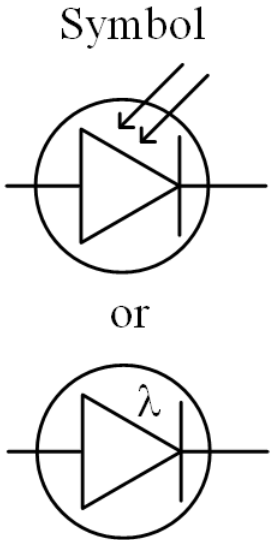
FIGURE 3–32

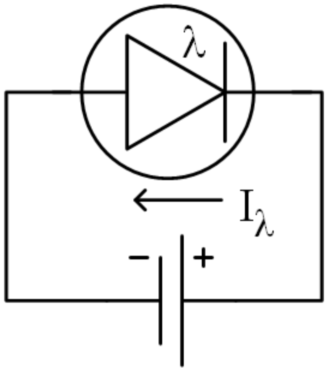
The 7-segment LED display.

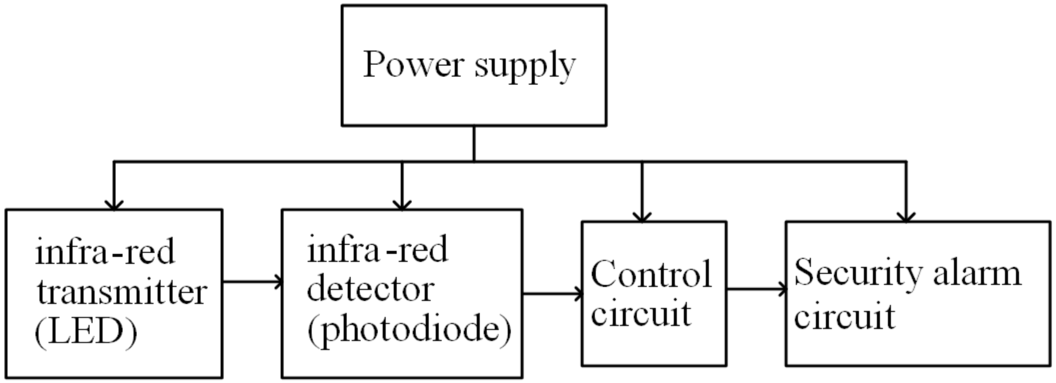
3. PHOTODIODE

The photodiode operates under rb condition. There is a small transparent window on the photodiode that allows light to strike the p-n junction. For the rectifying diode, when T↑ I_R↑. For the photodiode, when irradiance, H, ↑ I_λ↑.









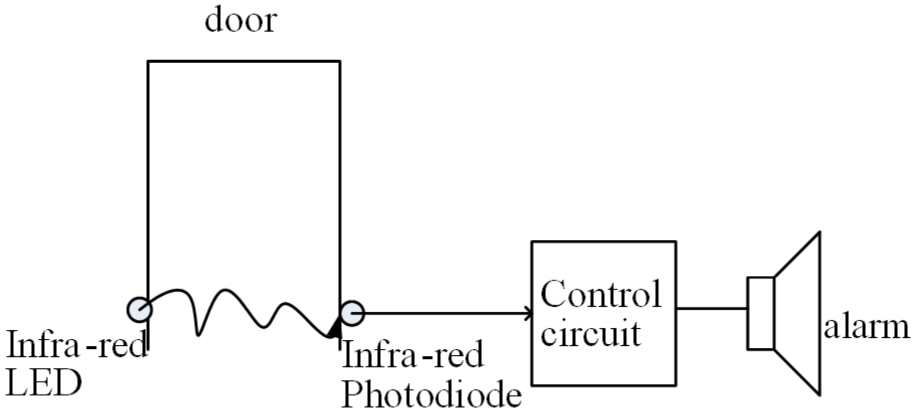
Application:

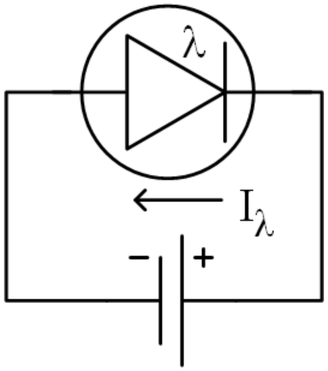
1. **In security alarm system – circuit containing both infra-red LED and photodiode.**
2. **Variable resistor**

   $R = V_R / I_\lambda$

   $H \uparrow I_\lambda \uparrow R \downarrow$

   Resistance can be changed by varying H.

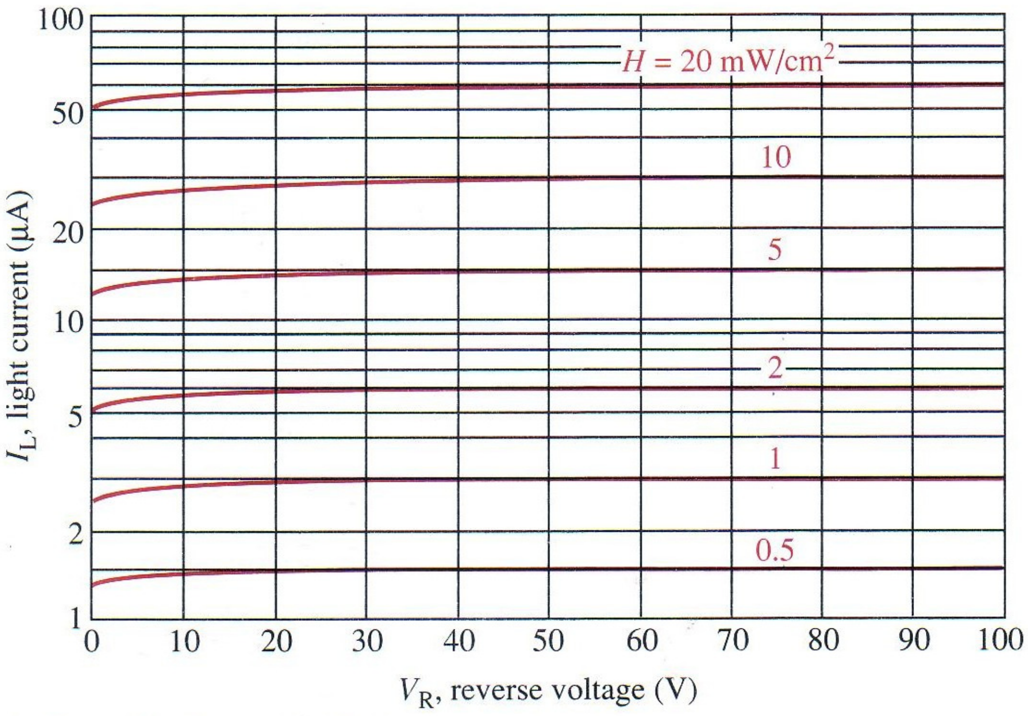




When V_R=10 V at H=0.5 mW/cm^2, I_L=0.9 µA. Hence, R=11 MΩ.

When V_R=10 V at H=20 mW/cm^2, I_L=55 µA. Hence, R=182 kΩ.

Hence, R can be changed when H is varied.

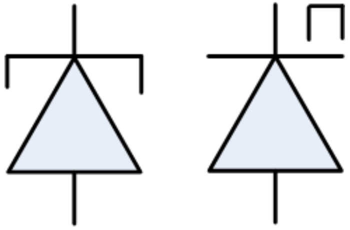


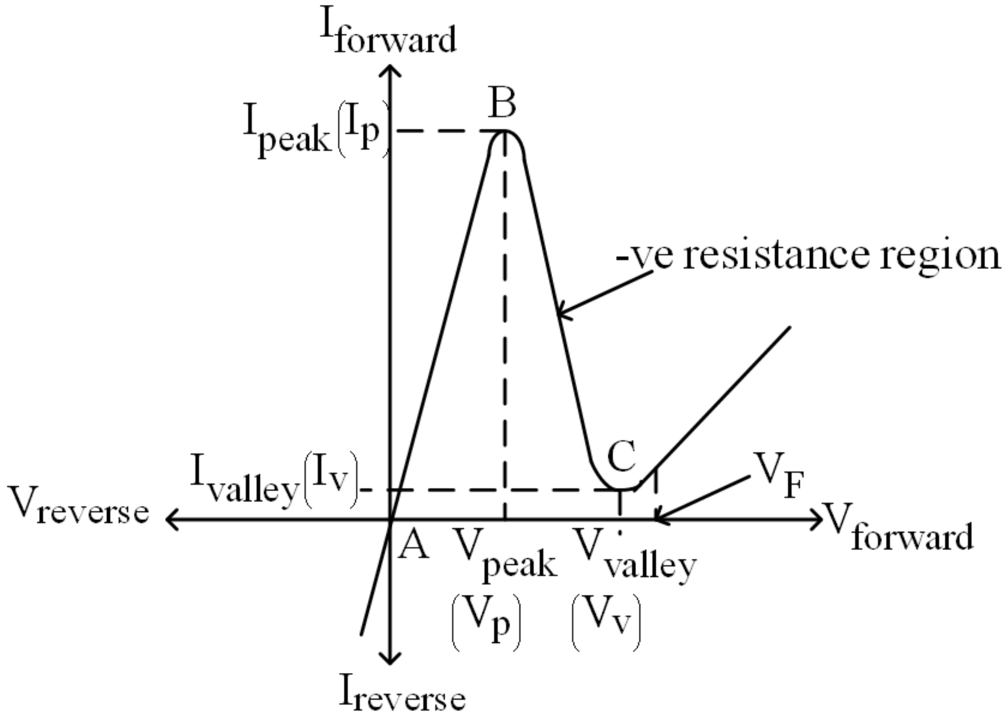
(b) Example of a graph of light current versus reverse voltage for several values of irradiance

4. Tunnel diode

- **Tunnel diodes are made of Ge or GaAs.**
- **Doping density is very high, i.e. $10^{25}/m^3$ or 1 impurity atom for every 10^4 semiconductor atoms. Depletion region is very narrow, electrons are able to tunnel to produce current.**
- **Tunnel diode is typically operated in its –ve resistance region. R = ΔV / ΔI = -ve**
- **Under its rb condition, an increment in the reverse voltage will increase the reverse current, i.e. $V_R \uparrow I_R \uparrow$**

Symbol





I-V characteristic

$E_F = E_C - kT\ln(N_C /N_D)$; N_C = conduction band energy level density

For light doping, $N_D < N_C$; $E_F < E_C$

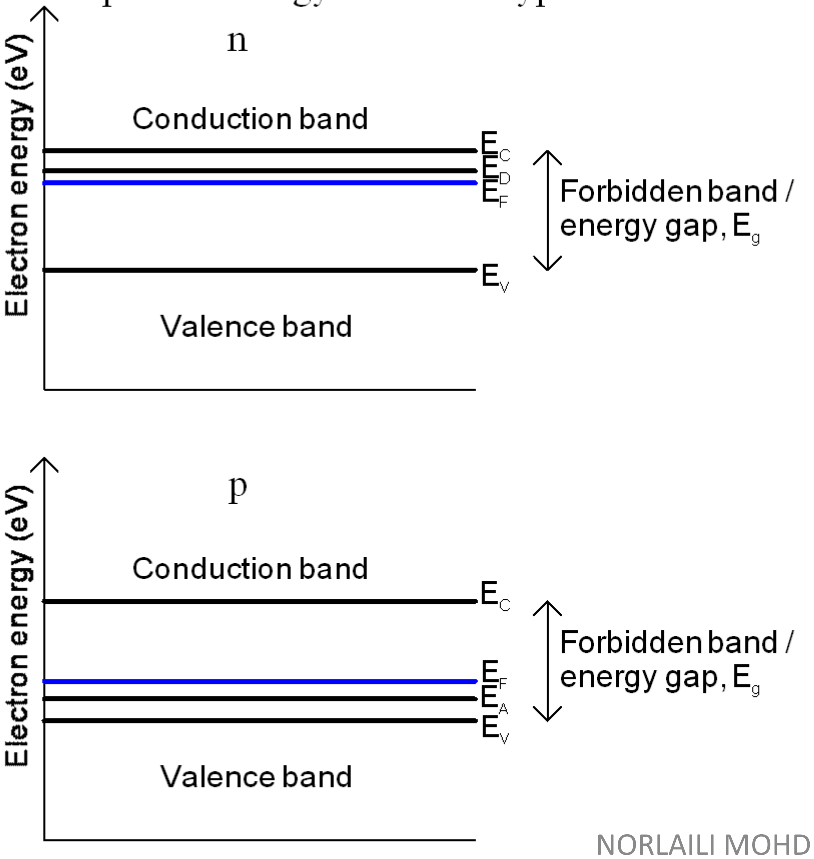
For heavy doping, $N_D > N_C$, $E_F > E_C$

$E_F = E_V + kT\ln(N_V /N_A)$; N_V = valence band energy level density

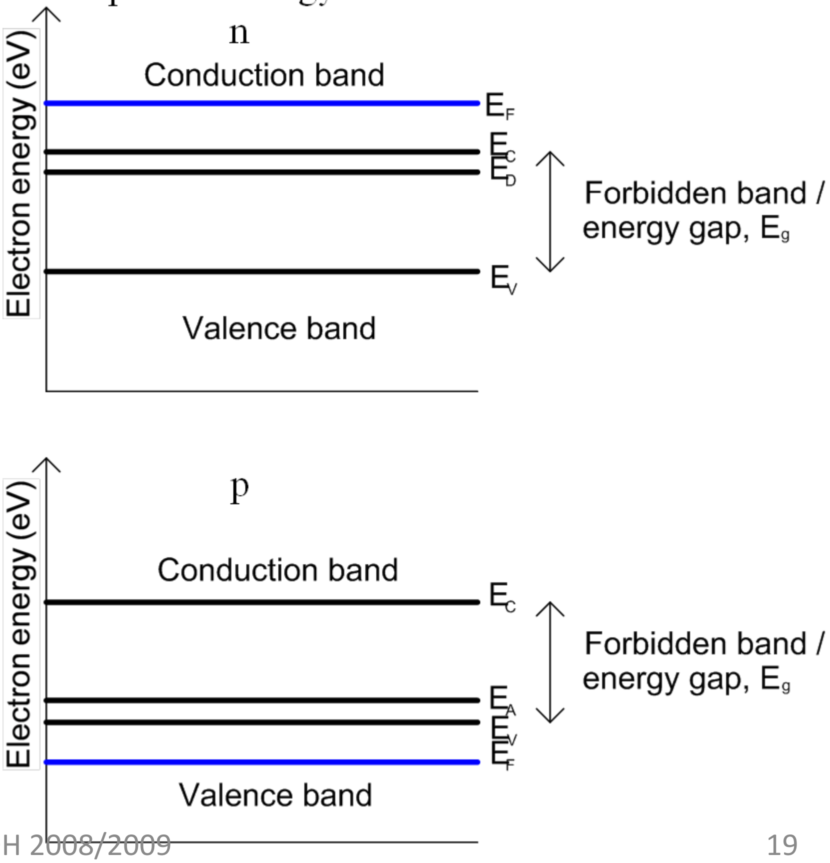
For light doping, $N_A < N_V$; $E_F > E_V$

For heavy doping, $N_A > N_V$, $E_F < E_V$

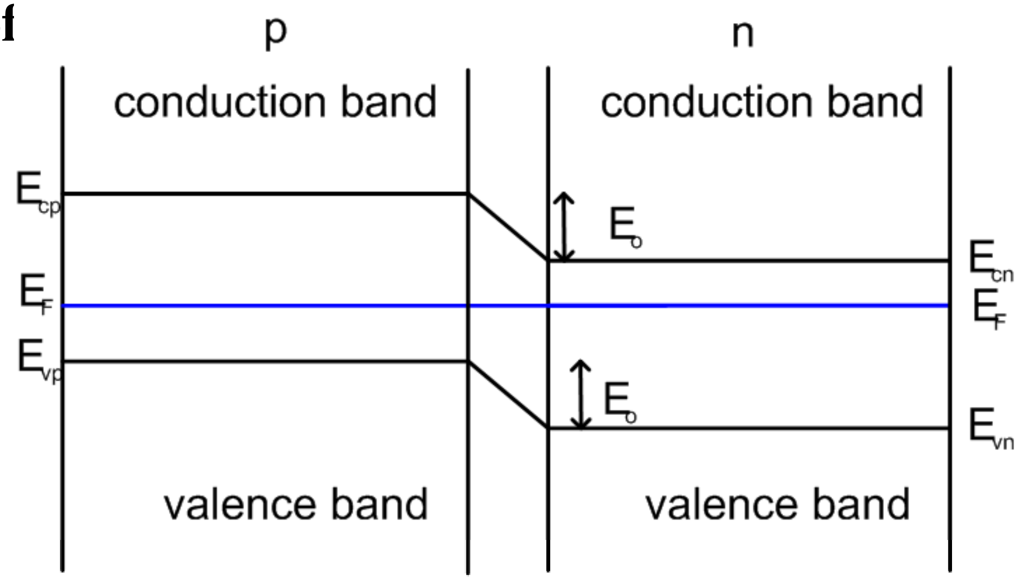
p and n energy levels in a typical diode



p and n energy levels in a tunnel diode

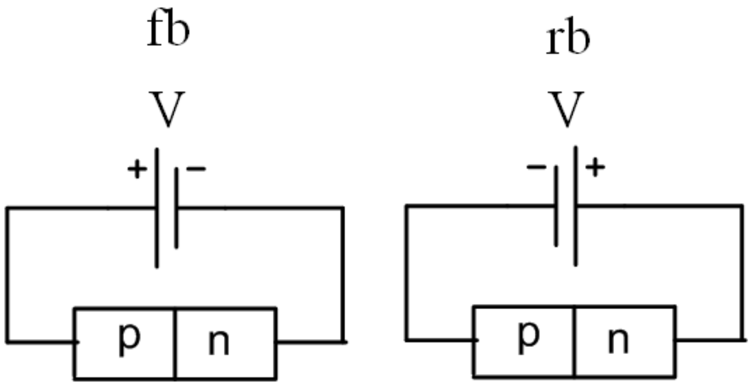


Unbiased p-n energy levels of a normal diode:

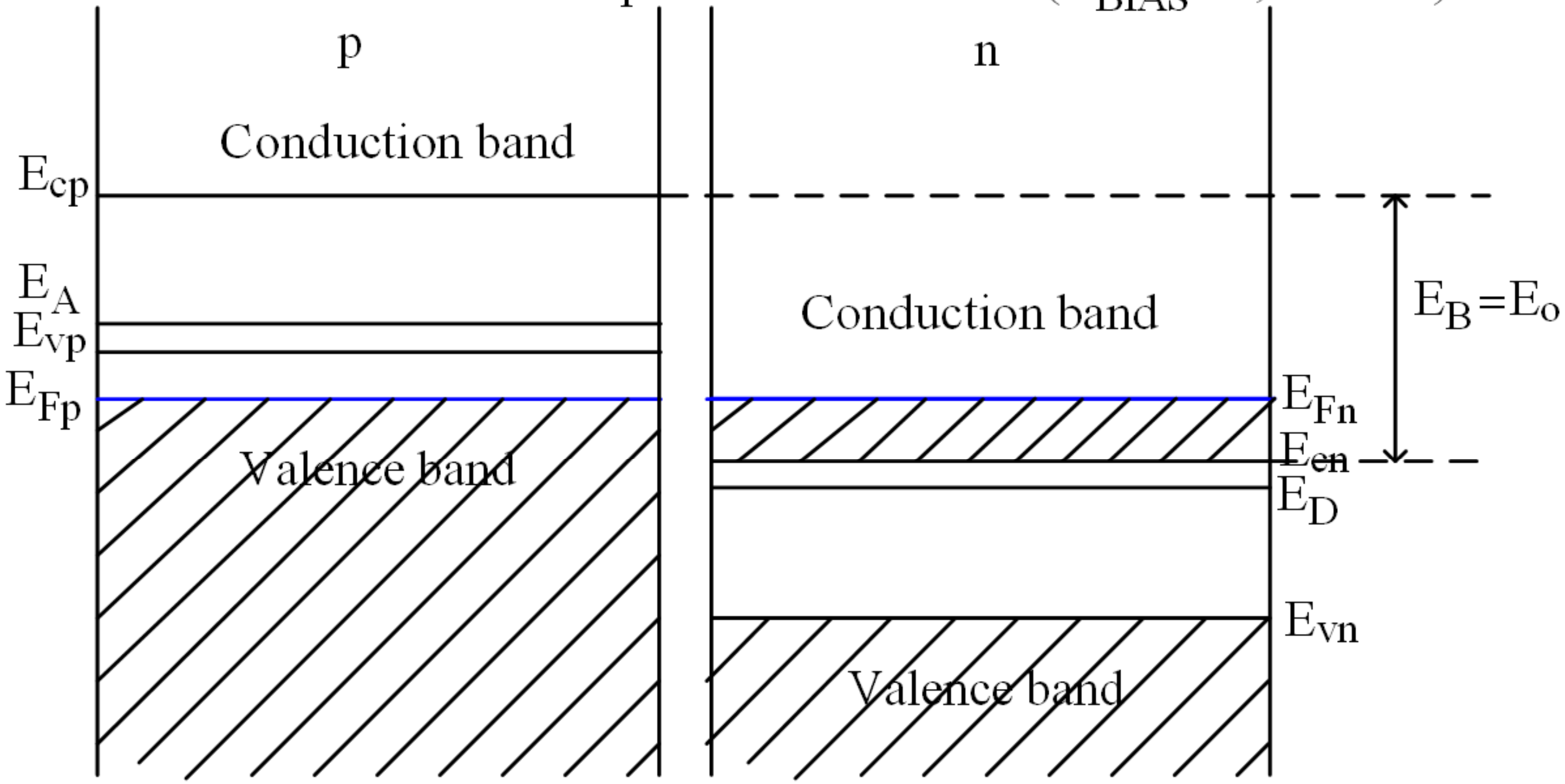


Under the condition of $V_{BIAS} < V_{BARRIER}$;
when diode is fb ($V_{BIAS} = V$) and V ↑ $V_{BARRIER}$ ↓
when diode is rb ($V_{BIAS} = -V$) V ↑ $V_{BARRIER}$ ↑

$$E_o = \text{level shift}$$
$$E_o = eV_o$$
$$V_{BARRIER} = V_o - V_{BIAS}$$



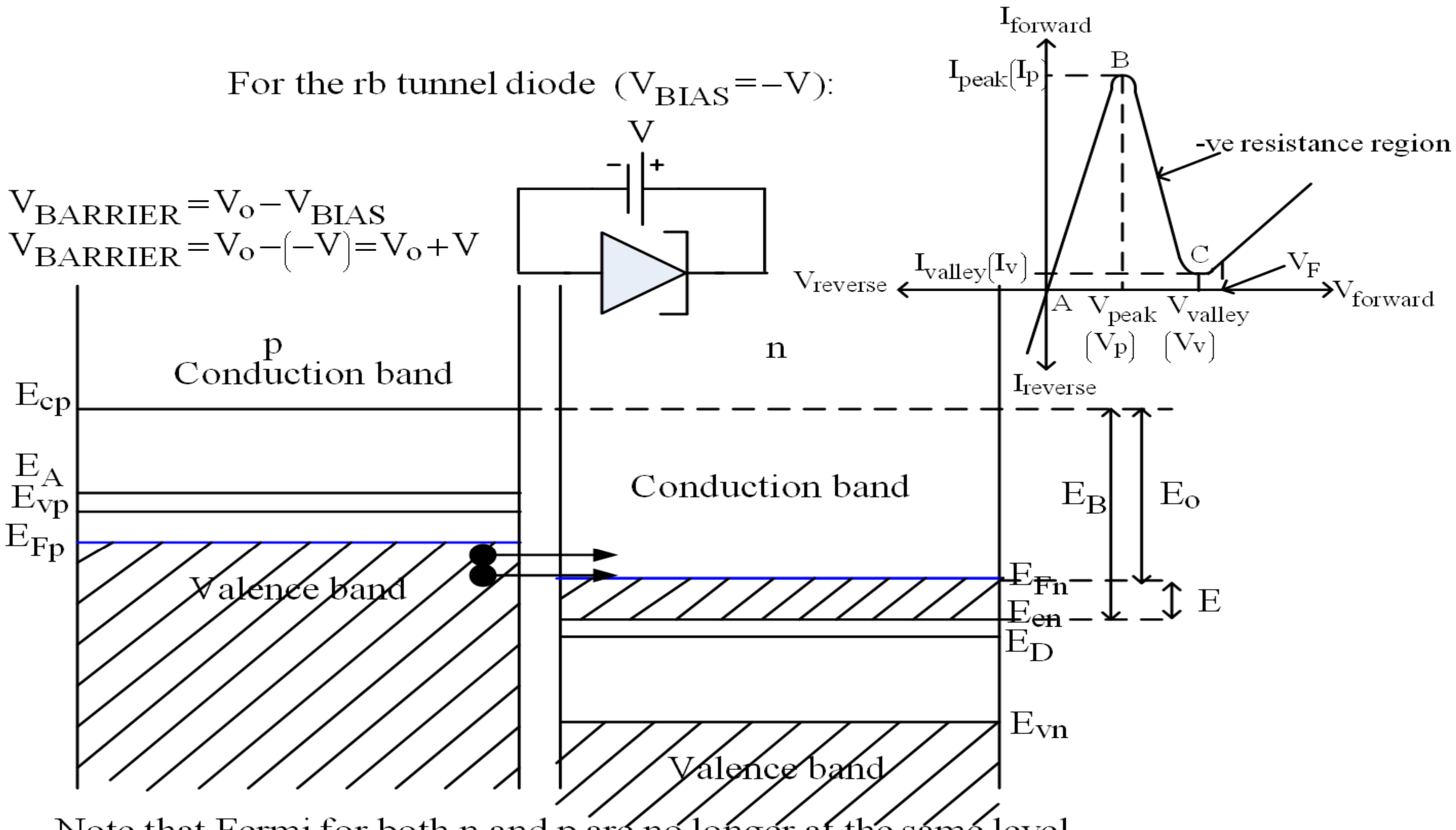
For the tunnel diode under equilibrium condition (V_{BIAS} =0, T =0°K):



Note that Fermi for both n and p are at the same level

For the rb tunnel diode ($V_{BIAS}=-V$):

$$V_{BARRIER}=V_o-V_{BIAS}$$
$$V_{BARRIER}=V_o-(-V)=V_o+V$$

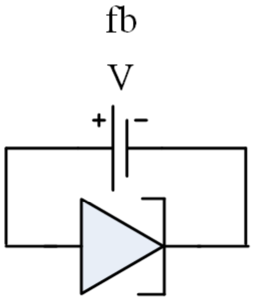


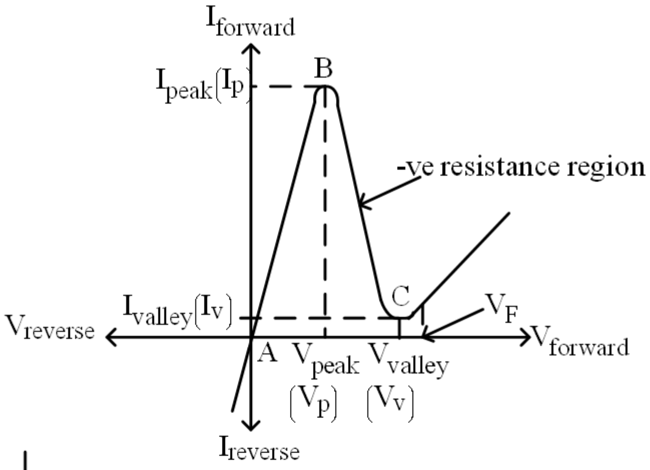
Note that Fermi for both n and p are no longer at the same level.
Electrons from p can tunnel into n.
Tunneling can only happen at the same energy level.
$V\uparrow I_R\uparrow V_{BARRIER}\uparrow$ Hence, more difficult for the electrons in n (majority carriers) to diffuse to p.

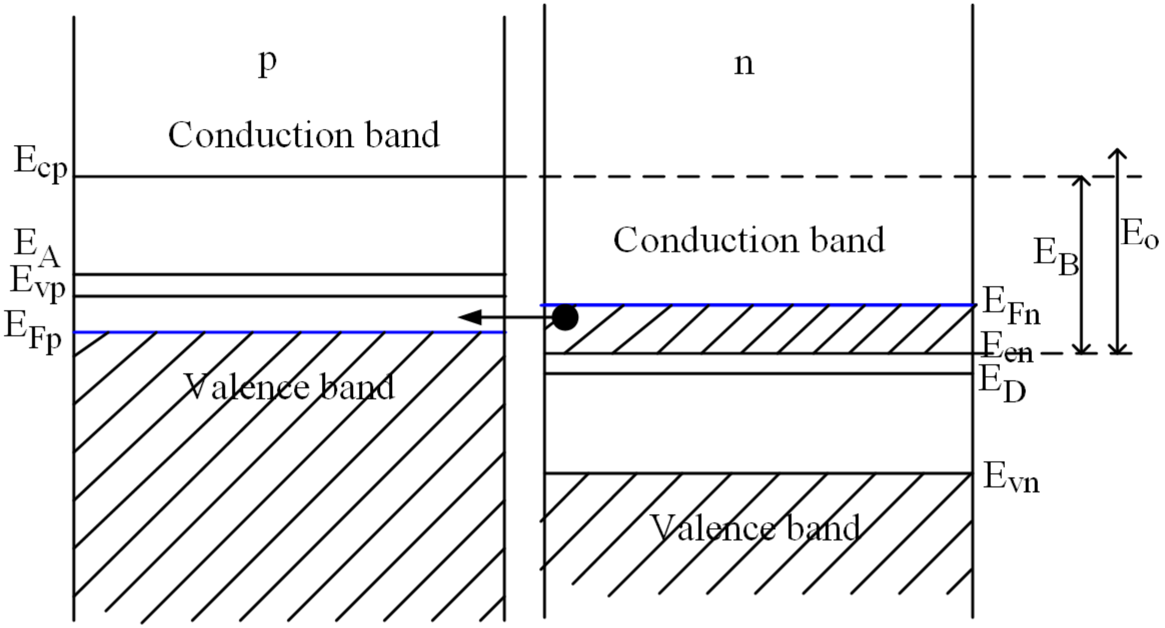
For the fb tunnel diode ($V_{BIAS} = +V$, $V < V_o$):

$$V_{BARRIER} = V_o - V_{BIAS}$$

$$V_{BARRIER} = V_o - V$$

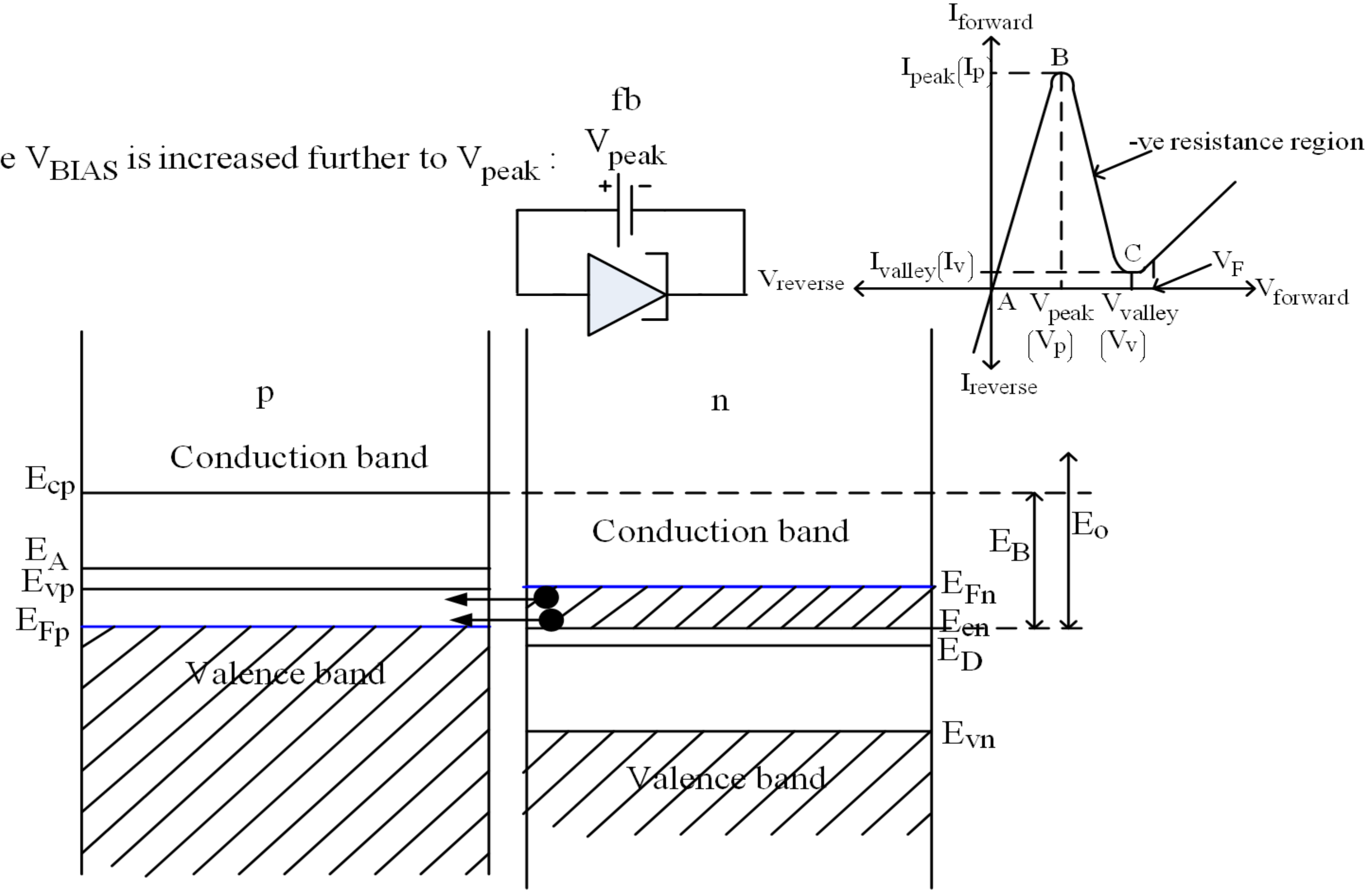






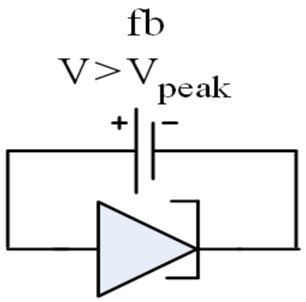
Note that Fermi for both n and p are no longer at the same level.
Electrons from n can tunnel into p.
Tunneling can only happen on the same energy level.
$V\uparrow V_{BARRIER}\downarrow I_F\uparrow$ (Condition $A \rightarrow B$)

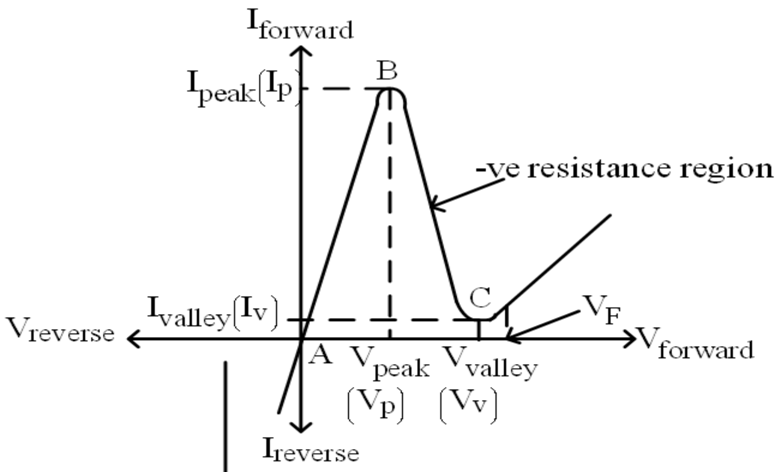
If the V_{BIAS} is increased further to V_{peak} :

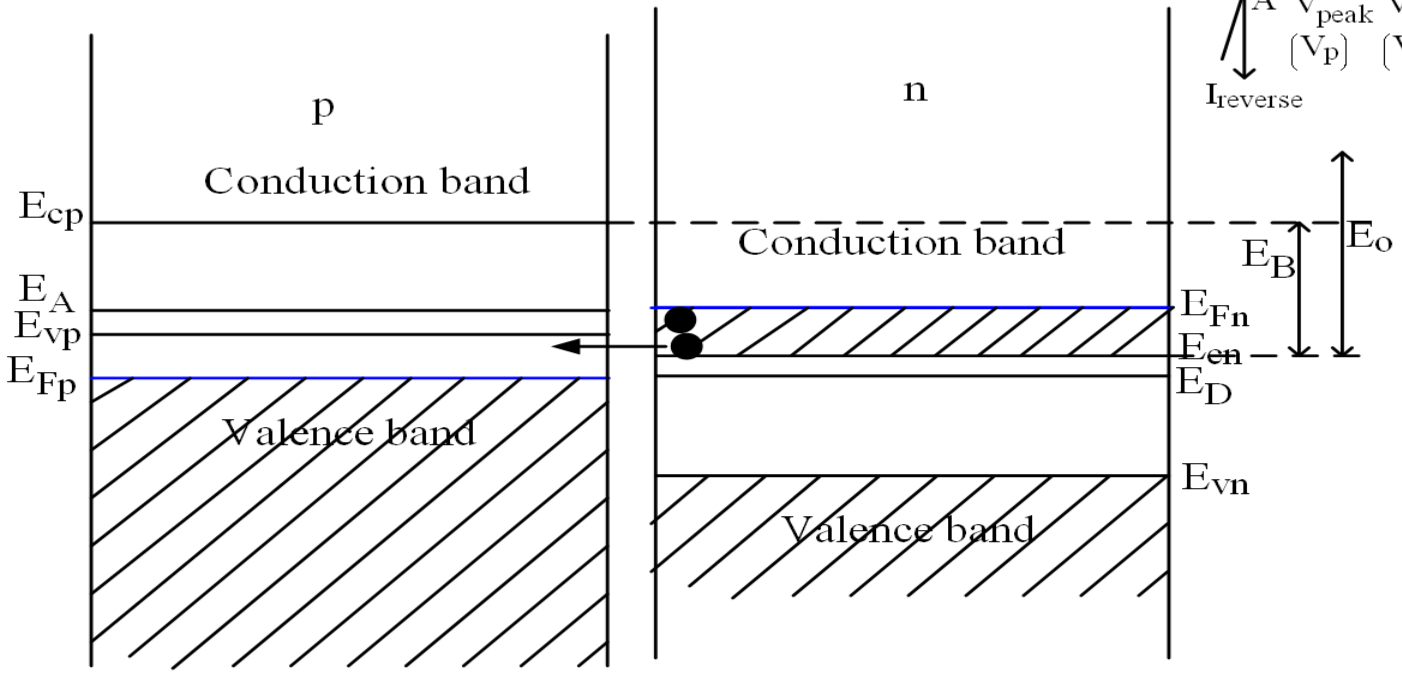


The number of electrons that can tunnel through the depletion region is at its maximum. Almost all of the electrons in the E_{cn} to E_{Fn} range can tunnel. At this time, $I = I_{max} = I_p$(Condition B).

If the $V_{BIAS} > V_{peak}$:



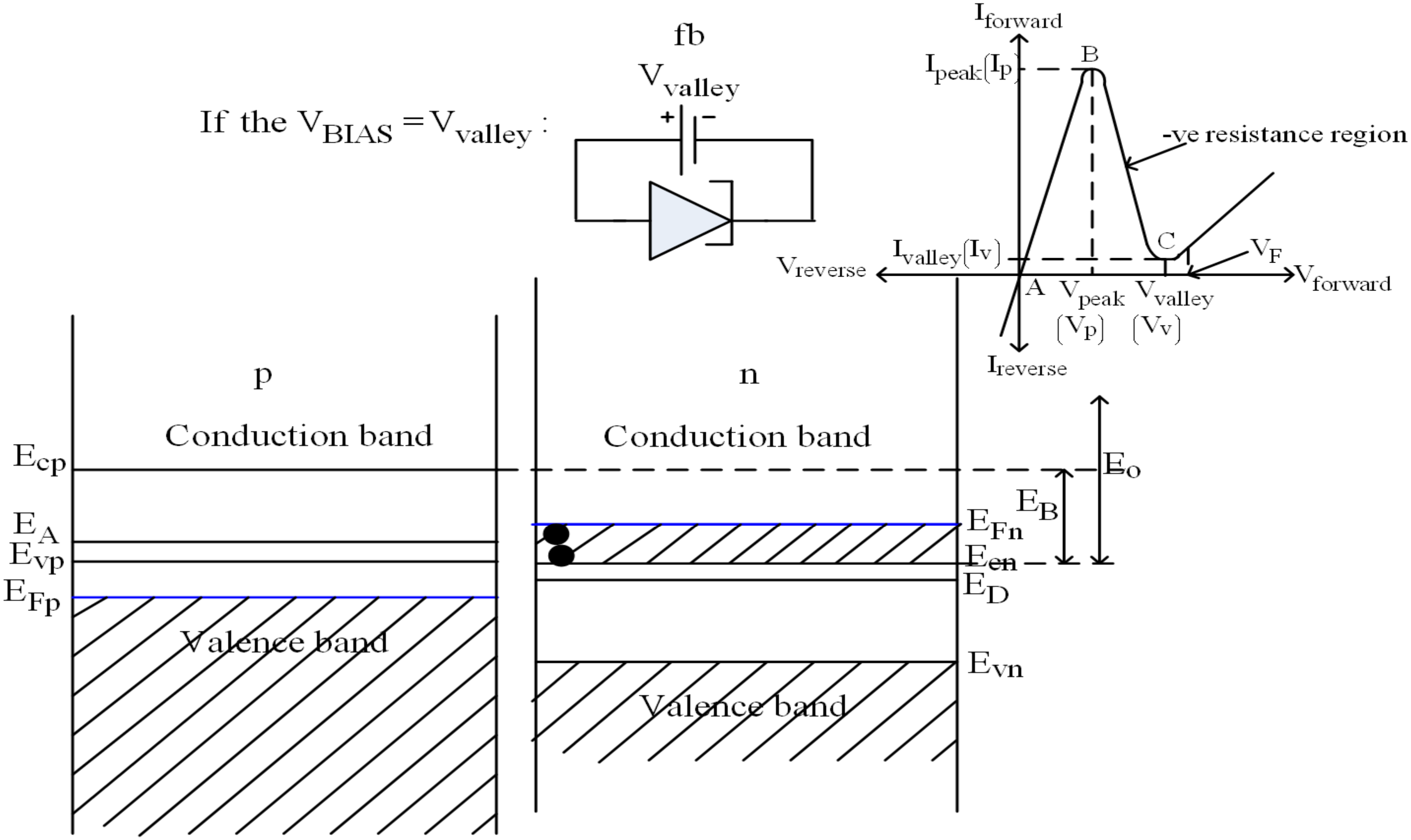




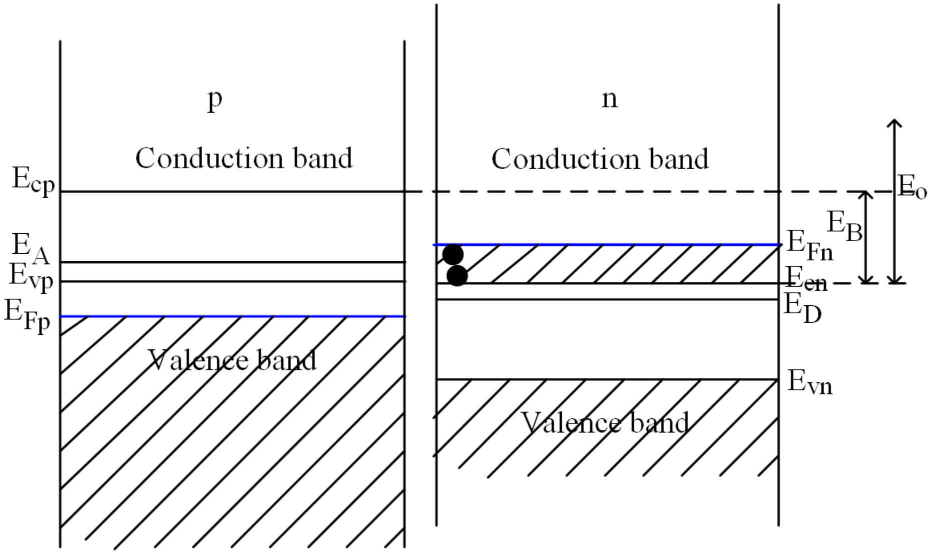
The number of electrons that can tunnel through the depletion region is now less than when $V = V_{peak}$. At this time, $I < I_p$(Condition B→C, −ve resistance region).

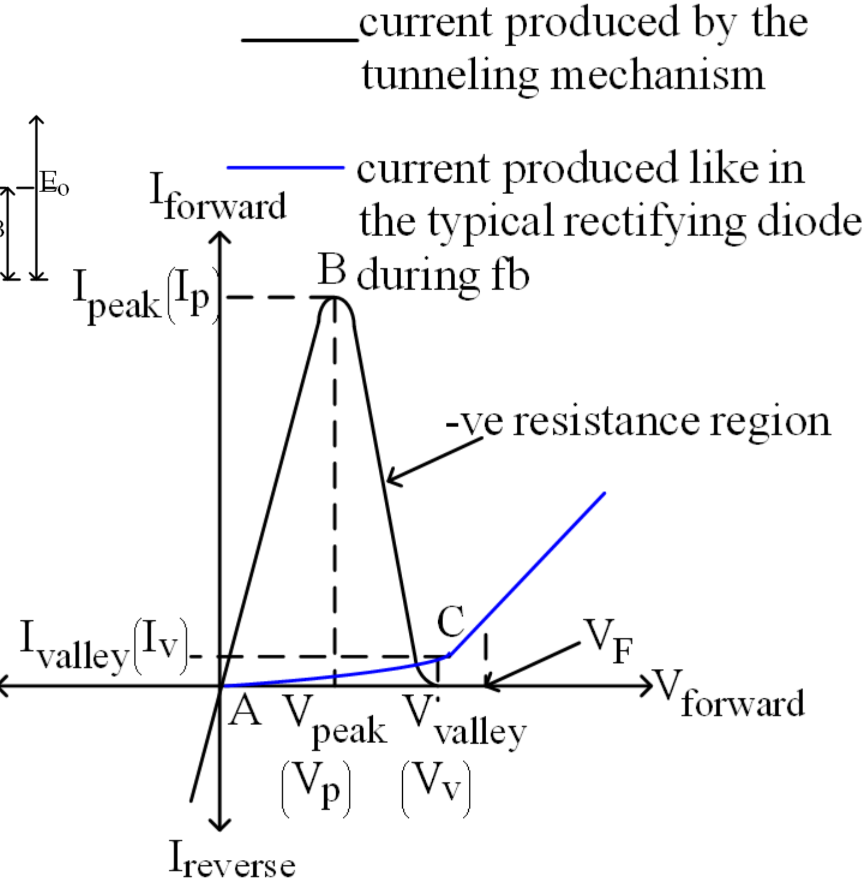
$V_{forward}\uparrow I_{forward}\downarrow$

If the $V_{BIAS} = V_{valley}$:

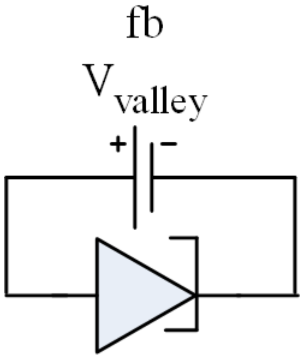


No more electrons that can tunnel through the depletion region as the electrons from E_{cn} to E_{Fn} are now at the same levels as the energy levels in the forbidden band of the p. $I_{tunnel} = 0$. (Condition C)





At V=V_{valley} , I produced by the tunneling mechanism is 0. However, there is the current produced by the electrons in the conductance band of n (majority carriers) that are able to overcome the potential barrier and cross the junction to enter the conduction band of p. At this time, I=I_{valley}



I_p = 50 µA → 5 A

I_p / I_v = 5 → 15

For Ge:

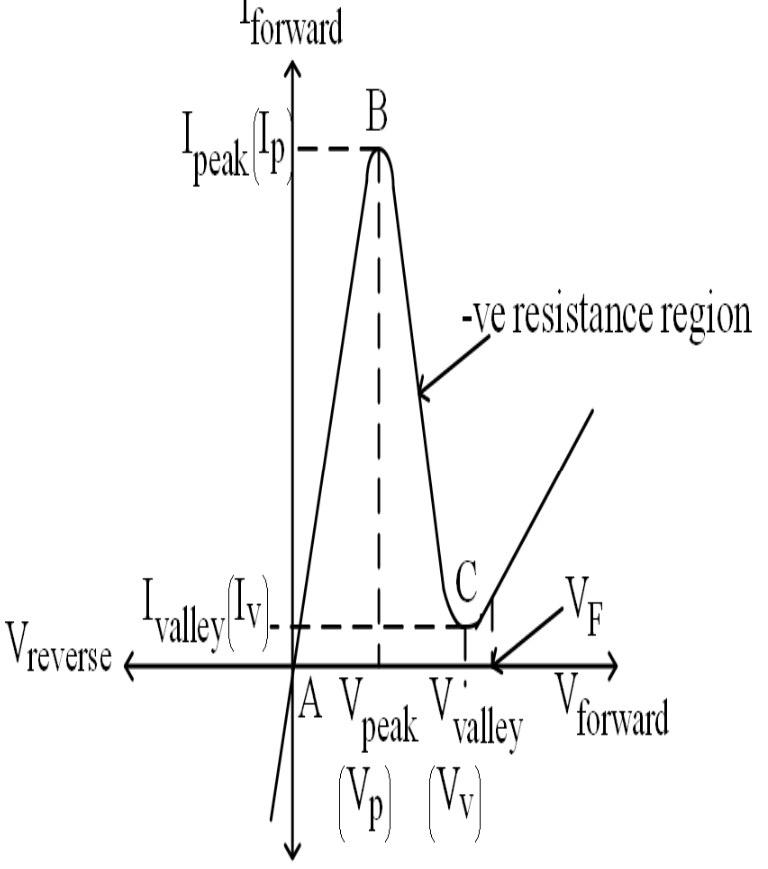
V_p = 0.055 V

V_v = 0.32 V

V_F = 0.48 V

Under the fb condition (A→B), the narrow depletion region enables the electrons from the n (majority carriers) to tunnel across the junction and enter p. Current flows in the diode and $V_{forward} \uparrow I_{forward} \uparrow$. From B→C, there is a constraint towards the flow of current and $V_{forward} \uparrow I_{forward} \downarrow$.

After C, the tunnel diode operates like a normal rectifying diode.

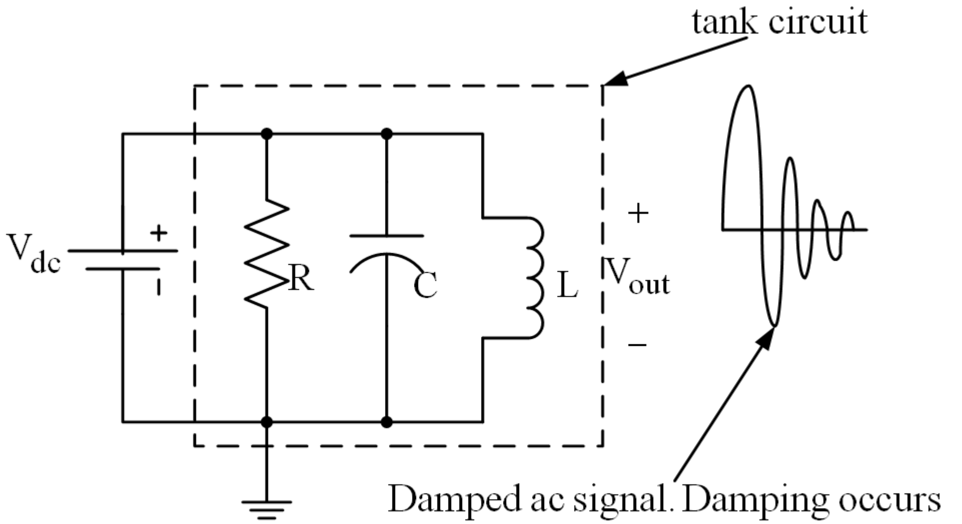


I-V characteristic of the tunnel diode

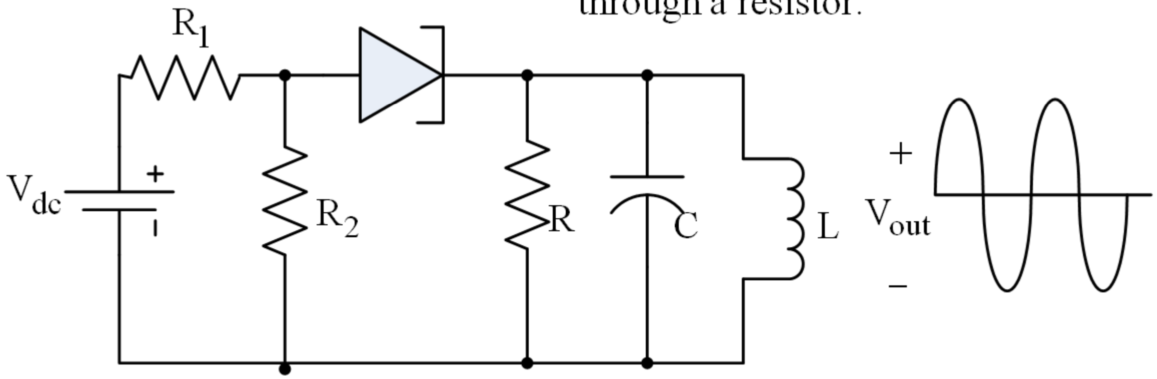
Tunnel diode application:

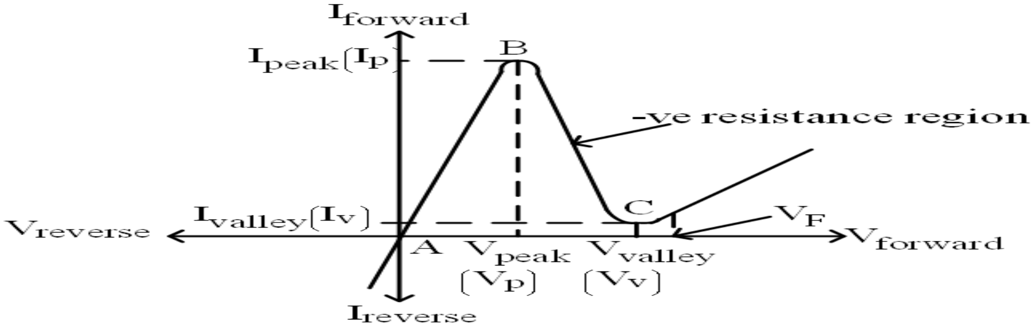
Tunnel diodes are used in oscillators (i.e. in parallel resonant circuits). Oscillator circuits are normally found in function generator. The –ve resistance characteristic of the tunnel diode cancels of the +ve resistance characteristic of the tank circuit.

The biasing voltage for the tunnel diode should be between V_p to V_v to obtain the –ve resistance effect.



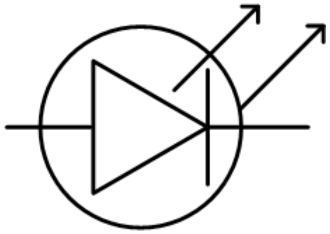
Damped ac signal. Damping occurs when energy is lost as current flows through a resistor.





LASER - Light Amplification by Stimulated Emission of Radiation

Symbol



- LED – emits incoherent light; has many wavelengths, λ
- LASER – emits monochromatic/coherent light (a single λ) ; the generated light waveforms are in phase, with the same energy level and at the same frequency (hence, a single colour). The light emitted is of high intensity.
- LASER will emit monochromatic light when the current, I, is above a threshold value, $I_{threshold}$. If $I < I_{threshold}$, the LASER operates as an LED. Every LASER is an LED if $I < I_{threshold}$ but an LED is not a LASER.
- LASER operates when it is fb.
- LASER is made of GaAs.
- <u>Application</u> of LASER diode - in compact disc (CD) players.

In the region near the junction, recombinations occur.

Bohr's atomic theory:

$\Delta E = E_2 - E_1$

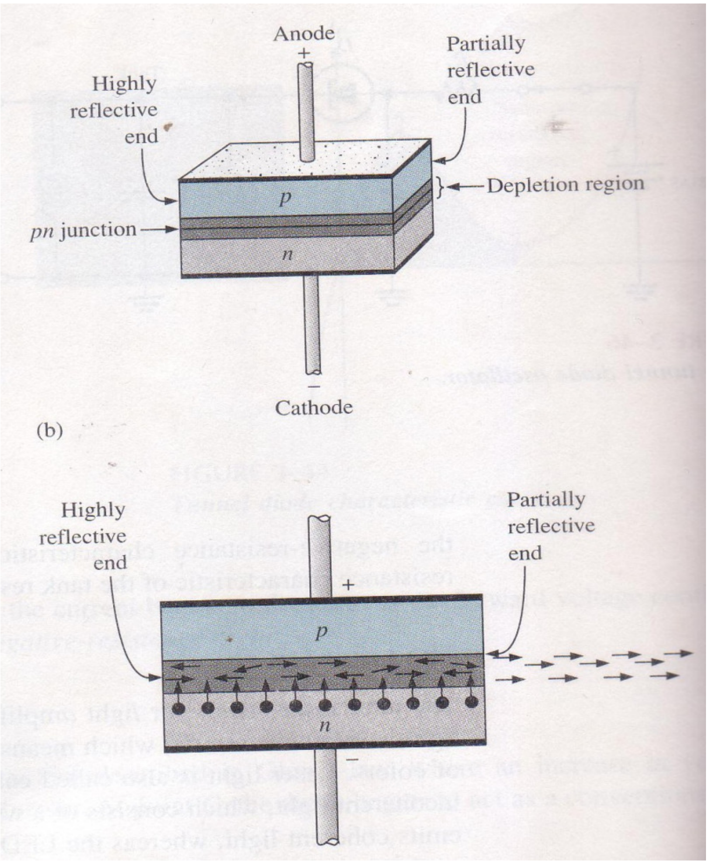
Light frequency, $f = (E_2 - E_1)/ h$

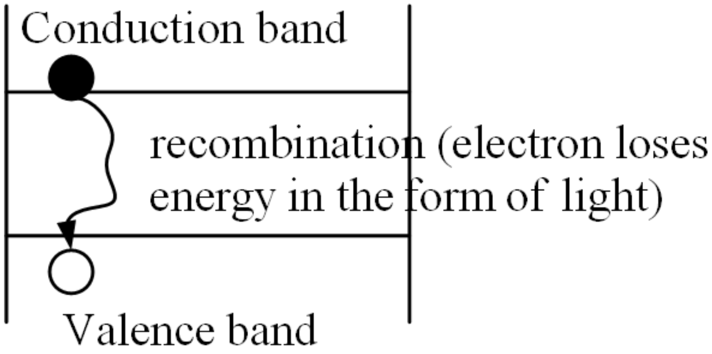
where h **= Planck's constant**

$= 6.63 \times 10^{-34}$ **Js**

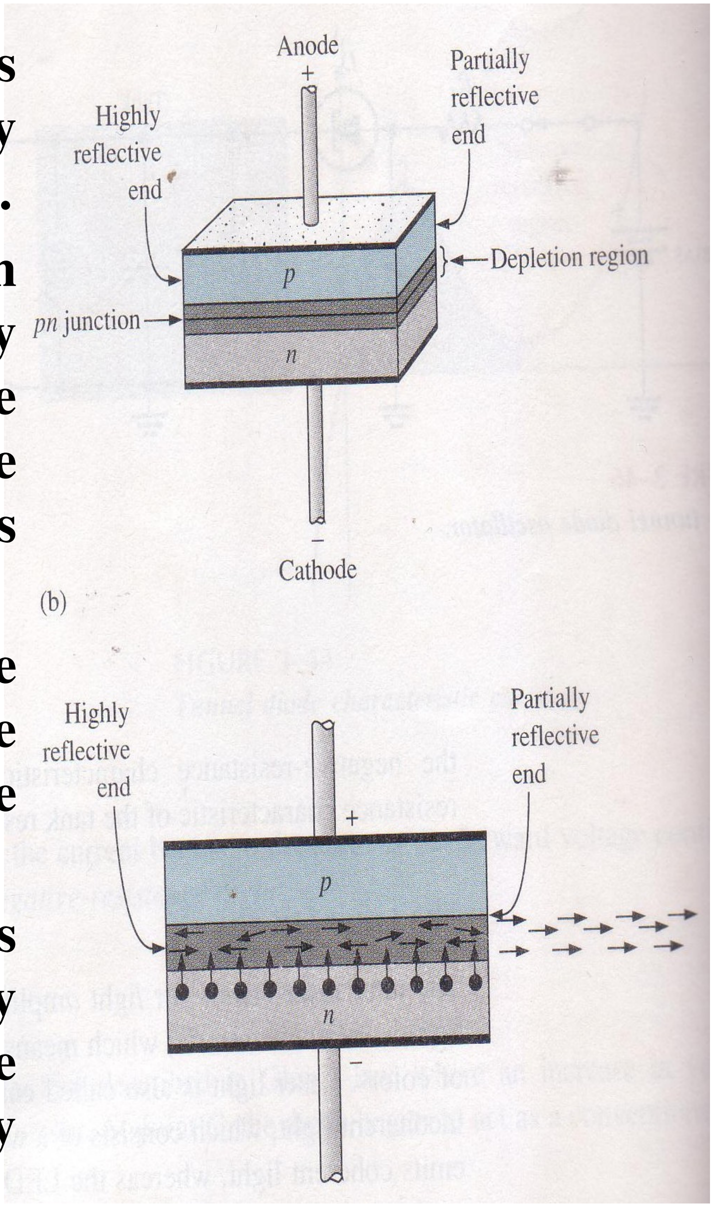
Energy is radiated in one light photon; photon $= E_2 - E_1 = fh$

Light wavelength, λ, is dependent on the length of the junction.



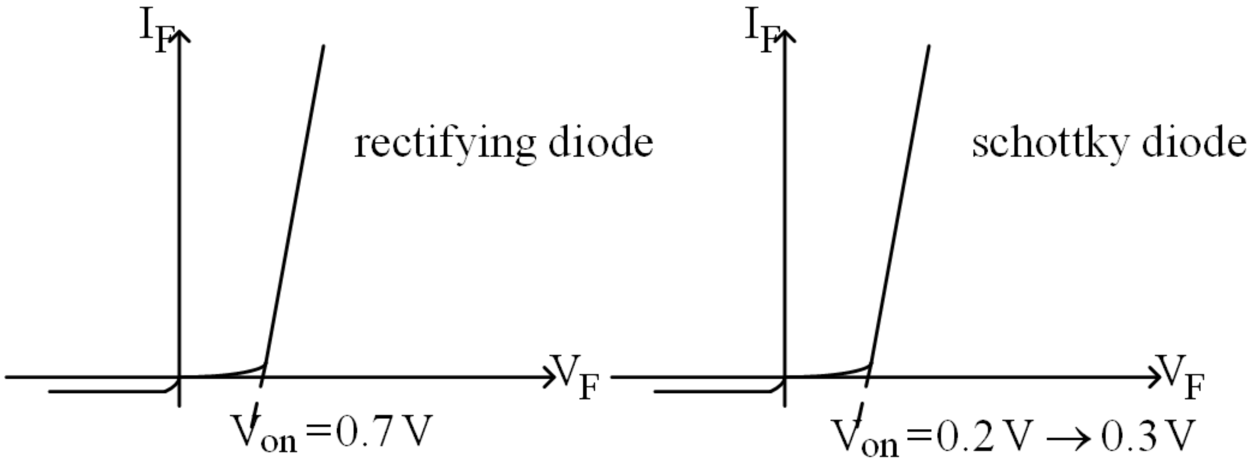


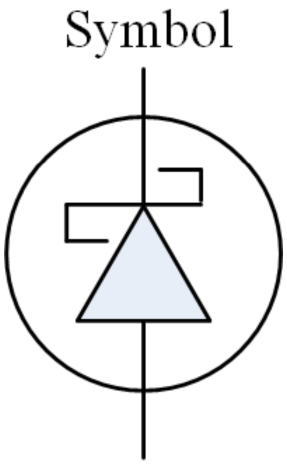
- **When $V_F \uparrow$, $I_F \uparrow$ as many majority carriers move across the junction. Many recombinations occur. Many photons released.**
- **Photons drift randomly in the depletion region and some will collide with the highly reflective surface perpendicularly. These photons will be reflected and move along the depletion region, colliding with other atoms and consequently generating more photons.**
- **These photons will then collide perpendicularly with the partially reflective surface and some will be reflected back to the highly reflective end. The process repeats.**
- **This back-and-forth movement of the photons will produce photons snowballs until a very intense beam of laser light is formed by the photons that pass through the partially reflective end of the p-n junction.**

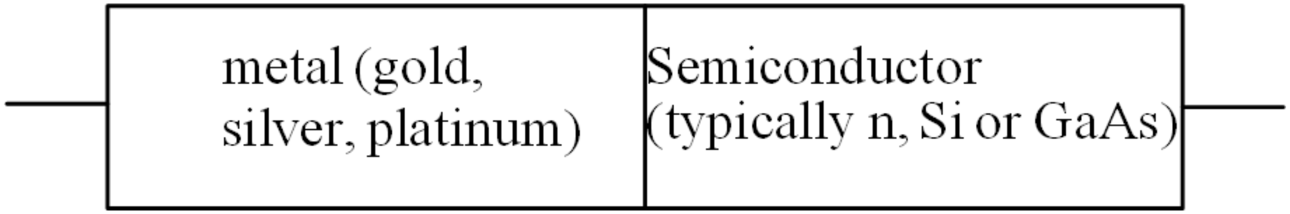


SCHOTTKY DIODE

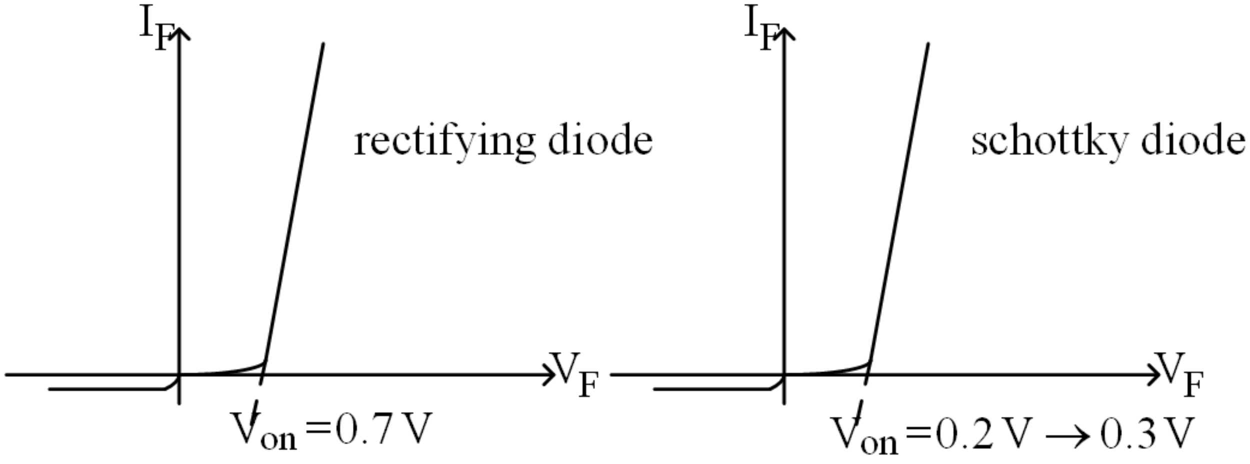
- **The Schottky diode is also known as the ‘hot-carrier’ diode.**
- **The operation is during fb.**
- **Reverse current in a rectifying diode is generated by minority carriers.**
- **Reverse current in a Schottky diode is generated by electrons.**

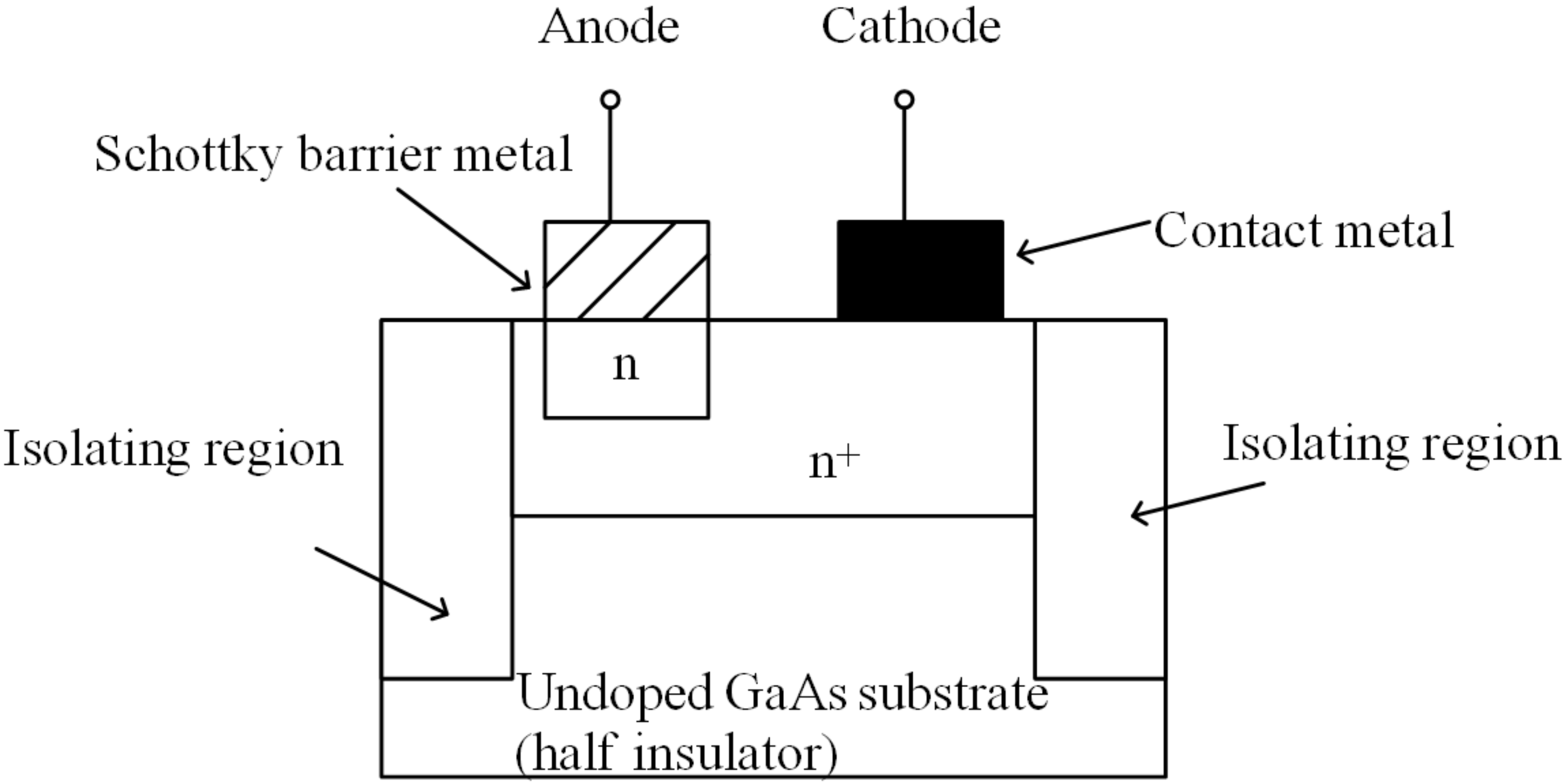






- **Schottky diode is easier to ON (smaller V_{on}). Switching rate is faster. As a result, propagation delay is reduced.**
- **Application: circuit with high frequency of operation.**





Cross-section of the Schottky diode

n^+ has a higher doping rate than n.
The n^+–n–Schottky barrier metal
is to reduce the series parasitic
resistance. Conductivity is increased.

- **Holes do not take part in current generation. Current is produced by the majority carriers only.**
- **As the electrons are the only current carriers, the response is fast towards any biasing voltage. This is because the mobility of the electrons > than the mobility of the holes. As an example, under equilibrium condition, μ_n = 1300 cm^2/Vs and μ_p = 500 cm^2/Vs for the Si.**
- **Electrons in the semiconductor are more energetic than the electrons in the metal as their kinetic energy is higher. This is the reason why the semiconductor's electrons are called 'hot carriers'. Hence, the Schottky diodes are also known as the 'hot carrier diode'.**
- **Under the fb condition, electrons from the semiconductor will cross the junction and flow into the metal. I↑.**
- **Under the rb condition, electrons from the metal will cross the junction and enter the semiconductor. I↓↓.**