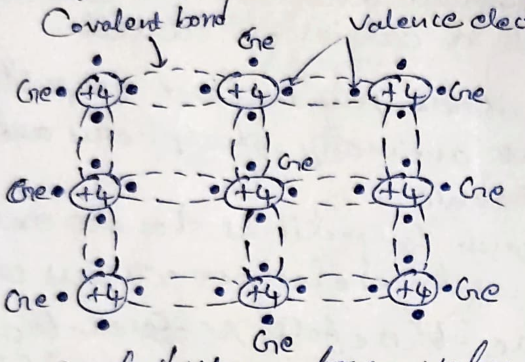
UNIT- I

PN JUNCTION DIODE, RECTIFIERS [redacted]

Qualitative Theory of p-n Junction

→ Germanium and Silicon are the two most important semiconductors used in electronic devices.

→ The crystal structure of these materials consists of a regular repetition in three dimensions of a unit cell having the form of tetrahedron with an atom at each vertex.



→ Germanium has a total of 32 electrons in its atomic structure, arranged in shells as $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$

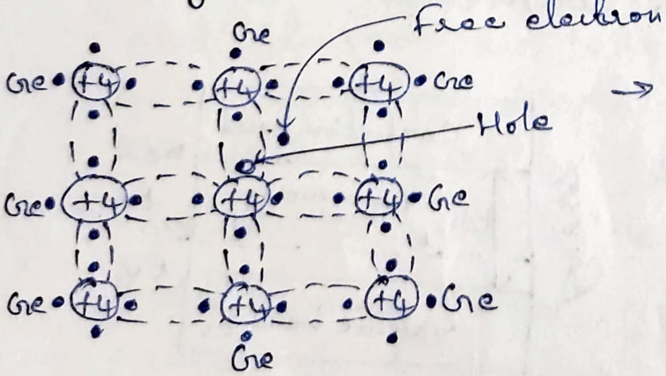
→ Each atom in a germanium crystal contributes four valence electrons, so the atom is tetravalent.

→ The inert ionic core of germanium atom carries a positive charge of +4 measured in units of electronic charge

→ The binding forces between neighbouring atoms result from the valence electrons of a germanium that is shared by one of its four nearest neighbours.

→ At a very low temperature (at 0°K), the crystal behaves as an insulator, since no free carriers of electricity are available.

→ At room temperature, some of the covalent bonds will be broken because of thermal energy supplied to crystal, and conduction is made possible.

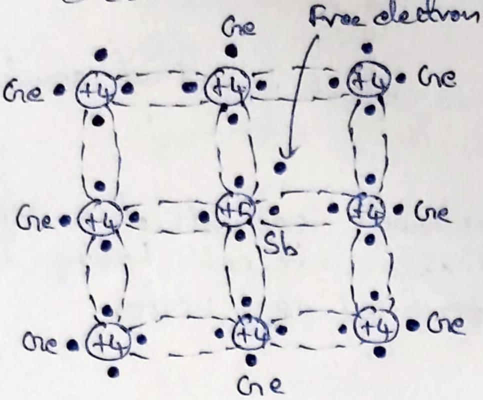


→ The energy E_G required to break such a covalent bond is about 0.72 eV for germanium & 1.1eV for silicon at room temperature

→ The absence of the electron in the covalent bond is represented by a small circle is called a hole.

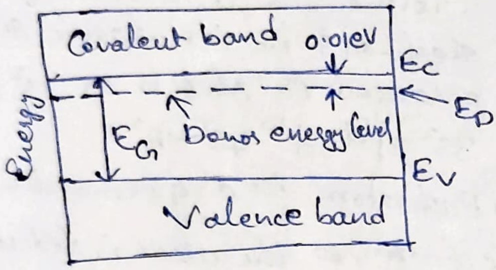
→ The importance of the hole is that it may serve as a carrier of electricity.

→ If, to pure germanium, a small amount of impurity is added in the form of a substance with five valence electrons



→ The impurity atoms will displace some of the germanium atoms in crystal lattice.

→ Four of five valence electrons will occupy covalent bonds, and fifth will nominally unbound and will be available as a carrier of current.



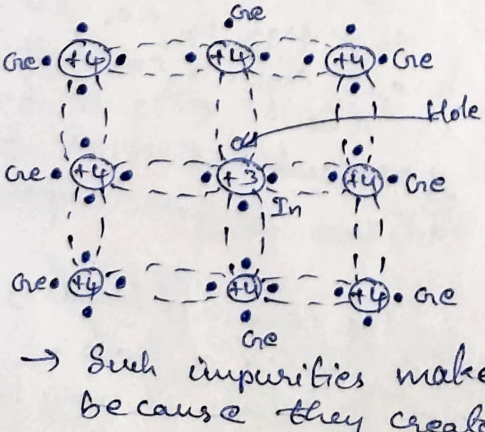
→ Suitable pentavalent impurities are antimony, phosphorus and arsenic.

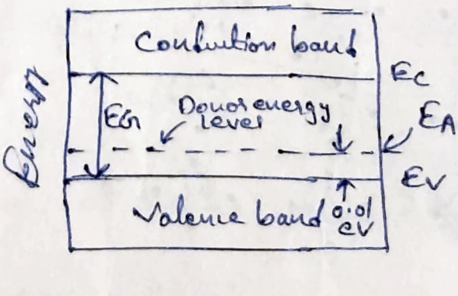
→ Such impurities donate excess (negative) electron carriers and are therefore referred to as donor, or n-type impurities.

→ When donor impurities are added to a semi conductor, allowable energy levels are introduced a very small distance below the conduction band

→ In case of germanium, the distance of new discrete allowable energy level is only 0.01 eV (0.05 eV in silicon) below the conduction band, and therefore at room temperature almost all of the "fifth" electrons of the donor material are raised into the conduction band.

→ If a trivalent impurity (boron, gallium, or indium) is added to an intrinsic semiconductor, only three of the covalent bonds can be filled, and the vacancy that exists in fourth bond constitutes a hole.



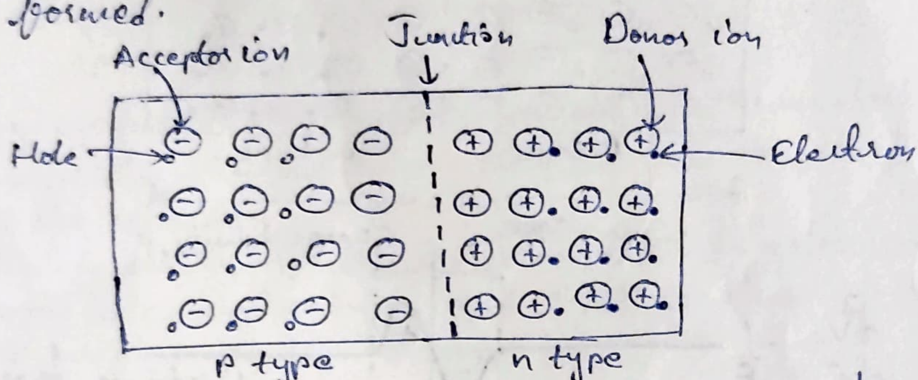


→ Such impurities make available positive carriers because they create holes which can accept electrons. So these impurities are known as acceptor or p-type impurities.

→ When acceptor, or p-type impurities are added to the intrinsic semi-conductor, they produce an allowable discrete energy level which is just above the valence band.

Qualitative Theory of p-n Junction

→ If donor impurities are introduced into one side and acceptors into the other side of a single crystal of a semiconductor (say germanium), a p-n junction is formed.



→ Donor ion is indicated by a plus sign because, after this impurity atom "donates" an electron, it becomes a positive ion.

→ Acceptor ion is indicated by a minus sign because, after this atom "accepts" an electron, it becomes a negative ion.

→ Initially, there are p-type carriers to the left of the junction and only n-type carriers to the right.

→ Because of density gradient across the junction, holes will diffuse to right across the junction, and electrons to left.

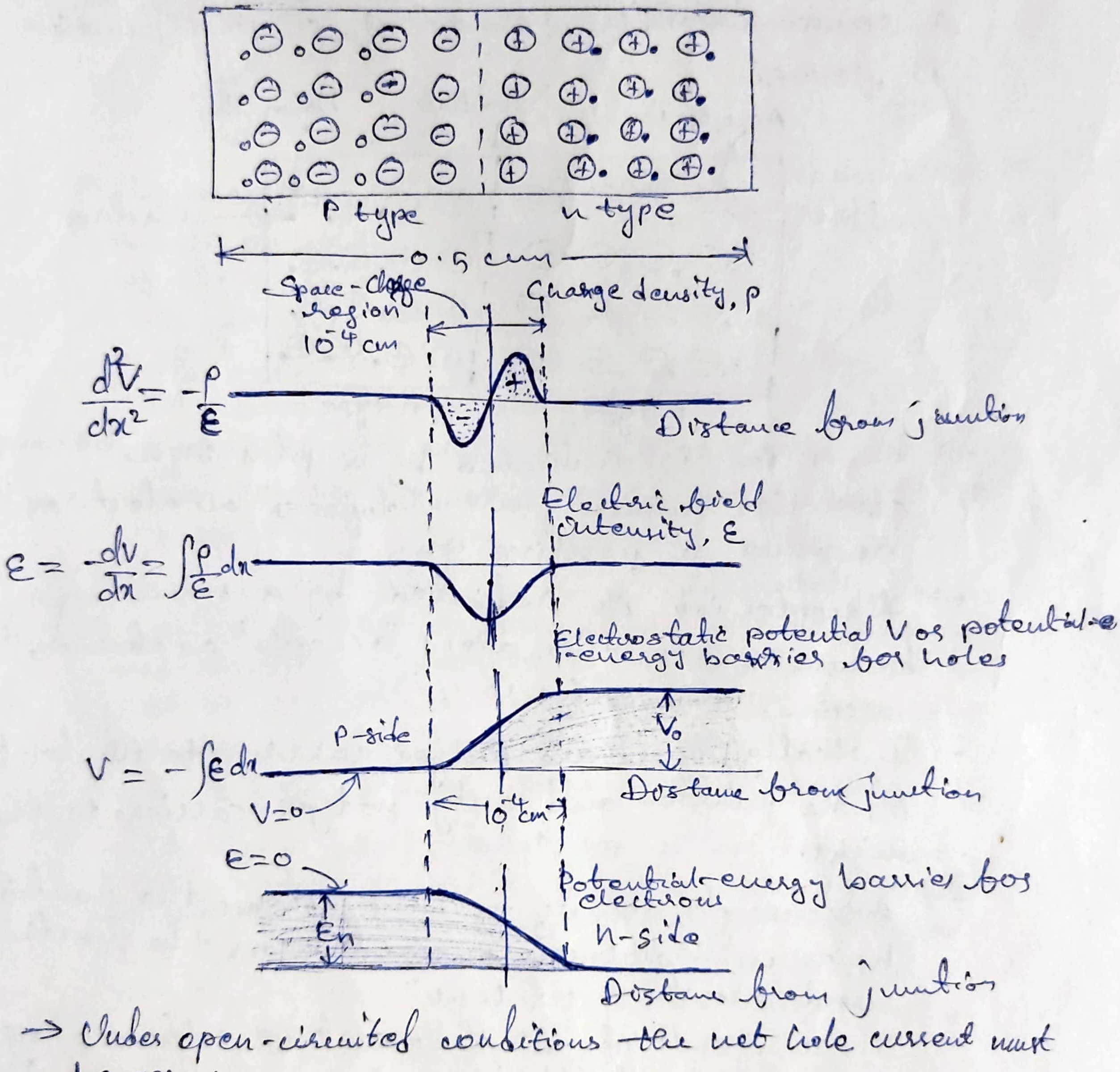
→ As a result of displacement of these charges, an electric field will appear across the junction.

→ Equilibrium will be established when the field becomes large enough to restrain the process of diffusion.

→ The positive holes which neutralized the acceptor ions near the junction in the p-type germanium have disappeared as a result of combination with electrons which diffused across the junction.

→ Similarly, neutralizing electrons in n-type germanium have combined with holes which have crossed the junction from p material.

→ The region which is depleted of mobile charges is called depletion region, space-charge region or transition region. The thickness of this region is of the order of 10^{-4} cm $= 10^{-6}$ m $= 1$ micron



→ Under open-circuited conditions the net hole current must be zero.

→ Since the concentration of holes in the p-side is much greater than that in n-side, a very large diffusion current tends to flow across the junction from the p to n material.

→ Hence an electric field must build up across the junction in such a direction that a drift current will tend to flow across the junction from n to p side in order to counterbalance the diffusion current.

p-n Junction as a Diode

→ Essential characteristic of p-n junction is that it constitutes a diode which permits easy flow of current in one direction but restrains the flow in the opposite direction.

→ Reverse Bias

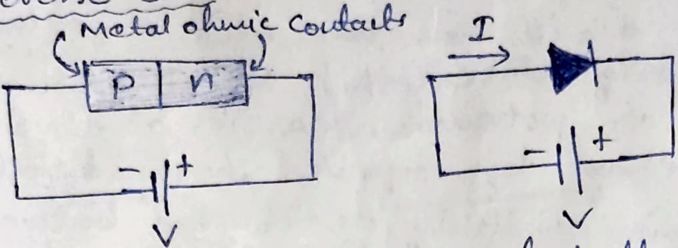


Fig. 1

→ The negative terminal of battery is connected to p-side of the junction, and positive terminal to the n-side.

→ The polarity of connection is such as to cause both holes in p-type and the electrons in n-type to move away from the junction.

→ Consequently, the region of negative-charge-density is spread to the left of junction and the positive-charge-density region is spread to the right.

→ This process cannot continue indefinitely, because in order to have a steady flow of holes ~~in p-type and electrons in n-type~~ to the left, these holes must be supplied across the junction from n-type germanium. And there are very few holes in n-type side. Hence, zero current results.

→ Actually, a small current does flow because a small number of hole-electron pairs are generated ~~in the p-type germanium~~ throughout the crystal as a result of thermal energy. The holes so formed in the n-type germanium will wander over to the junction.

→ A similar remark applies to electrons thermally generated in p-type germanium.

→ This small current is the diode reverse saturation current, and its magnitude is designated by I_o. This reverse current will increase with increasing temperature.

⇒ The applied voltage in this direction (as in diagram) is called reverse bias or blocking bias.

→ Forward Bias

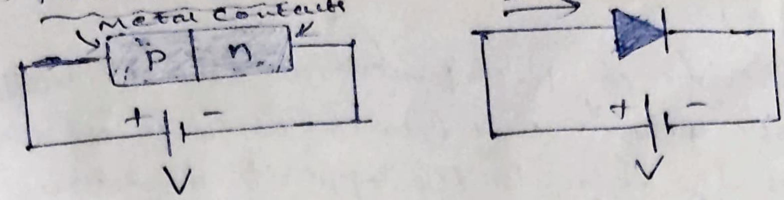


Fig. 2

→ An external voltage applied with polarity (as shown in diagram) is called a forward bias.

→ An ideal p-n diode has zero ohmic voltage drop across the body of crystal. For such a diode the height of potential barrier at the junction will be lowered by applied forward voltage V.

→ The equilibrium initially established between the forces tending to produce diffusion of majority carriers and the restraining influence of potential energy barrier at the junction will be disturbed.

→ Hence for a forward bias, the holes cross the junction from p-type to n-type, and electrons cross the junction in the opposite direction.

→ These majority carriers can then travel around the closed circuit, and a relatively large current will flow.

→ Short-circuited and Open-circuited p-n Junction:

→ If the Voltage V in Fig1 or Fig. 2 were set equal to zero, the p-n junction would be short-circuited.

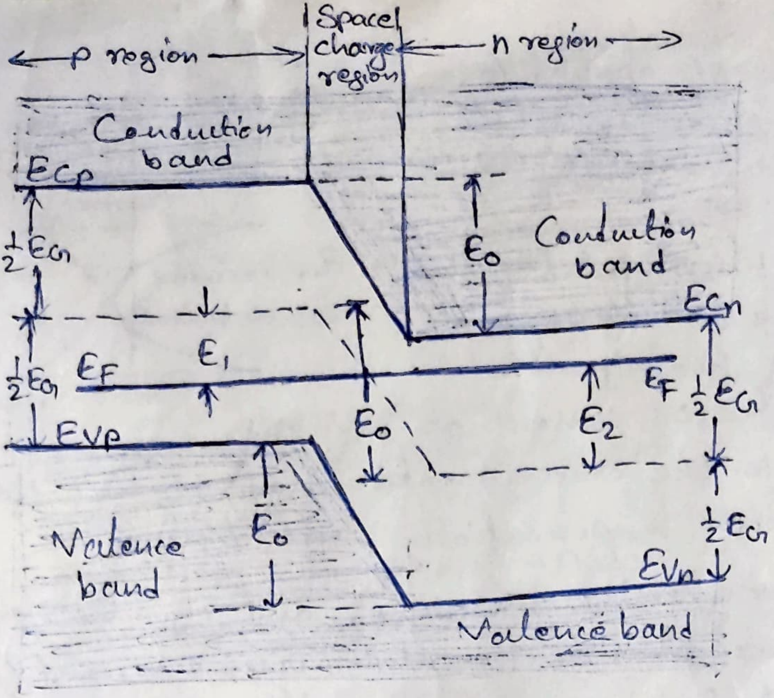
→ Under these conditions, no current can flow ($I = 0$) and the electrostatic potential V_0 remains unchanged and equal to the value under open-circuit conditions.

→ Since under short-circuit conditions the sum of the voltages around the closed loop must be zero, the junction potential V_0 must be exactly compensated by metal-to-semiconductor contact potentials at ohmic contacts.

→ Band structure of an Open-Circuited p-n Junction:

→ The fermi level E_F is closer to the conduction band edge E_{Cn} in n-type material and closer to the valence band edge E_{Vp} in the p side

→ Then the conduction band edge E_{Cp} in p material cannot be at same level as E_{Cn}, nor can the valence band edge E_{Vn} in n side line up with E_{Vp}



$E_0 = E_{Cp} - E_{Cn}$
$= E_{Vp} - E_{Vn}$
$= E_1 + E_2$

where E_0 represents the potential energy of electrons at junction

From the above diagram $E_F - E_{Vp} = \frac{1}{2}E_G - E_1$

and $E_{Cn} - E_F = \frac{1}{2}E_G - E_2$

$$E_0 = E_1 + E_2 = E_G - (E_{Cn} - E_F) - (E_F - E_{Vp}) \quad \text{— (1)}$$

We have $E_G = kT \ln \frac{N_C N_V}{n_i^2}$ — (2)

and $E_{Cn} - E_F = kT \ln \frac{N_C}{N_D}$ — (3)

$E_F - E_{Vp} = kT \ln \frac{N_V}{N_A}$ — (4)

For N-type material
$E_F = E_C - kT \ln \frac{N_C}{N_D}$
$N_D = N_C e^{-(E_C - E_F)/kT}$
For P-type material
$E_F = E_V + kT \ln \frac{N_V}{N_A}$
$N_A = N_V e^{-(E_F - E_V)/kT}$

From (1), (2), (3), (4)

$$E_0 = kT\left(\ln \frac{N_C N_V}{n_i^2} - \ln \frac{N_C}{N_D} - \ln \frac{N_V}{N_A}\right)$$
$$= kT \ln\left(\frac{N_C N_V}{n_i^2} \cdot \frac{N_D}{N_C} \cdot \frac{N_A}{N_V}\right)$$
$$= kT \ln \frac{N_D N_A}{n_i^2}$$

→ Other expression for E_0 are obtained from equilibrium concentrations

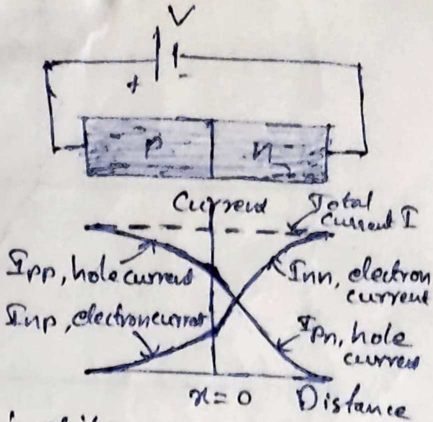
$$E_0 = kT \ln \frac{p_{p0}}{p_{n0}} = kT \frac{n_{n0}}{n_{p0}}$$

0 → indicates "under conditions of thermal equilibrium"

→ For reasonable values $p_{p0} = 10^{16}\ cm^{-3}$, $p_{n0} = 10^{14}\ cm^{-3}$, and $kT = 0.026$ eV at room temperature, we obtain $E_0 \simeq 0.6$ eV

Diode Equation

→ Current Components in a p-n Diode



→ When forward bias is applied to a diode, holes are injected into the n side and electrons into the p side.

→ The number of these injected minority carriers fall off exponentially with distance from junction.

→ Since the diffusion current of minority carriers is proportional to the concentration gradient, this current must also vary exponentially with distance.

→ There are two minority currents I_{pn} and I_{np}. The symbol $I_{pn}(x)$ represents hole current in n material, and $I_{np}(x)$ indicates electron current in p side as a function of x.

→ Electrons crossing the junction at $x=0$ from right to left constitute a current in same direction as holes crossing the junction from left to right. Hence total current I at $x=0$ is

$$I = I_{pn}(0) + I_{np}(0)$$

→ Since current is same throughout a series circuit I is independent of x.

→ In p-side, there must be a second component of current I_{pp} which, when added to I_{np} gives the total current I. Hence this hole current in p side I_{pp} (a majority carrier current) is given by

$$I_{pp}(x) = I - I_{np}(x)$$

→ Deep into the p side, current is a drift (conduction) current I_{pp} of holes sustained by small electric field in the semiconductor.

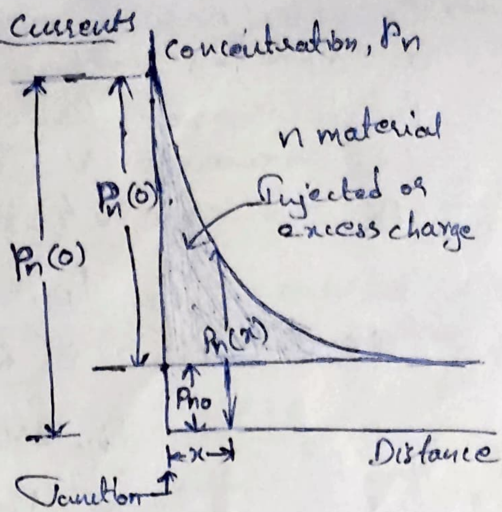
→ As holes approach the junction, some of them recombine with the electrons, which are injected into p side from the n-side. Hence part of current I_{pp} becomes a negative current just equal in magnitude to diffusion current I_{np}

→ Thus current I_{pp} decreases toward the junction.

→ Remains of I_{pp} at the junction enters the n-side and becomes the hole diffusion current I_{pn}

→ Similar remarks can be made with respect to current I_{nn}

Quantitative Theory of p-n Diode currents



→ Assuming the barrier width is zero, if a forward bias is applied to the diode, holes are injected from p-side into the n-material.

→ The concentration P_n of holes in n side is increased above its thermal-equilibrium value P_{no} and is given by

$$P_n(x) = P_{no} + P_n'(0) \exp(-x/L_p) \quad \text{--- (1)}$$

where the parameter L_p is called diffusion length for holes in n material

→ The injected or excess concentration at $x=0$ is

$$P_n'(0) = P_n(0) - P_{no} \quad \text{--- (2)}$$

→ These several hole-concentration components shows the exponential decrease of density $P_n(x)$ with distance x into the n material.

→ The diffusion hole current in n side is given by

$$I_{pn} = -A e D_p \frac{dp_n}{dx} \quad \text{--- (3)} \qquad \left(J_p = e D_p \frac{dp}{dx}\right)$$

Substituting (1) in (3)

$$I_{pn}(x) = \frac{A e D_p P_n'(0)}{L_p} \exp(-x/L_p) \quad \text{--- (4)}$$

→ This equation verifies that hole current decreases exponentially with distance.

→ The dependence of I_{pn} upon applied voltage is contained implicitly in the factor $P_n'(0)$ because injected concentration is a function of voltage.

→ Law of Junction:

→ If hole concentrations at the edges of space-charge region are P_p and P_n in p and n materials respectively and if the barrier potential across this depletion layer is V_B, then

$$P_p = P_n \exp(V_B/V_T) \text{ ---}$$

In case of an open-circuited p-n junction, $P_p = P_{po}$, $P_n = P_{no}$ and $V_B = V_o$ then above equation reduces to

$$P_{po} = P_{no} \exp(V_o/V_T) \quad \text{--- (5)}$$

→ Consider now a junction biased in forward direction by an applied voltage V. Then the barrier voltage V_B is decreased from its equilibrium value V_0 by the amount V, or $V_B = V_0 - V$

→ At the edge of depletion layer, $x=0$, $P_n = P_n(0)$.

$$P_{p0} = P_n(0)\left[\exp(V_0 - V)/V_T\right] \quad \text{—} ⑥$$

→ Combining ⑤ & ⑥ with $V_0 = 0$

$$P_{n0} \exp\left(\frac{V_0}{V_T}\right) = P_n(0)\left[\exp(V_0 - V)/V_T\right]$$

$$\Rightarrow P_n(0) \exp\left(-\frac{V}{V_T}\right) = P_{n0}$$

$$\Rightarrow P_n(0) = P_{n0} \exp(V/V_T) \quad \text{—} ⑦$$

→ This boundary condition is called law of junction. It indicates that for a forward bias ($V>0$), the hole concentration $P_n(0)$ at the junction is greater than thermal equilibrium value P_{n0}

→ A similar law, valid for electrons, is obtained by interchanging p and n in ⑦

→ The hole concentration $P_n(0)$ injected into n-side at the junction is obtained by substituting ⑦ in ②, yielding

$$P_n(0) = P_{n0}\left[\exp(V/V_T) - 1\right] \quad \text{—} ⑧$$

→ Forward Currents

→ The hole current $I_{pn}(0)$ crossing the junction into n-side is given by ④ with $x=0$. Using ⑧ for $P_n(0)$ we obtain

$$I_{pn}(0) = \frac{A e D_p P_{n0}}{L_p}\left[\exp(V/V_T) - 1\right] \quad \text{—} ⑨$$

→ The electron current $I_{np}(0)$ crossing the junction into p side is obtained from ⑨ by interchanging n and p

$$I_{np}(0) = \frac{A e D_n n_{p0}}{L_n}\left[\exp(V/V_T) - 1\right] \quad \text{—} ⑩$$

→ The total diode current I is the sum of $I_{pn}(0)$ and $I_{np}(0)$

$$I = I_0\left[\exp(V/V_T) - 1\right] \quad \text{—} ⑪$$

where $$I_0 \equiv \frac{A e D_p P_{n0}}{L_p} + \frac{A e D_n n_{p0}}{L_n} \quad \text{—} ⑫$$

→ Also I_o is now found to be proportional to n_i instead of n_i^2. Hence if K_2 is a constant

$$I_o = K_2 T^{1.5} \exp(-V_{Go}/2V_T) \quad \text{— (17)}$$

Volt-Ampere Characteristic

→ For a p-n junction, the current I is related to the voltage V by the equation

$$I = I_o[\exp(V/\eta V_T) - 1] \quad \text{— (16)}$$

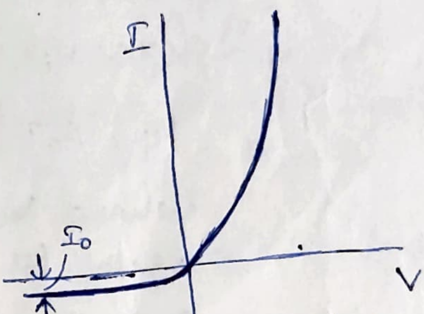
→ A positive value of I means that current flows from p to n side

→ The diode is forward-biased if V is positive, indicating that p-side of junction is positive with respect to n side.

→ The symbol η is unity for germanium and is approximately 2 for silicon.

→ When voltage V is positive and several times V_T, the unity in the parathesis may be neglected.

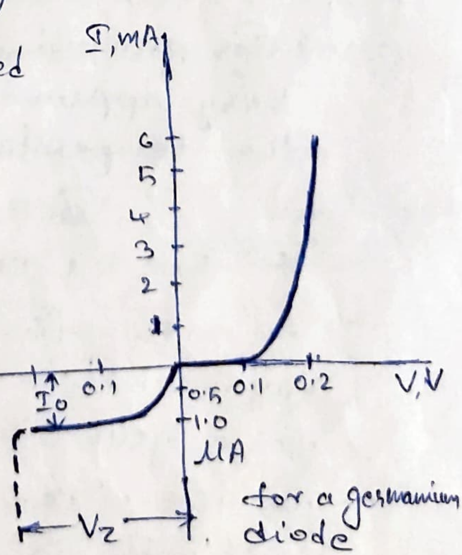
→ So except for a small range in the neighbourhood of the origin, the current increases exponentially with voltage.



For an ideal p-n diode

→ When the diode is reverse-biased and $|V|$ is several times V_T, $I \approx -I_o$.

→ So the reverse current is constant, independent of the applied reverse bias and I_o is referred to as reverse saturation current.



for a germanium diode

→ The dashed portion of the curve indicates that, at a reverse biasing voltage V_Z, the diode characteristic exhibits an abrupt and marked departure from (16)

→ At this critical voltage, a large reverse current flows, and the diode is said to be in breakdown region

→ Reverse Saturation Current

→ Consider a positive value of V indicates a forward bias.

→ (11) is equally valid if V is negative, signifying an applied reverse-bias voltage.

→ For a reverse bias whose magnitude is large compared with V_T (~26 mV at room temperature), $I \to -I_0$. Hence I_0 is called reverse saturation current.

→ For a p-type semiconductor

$$n_p p_p = n_i^2 \qquad p_p \simeq N_A \qquad n_p = \frac{n_i^2}{N_A} \quad \text{— (13)}$$

& $N_D + p = N_A + n$

→ for a n-type semiconductor

$$n_n p_n = n_i^2 \qquad n_n \simeq N_D \qquad p_n = \frac{n_i^2}{N_D} \quad \text{— (14)}$$

& $N_D + p = N_A + n$

→ From (13), (14) and (12)

$$I_0 = Ae\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right) n_i^2$$

where n_i^2 is given by

$$n_i^2 = A_0 T^3 \exp(-E_{G0}/kT) = A_0 T^3 \exp(-V_{G0}/V_T)$$

where V_{G0} is a voltage which is numerically equal to forbidden-gap energy E_{G0} in eV, and V_T is volt equivalent temperature ($V_T = \frac{\bar{k}T}{e} = \frac{T}{11{,}600}$ where k is Boltzmann constant in J/°K and $\bar{k}$ is Boltzmann constant in eV/°K)

→ For germanium the diffusion constants D_p and D_n vary approximately inversely proportional to T. Hence the temperature dependence of I_0 is

$$I_0 = K_1 T^2 \exp(-V_{G0}/V_T) \quad \text{— (15)}$$

where k_1 is a constant independent of temperature

→ An assumption of neglecting carrier generation and recombination in space-charge region is valid for a germanium diode, but not for a silicon device.

→ For the silicon diode, the diffusion current is negligible compared with transition layer-charge-generation current, which is given by

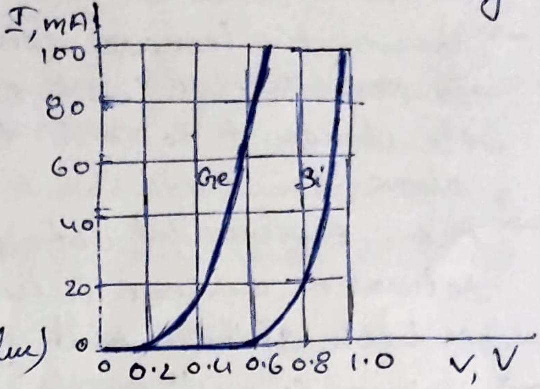
$$I = I_0\left[\exp(V/\eta V_T) - 1\right] \quad \text{— (16)}$$

where $\eta = 2$ for small (rated) currents and $\eta = 1$ for large currents.

Cutin Voltage V_γ

→ A numbers of differences between silicon and germanium diodes which are used in circuit design

→ There exists a cutin, offset, break-point, or threshold voltage V_γ below which the current is very small (say, less than 1 percent of maximum rated value)



germanium (1N270) and silicon (1N3605) diodes at 25°C

→ Beyond V_γ the current rises very rapidly

→ V_γ is approximately 0.2 V for germanium and 0.6 V for silicon from above diagram

Temperature Dependence of V-I Characteristics

→ The diode voltage variation with temperature at fixed current may be calculated from (16) where the temperature is contained implicitly in V_T and also in the reverse saturation current.

→ The dependence of I_0 on temperature T is from (15) and (17), given approximately by

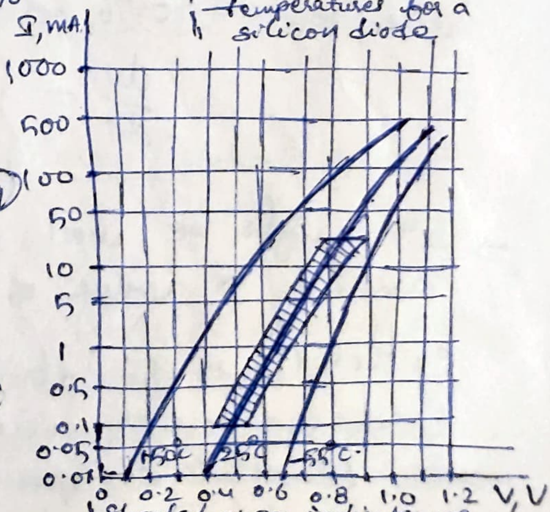
$$I_0 = KT^m \exp(-V_{G0}/\eta V_T) \quad (18)$$

where K is a constant and eV_{G0} (e is magnitude of electronic charge) is the forbidden-gap energy in joules.

For Ge: $\eta = 1$ $m = 2$ $V_{G0} = 0.785V$

For Si: $\eta = 2$ $m = 1.5$ $V_{G0} = 1.21V$

At three different temperatures for a silicon diode



Shaded area indicates 25°C limits of controlled conductance

→ Taking the derivative of logarithms of (18) we get $\left(\log I_0 = \log k + m\log T - \frac{V_{G0}}{\eta V_T}\right)$

$$\frac{1}{I_0}\frac{dI_0}{dT} = \frac{d(\ln I_0)}{dT} = \frac{m}{T} + \frac{V_{G0}}{\eta T V_T} \quad (19)$$

→ At room temperature, we define from (19) that $\frac{d(\ln I_0)}{dT} = 0.08°C^{-1}$ for Si and $0.11°C^{-1}$ for Ge

$$\frac{dV}{dT} = \frac{V}{T} - \eta V_T\left(\frac{1}{I_0}\frac{dI_0}{dT}\right) = \frac{V - (V_{Go} + m\eta V_T)}{T}$$

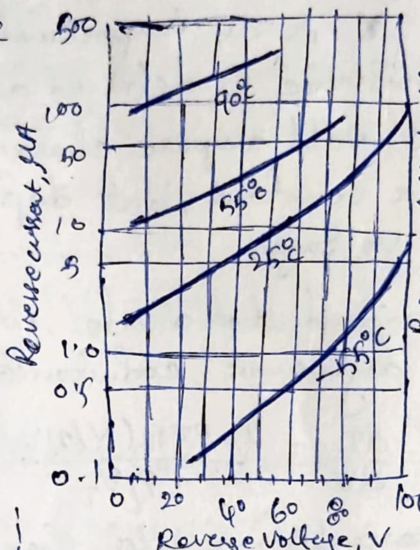
→ The positive term $\frac{V}{T}$ on right hand side results from the temperature dependence of V_T

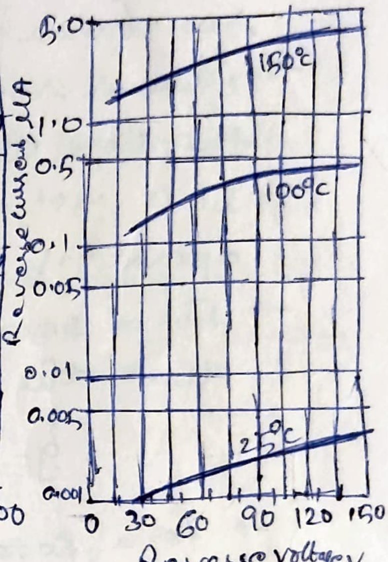
→ The negative term results from temperature dependance of I_0, and does not depend on voltage V across the diode.

→ For increasing V, $\frac{dV}{dT}$ should become less negative, reach zero at $V = V_{Go} + m\eta V_T$ and thereafter reverse sign and go positive.

→ This reversal takes place at a current which is higher than the maximum rated current.

→ From the reverse characteristics of germanium and silicon diodes observing the dependance of current on reverse voltage, result is not consistent with our expectation of a constant saturated reverse current.





Reverse characteristics of germanium diode IN270

Reverse characteristics of Silicon diode IN461

→ This increase in I_0 results from leakage across the surface of the diode, and also from new current carriers that may be generated by collision in transition region at the junction.

→ Since the temperature dependance is approximately the same in both types of diodes, at elevated temperature, the germanium diode will develop an excessively large current, whereas for silicon, I_0 will be quite modest.

Ideal versus Practical Resistance Levels (Static & Dynamic)

→ Diode Resistance

→ The static resistance R of a diode is defined as the ratio V/I of the voltage to the current.

→ At any point on the volt-ampere characteristics of the diode, the resistance R is equal to the reciprocal

→ of the slope of a line joining the operating point to the origin.

→ Static resistance varies widely with V and I.

→ Rectification property of a diode is indicated on manufacturer's specification sheet by giving the maximum forward voltage V_F required to attain a given forward current I_F and also the maximum reverse current I_R at a given reverse voltage V_R.

→ Typical values for a silicon planar epitaxial diode are $V_F = 0.8\,V$ at $I_F = 10\,mA$ (corresponding to $R_F = 80\,\Omega$) and $I_R = 0.1\,\mu A$ at $V_R = 50\,V$ (corresponding to $R_R = 500\,M$)

→ For small-signal operation, the dynamic, or incremental resistance r is an important parameter.

→ Dynamic resistance is defined as the reciprocal of the slope of volt-ampere characteristic, $r \equiv dV/dI$.

→ It is not a constant, but depends upon the operating voltage.

→ For a semiconductor diode, we find from (16) that the dynamic conductance $g \equiv 1/r$ is

$$g \equiv \frac{dI}{dV} = \frac{I_o \exp(V/\eta V_T)}{\eta V_T} = \frac{I + I_o}{\eta V_T}$$

→ For a reverse bias greater than a few tenths of a volt (so that $|V/\eta V_T| >> 1$), g is extremely small and r is very large.

→ For a forward bias greater than a few tenths of a volt, $I >> I_o$, and r is given approximately by

$$r = \frac{\eta V_T}{I}$$

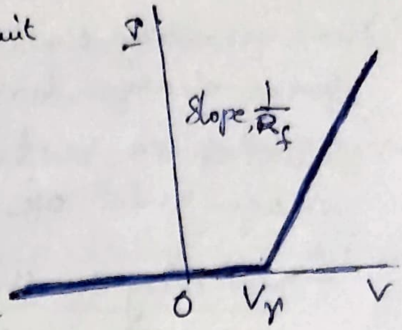
→ Dynamic resistance varies inversely with current, at room temperature and for $\eta = 1$, $r = 26/I$, where I is in milliamperes and r in ohms. So for a forward current of 26 mA, the dynamic resistance is $1\,\Omega$

→ Piecewise Linear Diode Characteristic

→ A large-signal approximation which often leads to a sufficiently accurate engineering solution is piecewise linear representation.

→ The break point is not at the origin, and hence V_γ is also called the offset, or threshold voltage.

→ The diode behaves like an open circuit if $V < V_\gamma$ and has a constant incremental resistance $r = dV/dI$ if $V > V_\gamma$



→ The resistance r (also designated as R_f and called the forward resistance) takes on added physical significance even for this large-signal model, whereas the static resistance $R_F = V/I$ is not constant and is not useful.

→ The numerical values V_γ and R_f to be used depend upon the type of diode and contemplated voltage and current swings.

→ For a current swing from cutoff to 10mA, with a germanium diode (1N270), reasonable values are $V_\gamma = 0.6V$ and $R_f = 15\Omega$.

→ A better approximation for current swings up to 50 mA leads to $V_\gamma = 0.3V$ and $R_f = 6\Omega$ for germanium diode (1N270)

Transition and Diffusion Capacitances

→ Space-Charge, or Transition Capacitance C_T

→ A reverse bias causes majority carriers to move away from the junction, thereby uncovering more immobile charges.

→ Hence the thickness of the space-charge layer at the junction increases with reverse voltage.

→ This increase in uncovered charge with applied voltage may be considered a capacitive effect.

→ We may define an incremental capacitance C_T by

$$C_T = \left|\frac{dQ}{dV}\right| \quad \text{— (22)}$$

where dQ is the increase in charge caused by a change in dV in voltage.

→ A change in voltage dV in a time dt will result in a current $i = dQ/dt$, given by

$$i = C_T \frac{dV}{dt}$$