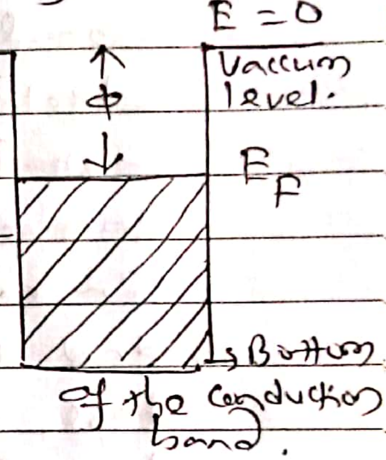
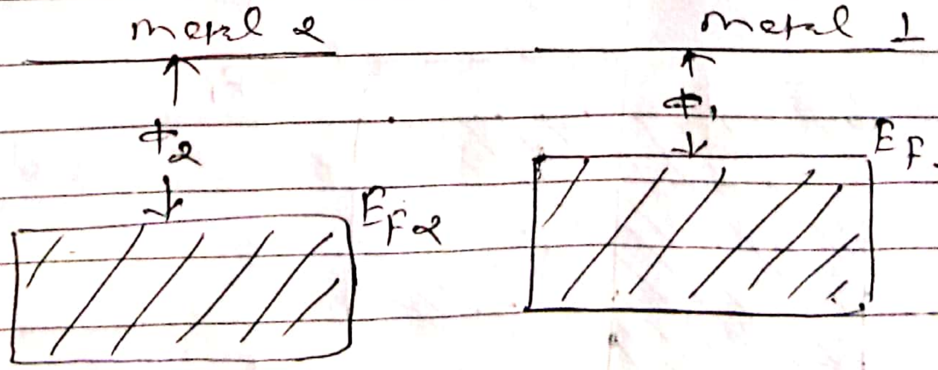
Semiconductor Devices

Metal-metal Junction
The Contact potential:

In metals, electrons occupy the highest energy levels, called the conduction band. According to quantum mechanical free electron model, electrons occupy all the energy levels from the bottom of the conduction band to the Fermi Level, E_F.



For the electrons outside the metals, they are in vaccum with zero energy (E = 0).
The energy difference between the topmost energy level, called E_F the Fermi level E_F and the vacuum level is the work function ϕ. The more the difference, the greater is the work function.



For the electrons in Fermi level, they absorb photons of less energy while the electrons below the Fermi level absorb photons

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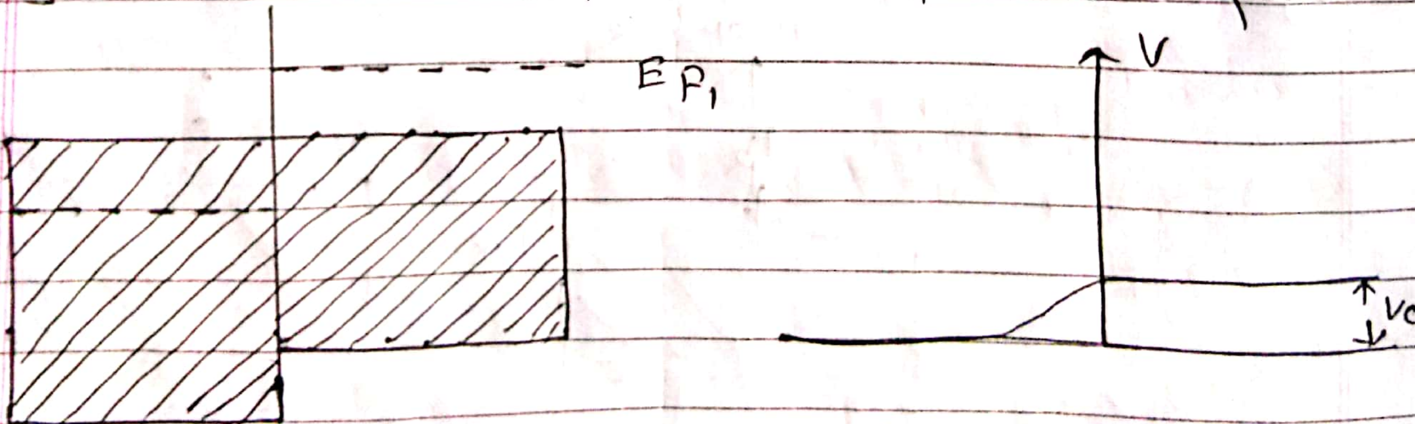
of higher energy. If the electrons in Fermi level absorb such photons of higher energy, the extra energy is employed to impart the K.E to the electrons.

Let us take two ~~photons~~ metals of work functions ϕ_1 and ϕ_2 ($\phi_1 < \phi_2$) respectively. Since the Fermi level of metal 1 is higher ($E_{F_1} > E_{F_2}$), the electrons begin to flow ~~untill~~ from metal 1 to metal 2 untill there is common ~~potent~~ Fermi level is maintained. In doing so, metal 2 gain electrons and is -vely charged while metal 1 loss electrons and is +vely charged. Hence a p.d. is maintained, called as <u>contact potential</u>, V_c

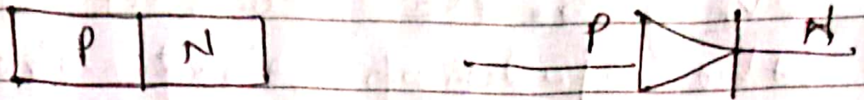
Hence an important principle here is "The Fermi levels of two conducting solids in contact must be equal."



Clearly, the potential of metal 1 is higher by an amount V_c as compared to the potential of metal 2.

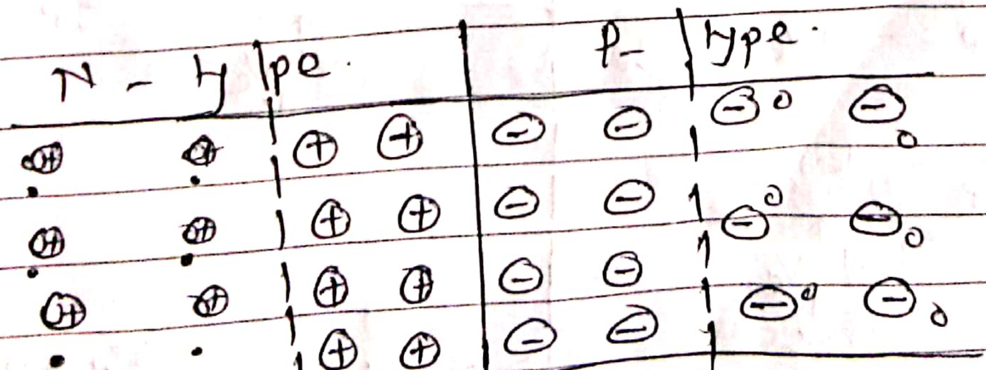
15.3 The Semiconductor Diode

Contact potential: Band scheme of a PN junction:



Physical Form Symbol.

When P-type is made contact with the N-type, the majority charge carriers diffuse to each other across the junction. Electrons from the N region diffuse to the P region and the holes from the P region diffuse to the N region. The effect of such double diffusion is to deplete the region near the junction and hence to create a resistive path. In doing so, the immobile ions on the either sides are left charged. There is +ve charged layer near the N region and a -ve charged layer near the P region on the junction. Thus an internal electric field E is created that prevents the further diffusion and equilibrium is established.



Positive donor ion and electron. ← Depletion layer → Negative acceptor ion and hole.

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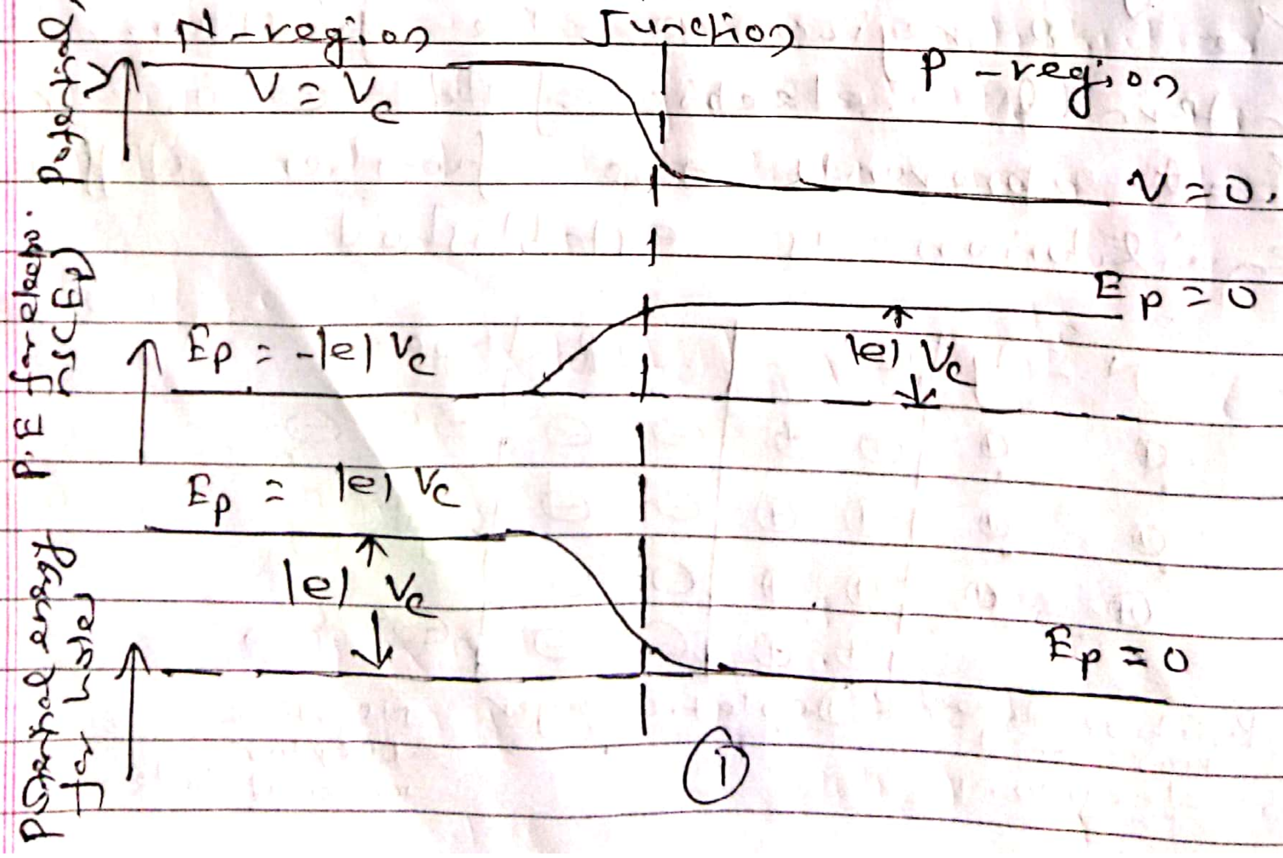
Let V_e be the contact potential near the junction that the N region is positive by V_e w.r. to the p-region. The potential energy for the electron in N region is $-|e|V_e$ whereas it is zero in the p region. The potential energy of the holes in the N region is $+|e|V_e$ whereas it is zero in the p side. Hence one of the consequences of the contact potential is the upward shift of the electronic energy bands in the p side relative to the bands in the N side. Such energy shift on the bands $|e|V_e$ must be equal to the difference of the two Fermi levels before contact.

i.e. $|e|V_e = E_{Fn} - E_{Fp}$.



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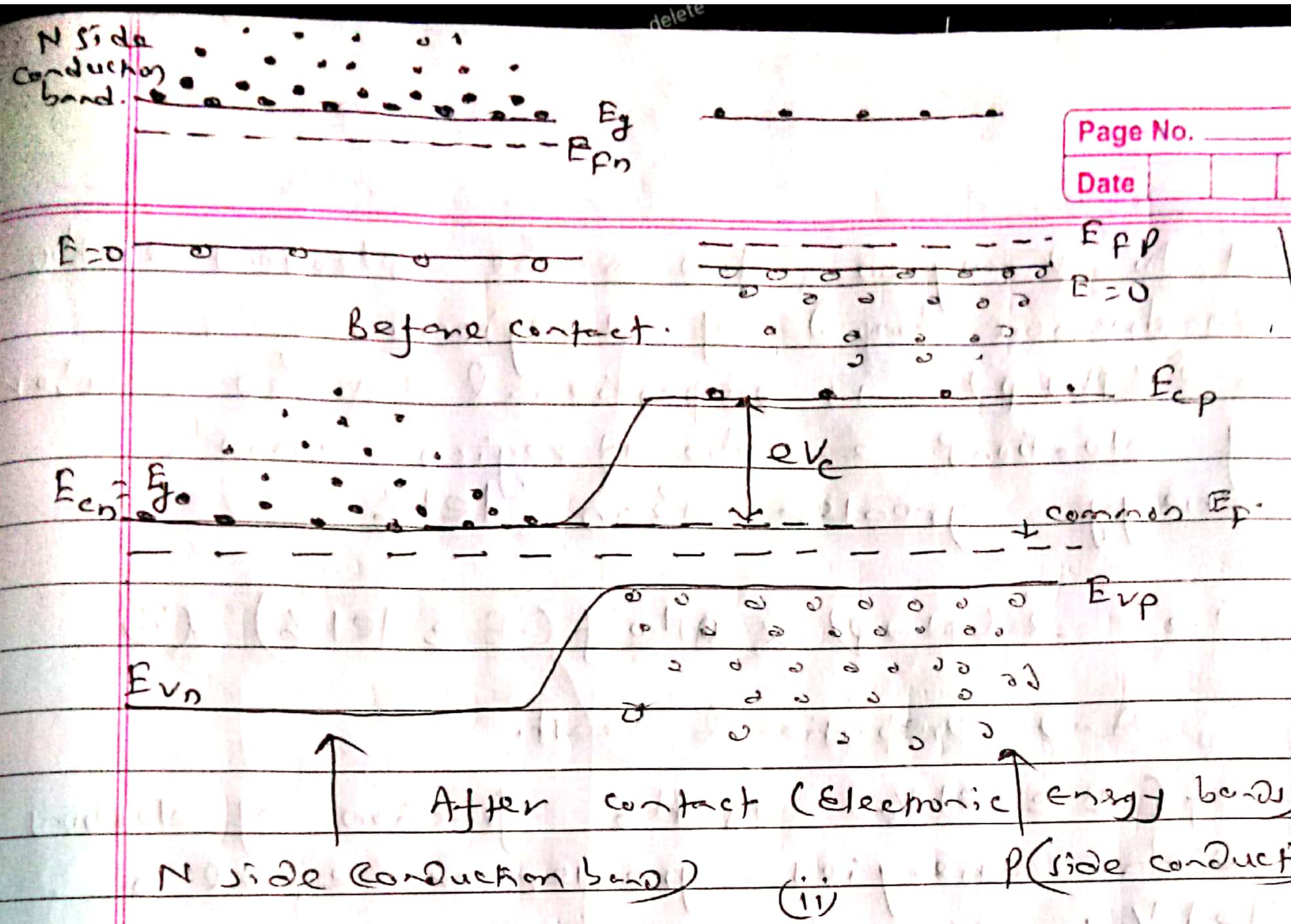

After PN junction is formed, the shifting upwards is in accordance with the fig (i)

Equilibrium current Across the PN junction:

In Dynamic equilibrium, the majority charge carriers stop to diffuse due to the contact potential V_c at junction of a diode. However, electrons and holes continuously flow across the junction.

Let $i^{o}(P \to N)$ be the current due to the minority charge carriers (electrons) from the P region to the N region.

Therefore, $i^{o}(P \to N)$ is proportional to the electrons (N_e) in the P region.

i.e, $i^{o}(P \to N) = A e^{-E_1/k_BT}$ —— (i)

A → proportional const.

Moreover, $i(N \to P)$ be the current from

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N to P region due to the electrons in the conduction band of N-region.

$i(N \to P)$ is proportional to the number of electrons in the N region with energy greater than $|e|V_c$

i.e $$i(N \to P) \propto A N_e f(E \geq |e|V_c) \quad \text{---(ii)}$$

~~A → proportional const.~~

$f(E \geq |e|V_c)$ is the fraction of electrons with energies greater or equal to $|e|V_c$.

For the electrons in conduction band for Si at ambient (surrounding) tempr, the F-D statistics is approximated by maxwell-Boltzmann statistics. Hence for the M-B distribution of energies, ~~the~~ $f(E \geq |e|V_c)$ is approximated by Boltzmann factor, e^{-E_i/K_BT}

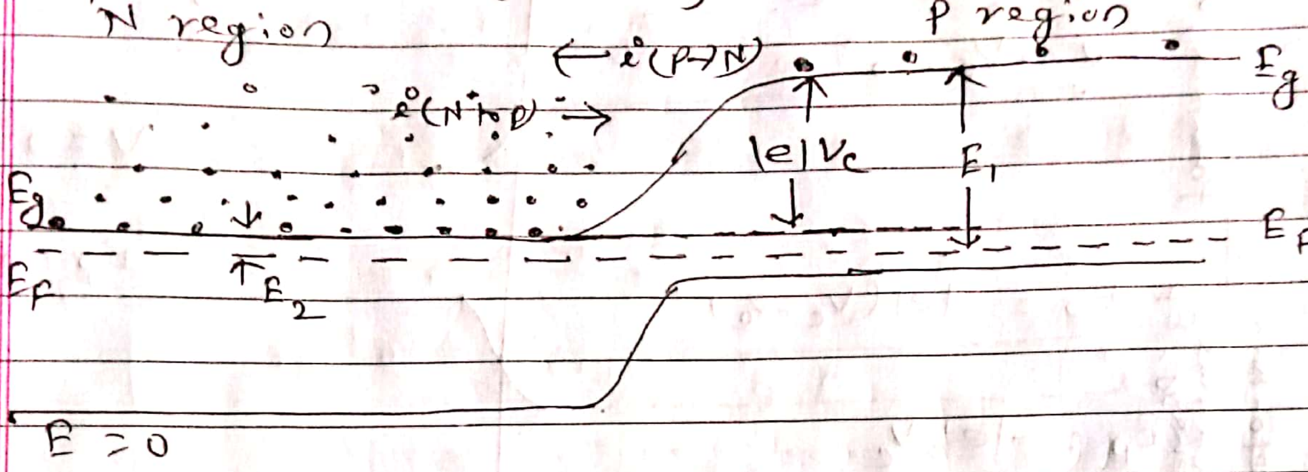
Therefore,
$$f(E \geq |e|V_c) = A e^{-\frac{eV_c}{K_BT}} \quad \text{---(iii)}$$

Now eqn (ii) ⇒

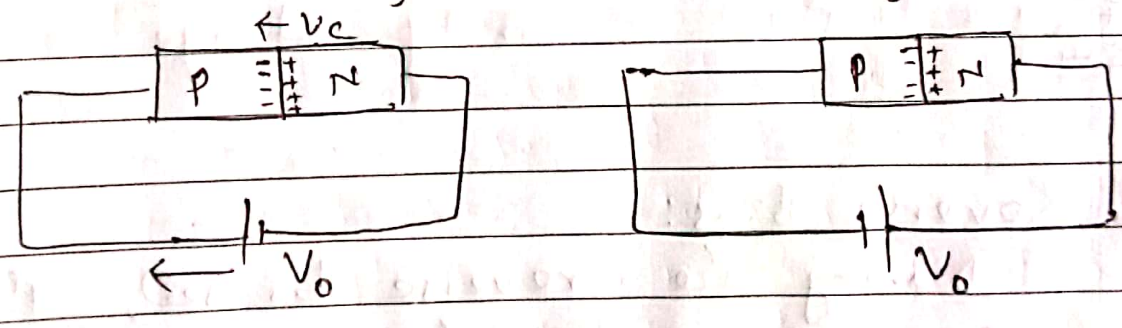
$$i(N \to P) \propto A N_c e^{\frac{E_F - E_g}{K_BT}} \cdot e^{-\frac{eV_c}{K_BT}}$$
$$= A N_c e^{-(E_g - E_F + |e|V_c)}$$
$$= A N_c e^{-(E_2 + |e|V_c)} = A e^{-E_1/K_BT}$$

$\therefore \; i(P \to N) = i(N \to P)$

i.e, the flow of electrons from N to P is equal to the flow from P to N.



Voltage - Current Characteristics of a diode: Rectification.



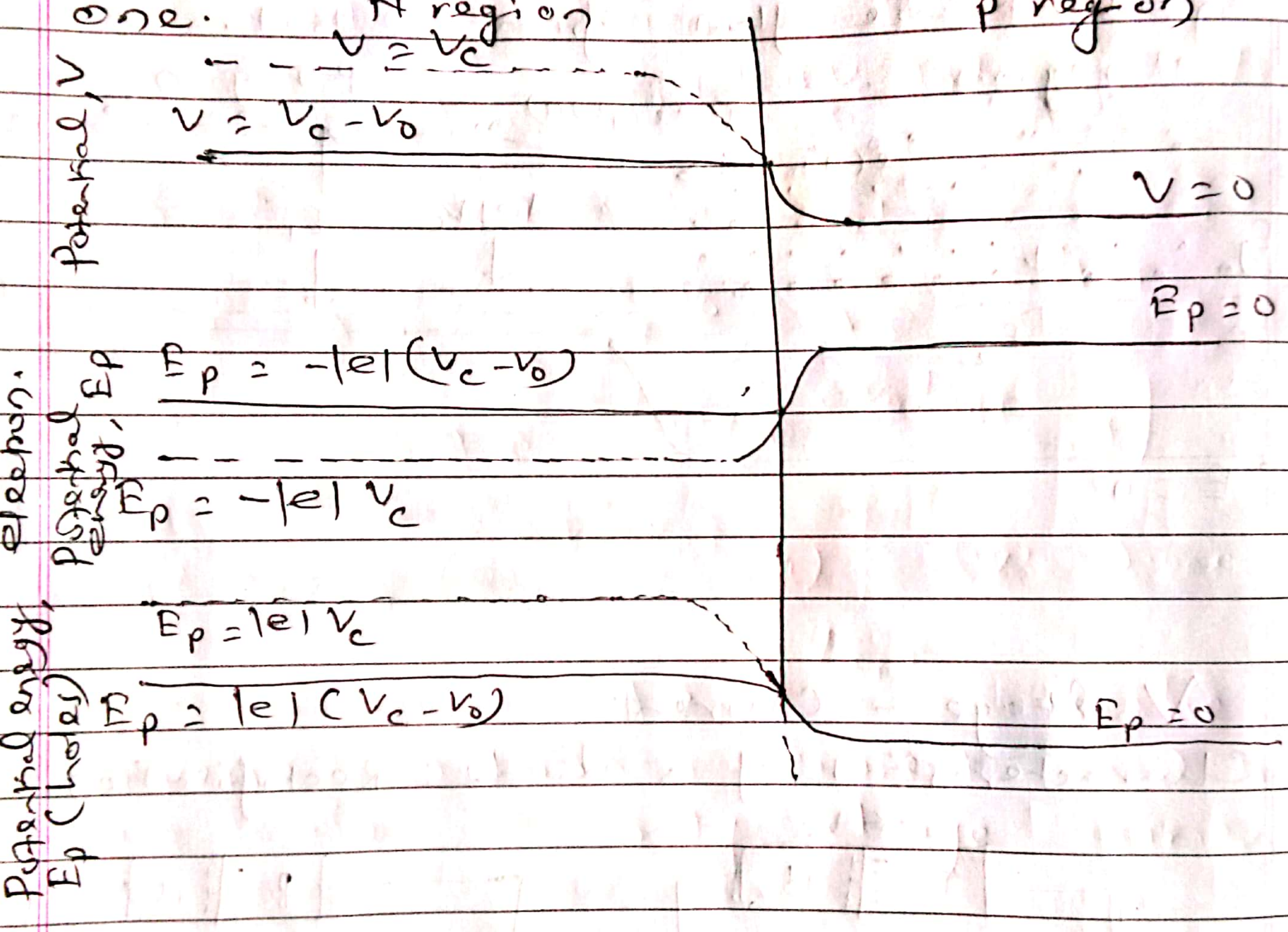
Forward Biase:

During the forward biase the applied voltage V_0 appears across the high resistive path of depletion layer. The potential of the N side lowers from V_c and becomes $V_c - V_0$.

The detail is illustrated in the fig.

The thick line represents the new one

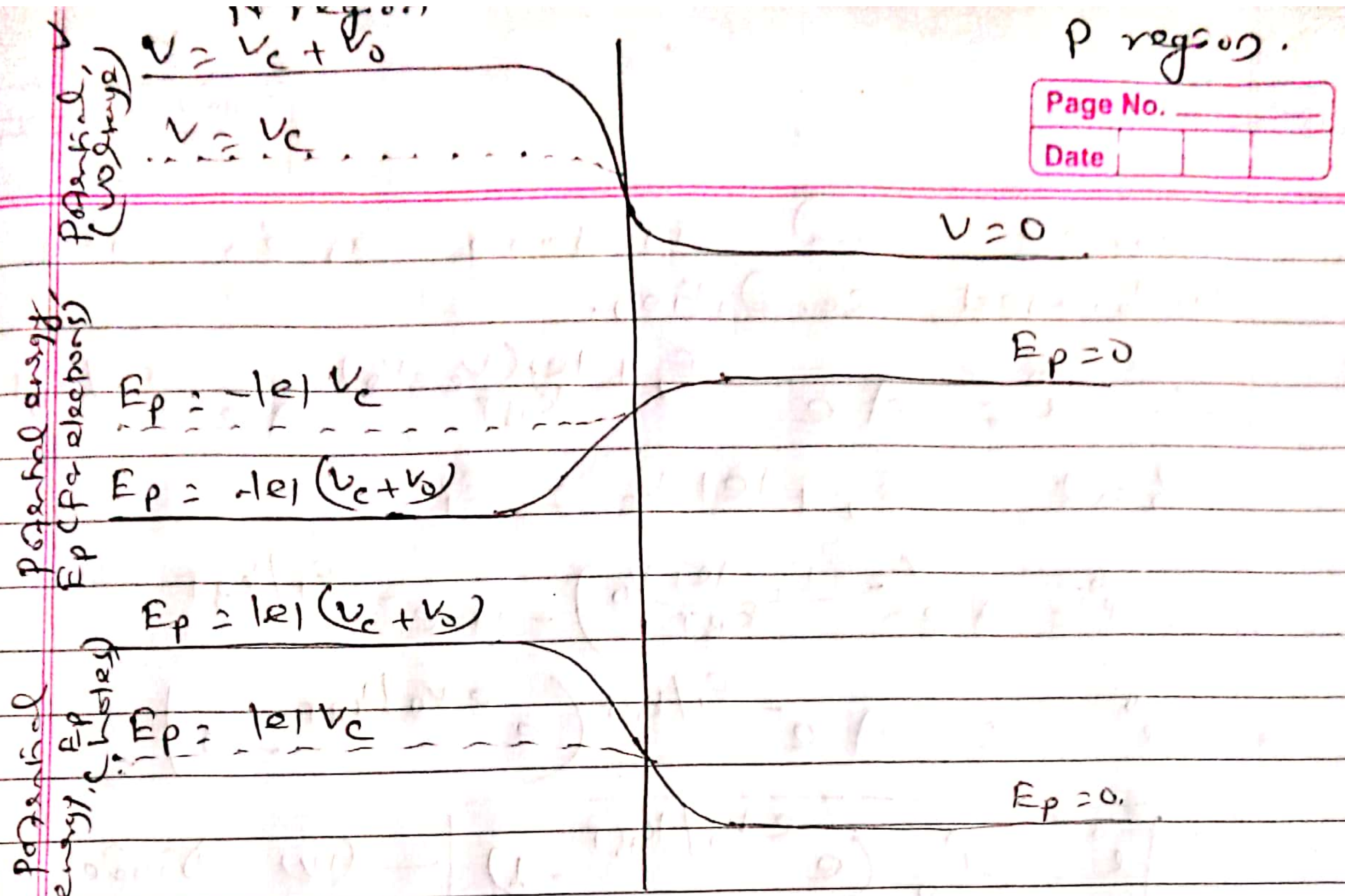
and the dashed line as the initial one.



Reverse Bias:

During the reverse biased, the depletion region increases, the potential of N region V_c goes to increase to $V_c + V_0$

The detail is illustrated in the fig.



Let us take the case of net flow of charge carriers from N to P.

The net electron current from the N side to the P side is written as

$$\dot{e} = \dot{e}(N \to P) - \dot{e}(P \to N)$$

Here, $\dot{e}(N \to P) \propto N_e f(E \geq |e|(V_c - V_0))$

$$\propto N_c e^{-\frac{(E_g - E_F)}{k_B T}} \cdot e^{-E_i/k_B T}$$

Here, $e^{-E_i/k_B T}$ is the Boltzmann factor.

$$\therefore \dot{e}(N \to P) = A e^{-\frac{(E_g - E_F)}{k_B T}} \cdot e^{-|e|(V_c - V_0)/k_B T}$$

$$= A e^{-\frac{E_2 + |e|(V_c - V_0)}{k_B T}} \quad \Big| \; E_g - E_F = E_2$$

$\dot{e}(P \to N)$ is due to the minority charge carrier and is same as in the unbiased condition.

$$\therefore\ i = Ae^{-\frac{E_2 + |e|(V_c - V_0)}{k_BT}} - Ae^{-E_1/k_BT}$$

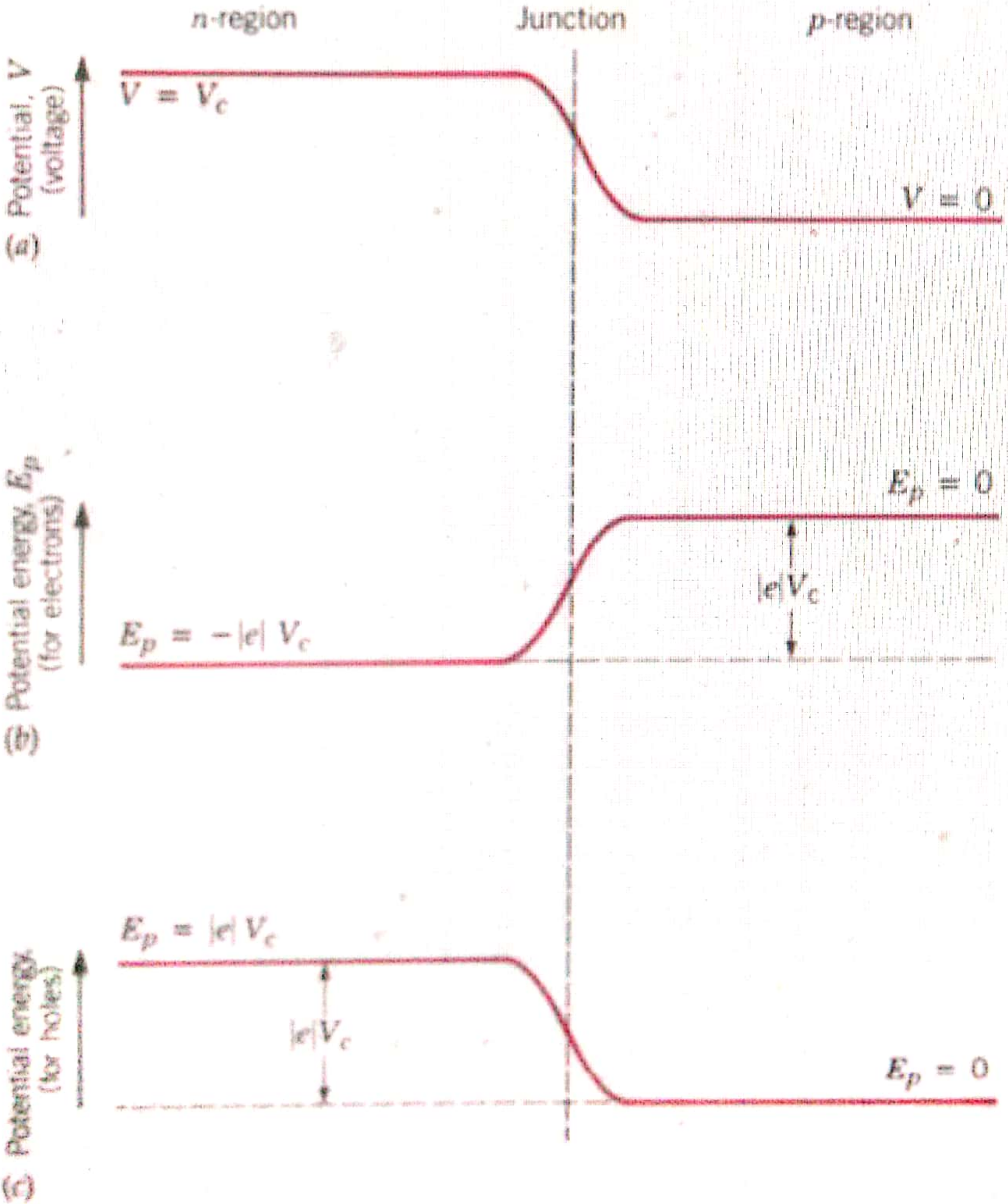
But $E_2 + |e| V_c = E_1$

$$\therefore\ i = Ae^{\left(-\frac{E_1 - |e| V_0}{k_BT}\right)} - Ae^{-E_1/k_BT}$$

$$i = Ae^{-E_1/k_BT}\left(e^{eV_0/k_BT} - 1\right)$$

$$\therefore\ \boxed{i = i_0\left(e^{eV_0/k_BT} - 1\right)} \text{ — (iv)}$$ Diode Eqⁿ

where, $i_0 = Ae^{-E_1/k_BT}$ is the reverse saturation current and is due to the minority charge carrier.



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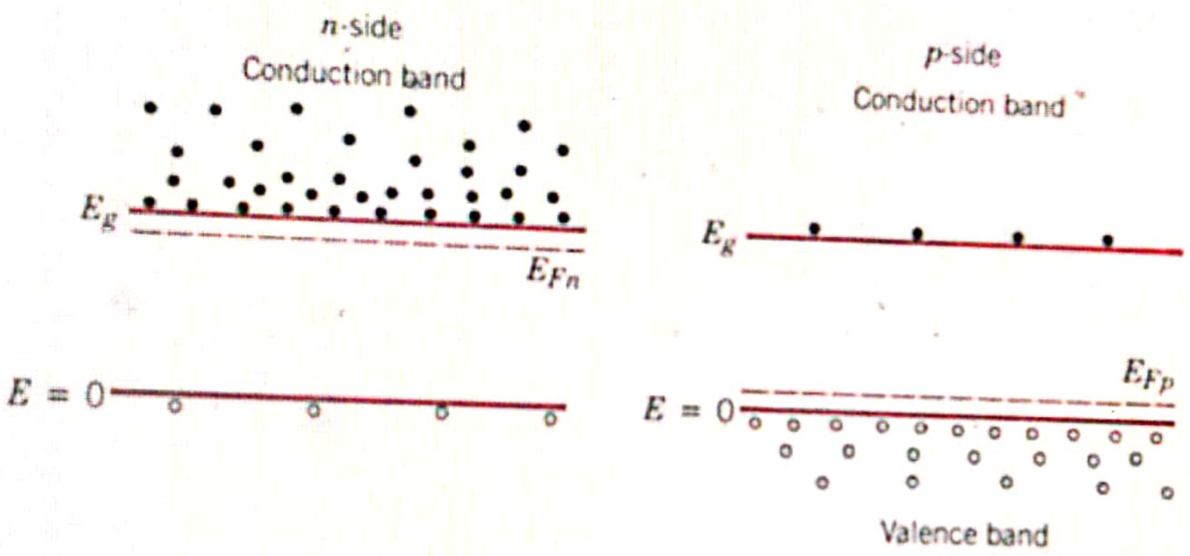
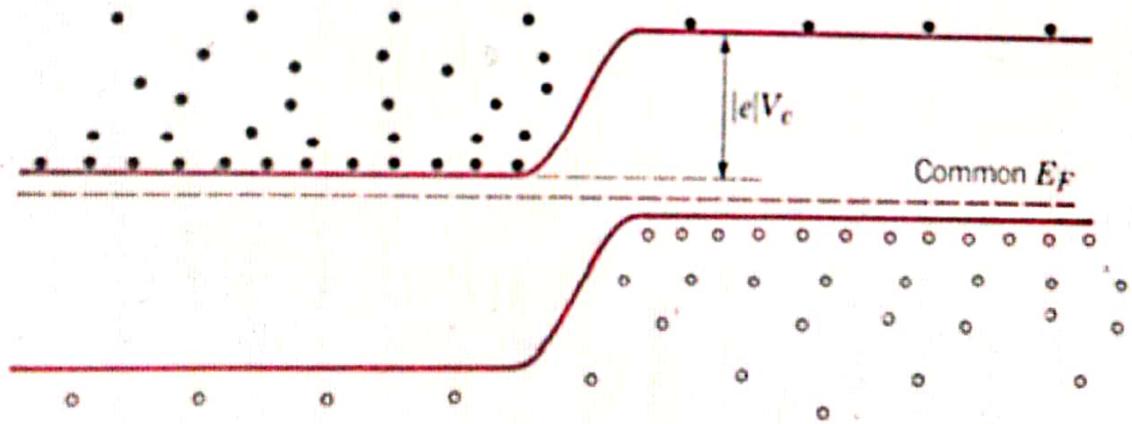
$$|e|V_c = E_{Fn} - E_{Fp} \tag{26.1}$$





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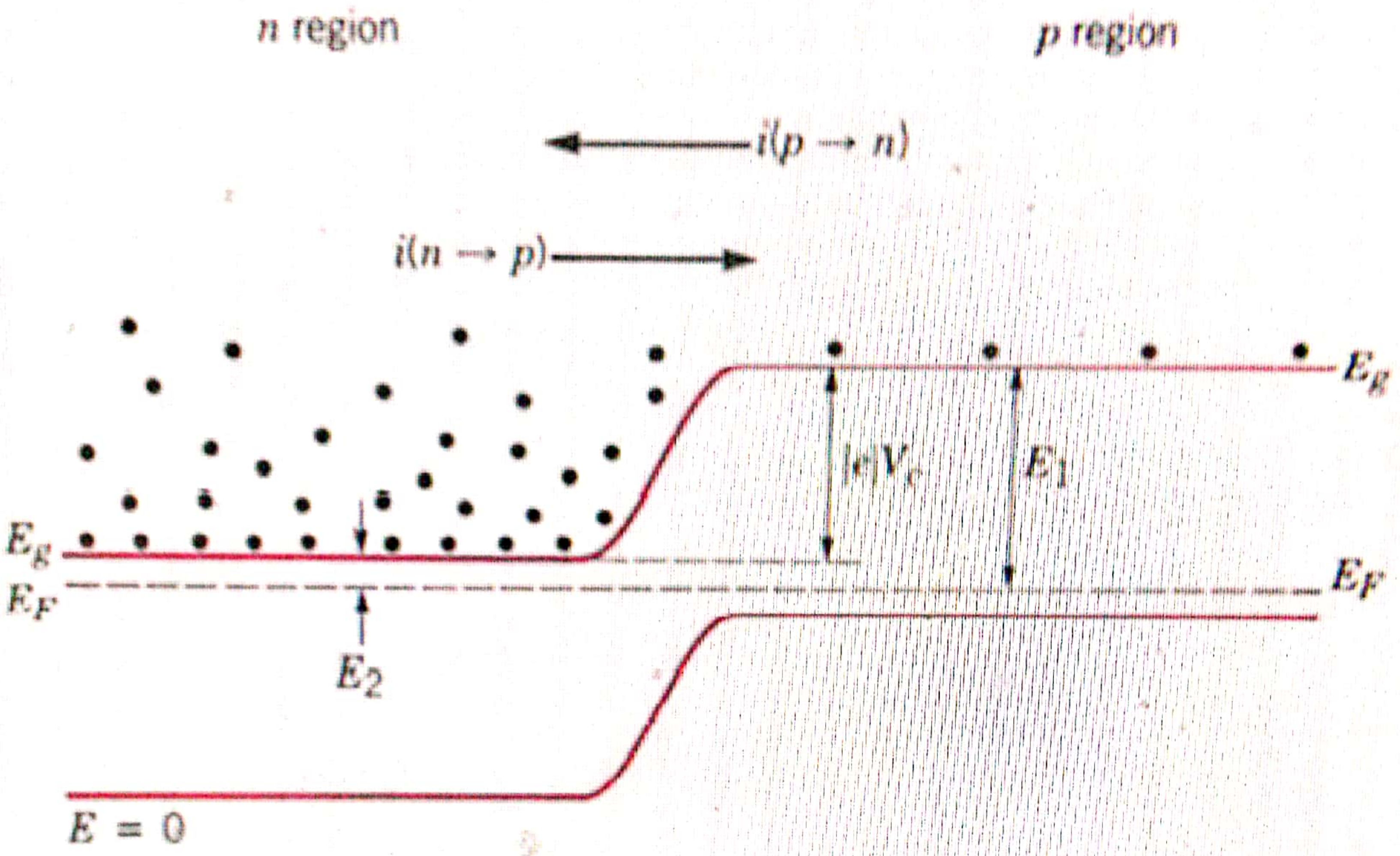

n region
p region
i(p → n)
i(n → p)
E_g
|e|V_c
E_1
E_g
E_F
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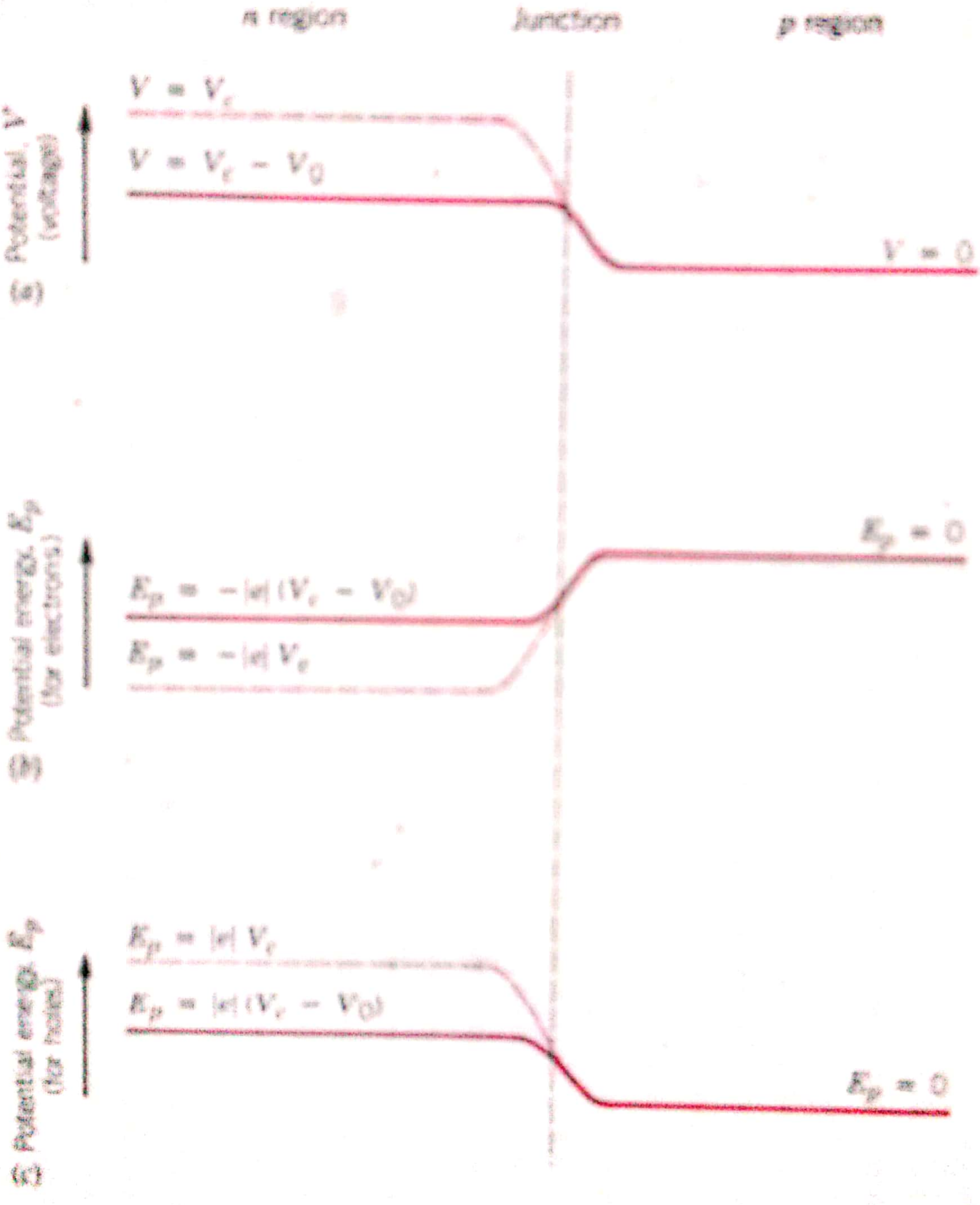
E_2
E = 0



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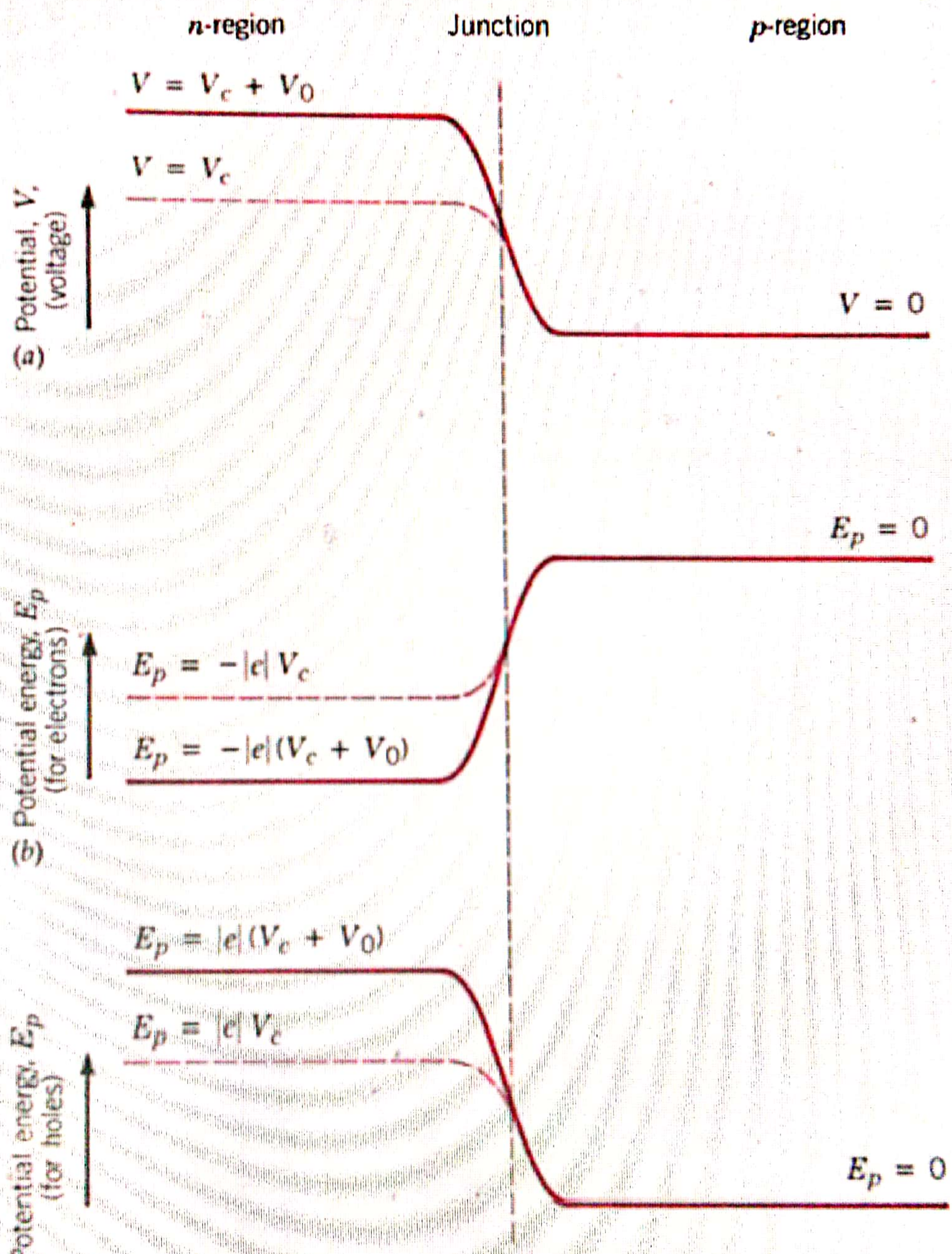

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