Chapter 6-1. PN-junction diode: *I*-*V* characteristics

Topics:

PN Junction under bias (qualitative discussion)

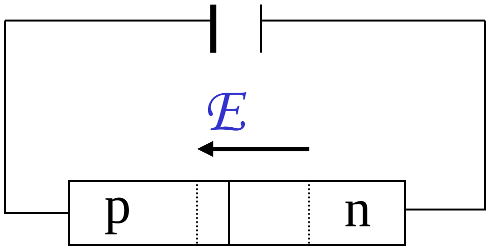
Ideal diode equation

Deviations from the ideal diode

Charge-control approach

PN junction under various bias conditions

$V_A = 0$



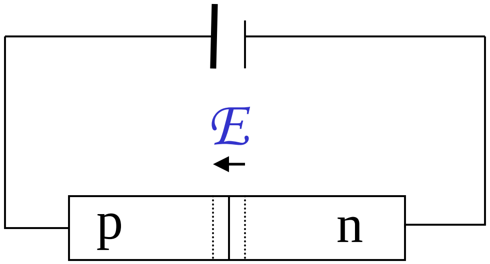
Hole diffusion current

Hole drift current

Electron diffusion current

Electron drift current

$V_A > 0$



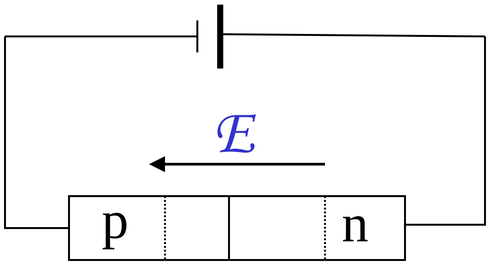
Hole diffusion current

Hole drift current

Electron diffusion current

Electron drift current

$V_A < 0$



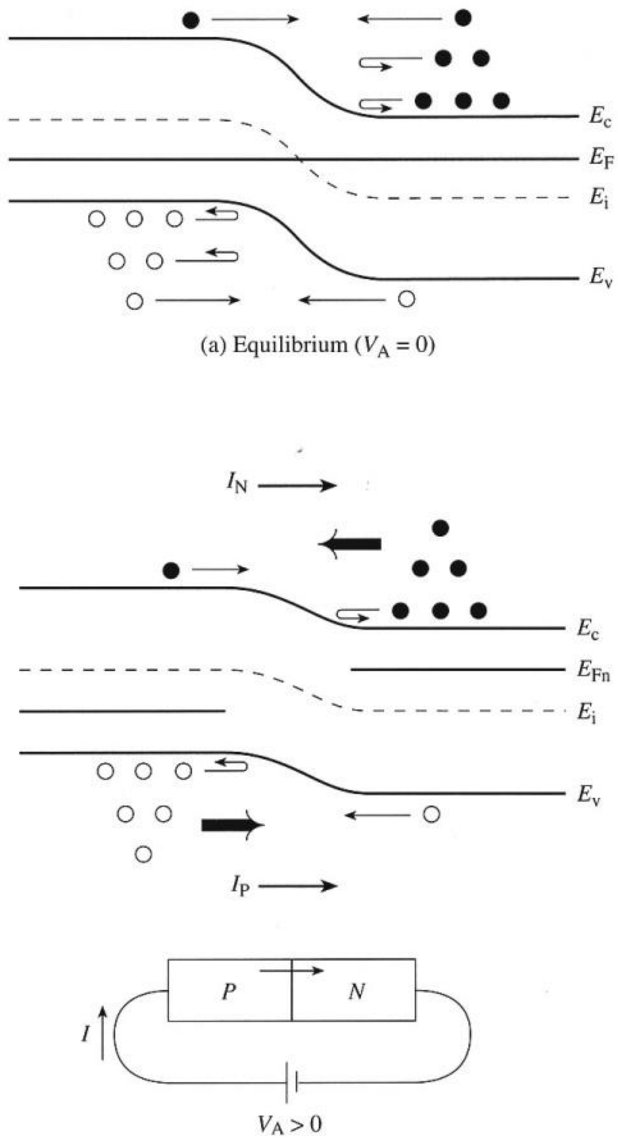
Hole diffusion current

Hole drift current

Electron diffusion current

Electron drift current

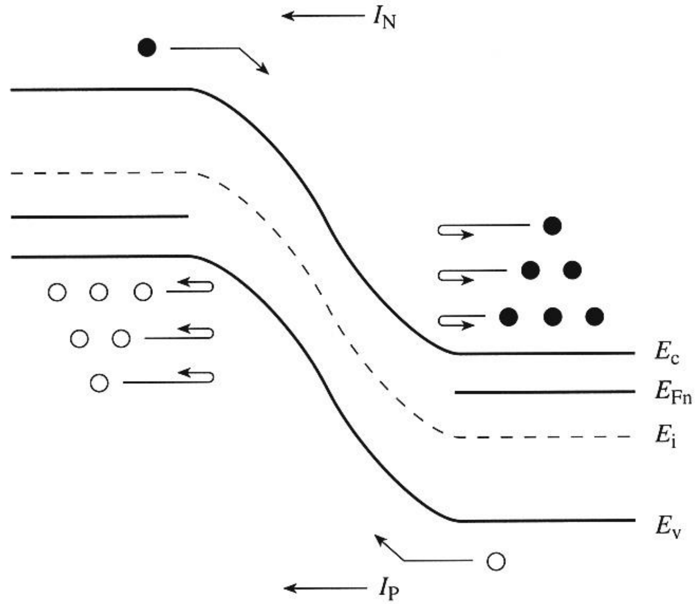
Band diagram and carrier flow under bias



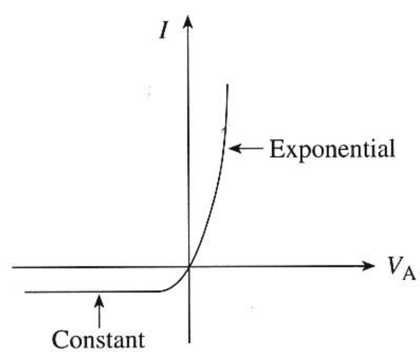
(b) Forward bias ($V_A > 0$)

Fig. 6.1(Pierret, 1996)

Band diagram and carrier flow under bias



(c) Reverse bias ($V_A < 0$)



(d)

Figure 6.1 *Continued.*

Effect of bias on diffusion current

When the diode forward-bias-voltage is increased, the barrier for electron and hole diffusion current decreases linearly. See the band diagram.

Since the carrier concentration decreases exponentially with energy in both bands, diffusion current increases exponentially as the barrier is reduced.

As the reverse-bias-voltage is increased, the diffusion current decreases rapidly to zero, since the fall-off in current is exponential.

Effect of bias on drift current

When the reverse-bias-voltage is increased, the net electric field increases, but drift current *does not* change. In this case, drift current is limited NOT by HOW FAST carriers are swept across the depletion layer, but rather HOW OFTEN.

The number of carriers drifting across the depletion layer is small because the number of minority carriers that diffuse towards the edge of the depletion layer is small.

To a first approximation, the drift current does not change with the applied voltage.

Effect of bias on the "net" current

$|I_{drift}|$ does not change with applied voltage, V_A

$|I_{diff}|$ varies exponentially with applied voltage (Why?) $|I_{diff}| = I_0 \exp(V_A/V_{ref})$ where I_0 and V_{ref} are constants.

Net current = $I_{diff} - I_{drift}$

At equilibrium, $V_A = 0$; Net current = 0

$$|I_{diff}|_{VA=0} = |I_{drift}|_{VA=0} = I_0$$

At any applied voltage, V_A,

$$I = I_0 \, e^{\frac{V_A}{V_{ref}}} - I_{drift} = I_0 \left(e^{\frac{V_A}{V_{ref}}} - 1 \right)$$

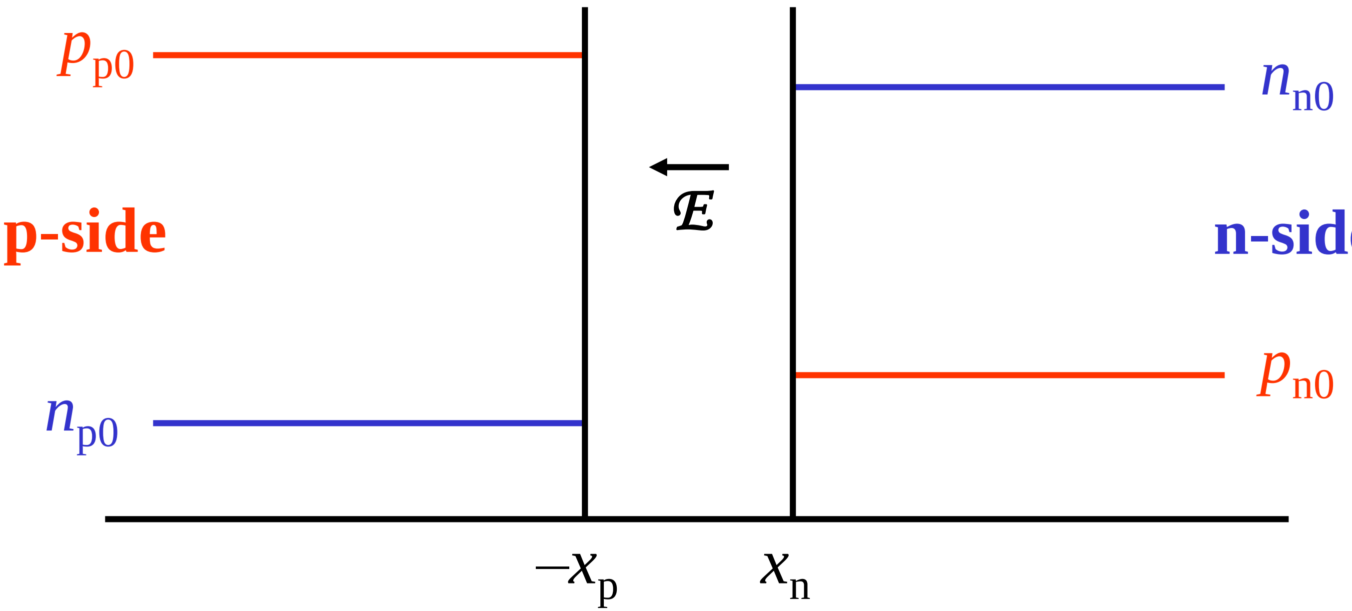
since $I_{drift} = I_0$ at any voltage.

Quantitative solution

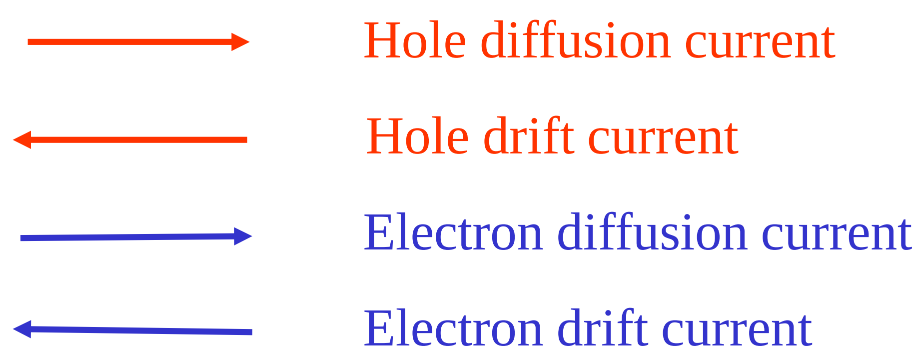
Assumptions which must hold

- The diode is being operated under steady state conditions
- A non-degenerately doped step junction models the doping profile
- The diode is one-dimensional
- Low-level injection (conditions) prevail in the quasi-neutral regions
- There are no processes other than drift, diffusion, and thermal recombination-generation taking place inside the diode, $G_L=0$

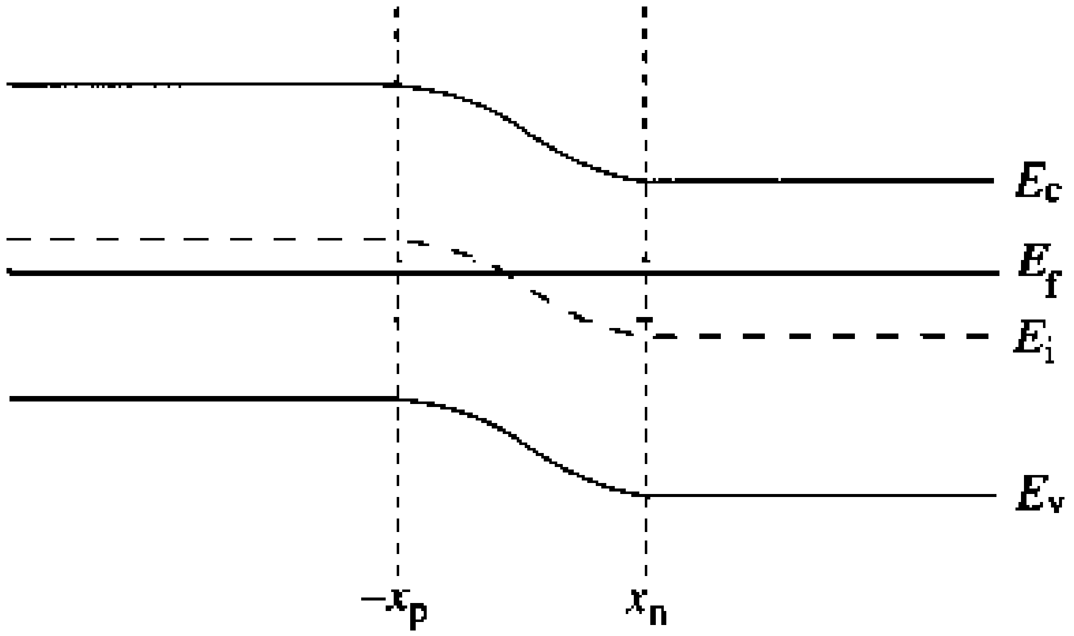
Majority and minority carrier concentration under equilibrium



Note: Subscript "0" refers to equilibrium conditions



Relationship between carrier concentration and V_{bi}



$$qV_{bi} = \left(E_i - E_F\right)_{\text{p-side}} + \left(E_F - E_i\right)_{\text{n-side}}$$

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{p_{p0}}{n_i}\right) + \frac{kT}{q} \ln\left(\frac{n_{n0}}{n_i}\right)$$

Relationship between carrier concentration and V_{bi}

$$V_{\mathrm{bi}} = \frac{kT}{q} \ln\left(\frac{p_{\mathrm{p0}}\, n_{\mathrm{n0}}}{n_{\mathrm{i}}^{2}}\right)$$

$$= \frac{kT}{q} \ln\left(\frac{p_{\mathrm{p0}}}{p_{\mathrm{n0}}}\right) \qquad \text{because} \qquad \frac{n_{\mathrm{i}}^{2}}{n_{\mathrm{n0}}} = p_{\mathrm{n0}}$$

Therefore, $\dfrac{p_{\mathrm{p0}}}{p_{\mathrm{n0}}} = \mathrm{e}^{\frac{qV_{\mathrm{bi}}}{kT}}$ and $\dfrac{n_{\mathrm{n0}}}{n_{\mathrm{p0}}} = \mathrm{e}^{\frac{qV_{\mathrm{bi}}}{kT}}$

$$\frac{\text{hole concentration on p-side}}{\text{hole concentration on n-side}} = \mathrm{e}^{\frac{qV_{\mathrm{bi}}}{kT}} = \frac{\text{electron concentration on n-side}}{\text{electron concentration on p-side}}$$

Strictly, these concentrations are at the depletion layer edge

Majority and minority carrier concentration under bias

When an external voltage is applied, the minority carrier concentration at the edge of the depletion layer will change. If a forward voltage (V_A=positive) is applied, the barrier will be lower and carrier injection (diffusion part) will increase. The minority carrier concentration at the edge of the depletion layer will increase.

If a reverse voltage (V_A = negative) is applied, the barrier for carrier injection (diffusion part) will increase, and the minority carrier concentration at the edge of the depletion layer will decrease.

The drift of minority carriers across the junction does not change much with applied voltage. Why?

At $V_A = 0$, the carrier injection and the drift of minority carriers cancel each other such that an equilibrium conc. is maintained.

If "low-level-injection" condition is assumed, then the majority carrier concentration will not change under any of the above conditions.

Relationship between carrier concentration and V_A

$$\frac{p_p}{p_n} = e^{\frac{q(V_{bi} - V_A)}{kT}}$$

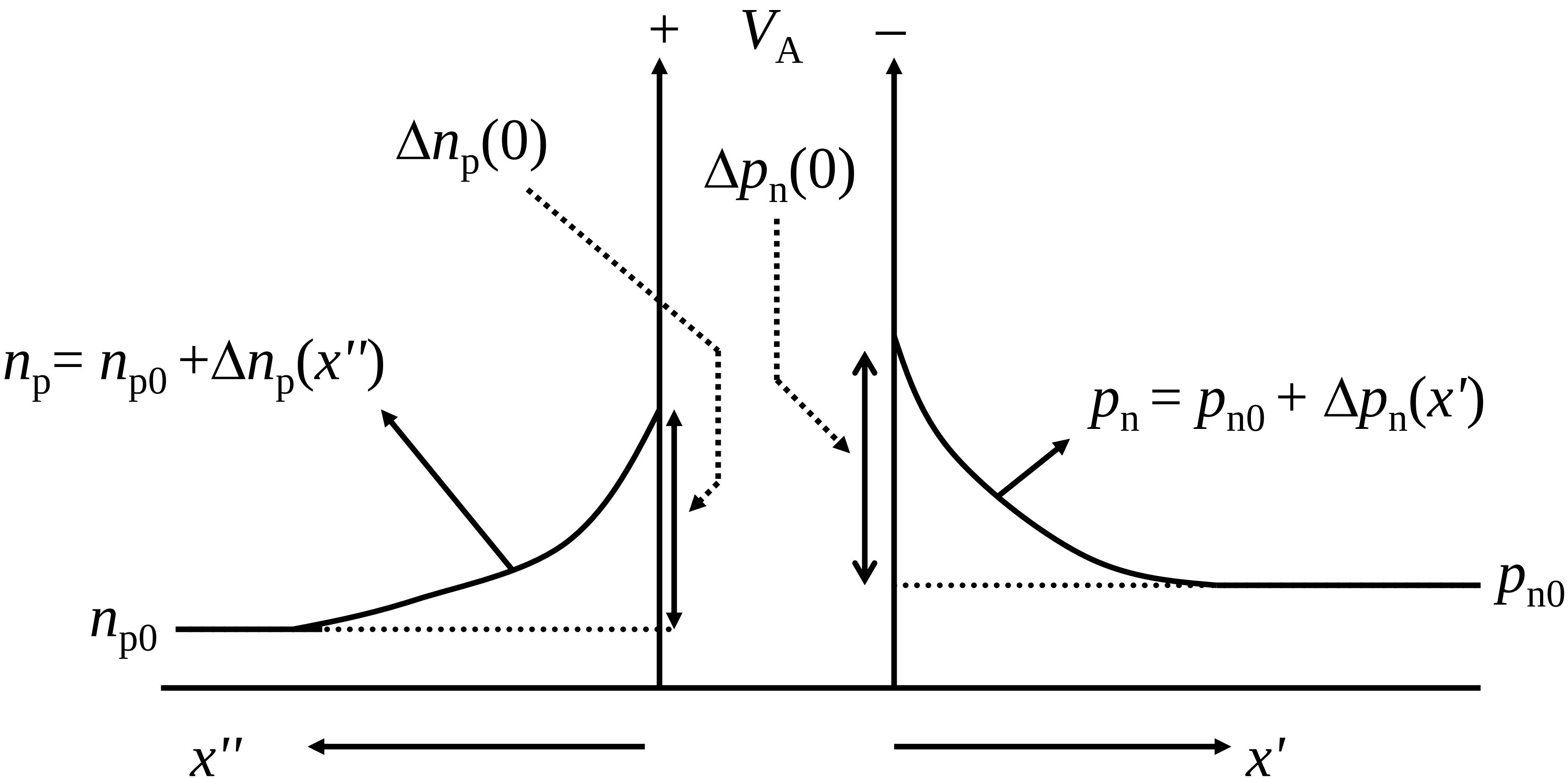
since (V_{bi} – V_A) is the net voltage (or barrier) when a forwarded voltage is applied.

At low-level injection: $p_p = p_{p0}$; Recall that $$\frac{p_{p0}}{p_{n0}} = e^{\frac{qV_{bi}}{kT}}$$

$$p_n = p_{p0}\, e^{-\frac{q(V_{bi} - V_A)}{kT}} = p_{p0}\, e^{\frac{-qV_{bi}}{kT}}\, e^{\frac{qV_A}{kT}} = p_{n0}\, e^{\frac{qV_A}{kT}}$$

then $$\boxed{\frac{p_n}{p_{n0}} = e^{\frac{qV_A}{kT}} \qquad \frac{n_p}{n_{p0}} = e^{\frac{qV_A}{kT}}}$$

Minority carrier concentration profile under bias



$$\Delta n_p(x'') = \Delta n_p(0)\, e^{-\frac{x''}{L_n}} \qquad \Delta p_n(x') = \Delta p_n(0)\, e^{-\frac{x'}{L_p}}$$

Relationship between applied voltage and excess minority carrier concentration

$$\frac{n_{\mathrm{p}}(0)}{n_{\mathrm{p0}}} = \mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}}$$

$$\frac{p_{\mathrm{n}}(0)}{p_{\mathrm{n0}}} = \mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}}$$

$$n_{\mathrm{p}}(0) = n_{\mathrm{p0}}\,\mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}}$$

$$p_{\mathrm{n}}(0) = p_{\mathrm{n0}}\,\mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}}$$

$$\Delta n_{\mathrm{p}}(0) = n_{\mathrm{p}}(0) - n_{\mathrm{p0}} = n_{\mathrm{p0}}\left(\mathrm{e}^{\frac{qV_{\mathrm{A}}}{kT}} - 1\right)$$

$$\Delta p_{\mathrm{n}}(0) = p_{\mathrm{n}}(0) - p_{\mathrm{n0}} = p_{\mathrm{n0}}\left(e^{\frac{qV_{\mathrm{A}}}{kT}} - 1\right)$$