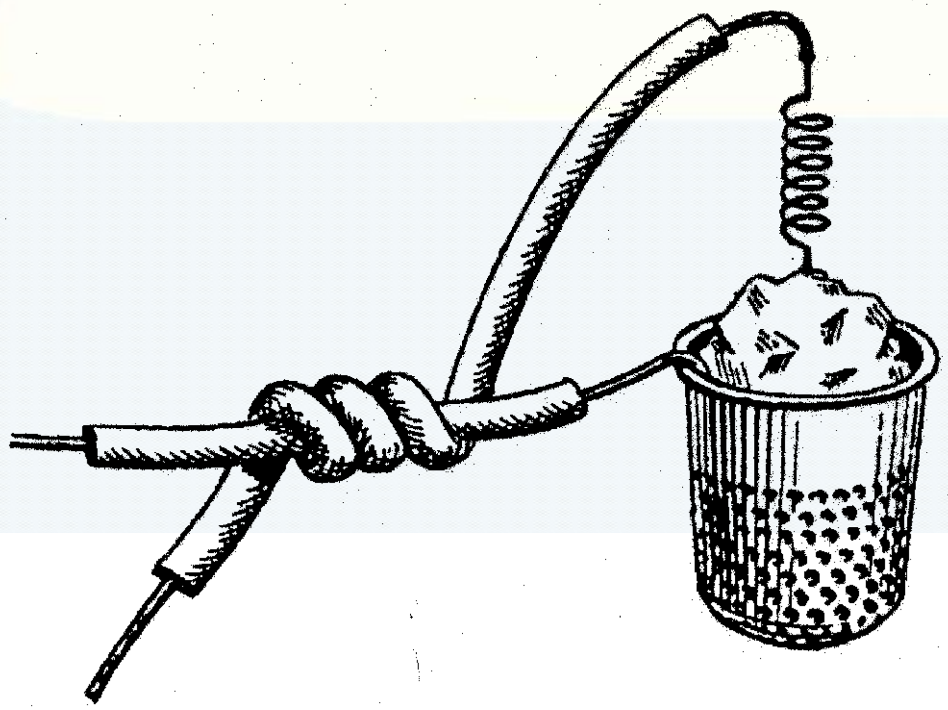
ELECTRONICS
Design Division

Introduction to semiconductor technology



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Outline

- 7 Field effect transistors
  - MOS transistor ”current equation"
  - MOS transistor channel mobility
  - Substrate bias effect
- **7 Bipolar transistors**
  - Introduction
  - Minority carrier distribution and terminal currents
  - Ebers Moll
  - 2nd-order effects

N-Channel MOS-transistor "current equation"

Differences in work function and charges in the oxide

$$V_{FB} = \Phi_{ms} - \frac{Q_i}{C_i}$$

Both fixed and moving charge carriers

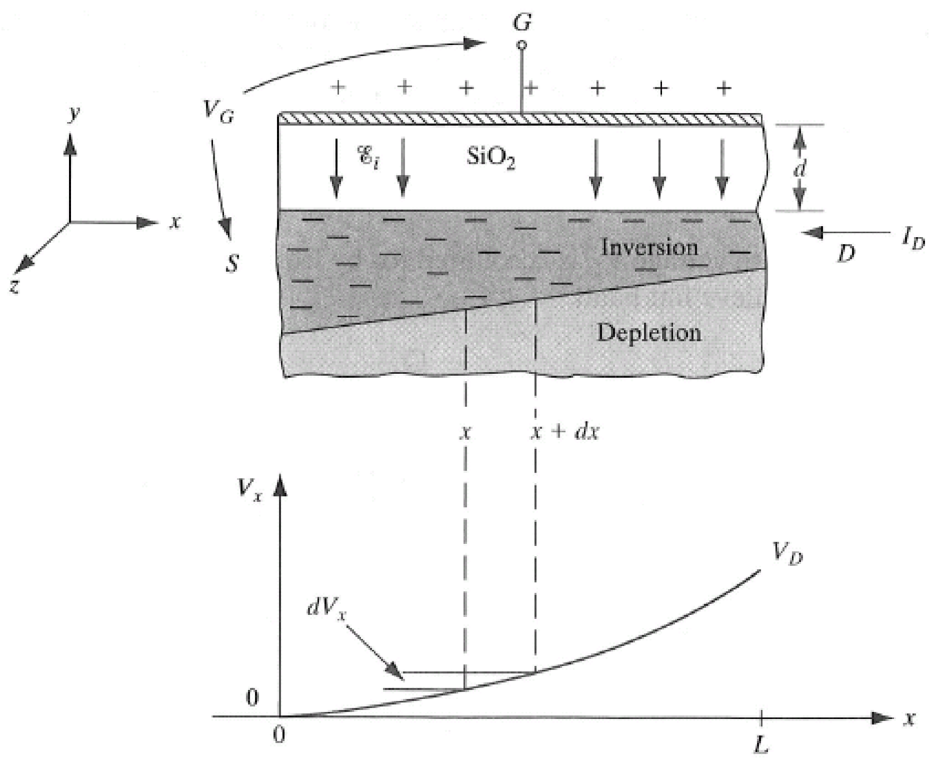
$$V_G = V_{FB} - \frac{Q_s}{C_i} + \phi_s$$

$Q_s = Q_n + Q_d$

Löser ut Q_n

$$Q_n = -C_i\left[V_G - \left(V_{FB} + \phi_s - \frac{Q_d}{C_i}\right)\right]$$

The moving charges in the channel



$$Q_n = -C_i\left[V_G - V_{FB} - 2\phi_F - V_x - \frac{1}{C_i}\sqrt{2q\epsilon_s N_a(2\phi_F + V_x)}\right]$$

N-Channel MOS-transistor ”current equation"

$$Q_n = -C_i\left[V_G - V_{FB} - 2\phi_F - V_x - \frac{1}{C_i}\sqrt{2q\epsilon_s N_a(2\phi_F + V_x)}\right]$$

Neglecting the voltage dependence of Qd (x)

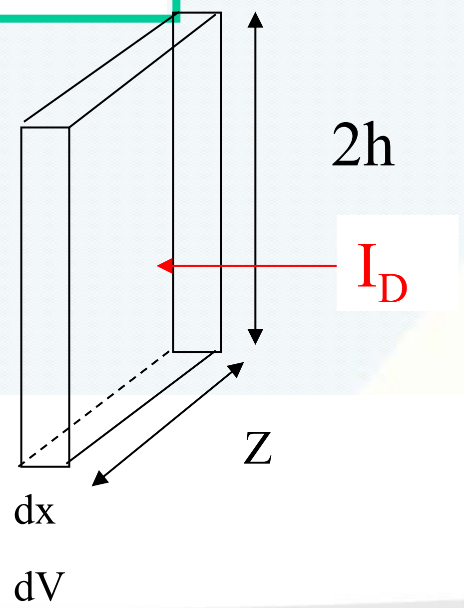
$$V_T = V_{FB} + 2\phi_F + Q_d(x)/C_i$$

$$Q_n(x) = -C_i(V_G - V_T - V_x)$$

JFET

$$I_D = \frac{Z2h(x)}{\rho}\frac{dV_x}{dx}$$

Resistivity (Ωcm)



$$I_D = \frac{dV_x}{R} = \frac{U}{R}$$

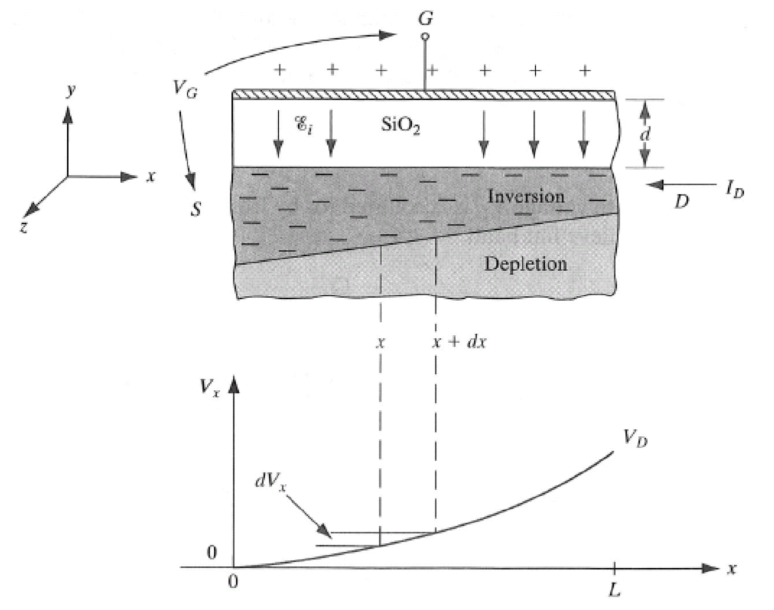
N-Channel MOS-transistor ”current equation"

For the MOS channel applies:

$$I_d = |Q_n(x)| \cdot Z \cdot v(x) = |Q_n(x)| \cdot Z \cdot \overline{\mu_n} \cdot \overline{E} = |Q_n(x)| \cdot Z \cdot \overline{\mu_n} \cdot \frac{dV_x}{dx}$$

$$\int_0^L I_D dx = \overline{\mu}_n Z C_i \int_0^{V_D} (V_G - V_T - V_x) dV_x$$

$$I_D = \frac{\overline{\mu}_n Z C_i}{L} [(V_G - V_T) V_D - \tfrac{1}{2} V_D^2]$$



N-Channel MOS-transistor ”current equation"

$$Q_n = -C_i\left[V_G - V_{FB} - 2\phi_F - V_x - \frac{1}{C_i}\sqrt{2q\epsilon_s N_a(2\phi_F + V_x)}\right]$$

$$I_D = \frac{\overline{\mu}_n Z C_i}{L}$$

”pust”

$$\times\left\{\left(V_G - V_{FB} - 2\phi_F - \tfrac{1}{2}V_D\right)V_D - \frac{2}{3}\,\frac{\sqrt{2\epsilon_s q N_a}}{C_i}\left[(V_D + 2\phi_F)^{3/2} - (2\phi_F)^{3/2}\right]\right\}$$

The conductivity in the linear part can be described by

$$g = \frac{\partial I_D}{\partial V_D} \simeq \frac{Z}{L}\overline{\mu}_n C_i(V_G - V_T)$$

$V_D << V_G - V_T$

N-Channel MOS-transistor ”current equation"

In the saturated region applies:

$$V_D(\text{sat.}) \simeq V_G - V_T$$

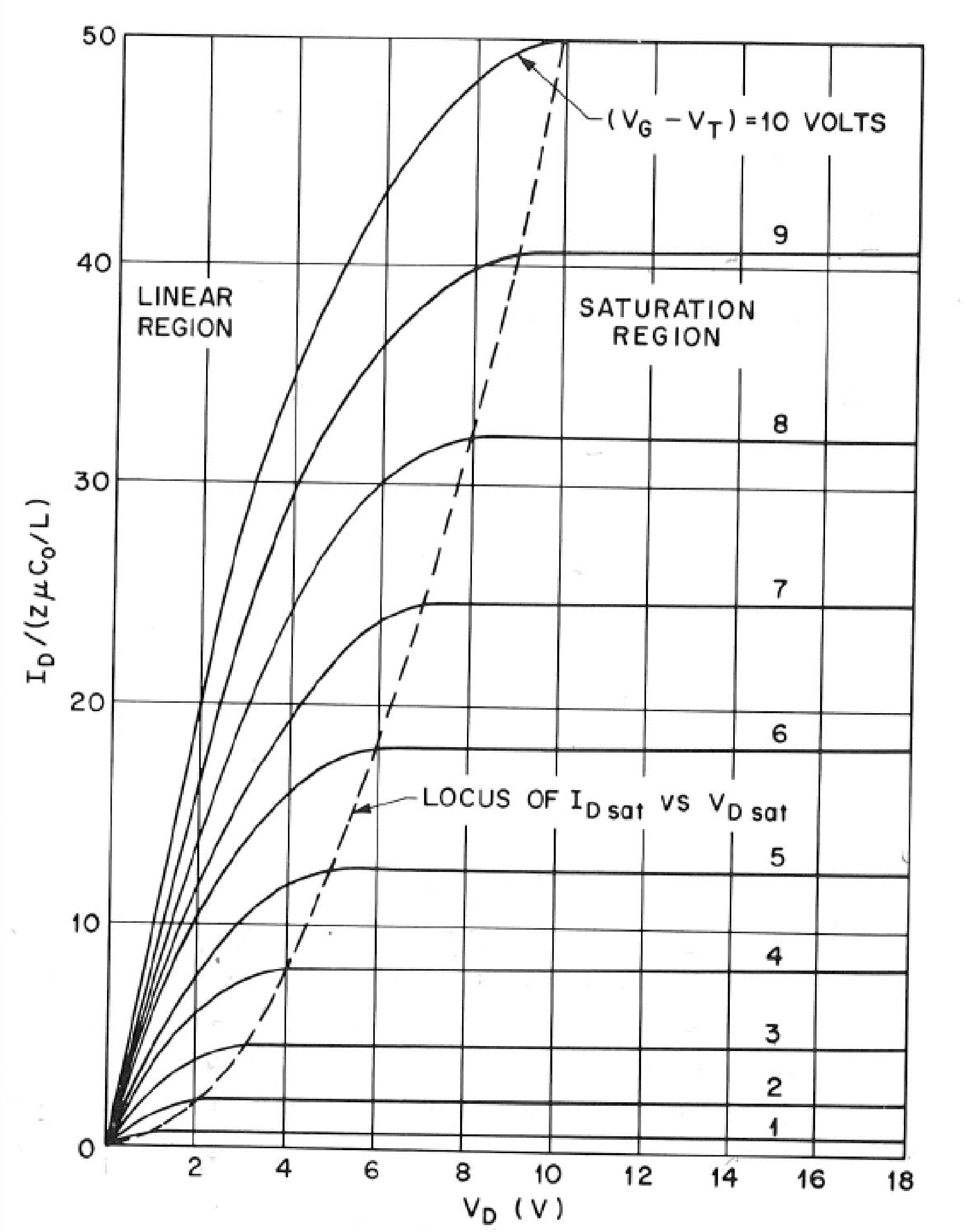
$$I_D = \frac{\bar{\mu}_n Z C_i}{L}\left[(V_G - V_T)V_D - \tfrac{1}{2}V_D^2\right]$$

$$I_D(\text{sat.}) \simeq \tfrac{1}{2}\bar{\mu}_n C_i \frac{Z}{L}(V_G - V_T)^2 = \frac{Z}{2L}\bar{\mu}_n C_i V_D^2(\text{sat.})$$

N-Channel MOS-transistor ”current equation"

Transconductance in saturerad region:

$$g_m(\text{sat.}) = \frac{\partial I_D(\text{sat.})}{\partial V_G} \simeq \frac{Z}{L}\overline{\mu}_n C_i (V_G - V_T)$$



MOS transistor channel mobility

$$\mathscr{E}_{eff} = \frac{1}{\epsilon_s}\left(Q_d + \frac{1}{2}Q_n\right)$$

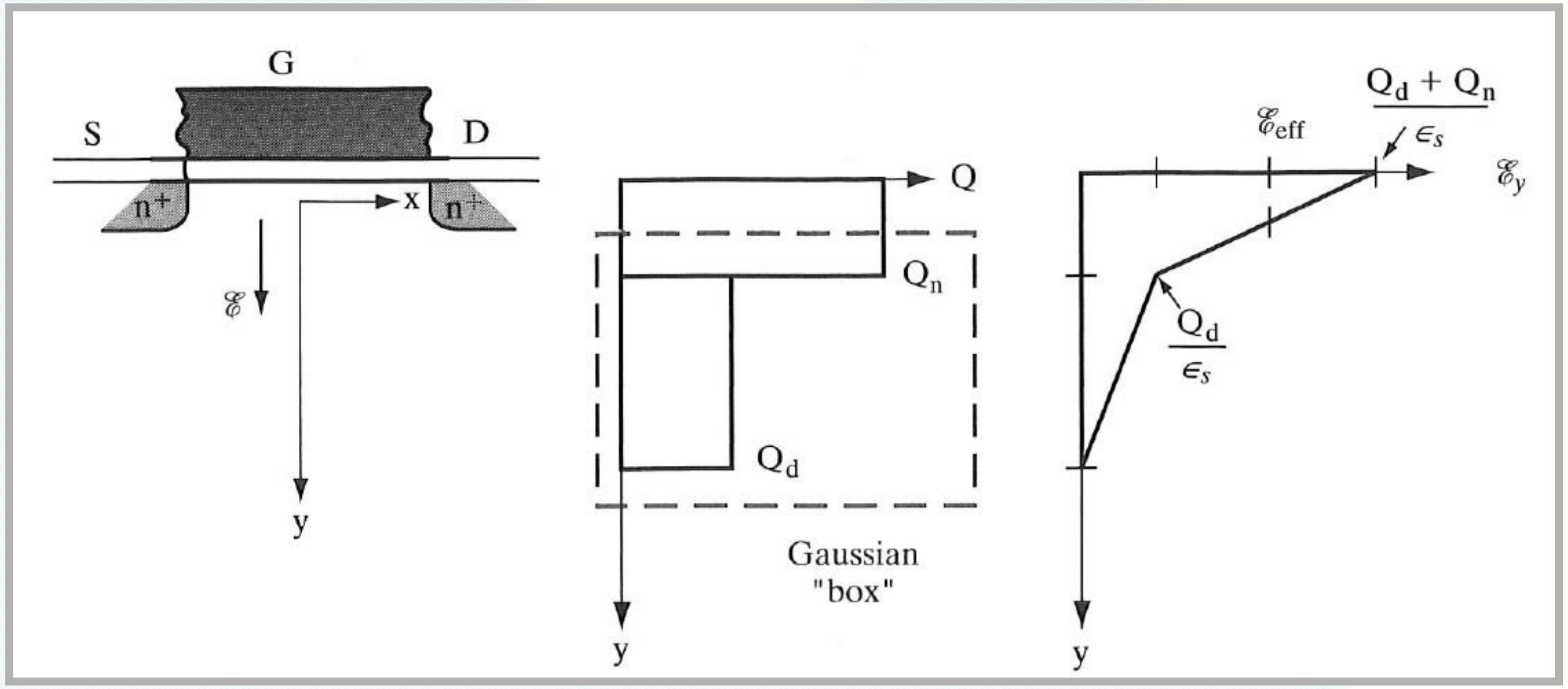
$$\mathscr{E}_{eff} = \frac{1}{\epsilon_s}\left(Q_d + \frac{1}{3}Q_n\right)$$

The effective electric field according to the enclosed charging according to the "gauss theorem"

Electron

hole

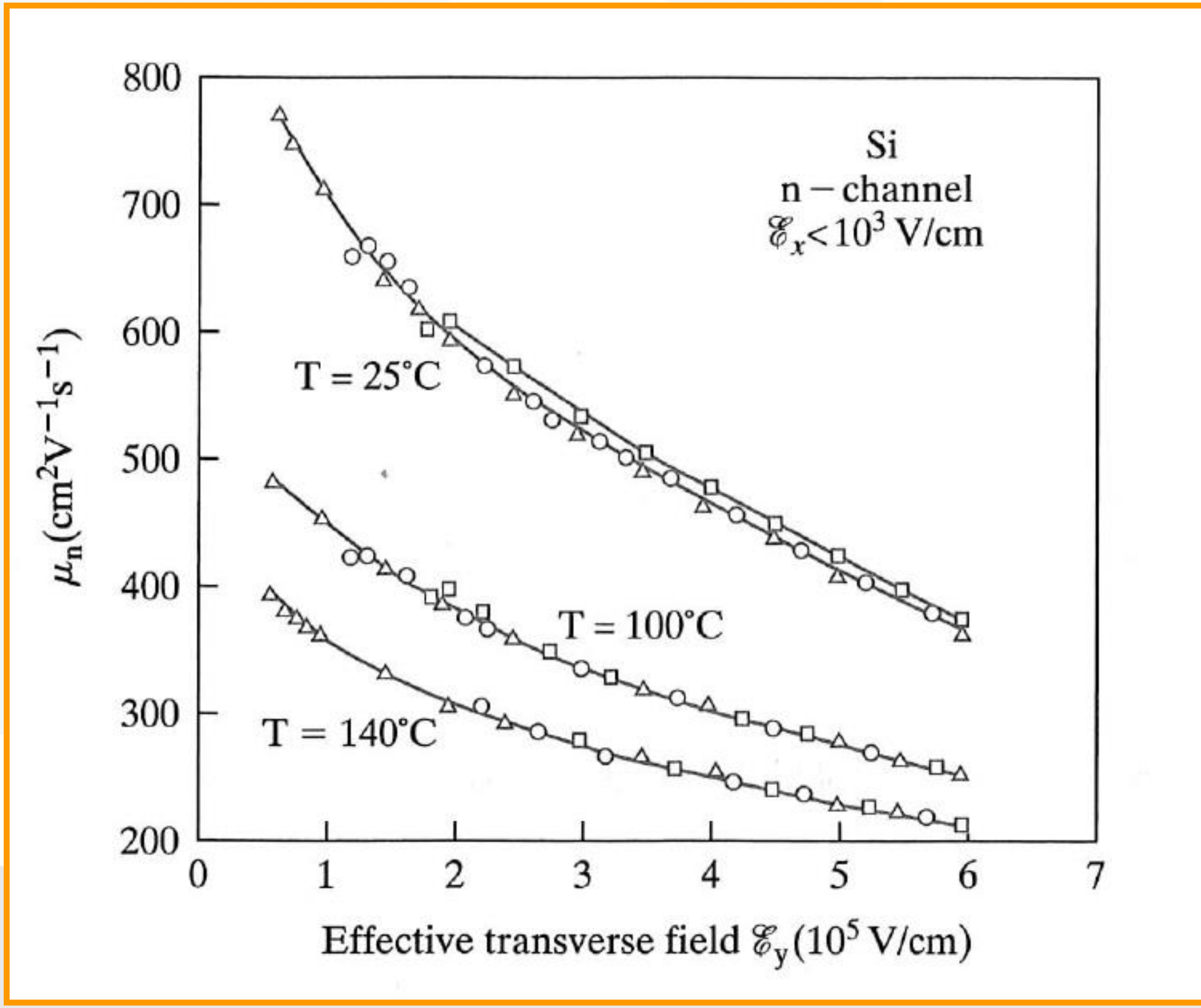
MOS transistor channel mobility



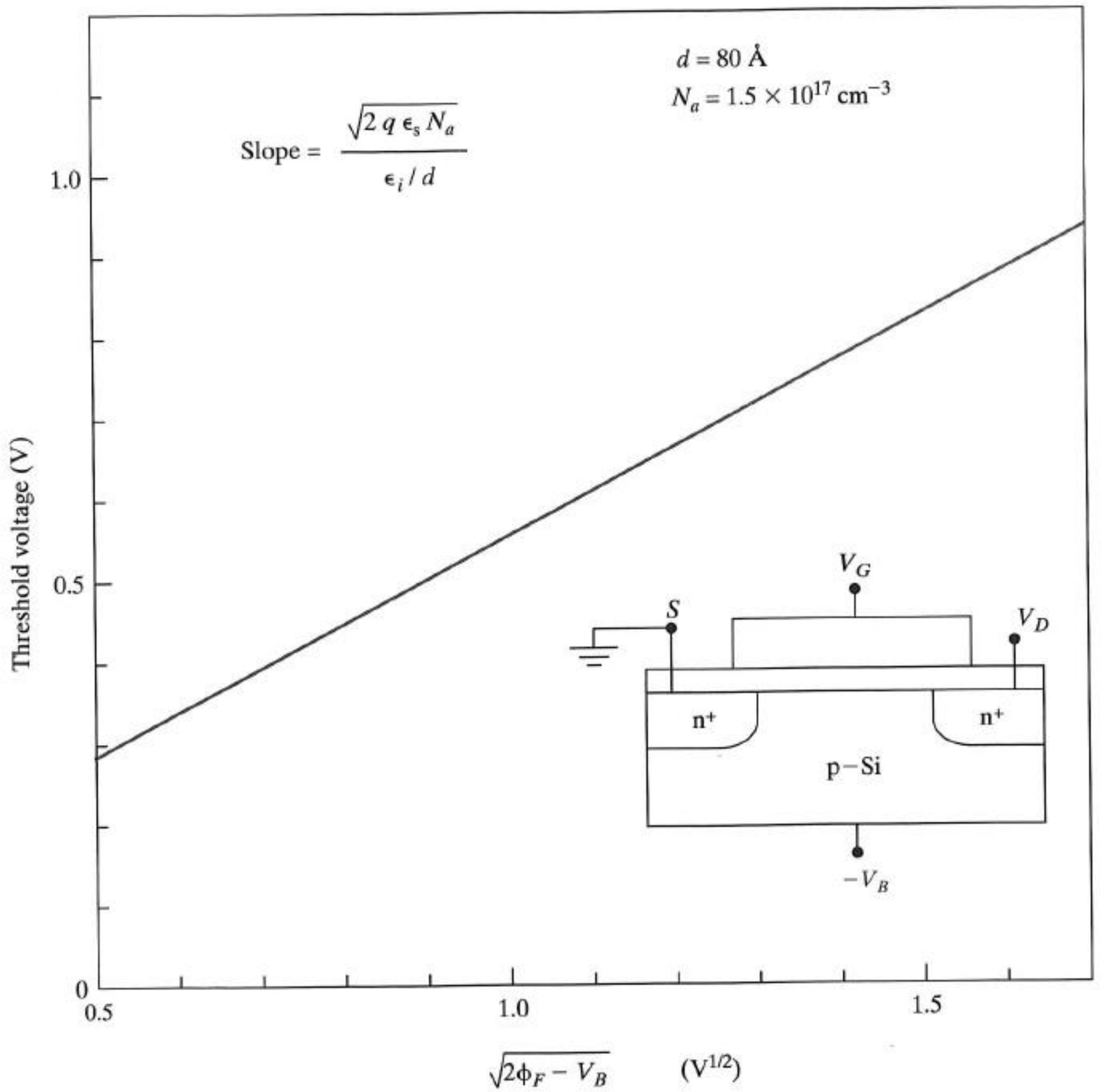
$$I_D = \frac{\overline{\mu}_n Z C_i}{L\{1 + \theta(V_G - V_T)\}}\left[(V_G - V_T)V_D - \frac{1}{2}V_D^2\right]$$

Mobility degrading factor

MOS transistor channel mobility



Substrate bias effect



The substrate has previously been connected to the source terminal. In some cases, a potential arise between the source and the substrate. One example is the integrated circuits in which the source electrode must be kept insulated from the substrate. A number of transistors can then be attached optionally, without interfering. Note the substrate must be reverse biased relative to the source and drain

Substrate bias effect

MOS capacitance at strong inversion

$$Q'_d = -[2\epsilon_s q N_a (2\phi_F - V_B)]^{1/2}$$

$$= -2(\epsilon_s q N_a \phi_F)^{1/2}$$

$$\Delta V_T = \frac{\sqrt{2\epsilon_s q N_a}}{C_i}[(2\phi_F - V_B)^{1/2} - (2\phi_F)^{1/2}]$$

$$V_T = -\frac{Q_d}{C_i} + 2\phi_F \quad (ideal\ case)$$

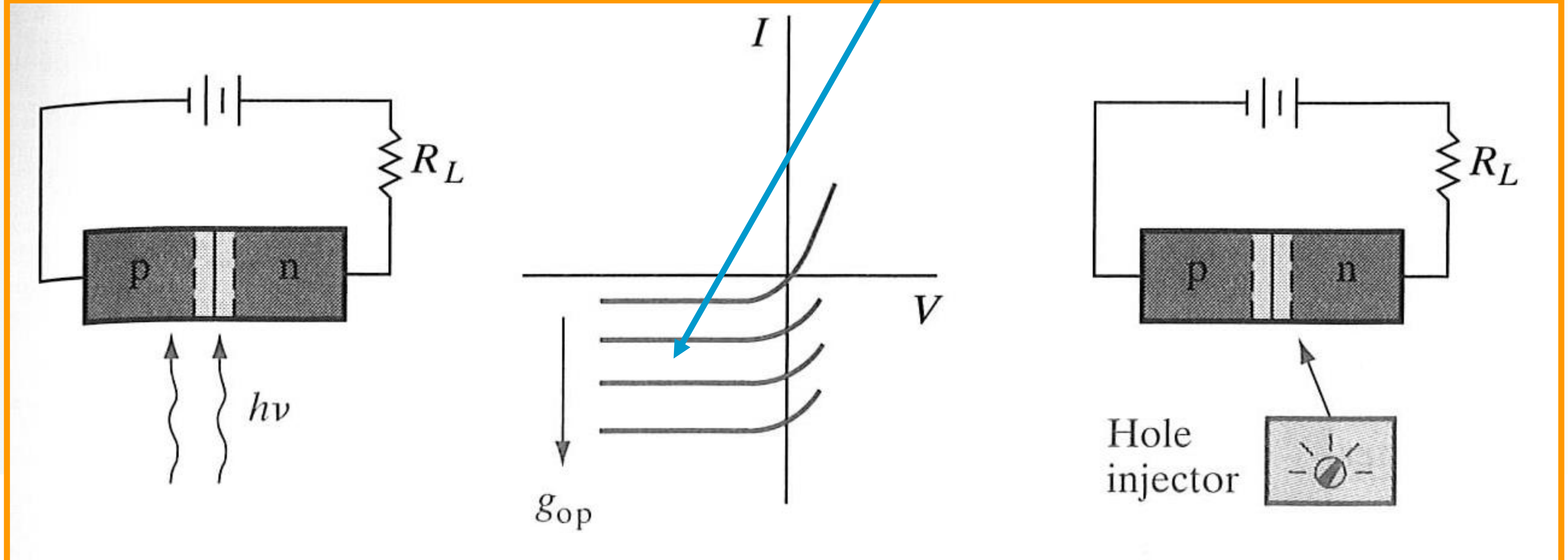
$$\Delta V_T \simeq \frac{\sqrt{2\epsilon_s q N_a}}{C_i}(-V_B)^{1/2} \quad \text{(n channel)}$$

If $V_B >> 2\Phi_F (0.6V)$

Bipolar transistor, introduction

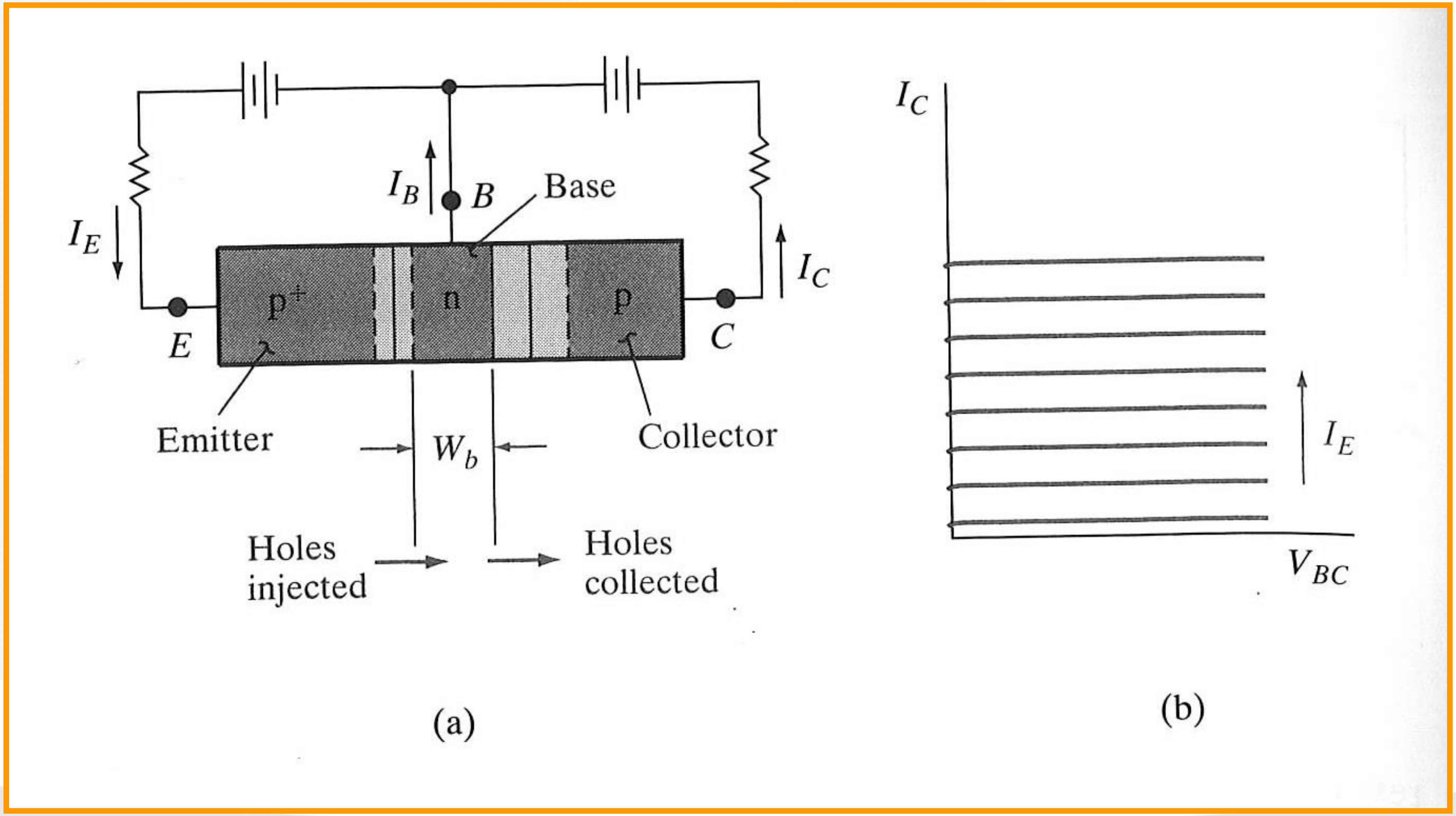
a) A diode with lighting

controllable diode!

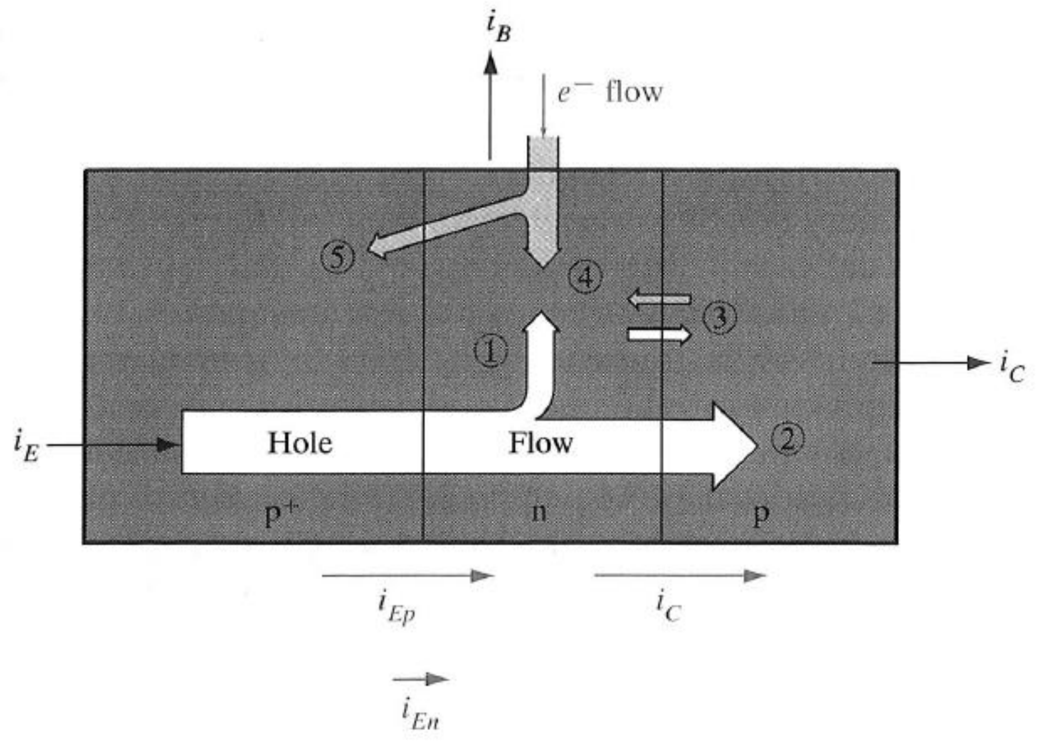


(a) (b) (c)

Bipolar transistor, introduction (pnp)



the transistor, introduction (pnp)



In broad terms is the fkn as follows, The Emitter injecting minority carriers (holes) in the base, hopefully recombines the holes not in too large amount with electrons entering the base, instead diffuses the hole towards to the collector. The collector is reverse biased and when the holes is close to the junction they swept by the electric field into the collector. The holes reaching the collector contact recombines in equivalent amount of as electrons are added to the contact via the “collector” wire

$$W_b << L_p$$

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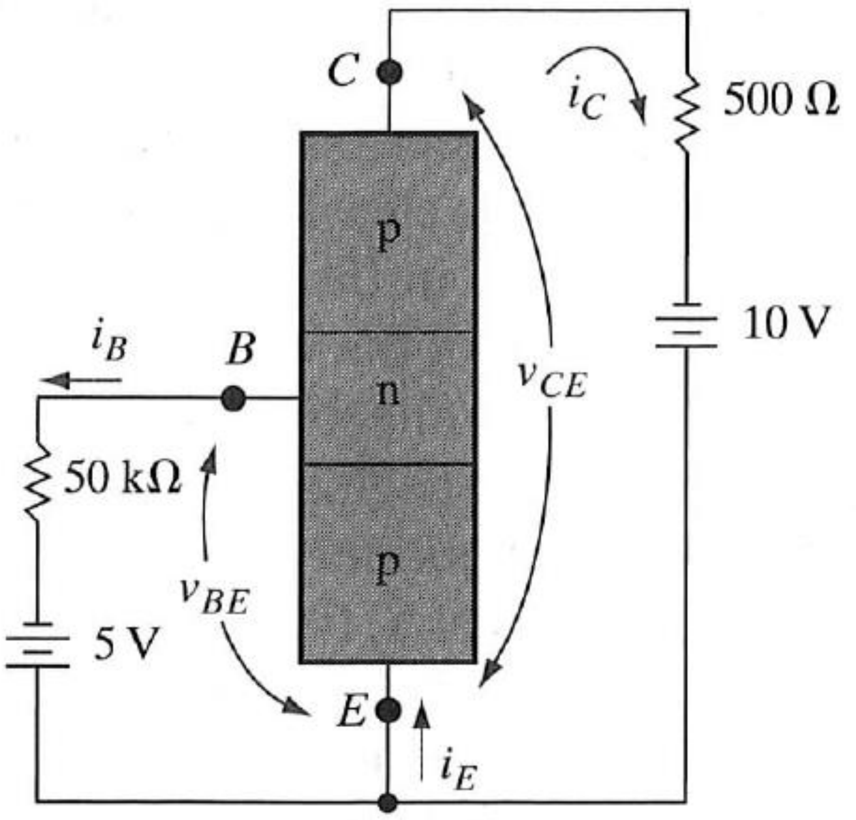
the transistor, introduction, terminal currents and parameters



$$i_C = Bi_{Ep}$$

Hole current

Base transport factor

$$\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}$$

Emitter injection efficiency

$$\frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma \equiv \alpha$$

Current transfer ratio

$$\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$$

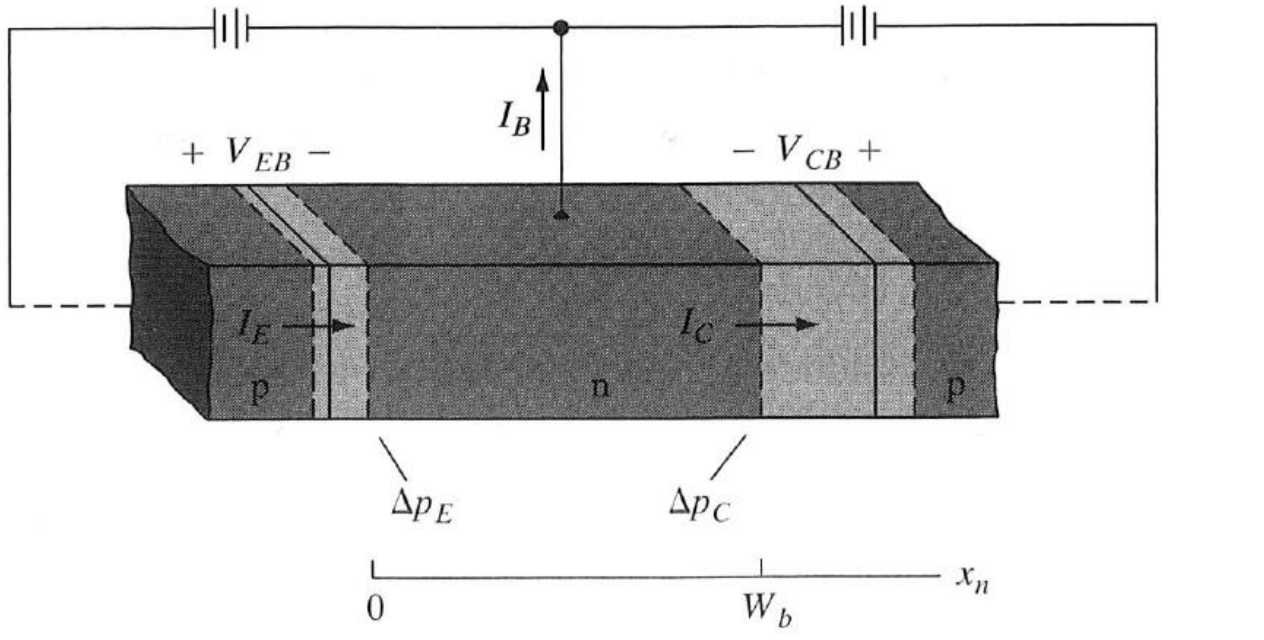
Current amplification factor

Minority carrier distribution and terminal currents (pnp)

Some simplifications and assumptions:

- Holes diffuse from emitter to collector "no drift in base“
- Emitter current consists only of hole current
- No saturation in the collector current
- A dimensional analysis
- Currents and voltages are in the "steady state"-no change

Minority carrier distribution (pnp)



(a)

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$
$$\Delta p_C = p_n(e^{qV_{CB}/kT} - 1)$$

Emitter diode is forward biased and the collector-diode is reversed biased, which results in:

$$\Delta p_E \simeq p_n e^{qV_{EB}/kT}$$
$$\Delta p_C \simeq -p_n$$

Minority carrier distribution (pnp)

$$\frac{d^2\delta p(x_n)}{dx_n^2} = \frac{\delta p(x_n)}{L_p^2}$$

Possible to solve the distribution of hole concentration in the base (see 4-34b)

$$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}$$

The solution for hole in the base region

$$\delta p(x_n = 0) = C_1 + C_2 = \Delta p_E$$

$$\delta p(x_n = W_b) = C_1 e^{W_b/L_p} + C_2 e^{-W_b/L_p} = \Delta p_C$$

Constraints

Minority carrier distribution

$$C_1 = \frac{\Delta p_C - \Delta p_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$C_2 = \frac{\Delta p_E e^{W_b/L_p} - \Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

The solution gives C_1 and C_2

$$\delta p(x_n) = \Delta p_E \frac{e^{W_b/L_p} e^{-x_n/L_p} - e^{-W_b/L_p} e^{x_n/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \quad (\text{for } \Delta p_C \simeq 0)$$

Hole distribution in the base

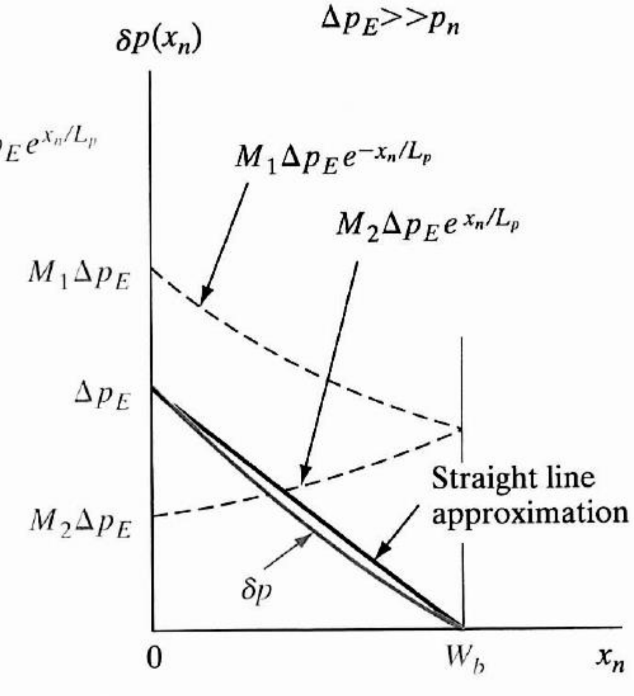
Minority carrier distribution

$$\delta p(x_n) = M_1 \Delta p_E e^{-x_n/L_p} - M_2 \Delta p_E e^{x_n/L_p}$$

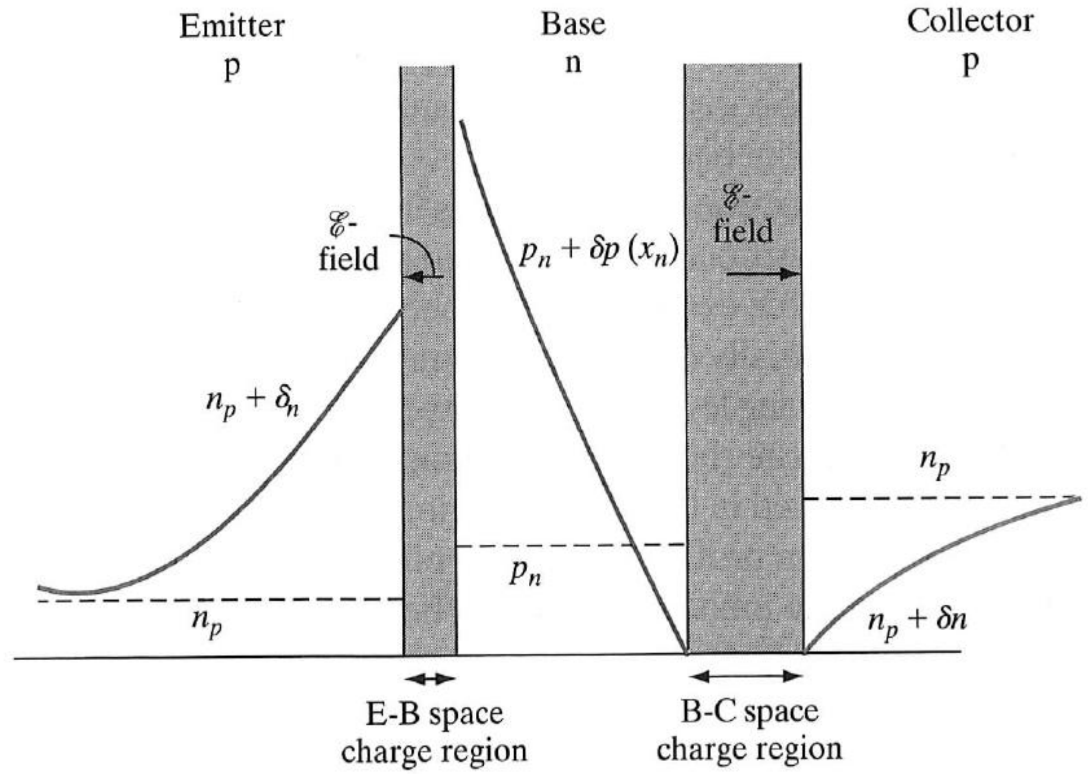
where

$$M_1 = \frac{e^{W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$M_2 = \frac{e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$



(a)



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Terminal currents

$$I_p(x_n) = -qAD_p \frac{d\delta p(x_n)}{dx_n}$$

From EQ. 4-22b, hole current in the base

$$I_{Ep} = I_p(x_n = 0) = qA\frac{D_p}{L_p}(C_2 - C_1)$$

Emitter current

$$I_C = I_p(x_n = W_b) = qA\frac{D_p}{L_p}(C_2 e^{-W_b/L_p} - C_1 e^{W_b/L_p})$$

Collector current

Terminal currents

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta p_C \operatorname{csch}\frac{W_b}{L_p}\right)$$

$$I_C = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{csch}\frac{W_b}{L_p} - \Delta p_C \operatorname{ctnh}\frac{W_b}{L_p}\right)$$

Hyperbolic fkn!

$$I_B = I_E - I_C = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\left(\operatorname{ctnh}\frac{W_b}{L_p} - \operatorname{csch}\frac{W_b}{L_p}\right)\right]$$

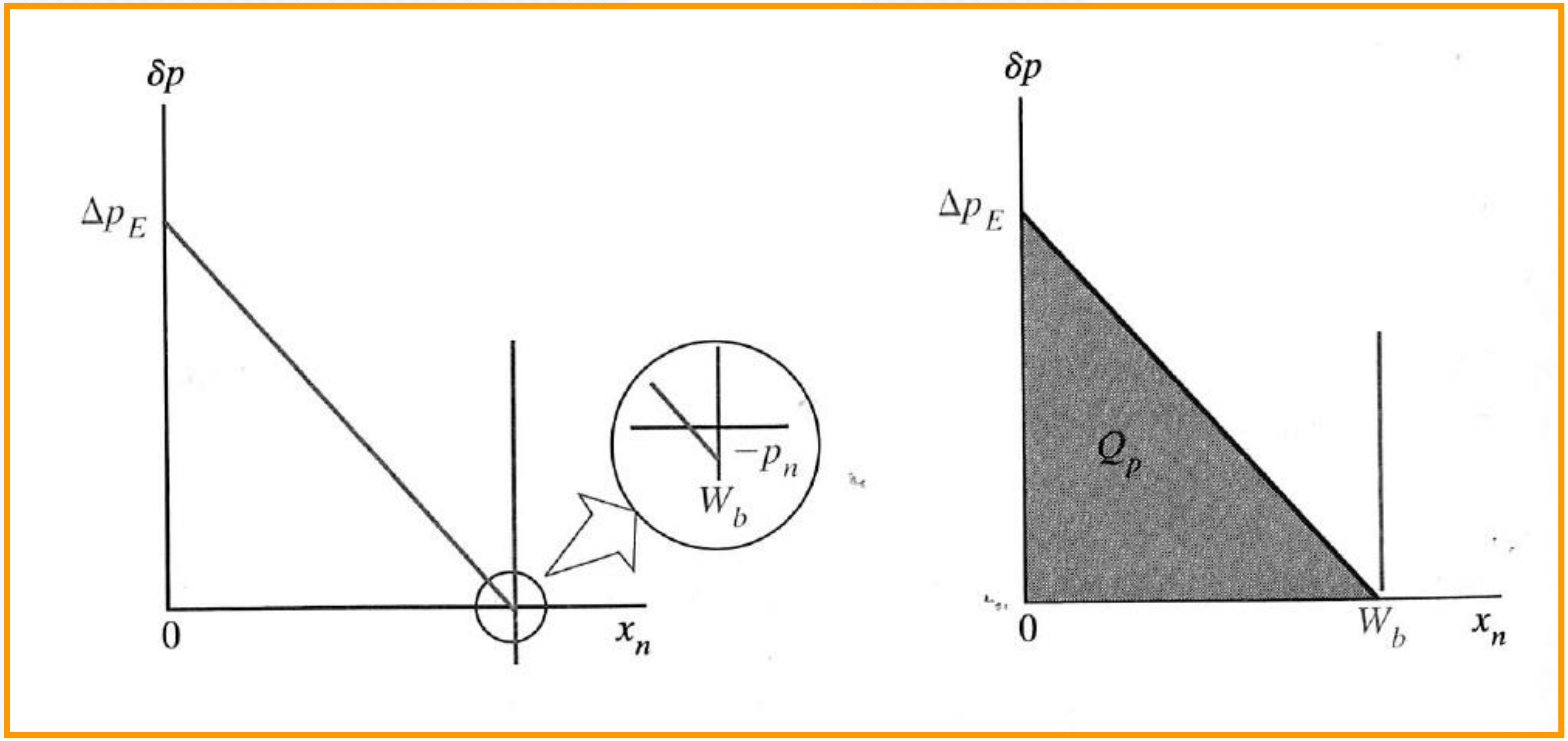
$$I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_b}{2L_p}\right]$$

If

$I_E \simeq I_{Ep}$ for $\gamma \simeq 1$

gives the base current

Terminal currents, approximation



If the collector diode is greatly reverse biased applies

$\Delta p_c \sim -p_n \ (\sim 0)$

Terminal currents, approximation

If the collector diode is greatly reverse biased applies
$\Delta p_c \sim -p_n (\sim 0)$

$$I_E \simeq qA\frac{D_p}{L_p}\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p}$$

$$I_C \simeq qA\frac{D_p}{L_p}\Delta p_E \operatorname{csch}\frac{W_b}{L_p}$$

$$I_B \simeq qA\frac{D_p}{L_p}\Delta p_E \tanh\frac{W_b}{2L_p}$$

Terminal currents, approximation

$$\operatorname{sech} y = 1 - \frac{y^2}{2} + \frac{5y^4}{24} - \ldots$$

$$\operatorname{ctnh} y = \frac{1}{y} + \frac{y}{3} - \frac{y^3}{45} + \ldots$$

$$\operatorname{csch} y = \frac{1}{y} - \frac{y}{6} + \frac{7y^3}{360} - \ldots$$

$$\tanh y = y - \frac{y^3}{3} + \ldots$$

$W_b/L_p<<1$

$$I_B \simeq qA\frac{D_p}{L_p}\Delta p_E\frac{W_b}{2L_p} = \frac{qAW_b\Delta p_E}{2\tau_p}$$

Use two terms from the serie

$$\begin{aligned} I_B &= I_E - I_C \\ &\simeq qA\frac{D_p}{L_p}\Delta p_E\left[\left(\frac{1}{W_b/L_p} + \frac{W_b/L_p}{3}\right) - \left(\frac{1}{W_b/L_p} - \frac{W_b/L_p}{6}\right)\right] \\ &\simeq \frac{qAD_pW_b\Delta p_E}{2L_p^2} = \frac{qAW_b\Delta p_E}{2\tau_p} \end{aligned}$$

Terminal currents, approximation, charge model

$$Q_p \simeq \tfrac{1}{2} q A \, \Delta p_E W_b$$

Hole distribution in the base,
Triangle-approximation

$$I_B \simeq \frac{Q_p}{\tau_p} = \frac{q A W_b \Delta p_E}{2\tau_p}$$

The holes must be replaced with the same speed according to the recombination

The equation is consistent
with previous derivation!

Emitter-injection factor, base-transport factor

Emitter current consists of holes-injection and electron-injection charges only if γ=1
For γ<1 ;

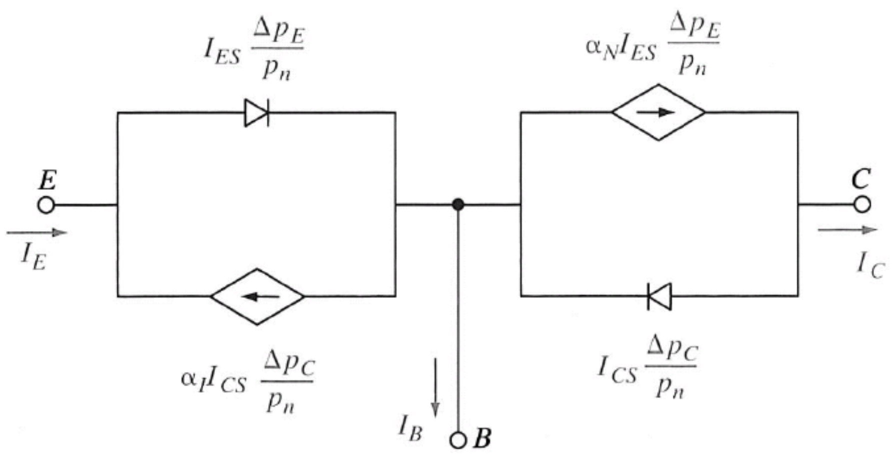
$$\gamma = \left[1 + \frac{L_p^n n_n \mu_n^p}{L_n^p p_p \mu_p^n} \tanh \frac{W_b}{L_p^n}\right]^{-1} \simeq \left[1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n}\right]^{-1}$$

$$B = \frac{I_C}{I_{Ep}} = \frac{\operatorname{csch} W_b/L_p}{\operatorname{ctnh} W_b/L_p} = \operatorname{sech} \frac{W_b}{L_p}$$

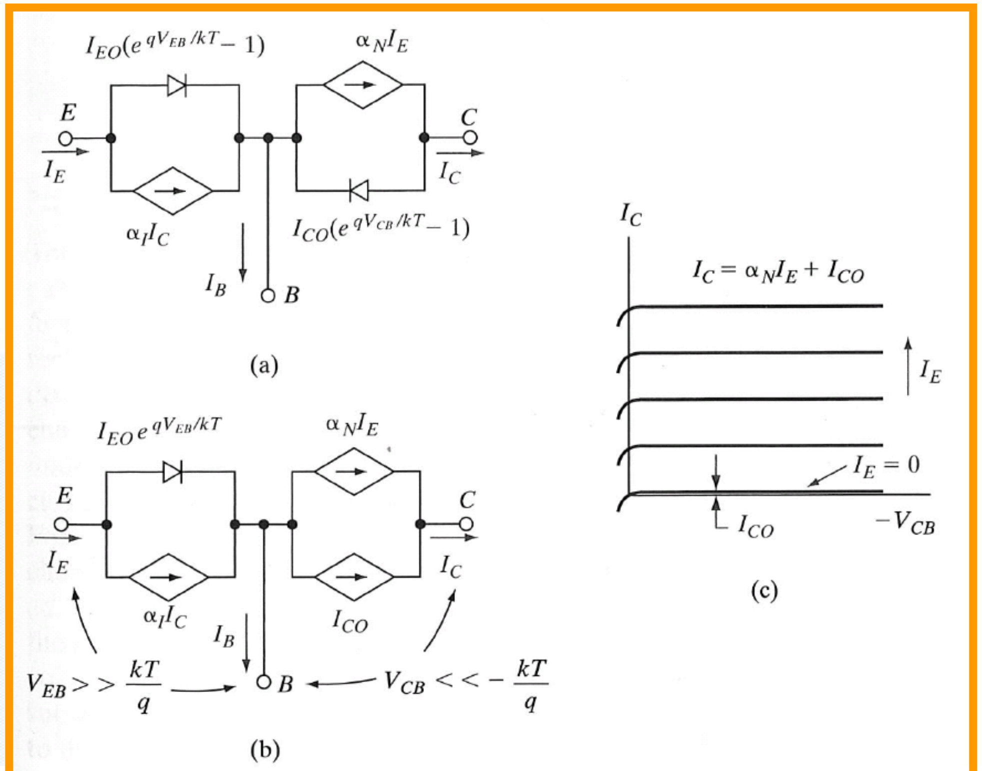
$$i_C = B i_{Ep}$$

Ebers-Moll Equations coupled diode model, overview

$$I_E = I_{ES}\frac{\Delta p_E}{p_n} - \alpha_I I_{CS}\frac{\Delta p_C}{p_n} = \frac{I_{ES}}{p_n}(\Delta p_E - \alpha_N \Delta p_C)$$

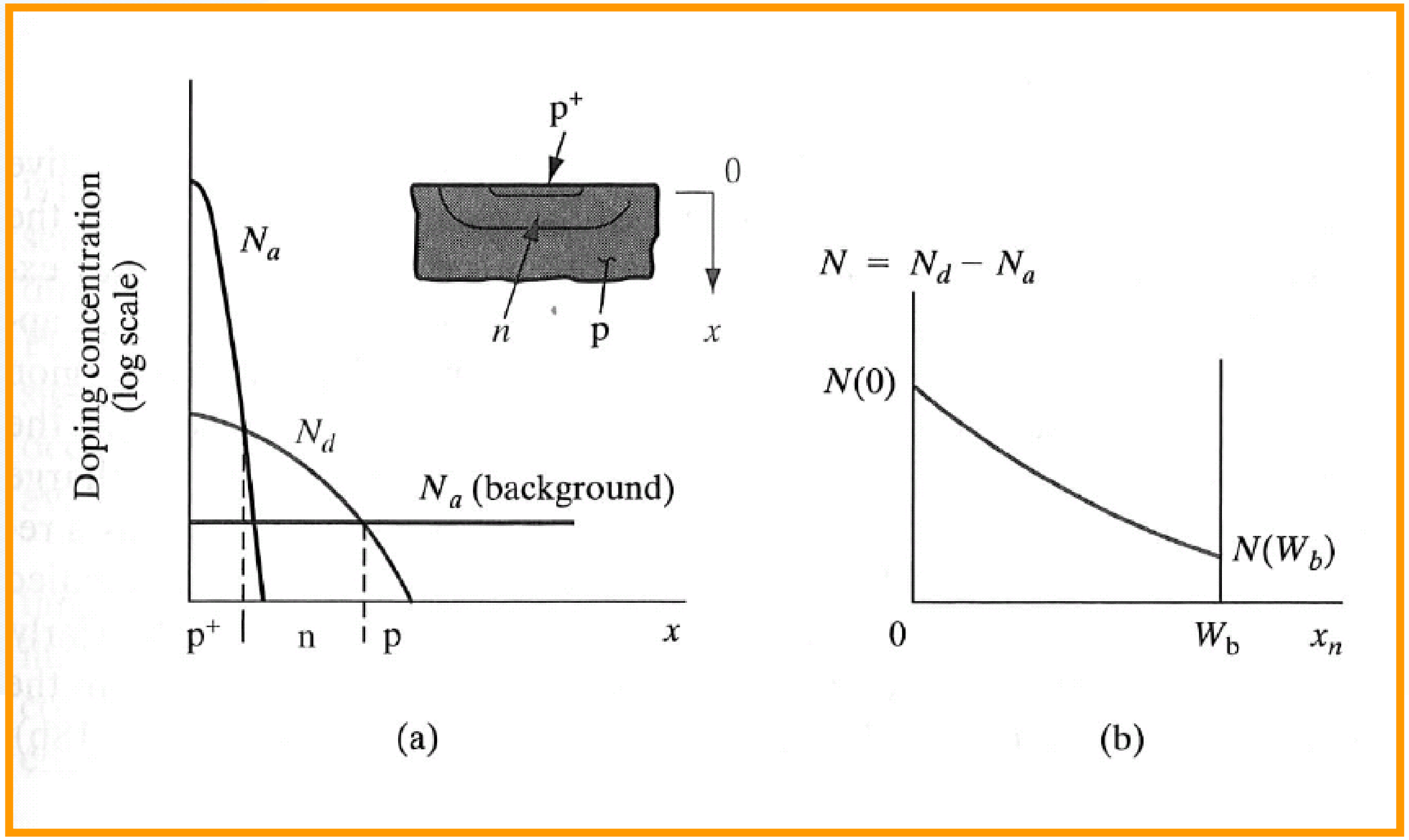


$$I_B = (1-\alpha_N)\, I_{ES}\frac{\Delta p_E}{p_n} + (1-\alpha_I)\, I_{CS}\frac{\Delta p_C}{p_n}$$



2nd-order effects, doping profile base

The base is not homogeneously doped but instead has a decreasing doping profile! The doping profile creates an electric field



2nd-order effects, doping profile base

$$I_n(x_n) = qA\mu_n N(x_n)\mathscr{E}(x_n) + qAD_n \frac{dN(x_n)}{dx_n} = 0$$

Balance of drift and diffusion-currents in the base (majority carrier, electrons in this case)

$$\mathscr{E}(x_n) = -\frac{D_n}{\mu_n}\frac{1}{N(x_n)}\frac{dN(x_n)}{dx_n} = -\frac{kT}{q}\frac{1}{N(x_n)}\frac{dN(x_n)}{dx_n}$$

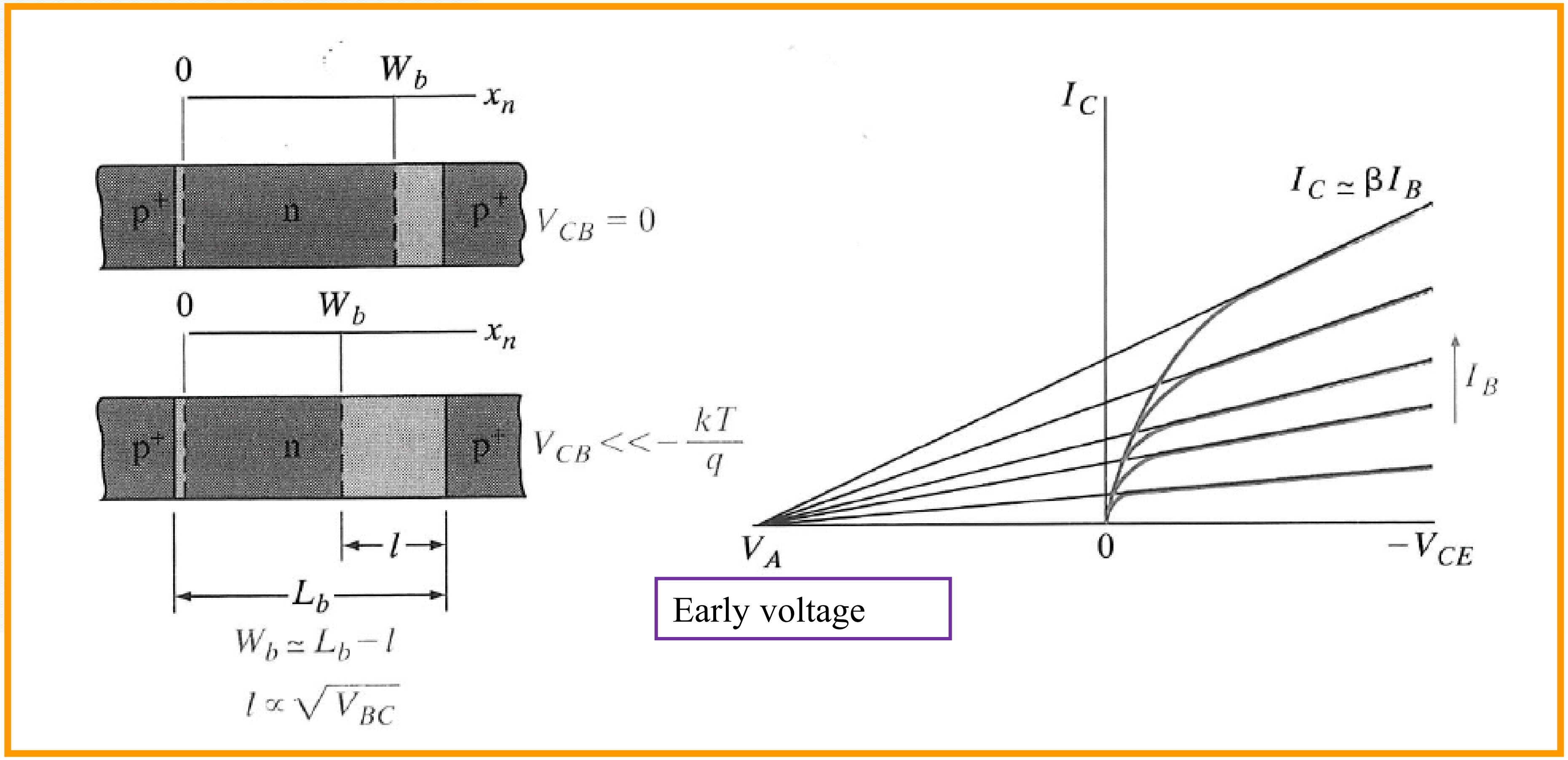
$$N(x_n) = N(0)e^{-ax_n/W_b} \qquad \text{where } a \equiv \ln\frac{N(0)}{N(W_b)}$$

$$\mathscr{E}(x_n) = \frac{kT}{q}\frac{a}{W_b}$$

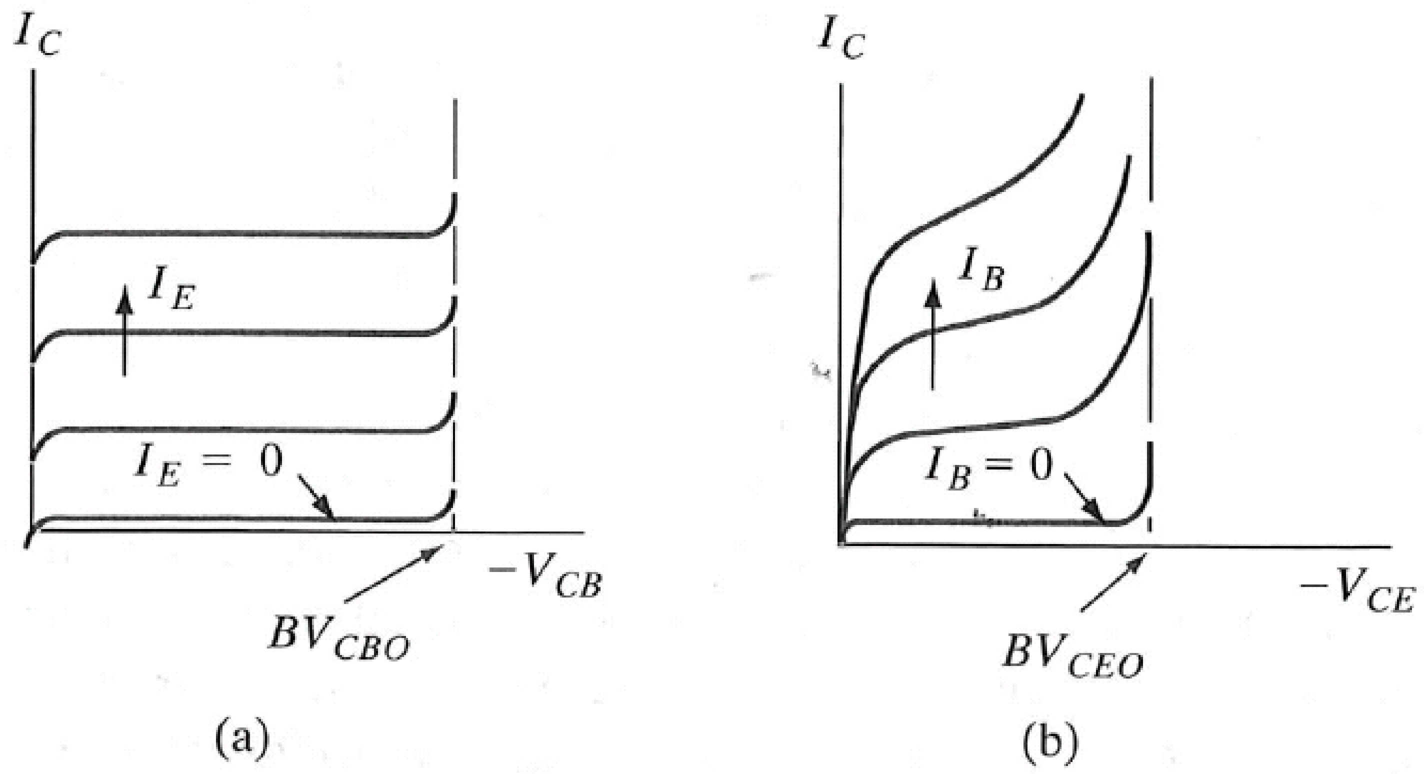
The electric field will helps the holes above the base region

Base width modulation

Especially when the collector has a higher doping

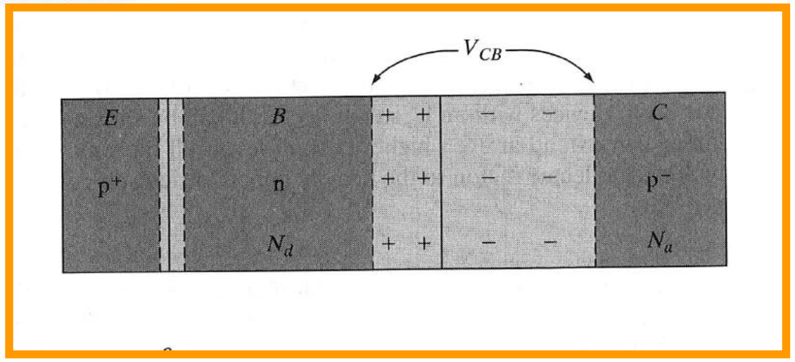


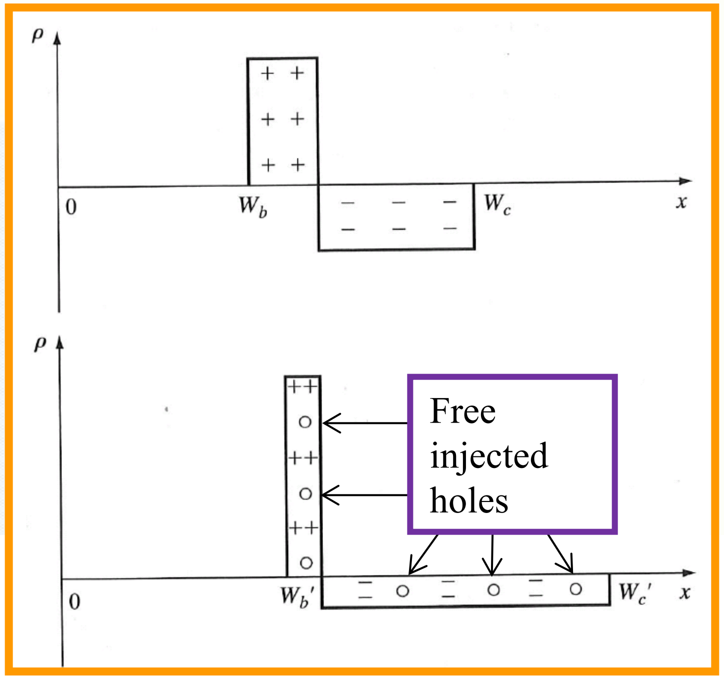
Avalanche breakthrough in collector base diode



current gain factor decreases with higher currents

- Pga
  - High injection in emitter-diode
    - Minority carrier concentration is approaching the majority carrier concentration, n = 2 in the diode equation and current does not increase as fast
  - Kirk effect
    - –Free charge carrier (as hole) as they injected in the base collector diode, increases the concentration on the n-side and reduces the concentration on the p-side. As a result, the transition moves instantaneously, as well as the base transport time increases





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