ECE4904 Lecture 9

BJT Performance Parameters (10.5)

- γ Emitter Efficiency
- α_T Base Transport Factor
- α_{dc} Common Base Current Gain
- β_{dc} Common Emitter Current Gain

Ideal Transistor Equations (11.1)

- Simplified Relationships (11.1.3)
- Ebers-Moll Model (11.1.4)
- Charge Control Model

Nonideal Effects:

Real BJT (11.2):

- Base width modulation
- Geometrical Effects
- Graded Base
- Gummel Plot

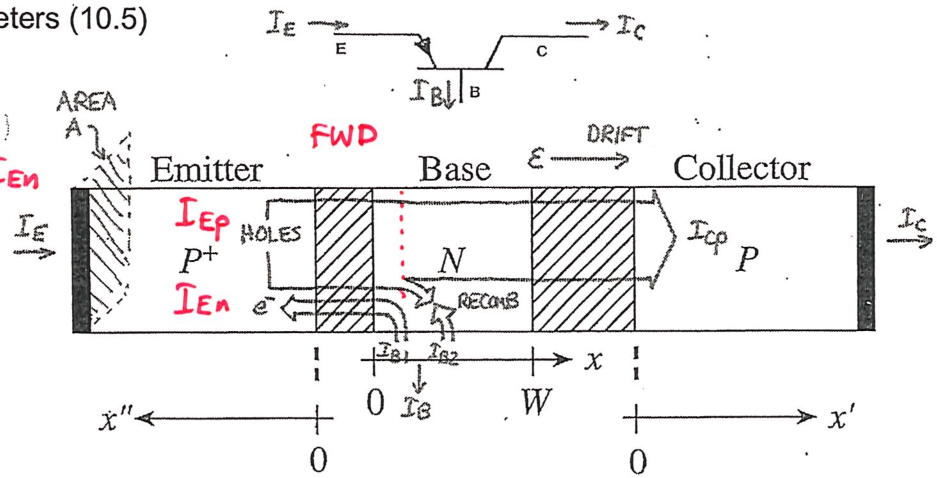
Real Diode: (6.2)

- Reverse bias breakdown (6.2.2)
  - Avalanching
  - Zener (Quantum "tunneling")
- Recombination-Generation in Depletion Region (6.2.3)
- High current effects (6.2.4)
  - Series resistance
  - High-level injection

Handouts

Ch. 6, 10, 11 Figures

BJT Performance Parameters (10.5)



GOALS FOR BJT OPERATION:
- ALL OF $I_E \Rightarrow I_C$
- $I_B \to 0$

WHAT COULD GO WRONG?

DEVICE

IDEAL $\to 1$

Emitter Efficiency γ

HOW MUCH OF I_E IS $\underbrace{\text{HOLES}}$? CAN GET TO COLLECTOR

$$\gamma = \frac{I_{Ep}}{I_{Ep} + \underbrace{I_{En}}_{I_{B1}}} = \frac{1}{1 + \frac{I_{En}}{I_{Ep}}}$$

Base Transport Factor α_T

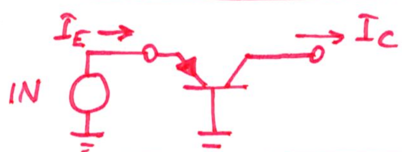
HOW WELL DO WE MOVE HOLES (MINORITY CARRIERS) THRU BASE BEFORE RECOMB

$$\alpha_T = \frac{\text{OUT}}{\text{IN}} = \frac{I_{Cp}}{I_{Ep}} = \frac{I_{Ep} - I_{B2}}{I_{Ep}} = 1 - \frac{I_{B2}}{I_{Ep}} \approx \frac{1}{1 + \frac{I_{B2}}{I_{Ep}}}$$

CIRCUIT

Common Base Current Gain α_{dc}

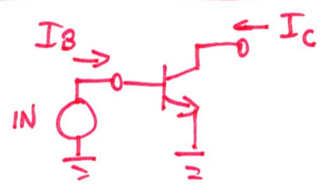
IDEAL $\to 1$



$$\alpha_{dc} = \frac{I_C}{I_E}$$

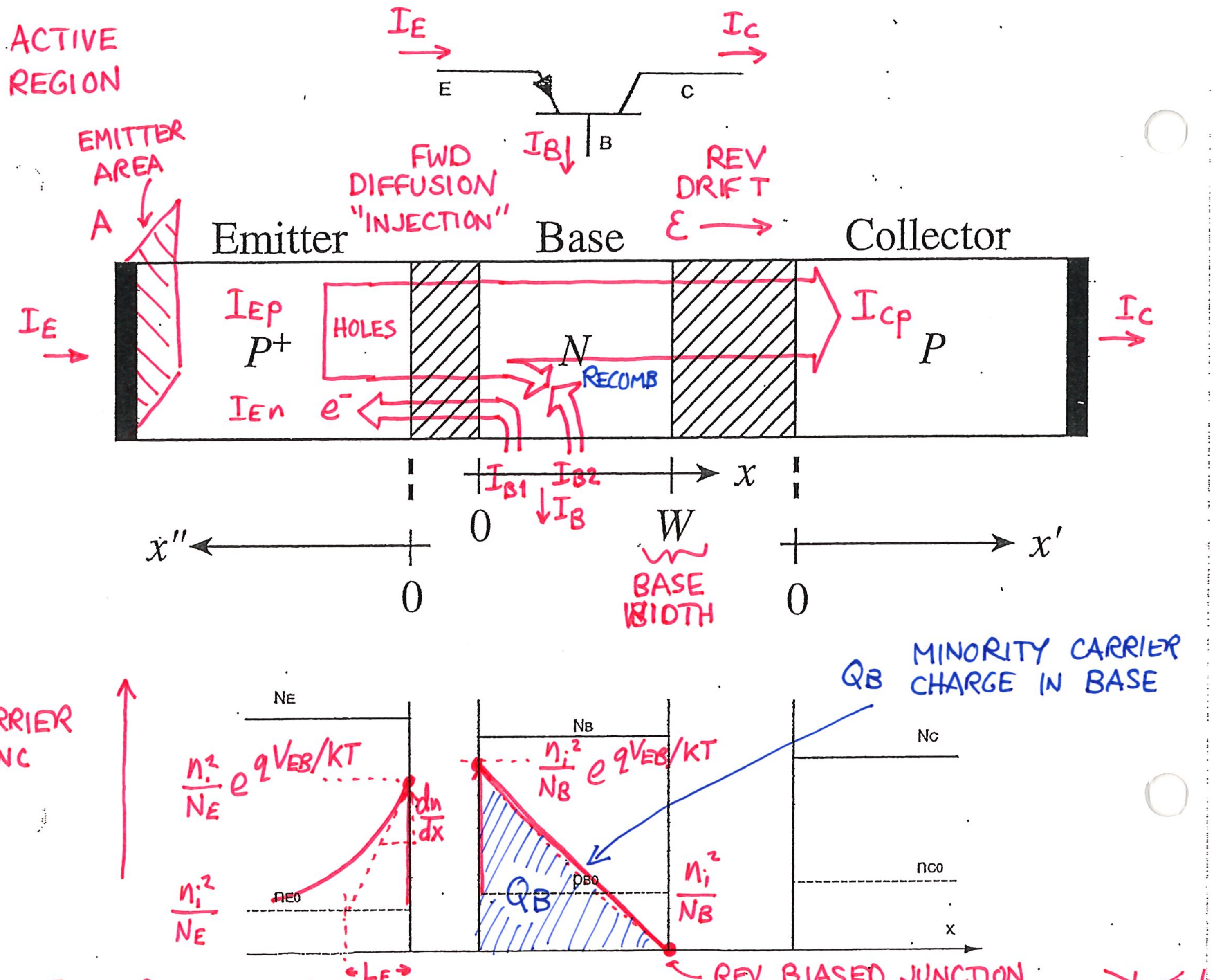
Common Emitter Current Gain β_{dc}

IDEAL $\to \infty$



$$\beta_{dc} = \frac{I_C}{I_B}$$

ACTIVE REGION



EMITTER: JUST LIKE FWD BIASED DIODE

LAW OF THE JUNCTION

I_{En} FROM DIFF EQUATION

$$J_{En} = qD\underbrace{\frac{dn}{dx}} = qD_E \frac{\frac{n_i^2}{N_E}e^{qV_{EB}/KT}}{L_E}$$

$I = JA$

$$I_{En} = qA\frac{D_E}{L_E}\frac{n_i^2}{N_E}e^{qV_{EB}/KT}$$

IN BASE: ASSUME NO RECOMBINATION

~~COSH, SINH~~ STRAIGHT LINE!

$$J_{Ep} = qD\frac{dp}{dx}$$

$$J_{Ep} = qD_B\frac{\frac{n_i^2}{N_B}e^{qV_{EB}/kT}}{W}$$

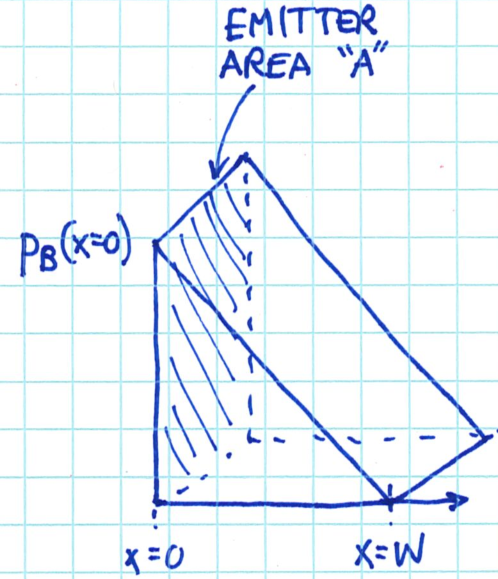
$$I_{Ep} = qA\frac{D_B}{W}\frac{n_i^2}{N_B}e^{qV_{EB}/kT}$$

$N_E = N_{AE}$	$N_B = N_{DB}$	$N_C = N_{AC}$
$D_E = D_N$	$D_B = D_P$	$D_C = D_N$
$\tau_E = \tau_n$	$\tau_B = \tau_p$	$\tau_C = \tau_n$
$L_E = L_N$	$L_B = L_P$	$L_C = L_N$
$n_{E0} = n_{p0}$	$p_{B0} = p_{n0}$	$n_{C0} = n_{p0}$

Figure 11.1 Coordinate systems and material parameter symbols (in bold) employed in the ideal transistor analysis.

"CHARGE CONTROL MODEL"

LOOK AT MINORITY CARRIER CHARGE IN BASE: Q_B



$p_B(x=W)=0$

$\mathcal{E}$ FIELD AT C-B JUNCTION (REV BIAS)

I_{B2}: BALANCE RECOMBINATION LOSS
HOW MUCH NEEDED? ON AVERAGE;

$$I_{B2} = \frac{Q_B}{\underbrace{\tau_B}_{\text{MINORITY CARRIER LIFETIME}}}$$

Q_B IN VOLUME

$$Q_B = \underbrace{q}_{\frac{\text{CHARGE}}{\text{CARR}}} \; \underbrace{\tfrac{1}{2}AW}_{\text{VOL}} \; \underbrace{p_B(x=0)}_{\frac{\text{CARR}}{\text{VOL}}}$$

LAW OF JCT: $p_B(x=0) = \frac{n_i^2}{N_B} e^{qV_{EB}/kT}$

$$\cancel{I_{B2}=}\; Q_B = qA\frac{W}{2}\frac{n_i^2}{N_B}e^{qV_{EB}/kT}$$

$$I_{B2} = qA\frac{W}{2\tau_B}\frac{n_i^2}{N_B}e^{qV_{EB}/kT}$$

BJT CURRENT COMPONENTS

DIFFUSION

$$\approx I_{Ep} \qquad I_C = qA\,\frac{D_B}{W}\,\frac{n_i^2}{N_B}\,e^{qV_{EB}/kT}$$

LAW OF THE JUNCTION
INJECTION OF (MINORITY) CARRIERS AT FORWARD BIASED B-E JUNCTION

$$I_{B1} = I_{En} = qA\,\frac{D_E}{L_E}\,\frac{n_i^2}{N_E}\,e^{qV_{EB}/kT}$$

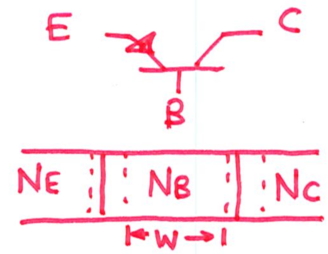
$$I_{B2} = qA\,\frac{W}{2\tau_B}\,\frac{n_i^2}{N_B}\,e^{qV_{EB}/kT}$$

JUNCTION AREA

EQUILIBRIUM <u>MINORITY</u> CARRIER CONCENTRATION

CAUTION! n_i^2 "HIDES" STRONG TEMPERATURE DEPENDENCE!

MINORITY CARRIER LIFETIME (RECOMBINATION)



			IDEAL	N_E	N_B	W	N_C
EMITTER INJECTION	(11.41)	$\gamma = \dfrac{1}{1 + \underbrace{\dfrac{D_E}{D_B}\dfrac{N_B}{N_E}\dfrac{W}{L_E}}_{\text{SMALL}}}$	1	↑	↓	↓	×
BASE TRANSPORT	(11.42)	$\alpha_T = \dfrac{1}{1 + \dfrac{1}{2}\left(\dfrac{W}{L_B}\right)^2}$	1	×	×	↓	×
$\dfrac{I_C}{I_E}$	(11.43)	$\alpha_{dc} = \dfrac{1}{1 + \dfrac{D_E}{D_B}\dfrac{N_B}{N_E}\dfrac{W}{L_E} + \dfrac{1}{2}\left(\dfrac{W}{L_B}\right)^2}$	1	↑	↓	↓	×
$\dfrac{I_C}{I_B}$	(11.44)	$\beta_{dc} = \dfrac{1}{\dfrac{D_E}{D_B}\dfrac{N_B}{N_E}\dfrac{W}{L_E} + \dfrac{1}{2}\left(\dfrac{W}{L_B}\right)^2}$	∞	↑	↓	↓	×

2 REASONS FOR SHORT W

① $\dfrac{dp}{dx}$ STEEPER $qD\dfrac{dp}{dx}$

② LESS DISTANCE TO GO!

EMITTER MUCH MORE HEAVILY DOPED

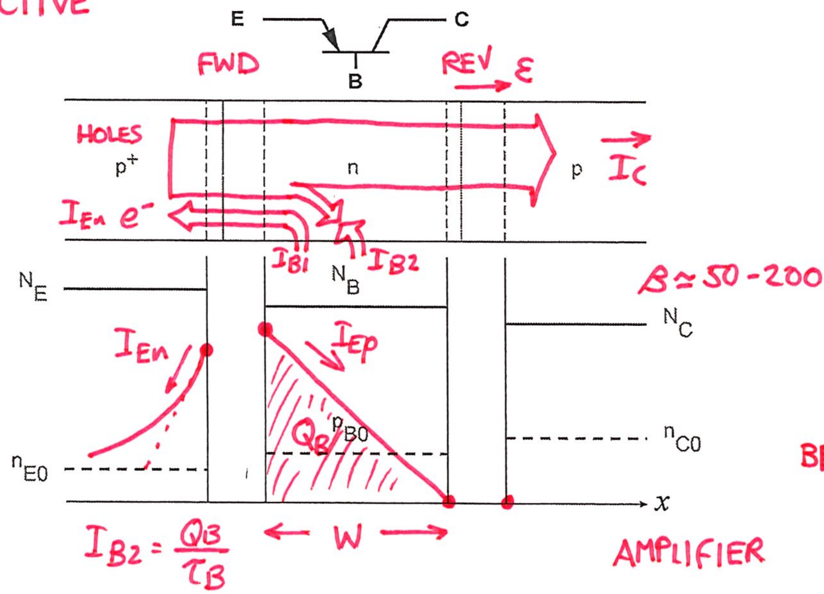
$N_E \gg N_B$

MAKE W "SMALL"

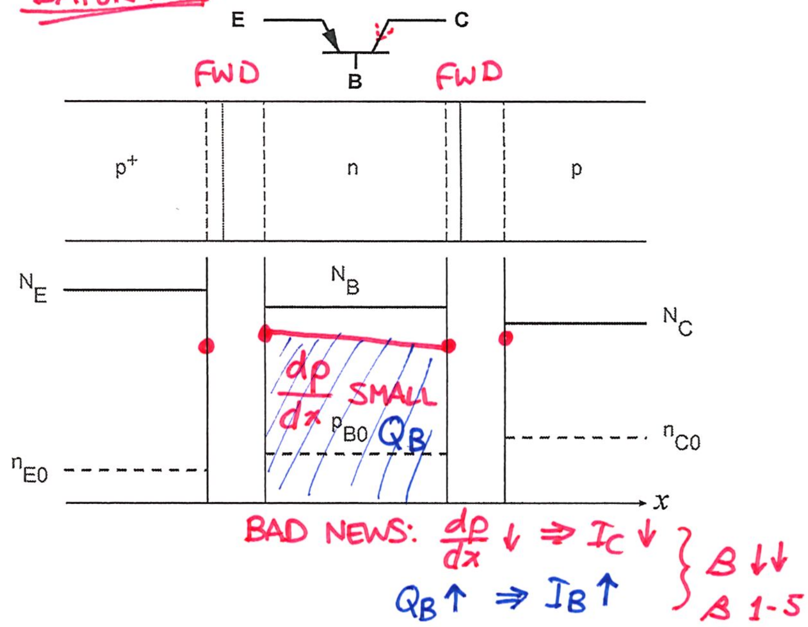
$W \ll L_B, L_E$

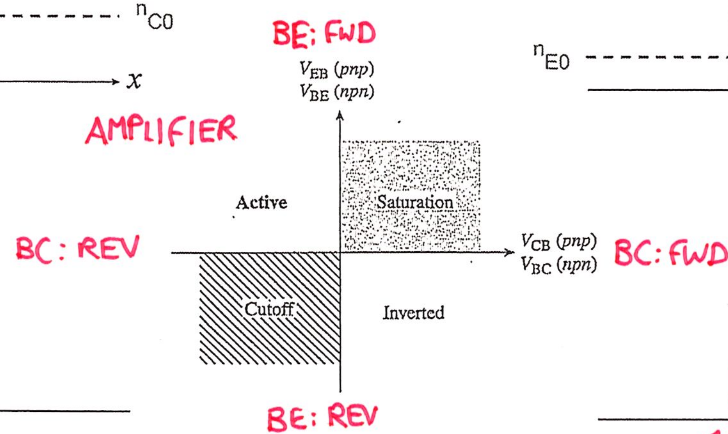
CHOOSE FOR SOMETHING ELSE (BASE WIDTH MODULATION)

ACTIVE

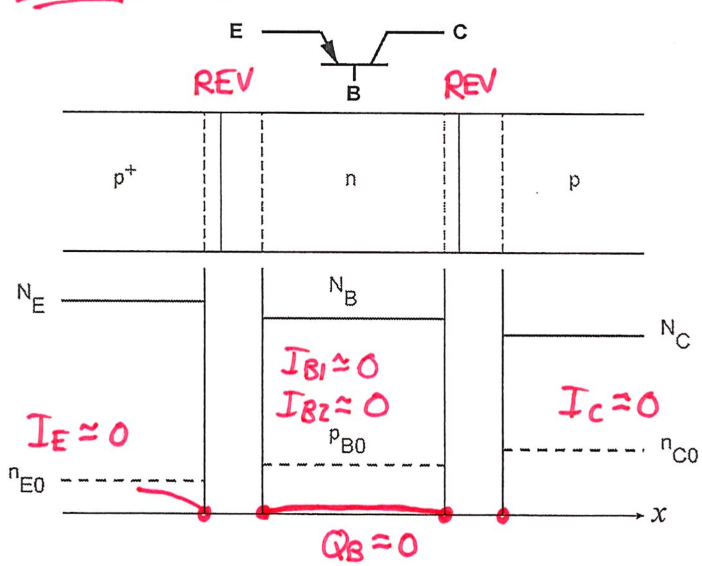


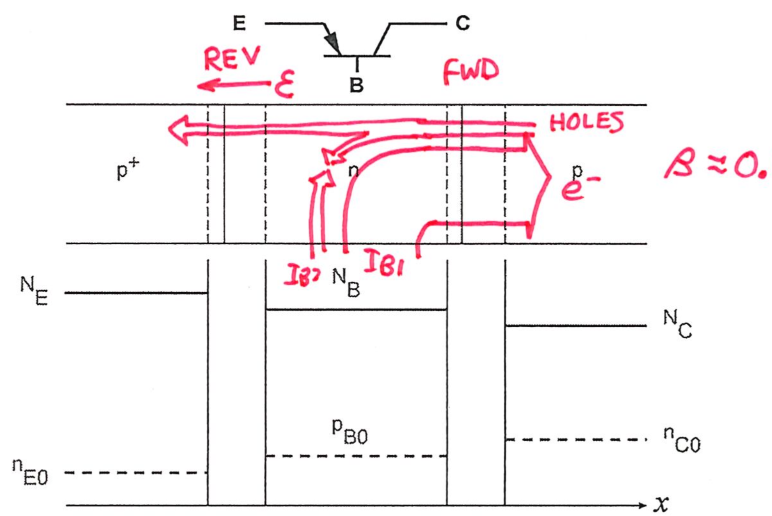
SATURATION $V_{CE} \approx 0.2V$





CUTOFF: OFF





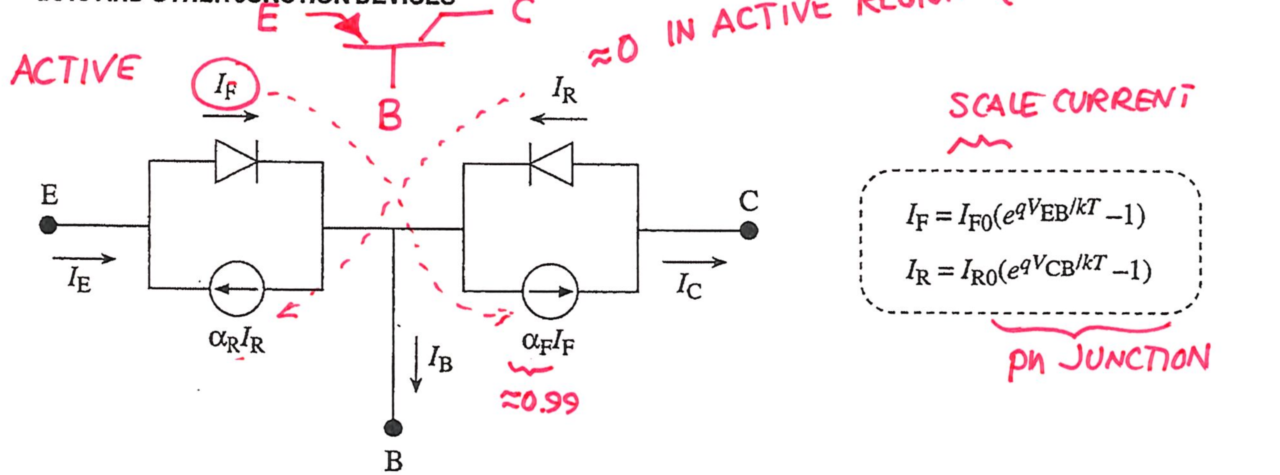


Figure 11.3 Large signal equivalent circuit for a *pnp* BJT based on the Ebers–Moll equations.

ACTIVE REGION $\quad I_F \gg I_R \quad I_C = \underbrace{qA\frac{D_B}{W}\frac{n_i^2}{N_B}}_{\text{SCALE CURRENT [DOUBLES EVERY 10°C]}}\left(e^{qV_{EB}/kT} - 1\right)$

IN SPICE MODELS (DC)

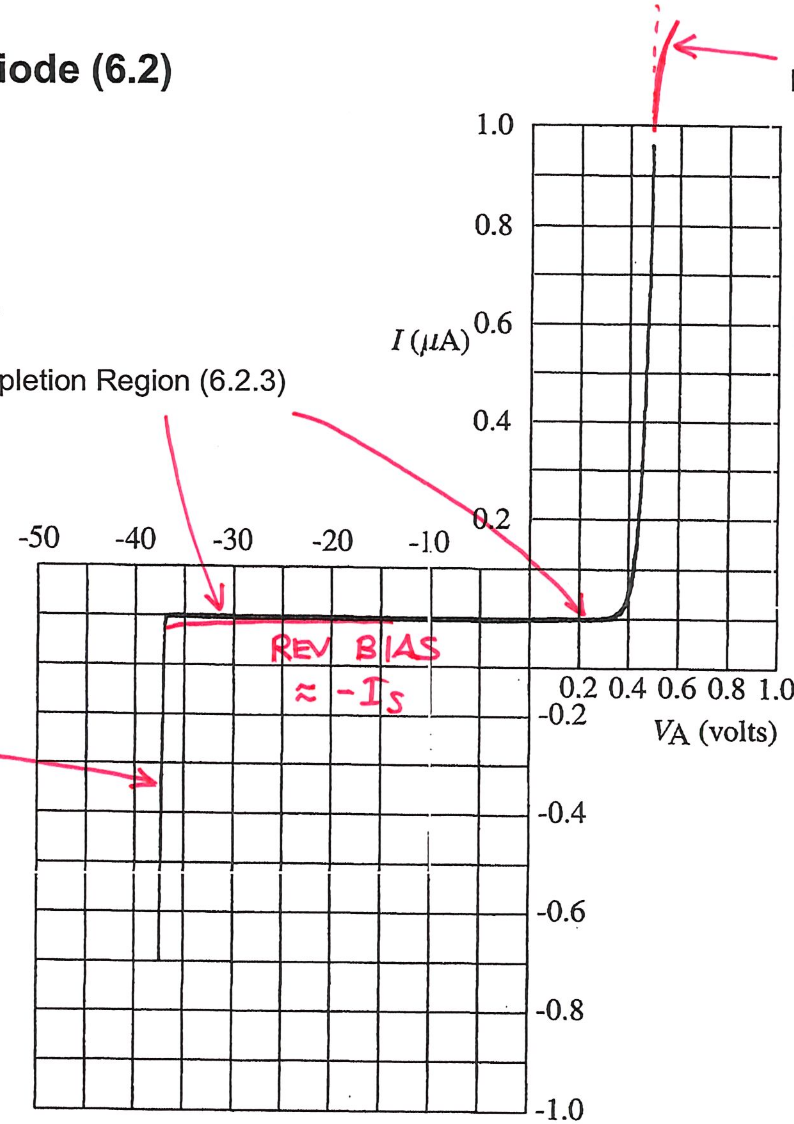
$$\boxed{\begin{aligned} I_E &= I_{F0}(e^{qV_{EB}/kT} - 1) - \alpha_R I_{R0}(e^{qV_{CB}/kT} - 1) \quad (11.47a) \\ I_C &= \alpha_F I_{F0}(e^{qV_{EB}/kT} - 1) - I_{R0}(e^{qV_{CB}/kT} - 1) \quad (11.47b) \end{aligned}}$$

Nonideal Effects: Real Diode (6.2)

High current effects (6.2.4)
Series resistance
High-level injection

Recombination-Generation in Depletion Region (6.2.3)

Reverse bias breakdown (6.2.2)
Avalanching
Zener (Quantum "tunneling")



FWD BIAS

$I_D = I_S\left(e^{qV_A/kT} - 1\right)$

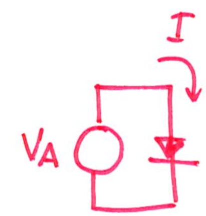


Figure 6.9 Linear plot of the measured I–V characteristic derived from a commercially available Si *pn* junction diode maintained at room temperature. The plot permits a coarse evaluation of the diode characteristic. Note the change in voltage scale in going from forward to reverse bias.

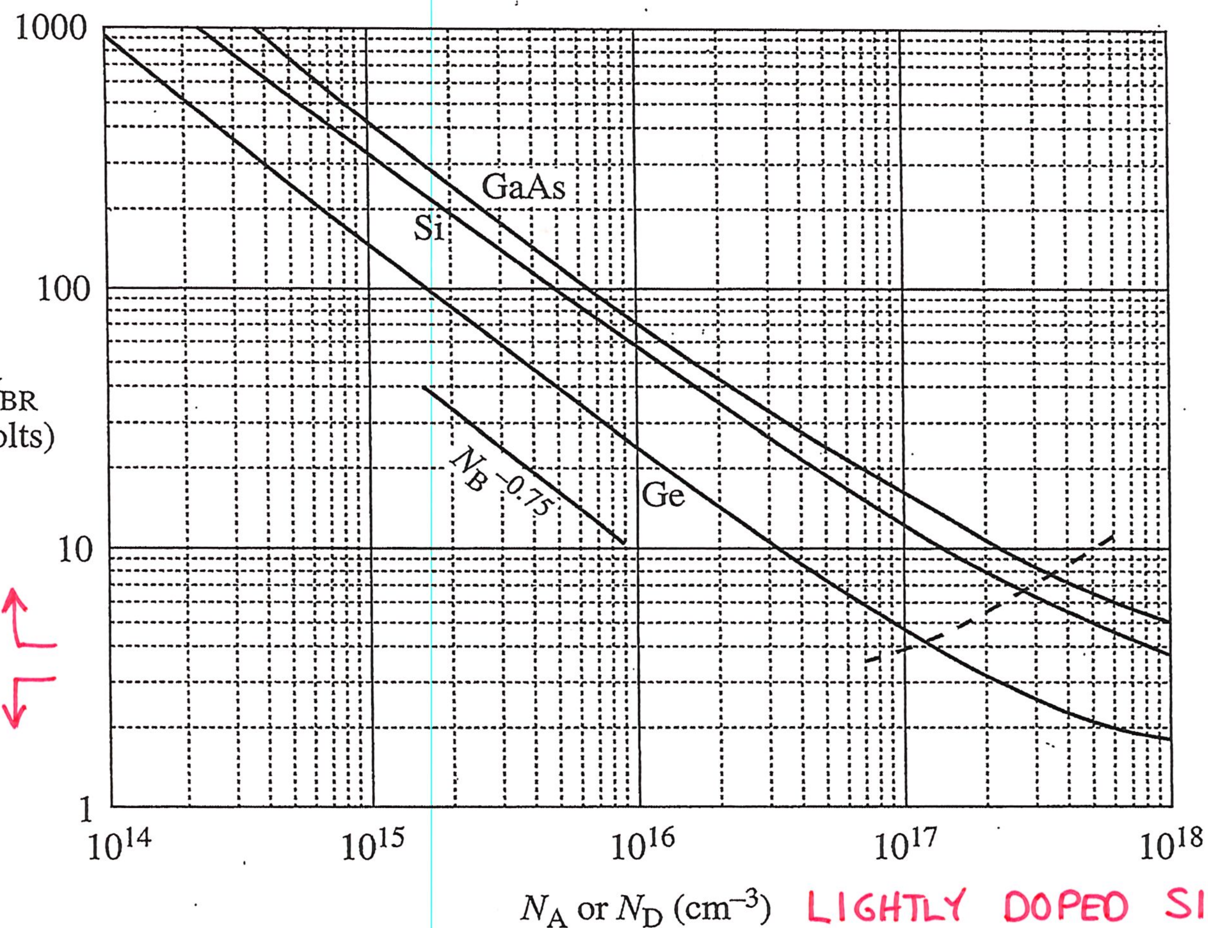
HIGH VBR :

LIGHT DOPING

(Nc)

AVALANCHE

TUNNELING



LIGHTLY DOPED SIDE

Figure 6.11 Breakdown voltage as a function of the nondegenerate-side doping in planar p^+-n and n^+-p step-junction Ge, Si, and GaAs diodes. Avalanche is the dominant breakdown process for dopings above the dashed line. $T = 300$ K. (After Sze[1], © 1981 by John Wiley & Sons, Inc. Reprinted with permission.)

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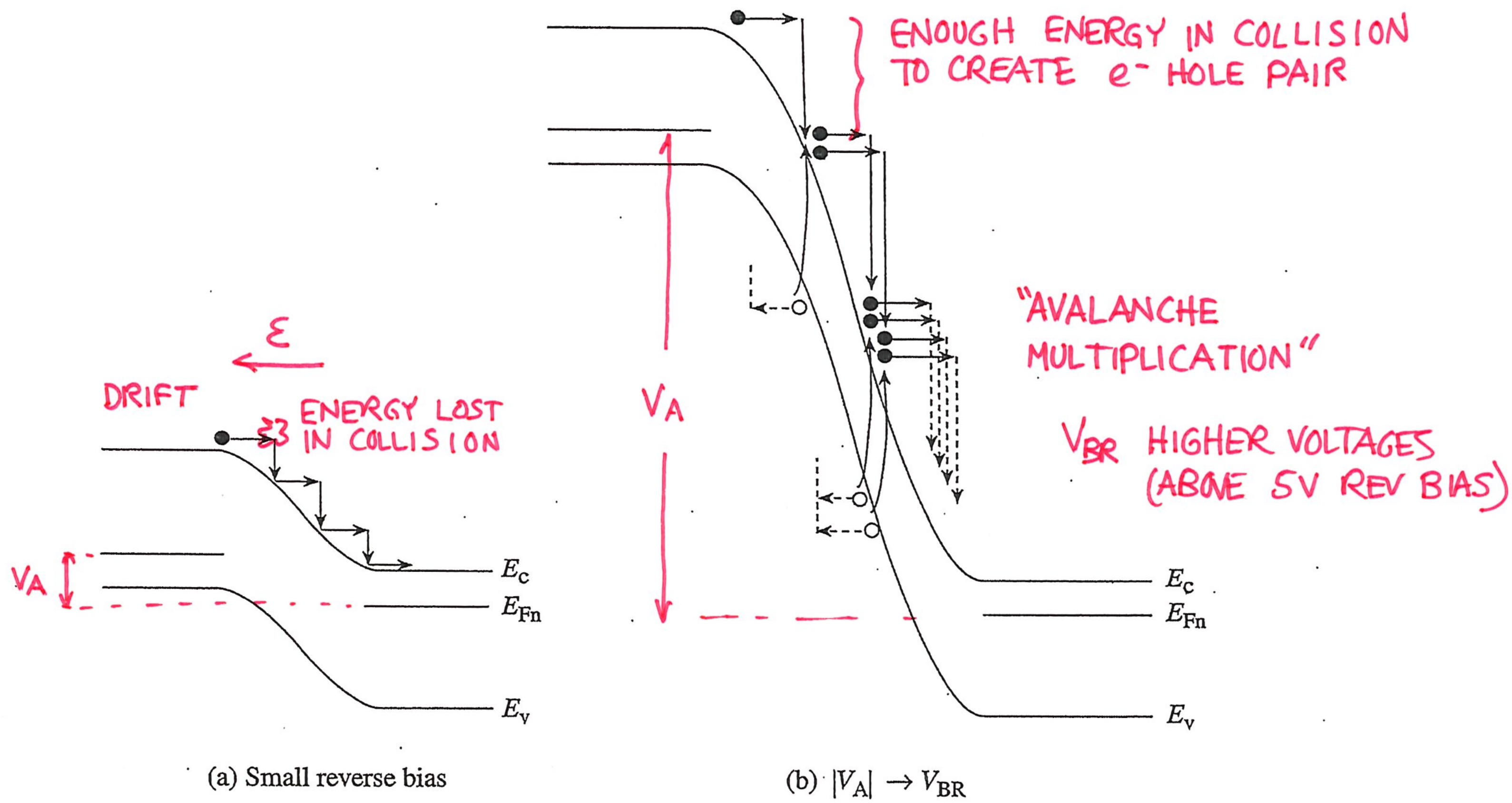


Figure 6.12 Carrier activity inside the depletion region of a reverse-biased *pn* junction diode when (a) $|V_A| \ll V_{BR}$ and (b) $|V_A| \to V_{BR}$. Carrier multiplication due to impact ionization and the resultant avalanche is pictured in (b).

4904 B2018 9-11

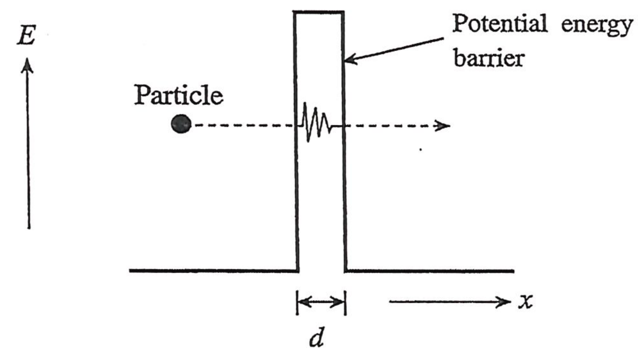
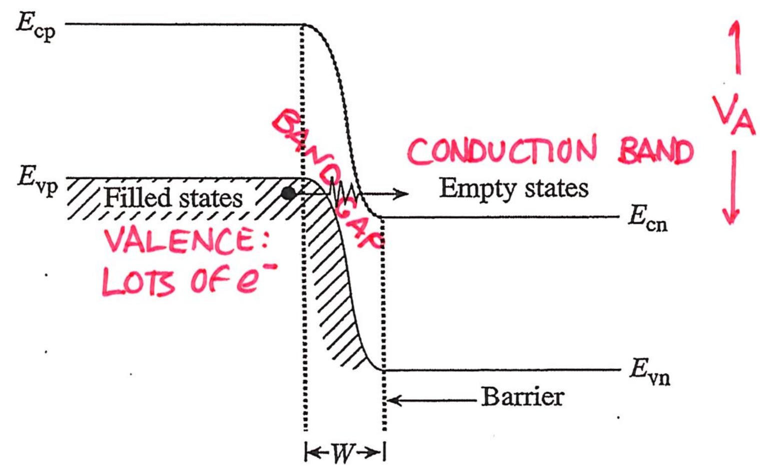


Figure 6.13 General visualization of tunneling.



LOWER $|V_{BR}| < 6V$
"ZENER"

Figure 6.14 Visualization of tunneling in a reverse-biased *pn* junction diode.

QUANTUM MECHANICAL EFFECT

FORWARD BIAS

LOG SCALE ↑

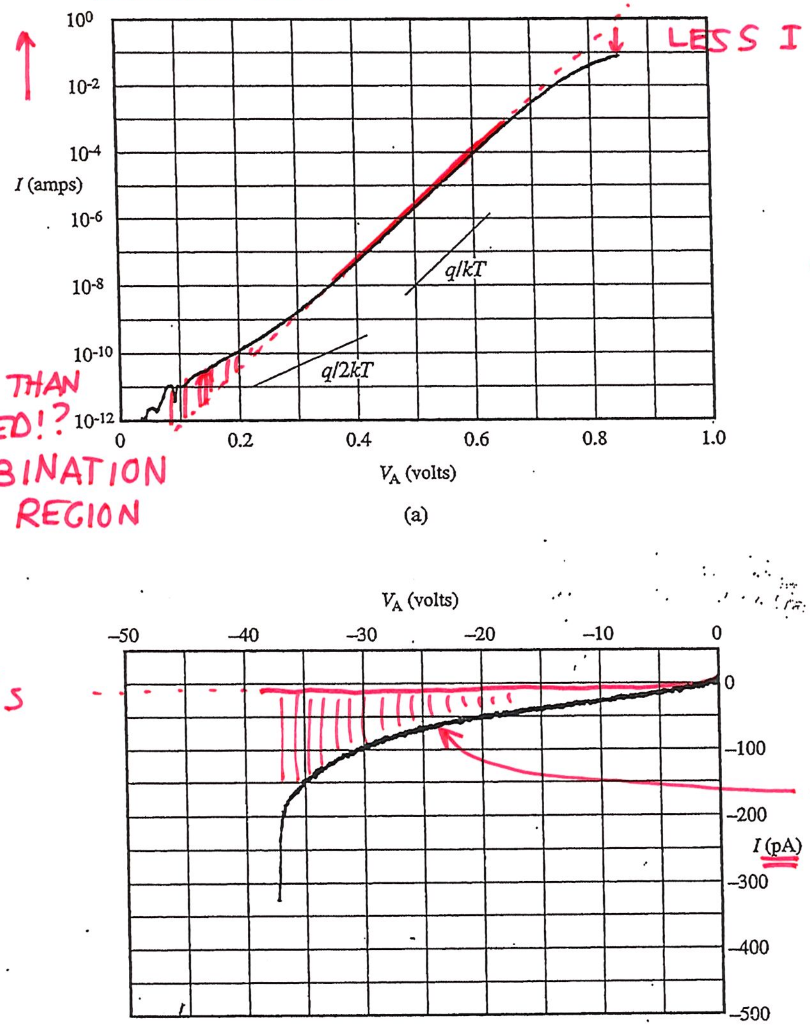
LESS I THAN PREDICTED!?

$$I = I_S\left(e^{qV_A/kT} \cancel{-1}\right)$$

$$\ln\left(\frac{I}{I_S}\right) = \frac{V_A}{kT/q}$$

MORE I THAN PREDICTED!?

RECOMBINATION IN DEPL REGION



$-I_S$

GENERATION IN DEPLETION REGION

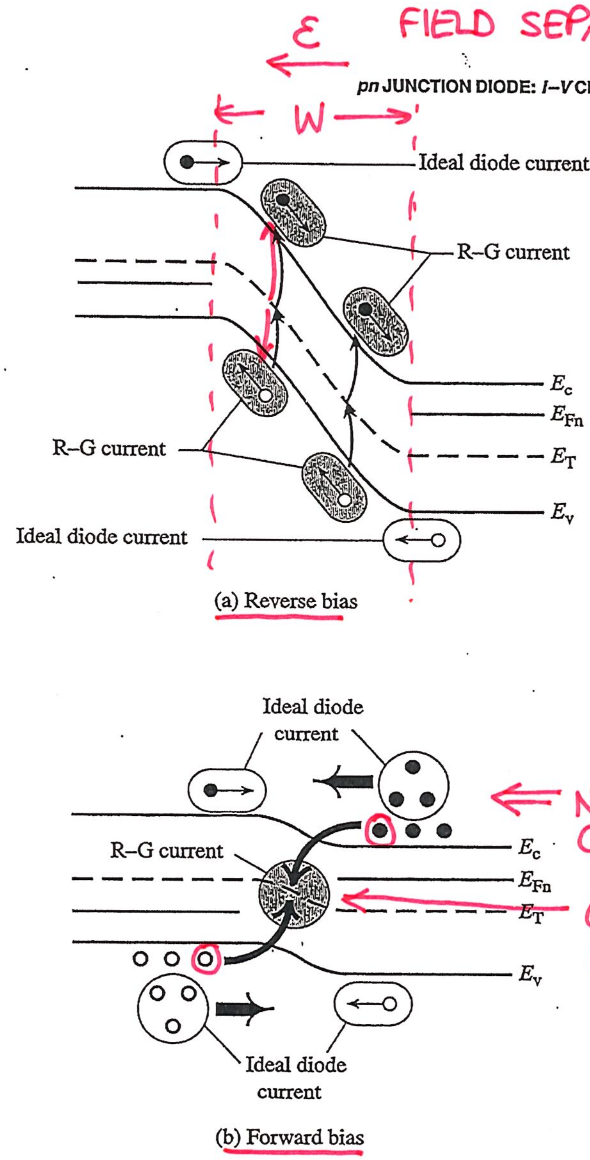
REV BIAS

Figure 6.10 Detailed plots of the measured I–V characteristic derived from a commercially available Si pn junction diode maintained at room temperature. The Fig. 6.9 and Fig. 6.10 characteristics are from the same device. (a) Semilog plot of the forward-bias current versus voltage. (b) Expanded scale plot of the reverse-bias current versus voltage.

FIELD SEPARATES e^-, HOLE IN GENERATED PAIR $\Rightarrow$ EXTRA CURRENT

W BIGGER AS REV BIAS ↑

~~NO R-G IN DEPLETION REGION~~

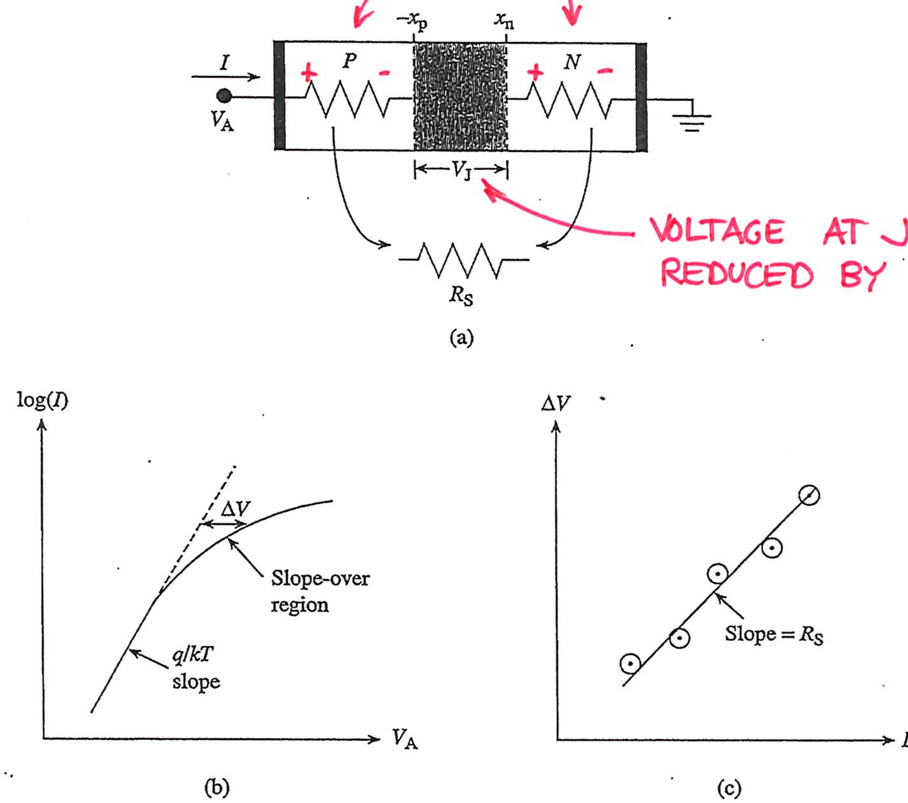


⇐ NEED TO HAVE "EXTRA" CURRENT FLOWING IN

CARRIERS LOST DUE TO RECOMBINATION

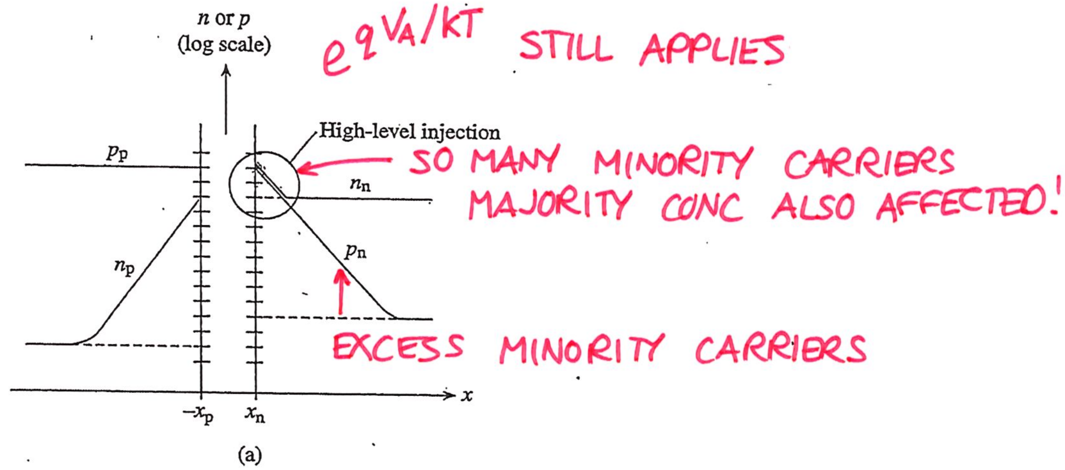
Figure 6.15 The R–G current. Visualization of the additional current resulting from (a) reverse-bias generation and (b) forward-bias recombination in the depletion region.

"QUASI NEUTRAL REGIONS": ASSUMED NO VOLTAGE DROP

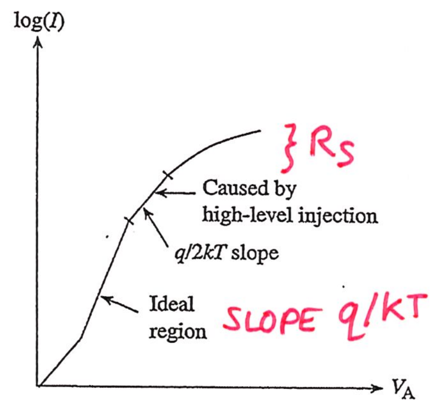


VOLTAGE AT JUNCTION REDUCED BY $\Delta V = IR_S$

Figure 6.16 Identification and determination of the series resistance. (a) Physical origin of R_S. (b) Forward-bias semilog plot used to deduce ΔV versus I. (c) ΔV versus I plot used to deduce R_S.



(a)



(b)

Figure 6.17 High-level injection. (a) Carrier concentrations under high-level injection conditions. (b) Predicted effect on the observed characteristic.