ECE3201

Electronic Circuit Design and Analysis

Physical electronics underlying the operation of electronic devices. Diodes, diode models, and diode circuits. Transistors, transistor models, and transistor circuits. DC, small signal, and frequency analysis of transistor amplifiers. Compound transistor configurations. Computer analysis tools. Design projects are implemented and tested in the laboratory. Laboratory reports with revisions are required for each project.

Book: Electronic Devices and Circuit Theory
by Robert L Boylestad and Louis Nashelsky; Eleventh Edition

Chapter 1.

(1.2) Semiconductors

Single Crystal

Germanium - Ge
Silicon - Si

most freq. used:
Ge Si GaAs

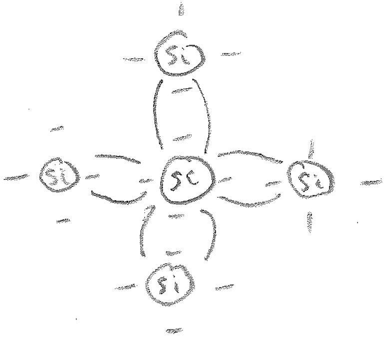
Compound

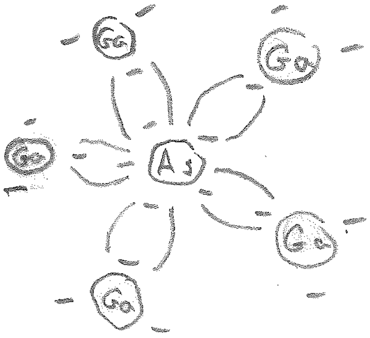
GaAs - Gallium Arsenide
CdS - Cadmium Sulfide
GaN - Gallium Nitride
GaAsP - Gallium Arsenide Sulfide

(1.3) Covalent Bonding

trivalent - Ga
tetravalent - Si, Ge
pentavalent - As

Si
OR
Ge





GaAs

INTRINSIC Si

@ Room T

$n_{i_{si}} = 1.5\times10^{10}$ free carriers/cm^3

$n_{i_{GaAs}} = 1.7\times10^{6}$

$n_{i_{Ge}} = 2.5\times10^{13}$

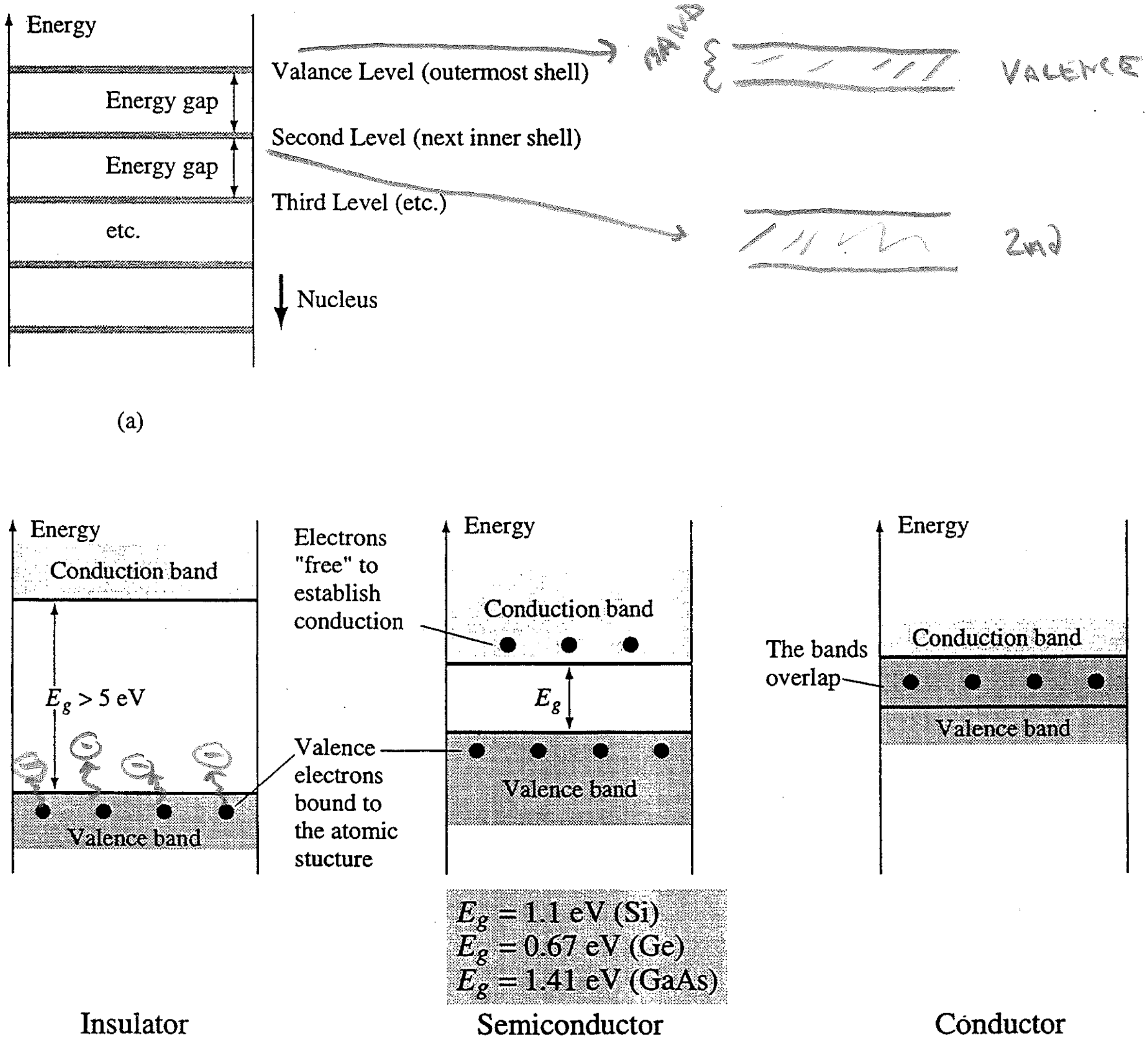
μ_n - **RELATIVE MOBILITY** (ABILITY TO MOVE THROUGH MATERIAL)

[SPEED OF DEVICE INCREASES WITH ↑ μ_n]

Si 1500 cm^2/V-s
Ge 3900
GaAs 8500

SEMICONDUCTOR HAS NEGATIVE TEMPERATURE COEFFICIENT
CONDUCTORS HAVE POSITIVE " "

Figure 1.6 ENERGY LEVELS: (A) DISCRETE LEVELS IN ISOLATED ATOMIC STRUCTURES; (B) CONDUCTION AND VALENCE BANDS OF AN INSULATOR, SEMICONDUCTOR, AND CONDUCTOR.



(a)

(b)

ELECTRONIC DEVICES AND CIRCUIT THEORY, Seventh Edition
by Robert Boylestad, Louis Nashelsky

Simon & Schuster/A Viacom Company
Upper Saddle River, New Jersey 07458

eV - electron Volt

(1.4) ENERGY LEVELS

eV – electronvolts

ENERGY: $W = QV$ = charge of one electron × POTENTIAL DIFFERENCE OF 1V

FOR ONE ELECTRON –

$Q_{e^-} = 1.6 \times 10^{-19}$ Coulumbs

$V = 1$ volt

⇒ $W = (1.6 \times 10^{-19})(1)$ Coulomb-volt

$= 1.6 \times 10^{-19}$ Joules

∴ $\boxed{1\ eV = 1.6 \times 10^{-19}\ J}$

(1.5) n-Type & p-type materials

INTRINSIC MATERIAL ⇒ EXTRINSIC MATERIAL

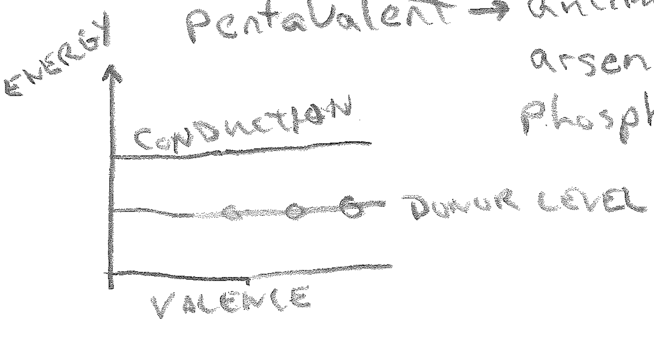
↑ IMPURITY

≈ 1 PART / 10 MILLION

n-type

MORE e^-

pentavalent → antimony, arsenic, Phosphorous



in Si, ≈ 1 free e^- / 10^{12} ATOMS

FOR 10 MILLION IMPURITY ATOMS, RATIO = $\frac{10^{12}}{10^{7}} = 10^{5}$

CARRIER CONC ↑ $\frac{100{,}000}{1}$

p-type

DOPE w TRIVALENT ATOMS

BORON
GALLIUM
INDIUM

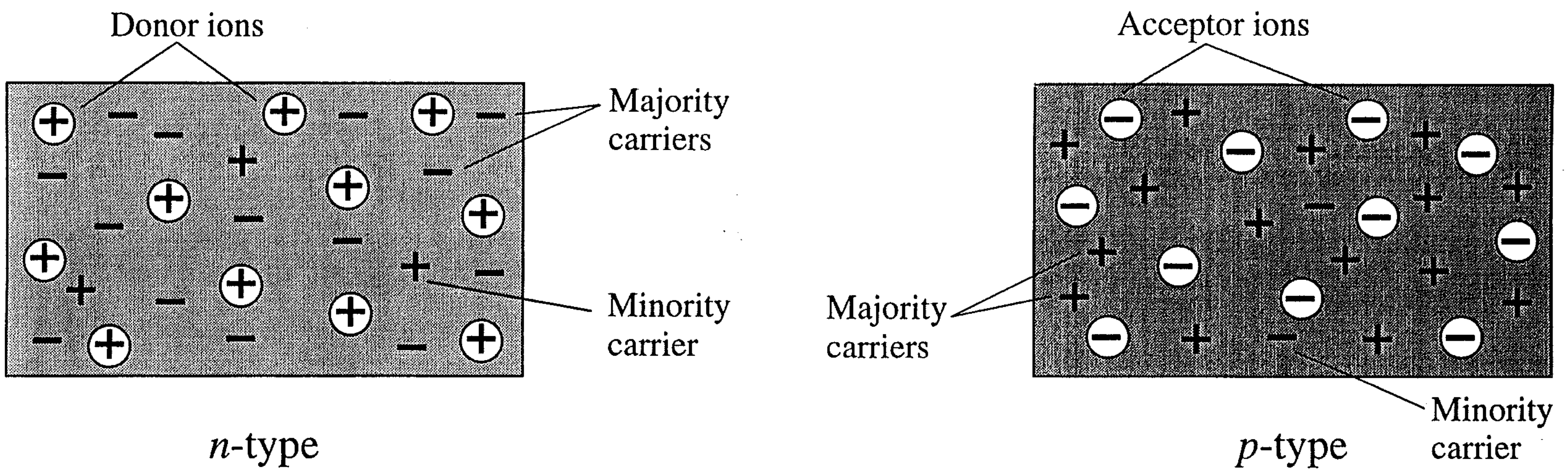
→ VACANCY IN LATTICE

↓

WILL ACCEPT A FREE ELECTRON

HOLE

Figure 1.1 (A) *N*-TYPE MATERIAL; (B) *P*-TYPE MATERIAL.



n-type

(a)

p-type

(b)

ELECTRONIC DEVICES AND CIRCUIT THEORY, Seventh Edition
by Robert Boylestad, Louis Nashelsky

Simon & Schuster/A Viacom Company
Upper Saddle River, New Jersey 07458

1.5 cont

HOLES FLOW OPPOSITE OF ELECTRON FLOW
(VACANCY) WITH SIGNIFICANT KE

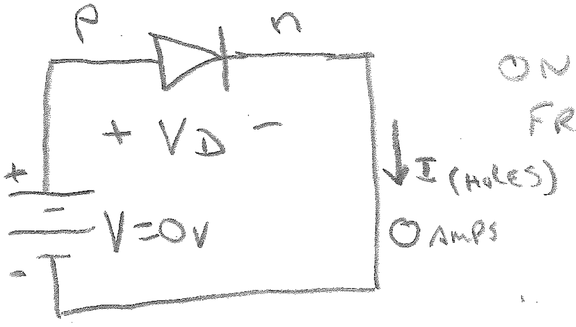
MAJORITY - MINORITY CARRIERS

n-type majority carrier $= e^-$ [ADDED e^-]
minority $=$ holes $e^- >$ holes

p-type MAJORITY CARRIER $=$ holes [ADDED HOLES]
MINORITY $= e^-$
holes $> e^-$

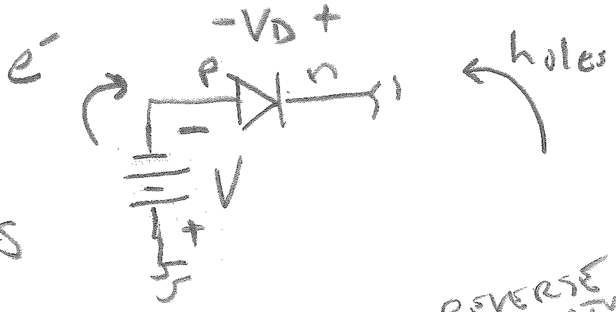
1.6 SEMICONDUCTOR DIODE

Join n-type with p-type material



ONCE JOINED - JUNCTION
FREE CARRIERS COMBINE ⇒
DEPLETION REGION

REVERSE BIAS $V_D < 0$



DEPLETION REGION WIDENS

MAJORITY CARRIER FLOW → 0

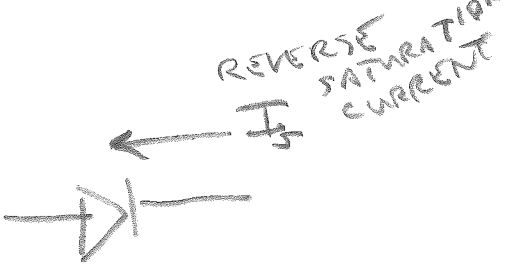


Figure 1.12 *P-N* JUNCTION WITH NO EXTERNAL BIAS.

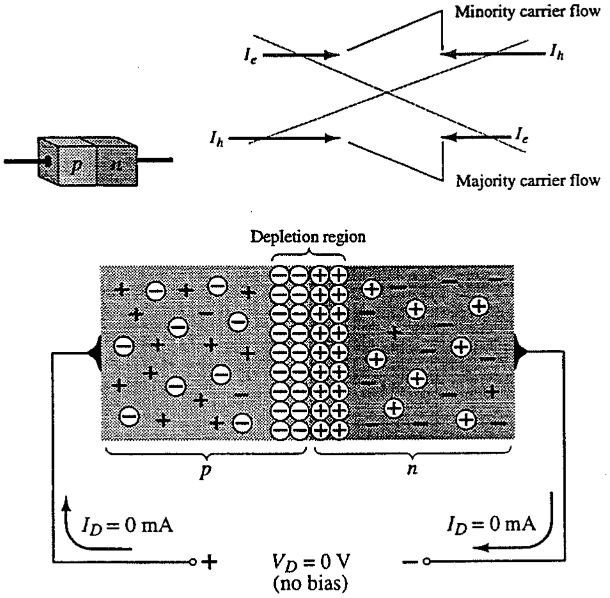


Figure 1.13 REVERSE-BIASED *P-N* JUNCTION.

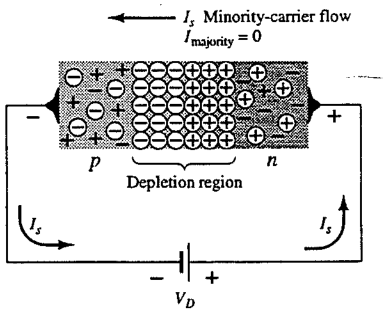
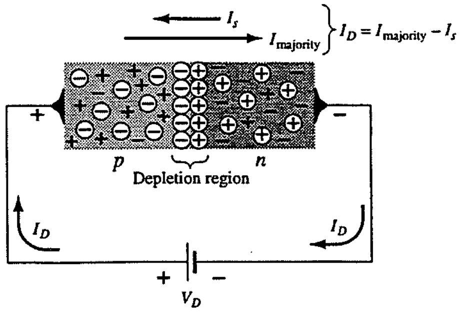


Figure 1.14 FORWARD-BIASED *P-N* JUNCTION.



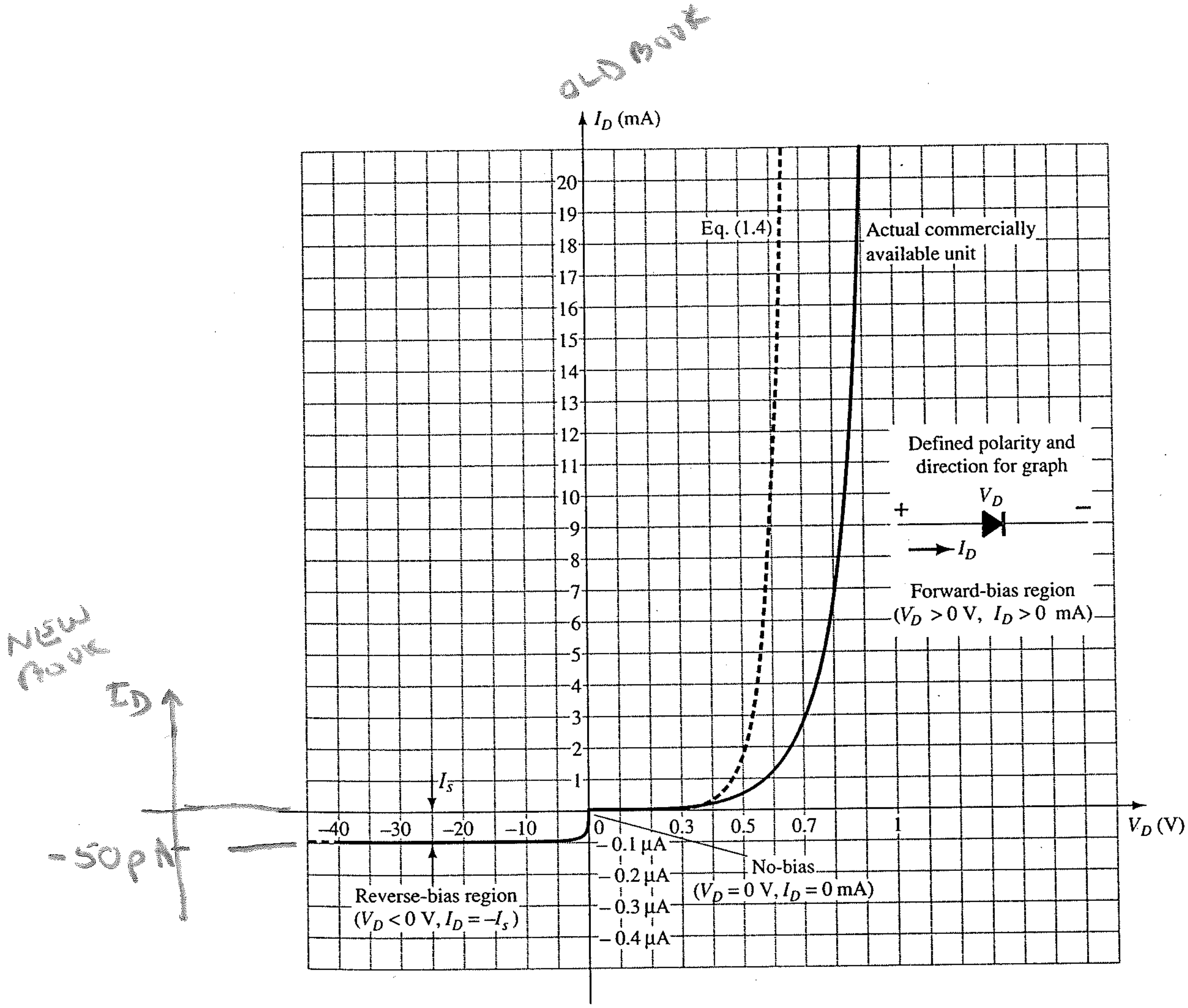
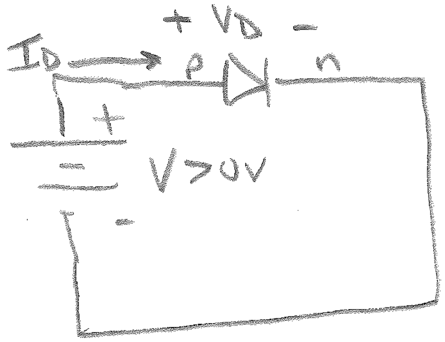

OLD BOOK
I_D (mA)
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Eq. (1.4)
Actual commercially available unit
Defined polarity and direction for graph
V_D
+
−
I_D
Forward-bias region ($V_D > 0$ V, $I_D > 0$ mA)
NEW BOOK
I_D
−50pA
I_s
−40
−30
−20
−10
0
0.3
0.5
0.7
1
V_D (V)
− 0.1 μA
− 0.2 μA
− 0.3 μA
− 0.4 μA
No-bias ($V_D = 0$ V, $I_D = 0$ mA)
Reverse-bias region ($V_D < 0$ V, $I_D = -I_s$)

FIG 1.15

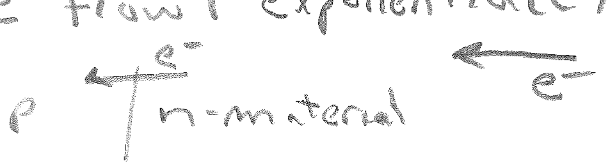
1.6 CONT FORWARD BIAS ($V_D > 0$)



$+V_D$ PRESSURES e^--hole to combine

depletion region ↓

e^- flow ↑ exponentially



SEE FIG 1.15 DIODE $\boxed{\text{V-I}}$

EQ 1.2 $$I_D = I_S\left(e^{V_D/nV_T} - 1\right)$$ AMPERES (A)

I_S = REVERSE SATURATION I

V_D = APPLIED FWD BIAS V

n = IDEALITY FACTOR (1-2)

V_T = THERMAL VOLTAGE

$$V_T = \frac{kT_K}{q} \text{ Volts}$$

k = Boltzmann's CONSTANT 1.38×10^{-23} J/°K

T_K = TEMP. IN kelvins [273+°C]

q = magnitude of electronic charge 1.6×10^{-19} C

EX 1.1 @ 27°C $V_T = ? = \frac{kT_K}{q} = \frac{(1.38\times10^{-23}\,\frac{J}{°K})(273+27)°K}{1.6\times10^{-19}\,C}$

$V_T = 25.875$ mV $\cong 26$mV

$\boxed{\text{FIG 1.15}}$

$I_D \rightarrow \approx I_S e^{V_D/nV_T}$ for positive V_D

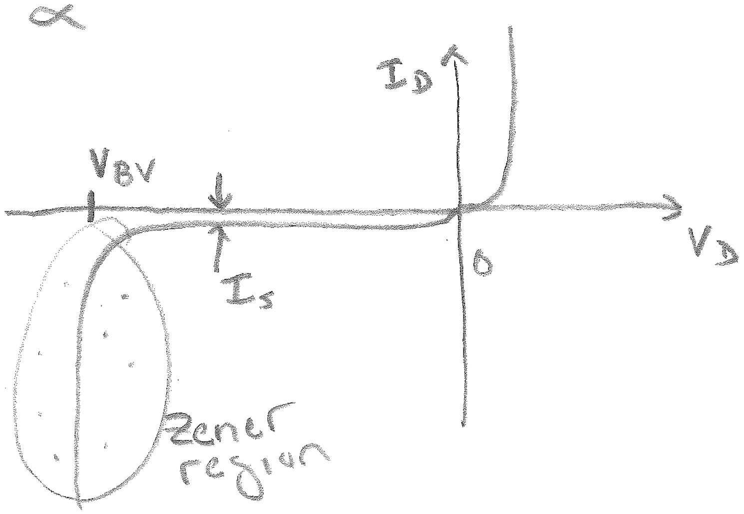
$[I_S e^x]$

for V_D NEGATIVE

$I_D \approx -I_S$ (exponential component small)

body resistance of diode and contact resistance shifts graph from ideal

<u>I_S</u> - leakage currents
- carrier generation in depletion region
- higher doping levels
- sensitivity to intrinsic level of carriers^2
- Junction area $\propto$
- T sensitivity



BREAKDOWN REGION

V_{BV} BREAKDOWN POTENTIAL

$|-V_D| \uparrow$ vel. of minority carriers $\uparrow$

$W_K = \frac{1}{2}mv^2 \uparrow$ releasing additional carriers by collisions > IONIZATION PROCESS

VALENCE e^- leave → avalanche I → avalanche breakdown

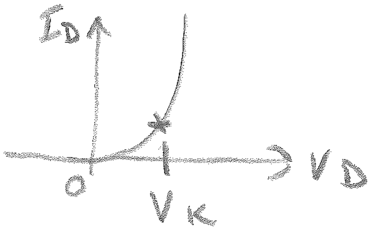
1.6 cont

Increasing doping levels ↓ V_{BV}

strong electricfield generated - disrupt binding forces

Ge	Si	GaAs
$V_K = 0.3V$	$V_K = 0.7V$	$V_K = 1.2V$

Knee voltages



EXAMPLE 1.2

From graph (fig 1.18)

TEMP EFFECTS

FWD BIAS CHARACTERISTICS

2.5mV/°C

20°C → 100°C gives $(100-20)(-2.5mV) = -0.2V$

REVERSE BIAS

$+\Delta 10°C \rightarrow 2 \times I_s$

20°C → 100°C gives ($I_s = 10nA$) ⇒ DOUBLES 8 times

10 → 20 - 40 - 80 - 160 - 320 →

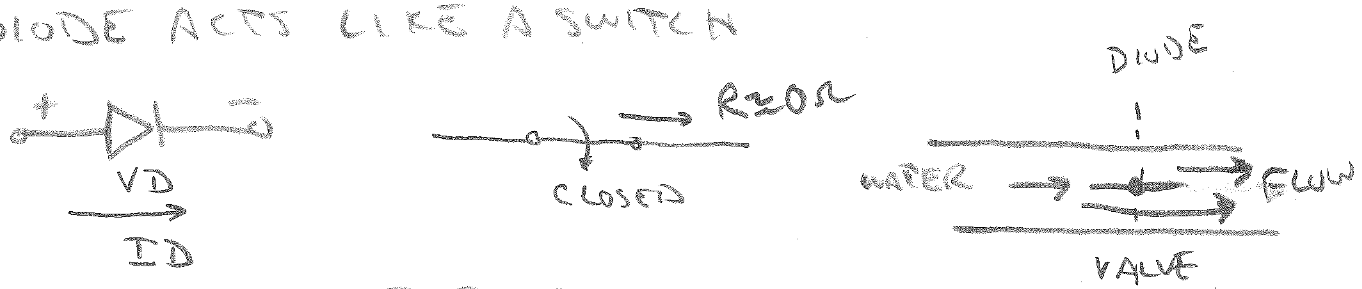
640 → 1280 → 2560nA

$= \boxed{2.56\mu A}$

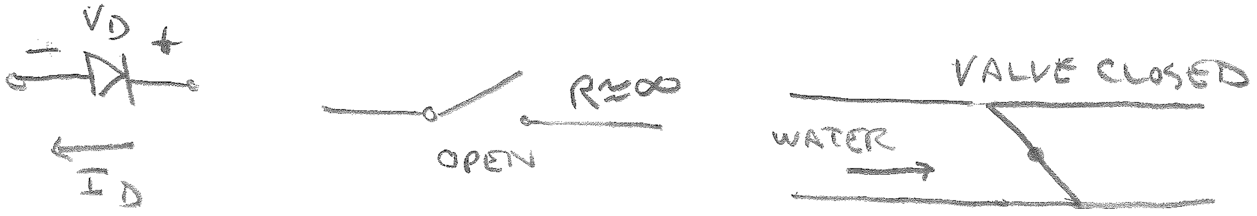
Increase to 200°C → 2.62mA

(1.7) IDEAL V'S PRACTICAL

DIODE ACTS LIKE A SWITCH



FWD BIAS



REVERSE BIAS

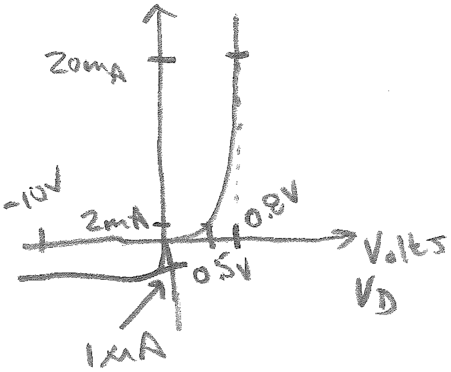
(1.8) Resistance Levels

Curve non-linear R_D ↑ as you approach the axis

$$\boxed{R_D = \frac{V_D}{I_D}}$$

as I_D ↑ R_D ↓ 10Ω to 80Ω Typical Value

Ex 1.3



@ 2mA = I_D , $V_D = 0.5V$ $R_D = \frac{0.5}{2\times10^{-3}} = 250\Omega$

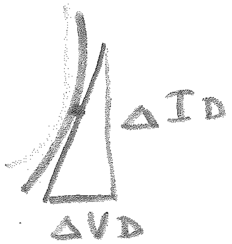
@ 20mA = I_D , $V_D = 0.8V$ $R_D = \frac{0.8}{20\times10^{-3}} = 40\ \Omega$

@ -10V , $I_D = -1\times10^{-6}A$ $R_D = \frac{-10}{-10^{-6}} = 10M\Omega$

AC OR DYNAMIC RESISTANCE

$R_D = \frac{V_D}{I_D}$ ⇒ small values $\boxed{\frac{\Delta V_D}{\Delta I_D} = r_d}$ Slope

DRAW TANGENT LINE →

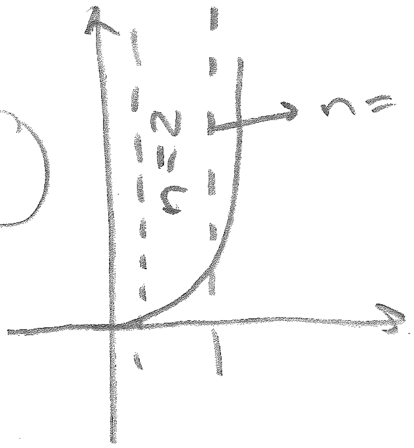


DYNAMIC $I_D = I_S\left(e^{V_D/nV_T} - 1\right)$

$$\frac{\partial I_D}{\partial V_D} = I_S\left(e^{V_D/nV_T}\right)\frac{1}{nV_T} = (I_D - I_S)\frac{1}{nV_T}$$

Since $I_D > I_S$ ⇒ $\frac{\partial I_D}{\partial V_D} \cong \frac{I_D}{nV_T}$ OR $\boxed{\frac{\partial V_D}{\partial I_D} = \frac{nV_T}{I_D}}$

Si



using n = 1 $\boxed{nV_T \cong 26mV}$ (27°C) $V_T = \frac{kT_K}{q}$

and

1.6 $\boxed{r_d \cong \frac{26mV}{I_D}}$

for additional resistances (body) $R_b \simeq 0.1\Omega$ to 2Ω

$r_d' = r_d + r_B$

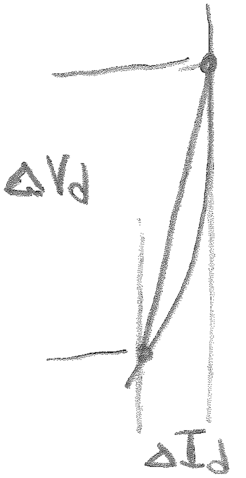
if $\left.\frac{\Delta V_D}{\Delta I_D}\right|_{\text{FROM GRAPH } 25mA} = 2\Omega$ and $r_d = \frac{26mV}{25mA} = 1.4\Omega$, then

$r_B \overset{\text{COULD BE}}{=} \frac{\Delta V_D}{\Delta I_D} - r_d \cong 1\Omega$

Book assumes r_B ignored - use r_d (AC Resistance)

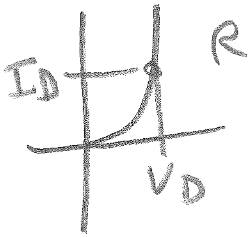
Average AC resistance

$$r_{av} = \frac{\Delta V_d}{\Delta I_d}\Bigg|_{\text{point to point}}$$



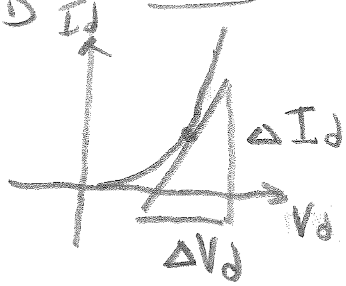
as $I_D \downarrow$ $r_d \uparrow$

DC



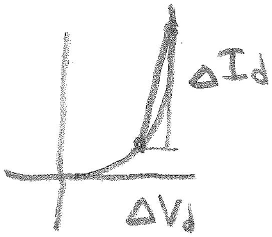
$R_D = V_D / I_D$

AC



$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{26\text{mV}}{I_D}$$

AVG

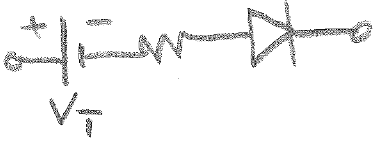


$$r_{av} = \frac{\Delta V_d}{\Delta I_d}\Bigg|_{\text{pt to pt}}$$

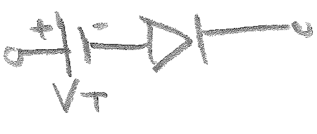
DIODE EQUIV CKT

SEE FIG 1.7

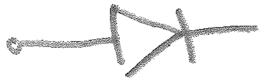
PIECEWISE



SIMPLIFIED



IDEAL



1.10

Transition and Diffusion Capacitance

$X_C = \frac{1}{2\pi F C}$ → Large for low F's

Very high freq's can't be ignored.

Reverse bias region - Transition (diffusion) Capacitance

(VARACTOR DIODE) $C_T \downarrow$ as $V_{Rev} \uparrow$ (V_D becomes more negative)

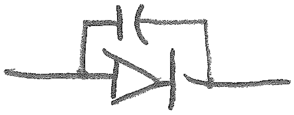
$C = \frac{\epsilon A}{d}$ d is width of depletion region

Forward bias

$C \propto$ rate of charge injected into regions outside the depletion region

$\uparrow V_D \rightarrow \uparrow C_D$ also: $\uparrow V_D \rightarrow \downarrow R_D$

$\therefore \quad \tau = \overset{\downarrow}{R}\overset{\uparrow}{C}$ doesn't change much



1.10 cont

REV. BIAS

$$C_T = \frac{C(0)}{(1+|V_R/V_K|)^n}$$

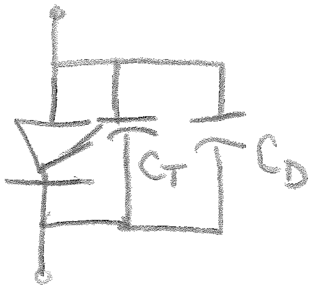
$C(0)$ = no bias

V_R = REVERSE BIAS

$n = 1/2$ OR $1/3$
(MANUF. PROCESS)

FWD BIAS

$$C_D = \left(\frac{\tau_r}{V_K}\right) I_D$$



τ_r = MINORITY CARRIER LIFETIME

C_D = DIFFUSION C

1.11

REVERSE RECOVERY TIME

t_{rr}

Forward bias — REQUIREMENT FOR CONDUCTION
- large # holes → n material
- large # electrons → p- material

ESTABLISH LARGE # OF MINORITY CARRIERS IN EACH MAT'L

FWD → REVERSE TRANSITION

TAKES TIME FOR THESE MINORITY CARRIERS TO RETURN TO MAJORITY CARRIER STATE ON OTHER SIDE OF DEPLETION REGION, SO DIODE I CONTINUES FOR A PERIOD OF TIME.

t_s = STORAGE TIME (MINORITY $\xrightarrow[I_{reverse}]{}$ MAJORITY)

t_r = transition interval

$t_r = t_s + t_r$

$t_{rr} \approx 2ns \to 1NS$

Switching diodes few hundred pico seconds

(10^{-12} s)

$P_{D_{MAX}} = V_D I_D$

$P_{DISCIPATED} = (0.7v) I_D$

p. 36

Figure 1.35 ELECTRICAL CHARACTERISTICS OF A HIGH-VOLTAGE, LOW-LEAKAGE DIODE.

TM 11

DIFFUSED SILICON PLANAR

MIN REV BIAS V

A — **• BV . . . 125 V (MIN) @ 100 μA (BAY73)**

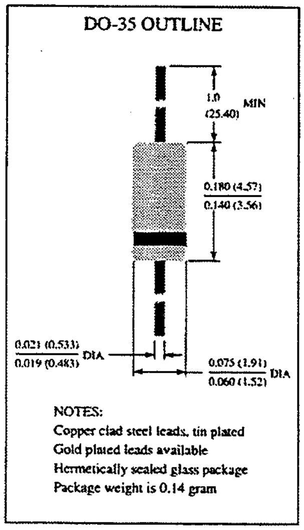
ABSOLUTE MAXIMUM RATINGS (Note 1)

T oper.

$P_D = V_D I_D$

MAX sustainable I_D

	Temperatures			
B		Storage Temperature Range		−65°C to +200°C
		Maximum Junction Operating Temperature		+175°C
		Lead Temperature		+260°C
	Power Dissipation (Note 2)			
C		Maximum Total Power Dissipation at 25°C Ambient		500 mW
		Linear Power Derating Factor (from 25°C)		3.33 mW/°C
	Maximum Voltage and Currents			
	WIV	Working Inverse Voltage	BAY73	100 V
	I_O	Average Rectified Current		200 mA
D	I_F	Continuous Forward Current		500 mA
	i_f	Peak Repetitive Forward Current		600 mA
	$i_{f\,(surge)}$	Peak Forward Surge Current		
		Pulse Width = 1 s		1.0 A
		Pulse Width = 1 μs		4.0 A


DO-35 OUTLINE

NOTES:
Copper clad steel leads, tin plated
Gold plated leads available
Hermetically sealed glass package
Package weight is 0.14 gram

V/I range

ELECTRICAL CHARACTERISTICS (25°C Ambient Temperature unless otherwise noted)

	SYMBOL	CHARACTERISTIC	BAY73		UNITS	TEST CONDITIONS
			MIN	MAX		
E	V_F	Forward Voltage	0.85	1.00	V	$I_F = 200$ mA
			0.81	0.94	V	$I_F = 100$ mA
			0.78	0.88	V	$I_F = 50$ mA
			0.69	0.80	V	$I_F = 10$ mA
			0.67	0.75	V	$I_F = 5.0$ mA
F			0.60	0.68	V	$I_F = 1.0$ mA
					V	$I_F = 0.1$ mA
G	I_R	Reverse Current		500	nA	$V_R = 20$ V, $T_A = 125$°C
				5.0	nA	$V_R = 100$ V
				1.0	μA	$V_R = 100$ V, $T_A = 125$°C
					nA	$V_R = 180$ V
					μA	$V_R = 180$ V, $T_A = 100$°C
	BV	Breakdown Voltage	125		V	$I_R = 100$ μA
H	C	Capacitance		8.0	pF	$V_R = 0$, f = 1.0 MHz
I	t_{rr}	Reverse Recovery Time		3.0	μs	$I_F = 10$ mA, $V_R = 35$ V $R_L = 1.0$ to 100 kΩ $C_L = 10$ pF, JAN 256

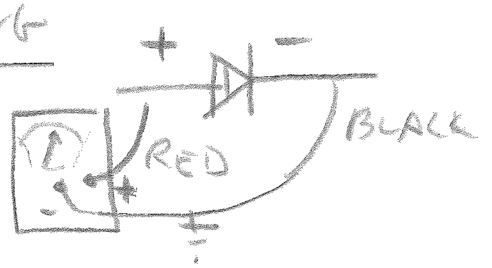
NOTES
1 These ratings are limiting values above which the serviceability of the diode may be impaired.
2 These are steady state limits. The factory should be consulted on applications involving pulses or low duty-cycle operation.

Electronic Devices and Circuit Theory, Seventh Edition
by Robert Boylestad, Louis Nashelsky

Simon & Schuster/A Viacom Company
Upper Saddle River, New Jersey 07458

1.13

1.14 DIODE TESTING



CURVE TRACER

1.15 Zener DIODE ±20% variation

I_{Z_T} (1/4 POWER LEVEL)

$P_{Z_{MAX}} = 4 I_{Z_T} V_Z$

$$T_C = \frac{\Delta V_Z}{V_Z}\frac{1}{(T_1 - T_0)} \times 100\% \ (\%/^\circ C)$$

T_C = Temp coef.
T_0 = Room T (25°C)
T_1 = NEW T
V_Z = NOMINAL @25°C

EX 1.5 TABLE 1.8 $V_Z = 10V$ $I_{Z_T} = 12.5mA$
$T = 25^\circ C$ $T_Z = +0.072\%/^\circ C$

IF $T \uparrow$ TO 100°C $\Delta V_Z = \frac{T_Z V_Z}{100\%}(T_1 - T_2) = \frac{0.072\%/^\circ C}{100\%}(100-25)^\circ C$

$\Delta V_Z = 0.54V$

$V_Z' = V_Z + \Delta V_Z = (10 + 0.54)V = \boxed{10.54V}$

FIG 1.48 DYNAMIC R ↓ with ↑ I_Z

(1.16) LED

VISIBLE   INFRARED

Si, Ge → energy of recombination mostly heating

TABLE 1.9

COLOR	MAT'L	FWD V	
Amber	AlInGaP	2.1V	610nm
Blue	GaN	5.0V	480nm
GREEN	GaP	2.2V	550nm
ORANGE	GaAsP	2.0V	630nm
RED	GaAsP	1.8V	654nm
White	GaN	4.1V	
YELLOW	AlInGaP	2.1V	620 nm

VISIBLE LIGHT   400 - 750 THz

INFRARED   100 - 400 THz

$\lambda = \frac{c}{f}$ (meters)

c = 3×10^{8} m/s
f = freq. in Hz
λ = wavelength (meters)

EX 1.6 RANGE OF VISIBLE LIGHT (in nm)

$\text{nm} = 10^{-9}\,\text{m} \quad c = 3\times10^{8}\,\text{m/s} \times 10^{+9}\,\frac{\text{nm}}{\text{m}} = 3\times10^{17}\,\text{nm/s}$

$$\lambda_{400\,\text{THz}} = \frac{3\times10^{17}\,\text{nm/s}}{400\times10^{+12}\,\text{Hz}} = \boxed{750\,\text{nm}}$$

$$\lambda_{750\,\text{THz}} = \frac{3\times10^{17}\,\text{nm/s}}{750\times10^{12}\,\text{Hz}} = \boxed{400\,\text{nm}}$$

$\boxed{\text{Å} = 10^{-10}\,\text{m}}$

CORRECTION P.43

GaAs $E_g = 1.43\,ev$

Si $E_g = 1.1\,ev$

$$E_g = \frac{hc}{\lambda}$$

h = Planck's constant $= 6.626\times10^{-34}\,J\cdot s$

$c = 3\times10^{8}\,m/s$

λ in meters

E_g in Joules → $1ev = 1.6\times10^{-19}\,J$

<u>for</u> $E_g = 1.43\,ev$

$$\lambda_{1.43ev} = \frac{hc}{E_g} = \frac{(6.626\times10^{-34}\,J\cdot s)(3\times10^{8}\,m/s)}{1.43\,ev(1.6\times10^{-19}\,J/ev)}$$

$$= 8.69\times10^{-7}\,m = \boxed{869\,nm}$$

↙ infrared

$$\boxed{\begin{array}{l} E_{g_{Si}} = 1.1\ ev \\ \lambda_{Si} = 1130\,nm \end{array}}$$

$$\boxed{\begin{array}{l} E_{g_{GaAsP}} = 1.9\,ev \\ \lambda_{GaAsP} = 654\,nm \end{array}}$$ red zone

FIG 1.52 TYPICAL RED LED Characteristics

Reverse Breakdown 3-5V

I typically 20mA

V 2-5V

FIG 1.54 7 segment display