Chapter 14

Semiconductor Electronics

What this chapter is about

Devices made from Si and Ge (semiconductors) have replaced bulky vacuum tubes since the 1950s. Smaller, cheaper, low power, longer life.

Solids classified by resistivity

Conductors : 10 -8 to 10 -6 ohm m

Semiconductors : 10 -5 to 10 6 ohm m

Insulators : 10 11 to 10 19 ohm m

Conductivity sigma = 1 / resistivity.

Energy bands at a glance :

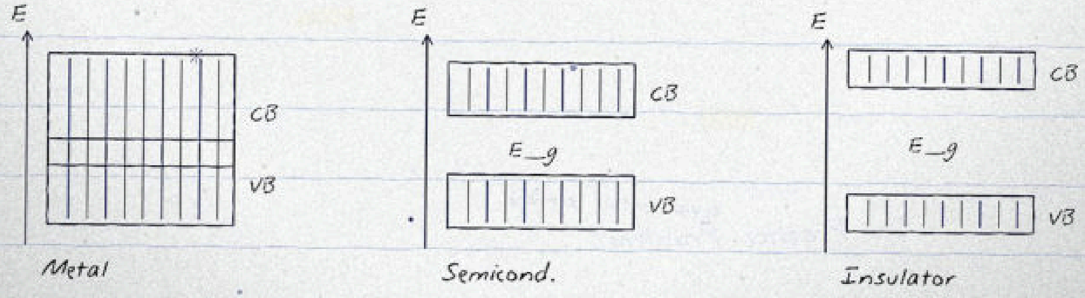


Fig. energy band picture of three classes of solids

Energy Band Theory

In a single atom, electrons occupy discrete energy levels. In a crystal, atoms are close enough that levels split into broad bands.

Valence and conduction bands

Valence band (VB) : highest fully-filled band at $T = 0$ K.

Conduction band (CB) : next allowed band, usually empty at $T = 0$ K.

Energy gap E_g : gap between VB top and CB bottom (forbidden zone).

Classification by E_g

Metal : $E_g = 0$ (bands overlap)

Insulator : $E_g > 3$ eV <- diamond 6 eV

Semiconductor : E_g 1 eV <- Si : 1.1 eV

<- Ge : 0.72 eV

At 0 K a pure semiconductor behaves like an insulator. As T rises, electrons jump VB ~~up~~ to CB. Conductivity rises with T (opposite to metals).

Intrinsic Semiconductors

A pure single crystal of Si or Ge with no impurity is called intrinsic.

Covalent bonding in Si / Ge

Si and Ge are tetravalent (4 valence electrons).

Each atom forms 4 covalent bonds with neighbours.

At $T = 0$ K all bonds intact → no free carriers.

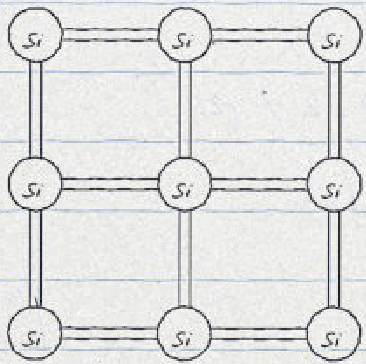


Fig. Si crystal - each atom shares 4 valence electrons with 4 nearest neighbours.

Thermal generation

At $T > 0$ K some bonds break. Each broken bond gives one free electron (CB) and one hole (VB). These come in pairs.

Electrons and Holes

What is a hole ?

A vacancy in a covalent bond acts like a positively charged carrier (charge = +e).
Neighbour electron jumps into vacancy -7 the vacancy effectively moves.
Holes move in valence band, electrons in CB.

Intrinsic carrier concentration

In a pure semiconductor :

$$\boxed{n\_e = n\_h = n\_i}$$ <- thermal eqm.

<- in pure crystal

n_i = number of electron-hole pairs / m^3
For Si at 300 K 1.5 x 10 16 / m 3.
For Ge at 300 K 2.4 x 10 19 / m 3.

Conduction in intrinsic

Total current : $I = I_e + I_h$
sigma = e (n_e mu_e + n_h mu_h)
mu_e , mu_h = electron and hole mobilities.
Usually mu_e 7 mu_h (electrons faster).

Intrinsic conductivity grows rapidly with T.

Extrinsic Semiconductors

Intrinsic conductivity is too small for real devices. Doping = adding a tiny amount of impurity (1 in 10 6 atoms) to drastically increase conductivity.

Two types of dopant

① Pentavalent (5 valence e) -> n-type

Examples : P , As , Sb.

② Trivalent (3 valence e). -> p-type

Examples : B , Al , In.

n-type formation

P atom replaces a Si atom. 4 of its 5 valence electrons make covalent bonds. The 5th is loosely bound (0.01 eV) - easily ~~released~~ ionised.

Donor atom -> gives up an electron to CB.
Majority carriers : electrons (n)
Minority carriers : holes (very few)

n_e >> n_h in n-type

<- P, As, Sb

p-type & Mass-Action Law

p-type formation

B atom replaces a Si atom. It has only 3 valence electrons - one bond stays incomplete.
That missing bond is a hole.
Acceptor atom -> accepts an electron from valence band leaving a hole behind.

Majority carriers : holes (p)
Minority carriers : electrons (very few)

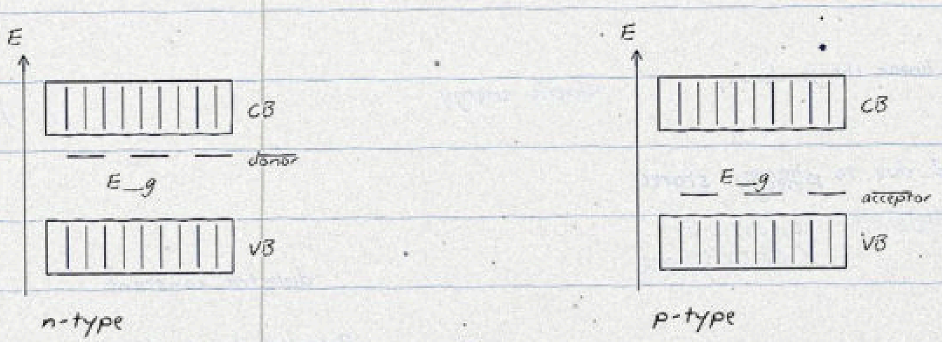


Fig. donor levels (just below CB) and acceptor levels (just above VB).

Mass-action law

$\boxed{n_e \times n_h = n_i}$ <- at fixed T

Holds for both n-type and p-type at equilibrium.

Charge Neutrality & Examples

Charge neutrality

An extrinsic semiconductor is overall neutral.

N_D + n_h = N_A + n_e

N_D = donor density , N_A = acceptor density.

If only donors : n_e N_D , n_h = n_i 2 / N_D.

If only acceptors: n_h N_A , n_e = n_i 2 / N_A.

Example 14.1

Si has n_i = 1.5 x 10 16 / m 3. Doped with donors at N_D = 5 x 10 22 / m 3. Find n_e, n_h.

Solution :

n_e N_D = 5 x 10 22 / m 3:

n_h = n_i^2 / n_e

= (1.5 x 10 16) 2 / (5 x 10 22)

= 2.25 x 10 32 / 5 x 10 22

* = $4.5 \times 10^9 / m^3$ (minority)

Notice : n_e / n_h 10 13 - huge ratio !

Doping changes carrier balance dramatically.

Conductivity goes up by 10 6 on doping.

p-n Junction Formation

A p-n junction is made by suitably doping one side of a single Si crystal p-type and the other side n-type (not by gluing two pieces).

Two processes at the junction

① Diffusion : majority carriers

Holes diffuse p -> n ;

electrons diffuse n -> p.

This is the diffusion current.

② Drift : minority carriers

Once ions are exposed, an E field is set up in depletion region (n -> p direction).

This E pushes minority carriers -> drift current (opposite to diffusion).

At equilibrium : diffusion = drift ;

net current = 0.

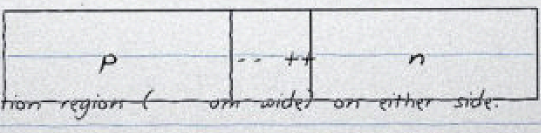


Fig. depletion region (om wide) on either side.

Depletion Region & Barrier

Depletion region

When majority carriers diffuse across the junction they leave behind ionised donors on n-side (+) and ionised acceptors on p-side (-). These fixed ions form a thin region devoid of free carriers - the depletion region (width 0.1 to 1. micron).

Built-in barrier

Fixed ions set up an internal E field from n (+ions) to p (-ions). It opposes further diffusion of majority carriers.

V_b	0.3 V (Ge) ,	0.7- vhee (voltage

V_b is also called potential barrier or junction / cut-in voltage.

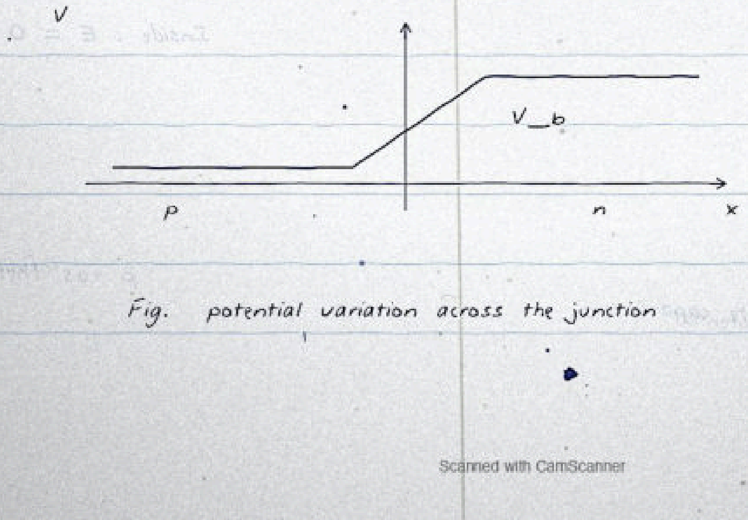


Fig. potential variation across the junction

Forward Bias

External battery : + to p-side , - to n-side.

External V opposes the built-in barrier.

What happens

① Barrier : effective barrier = $V_b - V$

② Depletion width decreases.

③ Diffusion current rises sharply.

④ Current *is mainly due to majority carriers.

After $V > V_b$ (knee voltage), I rises almost exponentially with V :

$$\boxed{I = I_0 (e \ (eV/kT) - 1})$$ <- Shockley diode <- equation

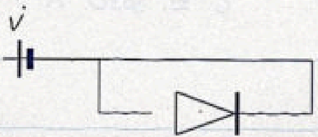


Fig: forward biased p-n junction (low resistance)

Reverse Bias

External battery : + to n-side , - to p-side.
External V adds to the built-in barrier.

What happens

① Barrier : effective barrier $= V_b + V$

② Depletion width increases.

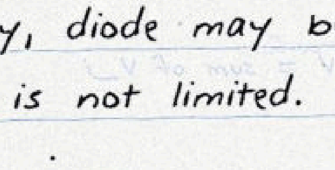
③ Diffusion of majority carriers 0.

④ Current is due to minority carriers only.

This small current saturates - independent of V -> reverse saturation current I_0.

I_0 micro A (Ge) , nA (Si)ority

Very high V -> avalanche / Zener breakdown : current rises suddenly, diode may be damaged if ~~voltage~~ power is not limited.



V-I Characteristic of Diode.

Plot of diode current I versus applied voltage V (sign included).

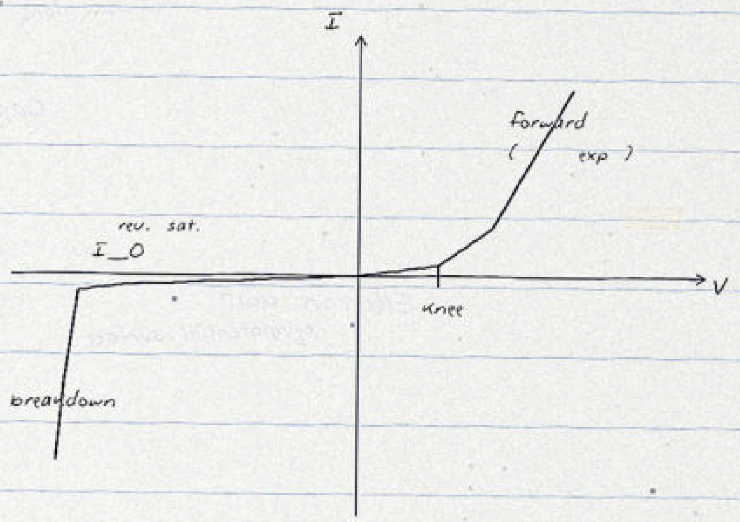


Fig. V-I curve of a p-n junction diode

Forward : current rises sharply after V_b.

Reverse : tiny constant I_O until breakdown.

Dynamic Resistance & Ideal Diode

Static (DC) resistance

$$\boxed{R = V / I}$$ <- at a chosen point

Useful only at one operating point.

Dynamic (AC) resistance

$$\boxed{r_d = dV / dI}$$ <- slope of V-I curve

<- (small signal)

Forward bias : r_d is small (few ohm).

Reverse bias : r_d is huge (M ohm).

Ideal diode (model)

① Forward : zero resistance ; acts as short.

② Reverse : infinite resistance ; open circuit.

Real diode : V_b drop + small forward R.

An ideal diode lets current pass in only one direction - a one-way value for charge.

Junction Diode as a Rectifier

Rectifier = device that converts AC voltage into DC. Uses the one-way property of diode.

Why diode rectifies

During +ve half cycle -> forward biased
-> current flows ; output across R_L.
During -ve half cycle -> reverse biased
-> current 0 ; output across R_L = 0.

Two configurations

① Half-wave : single diode , only half the AC cycle.

② Full-wave :
   (a) Centre-tap with 2 diodes.
   (b) Bridge rectifier with 4 diodes.

Transformer + diode

AC mains (220 V , 50 Hz) is stepped down by a transformer. Diode(s) then rectify it.

Ripple frequency : half-wave -> ~~100~~ 50 Hz.
Full-wave -> 100 Hz (input was 50 Hz).
Higher ripple freq is easier to smooth.

Half-Wave Rectifier

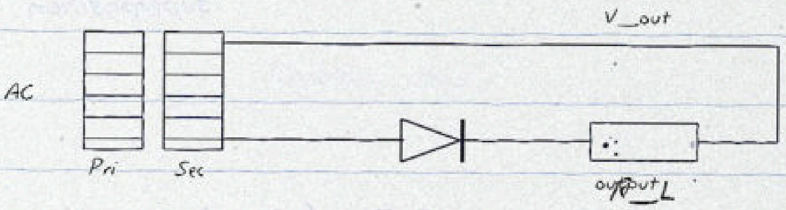


Fig. half - wave rectifier circuit

Output waveform

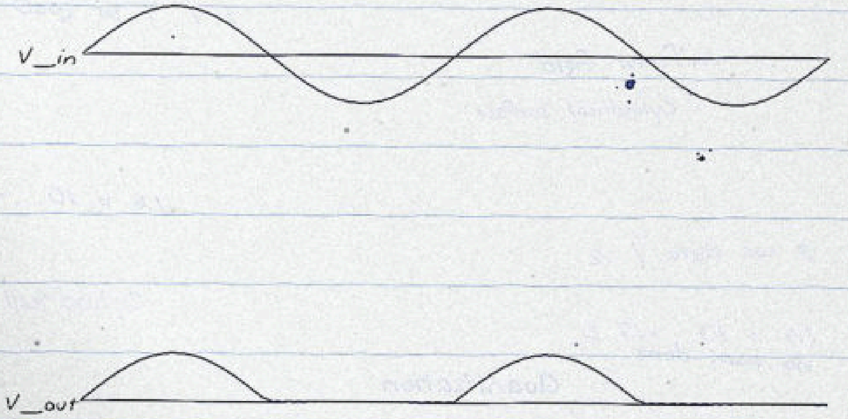


Fig. input AC & half-wave output (+ve only)

Full-Wave Rectifier (Centre-Tap)

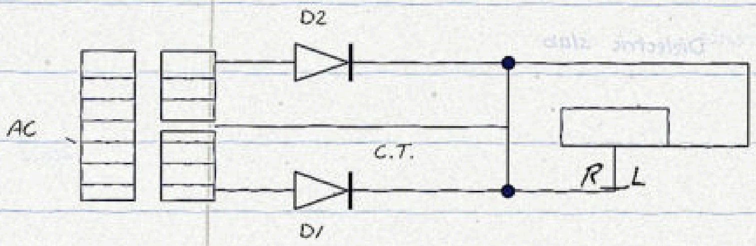


Fig. centre - tap full - wave rectifier

Working

+ve half cycle : D1 on , D2 off -> top half delivers current.

-ve half cycle : D2 on , D1 off -> bottom half delivers current.

In both halves, current through R_L flows in the SAME direction -> full-wave DC.

Ripple frequency = $2 f_{in}$ = ~~50~~ 100 Hz.

Efficiency 81% (vs 40.6% half-wave).

Bridge Rectifier

Uses 4 diodes in a bridge (Wheatstone-like) arrangement. No centre-tap needed.

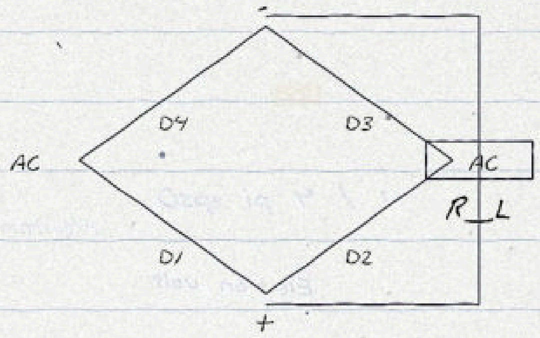


Fig. 4-diode bridge rectifier (full-wave)

Advantages

① No centre-tap transformer needed.

② Better transformer utilisation.

③ Same efficiency 81% as centre-tap.

Filtering & Ripple Factor

Why we need a filter

Output of a rectifier is pulsating DC :
DC plus an AC ripple component.
Filter smoothens it into steady DC.

Capacitor (shunt) filter

A capacitor C is connected across R_L.
When V_out rises -> C charges to peak V_m.
When V_out falls -> C discharges through R_L,
holding output near V_m.

Larger time constant tau = R_L C -> smaller ripple , better DC.

Ripple factor

r = V_rms (ripple) / V_dc <- smaller = better

Half-wave (no filter) : r 1.21
Full-wave (no filter) : r 0.482
With capacitor filter : r << 0.01

Efficiency eta = P_dc / P_ac :
Half-wave 40.6% , Full-wave 81.2%.

Special Purpose Diodes

(1) Zener diode

A heavily doped p-n junction designed to operate in the reverse breakdown region.
At $V = V_z$, voltage stays almost constant even when reverse current changes a lot.

Two breakdown mechanisms :

(a) Zener breakdown - field ionisation
(heavy doping, thin depletion).

(b) Avalanche breakdown - chain collisions.

Use : voltage regulator

Connected in reverse bias across a load.
Series resistor R_s drops excess voltage.

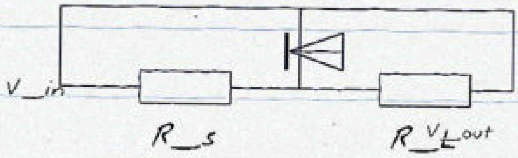


Fig. Zener as a constant voltage source

Output $V_{out} = V_z$ stays nearly constant.

Optoelectronic Devices

(2) Photodiode

A p-n junction operated under reverse bias with a transparent window. Light photons of energy h nu 7 E_g create extra electron-hole pairs in the depletion region.
These add to reverse saturation current.

Reverse current grows with light intensity
-7 used in light detectors, optical fibre Rx.

(3) Light Emitting Diode (LED)

Forward biased junction made of GaAs, GaP, InP etc. Electrons recombine with holes in the junction, releasing photons.

h nu E_g <- colour set by E_g

Threshold V V_b of material.
Different E_g -7 different colours.

(4) Solar cell

Unbiased illuminated junction. Photons make e-h pairs ; built-in field separates them -7 open-circuit voltage V_oc across load.

Solar Cell Details

Material choice

Used semiconductors : Si , GaAs , CdTe , CIGS.

E_g 1 - 1.8 eV · matches solar spectrum.

Top layer thin (transparent) , bottom layer thick. Top contact is a finger grid.

Key parameters

V_{oc} : open-circuit voltage . 0.5 - 0.6 V · (Si)

I_{sc} : short-circuit current 40 mA / cm^2

FF : fill factor = $P_{max} / (V_{oc} I_{sc})$

ε : efficiency 15 - 25%.

I - V curve of solar cell

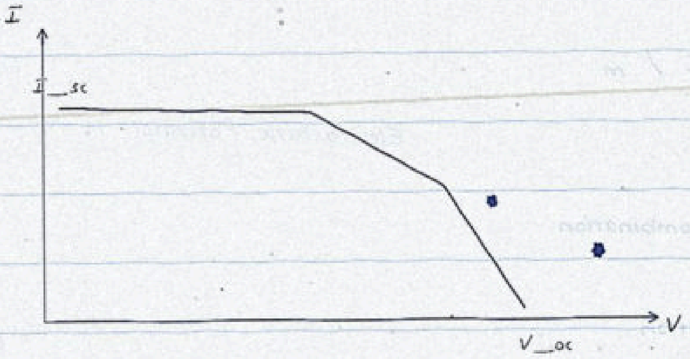


Fig. Solar cell I - V (operating in 4th quadrant)

Power output = V x I , maximised at the knee.

Worked Example - Diode Current

Example 14.2

A Si diode in series with R = 1 k ohm and a 12 V battery. Find the current through R.
Take V_b = 0.7 V (Si), ideal diode otherwise.

Solution :

KVL around the loop :

$$\boxed{V - V\_b - I R = 0}$$ <- Kirchhoff

Hence I = (V - V_b) / R
= (12 - 0.7) / 1000
= 11.3 / 1000
= 11.3 mA

If Ge had been used (V_b = 0.3 V) :
I = (12 - 0.3) / 1000 = 11.7 mA

Note

Drop across the diode (V_b) is small compared to source V, so current is nearly the ohmic value V / R = 12 mA.

Diode is ON only when V_app > V_b.

Worked Example - Rectifier Eff.

Example 14.3

A full-wave bridge rectifier feeds R_L = 1 K.

Peak secondary voltage V_m = 14.14 V.

Take 2 diode drops = 1.4 V total.

Find V_dc , I_dc and eta.

Solution :

Effective peak V_peak = 14.14 - 1.4 = 12.74 V.

V_dc (full-wave) = 2 V_peak / π

= 2 × 12.74 / 3.14

= 25.48 / 3.14   8.11 V

I_dc = V_dc / R_L = 8.11 / 1000

= 8.11 mA

I_rms = I_m / sqrt(2) ; V_rms = V_peak / sqrt(2)

$\varepsilon = 8 / \pi^2$ 0.812

i.e. 81.2 % (ideal full-wave).

For half-wave : V_dc = V_peak / pi

and eta_max   40.6 %.

Bridge wins by factor 2 in V_dc and in eta.

Worked Example - Carrier Ratio

Example 14.4

Pure Ge has n_i = 2.4 x 10 19 / m 3 at 300 K.

Doped p-type with N_A = 4.5 x 10 22 / m 3.

Find n_h , n_e and the ratio n_h / n_e.

Solution :

Since N_A 77 n_i , n_h N_A.

n_h 4.5 x 10 22 / m 3.

Mass-action law : n_e n_h = n_i 2

$n\_e = n\_i^2 / n\_h$

= (2.4 x 10 19) 2 / (4.5 x 10 22)

= 5.76 x 10 38 / 4.5 x 10 22

= 1.28 x 10 16 / m 3.

Ratio n_h / n_e 4.5 x 10 22 / 1.28 x 10 16

3.5 x 10 6 .

Holes outnumber electrons by 10 6 - the sample is firmly p-type.

Note : n_h is set almost entirely by N_A , not by temperature (so long as N_A 77 n_i).

Quick Comparison Tables

Conductor vs Semicond. vs Insul.

Property	Cond.	Semi.	Insul.
rho (ohm m)	10 -8	10 -5 to6	10 11 +
E_g	0	1 eV	> 3 eV
dR / dT	+ve	-ve	n/a
carriers	e	e + h	0

n-type vs p-type

Property	n-type	p-type
dopant	P, As, Sb	B, Al, In
valency	5	3
majority	electrons	holes
minority	holes	electrons
extra level	donor (CB-)	acceptor (VB+)

Half-wave vs Full-wave

Quantity	Half	Full
Diodes used	1	2 or 4
Ripple frequency	f	2 f
eta_max	40.6 %	81.2 %
Ripple r (no filter)	1.21	0.482

Key Formulas

Carriers

n_e x n_h = n_i 2 <- mass-action

sigma = e (n_e mu_e + n_h mu_h) <- conductivity

Diode

I = I_O (e (eV/kT) - 1) <- Shockley

r_d = dV / dI <- dynamic R

Rectifier

V_dc (HW) = V_m / pi

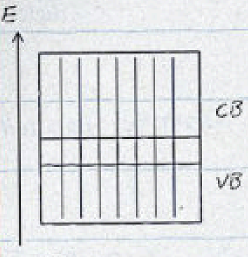
V_dc (FW) = 2 V_m / pi

eta_HW 40.6% , eta_FW 81.2%

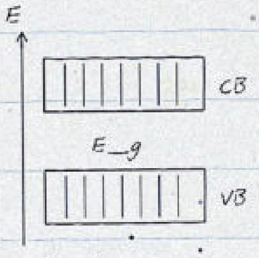
ripple r = V_rms,ac / V_dc

Constants used : k = 1.38 x 10 -23 J / K ;
e = 1.6 x 10 -19 C ; kT/e 0.026 V at 300 K.

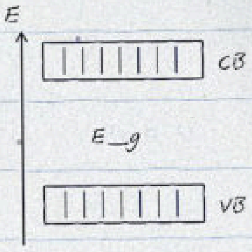
Summary - Band Picture



Metal



Semi.



Insul.

$E_g \doteq 0$ E_g 1 eV $E_g > 3$ eV

Quick takeaways

① Doping changes carrier balance by 10 6.

② p-n junction shows one-way conduction.

③ Forward bias -> low R ; reverse -> high R.

④ Diode rectifies AC into pulsating DC.

⑤ Filter capacitor smoothens it to steady DC.

End of chapter ~~13~~ 14 - revise tables !