Analog Electronic Circuit Design

As per KL University Vijayawada Syllabus 2018-19

V Ramani Kumar
Prof (ECE) – KL University,
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About the book and the author……………..·

Why I wrote (write?) this book?
There are so many books on Analog Electonic Circuit Design· Why one more?

I thought quite a lot about it·
I am from the Industry· I had worked in Telecom R&D for nearly 35 years (electronics, embedded and wireless)·
I have been part of huge R&D teams of some of the best Telecom institutions of India

- *DRDO Bangalore, Gujarat communications Baroda, Escorts Telecom Delhi· Solidaire Chennai, Telecom Technology Ltd Hong Kong, Tata Telecom Chennai, Bharti Telecom, Delhi and Premier Evolvics, Coimbatore*

So what?
I had the fortune of working with hundreds of engineers everywhere …··fresh engineers straight out of the college· I had trained them in circuit designs, embedded designs and system designs· I understand the gap between the industry expectations and the academic objectives, better than many professionals or academicians·

I thought I am qualified enough to address this gap· I teach in Engineering colleges too and try my best to bring an Industry perspective into every lecture of mine· The students, as well as the faculty· seem to like this approach·

This encouraged(s) me to write a book on basic electronics first for VTU Bangalore and now on Analog Electronic Circuits Design for KLU Vijayawada· This maybe a one-stop-solution for a good book on AECD·
The approach is simple, bringing out the design issues at every opportunity, with an objective to make the student master the concepts·

Simple structured presentation of the syllabus, with plenty of illustrations, should help demystification of Analog electronics·

I dedicate this book to

> ***My wife Karpagam – For her great contribution in bringing out this book·***
> ***KLU family of Students - Vijayawada and Hyderabad***

This text book follows the KLU syllabus verbatim and is brought out in fewer than 200 pages· I am sure, the student world will welcome this·

My sincere and special thanks to President KL University, for encouraging me to write this book· As always, he is a great source of inspiration……………..

Pls explore my animation videos at ***https://www·youtube·com/dashboard?o=U***

Good luck,

ramani kumar

AECD – Proposed new syllabus

Diodes: Diode theory, forward and reverse-biased junctions, reverse-bias breakdown, load line analysis, diode applications - Limiters, clippers, clampers, voltage multipliers, half wave & full wave rectification, Capacitor filters, ripple factor, Zener diode,. Regulators: Series and shunt voltage regulator,

Transistors: Q point, Self-Bias-CE, h-model of Transistor, Expression of voltage gain, current gain, input & output impedance, Emitter follower circuits, High frequency model of Transistor, FET fundamentals, Configurations, current-voltage characteristics, parameters of JFET, Biasing of JFET, Biasing of MOSFET. RC coupled amplifier and analysis, FET small signal model, Concept of Feedback, Feedback amplifier configurations.

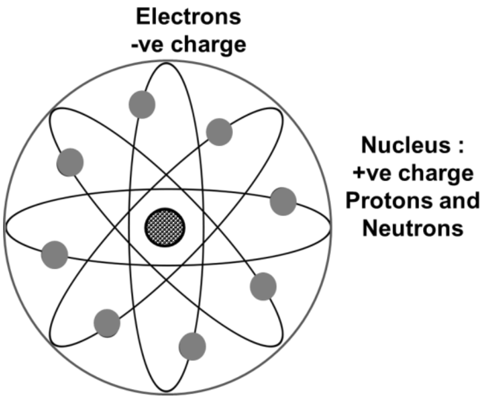
Op-amps: Ideal OPAMP, Concept of differential amplifier, CMRR, Open & closed loop circuits, importance of feedback loop (positive & negative), inverting & non-inverting amplifiers, Voltage follower circuits. Adder, Integrator & Differentiator, Comparator, Schmitt Trigger, Instrumentation Amplifier. Filter Circuits**:** Analysis of Low pass, High pass, Bandpass, Band reject,

Oscillators: Barkhausen criterion, Colpitt, Hartley's, RC Phase shift, Wien bridge, & Crystal oscillators.

555 applications: Monostable & Astable operation using 555 timers

Chapter 1: Semiconductor Theory

1.1 ATOM –Structure



- Atom consists of a nucleus. Electrons in several orbits move around the **nucleus**..
- Contains three basic Particles –**Protons, Neutrons & electrons.**
- Nucleus contains two types of particles
  - **Protons** **:** Positively charged particles.
  - **Neutrons** **:** Particles with neutral charge.
- **Electrons:** Negatively charged particles (Charge = 1.602X 10^{-9} Coulombs).

Fig 1.1 Atom - Structure

Usually protons and electrons will be equal in number .Therefore, atoms are normally neutral, electrically.

- If an atom loses an electron, it means that it has lost some -ve charge & hence has a net + ve charge ……….. and vice versa.

1.1.1 Holes & Electrons (Silicon & Germanium)

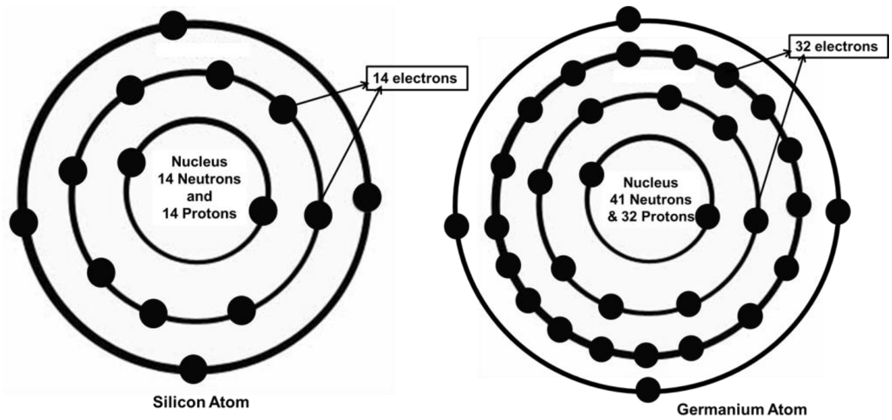


Fig 1.2

Pls recall,

1. Electrons can occupy only some fixed orbits, called **shells**.
2. Each shell can be occupied by only some **specific number of electrons**.
3. The outer most shell called **valence shell**, may be only partially filled by electrons.
4. Figure 1.2 gives a 2 D simplified orbital arrangement of silicon & germanium atom.
5. Absence of an electron in a shell, is defined as a **hole**.
6. Silicon & Germanium atoms are **electrically neutral (outer shell has 4 holes and 4 electrons each**)

1.2 Electron & Hole Dynamics

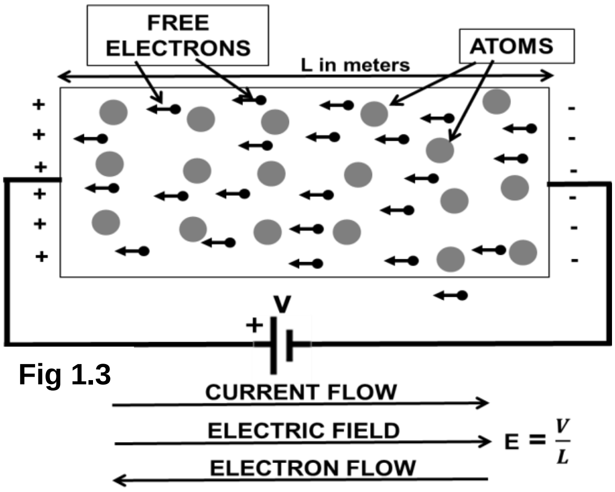


Fig 1.3

Refer fig 1.3.

- **Electrons** are –vely charged particles. Electrons are **repelled by –ve voltage**. Therefore, they will move towards a terminal **where + ve voltage is applied**.
- **Holes** are **+vely charged** particles. Holes are repelled by + ve voltage. They will move towards a terminal **where -ve Voltage is applied**.
- Please note the direction of the current flow is **always opposite** to the direction of electron flow.

1.3 N type & P type Semiconductors

1.3.1 Intrinsic semiconductor: It is very pure chemically. It has **equal numbers of** electrons (-ve) and holes (+ve). It has **poor conductivity.**

1.3.2 Extrinsic semiconductor:

- When a **small amount, of impurity is added** to a pure semiconductor, the conductivity of the semiconductor is increased manifold.
- Such materials are known as extrinsic semiconductors.
- The deliberate addition of a **desirable impurity**, is called **doping.**
- Doping yields two types of semiconductors viz p type and n type.
- The impurity atoms are called **dopants.**
- Such a material is also called a **doped semiconductor.**
- **Silicon & Germanium** are the standard semiconductor atoms, used by the industry.

Some of the popular dopants used, in doping the tetravalent Si or Ge are,
Trivalent atoms such as Boron or Aluminium, for producing p type semiconductors.
Pentavalent atoms such as Arsenic or Phosphorous, for producing n type semiconductors.

n type: Refer fig 1.4. **Pentavalent (5)** impurities like Arsenic (As), Antimony (Sb), Phosphorous (P), when added to either silicon or germanium, will produce N type semiconductors. **Electrons are the majority carriers**.

p type: Refer fig 1.5. **Trivalent (3)** impurities like Indium (In), Boron (B), Aluminium (Al) when added to either Silicon or Germanium, will produce P type semiconductors. **Holes are the majority carriers**.

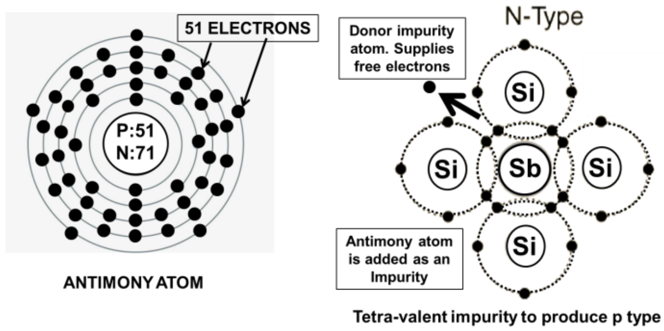


Fig 1.4 n-type pentavalent atom

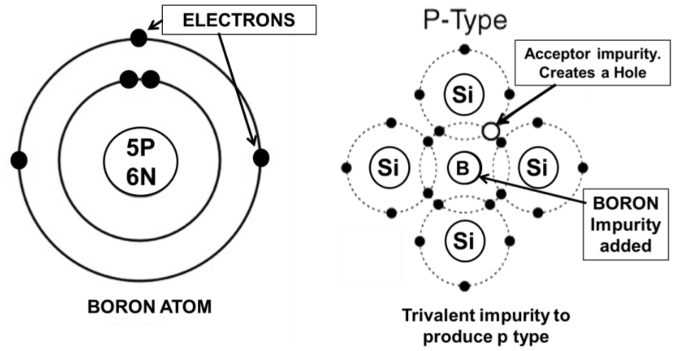


Fig 1.5 p-type trivalent atom

Majority and minority carriers

Majority carriers:

- The more abundant charge carriers
- Primarily responsible for current transport in a semiconductor.
- n-type semiconductors: Electrons
- p-type semiconductors: Holes.

Minority Carriers:

- The less abundant charge carriers
- n-type semiconductors: Holes
- p-type semiconductors: Electrons.

1.4 pn junction

Figure 1.6 shows independent p type independent n type semi-conductor.

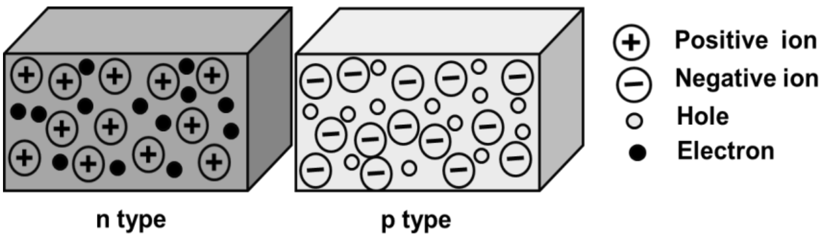


Fig 1.6 Semiconductor material n-type and p-type

Fig 1.7 shows a p type and n type conductor joined together (fabricated) to form a p-n junction

- There is no external voltage (bias) applied.
- Initially, pn junction is electrically neutral.

- **Majority carriers of n type are electrons.**
- **Majority carriers of p type are holes.**

1.4.1 Diffusion

Refer fig 1.7. Due to thermal agitation, electrons and holes start moving randomly, even if there is no bias. Look at the diffusion process below.

Few electrons close to the junction, start crossing the junction, to reach p side	Few holes close to the junction, start crossing the junction, to reach the n side
These electrons combine with some holes in the p side, to create some –ve ions.	These holes combine with electrons in the n side to create some +ve ions.
Due to these ions, a -ve voltage build up (barrier) is created, on the p side.	Due to these ions, a +ve voltage build up (barrier) is created on the n side.

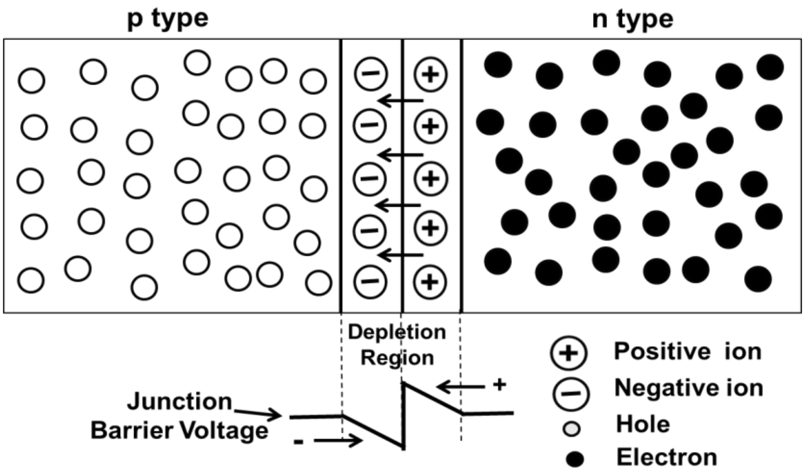


Fig 1.7 p-n junction diode – No bias voltage

This barrier voltage build up is shown in the figure 1.8.

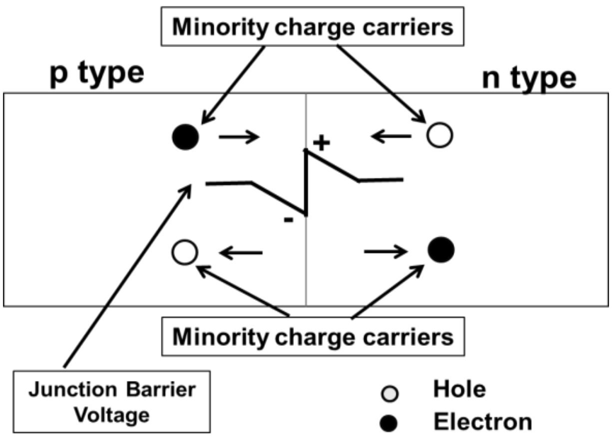


Fig 1.8 Barrier Voltage at p-n junction

- Barrier voltage is typically **0.7 V, for Silicon**.
- Barrier voltage is typically **0.3 V, for Germanium.**
- At around the barrier voltage, **electrons (from n side) are repelled by the – ve barrier voltage in the p side.**
- At around the barrier voltage**, holes (from p side) are repelled by the +ve barrier voltage in the n side.**
- Therefore further diffusion stops.

1.4.2 Depletion region

- In the diffusion process mentioned above, **when the barrier potential is reached, further diffusion stops.**
- No charge carriers (electrons or holes) will be present, closer to the junction.
- Only ionized atoms (+ve and –ve), will be present on either side of the junction.
- This region is known as **depletion region**.

1.5 pn junction biasing

1.5.1 Reverse biased p-n junction

Refer figure 1.9.

What is reverse bias?

An external dc voltage (bias) is applied to a diode such that, p side is connected to the –ve terminal and n side is connected to the +ve terminal of a battery.

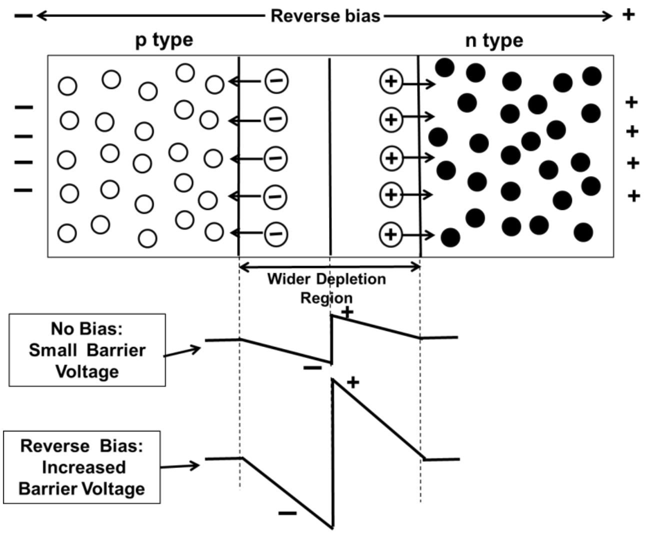


Fig 1.9 Reverse biased p-n junction

- This biasing arrangement increases the barrier voltage, as shown in the figure.
- Barrier voltage at n, becomes more +ve and the barrier voltage at p becomes more –ve.
- Electrons (majority carriers) in the n side, are repelled away from the junction and are attracted towards the +ve terminal.
- Holes (majority carriers) in the p side, are repelled away from the junction, and are attracted towards the –ve terminal.
- Consequently, depletion region further widens and barrier voltage increases as shown.

Result: Majority carriers cannot flow across junction and therefore, under reverse bias conditions, no current flow is possible. In other words, forward current does not flow.

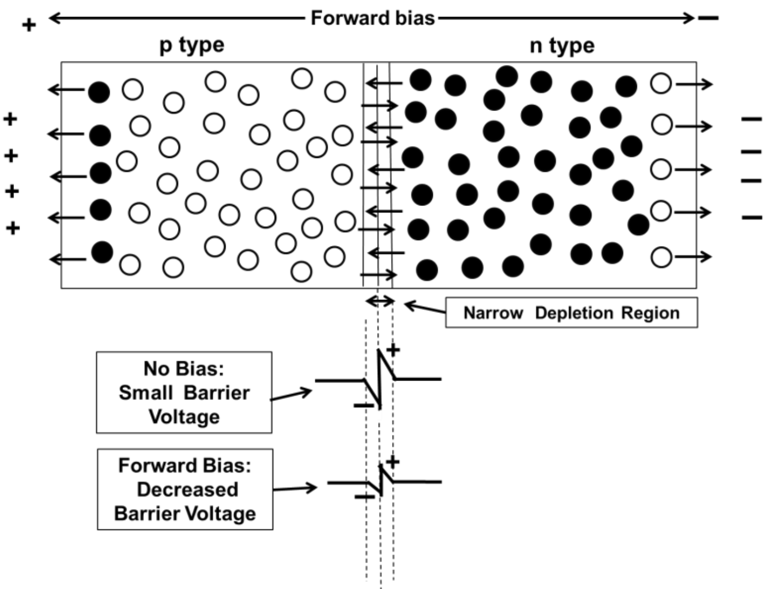
1.5.2 Forward biased p-n junction

Refer figure 1.10.

What is forward bias?

An external dc voltage (bias) is applied to a diode such that **n side is connected to the – ve terminal and p side is connected to the +ve terminal of a battery.**

- This biasing arrangement decreases the barrier voltage, as shown in the figure 1.10.
- Barrier voltage at n, becomes less +ve and the barrier voltage at p becomes less –ve.
- Electrons (majority carriers) in the n side, are attracted across the junction, **towards the p side and are attracted towards the +ve terminal.**
- Holes (majority carriers) in the p side, are attracted across the junction, **towards the n side and are attracted towards the –ve terminal.**



- Consequently, depletion region decreases and the barrier voltage also reduces, as shown.

Result: Majority carriers will flow across junction and therefore, under positive bias conditions, current flow is possible. In other words, forward current flows.

Fig 1.10 Forward biased p-n junction

Chapter 2: Semiconductor Diodes and Applications

2.1 p-n junction diode

What is a diode?

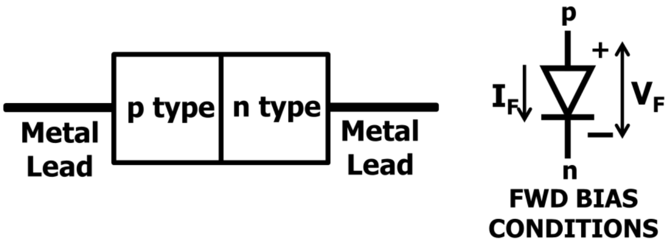


Fig 2.1 Semiconductor diode with leads

Draw the circuit symbol and indicate current flow.

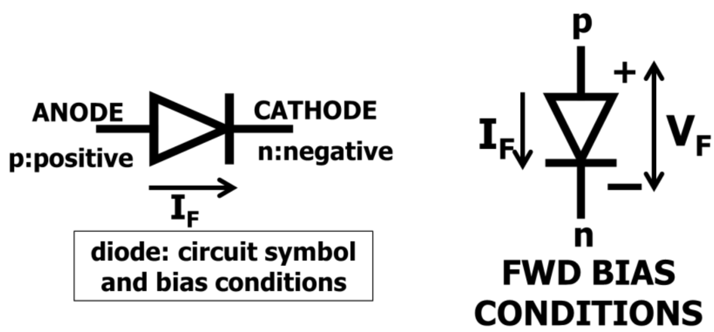


Fig 2.2

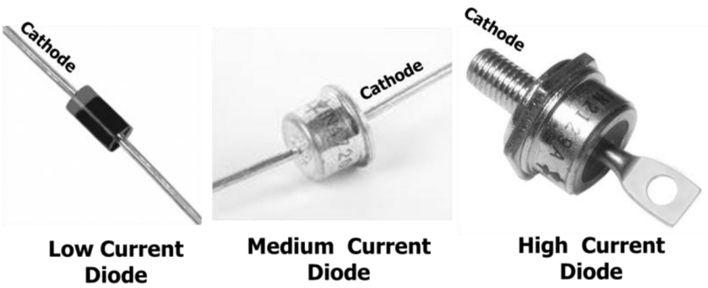


Fig 2.3

Refer fig 2.1 and 2.2

- It is a semiconductor device with a p-n Junction.
- It is a one way device.
- Allows current to flow when forward biased (p: + ve and n: -ve).
- Almost totally blocks current flow when reverse biased (p: - ve and n: +ve).
- Therefore, a diode is a 2 terminal component.
- It has two electrodes called anode and cathode.
- Anode is attached to p side and cathode to n side.

Diodes Power classification: Refer fig 2.3.

- **Low power diodes:** Usually small diodes can handle low currents up to 100mA. Power dissipation will be less than 800 milli-watts.
- **High power diodes:** Large diodes can handle high currents (1 to 10 Amperes). Power dissipation will be between 1 watt and 10 watts.
- Look at the table below

Diode size	Cathode Identification	Forward current (mA)	Reverse voltage (V)
Small-	Color band or dot	100	75
Medium	Diode Symbol	400	200
Large	Threaded portion	Few amperes	Few hundreds

2.2 Characteristics and parameters:

2.2.1 Diode characteristics: Refer fig 2.4 and 2.5

- It is the study of, 'voltage-across-the-diode' versus 'current- through-the-diode'.
- As we know, diode is a p-n junction semi-conductor device.

- When it is **forward biased**, diode characteristics is a **study of forward voltage (or threshold voltage) V_F & forward current I_F.**
- When it is **reverse biased**, the diode characteristics is a study of reverse voltage **(or threshold voltage) V_R & reverse current I_R**.

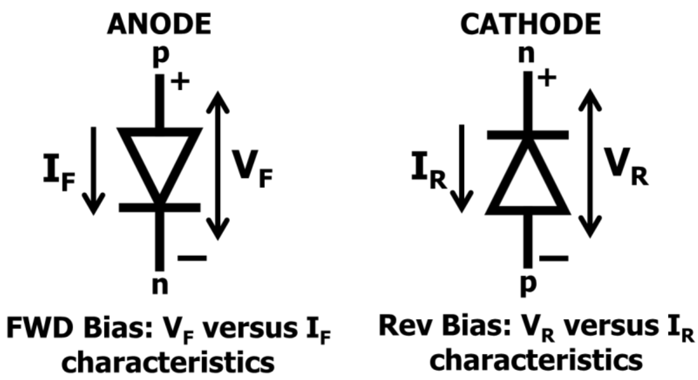


Fig 2.4

2.2.2 Diode equation

Current contribution in Diode is due to majority charge c
exponentially increases with applied voltage as given diode equation by

$$I = I_0\left(e^{\frac{v_d}{\eta\, V_T}} - 1\right) \approx I_0 e^{\frac{v_d}{\eta\, V_T}}$$

.

I Current through the diode, in Amps
v_d Diode voltage with the anode positive with respect to the cathode, in V
I_0 Leakage (or reverse saturation) current.
η empirical constant known as the emission coefficient or the ideality factor**.**
V_T Voltage equivalent of temperature (= kT/q**)**

2.2.3 Forward characteristics (Silicon): Refer fig 2.5

Up to 0.7 V

- As the forward bias is increased from **0.1 to 0.7 V**, the diode hardly conducts the **forward current is very low** (less than 5 mA).

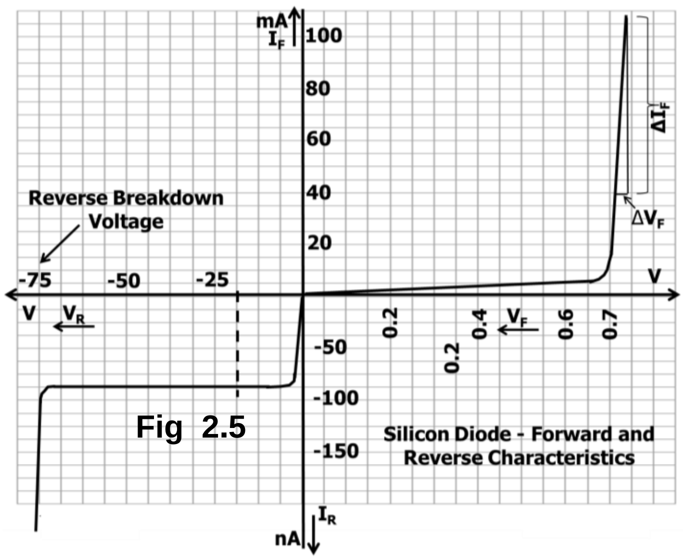


Fig 2.5

Beyond 0.7 V

- As the forward bias is increased **beyond 0.7 V**, the **forward current increases** very sharply.
- Increasing the **forward bias beyond say 1.0 V, will destroy a diode** due to excessive forward current.
- A **current limiting resistor is needed** in the circuit to protect the diode.

2.2.4 Reverse characteristics (Silicon)

0 to -75 V

- Please **note the change of scale, in the y axis between forward & reverse characteristics**.
- **Reverse current I_R, is often very low** (not more than 1 μA) for reverse voltages up to -75 V for silicon
- **I_R is negligible compared to I_F.**

- For all practical purposes the diode behaves like an open circuit.

Beyond -75 V:

- **Reverse break down** happens (we shall study this later).
- The current **increases abruptly**.
- This **can destroy the diode**, unless protected by a **current limiting resistor**
- **Peak Inverse Voltage (PIV):** The maximum reverse-bias voltage that a diode can withstand without "breaking down" is called the **Peak Inverse Voltage, or PIV rating**.

2.2.5 Diode characteristics (germanium)

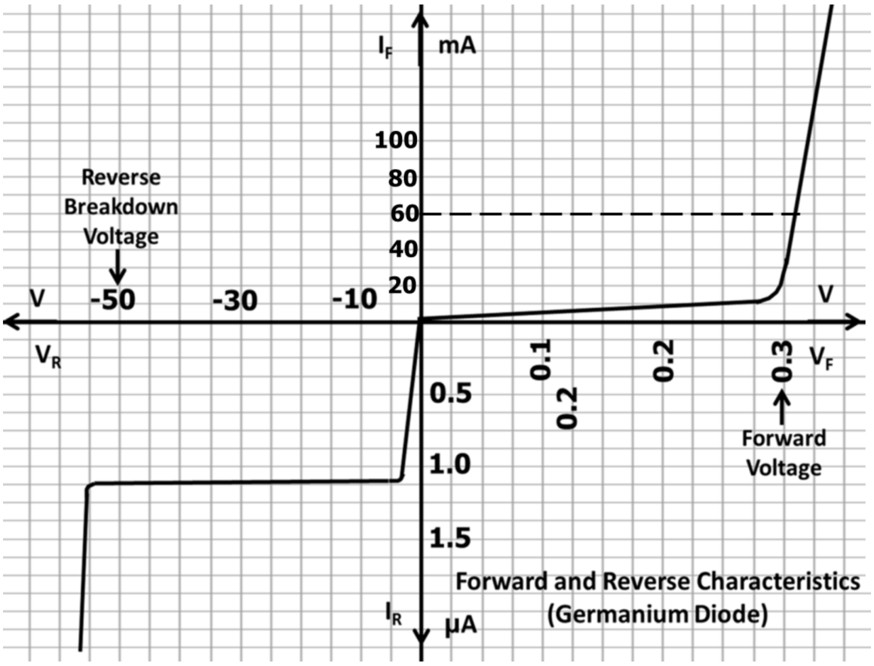


Fig 2.6 Germanium diode – Fwd and Rev characteristics

Refer fig 2.6.

- The characteristics are similar to that of silicon diode.
- Forward voltage is 0.3 V instead of 0.7 V.
- Reverse break down voltage is -50 V instead of -75 V.
- Reverse current is -1.0 μA instead of -100 nA.

2.2.6 Variation of forward voltage (Threshold voltage) with temperature

We know, Silicon diode has a forward voltage of is 0.7 V at 25°C and Germanium diode has a forward voltage of is 0.3 V at 25°C

Temp Coefficient of Silicon is given by $K_{TC(Silicon)} = - 2\ mV / {}^oC$.

Temp coefficient is negative, meaning that forward voltage decreases as temperature increases.

Find the threshold voltage at 100°C for Germanium and Silicon.

Ans: 0.15V and 0.55V

2.2.7 Reverse bias break down mechanism

Case 1

Very narrow depletion region

- **Reverse voltage produces very high field strength**.
- What is field strength? Voltage per distance **(Volts / Distance.)**
- **Electrons break away from their atoms due to this field strength**.
- ∴Due to this electron flow, depletion region is converted into a conductor (from insulator)
- This is called **ionization by electric field**
- This is known as Zener break down mechanism
- Usually occurs when **reverse bias is < 5V**

Case 2

Depletion region very wide

- In the reverse bias mode reverse saturation current flows.
- There are electrons moving in reverse saturation current.
  - **When these electrons travel in the wide depletion region, these electrons gain a lot of energy**
  - These energetic electrons **collide with atoms** and cause their **electrons to break-free**.
  - Due to these new electrons, **more collisions** occur and more electrons get released
- This is known as **Avalanche break-down**.
- Also known as **Ionization by collision**
- Usually occurs when **reverse voltage is > 5V**

2.2.8 What is reverse saturation current (ICO)?

Occurs during reverse bias conditions

When a diode is reverse biased, we know the depletion region width increases.

Therefore no current flow happens due to majority carriers

However minority carriers diffuse through this depletion region

In a PN junction diode, the reverse saturation current occurs due to diffusion flow of electrons (minority carriers) from p region to n region and flow of holes (minority carriers) from n region to p region.

This current is nearly constant and is known as **reverse saturation current ICO**

2,2,9 How does reverse saturation current (ICO) behave with temperature?

Reverses saturation current is a nuisance.

It **increases** rapidly with temperature.

The increase is of the order of 7%/ºC for both germanium and silicon

In other words ICO doubles for every 10ºC rise in temperature and is definitely serious.

$I_2 = I_1 * 2^{\frac{(T2-T1)}{10}}$ (I_2 = Current at new temperature and I_1 = Current at old temperature)

2.2.10 Forward & Reverse resistance : Refer fig 2.7

Problem 2.1: In fig 2.6, calculate the forward resistance of the germanium diode, at I_F= 60mA

At I_F = 60 mA, V_F = 0.33 V (approx)

Therefore, forward resistance

(R_F) = $\frac{V_F}{I_F} = \frac{0.33\,V}{60\,mA}$ = 5.5 ohms.

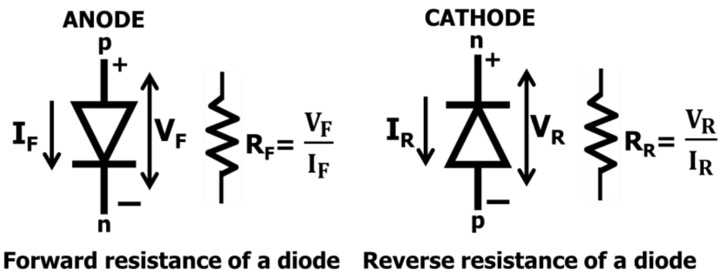


Fig 2.7

Problem 2.2: In fig 2.5, calculate the reverse resistance of the silicon diode at V_R =20V.

At V_R = 20 V, I_R = 90 nA (approx)

Therefore, reverse resistance (**R_R**) **=** $\frac{V_R}{I_R} = \frac{20\text{ V}}{90\text{ nA}}$ = 222 Mega ohms (approx)

2.2.11 Some of the important diode parameters.

V_F - Forward voltage drop (0.3 V for Ge and 0.7 V for silicon).

I_F - Forward current .

V_R - Reverse voltage.

r_d - Dynamic resistance = $\frac{\Delta V_F}{\Delta I_F}$

V_{BR} - Break down voltage {50 V for Ge and 75 V for Si).

P_D - Power dissipation.

2.2.12 Dynamic resistance r_d

Recall the forward resistance that was calculated in problem 2.1. **$R_F = \frac{V_F}{I_F}$.** This is the **DC resistance** of the diode, at one particular value of forward current. When the input varies by ΔV_F, there will be large variation, in forward current (ΔI_F). This is shown in fig 2.5

Dynamic resistance $r_d = \frac{\Delta V_F}{\Delta I_F}$. r_d is also known as ac resistance or incremental resistance

There is another way of calculating dynamic resistance. It is not discussed here since it is beyond the scope of this book.The formula is $r_d = \frac{26\text{ mV}}{I_F}$

Problem 2.3: What is the dynamic resistance of a diode with a forward current of 5 mA

$r_d = \frac{26\text{ mV}}{5\text{ mA}}$ = 5.2 Ω.

Problem 2.4: For the dynamic characteristic shown in fig 2.8, determine the dynamic resistance at 40 mA.