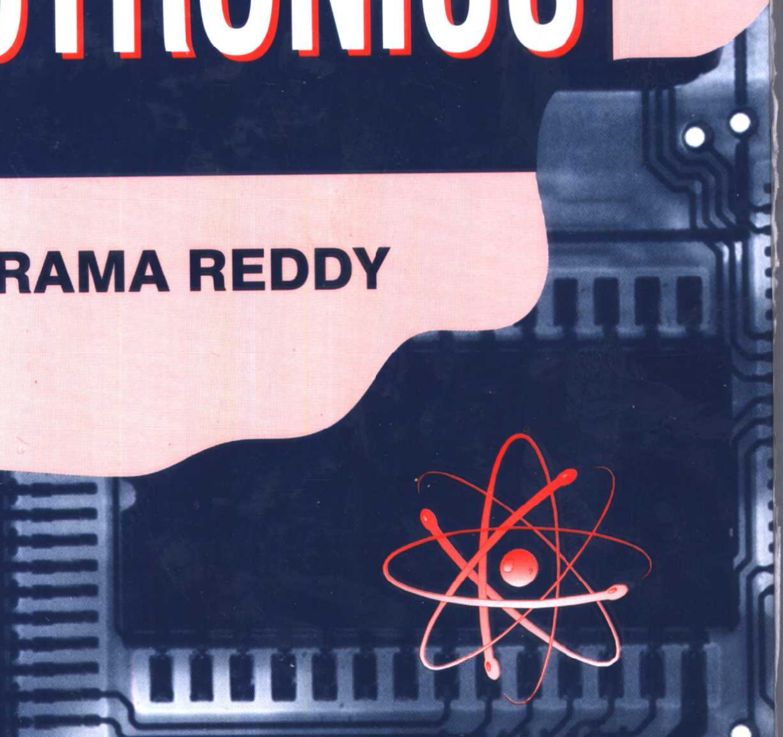
FUNDAMENTALS OF POWER ELECTRONICS

S. RAMA REDDY



Alpha Science

Fundamentals of
POWER ELECTRONICS

S. Rama Reddy

Alpha Science International Ltd.

Dr. S. Rama Reddy
Professor and Head
Electrical and Electronics Engineering Department
S.R.M. Easwari Engineering College, Chennai-600 089, India

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Preface

The present book with simple treatment is the outcome of my many years of teaching. It will serve as an ideal textbook for courses on Power Electronics and Industrial Electronics at polytechnic and undergraduate levels. It will also be very useful to students preparing for professional courses like A.M.I.E. and A.M.I.T.E.

This book is divided into twelve chapters. The first chapter deals with various types of devices, protection, series and parallel operation of SCRs. Chapters 2 and 3 describe various triggering circuits used for SCRs and methods of commutation of SCRs, respectively. Chapter 4 discusses phase controlled converters while Chapter 5 deals with DC to DC choppers. Chapters 6 and 7 deal with various types of inverters and cycloconverters, respectively. Various AC chopper circuits are described in Chapter 8. Chapter 9 gives various applications like speed control of DC and AC motors, heating, welding, UPS, SMPS and HVDC system. Chapter 10 gives analysis of resonant inverters with R and R-L loads. Principle of operation of quasi-resonant converters are given in Chapter 11. Chapter 12 describes microprocessor based triggering schemes for three-phase converter. All the chapters carry short questions and answers at the end.

Appendix I contains basic experiments in power electronics while short question and answer banks are given in Appendix II.

I would like to convey my deep sense of gratitude to Dr. B. Ilango and Dr. V.P. Ramamurthy who taught me this subject.

The author owes his deep gratitude to Mr. T.R. Pachimuthu (Chairman), Dr. T.P. Ganesan (Director) and Prof. V. Subramaniam (Principal), Easwari Engineering College, Chennai for their keen interest in bringing out this book.

The author would like to thank Mr N Jayaraman and Mr. N.A. Abbu for drawing the illustrations and Mr. T Rajasekar for typing the manuscript. Thanks are due to M/s Narosa Publishing House for bringing out this book in its present form.

I would be glad to receive comments and suggestions for the improvement of this book.

S. RAMA REDDY

Contents

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1

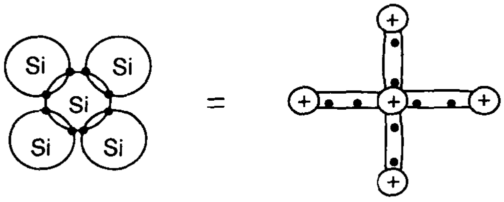
Semiconductor Devices

1.1 INTRODUCTION

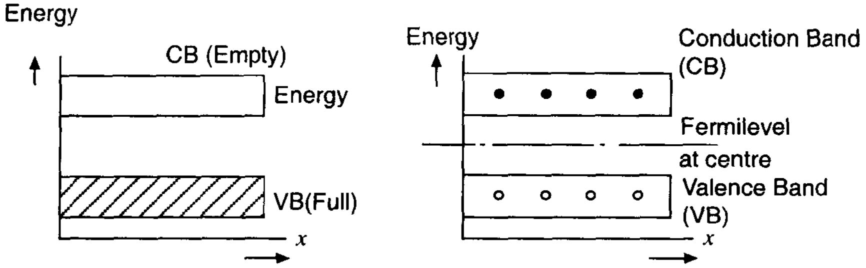
In this chapter, types of semiconductors, various devices and protection of SCR circuits are discussed.

1.1.1 Intrinsic Semiconductor

Intrinsic semiconductor is a pure semiconductor. Silicon and germanium are the semiconductor materials. To form a stable covalent bond, 8 valence electrons are required. The silicon atom at the centre has 4 valence electrons. It shares 4 electrons from the neighbour atoms to form a covalent bond. The symbol of the covalent bond is shown in Fig. 1.1(a).



(a) Covalent bond



(b) Energy band diagram at 0°K **(c) Energy band diagram at room temperature**

Fig. 1.1

At absolute zero temperature, no energy is supplied to the crystal. All the electrons are engaged in forming covalent bond and no free electrons are available. Hence there is no conduction. Thus the semiconductor acts as an insulator at 0°K. The Energy band diagram for this condition is shown in Fig. 1.1(b). The conduction band is empty as no conduction electrons are available.

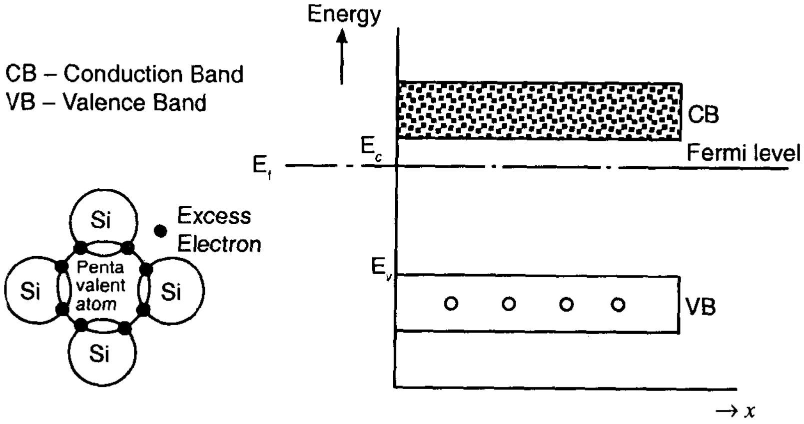
When thermal energy is supplied to the semiconductor, some of the covalent bonds are broken due to the energy supplied. These electrons jump from valence band to the conduction band as shown in Fig. 1.1(c).

1.1.2 Extrinsic Semiconductor

Extrinsic semiconductor is also called impure semiconductor. They are classified as N-type and P-type. N stands for negative and P stands for positive.

(a) Negative Type or N-Type

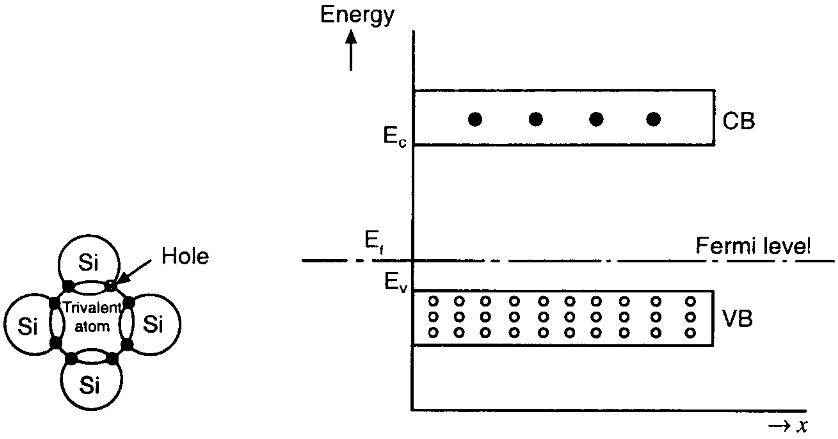
When the intrinsic semiconductor is doped with pentavalent impurity, negative type semiconductor is formed. The pentavalent impurities are antimony, arsenic and bismuth. The pentavalent atom at the centre has 5 valence electrons. This atom shares four electrons from the neighbour atoms. For the formation of stable covalent bond, only 8 electrons need to rotate in the valance orbit. Thus one excess electron is produced by each impurity atom. Several impurity atoms donate several electrons. Since the impurity atoms donate electrons, they are known as *donors*. The energy band diagram is shown in Fig. 1.2(b). A few covalent bonds are broken at room temperature due to the thermal energy supplied by the nature. The vacancies are shown as holes in the valence band. The majority carriers are electrons and the minority carriers are holes.



(a) N-Type **(b) Energy Band Diagram**

Fig. 1.2

E_c is the lowest energy level of the conduction band and E_v is the highest energy level of the valence band. E_f is the Fermi Energy level. Fermi level corresponds to the centre of gravity of the electrons and holes. In the case of intrinsic semiconductor, the number of electrons are equal to the number of holes. The Fermi level lies midway between the valence band and conduction band. In the N-type semiconductor the fermi level is lifted towards the conduction band as the conduction electrons are the majority carriers.



(a) P-Type **(b) Energy Band Diagram**

Fig. 1.3

(b) Positive Type or P-Type

When the intrinsic semiconductor is doped with trivalent atoms, positive type semiconductor is formed. The trivalent atoms are indium, gallium, boron and aluminum. The trivalent atom at the centre has 3 valence electrons. This atom shares 4 electrons from the neighbour atoms. 8 electrons are required to form the valence orbit. In other words the trivalent atom can accept one electron. This vacancy is known as a *hole*. The holes have positive charge. Millions of impurity atoms can accept millions of electrons. Hence they are called as *acceptors*. The majority carries are holes and the minority carriers are electrons.

The electrons jumped from the valence band to the conduction band due to thermal energy are represented in the conduction band. Valence orbit of each impurity atom has one hole. Thus, holes in the valence orbits of the impurity atoms are represented in the valence band as shown in the energy band diagram. The Fermi level is shifted down as the majority carriers are the holes in the valence orbits.

1.1.3 P-N Junction

Holes are represented by +ve sign and the impurity atoms by –ve ions in P-type semiconductor. Electrons are represented by –ve sign and the impurity atoms by +ve ions in N-type semiconductor.

When the P-N junction is formed, the conduction electrons in the N-region will diffuse (penetrate or enter) into the P-region. The holes in the P-region will diffuse into the N-region. The electrons fall into the holes. This process is known as Recombination. The average time for which the electron travels before it recombines, is known as the Life Time. A depletion layer is formed at the junction. The recombination stops after some time. The conduction electrons on the N-side are repelled by the negative ions on the P-side. The holes on the P-side are repelled by the positive ions on the N-side. Thus a restraining force is set up at the junction and this prevents further recombination.

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In the graph, the charge density on the left side of the potential barrier is negative and it is positive on the right side of the potential barrier as indicated in the charge density curve.

The Electric Field Intensity is maximum at the centre and the magnitude of electric field Intensity decreases on either side. Potential is the work done in moving a unit positive charge from the left to the right side of depletion layer. The work done has to be increased as the charge is moved to the right side. Therefore the potential value increases as we proceed to the right side.

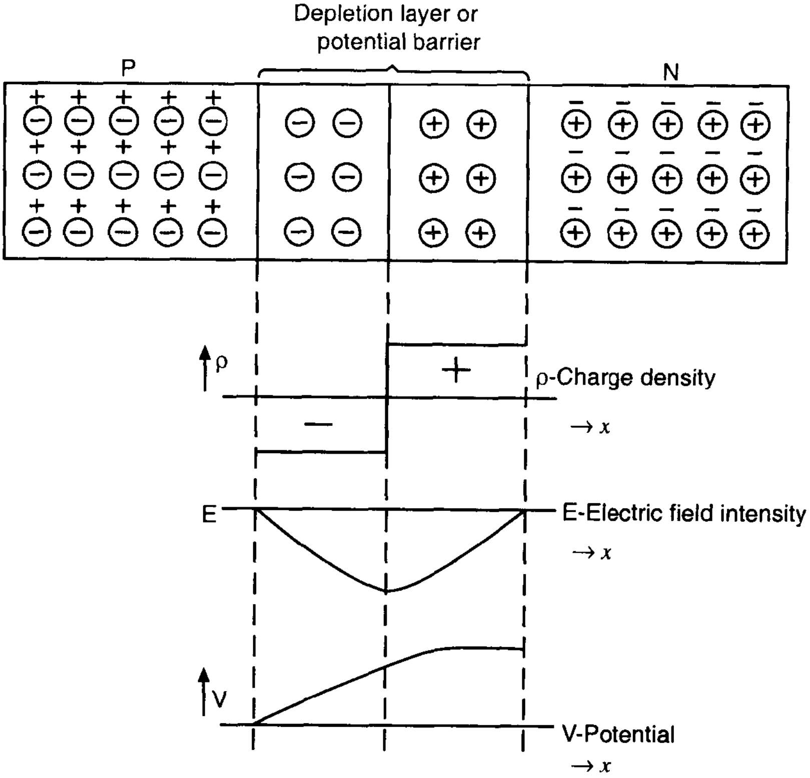


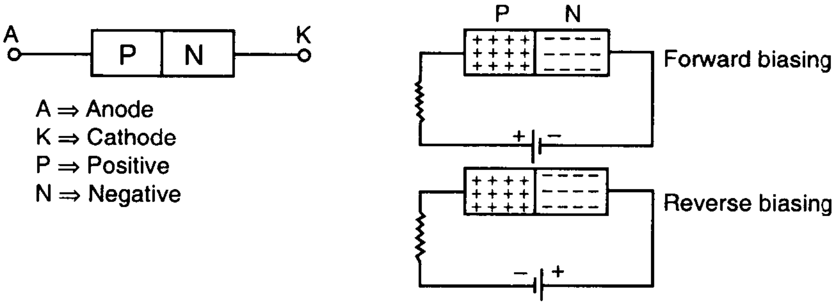
Fig. 1.4 PN Junction

(a) Depletion Layer

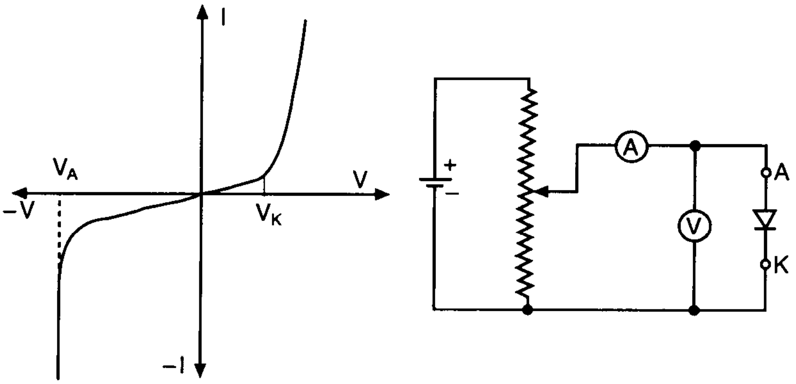
When the P-N junction is formed, the electrons and holes move towards the junction. The electrons will fall into the holes. At the junction, a charge free region is formed. The positive ions and the negative ions are separated by a small distance. These are nothing but the dipoles. The direction of the Electric field is given by the force experienced by the unit positive charge kept in the electric field. The direction is away from the positive charge. An electric field at this layer implies that there is a potential due to the separation of the charges. This potential is known as the barrier potential. This is equal to 0.3 V for germanium and 0.7 V for Silicon.

1.2 PN-DIODE

Diode is a two layer device as shown in Fig. 1.5(a). The junction is formed using P and N layers. The two electrodes of the diode are anode and cathode. When positive terminal of the battery is connected to the anode and negative terminal to the cathode, the diode is said to be forward biased. A stream of electrons start from the negative terminal of the battery and they flow through the N layer as conduction electrons. Near the junction, electrons fall into the holes and they become valance electrons. They travel through the P-layer as valance electrons and later these electrons are attracted by the positive terminal of the battery. This explains the conduction of diode when it is forward biased. From the forward characteristic it can be seen that there is no current till the applied voltage is less than the knee voltage (V_k). When the voltage is more than the V_k, the current through the diode increases with the increase in the applied voltage as shown in Fig. 1.5(b).



(a) PN diode



V_K = Knee voltage (0.3 for Germanium and 0.7 for Silicon)
V_A = Avalanche breakdown voltage

(b) Characteristics of diode

Fig. 1.5

When the anode is connected to the negative terminal and cathode to the positive terminal of the battery, the diode is said to be reverse biased. Current of the order of micro Amperes flows due to the minority carriers.

When the voltage is increased beyond V_A, electric field increases. The electron entering this field experiences more force and this electron can knock off another electron from the covalent bond. Again these two can knock off another two and this process continues. A large current flows through the diode. This effect is called avalanche effect. If the current is not limited, the device gets damaged.

The diode can be represented as a closed switch when it is forward biased and a open switch when it is reverse biased.

Signal diodes are rated for low voltage and low current. The wattage will be 1/2 watt or 1 watt. Power diodes are rated at high voltage and high current. They are of the order of Kilovolts and Kiloamperes. The frequency of operation of the signal diodes will be higher than that of power diodes.

1.3 BIPOLAR JUNCTION TRANSISTOR (BJT)

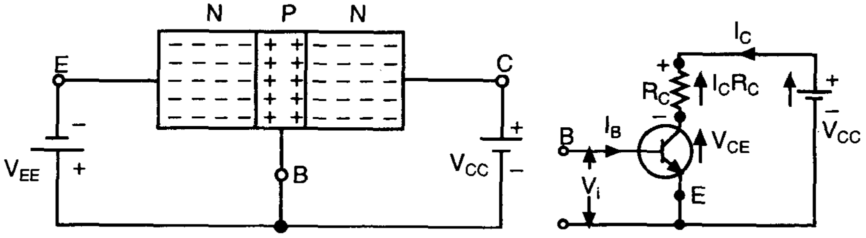
Transistor is a three layer device having two Junctions. Three terminals are emitter, base and collector. The principle of transistor operation can be explained with Fig. 1.6(a). It can be seen that the base is very thin. Let 100% of electrons start from the negative terminal of the input battery. These electrons flow through the emitter. In the base region, about 1% of conduction electrons fall into the holes and the remaining 99% flow through the collector terminal. These electrons are attracted by the positive terminal of the Output battery, thus

$$I_e = I_b + I_c$$

In common base configuration, the base terminal is used as the common terminal for input and output. The gain $\alpha = I_c/I_e$. This is approximately equal to 1. In common emitter configuration, emitter terminal is grounded. The gain $\beta = I_c/I_b$. This varies between 10 to 250.

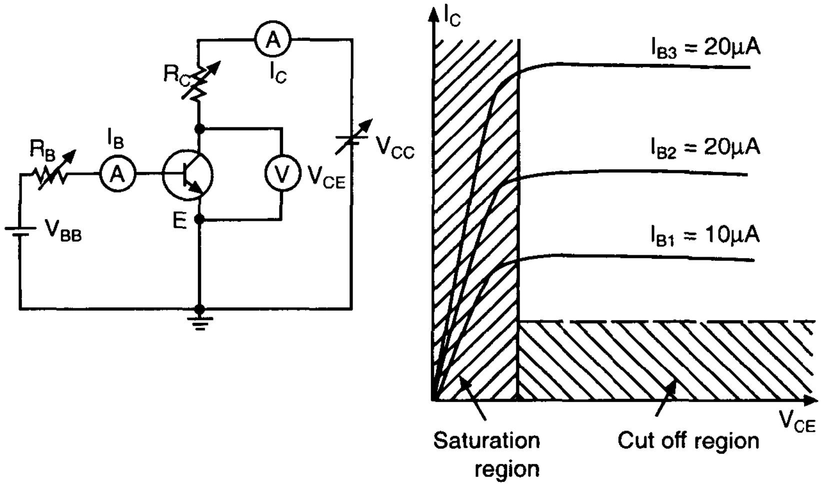
The output characteristic can be plotted with the observations of circuit shown in Fig. 1.6(b). For a fixed base current the variation of output current with the variation in the output voltage is noted. Similarly, readings are obtained for various values of base currents and the output characteristics are plotted. From the characteristic shown in Fig. 1.6(b), it can be seen that the current is negligible in the cut off region. In the saturation region, the voltage across the transistor is very small (about 1 V). This state is ON state.

Transistor is a current controlled device. When base drive is given, the transistor conducts, the entire voltage drops across R_c and $V_{CE} = 0$. When there



E = Emitter; B = Base (Very thin layer); C = Collector

(a) Bipolar junction transistor



(b) Characteristics of BJT

Fig. 1.6

is no base drive, the transistor does not conduct and $V_{CE} = V_{cc}$. Thus transistor act as a controlled switch.

When the transistor is saturated, it acts as a closed switch and when it is in the cut off region, it acts as an open switch.

If a pulse or base drive is given at the base, the transistor acts as a closed switch. If the pulse is not given, it acts as open switch. This concept is very useful in understanding power electronic circuits.

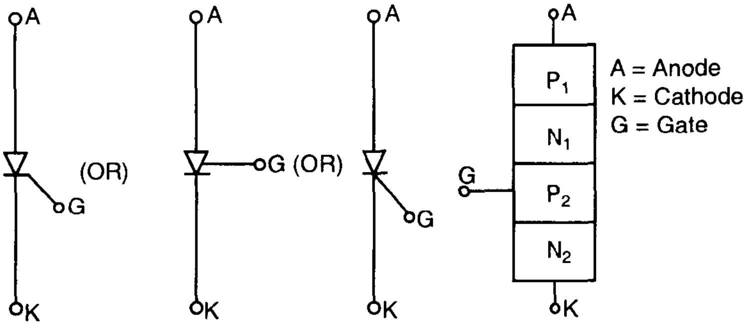
1.4 SILICON CONTROLLED RECTIFIER (SCR)

SCR is a four layer device having three junctions namely J_1, J_2, and J_3. When the SCR is forward biased, the junctions J_1 and J_3 act as closed switches since they are forward biased. J_2 acts as a open switch since it is reverse biased. There cannot be a current from anode to cathode. The SCR is said to be in forward blocking state. The configuration and characteristic are shown in Fig. 1.7(a) and 1.7(b) respectively.

If the voltage is increased beyond $V_{FB,}$ the junction J_2 breaks down and the SCR goes to conduction state. The voltage across the device reduces to 1 V since most of the applied voltage drops across the resistance in the anode circuit.

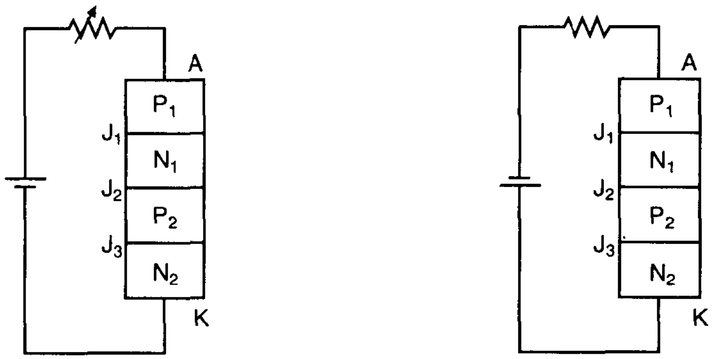
When the anode of the SCR is connected to the negative terminal and the cathode to the positive terminal of the battery, the junctions J_1 and J_3 are reverse biased and J_2 is forward biased. There cannot be a current from cathode to anode. The SCR is said to be in reverse blocking state. The equivalent circuit of the SCR in the reverse bias condition has two diodes in series with reverse voltage being applied. Therefore the characteristic of the thyristor in the reverse biased condition is similar to that of a diode.

The process of changing the SCR from OFF state to ON state is called turn on. The process of bringing the SCR from ON state to OFF state is called turn-off.



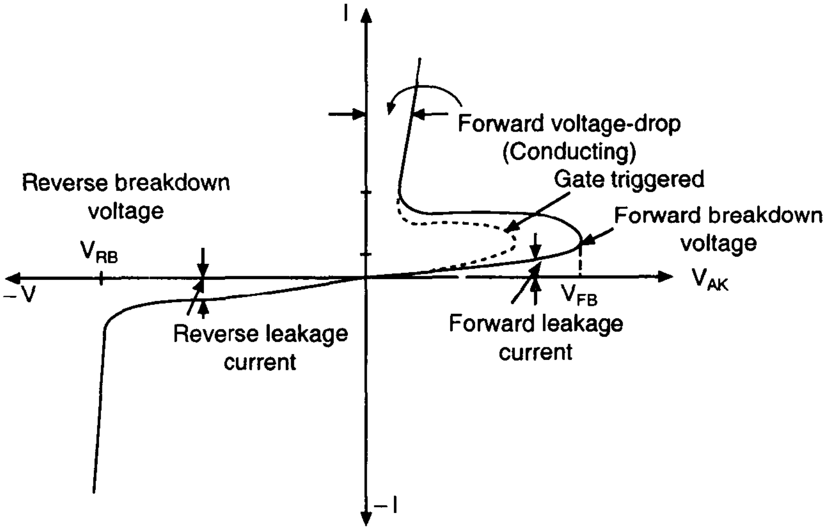
Symbol of SCR

Structure



(a) Forward biasing

(b) Reverse biasing



(c) Characteristics of SCR

Fig. 1.7

1.4.1 Two Transistor Analogy of SCR

The two transistor analogy of SCR is shown in Fig 1.8(a). When gate is made positive with respect to cathode, the NPN transistor conducts and this provides base current for the PNP transistor. The output of PNP is the input to the NPN transistor. Even though the gate voltage is removed the transistors continue to conduct since they are connected back to back. The two transistors finally get saturated and thus the SCR acts as a closed switch when it is forward biased and a positive pulse is applied at the gate. Without gate voltage (pulse), a large voltage has to be applied between anode and cathode. With a gate pulse, a small voltage is sufficient to make the SCR conduct. The arrangement shown in Fig. 1.8b is similar to an ideal motor generator set which can run without external supply. The two machines are connected back to back.

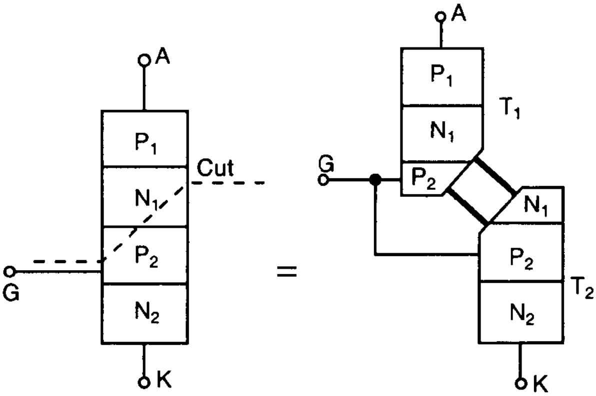


Fig. 1.8(a) Two transistor analogy

The anode voltage required for conduction is a function of the gate current. From the characteristic, it can be seen that larger the value of gate current, smaller the anode voltage required for conduction.

For transistor (1),

$$I_{E1} = I_{C1} + I_{B1}$$

Dividing the above throughout by I_{E1}, we get

$$1 = \frac{I_{C1}}{I_{E1}} + \frac{I_{B1}}{I_{E1}}$$

Substitute $\alpha_1 = \dfrac{I_{C1}}{I_{E1}}$

$$1 = \alpha_1 + \frac{I_{B1}}{I_{E1}} \quad \text{or} \quad 1 - \alpha_1 = \frac{I_{B1}}{I_{E1}}$$

that is $\qquad I_{B1} = (1 - \alpha_1)\, I_{E1},$

From Fig. 1.8(b) $I_{B1} = I_{C2} = (1 - \alpha_1)\, I_A$ (1.1)

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