FIELD EFFECT TRANSISTOR

Dr.R.Radha

Associate Professor of Physics
Centre for Nonlinear Science PG & Research Dept of Physics
Government College for Women (Autonomous)
Kumbakonam-612001.

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Introduction

Introduction

- The invention of the BJT has brought about a great twist in the modern era of semiconductor technology. This device, along with its field-effect counterpart, known as the field-effect transistor (FET), has had a huge impact on virtually every area of modern life.
- Practical field-effect transistors were first made in the form of JFET in 1953 and MOSFET in 1963.

The field-effect transistor has taken various forms like

- The junction field-effect transistor (JFET),
- The metal semiconductor field-effect transistor (MESFET),
- The metal-insulator-semiconductor field-effect transistor (MISFET),
- The metal-oxide-semiconductor field-effect transistor (MOSFET).

Field Effect Transistor

- The FET is a single carrier device and is often called the unipolar transistor because the carriers involved in the operation are either electrons or holes.
- The FET is also a semiconductor device in which the output quantity is controlled by an electric field, which is often the input quantity.
- The phenomenon where the conductivity of the semiconductor is modulated by an electric field applied normally to the surface of the semiconductor is called field effect, and this principle is brought into operation by extending the depletion region deep into the bulk of the semiconductor.

Types of FET

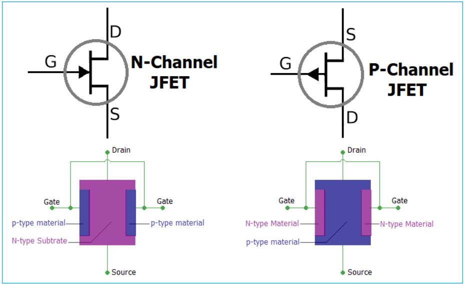
- **Junction Field-effect Transistor (JFET)** In a junction FET, the control voltage modulates the depletion width of a reverse-biased p –n junction which, in turn, varies with the various parameters of the device.
- **Insulated Gate Field-effect Transistor (IGFET)** The IGFET is also called the metal-oxide-semiconductor field-effect transistor (MOSFET). In this, the metal gate electrode is separated from the semiconductor by an insulator.
- **Metal-semiconductor Field-effect Transistor (MESFET)** If the MOS junction is replaced by a direct metal-semiconductor contact, i.e., a Schottky barrier, it is called metal-semiconductor FET (MESFET). A MESFET is similar to a JFET except for the following differences:(i) It has a single gate (ii) The gate is formed by a metal-semiconductor junction

Difference between BJT and FET

BJT	FET
Two types of charge carriers (electron and hole) required	Only one type of carrier (electron or hole) is required
Carriers move through the base by diffusion	Carriers move through the channel by drift process
It has a lower switching speed	FET has higher switching speed due to drift
The BJT is a current controlled device	FET is voltage controlled device
BJT is much noisier than FET	FET is less noisy
At audio frequencies the BJT offers less power gain	At audio frequencies the FET offers greater power gain
The BJT has offset voltage	The FET has no offset voltage
The BJT offers low input impedance	It can be used as a buffer due to high input impedance
It is not a thermally stable device	The FET has a negative-temperature coefficient and thermally stable device.

JFET

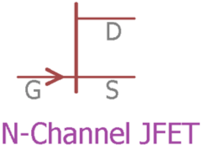
- JFET is Junction gate field-effect transistor. Normal transistor is a current controlled device which needs current for biasing, whereas JFET is a voltage controlled device. JFET has three terminals **Gate, Drain, and Source**.
- JFET is an essential component for precision level voltage operated controls in analog electronics. We can use JFET as voltage controlled resistors or as a switch, or even make an amplifier using the JFET.
- It is also an energy efficient version to replace the BJTs. JFET provides low power consumption and fairly low power dissipations, thus improving the overall efficiency of the circuit. It also provides very high input impedance which is a major advantage over a BJTs.

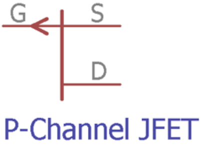


Types of JFET

It has two types- **N - Channel JFET** and **P - Channel JFET**.

- N channel JFET and P channel JFET schematic model are shown in the image above. The arrow denotes the types of JFET.
- The arrow showing to the gate denotes that the JFET is N-channel and on the other hand the arrow from the gate denotes P-channel JFET. This arrow also indicates the polarity of P-N junction, which is formed between the channel and the gate.

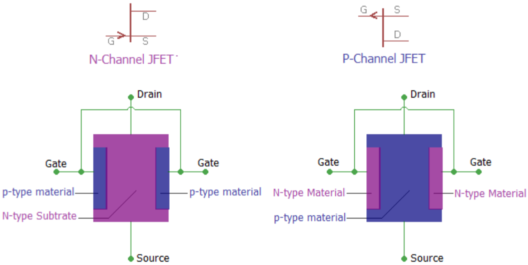




The current flowing through the Drain and Source is dependable on the voltage applied to the Gate terminal. For the N channel JFET, the Gate voltage is negative and for the P channel JFET the Gate voltage is positive.

Structure of JFET

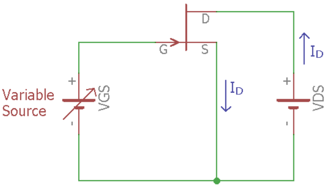
- The N-Channel JFET consists of P-type material in N-type substrate whereas N-type materials are used in the p-type substrate to form a P channel JFET.
- JFET is constructed using the long channel of semiconductor material. Depending on the construction process, if the JFET contains a great number of positive charge carriers (refers as holes) is a P-type JFET, and if it has a large number of negative charge carriers (refers as electrons) is called N-type JFET.
- In the long channel of semiconductor material, Ohmic contacts at each end are created to form the Source and Drain connections. A P-N junction is formed in one or both side of the channel.

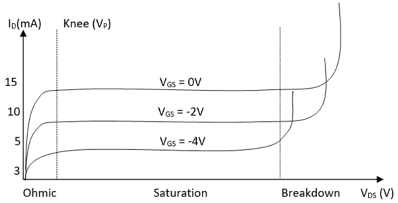


JFET Characteristics Curve

JFET is biased through a variable DC supply, which will control the V_{GS} of a JFET. We also applied a voltage across the Drain and Source. Using the variable V_{GS}, we can plot the I-V curve of a JFET.

There are three different regions Ohmic, Saturation, and Breakdown region. During the Ohmic region, the JFET acts like a voltage controlled resistor, where the current flow is controlled by voltage applied to it. After that, the JFET gets into the saturation region where the curve is almost straight. That means the current flow is stable enough where the V_{DS} would not interfere with the current flow. But when the V_{DS} is much more than the tolerance or the breakdown voltage of reverse biased PN junction, the JFET gets into the breakdown mode where the current flow is uncontrolled.





JFET Parameters

- **Drain resistance** It is defined as the ratio of the change in the drain to the source voltage to the corresponding change in drain current at a constant gate-source voltage.

$$r_d = \left.\frac{\Delta V_{DS}}{\Delta I_D}\right|_{V_{GS}=\text{constant}} \tag{1}$$

- **Transconductance** It is defined as the ratio of the change in the drain current to the corresponding change in gate-source voltage at a constant drain-source voltage.

$$g_m = \left.\frac{\Delta I_D}{\Delta V_{DS}}\right|_{V_{DS}=\text{constant}} \tag{2}$$

- **Amplification factor** It is defined as the ratio of the change in the drain-source voltage to the corresponding change in gate-source voltage at a constant drain current.

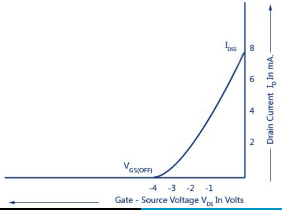
$$\mu = \left.\frac{\Delta V_{DS}}{\Delta V_{GS}}\right|_{I_D=\text{constant}} = r_d \times g_m \tag{3}$$

JFET Transfer characteristics

The transfer characteristic for a JFET can be determined experimentally, keeping drain-source voltage, V_{DS} constant and determining drain current, I_D for various values of gate-source voltage, V_{GS}. It is observed that

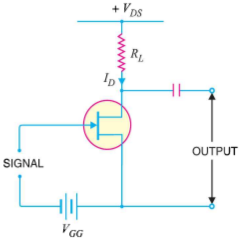
1) Drain current decreases with the increase in negative gate-source bias
2) Drain current, $I_D = I_{DSS}$ when $V_{GS} = 0$
3) Drain current, $I_D = 0$ when $V_{GS} = V_D$

- The transfer characteristic can also be derived from the drain characteristic by noting values of drain current, I_D corresponding to various values of gate-source voltage, V_{GS} for a constant drain-source voltage and plotting them.
- It may be noted that a P-channel JFET operates in the same way and have the similar characteristics as an N-channel JFET except that channel carriers are holes instead of electrons and the polarities of V_{GS} and V_{DS} are reversed.



FET as an amplifier

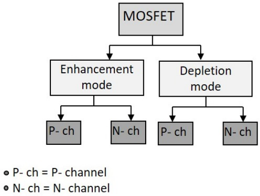
- The weak signal is applied between gate and source and amplified output is obtained in the drain-source circuit. For the proper operation FET , the gate must be negative with respect to source i.e., input circuit should always be reverse biased.
- In the present case, we are providing biasing by the battery V_{GG}.
- A small change in the reverse bias on the gate produces a large change in drain current and strengthen the weak signal. During the positive half signal, the reverse bias on the gate decreases. This increases the channel width and hence the drain current.
- The negative half-cycle of the signal, the reverse voltage on the gate increases, drain current decreases.
- The result is that a small change in voltage at the gate produces a large change in drain current. These large variations in drain current produce large output across the load R_L.

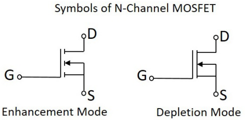


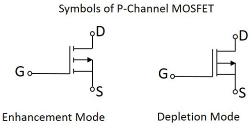
Construction of MOSFET

MOSFET

- FETs have a few disadvantages like high drain resistance, moderate input impedance and slower operation. To overcome these disadvantages, the MOSFET which is an advanced FET is invented.
- MOSFET stands for Metal Oxide Silicon Field Effect Transistor or Metal Oxide Semiconductor Field Effect Transistor.
- Depending upon the type of materials used in the construction, and the type of operation, the MOSFETs are classified as in the following figure.
- The N-channel MOSFETs are simply called as NMOS. The P-channel MOSFETs are simply called as PMOS.

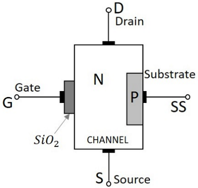


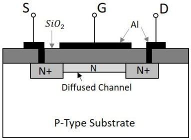




MOSFET

- The construction of a MOSFET is a bit similar to the FET. An oxide layer is deposited on the substrate to which the gate terminal is connected. This oxide layer acts as an insulator (sio$_2$ insulates from the substrate).
- In the construction of MOSFET, a lightly doped substrate, is diffused with a heavily doped region. Depending upon the substrate used, they are called as P-type and N-type MOSFETs.
- It can only have negative gate operation for n-channel and positive gate operation for p-channel. This means that we can only decrease the width of the channel (i.e. decrease the conductivity of the channel) from its zero-bias size. This type of operation is referred to as depletion-mode operation. Therefore, a JFET can only be operated in the depletion-mode.
- However, there is a field effect transistor that can be operated to enhance (or increase) the width of the channel (with consequent increase in conductivity of the channel) i.e. it can have enhancement-mode operation.

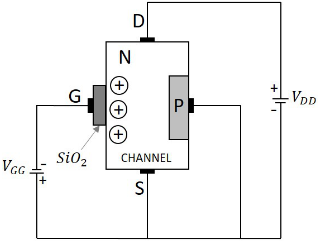




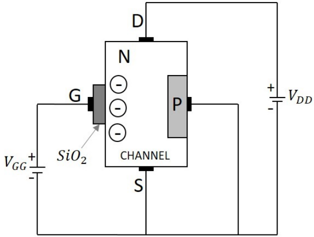
Structure of N-channel MOSFET

Depletion mode MOSFET

- Since gate is negative, then the electrons on the gate repel the free electrons in the N-channel in a part of the channel as shown in figure.
- In other words, we have depleted the n-channel of some of its free electrons and the available conduction electron is less. Hence the resistance of the channel is increased.
- The greater the negative voltage on the gate, the lesser is the current from source to drain, implying that varying the negative voltage on the gate, we can adjust the resistance of the N-channel.
- With negative potential to the gate, the action of MOSFET is similar to FET. Because the action with negative gate depends upon depleting the channel of the free electrons, the negative-gate operation is called depletion mode.



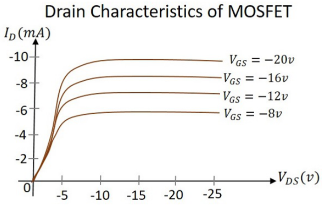
Working of MOSFET in depletion mode

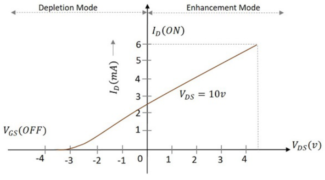


Working of MOSFET in Enhancement mode

Enhanced Mode MOSFET

- The same MOSFET can be employed in enhancement mode, if the gate is positive. It induces the negative charges in N-channel.
- These negative charges are the free electrons drawn into the channel and added with the already available free electrons in the channel. The total number of free electrons in the channel increases and the conductivity of the channel increases.
- Thus by changing the positive voltage on the gate, we can change the conductivity of the channel. The main difference between MOSFET and FET is that we can apply positive gate voltage to MOSFET and still have essentially zero current.
- The current flow gets enhanced due to the increase in electron flow better than depletion mode. Hence this mode is termed as Enhanced Mode MOSFET.





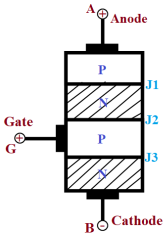
Transfer Characteristics of a MOSFET

Silicon controlled rectifier

- The silicon-controlled rectifier(SCR) is a power electronic device. It was first introduced in 1956 by Bell Telephone Laboratories.
- It can convert alternating current into direct current and at the same time can control the amount of power fed to the load. Thus it combines the features of a rectifier and a transistor.
- A Silicon Controlled Rectifier (SCR) – controls current flow.
- The terminals are: Gate (G), Anode (A) and Cathode (K).
- Two main uses of SCR are: Switching and Amplification

Basic SCR structure

The SCR consists of a four layer p-n-p-n structure with the outer layers are referred to as the anode (p-type) and cathode (n-type). The control terminal of the SCR is named the gate and it is connected to the p-type layer located next to the cathode. The three junctions are normally denoted as J_1, J_2, and J_3. They are numbered serially with J_1 being nearest to the anode.



Working of SCR

To understand the SCR working principle, we have to look into the different ways it can operate. Depending on the polarity of the voltage applied and the gate pulse given to the SCR, it can operate in three different modes such as

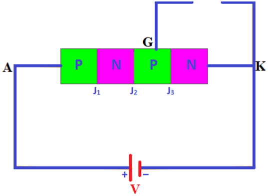
- Forward Blocking mode
- Forward Conduction mode
- Reverse Blocking mode

Forward Blocking Mode

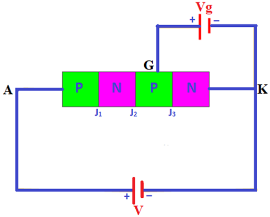
- In this mode of operation, the positive voltage is applied to the anode and the negative voltage applied to the cathode, there will not be any pulse applied to the gate, it will be kept in the open state.
- Once the voltage is applied, the junctions J_1 and J_3 will be forward biased and the junction J_2 will be reverse biased. Since J_2 is reverse biased, the width of the depletion region increases and it acts as an obstacle for conduction, so only a small amount of current will be flowing from J_1 to J_3.
- When the voltage applied to the SCR is increased and if it reaches the breakdown voltage of the SCR, the junction J_2 gets broken due to avalanche breakdown.
- Once the Avalanche breakdown occurs, the current will start flowing through the SCR. In this mode of operation, the SCR is forward biased, but, there will not be any current flow.

Forward Conduction Mode

- The Forward Conduction Mode is the only mode at which the SCR will be in the ON state and will be conducting. We can make the SCR conduct in two different ways, one we can increase the applied forward bias voltage beyond the breakdown voltage or else we can apply a positive voltage to the gate terminal.
- When we increase the Applied forward bias voltage between the anode and cathode, the junction J_2 breaks down due to the avalanche breakdown and the SCR will start conducting.
- If you want to use the SCR for low voltage applications, you can apply a positive voltage to the gate of the SCR.
- The applied positive voltage will help the SCR to move to the conduction state. During this mode of operation, the SCR will be operating in forward bias and current will be flowing through it.

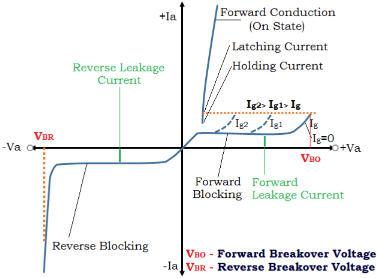


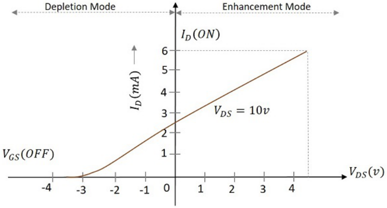
Forward Blocking Mode of SCR



Forward Conducting Mode of SCR

I-V Characteristics

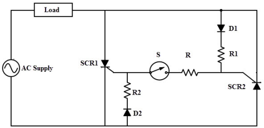




Transfer Characteristics of a MOSFET

SCR as Switch

- In the reverse blocking mode, the positive voltage is applied to the Cathode (-) and the Negative voltage is given to the Anode (+), There will not be any pulse given to the gate, it will be kept as an open circuit.
- During this mode of operation the Junctions J_1 and J_3 will be reverse biased and the junction J_2 will be forward biased. Since the junctions J_1 and J_3 are reverse biased there will not be any current flowing through the SCR.
- During the positive half cycle of the input, SCR1 is forward biased and SCR2 is reverse biased. If the switch S is closed, gate current is applied to the SCR1 through diode D1 and hence SCR1 is turned ON. Therefore, the current flows to the load through SCR1.
- Similarly, during the negative half cycle of the signal, SCR2 is forward biased and SCR1 is reverse biased. If the switch S is closed, gate current flows to the SCR2 through diode D2. Hence the SCR2 is turned ON and the load current flows through it.
- Therefore, by controlling the switch S the load current can be controlled at any desired position. It is observed that, this switch handles a few mill ampere current to control the several hundred ampere current in the load. So this method of switching is more advantageous than mechanical or electromechanical switching.



SCR Applications

Half wave rectifier

Silicon Controlled Rectifier (SCR) may be used as a controlled half wave rectifier unlike normal half wave rectifier. The AC voltage to be rectified is applied to the input of the power transformer.

- The voltage V_i across the secondary of the power transformer drives the SCR. We assume that the amplitude V_m of the input voltage to SCR is less than the reverse breakdown voltage of the SCR. Then the SCR will not breakdown during the negative half cycle of the ac input voltage.
- During the negative half cycle of the input ac voltage, anode is negative with respect to the cathode and hence the SCR does not conduct. However, SCR conducts during the positive half cycle after the time instant when the input voltage exceeds breakdown voltage V_{BO}.

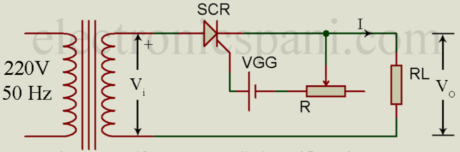


Figure 1: Half Wave Controlled Rectifier using SCR

Let, the input voltage V_i be a sinusoidal voltage of amplitude V_m and frequency f and let be given by,

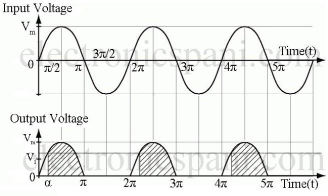
$$V_i = V_m sin\omega t = V_m sin\theta \tag{4}$$

where ω is the angular frequency in radians/second. Let, α be the firing angle i.e. the angle at which conducting begins. The SCR conducts from α to π radians during the positive half cycle and does not conduct during the negative half cycle.
Then the average output voltage V_{av} is given by,

$$V_{av} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m sin\theta d\theta = \frac{V_m}{2\pi}(1 + cos\alpha) \tag{5}$$

Average Current

$$I_{av} = \frac{V_{av}}{R_L} = \frac{V_m}{2R_L\pi}(1 + cos\alpha) \tag{6}$$



Full wave rectifier

- The ac input voltage is fed to the input of a power transformer TR which has centre-tapped secondary. Thus, the voltage V_{i1} and V_{i2} developed across the two halves of the secondary are equal in magnitude but opposite in phase.
- During the positive half cycle of voltage V_{i1}, SCR1 conducts during the period α to π radians where α is the firing angle. The negative half of V_{i1}, corresponds to the positive half of V_{i2}. During this positive half of V_{i2}, SCR2 conducts during the interval α and π radians. The two outputs get added.

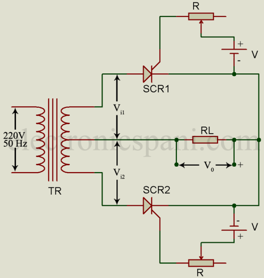


Figure 1: Basic Circuit of Fullwave Rectifier using two SCRs

Let the input voltage V_{i1} be a sinusoidal voltage of amplitude V_m and frequency f and let it be given by,

$$V_i = V_m sin\omega t = V_m sin\theta \tag{7}$$

The average output voltage Vav1 contributed by SCR1 is given by,

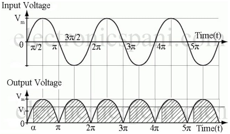
$$V_{av1} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m sin\theta d\theta = \frac{V_m}{2\pi}(1 + cos\alpha). \tag{8}$$

Similarly, the average voltage contributed by SCR2 due to input voltage V_{i2} is equal to V_{av1}. Hence, the total value of average output voltage V_{av} is given by,

$$V_{av} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m sin\theta d\theta = \frac{V_m}{\pi}(1 + cos\alpha). \tag{9}$$

Average Current

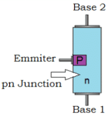
$$I_{av} = \frac{V_{av}}{R_L} = \frac{V_m}{R_L\pi}(1 + cos\alpha) \tag{10}$$



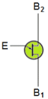
Unijunction Transistor

Introduction

- UJT stands for UniJunction Transistor. It is a three terminal semiconductor switching device.
- The Unijunction Transistor is a simple device that consists of a bar of n-type silicon material with a non-rectifying contact at either end (base 1 and base 2), and with a rectifying contact (emitter) alloyed into the bar part way along its length, to form the only junction within the device (hence the name 'Unijunction').
- The unique switching characteristics of UJT makes it different from conventional BJT's and FET's by acting as switching transistor instead of amplifying the signals. It exhibits negative resistance in its characteristics which employs it as relaxation oscillators in variety of applications.



Basic Construction



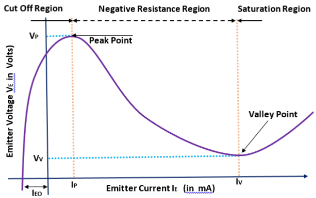
Symbol

- In Unijunction Transistor, the PN Junction is formed by lightly doped N type silicon bar with heavily doped P type material on one side. The ohmic contact on either ends of the silicon bar is termed as Base 1 (B1) and Base 2 (B2) and P-type terminal is named as emitter.

Unijunction Transistor

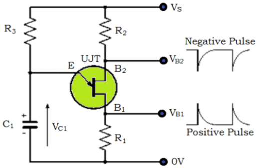
The characteristics of Unijunction Transistor (UJT) can be explained by three parameters:

- **Cutoff** Cutoff region is the area where the Unijunction Transistor (UJT) doesn't get sufficient voltage to turn on. The applied voltage hasn't reached the triggering voltage, thus making transistor to be in off state.
- **Negative Resistance Region** When the transistor reaches the triggering voltage, VTRIG, Unijunction Transistor (UJT) will turn on. After a certain time, if the applied voltage increases to the emitter lead, it will reach out at VPEAK. The voltage drops from VPEAK to Valley Point even though the current increases (negative resistance).
- **Saturation** Saturation region is the area where the current and voltage raises, if the applied voltage to emitter terminal increases.



UJT as relaxation oscillator

UJT Relaxation Oscillator can be practically viewed by the following circuit:



- The resistance R_3 charges the capacitor C_1 until the peak point. The UJT's emitter terminal has no effect on C_1 until peak point is reached. When the emitter voltage reaches peak voltage point, the lowered emitter base 1 resistance rapidly discharges the capacitor.
- As the capacitor C_1 discharges beneath the valley point, the emitter base 1 resistance will return back to high resistance, thus making capacitor free to charge again.