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Prepared by:
Training Group.

Authorised by:
Superintending Engineer,
Operations Planning and Programming Branch, HQ.

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SEMICONDUCTORS

SELECTED DEVICES AND CIRCUIT APPLICATIONS

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1. INTRODUCTION.

1.1 Since the introduction of the transistor and semiconductor diode a number of new semiconductor devices have been introduced into the field of electronics, each having numerous circuit applications, diodes, transistors, thyristors, have been dealt with in other Technical Training Publications, this publication gives an introduction to three additional semiconductor devices namely the field effect transistor, the unijunction transistor and the integrated circuit and covers the road principles of some circuit configurations which are in common use. The configuration described include the difference amplifier, the impedance converter, the Schmitt trigger and some basic electronic voltage regulation circuits.

2. UNIJUNCTION TRANSISTORS.

2.1 SYMBOL AND GENERAL CHARACTERISTICS. The unijunction transistor is a three terminal semiconductor device which has only one rectifying semiconductor junction, formed on a base of n type material. The unijunction transistor symbol is shown in Fig. 1. The terminal designated E is the emitter terminal, and there are two base connections, designated B1 and B2. B1 is normally connected to earth or common, and B2 is normally connected to the positive supply.

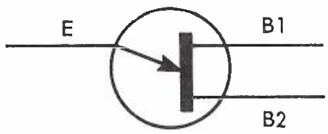


FIG. 1. UNIJUNCTION TRANSISTOR SYMBOL.

The unijunction transistor has a negative resistance characteristic, which allows the device to be used with very simple circuitry to form relaxation oscillators, and voltage and current sensing circuits. Its other important characteristics are that it has a trigger voltage which is a fixed fraction of the voltage across the base terminals, and that it needs only a low value of trigger current.

A device known as a complementary unijunction transistor can be constructed with p type base material, and its symbol is similar to that of Fig. 1, with the arrowhead reversed. This type of device is not normally available, but a composite device constructed by integrated circuit techniques is available, and has the same characteristics. The complementary unijunction transistor is not described in this publication.

2.2 CONSTRUCTION. A unijunction transistor is formed from either a bar or a cube of n-type silicon as a base, to which three connections are made. The two base connections B1 and B2 are direct non-rectifying contacts, one at each of the silicon bar, or on opposite faces of the cube, as shown in Fig. 2. The emitter is p-type material and forms a p-n junction with the base material.

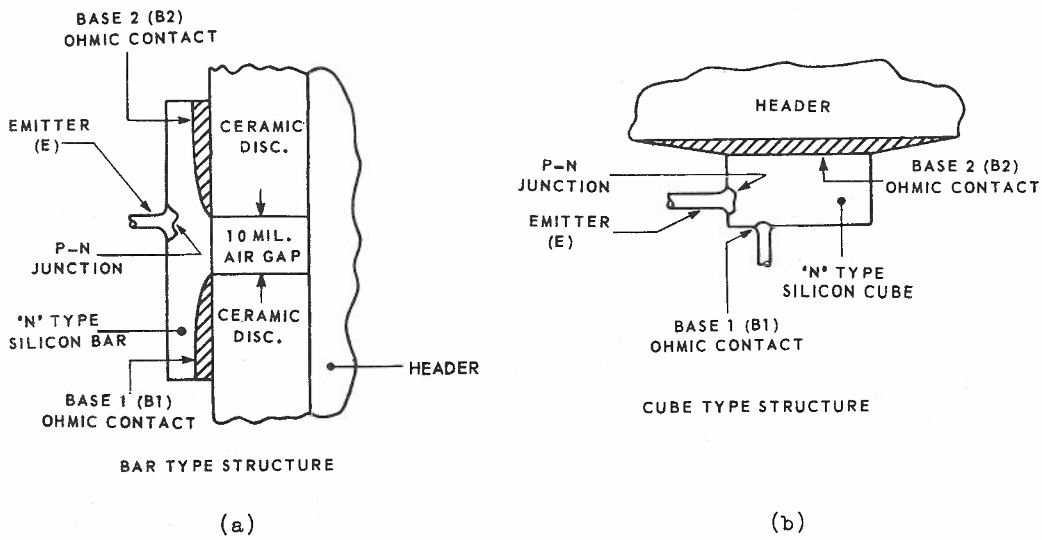


FIG. 2. CROSS SECTION OF UNIJUNCTION TRANSISTORS.

The bar-type construction includes ceramic disc spacers for additional isolation from the mounting-plate or header, and all leads are electrically isolated from the case. The cube type base is mounted directly on the header, and the case is the base 2 connection. Both types of construction have similar characteristics, but the magnitudes of their parameters differ slightly.

2.3 CHARACTERISTICS. Fig. 3a is a simplified equivalent circuit of the unijunction transistor in the cut-off condition. The interbase resistance R_{BB} of the base material, measured between base 1 and base 2 terminals, is between 5 kΩ and 10 kΩ, and is represented by the resistors R_{B1} and R_{B2}. V_{BB} represents the voltage present between the two base terminals, and V_{EB1} represents the voltage present between the emitter and base 1 terminals.

The diode SC1 represents the p-n junction between the emitter and the base material. When there is no interbase voltage V_{BB} and no interbase current, the characteristic of the unijunction transistor between the emitter and either base terminal is similar to that of an ordinary diode. This characteristic is shown in Fig. 3b, for the emitter to base 1, with base 2 open circuit so that there is no base 2 current (I_{B2} = 0).

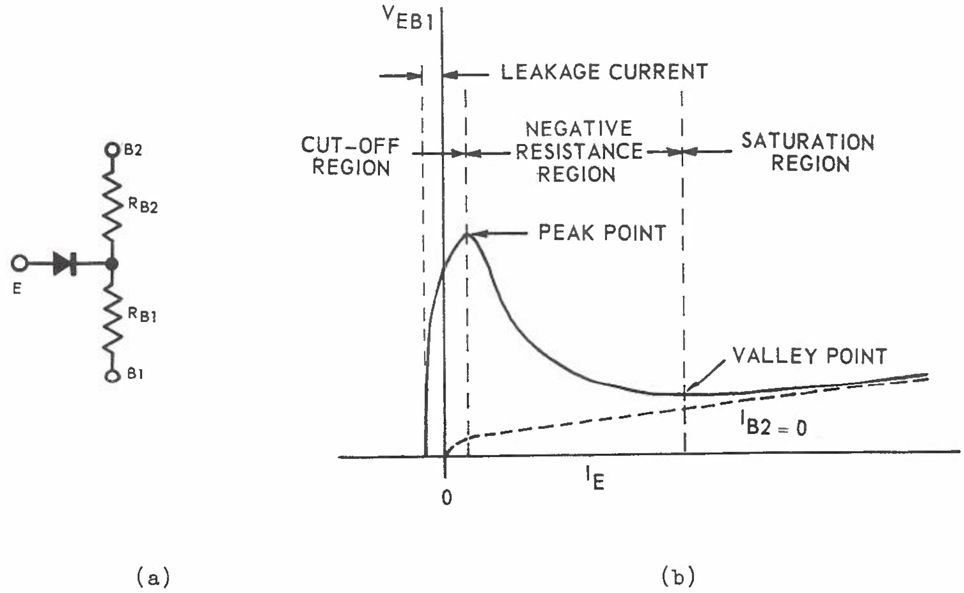


FIG. 3. UNIJUNCTION TRANSISTOR EQUIVALENT CIRCUIT AND EMITTER STATIC CHARACTERISTIC.

When a voltage source V_S applied, and no connection made to the emitter terminal, the n-type silicon base acts as a voltage divider, and a fraction η of V_{BB} appears across R_{B1} as shown in Fig. 3a. This fraction η is the ratio of R_{B1} to the total resistance R_{B1} + R_{B2} and is called the 'intrinsic stand-off ratio'. The value of η is usually in the range 0.5 to 0.8 and is constant for a particular device over wide ranges of temperature and interbase voltage V_{BB}.

Assume also that a voltage is connected via a high value of resistance between E and B1, and that the voltage is gradually increased. When the emitter-base 1 voltage is less positive than ηV_{BB}, the emitter is reverse biassed. In this circuit condition, there is a very small leakage current in the emitter circuit, typically 2 µA, as shown in Fig. 3b.

When the emitter base 1 voltage V_{EB1} is more positive than ηV_{BB}, the emitter-base junction is forward biassed. The unijunction transistor remains in the cut-off condition, with negligible forward diode current, until V_{EB1} exceeds ηV_{BB} by about 0.6 V. When this peak point voltage is attained, the emitter current produces a greater current-carrier density between E and B1, which decreases the base resistance R_{B1}.

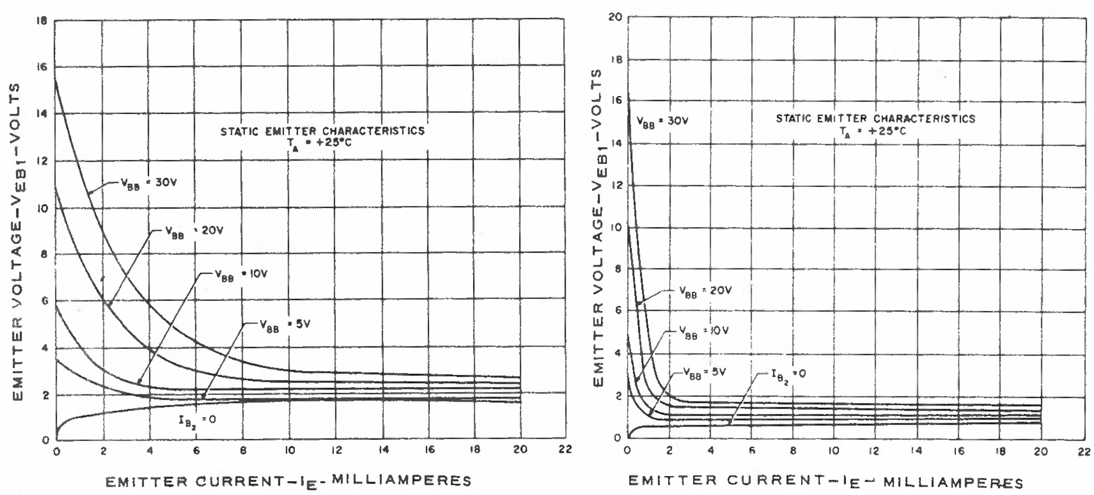
Because R_{B1} is lower, the voltage drop across R_{B1} is lower, and this allows the emitter current I_E to increase. The increased emitter current reduces the emitter voltage, because this voltage is supplied from a large value of resistance. Although the emitter current has increased, the emitter-base voltage V_{EB1} has decreased. The regeneration has produced a negative resistance region in the emitter-base 1 characteristic, as shown in Fig. 3b.

The negative resistance region of the characteristic continues with increase in emitter current, until the emitter current becomes large compared with the base 2 current, and the effect of base 2 current on the operation of the device becomes negligible. This portion of the emitter characteristic is not as sharply defined as the peak point, and is called the 'valley point'. When I_E is increased beyond the valley point value, the characteristic enters the saturation region and approaches the emitter-base 1 characteristic for zero base 2 current.

The two main points on the characteristic curve are the peak point, which is the beginning of the negative resistance region, and the valley point, which marks the end of the negative resistance region.

In the cut-off region, to the left of the peak point, the emitter is reverse biassed, and conducts only a small leakage current. To the right of the valley point, the saturation region is that part of the characteristic curve where the emitter is forward biassed, the current is greater than the valley current, and the dynamic resistance is positive.

A family of characteristics for both bar and cube type unijunction transistors is shown in Fig. 4, for a range of interbase voltages. They show typical values of peak point voltage, and that the negative resistance region starts from almost zero emitter current.



(a) (b)

FIG. 4. TYPICAL STATIC EMITTER CHARACTERISTIC CURVES

Comparison of the characteristics for the two types of construction shows that the cube type has a lower valley point voltage, and a steeper slope in the negative resistance region of the characteristic. The slope of the curve is steeper because the cube type construction has a higher value of negative resistance.

2.4 PARAMETERS. This paragraph defines the important parameters of unijunction transistors.

- PEAK POINT. This point marks the beginning of the negative resistance region of the characteristic. This is the point where V_{EB1} exceeds ηV_{BB} by about 0.6 V.

- PEAK POINT VOLTAGE Vp. The V_{EB1} voltage at which the peak point occurs is proportional to the interbase voltage V_{BB}, and is the sum of the intrinsic stand-off ratio voltage ηV_{BB}, and the forward voltage drop V_{SC} across the emitter diode.

- PEAK POINT CURRENT Ip. This is the emitter current at the peak point, and is the minimum current required to trigger the unijuhction transistor into conduction. It is typically 10 µA.

- VALLEY VOLTAGE V_V. The valley voltage is the emitter voltage V_{EB1} at the valley point.

- VALLEY CURRENT I_V. The valley current is the emitter current at the valley point.

- EMITTER REVERSE CURRENT I_{EO}. The emitter reverse current is measured with voltage applied between base 2 and the emitter, with base 1 open circuit. This current varies with temperature in the same way as the I_{CO} of a conventional transistor.

- INTERBASE RESISTANCE R_{BB}. This is the resistance measured between base 1 and base 2 with the emitter open circuited. It can be measured with an ohmmeter if the ohmmeter voltage is 5 V or less.

2.5 UNIJUNCTION TRANSISTOR RELAXATION OSCILLATOR. The circuit shown in Fig. 5a illustrates a relaxation oscillator which includes a unijunction transistor. The circuit waveforms are shown in Fig. 5b.

When the supply voltage Vp is first applied to the circuit, the capacitor C1 is in the discharged condition. The unijunction transistor is reverse biassed to the cut-off condition by ηV_{BB}.

The capacitor charges towards the supply voltage via resistor R1. When the voltage V_{EB1} between E and B1 of SC1 reaches the peak point Vp on the unijunction characteristic, the regeneration-produced negative resistance causes the emitter current I_E to switch rapidly to a point on the characteristic well into the saturation region, to a typical value of 100 mA.

This value of I_E is determined by Vp, the effective resistance of the emitter-base 1 region in its high conductivity state (about 50 to 100 ohms), and the value of R3. R3 is chosen to determine the valley point and the shape of the negative resistance portion of the characteristic. Because it is in series with the terminals between which the negative resistance appears, R1 must be less than 100 ohms so that it does not cancel the negative resistance.

The emitter current is the greater portion of the base 1 current, and discharges C1 in a short time constant circuit. The current change is almost exponential, and a corresponding voltage V_{B1} appears across R3. While the capacitor discharges, I_E falls and moves to the left along the characteristic until the valley point I_V is reached. When the current falls slightly further, the unijunction transistor switches regeneratively through the negative resistance region to the cut-off condition, and the emitter current steps to zero. The only base current is the low interbase current I_{B2}, and V_{B1} is almost zero. The cycle then recommences with C1 recharging via R1.

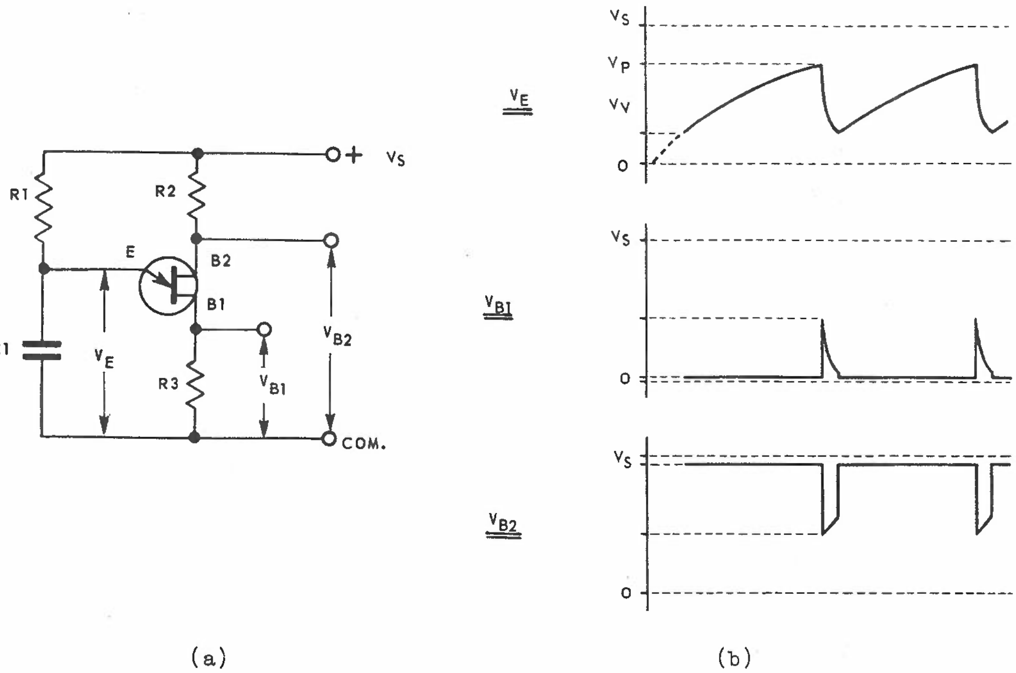


FIG. 5. UNIJUNCTION TRANSISTOR ASTABLE RELAXATION OSCILLATOR.

The value of R1 determines the state of operation of the unijunction relaxation oscillator. For an astable oscillator, the load line formed by the resistor R1 and the supply voltage V_S must cut the emitter characteristic once only in the negative resistance region. If this load line cuts the emitter curve in the saturation region, the unijunction transistor may not turn off after it triggers on the first cycle.

To meet these requirements, R1 must be greater than the value of negative resistance represented by the characteristic, and can have a value up to 3 MΩ. The highest negative resistance is typically 4 kΩ for bar type unijunction transistors and 16 kΩ for cube type unijunction transistors. R1 and C1 determine the frequency of oscillation of the circuit. Typical values of C1 are from 0.01 μF to 10 μF.

The base 2 resistor R2 provides temperature stability of the peak point of the characteristic, and is normally in the range of 200 Ω to 1 kΩ. The current I_{B2} through R2 during the cut-off time is the interbase current. When the emitter is conducting heavily I_{B2} increases, and the resultant voltage waveform at base 2 is shown in Fig. 5b.

The unijunction transistor relaxation oscillator circuit provides an approximate sawtooth output voltage at the emitter (V_E), a low impedance positive pulse output voltage at base 1 (V_{B1}), and a higher impedance negative pulse output voltage at base 2 (V_{B2}). The circuit has applications as a sawtooth generator, as a pulse generator for triggering other circuits, and as a timing circuit.

2.6 UNIJUNCTION TRANSISTOR USED AS THYRISTOR TRIGGER. Thyristors are used to control the output voltage of some a.c. and rectifier circuits. When the conduction time of the thyristor is altered, the average amplitude of the dependent output is altered.

The thyristor begins conduction when triggered by an external pulse, and turns off when the input waveform returns to zero each half cycle. The timing of the arrival of the triggering pulse with respect to the waveshape of the input to the thyristor determines the waveshape and average amplitude of the output voltage.

A unijunction transistor can be used to control the conduction time of a thyristor, as it can be arranged in a circuit to oscillate at a stable frequency. Positive low impedance pulses are available from base 1 to trigger the thyristor at accurately-timed intervals.

3 IMPEDANCE CONVERTERS.

3.1 When two circuits with different impedances are connected together, the mismatch often causes unsatisfactory operation of one of the stages. The use of an impedance converter between the two circuits overcomes this difficulty. One kind of impedance converter is a transformer; another is the emitter follower or common collector amplifier. This circuit has a high input impedance, a low output impedance and a stage gain of slightly less than unity. Fig. 6 shows the basic arrangement.

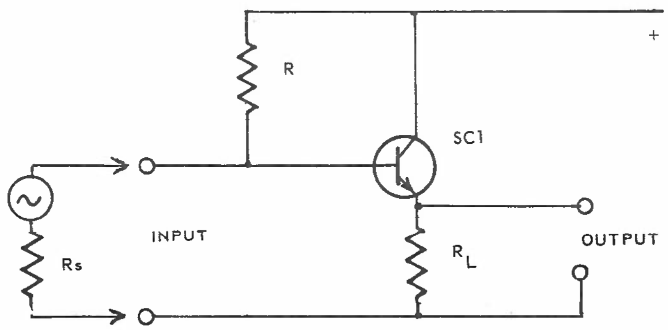


FIG. 6. EMITTER FOLLOWER AMPLIFIER.

3.2 INPUT AND OUTPUT IMPEDANCE. The input impedance is high due to negative feedback. The voltage developed across R_L is in opposition to the input signal voltage, and, as only a small current flows, the input behaves as a high impedance. The input impedance is approximately equal to the product of resistance R_L and the current gain (β) of the transistor. For example, if the value of R_L is 5,000 Ω and the β of the transistor is 50, the input impedance is approximately 250 kΩ.

The output impedance is low because, due to negative feedback, the output voltage is constant for all values of load, and any device which provides a constant voltage with varying loads has low internal impedance. The output impedance is a function of the impedance of the source (R_S) connected to the input and R_L as both are effectively in parallel. Generally the output impedance is given as approximately $R_S \div \beta$, but where R_S is very high compared to R_L, the output impedance is approximately equal to R_L.

The emitter follower circuit can thus be arranged to obtain any desired value of input and output impedance and is used for matching amplifier stages.

3.3 DARLINGTON PAIR CIRCUIT. For some applications, the emitter follower is unsatisfactory as an impedance converter, due to its relatively low input impedance. For example, when an input impedance of 2 MΩ is required and a transistor with a current gain of 50 is used, the value of R_L would have to be 40 kΩ. This is unsatisfactory as a supply voltage of approximately 45 volts would be needed to provide a collector current of 1 mA.

To overcome this problem the effective current gain can be increased by using a configuration known as the DARLINGTON PAIR. Fig. 7 shows the basic DARLINGTON circuit.

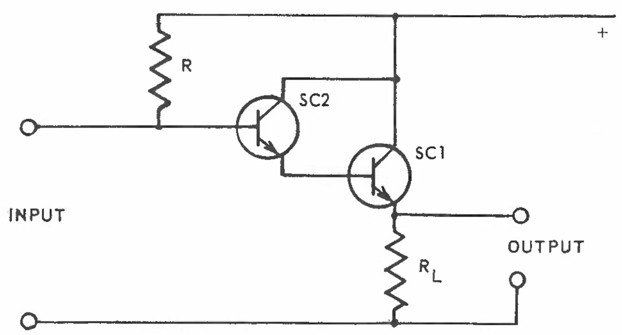


FIG. 7. DARLINGTON PAIR CIRCUIT.

3.4 In this configuration, the two transistors act like one transistor with a current gain equal to $\beta1 \times \beta2$, where $\beta1$ and $\beta2$ are the current gains of SC1 and SC2 respectively. Transistor SC1 is connected as a conventional emitter follower circuit. Transistor SC2 precedes the emitter follower and is connected in such a manner that the emitter current of SC2 flows directly into the base of SC1. If the β of both transistors is 50, the current flowing in the emitter of SC2 (and therefore the base of SC1) will be 50 times that in the base of SC2, and the current in the emitter of SC1 will be 50 times greater again making an overall gain of $\beta1 \times \beta2 = 2500$.

The input impedance of the configuration is determined in the same manner as the emitter follower circuit and is given as approximately the product of the current gain of the transistor and R_L or $\beta1 \times \beta2 \times R_L$. Where an input impedance of 2 MΩ is required, the value of R_L for the Darlington configuration is 2 MΩ ÷ 2500 = 800 Ω. The output impedance of the Darlington circuit is approximately equal to the internal impedance of the source connected to the input divided by $\beta1 \times \beta2$.

3.5 THREE TRANSISTOR CIRCUIT. In practice, leakage paths and bias networks limit the value of input impedance which can be obtained, as the leakage and bias resistance paths are effectively in parallel with the input circuit. For germanium transistors, the maximum value of input impedance that can be obtained is in the order of 2 MΩ using the Darlington pair circuit; for silicon transistors the maximum value is about 10 MΩ. By adding an additional transistor SC3, as shown in Fig. 8 in front of SC2, the current gain of the configuration is increased to $\beta1 \times \beta2 \times \beta3$ (where $\beta3$ is the current gain of the extra transistor) and the input impedance will be raised to $R_L \times \beta1 \times \beta2 \times \beta3$. The operation of the three transistor circuit is similar to the operation of the two transistor circuit and the same limitations are still imposed by the leakage and bias resistances. It is not practicable to use more than three transistors in the Darlington type of configuration.

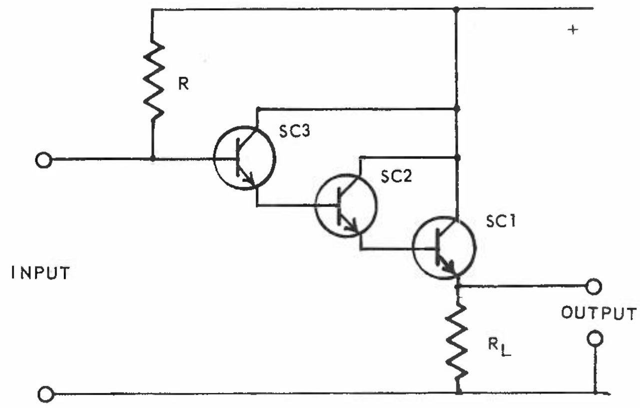


FIG. 8. DARLINGTON CIRCUIT USING THREE TRANSISTORS.

3.6 APPLICATIONS. The emitter follower and Darlington pair circuits have many applications because of their high impedance input and low impedance output features. In some applications, such as amplifier circuits, both features are used when matching a high impedance output stage to a low impedance input stage. In some voltage regulator circuits, use is made of the low impedance output feature of the Darlington pair circuit to provide good voltage regulation. In other applications, such as shown in Fig. 9, use is made of the high input impedance feature in a time delay circuit for a relay.

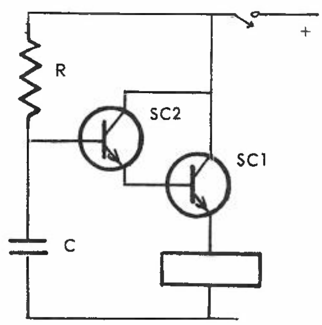


FIG. 9. DARLINGTON PAIR USED TO OPERATE A RELAY.

In this circuit, the operation of the relay is delayed for some time after the switch is closed. The delay is primarily dependent on the time constant of the C and R components. However, the high impedance input of the Darlington pair configuration ensures that the amplifier stages do not shunt one or other of the time constant components. When the switch is closed and the supply is connected to the circuit, only a very low emitter current is flowing and the relay does not operate. As time passes, the voltage across the capacitor builds up, the emitter current rises and, after a fixed time delay, the relay operates.

4. FIELD EFFECT TRANSISTORS.

4.1 Field effect transistors (FETs) are three terminal devices which perform similar functions to ordinary bipolar transistors in amplifier and oscillator circuits, but have the additional feature of a very high input impedance. Although the operating principles and electrical characteristics of FETs differ from the conventional transistors, a comparison may be found between the three terminals, source, gate and drain of the FET and the emitter, base and collector of the conventional transistor. Basically the FET consists of a narrow strip, or channel, of semiconductor material, the conductivity of which is varied by the width of depletion layers of PN junctions either side of the channel.

There are many different varieties of FETs and they are also manufactured in complementary versions, that is in N-channel type or P-channel type. The basic type of FET is the junction field effect transistor (JFET); the symbols for an N-channel and a P-channel JFET are shown in Fig. 10.

(a) N-CHANNEL. (b) P-CHANNEL.

FIG. 10. JUNCTION FIELD EFFECT TRANSISTOR SYMBOLS.

4.2 **CONSTRUCTION.** The basic construction of an N-channel JFET is shown in Fig. 11. A layer of N type material is diffused into a piece of P type material called the substrate, and then into the N type material is diffused a layer of P type material. This leaves a strip or channel of N type material to which connections, labelled drain and source, are made at each end. Connections are made to the two sections of P type material and these are labelled gate 1 and gate 2. The gates are normally connected together and regarded as a single gate electrode.

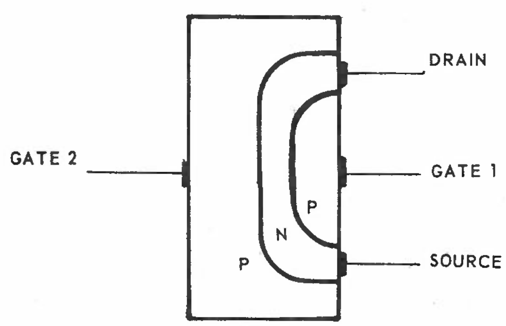


FIG. 11. JFET CONSTRUCTION.

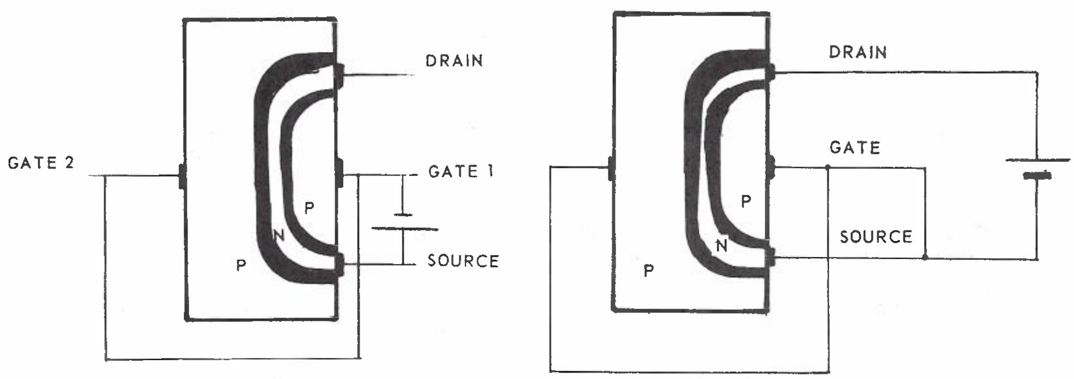
4.3 OPERATION. When a potential is connected across a PN junction, the thickness of the depletion layer increases or decreases according to the value of potential applied. Since a depletion region is one which is depleted of current carriers, and is therefore, almost non-conducting, the depletion regions in a field effect transistor reduce the effective electrical size of the channel between the drain and source. The operation of the JFET shown works on the principle of varying the effective width of the N-channel by means of the depletion regions.

When an external reverse bias is applied between the gates and the source, the depletion layers are made to extend further into the N type channel. Increasing the reverse bias potential, reduces the effective channel width until it is ultimately closed off completely. Conversely, reducing the reverse bias increases the channel width.

Fig. 12a shows the depletion regions for both PN junctions when a reverse bias potential is applied between the source and the gate. With no current flowing in the channel, and with the junctions reverse biased, the depletion regions are extended evenly along the length of the channel.

When the potential is applied between the source and the drain, as shown in Fig. 12b, current flows in the N-channel. However, in flowing through the channel material, a voltage drop is produced along the length of the channel, causing the bias at each end of the channel to be different, since the gate and source electrodes are tied externally. Accordingly, the depletion regions grow in width along the channel and produce the pinching effect of the channel at the drain end. This pinching effect limits the current and has the effect of an internal feedback mechanism. The feedback, caused by the pinching, gives the JFET some measure of stability and self protection.

The JFET transistors explained in the previous paragraphs generally have a reverse bias connected to the gate to deplete the channel of carriers; this is called the 'depletion mode' of operation. Other types have forward bias connected and this is called the 'enhancement mode' of operation.



(a) Gate-source bias. (b) Source-drain current.

FIG. 12. DEPLETION REGIONS IN AN N-CHANNEL JFET.

4.4 CHARACTERISTICS. A set of drain-source voltage (Vds) versus drain-source current (Ids) curves for various value of gate voltages is shown in Fig. 13. The sections where the current begins to level off are known as the knees and this is where pinching begins. Beyond the knees into the pinched-off regions, any increase in voltage produces little change in current. Consequently the JFET has a high output impedance above the knee of its characteristic thus giving it a strong functional resemblance to the pentode electron tube. In most circuit applications the JFET is operated above the knee.

Below the knees in the non-pinched-off region, the characteristics resemble those of a triode electron tube. The characteristics are linear and in this region the JFET has applications as a voltage dependent resistor.

As can be seen from the characteristics, a value of Vds is reached where the current increases abruptly. This is known as avalanche breakdown and is caused by some current carriers developing sufficient energy to dislodge other valence electrons resulting in a chain reaction. The avalanche breakdown voltage should not be exceeded or the device will be permanently damaged unless power dissipation is limited to a safe level. The avalanche breakdown point is a function of Vgs and Vds, and a common way of rating a JFET in terms of its avalanche breakdown is to quote its drain-gate breakdown voltage, BVdgo.

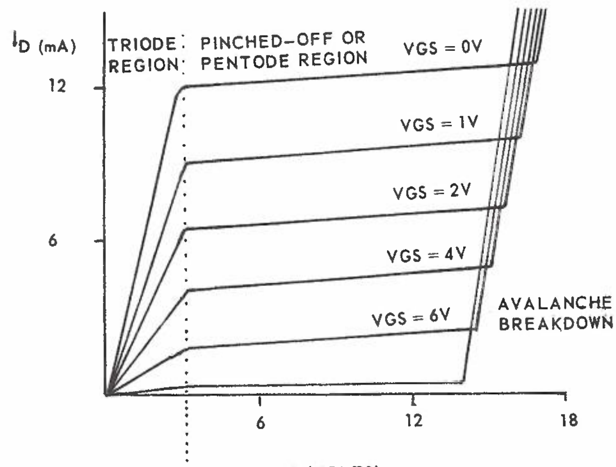


FIG. 13. JFET CHARACTERISTICS.

The input characteristics are not shown but the input voltage is applied across a reverse biased junction making the input resistance much higher than the bipolar transistor. It is in the order of megohms which for many purposes compares with the open circuit of the negatively biased grid-cathode in an electron tube.

4.5 MOSFET. The metal oxide semiconductor field effect transistor (MOSFET) is another type of FET in use. The input resistance of this FET is even higher than that of the junction field effect transistor because its gate terminal (metal) is insulated from the semiconducting material by a thin layer of oxide. The MOSFET is also sometimes called an insulated gate field effect transistor (IGFET).

The construction of the MOSFET is different from the JFET and generally uses the enhancement mode of operation. However, both have similar terminals, source, drain and gate, and both control the current between drain and source by means of the gate potential which varies the effective size of the channel (N or P type) by controlling the depletion regions. The symbols for N-channel and P-channel MOSFETS are shown in Fig. 14.

FIG. 14. MOSFET SYMBOLS.

4.6 FETS AS AMPLIFIERS. The FET, like any other three terminal active network, can be operated with any of its three terminals common in an amplifier circuit. The three basic configurations, shown in Fig. 15, are common source, common gate and common drain; these are analagous to the common emitter, common base and common collector configurations. Common gate circuits have limited applications and are not further explained.

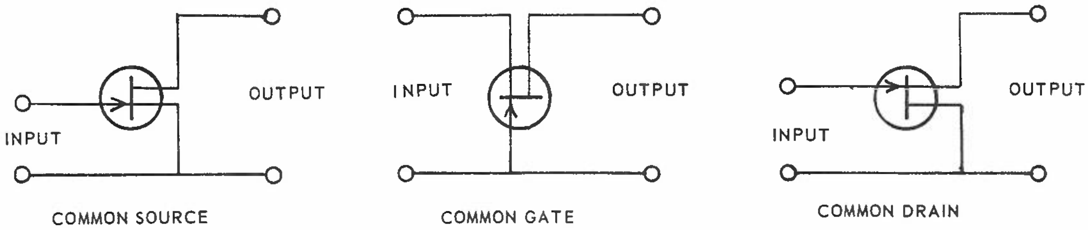


FIG. 15. JFET AMPLIFIER CONFIGURATIONS.

4.7 COMMON SOURCE AMPLIFIER. Many audio and video amplifiers are now designed with FETS which are either used exclusively or in conjunction with bipolar transistors. Fig. 16a shows a single stage common source amplifier using RC coupling at the input and output and an N-channel JFET.

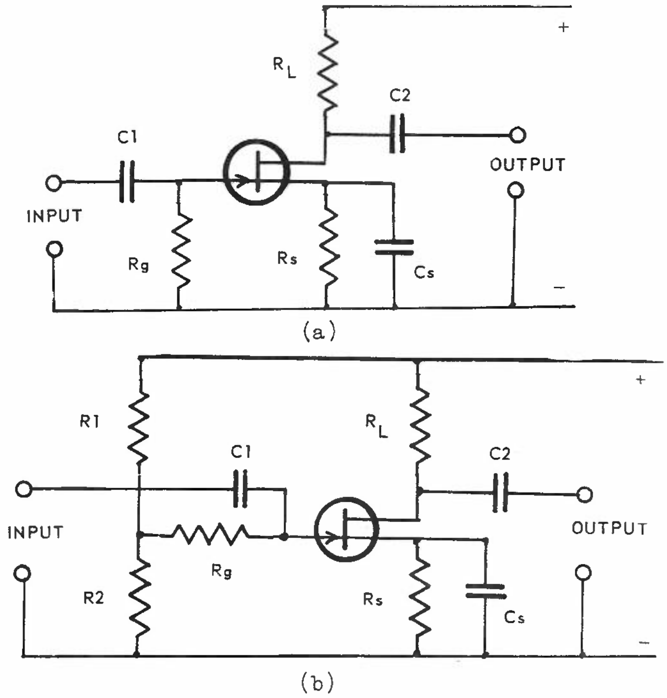


FIG. 16. COMMON SOURCE AMPLIFIER.

Resistor R_L is the load resistor and capacitor C2 provides the output coupling to the next stage. Capacitor C1 and resistor R_L form the input circuit, and resistor Rs provides the bias. A d.c. voltage is developed across Rs and extended via Rg to make the gate negative with respect to the source. Capacitor Cs is a bypass capacitor across Rs to prevent negative current feedback. The biasing arrangement is similar to that used for electron tube amplifiers.

To compensate for temperature variations and variations in FET characteristics, some amplifier circuits use a voltage divider biasing arrangement, similar to that used for common emitter amplifiers. A circuit of this type of biasing for common source amplifiers is shown in Fig. 16b.

4.8 COMMON DRAIN AMPLIFIER. The common drain amplifier is also known as a source follower amplifier. It is non-phase inverting, has a high input impedance, a low output impedance, and has a voltage gain of slightly less than one. The source follower features are analagous to the emitter follower and cathode follower in transistors and electron tubes. The source follower is useful as an impedance converter and is often used to transform impedances when FETS are used with bipolar transistors. The circuit in Fig. 17 is an example of a common drain or source follower amplifier.

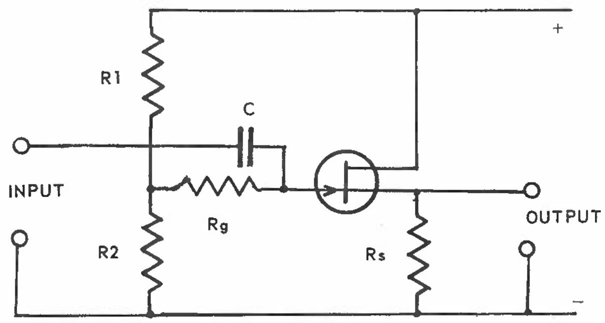


FIG. 17. COMMON DRAIN AMPLIFIER.

4.9 FET MULTIVIBRATORS. FETS are not as suitable as bipolar transistors in many non-linear circuit applications because of their relatively low switching speed. However, they are used in some low speed multivibrator circuits where periods of several minutes are required. Because of their high input impedance, high values of resistance can be used with FETS and long time constants obtained without the need for large capacitance. The circuit of an astable multivibrator using N-channel JFETS is shown in Fig. 18.

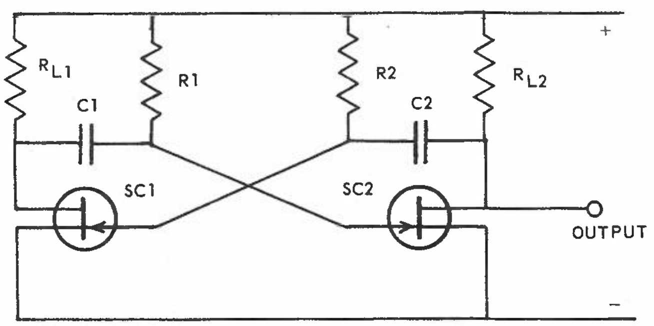


FIG. 18. ASTABLE JFET MULTIVIBRATOR.

The duration of the output pulses is governed by the time constant of C1 and R1 and C2 and R_2 respectively. With SC2 on and SC1 off, C2 is discharging and C1 is charging. The discharge path for C2 is via R2, the supply and the source-drain of SC2. The charge path of C1 is via the gate-source of SC2, the supply and R_{L1}.

When C2 discharges, the negative potential holding SC1 off, is removed and SC1 conducts. C1 now commences to discharge and in so doing switches SC2 off. C2 now commences to charge. The discharge path for C1 is via R1, the supply and the source-drain of SC1. The charge path for C2 is via the gate-source of SC1, the supply and R_{L2}. When C1 discharges, SC2 conducts again and the cycle is repeated.

With values of 10 MΩ for R1 and R2, and values of 10 µF for C1 and C2, the circuit has a frequency of less than one cycle per minute.

4.10 The field effect transistor has overcome many disadvantages of the bipolar transistors due to its high input impedance feature. However, one disadvantage of FETS is that they cannot produce much output power, and at the time of writing, are limited to several hundred milliwatts. As a result, many amplifier and oscillator circuits combine the best features of both FETS and bipolar transistors.

5. DIFFERENCE AMPLIFIER.

5.1 CONFIGURATION. The difference amplifier configuration is one in which two transistors share a common resistor in their emitter circuits. The circuit has excellent stability, as changes in one transistor due to variations in temperature, supply voltage etc., are offset by changes in the second transistor, and can be used amplify d.c. signals as well as high frequency a.c. signals. The basic circuit of a difference amplifier (sometimes call differential) is shown in Fig. 19. The circuit has two separate input and output terminals and can be used to amplify a single-ended input by setting one input at zero, or to amplify the difference between two isolated circuits.

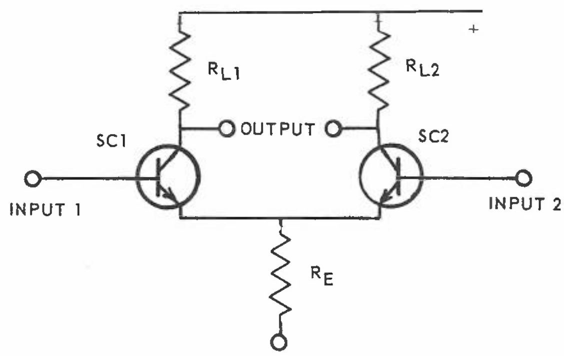


FIG. 19. DIFFERENCE AMPLIFIER.

5.2 OPERATION. In the circuit shown, both transistors have similar characteristics, the biasing arrangements (not shown) are the same and the load resistors RL1 and RL2 are of equal value. Under no-signal or balance conditions, the current in the emitter resistor R_E is shared equally by both transistors, the collectors are at equal potential, and there is no signal between the output terminals.

When used as a single-input amplifier and a positive going signal is applied to the base of SC1:

- SC1 collector current increases,
- the current through and voltage across R_E increases,
- the base emitter bias voltage (V_{BE}) of SC2 decreases,
- the current through SC2 is decreased.

As the current through SC1 increases, and the current through SC2 decreases the collector voltages will change in different directions and are said to be anti-phase. Likewise, a negative signal applied to the input causes the SC1 collector current to decrease, the voltage across R_E to decrease, the base emitter voltage to increase, the collector current of SC2 to increase and an antiphase voltage at the output.

5.3 **CONSTANT CURRENT SOURCE.** As an increase in collector current in one transistor results in a decrease in collector current in the other, the total current through the common emitter resistor rises only slightly and tends to remain constant. The larger the value of resistor R_E the more nearly constant will be the current. The ultimate in stability would be when a 1 mA increase in one transistor causes a 1 mA decrease in the other. If the resistor is too large however, the operating current for the transistors is insufficient. In some circuits, a transistor is used in place of R_E as a constant current source, as it provides a high impedance and yet allows sufficient current for the operation of the differential pair.

5.4 **TWO INPUT OPERATION.** When two inputs are used, only the difference between the input signals is amplified. The amplifier operates in a similar manner to that described for one input, except that when two input signals of equal amplitude and phase are applied, the increase in the emitter current of one transistor is cancelled by a decrease in emitter current caused by the other. There are no changes of current and no output signal results. When the two inputs are not of equal amplitude, the currents do not cancel out and a voltage, proportional to the difference between the input signals, appears at the output. In this type of amplifier the signal common to both inputs is rejected and this property has been termed common mode rejection.

A typical use of the two input differential circuit is in power supply circuits, where the amplifier compares the output voltage of the supply with a reference voltage. An output signal, proportional to the difference between the two voltages, is derived and used to regulate the voltage of the power supply. Under these conditions the difference amplifier functions as a comparator.

5.5 The difference amplifier is versatile in that it is a d.c. amplifier which amplifies signals of very low frequency, including direct current signals such as in voltage regulation circuits, and in that it forms the basis of many integrated circuits used to amplify a.c. signals in the audio, video, IF and RF range. The difference amplifier is also the basic configuration used in operational amplifier integrated circuits which perform mathematical functions and have wide application in the field of automatic control and analog computers.

6. INTEGRATED CIRCUITS.

6.1 An integrated circuit (IC) is one in which all components and connecting paths are grouped together in a single protective container or encapsulation. Complete circuit functions are performed by ICs in a space the size of a single transistor, and as a result, the integrated circuit is extremely reliable and is becoming the basic component of electronic equipment.

Two distinctly different integrated circuit technologies are in use and are referred to as monolithic technology and hybrid technology. A monolithic circuit is one in which all circuit components are formed on the one piece of silicon and interconnected by a metallisation pattern. The monolithic (single stone) circuit is often referred to as a fully integrated circuit. A hybrid circuit is one in which the circuit components are formed separately and interconnected by a metallisation pattern or wire bands. The circuit may consist entirely of individual components or of a number of monolithic sub-circuits all interconnected, but, as long as all are housed in a single package, the device is called a hybrid circuit.

6.2 FORMING A TRANSISTOR. The basic fabrication processes for integrated circuits are almost identical with those used to fabricate transistors.
One common method used to develop a transistor is to take a single chip or wafer of semiconductor material, for example, N type silicon, and diffuse P type dopant into the surface and form a diode as shown in Fig. 20a.

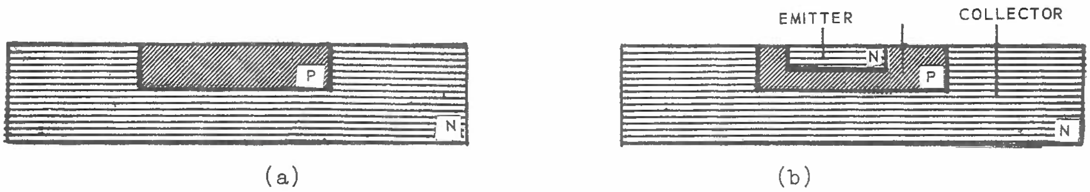


FIG. 20. CONSTRUCTION OF SILICON PLANAR TRANSISTOR.

Into the P type material a small area of N type dopant is diffused. This creates three separate elements and these form the base, emitter and collector of an NPN transistor as shown in Fig. 20b. The name silicon planar is given to this type of process where each element is formed one plane above the other. This is distinct from the junction transistor where a thin strip of doped material has a small dot of oppositely doped material fused on either side.

6.3 INTEGRATED CIRCUIT ELEMENTS. Integrated circuits contain resistors, capacitors and diodes as well as transistors. As these elements are formed on the same silicon wafer, some methods of electrical isolation has to be provided.

In IC construction, the parent material of the wafer is generally a P type material and is called the substrate. On the substrate is grown a layer of N type material known as the epitaxial layer. On top of the epitaxial layer is formed a film of silicon dioxide which is an insulating material. Where a circuit contains three elements, for example, a transistor, and a capacitor, three islands are created by etching away unwanted areas of the epitaxial layer as shown in Fig. 21a.
The transistor would be formed in island A, the resistor in B and the capacitor on G. The islands are electrically isolated because the diodes formed by the islands and the substrate are connected back to back in a circuit as shown in Fig. 21b.

Interconnection between each island component is done by a metallisation layer above the oxide coating. The insulating oxide is selectively opened to permit connection between component and metallisation.

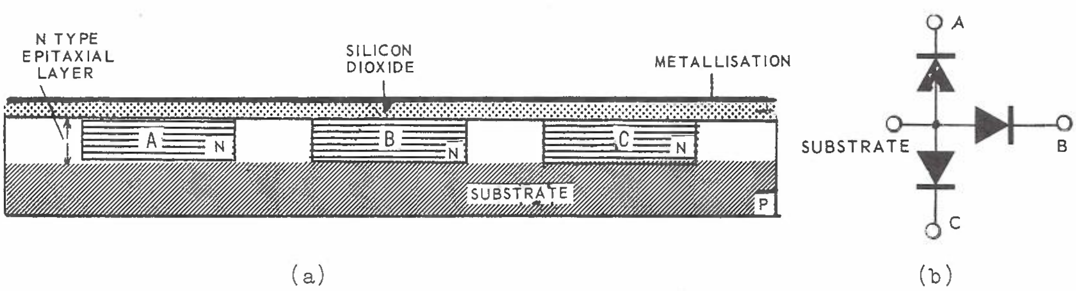
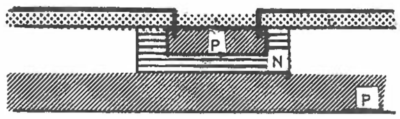
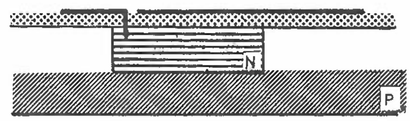


FIG. 21. ISOLATED AREAS ON SILICON WAFER.

6.4 RESISTOR CONSTRUCTION. The resistor is formed by diffusing a layer of P type material into an island and making connectins to opposite ends of the P type material. The resistance between these connections is determined by the resistivity of the P type material, the length and the cross-sectional area. The resistivity cannot be varied greatly but the length or cross-sectional area can. The resistor value in ICs is determined by the thickness and length between the connection points. As a result, large resistors are long and narrow and small resistors are short and squat. Fig. 22a shows connection of contacts into the P type material to form an integrated resistor.



(a) Resistor.

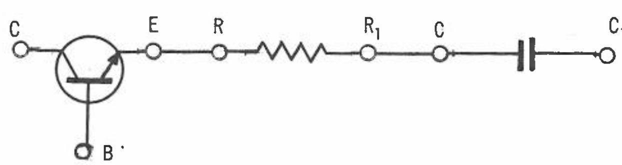


(b) Capacitor.

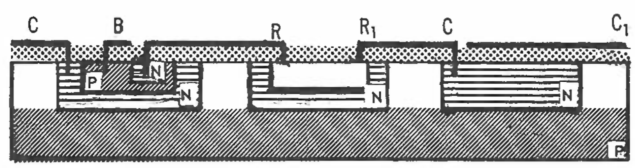
FIG. 22. FORMING RESISTORS AND CAPACITORS.

6.5 CAPACITOR CONSTRUCTION. A capacitor consists of two plates separated by a dielectric or insulating material. In IC construction, one plate is formed by the N type material of an island, the dielectric is the oxide coating and the metallisation on the surface of the oxide coating acts as the second plate. The value of capacitance is determined by the area of the plates, the dielectric constant and the thickness of the dielectric. Because the thickness is kept constant, the capacitance value varies directly with the area. Fig. 22b shows the N type island forming one plate of a capacitor, the metallisation forming the second plate and the oxide acting as the dielectric. In some circuits, a reverse biased PN junction is used as a capacitor.

6.6 COMPLETED CHIP. A combination of the three elements is shown in Fig. 23a. The emitter of the transistor is connected to the resistor, which in turn is connected to the capacitor, Fig. 23b shows the schematic arrangement.



(a)



(b)

FIG. 23. SILICON CHIP CONTAINING A TRANSISTOR, RESISTOR AND CAPACITOR.

During manufacture, the processes for each component are formed simultaneously. For example, after the N type islands have been created, the P material for the resistor and base of the transistor are diffused into the N type material in the one operation. The processes used to add components to the silicon wafer include photo-sensitising, coating, masking, exposing, etching and diffusing. Other electronic components, which are included in integrated circuits, include unijunction transistors, varactors, thyristors and field effect transistors.

6.7 CHIP SIZES. Circuits are not made individually. A silicon wafer 1 inch square may be divided into between 300 and 400 parts, each about 0.05 inches square, and a similar circuit is made in each part. A drawing of the circuit is laid out about 500 times full size, and from this a series of related drawings, one of each process, is made. These are reduced to normal size by a photographic process and repeated according to the number of circuits required. Fig. 24 gives some idea of relative sizes.

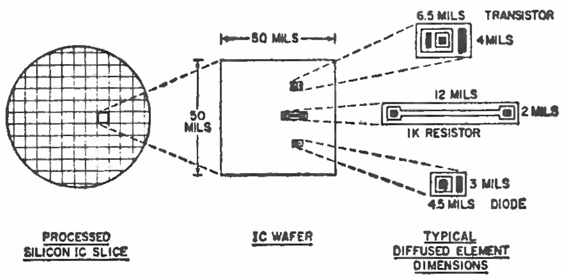
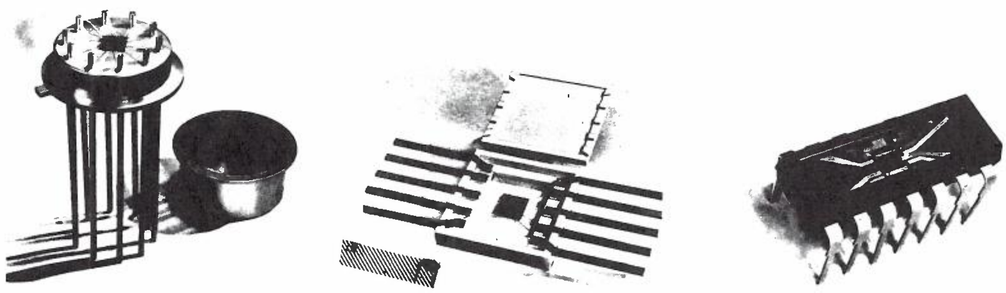


FIG. 24. IC WAFER AND COMPONENT SIZES.

6.8 PACKAGING. After the circuits are formed, they are tested and failures are marked. The wafer is sliced into individual circuits, assembled in packages and tested. Three common types of package used are the hermetically (air tight) sealed TO-5 types, the ceramic or metal flat-pack and the plastic dual-in-line pack. Examples are shown in Fig. 25.



(a) TO-5 PACK. (b) FLAT PACK. (c) DUAL-IN-LINE PACK.

FIG. 25. IC PACKAGE TYPES.

6.9 CHOICE OF COMPONENTS. Since most of the costs are incurred in the manufacturing processes, it is desirable to make the circuit as small as possible so that the maximum number of circuits can be formed on the one silicon wafer. The area of the relative components is therefore important. A resistor generally occupies more space than a transistor, and a capacitor occupies more space than a resistor. (Field-effect transistors use much less space than conventional transistors). Because area determines the cost, the circuit is designed to keep the number of resistors and capacitors to a minimum, and in some circumstances transistors are used instead of resistors. An integrated circuit and a circuit composed of discrete components will be different even though they perform similar functions.

6.10 Integrated circuits are designed to perform a number of functions. Those which serve as amplifiers, audio, video etc., are generally called linear integrated circuits; those used in switching circuits and which perform such functions as AND, OR and flip-flop, are generally called digital integrated circuits.

6.11 LINEAR ICs. In linear integrated circuits, the basic circuit configuration used is the differential amplifier. Some reasons for choosing the differential amplifier over other circuits are:

- the differential amplifier requires a minimum number of capacitors,

- the use of large resistors can be avoided and the gain of the circuits is a function of the resistor ratios rather than the actual values of resistance,

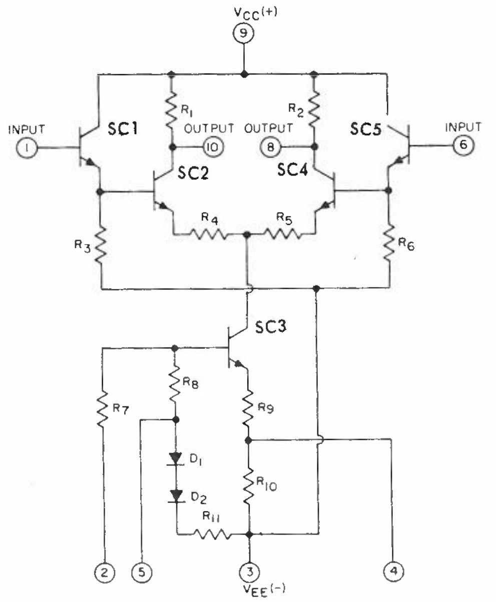
- each component of a transistor is physically close to the corresponding component of the second transistor of a differential pair and so effects due to temperature changes are cancelled.

- the differential amplifier is versatile and can provide linear amplification from d.c. through the audio and video frequencies to the v.h.f. region.

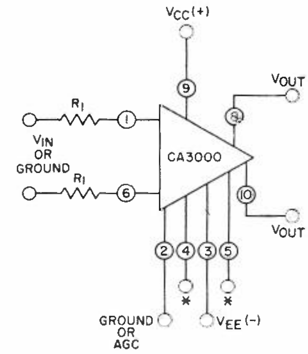
The basic differential amplifier is augmented, according to the requirements of the circuit. Practical circuits contain a transistor in the emitter circuit to provide a constant current source for the differential pair. An emitter follower configuration is included with each transistor and provides a high impedance input. Fig. 26a is an example of an integrated circuit (CA 3000) amplifier which has a gain of 30 dB at frequencies up to 1 MHz. Fig. 26b shows the IC in symbol form together with external connecting points.

Transistors SC2 and SC4 together with resistors R1, R2, R4 and R5 form the basic differential amplifier. Transistors SC1 and SC5 are the input emitter followers and SC3 is the constant current source. The network of resistors around SC3 is a temperature compensating arrangement for that transistor.

This IC is supplied in a TO-5 style package and has 10 terminals. Terminals 1 and 6 and 10 and 8 are the input and output terminals respectively; supply is connected to terminals 3 and 9. External potentials are applied to terminals 2, 5 and 6, and these determine the operating characteristics of the IC.



(a)



(b)

FIG. 26. SCHEMATIC DIAGRAM OF AN INTEGRATED CIRCUIT.

6.12 DIGITAL ICs. Digital circuits were the first to be built into IC form.
A simple switching circuit can be made from a few resistors and transistors and can tolerate a wide range of resistor values. The three principal families of logic circuits used are resistor-transistor logic (RTL), diode-transistor logic (DTL) and transistor-transistor logic (TTL). An example of a basic digital IC is shown in Fig. 27. The circuit is a two input gate with a transistor for each input. When either or both of the inputs is positive, the output is 0V; when both inputs are at 0V the output will be positive. The circuit performs the NAND or NOR functions according to the type of logic used.

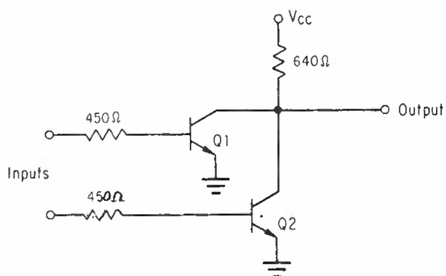


FIG. 27. TWO INPUT RTL GATE USING ICs.

The basic RTL gate shown in an early development and is similar to an equivalent circuit using discrete components. Later circuits however in DTL and TTL take advantage of IC design techniques to make devices not practical in descrete component circuitry. Circuits of DTL and TTL gates are discussed in other papers.

7. THE SCHMITT TRIGGER.

7.1 CIRCUIT FEATURES. The Schmitt Trigger circuit is an amplitude-dependent switch whose output condition changes state when the input signal passes through certain voltage amplitudes. It produces a rectangular output signal waveshape which is independent of the waveshape or rate of change of the input signal.

The Schmitt Trigger is a special type of bistable multivibrator circuit in which only one collector is coupled to the opposite base, and the two transistors share a common emitter resistor, as shown in Fig. 28. Because the switching action is sensitive to a precise level of input signal, called the trigger level, the circuit is generally not susceptible to noise.

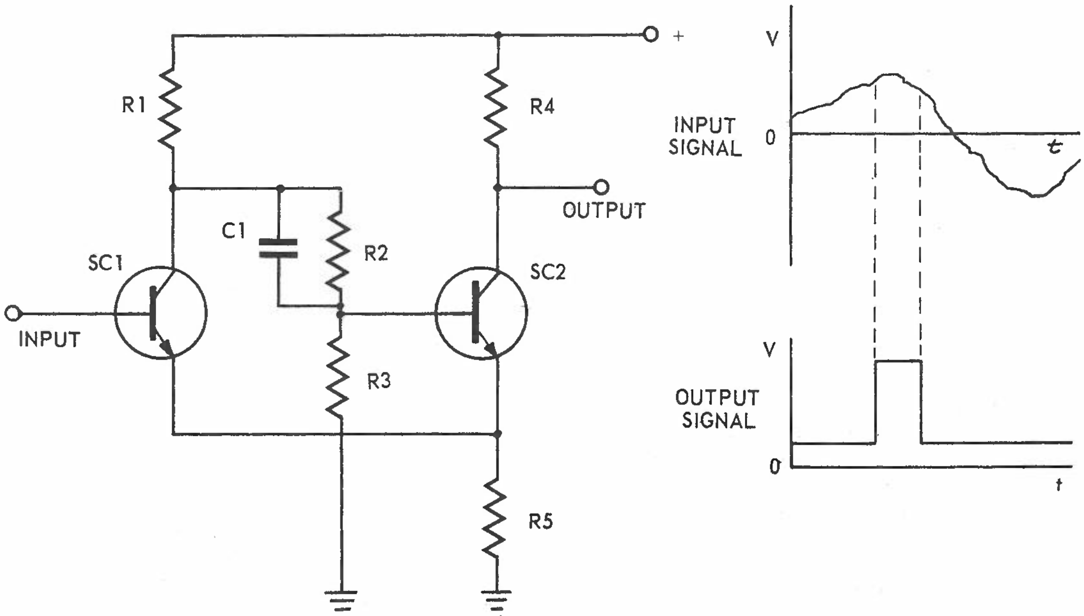


FIG. 28. SCHMITT TRIGGER BASIC CIRCUIT.

The circuit is used for:

- Reforming or reshaping rectangular waveforms which have become distorted;
- converting input waveshapes to rectangular waveform;
- signal-level detection;
- eliminating contact bounce from mechanically generated signals;
- eliminating transient overshoot from pulses;
- eliminating noise signals from pulses.

The Schmitt Trigger rests in its stable state, with SC2 on and SC1 off, until the input signal rises to the trigger level. The circuit then switches regeneratively to its second state, SC1 on and SC2 off, until the input signal falls to a level at which SC1 ceases to conduct. The circuit then switches regeneratively to the original condition. The input signal level at which the circuit reverts to normal is generally of a lower value than that at which the circuit triggers to its second state.

The differing switching-level feature is termed hysteresis. The amount by which the two switching levels differ from one another is called the 'hysteresis range', and the two input signal values at which switching takes place are called the 'hysteresis limits'.

7.2 CIRCUIT OPERATION. The normal circuit condition is that SC2 is conducting heavily in the saturation region of its characteristic, and SC1 is reverse biassed into the cutoff region of its characteristic. Because SC2 is on, its collector voltage V_{CE} is a minimum, and the output voltage is a minimum. Conversely, the SC1 collector voltage is a maximum, because SC1 is off.

The circuit shown in Fig. 29 uses npn transistors, but pnp transistors could be used with the supply potential reversed. The resistors R4, R5 in Fig. 29 form a voltage divider network between the SC1 collector and earth. The voltage drop across R5 has a positive potential at the base of SC2, and a negative potential at the emitter. This provides the necessary forward bias for the npn transistor.
The series resistor R6 provides the SC2 collector supply voltage, and SC2 conducts at saturation. In this region the base voltage is greater than the collector voltage, and the collector-base junction is forward biassed.

The SC2 collector current develops a positive potential across the common emitter resistor R7, which makes the base of SC1 negative with respect to the emitter. This is the reverse bias condition for both transistors, but only SC1 is biassed off while the SC2 base potential is positive with respect to the emitter potential.

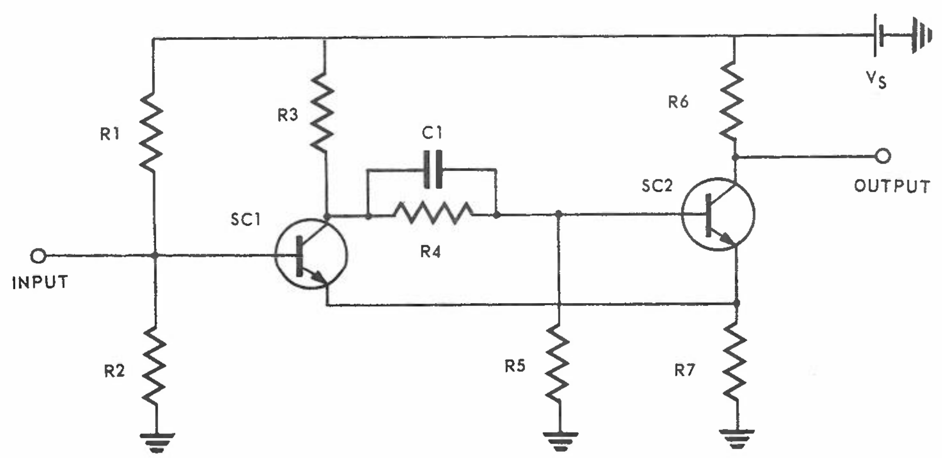


FIG. 29. SCHMITT TRIGGER CIRCUIT.

To turn SC1 on, the input voltage amplitude must exceed the reverse bias voltage by about 0.2 V. This is the trigger level, and when a signal of this amplitude is applied, SC1 conducts. Increased current through R3 increases the voltage drop across it. The SC1 collector voltage falls, and the speed-up capacitor C1 rapidly transfers this negative-going change to the base of SC2.

The conduction of SC2 is decreased by the negative-going voltage applied to its base, and the voltage drop across R7 is decreased. This change increases the effective forward bias of SC1, which increases its conduction. This increases the current through R3, its voltage drop increases, further reducing the SC1 collector voltage, and similarly reducing the forward bias of SC2, and the voltage drop across R7. This regenerative action quickly takes SC1 to saturation and turns SC2 off.

When SC2 is off, there is no voltage drop across R6, and the collector voltage of SC2 rises in amplitude to the source potential. The output voltage is a maximum, and maintains this constant amplitude regardless of any input amplitude changes above the trigger level.

The Schmitt Trigger has now attained its second stable state, and remains in this state, with SC1 on and SC2 off, until the input signal amplitude falls to the level at which SC1 is turned off.

7.3 HYSTERESIS. The trigger level V_1 at which the circuit changes to the second state differs from the trigger level V_2 at which the circuit reverts to its normal state. Because V_1 and V_2 differ, the circuit is said to exhibit hysteresis.

A practical Schmitt Trigger circuit is not designed to change state when V_2 is equal to V_1. Small variations in circuit component behaviour would make the circuit operation unreliable, and demand frequent readjustment. It is also impractical to make V_2 greater than V_1 in amplitude, as the circuit would become astable, and oscillate continuously.

In practice, the hysteresis limit V_1 is greater than the hysteresis limit V_2, as shown in Fig. 30, and the difference between these values (the hysteresis range), can be adjusted by variation of the value of the common emitter resistor. The time the normally-on transistor is off is reduced by increasing the value of the common emitter resistor.

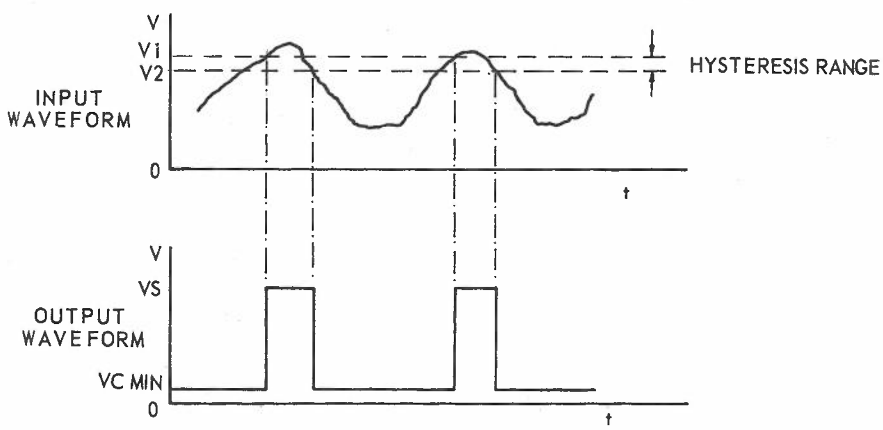


FIG. 30. SCHMITT TRIGGER RESPONSE TO INPUT SIGNAL.

The Schmitt Trigger circuit responds to an input signal which has a peak-to-peak amplitude greater than the hysteresis range, but the input signal d.c. level must be adjusted to make the input signal pass through the hysteresis limits. The hysteresis limits can be changed by adjustment of the values of the voltage divider resistors in the base circuit of the normally-on transistor.

7.4 APPLICATIONS. The Schmitt Trigger circuit can be used when the output required is related to the amplitude of the input signal, but is not related to the waveshape or rate of change of the input signal.

- AMPLITUDE COMPARATOR. In use as an amplitude comparator, the Schmitt Trigger defines the moment at which the input waveform attains a particular reference level. When the comparison point V_1 or V_2 is reached, the comparator output has an abrupt well-defined change of amplitude.

- SQUARING CIRCUIT. An input signal which has a non-rectangular waveshape can be transformed to a square wave, if its peak-to-peak amplitude exceeds the hysteresis range of the Schmitt Trigger circuit. The amplitude of the output square wave is independent of the input signal amplitude, and may have much steeper leading and trailing edges than appear on the input signal.

- SHAPING CIRCUIT. A rectangular waveform that has degenerated from its correct shape and become distorted, can be restored to its correct waveshape. Choice of the hysteresis limits determines the pulse length of the restored waveform.

8. ELECTRONIC VOLTAGE REGULATORS.

8.1 REGULATION. Communications circuits are often required to work within specified signal limits of currents, or voltage, or frequency. Whether or not these limits are exceeded depends on the stability of the power supply to which the circuit is connected, and the stability of components under varying load and temperature conditions. The stability of components can be accomplished within acceptable limits by component design. Power supply stability can be obtained by regulation.

Voltage regulation is the name given to the process by which the output voltage of a power supply is made almost independent of changes in the voltage or frequency of an input a.c. supply, changes in the voltage of an input d.c. supply, or changes in the load current. Voltage regulation can be attained by using mechanical, magnetic, or electronic control components.

Mechanical voltage regulation uses the reaction of magnetic fields to changes in circuit current to control the output voltage. Voltage regulators using mechanical control components include heavy duty rectifier sets which use mechanically controlled variable transformers, and vibrator type power supplies.

Voltage regulators using magnetic control components include rectifier sets which use saturable transformers, saturable reactors and transductors.

Electronic voltage regulators use active electronic circuit components to control the output voltage. Simple electronic voltage regulators rely on the characteristics of diodes for output regulation, but have limitations in allowable load resistance and load current. These limitations are minimised by using sampling and feedback techniques to control the output of the regulator.

8.2 ELECTRONIC VOLTAGE REGULATORS. There are two broad categories of electronic voltage regulation circuits:

- VOLTAGE DIVIDER TYPE regulation circuits, in which the control component forms part of a voltage divider network into which the controlled circuit is connected.

- SWITCHING TYPE regulation circuits, in which the control component acts as a switch that can be turned on or off. The output voltage is dependent on the ratio of the on time to the off time of the switch.

8.3 VOLTAGE DIVIDER TYPE REGULATORS. There are two types of voltage divider type regulators, which are named according to the way the control component is connected in the circuit:

- SERIES REGULATORS (Fig. 31a). In a series type voltage divider regulator, the control component is in a series circuit with the power supply and the load. The control element and the load comprise the voltage divider network as shown in Fig. 31a, where R_c represents the control component, and R_L represents the load.
- SHUNT REGULATORS (Fig. 31b). In a shunt type voltage divider regulator, the control component is connected in parallel with the load. A series resistance (Rs in Fig. 31b) is included in the circuit to make control possible. Rs and the parallel combination of the control component R_c and the load resistance R_L form the voltage divider network.

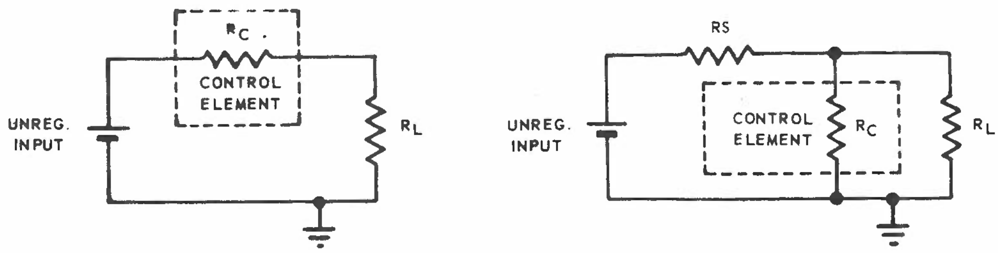


FIG. 31. VOLTAGE DIVIDER TYPE REGULATORS.

8.4 SERIES VOLTAGE REGULATOR. A block diagram of a series voltage regulator is shown in Fig. 32. The control component is in series with the power supply and the load R_L. The output voltage is sampled, and the sample is compared with a reference voltage.

The two voltages are compared in the comparator circuit, or difference amplifier. The comparator circuit produces an output which is proportional to the difference between the reference voltage and the sample of the output voltage.

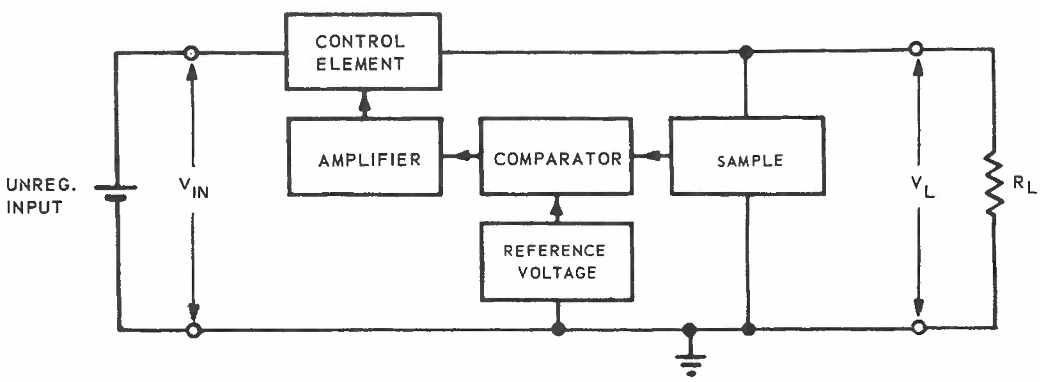


FIG. 32. SERIES VOLTAGE REGULATOR BLOCK DIAGRAM.

The difference voltage, or error signal output, of the comparator circuit is amplified and applied to the control component to change its characteristics in such a way that the error signal is reduced.

8.5 EMITTER FOLLOWER REGULATOR. A simplified circuit of an emitter follower regulator which uses an npn transistor as the control component is shown in Fig. 33. In this simplified circuit, the control component SC1 also performs the functions of sampling, voltage comparison, and amplification, which are shown in the block diagram in Fig. 32.

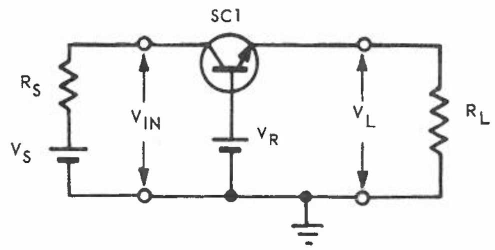


FIG. 33. BASIC SERIES VOLTAGE REGULATOR.

The output voltage positive potential V_L across the load is applied to the emitter of SC1, and in this case acts as the sample which is taken for comparison. The reference voltage V_R is applied to the base of SC1 and must be greater than V_L to give forward bias to the base-emitter junction. The difference V_R - V_L between the reference voltage V_R and the output voltage V_L is the base-emitter voltage, and controls the collector current of SC1.

When V_L tends to rise, the difference voltage V_R - V_L tends to decrease, which decreases the forward conduction of SC1, and opposes the tendency of V_L to rise. When V_L tends to fall, the difference voltage V_R - V_L tends to increase, which increases the forward conduction of SC1, and opposes the tendency of V_L to fall. The output voltage settles to a value determined by the designed forward bias of SC1, and follows closely the voltage V_R applied to the base. This tendency of the emitter voltage to maintain a close relationship to the base voltage is a characteristic of the emitter follower circuit.

8.6 SERIES VOLTAGE REGULATOR WITH ZENER DIODE. A simplified circuit of a series voltage regulator which uses a zener diode as the reference voltage source is shown in Fig. 34. The transistor SC2 is wired in the emitter follower configuration, and acts as the sampling device, comparator, amplifier, and control component. R_L represents the load of the regulator.

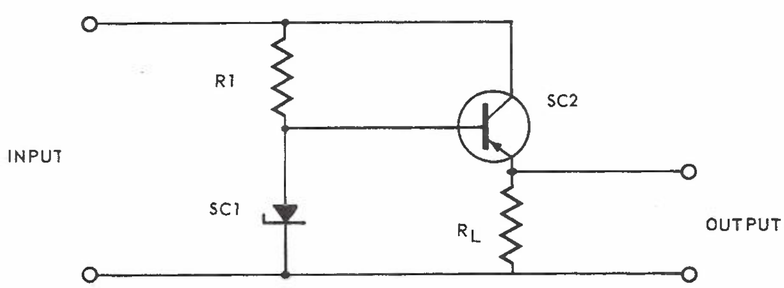


FIG. 34. SERIES VOLTAGE REGULATOR WITH ZENER DIODE.

A limiting resistor R_1 is wired in series with the zener diode SC1. The unstabalised input supply voltage is applied across this combination, and the potential across the zener diode is taken as the voltage reference V_R for the regulator circuit. This reference voltage is applied to the base of SC2.

The emitter voltage of SC2 is the output voltage V_L of the regulator circuit, and acts as the sample voltage which is compared with the reference voltage. The difference voltage $V_L - V_R$ determines the forward bias of the transistor SC2, which controls the collector current of SC2.

Tendency of the output voltage V_L to change is corrected by a resultant change in the forward bias of the emitter-base junction. The emitter voltage of the emitter follower configuration tends to "follow" very closely the voltage applied to its base, so the voltage on the emitter of SC2 tends to remain almost the same as that applied to the zener diode, irrespective of the emitter current.

The circuit shown in Fig. 34 has the advantages that the transistor delivers the output power, and that negligible power is handled by the zener diode, but has some disadvantages. The main disadvantage is that the output voltage is not variable and the circuit is modified as shown in Fig. 35a to overcome this problem.

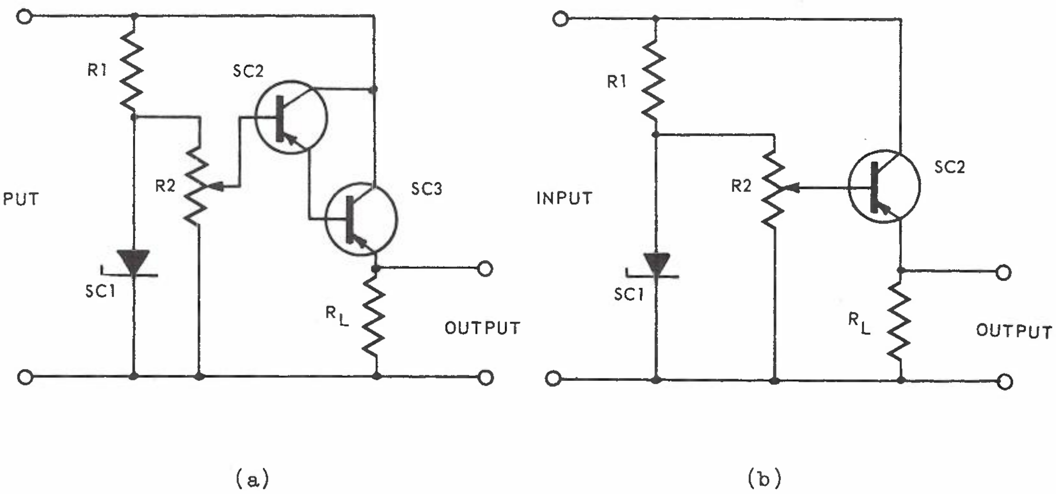


FIG. 35. BASIC CIRCUITS OF ZENER REFERENCE SERIES VOLTAGE REGULATORS.

The modified circuit shown in Fig. 35a allows variation of the output voltage of the regulator. The moving arm of a potentiometer R2 fitted in parallel across the zener diode is used to select a base voltage. The base voltage selected determined the output voltage of the regulator. The circuit retains a disadvantage of the circuit in Fig. 34, in that the output impedance of the transistor SC2 causes the output voltage to vary slightly with changes in the output current.

In the circuit shown in Fig. 35b, a further modification of the basic circuit, the single transistor of Fig. 35a is replaced by two transistors SC2 and SC3 connected as a Darlington pair. This circuit has a very low output impedance, gives good voltage regulation, and the output voltage is fully variable.

8.7 **SHUNT VOLTAGE REGULATOR.** A block diagram of a shunt voltage regulator is shown in Fig. 36. The reference standard, and those parts of the regulator which sample, compare and amplify are similar in design and function to those in the series voltage regulator.

The main difference between the two types of regulator is in the position in which the control component is wired in the supply circuit. The control component of the regulator is in shunt across the load.

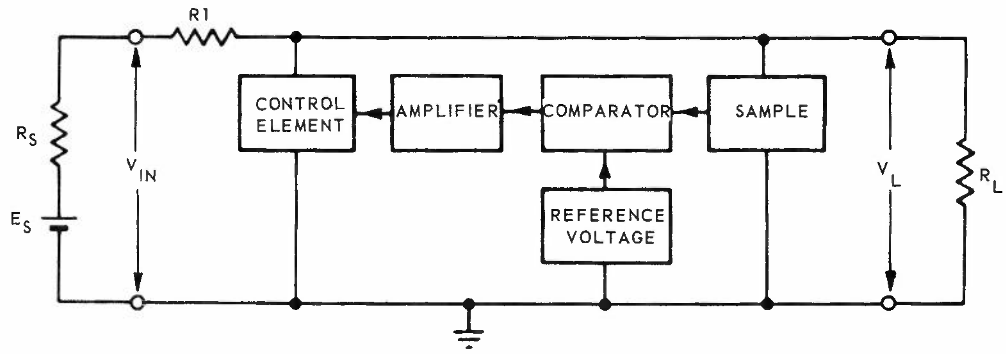


FIG. 36. SHUNT VOLTAGE REGULATOR BLOCK DIAGRAM.

The output voltage is sampled and compared with the reference voltage, the difference amplified and applied to the control component. The difference signal causes the control component to react in such a way that the difference voltage or error signal is reduced.

Shunt regulators are best suited to circuits in which the load current change is small. Series regulators are more generally used than shunt regulators, and typical circuits of shunt regulators are not described in this publication.

END OF PAPER