CP 311
PRICE 25c

THE AUSTRALIAN POST OFFICE

COURSE OF TECHNICAL INSTRUCTION

Engineering Training Section, Headquarters, Postmaster-General's Department, Melbourne C.2.

CLIPPING

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1. INTRODUCTION.

1.1 A clipping circuit is a non-linear shaping circuit which selects a section of a wave either above or below a reference voltage, or limits an excursion of a waveform to a reference voltage. Circuits include diodes, thermionic valves and transistors operated under non-linear conditions.

1.2 In pulse applications, clipping circuits, in association with amplifiers, are used to control the amplitude of rectangular pulses, to reshape rectangular pulses or to generate rectangular pulses from sine waves, to select required sections and to remove unwanted sections of a waveform, and to clip noise components from rectangular pulse waveforms. More specifically in television applications, clippers are required to separate the synchronizing information from a composite video signal, to prevent black picture signals from extending into the sync. region of a broadcast television signal, and to prevent white picture signals from reducing the carrier level of a broadcast television signal below the minimum value specified in the television "standards".

1.3 This paper discusses the general considerations of circuits used to produce clipping and sync. separation. Modifications to sync. separator circuits to improve their noise immunity are not considered. Also examined are voltage comparator circuits which introduce clipping at two adjacent levels in order to produce an output when the input signal has a particular level.

Circuits that are similar or identical to the clipping circuits considered in this paper are used in the intermediate frequency stages of frequency modulation (F.M.) receivers and are invariably known as limiters in this application. The term "limiter" is sometimes used to describe the clipping circuits of pulse applications. The purpose of a limiter in an F.M. receiver is to remove any amplitude modulation components from the required frequency modulated signal, but the operation of circuits for this purpose is not examined in detail in this paper.

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2. DIODE CLIPPING CIRCUITS.

2.1 Series Diode Clipping Circuit. The unilateral characteristic of diodes which allows current to flow in one direction but not in the other, makes diodes useful in clipping circuits. The characteristic can be used in two ways. The first is by arranging a diode in series with the signal path so that the diode is non-conducting for input signal amplitudes to be clipped. Secondly the diode can be arranged in shunt across the signal path in such a way that it is conducting for signal amplitudes to be clipped.

A series diode clipping circuit is shown in Fig. 1a. Considering a perfect diode with zero forward (conducting) resistance and infinite reverse (non-conducting) resistance, the diode conducts when the input signal (e_{in}) is positive and the input is directly connected to the output. However, when the input is negative the diode becomes non-conducting, and the output is zero. The input and output waveforms for the circuit are illustrated in Fig. 1b.

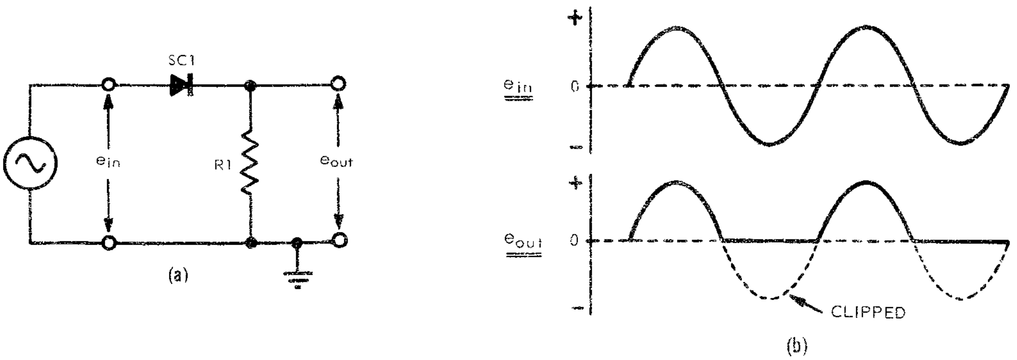


FIG. 1. SERIES DIODE CLIPPING CIRCUIT.

A sine wave input signal is used as this gives a good indication of the clipping level. The output waveform indicates that the section of the waveform which is more negative than the clipping level has been removed and the circuit is therefore a negative series diode clipping circuit. The output waveform also shows that the circuit of Fig. 1a is a half wave rectifier circuit. Used as a clipper, however, greater attention must be directed towards the relative values of the circuit resistance and capacitance, than would be necessary for a rectifier circuit.

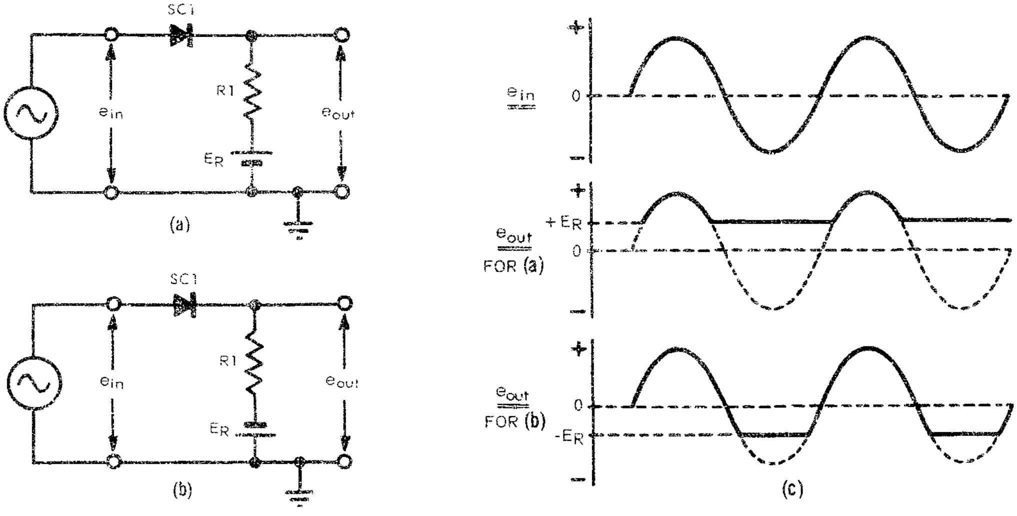


FIG. 2. BIASSED CLIPPING CIRCUITS.

2.2 The series diode clipping circuit can be arranged to clip at levels other than zero by including a reference voltage in series with the resistor R1 as shown in Figs. 2a and b. The reference voltage can be of either polarity. The reference voltage biasses the clipping diode and the input voltage must be more positive than the reference potential before the diode can conduct to produce an output (Fig. 2c). Any section of the input signal that is more negative than the reference potential causes the diode to become non-conducting and the output remains at the clipping reference potential.

Reversing the connections to the diode to give circuits as in Figs. 3a and b, allows the sections of the waveform that are more positive than the reference potential to be clipped. Examples of output waveforms for two different bias conditions are illustrated in Fig. 3c.

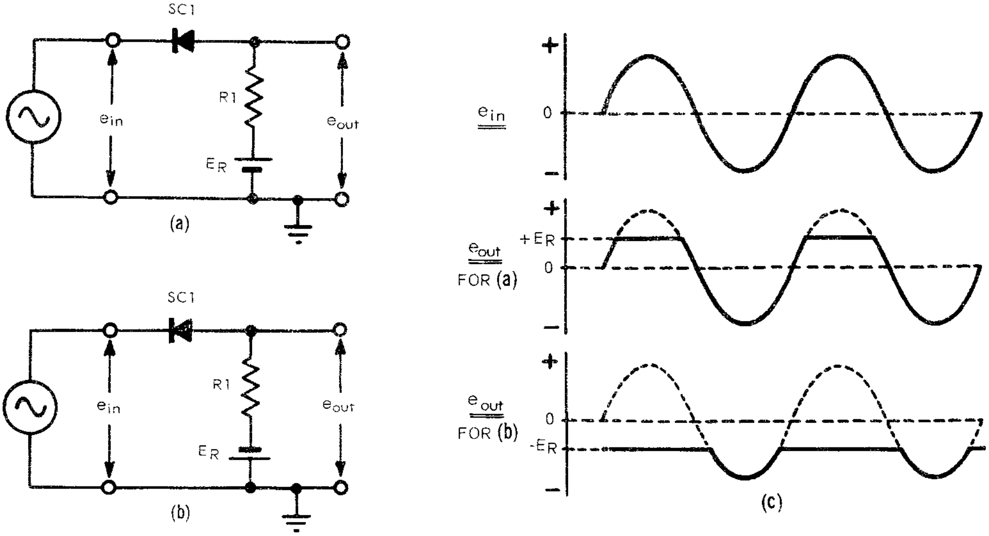


FIG. 3. BIASSED CLIPPING CIRCUITS.

A convenient means of providing the bias for a series diode clipping circuit is to use the shunt resistor as part of a voltage divider supplied from a conveniently available voltage as shown in Fig. 4. The input voltage to this circuit must be more positive than the voltage at the output set by the voltage divider, before the diode can conduct and transmit the input signal to the output. The effective values of the circuit shunt resistance and the clipping reference potential can be determined by applying Thevenin's Theorem. The circuit in Fig. 4 is exactly equivalent to the circuit in Fig. 2a when $R1 = \frac{R2\ R3}{R2+R3}$ and $E_R = \frac{R2}{R2+R3} E_{HT}$.

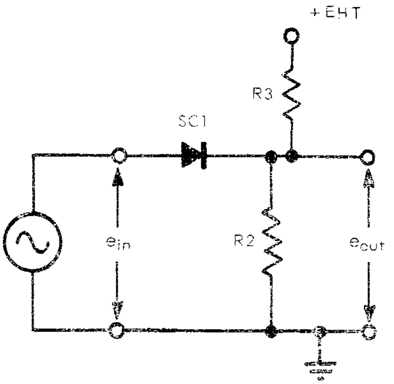


FIG. 4. BIAS FOR CLIPPING CIRCUIT.

2.5 Shunt Diode Clipping Circuit. Fig. 5a illustrates a shunt diode clipping circuit. When the input signal is positive with respect to earth, the diode is biassed in the non-conducting direction. Since no load resistance is present across the output, no voltage drop is present across the series resistor (R1) and the input appears at the output without attenuation. For negative input signals the diode becomes conducting and represents a low resistance - zero in the case of a perfect diode. The complete input signal is then present across the series resistor (R1) and no voltage appears at the output. The section of the waveform that is more negative than the clipping level has therefore been clipped from the signal (Fig. 5b) and the circuit is a negative shunt diode clipping circuit.

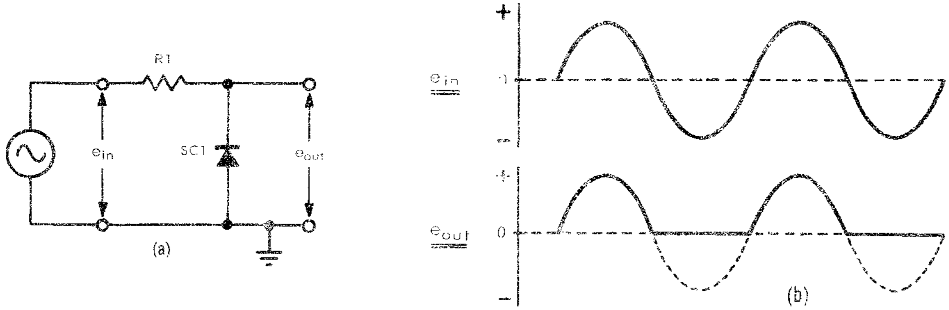


FIG. 5. SHUNT DIODE CLIPPING CIRCUIT.

The shunt diode clipper can be arranged to clip at levels other than zero by including a reference voltage in series with the diode as shown in Figs. 6a and b. The reference voltage, which can be of either polarity, biasses the diode so that the input signal must be more negative than the reference voltage, before the diode will conduct and produce negative clipping. When clipping occurs, the output voltage is "clamped" at the reference potential. "Clamped" is used here in the general sense where it means that a point in a circuit is connected to a reference potential via a low impedance and its potential cannot vary appreciably from the reference potential. In the course paper, "D.C. Restoration and Clamping", a special case of clamping adds a D.C. component to maintain a section of the signal at the reference level without a significant change in the wave shape. Fig. 6c illustrates the waveforms associated with the biassed shunt diode clipping circuits. Comparison of waveforms for the shunt and series diode circuits indicates that the circuits in Figs.6a and b give equivalent results to the circuits in Figs. 2a and b respectively. By reversing the connections to the diode the shunt diode clipping circuit clips input levels that are more positive than the reference voltage to produce output waveforms which are the same as those from the circuits in Figs. 3a and b. Series and shunt clipping circuits can be used in cascade to clip at one level, but, in most cases, this gives little advantage.

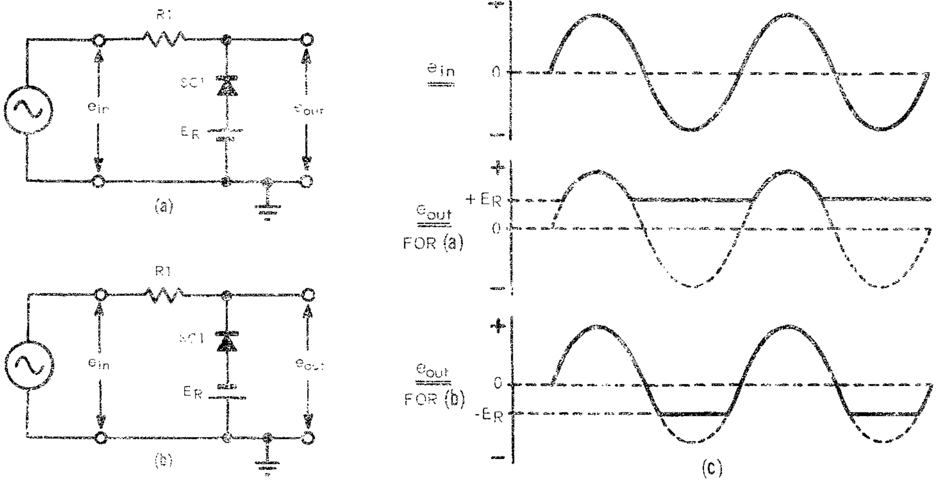


FIG. 6. BIASSED CLIPPING CIRCUIT.

2.4 Transfer Characteristics. The effect of a clipping circuit on an input waveform is conveniently estimated from a transfer characteristic for the circuit. The transfer characteristic is a graph of output voltage (on the "Y" axis) for each value of input voltage (on the "X" axis). Consider the clipping circuit in Fig. 6b. When the input voltage is such that the diode is non-conducting, that is, the input is more positive than $-E_R$, the input is transferred directly to the output.

The transfer characteristic for these input voltages (Fig. 7) is a straight line with a slope of 1 (the circuit has no loss or gain). Notice that the line (or an extension of the line in some cases) pass through the origin. For any input signals more negative than $-E_R$ the diode conducts and the output remains at $-E_R$. The transfer characteristic for voltages below $-E_R$ is, therefore, a straight line parallel to the "X" axis. The total characteristic is illustrated in Fig. 7. This characteristic is also obtained with the circuit of Fig. 2b. Transfer characteristics for other circuits can be prepared in a similar way.

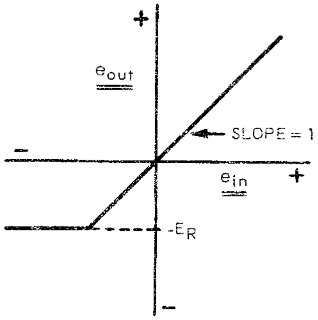
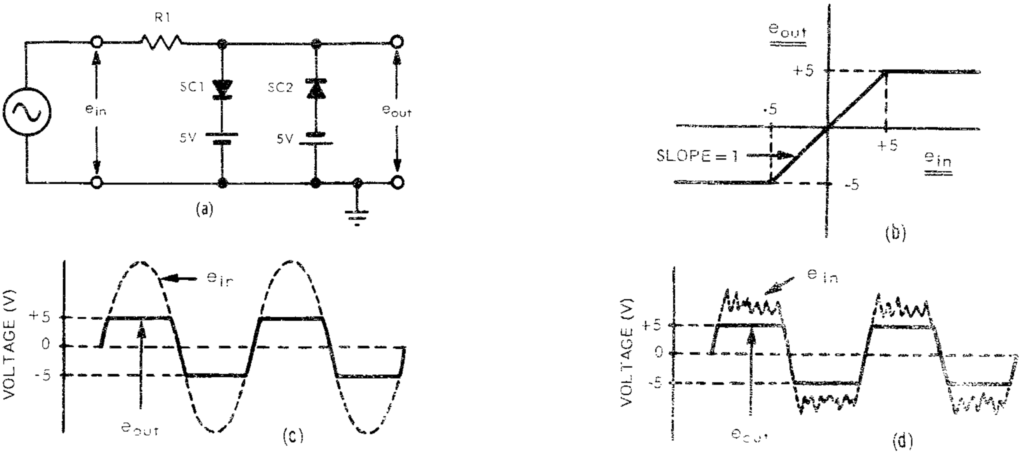


FIG. 7. TRANSFER CHARACTERISTICS.

2.5 Clipping at Two Levels. Two biassed diode clipping circuits arranged to clip at two levels will select a section of an input waveform. This is often called "slicing". The circuit in Fig. 8a includes two shunt diode clippers; a positive clipper which clips the sections of the input signal that are more positive than +5V, and a negative clipper to remove section more negative than -5V. The section of the signal between these clipping levels is transmitted directly to the output. The transfer characteristic for the complete circuit is illustrated in Fig. 8b. It has a centre section with a slope of 1 indicating the levels for which the input is transferred directly to the output. This concludes at +5V and -5V in horizontal sections indicating no additional output for input signals above +5V and below -5V.

Waveforms for the circuit (Fig. 8c) illustrate an application for clipping at two levels. The sine wave input clipped symmetrically about the zero axis has become approximately a square wave. The transitions have a definite rise time but are almost straight since the slope of a sine wave close to the zero axis is almost constant. For given clipping levels, the rise time of the output square wave is inversely proportional to the frequency, and approximately inversely proportional to the amplitude of the input signal. The rise time of rectangular waves can be reduced using the same technique of amplifying the signal and clipping at two levels to select a "slice" of the input waveform. In addition, noise components of the input rectangular wave are removed as shown in Fig. 8d.



(a) (b) (c) (d)

FIG. 8. CLIPPING AT TWO LEVELS.

2.6 Series diode clippers can also be arranged to perform two level clipping, but more consideration must be given to the component values to obtain the desired clipping levels. Fig. 9a shows an example of a circuit which has the same output waveforms as those in Fig. 8.

Consider an input signal such that SC1 is non-conducting. The circuit voltages forward bias SC2 and current through R1, SC2 and R2 produces a 100V P.D. across R1 and a 10V P.D. across R2. The voltage at point A and the output voltage is therefore +5V. The input voltage required for SC1 to be non-conducting is therefore a voltage greater than +5V, and input signals greater than +5V, are clipped. As the input signal is decreased below +5V, SC1 conducts and, with SC2 still conducting, the input signal is transferred to the output. Because of the bias in series with R2, SC2 ceases to conduct when the input signal (and therefore the voltage at A) is less than -5V. Clipping of the negative extreme of the input signal is then produced. The circuit clips all input signals above +5V and below -5V. The circuit in Fig. 9b is equivalent to the circuit in Fig. 9a but includes a more convenient method of obtaining the -5V reference potential. This is a common practical form of the circuit. In some applications this type of clipping circuit is associated with the anode circuit of a valve and is required to clip at two positive values of voltage. The opposite polarity bias voltages of Fig. 9 are then not necessary.

Series and shunt diode clippers can also be combined to provide clipping at two levels. Fig. 9c illustrates a satisfactory arrangement that has output waveforms as in Fig. 8.

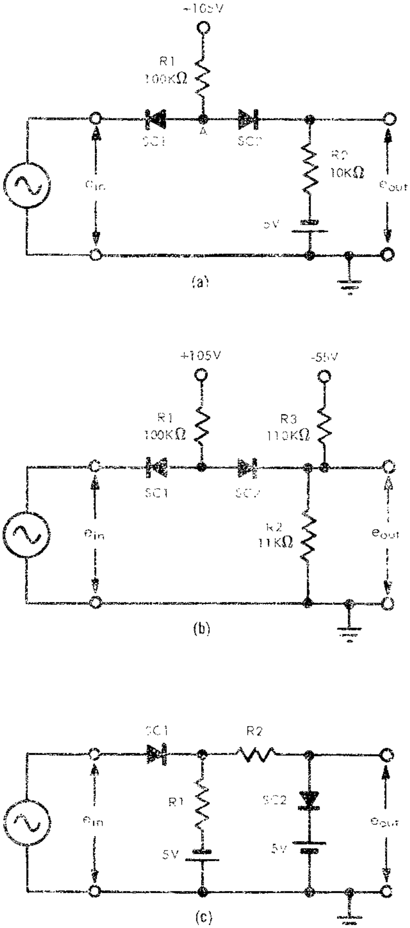


FIG. 9. CLIPPING AT TWO LEVELS.

2.7 Effect of Diode Resistance. Practical diodes differ from the ideal diodes so far considered in that their forward resistance (R_f) is not zero and their reverse resistance (R_r) is not infinite. Further, the forward resistance is not constant, since the current-voltage characteristic of diodes is curved, and also the "break" in the characteristic representing the division between the low and high resistance sections may not occur at zero voltage.

For the series diode clipping circuit to perform satisfactorily it is necessary for th shunt resistance (R1) to be much greater than the forward resistance of the diode (R_f) but for R1 to be much less than the diode reverse resistance (R_r). If this relationship is not maintained, when the diode is conducting, R1 and R_f form a voltage divider which could attenuate the required section of the waveform. This is the most important consideration when the value of R1 is reduced in an attempt to reduce the effect of circuit capacitance as discussed in para. 2.13.

Also, when the diode is non-conducting, the voltage divider formed by R1 and R_r could allow portion of the waveform that should be clipped to be passed to the output. The latter effect is most likely to be troublesome when germanium diodes are used, and can set a maximum value for R1.

A diode suitable for use in a clipping circuit should be selected to have a low R_f, a high R_r and so give a high value for the ratio R_r to R_f. The output waveform for an exaggerated example of a negative series diode clipper where R_r and R_f are considered constant with $R_r = 9R1$, $R1 = 9R_f$ and the ratio of R_r to $R_f = 81$, is shown in Fig. 10a. The output waveform for the same circuit with an ideal diode is also shown.

The transfer characteristic for the circuit can be drawn to take into account the diode resistances. Consider diode resistance in the negative series diode clipper of Fig. 1 such that $R_r = 9R1$ and $R1 = 9R_f$. When the diode is conducting the input is transferred to the output but with a loss and, in this case, the ratio of e_{out} to $e_{in} = 0.9$. This is represented by a line with a slope of 0.9. For negative input signals, the diode is reverse biassed but R_r still transfers some of the input signal to the output and, in this example, the ratio of e_{out} to $e_{in} = 0.1$. The transfer characteristic for this section, therefore, has a slope of 0.1. The complete characteristic is shown in Fig. 10b. For comparison a transfer characteristic for the same circuit including an ideal diode is shown dotted.

As a matter of interest, when the transfer characteristic is determined for a clipping circuit including bias and a diode with resistance, the curve does not pass through the origin. The diode current is zero when the input voltage equals the bias voltage. Under this condition no potential difference occurs across any of the circuit components and the output voltage equals the input voltage. This means that at this point the characteristic coincides with the ideal characteristic as shown in Fig. 10c. For input levels that are transmitted to the output by the clipper, the diode resistance causes the transfer characteristic to have a slope less than unity and therefore the transfer characteristic cannot follow the ideal characteristic through the origin.

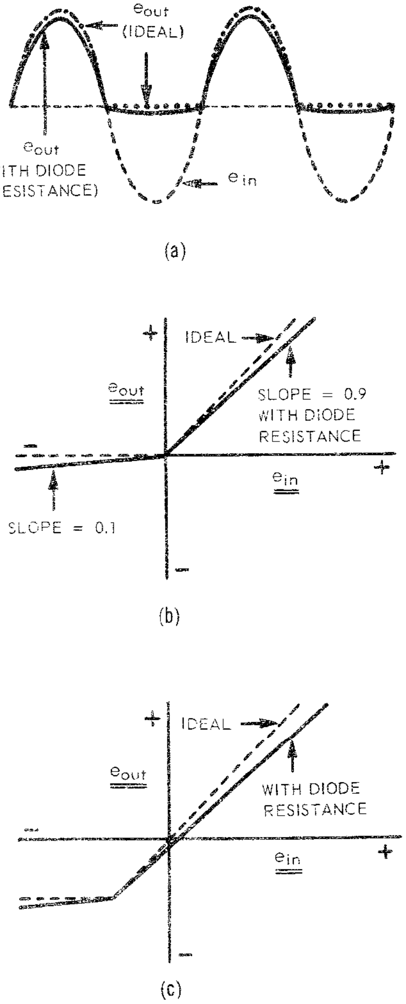


FIG. 10. EFFECT OF DIODE RESISTANCE.

For satisfactory operation of a shunt diode clipping circuit, the circuit resistances must have the same relationships as those for the series diode clipping circuit; that is, R_f must be much less than R1 and R1 much less than R_r. However, as the clipping in this case is caused by the diode conduction, diode forward resistance results in poor clipping, and diode reverse resistance results in attenuation of the transmitted section of the waveform. This is the reverse of the effect of the circuit values in the series diode clipping circuit. The waveforms and the transfer characteristics in Fig. 10 for a series diode clipper are also applicable to a shunt clipper, when the relationships of the components are $R_r = 9R1$ and $R1 = 9R_f$ as previously considered.

2.8 The current-voltage characteristic of a diode is curved, with the diode resistance decreasing as the diode voltage and current is increased. Therefore, increasing the signal amplitude decreases the diode resistance and improves the effectiveness of the clipping circuit. For this reason, clipping is best carried out at high signal levels.

The curved nature of diode characteristics produces curvatures in the transfer characteristics of clipping circuits which include practical diodes. Fig. 11 shows a typical characteristic for a germanium point contact diode.

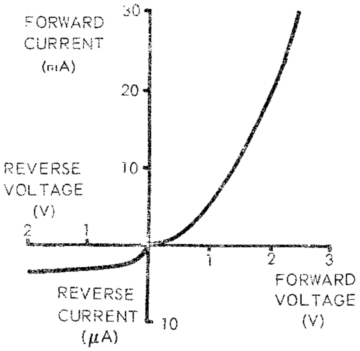
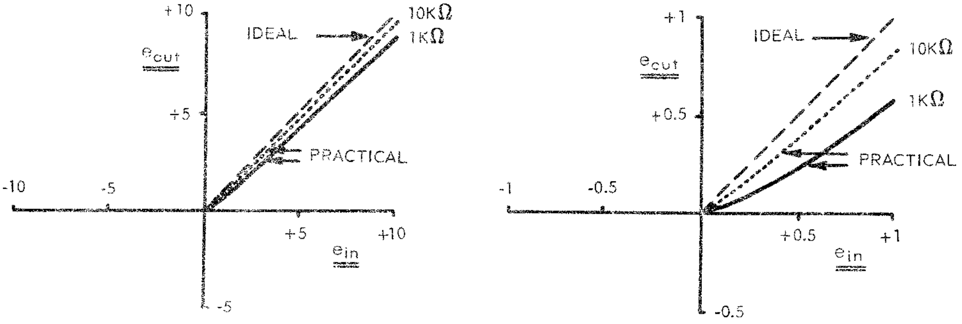


FIG. 11. DIODE CHARACTERISTIC.

The transfer characteristic for a circuit using this diode can be obtained by drawing "load lines" on the diode characteristic for various values of input voltage. Fig. 12a shows the transfer characteristic for a series diode clipping circuit including a diode with the characteristic of Fig. 11, and a shunt resistance of 1,000Ω. The diode reverse resistance is considered much greater than the circuit shunt resistance and is neglected. The amount that the characteristic deviates from the ideal characteristic has the same form as the section of the diode characteristic used. Notice that, in the series diode clipping circuit, the non-linearity of the diode characteristic introduces non-linearity distortion onto the transmitted section of the signal.

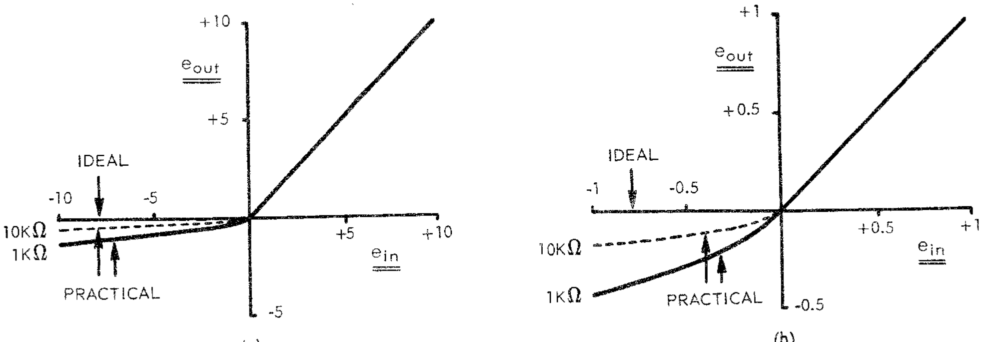
Increasing the shunt resistance of the clipping circuit should improve the transfer characteristic. However, the improvement is not as great as might be expected because, for a given input voltage, increasing the circuit resistance reduces the diode current and increases the diode resistance. This tends to offset the original improvement. The transfer characteristic for a 10kΩ shunt resistance is shown dotted in Fig. 12a. The small signal amplitude sections of the transfer characteristics in Fig. 12a are shown to a larger scale in Fig. 12b. These characteristics indicate the poor performance of the clipping circuit at low signal levels.



(a) (b)

FIG. 12. CHARACTERISTICS USING PRACTICAL DIODES.

The effect of the characteristic of practical diodes on shunt clippers is illustrated by the transfer characteristics in Fig. 13a. Again the curvature of the section of the diode characteristic used appears on the transfer characteristic, but in this case it determines the shape of the section of the waveform that should be clipped. With a diode reverse resistance large enough to be neglected no non-linearity distortion is introduced onto the section of the signal that is required to be transmitted to the output. As in the series clipping circuit, an increase in the circuit series resistance does not improve the clipping greatly, because of the increase in diode resistance with reduction in diode current. Fig. 13b shows the rather poor clipping achieved at low signal levels.



(a) (b)

FIG. 13. CHARACTERISTICS USING PRACTICAL DIODES.

Junction diodes have a lower forward resistance than point contact diodes, but because of their smaller junction capacitance, point contact types are usually preferred in high speed switching applications. Also, transfer characteristics for clippers including junction diodes and suitable values of circuit resistance, have effective clipping levels that are displaced from the clipping reference potential. This is because junction diode characteristics, when plotted on linear-linear paper, have a sharp change between their high resistance and low resistance regions, which does not occur when the diode voltage is zero.

The non-linearity of diodes at low voltages is used to advantage in the "click" suppressors of telephone circuits where two diodes are connected in opposite directions across the telephone receiver. They act as positive and negative shunt clippers, but because of diode non-linearity, clipping does not commence until the signal at the receiver exceeds the normal maximum signal level.

2.9 Effect of Source Impedances. Zero input signal source impedance has been considered in paras. 2.1 to 2.8. With a series diode clipping circuit (Fig. 14a), when the source resistance (R_S) becomes comparable with the resistance R1, it must be considered. This is likely to occur when R1 has a low value, in an attempt to reduce the effect of circuit capacitance. The resistors R1 and R_S in Fig. 14a form a voltage divider which attenuates the signal passed by the circuit during its transmission time.

A practical circuit which has source resistance similar to the circuit of Fig. 14a is shown in Fig. 14b. The valve and its anode load (R2) can be considered as a generator with a source resistance equal to the parallel resistance of R2 and the anode resistance (r_a) of the valve. The resistor R3 forms the shunt resistance of the clipping circuit, and the +200V supply is the clipping reference potential. Alternately the anode voltage can be found by considering the circuit as an amplifier in which the value of load resistance changes dependent on whether or not the diode is conducting. Calculations to find the output voltage using either approach produce the same results. The diode in Fig. 14b conducts whenever the anode voltage is greater than +200V and the signal is present at the output. For signal voltages that cause the anode voltage to fall below +200V, the diode becomes non-conducting and the signal is clipped.

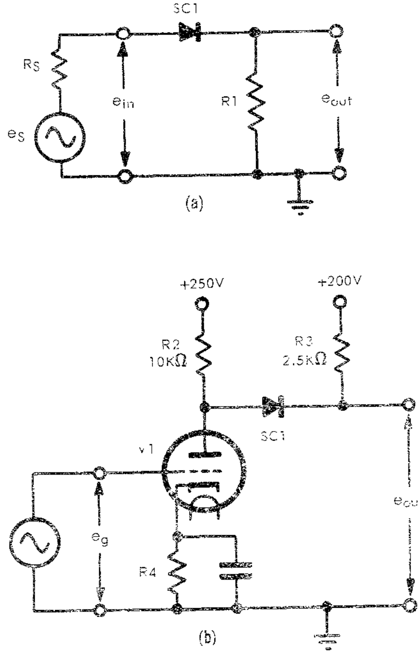


FIG. 14. EFFECT OF SOURCE RESISTANCE.

The source resistance is less important with shunt diode clipping circuits (Fig. 15a), since it is in series with R1 which should be as large as possible within the limitatations set by the diode reverse resistance and the circuit stray capacitance. In many cases, the source resistance is used as the only series resistance in the shunt diode clipping circuit. The circuit in Fig. 15b is in this category. Notice that diode clipping circuits are often an integral part of amplifier circuits, though this is not a necessity.

In Fig. 15b, for large values of anode current, giving anode voltages less than the reference voltage of +200V on the cathode of the diode, the diode is non-conducting and the circuit behaves as an ordinary amplifier. Additional negative voltage on the grid causes the anode current to decrease and the anode voltage to increase until, at an anode voltage of 200V, the diode commences to conduct and the anode potential is clamped, by the low resistance of the diode, to +200V. Further decrease in the anode current, therefore, has no effect on the anode voltage and the positive extreme of the output signal is clipped at +200V. The diode in this application is sometimes referred as a "catching diode" as it "catches" or stops the increasing anode voltage.

The anode voltage can be confined between two specific levels by including in the circuit both a positive and a negative clipper with appropriate reference potentials as in Fig. 15c. Here the output signal is confined between +150V and +200V. This technique is commonly used in high speed transistor switching circuits to prevent the transistor from being operated in the saturation region, and to accurately set the limits of the switching waveforms at the output, under varying external load conditions. It is also used to protect circuit elements, particularly transistors, from excess voltage.

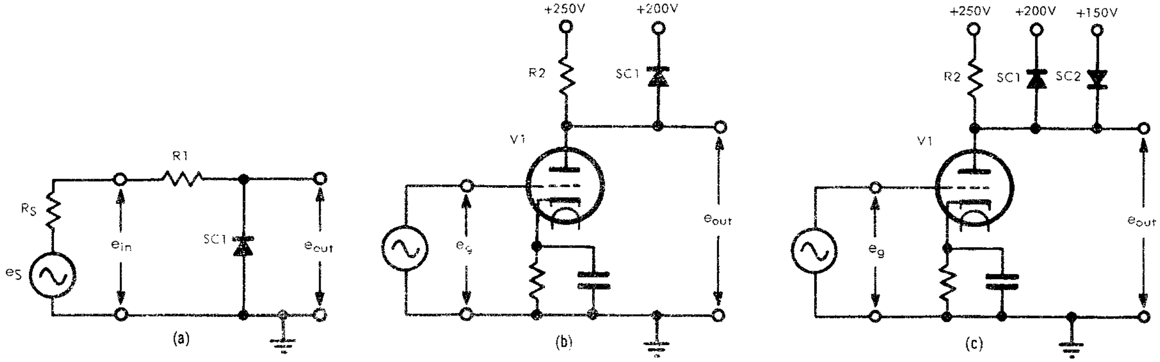


FIG. 15. EFFECT OF SOURCE RESISTANCE.

2.10 A further consideration for correct operation of clipping circuits is the impedance of the clipping reference potential. The reference voltage for a shunt diode clipping circuit must be obtained from a low impedance source as any source impedance has the same effect as increasing the forward resistance of the diode, which reduces the effectiveness of the circuit. The reference source for the series diode clipper is connected in series with the shunt resistor, and the internal impedance of the source is far less important. For the clipping of the A.C. component of waveforms, it is satisfactory that the reference potential be maintained by a charged capacitor with a value such that little change of charge occurs during the clipping time; that is the reactance of the capacitance is small compared with R1 for the series clipper and R_f for the shunt clipper, at the repetition frequency of the input waveform.

2.11 R-C Input Circuit with Clipping Circuits. For correct operation of the clipping circuit it is necessary for the input signal to be direct coupled from a source having a resistance that is low compared with the clipping circuit resistance. If an R-C coupling circuit is included in the input as in Figs. 16a and b, the circuit has a peak rectifier clamping effect on the signals present across R2. Accurate clamping of the peaks does not occur, however, because of the high resistance in series with the diodes. For the peak rectifier clamping action to be negligible, R1 must be much larger than R2.

Fig. 16c shows the waveforms applicable to the series and shunt diode clipping circuits of Figs. 16a and b. In each of these examples the discharge time constant of the coupling capacitor is twice the charge time constant, and the waveform across R2 has a negative area that is twice its positive area, because of peak rectifier clamping. Also a tilt dependent on the circuit time constant is introduced onto a rectangular input signal.

With no clamping action the coupling circuit would remove any D.C. component at the input and the waveform would be clipped at the average axis of the input signal. The circuits in Fig. 16, however, do not clip at this level, but clip at the zero axis of the waveform across R2. Note that the clipping level will not be changed when the input signal contains a D.C. component.

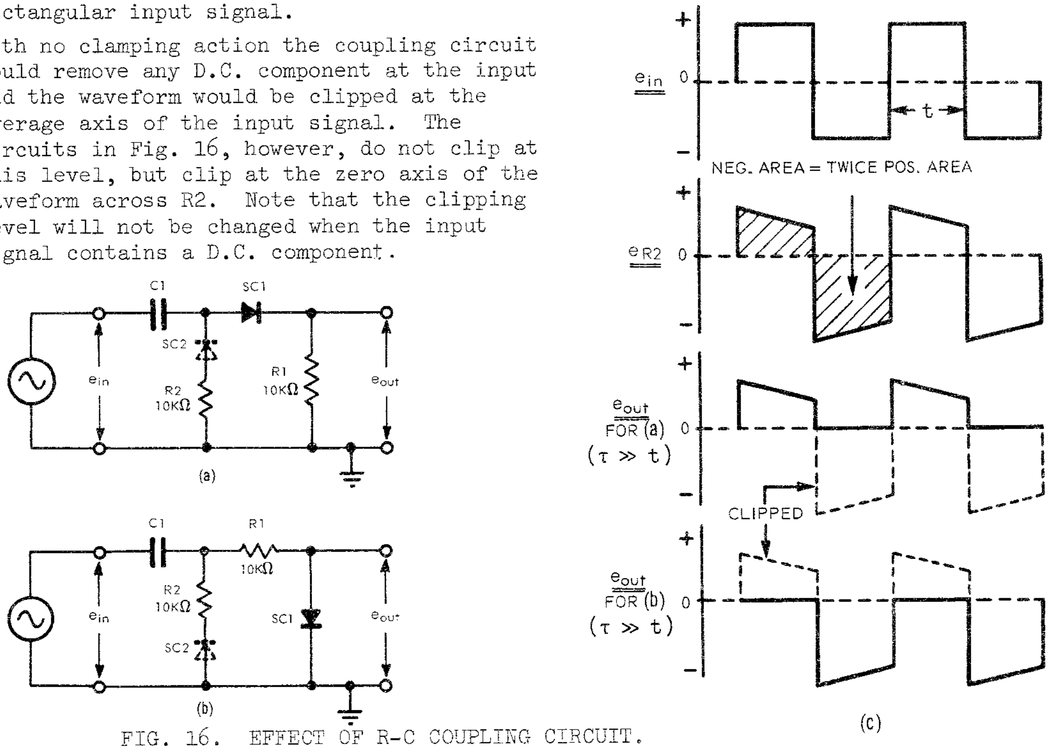


FIG. 16. EFFECT OF R-C COUPLING CIRCUIT.

The clamping action can be removed by making R1 equal to R2 and including a diode in series with R2 as shown dotted in Fig. 16. Both charge and discharge circuits of the capacitor then have the same time constant.

.12 When the R-C combination of either Figs. 16a and b has values so proportioned that the circuit is a differentiating circuit, and any change of charge on the capacitor is completed between transitions of an input rectangular waveform, no peak rectifier clamping occurs. With a square wave input to the differentiating circuit the output is a series of "spikes" with polarities corresponding to the directions of the transitions of the input as shown in Fig. 17.

Because the time constant of the circuit is changed when the clipping diode changes from conducting to non-conducting, the shapes of positive and negative pulses across R2 differ slightly. After a negative clipping stage (for example Fig. 16a) the negative "spikes" are removed and the output is a series of pulses coincident with only the positive transitions of the input waveform. A positive clipper associated with the differentiating circuit will produce output pulses coincident with the negative transitions of the input.

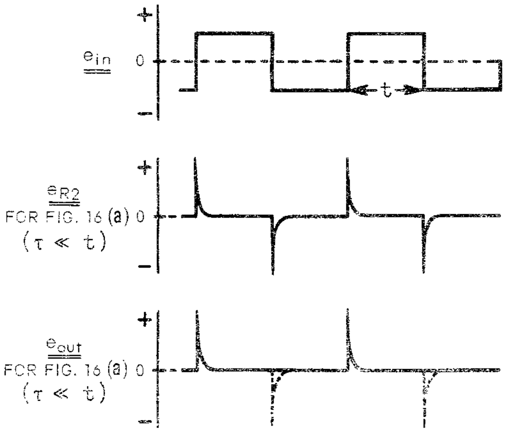


FIG. 17. EFFECT OF DIFFERENTIATING CIRCUIT.

2.13 Effect of Stray Capacitance. The stray capacitance in both series and shunt diode clipping circuit places a limit on the maximum values of shunt and series resistors respectively that are allowable while the rise time of the output waveform is maintained within prescribed limits.

Typical values of the capacitances across the diode and across the output of a series diode clipping circuit are as indicated in Fig. 18a. For simplicity the diode capacitance is considered to be fixed, although the junction capacitance of a practical semi-conductor diode depends on diode bias. Consider the circuit at a time when the input is -5V and the diode is clipping the input square wave of 10V p-p as in Fig. 18b. The diode is non-conducting and the output is zero. The output capacitance (C1) is therefore uncharged.

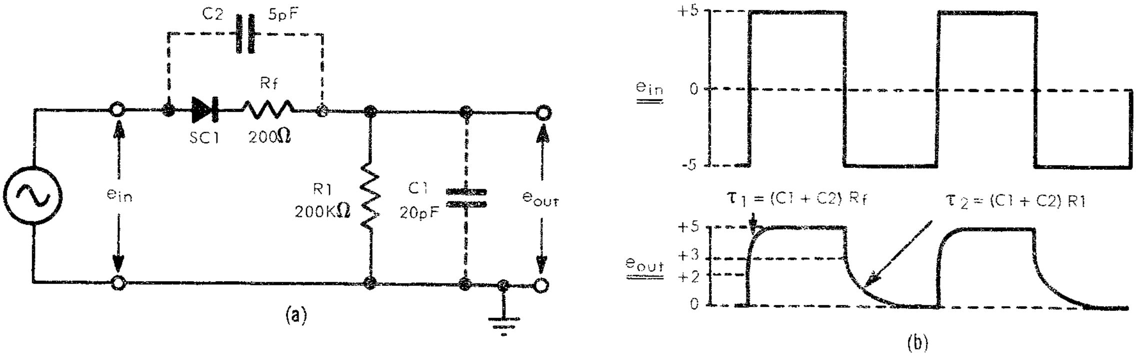


FIG. 18. EFFECT OF STRAY CAPACITANCE.

At the commencement of the positive half cycle of the input square wave the input voltage steps by 10V and this change is divided between the capacitors in inverse proportion to their values. The output voltage, therefore, steps by 0.2 of the input voltage step, from zero to +2V. It then rises exponentially to a value determined by the circuit resistances. In Fig. 18a, since R_f is negligible compared with R1, the output voltage rises to +5V. Using Thevenin's Theorem it can be derived that the charge circuit is equivalent to a circuit consisting of C1 and C2 in parallel, in series with R_f and R1 in parallel. But R1 can be neglected because of its high value compared with R_f and the circuit time constant is:-

$$\tau 1 = (C1 + C2)\, R_f$$

With the values chosen in Fig. 18a the equivalent circuit time constant is 0.005μS and can be neglected.

At the end of the positive half cycle of the square wave, however, the effect of the capacitance cannot be neglected. The 10V step in the negative direction again divides in inverse proportion to the circuit capacitance and the output steps by 2V to +3V. However the input has stepped to -5V and has caused the diode to become non-conducting. Therefore, the time constant for the change of charge of the capacitors is:-

$$\tau 2 = (C1 + C2)\, R1.$$

This is 5μS with the values as in Fig. 18a, giving a rise time of $2.2\ \tau 2 = 11$μS. To reduce the degradation caused by the circuit it is necessary to minimise the stray capacitance and to reduce R1 to give a suitable rise time for the output waveform. To achieve a rise time of 0.1μS, R1 in Fig. 18a has to be reduced to 4kΩ, and values of this order are common in practical circuits. However, this low value is becoming comparable with R_f and attenuation and non-linearity distortion of the transmitted section of the waveform may be introduced. This type of deterioration is partly offset since the low value for R1 increases the diode current and decreases the diode forward resistance.

2.14 In a shunt diode clipping circuit both the diode and the load capacitances are directly across the output and during the transmission time of the circuit these capacitances must be charged via the series resistor R1. The circuit therefore introduces loss at high frequencies and increases the rise time of transitions of the waveform when the diode is non-conducting.

Consider the circuit in Fig. 19a at a time when clipping is occurring. The circuit waveforms for a square wave input are illustrated in Fig. 19b. Since R1 is much greater than the diode forward resistance (R_f), the output is zero and no charge exists on the output capacitance. With the positive step at the commencement of the next half cycle, the output capacitance is charged via the series resistor and the output voltage rises exponentially with a time constant given by $\tau 1 = (C1 + C2)\, R1$. The value of $\tau 1$ for the components in Fig. 19a is 5μS.

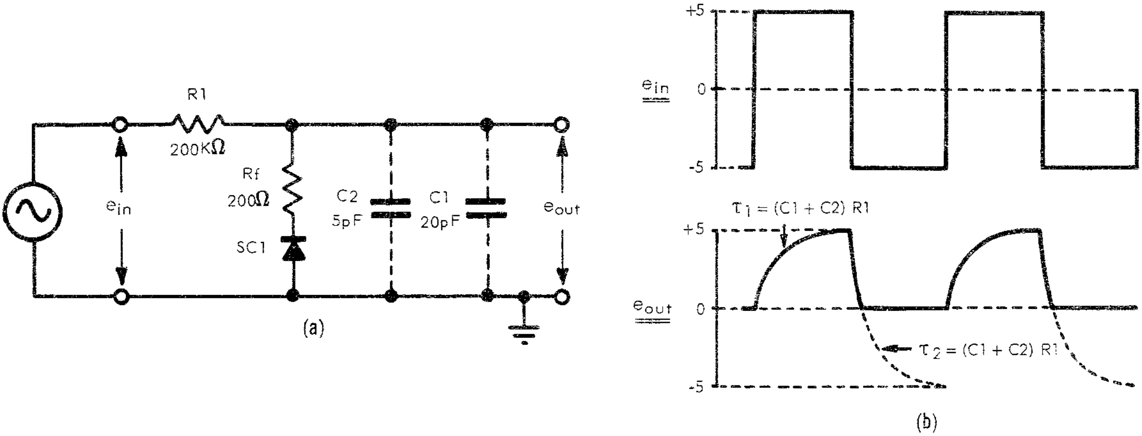


FIG. 19. EFFECT OF STRAY CAPACITANCE.

The next transition causes the input to fall to -5V, but the output capacitor still maintains its charge and the shunt diode is still maintained non-conducting. The output voltage changes exponentially towards -5V with a time constant equal to $\tau 2 = (C1 + C2)\, R1$ until the clipping level is reached. The diode then conducts and the output cannot change further. The negative transition is, therefore, the first section of an exponential curve. The rise times of both transitions of the output waveform of a shunt diode clipping circuit are improved by reducing the value of R1. When the diode has some forward resistance, and this is comparable with R1, incomplete clipping occurs.

Comparing the output waveforms of the shunt and series clipping circuits indicates that the series circuit has an advantage of a faster rise time for one of its transitions. However, when the diode resistance is significant, the incomplete clipping of the shunt circuit may be more acceptable than the non-linearity distortion introduced by the series circuit during the transmission time.

2.15 There is an additional effect which increases the rise times of waveforms from clipping circuits using semi-conductor diodes. The switching time of a diode from the conducting condition to the non-conducting condition is not instantaneous. A study of the physics of the operation of a diode shows that, when a diode is conducting, minority carriers are concentrated in the region of the diode junction. When a reverse bias is applied, a large reverse current flows until the minority carriers are removed from the junction region mainly by diffusion across the junction. The effect produces results which make the diode appear to have a shunt capacitance which is larger than its expected value. In point-contact diodes, which are usually used in high-speed pulse circuits, the effect is at a minimum.

2.16 Reducing the Effect of Stray Capacitance. Besides the improvement in the rise time obtained by reducing the values of the shunt and series resistances of series and shunt diode clipping circuits respectively, an improvement in the rise time of a clipped waveform can be achieved by using the circuit in Fig. 20a. The circuit produces clipping of the negative extremes of a waveform at a level set by the clipping reference potential associated with the shunt diode. The shunt resistor is returned to a large negative potential. An output capacitance of 25pF is included in the circuit, but in Fig. 20 diode capacitance is neglected and the clipping level is considered as zero. The circuit waveforms are shown in Fig. 20b.

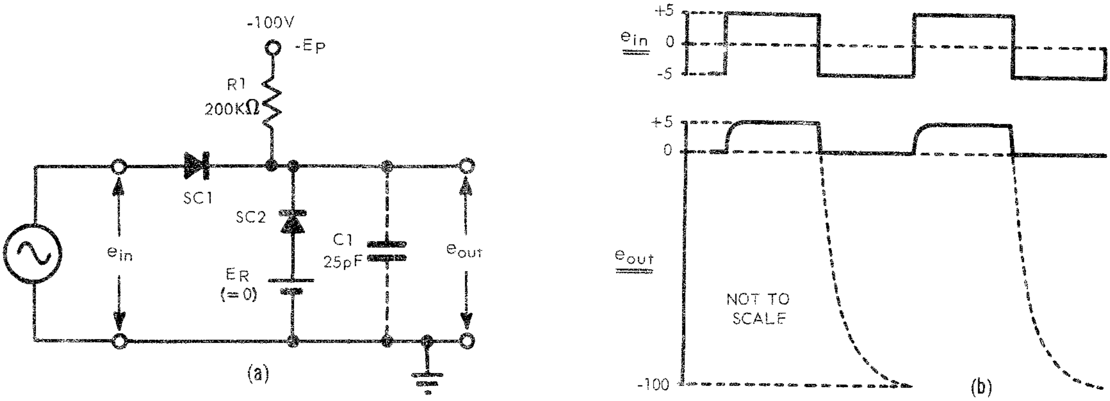


FIG. 20. EFFECT OF STRAY CAPACITANCE.

Consider the circuit during the clipping time. The output voltage and the charge on the output capacitance is zero. Following the positive transition of the input square wave, SC1 conducts and the output capacitance is charged in a very short time constant circuit to the positive peak of the input square wave. With the negative transition of the input signal, SC1 is reverse biassed, but the output capacitance maintains its charge and SC2 is held reverse biassed. The charge on C2 changes via R1, but, since the asymptote of the exponential charge curve is -100V, it takes only a fraction of the time constant of the circuit for the output voltage to reach zero voltage. At this time the diode SC2 commences to conduct and the output voltage cannot change further. SC2 is maintained conducting by the current through R1 and the output voltage is "clamped" at the clipping level. Negative input voltages causing SC1 to be non-conducting, produce clipping of input signals that are more negative than the clipping level. During clipping the series diode is non-conducting and the shunt diode is conducting.

The circuit is the optimum combination of series and shunt diode clipping circuits with both circuits clipping at the same level. The circuit can be arranged to clip input signals more positive than the clipping reference potential by reversing the polarity of the diodes and the asymptote supply (EP).

The rise time of the negative transition of the output waveform from the circuit of Fig. 20a is approximately 0.2µS compared with 11µS for the simple series diode clipping circuit, considering an output capacitance of 25pF and no diode capacitance. If diode capacitance had been considered in Fig. 20, an initial step preceding any exponential changes would have been introduced onto the output waveform.

2.17 Thermionic Diodes. The preceding circuits have included a semiconductor diode symbol. Thermionic diodes may also be used in clipping circuits. Their main advantage is their infinite reverse resistance. However, they have the disadvantages that they require a heater supply, and that capacitive coupling of the heater to the cathode may introduce hum, particularly when the cathode is not connected to earth.

Also, the anode current does not fall to zero until the anode is slightly negative relative to the cathode (up to approximately 1V depending on the circuit resistance). The latter is caused by contact potential and the initial electron velocity of emitted electrons, both of which vary with cathode temperature.
As semi-conductor diodes continue to improve in their characteristics, thermionic diodes continue to fade from practical circuits.

2.18 Zener Diode Clippers. Zener diodes have a sharply defined "knee" in their reverse (normally non-conducting) characteristic (Fig. 21) and, for higher reverse voltages than this "knee", the dynamic resistance of the diode is low. The forward characteristic of the zener diode is similar to that of a normal diode.

The reverse characteristic of a zener diode can provide clipping at a fixed level. The single diode circuit in Fig 22a causes very effective clipping for input signals more negative than the zener voltage (knee voltage), but, because of the forward characteristic of the diode, clipping also occurs when the input signal exceeds zero voltage. For this reason the circuit has application when clipping at two levels separated by the magnitude of the zener voltage is required.

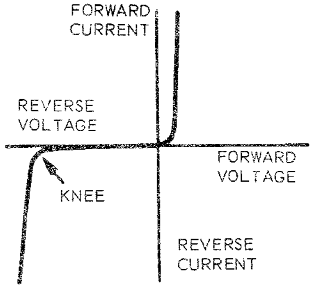


FIG. 21.
ZENER DIODE CHARACTERISTICS.

The transfer characteristic for the circuit is shown in Fig. 22c. The clipping produced by the forward characteristic is not as effective as that produced by the zener characteristic because of the higher dynamic resistance of the forward characteristic. The dynamic resistance is inversely proportional to the slope of the characteristic in Fig. 21.

Notice that the circuit is exactly the same as the shunt regulator circuit used in power supplies, in which case the input is a D.C. voltage more negative than the zener voltage, and the output is a regulated supply with a magnitude equal to the zener voltage.

Clipping of the input signal at two levels on either side of the zero axis is conveniently achieved with the circuit in Fig. 22b. When the input voltage is more negative than the zener voltage of SC1 this diode has a low dynamic resistance and SC2 is forward biassed. Jointly they form a low resistance path across the output, and because of the series resistance (R1), the input signal is clipped at approximately the zener voltage of SC1. When the input voltage is more positive than the zener voltage of SC2 the reverse occurs. SC2 has a low dynamic resistance because of the zener characteristic and SC1 is forward biassed. Therefore clipping again occurs. Between these two limits, one of the two diodes is reverse biassed below the zener voltage and is non-conducting, and the input is transferred directly to the output. The transfer characteristic of the circuit is illustrated in Fig. 22c. This circuit, with a large amplitude sine wave input, provides a simple means of obtaining an accurate approximately square wave reference voltage suitable for C.R.O. calibration. The high shunt capacitance of zener diodes limits their use to relatively low frequency circuits.

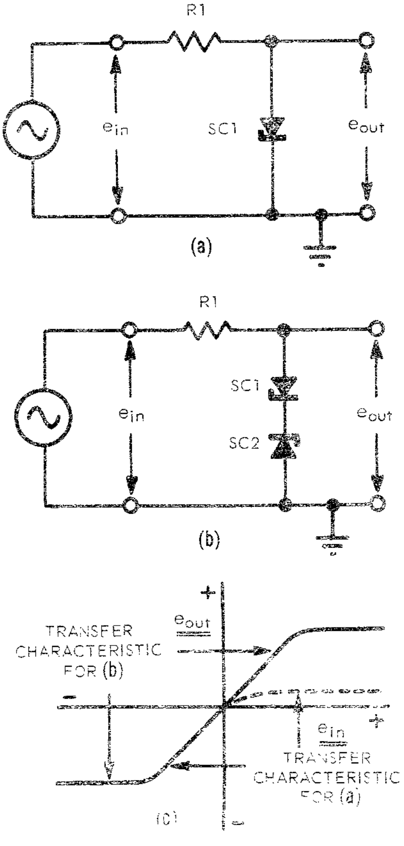


FIG. 22. ZENER DIODE CLIPPERS.

3. THERMIONIC VALVE CLIPPING CIRCUITS.

3.1 Grid Current Clipping. Multi-element thermionic valves can be arranged in a number of ways to produce clipping. The circuit in Fig. 23a is equivalent to a shunt diode clipper followed by a triode amplifier. When the grid is driven positive with respect to the cathode, grid current flows. If R1 is much greater than the grid-cathode resistance, the grid potential cannot vary far from the cathode potential. A typical dynamic grid characteristic for a triode is shown in Fig. 23b. Without the grid resistor the anode current would continue to increase as the input to the grid was made positive. The grid resistor, however, causes an almost constant anode current for positive input signals. A deviation from this condition is caused by resistance of the conducting grid-cathode diode similar to that considered for the shunt diode clipper in paras. 2.7 and 2.8. An input signal which causes grid current is clipped in the grid circuit and results in a clipped anode current waveform. The output voltage (Fig. 23c) is an amplified and inverted replica of the input, but with its negative extreme clipped at a voltage level dependent on the anode supply voltage, the anode load resistance and the anode current for zero grid-cathode voltage.

The transfer characteristic for the circuit can be found from the dynamic grid characteristic when the anode load resistance and the high tension voltage are specified. The transfer characteristic has the same shape as the grid characteristic but, as is normal for common cathode amplifiers, the characteristic appears inverted. The output decreases as the grid voltage goes positive and the slope of the transmission section of the characteristic is negative. The transfer characteristic is shown in Fig. 23d. The "break" in the right hand section of the characteristic at point P is caused by grid current clipping. The slope of the characteristic indicates the gain of the circuit which is normally greater than one for levels that are not clipped. The circuit gain for the transmission condition is calculated in the same way as it is for a normal amplifier.

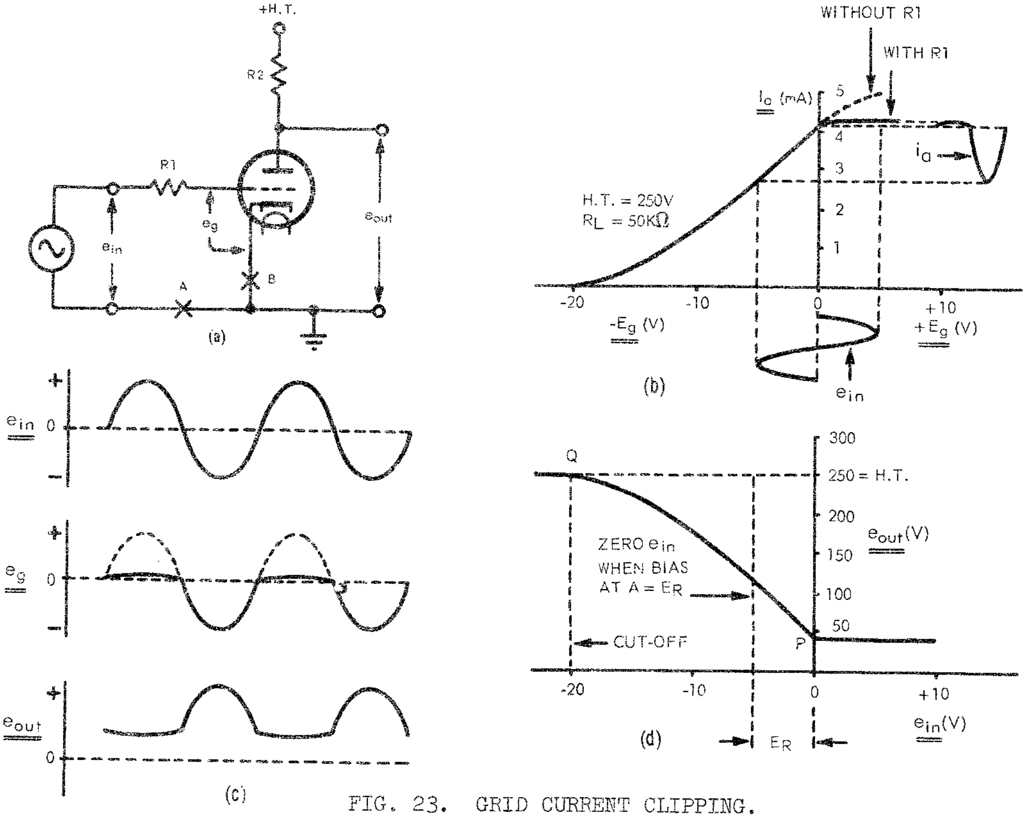


FIG. 23. GRID CURRENT CLIPPING.

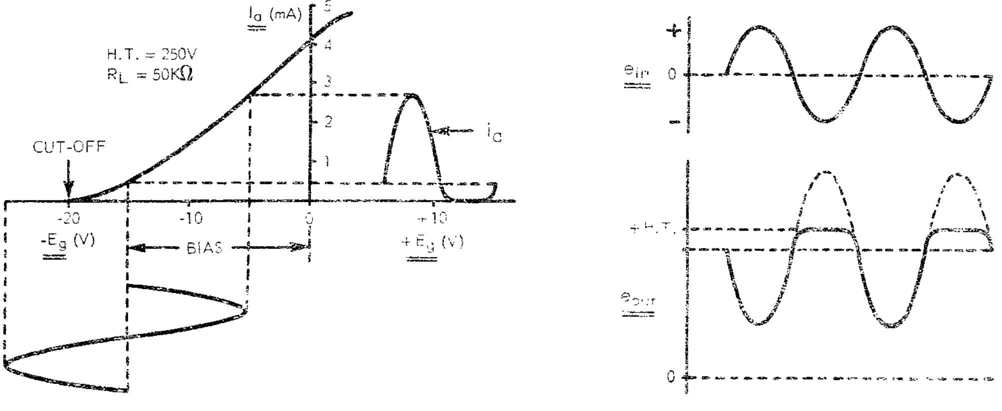
The circuit can provide clipping at other input signal levels if a bias is included. Bias inserted at point A in Fig. 23a does not alter the level for the clipped section of the output waveform. The clipping point is changed by shifting the input waveform relative to the fixed clipping level at zero grid-cathode voltage. On the transfer characteristic this is equivalent to shifting the designations for e_{in} horizontally by an amount equal to the bias voltage as shown in Fig. 23d. A convenient place to provide bias in a practical circuit is at point B in Fig. 23a. Bias at this point changes the effective high tension supply to the valve.

A disadvantage of the grid current clipper is that, as a result of Miller effect when the valve is amplifying, the anode-grid capacitance multiplied by approximately the amplification of the stage, appears across the grid-cathode circuit. The grid-cathode capacitance and the series resistance, limits the rise time of rectangular waves at the grid in the same manner as a shunt diode clipper. The effect is greater in this case because of the larger effective shunt capacitance. An improvement is obtained with pentodes since pentodes have a very small anode-grid capacitance.

3.2 Cut-off Clipping. In the amplifier stage of Fig. 23a, the anode current ceases when, because of signal amplitude and bias, the grid-cathode voltage is made more negative than the cut-off potential. The input signal and the bias shown in relation to the grid characteristic in Fig. 24a causes anode current cut-off for a section of each cycle. With no anode current, and therfore no voltage drop across the anode load resistor, the anode voltage equals the high tension voltage. The section of the input signal that extends beyond the cut-off potential of the valve characteristic is clipped. The output signal (Fig. 24b) is inverted and the clipped level is established at the high tension potential. The transfer characteristic for cut-off clipping corresponds to the left hand section of the characteristic in Fig. 23d where the output voltage equals the high tension voltage when clipping occurs.

The resistor R1 in Fig. 23a is not necessary for cut-off clipping, but it is often included to limit the possible grid current should the grid go positive. Capacitance in the grid circuit is less of a problem with cut-off clipping than with grid current clipping, since the series resistance in the grid circuit can be kept small. Also, when the valve is cut-off the circuit has no gain and no Miller effect capacitance is reflected into the grid circuit.

Cut-off clipping is commonly used, particularly for non-exacting applications, but the clipping level is not very stable. It is dependent on anode voltage, screen voltage for pentodes, and cathode temperature (heater voltage). Also, because of curvature of the valve characteristics, the "break" between the transmission and the clipping sections of the transfer characteristic is not very sharp. This is apparent in Fig. 23d in the vicinity of point Q. Sharp cut-off valves with high amplification factors, particularly pentodes with fixed screen voltages give the most definite division between the transmission and the clipping conditions.



(a)

(b)

FIG. 24. CUT-OFF CLIPPING.

3.3 Basic Sync. Separator. Clipping at two levels is possible with thermionic valves using both grid current and cut-off clipping. The transfer characteristic in Fig. 23d indicates this. The voltage between the two clipping levels, referred to the input signal, is fixed and equal to the magnitude of the cut-off voltage. A more usual combination than this for clipping between two levels combines peak rectifier clamping and cut-off clipping.

The circuit of Fig. 25a illustrates a typical example of a clipping circuit combining peak rectifier clamping and cut-off clipping. The positive extreme of the signal is clamped to the cathode potential by peak rectifier action (as with grid leak biassing) and the signal is of sufficient amplitude to make the required clipping level coincide with the cut-off potential.

An application for this type of clipping is the removal of amplitude variations of rectangular pulses. In television practice the circuit is used for sync. separation. The composite video signal with sync. pulses positive going (Fig. 25b) is applied to the grid circuit and the tips of the sync. pulses are clamped to the cathode potential. The tips of the sync. pulses produce grid current and a charge is accumulated on the series capacitor (C1). This charge is maintained between sync. pulses, because of the long time constant of the discharge circuit and it inserts a D.C. component which maintains the sync. tips at approximately the cathode potential.

The signal amplitude and the cut-off potential are arranged so that blanking level is more negative than the cut-off potential and all of the picture information causes anode current cut-off. The output signal at the anode is inverted and contains the sync. information only. It has a constant amplitude varying from the high tension potential to the anode potential for zero grid voltage.

Details of peak rectifier clamping circuits are discussed in the course paper "D.C. Restoration and Clamping". From this discussion we see that the time constant of the peak rectifier clamp circuit must be long so that little change of charge occurs between clamping times, but short enough so that clamping is maintained in the presence of changes in the D.C. component of the input signal. The time constant required is related to the low frequency characteristics of the preceding amplifier stages since any tilt introduced by these stages will affect the extent of the variation of the sync. level to be clamped.

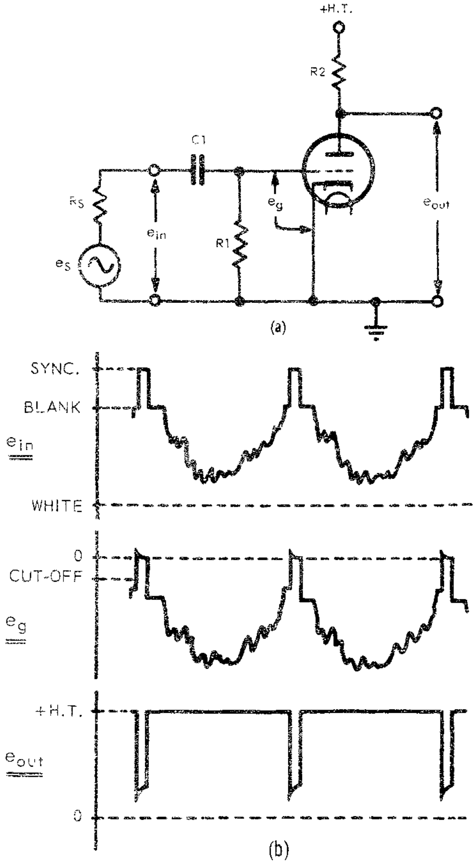


FIG. 25. BASIC SYNC. SEPARATOR.

The design of the peak rectifier clamp circuit for sync. separator applications is far less exacting than that for restoration of the D.C. component to establish reference levels of a composite video signal. The circuit is commonly designed so that the signal at the grid is considerably clipped because of grid current through a high source resistance as is considered in the course paper "D.C. Restoration and Clamping". When this occurs the grid can only become slightly positive with respect to the cathode and the negative peaks of the pulses at the output are always at the same low anode voltage level as determined by the high tension potential, the anode load resistance and the anode current for zero grid-cathode voltage. The circuit, then, combines cut-off clipping, grid current clipping and D.C. restoration by peak rectifier clamping.

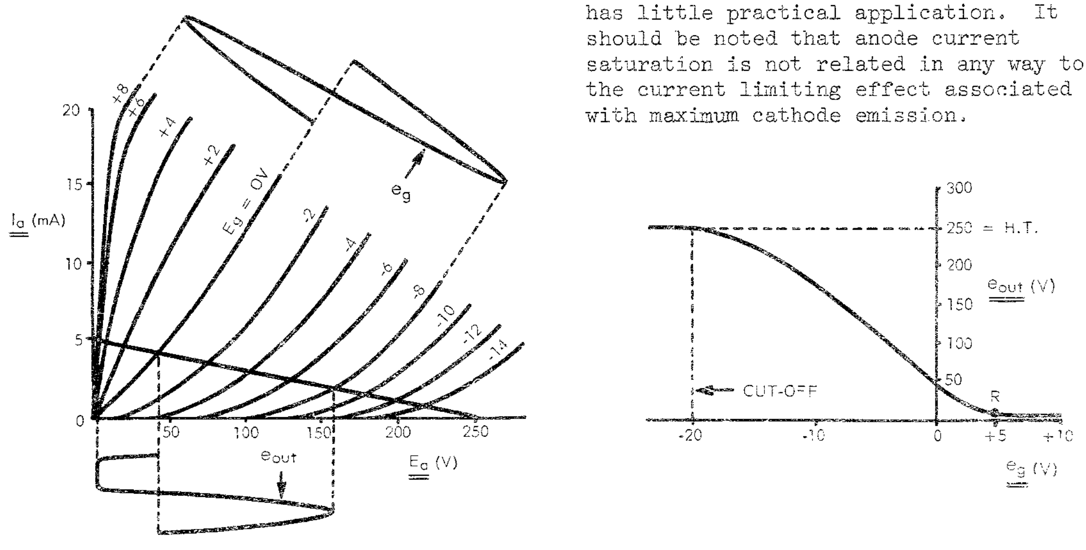
It is also common in sync. separator circuits for considerable tilt to exist on the grid waveform between line times. This makes the circuit fast acting to prevent the loss of clamping in the presence of rapid changes of input signal levels. The shape of the output signal is not changed as long as a large signal amplitude always maintains the blanking level beyond cut-off.

Valves used as sync. separators are selected so that they have a short grid base; that is, the range of grid voltages between zero volts and cut-off is small. This is often obtained by reducing the anode voltage, and also the screen voltage for pentodes. Sync. separators sometimes have anode and screen voltages as low as 20V. Under these conditions the cut-off voltage is typically -2V and large amplitude video signal inputs are not required.

This simple type of sync. separator circuit is only adequate if no noise, particularly no pulse noise such as petrol engine ignition interference, is present. For signals containing noise components some gating technique is required to reduce the possibility of generation of false sync. pulses. Sync. separators designed for noise immunity are not considered at this stage.

3.4 Saturation Clipping. A third type of clipping is possible using thermionic valves and this makes use of the anode current saturation characteristic of valves at low anode voltages. In this region the anode current is determined mainly by the resistance in the anode circuit and grid voltage has very little effect.

The circuit for a saturation clipper is the same as the grid current clipper in Fig. 23a but without the series grid resistor. The operating conditions of the circuit can be examined by superimposing a load line on the anode characteristic. The anode characteristic of a triode is illustrated in Fig. 26a. Curves for positive values of grid voltage are included. The load line for an anode supply voltage of 250V and an anode load resistance of 50kΩ is straight and passes through $E_a = 250V$, $I_a = 0$ and $E_a = 0$, $I_a = 5mA$. The output waveform at the anode of the valve can be found by projecting the grid voltage via the load line to find the anode voltage. This is illustrated in Fig. 26a. By similar projection, the transfer characteristic in Fig. 26b is constructed. The characteristic shows output voltage versus grid voltage. The input voltage will be displaced from the grid voltage by an amount equal to the bias included in the grid circuit. The characteristic has a "break" at point R corresponding to a grid voltage of approximately +5V but the position of the break is not very well defined. Because of this and because the clipping occurs in the positive grid voltage region where considerable grid current would be produced, saturation clipping using triodes has little practical application. It should be noted that anode current saturation is not related in any way to the current limiting effect associated with maximum cathode emission.

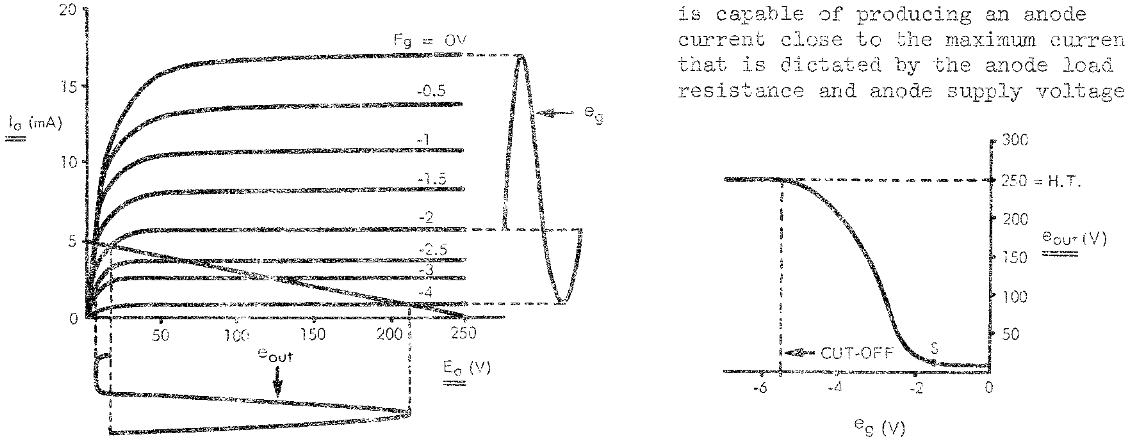


(a) (b)

FIG. 26. TRIODE SATURATION CLIPPING.

3.5 Pentodes are more useful than triodes as saturation clippers because, with suitable values of anode load resistance, the break in the dynamic characteristic can be arranged to occur while the grid is still negative. The anode characteristic of a pentode is shown in Fig. 27a and superimposed is a load line for an anode load of 50kΩ. The transfer characteristic derived from this information is shown in Fig. 27b. This shows a "break" at approximately -1.5V which will provide effective clipping. The "break" is usually sharper than that provided by saturation clipping with a triode. When saturation clipping occurs at negative grid voltages, it overrides any grid current clipping. With low values of load resistance the slope of the load line can cut the zero grid voltage curve at higher anode voltages than the knee in the characteristic. The saturation region is then outside the negative grid voltage region.

The output voltage at the anode of the valve, derived by projection of the grid voltage via the load line, is shown in Fig. 27a. During saturation clipping the output voltage is very low, typically less than 10V. The valve in this condition is sometimes referred to as being "bottomed". This is because the anode voltage in this condition is the minimum that is capable of producing an anode current close to the maximum current that is dictated by the anode load resistance and anode supply voltage.



(a) (b)

FIG 27. PENTODE SATURATION CLIPPING.

3.6 Overdriven Amplifier Squarer. It is commonly required to produce approximately square waves from a sine wave input. One convenient means of doing this makes use of two methods of clipping possible with thermionic valves to clip both positive and negative peaks approximately symmetrically about the axis of the sine wave. Saturation and cut-off clipping are normally combined for this purpose, but grid current and cut-off clipping is also satisfactory. The combination of peak rectifier clamping at the grid and cut-off clipping is not usually suitable for symmetrical clipping. If the input signal is to be capacitively coupled into the circuit, a high value of resistance could be included in series with the input to prevent effective clamping. Alternatively, a diode could be included in series with R2 (as shown dotted in Fig. 28) with R1 equal to R2, so that the time constants for charge and discharge of C1 are the same.

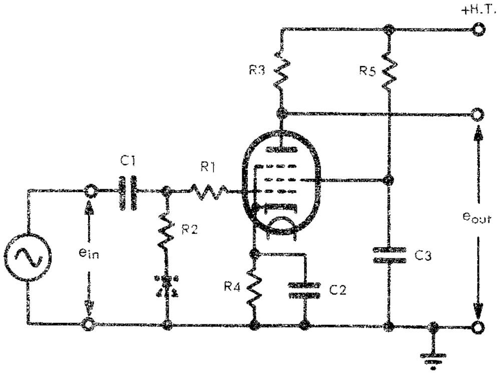


FIG. 28.
OVERDRIVEN AMPLIFIER SQUARER.

A typical circuit for an overdriven amplifier for producing "squaring" is illustrated in Fig. 28. Pentodes are usually used when saturation clipping is required and low anode and screen voltages give a short grid base if this is required. The transfer characteristic for the circuit is as shown in Fig. 27b. In this case, however, both "breaks" in the characteristic are used. To provide symmetrical clipping the valve is biassed so that the axis of the input signal is midway between the signal levels for cut-off and saturation clipping. The peak-to-peak amplitude of the input signal must be large, relative to the voltage difference between the two clipping levels, for square waves with fast rise times to be produced. As discussed in para. 2.5 the rise time of the output square wave is inversely proportional to frequency and approximately inversely proportional to amplitude.

3.7 Cathode Coupled Squaring Amplifier. The three types of clipping using multi-element valves are possible in any configuration; that is, common cathode, common (grounded) grid and common anode (cathode follower). The preceding paragraphs have discussed the popular common cathode circuit. An example of a circuit which combines a common anode stage and a common grid stage to give cut-off clipping in each stage is shown in Fig. 29. The circuit is a cathode coupled amplifier and is often called a difference amplifier or a "long tailed pair". When driven with input signals of sufficient amplitude the circuit provides clipping of the input signal at two levels.

Consider that the circuit in Fig. 29 has no input. The operating conditions of the circuit are determined largely by the common cathode resistance (R_K) through which both valve currents flow. The voltage across R_K provides the bias for both valves. A more detailed analysis to indicate a method of determining the operating conditions of this and similar circuits is included in Section 5. For best performance, the cathode resistor must have a relatively large value ($R_K >> \frac{ra}{\mu + 1}$) and is typically 10kΩ or greater. The valve currents cause considerable voltage drop across such a resistance. Suitable bias for the valves is provided in Fig. 29 by returning the grids to earth and the cathode resistor to a negative high tension supply. Alternatively the bias can be derived from a voltage divider across the +H.T. supply with the cathode resistor returned to earth potential.

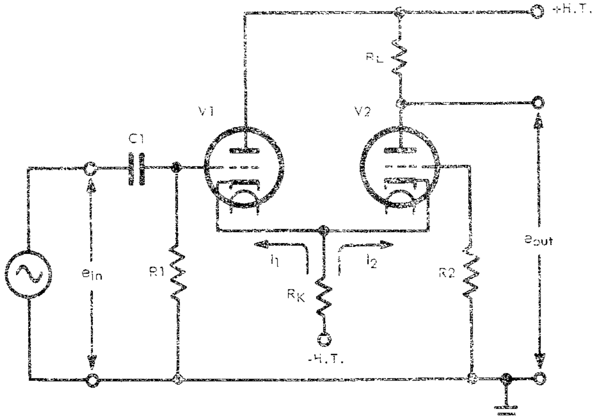


FIG. 29. CATHODE COUPLED CLIPPER.

When a signal input causes the grid of V1 to go negative, I1 decreases. This reduces the cathode voltage and causes an increase in I2 which tends to offset the decrease in total cathode current caused by the input signal. It can be proved that, when R_K is very large, the cathode voltage varies by an amount equal to half the input voltage variation. To provide cut-off clipping in both valves, the circuit is designed so that, under no signal conditions, the valves are closer to cut-off than to either grid current or anode saturation. Because of this design, when the grid of V1 has gone negative by an amount sufficient to cut-off V1, the grid-cathode voltage of V2 is still negative. However, a further negative change on V1 grid causes no further alteration of I2 which is at a maximum.

When the voltage at the grid of V1 changes in a positive direction, I1 increases, and increases the voltages at the valve cathodes. This increase reduces I2, and, as before, the change in total cathode current is partly offset. Because of the initial bias selected, before the input has increased sufficiently for the grid of V1 to become positive with respect to its cathode, V2 is cut-off by the voltage introduced at its cathode and I2 is zero. Further increase in input voltage increases the cathode voltage, but since V2 is cut-off this valve no longer influences the operating conditions of V1. The cathode voltage of V1 tends to follow its grid voltage.

The output voltage at the anode of V2 is dependent on I2. When V2 is cut-off the output voltage equals the high tension voltage. When V2 is fully conducting with V1 cut-off, the output falls to its minimum value. The input signal is clipped at two levels by the cut-off characteristics of the two valves. The transfer characteristic of the circuit is illustrated in Fig. 30. The circuit voltages and currents are considered in more detail in Section 5. Because the circuit is not balanced, since V1 has no resistance in its anode circuit, the output signal is not clipped symmetrically on either side of the zero axis. An anode load is included for V1 in some cases to provide circuit symmetry. Assymmetry in clipping is also introduced by the change in the mutual conductance of valves throughout their operating range. Compensation to produce symmetrical clipping can be provided by returning one grid to a small adjustable voltage supply.

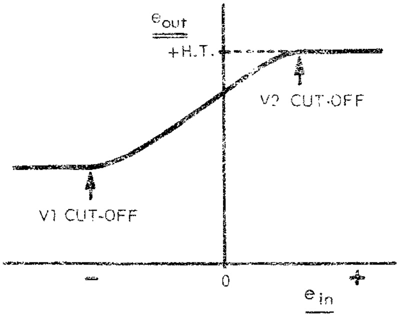


FIG. 30. TRANSFER CHARACTERISTIC.

The cathode coupled circuit is very useful for producing a square wave from a sine wave input and also for decreasing the rise times of a rectangular wave input. The peak-to-peak amplitude of the input signal must be much greater than the difference between the clipping levels at the input.

In the example of Fig. 29 the input signal is capacitively coupled to the cathode coupled clipper. If the signal produces grid current, peak rectifier clamping occurs and symmetrical clipping will be upset. Peak rectifier clamping can be reduced as considered in para. 3.6.

3.8 Effect of Anode Circuit Capacitance. All of the clipping circuits considered in this section are affected by capacitance at the circuit output. This capacitance is across the anode load resistor. The effect of the capacitance is the same as its effect in video amplifiers; that is, the higher frequency output signals are attenuated and the rise times of such signals are increased. An improvement, at the expense of loss of gain, is obtained by reducing the value of the load resistor. Compensation in the form of "peaking" inductances, as is included in video amplifiers, can also be used to both improve the amplitude-frequency and phase-frequency characteristics. Since the details of the compensation in the anode circuit of clippers corresponds to that for video amplifiers, it is not examined at this stage.

4. TRANSISTOR CLIPPING CIRCUITS.

4.1 Effect of Series Base Resistance. Clipping circuits using transistors are allied to circuits using thermionic valves in many respects. However, in some cases they are quite different. An example of their difference occurs in a transistor circuit with a configuration similar to that for a valve grid current clipper. Such a circuit is shown in Fig. 31. The series resistor (R_B) in the base circuit has a high value compared with the base-emitter resistance. Because of this the base current is practically independent of the base-emitter characteristic and is approximately proportional to the input voltage.

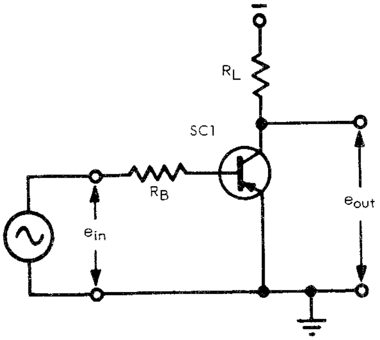


FIG. 31. TRANSISTOR AMPLIFIER.

The common emitter current gain of a transistor is almost constant throughout the operating range. This is indicated in Fig. 32 by the almost constant slope of the current transfer characteristic for a particular collector voltage. Where a load resistor (R_L) is included in the collector circuit, the collector-emitter voltage varies as the collector current varies, an increase in collector current reducing the collector voltage. In an approximate examination, the collector (output) characteristic of the transitor (Fig. 32) shows that for collector voltages above about 400mV, the collector current (I_C) is affected only slightly by the collector voltage. The output voltage at the collector, therefore, is approximately equal to the product of the change in collector current and the load resistance (when R_L << the A.C. resistance of the collector-emitter circuit) but is reversed in phase compared with the voltage at the input.

Since output voltage is proportional to collector current, collector current to base current, and base current to input voltage, the output voltage is proportional to the input voltage. The circuit is, therefore, linear and no clipping occurs because of base current. This circuit does not produce clipping because the transistor is basically a current controlled device, and because the input circuit gives current approximately proportional to input voltage.

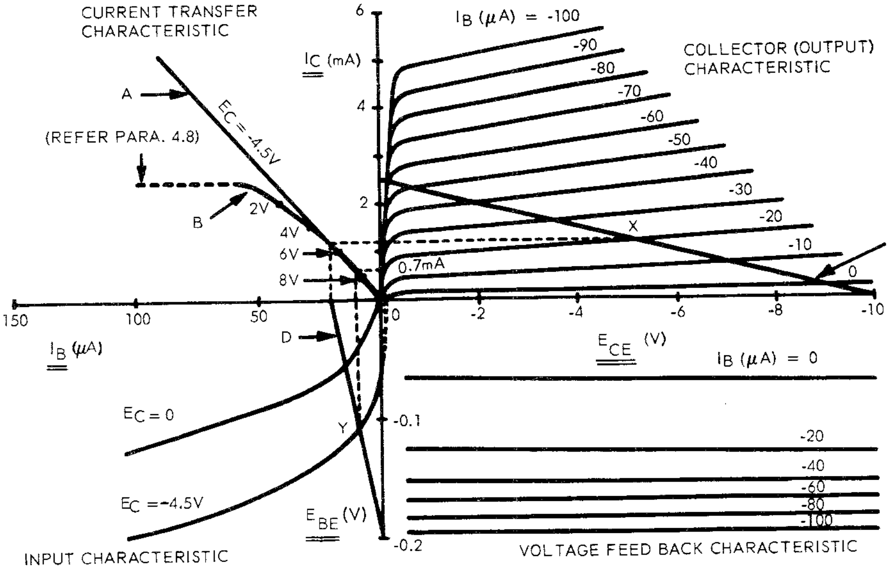


FIG. 32. TRANSISTOR CHARACTERISTICS.

4.2 Transistor Characteristics. A more detailed graphical analysis of a transistor circuit operating in its "linear" region indicates that the collector load resistor does have an effect on the linearity of a typical circuit, but not to the extent that a sharp break in produced in the characteristic that will cause clipping. Consider a transistor, with a collector characteristic as in Fig. 32, in the circuit of Fig. 31. A collector supply voltage of 10V and a load resistance of 4kΩ gives the load line indicated (line C). The transistor voltages and currents for these operating conditions must be at some point on the load line.

A dynamic current transfer characteristic can be plotted using this information. As an example, point X representing a base current of 20μA is projected horizontally until it intersects the 20μA base current ordinant in the base current-collector current quadrant. Other points on the load line are transferred in a similar manner. Joining the points obtained gives the dynamic characteristic (Curve B). For reference the collector voltages have been included at several points on the characteristic. Note that the characteristic is curved and indicates that the small signal current gain of the transistor amplifier is reduced slightly when the collector voltage is reduced by voltage drop across the load resistance. Smaller values of collector load resistance cause less departure of the dynamic characteristic from the practically linear static characteristic.

When the input to the base circuit is supplied from a current source with current proportional to input voltage, the characteristic relating input voltage to collector current has the same shape as the current transfer characteristic. To examine the effect of the input voltage being supplied via a finite resistance in series with the base circuit of the transistor, the dynamic input characteristic must be known. This characteristic can be derived from information about the collector voltage and base current at points along the load line on the collector characteristic and from information obtained from the voltage feedback characteristic. However, it is usually found that the static input characteristic varies very little with variation of collector voltage, except at very low collector voltages. Therefore the dynamic input characteristic is almost the same as a typical static characteristic.

Assuming that the dynamic input characteristic for the transistor circuit is the same as the static characteristic for a collector voltage of 4.5V as in Fig. 32, the base current for a given input voltage is found by constructing a "load line" on the characteristic corresponding to the input voltage and the series base resistance. When the input voltage is 0.2V and the series base resistance is 10kΩ, the required load line is line D in Fig. 32. This intersects the input characteristic at point Y and gives a base current of approximately 9.5μA. Projecting the base current via the dynamic current transfer characteristic the collector current is obtained and is approximately 0.7mA. By assuming other input voltages, other points on the input voltage-collector current characteristic can be determined. Fig. 33 shows the results obtained with series base resistances of zero, 5kΩ, 10kΩ, and 20kΩ.

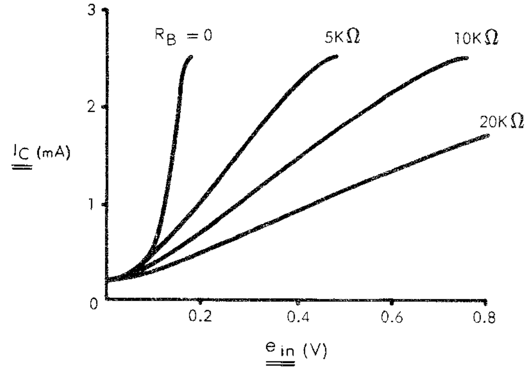


FIG. 33. EFFECT OF SERIES BASE RESISTANCE.

Notice that with zero base resistance the characteristic is very non-linear with an abrupt knee at approximately 70mV. This knee straightens as the series base resistance is increased, indicating that the input voltage must be supplied via a high value of resistance to obtain linear operation over a large signal range. The effect of the curvature of the dynamic current transfer characteristic is evident in the input voltage-collector current characteristic (Fig. 33).

4.3 Cut-off Clipping. In the circuit of Fig. 31, when the base current is zero, the only collector current is a very small "leakage" current caused by minority carriers.

The input current and output voltage waveforms for the circuit in Fig. 31 are shown relative to the collector characteristic in Fig. 34. When the base-emitter junction is forward biassed the circuit is an amplifier and the input signals appear amplified and inverted at the output. The voltages corresponding to the input currents are determined by projection via the load line.

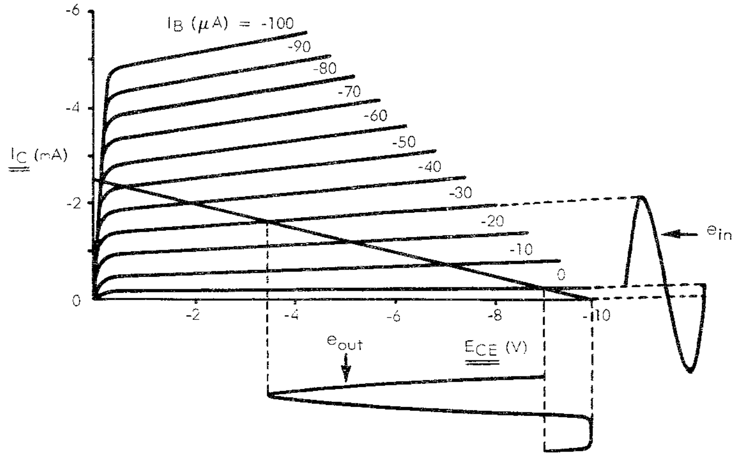


FIG. 34. CUT-OFF CLIPPING.

When the input current is zero, the output voltage is almost equal to the collector supply voltage, the deviation from this voltage being because of the leakage current. The leakage current in this case is that obtained in the common emitter connection. This is the base-collector leakage current amplified by the transistor action as the current flows across the base-emitter junction. The common emitter leakage current is significant for germanium transistors but negligible for silicon transistors.

When a reverse voltage is applied to the base-emitter junction, the base-collector leakage current is prevented from crossing the base-emitter junction, and no amplification of this leakage current occurs. The collector current, then reduces to a low value equal to the leakage current for the common base connection. Input signals that reverse bias the input, therefore, almost cut-off the collector current making the collector voltage practically equal to the collector supply voltage. The input signal is clipped at approximately the zero axis and the clipped level at the output is established at the collector supply voltage.

A p-n-p transistor is cut-off when the base is more positive than the emitter and negative base-emitter voltages will cut-off an n-p-n transistor. The clipping produced by the cut-off region is not particularly sharp. This is indicated by the curvature near zero input voltage in the characteristics in Fig. 33 relating input voltage and collector current.

4.4 The circuit in Fig. 31 is not very suitable in practice since it does not include any circuitry to improve its thermal stability. Further the base resistance (R_B) is often not present as a separate identity, but is commonly the output resistance of the preceding stage. Also a means of varying the clipping level is often required.

A more useful circuit is shown in Fig. 35 where the clipping stage is direct coupled to the preceding stage. The series base resistance for improving linearity is the output resistance of the first stage. The emitter resistance provides D.C. negative feedback to achieve satisfactory thermal stability. This resistor can be bypassed to prevent loss of gain when the A.C. component of the input signal is to be clipped. Variation of the clipping level is arranged by changing the bias on the clipping stage by altering R2 or the amplitude or polarity of the bias supply.

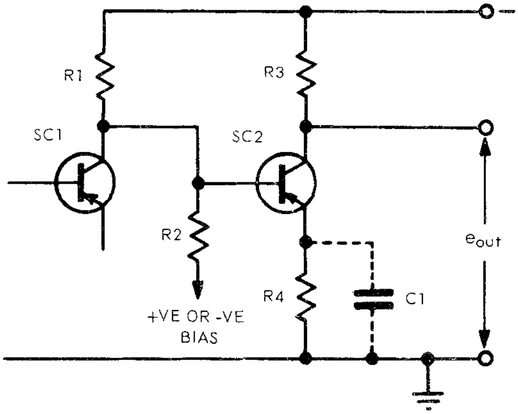


FIG. 35. CLIPPING CIRCUIT.

4.5 Effect of Emitter Resistance. An alternative method to series base resistance, for improving the linearity of the input voltage-collector current characteristics of a transistor operating as an amplifier makes use of an unbypassed emitter resistance as shown in Fig. 36. This produces negative current feedback at all frequencies and gives a feedback voltage proportional to the emitter current, which is, in turn, approximately proportional to the base current. The input voltage between the base and earth is the sum of the base-emitter voltage (E_{BE}) and the voltage across the emitter resistor (E_{RE}). When E_{RE} is much greater than E_{BE}, the input voltage differs only slightly from E_{RE}. The input voltage then, is approximately proportional to the base current, or inversely, the base current is approximately proportional to input voltage. This means that the input circuit is approximately linear and the input resistance is approximately constant. Also, since the input voltage is much greater than E_{BE}, but the base current is unchanged, the input resistance is much greater than it was without negative feedback.

A graphical analysis can be carried out to show the effect of an emitter resistance. A load line is drawn on the collector characteristic for a resistance equal to the sum of R_L and R_E. The collector current for selected values of base current is read from the load line. The sum of the base current and the collector current gives the emitter current from which the emitter voltage (E_{RE}) is calculated.

The base-emitter voltage (E_{BE}) for the selected values of base current is determined from the input characteristic. The input voltage is $E_{RE} + E_{BE}$. Fig. 37 shows the relationship between collector current and input voltage when the transistor has characteristics as in Fig. 32. Curves are drawn for emitter resistors of 100Ω, 200Ω and 400Ω when the collector load resistance is 4kΩ. The characteristics derived for series base resistance are included for comparison. The curves show that the linearity is good except in the region approaching cut-off.

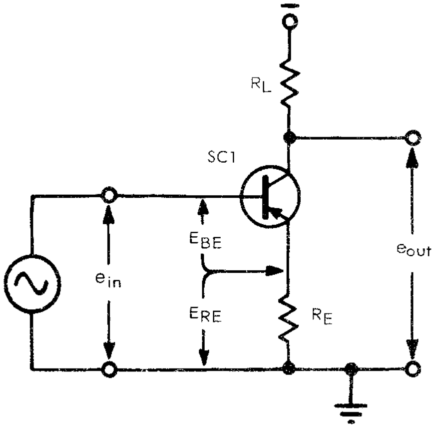


FIG. 36. TRANSISTOR CIRCUIT WITH EMITTER RESISTANCE.

.6 Reverse Voltage Protection. Many transistors can be damaged by a small reverse voltage on the base-emitter junction. The maximum reverse voltage for germanium "drift" type transistors is approximately 0.5V. To prevent damage, a diode is often provided in parallel with the base-emitter circuit as in Fig. 38a. When the transistor is cut-off, the diode is forward biassed and it limits the maximum transistor base-emitter voltage.

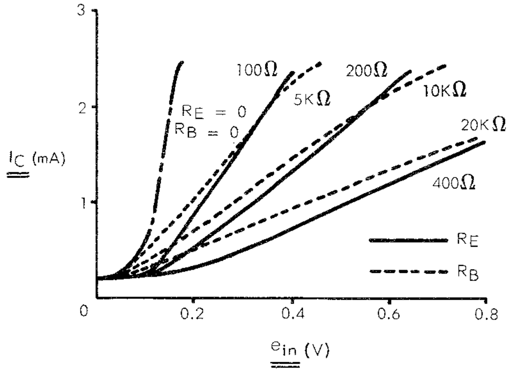


FIG. 37. EFFECT OF EMITTER RESISTANCE.

The diode has an additional effect when signals are capacitively coupled into the base circuit. With no diode, input current flows only when the base-emitter junction is forward biassed. This causes a D.C. component to be introduced by peak rectifier clamping action. The inclusion of the diode maintains input current during the transistor cut-off time, thus tending to prevent the introduction of the D.C. component.

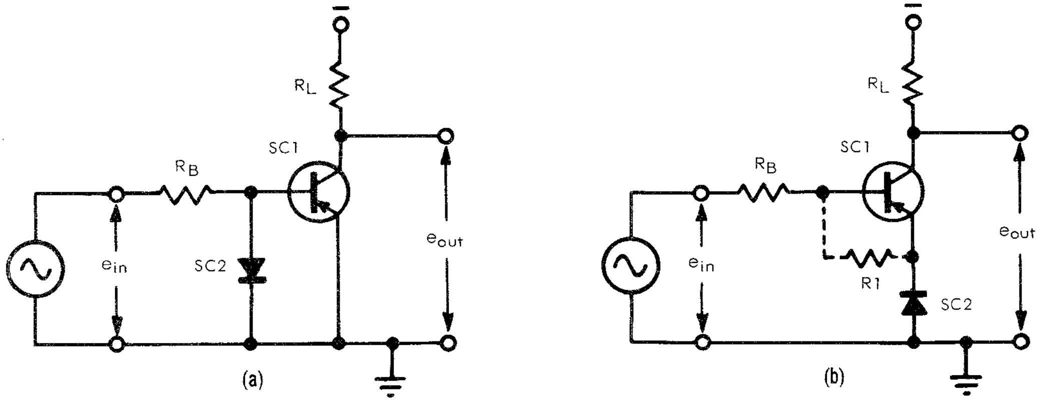


FIG. 38. REVERSE VOLTAGE PROTECTION.

Another method of using a diode to prevent damage to the base-emitter junction is to include the diode in series with the emitter connection as shown in Fig. 38b. When the base-emitter junction is forward biassed, so also is the diode, and the circuit is affected little by the presence of the diode. An input to reverse bias the emitter-base junction, also reverse biasses the diode. The applied voltage then divides in proportion to the reverse resistances of the transistor junction and the diode. These resistances are selected (or obtained artificially by including a high resistance in parallel with the base-emitter junction) so that the majority of the applied voltage appears across the diode. A diode used in this way still allows peak rectifier clamping to be used to establish the position of the input signal on the input characteristic.

4.7 Peak Rectifier Clamping and Cut-off Clipping. When a large amplitude input signal is capacitively coupled into the base-emitter circuit of a transistor amplifier, base current causes peak rectifier clamping to occur. Consider a square wave input signal to the circuit in Fig. 39a which includes a p-n-p transistor. Resistors R1 and R2 provide bias in the absence of an input signal.

For effective peak rectifier clamping to occur, the input signal must be supplied from a low resistance source. Under these conditions the input signal (e_{in}) is almost the same as the source voltage (e_S). During the negative section of the square wave input signal, base current is produced and the capacitor in the base circuit is charged with a polarity as indicated in Fig. 39a. For the positive section of the signal, with a signal amplitude sufficient to cause cut-off, the capacitor discharges slightly via the base bias resistors. However, the time constant for change of charge under these conditions is arranged to be long and little of the charge on the capacitor is lost. The capacitor, therefore, provides a bias which introduces a D.C. component to the signal at the base.

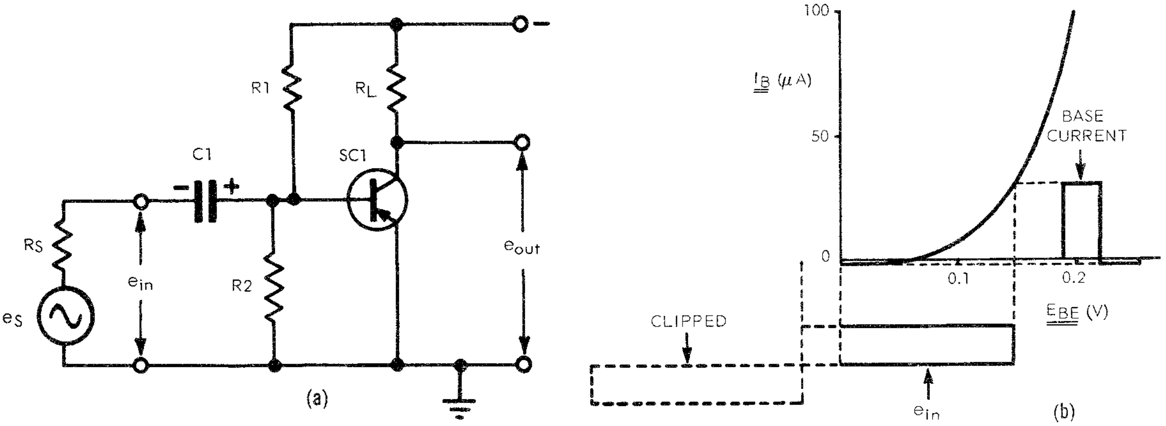


FIG. 39. PEAK RECTIFIER CLAMPING AND CUT-OFF CLIPPING.

Since the break in the base-emitter characteristic is not well defined, the level at which the negative peaks of the input signal are established is also not very definite. The clamping level also depends greatly on the signal amplitude and the source resistance as discussed in the paper "D.C. Restoration and Clamping". In practical examples the negative extreme of the input signal will be established approximately coincident with the apparent knee in the input characteristic when it is drawn on linear graph paper. The knee occurs at approximately 0.2V for germanium transistors and at approximately 0.6V for silicon transistors.

The input signal is shown relative to the input characteristic in Fig. 39b. Since negative peaks of the input signal are clamped at approximately 0.2V or 0.6V, only a small amplitude input signal is required, to cause cut-off. The output voltage with the transistor cut-off is approximately equal to the collector supply voltage. On negative peaks of the input signal the output voltage can be found at the point on the collector load line corresponding to the base current determined from the input characteristic. In many practical cases the clamped peak of the input signal will give a base current that is sufficient to produce saturation clipping (see para. 4.8) in the collector circuit.

Since, for effective clamping to be produced, the source resistance must be low, the circuit in Fig. 39a is non-linear when it is operating as an amplifier between the clamping level and the cut-off clipping level. The circuit is, however, very useful for clipping of signals when the output signal is a rectangular wave. Applications are, stabilization of the amplitudes of rectangular pulses and sync. separation.

The linearity of the circuit is improved by adding series base resistance or by using negative feedback. This, however, reduces the effectiveness of the input circuit as a peak rectifier clamp, and the input signal extends further into the negative region. Therefore, large amplitude input signals are required to produce cut-off clipping.

The non-linearity of the base-emitter characteristic, indicates that the base-emitter resistance varies with base current. Because of this, a D.C. component is introduced even when the input signal amplitude is not sufficient to cause transistor cut-off.

4.8 Saturation Clipping. The collector characteristic of a common emitter connected germanium p-n-p transistor is shown in Fig. 40. As the magnitude of the collector voltage of a transistor is reduced, for a given base current, the collector current decreases only slightly until, at low values of collector voltage, the collector current rapidly falls to zero. The section of the collector characteristic at lower voltages than the voltage at the "knee" in the characteristic is known as the saturation region. In this region the collector voltage is smaller in magnitude than the base voltage and both the collector-base and the base-emitter junctions are forward biassed. The minimum collector voltage that can maintain the collector in saturation with a particular value of collector current is known as the "saturation voltage". This voltage is indicated for a particular operating condition at Point A in Fig. 40. The saturation voltage of germanium transistors is in the region of 0.2V, and of silicon transistors, approximately 0.6V, the actual potential depending on the values of the collector and base currents.

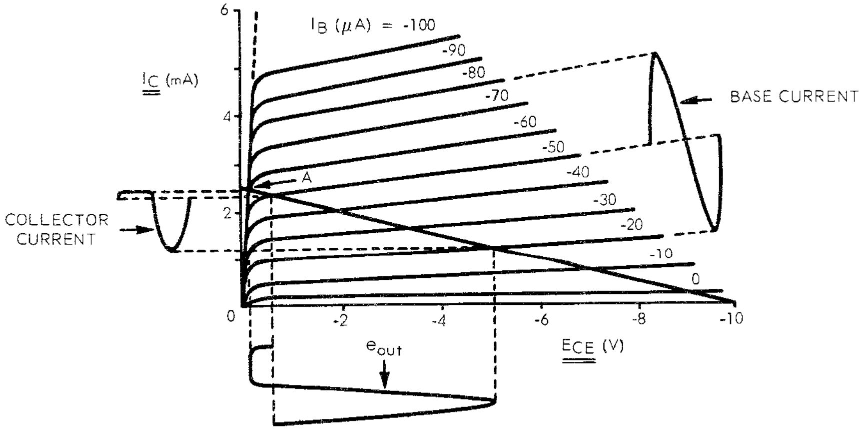


FIG. 40. SATURATION CLIPPING.

The clipping produced by collector saturation is examined by considering a load line on the collector characteristic. As the base current is increased by the input signal, the collector current increases and the collector voltage decreases following the load line. When the base current is increased sufficiently, the load line cuts the collector characteristic, for the base current in question, below the "knee" in the saturation region. Further increases in base current produce negligible changes in collector current and collector voltage. The collector current is at its maximum value which is determined mainly by the resistance in the collector-emitter circuit. The collector voltage is at its saturation or "bottomed" value of approximately 0.2V or 0.6V for germanium or silicon transistors respectively. In Fig. 40 the collector current and output voltage waveforms, which show saturation clipping, are obtained by projection from the base current via the load line. Saturation clipping is responsible for the "break" at high base currents in the dynamic current transfer characteristic shown by the dotted section of curve B in Fig. 32.

So that the base current is proportional to the input signal amplitude when the circuit is operating as amplifier, the signal is provided from an approximately constant current source (by including a high value of resistance in series with the source generator) or negative feedback is included (by an unbypassed emitter resistor). Both methods increase the source voltage required to cause clipping. The curves in Fig. 41 indicate the linearity of the input voltage-collector current characteristic and show the "break" at high collector currents produced by saturation clipping. The "break" is usually very sharp and good clipping is produced.

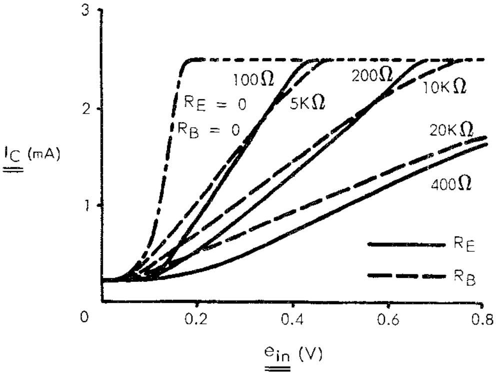


FIG. 41. TRANSFER CHARACTERISTICS.

However, saturation clipping has a disadvantage. When a transistor is rapidly switched from the saturation region to the linear active region of its characteristic, the collector current is maintained for a significant time at almost its maximum value before a decay occurs. This results from minority carrier storage in the base region at the instant that the input is removed. This effect will be discussed further in a paper considering the transistor as a switch.

4.9 Overdriven Amplifier. For clipping at two levels both cut-off and saturation clipping can be used. This makes use of both "breaks" in the input voltage-collector current characteristics of Fig. 41. A typical circuit, shown in Fig. 42, is that of a normal amplifier, but greater than normal input signal is provided to drive the stage into its non-linear operating sections.

The amplifier provides a convenient means of obtaining an approximately square wave from a sine wave input. For symmetrical clipping of the input signal the circuit is biassed half way between the two clipping levels. The diode in Fig. 42 prevents high reverse base-emitter voltages and reduces peak rectifier clamping.

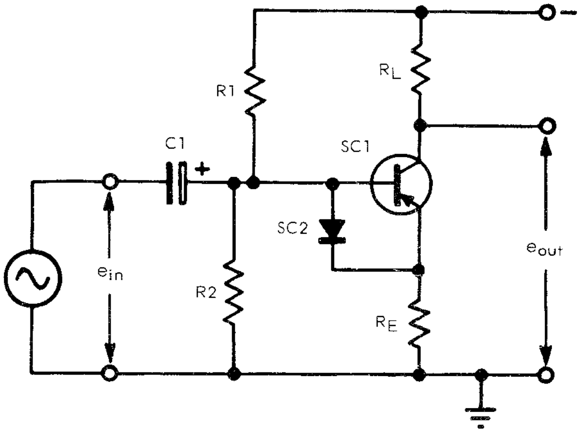


FIG. 42. OVERDRIVEN AMPLIFIER CLIPPER.

4.10 Emitter Coupled Clipping Circuit. Transistors can be used in any configuration to produce either cut-off or saturation clipping. An emitter coupled circuit (long-tailed pair) is commonly used, and, by suitable design, clipping can be produced at two levels by the cut-off characteristics of the transistors. A circuit in a symmetrical form with load resistors in each collector circuit is illustrated in Fig. 43a. The circuit is useful for producing "squaring" of sine waves and for decreasing the rise time of rectangular pulses.

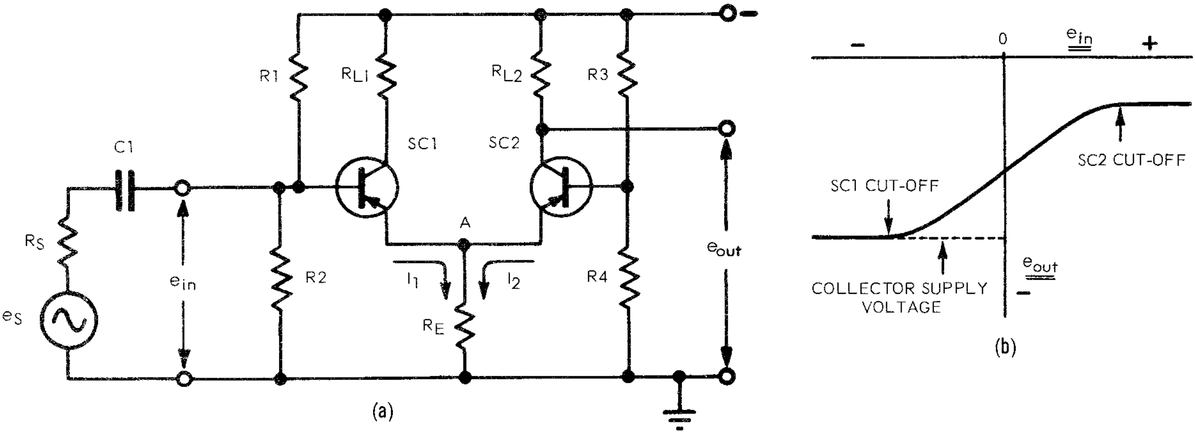


FIG. 43. EMITTER COUPLED CLIPPING CIRCUIT.

With no input signal the circuit is balanced and equal currents flow in each transistor. When the input signal causes the base of SC1 to go negative, base current increases, the emitter current of SC1 increases, and the current through the common emitter resistor tends to increase. This causes the voltage at the emitters (point A) to go negative which decreases the base current of SC2. The reduction in base current reduces the emitter current of SC2 which partly offsets the original increase in total emitter current. This total current through the common emitter resistor (the "tail" current) is maintained approximately constant. Any variation is reduced when R_E is increased. Further negative changes on the base of SC1 will eventually cause SC2 to be cut-off (if the circuit is designed so that SC1 does not saturate before this occurs) making the collector current of SC2 practically zero.

When the input signal produces a positive change at the base of SC1, I1 decreases, the potential at the emitters goes positive and I2 changes to partly offset the initial change in I1. With a large enough positive change of input signal SC1 is cut-off and I2 reaches its maximum value.

The output voltage at the collector of SC2 depends on I2, being a minimum negative value when I2 is a maximum and approximately equal to the collector supply voltage when SC2 is cut-off. The transfer characteristic for the circuit is shown in Fig. 43b. The voltages and currents in the circuit are considered in more detail in Section 5. In a symmetrical circuit using capacitive coupling of the input signal to the base of SC1, clipping occurs approximately equally on either side of the average axis of the input signal. Unbalance will upset this symmetry. Diodes may be necessary to protect the base-emitter junctions of the transistors against excess voltages and to reduce the possibility of peak rectifier clamping for capacitively coupled inputs.

4.11 High Frequency Characteristics. The high frequency response, and, therefore, the rise time of output rectangular waves from a clipping circuit, are limited by shunt capacitance across the load resistor. This effect can be reduced, by including "peaking" or selective negative feedback, to improve both amplitude-frequency and phase-frequency characteristics. However, this is often not the limiting factor in transistor circuits when the load resistor is low in value. The high frequency cut-off characteristic of the transistor itself may be the limiting factor. This cut-off depends on the transistor mechanism and is related to the transit time of minority carriers in the base region. The above considerations apply also to video amplifiers and will not be discussed further at this stage.

5. VOLTAGE COMPARATORS.

5.1 Applications. In many electronic circuits, it is required to derive output pulses coincident in time with the input signal being equal to a selected reference level. Such circuits are known as voltage comparators or voltage selectors. Applications for voltage comparators are found in the trigger circuits of high grade C.R.O's and in electronic counters used for time and frequency measurements. Trigger pulses have to be derived from the input signal to trigger the time bases and counting circuits. A suitable method for determining the timing of the trigger pulses is to compare in a voltage comparator the input signal and a variable reference voltage provided by the "trigger level" control. Trigger pulses are generated when the two signals have equal amplitudes. Varying the reference voltage by operation of the "trigger level" control, allows pulses to be produced at any selected time throughout the cycle of the input signal.

Another important use for a voltage comparator occurs in the delayed sweep circuits of many C.R.O's. A timebase sawtooth signal is generated, triggered from some section of the incoming signal. This sawtooth and a variable reference voltage derived from a "delay" control are both fed into a voltage comparator. An output is produced when the sawtooth signal equals the reference voltage. The output will be a definite time after the commencement of the sawtooth, the time being dependent on the rate of change of the sawtooth and the amplitude of the reference voltage. When both of these variables are known, the "delay" control can be calibrated directly in "time".

Some types of digital voltmeters also use voltage comparators. In one possible type an internally generated sawtooth signal is applied to two voltage comparators. Earth is the reference for one comparator and the D.C. input signal is the reference for the other. Pulses are generated when the sawtooth voltage equals zero and also when the sawtooth voltage equals the input voltage. The time between the two pulses is proportional to the input voltage and the rate of change of the sawtooth waveform. This time is measured by counting the number of cycles of an accurate oscillator which occur between the leading edges of the two pulses. The time measured is calibrated directly as voltage.

5.2 Possible Comparator Circuits. The main difference between voltage comparator circuits and clippers is that in a clipper sections of the output waveform are required to maintain their original shape, while in a voltage comparator, the shape of the output is not important. It is required to derive a pulse or a step coincident in time with equality of two signals. Most of the clipping circuits so far considered can give this information, for example, a negative diode clipping circuit with the reference voltage used as diode bias (Fig. 44a) will give no output when the input is less than the reference, but the input will be transferred to the output, when the input is greater than the reference. Equality of the two signals occurs at the time the output starts to increase. Diode non-linearity causes the position of the break in the diode clipper characteristic to be indefinite so that voltage comparison is not very precise. Amplifiers either before or after the clipper can give some improvement in the accuracy of voltage comparison but these systems are little used.

Some regenerative circuits, for example, the "Schmitt Trigger" multivibrator, can be used as voltage comparators, but these will not be considered in this paper.

Cut-off clipping in valves and transistors can also be used to give the information required for voltage comparison. To allow the use of an input and a reference potential each with one terminal earthed, the reference can be included in the cathode or emitter circuit as shown in Figs. 44b and c. Output commences when the input signal causes the valve or transistor to become conducting. One disadvantage of this arrangement is that the reference supply must carry the current for the circuit and it must have a low output impedance so that changes in the circuit current do not change the reference voltage.

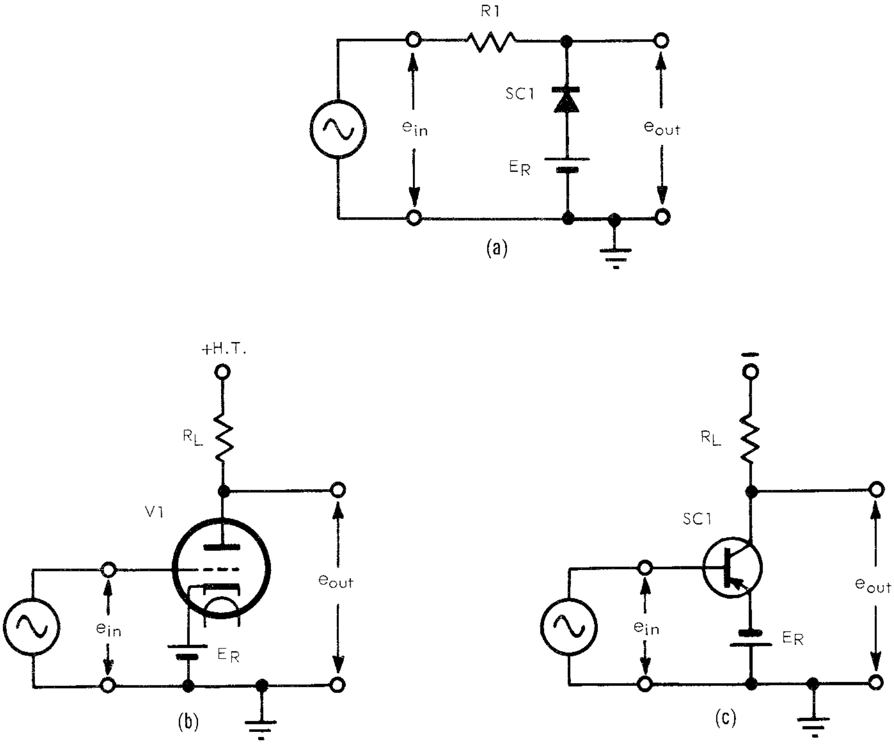


FIG. 44. BASIC VOLTAGE COMPARATOR CIRCUITS.

Another disadvantage of the circuits in Figs. 44b and c is brought about because the reference potential is required to vary over a large range. For trigger circuits of C.R.O's and electronic counters a typical reference voltage variation is from -10V to +10V. In C.R.O. timebase delay circuits, the range is typically 200V for valve circuits and 20V for transistor circuits. The voltage applied to the valve or transistor, therefore, is varied over an appreciable range and this may produce variations in the cut-off potential. (The cut-off potential of triodes will vary with anode voltage change and of pentodes with screen voltage change. The collector voltage of transistors has little effect on their cut-off potential). A cut-off potential variation prevents a variation in the reference potential from being accompanied by a similar variation in the clipping level of the input signal. Ideally, an equal change in both reference and input should leave the valve operating under unchanged conditions. Variations which cause equal changes at each input are called "common mode" signals. Voltage comparator circuits should be independent of "common mode" signals.

5.3 Common Mode Rejection. The effect of common mode signals on a circuit is usually defined by the "common mode rejection ratio". Consider that both the input and the reference signals to a voltage comparator circuit change by an amount equal to ΔE. If there is some common mode effect, this will cause some output from the circuit. This output could have been caused by a change (Δe_{in}) in the input signal. The ratio $\frac{\Delta E}{\Delta e_{in}}$ is the common mode rejection ratio.

The common mode rejection of voltage comparators can be examined by considering the circuits in their linear operating region before the onset of clipping. In the linear region the voltage comparator is called a differential amplifier or a difference amplifier, because the signal output is proportional to the difference between the two input signals with minimum effect being produced by common mode signals.

In the circuit of Fig. 44b the grid-cathode voltage of the triode is the difference between e_{in} and E_R. This is one factor determining the anode current, and therefore the output voltage (e_{out}) is approximately proportional to the difference between the input signals. To examine the common mode rejection consider e_{in} and E_R are both varied by the same amount. This leaves the difference unchanged and the grid-cathode voltage unchanged. However, the variation of E_R changes the high tension to the valve, which changes the anode current and produces an output voltage dependent on the common anode signal.

The common mode rejection ratio of this circuit is poor and is approximately equal to the amplification factor of the valve. The common mode rejection of the circuit using a pentode is better than one using a triode, but there is the inconvenience of having to maintain a constant screen to cathode (not earth) voltage. Transistors are similar in characteristics to pentodes but without the complication of the screen supply, however, the reference voltage, current and impedance disadvantages still exist.

5.4 Triode Cathode Coupled Voltage Comparator. The circuits using cut-off characteristics as voltage comparators are improved if a cathode follower (or emitter follower) is used to apply the reference voltage to the cathode (or emitter) of the clipper. It is also common for the two inputs to be reversed. A typical arrangement using triodes, as shown in Fig. 45, has the "input signal" applied via the cathode follower, and the reference voltage connected to the grid of the clipper. This circuit has the same form as the cathode coupled clipper of para. 3.7, but a variable reference voltage has been added to one grid and the "input" is, in most cases, direct coupled. An advantage of the cathode coupled circuit is that the reference voltage is connected to a high impedance point in the circuit, thus giving no current or impedance problems.

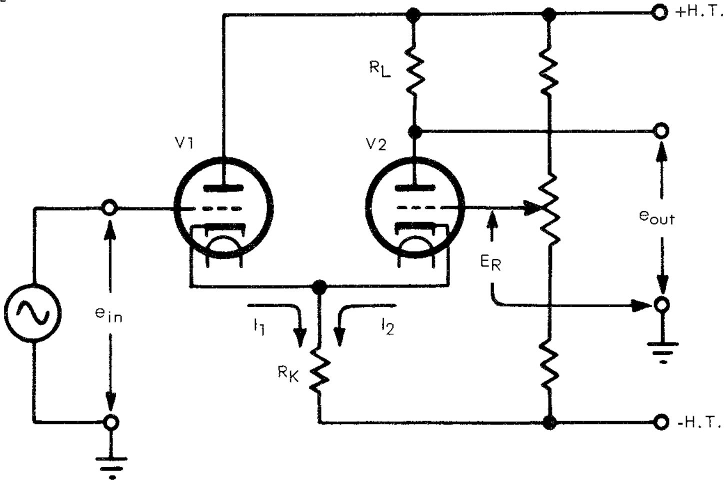


FIG. 45. TRIODE CATHODE COUPLED VOLTAGE COMPARATOR.

As a voltage comparator the circuit is conveniently considered as a two level clipper which selectes a small section of the input waveform. The section selected is varied by varying the reference voltage and the input is clipped approximately symmetrically (depending on the symmetry of the circuit) about the reference voltage. The rise time of the output "rectangular" waveform depends on the rate of change of the selected section of the input waveform. Rise time is improved by reducing the voltage between the two clipping levels, or by including amplification before the comparator.

5.5 The operation of the cathode coupled circuit is now examined. Values of R_L and R_K are each equal to 10kΩ and the two triodes each have anode characteristics as in Fig. 46 (12AT7). The methods used to obtain values of voltage and current in the circuit under various conditions, are also useful for the examination of other similar circuits.

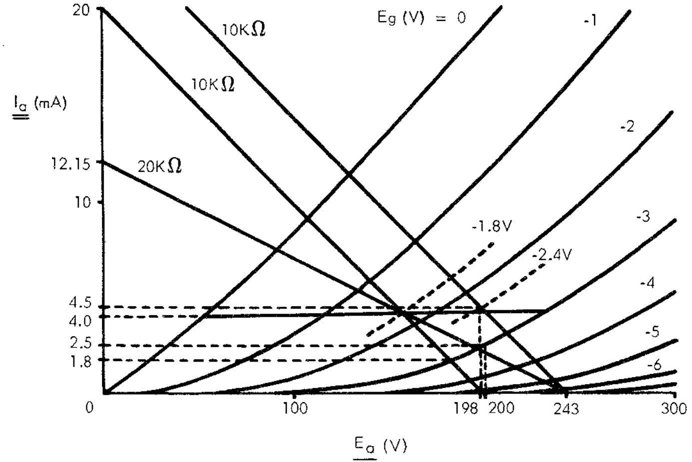


FIG. 46. ANODE CHARACTERISTIC OF TRIODE.

Consider that the input voltage (e_{in}) and the reference voltage (e_R) are both zero, and that the voltage between +H.T. and the valve cathodes is +200V as shown in Fig. 47. Consider also that the cathode potential is +3V with respect to earth and, therefore, each valve has a grid-cathode voltage of -3V. From the valve characteristics, V1 with no anode load has an anode current of 2.5mA. V2 has an 10kΩ anode load and 200V is applied to the valve and load. The 10kΩ load line from +200V in Fig. 46 indicates that with 3V bias the anode current is 1.8mA. The total cathode current is then 4.3mA and the voltage across R_K is 43V. These conditions are satisfied when a negative supply of 40V is provided as shown in Fig. 47.

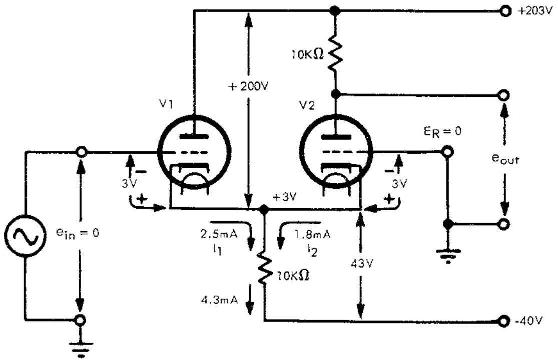


FIG. 47. OPERATING CONDITIONS.

An input signal is now applied which causes V1 grid to go negative. This decrease I1 and therefore reduces the cathode voltage. As a result the grid to cathode voltage of V2 becomes less negative producing an increase in I2 which tends to offset the original decrease. The circuit tries to maintain a constant cathode current. Some change must occur, but this is small and decreases as the value of cathode resistance is increased. Consider that the input signal is decreased by an amount sufficient to cut-off V1. The cathode current then equals the current through V2. V2 has a total of 20kΩ resistance in its anode and cathode circuits and a 243V supply. A load line for this voltage and resistance is shown in Fig. 46. Half of the total circuit resistance is in the cathode circuit providing cathode bias. Note, however, that the grid is not at the same potential as the lower end of the cathode resistance. To determine the bias on V2, assume various values of bias, determine the cathode current that will give these conditions and plot these values on the anode characteristic to form a line which intersects the load line. For example, if the bias on the valve was zero, the cathode voltage (relative to earth) would be zero, and the voltage across R_K would be 40V. The current through R_K would then be 4mA. Similarly if the bias on V2 was -1V, since the grid is earthed the cathode voltage would be +1V, the voltage across R_K, 41V, and the cathode current, 4.1mA. Further, if the bias was -2V, the cathode current would be 4.2mA. The line joining these points is almost straight and horizontal, and it cuts the load line at a grid cathode voltage of -1.8V.

The stable condition of the circuit gives a cathode voltage of +1.8V with respect to earth. From the valve characteristics, with an anode voltage of approximately 200V, approximately -5V bias between grid and cathode is required to produce cut-off. Therefore, V1 will be cut-off when its grid is more negative than -3.2V (+1.8 -5V). With a cathode voltage of +1.8V, the voltage across R_K is 41.8V giving a current of 4.18mA. The reduction of cathode current below its no signal value is only 0.12mA. The circuit voltages and currents for this condition are shown in Fig. 48a.

When the input voltage is made positive I1 increases above its no signal value and the voltage across R_K increases. This makes the grid of V2 more negative relative to its cathode, which reduces I2 thus tending to maintain the cathode current approximately constant. When the input is increased sufficiently to make the cathode voltage +5V, V2 is cut-off. The cathode current under these conditions (Fig. 48b) is 4.5mA, an increase of only 0.2mA from the no signal condition. The anode to cathode voltage of V1 is +198V and with this voltage 4.5mA is produced when the bias is -2.4V. (This same value is obtained by finding the intersection of a 10kΩ load line from 243V, with 4.5mA anode current). An input voltage of +2.6V(+5-2.4V) or greater will therefore cause V2 to be cut-off).

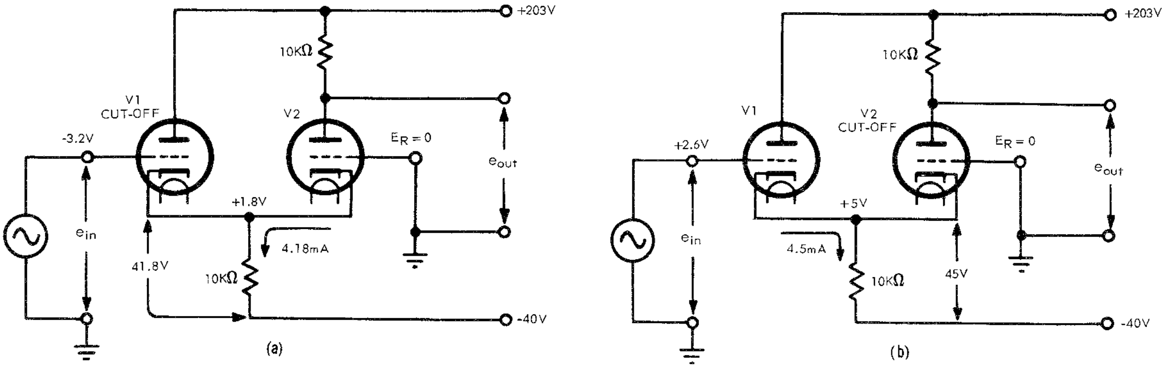


FIG. 48. OPERATING CONDITIONS OF CATHODE COUPLED CIRCUIT.

Input voltages more positive than +2.6V will still cause I1 to increase, but without the compensating decrease in I2 (since V2 is cut-off) V1 behaves as a simple cathode follower. Increase in I1 causes an increase in cathode voltage which provides cathode bias attempting to offset the input voltage change. The result is that large increases in input voltage produce only small changes in grid-cathode voltage and small increases in cathode current. The cathode current actually continues to increase at approximately twice the rate of the total cathode current increase when both halves are conducting. Considerable increase in input voltage is possible before zero grid-cathode voltage is produced on V1. In the example considered the input voltage required for this condition is +72V.

The output voltage at the anode of V2 is dependent on I2. When V2 is cut-off the output equals the +H.T. voltage of +203V. When V2 is conducting fully with V1 cut-off V1 is 4.18mA, causing 41.8V to be present across R_L, so that the output voltage is 161.2V (203-41.8V).

5.6 The operation of the cathode coupled circuit can be summarised with the aid of Fig. 49. Imagine an input signal increasing from a very negative voltage at a linear rate. With input signals more negative than -3.2V, V1 is cut-off and V2 is conducting fully with I2 = 4.18mA. When the input signal is made more positive, V1 starts to conduct and, as I1 increases, I2 decreases, so that the total cathode current (I1 + I2) increases only slightly. An input signal increase to +2.6V causes V2 to cut-off and V1 supplies the total cathode current of 4.5mA. Further increase in the input signal produces a small increase in cathode current, but does not modify the output voltage at the anode of the cut-off V2.

Because of the linearly increasing input voltage, the output voltage shown in Fig. 49c has the same shape as the transfer characteristic for the circuit. Notice that the circuit produces a gain but no phase reversal.

From the preceding we see that the input signal is not clipped symmetrically on either side of the zero axis. This is because of the unbalance of the circuit, since V1 has no resistance is its anode circuit. An anode load is included for V1 in some cases. Assymmetry in clipping is also caused by the change in the mutual conductance of valves throughout their operating range. Compensation to provide symmetrical clipping of the input signal about the zero axis can be provided by changing slightly the reference voltage.

The example illustrates the small variation of cathode current in the circuit between clipping levels. This variation is further reduced if the value of the common cathode resistor is increased, but this necessitates the use of a higher negative H.T. supply if the operating conditions of the valve are to be unchanged. Another method of increasing the effective resistance of the common cathode circuit uses a valve and is considered in para. 5.8.

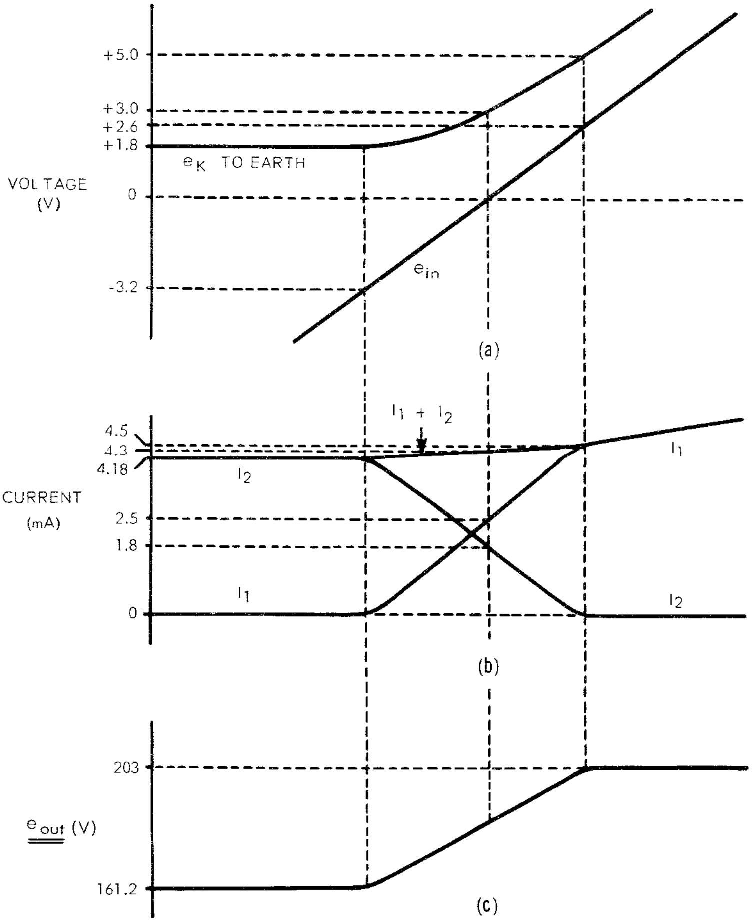


FIG. 49. CATHODE COUPLED CIRCUIT WAVEFORMS.

The cathode voltage variation is shown in Fig. 49a with the input voltage. The cathode voltage remains constant below the lower clipping level and is slightly more positive than the voltage on V2 grid. For input signals above the upper clipping level the cathode voltage is approximately a constant amount above the input at V1 grid. This shows that the cathode voltage tends to follow the more positive of the voltages at the two grids.

Between clipping levels the cathode voltage change is approximately equal to half the input voltage change. This can be justified by considering the cathode coupled circuit in its balanced form as in Fig. 50. With e_{in} equal to E_R, and identical valves, I1 equals I2. If e_{in} is increased and E_R decreased by a small amount (ΔE), I1 will increase and I2 decreases by the same amount, when both valves are operating on linear sections of their characteristics. The total cathode current is therefore unchanged, and the cathode voltage unchanged. If, however, both e_{in} and E_R are increased by the same small amount (ΔE), when a large cathode resistor is included, the cathode voltage will tend to follow the grid voltages and also increase by ΔE.

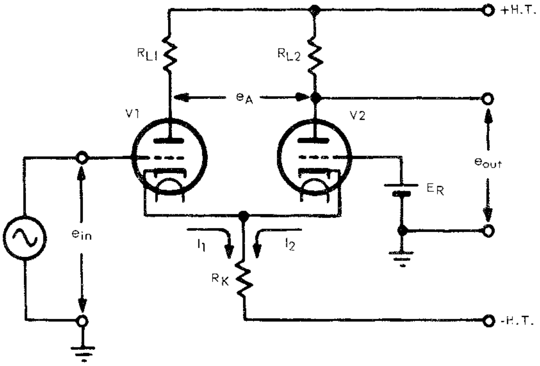


FIG. 50. VOLTAGE COMPARATOR.

Adding these two changes gives a change of $2\Delta E$ on V1 grid, no change on V2 grid and a change of ΔE at the cathodes. That is, with a constant reference voltage, the cathode voltage variation is half the grid voltage variation. This is also approximately correct when the load resistance is not included in the anode circuit of V1. It will be noticed that, in the example, the no signal bias was chosen greater than half the cut-off bias. This was so that one tube is always cut-off before the other tube reaches the zero bias condition which may cause grid current clipping.

5.7 Common Mode Rejection. To examine the effect of the common mode signal, consider the balanced cathode coupled circuit (Fig. 50) with e_{in} equal to E_R. With identical valves, I1 equals I2 and e_A between the anodes of V1 and V2 is zero. An equal variation of e_{in} and E_R causes both anode currents to change by the same amount. The circuit remains balanced with e_A still zero, so that the common mode signal does not appear between the two anodes. However, since both anode currents change, e_{out} must also change and the unbalanced output from the circuit contain a proportion of the common mode signal. The common mode rejection is improved when the effect of the common mode signal on the total cathode current is reduced. Therefore, the improvement can be obtained by making R_K very large so that the valve has only a small effect on the total cathode current. The combined valve currents can be considered as being from an approximately constant current source and large common mode signals can cause only a small variation in valve current and a small change in output voltage.

The effect of the cathode resistor value can be explained in an alternative way. The voltage variation at the cathodes of the circuit follows closely the common mode variations of e_{in} and E_R being considered. The variation is present across any large value of common cathode resistor, practically independent of its value. But the cathode current variation (ΔI) is equal to $\frac{\Delta E}{R_K}$. Therefore, ΔI is smaller and the common mode rejection ratio is improved when R_K is made larger. The common mode rejection is approximately proportional to the value of the common cathode resistor.

This information can be used to make a further observation. Considering on input signal variation only, for any large value of cathode resistance in a linear circuit, the cathode voltage variation is approximately half the input voltage change. The change in total cathode current (ΔI) is approximately equal to $\frac{\Delta e_{in}}{2R_K}$. Therefore, for a given input voltage variation, the change in total cathode current is reduced when R_K is increased; that is, when the common mode rejection ratio is improved. The variation in the total cathode current between clipping levels is, therefore, an indication of the common mode rejection ratio.

For a given change in total cathode current, the common mode rejection of the circuit with a single load as in Fig. 45 is slightly better than that for the balanced circuit of Fig. 50. This is because the load resistance in V2 anode only, makes the variation of I2 (which determines the output) less than the variation of I1, and therefore less than either valve current variation in Fig. 50. For the common mode rejection ratio of an unbalanced cathode coupled comparator to be better than that for the basic triode clipper (Fig. 44) R_K must be greater than the anode resistance of the valves.

5.8 Increasing the common cathode resistance improves the common mode rejection, but this has the disadvantage that large voltage drops occur across the resistance, and large D.C. potentials are required. For example, if the common cathode resistance (R_K) is 1MΩ and the cathode current is 1mA, the voltage across R_K is 1,000V. This disadvantage is removed by using either a pentode, or a valve including negative current feedback, as the common cathode resistance. This gives an effective cathode resistance equal to the A.C. output resistance at the anode of the valve.

The output resistance of a pentode is equal to its A.C. anode resistance (r_a) when it is operating above the knee of its characteristic, and this is typically 1MΩ. However the voltage across the valve needs only to be greater than approximately 50V. Negative current feedback, as can be obtained by including an unbypassed cathode resistance, increases the output resistance of a valve. The output resistance is approximately equal to the products of the amplification factor (μ) and the cathode resistance (R_K). In an example where $\mu = 50$ and $R_K = 0.1$MΩ the output resistance equals approximately 5MΩ. A circuit of a voltage comparator, which includes as a common cathode resistance, a triode with negative current feedback, is shown in Fig. 51a.

5.9 When precise selection of a particular level is required, two cascaded cathode coupled stages are sometimes employed. An example is illustrated by the simplified circuit in Fig. 51b. The first stage is a differential amplifier with load resistances in each anode circuit. The push-pull outputs available at the anodes are direct coupled to the second stage which gives the required single ended output.

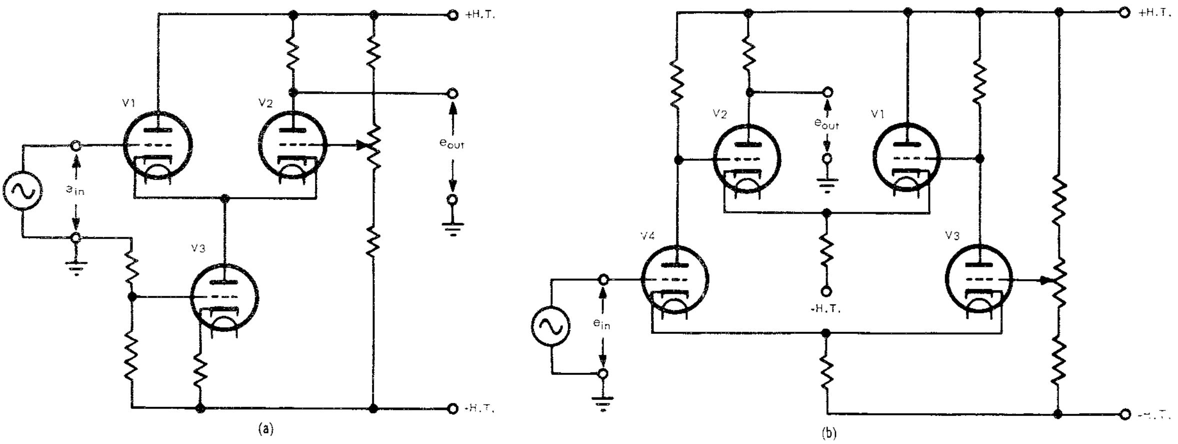


FIG. 51. VOLTAGE COMPARATOR CIRCUITS.

5.10 Transistor Cathode Coupled Voltage Comparator. The collector current and the cut-off point of a transistor are affected very little by change of collector voltage. Because of this the basic transistor voltage comparator (Fig. 44c) inherently has better common mode rejection than the triode circuit. However, this is often not adequate, and also the reference power supply impedance and current carrying requirements are still a problem. The cathode coupled configuration is therefore, commonly found using transistors. A typical symmetrical circuit using p-n-p transistors is illustrated in Fig. 52.

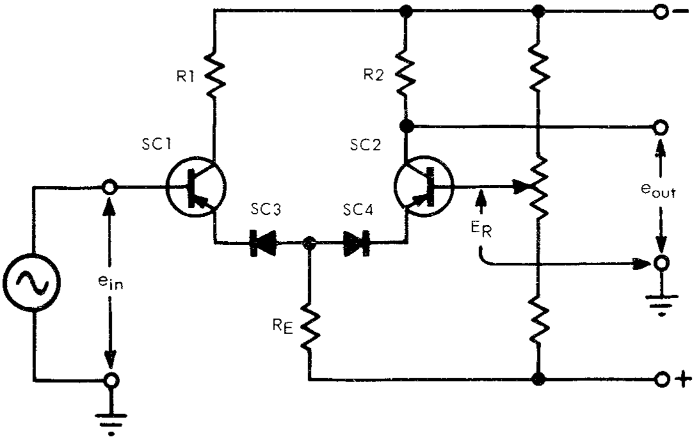


FIG. 52. TRANSISTOR CATHODE COUPLED COMPARATOR.

A detailed analysis for the transistor "long tailed pair" can be carried out in a similar manner to that explained for the valve circuit in para. 5.5. However, in the transistor case there are the extra complications of base currents and leakage currents. The details of a graphical analysis are not considered here but the results are shown in Fig. 53. These waveforms summarise the operation of the circuit.

5.11 Consider the circuit in Fig. 52 with a reference voltage of zero and an input voltage that is decreasing linearly but is sufficiently positive to cause SC1 to be cut-off. It will be assumed that germanium transistors are used and that the leakage current is negligible. With SC1 cut-off the collector current of SC2 is determined largely by the values of the emitter resistor and the positive supply voltage. This transistor will be operating at its maximum base and collector currents (for the assumed reference voltage) and the emitter will be typically between +150 and +200mV (say +180mV) with respect to the base voltage of zero. The total emitter current is the emitter current of SC2 which is greater than the collector current by an amount equal to the base current. This condition is maintained for all values of input voltage that cause SC1 to be cut-off and is shown by the waveforms at the left hand end of Fig. 53. Notice that the currents are shown with negative values, because of the use of p-n-p transistors, so that the input voltage and current variations have the same polarity. However in the following discussion a "reduction in current" will mean that the magnitude of the negative value of current is decreased. The base currents in Fig. 53 are drawn to a different vertical scale to that used for the collector and emitter currents.

SC1 will remain cut-off until the input voltage is negative with respect to the emitter voltage. Therefore SC1 will come out of cut-off when the input voltage decreases to less than +180mV. When this occurs base current will commence in SC1, producing collector and emitter currents. The emitter current tends to increase the total emitter resistor current, but the voltage developed across this resistor is of such a polarity that the base, collector and emitter currents of SC2 are reduced. Any change in emitter current in SC1 tends to be offset by an opposite change in emitter current in SC2, and the total emitter current is maintained almost constant.

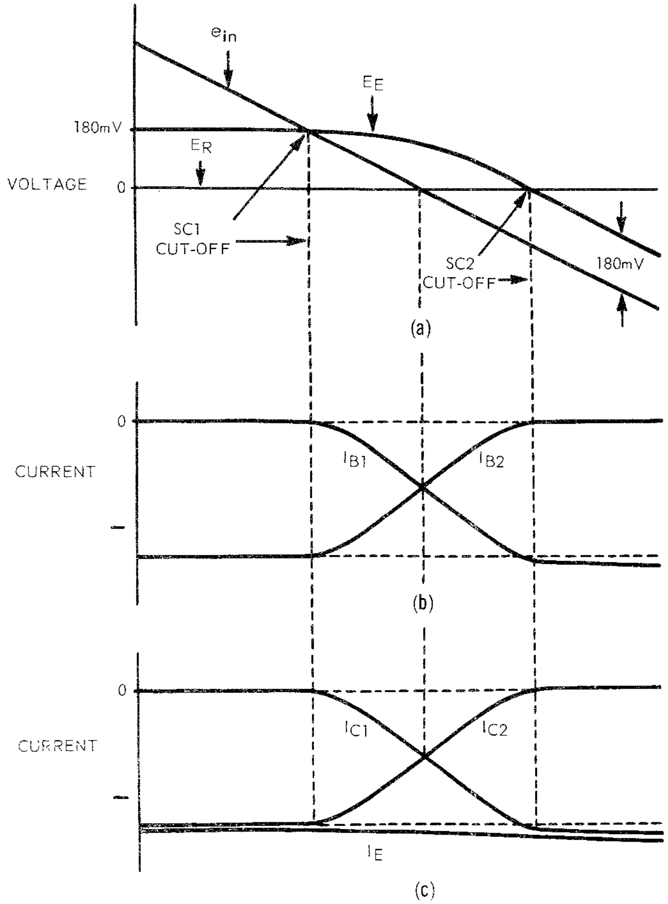


FIG. 53. EMITTER COUPLED CIRCUIT WAVEFORMS.

A slight increase must occur with increase in input base current to SC1, but the magnitude of the change reduces as the value of the common emitter resistor is increased. Since a small change in transistor base-emitter voltage has a large effect on collector current, the total collector current is almost constant even with a relatively small value of emitter resistor of approximately 1,000Ω.

As the input voltage continues to decrease, the exchange of currents between the two transistors continues, as shown in the centre section of Fig. 53, while the total emitter current is maintained practically constant. In the balanced circuit being examined, when the input voltage has fallen to zero, the two transistors share equally the total emitter current. When the input voltage becomes negative SC1 provides the major share of the total current and SC2 approaches cut-off.

Accompanying the decrease in input voltage while both transistors are conducting the emitter voltage decreases as indicated in Fig. 53. When the emitter voltage has reached zero SC2 is cut-off and has no further effect on the emitter current. The emitter current of SC1 is then determined mainly by the input voltage, the positive supply voltage and the emitter resistance. In this condition the emitter current is approximately at its maximum value and the base-emitter voltage will be typically -180mV. Further negative changes in the input voltage will cause only small changes in both emitter current and base-emitter voltage. The emitter voltage of the circuit, therefore, tends to follow the input voltage but is more positive than it by approximately 180mV.

5.12 The clipping levels of the signal at the input are small compared with similar valve circuits. In the example of Fig. 53, clipping occurs at input signal levels of ±180mV. Leakage current in the transistors causes the emitter current to be slightly greater than that considered and each transistor in turn is cut-off with a slightly smaller input voltage.

The output voltage from the circuit at the collector of SC2 is equal to the collect supply voltage when SC2 is cut-off and leakage current is zero. It is more positive, by an amount determined by the collector load resistance and the collector current, for other conditions. The output voltage variations at this point have the same polarity as the input voltage variations. Variations of opposite polarity are available at the collector of SC1.

Fig. 53 shows that for a linear change in input voltage the collector current between clipping levels is non-linear. This is caused by the non-linearity of the transistor input characteristic. However both the base current and collector current waveforms have similar shapes and this suggests that, if linearity is required, it can be obtained by feeding the circuit from an approximately constant current source.

5.13 Common Mode Rejection. In para. 5.7 relating to the valve cathode coupled circuit it was derived that an indication of the common mode rejection was obtained from the variation of the total cathode resistor current with change of input voltage. This applies also to the transistor emitter coupled circuit; that is, the common mode rejection is improved when the variation of emitter current, for a given change in input voltage, is reduced.

Increasing the value of the common emitter resistance improves the common mode rejection. However, since the base-emitter voltage has a large control over the collector current and collector-emitter voltage has only a small effect, the common mode rejection of the transistor circuit is good even with relatively small values of emitter resistance.

The effective emitter resistance can be increased by substituting a transistor for the emitter resistance. However, this is not usually necessary, since high values of resistance of the order of 20kΩ to 100kΩ give extremely good common mode rejection. These values require high voltages by transistor standards, but the voltages are not hard to obtain. For example, with a 100kΩ common emitter resistance and a 1mA "tail" current, the emitter supply voltage required is 100V.

5.14 Voltage Limitations. The amount of variation of reference voltage (and also input voltage) possible in a voltage comparator circuit, is limited by a number of factors. It is required that sufficient voltage be present across the valve or transistor to allow it to operate correctly, therefore, the reference voltage cannot approach too closely, or exceed, the anode or collector supply voltage. The other extreme of reference voltage depends on the requirement that a considerable voltage be present across a common cathode or emitter resistance for it to appear as a constant current source. If an active device is used as the common coupling "resistor" a minimum voltage must appear across it to give correct operation. At the latter extreme of the reference voltage, the voltage across the cathode or emitter coupled valves or transistors is at a maximum, and the maximum voltage ratings of the device must be considered. Because of the lower values of supply voltage and the lower maximum voltage ratings of transistors as compared with valves, the change in comparator reference voltage allowable in transistor circuits is normally considerably less than that possible in valve circuits.

6. *TEST QUESTIONS.*

1. (i) Draw a basic series diode clipping circuit which will clip voltages more positive than +20V.

(ii) Draw a transfer characteristic for the circuit and describe how the circuit produces the sections of the characteristic.

2. (i) In the circuit of Fig. 54a, at what input voltage would clipping occur?

(ii) Considering an ideal diode, illustrate the effect of the circuit on a sawtooth input waveform which varies between +70V and +110V.

(iii) If the diode in Fig. 54a has a constant forward resistance of 300Ω and a constant reverse resistance of 60kΩ, what is the output waveform from the circuit when the input waveform is the same as that in Question 2(ii)? Mark significant voltages on the waveform.

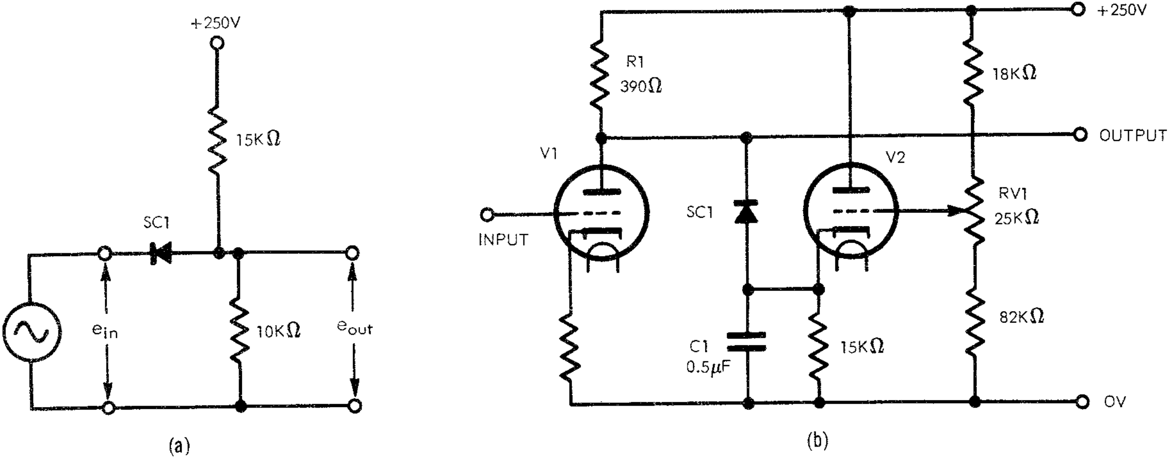


FIG. 54. CIRCUITS FOR QUESTIONS 2 AND 3.

3. What functions would the following components perform in the circuit of Fig. 54b?

(i) R1, (ii) SC1, (iii) V2, (iv) C1, (v) RV1.

4. (i) Draw a basic shunt diode clipping circuit which will produce negative clipping at -15V.

(ii) Sketch the ideal output waveform from the circuit for a sine wave input of 40V p-p.

(iii) How would the output waveform be affected if the diode forward resistance was significant?

5. Explain, with the aid of approximate transfer characteristics, why clipping circuits using practical diodes are not very effective with low input signal voltages.

6. (i) Draw a circuit of a valve amplifier which uses two "catch diodes" to limit the anode voltage variation to between +160V and +180V.

(ii) This circuit can be considered as a shunt diode clipping circuit. What components form the equivalent of the series resistor of the shunt diode clipping circuit?

7. A circuit consists of a differentiating circuit followed by a positive clipping circuit. What would be the output waveform if the input waveform is rectangular with peak values at:- (i) +100V and +150V, (ii) +140V and +240V?

8. *Describe the forms of clipping that can be produced with valves. Use typical valve characteristics to illustrate valve operating conditions.*

9. *In the circuit of Fig. 55a, V1 operates as a linear amplifier and the anode current with no input signal is 20mA. V1 has a* $\mu = 20$ *and an* $r_a = 5k\Omega$. *When a sine wave input signal of 12V p-p is applied, clipping is produced by SC1. Draw the voltage waveforms that will exist on the anode of V1* (e_A) *and at the output* (e_{out}). *Mark on the waveform significant voltage values.*

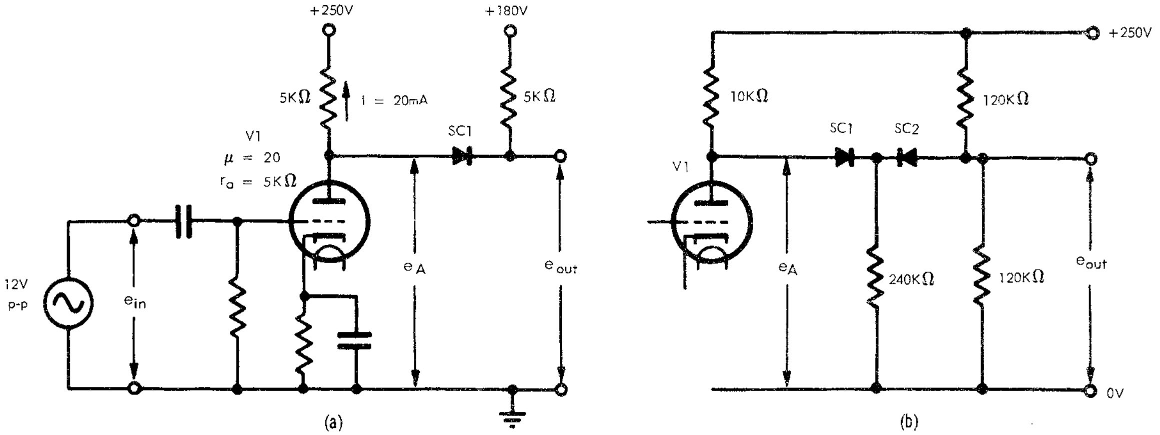


FIG. 55. CIRCUITS FOR QUESTIONS 9 AND 10.

10. *Draw a transfer characteristic relating anode voltage of V1* (e_A) *and output voltage* (e_{out}) *for the circuit of Fig. 55b. Show the voltages at which clipping occurs and explain the operation of the circuit.*

11. *A negative series diode clipping circuit, which clips at zero voltage, has a shunt resistance of 10kΩ and a shunt capacitance across the output of 20pF. What is the output waveform when the input is a 20V p-p square wave with no D.C. component? Mark significant voltages and time constants on the relevant sections of the waveform. Consider that the diode forward resistance is constant at 100Ω, the reverse resistance is negligible and the diode capacitance is a constant 4pF.*

12. *(i) Draw a basic circuit that would be suitable for extracting synchronising information from a television composite video signal.*

    (ii) Describe the operation of the circuit and show the circuit waveforms.

13. *Does the addition of a series base resistance in a transistor amplifier produce clipping? Give reasons for your answer.*

14. *Describe, with the aid of a circuit, how a transistor cut-off clipping circuit, can be protected against excess reverse base-emitter voltage.*

15. *Draw an emitter coupled clipping circuit and briefly describe its operation.*

16. *Describe briefly two applications of a voltage comparator in a high quality C.R.O.*

17. *What is meant by:- (i) Common mode signals, (ii) Common mode rejection ratio?*

18. *Describe briefly the operation of a cathode coupled voltage comparator. Draw typical circuit waveforms or characteristics to assist in the description.*

19. *(i) Draw a circuit of a cathode coupled voltage comparator using a triode valve, with negative current feedback, as the common cathode resistance.*

    (ii) What advantages are obtained by using this form of common cathode resistance?

END OF PAPER