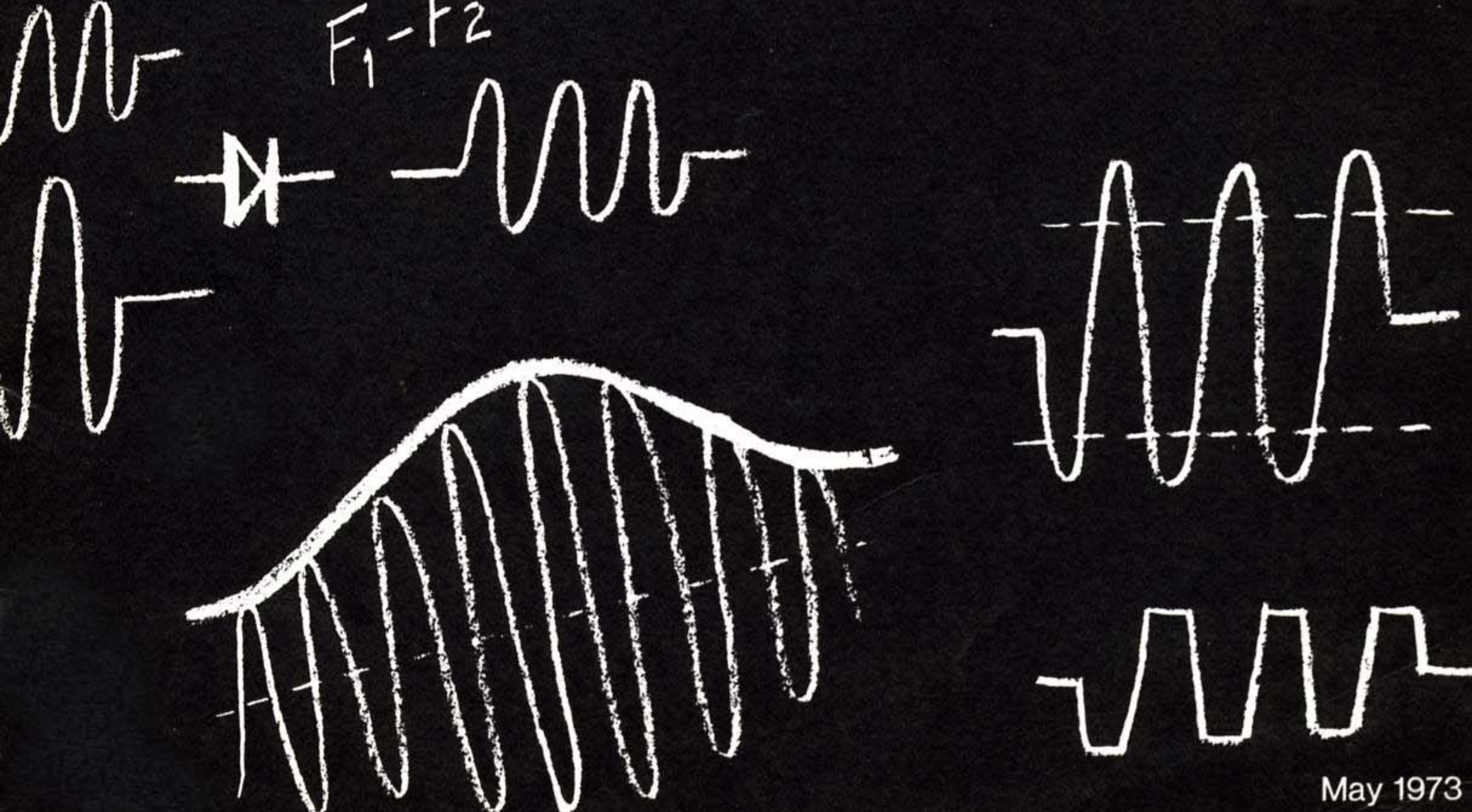
HEWLETT PACKARD
COMPONENTS

Schottky Diodes for High Volume, Low Cost Applications

Application Note 942



May 1973

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INTRODUCTION

Recent developments in Schottky diode processing at Hewlett Packard have reduced manufacturing costs to make these diodes competitive with PN junction diodes in high volume production applications.

Both PN junctions and Schottky barrier diodes are non linear devices useful for rectification and frequency conversion. The presence of minority carriers in PN junctions causes imperfect rectification. Instead of an abrupt end to current flow when the applied voltage becomes negative, there is a partial cycle of reverse current flow which ends when the minority carriers are swept out or have recombined.

The performance improvement afforded by the lack of minority carrier storage in Schottky barrier diodes has long been recognized. Now these improvements can be designed into low cost, high volume applications. This note will discuss switching, sampling, mixing, and other applications where substitution of Schottky diodes will provide significant improvement over PN junction devices.

SIGNAL CONVERSION

MIXING AND DETECTING APPLICATIONS

The absence of minority carriers results in more perfect rectification and more efficient frequency conversion. For example, when Schottky diodes such as the HP 5082-2835 are substituted for 1N82 diodes in television mixer circuits, the typical improvement in noise figure is two to three dB.

In many applications, such as converters for cable television, double balanced mixers (DBM) are used to reduce the level of harmonic distortion products. The DBM circuit shown in Figure 1 has the additional advantage of isolation among the three ports. This simplifies the problem of:

1. Filtering at the output port and,
2. Radiation of local oscillator power at the input port.

This double balanced mixer circuit is also useful as a balanced modulator and a phase detector. In all these applications, Schottky diodes have the additional advantage of greater uniformity. The manufacturing process results in diodes with nearly identical contact area, semiconductor thickness, and doping level. In many applications requiring multiple diodes, standard units may be used without special tests. For critical applications, appropriate matching tests may be performed. For example, the 5082-2815 is a matched bridge quad of the 5082-2811. The 5082-2814 is an encapsulated version of this quad. The 5082-2826 is the 5082-2811 supplied in matched batches.

Either 5082-2811 or 5082-2835 diodes are suitable for mixing applications. There is a difference in impedance between the two types because the 5082-2835 has a smaller junction capacitance and series resistance. This will also result in improved noise figure at higher frequencies for the 5082-2835. However, the main difference is in the metal used in the Schottky contact which results in a difference in turn-on voltage. The 5082-2835 has a lower turn-on voltage with corresponding improved performance at lower local oscillator levels.

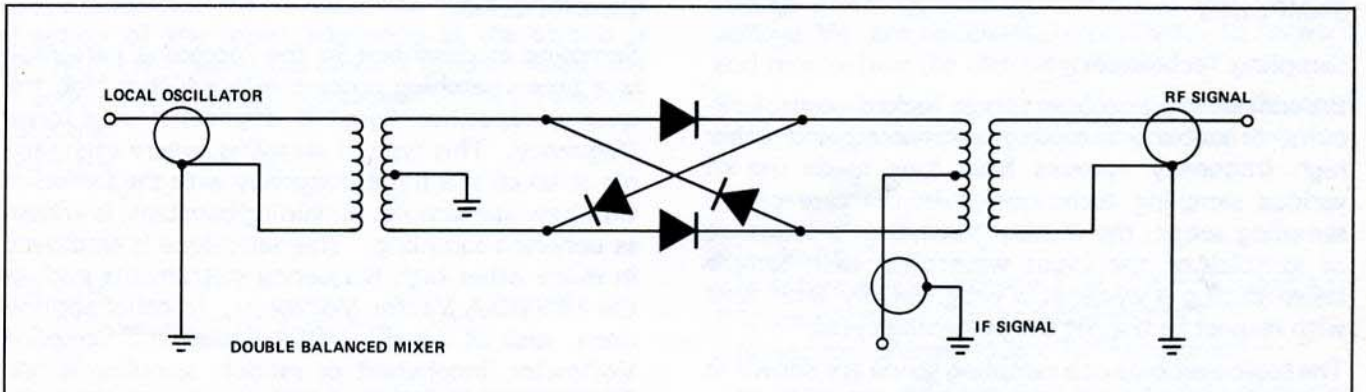

Figure 1.

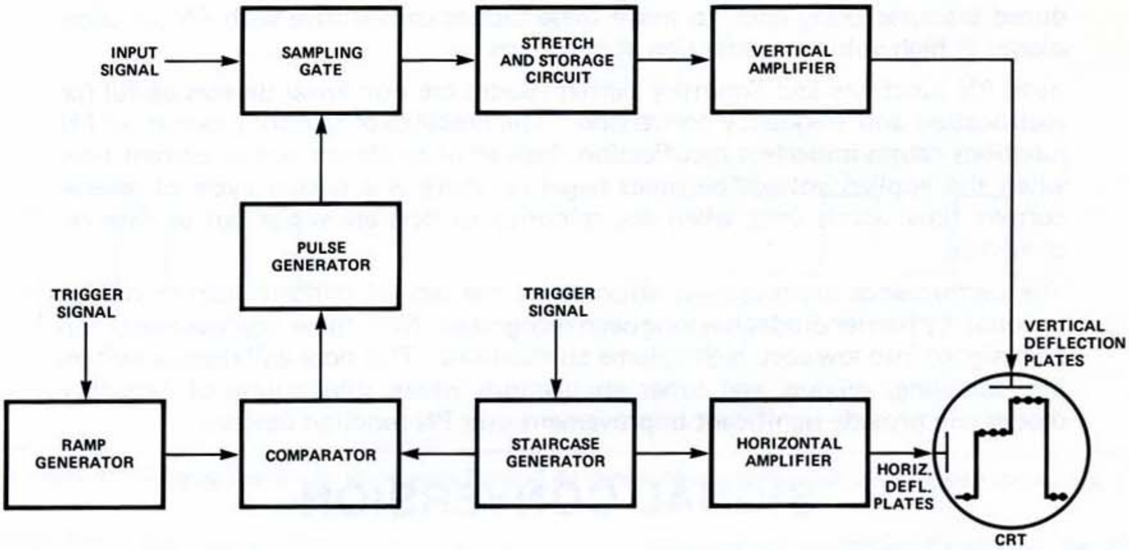

Figure 2. Block Diagram of the Basic Elements of a Sampling Scope

The 5082-2811 has lower flicker noise and higher breakdown voltage. It is preferred for Doppler applications and for phase detection. Both these diodes are also useful in detector and power monitor applications. The lower capacitance of the -2835 will give better sensitivity at higher frequencies, while the lower flicker noise of the 2811 will give better tangential sensitivity at video frequencies below 100kHz. At input power levels below approximately −20dBm, the output voltage is proportional to the input power, a square law response. At higher levels the response is linear. The 5082-2811, with its higher breakdown voltage, will follow the linear response to higher output levels. The output will level off, or saturate, when the detected voltage reaches half of the breakdown voltage.

SAMPLING

Sampling Techniques

Broadband oscilloscopes, phase-locked control circuits, broadband sampling voltmeters, and other high frequency systems have long made use of various sampling techniques. In the case of the sampling scope, the display consists of a sequence of samples of the input waveform, each sample taken during a cycle at a progressively later time with respect to that of the preceding cycle.

The basic elements of a sampling scope are shown in the block diagram in Figure 2 and the sampling technique illustrated in Figure 3. To attain proper timing, trigger signals into the ramp generator and staircase generator control, respectively, a swept ramp signal and a staircase signal (which remains constant between triggers, but jumps to another level at each trigger). When the positive-going ramp voltage is equal to the staircase reference voltage, the comparator triggers the pulse generator to transmit a pulse to turn on the sampling gate (normally reverse biased off). This action stores in the load capacity a very short pulse of current proportional to the instantaneous input signal amplitude. These very short samples are then stretched in time into much longer samples, which are amplified and applied to the CRT at the vertical plates. The storage provision allows the sample to be displayed on the CRT until the next sample is taken. The staircase voltage is applied to the horizontal amplifier and thus determines the horizontal position of the CRT beam.

Sampling as described in the foregoing paragraph is a time stretching process with which a high frequency repetitive signal is duplicated at a lower frequency. This type of sampling, where each sample is taken at a fixed frequency with the period of time between samples remaining constant, is known as coherent sampling. This technique is employed in many other high frequency instruments such as the HP8405A Vector Voltmeter. In other applications, such as the HP 3406A Broadband Sampling Voltmeter, incoherent or random sampling is preferred to avoid difference frequencies or "beat signals" within the passband of its metering circuit. This type of sampling will not reconstruct the input

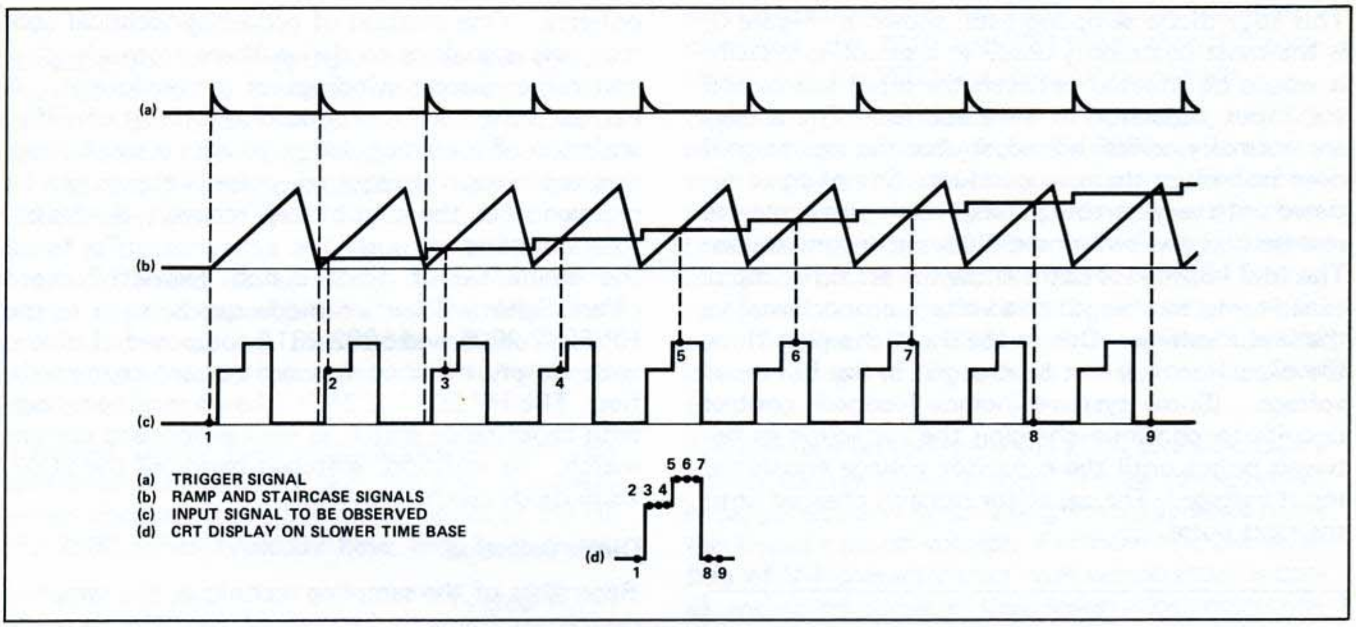

Figure 3. Sampling Scope Technique

waveform, but statistical properties (average, peak, and RMS values) of the input signal can be derived if a sufficient number of samples are taken in this random fashion.

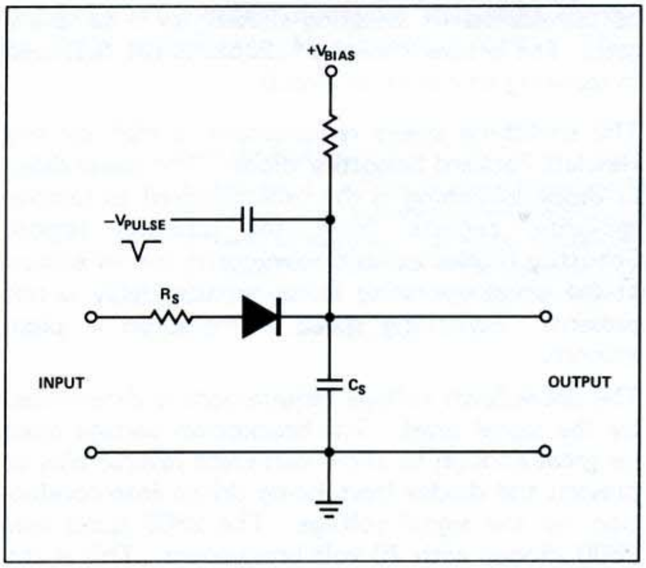

Figure 4. Single Diode Sampling Gate

Sampling Gates

A simple single diode sampling gate is shown in Figure 4. The diode is essentially a switch, normally "open" (diode reverse-biased). A short pulse momentarily closes the switch (diode forward-biased) allowing charge to flow from the source to be stored in the capacitor C_S, which results in a voltage across C_S proportional to the input signal. The pulse width must be narrow compared to the period of the input signal so that the sample corresponds to a specific portion of the input waveform. The capacitor charging time must be fast enough to accept the charge during this pulse time.

The problems of isolation between the signal circuit and the sampling pulse and bias circuits can be serious with the single diode sampler. Figure 5 shows a two diode sampler that simplifies the isolation problem by symmetry. However, this arrangement has a low sampling efficiency due to the voltage drop in the resistors. The efficiency can be improved by substituting two more diodes for the two resistors in the bridge.

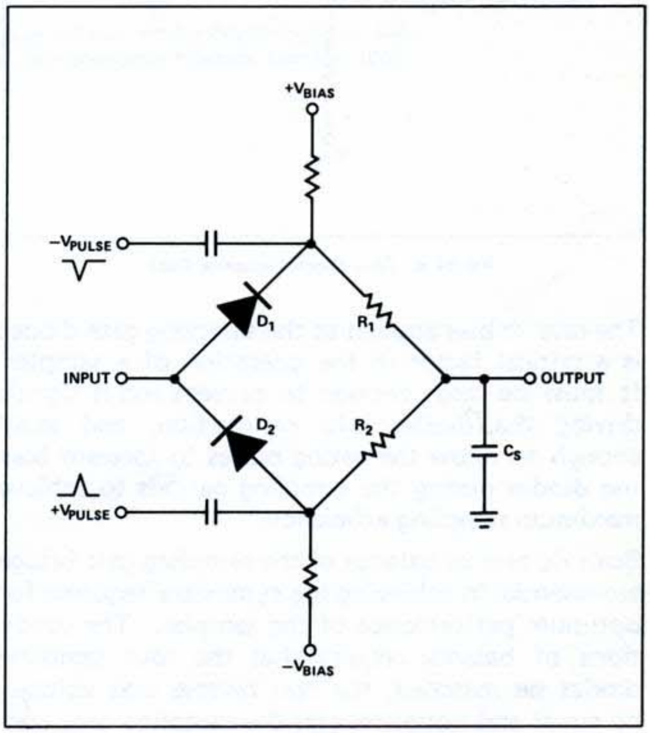

Figure 5. Two Diode Sampling Gate

This four diode sampling gate, shown in Figure 6, is the most commonly used. In a sampling system, it would be situated between the input source and the input capacitor of an amplifier. The diodes are normally reverse biased, so that the input signal does not cause them to conduct. Sampling is initiated with very narrow pulses, which overcome the reverse bias and switch the diodes into conduction. The low impedance paths allow the amplifier input capacitor to be charged to a voltage proportional to the input voltage. Due to the short charging time, the capacitor may not be charged to the full input voltage. (Some systems include feedback control circuits to continue charging the capacitor in between pulses until the capacitor voltage equals the input voltage.) The capacitor remains charged until the next pulse.

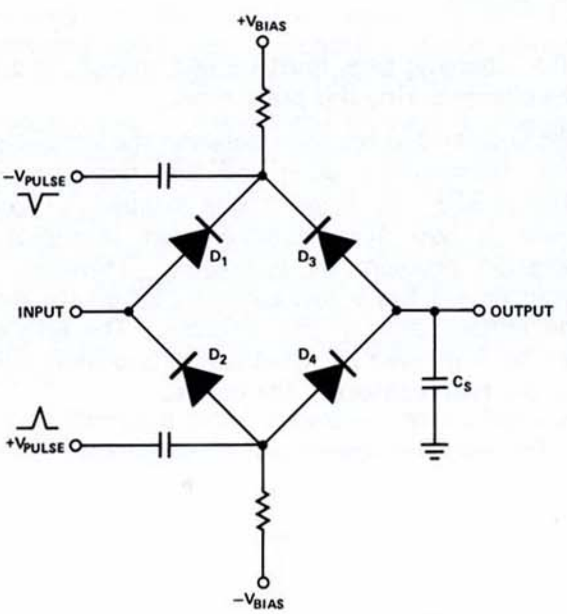

Figure 6. Four Diode Sampling Gate

The reverse bias applied to the sampling gate diodes is a critical factor in the operation of a sampler. It must be large enough to prevent input signals driving the diodes into conduction, and small enough to allow the gating pulses to forward bias the diodes during the sampling periods to achieve maximum sampling efficiency.

Both dc and ac balance of the sampling gate bridge are essential in achieving the symmetry required for optimum performance of the sampler. The conditions of balance require that the four sampling diodes be matched, the two reverse bias voltages be equal and opposite, and the sampling gate control voltage be identical in waveshape except for polarity. One method of providing identical control gate signals is to derive them from identical and bifilar-wound windings of a transformer. A narrow pulse can be produced as a result of differentiation of a rectangular pulse with a small coupling capacitor. If required, pulse risetimes can be reduced with the help of step recovery diodes before coupling through the capacitor. To fulfill the conditions of diode match, Hewlett Packard offers Schottky barrier diode quads, such as the HP 5082-2805 and 5082-2813 composed of diodes with closely matched forward current characteristics. The HP 5082-2826 is a batch matched diode with capacitance match as well as forward current match. In addition, matched quads of the 5082-2835 diode can be provided.

Diode Selection

Regardless of the sampling technique, the sampling device requirements for each of the different applications mentioned are basically the same. Ideally, a sampling gate would be a transmission circuit in which the output is an exact reproduction of an input waveform during a selected time interval and zero otherwise. These requirements dictate certain important device parameters, such as breakdown voltage, switching speed, and turn-on voltage, to be considered in selecting diodes for a sampling gate. The proper choice of diodes is the first step in realizing an optimum circuit.

The switching speed requirement is met by any Hewlett Packard Schottky diode. The usual delay in diode switching is the time required to remove minority carriers from the junction region. Schottky diodes exhibit no minority carrier effects at the usual operating levels, so this delay is not present. Switching speed is measured in picoseconds.

The breakdown voltage requirement is determined by the signal level. The breakdown voltage must be great enough to allow sufficient reverse bias to prevent the diodes from being driven into conduction by the signal voltage. The 2805 quad uses 2800 diodes with 70 volt breakdown. This is the logical choice for high level signal applications. For example, it is used in the HP 4920A Coaxial Fault Analyzer.

High voltage diodes have higher series resistance with correspondingly lower sampling efficiency. Therefore, it is best to use the lowest possible breakdown voltage. Maximum peak carrier voltage is half the breakdown voltage, since the dc bias for maximum signal is set to half the breakdown voltage to prevent breakdown by the signal voltage with resultant diode damage and to prevent forward bias by the signal voltage with resultant leakage of signal past the sampler. Thus, for signal voltage less than 7.5 volts, it is not necessary to use the 2800 type of diode. The 2813 quad with breakdown voltage of 15 volts is more suitable. Below 2.5 volts peak, the 2835 diode with a breakdown voltage of 5 volts should be used.

In addition to better sampling efficiency, the lower breakdown 2835 diode has another advantage when the signal level is so small that dc bias to prevent breakdown or turn-on is not necessary. Because of its lower turn-on voltage, this diode can use a sampling pulse of lower amplitude. A forward voltage of .35 volt will reduce the resistance of the 2835 diode below 15 ohms, while .55 volt is required for the 2811 diode.

There is an intermediate signal level where the higher turn-on voltage of the 2811 diode has an advantage. A peak signal voltage in the region of .4 to .5 volts would require dc bias for the 2835 diode but not for the 2811. This feature could outweigh the improved sampling efficiency of the 2835 in some cases.

A quad with poorly matched diodes would result in loss of isolation between the signal and sampler pulse circuits. The advantages of the bridge over the single diode sampler are lost in this case. Quantitative correlation between degree of matching and sampler performance is difficult to state because it is circuit dependent. The matching provided in Hewlett Packard bridge quads assures dependable operation in this application.

The fast response and uniform characteristics of Schottky diodes make them ideally suited for sampler gates. Diodes with different values of breakdown voltage and turn-on time are available so that the correct model may be chosen for each application.

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SPEED UP TRANSISTOR SWITCHING

Nonsaturating Transistor Switches

The operation of a transistor switching circuit in the saturation region produces fast turn-on times, but slow turn-off times as a result of storage delay. Excess base current needed to drive the transistor into saturation causes an accumulation of stored charge in the base region, which must be removed before the transistor switch can turn off. Various schemes have been devised to overcome the storage delay and speed up switching time by not allowing the transistor switch to attain saturation.

One possible method of avoiding saturation in a transistor switch is shown in the circuit in Figure 7. A capacitor C_d in parallel with the base drive resistor R_d is used to initiate an impulse of current to turn on the transistor. Current through R_d keeps the transistor on. Saturation of the transistor is avoided by charge removal from the base by an impulse of current through C_d. One of the drawbacks of this method is that the output impedance of the preceding stage must be low enough to permit the required peak reverse current to pass.

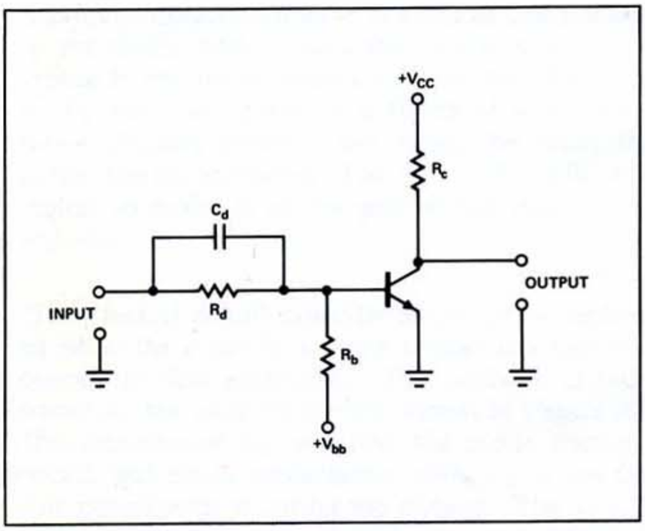


Figure 7. The Use of R-C Drive to Avoid Saturation in a Transistor Switch.

A more effective way of preventing saturation, using Hewlett Packard diodes, is illustrated in the circuit in Figure 8. To insure that the collector to base junction can never become forward-biased (to avoid saturation), it is required that the voltage across diode D_2 be greater than that across diode D_1. In order for the circuit to be useful, the recovery time of diode D_1 must be small in relation to that of the transistor. Circuit operation is based upon nonlinear feedback provided by the two diodes between the collector and base. When the collector current increases as a result of a change in current gain, h_{FE}, the current through diode D_1 increases. This results in some of the base current being diverted from the base, thus preventing saturation. The function of diode D_2 is to allow the base current of the transistor to be channeled through diode D_1 to the collector, even when the collector and base are at the same potential. Although this raises its "on" voltage, the transistor will have a high f_t in its "on" state and a fast turn-off time.

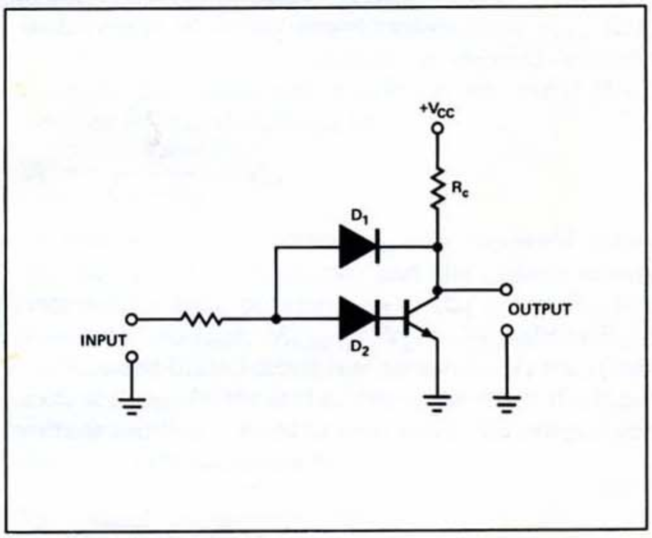


Figure 8. The Use of Diodes as Feedback Elements to Avoid Saturation in a Transistor Switch.

Performance Characteristics

The reduction of storage delay in transistor switching by diode controlled current feedback has been demonstrated in the circuit shown in Figure 9. The input and output pulses with variations in circuit configuration are shown in Figures 10, 11 and 12. In each case, the output pulse is shown inverted to facilitate delay time measurements.

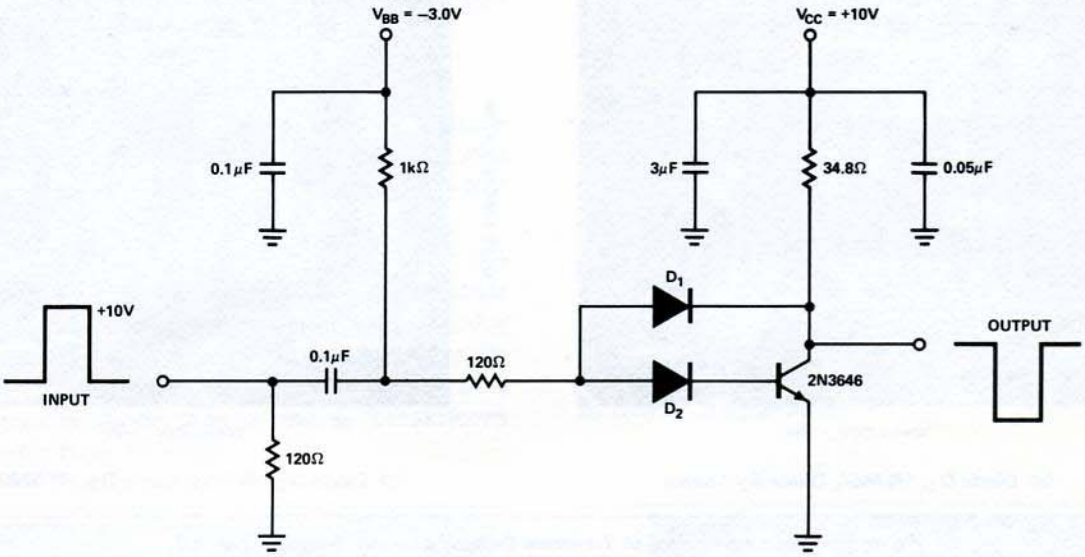


Figure 9. Circuit Used for Measurement of Time Delay in Transistor Switching Circuit with Diode Controlled Feedback.

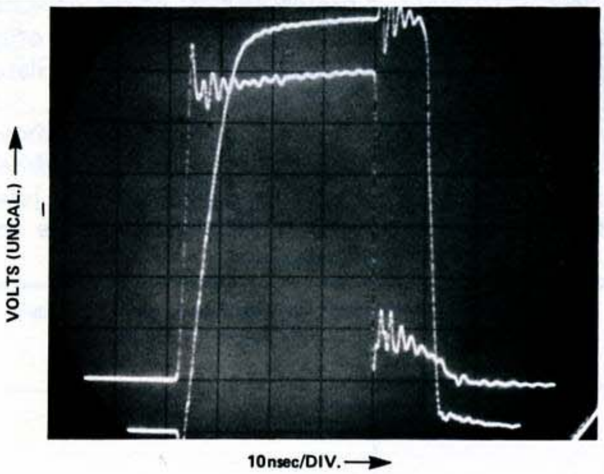
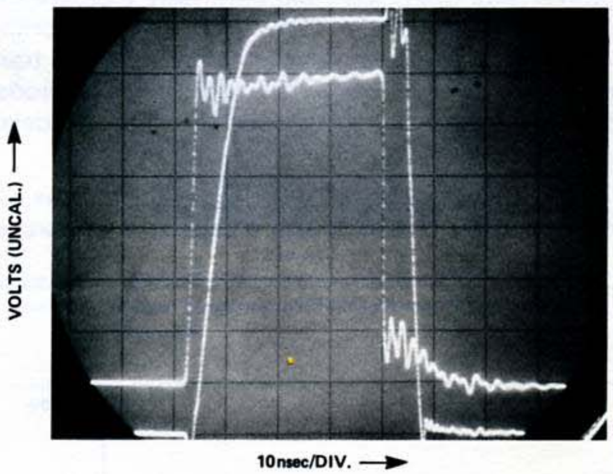


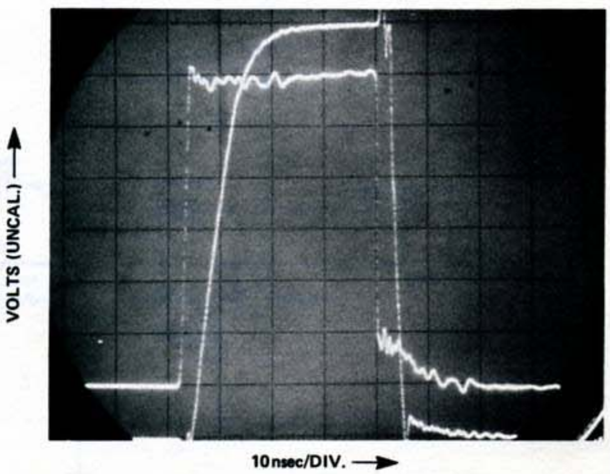
Figure 10. Input and Output of Transistor Switching Circuit Shown in Figure 9 Without Diodes D_1 and D_2 (i.e., D_1 open, D_2 shorted).

It can be seen from Figure 10 that without the aid of any diodes, (i.e., with D_1 open and D_2 shorted), the turn-off delay at the half voltage point is 11 nanoseconds. Using an HP 5082-2811 Schottky diode as D_1 but without D_2, the delay is reduced to 6 nanoseconds as shown in Figure 11(a). The addition of an HP 5082-3001 PIN diode as D_2 results in a further reduction of the delay to 3.5 nanoseconds as seen in Figure 11(b).

The response of the circuit using a 1N4454 PN junction diode as D_1 is illustrated in Figure 12. With D_2 absent, the turn-off delay is 12 nanoseconds, Figure 12(a), which is longer than the de-



(a) Diode D_1, HP 5082-2811; Diode D_2 Absent



(b) Diode D_1, HP 5082-2811; Diode D_2, HP 5082-3001

Figure 11. Input and Output of Transistor Switching Circuit Shown in Figure 9.

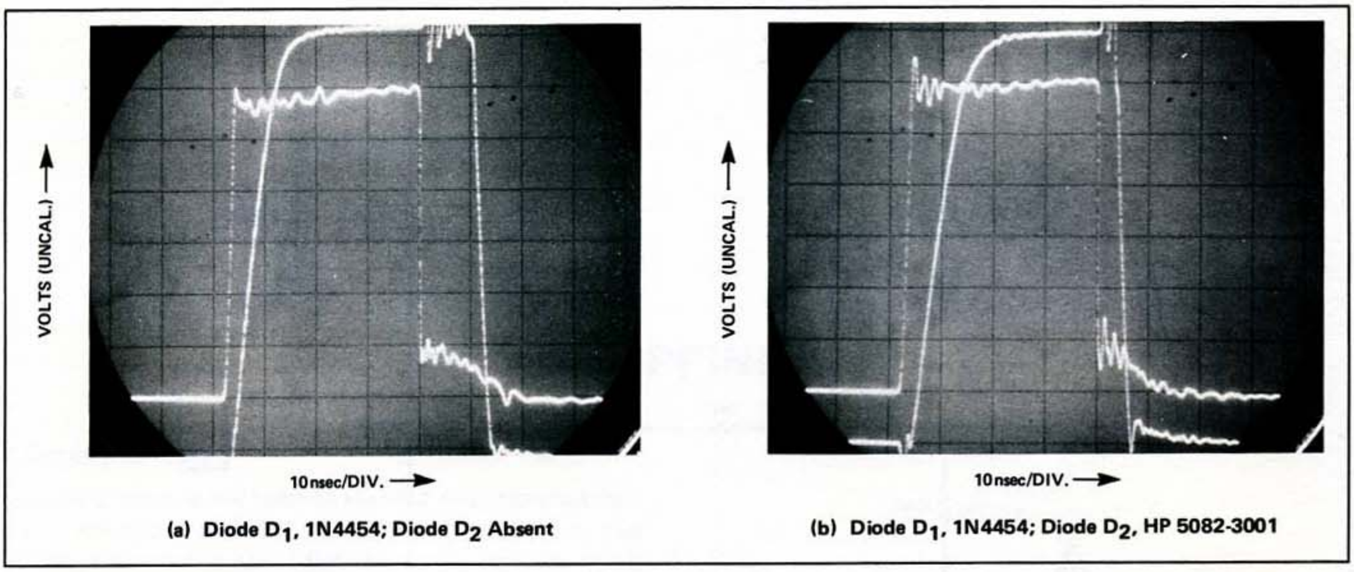


Figure 12. Input and Output of Transistor Switching Circuit Shown in Figure 9.

lay without diodes. With the addition of an HP 5082-3001 PIN diode as D_2, the delay is 4.5 nanoseconds, Figure 12(b).

The foregoing observations definitely indicate the superiority of the Schottky barrier–PIN combination as feedback elements in a nonsaturating transistor switching circuit. The use of these diodes in the circuit helps to reduce the turn-off delay by 70%.

The circuit shown in Figure 13 incorporates the use of both diode feedback and a capacitor in parallel with the base drive resistor. This combination helps to achieve a turn-off delay of less than 2 nanoseconds as shown in Figure 14.

The high f_t and fast switching time of the nonsaturating transistor switch suggest the feasibility of its application in an oscillator. Such an R-C oscillator (multi-vibrator) is illustrated in Figure 15. Its output waveform, pictured in Figure 16, shows the frequency of oscillation to be 66MHz. When the PIN diode is replaced by the 1N4454 PN junction diode, the increased delay reduces the fre-

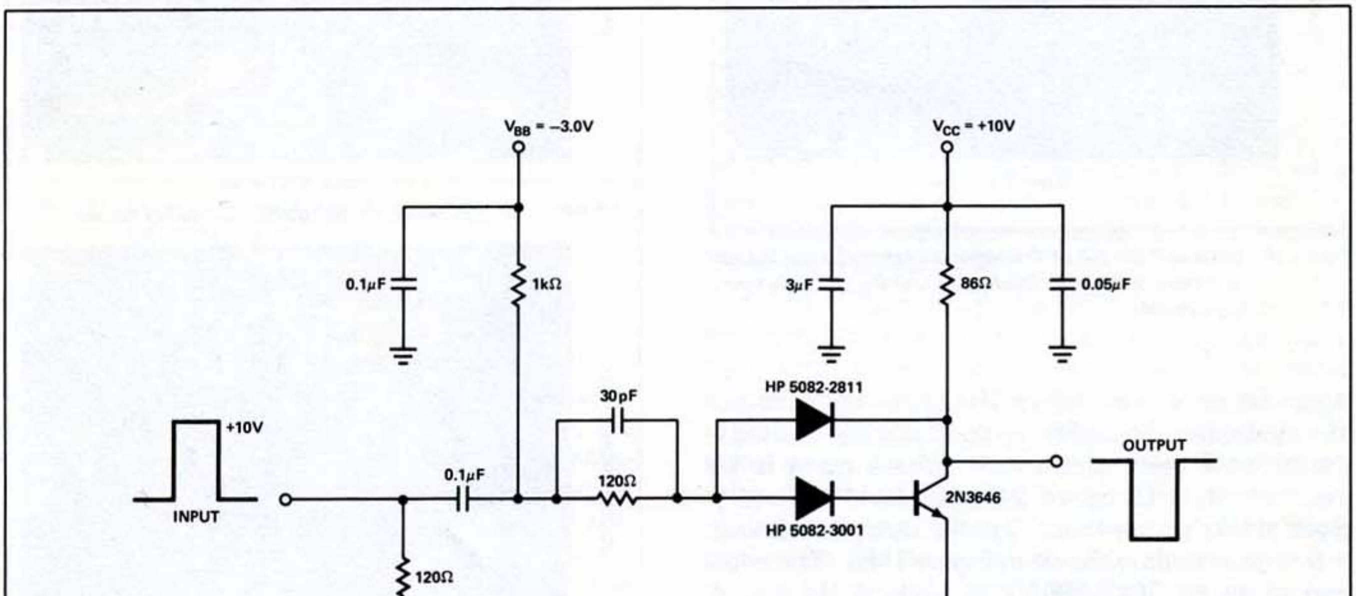


Figure 13. Nonsaturating Transistor Switch Using R-C Drive and Diode Controlled Feedback

quency to 33MHz. Higher frequencies can be achieved when the faster HP 5082-3042 PIN diode is substituted for the HP 5082-3001.

Diode Considerations

The problems of speed, charge storage, and voltage levels can be overcome with proper choice of diodes that are to be used in a nonsaturating transistor switching circuit.

The HP 5082-2811 is ideally suitable for use as the clamp diode D_1. Being a hybrid device, it consists of a conventional PN junction and two Schottky barrier junctions. This type of construction results in a low turn-on voltage, fast switching speed of a Schottky barrier diode, and a reverse breakdown voltage greater than 15 volts.

Diode D_2 must have a forward voltage drop greater than that of diode D_1 and also possess charge storage capability. Either the HP 5082-3001 or the HP 5082-3042 PIN diode can be used to perform the functions of diode D_2. The HP 5082-3042 is the faster of the two and is capable of higher frequency operation.

Summary

Significant reduction in transistor switching delay time can be achieved by adding a Schottky diode and a PIN diode to the transistor switching circuit. This improvement in switching performance also extends the oscillator capability of the transistor to higher frequencies.

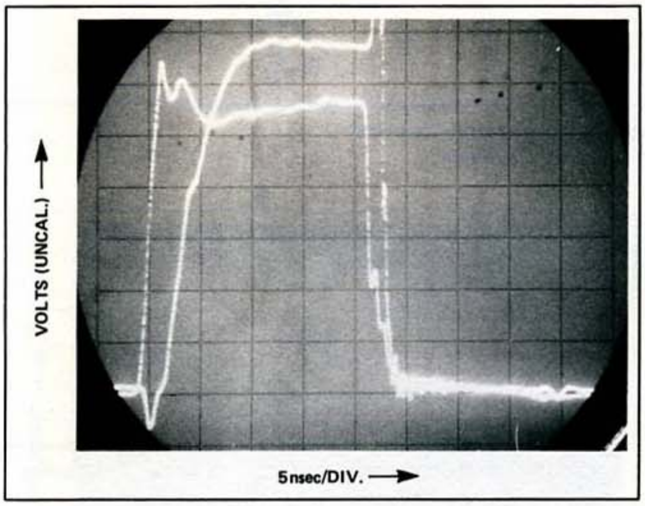


Figure 14. Input and Output of Transistor Switching Circuit Shown in Figure 13.

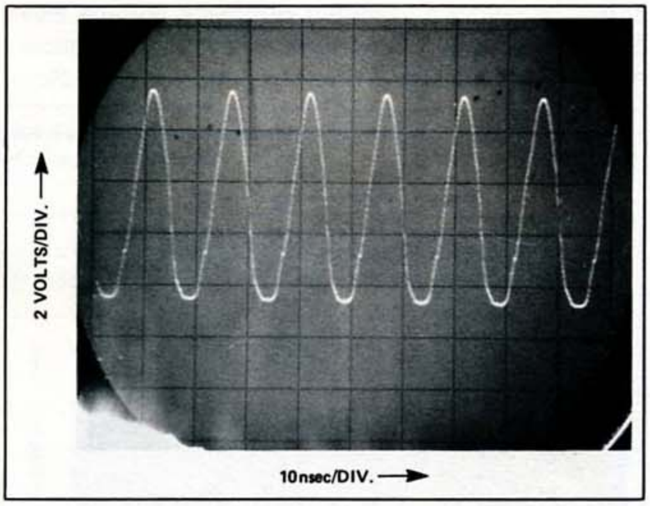


Figure 16. Output Waveform of R-C Oscillator Circuit Shown in Figure 15.

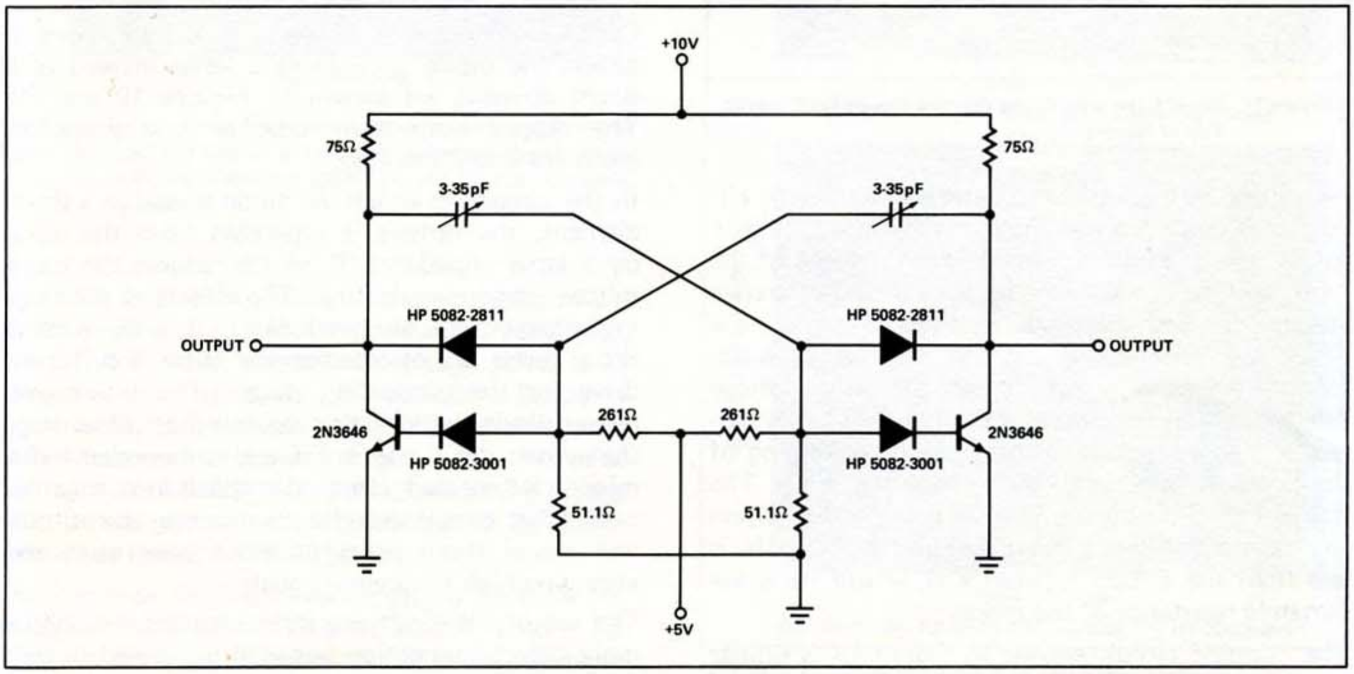


Figure 15. Use of Nonsaturating Transistor Switches In An R-C Oscillator Circuit.

CLIPPING

Clipping Circuits

Clipping circuits are used to restrict the transmission of a voltage waveform to that portion which lies above or below a specified reference voltage level. Because of their functions, they are sometimes referred to as voltage limiters or amplitude selectors.

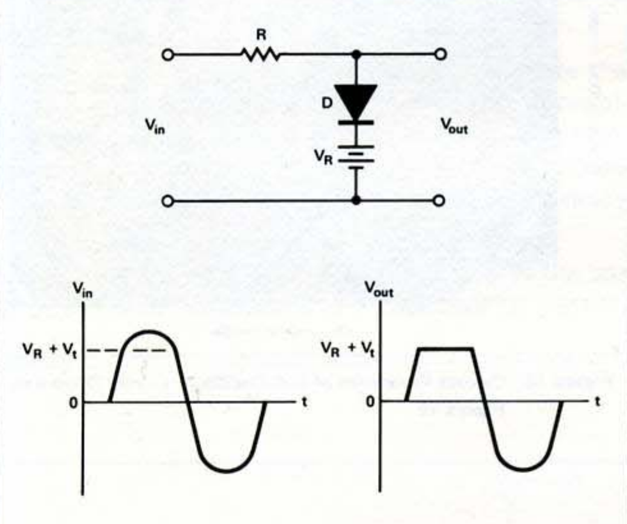


Figure 17. Shunt Connected Diode Clipping Circuit for Clipping Top of Waveform.

Illustrated in Figure 17 is a basic diode clipping circuit and its output waveform in response to a sinusoidal input. While the instantaneous value of the input voltage is less than the sum of the reference voltage V_R and the diode turn-on voltage V_t, the diode is reverse-biased off, and the output waveform follows the input. When the input voltage becomes equal to or greater than $V_R + V_t$, the corresponding output waveform exhibits clipping of the positive peak above the voltage $V_R + V_t$. The flatness of this clipped portion is dependent upon the degree that the forward biased resistance R_f is less than the circuit resistance R, where R_f is the dynamic resistance of the diode.

The clipping circuit shown in Figure 18 is similar to the one in Figure 17 except for the polarity of the diode. The output of this circuit is clipped below the voltage $V_R - V_t$.

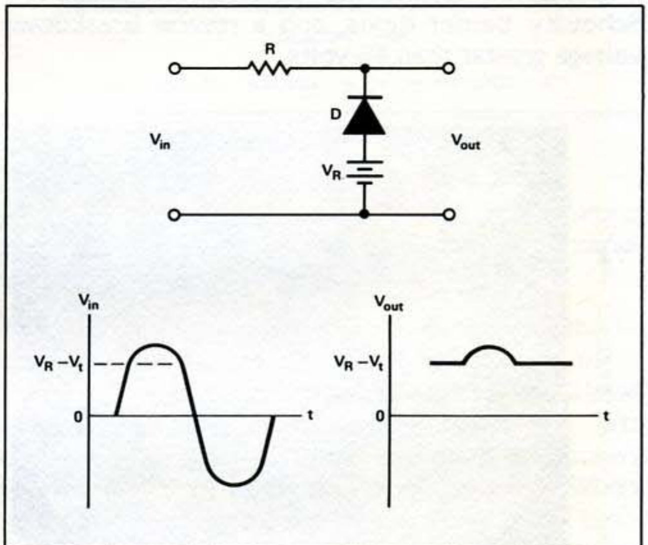


Figure 18. Shunt Connected Diode Clipping Circuit for Clipping Bottom of Waveform.

Other configurations of basic clipping circuits in which the diode appears as a series instead of a shunt element are shown in Figures 19 and 20. The clipped outputs in response to a sinusoidal input are also illustrated.

In the circuits in which the diode is used as a shunt element, the output is separated from the input by a large impedance R, which reduces the transmitted signal appreciably. The effects of this large impedance may be overlooked, if only relative signal levels are of interest and there is sufficient drive for the succeeding stage. The shunt connected diode configuration also has the disadvantage that when the diode is off and unimpeded transmission is expected, the diode capacitance, together with other circuit capacitance shunting the output, will round sharp edges of input waveforms and attenuate high frequency signals.

The use of the diode as a series element results in a more direct connection between input and output during the transmission period when the diode is

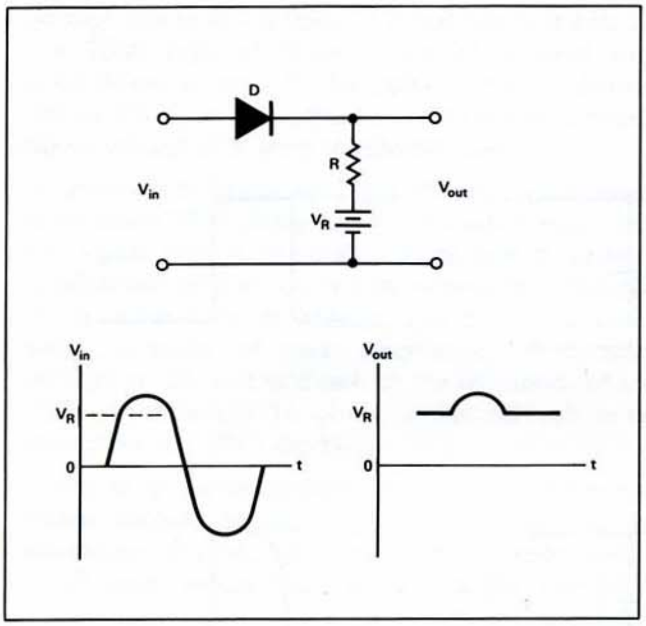


Figure 19. Series Connected Diode Clipping Circuit for Clipping Bottom of Waveform.

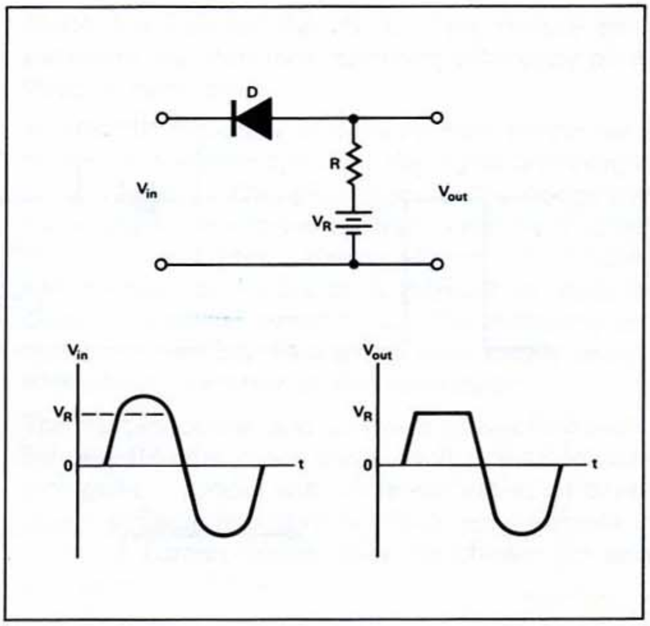


Figure 20. Series Connected Diode Clipping Circuit for Clipping Top of Waveform.

conducting. However, when the diode is off and it is intended that there be no transmission, fast signals and high frequency waveforms may find a low impedance path between input and output through the diode capacitance. In high power clippers requiring dissipation of large amounts of energy, it is difficult to heat sink a series connected diode.

Double ended clipping (limiting) of signal waveforms can be accomplished with the use of a pair of diode clippers in a parallel series, or series-parallel configuration. Such a circuit with its input and output voltage waveforms is illustrated in Figure 21. When the input voltage is negative and less than $-(V_{R1} + V_{t1})$, diode D_1 is conducting and diode D_2 is off. In this state the output is clamped to the voltage $-(V_{R1} + V_{t1})$. As the input voltage rises greater than $-(V_{R1} + V_{t1})$ but less than $V_{R2} + V_{t2}$, both diodes are off and the output follows the input. When the input voltage is larger than $V_{R2} + V_{t2}$, D_1 is off and D_2 is on. The output is thus clamped to $V_{R2} + V_{t2}$. If V_{R1} is made equal to V_{R2} and the amplitude of the sinusoidal input is sufficiently high, a square wave will be approached in the output. This application is in essence sine wave to square wave conversion.

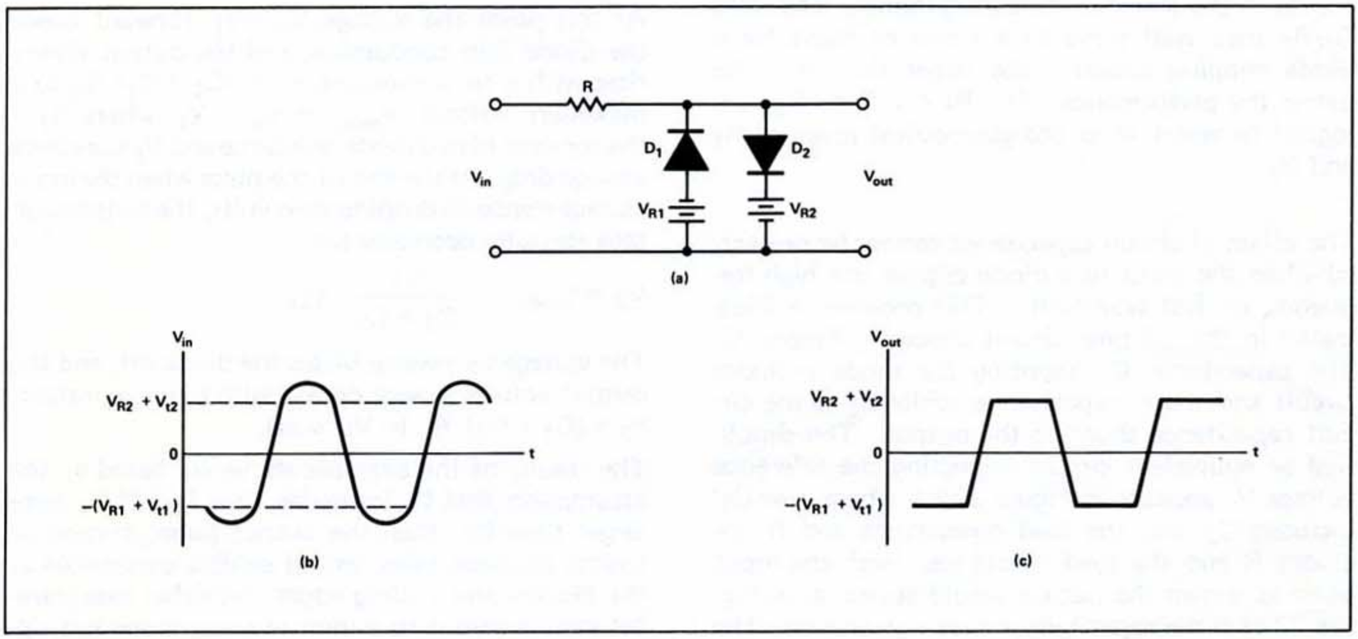


Figure 21. Double-Ended Diode Clipping Circuit with Input and Output Voltage Waveforms (Sine Wave to Square Wave Conversion).

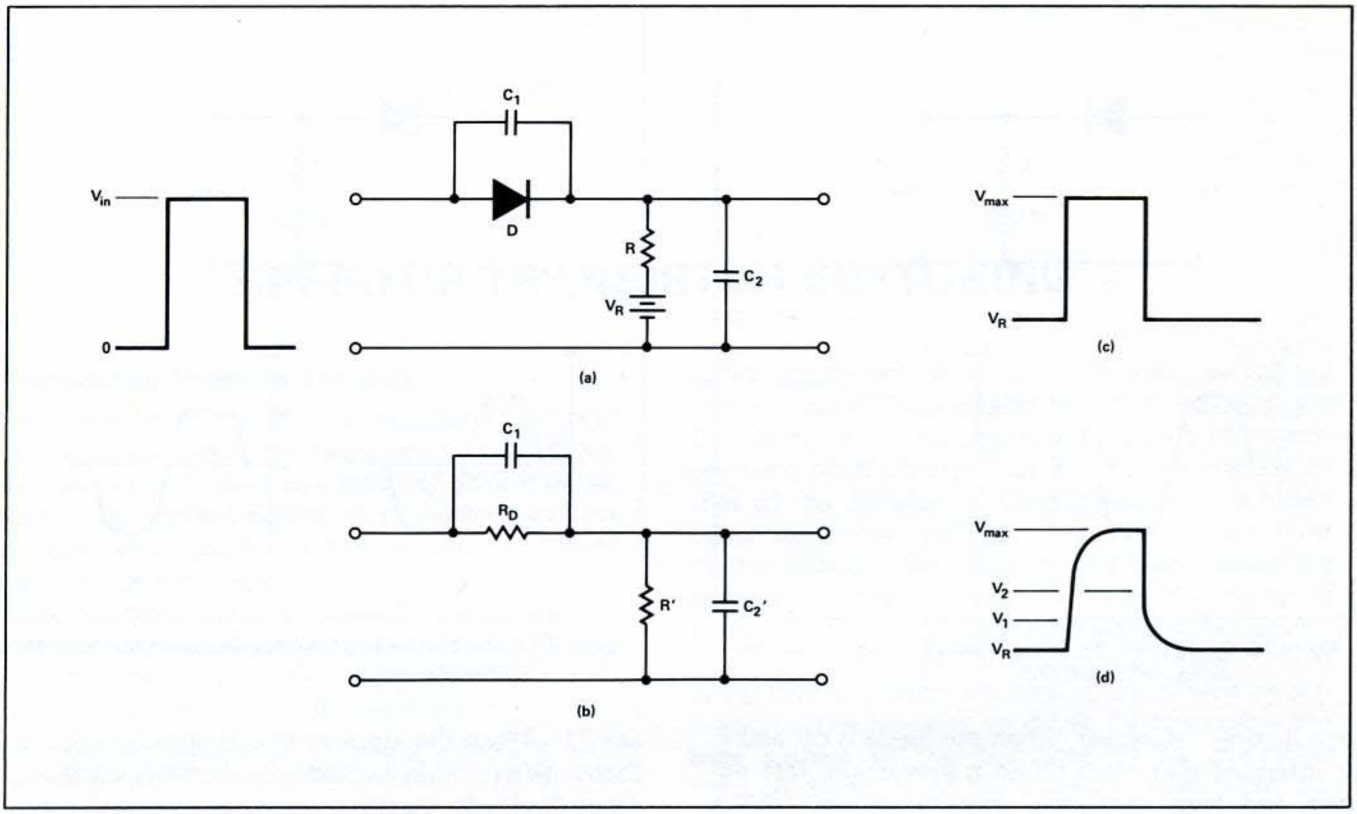


Figure 22: (a) Diode Clipping Circuit with Pulse Input, (b) Simplified AC Equivalent Circuit, (c) Output Without Capacitance in Circuit, (d) Actual Output with Capacitances in Circuit.

Circuit Requirements

In all the foregoing described clipping circuits it is required that the forward-biased diode resistance R_f be much less than the circuit resistance R and the reverse-biased resistance R_r be much larger than R. These requirements are important in providing maximum isolation between the source and the load in the series diode circuit and precise voltage reference in the shunt diode configuration. The ratio R_r/R_f may well serve as a figure of merit for a diode clipping circuit: the larger the ratio, the better the performance. For $R_f << R << R_r$, it is logical to select R as the geometrical mean of R_f and R_r.

The effect of circuit capacitance cannot be neglected when the input to a diode clipper is a high frequency or fast waveform. This problem is illustrated in the clipping circuit shown in Figure 22. The capacitance C_1 shunting the diode includes circuit and diode capacitance, while C_2 is the circuit capacitance shunting the output. The simplified ac equivalent circuit neglecting the reference voltage V_r appears in Figure 22(b), where now C_2' includes C_2 and the load capacitance and R' includes R and the load resistance. With the input pulse as shown the output would appear as in Figure 22(c) if the capacitances were not present. The actual output is shown in Figure 22(d).

Initially, under steady state conditions, when the input is zero the output voltage is V_R. Then the input pulse abruptly rises to the voltage V_{in}. With negligible source impedance, a current impulse through the capacitors results in an initial sharp increase in output voltage to:

$$V_1 = \frac{C_1}{C_1 + C_2} V_{in}$$

At this point the voltage $V_{in} - V_1$ forward biases the diode into conduction, and the output slowly rises with a time constant, $\tau_1 = (C_1 + C_2) R_f$, to a maximum voltage, $V_{max} = V_{in} - V_f$, where R_f is the forward-biased diode resistance and V_f the diode voltage drop. At the end of the pulse when the input voltage suddenly drops to zero volts, the output voltage abruptly decreases to:

$$V_2 = V_{max} - \frac{C_1}{C_1 + C_2} V_{in}$$

The voltage V_2 reverse biases the diode off, and the output voltage slowly decays with a time constant, $\tau_2 = (C_1 + C_2) R'$, to V_R volts.

The results of the example above are based on the assumption that C_1 is smaller than C_2. If C_1 were larger than C_2, then the output pulse, instead of having rounded sides, would exhibit overshoots at the leading and trailing edges. In either case, careful circuit layout to minimize capacitance is a significant factor in optimizing performance.

Diode Considerations

The realization of a clipping circuit to give the optimum performance demands fulfillment of certain requirements in circuit design and considerations in diode selection. The significance of passive circuit elements and their effects on performance characteristics have already been discussed. Inseparably related to those factors are diode parameters such as forward biased resistance R_f, reverse biased resistance R_r, and capacitance C. Other important considerations not yet mentioned include breakdown voltage, switching speed, and temperature characteristics.

To achieve nearly ideal clipping performance, the importance of a high R_r/R_f ratio has been discussed. Hewlett Packard Schottky barrier diodes of the HP 5082-2800 series typically have very high ratios:

	Typical R_r/R_f
HP 5082-2800	10^7-10^8
HP 5082-2810	10^6-10^7
HP 5082-2835	10^5-10^6

This data is based on a reverse bias of 5-10 volts and a forward bias of 100μA to 10mA.

To minimize capacitance for the least distorted output, Schottky barrier diodes of the 2800 series add little capacitance to clipping circuits. The total capacitance of the 2835 diode is less than 1 picofarad, the 2810 and 2811 less than 1.2 picofarads, and the 2800 less than 2.0 picofarads.

Depending on the power level of operation, a choice of diode can be made from the 2800 series to provide the breakdown voltage required. For a high power clipper, the 2800 diode has a minimum breakdown voltage of 70 volts. For clipping at moderate power levels, the 2810 and 2811 have, respectively, minimum breakdown voltages of 20 and 15 volts. The 2835 with a minimum breakdown voltage of 5 volts is ideal for low level clipping.

The low turn-on voltage of the 2800 series Schottky barrier diodes allows a more precise voltage reference, particularly when using the 2835 since it has the lowest turn-on voltage. Furthermore, the variation of V-I characteristics with temperature is consistently predictable, so that design allowances compatible to a particular operating temperature range can be made.

The characteristics of the hybrid Schottky barrier diodes make them ideally suited for use in clipping circuits. The low minority carrier lifetimes and the fast switching speeds of the diodes are useful for high frequency operation. Diodes with slightly different features are available, so that a proper choice can be made for any particular application.

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CLAMPING

Clamping Circuit

In general, when a point in a circuit is connected through a low impedance path (such as through a forward biased diode) to a reference voltage V_R, that point is said to be clamped to V_R, since the voltage at that point cannot deviate very much from V_R, except perhaps for a small voltage drop across the diode. In this sense, the diode clipping circuits described in the previous section are also clamping circuits. In the section on Speed-Up Transistor Switching, a Schottky diode clamp is used to prevent saturation in the transistor.

When a signal is transmitted through a capacitive coupling network, its dc component is lost, and a clamping circuit is used to introduce a dc component. For this reason a clamping circuit is often referred to as a dc restorer or level shifter. Thus the main distinguishing feature between a clamping circuit and a clipping circuit is that in a clamp the input signal's dc level is not maintained in the output.

A basic clamping circuit together with its input and output waveforms is illustrated in Figure 23. If the diode were removed, the output waveform would have both positive and negative swings from the dc level at zero regardless of the dc level of the input, because of the capacitor. The presence of the diode in the polarity shown permits only negative excursions of the output waveform with the positive peaks clamped at zero (or more precisely V_t volts above zero, if the diode drop is taken into account).

If the resistor R were not in the circuit in Figure 23, the capacitor C would charge after a few cycles to a voltage, such that the positive peaks of the output waveform are clamped to zero. The diode would never need to conduct again unless there is an increase in input. As long as there is no reduction in input, the resistor R is not needed. When there is a decrease in input, the resistor R is needed to discharge the capacitor sufficiently to follow the input voltage. To allow for charge leakage from the capacitor, the positive excursions are not clamped to zero, but slightly above.

For simplicity the output waveform illustrated in Figure 23 for the clamping circuit is based on the

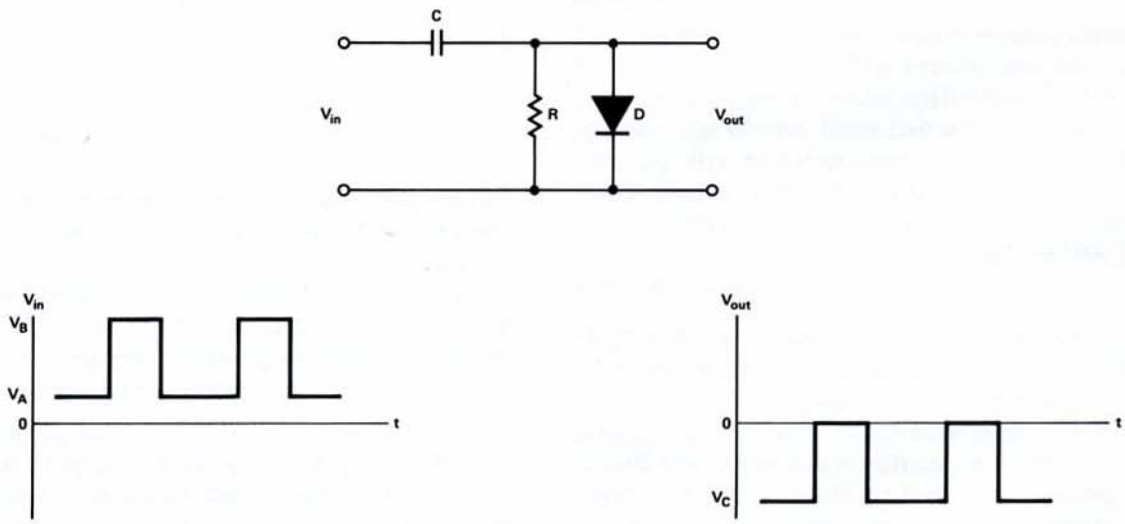

Figure 23. Basic Clamping Circuit with Input and Output Waveforms

assumption of an ideal diode in an ideal circuit. The actual waveform may appear as in Figure 24. Since the diode is conducting during the interval, t_1, the output decays with a time constant $\tau_1 = (R_f + R_S)\ C$, where R_f is the diode's forward biased resistance and R_S the source resistance.

Thus: $V_1' = V_1\ e - t_1/(R_f + R_S)C$ (1)

Similarly, in the interval t_2 when the diode is reverse biased, the output decays according to the time constant $\tau_2 = (R + R_S)\ C$, resulting in

$V_2' = V_2\ e - t_2/(R + R_S)\ C$ (2)

If the source resistance $R_S = 0$, then the input and output amplitudes are equal; i.e.:

$V_1 - V_2' = V_B - V_A$ (3)

$V_1' - V_2 = V_B - V_A$ (4)

From the four equations, the voltages V_1, V_1', V_2 and V_2' can be determined.

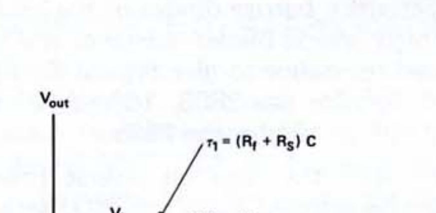

Figure 24. Actual Output Waveform of Clamping Circuit in Figure 1.

In general since R_S is not zero, equations (3) and (4) must be modified to account for the attenuation of the input appearing at the output according to the voltage divider formed by the source and output resistances. When the diode is conducting, the fraction of the input appearing at the output is $R_f/(R_f + R_S)$; when the diode is reverse biased, the fraction is $R/(R + R_S)$. Hence, equations (3) and (4) become:

$$\frac{R_f + R_S}{R_f} V_1 - \frac{R + R_S}{R} V_2' = V_B - V_A$$

$$\frac{R_f + R_S}{R_f} V_1' - \frac{R + R_S}{R} V_2 = V_B - V_A$$

As in the case of clipping circuits, the optimum performance of clamping circuits is strongly dependent on the relationship that $R_f << R << R_r$.

Circuit Suggestions

In order for the positive and negative peaks of the output to achieve near perfect flatness, a very large capacitor C would be required. In practice, when $t_1 >> (R_f + R_S)\ C$ and $t_2 << (R + R_S)\ C$, an output waveform with fairly flat peaks can be obtained as shown in Figure 25. In the very short time that the capacitor recharges through the conducting diode, there is a small overshoot in the positive peak. During the remainder of the interval t_1 the output is essentially flat. In the interval t_2 when the diode is reverse biased, there is a slight tilt in the output.

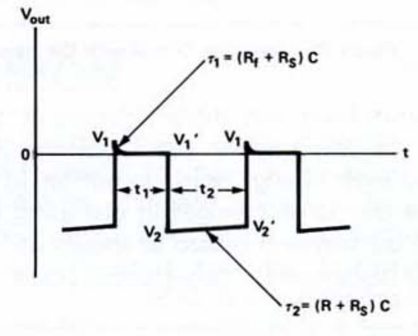

Figure 25. Output Waveform of Clamping Circuit with Square Wave Input and $t_1 >> (R_f + R_S)\ C$, $t_2 << (R + R_S)\ C$

In the clamping circuit of Figure 23, if the polarity of the diode is reversed, the negative rather than the positive peaks of the square wave will be clamped to zero. The addition of a reference voltage V_R as shown in the circuit of Figure 26 will clamp the negative peaks of the output waveform to the voltage V_R. In a practical situation the resistance R would be the input resistance of the succeeding stage, in which case R would be shunting both the diode and the reference voltage. As a result the circuit will function properly only if the input voltage levels V_A and V_B relative to the reference voltage V_R are adequate, respectively, to forward and reverse bias the clamping diode.

The clamping voltage level V_C varies with input level V approximately according to the relation,

$$\Delta V_C = n \frac{kT}{q} \frac{\Delta V}{V} \quad \text{where}$$

n is ideality factor $\simeq 1$

k is Boltzman's constant = 1.38×10^{-23} (joule/^oK)

T is temperature in degrees Kelvin (^oK)

q is electron charge = 1.6×10^{-19} coulomb

This equation indicates that the variation of clamping level with input level to be reduced at increased input levels. This relationship is valid, since at a

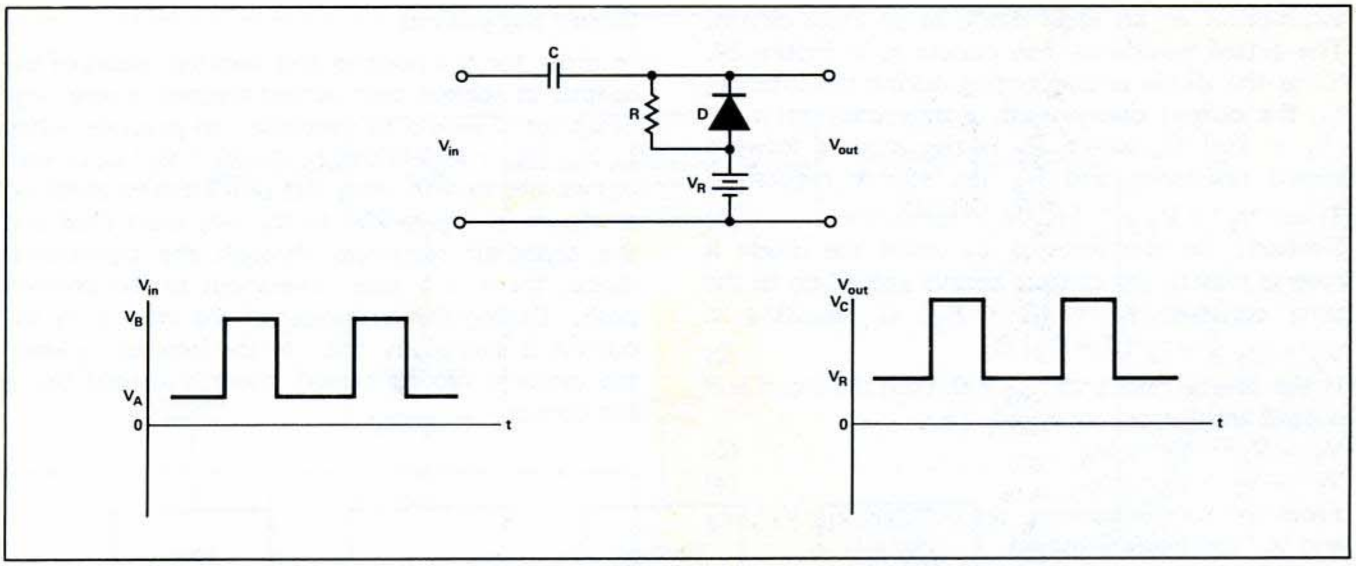

Figure 26. Clamping Circuit with the Negative Peaks of the Output Waveform Clamped to a Reference Voltage V_R.

higher input level the diode clamps at a steeper slope on its volt-ampere curve, where there is a smaller voltage change with variation in current. Thus, to avoid large changes in clamping level, the diode can be forward biased as shown in Figure 27 to operate higher on its volt-ampere curve.

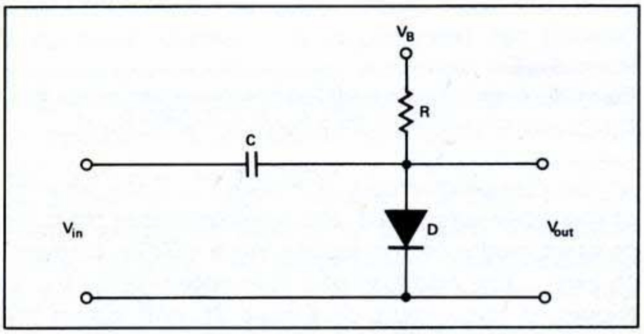

Figure 27. Clamping Circuit in which the Diode is Forward Biased to Operate Higher on its Volt-Ampere Curve to Avoid Large Changes in Clamping Level.

Diode Characteristics

Diode characteristics essential to the design of a properly functioning clamping circuit are similar to the requirements for a clipping circuit.

The significance of a high R_r/R_f ratio in relation to clamping performance has been mentioned. Hewlett Packard Schottky barrier diodes of the 2800 series have the high reverse biased resistance and low forward biased resistance to give typical R_r/R_f ratios of 10^7 to 10^8 for the 2800, 10^6 to 10^7 for the 2810, and 10^5 to 10^6 for the 2835.

The diode with the required reverse breakdown voltage can be selected from the 2800 series. The 2800 has a minimum breakdown voltage of 70 volt for high voltage applications. The 2810 has a reverse breakdown of 20 volts. The 2835 with a minimum breakdown of 5 volts is suited for low level applications.

The low turn-on voltage of the 2800 series Schottky barrier diodes (particularly the 2835) allows clamping more closely to a desired reference level. The fast switching speeds and low minority carrier lifetimes of these diodes make them suitable for high frequency applications.

Diode characteristics required in the design of a clamping circuit to achieve optimum performance can be found in Hewlett Packard Schottky barrier diodes. The manufacturing process used in the production of these diodes gives vituralIy absolute reproducibility of characteristics from one diode to the next. This feature can be added to the list of essentials required in producing clamping circuits for high volume applications.

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