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Author
Mack, Dick A.

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UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence Radiation Laboratory

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Introduction

Pulse-amplitude discriminators are useful in nuclear counting to separate signals of greater amplitude from a background of unwanted or noise signals of lesser amplitude. As used here, the term "fast" implies circuits capable of responding to pulses between a nanosecond and a microsecond in duration. An ideal discriminator would produce for any incoming signal whose amplitude is greater than a threshold bias level, an output pulse of constant amplitude, duration, and delay with respect to the input signal, regardless of the incoming duration and rate; and for signals less than the threshold, zero output. This may be expressed algebraically as follows: Let U be the output pulse defined above.

For $e_{in} = E_t$ and $\frac{de_{in}}{dt}$ positive, $E_o = U$

For all other conditions, $e_o = 0$,

where e_{in} = input pulse,

E_t = threshold bias level,

e_o = output signal.

Obviously, practical circuits operate well only for limited operating ranges.

Present discriminator circuits are subject to some operating limitations. The most common limitations usually are: the maximum counting rate, the threshold stability as affected by time and changes in temperature, the variation in delay as a function of signal amplitude above the threshold, and the "sharpness" of the discrimination characteristic (i.e., the difference in levels at which the circuit just does and just does not produce an output signal). In describing the performance of a discriminator it is important to specify the ranges for which satisfactory operation may be expected.

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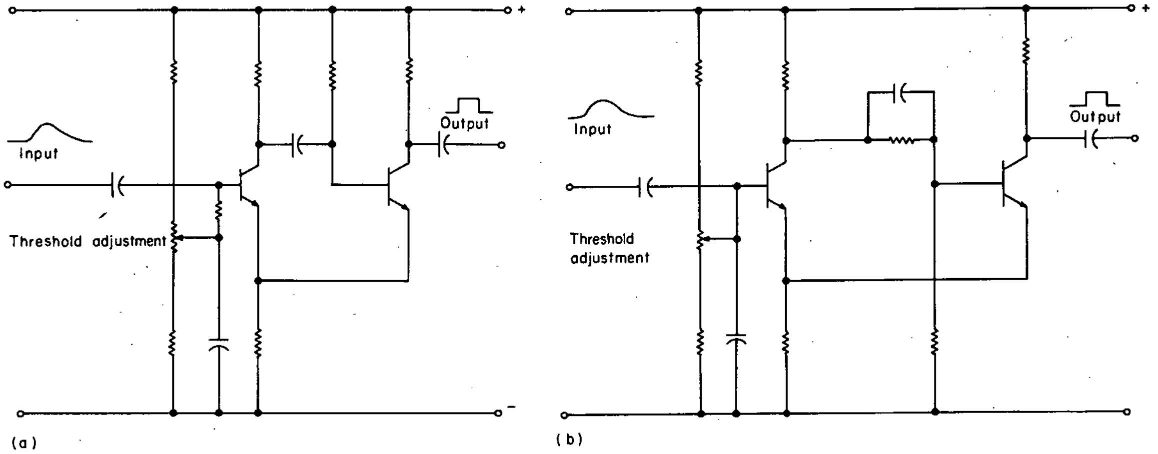

Fig. 1. Simple discriminator circuits
(a) Monostable multivibrator
(b) Schmitt trigger

Basic Circuits

It was not until about 1959 that transistor circuits matched electron-tube versions for speed of response. However, because of continuing improvements in gain-bandwidth product for transistors and the introduction of new solid-state devices, such as the tunnel diode, it is expected that most improvements in stability and response time will be made by using circuits employing solid-state components. For this reason, emphasis here is placed on semiconductor devices.

Normally, a discriminator combines at least three circuit functions: a nonlinear element, a means for obtaining threshold reference level, and a trigger circuit producing a standardized output pulse. The nonlinear element is usually either a diode, the emitter-base characteristic of a transistor, or the grid-cathode characteristic of an electron tube. The threshold voltage or current reference, which is often adjustable, is derived from a stabilized supply. Trigger circuits may assume a variety of forms. Some of the more common circuits are: the monostable multivibrator[1] (one-shot), the Schmitt trigger,[2] and the secondary-emission tube trigger.[3] Discrimination is obtained when the incoming signal has sufficient amplitude to overcome the threshold bias, thus moving the operating point around the "knee" of the nonlinear device to allow sufficient flow of signal energy to actuate the trigger circuit.

In simple discriminators the nonlinear device is often part of the trigger circuit. Figure 1 illustrates transistor versions of one type of monostable multivibrator, and the Schmitt trigger. Electron-tube versions of these circuits suffer from drift because of variations in heater-supply potentials, and tube aging. Kandiah states that a circuit set to operate with signals greater than 2 v will show about 5% change in threshold stability because of heater-voltage variations.[4] He describes an excellent method for reducing the effects of heater variations by using a clamp diode whose forward impedance normally shunts the plate-load resistance of one of the tubes of the regenerative circuit (see Fig. 2). Both pentodes V-2 and V-3 are normally conducting; however, the circuit is designed so that it will not trigger until the input signal overcomes the threshold sufficiently to lower the plate potential on V-2 and increase the impedance of diode V-1. When this occurs, the loop gain of the circuit is increased to the point where the circuit regenerates.

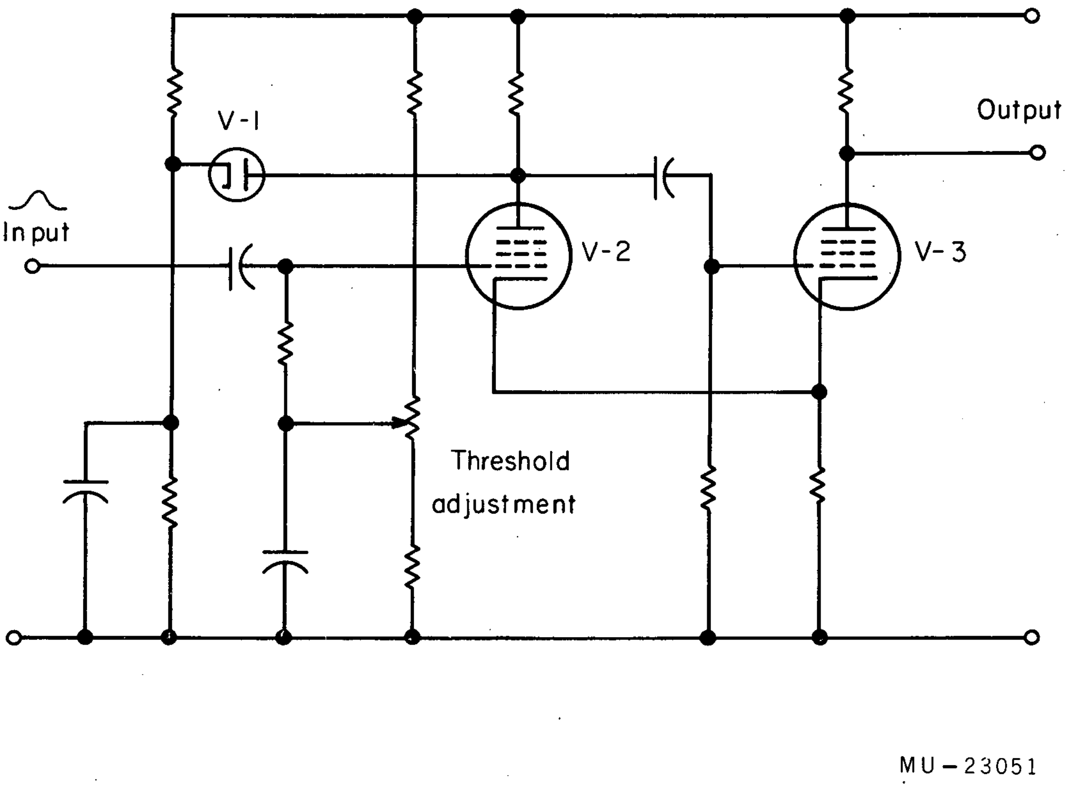

Fig. 2. Trigger circuit using Kandiah diode for improved stability.

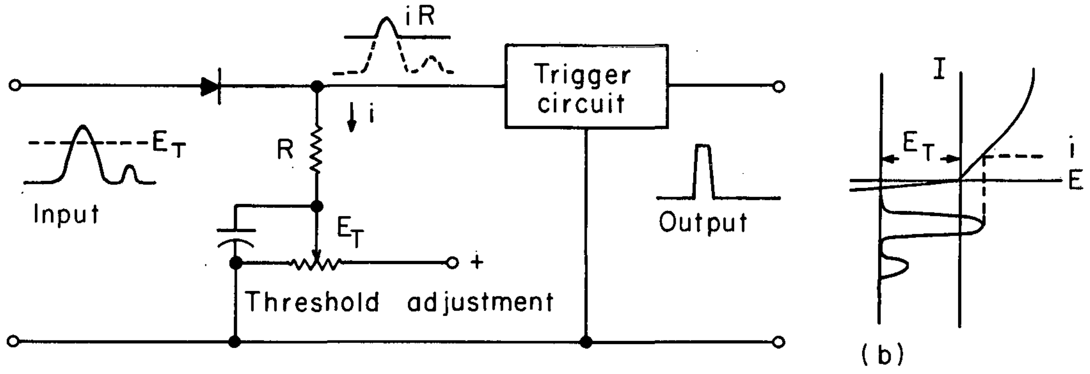

Fig. 3. Discriminator employing series threshold diode
(a) Simplified circuit
(b) Diode operating characteristic

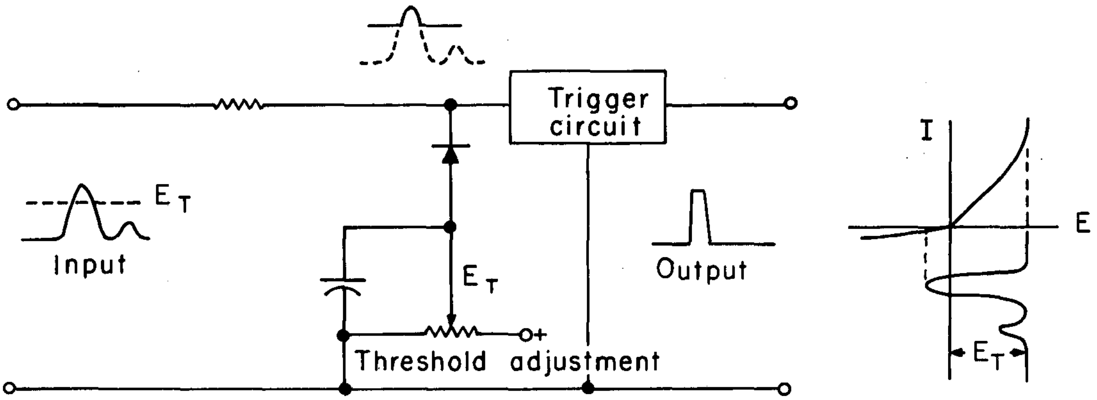

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Fig. 4. Discriminator employing shunt threshold diode
(a) Simplified circuit
(b) Diode operating characteristic

With further refinements a threshold of less than 100 mv is obtained with a stability within 2%.

Transistor circuits are not troubled by heater problems but do suffer from temperature effects, because of the dependence of collector cutoff current (I_{CBO}) and forward base-to-emitter junction voltage (V_{EB}) upon temperature. I_{CBO} approximately doubles for each 8°C rise in junction temperature, whereas V_{EB} may have a temperature coefficient of -2.0 to -2.5 mv/°C.[5] These effects can be minimized by appropriate temperature-compensating circuits.[6] Transistor characteristics also slowly degrade with time. This effect can be almost eliminated by selecting units with a good margin of safety for the parameters, such as current gain (β) and collector cutoff current (I_{CBO}).

Both tube and transistor trigger circuits similar to those illustrated in Fig. 1 suffer from "feed-through" effects, i.e., signals with less than sufficient amplitude to actuate the trigger reliably may produce some output signal. As the input amplitude approaches the threshold level in this type of circuit, a small output signal is first noted. With increased amplitude the circuit may trigger at a submultiple of the input signal rate. Finally, with sufficient signal, the circuit operates reliably. This effect may extend over an input signal range of as much as 0.5 v in a typical circuit.

Kandiah's clamping diode is also useful in transistor circuits to minimize feed-through effects.[4] It allows the trigger circuit to operate at a maximum sensitivity with both transistors in the active region; however, actual triggering is restrained by the shunt impedance of the clamping diode. As the signal rises above the threshold, the diode begins to cut off, thus unclamping the trigger and allowing it to regenerate.

Another method of minimizing feed-through is to place the nonlinear device ahead of the trigger circuit. The diode can be operated in either of two configurations. Figure 3 shows a series diode cutoff in the quiescent condition. It is rendered conducting by a signal of sufficient amplitude to overcome the threshold bias (E_t). Figure 4 illustrates a normally conducting shunt diode which is cut off by a signal greater than E_t. The base-to-emitter characteristic of a transistor or the grid-to-cathode characteristic of an electron tube can be used in the same manner. The series diode suffers from feed-through effects because of its leakage current, which is temperature-sensitive, and its junction capacitance. The shunt diode overcomes the feed-through difficulty, and if types with short recovery times are used, it is the preferred circuit.

Discriminators are usually required to respond to signals from nuclear events occuring at random. Because of this, the interval between some pulses may be very short. It is inevitable that a small fraction of the counts will be lost owing to the finite recovery time of any workable circuit. Obviously, the shorter the recovery time of the discriminator, the smaller will be the counting loss at any particular average counting rate. If a 1% counting loss is considered satisfactory, the discriminator must be able to respond to pulses that are separated by only 1/100 of that period equal to the average counting rate. Sometimes a 10% counting loss is tolerable; in this case the unit need only have a recovery time that is 1/10 the time of the average counting period. When a discriminator is followed by a scaler, the counting-loss restrictions must be applied to that unit as well.

Recovery time is often measured by the "double-pulse" response method. A pulser generating two pulses of variable separation is employed, usually at low repetition rates. The pulse separation at which the discriminator just responds to both pulses is called the double-pulse period. A more complete method is to also measure the continuous counting rate of a discriminator from low values to its maximum rate. The maximum continuous counting rate is usually somewhat less than the frequency corresponding to the reciprocal of the double-pulse period.

The response and recovery time of fast discriminators are directly related to: (a) the gain-bandwidth product of the active devices used in the trigger circuit, (b) the recovery time of the discriminating diode, and (c) the series inductances and shunt capacitances of the components employed in the circuit. Response and recovery time are also related to the voltage (or current) swing chosen by the designer; a smaller swing takes place in a shorter time. Circuits with continuous repetition rates of 10 Mc are now readily available, and experimental circuits to 100 Mc have been reported.[7,8]

Practical Circuits

Many practical circuits have been described in the literature. Gatti used a multielement electron tube to obtain both the clamping-diode effect and a differential negative resistance. A threshold in the range of 1 to 30 mv with a stability of less than 1% is reported.[9] Mey developed a pulse-amplitude discriminator capable of operating at repetition rates up to 10 Mc with an input threshold adjustable from 1 to 11 v.[10] Swift and Perez-Mendez describe a unit using an EFP-60 secondary-emission tube with a response to pulses as short as 3 nsec and a recovery time less than 0.15 μsec.[11]

Various circuits employing transistors have been described recently.[12, 13, 14] Verweij reports a discriminator using transistors with a threshold that can be varied from 100 mv to 2.1 v. Stable operation is obtained for counting rates up to at least 10 Mc.

A unit with similar operating specifications has been reported by Jackson. The schematic diagram is shown in Fig. 5. A common-base stage (Q-1) provides a good impedance match over a wide range of input signals. The threshold sensing element, diode D-1, is normally conducting; the current is set by a multiturn potentiometer acting through an emitter-follower (Q-2). The emitter-follower maintains the bias current constant over large ranges of counting rate. A three-stage amplifier (Q-3, Q-4, Q-5) provides a gain of 5 for pulses 10 nsec long; this gives sufficient amplification for signals above the threshold level to trigger the pulse-forming circuit. The monostable multivibrator (Q-6 and Q-7) uses an emitter-coupled timing circuit. For short input pulses the output-pulse length is 40 nsec; for wider input signals the output correspondingly increases in length. The output stage is an emitter-follower (Q-8) providing 8-v positive signals with a source impedance of about 25 ohms for counting rates up to 10 kc, increasing to 125 ohms at 10 Mc. Figure 6 shows the output signals at 1-Mc and 10-Mc repetition rates.

The variation of the threshold level with temperature is approximately 1 mv/°C when a single 15-volt zener-diode voltage regulator is used; this is reduced to 0.2 mv/°C by using a supply with improved temperature regulation. Threshold drift is not more than 1 mv/day at constant temperature.

The range of adjustment of threshold level is from 0.1 to 2.1 v for incoming signals 50 nsec or more in length. For shorter signals, the input

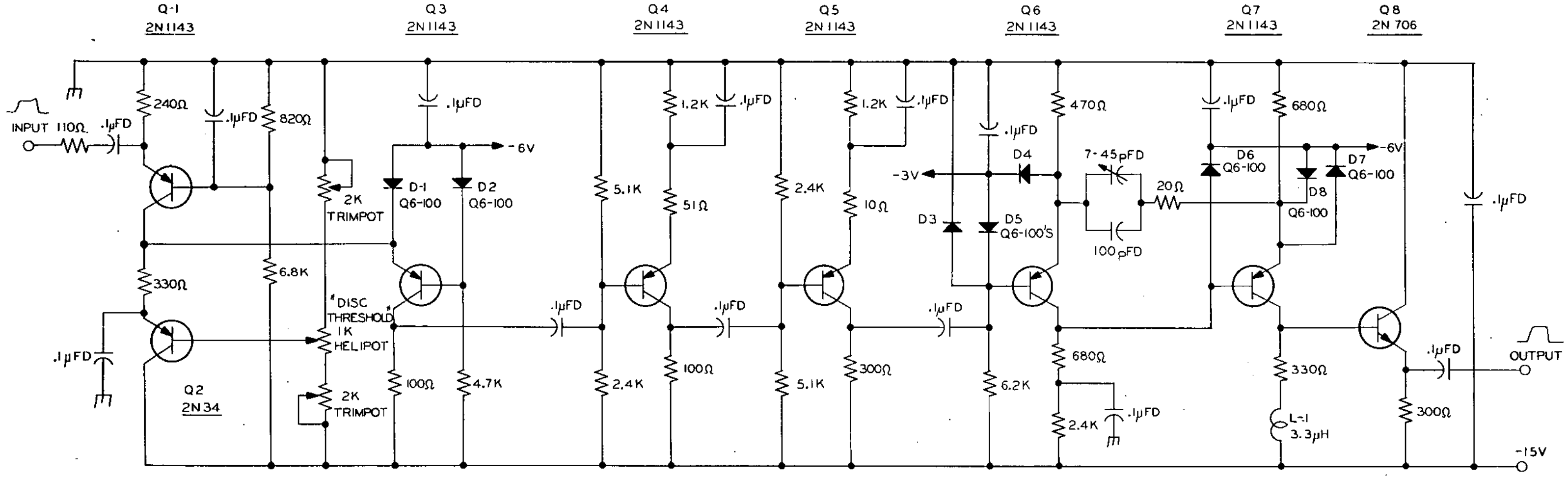

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Fig. 5. 10-Mc pulse discriminator (Jackson)

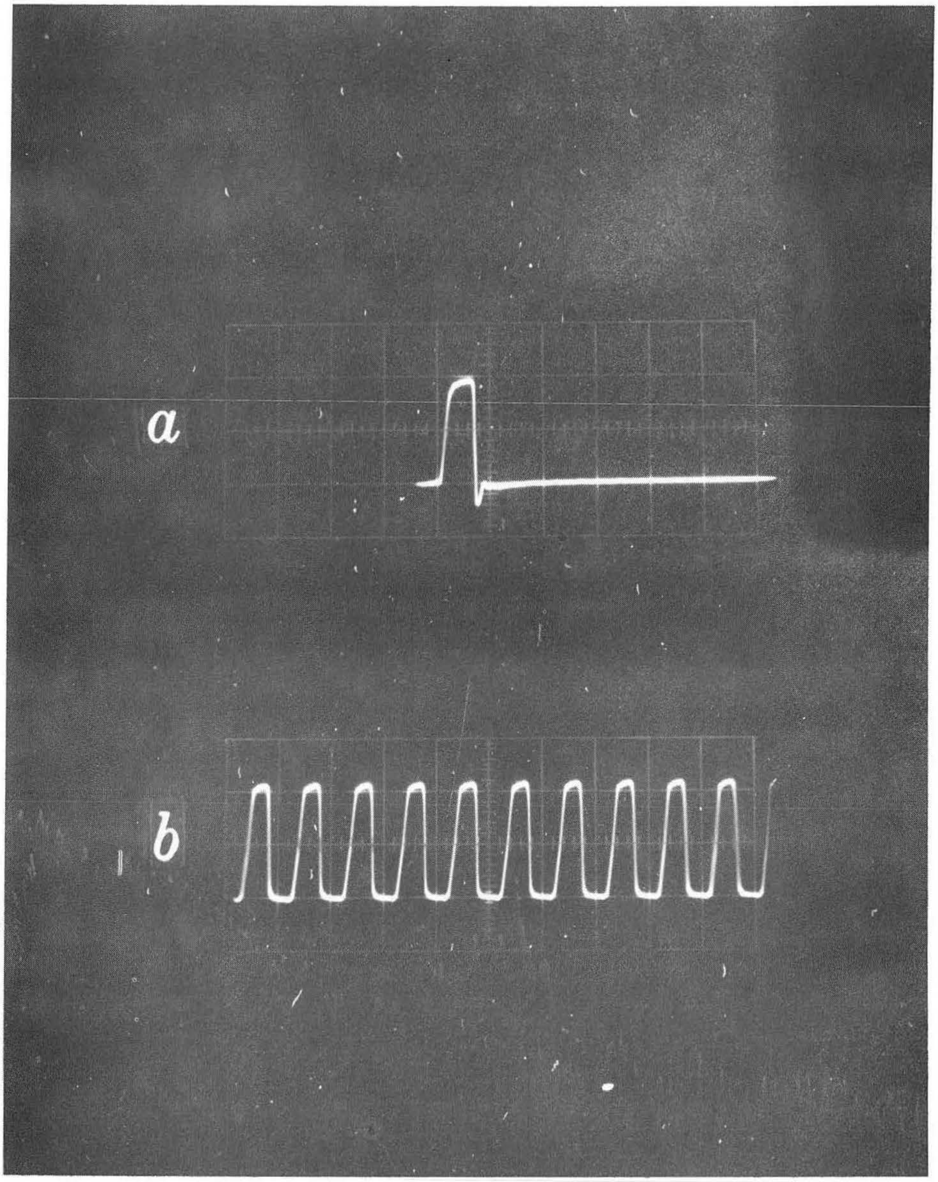

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Fig. 6. Discriminator output signal (Jackson)
(a) at 1 Mc
(b) at 10 Mc

Oscilloscope calibration: X Axis, 100 nsec/cm Y Axis, 3v/cm

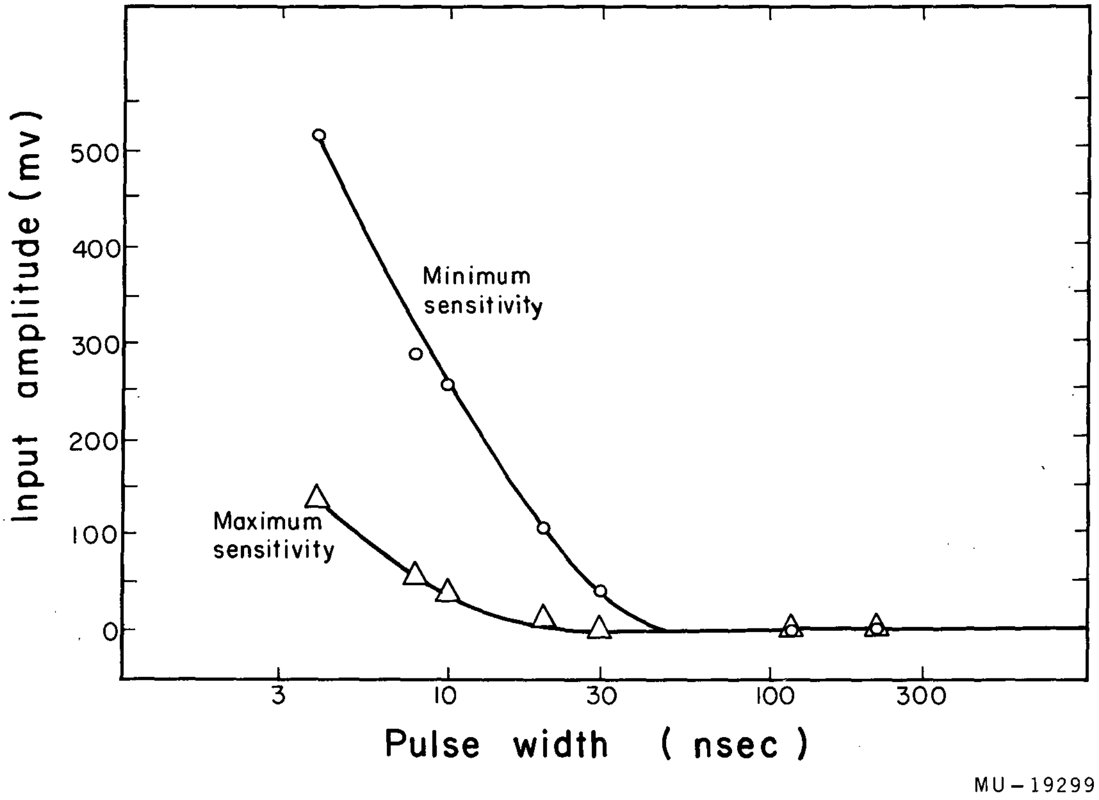

Fig. 7. Excess input signal needed for triggering with short pulse lengths at maximum (0.1-v) and minimum (2.1-v) sensitivity settings (Jackson)

circuits are charge-sensitive, and excess signal amplitude is required for adequate triggering. Figure 7 indicates the additional input signal required for pulses shorter than 50 nsec. Since the incoming pulse length is usually well defined, this variation in sensitivity with pulse width is not a serious deficiency. Figure 8 illustrates the variation in delay through the discriminator as a function of input signal amplitude above the threshold level.

Goulding and Robinson have reported a pulse-height diecriminator which makes use of a forward-biased diode shunting the regenerative loop of a trigger circuit to produce a stable triggering threshold.[15, 16] The schematic circuit diagram is shown in Fig. 9. The impedance of diode D-1 is a function of its forward current; therefore, the loop gain can be changed by varying the diode current. The circuit triggers at a value of input signal that decreases the diode current and increases its impedance to the point where the loop gain is greater than unity. This type of circuit has the advantage that changes of diode voltage drop have little effect on the threshold level. A discrimination stability of ± 1μa at a 50-μa triggering level or a ±0.4-mv stability at a 10-mv triggering level is reported over a ± 10°C temperature range. Either voltage or current input signals may be used to trigger the discriminator, as shown in Fig. 9. The trigger circuit (Q-1 and Q-2) is restrained from triggering because of the low forward impedance of diode D-1 (approximately 250 ohms at 100 μa) shunting the collector of Q-1. It will be noted that D-1 is effective in its operation although it is only capacitively coupled to the collector of Q-1.

The stability and reproducibility of the threshold level is primarily determined by the characteristics of diode D-1. For changes in temperature the threshold level depends upon the temperature stability of the diode incremental impedance characteristic as expressed by

$$R_D = \frac{n K T}{e(I + i_0)} ,$$

where R_D = diode incremental impedance (ohms),
n = a diode parameter (usually 1 to 1.4),
K = Boltzmann's constant (1.38×10^{-23} joule/°C),
T = temperature (°K),
e = electron charge (1.60×10^{-19} coulomb),
I = diode current (amperes),
i_0 = a parameter which may vary from diode to diode.

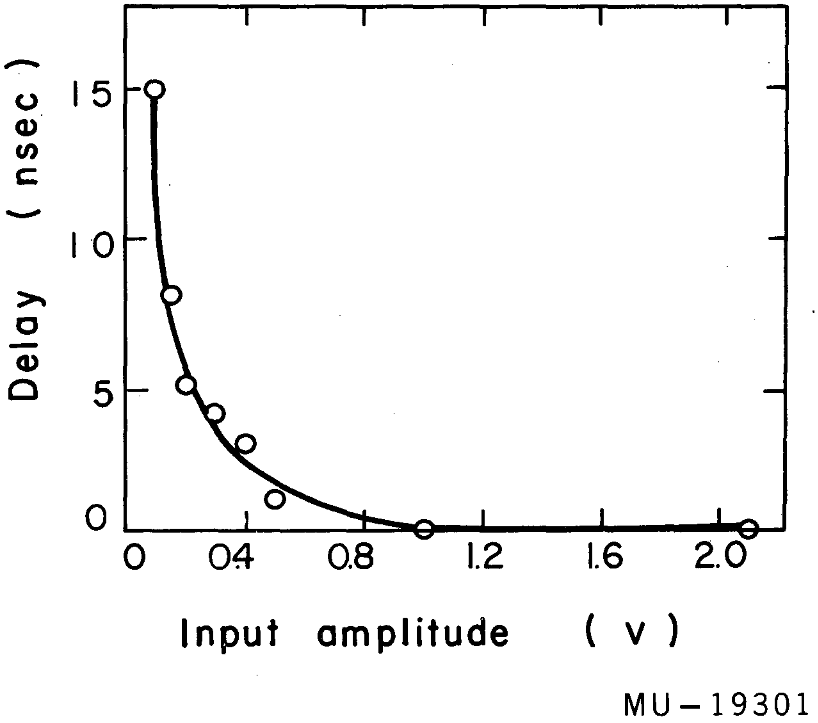

Fig. 8. Relative delay of output signal as a function of input amplitude (Jackson)

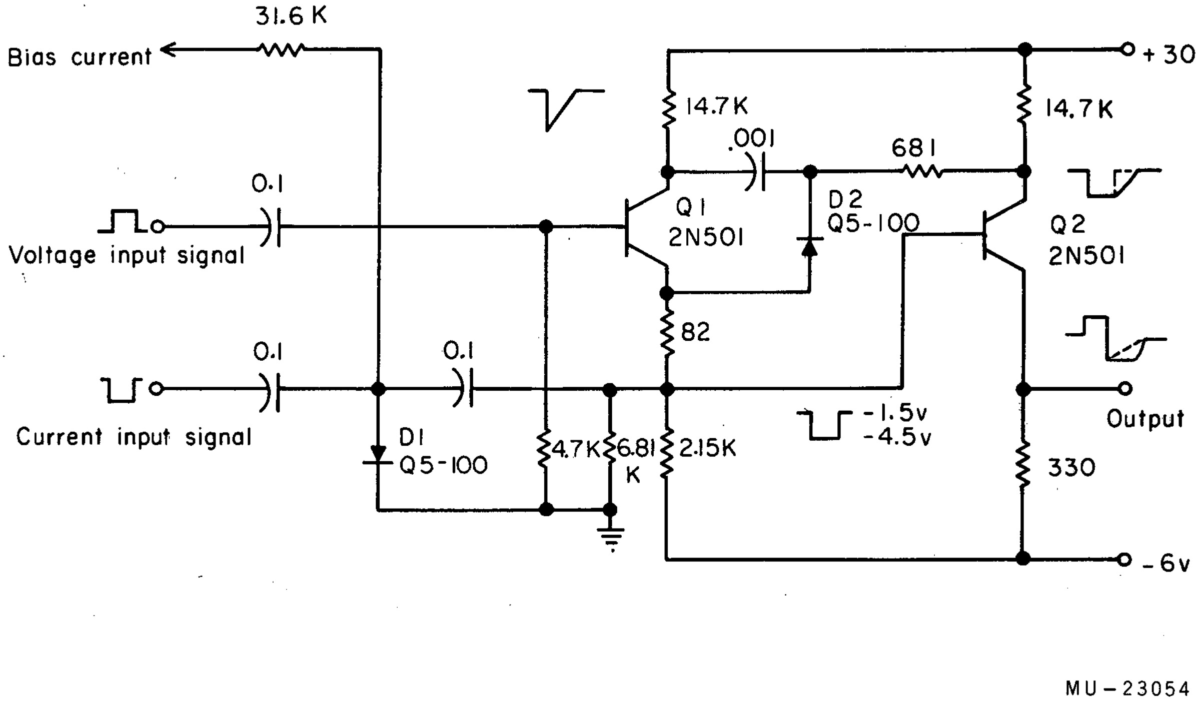

Fig. 9. Current or voltage pulse-amplitude discriminator (Goulding and Robinson)

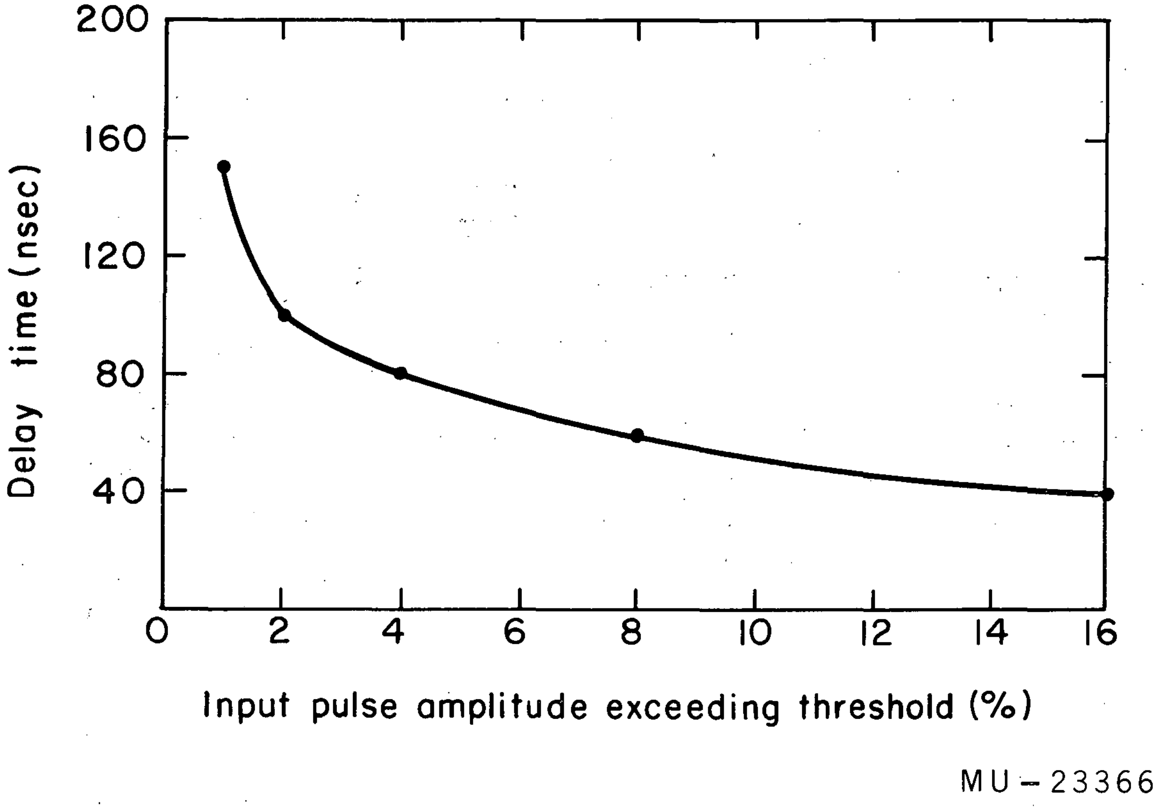

Fig. 10. Delay vs input amplitude exceeding threshold (Goulding and Robinson)

Since n, T, and i_0 are all functions of temperature, it is important to select a unit with a low coefficient of resistance change with temperature. An extensive treatment of this effect is given in Ref. 16.

Typical delay times for this unit are shown in Fig. 10. The delay is expressed as a function of the percentage excess input signal over a 100-μa threshold.

Tunnel diodes offer interesting possibilities as threshold sensing devices because of their nanosecond switching times and small coefficients of peak-point current (I_p) with temperature. Kerns has described a tunnel-diode discriminator operating over a wide range of input signal amplitude.[17] The tunnel diode is placed in one branch of the bridge as shown in Fig. 11. The difference in resistance between the two branches (R_1 and R_2) is made to approximate the positive resistance of the tunnel-diode characteristic before switching (region A of Fig. 12). For input signals insufficient to trigger the tunnel diode, the bridge is balanced and no output is seen at transistor Q-1. A larger signal causes the circulating current to increase until the tunnel diode regenerates; at this time the bridge is unbalanced. A differentiated pulse is then fed to the grounded-base transistor. A further increase of input signal causes the tunnel diode to operate along the characteristic in region C of Fig. 12. However, the increase in signal across the tunnel diode is again balanced by the IR drop of the other branch of the bridge, and no additional signal is produced at the discriminator output.

The lower threshold level for stable operation is about 100 mv; the temperature coefficient referred to the input is 0.1 mv/°C. The output signal is approximately 70 mv in amplitude, with a pulse width of 7 nsec at the base.

In order to minimize the variation of delay as a function of input pulse amplitude, the incoming signal is usually differentiated with a shorting stub and the circuit triggered at the zero crossing of the backswing of this differentiated signal, as shown in Fig. 13. By using this technique it has been possible to limit the variation in delay to approximately 0.5 nsec for a 50/1 change in input signal amplitude.

The circuits shown here are illustrative of the present state of the art. As new and improved components become available, the same threshold-discrimination principles can be applied with correspondingly better results.

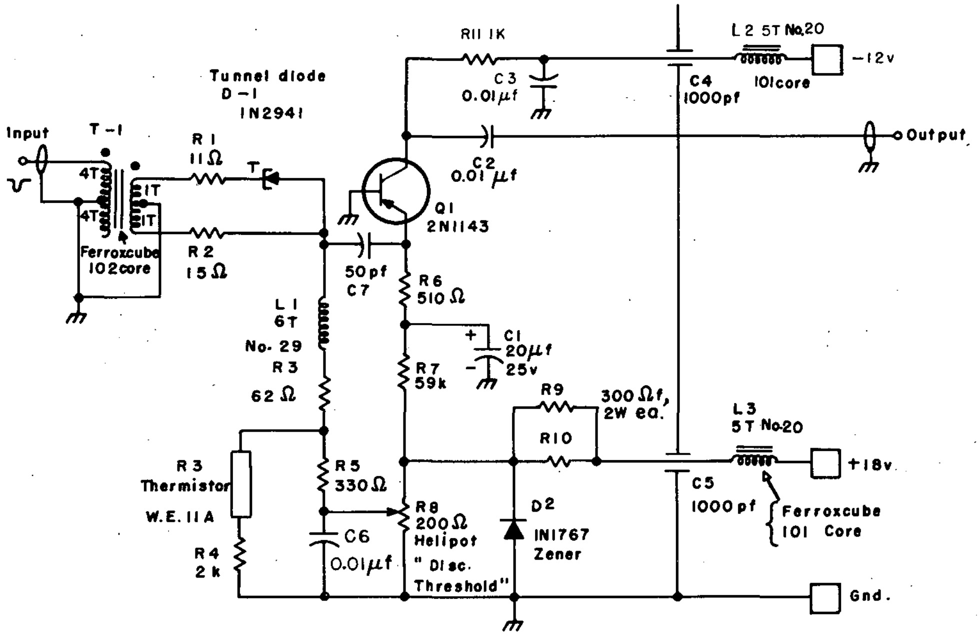

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Fig. 11. Tunnel diode discriminator (Kerns)

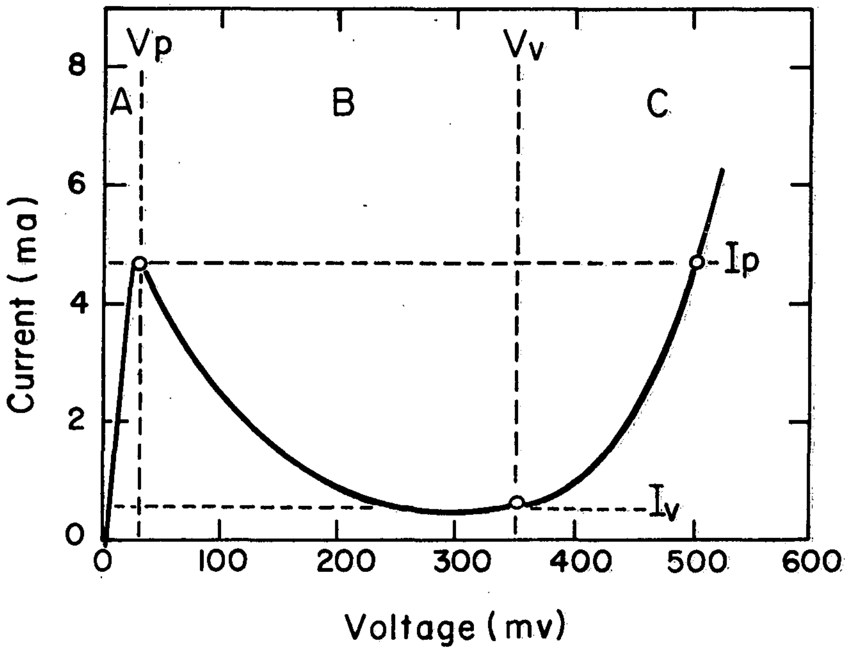

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Fig. 12. Typical germanium tunnel-diode characteristic (GE type 1N2941)

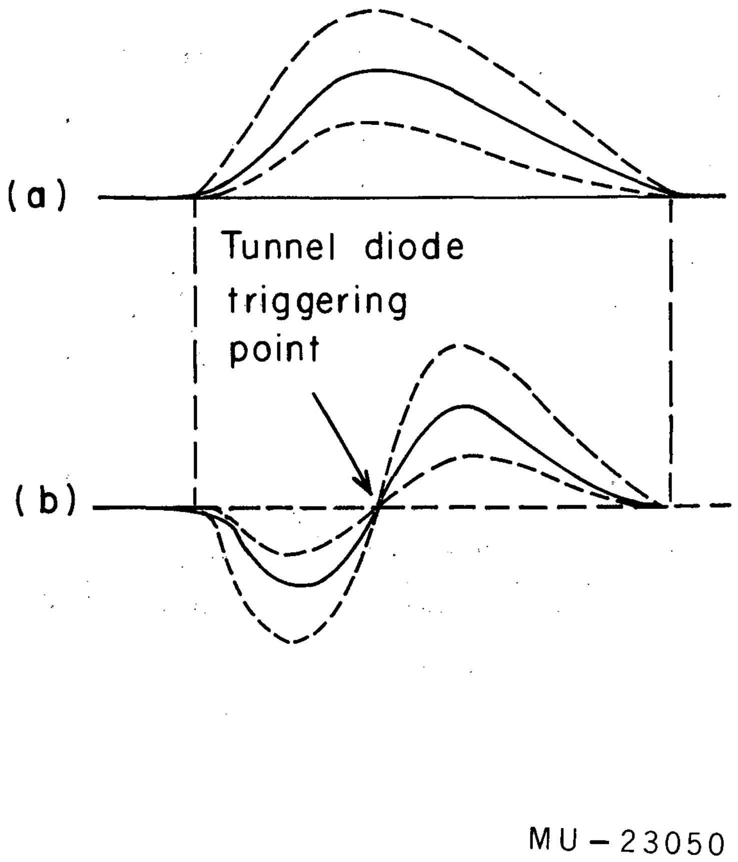

Fig. 13. Tunnel-diode discriminator triggering on differentiated input signal to minimize variation in delay with signal amplitude
(a) Normal input signal
(b) Differentiated input signal

Acknowledgments

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