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IIa. 9. REVIEW AND EVALUATION OF FAST INTEGRAL DISCRIMINATOR CIRCUITS

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Summary

A class of circuits, commonly called fast integral discriminators, is examined. A number of definitions, pertaining to parameters that determine circuit behavior, is proposed.

Diagrams and characteristics of circuits appearing in the literature or developed by the authors are given.

Finally the application of tunnel diodes in discriminators is discussed.

Introduction and Definitions

The aim of this work is to propose a number of definitions and of ways of measuring the relevant characteristics of a class of circuits that are commonly called fast integral discriminators. Ideally an integral discriminator is, of course, a circuit possessing an input-output relation according to the diagram in Fig. 1. That is, there is no output if the input voltage lies below a sharply defined threshold voltage V_s , and a certain output voltage E_1 if the input exceeds V_s . This relation should be time-independent in the sense that it should hold (with the same value of V_s) whatever the duration or the repetition frequency of the input signal. Another way of saying this is: in an ideal discriminator both the threshold and the output voltage should be independent of the shape of the input and of the time separation of successive input pulses. We have thus set down two distinct requirements for a discriminator: one relates to the "static accuracy" of discrimination, i.e., the threshold should be infinitely sharp; the second relates to the "speed" of the device. In other words, the selection of input pulses whose heights exceed V_s should occupy no time at all. Broadly speaking, these two requirements are conflicting in any practical device.

In the following we shall make frequent use of certain terms which we shall now define:

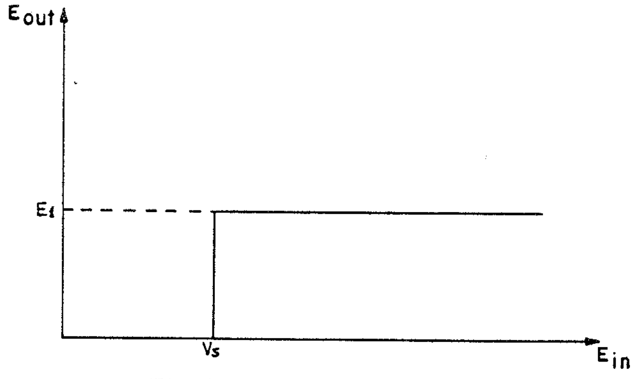


Fig. 1. Input-output relation.

a. Threshold uncertainty: the variation in input-pulse amplitude that will bring the output-pulse amplitude from zero to maximum. This is zero for an ideal discriminator and of the order of 0.1 volt for a conventional slow vacuum-tube discriminator of the Schmitt type. In the following we denote the threshold uncertainty by the symbol S.

b. Threshold drift: the long-term variation in discrimination level. It usually consists of a systematic component (filament-voltage variations for tubes and temperature variations for transistors) and of a random component (flicker effect, cathode-emission variations, or generation-recombination noise in semiconductor).

In the evaluation of a discriminator both figures should be stated.

c. Dead time: after a pulse has been amplitude-analyzed, a certain time must elapse before the threshold will recover to within S volts of its static value; this interval is defined as the dead time of the discriminator. A discriminator is considered "fast" if its dead time is not greater than 0.2 μsec.

d. Lambda pulse : in all practical discriminators, threshold is a function of input-pulse duration. For fast discriminators one would like to have equal response to equal-height pulses varying in width from a few nsec to about several μsec. When the input-pulse duration is such that the threshold differs by S volts from the value it had for a long pulse, one can state that the discriminator is analyzing its lambda pulse.[1] This definition is valid for infinitely fast pulses. The order of magnitude of the lambda-pulse duration is often between 5 and 20 nsec.

e. Maximum repetition rate: Because of duty-cycle effects all ac-coupled discriminators show a variation of threshold with input repetition frequency. When the repetition rate is such as to change the threshold by an additional S volts from the value it had at infinitely low repetition frequencies, we say that the discriminator is running at its maximum repetition rate. The above definition of course intentionally excludes limitations set by tube dissipations and the like. Maximum repetition rates are often in the range 0.1 to 10 Mc. Note that, according to the definitions given above, there is not necessarily a well-defined relation between dead time t_d and maximum repetition rate f_r ; i.e., the relation

$$f_r \approx \frac{1}{t_d}$$

holds only for dc-coupled discriminators; a discriminator may have a 0.1-μsec dead time but only a 10-kc maximum repetition rate. In conjunction with high-energy pulsed accelerators it is important that the maximum repetition rate be as high as possible.

f. Delay variation: when a discriminator has triggered it always introduces a certain delay between input and output pulses. This delay is often not fixed, but depends on how much the input pulse exceeds the threshold. The variation should be stated for the maximum permissible variation in the input-pulse amplitude: e. g., setting the discriminator threshold to its minimum value and measuring the relative delay as the input pulse goes through its maximum amplitude range. In certain discriminators this delay variation is of the order of 30 or 50 nsec; this means that it is difficult to preserve time information after a discriminator.

The variation of the delay of the output pulse with respect to the input pulse is due in essence to the variations of the delay Δt with which the trigger circuit fires. These delay variations can be calculated easily by analyzing the trigger circuit as a positive-feedback amplifier with a discontinuous characteristic so that the loop gain is zero when the input pulse is below the threshold and $G > 0$ for that part of the pulse that is above the threshold.

If τ is the circulating time around the feedback loop, ϵ is the part of the input pulse above the threshold, v^* is the saturation value of the input voltage at the end of the rise of the trigger pulse, and the input pulse is applied at t=0, then the input voltage is

$$\begin{aligned} v_0 &= \epsilon, && \text{at } t = 0, \\ v_1 &= G\epsilon + \epsilon, && \text{at } t = \tau, \\ v_2 &= G(G\epsilon + \epsilon = G^2\epsilon + G\epsilon + \epsilon, && \text{at } t = 2\tau, \end{aligned}$$

i. e., after a time $n\tau$ the input voltage is

$$V_n = \epsilon \sum_{0i}^{n} = \epsilon \, \frac{G^{n+1} - 1}{G - 1} .$$

If n-1 circulations through the loop were necessary to reach the voltage v^*, then one has

$$v^* = v_{n-1} = \epsilon \, \frac{G^n - 1}{G - 1} ,$$

i. e.,

$$n \log G = \log \left[v^*(G-1) + \epsilon \right] + \log \epsilon ,$$

so that the delay time $\Delta t = n\tau$ may be written as

$$\Delta t = \frac{\tau}{\log G} \left[\log \; v^*(G-1) + \epsilon \; - \log \epsilon \right] .$$

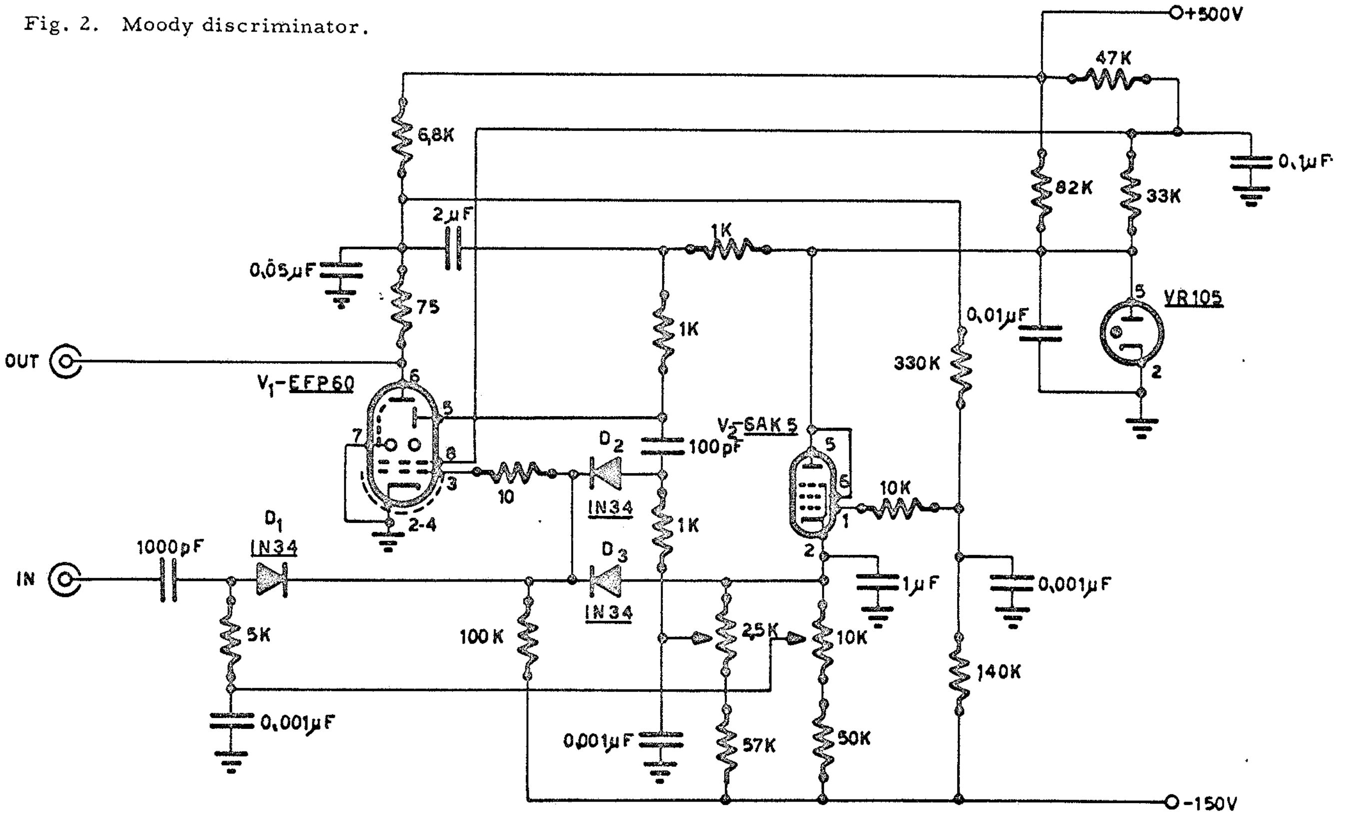
This expression is of the same form as proposed elsewhere.[2]

g. Overloading: in a fast discriminator it is important that pulses largely exceeding the threshold do not paralyze the circuit for a time longer than the dead time and do not produce multiple output pulses. Usually one requires that the circuit produce no spurious response to pulses whose amplitude is 100 times the minimum threshold setting. These effects are usually due to mismatch at the input or to capacitance feedthrough in the nonlinear element that determines the threshold, or both.

Vacuum-Tube Discriminators

One of the oldest fast discriminators is the well-known Moody circuit[3] based on the properties of the secondary-emission tube EFP60. Diode D_1 constitutes the comparator, while positive feedback from dynode to grid ensures fast triggering action (threshold uncertainty is less than 10 mv). The secondary-emission tube draws a slight current(normally about 10 ma), while diode D_2 is used to open the feedback loop, thus ensuring stability. A large amount of dc feedback from the plate of V_1 to the grid of V_1 is used to stabilize

Fig. 2. Moody discriminator.



the circuit against drift in the static characteristics of V_1. The circuit has much to recommend it in the way of simplicity: a large current (0.1 to 0.3 amp) is available for the duration of the pulse, thus allowing the generation of large and fast output pulses. Unfortunately the characteristics of the EFP60 differ largely from one tube to another, the tube itself is short-lived (3000 hr), and the average current it draws must be kept below 25 ma, thus limiting the maximum duty cycle to about 10%. Diagram of a typical circuit is given in Fig. 2. The relevant characteristics of the circuit are:

threshold range, 1 to 20 v;
threshold definition, 10 mv;
long-term drift, 0.2 v;
drift due to 10% variation in filament voltage, 0.3 v;
λ-pulse width, approx 25 nsec;
output pulse duration, ⩾ 20 nsec;
dead time, approx 0.2 μsec;
maximum repetition rate, 0.1 Mc;
reliability, poor.

Another discriminator in widespread use is the circuit developed by Farley.[4] It consists again of a biased diode comparator, followed by a trigger circuit. The comparator circuit is of the differential-amplifier derived type, with a diode inserted to improve the sharpness in breakpoint. The trigger circuit is more conventional. Although the threshold definition for long pulses is quite good (10 mv for 100-nanosec pulses), the circuit responds quite poorly to short pulses (0.3 v uncertainty for 20-nsec pulses), this is its severest limitation. Circuit diagrams are given in Fig. 3. Relevant characteristics are:

drift, 30 mv;
drift due to a 10% variation in filament voltage, 50 mv;
λ-pulse width, 40 nsec;
dead time, 60 nsec;
maximum repetition rate, 0.2 Mc.

A circuit that is similar to the Moody circuit in principle but that avoids the use of secondary-emission tubes has been developed by one of the authors; it consists of a diode comparator followed by a plate-to-grid-coupled monostable multivibrator (Fig. 4). Tubes V_3 and V_4 are added to isolate the trigger from the load, power tube V_4 being employed to produce a large output pulse. Relevant characteristics are:

threshold range, 1 to 10 v;
threshold uncertainty, 20 mv;
long-term drift, 0.1 v;
filament-induced drift, 50 mv;
λ-pulse width, 20 nsec;
output-pulse duration, 60 nsec;
dead time, 0.1 μsec;
maximum repetition rate, 1 Mc;
delay variation, 40 nsec.

The fast discriminator to be discussed next has been developed by one of the authors (see Fig. 5). Discrimination is done by vacuum tube V_1. This allows either positive or negative pulses to be discriminated, minimizing shunt-capacitance effects at the cost of increased threshold drift (50 mv with 1% regulated filament supply). V_2 constitutes an amplifying stage, and V_3 and V_4 make up the trigger circuit. Output-pulse duration is determined by the critically damped resonant circuit, and is about 70 nsec. Dead time is about 0.1 μsec; λ-pulse width, 10 nsec, and maximum repetition rate about 5 Mc.

A circuit that responds excellently to very short pulses has been proposed recently.[5] (Fig. 6.) Input pulses are inverted, passed through a diode comparator, amplified, and finally trigger a secondary emission tube normally biased below cutoff. Relevant characteristics are:

threshold uncertainty, 20 mv;
long-term drift, 25 mv;
filament-induced drift, 60 mv;
minimum pulse width, 10 nsec (negative polarity);
dead time, 0.1 μsec;
maximum repetition rate, 2 Mc;
delay variation, < 1 nsec.

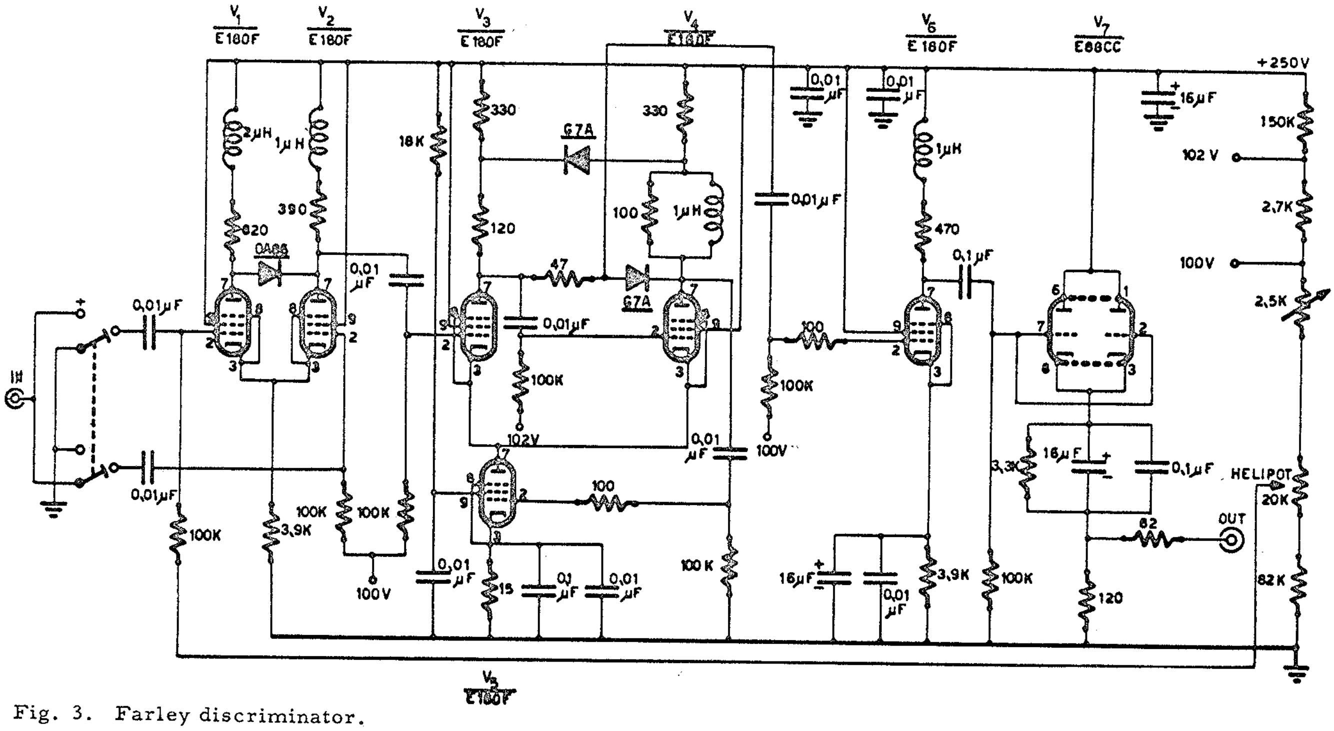


Fig. 3. Farley discriminator.

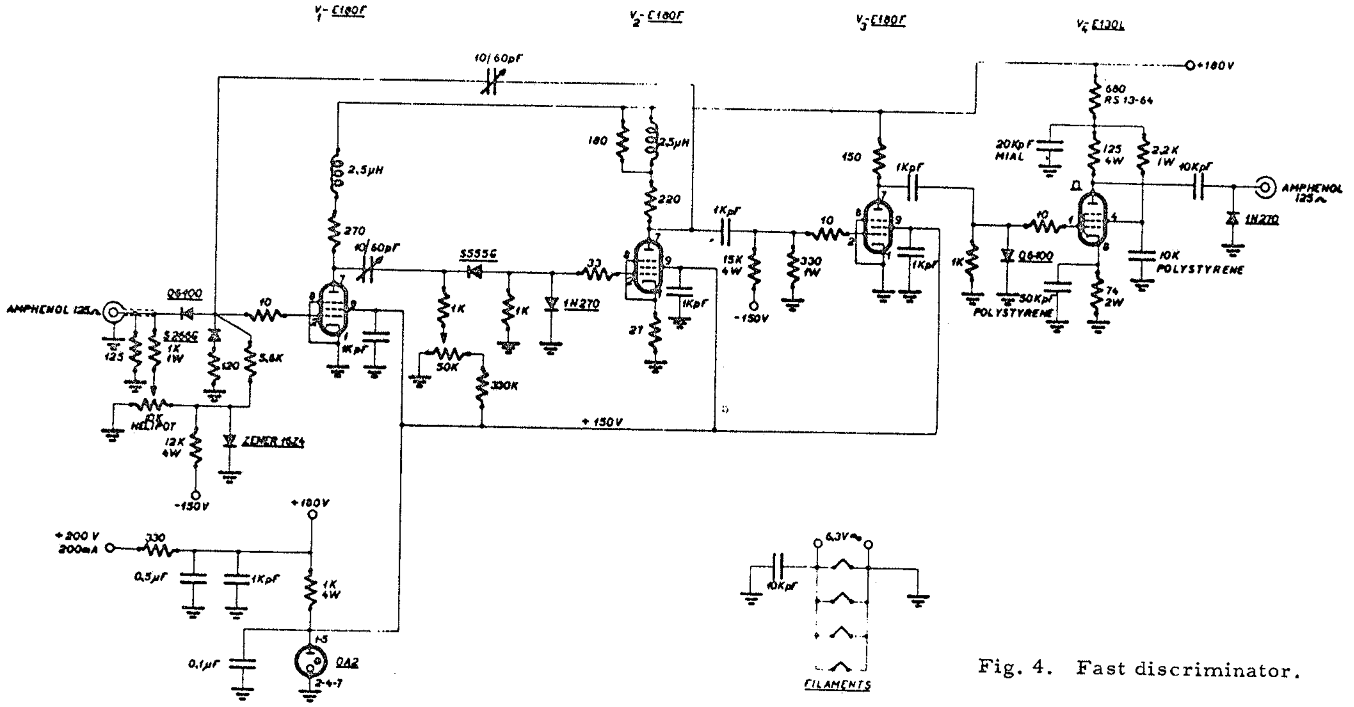


Fig. 4. Fast discriminator.

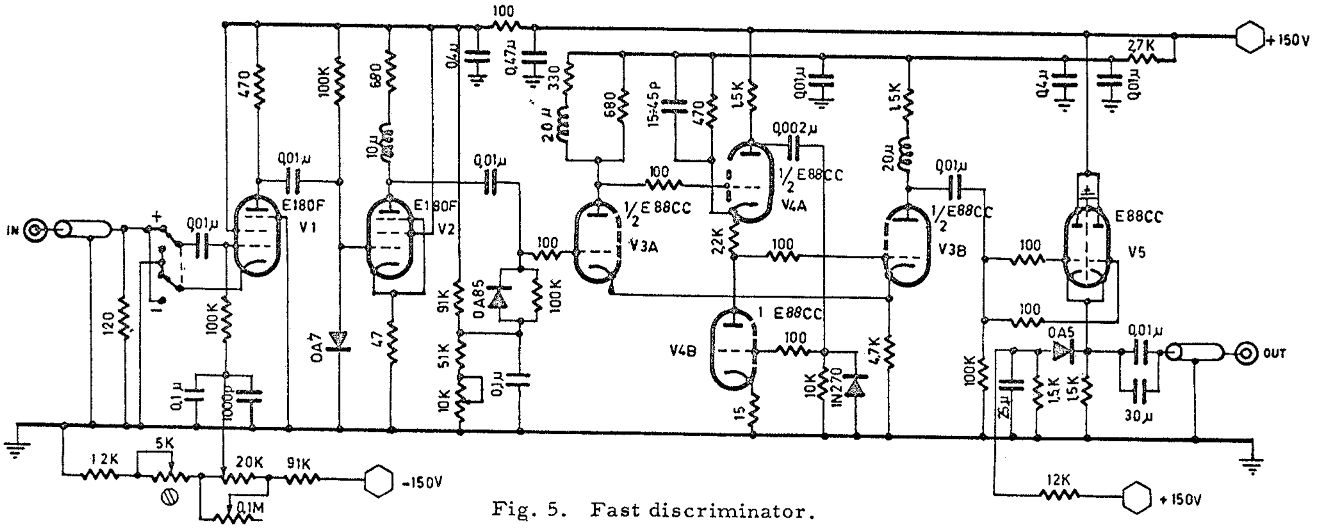


Fig. 5. Fast discriminator.

An excellent circuit proposed by J. Mey[6] is shown in Fig. 7. Once again it consists of a biased diode comparator and of a fast trigger generator. The comparator is of the differential-amplifier-derived type with pentode V_2 added to cancel shunt-capacitance effects of discriminating diode D_1. The fast trigger employs a diode-quenched resonant circuit (L_1, D_7, R_{16}) as the pulse-duration-determining element. Semiconductor diodes are used extensively as amplitude limiters and to clip undesirable undershoots, and zener diodes D_{14} and D_{11}, cathode follower V_6, and voltage regulator tube V_3 fix the voltages of certain critical points, so as to make them independent of input duty-cycle variations. A White follower circuit (V_5) ensures low output impedance. The relevant characteristics are:

threshold uncertainty, 10 mv;
long-term drift, 20 mv;
filament-induced drift, 25 mv;
λ-pulse width, 20 nsec;
dead time, 0.1 μsec;
maximum repetition rate, 4 Mc;
delay variation, 30 nsec.

To achieve higher speeds, a distributed amplifier has been used as the pulse-shaping element:[7] signals coming from a diode comparator (of the Mey type) are amplified with a distributed amplifier, the output of the latter being sufficient to turn a vacuum tube off, thus producing a signal of constant amplitude (see Fig. 8). Characteristics:

threshold uncertainty, 30 mv;
long-term drift, 20 mv;
drift due to a 10% variation in filament-voltage, 25mv;
λ-pulse width, 10 nsec;
dead time < 25 nsec;
maximum repetition rate > 20 Mc.

Transistor Discriminators

The excellent advantages of transistors--such as high reliability, small size and weight, and low power consumption--are often applied with good effect in switching circuitry. Transistors with α-cutoff frequencies (α_f) of the order of 500 Mc are commercially available now, and elements with α_f of the order of 10 to 20 kMc are announced for the near future. It is well known that transistors are ideally suited for on-off applications, switching times being of the order of $1/\alpha_f$ or longer owing to minority-carrier storage.

Transistors are also very well suited as the discriminating element in pulse-height discriminators because the sharp break in the characteristics of a

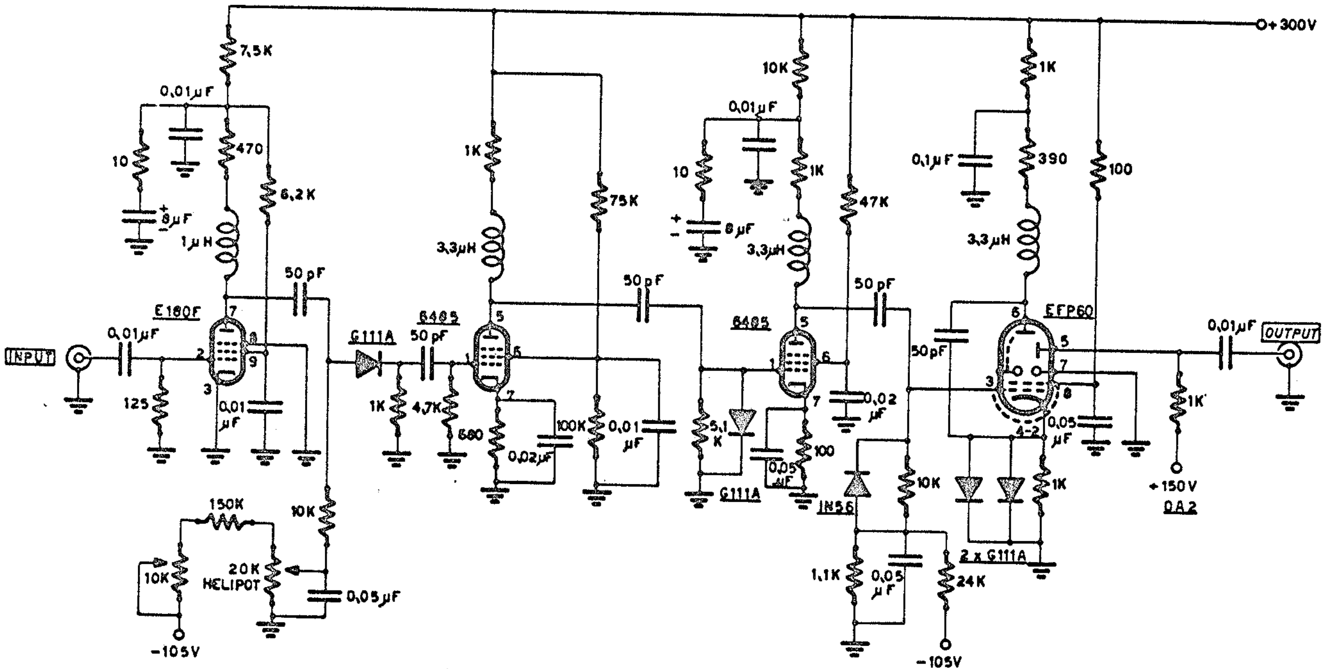


Fig. 6. Swift and Perez-Mendez discriminator.

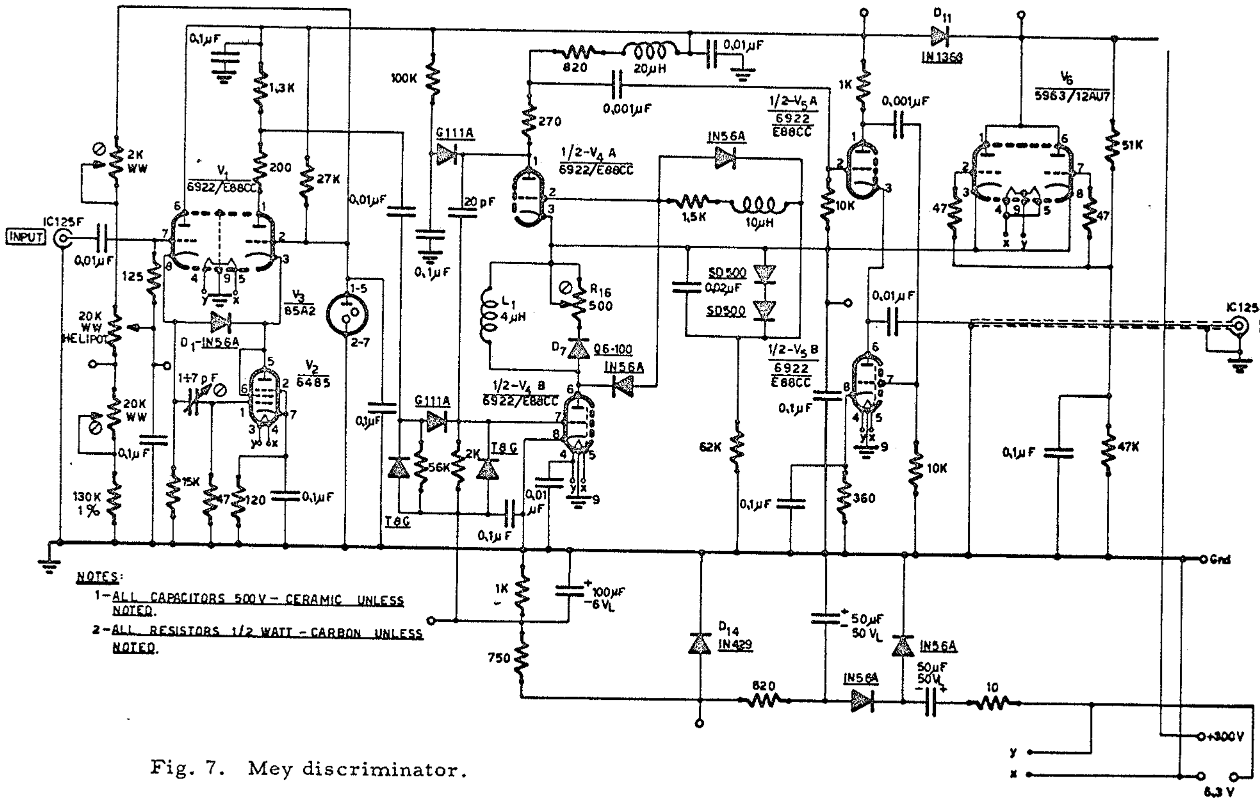


Fig. 7. Mey discriminator.

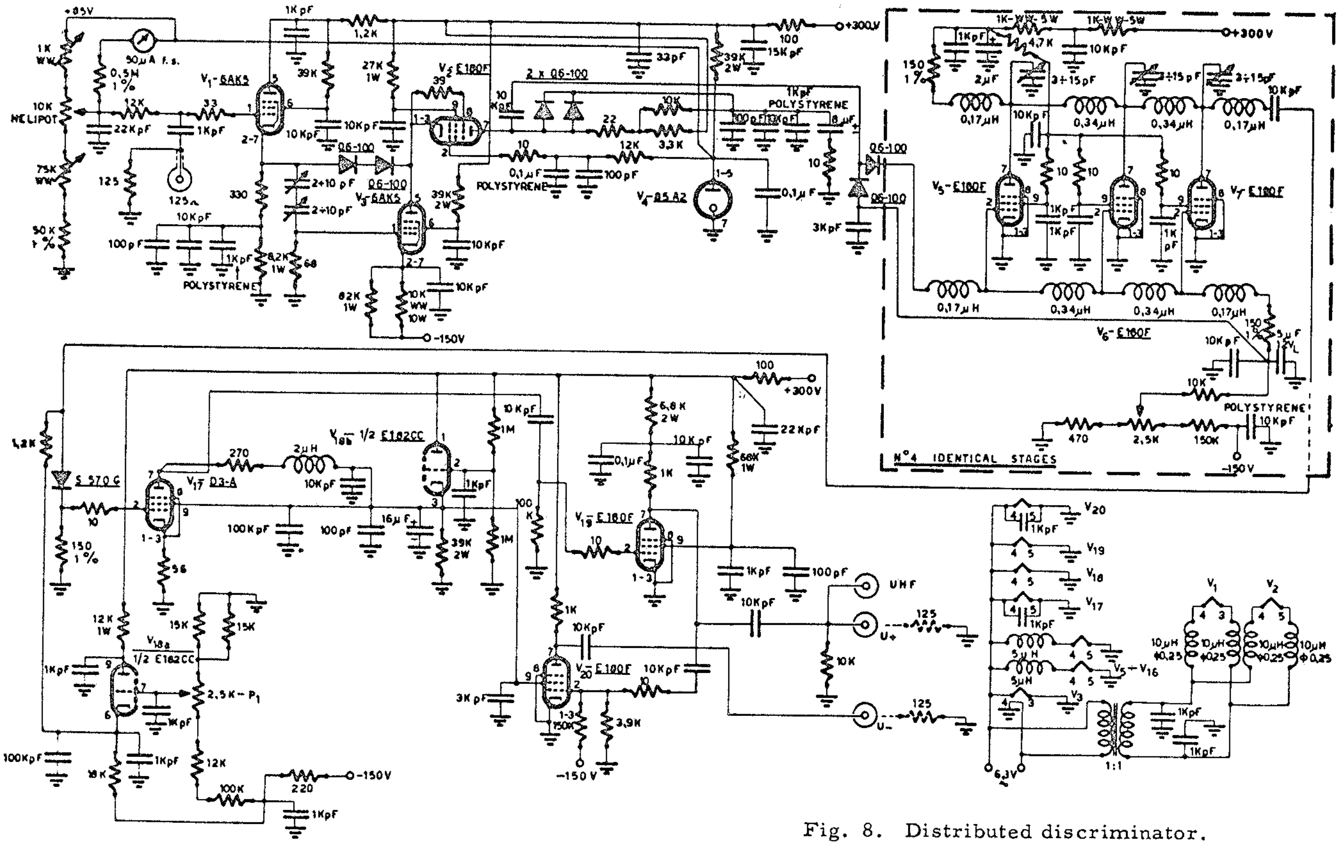


Fig. 8. Distributed discriminator.

semiconductor are of course much less sensitive to age, but much more sensitive to temperature variations. However, there is a wide variety of circuits designed to compensate temperature effects to a high degree. For normal ambient temperature ranges, threshold stability and definition of a conventional transistor discriminator are of the order of 10 mv. It should be borne in mind, however, that, owing to shunt capacitance effects, a fast-rising pulse may pass from base to emitter even under cutoff conditions.

A very simple trigger circuit, well suited for fixed threshold discrimination, has been developed by Miller,[8] and is shown in Fig. 9.

Normally T_3 is in the saturation region and T_2 is cut off: a negative pulse applied to the base of T_1 is amplified, inverted, and brought to the base of T_3. Positive feedback is hence obtained through the coupling network between T_3 and T_2, so that T_2 and T_3 are driven into saturation and cutoff respectively. Rise time and duration of the output signal are 20 and 100 nsec respectively; output amplitude is about 3 v, and threshold uncertainty is of the order of 5 mv; long-term drift depends upon ambient temperature variations and is proportional to collector voltage. Delay time is 30 nsec. The circuit will not overload on pulses up to 20 v in amplitude.

A fast discriminator developed by Pierre Piroué and described by Val L. Fitch[9] is shown in Fig. 10.

The circuit is in essence a transistorized version of the cathode-coupled monostable multivibrator, and discriminates pulses between 0.04 and 1.7 volts in amplitude. Rise time and duration of the output waveform are critically dependent upon the values of C and L: with the values shown these are about 10 and 35 nsec respectively. Output pulse amplitude is about 3 v; threshold uncertainty is less than 1 mv, long-term drift (5 days) at constant temperature is less than 1% of full scale, and threshold variations due to temperature effects are less than 1 mv/°C between 20 and 50°C. Dead time is of the order of 60 nsec; the circuit reliably discriminates pulses whose duration is between 20 and 100 nsec. If the input pulses are too narrow the threshold varies noticeably, as evidenced by Fig. 11, which is drawn for a nominal 0.5-v threshold setting. Owing to capacitance coupling, if the input pulse is too long, the circuit acts as an astable multivibrator, oscillating for the duration of the input pulse; coupling eliminates this at the cost of speed. Delay-time variation is of the order of 10 nsec.

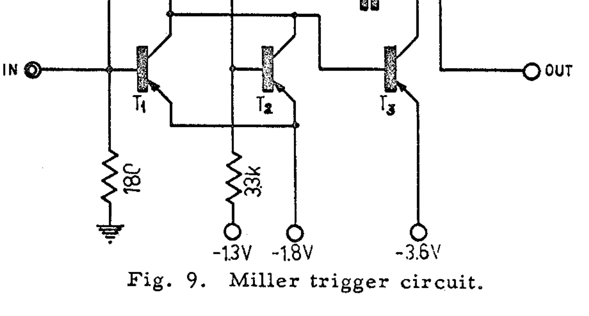


Fig. 9. Miller trigger circuit.

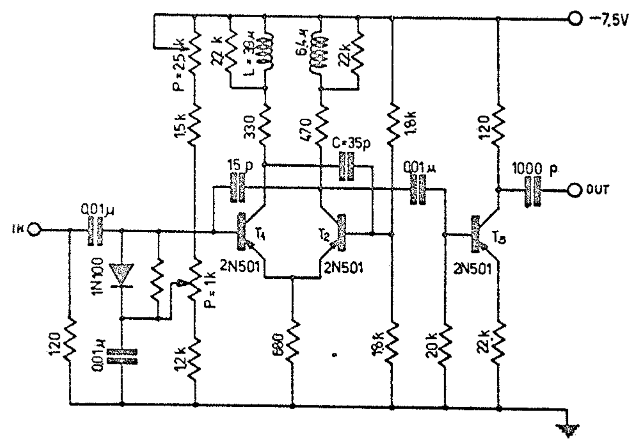


Fig. 10. Piroue-Fitch fast discriminator.

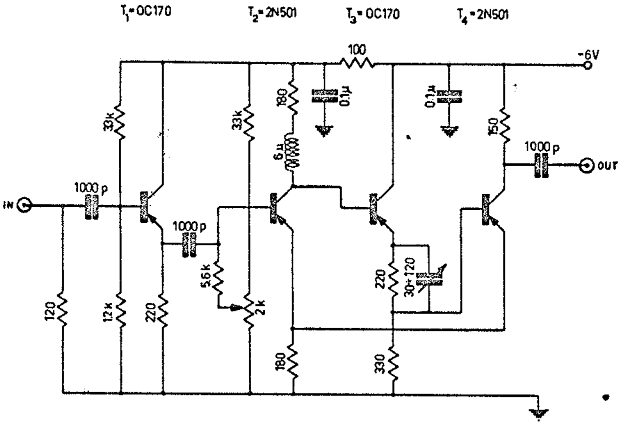


Fig. 12. Modified Piroue-Fitch circuit.

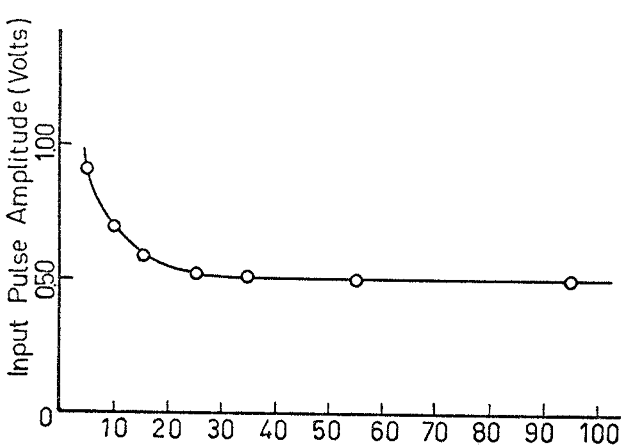


Fig. 11. Threshold variation for Piroué-Fitch fast discriminator.

A modification to the above-mentioned circuit has been made by one of the authors: the diagram is shown in Fig. 12.

Here dc coupling is realized through emitter-follower stage T_3. The current amplification thus gained is used to speed up charging and discharging the capacitance seen at the base of T_4. T_1 is used to keep the input matched at 125Ω also during the circuit's triggering action. Discrimination interval is between 0.2 and 1.8 v, and threshold uncertainty is less than 0.5 mv. Threshold variation due to temperature effects is about 10 mv between 20 and 50 °C. Dead time is about 90 nsec. Threshold setting and output-pulse shape are independent of input-pulse duration if the latter lies between 20 nsec and 10 μsec. For shorter input pulses threshold uncertainty increases, reaching 0.1 v for 5-nsec pulses. Maximum repetition rate is about 5 Mc. No spurious output has been noticed for input pulses up to 20 v in amplitude.

M. Gettner and W. Selove[10] have proposed the circuit of Fig. 13, mainly to obtain better resolving times.

A binary trigger circuit rather than a monostable one is used in this case; the reasons for this are the following: in monostable operation every triggering operation requires two transitions, one from the stable to the unstable state, the other from the unstable to the stable one. In binary operation, each time the circuit triggers, there is only one transition between states. Differentiation of the step generated in the above-mentioned fashion would thereby produce a standard pulse.

In the circuit of Fig. 13, input pulses are applied to the amplifying and limiting stage T_1; an emitter-follower T_2 is used to trigger the binary circuit by correctly biasing diodes D_1 and D_2. T_3 and T_4 are the binary transistors coupled by emitter-followers T_5 and T_6. The binary is a transistorized version of similar vacuum-tube binaries, which have appeared elsewhere.[11, 12]

The leading edges of the pulses thus generated are applied to T_7, T_8 and T_{10}, T_{11}. The biases on T_8 and T_{11} are set so as to equate pulse amplitudes on the collectors of T_7 and T_{10}. The pulses are then differentiated and applied to the T_9 - T_{12} configuration so that only the negative "spikes" are amplified.

Pulse amplitude on the collectors of T_9 and T_{12} is about 1 v; at the collector of T_{13} a scaled output is available. Discrimination interval is between 0.5 and 1.5v, and dead time is of the order of 18 nsec. One should note that the use of a binary introduces a certain asymmetry in the threshold. The authors state that this is less than 3% for pulses longer than 10 nsec. Using the limiting stage T_1 and dc coupling should ensure satisfactory operation for long pulses and against overloading.

Suggested Applications Using New Semiconductor Devices

Broadly speaking, any fast pulse-height discriminator may be thought of as shown in Fig. 14.

Usually the trigger circuit is the limiting one so far as resolving time and maximum repetition rate are concerned. Recently, to overcome the above-mentioned limitations, the use of certain semiconductor devices having peculiar characteristics has been proposed: i.e., those fast switching devices whose characteristics show a negative resistance region such as the tunnel diode (see Fig. 15).

From theoretical considerations regarding p-n junctions and tunneling effects that explain the above characteristic, and taking into account practical manufacturing limitations, one obtains for the tunnel diode an equivalent circuit like the one shown in Fig. 16. Here

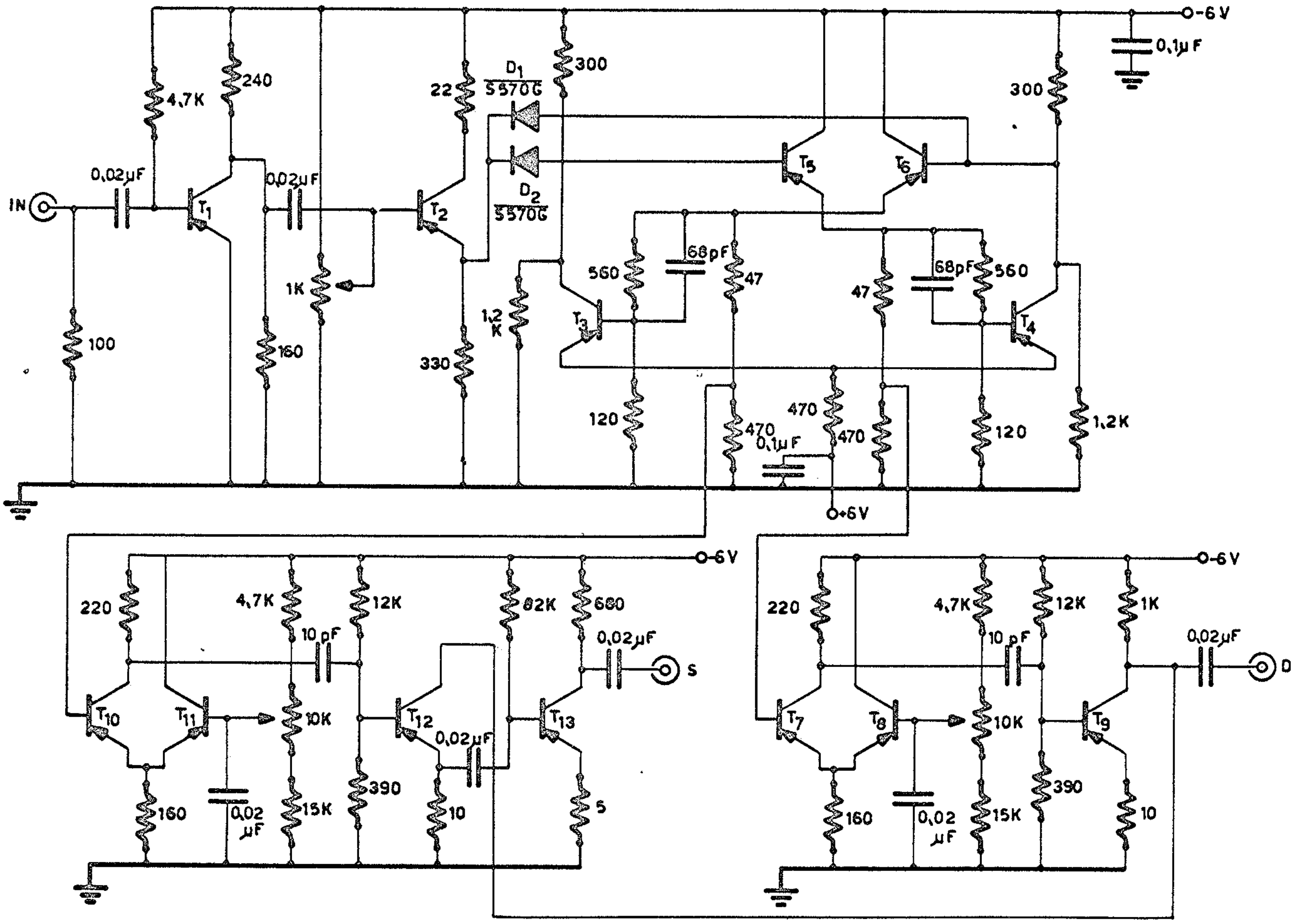


Fig. 13. Gettner and Selove circuit.

C is the junction capacity, and G is the differential conductance measurable from the static characteristics; L and R_s are due to the leads and to the semiconductor body. In the negative resistance region, putting G = -g, one finds that the impedance seen between A and B has a negative real part provided that

$$R_s < \frac{g}{g^2 + 4\pi^2 f^2 C^2},$$

where f is the frequency. A cutoff frequency can therefore be defined as

$$f_c = \frac{g}{2\pi C}\sqrt{\frac{1}{gR_s} - 1};$$

above f_c no negative "resistance" is possible; f_c may range from 0.2 to 10 kMC.

A trigger circuit may be realized according to the diagram in Fig. 17. Here V_0 and R are chosen as sketched in Fig. 15, so that three operating points are possible, with a and c stable states and b an unstable state.

A positive pulse applied to E travels down the delay line LT_1 and (if it is large enough) triggers the diode from state a to state c. The same pulse, after having gone through LT_2, is reflected with a change of sign, and resets the system from state c to state a.

Output-pulse duration is determined by the length of LT_2; its rise time is usually very short (< 1 nsec). Output-pulse amplitude is a few tenths of a volt.

Another tunnel diode discriminator that is extremely simple and that has stood up satisfactorily under tests is represented in Fig. 18.

The tunnel diode is in this case current-triggered. An input pulse that is large enough to inject a current $\geqslant I_p$ takes the diode into the negative resistance region, thus producing (at B) a pulse whose amplitude is at least $V_p + V_1$ (see Fig. 19). It is therefore sufficient to use a cutoff n-p-n transistor T_1 to eliminate all the pulses that have not triggered.

Thus one realizes a fixed-threshold discriminator whose threshold is surprisingly well defined and free from drift, since the "peak point" (defined by V_p, I_p in Fig. 19) is extremely stable with respect to age and temperature.

With these tunnel diode circuits, resolving times of the order of 10 nsec should be easily attainable, coupled with threshold definitions and stabilities of the order of 10 mv or better.

Acknowledgments

The encouragement and advice of Professor I. F. Quercia and Professor B. Rispoli are gratefully acknowledged.

Fig. 14. Block diagram of general discriminator.

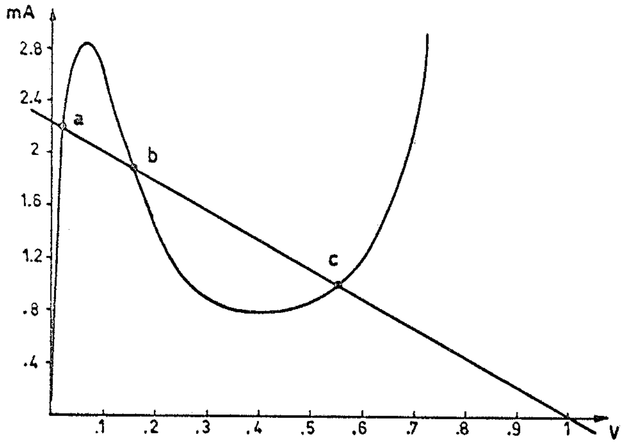


Fig. 15. Characteristic curve for a tunnel diode.

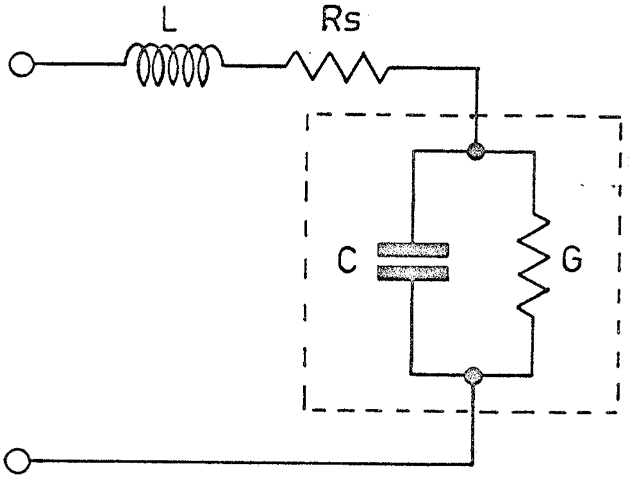


Fig. 16. Equivalent circuit of tunnel diode.

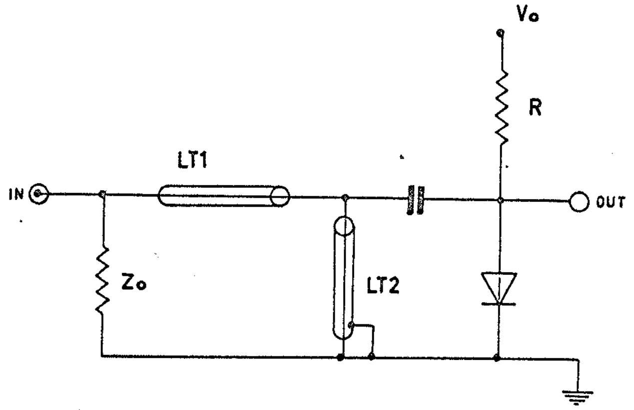


Fig. 17. Tunnel diode triggering circuit.

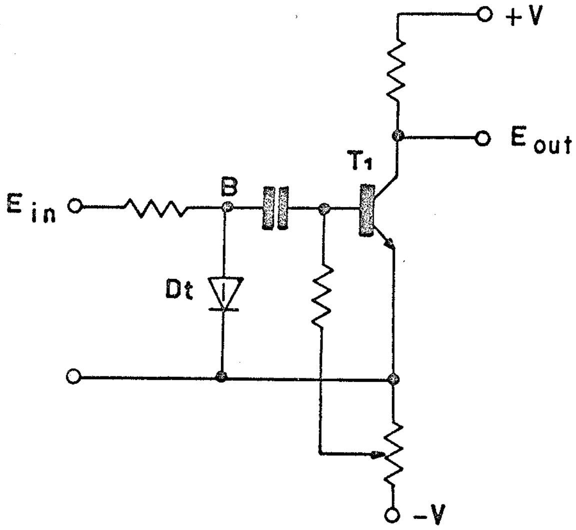


Fig. 18. Tunnel diode discriminator.

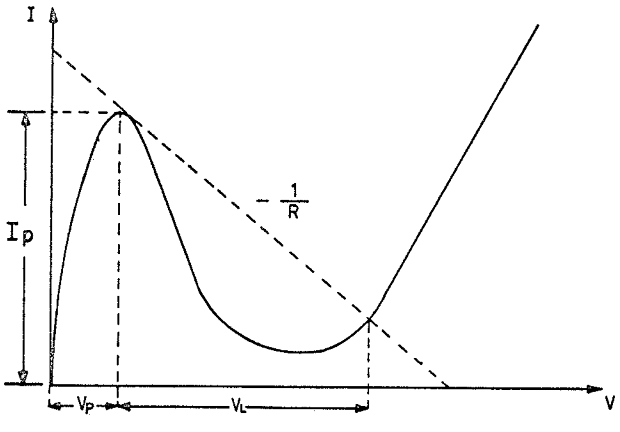


Fig. 19. Tunnel diode characteristic illustrating the operation of the discriminator in Fig. 18.

Footnotes and References

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