SOME NOTES AND APPLICATIONS ON TUNNEL DIODES

by

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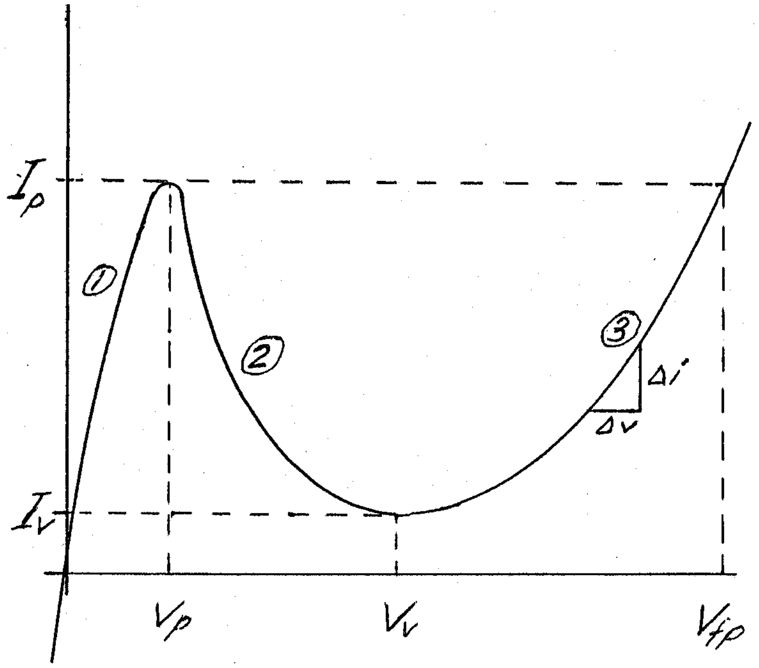


Fig. 1

The Tunnel Diode at Low Frequencies

The significant features of the tunnel diode are illustrated in Figure 1. This shows the two regions of positive resistance (1) and (3), joined by a region of negative resistance (2). The current, I_p, at the beginning of the negative resistance region is known as the peak current and ranges from 0.1 milliamps to 50 milliamps in commercially available tunnel diodes. The voltage at this current is called the peak voltage V_p and is typically 50 to 150 millivolts. Following the negative resistance region is a broad valley where the voltage, V_v, is typically 350 - 600 millivolts and occurs at the valley current, I_v. The ratio of the peak current to the valley current is an important figure of merit for tunnel diodes and ranges from 4 to 25 in typical units. The voltage at which the current is once again equal to the peak current on the high voltage side of the characteristic (3) is called V_{fp}.

V_{fp}/voltage is approximately equal to the size of the signal provided by tunnel diodes operated as switches and ranges from 500 millivolts to one volt. Tunnel diodes are built using gallium arsenide as well as germanium and silicon. Germanium units tend to have the lowest peak voltage and gallium arsenide the highest. One difference to be noted from Figure 1 between tunnel diodes and ordinary diodes, aside from the presence of negative resistance region, is the lack of any high impedance reverse current region. Due to the extremely high doping found on both sides of the junction of tunnel diodes, the reverse bias direction is characterized by heavy conduction which becomes purely ohmic at high currents (no curvature of characteristic). The incremental resistance of the diode in the three regions shown in Figure 1 may be determined from the relation $r_d = \frac{\Delta V}{\Delta I}$. In region (1) values from 20 to 50 ohms are typical for 1-5 ma tunnel diodes. In region (2) r_d is negative and ranges from 20 to 150 ohms depending upon diode type. (100 ohms is typical for 1 ma germanium diodes.) Here we can expect to see 10 ohms for a peak current, I_p, of 10 ma for germanium, and 20 Ω for a peak current of 10 ma for gallium arsenide. In region (3) r_d is once again positive and is typically 50 ohms.

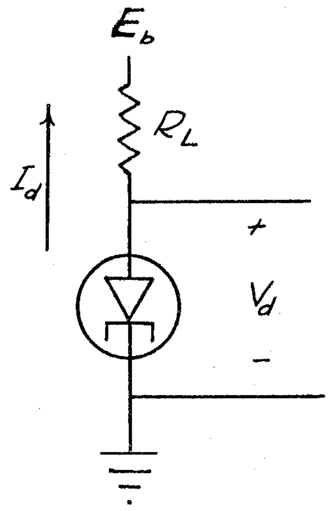


Fig. 2

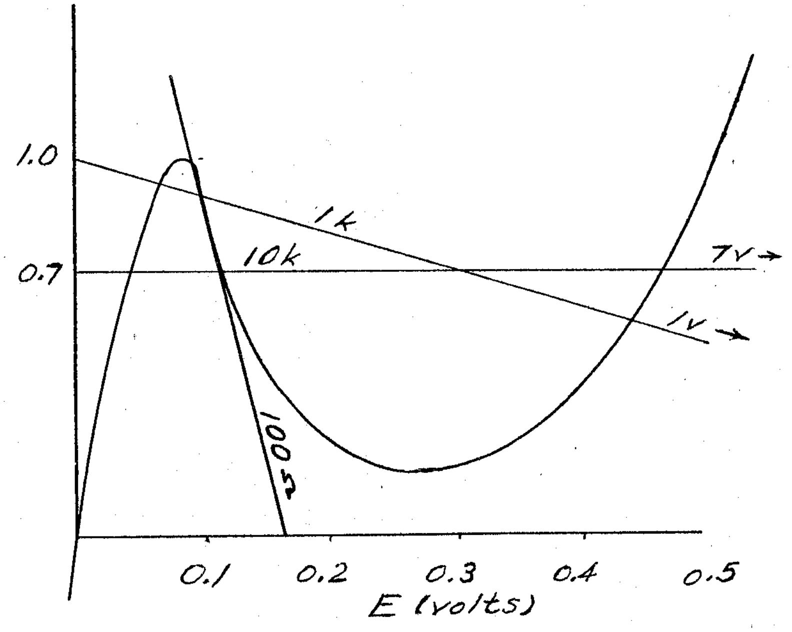


Fig. 3

DC Load Line

Figure 3 shows several load lines drawn on the tunnel-diode characteristic for the circuit of Figure 2. Just as with vacuum tubes and transistor characteristics, the load line itself is not related to the characteristic of the tunnel diode. It is simply another graph drawn upon the same axes as those used for the tunnel diode-characteristics. The supply voltage is E_b and resistance is R_L. The 100-ohm load line may be seen to intersect the tunnel diode characteristic at only one point. The 1-k and 10-k load lines however, intersect the curve at three points.

These two load lines could also be arranged to intersect at one point only, provided that they do not pass through the negative resistance region. The larger-valued load lines such as 10 k are used when the diode is operated as a switch. In this case the diode may be found in either one of two states represented by the intersection of the load line with one of the positive resistance regions of the diode characteristic. In order to obtain an operating point somewhere in the negative resistance region, it is necessary that R_L be less than r_d. (r_d is considered to be a positive quantity; r_d is then the diode incremental resistance in the negative-resistance region.)

Switches

Consider an input current as shown in Figure 4 which varies in time to a maximum and then returns to zero. This can be achieved by using a large value (Figs. 2, 3) for R_L and varying E_b up and down as is shown in Figure 4. On the diode characteristic, Figure 5, one passes in succession through the points number 1--8. The voltage resulting is shown in Figure 6. As may be seen, the voltage rises to a small value (approximately 50 millivolts) until shortly after (2) is reached. The sudden transition to (3) produces a voltage approximately equal to V_{fp}. A further increase in voltage between (3) and (4) is due to the small diode incremental resistance in this region. Upon reducing the current, the portion of the characteristic between (4) and (3) is retraced, but no transition takes place at (3). Instead, the points (6) and (7) are passed through. The voltage drops to V_v at (7). A sudden transition again takes place when the current equals I_v. The diode is then at point 8 and returns along the original characteristic to the origin. Referring to Figure 6, note that a somewhat larger voltage step occurs when switching in the positive direction as compared to the negative direction. The rise and fall time of this waveform is approximately two nsec for slow germanium units and extends down to less than .5 nsec for the faster gallium arsenide diodes. A circuit capable of displaying the waveform of Figure 6 in the range of 1 to 10 nsec is given under Tektronix Type N Sampling Plug-In Unit on page E-10 of Tektronix Catalog 19.

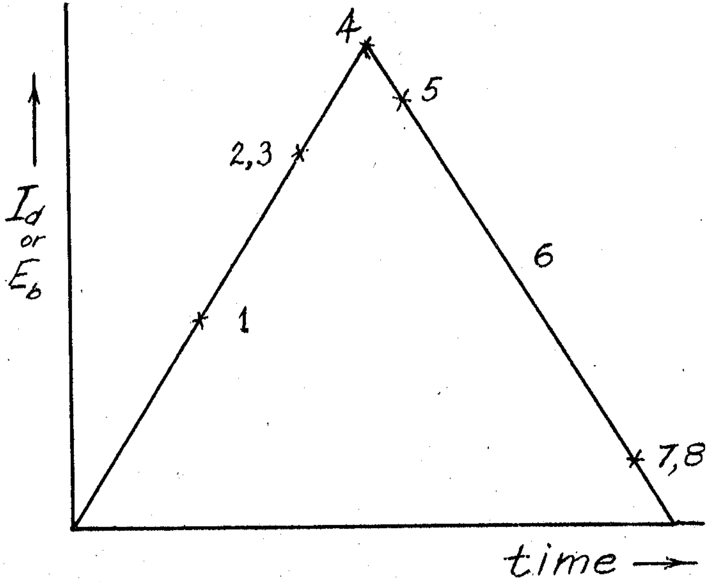


Figure 4

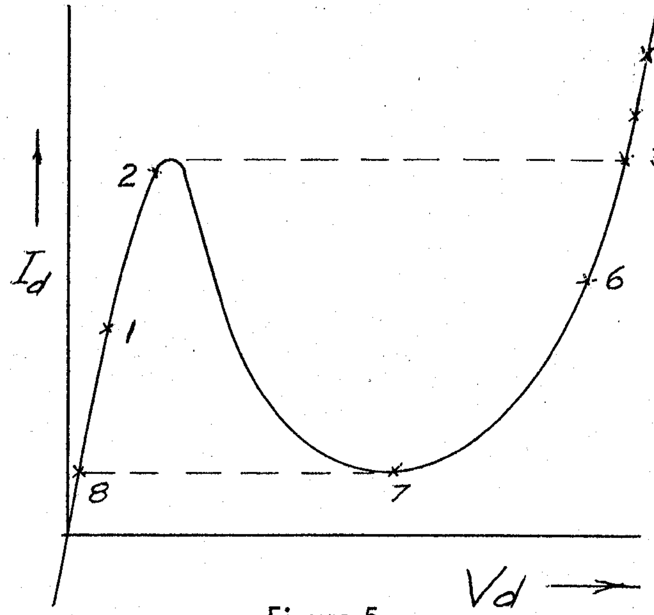


Figure 5

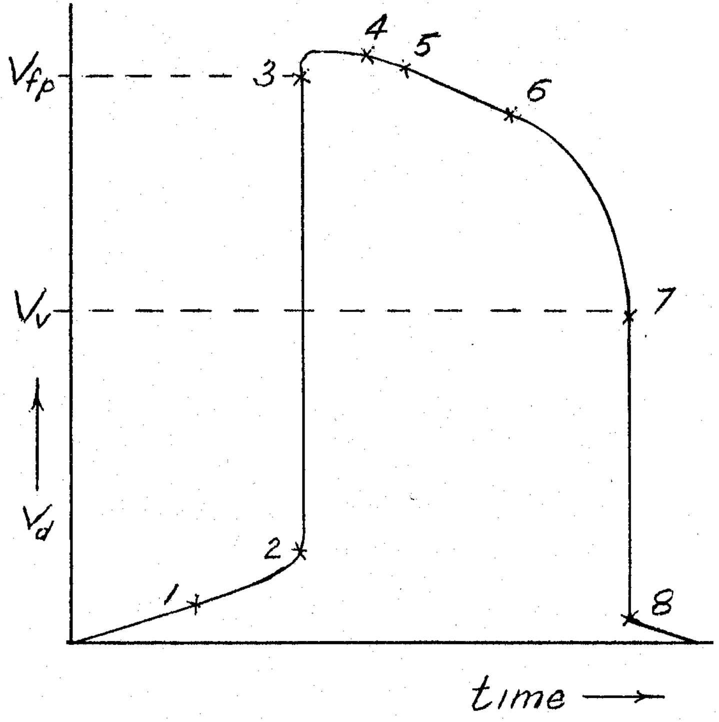


Figure 6

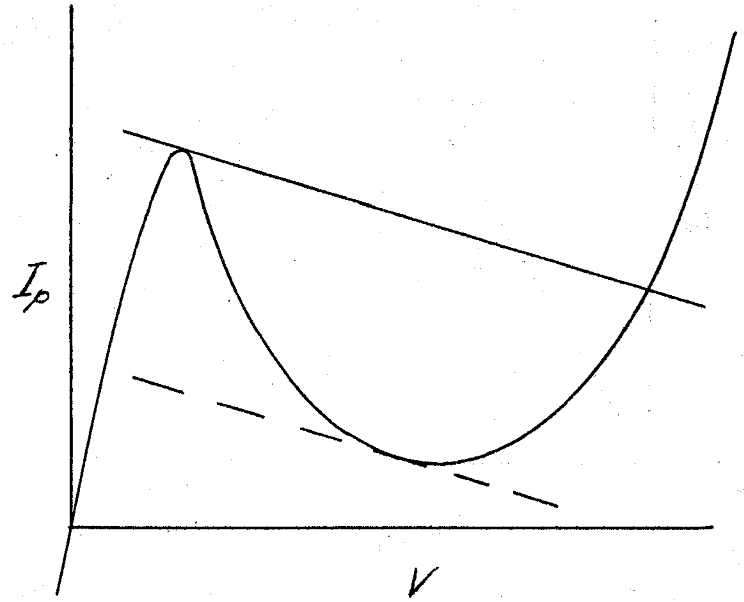


Figure 7

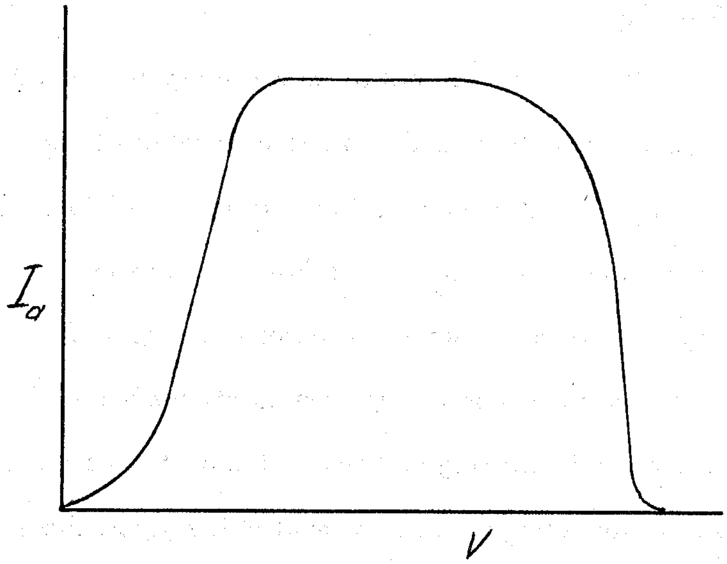


Figure 8

Switching Waveform

The current available for charging shunt capacity is the difference between the current demanded by the load and that demanded by the tunnel diode. As Figure 7 shows, for the case of a load line which is practically "constant current", the difference current is greatest when the diode is passing through the valley region. The maximum current occurs at the point where a line parallel to the load line is tangent to the diode characteristic. The waveform of the current, I_a, available for charging capacity is shown in Figure 8. A notable feature is the relatively long flat region which will produce a fairly linear portion on the voltage waveform.

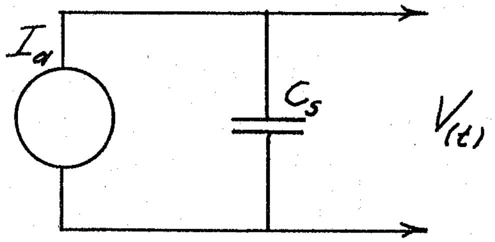


Figure 9

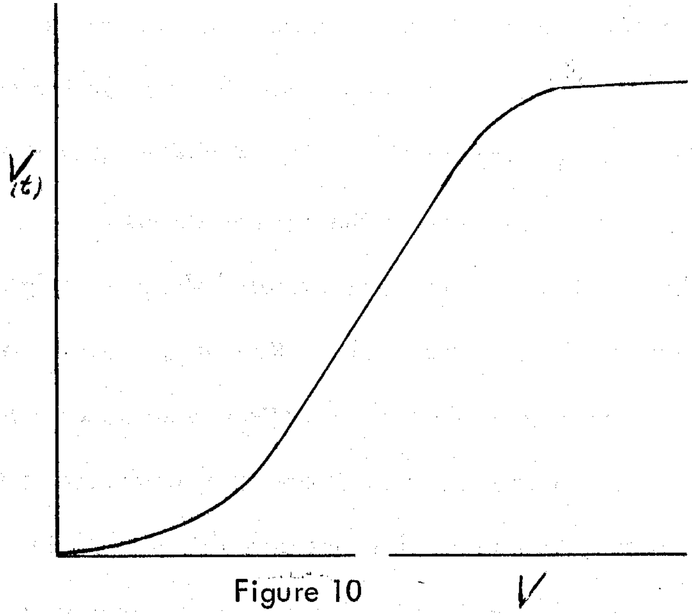


Figure 10

The shape of the voltage waveform, V(t), for the simple equivalent circuit shown in Figure 9 is obtained from the integral of I_a. This is shown in Figure 10.

Both the Type N and an analogue solution with operational amplifiers give curves which are like Figure 10.

Stability

The equivalent circuit of the tunnel diode in the negative resistance region is shown in Figure 11. R_s and L_s are the internal series resistance and inductance respectively. C is the junction capacity and r_d is the negative incremental resistance. Both r_d and C are dependent upon the operating point, although C varies slowly throughout the operating range. The variation of C with the applied voltage V is given by:

$$C = \frac{C_o}{\sqrt{1 - V/\varepsilon}} \qquad \text{(See Figure 12).}$$

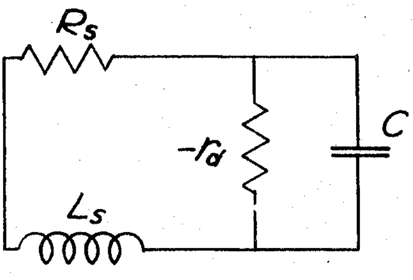


Figure 11

Figure 13 shows the equivalent circuit of the tunnel diode when connected to an external circuit. L and R represent the total series inductance and resistance. Figure 14 shows the three areas of operation. In the area of stable operation, the total diode functions as an amplifier while in the other two areas of unstable operation only rapid switching from one point to another on the characteristic is possible. The value of R is important in determining which of the three areas the diode is operating, and as may be seen from Figure 14, when R is greater than r_d a bi-stable switch results. Another instability arises from the case in which:

R is less than $\dfrac{L}{r_dC}$. Here a high frequency oscillation is produced and for a given r_d and C may only be avoided by lower values of inductance in the circuit. These three regions apply equally well to the tunnel diode circuit itself (Figure 11) in which a short circuit is produced across the tunnel diode terminals (by a large capacitor at high frequencies for example). In this case R_s and L_s replace R and L in Figure 14. This means that the inductance of the case and mounting hardware must be low if the external load is a low value of impedance. It is important to note that the stable region defined by:

$$\frac{L}{r_dC} < R < r_d$$ will vanish if L is greater than r_d C. This requires that the package and holder inductance be carefully minimized in order to realize any stable region at all.

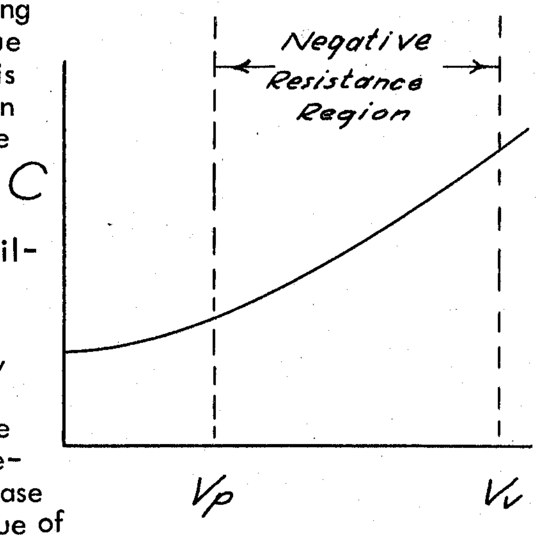


Figure 12

From the circuit of Figure 13, the following characteristic equation may be written describing the transform impedance seen looking into the terminals at A and B (jumper removed):

$$Z_{(p)} = \frac{p^{2LC} + (RC + L/r_d)\,p + (1-R/r_d)}{pC - 1/r_d}$$

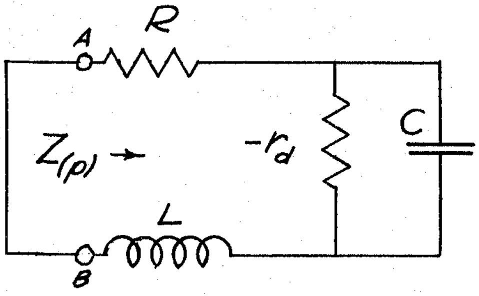


Figure 13

The zeros of this equation are:

$$p = -1/2\left(\frac{R}{L} - \frac{1}{r_dC}\right) \pm \sqrt{1/4\left(\frac{R}{L} - \frac{1}{r_dC}\right)^2 - \frac{1-R/r_d}{LC}}$$

p will have a negative real part (stable characteristic) only if:

$$\frac{R}{L} - \frac{1}{r_dC} > 0 \text{ and } 1 - R/r_d > 0$$

This may be written: $\dfrac{L}{r_d\,C} < R < r_d$ and is the basis for Figure 14.

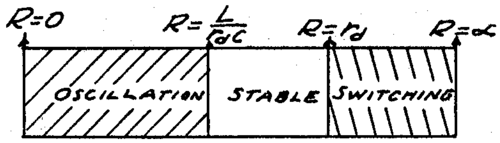


Figure 14

Circuits with Zero Standby Power

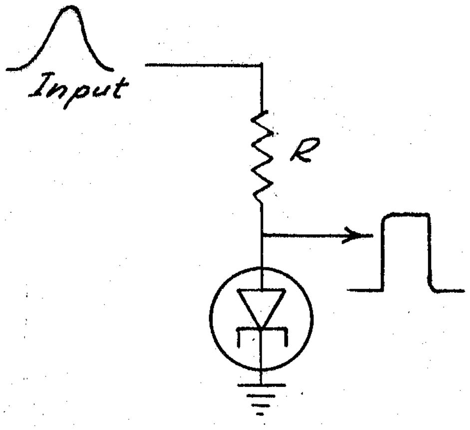


Figure 15

Tunnel diodes have made possible a number of circuits which have the unusual property that no standby power is required. In fact no B+ power in the usual sense is applied at all. These circuits can be quite important in low power drain applications such as satellite instrumentation. The source of power to operate the circuit is the input signal itself.

1. Simple Trigger: A circuit which produces a standardized amplitude pulse in response to an input signal which exceeds a given fixed amplitude is shown in Figure 15. The operation of this circuit may be understood by referring to Figures 4, 5, and 6. Here the input may be regarded as a pulse having the general shape of Figure 4, while the output is represented by Figure 6. The output appears when the input voltage exceeds I_pR. For example, using a 1-mil peak-current tunnel diode the trigger level is 1 volt if R = 1k. The output pulse amplitude is approximately equal to V_{fp}.

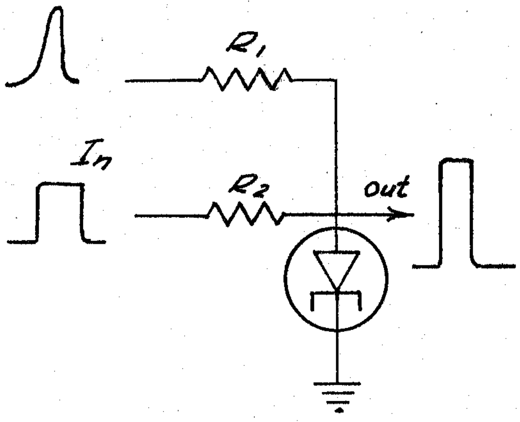


Figure 16

2. Coincidence Circuit: By using two input resistors driven by two input signals, a circuit similar to that in Figure 15, may be used to provide the function known as coincidence. Figure 16, when the two inputs are such that the sum of the current to the diode is greater than I_p, an output appears. Thus, when $\frac{E_1}{R_1} + \frac{E_2}{R_2} = I_p$, the diode switches to its high voltage forward state, producing a pulse whose amplitude is approximately V_{fp}. When the total input current drops below I_v, the output disappears. This coincidence circuit produces pulses whose width is governed by somewhat different rules than ordinary coincidence circuits. In Figure 17 it may be seen that the ordinary coincidence circuit produces a pulse whose width is equal to the overlap of the two input circuits.

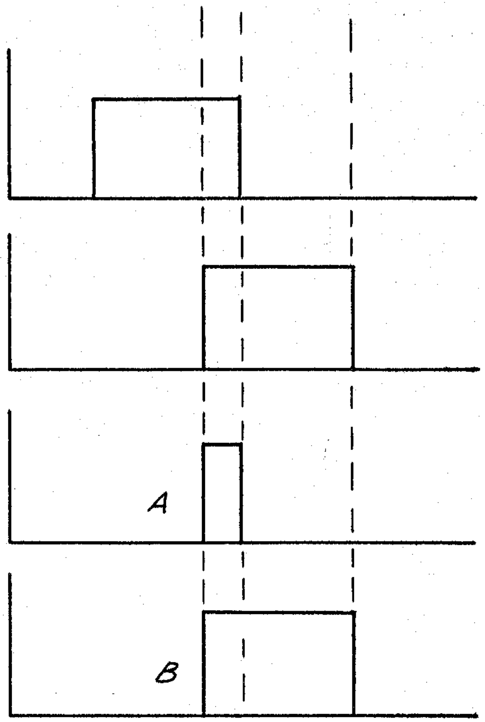


Figure 17

A. The tunnel diode coincidence circuit, however, produces an output pulse whose leading edge appears when the two input pulses are first in coincidence and whose trailing edge appears at the same time as the later of the two input trailing edges.

B. This means that the output from the tunnel diode coincidence circuit is always at least as wide as one of the input pulses. This situation should be compared with that of the ordinary coincidence circuit in which the output pulse may achieve extremely narrow widths. In many applications of coincidence circuits, the circuit following is some type of multivibrator which will cease triggering when the input to it becomes too narrow. This means that an ordinary coincidence circuit depends to some extent upon the succeeding circuit to make the decision as to whether or not there is a coincidence. With the tunnel-diode coincidence circuit, the task of the succeeding circuit is considerably easier due to the wider pulses available from the tunnel diode coincidence circuit.

3. Pulse Height Selector (Single Channel Analyzer): Figure 18 shows a simple pulse-height selector which uses no standby power but which gives an output whenever the input amplitude lies between two levels which are set by the size of R_1 and R_2. Assuming $I_p = 1$ ma, $R_1 = 1k$, and $R_2 = 1.1k$, then the inputs of amplitude greater than one volt will trigger D_1 but not D_2. An output pulse will then appear at the anode of D_1. As the input exceeds 1.1 volts, D_2 will also trigger. Q_1, acting as a shunt switch across the output from D_1, will prevent any output from appearing. The time between the firing of D_1 and D_2 must be small in order that no substantial output will be built up between the times D_1 and D_2 fire. Since this circuit operates on the leading edge of the input pulse, satisfactory operation will generally be obtained from the output of photomultiplier tubes (after suitable amplification) because there will be less than 100 nsec between the firing of D_1 and D_2. The output pulse will then be 100 nsec or less in duration for the case where the input exceeds the trigger level of both D_1 and D_2, but will be greater than 1/2 µsec when the input amplitude lies between the two trigger levels. The only precaution needed in this circuit is that of choosing for D_2 a diode whose peak to valley ratio is the higher (lower value of I_v) in order to insure that the blanking effect of D_2 extends completely beyond the on-time of D_1 (See Figure 19).

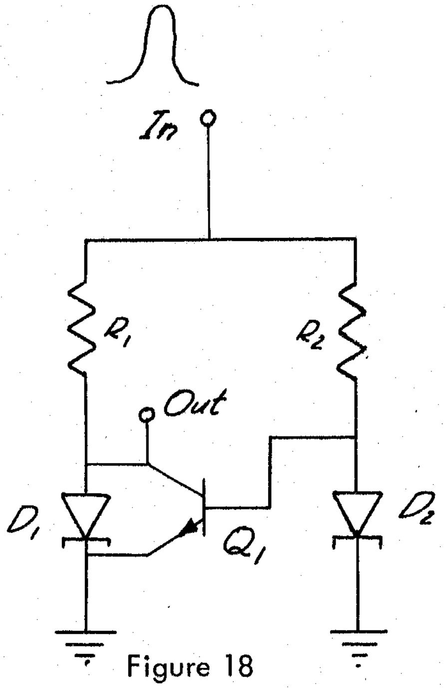


Figure 18

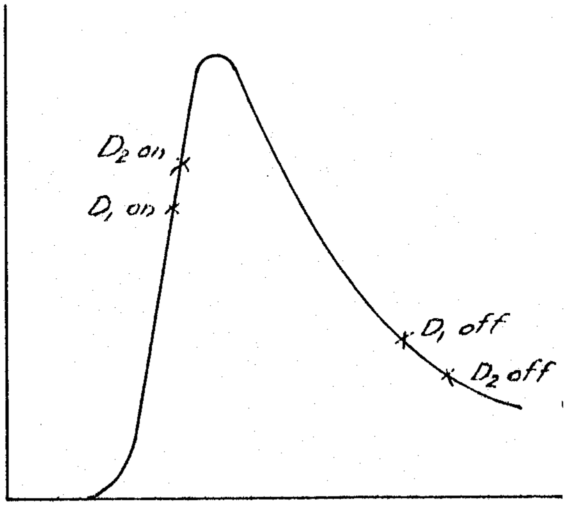


Figure 19

Multivibrator

A tunnel-diode single-shot multibrator is shown in Figure 20 which uses L/R timing rather than the RC timing usually found in multivibrators. The diode is biased at about 40 mv (assuming the peak voltage is 50 mv). This corresponds to point (2) in Figure 5. A small trigger causes the tunnel diode to switch with a virtually constant-current load line provided by the choke. The diode is now at point (3) in Figure 5 and progressing down toward point (6). When point (7) is reached, the reverse transitron to point (6) occurs. The waveform width is determined principally by the inductance and resistance of the tunnel diode along its high voltage characteristic, points 4, 5, 6, and 7 in Figure 5.

A shorted delay line may be used instead of the choke to provide a rectangular pulse having a width twice the length of the delay line.

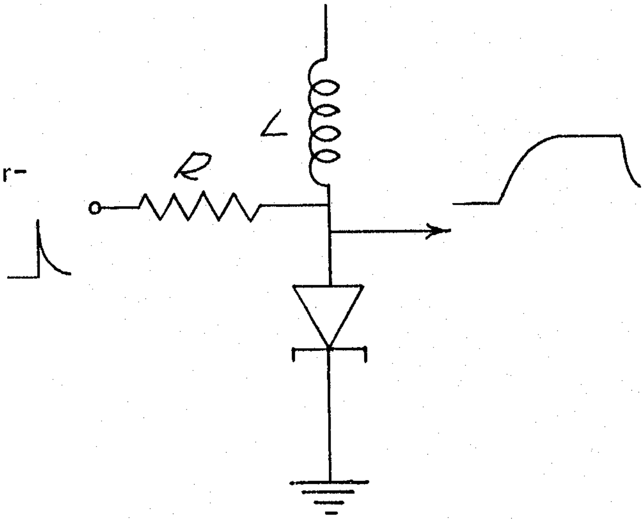


Figure 20

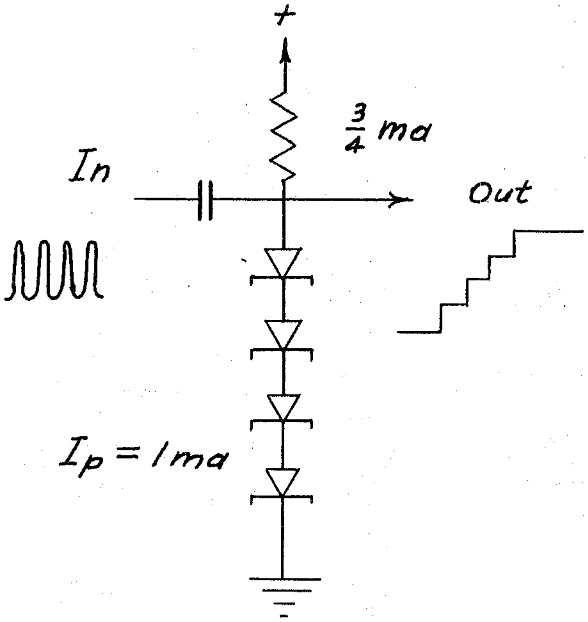


Figure 21

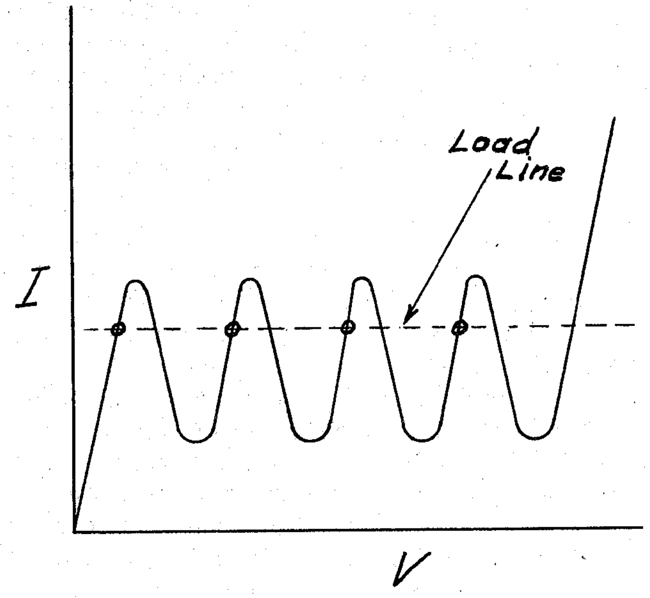


Figure 22

Scalers

A totem pole scaler of extreme simplicity may be constructed by arranging a string of diodes in series so that the same current is at a high impedance; the load line is horizontal.

Figure 22 shows a four-state characteristic obtained when four diodes are connected in series as in Figure 21. By triggering the circuit with a suitable pulse, the stack of diodes progressively increases the total voltage. A circuit which resets the diodes after the last one switches completes the scaler. Note that is is not necessary that the diodes turn on progressively (from top to bottom or vice versa). A delay should be inserted before resetting to insure that the last tunnel diode reaches a stable state.

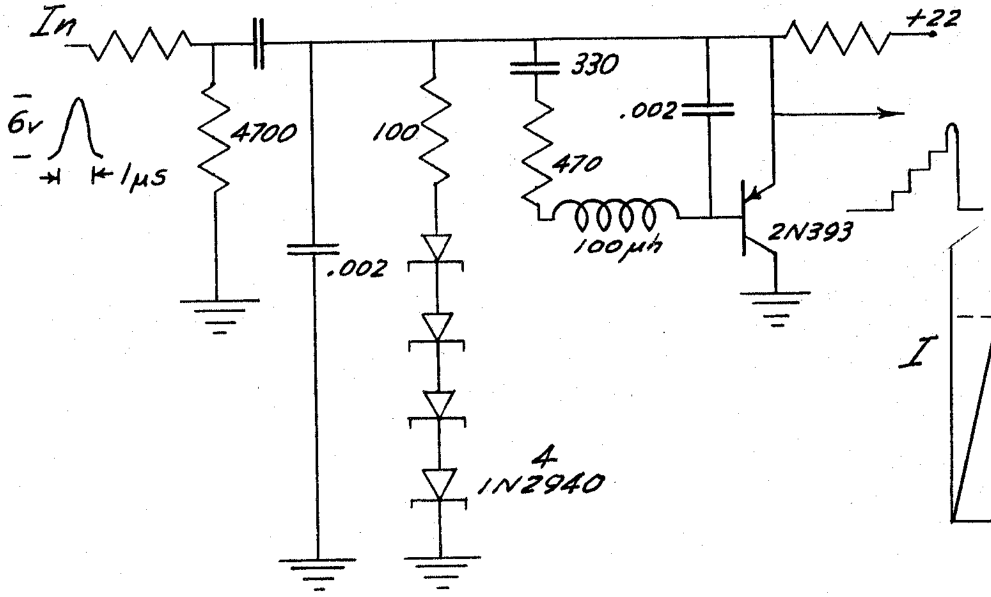


Figure 23

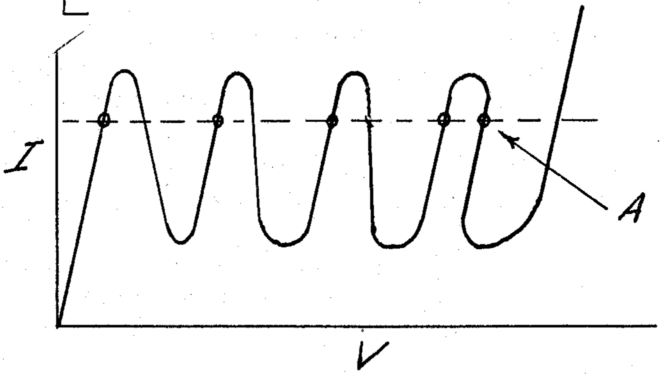


Figure 24

A practical circuit of a scale of four which is quite tolerant to supply and trigger voltage is shown in Figure 23. The actual characteristic is not quite as shown in Figure 22. Due to the progressive addition of negative resistance as more diodes come on, the characteristic looks more like Figure 24. This shows the appearance of an additional stable state at (A). This feature can cause considerable trouble when large numbers of diodes are stacked up.

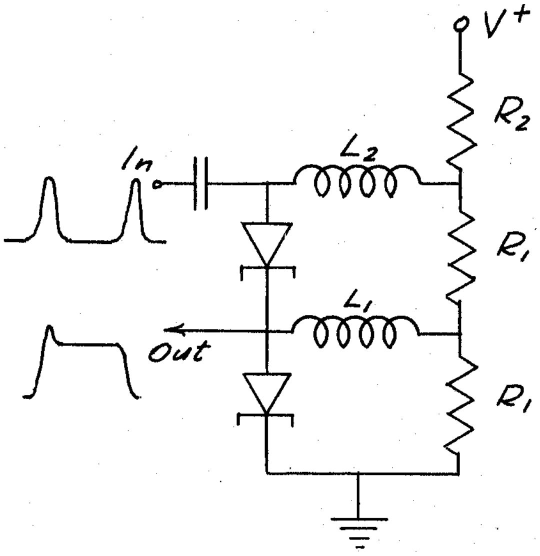


Figure 25

A binary scaler employing two tunnel diodes arranged in a circuit which is the dual of the neon binary, was reported in the 1960 Wescon Proceedings (Part 3). This scaler is shown in Figure 25. The considerations governing the choice of V^+, R_1, R_2, etc. are given in the article cited. Basically, this scaler employs a characteristic similar to Figure 22, but having only two peaks. The two stable states are obtained by having only one diode or the other in its high-voltage forward-biased direction. The trigger causes the two diodes to interchange conditions in a manner similar to that found in conventional cross-coupled binaries. In a cross-coupled vacuum tube or transistor binary, the trigger momentarily brings both halves into conduction and only the memory elements determine which state the circuit will assume when the trigger ends. L_1 is the memory element in the circuit above. The direction of this steady-state current flow through L_1 is reversed after the state of the binary changes. When the trigger appears, both diodes are momentarily put in their high-voltage states. The current through L_1, however, does not change significantly during the trigger due to the relatively long time constant of L_1 and R_1. This current is in the direction to hold "on" the diode which was previously off when the trigger ends. Thus the trigger causes the binary to change states. Circuits of this type, while displaying great simplicity and adequate power to operate another stage directly, do not make optimum use of the capabilities of tunnel diodes as switches because of the long recovery time associated with L_1.

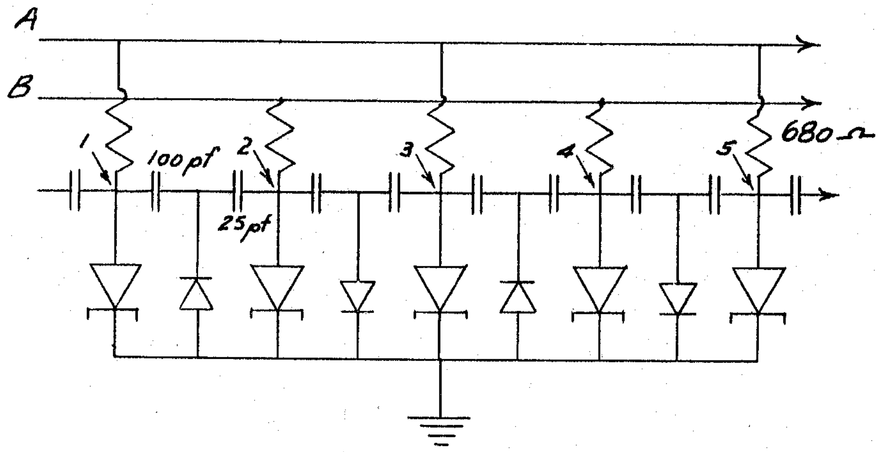


Figure 26

Shift Register

A shift register which appears capable of speeds well over 10 mc, and which possesses the ability to shift in either direction is shown in a preliminary form in Figure 26. Work is not yet complete on this circuit, so only a brief description is given.

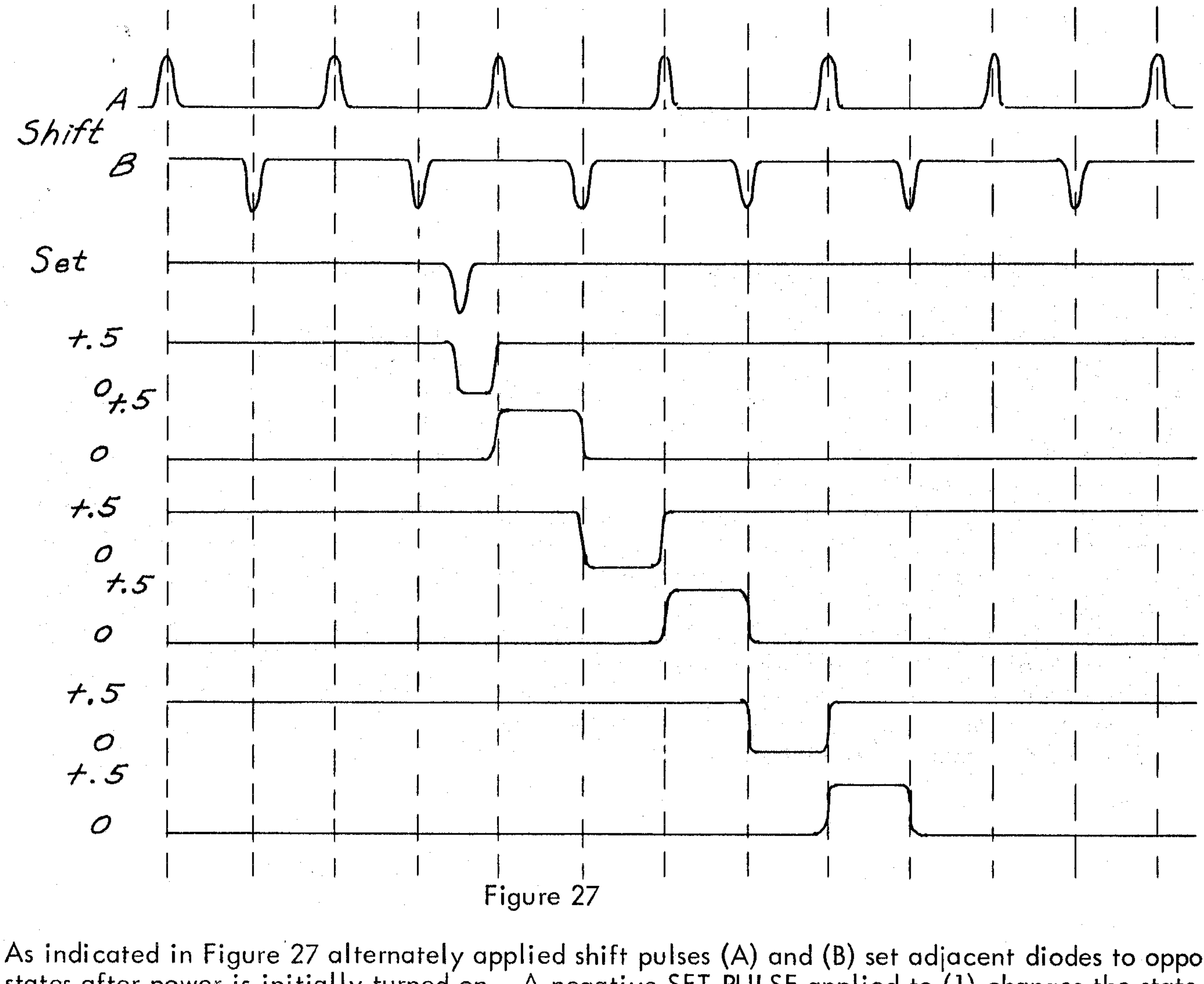


Figure 27

As indicated in Figure 27 alternately applied shift pulses (A) and (B) set adjacent diodes to opposite states after power is initially turned on. A negative SET PULSE applied to (1) changes the state of this diode until the next "(A)" shift pulse appears. The resetting of (1) by shift-pulse (A) causes (2) to change states until the next shift-pulse (B) occurs. The resetting of (2) by shift-pulse (B) causes (3) to change states until the next shift-pulse (A) occurs, and so on.

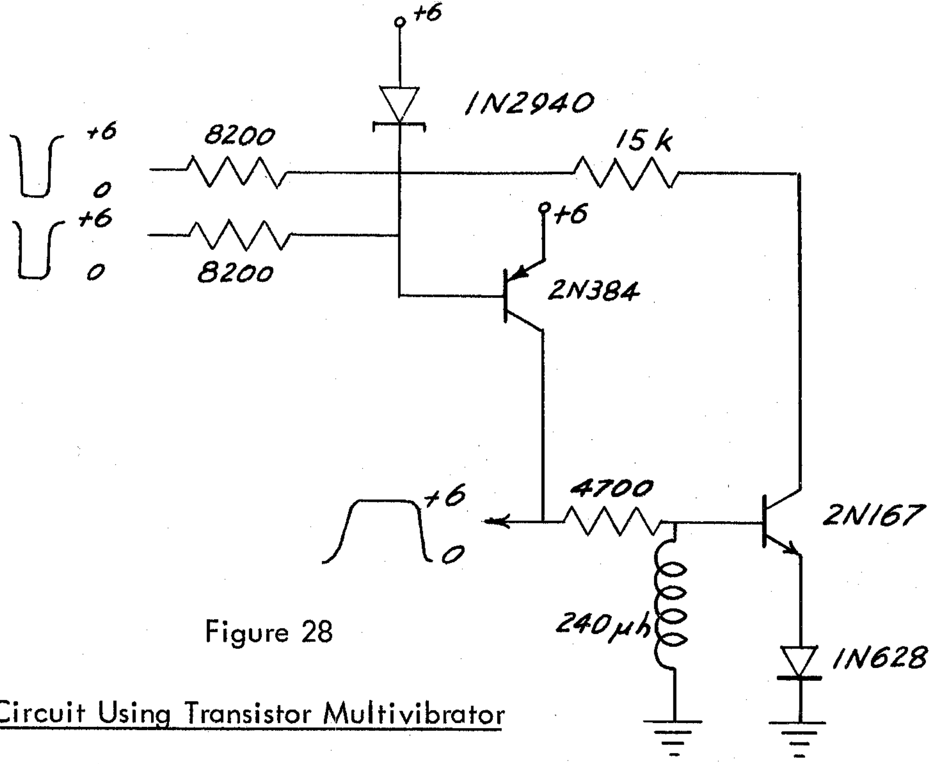
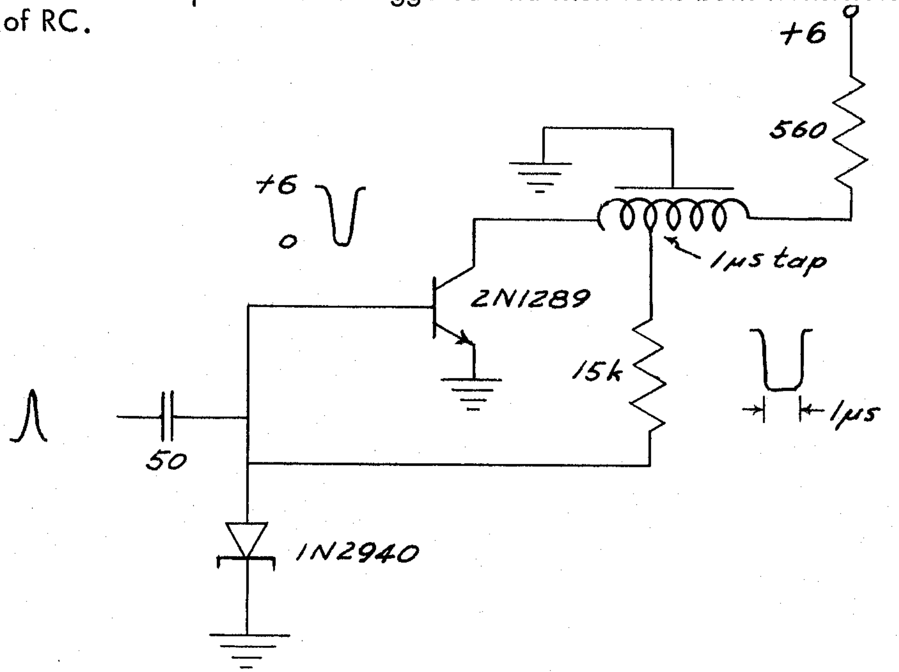


Figure 28

Coincidence Circuit Using Transistor Multivibrator

The circuit of Figure 28 uses the tunnel diode coincidence circuit of Figure 16 at the input. Feedback via the 15k resistor keeps the tunnel diode on, even after the inputs have vanished so the width of the multivibrator pulse is not affected by the inputs. The multivibrator is of the complimentary pair type which draws no power until triggered and then turns both transistors on. The timing is by L/R instead of RC.



Delay Line Driver

Figure 29

The circuit of Figure 29 is used to provide a 1-μsec pulse into a delay line which itself controls the width. The trigger causes the tunnel diode to fire, producing a negative pulse at the collector of the transistor. The tunnel diode is held "on" by the current to +6 volts in the 15-k resistor. One microsecond later, the negative pulse arrives at the tap and shuts off the tunnel diode. This causes the transistor to shut off and thus ends the cycle. No standby power is taken by the transistor, however 1/4 ma is drawn by the tunnel diode at all times.

It is convenient to supply the 6 volts by means of a zener diode supply. In the event the pulse from the tap fails to shut the tunnel diode off, this type of supply will collapse and allow the tunnel diode to shut off. This is a desirable feature, since it allows the circuit to reset itself in the event of a misfiring.

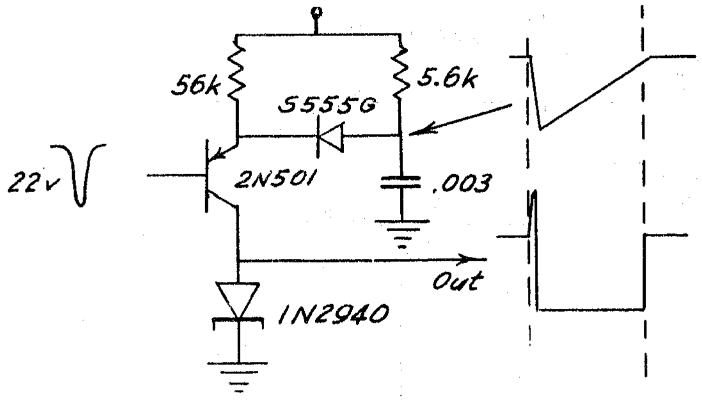


Figure 30

Pulse Height-to-Time Converter

The circuit of Figure 30 provides a pulse width proportional to the amplitude at the input. The circuit finds application in pulse-height analyzers and operates by measuring the time required by a linear ramp to return to its quiescent value after having been driven to a certain amplitude by the input pulse. The tunnel diode performs a very important function by providing a high speed regenerative "decision" to mark sharply the moment the ramp returns to its base line. Normally, the tunnel diode is biased about 100 μa beyond its peak current point so that it rests in its high voltage state at V_{fp} (Figure 1). A small positive spike is caused by the demand for heavy charging current through the collector circuit. Once the capacitor is charged, however, this demand vanishes, the transistors cuts off, and the tunnel diode returns to zero volts. Shortly before the ramp ends, the tunnel-diode current starts to rise, and at precisely I_p, the diode snaps back to V_{fp}. The excellent stability of this circuit (less than 1% drift in 50°) is due to the stability of the value of I_p in the tunnel diode.

Temperature Effects

The tunnel diode promises to provide a device which displays considerably less drift with temperature than other semiconductor devices. In particular, the values of the peak current and voltage are quite stable with temperature. A test setup permitting measurement of I_p without the use of a curve tracer is shown in Figure 31.

When the 150-volt sawtooth provided by an oscilloscope sweep output is applied through a 75-k resistor, the 1-ma point corresponds to half way across the screen. Figure 32 shows the display when the scope sweep is free run. Measurements on the GE 1N2939 and 1N2940 yielded the following coefficients:

	I_p	V_{fp}
1N2939	- .2%°C	- .22%/°C
1N2940	+ .14%/°C	- .24%/°C

The coefficient of typical diodes (not tunnel) is about 1%/°C. The region of normal forward conduction, (3) in Figure 1, displays the same temperature characteristic as ordinary junction diodes. The peak-current coefficients have both signs, depending upon the junction construction. It appears quite likely that a zero coefficient could be obtained for I_p. The fact that V_{fp} decreases with a temperature increase is fortunate when one considers that transistor junctions also do this. Thus compensation is obtained for direct coupled circuits.

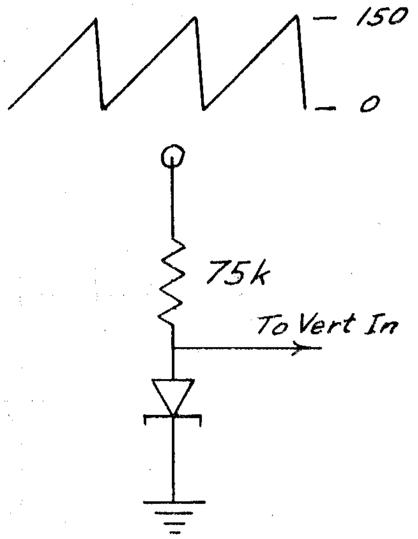


Figure 31

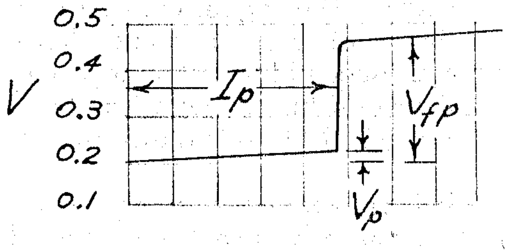


Figure 32