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Tunnel Diodes as Amplifiers and Switches

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High operating speed, low noise capabilities and resistance to nuclear radiation make tunnel diodes suitable for many applications in switching and amplifier systems. Circuits are inherently simpler than those using other techniques.

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Tunnel Diodes as Amplifiers

BECAUSE of its inherent negative conductance, the tunnel diode is particularly well-suited for operation as a sine-wave or relaxation oscillator. Its unique "S" characteristics make it useful for current sensing, current reference and as both an active and memory switching element in computer circuitry. Due to its region of relatively linear negative conductance, it can also be used as an amplifier. In general, its inherent high speed, resistance to nuclear radiation, low operating power requirements and wide operating temperature range can make it a valuable asset in a large variety of applications.

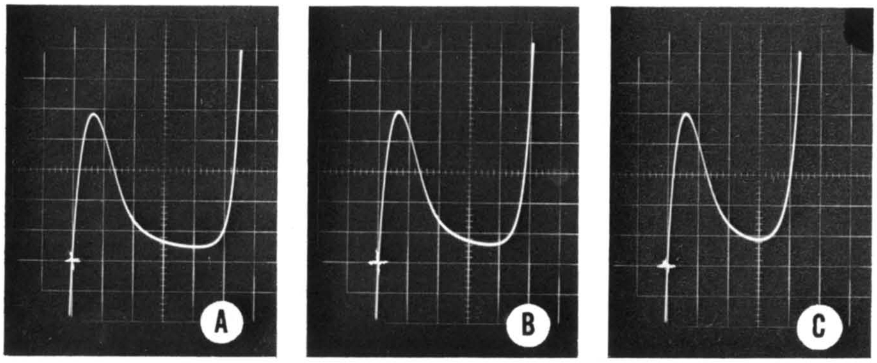

FIG. 3—Voltage-current characteristic curves of germanium tunnel diode at an ambient temperature of —50 C (A), 25 C (B) and 100 C (C).

The structure of a typical tunnel diode is shown in Fig. 1. The tunnel diode, seen in the center of the photograph, is mounted on a standard TO-18 transistor header directly between two of the lead posts. Contact to the top of the diode is made by a thin strip running between the tops of the two lead posts. This structure offers the advantage of a minimum inductance in a single-ended package, since the two leads connected to the top strip can be parallelled to reduce the series inductance. Another significant advantage of this structure is its mechanical strength. This is extremely important in the case of low current, low capacitance diodes where the diameter of the

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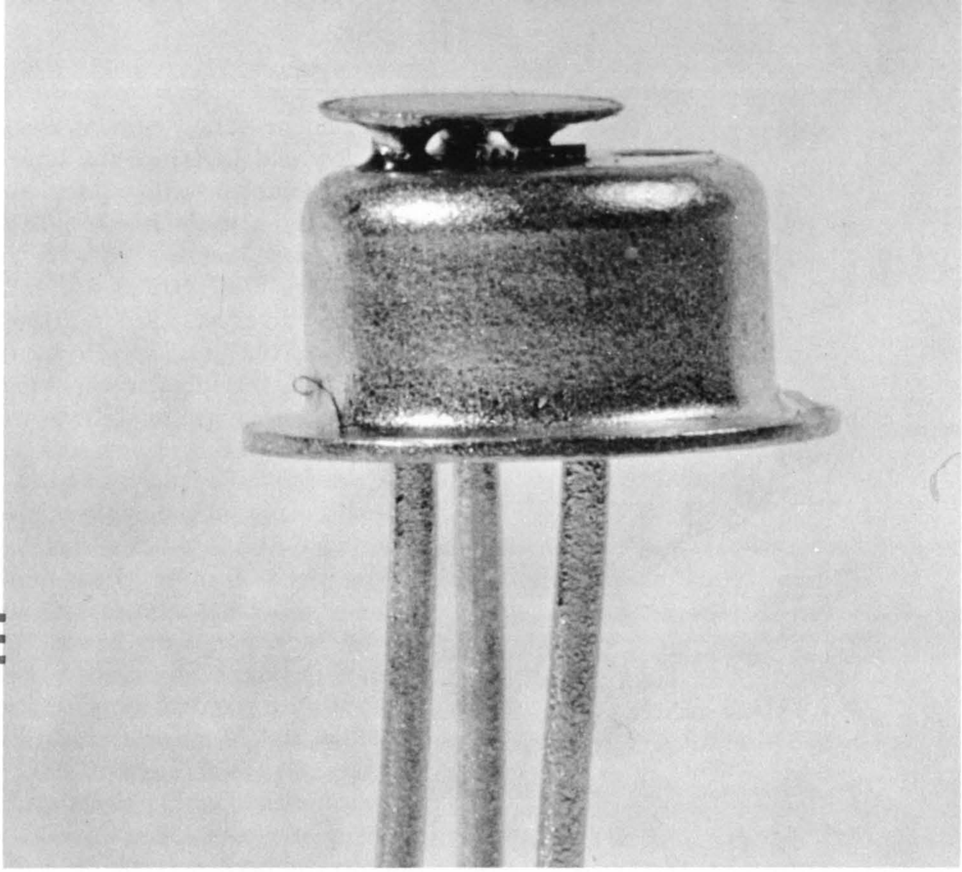


FIG. 1—Side view of typical tunnel diode structure.

and Switches

junction can be extremely small. For example, a high performance diode with a peak current of one milliampere will have a diameter of less than 3 × 10^{-4} inch.

The voltage-current characteristic of a germanium tunnel diode is shown in Fig. 2 together with the important dc parameters. The dotted line shows a normal diode characteristic resulting from minority carrier current. The tunnel diode follows this characteristic beyond point *C*. In the lower voltage region below point *C* and in the reverse biased state the diode current consists of majority carriers which tunnel through the narrow pn junction. The speed of the quantum mechanical tunneling gives the device its high frequency capabilities as compared to conventional diodes and transistors which rely on the relatively slow phenomena of drift or diffusion for their operation.

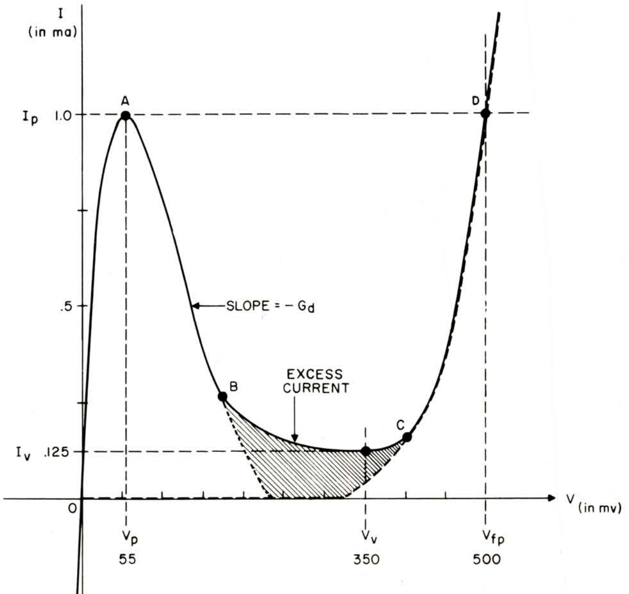


FIG. 2—Static characteristic curve of germanium tunnel diode.

A relatively linear negative conductance region exists between point *A* (the peak point) and point *B* in Fig. 2. Between point *B* and point *C* the current is greater than the sum of the theoretical majority and minority currents. The current in this region, identified as the excess current, cannot, as yet, be completely explained. Intuitively the excess current or valley current should be low and therefore the highest peak point to valley point current ratio seems desirable. There are some tangible reasons for this also. The greater this ratio, for any given value of peak point current, the greater will be the available output current swing. For example, a tunnel diode with a peak current of one ma and a peak-to-valley current ratio of 8 will have an available current swing of 1.0—0.125=0.875 ma. The peak current of a tunnel diode can be chosen at will and held to within tight limits. Germanium tunnel diodes have been made with peak currents between 100 μa and 10 amperes and tolerances on peak current can be maintained to within 10 per cent or better on a production basis. However, the peak voltage, V_p, valley voltage, V_v, and forward voltage, V_f, are determined by the semiconductor material and are largely fixed. For germanium these voltages are respectively 55 mv, 350 mv and 500 mv typical at 25C. For silicon, the voltages are 75 mv, 450 mv, and 750 mv, while for the recently announced gallium arsenide units the voltages are 150 mv, 500 mv and 1200 mv. Higher voltages offer the advantage of wider dynamic range and higher output power for applications where these are important.

The magnitude of the negative conductance is equal to the slope di/dv of the voltage current characteristic. For a one ma germanium tunnel diode the negative conductance is between 0.006 and 0.010 mho corresponding to a negative resistance between 100 ohms and 160 ohms. If tunnel diodes are to be used in linear amplifiers, the value of the negative conductance must be closely controlled.

Temperature Characteristics

Variation of the tunnel diode parameters with temperature is a matter of extreme importance to the circuit designer. Figure 3 shows the voltage-current characteristic of a typical germanium tunnel diode at temperatures of −55, 25, and 100C. Note that the peak voltage, valley voltage and forward voltage all decrease with increasing temperature while the valley current increases with increasing temperature. The peak current may increase or decrease with temperature depending on the doping agents and the resistivity of the semiconductor material. For the diode shown in Fig. 3, the peak current is a maximum at approximately 25C and decreases at higher and lower temperatures.

Each application generally has a different temperature problem. For example, in switching circuits the primary concern is the stability of the peak current since it determines the switching threshold, although the changing forward voltage can affect the amplitude of the output voltage.

Oscillators

In oscillators where matching is not required, it may be important only to make sure that at the lowest operating temperatures the device is driven from a voltage source which requires that the resistance of the source supplying the voltage to the tunnel diode is much less than the negative resistance of the diode. Oscillators have been operated successfully over a temperature range from 4°K to over 573°K, a remarkably wide operating range. In amplifiers where some degree of match between the diode conductance and the circuit conductance is required it is obvious that this match must be maintained over the required operating temperature range. Stable amplification can be achieved by using either negative feedback or direct temperature compensation with thermistors or other temperature sensitive devices.

The variation of the important DC parameters between −50°C and 100°C is shown in Fig. 4 for a 1 milliampere germanium tun-

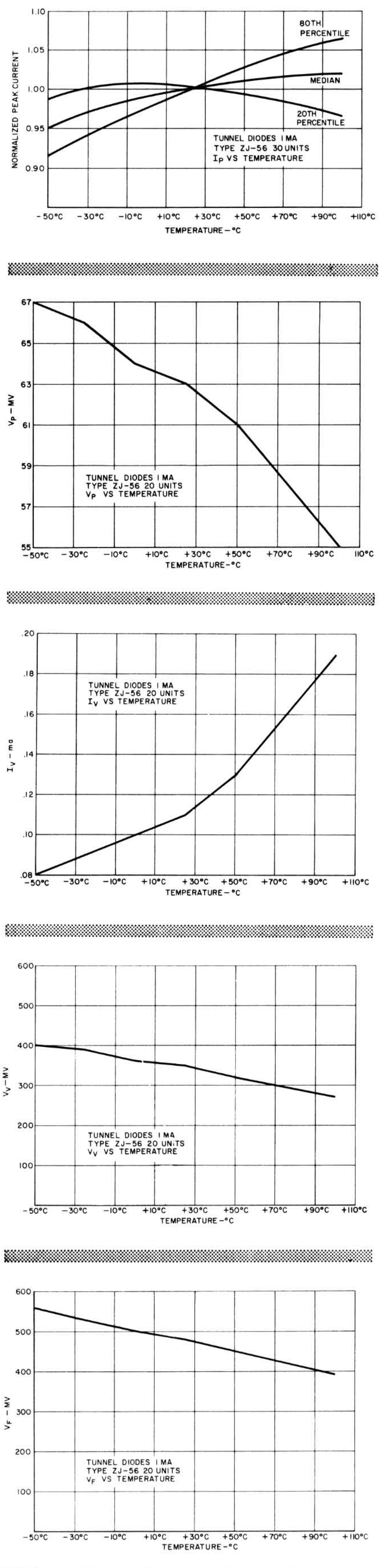


FIG. 4—Normalized peak point current (A), peak point voltage (B), valley point current (C), valley point voltage (D) and forward voltage (E) of tunnel diode plotted against temperature.

nel diode. Note that the peak point voltage has a temperature coefficient of −0.08 millivolts/°C and the forward voltage has a temperature coefficient of −1.0 millivolts/°C as compared with a value of −2.5 millivolts/°C for the forward drop of a conventional diode or transistor.

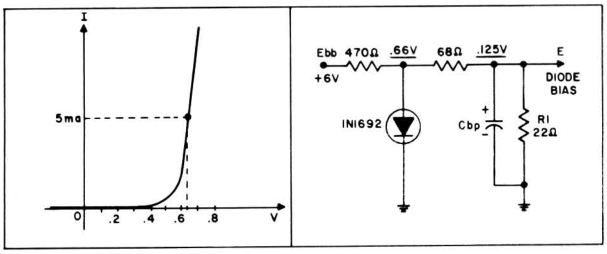


FIG. 6—Silicon diode used as regulator for bias supply.

Frequency Limitations

The small signal equivalent circuit for the tunnel diode when biased in the negative conductance region is shown in Fig. 5. The inductance, L_s, in the equivalent circuit is relatively low and is determined primarily by the inductance of the leads. A small amount of series resistance, R_s, is also present which is determined by the bulk resistance of the semiconductor material. The capacitance, C, is primarily due to the capacitance of the junction although a small portion of the capacity is due to the leads and the package. The negative conductance, $-G_d$, in the equivalent circuit is equal to the slope of the voltage-current characteristic at the particular bias point under consideration. The value of the negative conductance can be assumed to be independent of frequency, the chief limitations in the frequency response of the tunnel diode being determined by the parasitic elements in the equivalent circuit (R_s, L_s, C).

Two significant frequency figures of merit can be assigned to the tunnel diode:

(a) resistive cut-off frequency

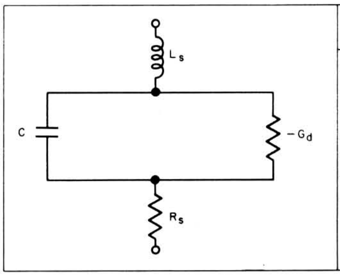
$$f_{go} = |G_d|/2\pi C \sqrt{(1/R_s|G_d|)-1}$$

(b) self-resonant frequency

$$f_o = 1/2\pi \sqrt{(1/L_sC)-(G_d/C)^2}$$

Both of these frequencies are derived from the equivalent circuit of Fig. 5. The resistive cut-off frequency is the frequency at which the real part of the diode impedance measured at its terminals goes to zero. The tunnel diode can not amplify above this frequency. The self-resonant frequency is the frequency at which the imaginary part of the diode impedance goes to zero.

Both frequencies are reduced by external circuit components and therefore the highest possible operating frequency is very circuit dependent. In a transistor package the tunnel diode is limited to frequencies below 1 kmc, this limit being due primarily to the lead inductance. Microstrip or microwave packaging, owing to its inherently lower inductance, can raise the frequency capabilities by an order of magnitude or more.



TYPICAL VALUES OF "ZJ56" PARAMETERS	
SERIES INDUCTANCE*, L_s	6 mμh
TOTAL CAPACITANCE*, C	7 μμfd
SERIES RESISTANCE, R_s	1 ohm
NEGATIVE CONDUCTANCE, G_d	.0065-.01 mho
NEGATIVE RESISTANCE, r_d	100-150Ω
PEAK POINT CURRENT, I_p	1 ma
VALLEY POINT CURRENT, I_v	.1 ma

* 1/8 INCH LEAD LENGTH

FIG. 5—Small signal equivalent circuit and typical values of parameters.

Noise Performance

In the tunnel diode, one of the major contributions to noise is shot noise. The noise figure in a correctly designed amplifier can be in the range of 3 or 4 db provided that the source conductance is matched to the negative conductance of the tunnel diode. The noise figure is also dependent on the load conductance which might be a mixer or converter stage and be relatively noisy. It is possible, however, to connect the tunnel diode in parallel with the input of vhf stage and obtain both reduced noise and increased gain. The noise figure is given by the equation:

$$\text{N.F.} = 1 + 20\, I_{dc}/G_g + T_l \cdot G_l/T_g \cdot G_g$$

where I_{dc} is the dc bias current through tunnel diode, G_g and G_l are the conductances of the generator and load, and T_g and T_l are the effective noise temperatures of the generator and load. From this equation it can be seen that it is desirable to make G_g large and G_l small. To achieve high gain it is necessary that $G_g + G_l$ be very nearly equal to the conductance of the diode, G_d. Thus to minimize the noise figure it is desirable to make G_g very nearly equal to G_d.

The value of I_{dc} should be chosen as low as possible consistent with a reasonable value of G_d. To satisfy this requirement, tunnel diodes with high values of peak current to valley current ratios are desirable.

Nuclear Radiation

Encouraging results have been obtained from preliminary investigations of the effects of nuclear radiation on the characteristics of tunnel diodes. Under a dosage of 3×10^{14} nvt (90 per cent thermal, 10 per cent fast), no apparent change in the electrical characteristics were observed except for the noise figure which increased by approximately 20 per cent at

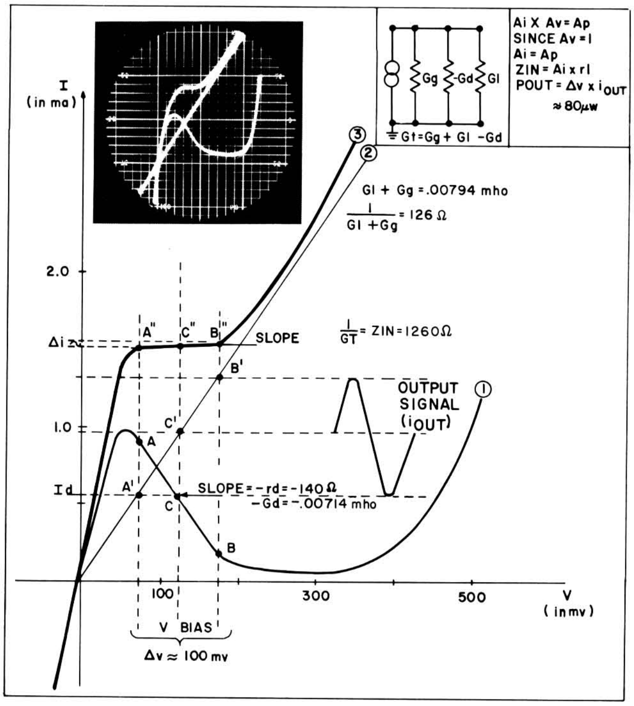


FIG. 7 — Graphical analysis of parallel amplifier stage.

the point of maximum negative conductance and by 100 per cent near the valley point.

At a dosage of 5 x 10^{15} NVT, the valley current increased by about 25 per cent while the other dc characteristics had not changed. The noise figure increased by a factor of 3 at the point of maximum negative conductance while the noise figure in the vicinity of the valley point was immeasurably high. In general, the radiation resistance of tunnel diodes appears to be considerably higher than some tubes or transistors and should be of definite value for military applications.

Linear Amplifiers

On examination of the voltage current characteristics of the tunnel diode as shown in Fig. 2 and 3, it is evident that for amplifier circuits the bias must be supplied from a voltage source in order to sustain a stable operating point. The bias point should be located near the center of the negative conductance region provided that the noise performance is not at a premium. Biasing at the center of the negative conductance region allows the greatest possible dynamic range to be achieved.

The greatest problem in biasing tunnel diodes is due to the fact that negative conductance region is not perfectly linear. In amplifier circuits it is necessary to match the diode conductance to the circuit if high gain is to be achieved. Slight variations in bias point with the consequent variations in diode conductance can cause large changes in circuit gain. Hence it is important to ensure a stable bias voltage. Some of the possible methods for obtaining stable, low-impedance supply voltages include the use of mercury cells, use of negative feedback or the use of forward biased diodes as voltage regulators.

An example of the use of forward biased diodes for bias stabilization is shown in Fig. 6. Here an inexpensive silicon diode is biased heavily in the forward direction so that it exhibits a low voltage and a low dynamic resistance. A low-impedance voltage divider is used to reduce the diode voltage to the value desired for biasing of the tunnel diode.

A graphical analysis of the operation of a parallel amplifier stage is shown in Fig. 7. The voltage-current characteristic of the tunnel diode is represented by curve 1, the net circuit conductance is represented by curve 2 and the resultant input characteristic of the overall amplifier stage is represented by curve 3. It is seen that the slope of the input characteristic in the active region (between *A″* and *B″*) is close to horizontal indicating a high input impedance. The value of the input impedance is given by:

$$Z_{in} = 1/G_T = 1/(G_g + G_l - G_d)$$

and the available power gain would be given by:

$$PG_{av} = 4G_gG^l/G_T^2$$

It can be seen both graphically and mathematically that to obtain a high value of available power gain it is necessary for Z_{in} to be very large and positive. This requires $G_g + G_l$ to be nearly equal to but larger than G_d. Since the voltage is the same across all the conductances in the circuit, the voltage gain of that parallel circuit will be unity.

The closer $G_g + G_l$ is to G_d, the greater is the current amplification obtained. A similar graphical analysis can be applied to the series connection resulting in a low impedance circuit

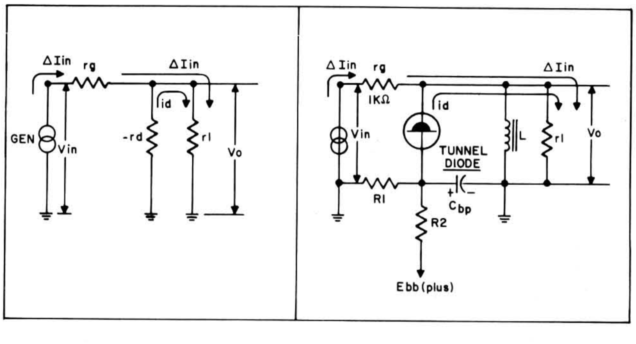


FIG. 8—Parallel amplifier stage and equivalent circuit.

and voltage gain.

Figure 8 shows an audio amplifier circuit yielding about 30-db gain. It is difficult to build a low-frequency amplifier circuit, incidentally, since the tunnel diode is inherently trying to oscillate at a very high frequency.

Use of audio components and audio type layouts generally results in enough stray inductance to enable the circuit to oscillate freely at high frequencies since bypassing is not a simple matter in the uhf range. Additional circuit stability criterias therefore are:

(1) f_{xo} of the circuit to be equal or above f_{ro} to avoid self-oscillations.
(2) the sum of the load and generator conductances must be nearly equal to, but always greater than the negative conductance of the diode (in the parallel type circuit).
(3) The total dc loop conductance must be larger than the negative conductance (voltage source).
(4) All above requirements must remain satisfied over a range of supply voltages and temperature conditions.

Amplifier circuits have been built anywhere from audio frequencies up to 225 mc yielding gains in the 30 db range with excellent bandwidth. As an example a 100 mc circuit was built having 32-db gain with a bandwidth of 20 mc.

Switching Circuits

One of the most promising areas for the application of tunnel diodes is in switching circuits, particularly in large scale computers where the tunnel diode can economically perform both the logic and memory functions. Here the tunnel diode offers the advantages of small size, low operating power, high speed, a potential low cost and high reliability.

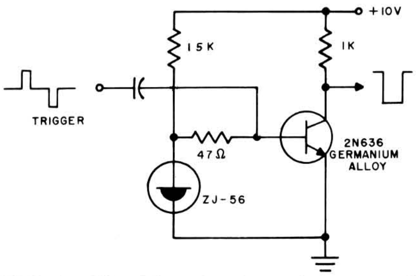


FIG. 9—Bistable circuit using tunnel diode and npn germanium alloy transistor.

It is possible to form a simple bistable circuit by connecting a tunnel diode in series with a voltage source and a single resistor. For bistable operation it is only necessary that the load line formed by the voltage source and resistor intersect the diode characteristic curve of Fig. 2 and 3 at two points where the characteristic curve has a positive slope. These two points represent the two stable states of the circuit. If a large series resistance is used, the diode can be considered to be biased from a constant current source. A constant current bistable load line would be represented in Fig. 2 or 3 by a horizontal line lying between the peak point and the valley point.

As an example, consider a constant current load line of 0.7 ma in Fig. 2. The diode would have approximately 30 mv across it in the "on" state and approximately 470 mv across it in the "off" state. In the "on" state the current through the diode consists entirely of majority carriers transported across the junction by the tunneling mechanism, while in the "off" state the current through the diode consists entirely of minority carriers transported across the junction by diffusion.

The diode can be triggered from the "on" state to the "off" state by means of a current pulse which temporarily increases the current through the diode to a value greater than the peak current. Similarly the diode can be triggered from the "off" state to the "on" state by means of a current pulse which temporarily reduces the current through the diode to a value less than the valley current. The switching speed is very high and is determined chiefly by the junction capacitance and the amount of charge available from the triggering pulse. If a constant current load line is used with a trigger of minimun amplitude, the rise time of the voltage across the diode between the 10 per cent and 90 per cent points will be given approximately by:

$$t_r = (V_{FP} - V_P)/(I_P - I_V)C$$

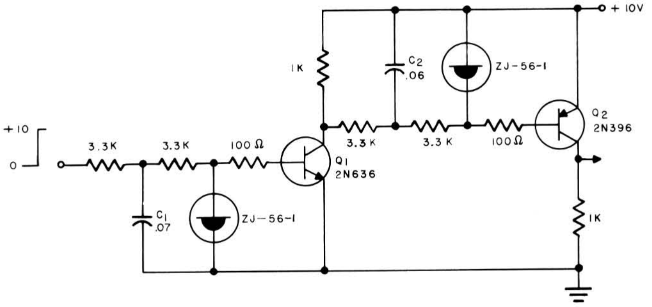


FIG. 10 — Tunnel diode time delay circuit with two cascaded complementary stages.

Using the typical parameters for the ZJ56 listed in Fig. 5, the rise time is calculated as 3.5 mμs, which is in close agreement with measured values. Since V_F, V_P, and $C/(I_P - I_V)$ are largely independent of I_P, the rise time will also be independent of I_p. The rise time can be decreased by reducing the ratio $C/(I_p - I_V)$ or the ratio C/G_d. Switching speeds of less than 1s have been measured for 10 ma versions of the ZJ56.

The voltage of the germanium tunnel diode in the "off" state, V_F, is approximately 0.50 volt which is considerably higher than the base to emitter voltage of a

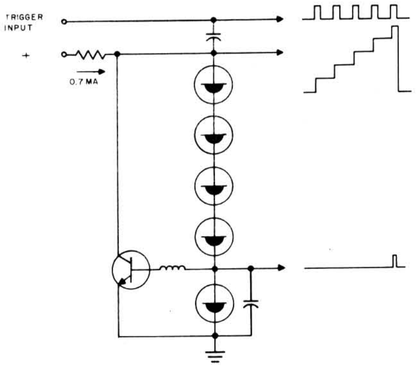


FIG. 11 — Series - connected tunnel diodes used for 5:1 pulse frequency divider or staircase wave generator.

germanium alloy transistor (approximately 0.30 volt with a base current of 1 ma). Accordingly, it is possible to switch a pnp or npn germanium alloy transistor directly with the output from a germanium tunnel diode. This permits the tunnel diode to be used in conjunction with conventional transistors to form many useful types of switching circuits.

One example is the simple flip-flop circuit shown in Fig. 9. In this circuit a current which is lower than the peak current is supplied by the 6.8K resistor. When the tunnel diode is "on" a low voltage exists at the base of the transistor and the transistor will be off. If a positive pulse occurs at the input, the current through the tunnel diode increases above the peak current and the tunnel diode switches to the high-voltage state. The tunnel diode will remain in the high voltage state and the major portion of the current from the 6.8 K resistor will be diverted into the base of the transistor causing it to turn on and the voltage at its collector will fall to a very low value.

Similarly, a negative pulse at the input will cause the current in the tunnel diode to drop below the valley current and cause the tunnel diode to switch to its low voltage state which in turn will cause the transistor to turn off. The 47-ohm resistor serves to bias the tunnel diode above the valley point voltage when it is in its "off" state and also serves to prevent the tunnel diode from loading the trigger pulse thus increasing the switching speed of the transistor.

The time delay circuit shown in Fig. 10 permits any number of consecutive time delays to be obtained with relatively simple circuitry. The timing cycle is initiated by applying a step voltage of +10 volts at the input. The capacitor, C_1, is charged through the 3.3K resistor and the current through the first tunnel diode increases to the peak current, the tunnel diode will switch to its high voltage state and cause Q_1 to turn on. The voltage at the collector of Q_1 will then fall from +10 volts to a low value and a similar timing sequence will be initiated for the second stage. Note that the second stage is a complementary version of the first stage.

At the end of the second timing sequence, Q_2 will turn on and the voltage at its collector will rise from zero to +10 volts. For the circuit shown each time delay is approximately 100 μsec. A multiple phase oscillator can be obtained by connecting an odd number of stages in a closed loop.

A simple 5:1 pulse frequency divider is shown in Fig. 11. Here five tunnel diodes are connected in series and biased from a current source which has a lower value than the peak current of any of the diodes. The bottom diode is selected to have a higher peak current than any of the other diodes in the circuit. Each time a positive pulse occurs at the input one diode is switched from its low voltage state to its high voltage state. When the fifth pulse occurs the bottom diode is switched to its high voltage state and turns on the npn transistor which reset the circuit by diverting the current from the tunnel diodes, and causing them all to revert to their low voltage state.

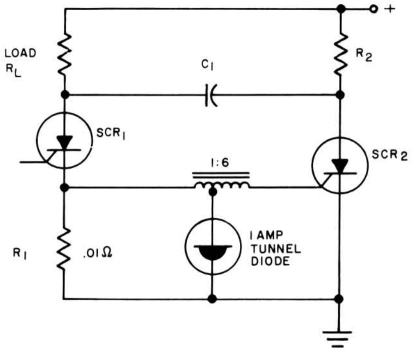


FIG. 12—Tunnel diode used as current sensing element in silicon controlled rectifier circuit breaker.

The capacitor across the bottom diode and the inductance in series with the base of the transistor serve to delay the signal to the transistor so that complete switching can occur. The waveform appearing across the tunnel diodes is a staircase with a risetime determined by the risetime of the trigger pulse. The operating frequency is limited chiefly by the switching speed of the reset transistor. A circuit using an avalanche transistor has been built which can perform the reset function in approximately 2 mμs.

The tunnel diode has many applications in current sensing and current limiting circuits for power equipment. An example of the use of a high current tunnel diode as the reference element in a silicon controlled rectifier circuit breaker is shown in Fig. 12.

When the load current increases above the limiting value the voltage across the 0.01 ohm current sensing resistor will exceed the peak point voltage and cause the tunnel diode to switch to its high voltage state. The voltage swing of the tunnel diode will be stepped up by the autotransformer to a value which is high enough to fire the silicon controlled rectifier, SCR_2. When SCR_2 fires, a negative voltage is coupled to SCR_1 by the capacitor C_1 which causes SCR_1 to turn off and interrupt the load current in 20 μsec or less. The chief advantage offered by the tunnel diode in this application is its ability to be triggered at a very low voltage level. This in turn results in a very low power loss in the current monitoring resistor.