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READING VOLTMETER

By
Anthony F. Schmidt

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A SINGLE PULSE PEAK
READING VOLTMETER

by

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B.S., Kansas State University, 1958

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Instructor in charge

February, 1965

For the department

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ABSTRACT

A circuit consisting of a number of tunnel diodes connected in series and biased from a current source is investigated for use as a single pulse peak reading voltmeter. The composite current-voltage characteristic of the circuit is examined for proper biasing and probable error.

Tests on a constructed circuit are discussed and some limitations on the type of pulses which can be measured are listed. Single pulses with rise times of 0.1 μ second, or greater, and widths 0.1 μ second, or greater, are measured to an accuracy of 0.5 volt.

CHAPTER I

INTRODUCTION

Purpose

Many problems are encountered in the measurement of fast non-repetitive pulses, particularly if information other than minimum or maximum amplitude is desired. This is especially a problem when such measurements are to be made in production line tests by unskilled personnel.

The tunnel diode has been used extensively as a level detector and has also been used as a memory element. By proper combination of these two capabilities, it seems reasonable to expect the tunnel diode memory level to be proportional to the detection level. The purpose of this thesis is to investigate the feasibility of using a number of tunnel diodes connected in series as a single pulse peak detecting and memory circuit.

Procedure

The composite characteristic I-V curve of series connected tunnel diodes is examined. An approximate mathematical analysis is made of the slopes of the composite characteristics of the tunnel diodes at both the high and low voltage end of the I-V composite characteristic. This analysis is used to calculate the maximum number of tunnel diodes which may be placed in series for a given maximum error of measurement.

Data are taken to substantiate the calculations. Limitations on accuracy are investigated. Experimental data are taken from a constructed

circuit and checked for conformity with the predicted performance.

CHAPTER II

STABLE POINTS ON TUNNEL DIODE CHARACTERISTICS

A Single Tunnel Diode with Resistive Load Line

The stability criteria¹ for the simple series circuit shown in Figure 1, page 4, dictate that the negative resistance portion of the tunnel diode characteristic yields an unstable region in a circuit if the total circuit resistance is larger than the negative resistance of the tunnel diode. The characteristic shown in Figure 2, page 4, is that of a typical tunnel diode. Superimposed on this characteristic is the conductance load line of R_g .

If the supply voltage, E , is adjusted such that the resistance load line R_g intersects the tunnel diode characteristic at points a and b, the points a and b are stable points provided point a is below and to the left of I_p and point b is above and to the right of point I_v . The tunnel diode will be switched from stable point a to b by a positive current pulse at the input terminals which momentarily increases the tunnel diode current to a value in excess of I_p . The diode will remain at stable point b until the current through the diode is reduced to a point less than I_v , whereupon it will return to its low voltage or "OFF" state.

¹General Electric Company. Tunnel Diode Manual. General Electric Company, Liverpool, New York, 1961. p. 43.

FIGURE 1

SINGLE TUNNEL DIODE WITH RESISTANCE BIAS

FIGURE 2

IV CHARACTERISTIC WITH LOAD LINE

Two Tunnel Diodes in Series with Resistive Load Line

The characteristic curve of two tunnel diodes in series with resistance load line is shown in Figure 4, page 6. If two diodes are series connected as in Figure 3, page 6, the conductance load line of R_x of Figure 3 can be superimposed as shown. The stability criteria of the series circuit dictates that there are now two unstable points on the composite tunnel diode curve. These two unstable points are points b and d, both of which are intersections of the conductance load line and the negative resistance portion of each of the two tunnel diode curves. Conversely, there are now three stable points along the R_x load line, these being points a, c, and e.

Consider now the introduction of a positive pulse of sufficient amplitude to raise the total tunnel diode current above the value I_{p1} , but below the value I_{p2} . Tunnel diode CR1 will switch to the high voltage state but tunnel diode CR2 will remain in low voltage state. The input pulse will cause the circuit to shift from stable point a to stable point c.

The DC voltage, V_o , in Figure 3, page 6, would then correspond to V_c in Figure 4, page 6. Note that the voltage of value V_c would be the output voltage for any current pulse input greater than I_{p1} but less than I_{p2} . The currents I_{p1} and I_{p2} correspond to voltages V_{p1} and V_{p2} . It is seen from Figure 4, page 6, that any voltage V , greater than V_{p1} but less than V_{p2} which is introduced on the input line of the circuit of Figure 3, page 6, would be retained as a DC voltage V_c . A pulse

FIGURE 3

TWO TUNNEL DIODES IN SERIES

FIGURE 4

A COMPOSITE IV CHARACTERISTIC OF
TWO TUNNEL DIODES IN SERIES

of greater amplitude than V_{p2} results in tunnel diode CR2 switching to its high voltage state and stable point e reached on the characteristic curves of Figure 4, page 6. As long as the current through the tunnel diode is maintained above the lowest I_v (valley current) of both diodes, stable point e (Figure 4) is maintained.

The series tunnel diode circuit is useful not only as a possible circuit for detecting voltage levels of pulses but also, if properly biased, can serve as a "level" memory element.

Tunnel Diodes with Constant Current Bias

If it is required that the bias load line intersect each diode characteristic in the high voltage region above the valley current point, only a few diodes can be connected in series when biased as shown by the solid line of Figure 4, page 6. A constant current bias, represented by the dashed line in Figure 4, suggests that a very large number of tunnel diodes may be series connected and stable points be established on each individual diode characteristic in the high voltage region.

CHAPTER III

COMPOSITE CHARACTERISTICS OF TUNNEL DIODES IN SERIES

Excluding the Negative Resistance Regions

For tunnel diodes connected in series, the composite characteristic of the tunnel diodes will be the sum of all the individual characteristics. If the negative resistance region of each diode is not made an unstable one, composite characteristics must include the sums of all the voltage combinations of all the diodes. In this thesis, the composite characteristic of interest excludes all the negative resistance regions. In practice, these regions can be excluded by superimposing a current bias that is larger than the valley current, I_V , of all the diodes in the circuit.

Constructed Characteristic of Two Tunnel Diodes

Figure 5, page 9, shows the constructed composite characteristic of two tunnel diodes in series. The diodes have a constant current bias of 0.5 milliamp superimposed to make the negative resistance region of each individual diode an unstable one. One of the diodes has a lower I_p than the other. It is assumed that diode 1 has the lower I_p .

Characteristic 1 of Figure 5, page 9, is the sum of the individual characteristics of the two diodes in the low voltage region. Characteristic 2 of Figure 5 is the sum of the high voltage characteristic of diode 1 and the low voltage characteristic of diode 2. Characteristic 3 is the sum of the high voltage characteristics of both diodes.

FIGURE 5

A CONSTRUCTED COMPOSITE CHARACTERISTIC OF
TWO TUNNEL DIODES IN SERIES WITH A CURRENT
BIAS

As expected, the sum of the decreasing slope characteristics of the individual diodes gives characteristic 1 an even smaller slope near I_p . Characteristic 3 has a slope which is much steeper than that of characteristic 1 in the vicinity of I_p . However, at the low currents, the slope of characteristic 3 is much less than the slope of characteristic 1.

From this composite characteristic of Figure 5, page 9, it can be deduced that, as more diodes are added in series, the composite characteristic tends to become flattened out in the vicinity of I_p in the low voltage region. As more diodes are switched to the high voltage state, the characteristic straightens up at higher currents; but, at lower currents, the characteristic is very skewed.

Plotted and Observed Composite
Characteristics

Twenty-eight 1N3715 germanium tunnel diodes were connected in series and data taken to construct the composite characteristic of Figure 6, page 11. Four readings were taken on each characteristic. The data are tabulated in Appendix D, Table IV, page 56.

An oscillographic photograph of the composite characteristic of the same twenty-eight tunnel diodes appears in Appendix D, Figure 16, page 54.

FIGURE 6

COMPOSITE CHARACTERISTIC OF 28
TUNNEL DIODES IN SERIES

Calculated Slopes

By using an empirical equation which closely approximates the tunnel diode curve, the slopes of the composite characteristics can be predicted. A. Feredeci and W. H. Ko¹ have shown that the tunnel diode curve is defined quite accurately by the equations

$$I = I_1 + I_2 \quad (1)$$

$$I = A V \exp (-aV) + B \left[\exp (bV) - 1 \right] \quad (2)$$

$$\text{where } I_1 = A V \exp (-aV) \quad (3)$$

$$I_2 = B \left[\exp (bV) - 1 \right] \quad (4)$$

For values of V less than the tunnel diode valley voltage, the second term of equation (1) may be neglected. For values of V somewhat beyond the valley voltage, the first term of equation (1) may be neglected. It is noted that the equation for I_2 is of the form of the ordinary forward diode current.

If the tunnel diode equation is split up into its two parts, equation (3) may be used to investigate the slope of the characteristic in the low voltage region just below the peak current point with all diodes in the low voltage region and equation (4) used to investigate the slope of the characteristic in the high voltage region just below the peak current point with all diodes in the high voltage region.

The constants A and a of equation (3) may be calculated if two pilot points are measured on the low voltage portion of the characteris-

¹A. Feredeci and W. H. Ko. "A Two Term Analytical Approximation of Tunnel Diode Characteristics." Proceedings of the IRE. v. 50, (August, 1962). pp. 1852-1853.

tic. Likewise, the constants B and b of equation (4) may be calculated if two pilot points beyond the valley current (I_v) are measured.

Such measurements are usually available in the form of typical characteristics from a tunnel diode specification.

As shown in Appendix A, for a typical General Electric 1N3715 germanium tunnel diode:

$$\text{Equation (15), page 43} \quad I_1 = \frac{I_p}{V_p} V \exp \left(1 - \frac{V}{V_p} \right)$$

$$\text{Equation (23), page 44} \quad I_2 = I_p \exp 23.1 (V - V_{fp})$$

where I_p is the peak current and V_p is the low voltage at the peak current and V_{fp} is the high voltage at the peak current.

From Appendix A, page 44, the derivatives of I_1 and I_2 with respect to V are:

$$\text{Equation (26), page 44} \quad \frac{dI_1}{dV} = (A - aV) \exp (-aV)$$

$$\text{Equation (28), page 44} \quad \frac{dI_2}{dV} = Bb \exp bV$$

The slopes of the characteristic curves near I_p are then calculated for the following conditions:

Condition 1 - One tunnel diode in the low voltage state

Condition 2 - Twenty-eight tunnel diodes in the low voltage state

Condition 3 - One tunnel diode in the high voltage state

Condition 4 - Twenty-eight tunnel diodes in the
high voltage state

The values are tabulated in Table II, page 45.

The calculated slopes predict that as I increases toward I_p the composite characteristic will have a decreasing slope at the low voltage extreme and an increasing slope at the high voltage extreme.

Summary

The calculated and the experimental data show that the slope of the composite characteristic curve in the low voltage region with all diodes in the low voltage region near the peak current point becomes very small. As more diodes switch, the slope near I_p becomes steeper.

This "skewing" effect is proportional to the number of diodes in series and also a property of the type of tunnel diode used. W. F. Chow² states that:

"Owing to the characteristic of the third region of an individual tunnel diode the composite I-V curve usually shows a skew toward the high voltage side as shown in - - -."

In the low current region, this was found to be true; however, with the type of diodes used for this study, in the high current region, the opposite was found to be true.

²W. F. Chow. Principles of Tunnel Diode Circuits. John Wiley and Sons, New York, 1964. p. 318.

CHAPTER IV

THE PEAK READING VOLTMETER

Circuit

The series tunnel diodes, biased from a current source, lead to the circuit of Figure 7, page 16. This circuit will be called the single pulse Peak Reading Voltmeter.

The circuit consists of three sections; the series tunnel diodes, an isolation and biasing diode, and a current source.

Voltage Range

The voltage which the diodes will sustain if all are switched to the high voltage region is approximately

$$V_h = N V_{fp} \quad (5)$$

where N = The number of diodes in series

V_{fp} = The typical forward voltage at the
peak current

For the 1N3715 germanium tunnel diode, V_{fp} typical = 0.51 volt.
For twenty-eight diodes, typically, $V_h = 28 \times .51$ or 14.3 volts.

The actual measured voltage was 14.5 volts. Since V_{fp} may vary from 0.535 to 0.475 volt, the voltage V_h could vary from 15 to 13.3 volts.

The minimum voltage across the diodes will be the voltage when all diodes are in the low voltage region. Typically, the minimum voltage will be

FIGURE 7

SINGLE PULSE PEAK READING VOLTMETER SCHEMATIC

$$V_1 = V_p N$$

(6)

where V_p = The typical low voltage at I_p

N = The total number of diodes in series

For the diodes used, typical $V_p = 65$ millivolts. Therefore,
 $V_1 = .065 \times 28$ or 1.84 volts.

According to the diode specification, V_p can vary between 58 and 72 millivolts. V_1 can then vary from 1.62 to 2.02 volts. The voltage measured near I_p was 1.7 volts.

For the given diodes, then, the range of voltage which can be detected is between 1.7 and 14.5 volts, a range of 12.8 volts.

Memory Errors

If a voltage pulse of sufficient magnitude to switch diodes one through five (it is assumed here that the diodes are numbered to correspond with their order of switching; i.e., CR1 has the lowest I_p , CR2 the next to lowest I_p , etc.) is introduced at the input of the circuit of Figure 7, page 16, and a current bias greater than the valley current, I_v , of all diodes in the circuit is superimposed, a voltage level can be measured across the diode string after the voltage pulse decays. This voltage level will be the intersection of the bias load line with the characteristic of V_{CR6} in Figure 6, page 11. (The notation V_{CR6} pertains to the sixth curve from the left in Figure 6, page 11; V_{CR7} pertains to the seventh; etc.). From Figure 6 it is seen that this voltage level can vary from 2.4 to 3.9 volts depending on the level of current bias. Figure 8, page 19, is an exploded view of Figure 6 in the vicinity of V_{CR5} through V_{CR7} . Since five tunnel diodes were switched,

it is known that the voltage which caused the switching was at least as great as V_{p5} of Figure 8, page 19, but less than V_{p6} . The difference between V_{p5} and V_{p6} is equal to the difference between V_{fp} and V_p .

If the constant current bias of 0.5 milliamp were used, the voltage across the tunnel diodes after the pulse decays would be the point of intersection of the 0.5 milliamp bias line and the characteristic V_{CR6} . As seen from the characteristics of Figure 6 or Figure 8, this voltage differs from the pulse voltage by about 1 volt. If, however, the load line were shifted to a point just below the peak current point, the difference in amplitude of the voltage pulse and the final voltage across the diodes becomes much smaller.

From the characteristic curves of Figure 6, page 11, and Figure 8, page 19, or the data of Table IV, page 56, the difference in the peak point voltage of V_{CR5} and the stable point voltage of V_{CR6} varies from $3.53 - 3.49 = +0.04$ volt at a bias level of 2 milliamperes to $3.12 - 3.49 = -0.37$ volt at a bias level of 1.5 milliamperes, and, finally, at a bias level of 0.5 milliamperes, the difference is -1.0 volt. The negative sign indicates that the final stable voltage point is less than the pulse or setting voltage.

As more of the diodes are switched, the difference between the peak voltage point on a given characteristic and the stable voltage point of the intersection of the bias load line and the next characteristic becomes greater and positive, providing the bias current is greater than approximately $I_p/2$. This difference between a peak voltage point and the stable point on the next characteristic is the amount by which the

FIGURE 8
COMPOSITE I V CHARACTERISTIC in VICINITY of V_{p4} THRU V_{p7}

retained voltage may be in error on the high side. The maximum high reading error occurs at the high end of the voltage range and approaches $V_{fp} - V_p$.

The difference in voltage between the peak point and the stable bias point on the same characteristic is the amount by which the retained voltage may be low. The maximum low error occurs at the low end of the range and, as has been noted, is very dependent on the current bias level.

To keep the error on the low end of the range to within, say 0.5 volt, the bias must be adjusted to such a level that the maximum difference between the peak voltage and the stable point voltage on a given characteristic is less than 0.5 volt.

This bias current can be calculated from equation (33) of Appendix B, page 46.

$$I_B = I_p \left[1 - \frac{V_E}{NV_p} \right] \exp \frac{V_E}{NV_p}$$

and for twenty-eight diodes in series using

$$V_E = 0.5 \text{ volt}$$

$$I_p = 2.2 \text{ ma}$$

$$V_p = 65 \text{ mv}$$

$$I_B = I_p (.96) = 2.1 \text{ ma}$$

The solution for the maximum number of diodes, N , which can be connected in series for a given maximum error of 0.5 volt is shown in Appendix B, page 47. For a bias current of 2 ma, for diodes having a 2.2 ma peak current, the solution, N , equals twenty-four diodes. Twenty-eight diodes in series were used for most of the experimental work. Readings

for pulses below three volts were, however, discarded. The characteristic curves indicate that with twenty-eight diodes in series the maximum error should be lower than 0.5 volt. It must be remembered that the Appendix B calculation assumes the tunnel diode equation to be exact and all tunnel diodes to have the typical characteristics.

The Isolation Diode

Another source for error in the detection of the voltage level is the isolation diode. The drop across this diode will not be seen by the tunnel diodes and as a result an error of magnitude equal to the diode drop may be added to the incremental memory errors already discussed. By connecting a similar diode in series with the bias current source and including this diode voltage drop in the measurement, the isolation diode drop is virtually eliminated. The effect of adding the diode in series with the current source is that the amount of error in the final voltage reading due to any diode voltage drop is now the difference in the voltage drops of the two diodes. This voltage difference should be very small if the two diodes are of a similar type and the current through each is approximately the same.

The isolation diode is necessary for two reasons. It keeps the tunnel diodes from resetting to a low voltage level when the input pulse decays and it provides a means of introducing a voltage bias to make the peak reading voltmeter range selective.

It has been determined that with twenty-eight diodes in series, in order to keep the maximum voltage error at 0.5 volt or less, the bias current must be very nearly equal to I_p when all diodes are in the un-

switched or low voltage state.

With germanium tunnel diodes of the type used in the lab, 1N3715's, the maximum voltage range that can be utilized and still maintain a stable bias level below the peak point voltage point is approximately 12 to 13 volts. Much higher voltages can be measured with the same margin of error if a reverse bias is applied to the isolation diode and the peak reading voltmeter is made range selective. A negative bias applied in 10 volt steps would make the peak reading voltmeter capable of measuring voltages within 10 volt ranges. By connecting the output meter to measure the bias voltage, as in Figure 7, page 16, the meter reading will indicate the pulse voltage directly. A voltage equal to the sum of the bias voltage and the sum of the tunnel diode low voltages at the bias current is indicated on the meter at all times.

The Bias Current

Examination of the composite characteristics of diodes in series shows that a proper bias current can contribute greatly to the accuracy of measurement. An ideal bias load line would appear to be "sagging" at the high voltage end of the range.

A constant current bias was used in the experimental work. A resistive load line which would allow the current to vary from approximately $.95 I_p$ at the low voltage end to $.75 I_p$ at the high voltage end would be quite adequate and should improve the accuracy of measurement toward the high end of the voltage range.

For the experiments, a transistorized constant current source, whose output characteristic is plotted in Figure 15, page 53, was used.

In Appendix C, this circuit is discussed. This current source has an impedance of approximately 1.6 megohms. Connecting the digital voltmeter, which has an output impedance of 10 megohms, causes the effective bias current load line to exhibit a very slight sag from the horizontal.

CHAPTER V

EXPERIMENTAL WORK

Mechanical Construction

The circuit described in Chapter III and Chapter IV was fabricated on a printed circuit board which had silver plating over copper on an epoxy base. For the series diode connections, a pattern of rectangular conduction planes was arranged so that the anode of one diode and the cathode of another were soldered to one rectangular conducting surface. The rectangles were three-eighths inch by one-half inch and are separated by non-conducting spaces one-sixteenth of an inch wide.

A ground plane on the circuit board itself was used to enhance the wiring. The circuit board was then mounted on a copper clad epoxy board which served as one side of the box in which the entire circuit is enclosed and shielded.

A picture of the assembly is shown in Figures 9 and 10, page 25.

All the bias supplies were connected to the peak reading voltmeter through capacitor feedthroughs which were mounted directly to the ground plane of the circuit board on which the circuitry was fabricated. The pulse input connector case was also mounted directly to the circuit board ground plane.

The isolation diode connection was particularly critical. The diode was finally mounted in a cylindrical shield as shown in Figure 12, page 36.

FIGURE 9

PHOTOGRAPH of PEAK READING VOLTMETER CIRCUIT BOARD

FIGURE 10

PHOTOGRAPH of PEAK READING VOLTMETER

More discussion concerning the isolation diode appears in Chapter VI.

Electrical Testing

Voltage pulses with a rise time of approximately one-tenth microsecond and a width of 0.08 μ second at the half amplitude point were measured with the equipment arrangement shown in Figure 20, page 59.

For the peak reading voltmeter output reading, a Non Linear Systems, three digit digital voltmeter was used. (A "noisy" mechanical chopper input digital voltmeter was also used; but, without filtering, it would, on occasion, introduce transients large enough to switch or reset some of the tunnel diodes). A high impedance D'Arsonval type meter movement, 0-100 microamp, with suitable resistance multipliers was also satisfactorily used. In order to establish a standard height pulse, the following procedure was followed:

The pulse generator was set to run continuously at approximately 100 pulses per second. The pulses were monitored on a dual beam oscilloscope with one Z type differential preamplifier and one fast rise time ($t_r = .006$ μ seconds) preamplifier.

The Z type plug-in was used to monitor the voltage amplitude on its expanded calibrated offset voltage scale while the other beam was monitored to insure that the slower response of the differential type preamplifier did not cause any error in readings on the expanded scale. After the pulse was adjusted for the desired

height, the pulse generator was then set to single shot, and the peak reading voltmeter reset by shorting out the bias current. A single pulse was then generated after which the digital voltmeter reading was read and recorded. The bias voltage was adjusted such that the range measured was never greater than 12 volts.

The results are tabulated in Table I, page 28.

The data of Table I are in very close agreement with the readings predicted by the intersections of the bias load lines and the composite characteristics. The data also verify that accuracy is very dependent on current bias levels.

With a bias current of 2 milliamps, the maximum error of measurement noted was 0.4 volt. A bias current of 1.8 milliamps allowed errors as high as 0.5 volt; and, at a bias of 1.5 milliamps, maximum errors at 0.8 volt were recorded. At the bias current of 1.5 milliamperes, the readings were consistently low. Bias currents of 1.8 and 2.0 milliamps resulted in some readings being high although the trend was to read low.

Accuracy of measurement was consistent for all pulses measured which had a rise time of 0.1 microsecond or greater and a half amplitude width of 0.08 microsecond or greater. Pulses wider than 5 microseconds were not measured.

A fast rise time pulse generator consisting of a mercury relay discharging a charged open circuited delay line was also used to supply pulses for testing the circuit. With pulse widths greater than about 60 to 80 nanoseconds, the peak reading voltmeter read consistently high.

BIAS VOLTS	TRUE* VOLTS	VDC OUT VOLTS $I_b = 1.5 \text{ ma}$	ERROR VOLTS	VDC OUT VOLTS $I_b = 1.8$	ERROR VOLTS	VDC OUT VOLTS $I_b = 2 \text{ ma}$	ERROR* VOLTS
0	3	2.2	-0.8	2.5	-0.5	2.6	-0.4
	4	3.6	-0.4	3.8	-0.2	4.0	
	5	4.5	-0.5	4.7	-0.3	4.8	-0.2
	6	5.5	-0.5	5.7	-0.3	5.9	-0.1
	7	6.4	-0.6	6.7	-0.3	6.8	-0.2
	8	7.4	-0.6	7.7	-0.3	7.8	-0.2
	9	8.4	-0.6	8.6	-0.4	8.7	-0.3
	10	9.3	-0.7	9.5	-0.5	9.7	-0.3
	11	10.9	-0.1	11.1	+0.1	10.7	-0.3
	12	11.8	-0.2	12		12.1	+0.1
-10	13	12.8	-0.2	12.9	-0.1	13.2	+0.2
	14	13.6	-0.4	13.8	-0.2	14.0	
	15	14.5	-0.5	14.7	-0.3	14.9	-0.1
	16	15.4	-0.6	15.7	-0.3	15.9	-0.1
	17	16.4	-0.6	16.7	-0.3	16.8	-0.2
	18	17.4	-0.6	17.7	-0.3	17.8	-0.2
	19	18.4	-0.6	18.6	-0.4	18.7	-0.3
	20	19.3	-0.7	19.5	-0.5	19.8	-0.2
	21	20.8	-0.2	20.6	-0.4	20.7	-0.3
	22	21.8	-0.2	22.0		22.1	+0.1
-20	23	22.8	-0.2	22.5	-0.5	23.2	+0.2
	24	23.7	-0.3	23.8	-0.2	24.0	
	25	24.6	-0.6	24.7	-0.3	24.9	-0.1
	26	25.5	-0.5	25.7	-0.3	25.9	-0.1
	27	26.4	-0.6	26.7	-0.3	26.8	-0.2
	28	27.5	-0.5	27.7	-0.3	27.8	-0.2
	29	28.5	-0.5	28.6	-0.4	28.7	-0.3
	30	29.4	-0.6	29.5	-0.5	29.7	-0.3
	31	30.9	-0.1	31.1	+0.1	30.7	-0.3
	32	31.8	-0.2	32.1	+0.1	32.2	+0.2
-30	33	32.8	-0.2	32.5	-0.5	33.2	+0.2
	34	33.6	-0.4	33.8	-0.2	34	
	35	34.5	-0.5	34.7	-0.3	34.9	-0.1
	36	35.5	-0.5	35.7	-0.3	35.9	-0.1
	37	36.4	-0.6	36.7	-0.3	36.8	-0.2
	38	37.4	-0.6	37.8	-0.2	37.8	-0.2
	39	38.4	-0.6	38.6	-0.4	38.7	-0.3
	40	39.3	-0.7	39.5	-0.5	39.7	-0.3

* Possible error of measurement due to differential pre amp offset voltage not included. This error is $\pm 10 \text{ mv}$ up to 10V and $\pm .100 \text{ volts}$ above 10 volts .

TABLE I

EXPERIMENTAL READINGS FROM
PEAK READING VOLTMETER

Placing a capacitor of 100 picofarads across the tunnel diodes and a 100 ohm resistor in series with the isolation diode improved the accuracy of reading. This improvement was probably due to the RC network increasing the rise time of the pulse seen by the tunnel diodes.

Data were taken and recorded at 1 volt increments from 3 to 40 volts. By varying the input voltage in smaller increments, the larger errors in measurement appear more often, particularly at the points where the pulse voltage is just slightly larger than the bias voltage.

CHAPTER VI

SOME LIMITATIONS OF THE PEAK READING VOLTMETER

Diodes with Equal Peak Currents

One of the requirements for proper switching is that the diodes must switch never more than one at a time. Two or more diodes may switch at the same time if two or more of the tunnel diodes in series have exactly the same peak current. If this happens, then the voltage readout will be in error and be too large. This problem will rarely occur in practice as there is a difference (possible as little as 0.1 microamp, but a difference) in the I_p 's of almost all diodes. If such a condition is suspected, a simple test will reveal if there are two diodes switching at the same time. Connect a slowly varying DC voltage to the input of the peak reading voltmeter circuit and observe the output voltage steps. If any of the voltage steps are larger than the V_{fp} of any diode, two or more diodes with the same I_p are in the circuit. Placing a resistor in parallel with one of the diodes will change the composite peak current point of that diode and resistor as demonstrated by Gentile¹ and as shown in Figure 11, page 31.

Tunnel Diode Switching Times

A second requirement for proper switching of all the series tunnel diodes is that all diodes must have sufficient time to switch. This re-

¹S. P. Gentile. Basic Theory and Application of Tunnel Diodes.
D. Van Nostrand Company, Inc., Princeton, New Jersey, 1962. P. 169.

FIGURE 11

INCREASING EFFECTIVE I_p
by ADDING PARALLEL R

quirement is the limitation on the narrowest width pulse and the fastest rise time pulse which can be properly measured.

The switching speed of a single diode has been determined to be closely approximated by the equation²:

$$t_r \cong \frac{V_{fp} - V_p}{I_p - I_v} C \quad (7)$$

where V_{fp} = Forward voltage at $I_f = I_p$

V_p = Peak point voltage

I_p = Peak point current

I_v = Valley point current

C = Valley point terminal capacitance

t_r = Switching time between 10 per cent

and 90 per cent voltage points

For a typical germanium 2.2 ma tunnel diode such as the 1N3715, $t_r \cong 1.6$ nanoseconds.

If the voltage across the series diodes is increased too rapidly, then diodes which are in a switching transition will not have the full diode voltage across them. This voltage will then be impressed across the remaining diodes allowing other diodes to switch prematurely and indicate a higher voltage than the correct voltage. Also, a tunnel diode must be driven to some minimum voltage point in the negative conductance region before it will continue³ in its switching process to the high

²Ibid. p. 217.

³Chow. Op. Cit. pp. 199-200.

voltage state and not return to its low voltage state. Thus, an input pulse with a faster rise time than the cumulative rise times of all the tunnel diodes in the circuit may be read inaccurately.

For a voltage pulse which is a linear ramp with a flat top, the maximum rate of rise which can be tolerated with the type of diodes used would be approximately $V_{fp}/2$ nanoseconds $\approx .25$ volt/nanosecond. In practice, though, practically any pulse will have a rounded top so some faster pulses can be measured.

Examination of different tunnel diode specifications indicates that if higher current tunnel diodes are used, faster switching is experienced and detection of faster rise time pulses is practical. However, most germanium tunnel diodes now commercially available have a power dissipation capability of approximately 5 milliwatts at 25° centigrade. Since the bias current level must be near the peak current point, the highest peak current diode which could be used at ambient temperatures is a 10 milliamp diode. A nominal 10 milliamp peak current diode switches in approximately 1.2 nanoseconds, compared to 1.6 nanoseconds for a 2.2 milliamp diode.

Higher peak current tunnel diodes may relieve the isolation diode problem in that more energy will be required to switch these tunnel diodes.

Pictures of switching time of five tunnel diodes in series were taken with a sampling scope. The pictures are shown in Figure 22, page 61. It is observed that switching time improves with increased current bias and the time at which switching did occur becomes more coincidental with the input voltage.

Isolation Diode Capacitance

The isolation diode which allows the application of reverse bias voltage, thereby reducing the number of diodes and making a range type meter, introduces still another problem.

The problem encountered in reverse biasing is as follows: Diode CRI of Figure 7 exhibits some small value of capacitance. This small capacitance is charged to the reverse bias voltage. With a fast rise time pulse $t_r \leq 2$ nanoseconds/volt, the diode capacitance will, on occasion, switch a tunnel diode prior to the time the isolating diode becomes forward biased. The diode capacitance decreases with increasing reverse bias by the relationship⁴:

$$C = \frac{E}{4\pi} \left(\frac{q a}{3E V_t} \right)^{1/3} \quad (8)$$

Where C is capacitance per unit area of junction. This expression can be stated as:

$$C = KV^{-1/3} \quad (9)$$

The energy E stored in the diode capacitance is:

$$E = \frac{CV^2}{2} = \frac{KV^{-1/3} V^2}{2} \quad (10)$$

$$= \frac{KV^{5/3}}{2} \quad (11)$$

This energy increases as 5/3 power of the reverse voltage V. At higher reverse bias the diode capacitance becomes more of a problem because more stored diode energy is transferred from the isolating diode

⁴R. D. Middlebrook. Junction Transistor Theory. John Wiley and Sons, Inc., New York, 1957. p. 158.

to the tunnel diodes as the reverse bias is removed; i.e., pulse applied.

Many wiring and layout techniques were attempted to reduce this effective diode capacitance. A significant decrease in effective diode capacitance was noted by putting the diode in a cylindrical shield shown in Figure 12, page 36. This shielding decreased the effective diode capacitance by a factor of two. No analysis of the diode shield was made.

It is interesting to note, however, that the isolation diode capacitance is not nearly as severe a limitation on detecting extremely fast rise time pulses as is the switching speed of the tunnel diodes themselves.

CAPACITANCE	CONDITION
1.49 uuf	0 Bias, shield ungrounded
1.08 uuf	0 Bias, shield grounded
0.906 uuf	4V Bias, shield ungrounded
0.504 uuf	4V Bias, shield grounded
3.0 uuf	Shield to both leads

Capacitance Measured with Boonton Electronics
Capacitance Bridge Model 75A-S8 @ 1 MC.

FIGURE 12

ISOLATION DIODE SHIELD
(1N914)

CHAPTER VII

CONCLUSIONS

General

The detection and memory properties of tunnel diodes were combined in the single pulse peak reading voltmeter. The performance of the single pulse peak reading voltmeter was analyzed and predicted from the current voltage characteristic of the circuit. A circuit was built and electrically tested.

Accuracy and Range

Tests showed that with a bias current of 2 milliamps, the accuracy of measurement was within 0.4 volt for all pulses measured between 3 and 40 volts. With a bias current of 1.5 milliamps, the measurement error was as great as 0.8 volt.

The input pulse was varied from 3 to 40 volts in one volt increments. For these measurements, only one reading with a 0.4 volt error was observed. Had the increment of input voltage change been less, say 0.1 volt over the same range, more errors as great as 0.4 volt would have been noted.

The maximum allowable measurement error limits the number of tunnel diodes which can be connected in series and the number of tunnel diodes sets the voltage range. For the 1N3715 tunnel diode with maximum allowable error arbitrarily set at 0.5 volt, the maximum number of diodes is limited to twenty-four to twenty-eight and the corresponding voltage range is limited to approximately 12 volts. Ranges were offset from 0

to as high as 30 volts with the use of a back biased isolation diode.

Rise Time and Pulse Widths

Pulses with a rise time in excess of 0.08 microsecond and widths in excess of 0.08 microsecond at the half amplitude point were satisfactorily measured. Rate of rise is restricted to a value slower than approximately .25 volt per nanosecond. Faster rise time pulses consistently produced higher than correct readings.

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BIBLIOGRAPHY

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APPENDIX

APPENDIX A

Constants and Derivatives of the Tunnel Diode Equation

Equation (2), page 12,

$$I = AV \exp(-aV) + B [\exp(bV) - 1]$$

Where: $I_1 = AV \exp(-aV)$ (3)

$$I_2 = B [\exp(bV) - 1]$$
 (4)

I_1 is the tunnel portion (region 1 and 2) and contributes nothing to the tunnel diode characteristic in the high voltage region.

I_2 is the forward diode current and contributes nothing to the tunnel diode characteristic in regions 1 and 2.

Splitting up these equations, and using as pilot points for equation 3, the points

$$I = I_p \text{ and } V = V_p$$

When $I = I_p$ and $V = V_p$, $\frac{dI}{dV} = 0$

differentiating equation (3)

$$\frac{dI_1}{dV} = -a AV \exp(-aV) + A \exp(-aV)$$
 (12)

Letting $V = V_p$ and $\frac{dI}{dV} = 0$

$$a AV_p \exp(-aV_p) = A \exp(-aV_p)$$
 (13)

$$a = 1/V_p$$

Letting $I_1 = I_p$, $V = V_p$

$$I_1 = I_p = AV_p \exp(-aV_p)$$
 (14)

$$A = \frac{I_p}{V_p} \exp (1)$$

$$\text{and } I_1 = \frac{I_p}{V_p} V \exp \left(1 - \frac{V}{V_p}\right) \quad (15)$$

Equation (4), page 12,

$$I_2 = B \left[\exp (bV) - 1 \right]$$

Since $\exp (bV) \gg 1$

$$I_2 \cong B \exp bV \quad (16)$$

From the tunnel diode specification

When $I = I_p$, $V = V_{fp}$ and

when $I = .25I_p$, $V = V_{fs}$

Writing

$$I_p = B \exp (bV_{fp}) \quad (17)$$

$$.25I_p = B \exp (bV_{fs}) \quad (18)$$

Dividing $\frac{(18)}{(17)}$

$$.25 = \exp b (V_{fs} - V_{fp}) \quad (19)$$

From a specification for a typical TD2A (IN 3715) tunnel diode

$$V_{fs} = .45 \text{ volts, } V_{fp} = .51 \text{ volts}$$

Use equation (19)

$$.25 = \exp b (-.06) \quad (20)$$

From logarithm tables

$$b(-.06) = -1.38629 \quad (21)$$

$$b = 23.105$$

When $I_2 = I_p$, $V = V_{fp}$

From equation (17)

$$B = I_p \exp (-bV_{fp}) \quad (22)$$

$$\text{and } I_2 = I_p \exp 23.1 (V - V_{fp}) \quad (23)$$

From equation (1), page 12,

$$\begin{aligned} I &= I_1 + I_2 \\ &= \frac{I_p}{V_p} \exp \left(1 - \frac{V}{V_p}\right) + I_p \exp 23.11 (V - V_{fp}) \end{aligned} \quad (24)$$

If N tunnel diodes are connected in series and all are in the low voltage state, the I, V , relationship may be expressed by

$$I_1 = A(VN) \exp (-aVN) \quad (25)$$

and

$$\frac{dI_1}{d(VN)} = [A - aAVN] \exp (-aVN) \quad (26)$$

If all these tunnel diodes are switched to the high voltage region, then the I, V relationship may be expressed by

$$I_2 = B \exp (bVN) \quad (27)$$

and

$$\frac{dI_2}{d(VN)} = B b \exp (bVN) \quad (28)$$

Values of V/V_p are assumed, and equation 15 used to solve for I and equation 26 used to solve for $\frac{dI_1}{d(VN)}$. These values of I and $\frac{dI_1}{d(VN)}$ are entered in Table II, page 45. Values of I from Table II are used in equation 23 to solve for V (V_f denotes V in the high voltage region.) Equation 28 is then used to solve for $\frac{dI_2}{d(VN)}$

V/V_p	$I(I_{ma})$	I/I_p	V/V_{fp}	$V_f(\text{volts})$	$\frac{dI_1}{d(VN)} (N=1)$	$\frac{dI_2}{d(VN)} (N=1)$	$\frac{dI_1}{d(VN)} (N=28)$	$\frac{dI_2}{d(VN)} (N=28)$
1.0	2.2	1	1	.51	0	50.8×10^{-3}	0	1.8×10^{-3}
.95	1.99	.905	.992	.506	1.78×10^{-3}	46.9×10^{-3}	$.063 \times 10^{-3}$	1.6×10^{-3}
0.9	1.79	.813	.982	.501	3.76×10^{-3}	41.2×10^{-3}	$.135 \times 10^{-3}$	1.5×10^{-3}
0.8	1.44	.654	.965	.492	8.306×10^{-3}	33.5×10^{-3}	$.296 \times 10^{-3}$	1.2×10^{-3}
0.5	.667	.303	.898	.458	28×10^{-3}	15.3×10^{-3}	1×10^{-3}	0.55×10^{-3}

TABLE II

TABULATION OF CALCULATED SLOPES
AT LOW VOLTAGE AND HIGH VOLTAGE EXTREMES
OF COMPOSITE IV CHARACTERISTIC

APPENDIX B

Solution for Maximum Number of Diodes Which can be Connected in Series for a Given Error

From Appendix A, equation (3)

$$I_1 = AV \exp(-aV)$$

for N diodes,

$$A = \frac{I_p}{V_p N} \exp \quad \text{and} \quad a = \frac{1}{V_p N}$$

The difference between the stable point voltage at the bias current I_B (all diodes in the low voltage state) and the peak point voltage point, $V_p N$, is constrained to be less than V_E volts. This difference is the maximum measurement error at the low end of the range. Let NV_p equal the peak point voltage point at the first characteristic and NV_B equal the stable point voltage at the bias current I_B . Then

$$NV_p - NV_B = V_E \text{ volts} \quad (29)$$

$$NV_B = NV_p - V_E \quad (30)$$

$$I_B = ANV_B \exp(-aNv_B) \quad (31)$$

$$= (NV_p - V_E) \frac{I_p}{V_p} \exp(1) \exp\left[-\frac{1}{NV_p}(NV_p - V_E)\right] \quad (32)$$

$$I_B = I_p \left[1 - \frac{V_E}{NV_p}\right] \exp \frac{V_E}{NV_p} \quad (33)$$

To solve for N, the maximum number of diodes, which can be connected in series, and biased to a current I_B with a maximum allowable error of V_E , write

$$\frac{I_B}{I_p} = \left[1 - \frac{V_E}{NV_p}\right] \exp \frac{V_E}{NV_p} \quad (34)$$

$$\text{let } \frac{V_E}{NV_p} = X \quad (35)$$

then

$$\ln \frac{I_B}{I_P} = \ln (1 - X) + X \quad (36)$$

To solve this equation for X let $y_1 = \ln \frac{I_B}{I_P}$ (37)

$$y_2 = \ln (1 - X) \quad (38)$$

$$y_3 = X \quad (39)$$

All three of these equations are plotted for assumed values of X in Figure 13, page 48. The equations $y_2 = \ln (1 - X)$ and $y_3 = (-X)$ are then added graphically. The resultant of this addition and the intersection of the horizontal line of $y_1 = \ln \frac{I_B}{I_P}$ is the solution for X.

For $I_B = 2 \text{ ma}$

$$\ln \frac{I_B}{I_P} = \ln \frac{2}{2.2} = -0.09541$$

From Figure 13, $X = .377$

If V_E , the error = 0.5 volts

use equation (35)

$$N = \frac{V_E}{XV_P} = \frac{.5}{(.377)(.065)} = 24.5$$

$N = 24$ represents the maximum number of diodes which can be connected in series and the expected low range error measurement limited to 0.5 volts.

PLOT OF SOLUTION FOR

$$\ln \frac{I_B}{I_P} = \ln (1 - X) + X$$

48

FIGURE 13

PLOT OF SOLUTION $I_n \frac{I_B}{I_P} = I_n(1-X) + X$

$$X = \frac{V_E}{NV_P}$$

APPENDIX C

The Constant Current Generator

Figure 14, page 50, shows the circuit of the constant current generator.

CRL, R_1 and R_2 form a voltage divider which sets the base voltage and consequently the emitter voltage of Q_1 . Zener diode CRL is used to keep the base voltage constant. Potentiometer R_1 allows for adjustment of V_B .

To solve for the current I_C :

The base current is very small compared to the current I_2 .

$$V_B \cong \frac{(V_{cc} - V_{CRL})(R_{1b} + R_2)}{R_1 + R_2} \quad (40)$$

$$V_E = V_B + V_{EB} \quad (41)$$

$$I_E = \frac{V_{cc} - V_E}{R_E} \quad (42)$$

$$I_1 = I_C = \frac{I_E}{1 + \frac{1}{h_{FE}}} \quad (43)$$

$$h_{FE} \text{ min} = 100$$

$$\text{therefore, } I_1 = I_C \cong I_E \quad (44)$$

Solving for maximum current ($R_{1b} = 0$)

$$V_B = \frac{(40 - 5.2)}{200 + 2.2K} (2.2K) = 31.9 \text{ Volts}$$

$$V_E = V_B + V_{EB} = 31.9 + 0.6 = 32.5 \text{ Volts}$$

$$I_E = \frac{40 - 32.5}{3.3 \times 10^3} = \frac{7.5}{3.3 \times 10^3} = 2.27 \text{ milliamps}$$

FIGURE 14

THE CONSTANT CURRENT GENERATOR

$$\text{For } I_E \text{ min: } V_B = V_{cc} - V_{CR1}$$

$$= 40 - 5.2V = 34.8 \text{ Volts}$$

$$V_E = 34.8 + 0.6 = 35.4 \text{ Volts}$$

$$I_E = \frac{40 - 35.4}{33 \times 10^3} = 1.4 \text{ milliamps}$$

A current-voltage plot for the current generator appears in Figure 15, page 53. To obtain data for the plot, a decade resistance box, R_4 , was placed in the circuit between collector and ground, R_4 was then varied from 0 to a value R such that V_C varied from zero to thirty volts. I_C and V_C were measured at increments of one thousand ohms.

Two sets of measurement were taken; the first with an initial adjustment of 2 ma, and the second with an initial adjustment of 1.5 ma.

The results are tabulated in Table III, page 52, and plotted in Figure 15, page 53. Output impedance, as calculated from Figure 15, is

$$R_o = \frac{\Delta V}{\Delta I} \quad (45)$$

$$= \frac{(20 - 5) \text{ volts}}{(2 - 1.991) \text{ ma}} = 1.66 \times 10^6 \text{ Ohms}$$

Set 1		Set 2	
V_c (Volts)	I_c (ma)	V_c (Volts)	I_c (ma)
2.002	2.002	1.506	1.506
4.000	2.000	3.009	1.505
5.997	1.999	4.511	1.503
7.994	1.999	6.012	1.503
9.987	1.997	7.511	1.502
11.976	1.996	9.010	1.502
13.965	1.995	10.507	1.501
15.951	1.994	12.003	1.500
17.934	1.993	13.498	1.500
19.913	1.991	14.991	1.500
21.883	1.989	16.490	1.500
23.862	1.989	17.982	1.499
25.840	1.988	19.473	1.498
27.809	1.987	20.962	1.497
29.776	1.985	22.445	1.496
		23.930	1.496
		25.408	1.495
		26.891	1.494
		28.369	1.493
		29.846	1.493

TABLE III
CONSTANT CURRENT
GENERATOR DATA

FIGURE 15

PLOT of CONSTANT CURRENT GENERATOR OUTPUT

COMPOSITE CURRENT - VOLTAGE CHARACTERISTIC DATA
AND MEASUREMENT SETUP

Vertical sensitivity 0.5 ma/cm

Horizontal sensitivity 1.4 volts/cm

FIGURE 16

COMPOSITE I V CHARACTERISTIC of
28 TUNNEL DIODES in SERIES

FIGURE 17.

CIRCUIT ARRANGEMENT FOR OBTAINING IV CHARACTERISTIC
OF 28 DIODES IN SERIES

$I=0.5$ ma	$I=1.0$ ma	$I=1.5$ ma	$I=2.0$ ma	$I=2.15$ ma
Volts	Volts	Volts	Volts	Volts
.193	.410	.718	1.22	1.70
.652	.878	1.20	1.69	2.18
1.06	1.35	1.66	2.14	2.64
1.57	1.86	2.16	2.60	3.03
2.04	2.30	2.62	3.06	3.49
2.49	2.79	3.12	3.53	3.95
2.95	3.30	3.61	4.03	4.43
3.38	3.75	4.05	4.47	4.92
3.82	4.21	4.51	4.93	5.40
4.28	4.67	5.02	5.43	5.86
4.73	5.15	5.49	5.91	6.33
5.16	5.62	5.93	6.33	6.81
5.61	6.10	6.42	6.81	7.27
6.1	6.58	6.93	7.32	7.75
6.54	7.07	7.39	7.82	8.23
7.03	7.51	7.88	8.25	8.72
7.50	8.05	8.37	8.69	9.19
7.96	8.49	8.85	9.19	9.67
8.42	8.97	9.34	9.64	10.1
8.87	9.44	9.79	10.2	10.6
9.34	9.94	10.4	10.7	11.0
9.76	10.5	10.9	11.2	11.5
10.4	11.0	11.3	11.7	11.9
10.8	11.5	11.8	12.1	12.3
11.2	11.9	12.3	12.6	12.8
11.7	12.4	12.8	13.1	13.2
12.2	12.9	13.2	13.5	13.7
12.6	13.3	13.7	14.0	14.1
13.0	13.8	14.2	14.5	14.5

TABLE IV

DATA TAKEN FOR CONSTRUCTION OF DC CHARACTERISTIC OF SINGLE PULSE PEAK READING VOLTMETER. BIAS HELD TO 0.5 ma TO KEEP SWITCHED DIODES IN HIGH VOLTAGE REGION.

FIGURE 18

EQUIPMENT ARRANGEMENT for OBTAINING DATA for
COMPOSITE IV CHARACTERISTIC of FIGURE 6

Equipments and Pulses Used for Standard
Pulse Measurements

Vertical Scale	5V/cm
Horizontal Scale	0.1 μ sec/cm
Oscilloscope used	TEKTRONIX 551 Rise time .012 μ s
Preamplifier used	TEKTRONIX Type K Rise time .006 μ s

FIGURE 19

PICTURE OF TYPICAL PULSE INPUT
USED FOR DATA OF TABLE I

FIGURE 20

EQUIPMENT ARRANGEMENT FOR OBTAINING VOLTAGE
MEASUREMENTS OF STANDARD HEIGHT PULSES

APPENDIX G

Data sheets for the following components
are attached:

1N3715	Tunnel Diode
1N914	Diode
2N2905A	Transistor

SERIES TUNNEL DIODE SWITCHING TIME MEASUREMENT SETUP and PHOTOGRAPH

FIGURE 21

EQUIPMENT SETUP for OBTAINING TUNNEL DIODE SWITCHING TIME PHOTOGRAPHS WITH SAMPLING SCOPE

HORIZONTAL
SENSITIVITY = 2NS/CM

VERTICAL
SENSITIVITY = .5V/CM
(INCLUDES 10:1 DIVIDER)

INPUT A - TUNNEL DIODES

INPUT B - INPUT PULSE

BIAS = 0MA

BIAS = 1.5 MA

BIAS = 2.0 MA

FIGURE 22

SWITCHING TIMES - FIVE TUNNEL DIODES IN SERIES

Computer-Industrial TUNNEL DIODES

SELECTION OF NEW TYPES

TD1A-5

TD1A-5A

The General Electric TD1 through TD5 and TD1A through TD5A are Germanium Tunnel Diodes offering peak currents of 1.0, 2.2, 4.7, 10, and 22 ma. These devices, which make use of the quantum mechanical tunneling phenomenon to obtain a negative conductance characteristic, are designed for low level switching and small signal applications at very high frequencies. All "A" version parameters are closely controlled for use in critical applications such as level detection, frequency converters, etc. These devices are housed in General Electric's new hermetically sealed subminiature axial package.

FEATURES:

- ▷ V_{FS} Specified for more accurate designing of load lines
- ▷ Low capacitance
- ▷ Fast speed

absolute maximum ratings

	TD-1 TD-1A	TD-2 TD-2A	TD-3 TD-3A	TD-4 TD-4A	TD-5 TD-5A	
Forward Current*	5	10	25	50	100	ma
Reverse Current*	10	20	50	50	100	ma
Storage Temperature	← -55 to +100 →					°C
Lead Temperature $\frac{1}{4}$ " $\pm$ $\frac{1}{32}$ " from case for 10 seconds	← 260 →					°C

*Derate maximum currents 1% per °C ambient temperature above 25°C.

AXIAL DIODE OUTLINE

ALL DIMENSIONS IN INCHES.
DIMENSIONS ARE REFERENCE UNLESS TOLERANCED.

ECI Semiconductors, Inc.
3265 Gillham Road
Kansas City 9, Missouri
WEsport 1-0829

TYPICAL STATIC
CHARACTERISTIC CURVE

EQUIVALENT CIRCUIT
(BIASED IN NEGATIVE
CONDUCTANCE REGION)

TUNNEL DIODE SYMBOL

GERMANIUM TYPES FORMERLY

1N3712	(TD-1)
1N3713	(TD-1A)
1N3714	(TD-2)
1N3715	(TD-2A)
1N3716	(TD-3)
1N3717	(TD-3A)
1N3718	(TD-4)
1N3719	(TD-4A)
1N3720	(TD-5)
1N3721	(TD-5A)

electrical characteristics:

		TD-1			TD-1A			TD-2			TD-2A		
STATIC CHARACTERISTICS		Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.
Peak Point Current	I_P	0.9	1.0	1.1	0.975	1.000	1.025	2.0	2.2	2.4	2.15	2.20	2.25
Valley Point Current	I_V		0.12	0.18	.075	.095	.140		0.29	0.48	.165	.210	.310
Peak Point Voltage	V_P		65		58	65	72		65		58	65	72
Valley Point Voltage	V_V		350		315	355	395		350		315	355	395
Reverse Voltage ($I_R = I_P$ typ.)	V_R			40		20	40			40		20	40
Forward Voltage ($I_F = I_P$ typ.)	V_{FP}		500		475	510	535		500		475	510	535
► ($I_F = .25 I_P$ typ.)	V_{FR}^*				410	450					410	450	
DYNAMIC CHARACTERISTICS													
Total Series Inductance	L_S		0.5			0.5			0.5			0.5	
Total Series Resistance	R_S		1.5	4.0		1.7	4.0		1.0	3.0		1.1	3.0
► Valley Point Terminal Capacitance	C		5	10		3.5	5.0		10	25		7.0	10.0
Max. Negative Terminal Conductance	$-G$		8		7.5	8.5	9.5		18		16	19	22
Resistive Cutoff Frequency	f_{ro}		2.3			3.2			2.2			3.0	
Self-Resonant Frequency	f_{xo}		3.2			3.8			2.2			2.7	
Frequency of Oscillation	F_{osc}^{**}		3.2			3.8			2.2			2.7	
► Rise Time	t_r^{***}					1.7						1.6	

* V_{FS} is defined as the value of forward voltage at a forward current of one quarter the typical peak current.

**The frequency of oscillation (under short circuit conditions) for steady state large signal sinusoidal oscillation is given by equation (3) which is the maximum frequency attainable without capacitance compensation.

***Switching speed with constant current drive. $t_r \approx \frac{V_{FP} - V_P}{I_P - I_V} C$

TD-3			TD-3A			TD-4			TD-4A			TD-5			TD-5A		
Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.
4.2	4.7	5.2	4.58	4.70	4.82	9.0	10.0	11.0	9.75	10.00	10.25	20	22	24	21.5	22	22.5 ma
0.60	1.04	1.04	.350	.45	.60		1.3	2.2	.75	.95	1.40		2.9	4.8	1.65	2.10	3.10 ma
65			58	65	72		65		58	65	72		65		58	65	72 mv
350			315	355	395		350		315	355	395		350		315	355	395 mv
	40			20	40			40		20	40			40		20	40 mv
500			475	510	535		500		475	510	535		500		475	510	575 mv
			410	450					410	450					410	450	
	0.5			0.5			0.5			0.5			0.5			0.5	nh
	.50	2.0		.52	2.0		.30	1.5		.36	1.5		.20	1.0		.22	1.0 ohms
	25	50		13	25		50	90		27	50		90	150		55	100 pf
	40		36	41	46		80		75	85	95		180		160	190	220 10 ⁻³ mho
	1.8			3.4			1.6			2.8			1.6			2.6	KMC
	1.4			1.9			.97			1.3			.67			.78	KMC
	1.4			2.0			1.0			1.4			.74			.95	KMC
				1.4						1.3						1.2	nsec

$$f_{ro} = \frac{|g'|}{2\pi C'} \sqrt{\frac{1}{R_S |g'|} - 1} \quad (1)$$

$$f_{xo} = \frac{1}{2\pi} \sqrt{\frac{1}{L_S C'} - \left(\frac{|g'|}{C'}\right)^2} \quad (2)$$

$$f_{osc} = \frac{1}{2\pi} \sqrt{\frac{1}{L_S C} - \left(\frac{R_T}{L}\right)^2} \quad (3)$$

ECI Semiconductors, Inc.
3265 Gilliam Road
Kansas City 9, Missouri
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RESEARCH AND DEVELOPMENT DEPARTMENT
SYRACUSE, N.Y.

GENERAL ELECTRIC

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MOTOROLA

Semiconductors

BOX 955 • PHOENIX, ARIZONA 85001

PNP SILICON EPITAXIAL STAR* TRANSISTORS

... designed for high-speed switching circuits, DC to VHF amplifier applications and complementary circuitry.

... made by Annular† process to provide:

- High Voltage Rating:
 V_{CEO} to 60 Vdc
- High Uniform Beta over Current Range
from 0.1 mA to 500 mA
- Designed for Complementary Applications with
NPN "Star" Transistors
- High Current-Gain - Bandwidth Product:
 $f_T = 200$ mc minimum
- Low Saturation Voltage:
 $V_{CE(sat)} = 0.4$ Volt maximum at 150 mA

ABSOLUTE MAXIMUM RATINGS

CHARACTERISTIC	SYMBOL	RATING	UNIT
Collector-Base Voltage	V_{CBO}	60	Vdc
Collector-Emitter Voltage 2N2904-2N2907, 2N3485, 2N3486 2N2904A-2N2907A, 2N3485A, 2N3486A	V_{CEO}	40 60	Vdc
Emitter-Base Voltage	V_{EBO}	5	Vdc
Collector Current	I_C	600	mA dc
Total Device Dissipation @ $T_C = 25^\circ\text{C}$	P_D		
TO-5: 2N2904, 2N2904A, 2N2905, 2N2905A DERATING FACTOR		3 17.2	W mW/°C
TO-18: 2N2906, 2N2906A, 2N2907, 2N2907A DERATING FACTOR		1.8 10.3	W mW/°C
TO-46: 2N3485, 2N3485A, 2N3486, 2N3486A DERATING FACTOR		2 11.43	W mW/°C
Total Device Dissipation @ $T_A = 25^\circ\text{C}$	P_D		
TO-5: 2N2904, 2N2904A, 2N2905, 2N2905A DERATING FACTOR		600 3.43	mW mW/°C
TO-18: 2N2906, 2N2906A, 2N2907, 2N2907A TO-46: 2N3485, 2N3485A, 2N3486, 2N3486A DERATING FACTOR		400 2.28	mW mW/°C
Operating Junction Temperature Range	T_J	-65 to +200	°C
Storage Temperature Range	T_{stg}	-65 to +300	°C

The Motorola developed Annular process marks a breakthrough in low-leakage silicon transistor technology. Prior to this development, maximum voltage rating was limited by a phenomenon called "channeling," a surface-induced condition whose uncontrolled characteristics resulted in instability during operation. Channeling is traceable to the SiO_2 passivating layer necessary for low-leakage devices. By deliberately introducing a terminated channel whose predictable characteristics completely swamp out those of the randomly induced channel, the high-voltage capability of low-leakage transistors is greatly enhanced.

*Trademark of Motorola Inc.

†Manufactured by the Annular process, Motorola patents applied for.

MOTOROLA Semiconductor Products Inc.

**2N2904-2N2905
2N2904A-2N2905A**

TO-5 CASE

**2N2906-2N2907
2N2906A-2N2907A**

TO-18 CASE

**2N3485-2N3486
2N3485A-2N3486A**

TO-46 CASE

PNP SILICON SWITCHING & AMPLIFIER TRANSISTORS

JULY 1964 — DS 5045 R1
(REPLACES DS 5045)

TO-5 TO-18 TO-46

	A	B
TO-18	0.185 MAX.	0.016 0.019 DIA
TO-46	0.060 0.080	0.012 0.019 DIA

PNP SILICON HF TRANSISTORS
2N2904 and A Series
2N3485 and A Series
DS 5045 R1

A SUBSIDIARY OF MOTOROLA INC.

ELECTRICAL CHARACTERISTICS (At 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
Collector Cutoff Current ($V_{CB} = 50 \text{ Vdc}$, $I_E = 0$) ($V_{CB} = 50 \text{ Vdc}$, $I_E = 0$, $T_A = 150^\circ\text{C}$)	I_{CBO}	---	.020 .010 20 10	μAdc
Collector Cutoff Current ($V_{CE} = 30 \text{ V}$, $V_{BE} = 0.5 \text{ V}$)	I_{CEX}	---	50	nAdc
Base Cutoff Current ($V_{CE} = 30 \text{ V}$, $V_{BE} = 0.5 \text{ V}$)	I_{BL}	---	50	nAdc
Collector-Base Breakdown Voltage ($I_C = 10 \text{ Adc}$, $I_E = 0$)	BV_{CBO}	60	---	Vdc
Collector-Emitter Breakdown Voltage* ($I_C = 10 \text{ mAdc}$, $I_B = 0$)	BV_{CEO}^*	40 60	---	Vdc
Emitter-Base Breakdown Voltage ($I_B = 10 \text{ Adc}$, $I_C = 0$)	BV_{EBO}	5	---	Vdc
Collector Saturation Voltage* ($I_C = 150 \text{ mAdc}$, $I_B = 15 \text{ mAdc}$) ($I_C = 500 \text{ mAdc}$, $I_B = 50 \text{ mAdc}$)	$V_{CE(sat)}^*$	---	0.4 1.6	Vdc
Base-Emitter Saturation Voltage ($I_C = 150 \text{ mAdc}$, $I_B = 15 \text{ mAdc}$) ($I_C = 500 \text{ mAdc}$, $I_B = 50 \text{ mAdc}$)	$V_{BE(sat)}^*$	---	1.3 2.6	Vdc
DC Forward Current Transfer Ratio ($I_C = 0.1 \text{ mAdc}$, $V_{CE} = 10 \text{ Vdc}$)	h_{FE}	20 35 40 75	---	---
($I_C = 1.0 \text{ mAdc}$, $V_{CE} = 10 \text{ Vdc}$)		25 50 40 100	---	---
($I_C = 10 \text{ mAdc}$, $V_{CE} = 10 \text{ Vdc}$)		35 75 40 100	---	---
($I_C = 150 \text{ mAdc}$, $V_{CE} = 10 \text{ Vdc}$)*		40 100	120 300	---
($I_C = 500 \text{ mAdc}$, $V_{CE} = 10 \text{ Vdc}$)*		20 30 40 50	---	---
Output Capacitance ($V_{CE} = 10 \text{ Vdc}$, $I_E = 0$, $f = 100 \text{ kc}$)	C_{ob}	---	8	pf
Input Capacitance ($V_{BE} = 2 \text{ Vdc}$, $I_C = 0$, $f = 100 \text{ kc}$)	C_{ib}	---	30	pf
Current-Gain — Bandwidth Product ($I_C = 50 \text{ mAdc}$, $V_{CE} = 20 \text{ Vdc}$, $f = 100 \text{ mc}$)	f_T	200	---	mc

*Pulse Test: Pulse Width = 300 μsec , duty cycle $\leq 2\%$

SWITCHING CHARACTERISTICS (At 25°C unless otherwise noted)

Characteristic	Symbol	Typical	Max	Unit
Delay Time (Figure 1)	t_d	6	10	nsec
Rise Time (Figure 1)	t_r	20	40	nsec
Turn-On Time (Figure 1)	t_{on}	26	45	nsec
Storage Time (Figure 2)	t_s	50	80	nsec
Fall Time (Figure 2)	t_f	20	30	nsec
Turn-Off Time (Figure 2)	t_{off}	70	100	nsec
Total Switching Time (Figure 3)	t_{total}	12	---	nsec

FIGURE 1 — SATURATED TURN-ON SWITCHING-TIME TEST CIRCUIT

FIGURE 2 — SATURATED TURN-OFF SWITCHING-TIME TEST CIRCUIT

FIGURE 3 — NON-SATURATED SWITCHING-TIME TEST CIRCUIT

TYPES 1N251, JAN 1N251, 1N914, USN 1N914, 1N914A, 1N914B, 1N915, 1N916, 1N916A, 1N916B and 1N917 DIFFUSED SILICON MESA COMPUTER DIODES

Extremely Stable and Reliable High Speed Switching Diodes
Meet All Requirements of MIL-S-19500B

mechanical data

Contained in the rugged MOLY/G** diode package—a hard glass hermetically sealed case with a platinum alloy-to-gold contact. Unit weight is 0.195 gram.

absolute maximum ratings at 25°C ambient temperature (unless otherwise noted)

V_R Reverse Voltage at -65 to +150°C
 I_o Average Rectified Fwd. Current
 I_o Average Rectified Fwd. Current at +150°C
 i_f Recurrent Peak Fwd. Current
 $i_{f(surge)}$ Surge Current, 1 sec
 P Power Dissipation
 T_A Operating Temperature Range
 T_{stg} Storage Temperature Range

1N251	1N914	1N914A	1N914B	1N915	1N916	1N916A	1N916B	1N917	Units
30	75	75	75	50	75	75	75	30	v
75	75	75	75	75	75	75	75	50	ma
†30	10	10	10	10	10	10	10	10	ma
†90	225	225	225	225	225	225	225	150	ma
200	500	500	500	500	500	500	500	300	ma
250	250	250	250	250	250	250	250	250	mW
-65 to +150									°C
200									°C

maximum electrical characteristics at 25°C ambient (unless otherwise noted)

BV_R Min Breakdown Voltage at 100μa
 I_R Reverse Current at V_R
 I_R Reverse Current at -20v
 I_R Reverse Current at -20v at 100°C
 I_R Reverse Current at -20v at +150°C
 I_R Reverse Current at -10v
 I_R Reverse Current at -10v at 125°C
 I_F Min Fwd Current at $V_F = 1$ vdc
 V_F at 250μa
 V_F at 1.5ma
 V_F at 3.5ma
 V_F at 5ma
 V_F Min at 5ma
 C Capacitance at $V_R = 0$ vdc

40	100	100	100	65	100	100	100	40	v
	5	5	5	5	5	5	5		μa
	0.025	0.025	0.025		0.025	0.025	0.025		μa
	3	3	3	5	3	3	3	25	μa
	50	50	50		50	50	50		μa
0.1				0.025				0.05	μa
10									μa
5	10	20	100	50	10	20	30	10	ma
								0.64	v
								0.74	v
								0.83	v
			0.72	0.73			0.73		v
				0.60					v
	4	4	4	4	2	2	2	2.5	pf

operating characteristics at 25°C ambient temperature (unless otherwise noted)

t_{rr} Max Reverse Recovery Time	††150	*4 °8	*4 °8	*4 °8	*10	*4 °8	*4 °8	*4 °8	*3 °3	nsec
V_f Fwd Recovery Voltage (50ma Peak Sq. wave, 0.1 μsec pulse width, 10 nsec rise time, 5Kc-100Kc rep. rate)		2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	v

** Trademark of Texas Instruments Incorporated : Military Specifications MIL-S-19500/116 USN
• Lumatron (10ma I_F , 10ma I_R , recover to 1ma) † at 125°C
• EG8G (10ma I_F , 6v V_R , recover to 1ma) †† I_F at 5ma, V_R at 10v, recover to .5ma — JAN 256
• Meets or exceeds MIL-E-1/1023 JAN

TYPES 1N251, JAN 1N251, 1N914, USN 1N914, 1N914A, 1N914B, 1N915, 1N916, 1N916A, 1N916B and 1N917
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