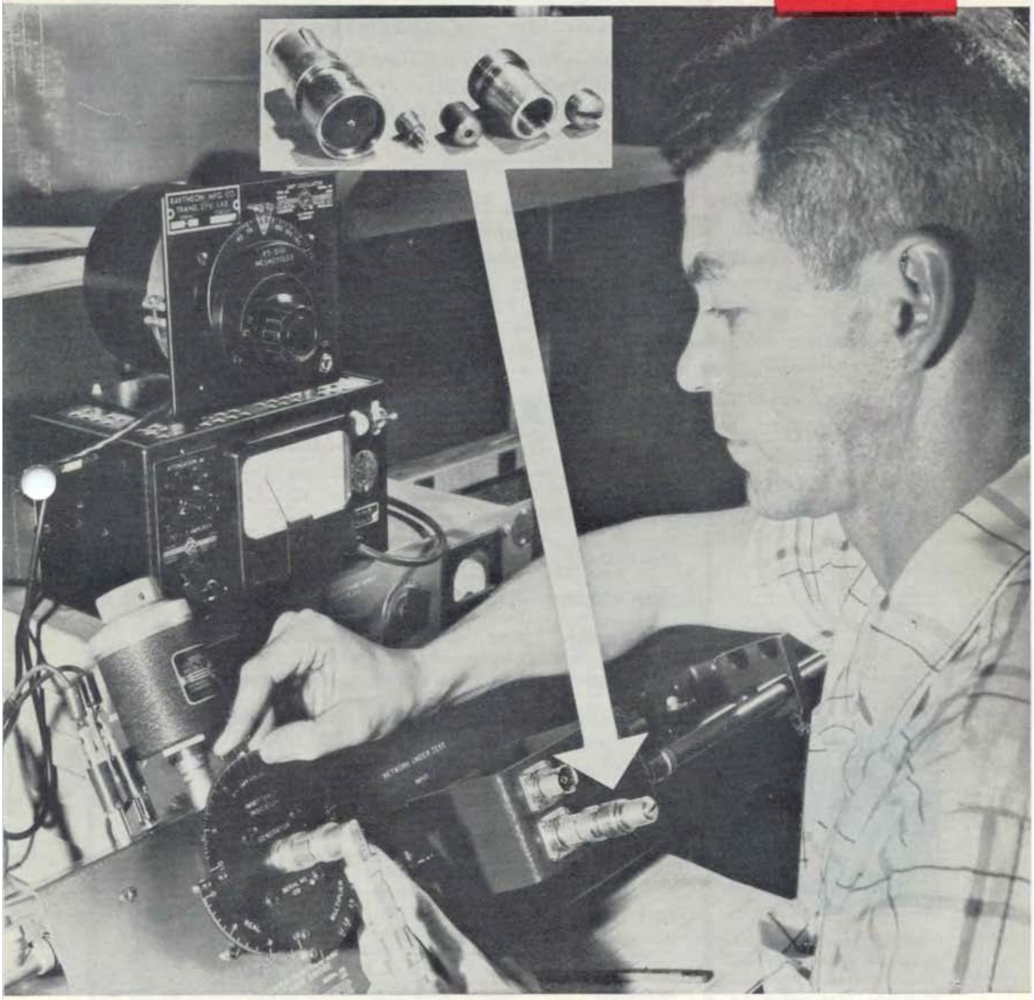
THE GENERAL RADIO

EXPERIMENTER



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IN THIS ISSUE

Tunnel-Diode Measurements

THE GENERAL RADIO
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COVER

In Raytheon's Semiconductor Advanced Development Laboratory, William F. Moloney, Engineering Assistant Technical, measures tunnel-diode parameters with the General Radio Transfer-Function and Immittance Bridge. Inset shows details of coaxial mount.

MEASUREMENTS OF THE EQUIVALENT-CIRCUIT PARAMETERS OF TUNNEL DIODES

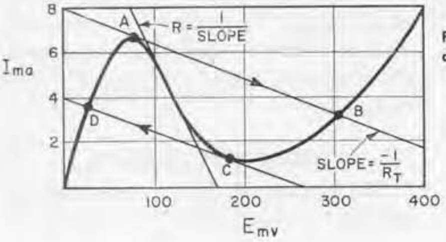
The measurement of equivalent-circuit parameters is of particular importance in the development of semiconductor devices, in the control of their uniformity in manufacture, and in their application in practical circuits. Tunnel diodes present unusual measurement problems, both because of their unstable behavior in the measuring circuit under certain bias conditions and because some of the characteristics to be measured are not directly accessible for measurement at the diode terminals. These problems, together with suggestions for their solution, will be discussed in this article.

Measurements are most conveniently made in the vhf-uhf ranges. Not only do the high-frequency characteristics give the best index of performance for practically all applications, but also the measuring instruments and circuits available at these frequencies offer the advantages of complete shielding and freedom from residual impedances that are characteristic of low-impedance coaxial systems.

TUNNEL-DIODE CHARACTERISTICS

The current-voltage relation for the tunnel diode is shown in Figure 1, and Figure 2 is an equivalent circuit. As is evident from Figure 1, the diode ac resistance, R, is a function of bias and can be either positive or negative. The capacitance, C, Figure 2, is also a function of bias, but changes more gradually. The small-signal ac characteristics of the diode are described in terms of the equivalent-circuit parameters, L, C, R, and R_s and of certain characteristic frequencies that are functions of these values, and which are usually defined in terms of operation in the region of minimum negative resistance. These frequencies are the self-resonant frequency, where the immittance of the diode is purely real, and the resistive cut-off frequency, where the immittance of the diode is purely imaginary, representing the upper frequency limit for diode negative resistance. A third characteristic frequency sometimes referred to is the oscillation frequency, which, by definition, is theoretically the frequency at which the diode will oscillate if short-circuited. In practice, the amplitude of this oscillation will be great enough to swing over the nonlinear region of the diode resistance and capacitance characteristics, so that the frequency of oscillation may not correspond to the true small-signal oscillation frequency.

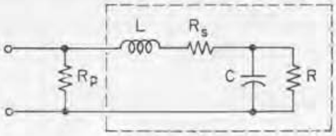
Figure 1. Current-voltage characteristic of a tunnel diode.



STABILITY CONSIDERATIONS

In the measurement of these quantities as well as in practical application of

Figure 2. Equivalent circuit of a tunnel diode (inside dotted rectangle), with shunting resistor, R_p, which stabilizes operation in a measuring circuit.



the diode, a number of precautions are necessary, owing to the negative-resistance, nonlinear, and multivalued-current characteristics of tunnel diodes. A shunt resistance, R_p, is generally required for stable operation. A specific choice of total circuit resistance is necessary for stability. Several modes of operation that depend upon this choice are shown graphically in Figure 3 as a function of the impedance, R_T, which is the sum of the diode resistance, R_s, and the equivalent source resistance, R_p'. The equivalent source resistance is, for ac, the shunt resistance, R_p, in parallel with the signal-source resistance. For dc, R_p' is R_p in parallel with the dc source resistance. If the dc circuit resistance of R_T is greater than the negative-resistance magnitude, R, operation will be unstable in the negative-resistance region. In Figure 1, R_T is large compared with the negative resistance, and, as the bias voltage is increased, the operating point of the diode will switch from A to B. If the bias voltage is then decreased, the operating point will switch back from C to D. If R_T is less than the negative resistance, no switching will occur. If the ac resistance of R_T is less than $\frac{L}{RC}$, the circuit will oscillate.

In the TYPE 1607-A Transfer-Function and Immittance Bridge, for example, the effective dc source resistance is the dc-bias-supply internal resistance, in series with the bias-filter resistance of 4 ohms. The ac source impedance at high frequencies is approximately 50 ohms at the operating frequency. At other frequencies the impedance may differ from 50 ohms, but will usually cause no difficulty if the shunt resistor is 50 ohms or less.

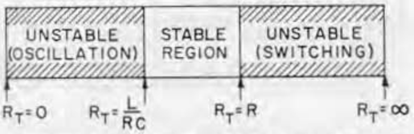


Figure 3. Modes of operation for the tunnel diode as a function of the total circuit resistance, R_T.

The stable region defined by $\frac{L}{RC} < R_T < R$ will vanish if the inductance L is greater than R^2C. With most currently available tunnel diodes, the package-and-holder inductance is small enough to permit stable operation. Since low-impedance diodes are necessarily designed with low parasitic inductances, the total circuit inductance between the diode and the equivalent source resistance R_p' must be exceedingly small. This is possible only in carefully designed mounts.

In the preceding analysis the source impedance is assumed to be purely resistive. In most practical applications this condition will not be exactly met, and the actual operating characteristics will differ somewhat from those outlined above. In actual measurements, in the negative resistance region, the best results have been obtained when the resistance of the shunt resistor itself is slightly lower than the minimum negative resistance of the diode.

As a further precaution, because the diode characteristic is nonlinear, the amplitude of the signal incident on the diode must be small. For the diode shown in Figure 1, a value of a few millivolts, rms, is a reasonable upper limit for small-signal measurements. Further, if a superheterodyne null detector is employed in the bridge measurements, local-oscillator leakage into the tunnel-diode circuit must not exceed a few millivolts.

DIODE TEST MOUNTS

The test mount for the diode must be designed to minimize stray inductance

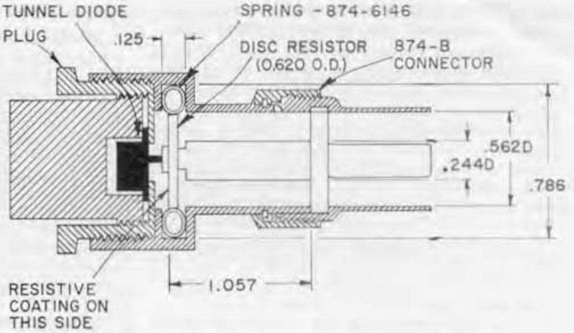


Figure 4. Suggested coaxial mount for connecting a tunnel diode into the measuring circuit.

The mount shown here is designed for the early Esaki diode manufactured by Sony, which has a single lead. A different arrangement is described in the article by Adler and Wonson (page 9) and is designed to accept the Raytheon CK40 type, which is in a microwave diode package. Diodes with two leads present a more difficult problem since the mount must be designed to accept the ground lead. For measurement purposes, the lead can be removed, but this is hardly a practical procedure for developmental and production testing.

and capacitance, particularly if the diode resistance, R, is low. Measurement accuracy is improved if the shunting resistor is located as close to the diode as possible, as shown in a suggested coaxial mount in Figure 4. This resistor should be lower than the negative resistance of the diode under test, be essentially noninductive, and have a negligible shunt capacitance. In coaxial systems film-type disk resistors are suitable. The electrical length of the coaxial mount shown in Figure 4 is equal to that of the General Radio Type 874-WN3 Short-Circuit Termination.

If a measurement of the diode capacitance and inductance outside the negative resistance region is desired, the shunting resistor is not necessary to obtain stable operation and can be omitted.

CHARACTERISTIC EQUATIONS

The diode admittance and impedance in terms of the circuit elements of the equivalent circuit, Figure 2, are

Admittance

$$G_e = -\frac{1}{R}\frac{1-\frac{R_s}{R}\left[1+(\omega CR)^2\right]}{\left(1-\omega^2LC-\frac{R_s}{R}\right)^2+\left(\frac{\omega L}{R}\right)^2\left(\frac{1-R\,R_s\,C}{L}\right)^2} \quad (1$$

$$B_e = \omega C\frac{1-\frac{L}{CR^2}-\omega^2LC}{\left(1-\omega^2LC-\frac{R_s}{R}\right)^2+\left(\frac{\omega L}{R}\right)^2\left(1-\frac{R\,R_s\,C}{L}\right)^2} \quad (2$$

Impedance

$$R_e = R_s - \frac{R}{1+(\omega CR)^2} \quad (3$$

$$X_e = \omega\left[L - \frac{R^2C}{1+(\omega CR)^2}\right] \quad (4$$

In these equations R is assumed to be negative, and no additional negative sign should be used.

CHARACTERISTIC FREQUENCIES

Self-resonant frequency

$$f_o = \frac{1}{2\pi\sqrt{LC}}\sqrt{1-\frac{L}{R^2C}} \quad (5$$

Resistive cut-off frequency

$$f_{G_0} = \frac{1}{2\pi RC}\sqrt{\frac{R}{R_s}-1} \quad (6$$

Oscillation frequency (low-level)

$$f_{osc} = \frac{1}{2\pi\sqrt{LC}}\sqrt{1-\frac{R_s}{R}} \quad (7$$

Typical diode immittance-frequency characteristics are shown in Figures 5 and 6, for $R^2 < \frac{L}{C}$ except as shown.

Simplification of these expressions is required, in general, to relate the unknown quantity to be measured to the actual measured value. Measurement frequency and operating bias, forward and reverse, must be so chosen as to permit this simplification. The choice of measuring conditions is further restricted by measuring-instrument resolution. With some diodes, in particular some galium-arsenide types, the simplifications lead to only approximate values for the unknown quantities, regardless of operating conditions and measuring-instrument accuracy.

MEASUREMENT OF TUNNEL DIODE EQUIVALENT CIRCUIT ELEMENT VALUES AND FREQUENCIES

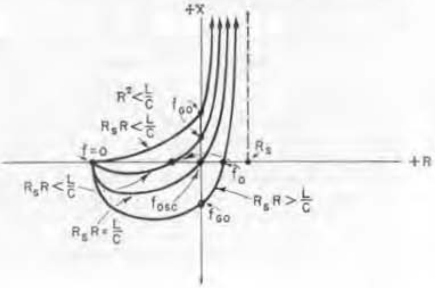
As indicated above, lead inductance between the diode and shunting resistance or between the diode and measuring terminals should be minimized to achieve stable operation in the negative-resistance bias region and to attain reasonable accuracy at any bias. Measurements are made at 25 Mc and above, and a coaxial mount, of the type shown in Figure 4, is necessary. The recommended measuring instrument is the Type 1607-A Transfer-Function and Immittance Bridge for frequencies up to 1500 Mc. Above 1500 Mc the Type 874-LBA Slotted Line can be used with appropriate provision for bias and in a reversed connection, that is, with the generator connected to the probe and the detector connected to the normal sending end of the line.

APPROXIMATE DIODE CIRCUIT VALUES NOT KNOWN

When the approximate negative-resistance value is not known, a dc measurement of the voltage-current characteristic will indicate the proper bias voltage and approximate negative-resistance value required to make a suitable shunting-resistance choice. When the other circuit constants are not known, the diode admittance or impedance is measured over a range of frequencies necessary to obtain a rough plot corresponding to Figures 5 and 6. From this plot the approximate self-resonant and resistive-cutoff frequencies can be obtained, as well as the upper boundary of the frequency range in which the measured conductance of resistance is essentially constant with frequency.

The desired characteristic frequencies and equivalent circuit constants can be determined from either admittance or impedance measurements. Admittance is the more convenient measurement, since the shunt admittance can be directly subtracted from the measured result to yield the diode admittance directly. When the diode impedance is low, however, better accuracy with the Type 1607-A Transfer Function and Immittance Bridge is achieved by an impedance measurement.

Figure 5. Plot of impedance characteristics as measured to obtain the approximate values for the self-resonant and resistive cut-off frequencies.



Measurement of Resistive Cut-Off Frequency, f_{G_o}

At the resistive cut-off frequency, the diode conductance is zero. With the shunting resistor installed, the frequency is sought at which the measured admittance is identically equal to the admittance of the shunt resistor. This frequency is best obtained by measurement, first of the shunt resistor alone and then of the diode plus the shunt resistor, at several frequencies in the expected range. A graph is made of these two measured values as a function of frequency to smooth the data and to reduce the number of measurements required. The frequency at which the two measured values are equal is the resistive cut-off frequency.

Measurement of Self-Resonant Frequency, f_o

At the self-resonant frequency, the diode susceptance or reactance is zero. Since the conductance at this frequency is high, measurement accuracy will be improved if impedance rather than admittance is measured. With the shunting resistor installed, the frequency is sought at which the diode reactance is zero. The diode impedance is measured over the region of the expected self-resonant frequency. A graph of reactance as a function of frequency is then made to smooth the data and to reduce the number of measurements required.

Measurement of Inductance, L

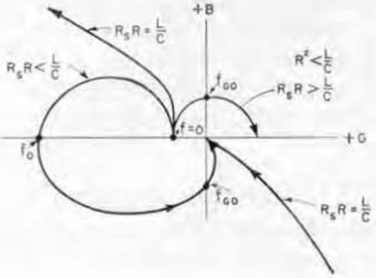
Back-Bias Method

With the diode biased in the reverse direction and in the ohmic region, the diode capacitance is essentially short-circuited, and inductance can be determined from an admittance measurement at some convenient frequency. From the diode reactance expression (equation 4), the following equivalent inductance expression is obtained:

$$L' = L\left[1-\frac{1}{\omega^2LC+\dfrac{L}{CR^2}}\right] \quad (8$$

$$= L\left[1-\frac{1}{\left(\dfrac{\omega}{\omega_r}\right)^2+\dfrac{L}{CR^2}}\right] \cong L \quad (9$$

Figure 6. Plot of admittance characteristics for determination of self-resonant and resistive cut-off frequencies.



where

L' = the inductance value measured

$$\omega_r = \frac{1}{\sqrt{LC}}$$

The diode capacitance, C, is, in this case, slightly lower than it is in the negative-resistance region.

Since the second term in the exact expression includes the unknown, L, it must be small, or the error in this approximation will be large. When $\frac{L}{CR^2}$ is sufficiently large (and this assumes that $\frac{L}{C}$ is known approximately), the measurement frequency choice is not critical. In order to reduce this term to 10% or less, then, at low frequencies (where $\left(\frac{\omega}{\omega_r}\right)^2 < \frac{L}{CR^2}$),

$$R \text{ must be less than } 0.3\frac{L}{C}$$

This requirement is met in most diodes, where typical values are $\frac{L}{C} = 100$, $R = 1$. A nominal low frequency choice would be about one fourth the self-resonant frequency, f_o. The shunt resistor is not required in this measurement.

Dummy-Diode Method

Since the diode inductance is principally in the connecting lead to the semiconductor element, an equivalent package can be made with the element replaced by a short-circuit. The inductance of this package can be measured without the above restrictions on frequency.

Capacitance Measurement

The diode capacitance can be directly measured at a frequency adequately below the self-resonant frequency. This capacitance can usually be measured in the negative resistance region, although instrument errors and errors from diode inductance and resistance can be serious. The frequency and diode ac resistance limitations are as follows:

From the diode susceptance expression (equation 2),

$$C' = C\,\frac{1-\frac{L}{CR^2}-\omega^2 LC}{\left(1-\omega^2 LC-\frac{R_s}{R}\right)^2+\left(\frac{\omega L}{R}\right)^2\left(1-\frac{R\,R_s\,C}{L}\right)^2} \quad (10$$

Where C' = apparent capacitance as measured.

The right-hand term therefore should be made to be near unity for maximum accuracy. The first step to achieve this is to lower the measurement frequency. If the capacitance is to be measured to within 10%, then

$$f_m << \frac{1}{8\pi\sqrt{LC}} \text{ assuming that } R^2 > \frac{10L}{C}$$

If the measurement frequency is well below this limit (it should not be so low that the capacitance susceptance is comparable to instrument resolution), the measured capacitance reduces to

$$C' = C\left[1-\frac{L}{CR^2}\right]$$

When $R >> R_s$

It is assumed that the diode circuit parameters are approximately known to permit the frequency choice.

The error term is therefore $\frac{L}{CR^2}$, which is independent of frequency.

If reasonably accurate measurements are desired in the negative-resistance region, this error term must be appropriately small. There is no means of controlling the error except by a bias shift away from the region where the negative resistance is the smallest or by a reduction in L. In fact, for some diodes it may be necessary to operate nearer the peak and valley regions to obtain sufficient accuracy, as shown in Figure 7. In this figure, representing the low-frequency case, the effect of R^2 approaching $\frac{L}{C}$ is shown. The extreme case where $R^2 \leq \frac{L}{C}$ is not usually encountered in practical diodes, since this corresponds to the oscillation region overlapping the switching region operation.

For a diode with C = 40pf, L = 2mμh, R = 30 ohms, R_s = 1 ohm, a suitable frequency is between 30Mc and 70Mc, and the measurement in the negative-resistance region will not yield greater than a 10% error. Sometimes the condition $\left|R^2_{min}\right| > 10\frac{L}{C}$ is not met. In this case, operation at or near the peak and valley points, where the diode ac resistance is large, usually yields reasonably accurate results.

In addition to the errors mentioned above, the measuring instrument can introduce a further error in the negative-resistance region. In most instruments, when the resistance component of the network under test changes greatly, a small error in the reactive component will be produced. When the measured reactive component is small, the percentage error can be large.

Negative Resistance or Conductance Measurement

For this measurement the same conditions and approximately the same frequency-choice considerations apply as for capacitance measurement. The resistance expression (3) reduces to

$$R' = R - R_s$$

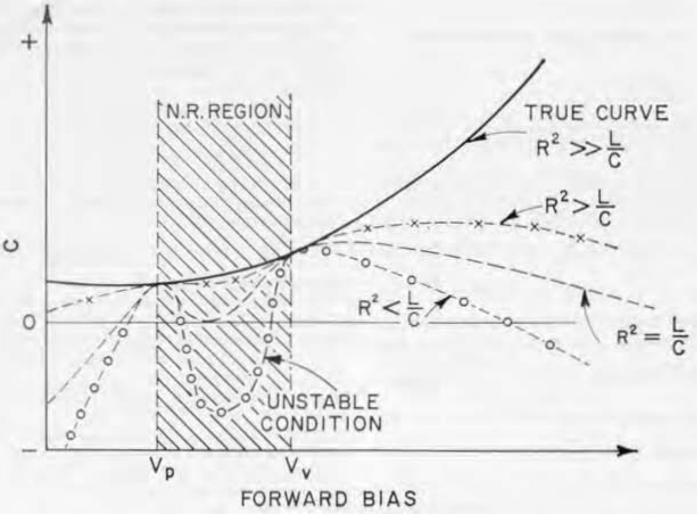


Figure 7. Plot showing how the magnitude of R^2 as compared with that of $\frac{L}{C}$ affects the measured values of capacitance.

where

R' = measured value

Usually R_s is sufficiently smaller than R that: $R' \cong R$, or $G' \cong G$

Series Resistance Measurement, R_s

Either of two procedures may be used. The first, the resistive cut-off frequency method, is reasonably accurate if the negative resistance and capacitance values are known accurately. The second, the back-bias method, yields an upper limit to this value and is accurate in most cases, since the actual series resistance and the diode back resistance, in series, are measured.

Resistive Cut-Off Method

The resistive cut-off frequency is measured as described in a preceding section. The capacitance, C, and the negative resistance, R, are measured as described above.

R_s is calculated from the expression:

$$R_s = \frac{R}{(R\omega_{G_0}C)^2 + 1}$$

where R, ω_{G_0}, and C are measured values.

Back-Bias Method

In the back-bias measurement, the diode impedance expression reduces to

$$Z_e = (R_s + R) + j\omega L$$

At a sufficiently large value of back bias, the barrier resistance, R, becomes very small, and

$$R_s \cong R_e$$

where R_e is the measured value. The shunt resistor is not required for this measurement.

Impedance vs. Admittance Measurements

In the measurement of the diode element values, greater accuracy is obtained if impedance and not admittance is measured when the impedance is much less than 50 ohms. The subtraction of the shunt impedance from the measured impedance to obtain the diode admittance is more complex in this case:

$$Y_e = \frac{1}{Z_m} - \frac{1}{Z_p}$$

where Z_m = measured impedance, diode plus shunt.

Z_p = measured shunt impedance.

Specific procedures for measuring tunnel diodes will be described in the Operating Instructions for the Type 1607-A Transfer-Function and Immittance Bridge.

— John Zorzy

The following article, published through the cooperation of the Raytheon Company, discusses a practical example of tunnel-diode measurements, made on that company's CK40 series developmental diodes.

THE USE OF THE GENERAL RADIO IMMITTANCE BRIDGE IN TUNNEL-DIODE MEASUREMENTS

by

E. Adler and R. C. Wonson*

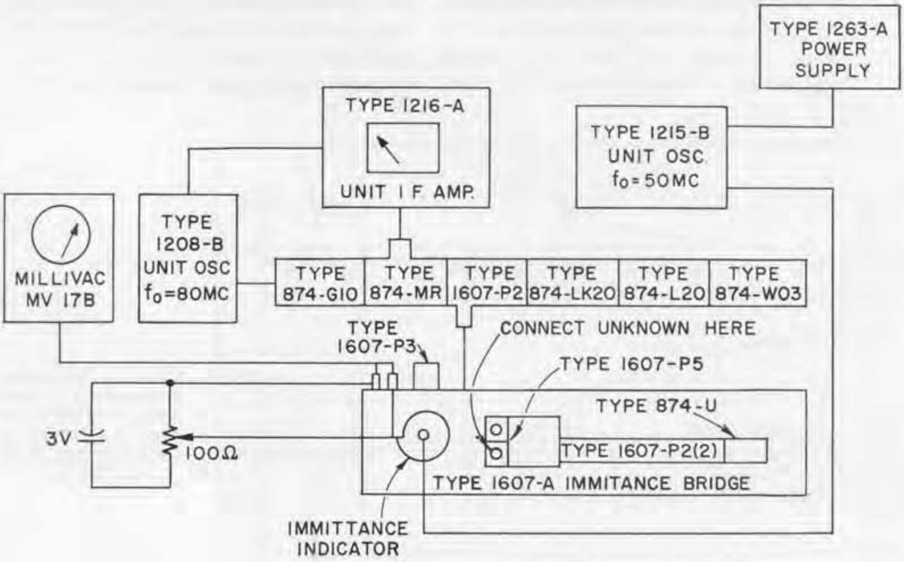
The General Radio Transfer-Function and Immittance Bridge, Type 1607-A, arranged with the immittance indicator in place, is highly suitable for making measurements of tunnel-diode parameters. The plane where the actual measurements are made may be easily adjusted and determined, bias can easily be applied to the diode and spurious oscillations damped out, and no difficulty stands in the way of making measurements, either over a range of bias voltages in order to obtain detailed information on the behavior of the diodes, or at a very limited number of bias points so as to permit the rapid relative classification of a group of diodes. These remarks are made on the basis of considerable experience gained in the use of the bridge, further details of which are set out below.

The discussion that follows is limited to the measurement of the diode capacitance and negative conductance. The series inductance, being constant for a given package design, need be measured only once, possibly by use of a dummy diode. The series resistance may most easily be measured at conditions of very

Figure 1. Block diagram of the measuring equipment. Items not identified by name are:

Type 874-G10 Fixed Attenuator (10 db)	Type 874-WO3 Open-Circuit Termination
Type 874-MR Mixer Rectifier	Type 1607-P2 Tee Assembly
Type 874-LK20 Line Stretcher	Type 1607-P3 Air Capacitor
Type 874-L20 20-cm Air Line	Type 1607-P5 Range Extension Unit

The last three items are supplied as a part of the bridge.



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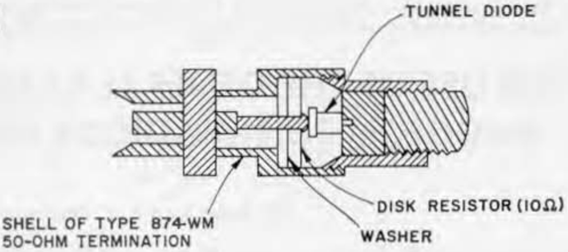
*Raytheon Co., Semiconductor Div., Newton, Mass.

Figure 2. Coaxial mount used to connect the diode to the bridge. See also cover photo.



large applied reverse bias, in which case methods employing techniques other than those associated with the bridge presently considered are preferable, except where a high-frequency measurement is specifically desired.

The conditions of measurement were similar to those outlined in the preceding article; a shunt resistor was used, to assure that the unknown element presented a positive conductance to the bridge; the mount was designed to locate the measurement point in the plane of the diode junction; and the signal level was kept low, one millivolt or less.

A block diagram of the bridge and ancillary equipment used for the tests described is shown in Figure 1. It was found necessary to construct a coaxial mount* to hold the diodes and the stabilizing resistor, so that the whole could be easily plugged into the appropriate bridge terminal. A modified General Radio Type 874-WM 50-ohm Termination was found to be easily adapted for this purpose (see Figure 2). The final unit consists of the 874-WM shell, a 10-ohm disk resistor, and fittings to hold the diode in place. A disk resistor is used, not only for convenience but also, and more importantly, to keep the series inductance in the diode-plus-parallel-resistor circuit low and thus very effectively to satisfy the diode stability criterion; in addition, this arrangement keeps the circuit to be measured as nearly as possible in one plane.

The successive steps in the measurement procedure are as follows:

1) The initial setting up of the bridge consists of setting the output line to one half wavelength and "trapping out" the local oscillator signal as prescribed in the instruction manual in order to prevent parasitic signals from reaching the diode.

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*After a design by S. Cohen of Raytheon Co. (Research Div.).

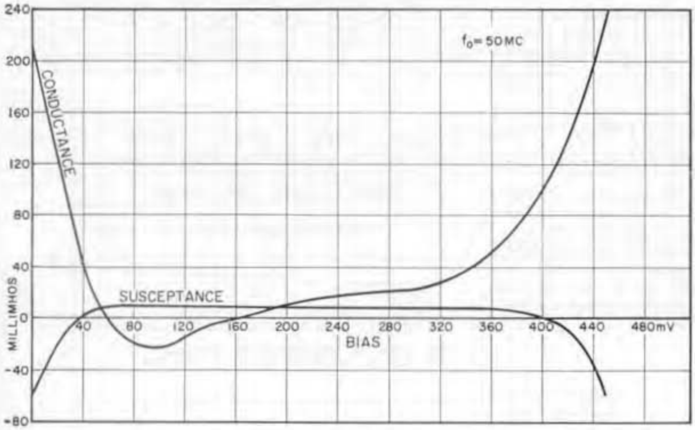

Figure 3. Admittance characteristics of Raytheon CK40 series diodes as a function of bias, measured at 50 Mc.

The correct setting of the output line may be performed with an 874-WN3 Short Circuit in place of the diode holder if desired, since this provides substantially the same reference plane as the latter. Alternatively a special (short circuited) diode may be placed in the holder; this choice is better in principle, since any lead inductance effects should be automatically compensated.

2) The admittance of the diode mount must be measured with the resistor, but no diode, in place. This value can then be subtracted from the readings taken with the diode in place, to obtain the true diode values.

3) A bias calibration is required. The components in the decoupling circuits which isolate the coaxial bridge lines from the external bias supply include series chokes having relatively large resistances. The complexity of the relation between the voltage applied to the bias terminals on the bridge and the actual bias applied at the diode will depend on the division of current between the diode and the stabilizing resistor, and thus it is simplest to take a direct calibration, connecting a coaxial tee between the diode mount and the bridge socket for this purpose. The tee should be removed when the diode admittance measurements are made.

4) The actual diode admittance measurement is made, the results being adjusted in accordance with (2) above.

Figure 3 shows typical results obtained from measurements, using the above techniques, made on a number of Raytheon CK40 series developmental tunnel diodes. These curves possess the shapes to be expected on the basis of theoretical predictions and agree closely with results obtained by alternative methods. It is intended to include a more detailed discussion of this subject in another article, but it might be mentioned that the change of diode susceptance from capacitive to inductive values at the extremes of the bias range is erroneous, being caused by the inductance and the decrease in diode resistance so that R^2 is not large compared with $\frac{L}{C}$. The effect of series inductance can be carried to the limit, i.e., to the extent where resonance with the diode capacitance takes place, by measurement at a higher frequency. Figure 4 shows curves obtained at a frequency of 500 Mc.

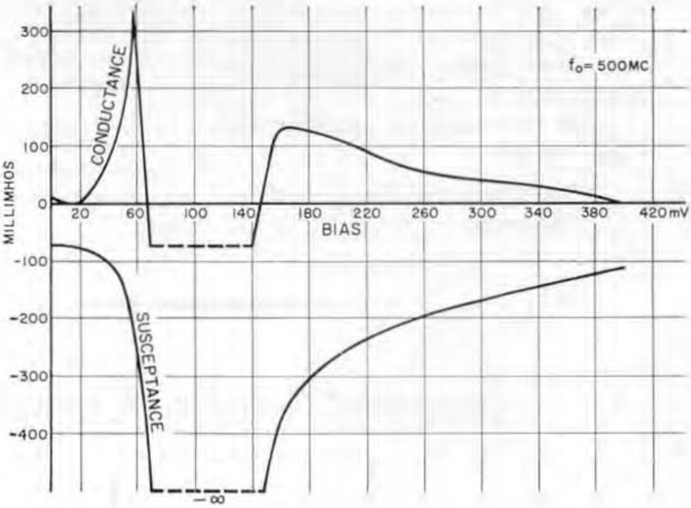

Figure 4. Admittance characteristics as measured at 500 Mc.

It should be pointed out that, under some circumstances, there are advantages in measurement at lower frequencies, and it is possible to operate the bridge at frequencies below the manufacturer's prescribed limit provided care is taken in connection with such difficulties as these:

a) self-resonance of the bias-circuit filters can occur, so that measurements must be confined to frequencies on either side of this resonance.

b) the three coupling circuits from the generator to the bridge elements become progressively less efficient as frequencies are lowered, but this problem can be overcome by the use of a detector having sufficiently high sensitivity.

c) the half-wavelength line connected in the "unknown" arm of the bridge can become very long and it may be necessary to use high-grade air line to keep losses to a minimum.

The modified microwave-diode-package form of the Raytheon tunnel diode, giving the advantage of very low series inductance, is well suited for connection to the Immittance Bridge. Diodes encapsulated in different packages, e.g. standard JETEC cases or designs intended for strip-line applications, can also be measured provided suitable jigs and fixtures are designed.

WESCON 1960

GENERAL RADIO COMPANY

BOOTHS 957-958

Measurements on semiconductors will be a feature of the General Radio exhibit at Wescon 1960. Operating exhibits will demonstrate the measurement of tunnel-diode parameters with the TYPE 1607-A Transfer-Function and Immittance Bridge and the rapid measurement of small capacitances in transistors and diodes with the TYPE 1605-A Impedance Comparator.

Other instruments in operating displays include:

- TYPE 1300-A Beat-Frequency Video Generator
- TYPE 1390-B Random-Noise Generator
- TYPE 1554-A Sound and Vibration Analyzer
- TYPE 1521-A Graphic Level Recorder
- TYPE 1570-A Automatic Voltage Regulator
- TYPE 1650-A Impedance Bridge

Variac® Autotransformers with *Duratrak* contact surface will also be displayed.

General Radio Company

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