LB-1005

A VARIABLE-CAPACITANCE GERMANIUM JUNCTION DIODE FOR UHF

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Approved

Stuart Wm Seeley

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A semiconductor junction when biased in the reverse (non-conducting) direction is a capacitance which can be varied by the bias voltage. Such a voltage-variable capacitance has many potential uses. In particular automatic frequency control (AFC) at ultra-high frequencies (UHF) is attractive provided the electrical losses are sufficiently small. In this bulletin the design, construction, and measurement of a junction diode useful throughout the UHF range are considered. The diode consists of a 0.020 inch dot of indium alloyed on to a 0.002 inch thick wafer of 0.1 ohm-cm n-type germanium and mounted with low-inductance connections. It has greater control sensitivity and better electrical characteristics than an electron reactance tube and, in addition, the operating power required by the diode is trivial in comparison with that of an electron tube. Typically, the performance at 6-volt bias is as follows: a capacitance of 38 $\mu\mu$f; a capacitance change of 3 $\mu\mu$f/volt; lead inductance of 2.6 millimicrohenries; effective series resistance of 0.5 ohm. Such a variable capacitor has a very high Q at the lower radio frequencies, decreasing to Q = 17 at 500 Mc. Only about 1 microwatt of d-c control power is needed. A Q of 36 at 500 Mc was obtained in one of the better units having a series resistance of 0.23 ohm.

General Discussion

A junction of two dissimilar semiconductors constitutes, generally, a junction diode with a variety of electrical properties. If the diode is biased in the reverse (non-conduction) direction, the mobile charge carriers are moved away from the junction, leaving uncompensated fixed charges in a region near the junction. The width, and hence the electrical charge of this region (space-charge layer), depends on the applied voltage giving rise to a junction transition capacitance whose small-signal value is shown as C_s in Fig. 1. The variation of a bias voltage is accompanied by a change in current and gives rise to a small-signal conductance, g, across C_s as seen in Fig. 1. At frequencies below a few hundred kilocycles, the parallel combination of C_s and g are sufficient to define the small-signal characteristics of the diode. At higher frequencies the inductance of the leads, L_o, and the series resistance of the semiconductors, r_s, become significant. The stray lead capacitance may also be significant, but in the units to be described is small enough to be neglected. Thus, the complete small-signal equivalent circuit of the reverse biased diode applicable from very low to ultra high frequencies is as shown in Fig. 1.

The factors which must be determined in the design of a diode for ultra-high frequencies are the semiconductor material, its conductivity, the junction area, the height of the semiconductor cylinder between the junction plane and the base plane of the wafer, W, (see Fig. 2) and the lead length. The semiconductor material, is chosen to give the highest Q at high frequencies, and of presently available semiconductors, n-type germanium is well suited. The germanium conductivity should be high to decrease electrical losses but an upper limit is determined by the maximum reverse bias. The desired capacitance for a particular bias voltage determines the area of the junction. The series resistance is determined by the junction area and the dimension W of Fig. 2. W should be as small as possible to decrease electrical losses, but a practical minimum value is imposed by the percentage of "short through" rejects during construction of the diodes. The diode leads should have a large diameter and short length to keep the lead inductance to a minimum.

This bulletin first considers the equations which govern the selection of design factors and which illuminate diode performance. Following this, the construction of a practical diode is described, and its measured performance is given.

Design Relations

The semiconductor junctions to be considered in this bulletin are made by alloying indium (p-impurity) on n-germanium.[1] This process gives an abrupt transition between the p-type indium-enriched germanium and the n-type germanium so that the resulting junction operates in accordance with a theory developed by Schottky.[2] Similar junctions can be made by alloying n-impurities on p-germanium, or by using a different semiconductor.

1. *Transition Capacitance*

The junction diode transition capacitance can be formulated as for a conventional parallel-plane capacitor. Thus:

$$C_s = \frac{K \epsilon_o}{W_j} A \text{ farads,} \qquad (1)$$

[1]LB-868 *Germanium P-N-P Junction Transistors.*

[2]For a summary of Schottky's work and complete references, see J. Joffe, "Schottky's Theories of Dry Solid Rectifiers, "*Electrical Communication*, Vol. 22, No. 3, pp. 217-225, 1945. For details of analysis, see W. Shockley, "The Theory of P-N Junctions in Semiconductors and P-N Junction Transistors," *Bell Syst. Tech. Jour.*, Vol. 28, pp. 435-489, July 1949.

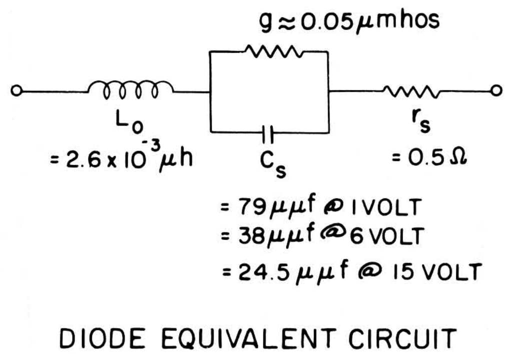

Fig. 1. Diode Equivalent Circuit.

where

K = relative permittivity = 16 for germanium

ϵ_o = permittivity of free space $\frac{1}{36\pi} \times 10^{-9}$ farads/meter;

A = junction area in meter^2; and

W_j = effective width of junction in meters.

The effective junction width is voltage dependent and for our case, in which the conductivity of the p-type indium enriched germanium is much greater than that of the n-type germanium, is

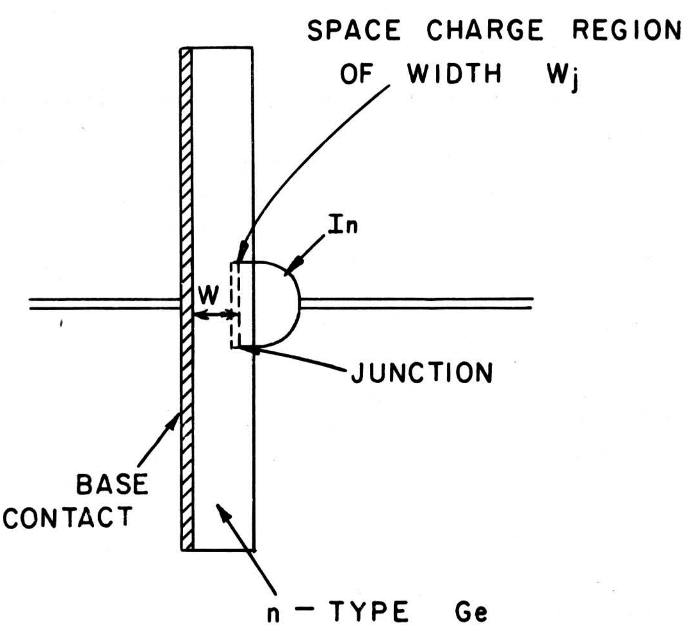

Fig. 2. Diode Geometry.

$$W_j = \sqrt{-(V_o + V)\frac{2K\varepsilon_o\mu_n}{\sigma_n}} \text{ meters,} \qquad (2)$$

where[3]

μ_n = mobility of electrons in n-germanium in $\frac{\text{meter}^2}{\text{volt sec.}}$

= $0.39 \frac{\text{meter}^2}{\text{volt sec.}}$ for intrinsic germanium

= $0.30 \frac{\text{meter}^2}{\text{volt sec.}}$ for $\sigma_n = 1000$ mhos/meter germanium used for the present diodes.

V_o = contact voltage in volts;

V = applied bias voltage in volts measured with n-germanium as reference (negative for reverse bias);

σ_n = conductivity of n-germanium in mhos/meter

= 1000 mhos/meter for the germanium used for the present diode.

Eq. (2) predicts that C_s should have a negligible variation with temperature since mobility and conductivity are proportional in doped germanium.

The fractional change in C_s as a function of V can be formulated from Eqs. (1) and (2) as

$$\frac{\Delta C_s}{C_s} = \frac{\Delta V}{2(-V_o - V)} \cdot \qquad (3)$$

The fractional change in C_s is one half the fractional change of applied voltage and is independent of diode dimensions and material properties, except that at small bias voltages the material properties may be significant in determining the contact voltage, V_o.

2. *Contact Voltage*

The voltage, V_o, of Equation (2) is an internal contact potential developed between the n and p type semiconductors. This voltage will be a few tenths of a volt negative and therefore negligible except at very small applied voltages. The contact voltage can be considered as composed of two parts: a contact voltage of the p-type germanium on intrinsic germanium; and a contact voltage of intrinsic germanium on n-type germanium. Since the p-type germanium conductivity approaches that of a metal, the first part of the contact voltage is very nearly half of the germanium voltage gap, namely, -0.36 volt. The second half of the contact voltage can be formulated analytically with the aid of usual junction equations in terms of the properties of the intrinsic and n-type germanium. The net result is a value between zero and -0.36 volt. For the diode herein described, the calculation gives a total contact voltage of -0.5 volt, which is in agreement with measurements (see appendix).

3. *Series Resistance*

The diode series resistance, r_s, is due to the wafer of germanium. When the junction diameter is much larger than W, the distance to the base contact (Fig. 2), the series resistance can be rather accurately formulated on the basis of a semiconductor cylinder of area, A, and height, W, provided that the diode is biased in the reverse direction. Thus:

$$r_s = \frac{W - W_j}{\sigma_n A} \text{ ohms.} \qquad (4)$$

W_j (Eq. 2) will generally be negligible in comparison with W. The temperature dependency of r_s will be that of σ_n and will be generally small for large σ_n as employed in diodes described herein.

4. *Lead Inductance*

The diode lead inductance is an important factor which cannot be neglected at ultra high frequencies. The lead inductance can be computed reasonably accurately from the formula[4] for a straight length of wire:

$$L_o = 5.08\, l \ln\left(\frac{4l}{d}\right) \text{ millimicrohenries,} \qquad (5)$$

where l is the length of the wire and d is the wire diameter in the same units. Diodes constructed as described in this bulletin require interpretation in determining appropriate values of l and d, since the wire cross section is not uniform. The bulk of the inductance will generally be due to the small wire contacting the diode dot.

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[3] M.B. Prince, "Drift Mobilities in Semiconductors I. Ge," *Phys. Rev.*, Vol. 93, pp. 681-687, November 1, 1953.

[4] Frederick E. Terman, *"Radio Engineer's Handbook,"* McGraw-Hill Book Co., p. 48, 1943.

5. *Maximum Junction Voltage*

The maximum reverse bias (breakdown voltage) which may be applied to a junction is determined by an avalanche breakdown phenomenon which causes a precipitous increase in the junction current. The breakdown voltage, V_B, is a function of the impurity density, N_D (number/meter^3), of the semiconductor material. According to measurements[5] on n-type germanium

$$V_B = -15 \times 10^{16} (N_D)^{-0.7} = -2460 (\sigma_n)^{-0.7} \text{ volts} \quad , \qquad (6)$$

where σ_n is in mhos/meter.

6. *Q Figure of Merit*

It is common practice to use Q (dissipation factor) as a figure of merit for capacitors. The diode Q taking into account both series resistance and shunt conductance is

$$Q_d = \frac{\omega C_s}{g + r_s (g^2 + \omega^2 C^2{}_s)} \quad , \qquad (7)$$

If the diode parameters are independent of frequency (this is a good assumption particularly in the case of r_s and C_s), Q_d has a maximum when

$$\omega = \frac{1}{C_s} \sqrt{\frac{g}{r_s} (1 + r_s g)} \quad , \qquad (8)$$

The maximum Q_d is

$$Q_d \text{ (max.)} = \frac{1}{2} \sqrt{r_s g (1 + r_s g)} \quad , \qquad (9)$$

At high frequencies, where the shunt conductance can be neglected, Q_d can be determined from Equation (1), (2), and (4). The result is

$$Q_d = \frac{1}{\omega C_s r_s} = \frac{1}{\omega (W - W_j)} \sqrt{-(V_o + V) \frac{2\mu_n \sigma_n}{K \varepsilon_o}} \qquad (10)$$

From this equation it can be concluded that:

(a) Q_d is independent of junction area and varies inversely with frequency.

(b) For a large Q_d: σ_n should be made as large as possible--the upper limit being determined by the junction breakdown voltage, Eq. (6) or by the fact that μ_n decreases as σ_n is made larger. For n-type germanium, the maximum Q_d occurs when σ_n is approximately 10,000 mhos/meter, and for this conductivity, $V_B \approx -3$ volts; W should be as small as construction techniques permit; and a large operating bias should be employed.

(c) Q_d can be increased by selecting a semiconductor material with the largest value of μ/K. Of the two commonly used semiconductor materials (germanium and silicon), n-type germanium has the largest value of μ/K. For this reason the presentation herein has centered around n-type germanium and this material is used in the diode described below.

A loss-free capacitor in series with the diode can be used as an impedance transforming means to increase the effective Q. This series combination decreases the net losses at the expense of the amount of variable capacitance. Placing a capacitor in series with the diode has other advantages such as blocking the d-c bias voltage, limiting a-c voltage across the diode, and eliminating lead inductive reactance at one frequency.

At low frequencies and when the diode is biased in the reverse direction, Q_d is determined by Eqs. (1) and (2) and the diode conductance, g, which is determined in practice by a leakage conductance. Thus:

$$Q_d = \frac{\omega C_s}{g} = \frac{\omega A}{g} \sqrt{\frac{K \varepsilon_o \sigma_n}{-2\mu_n (V_o + V)}} . \qquad (11)$$

7. *Saturation Current*

The saturation current is determined by the geometry and surface and volume recombination of hole-electron pairs. An exact calculation is difficult but with germanium of good quality the contribution from volume recombination is small and may be neglected. Further, the contribution from the base contact surface will outweigh the contributions of the free surfaces because of its higher surface recombination velocity, s, and, also, in a structure designed for UHF, because of its proximity to the junction. The saturation current may be found by formulating an equation for the terminal current, $I = -I_s$, which flows when the diode is biased in the reverse direction.

[5] S.L. Miller, "Avalance Breakdown in Germanium," *Phys. Rev.*, Vol. 99, pp. 1234-1241, August 15, 1955.

Under these conditions the hole density at the junction will be zero and will increase approximately linearly to a value p_n at the base contact. Analytically this requires $\frac{sW}{D_p} >> 1$ where D_p is the diffusion constant of holes in n-type germanium (D_p = 44×10^{-4} meters^2/sec for intrinsic germanium). It is believed that the s of the metallic base contact is large enough to satisfy the inequality if W is greater than 25 microns (0.001 inch). The actual value of s under these conditions does not enter into the calculation. The saturation current is thus determined by the hole density gradient p_n/W and is

$$I_s = q\ A\ D_p \frac{p_n}{W} = \frac{q^2\ n_i^2\ \mu_n\ A\ D_p}{\sigma_n W} \quad \text{amperes} \qquad (12)$$

where n_i is the carrier density in intrinsic material (n_i = 2.4×10^{18} carriers/meter^3 for germanium at room temperature).

The magnitude of I_s together with the bias voltage, V, will determine the amount of bias power required to operate the diode in the reverse direction. I_s will increase rapidly with temperature[6] (approximately 10 per cent per degree Centigrade near room temperature) due primarily to the increase in n_i^2.

Construction

The diode for which measurements will be given has a parallel plane geometry with axial leads, and is designed to give good performance through ultra high frequencies. In accordance with the design relations, n-type germanium is used since this semiconductor gives better performance than p-type germanium or p- or n-type silicon. A minimum germanium resistivity of 0.1 ohm-cm was selected to permit operation over a useful range of bias voltages. This resistivity material will permit a bias voltage as large as 16 volts. A junction diameter of 20 mils (area of 20×10^{-6} cm^2) was selected to achieve the desired range of diode capacitance. Lead inductance is kept small by using short, large diameter lead wires.

[6] P.G. Herkart and J. Kurshan, "Theoretical Resistivity and Hall Coefficient of Impure Germanium Near Room Temperature," RCA Review, Vol. 14, pp. 427-440, September 1953.

The completed diode is shown in the photograph of Fig. 3. For comparison purposes, a standard 1N82(K3E) UHF mixer diode is also shown.

1. *Parts Preparation*

The disassembled view of the diode showing the various component parts is shown in Fig. 4. The base stud is made of Kovar or Therlo (Driver-Harris Company, Harrison, N.J.) to match the germanium thermal expansion and is designed so that the diode can be screwed directly to a chassis. A 0.002 inch depression on the top of this stud aids in positioning the base wafer. The depression is covered with about 0.001 inch of high purity tin-lead-antimony solder. The wafers are chemically etched to 0.002 inch thickness. The dots are punched cylinders of indium 0.015 inch by 0.015 inch diameter. The nickel wire has one end balled and coated with indium and the wire is lightly tinned with a low-melting solder. The top stud has a 0.041 inch diameter hole through the center, and the inside of this hole is tinned with the same low-melting solder. The top stud is screwed to the ceramic body and bonded in place with Araldite (Ciba Inc., New York, N.Y.) to form a subassembly. The indium dot, germanium

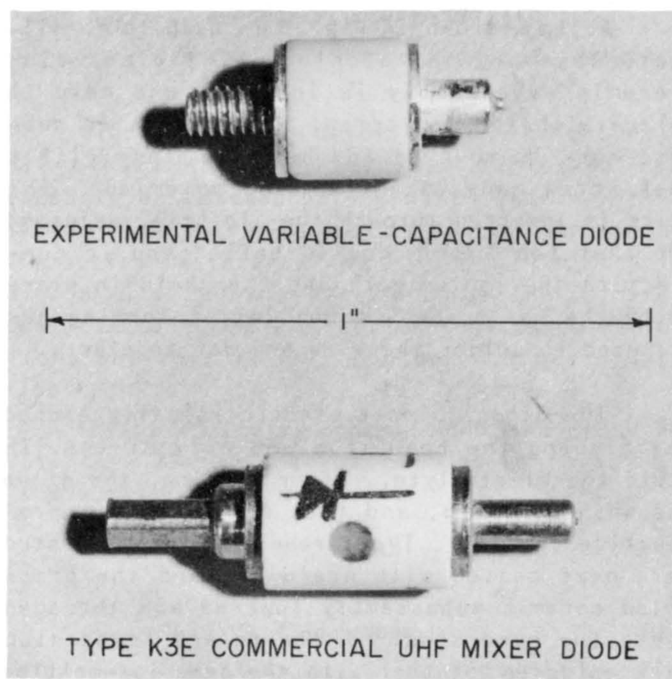

Fig. 3. Photograph of Variable Capacitance Diode and Type K3E Commercial UHF Mixer Diode.

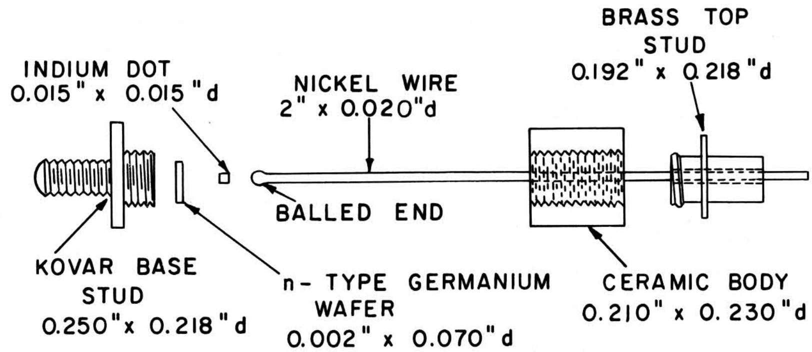

Fig. 4. Disassembled Drawing of Diode.

wafer, and base stud are also processed as a subassembly. This subassembly is made by mounting the base stud, germanium wafer, and indium dot together with the aid of carbon jigs.[1] The assembled unit is fired for five minutes at 550°C. in an atmosphere of dry hydrogen to both solder the germanium wafer to the stud and to alloy the dot into the germanium.

2. *Assembly*

A jig as shown in Fig. 5 is used to facilitate assembly and etching. The brass stud ceramic subassembly is inserted and held in place with the set screw. The base stud subassembly is mounted and held in place with a set screw made of insulating material. The wire is inserted through the jig hole, adjusted so that the indium coated balled end is contacting the indium dot, and then held in place with the set screw. A hot jet of forming gas is used to solder the wire and dot together.

The diode is next electrolytically etched by dipping the base stud end only of the jig into the electrolyte. After etching, the diode is washed, dried, and then coated with a protective coating. The threads of the base stud are next coated with Araldite, and the brass stud ceramic subassembly lowered and threaded onto the base stud. The wire and brass stud are soldered together with the same low-melting solder used to tin these parts. At this point, the diode is a completed unit and may be removed from the jig.

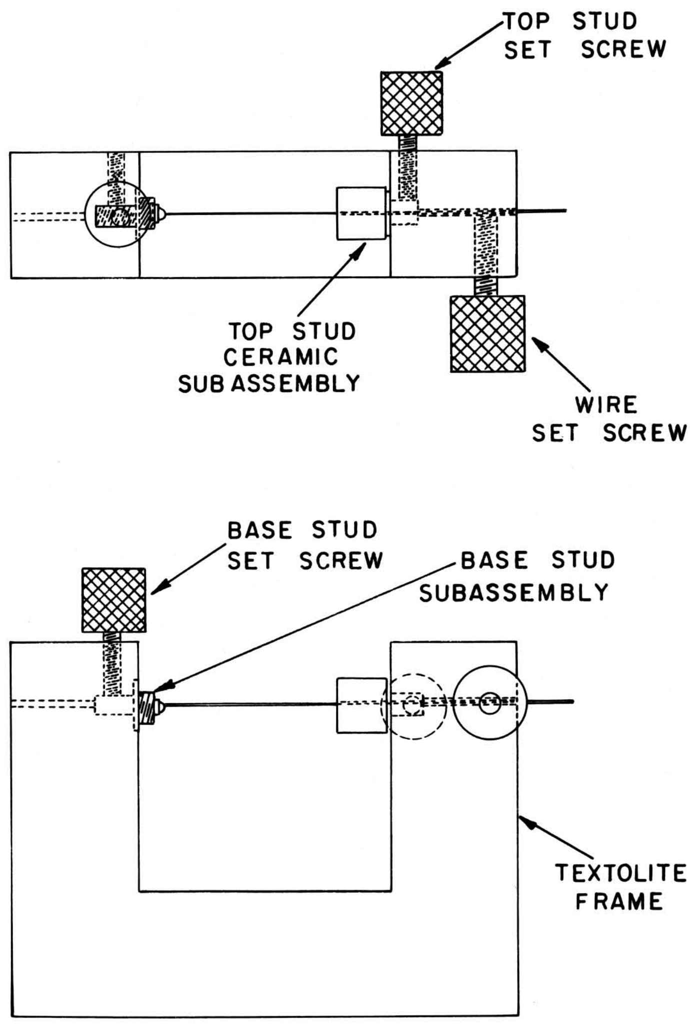

Fig. 5. Diode Fabrication Jig.

Measured Results on a Typical Unit

As a variable reactance device, the data of greatest interest are the capacitance vs reverse bias voltage (measured at low frequencies), the total reactance with variation of bias voltage and frequency, and the loss. Fig. 6 shows measured data at 1 and 2 Mc where lead inductance and loss resistance are negligible. The solid curve was computed from the design formulas and agrees with the data. At the nominal bias of -6 volts, the capacitance is 38 $\mu\mu$f, and the slope is about 3 $\mu\mu$f/volt. Over the useful range, up to -15 volts, the capacitance varies inversely with the square root of the bias voltage from about 160 $\mu\mu$f to 25 $\mu\mu$f.

The terminal reactance as a function of frequency, with the bias as a parameter, is plotted in Fig. 7. The measured points agree with the solid curves which were calculated from the theoretical junction capacitance (see Eqs. 1 and 2) and a lead inductance of 2.6 millimicrohenries. It is seen that the diode is useful as a controllable reactance well into the UHF range.

The loss resistance was measured in equipment specially designed for the purpose and was found to be approximately constant with frequency and bias vairations. Typical measured results correspond to a series resistance of about 0.5 ohm, and the Q at 500 Mc, with -6 volts bias, is about 17. Since all the data confirm the type of equivalent circuit shown in Fig. 1, it is possible to compute the diode behavior over a wide range of frequencies and operating conditions.

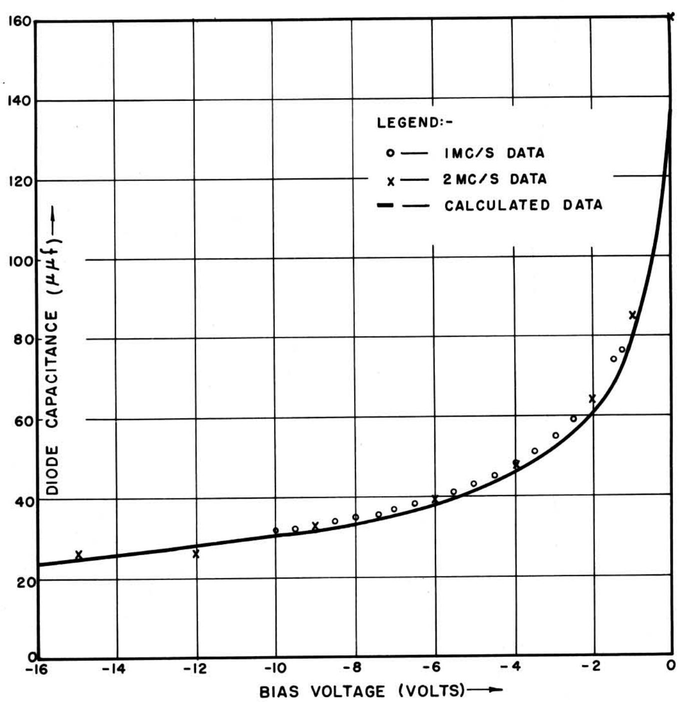

Fig. 6. Diode Capacitance Versus Bias Voltage.

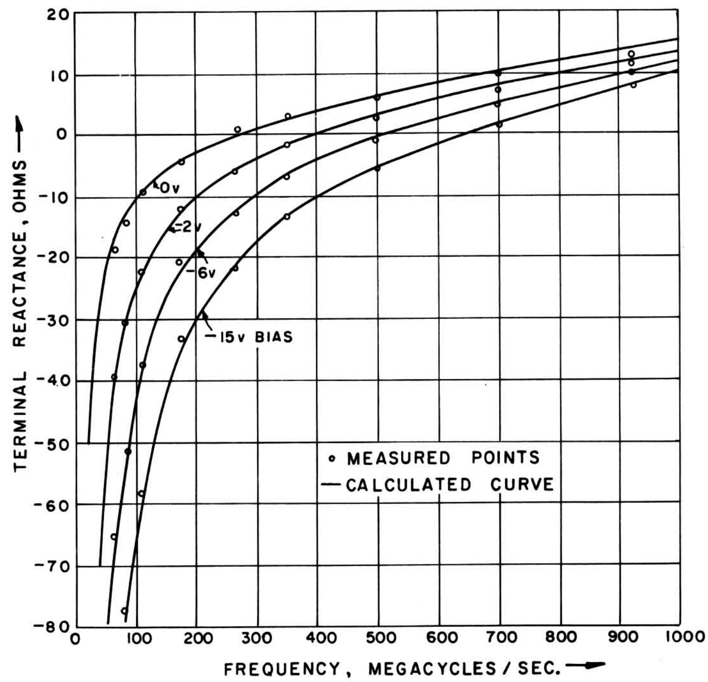

Fig. 7 - Terminal Reactance Versus Frequency.

Since the units described in the bulletin are experimental units, some variation was encountered between units, particularly in the series resistance. In one of the better units, the series resistance was 0.23 ohm resulting in a Q of 36 at 500 Mc. Variations in the soldered contacts contribute to series resistance variations but this is not considered a basic difficulty.

In the Appendix, comparison of the measured results with the theoretical design relations is discussed in more detail.

Conclusions

A junction diode has been described which has attractive operating characteristics over a wide range of frequencies including ultra high frequencies. Diodes of the type described can be used for automatic frequency control, frequency selection, mixing, voltage-controlled tuning, frequency modulation, and as dielectric amplifiers. It is found that the diodes follow theory very closely so that the design relations can be used for designing diodes for various applications.

John O'Connell

L. J. Giacoletto

Appendix

COMPARISON OF MEASUREMENTS WITH DIODE THEORY

It is of interest to compare the junction theory with measured data. The agreement in general is exceptionally good.

Consider first the forward volt-ampere characteristics of the diode. The current flow in an ideal diode is given by

$$I = I_S (e^{\Lambda V} - 1), \qquad (13)$$

where Λ is q/kT (equal to 38.8 volts^{-1} at 25° C.). In many conventional diodes, the series ohmic resistance is not negligible and the theoretical exponential diode equation is not found. Fig. 8 shows the measured forward characteristics of one of the present diodes. This figure indicates that the characteristics follow rather exactly the ideal diode Eq. (13) with the slope indicating an exponential factor Λ = 37.3, rather than the theoretical value of 38.8 at I = 25° C. In accordance with Eq. (13) the zero voltage intercept of the straight line on Fig. 8 is the saturation current, I_S = 0.15 μa.

Another method of determining I_S is to evaluate[7] the diode conductance, $g_o = \Lambda I_S$, at zero bias voltage and current. From the measured g_o = 7.2 μ mhos, I_S = 0.186 μa is computed using Λ = 38.8 for room temperature, T = 25° C. A third method of determining I_S is to measure the diode current for a reverse bias. By this means I_S = 0.17 μa was measured at V = -1 volt. The last two methods of measuring I_S include current flow due to any leakage across the junction; this current is not included in the first method of evaluating I_S. Therefore the difference between these values of I_S can be used as a rough estimate of the leakage conductance, which is about 1 μ mho by this method. The value is in reasonable agreement with direct measurement of diode conductance with reverse bias which ranges from 1 to 0.03 μ mho for bias voltages ranging from -1 to -6 volts.

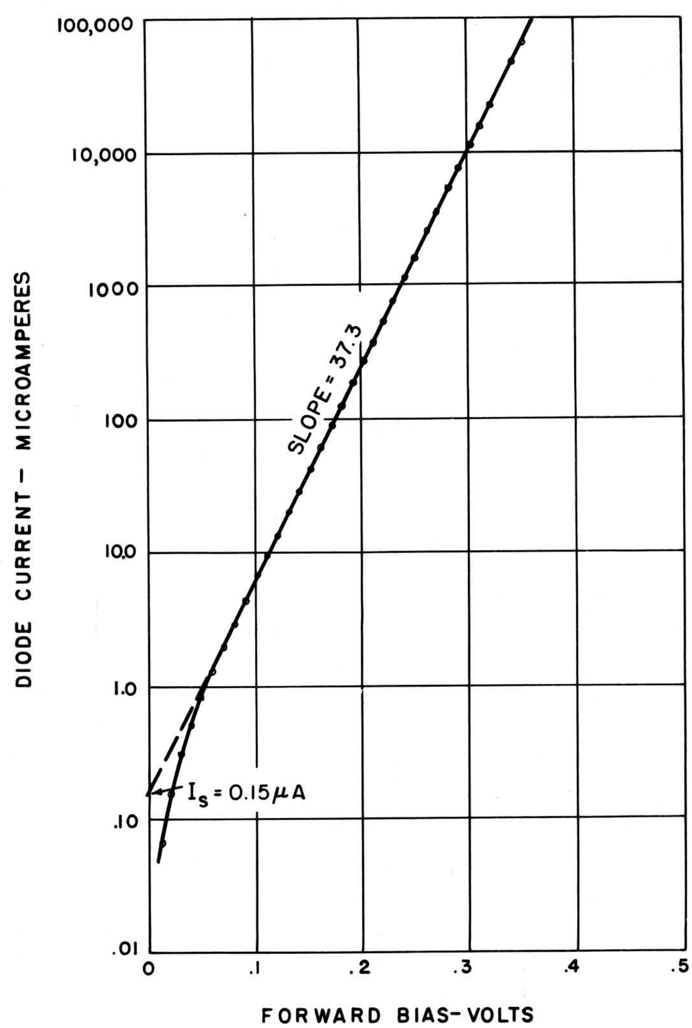

Fig. 8. Diode Current Versus Forward Bias Voltage.

When the diode bias is smaller than a few tenths of a volt in the reverse direction or when the diode is biased in the forward direction, a diode diffusion capacitance, C_d, must be added to the transition capacitance (Equations 1 and 2) to obtain the total junction capacitance. The diode diffusion capacitance when W is small compared with the diffusion length of minority carriers is

$$C_d = \Lambda (I + I_S) \frac{W^2}{2D_p} \text{ farads}, \qquad (14)$$

This diffusion capacitance relation is useful to determine the value W, i.e., the thickness

[7] *LB-900, Equipments for Measurement of Junction Transistor Small-Signal Parameters for a Wide Range of Frequencies.*

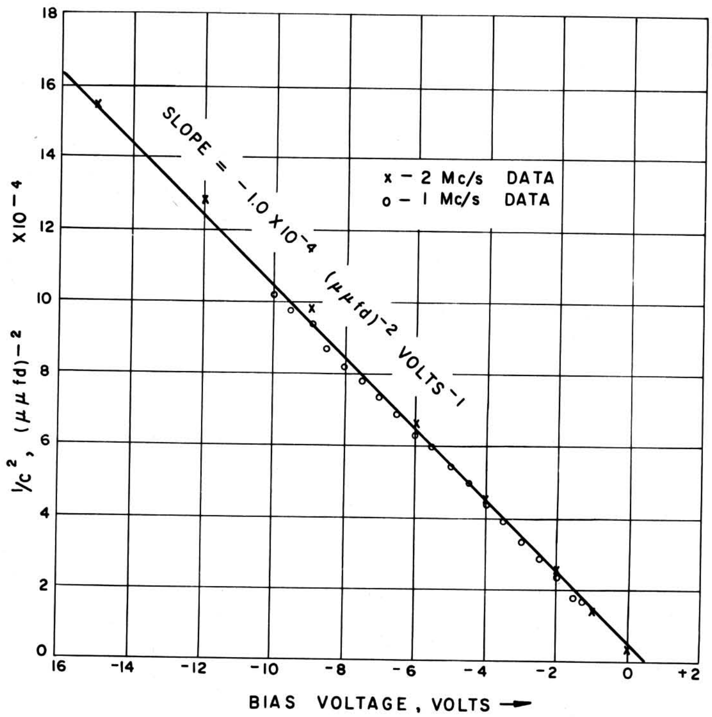

Fig. 9. $1/C^2$ Versus Bias Voltage.

of the semiconductor between junction and soldered connection. For example, on the present diode, C_d = 2120 μμf. at I = 285 μa was measured, and W = 4.1 x 10^{-5} meters is obtained. This value of W agrees reasonably well with 4.6 x 15^{-5} meters calculated from a resistance measurement (see below).

A plot of diode transition capacitance with bias voltage is shown in Fig. 9. The data of the figure are the same as for Fig. 6 but have been replotted to indicate that the transition capacitance obeys exactly the formulation of Eqs. (1) and (2). The intercept on the voltage axis gives the contact voltage, V_o = −0.5 volt, which is the expected value. The slope of the line in Fig. 8 should, according to theory, be

$$\frac{2\mu_n}{A^2 K \epsilon_o \sigma_n} = -1.06 \times 10^{-4} \ (\mu\mu f)^{-2} V^{-1}.$$

This can be compared with a measured slope of −1.0 x 10^{-4} $(\mu\mu f)^{-2}V^{-1}$.

The frequencies used for the data of Fig. 9 were low enough that lead inductive reactance is negligible. At higher frequencies the lead inductive reactance cannot be neglected. A plot of the type shown in Fig. 10 can be used in determining the lead inductance. Here, the intercept at zero net bias voltage corresponding essentially with zero diode impedance gives the lead inductive reactance. Due to small measurement errors the intercepts do not all give the same lead inductance. An average of the several inductance values indicates L_o = 2.6 millimicrohenries. According to theory this inductance for a wire diameter of 0.020-inch would correspond with a wire length of 0.15-inch. This wire length corresponds closely with the best estimate for the geometry employed. Also, the straight line plots of Fig. 8 indicate that stray capacitance is negligible for the range of operation considered here.

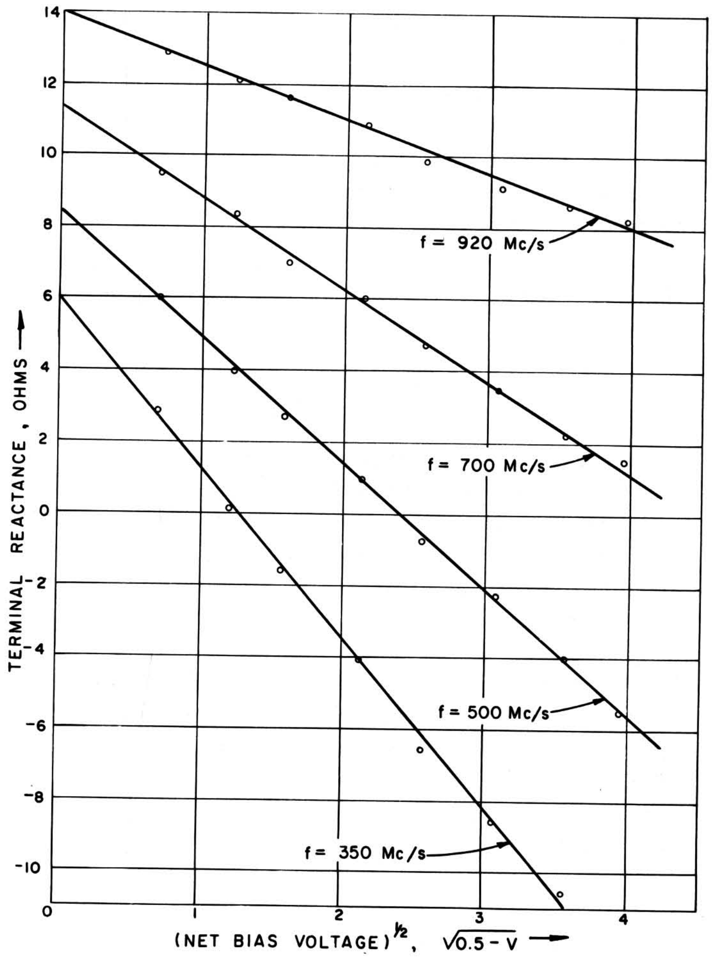

Fig. 10 - Terminal Reactance Versus (Net Bias Voltage)$^{\frac{1}{2}}$.

Using the measured value of the series resistance for this particular unit, i.e., r_s = 0.23 ohm, Eq. (4) indicates that W = 4.6x10^{-5} meters. As pointed out earlier, this value of r_s indicates that this diode is one of the better units. This was chosen because the low series resistance indicates a minimum of contact resistances. From the original wafer thickness of 5.1x10^{-5} meters, a penetration during alloying of 0.5×10^{-5} meters (0.2 mil) is obtained.

Calculations of diode Q (Eq. 7) using r_s = 0.23 ohm, C_s = 38 $\mu\mu$f. and g = 0.03×10^{-6} mho corresponding to -6 volts bias indicate values of Q_d = 175, 36, and 18 at 100, 500, and 1000 Mc . Eqs. (8) and (9) indicate a maximum Q of 6,015 at f = 1.5 Mc.