Microwave Diode Cartridge Impedance*

R. V. GARVER† AND J. A. ROSADO†

Summary—In any application of a semiconductor microwave diode, the impedance of the diode cartridge plays a very important role. Two commonly made assumptions, which are quite erroneous, are that 1) the impedance of the diode cartridge consists simply of a shunt capacitance and whisker inductance, and 2) the metal-to-semiconductor junction at microwave frequencies behaves approximately as it does at 10 mc. In this paper it is shown that the impedance of the diode cartridge at microwave frequencies can be measured accurately by substituting a carbon die for the semiconductor.

Introduction

NEW uses of junction diodes at microwave frequencies as switches,[1] attenuators, phases modulators, frequency translators,[2] and amplifying elements,[3] make it more important than ever to understand the semiconductor junction at these microwave frequencies. To measure junction impedance at microwave frequencies, the junction must be in a cartridge and the cartridge impedance must be known. Early work of this type was done by M. C. Waltz.[4] In the present work some of the error found in the original technique has been reduced and a reactive anomaly[5] has been investigated.

Measurement Technique

Historically, two techniques have been utilized for measuring diode cartridge impedance at microwave frequencies. M. C. Waltz[4] replaced the semiconductor die in the diode by a carbon die and then placed the diode in a rectangular waveguide mixer mount. Observation of the microwave reflections with changing contacts on the carbon revealed the cartridge impedance. Penin and Skvortsova[6] fabricated diodes at the end of a 50-ohm coaxial line and used an open, short, and forward-biased diode to determine the cartridge impedance. Both groups of experimentalists also placed transformers before their diodes as an alternate technique which allowed them to measure diode junction impedances directly.

One point should be borne in mind here. Impedance measurements made in a waveguide are made with respect to the characteristic impedance of the waveguide. Measured impedances that differ from the waveguide impedance by a factor of ten or more are increasingly obscured by the waveguide impedance. Thus a rectangular waveguide is most useful for measuring impedances on the order of 500 ohms, while a coaxial waveguide is most suitable for measurements of impedances on the order of 50 ohms. For the most accurate impedance measurement, one would ideally vary the waveguide impedance to match that being measured. The greater bulk of point-contact diode impedances at microwave frequencies are in the 500-ohm region; thus it is most desirable to use a rectangular waveguide to make point-contact diode measurements.

Equivalent Circuits

The diode cartridge can be visualized as a linear, passive, lossless four-terminal network with two accessible terminals, the outside ends, and two inaccessible terminals, the terminals of the rectifying contact. The frequency-independent equivalent circuit for the cartridge may be impossibly complex, but for a given frequency it can be represented by three reactive elements in a π or T arrangement, or by any three independent lossless impedance transformations. For example, the equivalent circuit used by M. C. Waltz[4] consisted of 1) a length of transmission line, 2) a parallel susceptance, and 3) a transformer-turns ratio.

In order to evaluate the three elements of the equivalent circuit, it is necessary to substitute three known impedances for the rectifying contact. It should be noted that for all diodes that are supposed to have the same cartridge impedance, precautions must be taken to maintain the following constant: diode whisker length, straight and bent; whisker diameter; bend configuration; whisker tilt and centering of contact; and whisker orientation with respect to the waveguide. Of the three known impedances to be substituted for the rectifying contact one is an open, one a short, and the other, some form of resistor. The open consists of a diode of the type to be measured with the contact separated only enough to impede direct current. It is important that the image capacitance of the whisker to semiconductor be included in the equivalent circuit of the cartridge. This is insured by separating them only enough to prevent the flow of direct current.

The short is obtained by substituting solder for the

* Manuscript received by the PGMTT, June 3, 1959. Revised manuscript received September 11, 1959.

† Diamond Ordnance Fuze Labs., Washington, D. C.

[1] R. V. Garver, E. G. Spencer, and M. A. Harper, "Microwave semiconductor switching techniques," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 378–383; October, 1958.

[2] E. M. Rutz and J. E. Dye, "Frequency translation by phase modulation," 1957 IRE WESCON Convention Record, vol. 1, pt. 1, p. 201.

[3] A. Uhlir, Jr., "The potential of semiconductor diodes in high-frequency communications," Proc. IRE, vol. 46, pp. 1099–1115; June, 1958.

[4] M. C. Waltz, "A Microwave Resistor for Calibration Purposes," Bell Telephone Labs., Third Interim Rept. on Task 8 (Crystal Rectifiers), Signal Corps Contract DA-36-039-sc-5589; April, 1955.

[5] D. Leenov, "Small-Signal Admittance of a Gold Bonded Diode," Bell Telephone Labs., Tenth Interim Rept. on Task 8 (Crystal Rectifiers), Signal Corps Contract DA-36-039-sc-5589; January, 1957.

[6] N. A. Penin and N. E. Skvortsova, "The impedance of the rectifying contact in germanium and silicon detectors at microwave frequencies," *Radiotekh. Elektron.*, vol. 3, pp. 267–275; February, 1958. (Complete translation from International Physical Index, Inc., New York 35, N. Y., Electronics Express No. Ex 1A13.)

semiconductor and by soaking the pedestal in mercury. The mercury insures a low-impedance contact without excessive contact pressure which would distort the whisker and would change its impedance. Penin and Skvortsova[6] used a forward-biased diode junction for the resistor and Waltz[4] used resistive dice fabricated from pencil lead and resistors. The dice are substituted for the semiconductor dice and "resistive" contacts are made upon them. There is no assurance that a forward-biased diode junction is purely resistive, nor is there any assurance that carbon is purely resistive at high frequencies. Since the diode cartridge is being evaluated to study the semiconductor junction, no assumptions will be assigned to the semiconductor junction. Therefore the carbon mixtures are used in evaluating the cartridge impedance. In pencil lead and in resistors the carbon mixtures consist of high-conductivity carbon particles held together by low-conductivity bonding material. This inhomogeneity of conductivity in the material results in a distributed capacitance, the effect of which is observed for small area contacts. For contact areas sufficiently large the distributed capacitance effect is negligible. It is noted that the radius of contact is less than the skin depth of the carbon even for the lowest resistance-calibrating resistors used.

Techniques for canceling out the elements of the equivalent circuit allow the contact impedance to be measured more directly. 1) Placing a tuner before the diode or changing the position of the short after the diode, so that the difference in minima for the open and shorted contacts is $\lambda_g/4$ (where λ_g is the waveguide wavelength), 2) making all measurements with reference to the shorted contact minimum, and 3) taking the impedance of the configuration (which is computed from the known resistor) to include the transformer-turns ratio and the waveguide impedance, all allow the impedance of the diode contact to be directly observed from the Smith Chart. The above technique would appear to be the most elegant for making measurements, but for some contact impedances the diode is partially reflecting and cavity effects take place between the diode, short, and any tuning elements present. For example, with an open contact, as much as 90 per cent of the incident power can be absorbed by wall losses and the diode ceramic, and 3 per cent of the incident power can be forced out the coaxial choke. This reduces what should be an infinite VSWR to 1.7. This is an extreme example, but it demonstrates the cavity effect. Elimination of this effect requires a calculation which makes this technique as indirect and undesirable as a more passive observational technique.

To assure that cavity effects are not present, measurements are made with a matched load behind the diode. All measurements are made with reference to the exact center of the cartridge. The conductance of the matched load is easily and accurately subtracted from the measured impedances to give the diode impedance. Fig. 1 represents the impedances involved in the above

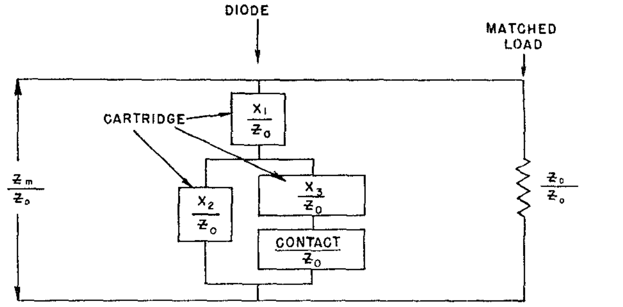

Fig. 1—Equivalent circuit of a microwave diode in a bilaterally matched waveguide section for a given frequency, using the T element arrangement for the diode cartridge impedance.

measurement technique. Z_m/Z_0 is the measured impedance taken with a slotted-line and Smith Chart Plot. X_1/Z_0, X_2/Z_0, and X_3/Z_0 are elements of a T equivalent circuit, for the cartridge. The T network is recommended for theoretical calculations of device behavior. For measurements of diode junctions and for less involved calculations of diode device behavior, simplicity is achieved by means of having the equivalent circuit consist of a length of transmission line, a series reactance, and a factor including the transformer-turns ratio and Z_0.

An Example—X Band

The 1N23 cartridge impedance has been extensively analyzed at 9300 mc. To mount the diode in the waveguide, a standard detector mount is modified by replacing the microwave-shorted end with a waveguide flange. The result is a transmission-type waveguide crystal mount. This crystal mount is connected directly to the SWR machine and a matched load is attached behind the crystal mount. The frequency remains constant and the reference plane of the diode center is constant; thus measurements can be facilitated by marking on the Smith Chart the minima that could be observed on the slotted line as shown in Fig. 2. Further simplification is attained by plotting the data across the center of the Smith Chart as admittance, subtracting $(Y_0/Y_0)=1+j0$, and crossing the center again to be rid of the matched load. By virtue of the matched load, all of the initial data in Fig. 2 falls within the small circle to the left of the chart center. If the resistors were all purely resistive, the data would lie on the dashed arc. Their deviation from the dashed arc was difficult to understand. Without knowledge of the mechanism causing the deviation, considerable uncertainty accompanies any evaluation of the equivalent circuit of the diode cartridge. Assuming the mechanism to be distributed capacitance from inhomogeneous conductivity in the resistive material, the dashed arc is drawn as the true curve from which to determine the equivalent circuit of the cartridge.

Fig. 3 is the initial data after computational removal of the matched load. Rotating the data points $0.233\lambda_g$ counterclockwise on the Smith Chart causes the $R=\infty$ data point to lie on $\infty+j\infty$. Subtraction of $+j$ 1.95

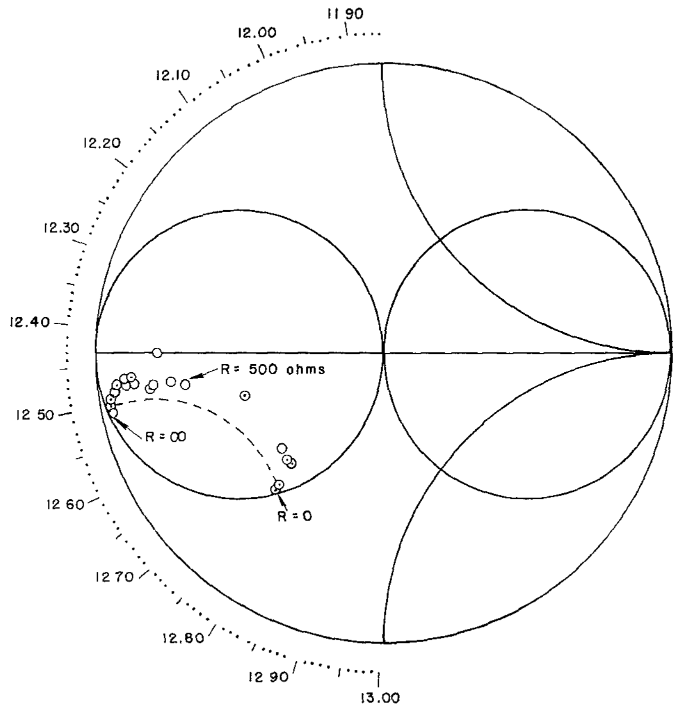

Fig. 2—Smith Chart plot of initial data from "resistive" contacts for evaluation of diode cartridge impedance. The data is measured with reference to the exact center of the diode. The matched load after the diode causes the data to fall within the circle to the left of the center of the chart.

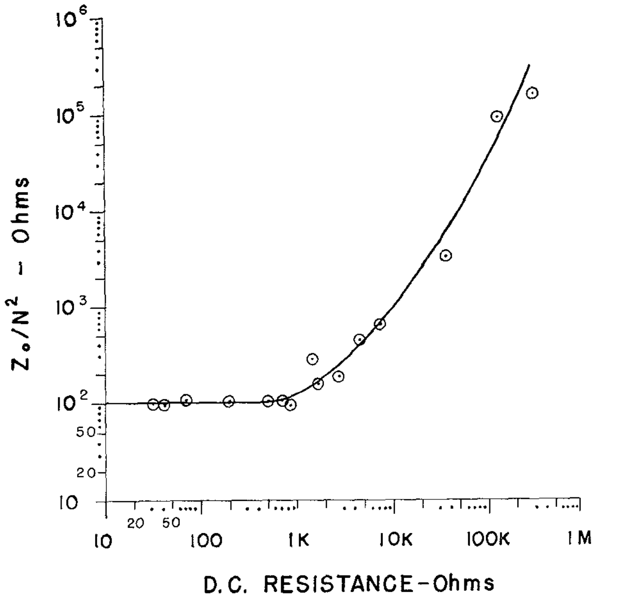

Fig. 4—Using an equivalent circuit for the diode cartridge consisting of a length of transmission line, a series reactance, and a transformer having turns ratio N, the factor Z_0/N^2 is plotted against the dc measured resistance to demonstrate the effect of the distributed capacitance of the carbonateous mixture upon which resistive contacts are made. The plot demonstrates that the effect is negligible for contacts whose dc resistance is less than 1000 ohms.

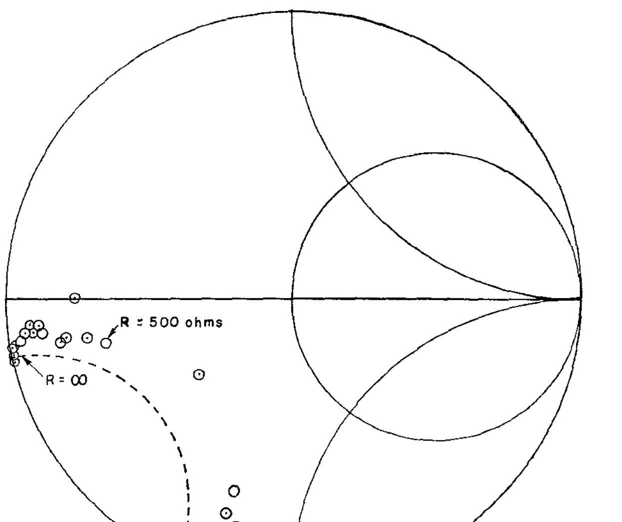

Fig. 3—Smith Chart plot of initial data after computational removal of the effect of the matched load.

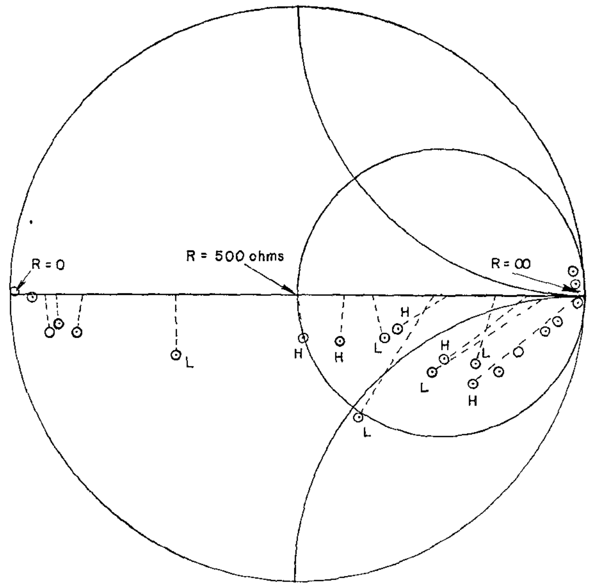

Fig. 5—Smith Chart plot of the "resistive" contact impedance with 500 ohms assumed as chart center. The L and H data points are from resistive contacts made respectively on pencil lead and on 10-ohm resistor material.

from the data points causes the $R=0$ data point to lie on $0+j0$. There remains the evaluation of the transformer-turns ratio factor. Dividing the Smith Chart resistive component of each data point into its dc measured resistance gives the factor Z_0/N^2 by which each data point must be multiplied in order to have it in units of ohms. In Fig. 4 this factor is plotted against the dc measured resistance. For high dc resistance (small area contact) it is seen that the factor is not a constant but increases with resistance. For low dc resistances it is a constant and this is assumed to be its correct value. With 500 ohms as the Smith Chart center and $Z_0/N^2=100$, the data of the resistors is plotted in Fig. 5. Dashed lines are drawn from the data points to the values they would have if they were purely resistive. Two points resulting from the distributed capacitance of the resistive material should be noted. One is that no high-frequency resistance can be greater than the dc resistance. This fact forced the choice of the minimum Z_0/N^2. The other point is that one should be able to combine small area impedances with shunting resistances and capacitances as the area of contact is increased by reasonable approximations to attain a large area impedances. This can be done reasonably well with the data as plotted in Fig. 5. Deviations from conformity to this second requirement may be caused by the whisker point digging pits in the resistive material and touching loose particles or by the whisker point sliding along the surface of resistive material. The resistive material is mounted on a pedestal which is the end of a threaded screw that turns to change the contact pressure. For light-pressure contacts, slight nonecentering of the whisker point could result in the whisker point sliding along the surface of the resistive material. Such jumps in microwave impedance could not be described by additional parallel capacitors and resistors in the contact region.

To determine the impedances shown in Fig. 1, reference is made to Fig. 3. By placing this plot upon another Smith Chart so that the $R=\infty$ data point falls on the $\infty+j\infty$ point of the underlying Smith Chart, a curve of constant resistance can be traced from a high resistive data point R (which demonstrated negligible deviation of Z_0/N^2 in Fig. 4), to intersect the dashed arc. In Fig. 3 the reactance of the $R=\infty$ data point is termed Δ. The reactance of the $R=0$ data point is termed X_0. Then the following formulas apply:

$$\frac{X_1}{Z_0} = \Delta - \frac{X_2}{Z_0},$$

$$\frac{X_2}{Z_0} = \delta\left(1 \pm \sqrt{1 + 2\frac{X_3/Z_0}{\delta}}\right),$$

and

$$\delta = \frac{\Delta - x_0}{2}.$$

X_3/Z_0 is found by trial and error by substituting R for the contact impedance of the equivalent circuit of Fig. 1 and computing the total diode impedance. Two values of X_3 can be found to satisfy the data, but the value which maintains all impedances nearest to unity is selected, since less error will be introduced into the calculations by it. The values found for the data shown are

$$\frac{X_1}{Z_0} = .474, \quad \frac{Z_0}{X_2} = 1.745, \quad \text{and} \quad \frac{X_3}{Z_0} = 1.15.$$

At first glance, it would appear that X_1 corresponds to the crystal holder choke, X_2 corresponds to the diode cartridge capacity, and X_3 corresponds to the whisker inductance. The whisker inductance would then be 10×10^{-9} henries, but physical measurements and lower-frequency measurements indicate its inductance to be 5×10^{-9} henries, ignoring whisker capacitance. X_2, the cartridge capacitance, measures 0.06 $\mu\mu$f here, but at lower frequencies it measures 0.02 $\mu\mu$f. The crystal holder choke is well designed and should exhibit no impedance. Consequently the impedances of the equivalent circuit of Fig. 1 cannot be attributed to individual effects but must be considered as a lumped equivalent circuit for the diode cartridge. The values of the equivalent circuit elements hold only at one frequency and in a full size X-band rectangular waveguide. At other frequencies or in a coaxial or a ridged waveguide or in other cartridges the parameters will have to be reevaluated. The technique presented here should work under any circumstances.

Conclusion

It is concluded that: 1) at a given frequency, the diode cartridge can be represented by three independent lossless impedances or impedance transformations; 2) the best technique for measuring microwave diodes is to place the diode in a rectangular waveguide with a matched load thereafter; 3) the best technique for the evaluation of the cartridge impedance makes use of the substitution of resistive dice for the semiconductor; 4) the reactive anomaly observed with the contacts on the resistive dice is from distributed capacitance of the inhomogeneous resistive material; and 5) this effect is negligible for large area contacts.

Acknowledgment

The authors would like to express their gratitude to J. E. Tompkins and R. D. Hatcher for their continued interest and helpful discussions.