GINZTON "MICROWAVE MEAS."

CHAPTER 2

DETECTION OF MICROWAVE POWER

2.1. Introduction. In all microwave experiments it is necessary to detect the presence of signal power. This chapter will be concerned with methods which are useful to indicate the presence of microwave signals and the measurement of their relative magnitudes. It is essential in some cases to determine the absolute magnitude of the power flowing through the system, but this topic will be reserved for discussion in connection with the more fundamental question of power measurement.

In order to detect microwave signals it is necessary to convert the signal power, directly or indirectly, into some form of mechanical or visible energy. Among the indicating devices which have been tried are the following:

1. Mechanical devices—force operated indicators, such as the gold-leaf electroscope[1,2] or direct measurement of radiation pressure[3]

[1] Gold-leaf electroscopes intended for operation at 10 and 3 cm have been described by Collard. By inserting a narrow strip of gold foil along a longitudinal slot in a coaxial line, an electroscope can be formed. It can be calibrated at low frequencies and used up to a limiting frequency beyond which the length of the gold leaf becomes appreciable when compared to the operating wavelength. Collard found that a sensitivity of about 20 volts could be obtained. By employing resonance methods, he could measure a power of 50 μw at 10 cm and 500 μw at 3 cm. The equipment is rather delicate and requires the use of a microscope for measurement of deflection. The effect of a gold foil in the slot on the resultant distribution of fields has not been studied in detail. However, for high-power measurements, such voltmeters could be made practical. For further description of the electroscope, see J. Collard, The Measurement of Voltage at Centimeter Wavelengths, *J. IEE*, March–May, 1946, p. 1393.

[2] A variation of the electroscope principle has been explored by Norton. As in the previous method, use is made of forces developed by electromagnetic fields upon the walls of the transmission line. If part of the wall is made in the form of a thin diaphragm, resonant at some audio frequency, then a modulated signal source will cause vibration of the diaphragm. The amplitude of the oscillations can be measured in several ways; one method makes the diaphragm a part of a condenser microphone arrangement. Forces acting upon the diaphragm are due to the electric and magnetic fields. Since the two are in opposite directions, the design must take this into account and emphasize one or the other. As in the electroscope, the forces are independent of the signal frequency subject to the limitation stated above. Norton has been able

2. Visual indicators—neon glow tubes, lamps, etc.[1]

3. Thermoelectrical indicators—various forms of thermometric devices,[2] thermocouples, thermistors, bolometers

4. Electrical rectifiers—various types of nonlinear elements, such as diodes, crystal rectifiers, triodes, klystrons, etc.

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to obtain satisfactory measurements, without the use of resonance, of microwave power in the vicinity of 1 mw with nearly constant sensitivity over the wavelength range of 3 to 30 cm. For further details, see L. E. Norton, Broad-band Power Measuring Method at Microwave Frequencies, *Proc. IRE*, p. 759, July, 1949.

[3] The radiation pressure of an electromagnetic wave impinging upon a plane surface can be measured by mechanical means. If a perfectly reflecting plane surface is placed normally to the direction of propagation, the pressure exerted on the surface will be equal to the total energy density in front of it. Such an effect was first anticipated by Kepler in 1619 and measured by Lebedew and also by Nichols and Hull in 1901 using visible radiation. (For a description of the theory and of the apparatus suitable for use in the optical range, see G. P. Harnwell and J. J. Livinggood, "Experimental Atomic Physics," chap. 1, McGraw-Hill Book Company, Inc., New York, 1933.) Cullen made use of radiation pressure as a basis for absolute power measurements at microwave frequencies. He suspended a reflecting vane in a waveguide so that the pressure of the radiation would cause a mechanical force, measurable directly in terms of mass, length, and time, without introducing secondary electrical standards, and obtained excellent agreement with a balanced calorimeter when measuring power in the range of 10 to 50 watts. However, the equipment is delicate and limited in accuracy by the same difficulties that confront the optical methods. These limitations are usually caused by the radiometer effect, i.e., heating of the reflecting vane which, in turn, causes convection of air and other complicated effects. For a detailed discussion, see A. L. Cullen, Absolute Power Measurements at Microwave Frequencies, *Proc. IEE*, vol. 99, pt. IV, p. 100, 1952. See also Sec. 3.12.

[1] Neon glow tubes, incandescent lamps, fluorescent lamps, etc., are often used to indicate the presence of microwave power. While it is satisfying to see a lamp glow in response to microwave power, such indications are seldom sufficiently accurate to be useful in actual measurements. Various attempts have been made to make glow lamps into quantitative indicators—such as the measurement of the length of an ionized column in a fluorescent lamp. In another application a visual pattern of standing waves has been obtained by inserting a row of identical glow tubes into a long longitudinal slot in a transmission line. As the strength of the field determines the length of ionization in each of the tubes, it is possible to give an immediate, though rough, idea of the standing-wave pattern.

[2] For example, Golay describes a pneumatic cell in which an expansion of a gas is caused by absorption of incoming radiation in a resistive film. A movable membrane, by mirror action, activates an optical detection system, and produces electrical signals from a photocell. A cell, 3 mm in diameter, may have a typical time constant of 0.003 sec and a minimum detectable power of approximately 10^{-8} watt. Use of helium, instead of air, results in a shorter time constant at the expense of sensitivity. These cells are suitable for use throughout the infrared region and up to several millimeters. For details, see M. J. E. Golay, A Pneumatic Infra-red Detector, *Rev. Sci. Instr.*, vol. 18, no. 5, pp. 357–363, May, 1947; M. J. E. Golay, Theoretical Consideration in Heat and Infra-red Detection, with Particular Reference to the Pneumatic Detector, *Rev. Sci. Instr.*, vol. 18, no. 5, pp. 347–356, May, 1947.

The first two of these detecting devices (1 and 2), are not generally useful for practical reasons and are mentioned merely for completeness. Thermoelectric devices, on the other hand, involve principles which are common to the entire electromagnetic spectrum and are useful in absolute measurements. One specific form of the thermoelectric detector is a device called a *bolometer*. A bolometer is a wire which, subjected to microwave radiation, changes its resistance because of the resultant heating. This resistance change can be easily detected by means of suitable circuits. In practice, bolometers need to be biased by direct currents; as long as the signal power is much smaller than the biasing power, the resultant output voltage signals are directly proportional to the incoming power. Such bolometers are useful in measurements in which accuracy is of importance, but they have comparatively low sensitivity. Thermometric methods are described here only to the extent that they are useful as indicating devices; a more complete description will be found in the discussion of power measurements in Chap. 3.

The electrical methods make it possible to convert microwave signals to d-c or low frequencies—which can then be measured by conventional methods. Such nonlinear elements can be used either as rectifiers or frequency converters. Rectifier-type detectors are relatively the most important because of their simplicity, versatility, sensitivity, and availability, and are the principle subject of discussion in this chapter.

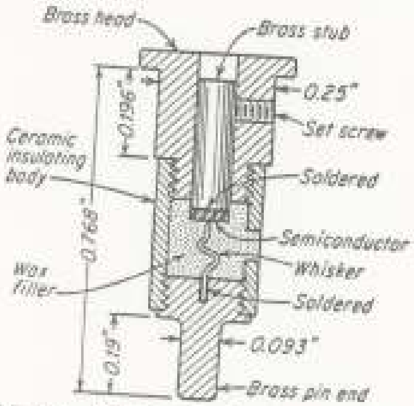
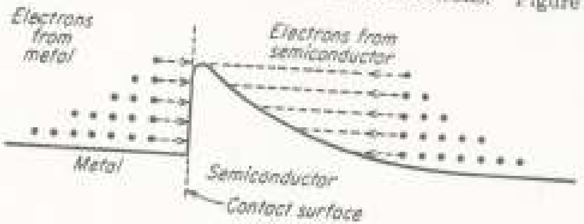


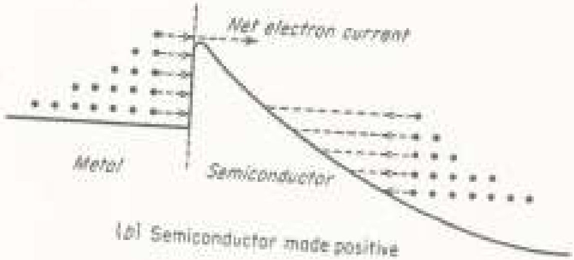
FIG. 2.1. Cross-sectional view showing the elements of a crystal rectifier. Details of construction differ among various manufacturers.

2.2. Crystal Rectifiers. The modern crystal rectifier is the most sensitive and the simplest of all rectifying devices. In spite of various defects, such as uncertain response law and the variation of sensitivity with temperature, it has many applications in measurement practice. The cross section of a typical rectifier is shown in Fig. 2.1. This consists of a fine wire (cat whisker) touching a suitable semiconductor, such as silicon, germanium, galena, or iron pyrite. Present-day crystals are usually made of germanium or silicon. The tungsten wire is carefully pointed and brought into contact with the semiconductor; by controlling the pressure against the semiconductor, the area of contact is adjusted to a desired value. This contact area determines the resistance of the barrier contact and its capacity, as well as the power-handling ability of the

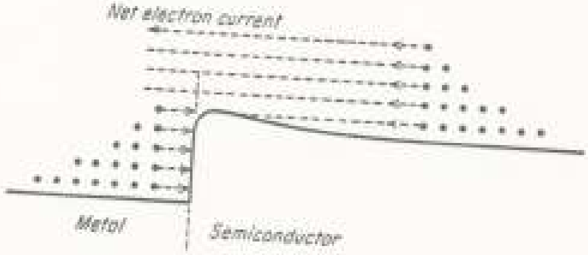
device.[1] The area is made either small or large depending upon the intended use of the crystal. The volume surrounding the point contact



(a) No external potential



(b) Semiconductor made positive



(c) Semiconductor made negative

FIG. 2.2. Diagrammatic illustration showing the potential barrier between the metal and germanium semiconductor for three different conditions of applied potential. The illustration is drawn for the case in which the semiconductor work function is less than that of metal. In (a) no external potential is applied. In (b) the potential of the semiconductor is raised, and in (c) the semiconductor is made negative. Substantial current can flow only in case (c). (*Courtesy of Crystal Rectifiers, by W. E. Stephens, Electronics, McGraw-Hill Publishing Company, Inc., New York, July,* 1946.)

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[1] Aside from the critical nature of the contact between the wire and the semiconductor, the gross features of the rectifier depend upon the nature of the latter. Semiconductors are materials having a high electrical resistance, intermediate between metals and insulators. It has been found that the addition of small amounts of suitable impurities improves the rectification properties of pure semiconductors. The work functions of the whisker and the semiconductor are generally different, which is believed to create a potential barrier to the flow of electrons. Figure 2.2 shows dia-

is usually filled with a wax to prevent the penetration of moisture and to provide some additional mechanical stability.

The static characteristic of a representative crystal detector is shown in Fig. 2.4. The nonlinear characteristic makes it possible to use the crystal detector either as a low-level detector or as a frequency converter. When used as a frequency converter, a local oscillator signal is supplied to the crystal in addition to the signal, and mixed currents flow in the output. One of the resultant components is the difference frequency

signal, whose amplitude is strictly proportional to the signal voltage as long as the local oscillator level is much larger than the signal level. For the low-level detector, a signal is introduced into the crystal causing the rectified current. Because in most measurement problems the crystal is used as a low-level detector, much of the following material is devoted to this topic.

2.3. Crystals as Low-level Detectors. When a crystal detector is used as a low-level detector, its output terminals are connected to a d-c meter, or an audio or video amplifier, depending upon the type of signal modulation. From the viewpoint of basic characteristics, it makes little difference what indicating device follows the detector. For simplicity, consider a circuit consisting of a load resistance and a d-c meter in series with the crystal. When a microwave signal is applied, a d-c signal will appear in the load circuit. The magnitude of the current will depend upon the characteristics of the crystal, r-f source impedance, and the d-c load impedance. As seen from its output terminals, the crystal acts as a current generator with a certain dynamic impedance. The important parameters of the crystal are *the response law, the dynamic impedance*, and *the sensitivity*.

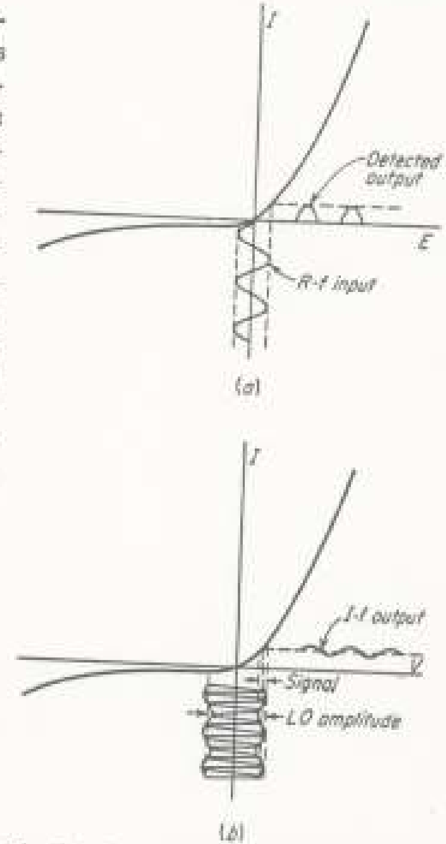

FIG. 2.4. A typical static characteristic of a silicon crystal rectifier when used (a) as a rectifier, (b) as a converter.

Response Law. When the r-f signal is applied to some nonlinear device, the resultant current can be predicted as follows: The nonlinear characteristic can be expressed analytically in the form of a Taylor series expansion about the operating point (the origin, if there is no d-c bias). If the current is expressed in this manner as a function of voltage, the series will begin in a linear term in voltage followed by quadratic and higher-order terms. The linear term does not contribute to rectification and is of no importance. If the signal voltage is small enough, higher-order terms will be negligible in comparison to the quadratic term; therefore, the rectified current must

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grammatically the potential barrier between the metal whisker and the semiconductor for three values of applied potential. The potential barrier is presumed to decrease slowly with distance on the semiconductor side because of the space charge created by the unneutralized impurity ions. While electronic conduction is possible both in the metal and the semiconductor, the barrier between the two effectively prevents the flow of electrons. If the potential of the semiconductor is raised as shown in Fig. 2.2*b*, few electrons can flow into the metal. However, if the electronic potential is lowered as in Fig. 2.2*c*, a slight flow of electrons from the semiconductor becomes possible. Thus, the potential barrier allows conduction of current in one direction, but nearly none at all in the other.

The action of the rectifier can, therefore, be represented by the equivalent circuit shown in Fig. 2.3. Resistance R represents the nonlinear action of the potential

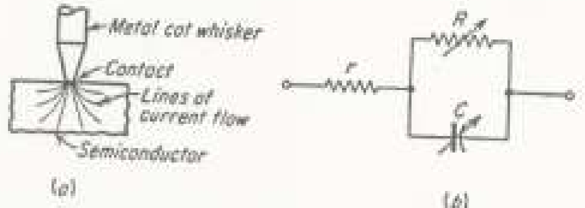

FIG. 2.3. Diagrammatic view of (*a*) the metal-semiconductor contact and (*b*) its equivalent circuit. r is the bulk resistance of a semiconductor (often called *spreading resistance*); R and C represent the nonlinear action of the potential barrier. (*Courtesy of Crystal Rectifiers, by W. E. Stephens, Electronics, McGraw-Hill Publishing Company, Inc., New York, July,* 1946.)

barrier and C the capacitance at the contact. Resistance r is the bulk resistance of the semiconductor, taking into account the spreading nature of the current from the whisker contact. The circuit constants can be obtained from low-frequency measurements, or approximately from the theory of the rectification process. The equivalent circuit can then be used to predict the behavior of the crystal rectifier at high frequencies. The presence of the capacity C makse it obvious that the high-frequency performance of the crystal cannot be predicted (or checked) by low-frequency measurements of the forward and backward resistance alone. Since the thickness of the barrier layer is small, on the order of 10^{-6} cm, the transit-time effects of electrons are not important.

For a more complete discussion of the properties of crystal rectifiers, see R. V. Pound, "Microwave Mixers," McGraw-Hill Book Company, Inc., New York, 1948; Technical Staff, Bell Telephone Laboratories, "Radar Systems and Components," pp. 710–739, D. Van Nostrand Company, Inc., Princeton, N.J., 1949; W. E. Stephens, Crystal Rectifiers, *Electronics*, July, 1946.

be strictly proportional to the square of applied voltage. Because of this, the low-level detectors are often called *square-law detectors.*

The low-level detector can be represented as a constant-current generator as shown in Fig. 2.5 with an internal dynamic impedance R_0. The magnitude of the current i will be proportional to the signal power. The dynamic impedance R_0 will also become a constant at low levels but will be a function of the signal power at higher levels. Rectification properties of a typical crystal rectifier are shown in Fig. 2.6.[1] This shows short circuit and open circuit d-c current and voltage, respectively, plotted as a function of r-f power, and the variation of the dynamic impedance of the crystal. It can be seen that above about 10 μw the square-law response is violated. In some crystals, the deviation from square-law may take place at power levels as low as 1 μw.

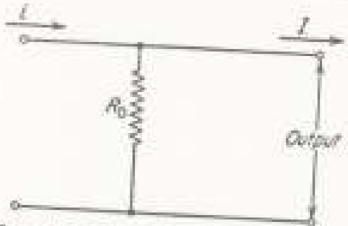

FIG. 2.5. Equivalent circuit of a low-level rectifier in constant-current form. The rectified current i is proportional to r-f power; R_0 is independent of r-f power at sufficiently low level.

It is also found that the response law above 1 μw can be affected by the r-f source impedance. Assume that the rectified current is expressed in the form $i = V^n$, where n is expected to be a function of voltage V and the r-f source impedance Z. In a series of tests conducted on about 25 silicon-tungsten rectifiers, the exponent n was observed to have the following properties.[2] If the rectified current is 1 μamp or less, n does not deviate from 2 for a wide range of source impedances. If Z is small compared to the crystal impedance (at low level), then n will increase with V and may reach a value of 3 at about 100 μamp. If Z is much higher than the impedance of the crystal, n will decrease with increasing V and may fall to 1.5 or less at current levels of about 100 μamp. For intermediate values of the source impedance, the exponent n may at first increase and then decrease.

Thus, it is apparent that, when using crystal current above approximately 1 μamp, one must calibrate the crystal under the precise conditions in which it is to be used. For example, in standing wave detector measurements probe adjustments must not be made once the crystal is calibrated—since such adjustments determine the r-f source impedance. It is also found that deviations of crystal response from square-law are

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[1] H. C. Torrey and C. A. Whitmer, "Crystal Rectifiers," p. 334, Massachusetts Institute of Technology Radiation Laboratory Series, McGraw-Hill Book Company, Inc., New York, 1948.

[2] R. C. Robbins and F. W. Black, An Investigation into the Use of Crystal Rectifiers for Measuring and Monitoring Purposes, *J. IEE*, p. 1343, March–May, 1946.

least when the load impedance is in the vicinity of 2,000–3,000 ohms. The methods of calibrating the crystal detector are described in Sec. 2.10.

Sensitivity. The current sensitivity of the detector is defined as the ratio of rectified current to the absorbed r-f power. It depends upon the nature of the semiconductor material and the contact area. The sensitivity of crystals does not vary greatly from crystal to crystal as might be suspected. Figure 2.7 shows the sensitivity for a few crystals as a function of frequency. The curves shown were computed on the basis of the equivalent circuit shown in Fig. 2.3, using the values of circuit parameters as determined by low-frequency impedance measurements.[1] Although sketchy experimental evidence does not permit verification of the theory, the trends are well indicated.

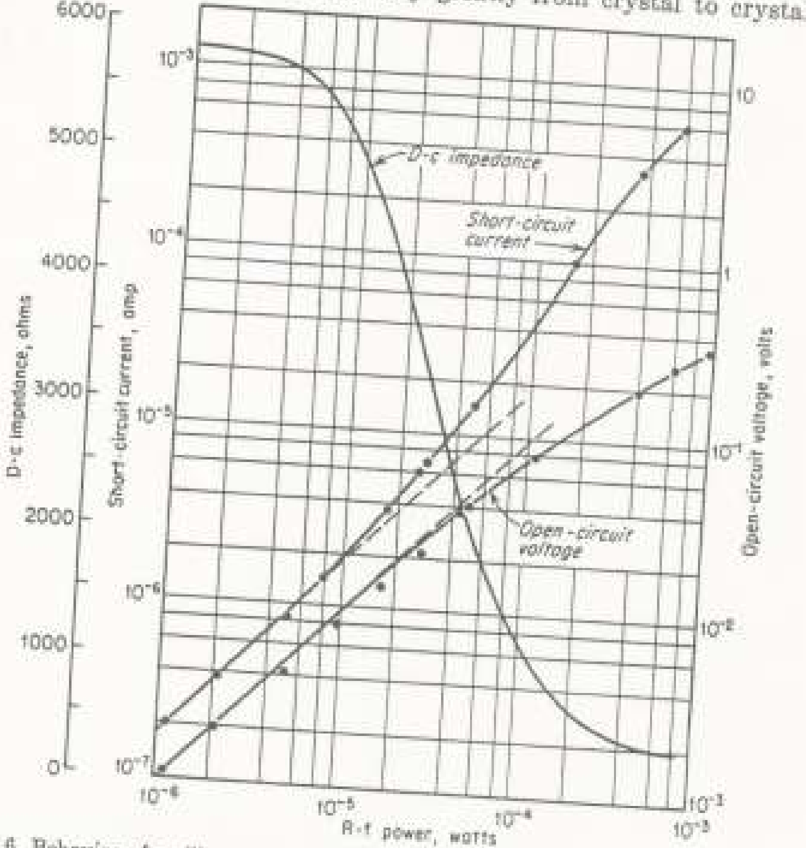

FIG. 2.6. Behavior of a silicon crystal rectifier in the vicinity of 3,000 Mc. (*By permission from "Crystal Rectifiers," by H. C. Torrey and C. A. Whitmer. Copyright,* 1948. *McGraw-Hill Book Company, Inc., New York.*)

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[1] For more complete discussion of the sensitivity of crystal rectifiers, see Torrey and Whitmer, *op. cit.*, pp. 335–340. They show that current sensitivity β can be