MICROWAVE DETECTORS

Microwave energy cannot be efficiently detected with equipment used for lower-frequency applications. Microwave-frequency voltage changes are too rapid to be captured on any but the fastest sampling oscilloscopes, and response time and parasitics of common test meters render them useless. Microwave detectors generally measure power in the controlled impedance environments afforded by transmission lines and waveguides. The system impedance is known, so voltage and current magnitudes can be derived. With the judicious application of other microwave components such as power splitters and quadrature couplers, phase information can be extracted from multiple power measurements; therefore, full characterization of a system or component is possible with only the microwave detector to convert microwave signal characteristics to the readily observable and measurable quantities of low-frequency voltages and currents.

Microwave detectors sense the amplitude or power of a signal, or the change in the amplitude or power of a signal. They are used for the determination of signal power level and for recovery of information placed upon the microwave signal amplitude. The microwave detector circuit, Fig. 1, consists of a

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

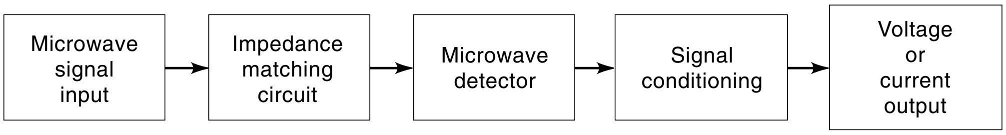

Figure 1. The impedance of the microwave detector should be matched to the impedance of the system being measured.

matching circuit to match the impedance of the circuit being measured to the impedance of the detector itself, along with an output signal conditioning circuit to convert the detector output to a voltage or current that is proportional to the microwave signal input. Ideally, the detector impedance directly matches the system impedance, and the matching circuit is not required.

Microwave detectors can be separated into two categories: thermally dependent detectors and diode detectors. Thermally dependent detectors absorb the incident microwave signal in a detector element, and the microwave energy is converted into heat energy. The increase in temperature of the detector element is directly detected, or a change in a physical parameter of the detector element due to the change in temperature, normally resistance, is detected. The diode detector rectifies the microwave signal, clipping either the positive or negative voltage of the alternating voltage waveform, and averages the resultant monopolar signal in a capacitive circuit to produce a dc signal with an amplitude related to the microwave signal amplitude.

The response time of the thermally dependent detector is a function of the thermal mass being heated by the incident energy and the thermal resistance of the detector to its surrounding environment. In general, the response time of a thermally dependent detector is slow compared to the response time of a diode detector and is on the order of milliseconds to seconds. Thermally dependent detectors are used primarily for the measurement of the power level of steady-state signals or to measure the average value of the power of a time-varying signal such as a pulsed radar transmitter output.

The response time of a diode detector can be within a few periods of the microwave signal being detected; hence, diode detectors can recover information placed in amplitude variations on a signal in addition to measuring the power of steady-state signals.

Small-signal thermally dependent detectors with a bandwidth of less than 100 Hz typically operate over a power range of +10 dBm to about −50 dBm, while diodes limited to the same bandwidth are useful from about +10 dBm to less than −80 dBm. Insertion of attenuators or couplers between the power source and the detector facilitates measuring much higher powers; however, measurement of very small amounts of power generally necessitates insertion of amplifiers or frequency conversion to lower frequencies where more sensitive techniques can be used to detect the signal.

THERMALLY DEPENDENT DETECTORS

Thermally dependent detectors depend upon the heating of the detector element by the incident microwave energy. The heating is proportional to the electrical energy dissipated in the detector element. Bolometers and thermocouples are typical of thermally dependent microwave detectors. Because absorption of the available power in the incident signal depends upon a proper impedance match between the transmission media and the absorbing detector circuit, the detector must have a well-established and controlled impedance.

The bolometer detects electromagnetic radiation by converting the energy in the transmission media to heat. It is placed across transmission line terminals, as shown in Fig. 2, or in the electric field of a waveguide. The nominal resistivity of the bolometer should be equal to the impedance of the transmission line or waveguide at the point of measurement, or the transmission media impedance should be matched to that of the bolometer. One method of making a detector that matches a 50 Ω coaxial system impedance while maintaining a relatively large 200 Ω dc resistance is to place two 100 Ω resistive elements in parallel for the microwave measurement but in series for the dc measurement, as shown in Fig. 3. Under matched conditions all the incident energy is dissipated and appears as heat in the bolometer. The change in the bolometer element resistivity is measured and equated to the magnitude of the incident electromagnetic radiation.

A significant change in the resistivity of a bolometer as power is absorbed can result in an impedance mismatch to the circuit being measured. This can result in unacceptable errors. A measurement circuit usually facilitates a method for accommodating the change in a bolometer element resistivity with the change in incident power. The most common is to use a power substitution technique. A bias current is passed through the bolometer as shown in Fig. 4. The bias current feeds more bias power to the element than the microwave energy that is to be measured. The bolometer element is designed to have an impedance equal to the characteristic impedance of the system being measured while the bias is at the quiescent level with no applied microwave energy. The resistance of the bolometer element becomes part of the resistive bridge. As microwave power is fed to the detector, its resistance changes; however, the bias power to the circuit must be reduced to balance the bridge. The reduction in bias power to the bolometer is equal to the applied microwave

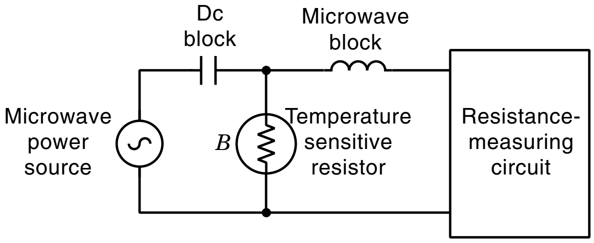

Figure 2. The bolometer B is a temperature-sensitive resistor.

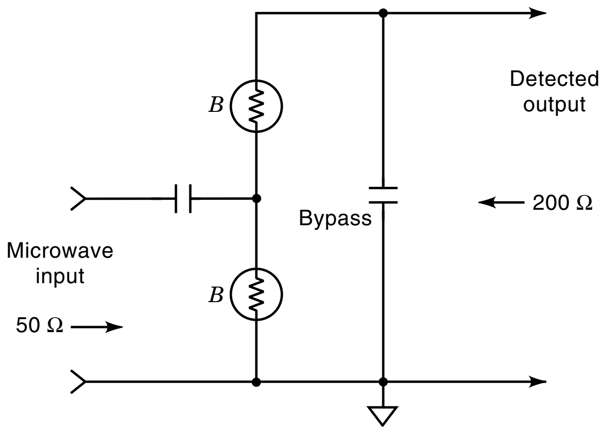

Figure 3. Using two bolometers increases detection sensitivity.

power; therefore, the external circuit measures this change in power, and the detector impedance remains matched to the system being measured. Numerous schemes for automatically balancing the bridge and deriving the change in bias power are used.

Bolometers are, by definition, temperature-sensitive. The more sensitive a bolometer detector is to incident microwave power, the more sensitive it will be to small ambient temperature variations; therefore, temperature compensation is virtually imperative for low-level power measurements. This is accomplished as shown in Fig. 5 by mounting two identical bolometer sets in the same detector package so that the thermal resistance path from each element is to the same heat sink. This forces changes in ambient temperature to cause identical temperature variations in both elements. Only one of the bolometer sets has microwave power applied. By effectively connecting the bolometers in a differential circuit, the common mode variations, introduced by ambient environmental temperature variations through the thermal resistance paths, are canceled.

The bolometer measures the power absorbed in its resistance. In many microwave circuits, unlike those at lower frequencies, current and voltage have little meaning because of the difficulty of their measurement. It is common in microwave applications to make power measurements in a controlled impedance environment; hence, the same circuit information is obtained but with different types of measurement.

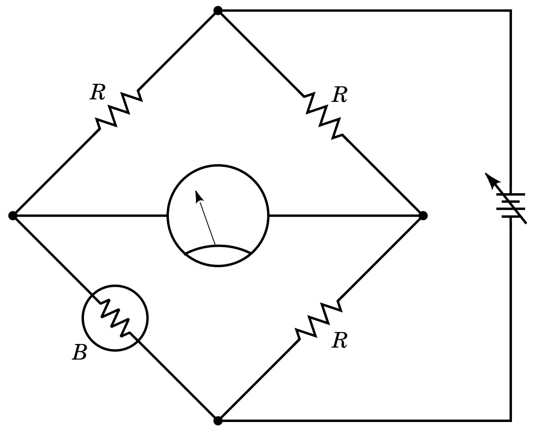

Figure 4. A bridge circuit is used to detect change in the bolometer resistance.

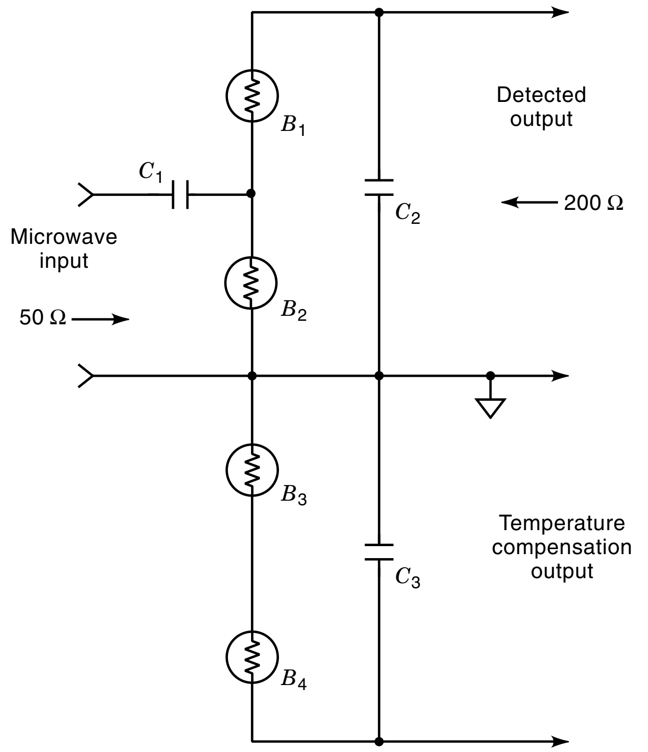

Figure 5. Bolometer set B1 and B2 are detectors, and set B3 and B4 are for temperature compensation.

A barretter is one form of bolometer. It is a small wire which increases its resistance because of the resultant heating when a microwave signal potential is placed across the ends of the wire. The wire is usually either platinum or tungsten. The response characteristic of a barretter is nominally

$$R - R_0 = JP^n \tag{1}$$

where R_0 is the room temperature resistance of the wire, R is the resistance of the wire with the power P being dissipated, and J and n are constants.

For a specific commercial barretter intended for low power measurements, $R_0 = 115\ \Omega$, $n = 0.9$, and $J = 7.57$. The power sensitivity S is found by differentiating the resistance with respect to the absorbed power giving

$$S = \frac{dR}{dP} = \frac{n(R - R_0)}{P} \tag{2}$$

This unit has a recommended operating point of $R_{\text{op}} = 200\ \Omega$ at an applied power of $P_{\text{mW}} = 15$ mW, which is achieved at a bias current of 8.7 mA. Substituting this into the equation yields a sensitivity of 5 Ω/mW. The change e_{out} in the voltage across the unit with the applied power being much less than the bias power will be

$$e_{\text{out}} = \sqrt{\frac{P_{\text{bias}}}{R_{\text{op}}}} \cdot S \cdot P_{\text{mW}} \tag{3}$$

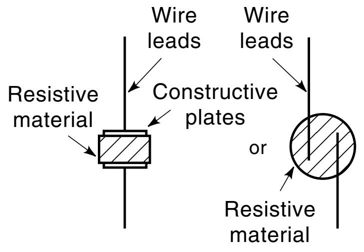

Figure 6. A thermistor is a resistor with a high temperature sensitivity.

Applying 1 μW of power to this detector produces an output voltage of 44 μV. The kTB thermal noise in a 100 Hz bandwidth at the terminals of the unit is about 2.5×10^{-8} V. This indicates that the smallest microwave signal that can be detected in the presence of the noise in the 100 Hz bandwidth is around 10 nW or -50 dBm. This is typical of low-power bolometers.

The thermistor is another form of bolometer. The thermistor consists of a small amount of resistive material with a high temperature sensitivity placed between two connecting wires as shown in Fig. 6. Typically, the material is a semiconductor with a large negative temperature coefficient of resistance; that is, the resistivity of the material decreases with an increase in temperature. Placing a microwave signal potential across the thermistor results in a current that heats the temperature sensitive material. With the semiconductor thermistor, this results in a reduction in the resistance between the terminals. The thermistor is used in the same bias substitution circuits as the bolometer with changes to allow for the negative change in resistance with increase in applied power. Because the magnitude of the negative temperature coefficient of the thermistor is typically much greater than the positive temperature coefficient of the barretter, the thermistor tends to be more sensitive than the barretter; however, the large volume of the thermistor leads to a larger thermal time constant, making its time response slower than that of the barretter.

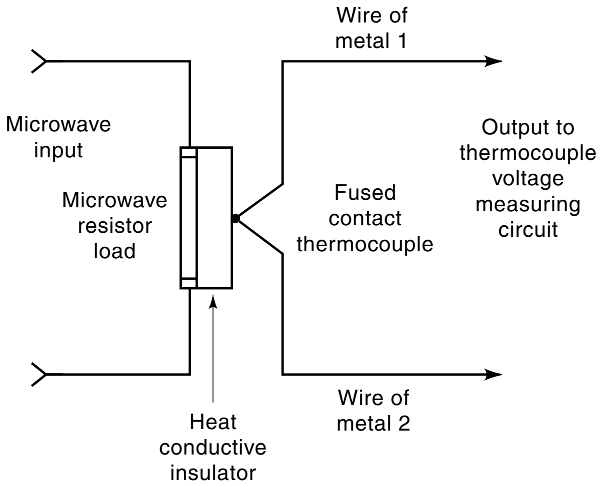

Figure 7. Microwave power is absorbed in the resistor, and the temperature increase is measured by the thermocouple.

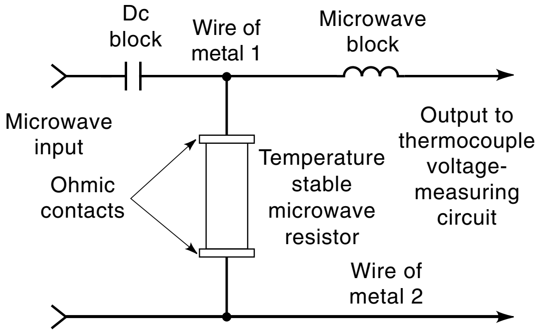

Figure 8. Direct series connection of the thermocouple to the resistor facilitates faster response because of the reduced thermal mass.

Other variations in the construction of bolometers are possible, such as the deposition of thin metal resistive films on insulating substrates. These implementations readily lend themselves to varied microwave construction techniques such as monolithic and thin-film integrated circuits, stripline, slotline, coplanar waveguide, and microstrip. Note that such construction also facilitates thermal isolation, cooling, and miniaturization for sensitive millimeter wave through infrared operation.

A thermocouple is formed by intimately joining two dissimilar pieces of wire, such as copper and constantan. A potential difference appears across the junction related to the temperature. Microwave energy can be detected by using the thermocouple to measure the change in temperature of a resistor that terminates the microwave circuit as shown in Fig. 7. Another method, resulting in a better form factor for microwave measurement, places a carbon resistor between the two dissimilar wires as in Fig. 8. This results in a smaller thermal mass and a resultant faster response time. In both examples, a standard thermocouple measurement system with a reference cold junction is required. Calibration of power into the detector as a function of thermocouple temperature must be experimentally derived.

Other calorimetric methods can be used for large signal levels. For example, water pumped through an incident microwave energy-to-heat converter (a calorimetric load) increases in temperature. The energy required to change the temperature of the water is the energy in the incident microwave signal. This is illustrated in Fig. 9 and is a common

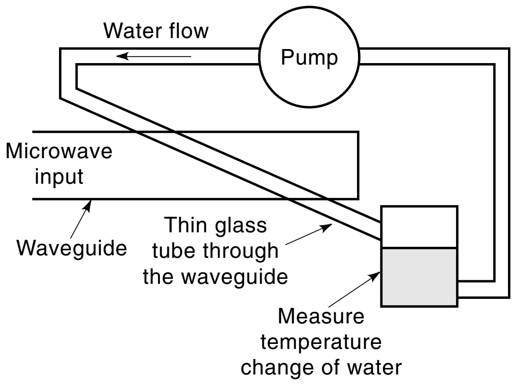

Figure 9. A water or calorimetric load can accurately measure large amounts of average power.

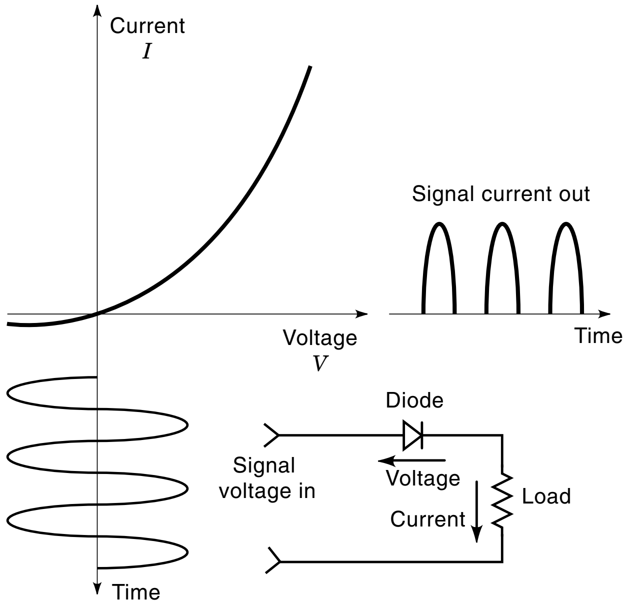

Figure 10. The diode detector rectifies the input signal.

method for measuring the average power output from large radar transmitters.

The ratio of the maximum power detected to the minimum detectable power with the thermal detector is relatively small; however, this is compensated for by measurement accuracy and repeatability. The time response of the thermal detector is a function of the thermal time response of the energy absorbing mass; therefore, barretters typically respond faster than a thermistor, and a thermistor is faster than a thermocouple. An advantage of the slowly responding detector is the ability to measure the average power of a pulsed signal, such as a radar.

Recent developments in temperature-dependent detectors is primarily focused in two areas. Increased miniaturization is intended to increase the frequency of operation up into the millimeter microwave range and to infrared. Arrays of these very small detectors can be used for imaging. There is also active research in cryogenic detectors because they produce less noise than heated detectors and hence yield improved small signal sensitivity.

DIODE DETECTORS

Semiconductor diode detectors respond rapidly to changes in the input signal. They rectify the voltage of the incident microwave signal, producing a direct current output that is related to the magnitude of the input. This process is illustrated in Fig. 10. The diode curve of current I through the diode versus the voltage V across the diode is roughly governed by the ideal diode equation

$$I = I_0(e^{qV/kT} - 1) \tag{4}$$

where

I_0 is the diode leakage current with a reverse voltage applied
q is the charge of an electron (1.60×10^{-19} C)

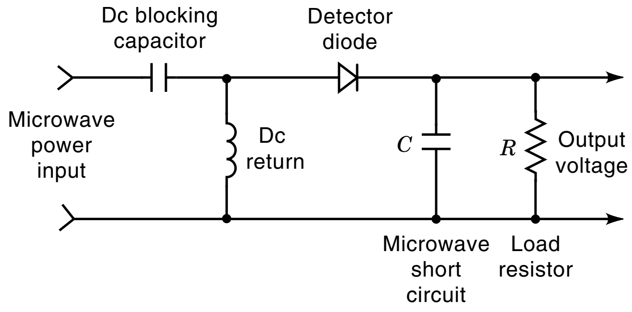

Figure 11. The rectified current through the series diode is averaged in the RC circuit to produce a dc or low-frequency output.

k is Boltzmann's constant (8.62×10^{-5} eV/K) and
T is the temperature in degrees kelvin (degrees centigrade + 273)

At room temperature, $kT/q = 26$ mV. By applying a voltage across the diode, a corresponding current is forced through the diode. Using the circuit in Fig. 11, the current is averaged in a parallel resistor and capacitor to produce a dc output voltage that is related to the magnitude of the input voltage. Note that the microwave voltage component of the output voltage is shorted by the averaging capacitor. This ac short circuit also forces all of the applied high frequency voltage to appear across the diode.

Two variations of the diode detector circuit are shown in Figs. 12 and 13. In the first, the applied voltage appears directly across the diode. On negative portions of the microwave cycle the voltage is shorted through the diode, resulting in a small negative voltage diode drop that is proportional to the current through the diode. On the positive portion of the cycle, all of the applied voltage appears across the diode. The RC circuit effectively integrates the voltage and produces a net positive output voltage that is proportional to the magnitude of the applied microwave signal. Figure 13 is a combination of the series and shunt connections. Each diode provides the necessary dc return path for the other, eliminating the necessity of the large biasing element.

Real semiconductor diode performance is more closely approximated by the equation

$$I = I_0(e^{qV/nkT} - 1) \tag{5}$$

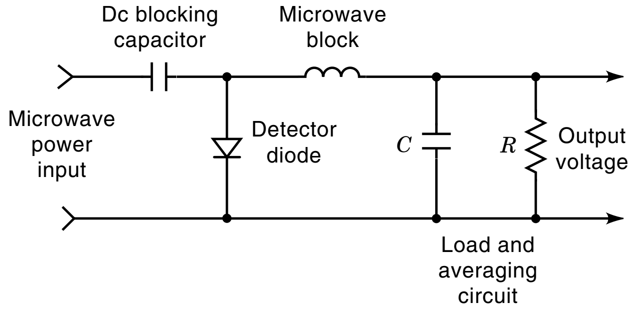

Figure 12. The rectified voltage waveform across the shunt diode is averaged in the RC circuit.

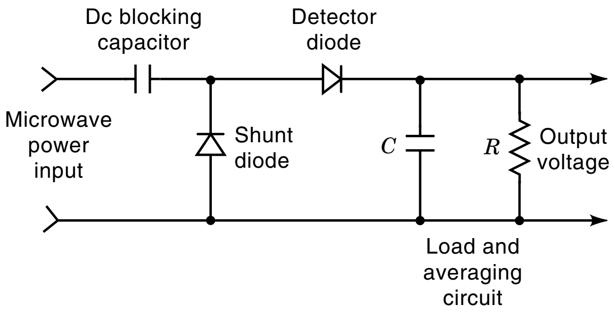

Figure 13. Combining the shunt and series diodes eliminates the inductors as the shunt diode provides the dc return path.

where n is called the ideality factor and is an indication of how close to ideal were the conditions under which the device was fabricated. It usually ranges from 1.0 to 1.06 for a silicon diode. The leakage current I_0 is a function of material, material doping, and various factors involved in the fabrication of the physical diode. The combination of all of these factors produces a distinct V–I curve for various classes of diodes. The most significant physical parameter of these devices is the maximum voltage drop across the diode with a moderate amount of applied current. This is referred to as the *diode voltage*. For silicon *pn* junctions the diode voltage is nominally 0.7 V. For germanium it is about 0.3 V. For metal semiconductor junctions, commonly called *Schottky barrier diodes*, the voltage drop can be tailored between nominally 0.2 V and 0.6 V by material selection and processing technique variations.

The Schottky barrier is the most commonly used high-frequency detector diode because its relatively low forward voltage drop results in excellent sensitivity to small signals. It also can be switched from forward conduction to reverse isolation faster than a *pn* junction because there is no charge storage within the device due to diffusion capacitance. Figure 14 is a first-order equivalent circuit for a detector diode. The L, R and C elements are commonly known as "parasitics." The series resistance is primarily the bulk loss due to the substrate. The shunt capacitor across the diode proper is the junction capacitance and is a strong function of the diode area. The series inductance represents bond wires, beam leads, or any connections to the semiconductor die. The capacitor surrounding the circuit is plate capacitance between metalized areas and, for a packaged device, the packaging capacitance. Inserting the diode model into any of the diode detector circuits of Figs. 11 to 13, note that the parasitic capacitors can short out the diode at high frequencies. The smaller the parasitic capacitances, resistance, and inductance, the higher in frequency the diode detector can be made to operate.

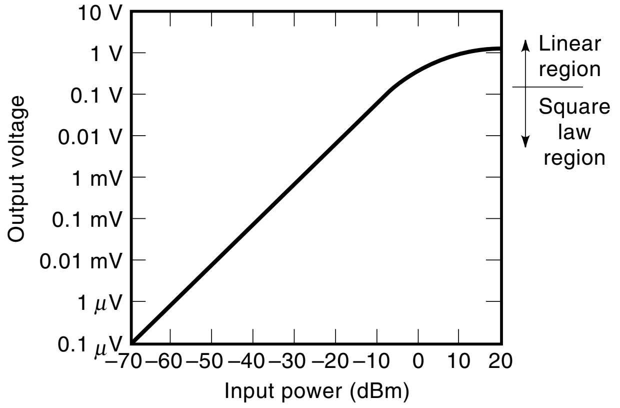

Figure 15. The diode detector follows a square law over most of its dynamic range.

Although the above equations roughly describe the transfer characteristic of the metal semiconductor diode, they do not properly define operation for very large input signals. As shown in Fig. 15 the diode detector actually has two operating regions. From very low power until about 0 dBm input, the detector output voltage is proportional to the input power. This is the square law region and is generally the desired region of operation. Further increasing the input results in an output proportional to the input voltage. This is the linear region.

Planar Schottky barrier diodes can be fabricated by evaporating a metal onto a wafer of doped semiconductor. Small dots or interdigitated patterns are photolithographically defined to establish the area and shape factor of the diodes to be made. The back side of the die is degenerately doped and metalized. Thermal activation of the metal semiconductor junctions results in a Schottky barrier diode on the top side and an ohmic contact on the back side of the semiconductor wafer.

The Schottky barrier diode, made by the deposition of thin metal films, represents an improvement in operational consistency and is a method of mass producing a type of diode originally requiring considerable fabrication labor. The point contact diode, Fig. 16, was the first microwave metal semiconductor detector. It consists of a small die of semiconductor alloyed to a metal header to form an ohmic contact. A

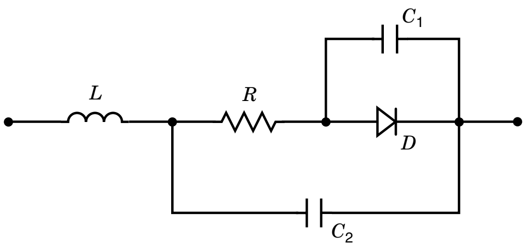

Figure 14. Parasitics limit the high-frequency performance of a diode detector.

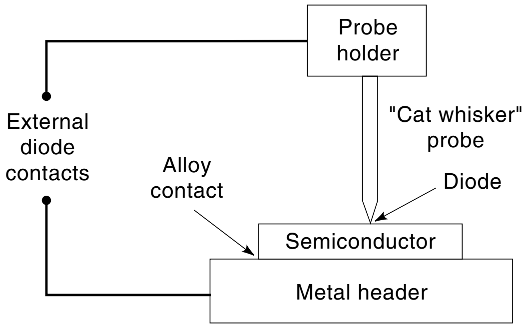

Figure 16. The point contact diode is a pressure contact between a stiff metal wire and a doped semiconductor die.

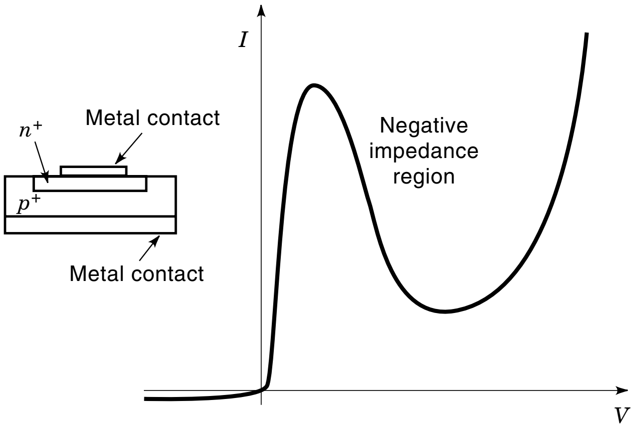

Figure 17. A tunnel diode is a highly doped *pn* junction with a very small low-current junction voltage.

thin "cat whisker" of a stiff metal such as tungsten with a sharp point is brought into contact with the semiconductor. Although a thin layer of oxide contamination probably exists between the metal and the semiconductor, a rudimentary junction similar to a Mott diode is formed. The junction area is nominally increased or decreased by increasing or decreasing the pressure of the cat whisker on the semiconductor. Obviously, aging and temperature cycling will change the junction characteristics, and vibration can be a definite hazard; however, there are many of these detectors, made in the early 1940s, still in service and doing an excellent job.

The diode parasitic capacitance is a function of the area of the junction; however, the power handling capability is also a function of diode area. As the maximum useable frequency of a diode made with a particular fabrication process increases, the maximum power that can be fed to the diode decreases.

Diode detector sensitivity can, to some extent, be increased by supplying a small amount of dc bias current to the diode in addition to the microwave signal that is to be detected. The bias current moves the operating point to the right of the current axis and up the *I*–*V* curve. Careful adjustment of this current can set the operating point at a region of maximum curvature, resulting in an increase in the output voltage from the detector for a given microwave power input; however, this does not necessarily indicate adjustment for maximum sensitivity because the diode generates $1/f$ noise due to the bias current. The increase in noise level from zero bias current kTB noise can exceed a factor of 10 to 1000 while significant amounts of the $1/f$ noise can extend well beyond 20 kHz. In general, maximum signal sensitivity with bias will occur somewhere between zero bias and the region of maximum curvature of the diode *I*–*V* curve.

By heavily doping both sides of a *pn* junction, a diode producing a very small initial voltage drop is obtained. Carriers "tunnel" through the quantum mechanical potential barrier; hence, the diode, referencing Fig. 17, is called a *tunnel diode*. Although this diode, when used as a detector, can suffer from the same charge storage capacitance malady of other *pn* junctions, judicious matching of the diode area to the maximum applied power can result in a very sensitive zero bias detector. As seen from the *I*–*V* curve, if bias current is increased beyond the usable detector range, the impedance of the diode becomes negative. Biased in this region, the diode can be used as an oscillator or amplifier.

The ratio of the maximum power detectable to the minimum detectable power with the diode detector is relatively large; however, the difficulty of compensating thermal drift in the detector limits its use in accurate absolute power measurement applications.

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MICROWAVE DIODES. See TRANSIT TIME DEVICES.