# Characteristics and Applications of Diode Detectors

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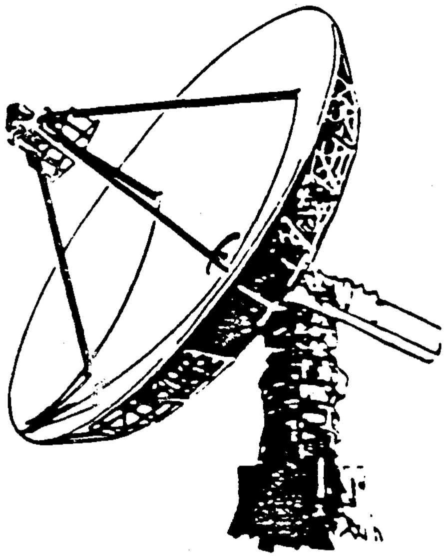
**RF & Microwave Measurement Symposium and Exhibition**



HEWLETT PACKARD

# Applications of Detectors

Absolute Power Measurements
Relative Power Measurements
Leveling Loops
Systems Monitoring
Pulsed RF Measurements

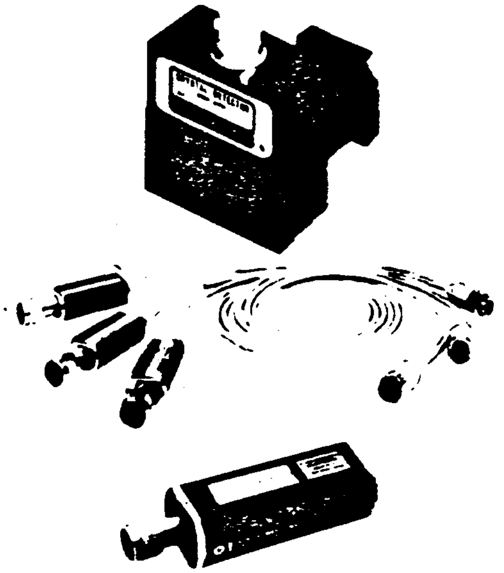
The diode detector is a very common element in microwave measurement setups and finds wide application in systems. Semiconductor diodes are used for measuring absolute power. Network characterization often employs diodes to measure relative power, and leveling loops, system monitors, and pulsed RF measurements are other applications which frequently employ diode detectors.

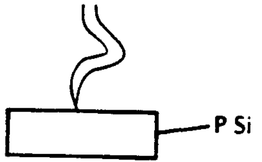
The system performance one obtains is a function of the detector diode, its associated RF matching circuit, the circuitry which processes the detected signal, and the environmental conditions over which the system must operate. The parameters which control the performance of a detector are present in all applications and it is important to understand how they interact so that the desired system performance will be obtained.

**Diodes for microwave detectors employ a metal-semiconductor interface**

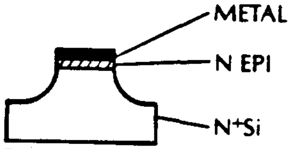
**They are majority carrier devices which minimize stored charge**

**Point contact and Schottky (hot carrier) diodes are the most common types of detectors**

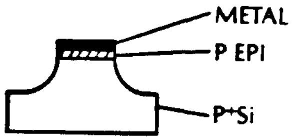




Point contact



High Barrier Schottky



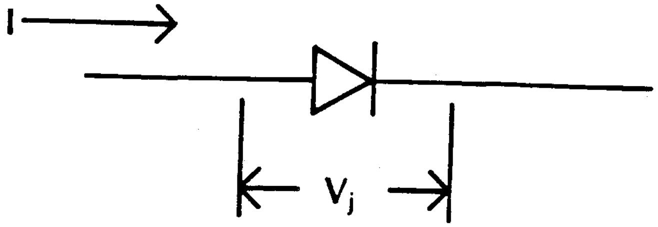
Low Barrier Schottky

Conventional PN junction diodes exhibit stored charge effects which limit their operating frequency. Current flow in a metal-semiconductor junction is due primarily to majority carriers, so the effect of charge storage is minimized. This makes devices such as the point contact diode or the Schottky junction perform as efficient rectifiers at microwave frequencies.

For many years, the only way to fabricate the required metal semiconductor interface was to employ a point contact system. This type of construction yielded diodes with a wide variation in unit to unit performance and the delicate assembly is subject to damage from excessive power, mechanical shock, or temperature cycling. A much more rugged structure evolved by depositing the barrier metal directly on an epitaxially grown layer. Ordinary Schottky diodes have a high potential barrier and require a bias current to achieve sensitivities equivalent to point contact diodes. The most recent development in detector diodes is the formation of a Schottky barrier on P type silicon which has a barrier height about ½ that of ordinary Schottky diodes. The low barrier height results in detectors which are electrically similar to point contact devices but much more rugged.

All three types of diodes are found in current HP products. The K and R 422A detectors use point contact diodes, and achieve a sensitivity at 40 GHz which is quite similar to lower frequency point contact detectors. The 11664A Amplitude Analyzer detectors use biased Schottky devices in conjunction with an AM modulated source to achieve a −50 dBm sensitivity, and the 8484A power sensor employs a low barrier Schottky detector and provides CW power measurement capability to −70 dBm.

# Diode Equation



$$I = Is[\exp(Vj/Vt) - 1]$$

I = diode current
Vj = junction voltage
Vt = "thermal voltage"

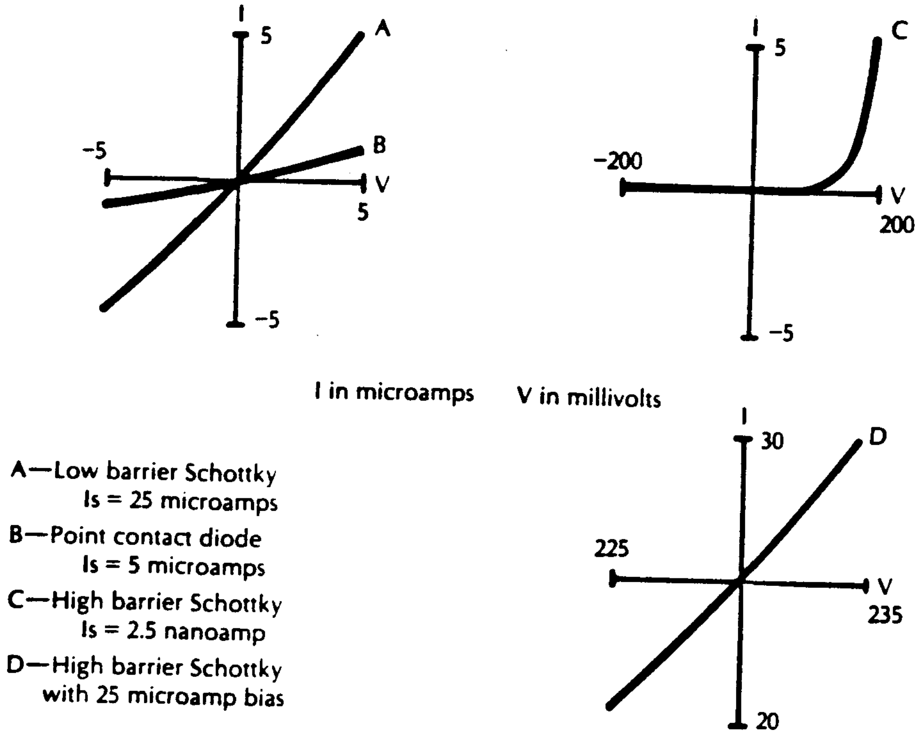
Vt = nKT/q
K = Boltzmann constant
T = Absolute temperature
q = Electron charge
n = ideality factor
(1 < n < 2)

Is = reverse saturation current
Determined by:
Junction area
materials
temperature

**Is changes by 2:1 for temperature change of about 20 degrees C**

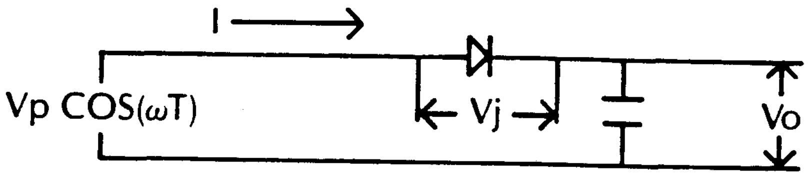
At low signal levels, all three types of diodes closely obey the equation for the ideal diode, and this will be the starting point for the discussion of detector action. The equation relates the current through the diode to the voltage appearing across the junction. The characteristics of the diode are reflected in the so-called "thermal voltage", Vt and the reverse saturation current Is. At a given temperature Vt will be different for various types of diodes, and this is reflected by the value of the ideality factor n which has a value in the range of 1 to 2. The predominant factor which determines the characteristics of the diode is the value of the reverse saturation current Is. This current is a function of device area, materials used to form the junction, and temperature. The temperature dependence is very important because most of the change in detector performance can be related to variations in Is, which changes by approximately a factor of 2 every 20°C.

## Effect of Reverse Saturation Current



By examining the IV curves for the various types of detector diodes, the influence of the reverse saturation current can be seen. Curve A is typical of a low barrier Schottky with Is = 25 microamps. This is contrasted against a point contact device (curve B) whose Is = 5 microamps. Curve C is for a typical high barrier Schottky having an Is = 2.5 nanoamps. The diodes described by curves A and B show significant current flow at very low junction voltages and this is the type of IV characteristic which is desirable for a low level detector. Similar behavior can be obtained with the high barrier Schottky by applying a bias current to shift the operating point to a region similar to that of the low barrier or point contact device. The penalty for doing this is the dc offset which is produced. Biased detectors are either used for detecting signal levels above −30 dBm in dc coupled systems or are used in ac coupled systems which eliminates the effect of the offset.

# Square Law Detection
# Simplified Analysis



$$I = Is[\exp(Vj/Vt) - 1] = Is[Vj/Vt + 1/2(Vj/Vt)^2 + \ldots]$$

Assume: $Vj = Vp \cos(\omega T)$; $Vo << Vp$; $Vp < Vt$

$$I = \frac{IsVp}{Vt} \mathrm{COS}(\omega T) + \frac{Is}{4}(Vp/Vt)^2 [1 + \mathrm{COS}(2\omega T)]$$

$$Idc = \frac{Is}{4}(Vp/Vt)^2$$

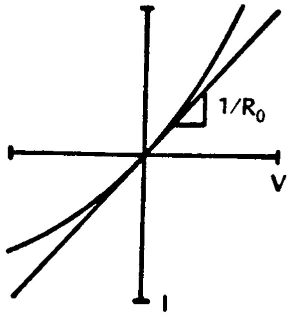
One of the major applications of diode detectors is to measure either absolute or relative power levels. At low power levels (<−20 dBm), the diode responds to the square of the voltage appearing across the junction so the detected signal becomes a function of power. An approximate but accurate analysis reveals the reason for the square law response. The diode current can be estimated by a series expansion of the diode equation. Upon substitution of a sinusoidal description for the signal voltage, restricting the analysis to signal levels less than Vt, and assuming that the detected signal is negligible with respect to the input voltage, one finds that three dominant terms appear in the expression. Two of these describe the fundamental and second harmonic of the input signal which are bypassed by a capacitor. A dc term which is proportional to the square of the input voltage represents the detected signal. Experimental evidence on a wide variety of detectors confirms the validity of the analysis. It should not be surprising that significant departure from square law is noted for signal levels exceeding 26 millivolts (about −22 dBm in a 50-ohm system) and the detected output level is about 15% of the peak RF input voltage at this power level.

# Equivalent Circuit of Diode Output

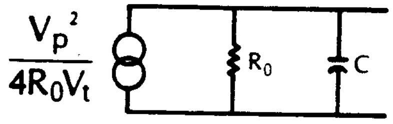
Detected current given by: $Idc = \frac{Is}{4}(Vp/Vt)^2$

Define "origin resistance" $Ro = Vt/Is$

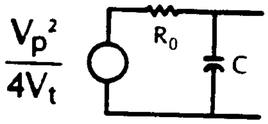
Substitution yields $I_{DC} = \frac{V_p^2}{4R_0V_t}$



Which suggests the following circuits:



OR



Biased detectors are similar except that

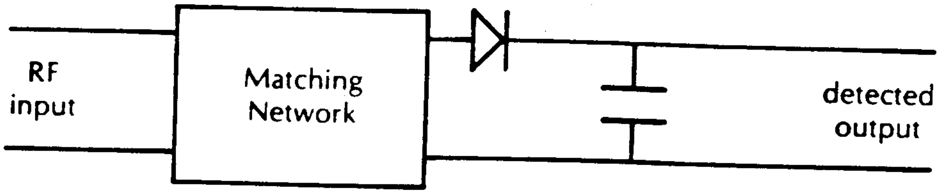
$R_0 = \frac{V_t}{I_0}$ $I_0$ = Bias current

and fixed current or voltage sources have to be added to account for the bias signal.

If a new term "origin resistance" is introduced, the analysis can be extended to obtain a useful model for the detected output. The origin resistance of the diode is simply the slope of the diode IV curve at the point of zero signal.

Since the RF components of the diode current are bypassed, the output of the diode is a dc voltage when a CW signal is applied. The analysis suggests that the diode output is in the form of a current source driving a shunt resistor with a value equal to the origin resistance. This can be transformed to an equivalent voltage source and series resistance. The RF bypass capacitor is included in the model to account for the transient response of the detector. An analysis of a biased detector will lead to a similar result except fixed sources have to be added and the origin resistance becomes a function of Vt and the bias current Io.

# Detector Circuit Considerations



The matching network determines these specs

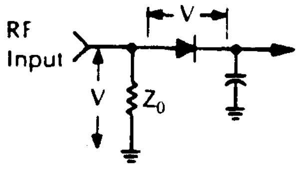
**BANDWIDTH**
**SWR**
**FREQUENCY RESPONSE**
**OPEN CIRCUIT VOLTAGE SENSITIVITY**

The diode and the matching network determine the tangential signal sensitivity **TSS**

The specifications which are obtained for a detector are governed primarily by the microwave circuit in which the diode is imbedded. The diode impedance is rarely equal to the Zo of the system so a matching network is necessary. The design of this circuit determines operating bandwidth, SWR, frequency response, and open-circuit voltage sensitivity. A systems related specification, tangential signal sensitivity (TSS), is governed both by the matching network and the characteristics of the diode.

# Matching Circuits

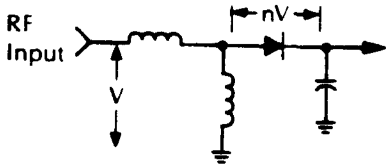
## Resistive Matching



## Point contact, low barrier Schottky or biased Schottky

Broad bandwidth (.01 – 26.5 GHz)
Low SWR (<1.3 to 18 GHz)
Moderate sensitivity (500 μV/μ watt)
Freq. response ±.35 dB .01 – 18 GHz (8484)

## Reactive Matching



$n = \sqrt{\frac{R_0}{Z_0}}$

## Biased Schottky (low $R_0$, low Q)

Narrow bandwidth (octave or less)
High SWR (2:1 typical)
High sensitivity (2000 μV/μ watt or higher)
Freq. response ±.5 dB/octave

Sensitivity specs on chips and packaged diodes almost universally refer to a reactively matched circuit.

There are two approaches to the design of the matching network, either resistive or reactive. The resistive network is used in broadband designs (.01 to 26.5 GHz) and can yield low SWR and flat frequency response. The sensitivity of resistively matched detectors is almost independent of the diode characteristics. The reactively matched detectors work over only modest bandwidths, generally have relatively high SWR, and the sensitivity obtained is a strong function of the diode characteristics. The advantage of reactive matching is a marked increase in sensitivity. This is due to the fact that the matching network acts as a transformer so the voltage applied to the diode junction is increased by the square root of the ratio of origin resistance to Zo. To obtain a reasonable bandwidth, biased diodes with an origin resistance of about 4 times Zo are often used in reactively matched designs. This results in a factor of 4 increase in sensitivity over the resistive matching network. It should be mentioned that the sensitivity specifications for diodes in chip or packaged form almost universally assume a reactively matched circuit. Regardless of the sensitivity spec on a reactively matched diode, they will all yield very similar performance in a resistively matched circuit because the transformer properties are not present.

# Departure from Ideal Diode

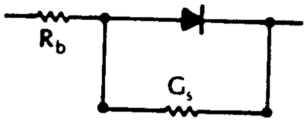
## 3 Key Elements to Look for are:

$R_b$ Spreading Resistance

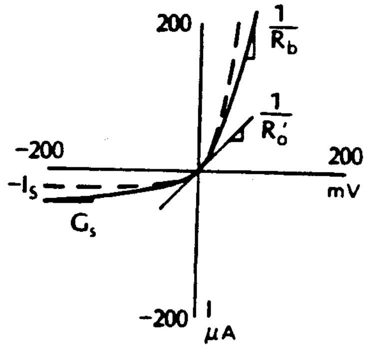
Ro Origin Resistance

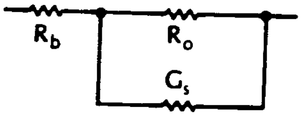
Ro = Vt/Is

$G_s$ Shunt Conductance



Non Linear Model





Linear Model
(Square Law Region)

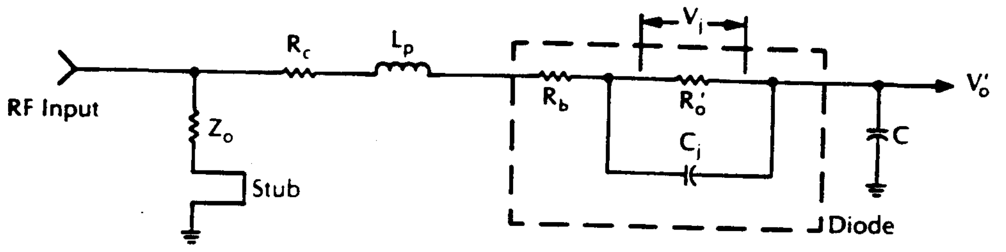
The slope through the origin is really the parallel combination of $R_o$ and $G_s$

These additional elements reduce the sensitivity of the detector from its theoretical value of

$$\text{Vdet} = \frac{V_p^2}{4V_t}$$

The actual diode will show some departure from the ideal device. Theoretically, the origin resistance is given by Vt/Is, but a conductance Gs shunts the junction of the actual diode, so the slope at zero signal is defined by the parallel combination of Ro and Gs. All diodes exhibit a spreading resistance Rb which is in series with the nonlinear portion of the diode. Rb, Gs, and the parallel combination of Gs and Ro may be determined from the device IV curve, and contribute to a reduction in sensitivity.

# Low Barrier Schottky Detector Circuit



Circuit was optimized to minimize change in $V_j$ with frequency and also provide a good match at the RF input

Ro = Origin Resistance   Rb = Spreading Resistance   Cj = Junction Capacitance

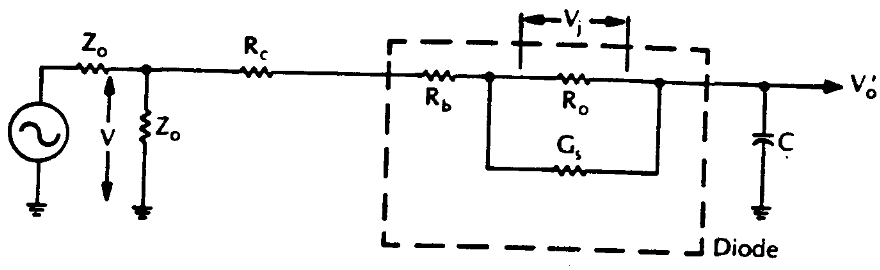
Lp = Lead Inductance   Zo = RF Load Resistor   C = RF Bypass Capacitor

Rc = Compensation for LpCj Resonance

Length and impedance of stub optimized to minimize SWR

A complete model of the HP low barrier Schottky detector shows the elements which have to be considered during the design of a broadband resistively matched detector. The capacitance of the diode Cj and its lead inductance Lp effect the match and frequency response. A resistor Rc damps the resonance of LpCj, and a stub is placed in series with the RF load to minimize SWR. The various elements in the circuit work together to keep the voltage across the junction constant with frequency.

# The Sensitivity of the Detector is Influenced by the Diode and the Matching Circuit



Ideally $V_0 = \frac{V_j^2}{4V_t}$ , but

1. **Ideality factor increases Vt:** $Vt = nKT/q \quad 1 < n < 2$
2. **Shunt conductance of diode:**

A. Lowers origin resistance $R_0' = \frac{R_0}{1 + G_s R_0}$ B. Self-loading $V_0' = \frac{V_0}{1 + G_s R_0}$

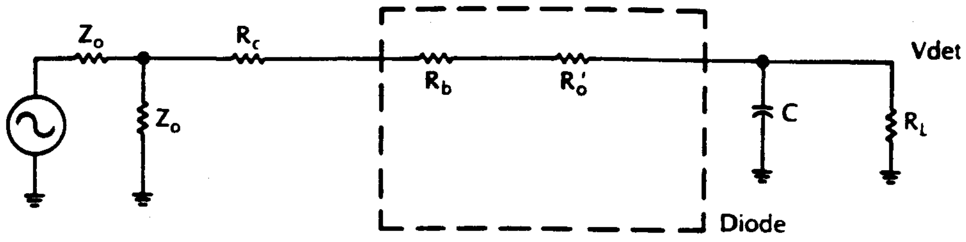
3. **Matching circuit loss:**

$$V_j = \frac{R_0'}{R_0' + R_b + R_C + Z_{0/2}} V$$

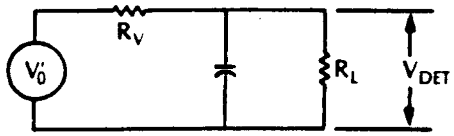
A finite output load resistor will have a dramatic effect on the detector performance

The sensitivity of the resistively matched detector is not a strong function of the diode characteristics, but the actual sensitivity will be somewhat lower than that predicted by the analysis. The ideality factor n causes an increase in the value of Vt. The shunt conductance Gs lowers the origin resistance and also acts as a built-in load for the video output. Finally, there is a reduction in the junction voltage Vj relative to the applied signal V due to the losses produced by the RF load, Rc and Rb. The combination of these effects causes the sensitivity of actual detectors to be 30 to 50% lower than ideal.

## Loading the Detector Output



### Equivalent Circuit for Output



$$V_{det} = \frac{R_L}{R_L + R_V} V_0'$$

Video resistance $R_V = R_0' + R_b + R_c + Z_0/2$

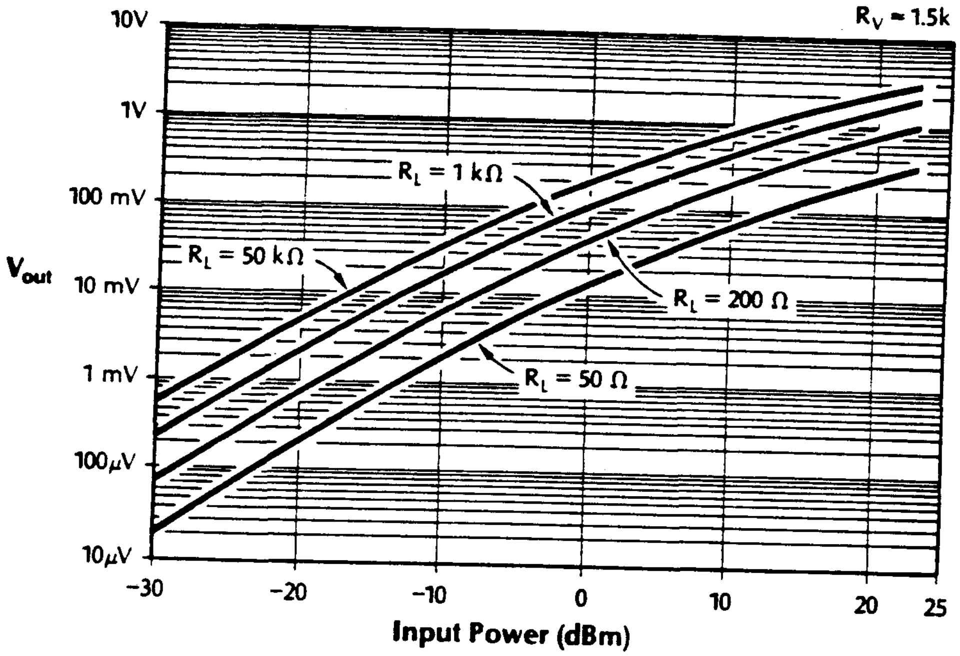
Rv is a function of power level, temperature and $R_L$

The most dramatic change in sensitivity is produced when the output of the detector is loaded. The finite video resistance Rv forms a voltage divider which can significantly decrease the output voltage. In the square law region, Rv is governed mainly by the origin resistance of the diode Ro, but as the diode is driven out of square law, Rv becomes a complicated function of power level, temperature, and $R_L$.

# Low Barrier Schottky Detector

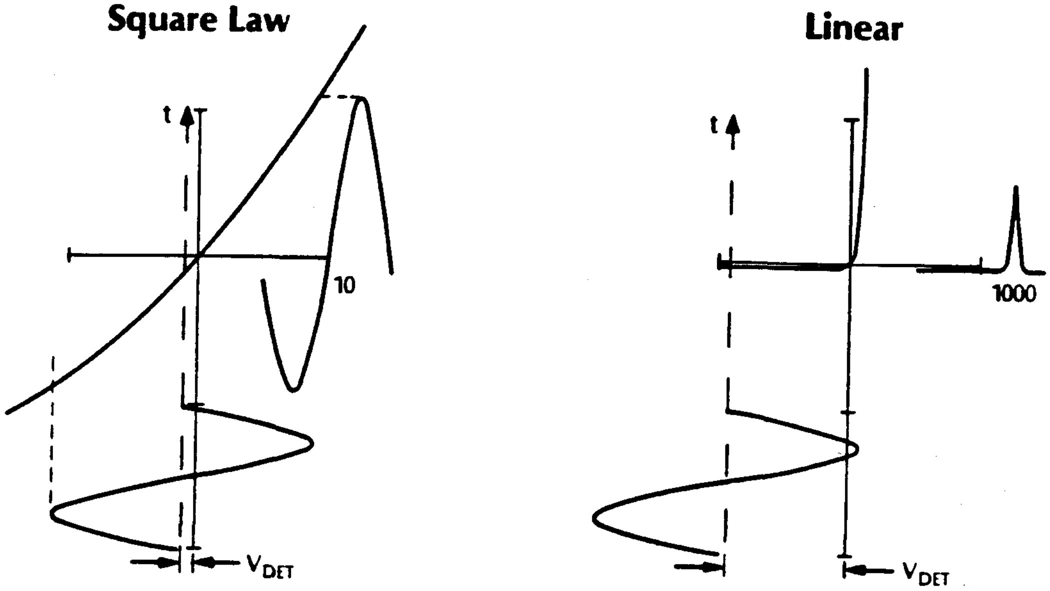
Typical Transfer Characteristics.

At 25°C



By examining the transfer characteristics of a typical low barrier Schottky detector, one can see the effect of load resistance on the output voltage. Note that in the range of −30 to −20 dBm the output voltage changes by 10 to 1, thus indicating square law operation. At higher power levels, the slope of the transfer function is cut in half, which is an indication of linear operation.

## Comparison of Low and High Level Signals



**Square Law**

P < 10 microwatts into 50 ohms
Detected voltage proportional to
the square of applied signal.

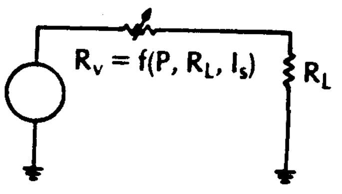
**Linear**

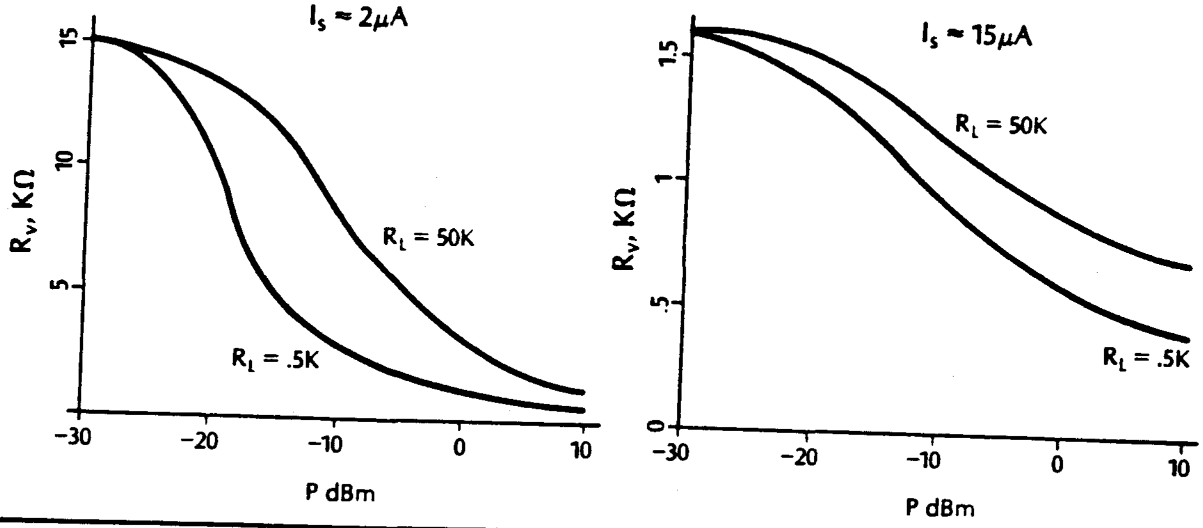
Power levels greater than 10 milliwatts
Detected voltage proportional to
the peak RF voltage.

**Video loading will lower the detected voltage**

In the square law region, the waveform of the diode current is almost identical to that of the input signal. Under large signal operation, the diode current waveform becomes a function of input signal level and video output voltage. The output voltage becomes a complicated function of load resistance, power level, and diode characteristics. The key point is that the detection law will undergo a transition from square law to linear. This occurs when the junction voltage exceeds Vt. In the linear mode the diode is acting like the familiar peak detector.

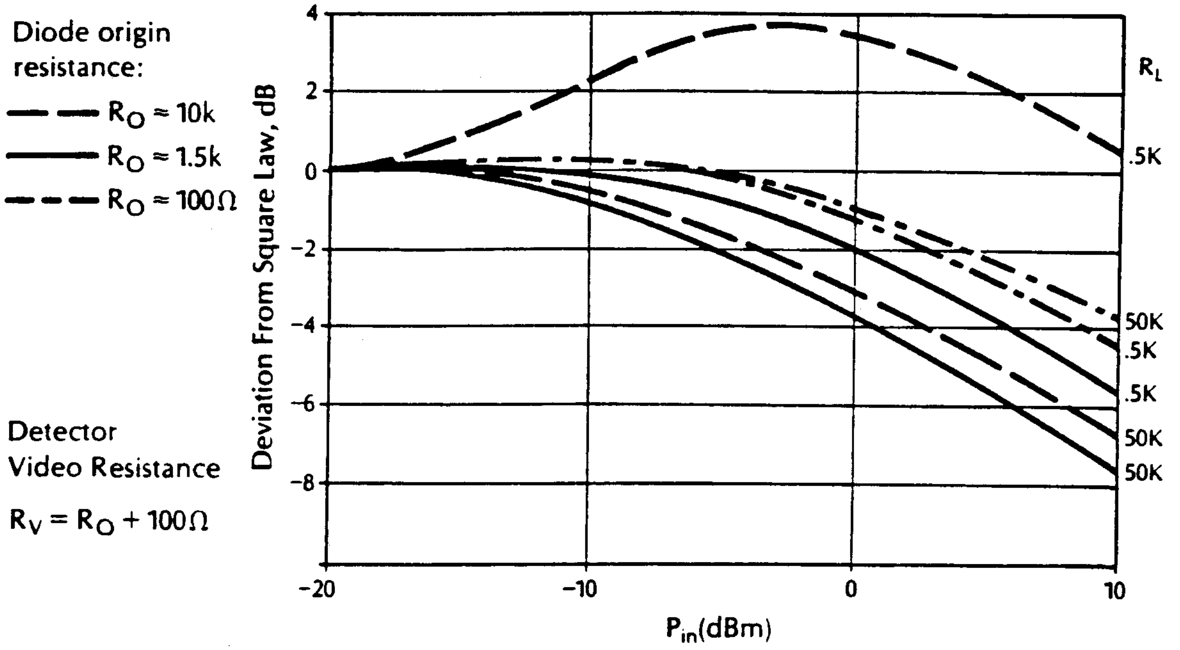
# Video Resistance Rv Varies with Power, $R_L$ and Is





When the diode is in square law, the video resistance is essentially constant, but at higher power levels the current through the diode exceeds Is and the video resistance becomes a complicated function of power, load resistance, and Is. For low barrier diodes, Is determines Rv at low levels. At high levels the value of Rv is determined by the actual diode current and the other resistors in the detector circuit. The percentage change in Rv and the actual transition from square law to linear is governed by Is and $R_L$ and the decreasing value of Rv can be used to extend the square law range.

## Transition from Square Law to Linear is Governed by Ratios $R_V/R_O$ and $R_L/R_O$



Typical Square Law Deviation

The square law deviation is a measure of the error between the diode output voltage relative to that produced by a true power sensing device. The data presented shows that the transition from square law to linear is a strong function of video load. This can be understood by observing that at high levels the output impedance of the detector is decreasing, thus the voltage divider action is reduced and tends to compensate for the compression in the diode output. This effect can be used to extend the square law region about 10 dB. The effect of load resistance on diode law is determined by the ratios of Rv/Ro and $R_L$/Ro. If Ro is large, the video resistance Rv is about equal to Ro and the diode law in the transition region of −20 to 0 dBm will be a strong function of $R_L$. If the Ro of the diode is lower, loading will not have as much effect.

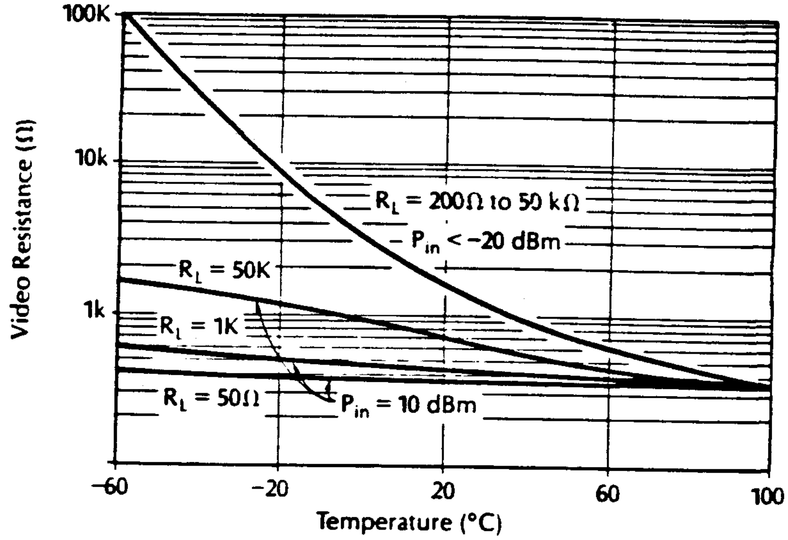
# Temperature Effects

With proper bias circuit design, temperature effects on high barrier detectors can be minimized

Performance of low barrier Schottky is governed by variation in $I_S$

$(R_O = \frac{V_t}{I_S})$ $I_S$ doubles for 20°C$\Delta$T

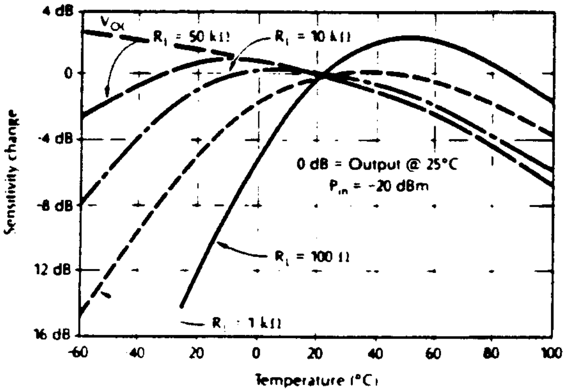
Video resistance is also a function of power and $R_L$. If diode is in linear region, temperature sensitivity decreases.



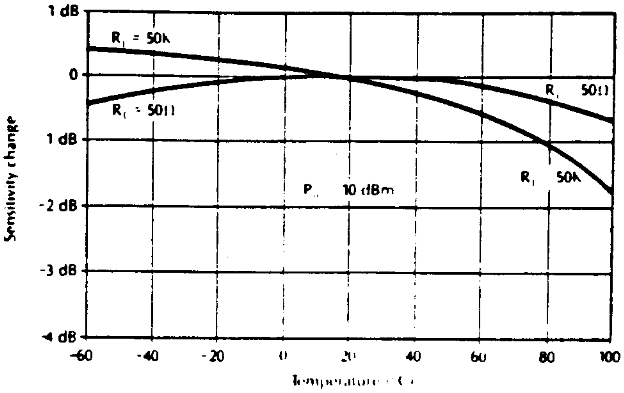
Typical Video Impedance Variation with Temperature.

The biggest contributor to temperature effects is the variation in Is. For the detector this translates to a change in video resistance. As can be seen, this change can span about 2½ decades over a −60 to 100°C temperature range. At higher power levels, the change in Is is masked by the large currents flowing in the diode, so the high level resistance may only change by a factor of 3 or less.

# Due to variation in $R_V$, the temperature coefficient of low barrier Schottky detectors is a strong function of load resistance and power level



**Low Power**



**High Power**

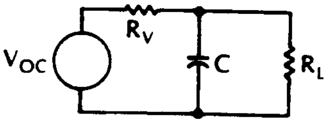
Since the square law deviation is governed by

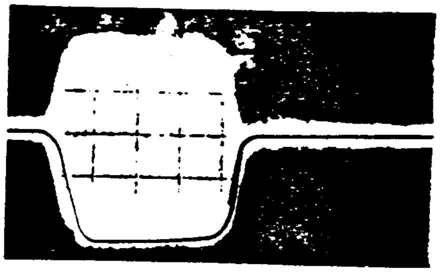
$$\frac{R_V}{R_O} \text{ and } \frac{R_L}{R_O}$$

the square law deviation will also be a temperature sensitive parameter when $R_L < R_O$

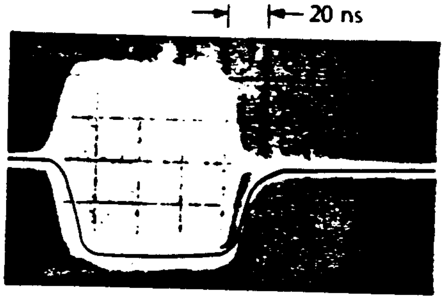
The effect of Is variations, power level, and video load makes the change in sensitivity with temperature a rather complicated function. The data presented here covers an extreme range. Over a narrower temperature range, sensitivity changes can be minimized by selection of an optimum video load, or by designing a temperature compensating amplifier. Since the ratio of $Ro/R_L$ determines the square law deviation, this parameter will also show a temperature dependence. The data presented earlier was actually obtained from the same diode measured at −25, 25 and 100°C. One can conclude from this that an optimum design exists for a specific application, but no optimum exists for all applications.

# Risetime of Detector

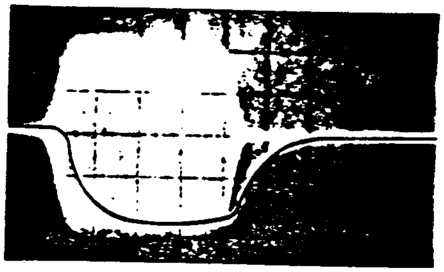




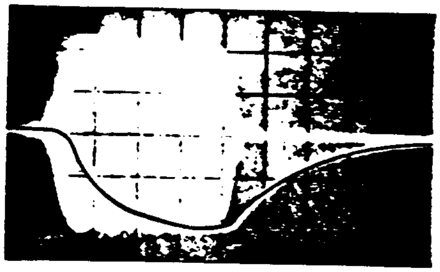
$R_L = 25\Omega$



$R_L = 50\Omega$



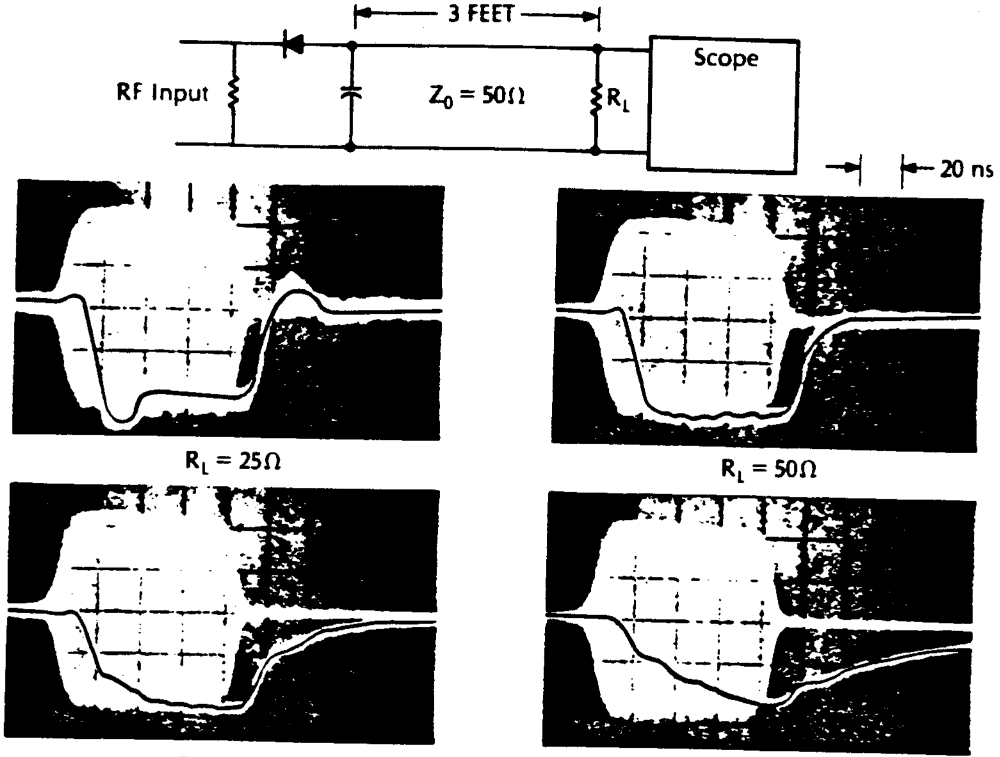
$R_L = 100\Omega$



$R_L = 300\Omega$

Video loading is an important consideration during the measurement of pulsed RF signals. If one is dealing with fast risetime pulses several precautions have to be exercised. The output of the detector is taken across a capacitor so the RC time constant of the detector and load has to be small. The data presented shows the envelope of a 10 mW pulse overlayed on the detected output. Since the diode is acting as a peak detector, the video impedance of the detector is low so the rise time is quite fast. The decay time is governed only by the load resistance and can be appreciably longer.

# Effect of Cable



$R_L = 25\Omega$

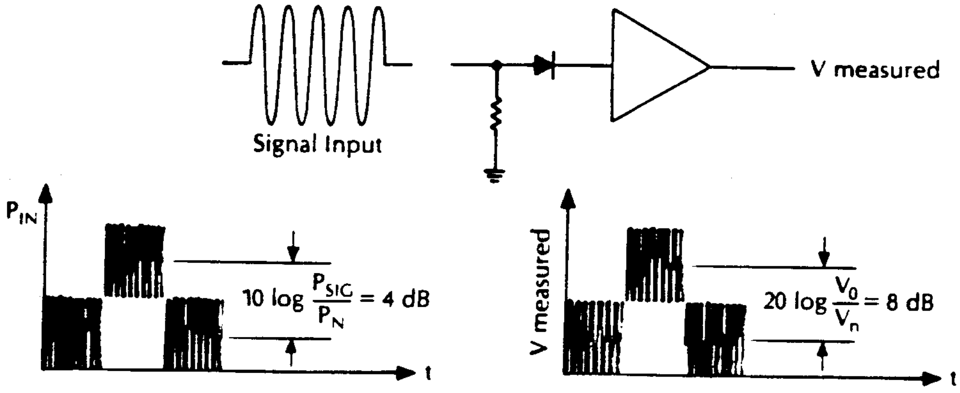
$R_L = 50\Omega$

$R_L = 100\Omega$

$R_L = 300\Omega$

Often a cable is used between the detector and the scope. This cable should be terminated in its Zo to minimize the effect of multiple reflections bouncing between the scope and the detector. If the rise times are long with respect to the time delay in the cable, an accurate estimate of cable effects can be obtained by simply adding the capacitance of the cable to the output capacitance of the detector.

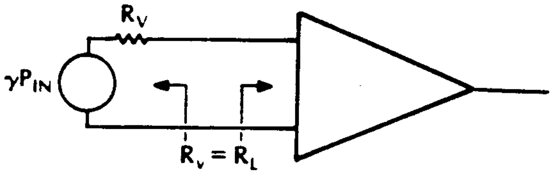
# Tangential Signal Sensitivity (TSS)



TSS is accepted to be the signal level required to produce an 8 dB S/N at the system output. This is equivalent to a 4 dB S/N at the detector input.

A very common systems specification for a detector is its tangential signal sensitivity (TSS). The TSS point is generally regarded as the amount of RF power required to produce an 8 dB S/N ratio at the system output. Sometimes this is referred back to the input of the square law device, and the ratio is that of power and is 4 dB. The derivation of the TSS level is interesting because it points out the parameters one can work with to maximize the sensitivity of a system.

# TSS Derivation



**For maximum power transfer $R_L = R_V$**

**Signal input power**

$$P_S = \frac{(\gamma P_{IN})^2}{4\,Rv}$$

$P_{IN}$ = RF power
$\gamma$ = Open circuit voltage sensitivity
$R_v$ = Video resistance of diode

**Equivalent input noise power**

$$P_N = KTBF$$

K = Boltzmann constant
T = Absolute temperature
F = Amplifier noise figure
B = Amplifier bandwidth

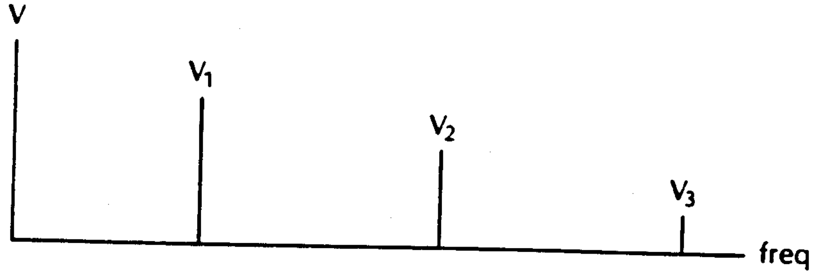
Using 8 dB S/N at output $\frac{P_S}{P_N} = 10^{8/10} = \frac{(\gamma P_{TSS})^2}{4R_V KTBF}$

$$P_{TSS} = 3.23 \times 10^{-10} \frac{\sqrt{BFR_V}}{\gamma} \text{ watts: at 300K}$$

Since the diode is operated in square law, its small signal model can be used. To extract maximum power from the diode it must be loaded by with $R_L$ = Rv. The video amplifier has a noise figure F so the equivalent input noise can be found. By finding the ratio of signal power to noise power and applying the appropriate ratio of S/N, the power at the tangential signal level can be computed. Note that the diode related parameters do not offer much help in obtaining higher sensitivities. In resistively matched detectors, the sensitivity is diode independent until Rv is reduced to rather low levels. In reactively matched detectors, high sensitivity can be obtained at the expense of RF bandwidth but the high Rv increases the noise, and biased diodes must be used to minimize the effect of Is variations with erature. The offset voltage produced by the bias makes it difficult to measure low level signals unless AC coupling is used. The biggest improvements in sensitivity are obtained by reducing the system noise figure and bandwidth. Note that the noise produced by the diode is the same as the noise produced by a resistor of value Rv. This discussion applies directly to zero biased diodes. For biased detectors the presence of excess noise (especially 1/F) produced by the bias current can place another limitation on their ultimate sensitivity.

# Non Sinusoidal Signals

$$V_{det} = KV_{rf}^2$$



The analysis predicts, and experimental evidence confirms, that the output of a square law detector will be:

$$V_{det} = K(V_1^2 + V_2^2 + V_3^2)$$

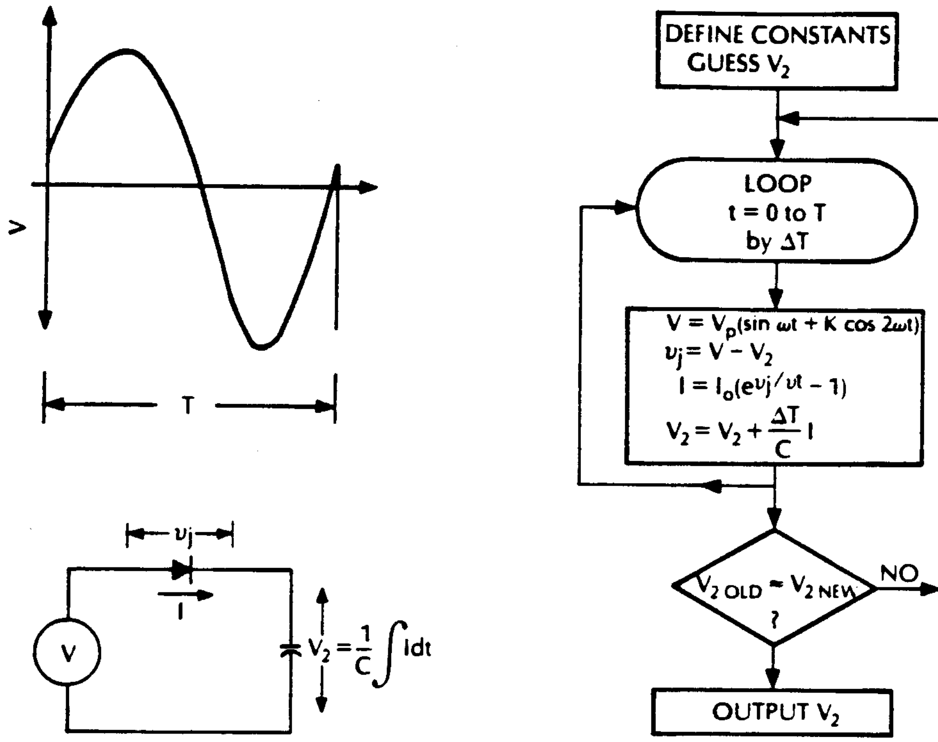
Signal Power

$$P_{sig} = \frac{1}{R}\ (V_1^2 + V_2^2 + V_3^2)$$

As we have seen, the output of a square law detector may be expressed by a constant multiplied by the square of the RF input voltage. If the signal is not sinusoidal, it can be described by a number of frequency components such as harmonics or modulation sidebands. It can be determined analytically and verified experimentally that the output of the square law diode will be proportional to the sum of the squares of the individual frequency components. Except for a constant, this is identical to the expression for the power content of the signal. Probably the most dramatic demonstration of the ability of the diode to measure total power is the application where the square law diode is used to accurately measure broadband noise power.

When the diode is operated out of square law its response transforms to a peak detector and the direct indication of power is not obtained. Circuits which compensate or "shape" the diode output will only correct for the diode's response to a particular signal, generally a sinusoid. If the signal is not sinusoidal, the relationship of peak to RMS voltage (power) is different and results in an error for the power measurement.

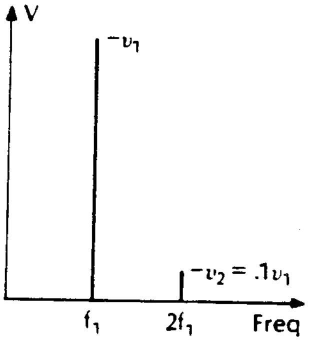
# Simplified Non Linear Detector Model

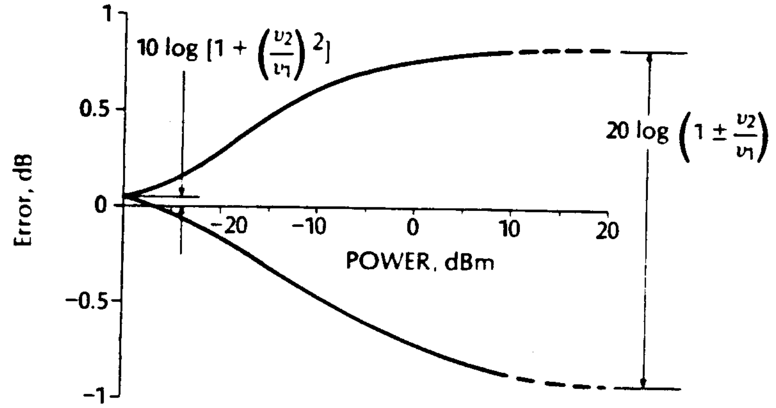


It is difficult to experimentally evaluate the error in power measurements introduced by the presence of harmonics because the diode output at high levels is a function of the precise phase relationship of the fundamental to the harmonic. A very simple nonlinear analysis procedure provides a method of studying this effect.

The analysis procedure is a numerical solution for the integral equation that describes the voltage appearing on the bypass capacitor. The instantaneous source voltage V is calculated, the junction voltage is determined, and the diode equation is applied to calculate the current I. This current is integrated over a complete cycle. After each cycle the capacitor voltage is tested to see if it changed appreciably. If a change is noted another calculation is made; if not, the results are printed.

# Error Produced by 2nd Harmonic Predicted by Simple Model





Estimated maximum error limits,
for harmonic 20 dB below fundamental

This analysis procedure was used to predict the worst case error a second harmonic 20 dB below the fundamental could produce when measuring power with a diode. At low power levels, the diode output is found to be .04 dB high which corresponds to the 1% additional power added by the harmonic. At high levels the detector output is seen to vary by the direct sum of the two voltages, which is an uncertainty range of 0.83 to −0.92 dB, or roughly ±20% when related back to an equivalent power input. The precise transition from square law to linear is a function of detector and load, and experimental evidence shows that actual diodes show somewhat less deviation than the simple analysis predicts.

# More Refined Models Can Predict Temperature Effects

Temperature Sensitive Parameters

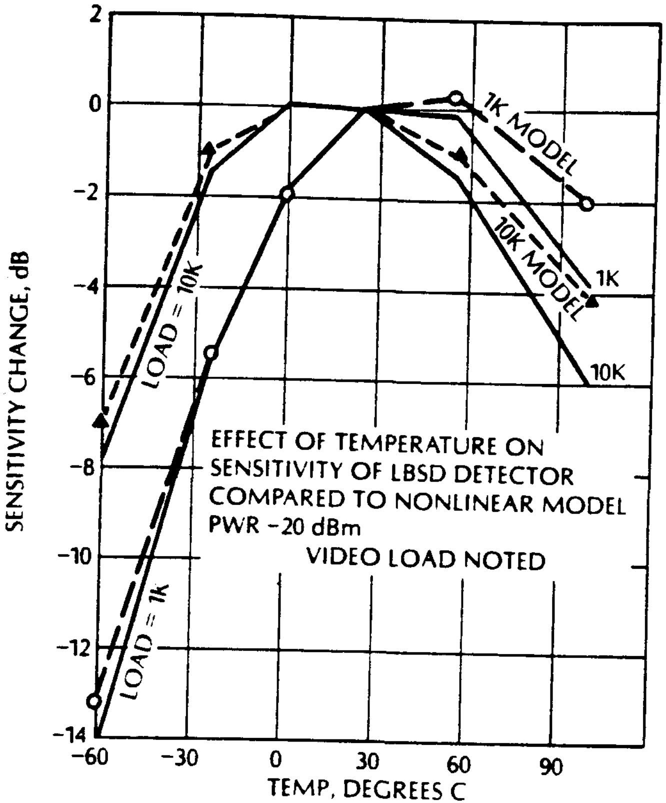
Reverse Saturation Current $I_S$
≈ 2:1 for 20°C $\Delta T$

Shunt Conductance $G_S$
Tracks $I_S$

"Thermal Voltage"

$$v_T = \frac{nKT}{q}$$

Spreading Resistance $R_B$
$R_B = k\,T_{ABS}$



While we are on the subject of modeling, it might be interesting to see the results obtained from a more detailed study which was performed to verify the results obtained from a temperature test of the low barrier Schottky detector. The only parameters which were varied in the model to account for a temperature range of −60 to 100°C were Is, Gs, Vt, and Rb. The fit between model and actual results is fairly good over from −60 to 55°C, but some error is noted at 100°C. Most likely, the simple "thumb rule" estimates for the diode parameters are breaking down and direct measurements of these as a function of temperature might yield a better fit.

## Summary

Square law detection
Circuit realizations
Performance characteristics
Temperature effects
Pulse measurements
Effect of signal waveforms

Various aspects of diode detectors have been discussed. Square law detection, circuit realizations, loading effects, temperature characteristics, tangential sensitivity, risetime, and effects of harmonics are all factors which effect the performance of a detector in a particular application. As with many devices, the multitude of interacting parameters makes it impossible to define a universal solution for all measurement problems. Hopefully, this work will aid in making the proper tradeoffs necessary to achieve the desired level of performance in a given system.

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