Errata

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HP References in this Application Note

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The Zero Bias Schottky Detector Diode

Application Note 969

Introduction

A conventional Schottky diode detector such as the Hewlett-Packard HSMS-8101 requires no bias for high level input power — above one milliwatt. However, at low levels, a small amount of dc bias is required for detection to take place. Even though this bias current is at the microampere level, this requirement is often difficult to supply. A Schottky diode has been developed to eliminate this need for dc bias.

Forward Voltage Characteristic

Since all diodes in this discussion are Schottky diodes, the forward current obeys the equation:

$$I = I_S \left(e^{\frac{q}{nkT} (V-IR_S)} -1 \right)$$

The ideality factor, n, is close to unity for these diodes, so the equation may be written:

$$I = I_S \left(e^{\frac{V-IR_S}{.026}} -1 \right)$$

where the values for the constants q, electron charge, T, room temperature, and k,

Table 1.

Part Number	I_S (Amps)	n	R_S (Ω)	C_j (pF)
HSMS-8101	9×10^{-8}	1.08	4	0.23
HSMS-2850	3×10^{-6}	1.06	25	0.17
HSCH-3486	5×10^{-6}	1.08	50	0.1

Boltzmann's constant, have been inserted. The main difference in the behavior of the different types of diodes is embodied in I_S, the saturation current, There may also be differences in R_S, the series resistance.

Figure 1 shows the forward current characteristics of the HSMS-8101 Schottky diode and two versions of zero bias diodes, HSMS-2850 and HSCH-3486. These curves are close to the curves predicted by the diode equation with the constants shown in Table 1. HSMS-8101, a conventional (n-type or mixer) Schottky requiring dc bias to operate as a detector, stands out from the two (p-type) zero bias diodes with its very low value of saturation current and its low series resistance.
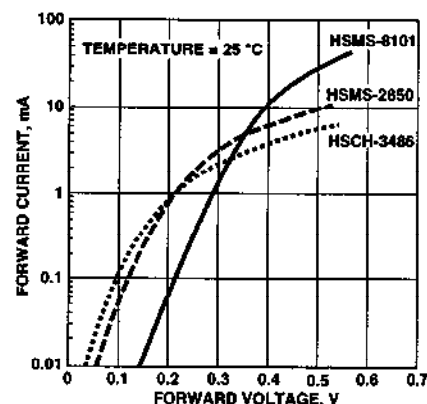

Figure 1. Forward Characteristics of Detector Diodes.

Voltage Sensitivity

A detector diode may be treated as a current generator across the diode video resistance.[1] The voltage sensitivity, γ, is the product of the current sensitivity, β, and the video resistance, the inverse of the derivative of current with respect to voltage.

The Perfect Detector

Neglecting parasitic and reflection losses:

$$\gamma = \beta \, / \, \frac{\partial I}{\partial V}$$

For small values of current:

$$I = I_S \left(e^{\frac{V}{.026}} - 1 \right)$$

and

$$\frac{\partial I}{\partial V} = \frac{I + I_S}{.026}$$

The theoretical current sensitivity is 20 amperes per watt [2] so:

$$\gamma = \frac{0.52}{I + I_S}$$

or, for zero bias current:

$$\gamma = \frac{0.52}{I_S}$$

This analysis indicates no advantage in using the zero bias diodes because sensitivity varies inversely as saturation current and the standard HSMS-8101 diode has the lowest saturation current. In fact, no improvement is needed since the sensitivity is:

$$\gamma = \frac{0.52}{9 \times 10^{-8}} = 5.8 \times 10^6 \text{ volts per watt}$$

or 750,000 millivolts per microwatt.

Since the actual sensitivity of the HSMS-8101 detector with zero bias is close to zero, some major corrections in the analysis are needed. Consideration of the effects of junction capacitance, load resistance, and reflection loss will bring this analysis close to reality.

Junction Capacitance

The effect of junction capacitance on current sensitivity has been derived in Section 11.2 of Reference 1. Adding this effect to the voltage sensitivity analysis gives:

$$\gamma_1 = \frac{0.52}{I_S (1 + \omega^2 \, C^2_j \, R_S \, R_V)}$$

For a typical case,

$$C_j = 0.1 \text{ pF}, R_S = 50 \text{ ohms},$$

and $R_V = \dfrac{0.026}{I_S}$,

so that:

$$\gamma = \frac{1,000}{f^2 + 2 \times 10^6 \, I_S} \quad \frac{mV}{\mu W}$$

with frequency in gigahertz and saturation current in amperes. Figure 2 shows how capacitance modifies voltage sensitivity. Since the change is due to the rf current split between C_j and R_V, the reduction is more severe at higher frequencies, when the capacitive susceptance is higher. The inverse relationship with saturation current is still present at low frequencies or high saturation current values. However, predicted values of voltage sensitivity are still unreasonably high.

Load Resistance

A detector diode may be considered as a video voltage source of impedance R_V feeding a load resistance R_L. The voltage across the load, γ_2, is reduced by the ratio of R_L to $R_V + R_L$:

$$\gamma_2 = \gamma_1 \, \frac{R_L}{R_V + R_L} = \frac{\gamma_1}{1 + \dfrac{R_V}{R_L}}$$

When the ratio of video resistance to load resistance is small, $\gamma_2 = \gamma_1$. This is a common condition for biased detectors. However, at zero bias, the diode resistance is usually not small compared to load resistance. For a typical load resistance value of 100 KΩ, the sensitivity is:

$$\gamma_2 = \frac{\gamma_1}{1 + \dfrac{26 \times 10^{-8}}{I_S}}$$
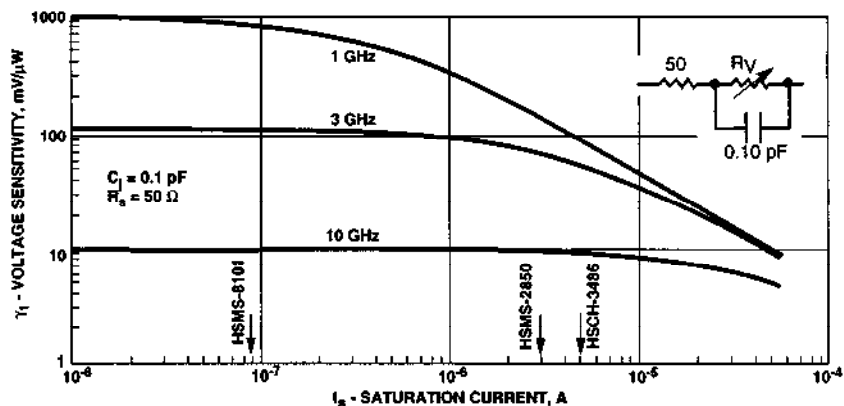

Figure 2. Effect of Capacitance on Voltage Sensitivity.

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The effect of load resistance is shown in Figure 3. The inverse relationship between sensitivity and saturation current in γ_1 combined with the direct relationship due to load resistance results in a maximum voltage sensitivity when $I_S = 3 \times 10^{-7}$ A. However, these theoretical results for γ are still unreasonably high, particularly at the lower frequencies.

Reflection Loss

The analysis so far has assumed that all incident power is absorbed by the diode. Normally this is a good assumption because low loss matching circuits can be designed to eliminate reflection losses. With zero bias detectors, however, the mismatch may be so severe that it is not possible to eliminate these reflection losses. In fact, most of the incident power may be absorbed by losses in the matching network. If we go to the other extreme and assume no matching, the sensitivity becomes:

$$\gamma_3 = \gamma_2 (1 - \rho^2)$$

where ρ is the reflection coefficient of the diode. Assuming the diode impedance, Z_D, terminates a 50 ohm system:

$$\rho = \frac{Z_D - 50}{Z_D + 50}$$

The diode impedance is a function of the package parasitics as well as the frequency.

While the calculation of ρ is straightforward, it requires a knowledge of the diode parasitics. In Figure 4, an equivalent circuit is shown for the HSCH-3486 zero bias Schottky diode, including package inductance and package capacitance. Assuming a value of $R_V = 5$ KΩ (calculated from the value of I_S given in Table 1), ρ can be calculated as shown in Figure 4. Note that the package inductance resonates with the package and diode junction capacitance to produce a partial impedance match near 7 GHz. Using these data for ρ, one can calculate γ_3, as shown in Figure 5, for a diode immersed in a 50 Ω system without impedance matching networks.

Note that the values of I_S for the three diodes under discussion are flagged in Figures 2, 3 and 5. However, those three curves were calculated based upon a value of R_S and C_j which are typical only of the HSCH-3486.
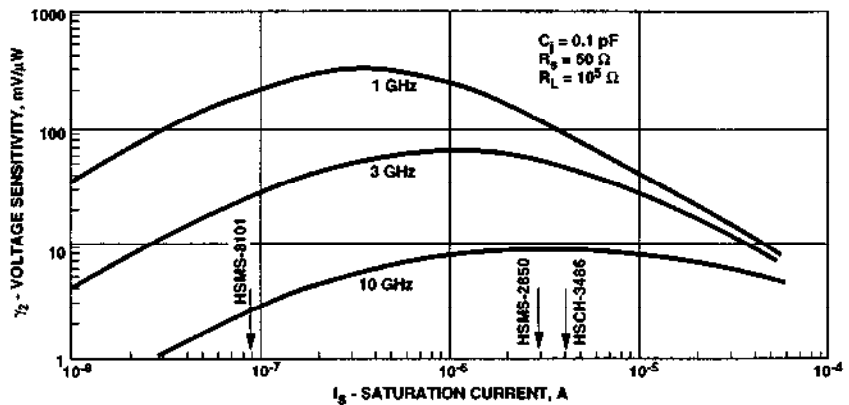

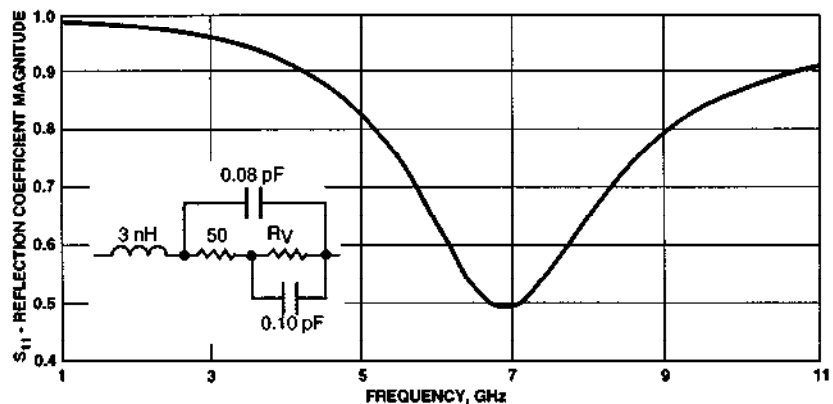Figure 3. Effect of Load Resistance and Capacitance on Sensitivity.

Figure 4. Reflection Coefficient for the HSCH-3486.

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The effects of the package parasitics show up clearly in Figure 5. Overall values of sensitivity are dramatically reduced at 1 GHz, where ρ is very nearly equal to unity. At 3 GHz, sensitivity is reduced, but not by so much as at 1 GHz, with the result that γ_3 is higher at 3 GHz than at the lower frequency. The reduction in sensitivity at 10 GHz due to package parasitics is quite small, since ρ is lower at that frequency for the HP package 18.

The calculations and discussions so far make it difficult to directly compare the two zero bias Schottky diodes. Using the equations given earlier, one can calculate γ_2 for the HSCH-3486 and the HSMS-2850 as a function of frequency, as shown in Figure 6.

The different values of C_j, I_S and R_S of the two diodes result in the HSMS-2850 providing greater performance at frequencies below 3 GHz while the HSCH-3486 yields superior sensitivity at higher frequencies.

In theory, one can achieve voltage sensitivities as shown in Figure 6 over a narrow band of frequencies through the use of a low loss impedance matching network at the input to the diode[3]. However, this is unfortunately not the case at the lower frequencies where the reactance of the C_j is low, resulting in a very high value of impedance for the R_V - C_j parallel combination (in excess of 1 KΩ). The finest silver-plated stub tuners lack sufficient Q to match the very high value of ρ to 50 Ω — the high standing wave at the diode terminals (output of the tuner)

cause losses in the best tuners to rise dramatically. The situation is even worse when the impedance matching network is realized in some lower-Q medium such as microstrip. As a result, a value of 40 mV/μW at 1 GHz and 30 mV/μW at 3 GHz represent a practical upper limit to γ in real-world detector circuits.
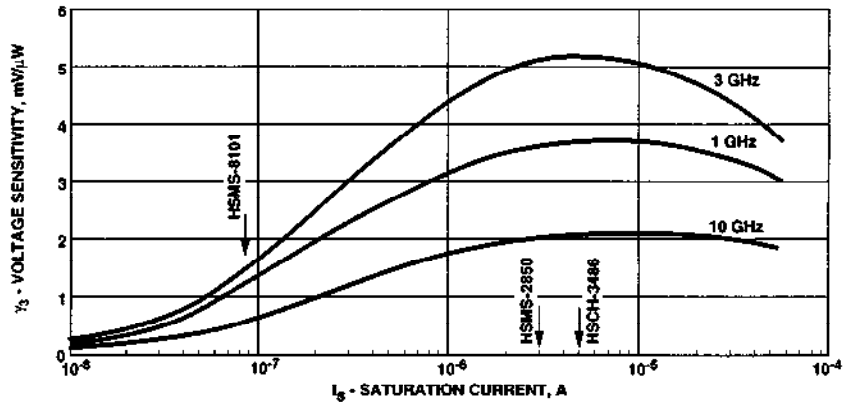

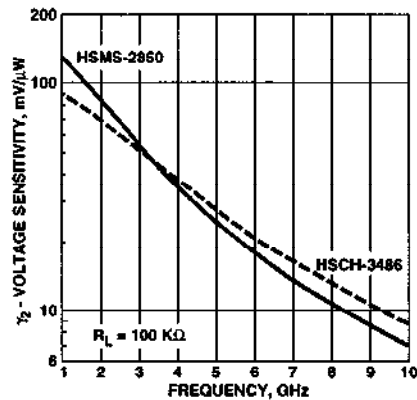Figure 5. Effect of Mismatch, Load Resistance and Capacitance on Sensitivity.

Figure 6. Comparison of Two Zero Bias Schottky Diodes.

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Temperature Effects

All of our computations so far have assumed a temperature of 300° K. The first equation in this note indicates that, for a given value of forward voltage, the forward current of a Schottky diode depends upon temperature. β, the diode's current sensitivity, is also a function of temperature[4]. Reference 4 gives a good treatment of temperature effects of a Schottky diode with fixed (external) bias. However, in a zero bias Schottky, I_s is also temperature-dependent, adding an extra variable to the total equation for γ vs. temperature. Thus it is that a complete discussion of the effects of temperature on voltage sensitivity is beyond the scope of this note.

Measurement of C_j and R_V

The Schottky diode (without package) can be represented by the three element equivalent circuit shown in Figure 2. R_s (50 Ω in this case) is easily measured. However, the measurement of R_V and C_j cannot be done by conventional means.

Typically, the junction capacitance of a Schottky diode is measured at 1 MHz. For a conventional diode such as the HSMS-8101, $R_V = 0.026/I_s$ is very high, permitting the measurement of junction capacitance at this low frequency. In these diodes, video resistance is determined by the external dc bias which is applied when they are used.

In a zero bias Schottky, however, R_V is set by the saturation current and is thus

an unknown. Moreover, it is the nature of zero bias Schottky diodes that R_V will be lower than $1/\omega C$ at 1 MHz, thus shorting out the capacitance and making it impossible to measure by conventional means. Some simple calculations, based upon the diode equivalent circuit shown in Figure 2, will reveal the fact that C_j for zero bias Schottky diodes must be measured at frequencies much higher than those used in capacitance or impedance bridges.

A convenient method of measurement involves measuring the diode's attenuation as a series element in a 50 Ω transmission line. Very low power levels are used in an instrument such as the HP8753C (which offers the advantage of a logarithmic frequency scale), resulting in a display like the example shown in Figure 7.

At low frequencies, the video resistance sets the attenuation, since $1/\omega C$ is so high. However, at VHF (and higher) frequencies, junction capacitance dominates the total attenuation. Straightforward modeling (as shown in the figure) permits the calculation of $C_j = 0.091$ pF and $R_V = 7.5$ KΩ for the sample tested.
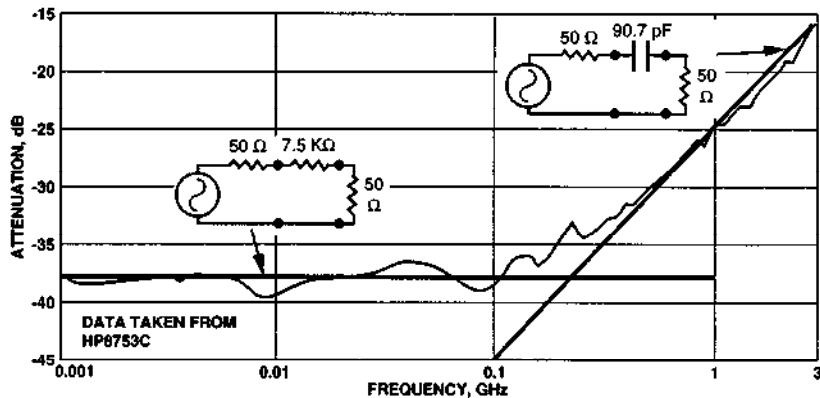

Figure 7. HP8753C Display

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Summary

Detector diodes are most sensitive at zero bias when the saturation current is small, corresponding to large video resistance. However, there is a limit to sensitivity when the resistance is so large that it cannot be matched. An optimum diode is designed to have the proper saturation current. Choice of saturation current involves a compromise between sensitivity due to large resistance and loss due to matching.

References

1. Torrey, H.C. and Whitmer, C.A., "Crystal Rectifiers", MIT Radiation Laboratory Series, Vol. 15, McGraw-Hill (New York) 1948.

2. Watson, H.A., "Microwave Semiconductor Devices and Their Circuit Applications", P. 379, McGraw-Hill, 1969.

3. Hewlett-Packard Application Note 963, *Impedance Matching Techniques for Mixers and Detectors.*

4. Hewlett-Packard Application Note 956-6, *Temperature Dependence of Schottky Detector Voltage Sensitivity.*