



# Responsivity and Noise Measurements of Zero-Bias Schottky Diode Detectors

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**Abstract** — Schottky barrier diodes can be used as direct detectors throughout the millimeter- and submillimeter-wave bands. When the diodes are optimized to have a low forward turn-on voltage, the detectors can achieve excellent frequency response and bandwidth, even with zero-bias. This paper reports on the characterization of VDI’s zero-bias Schottky detectors. Responsivity typically ranges from 4,000 V/W at 100 GHz to 400 V/W at 900 GHz and each detector achieves good responsivity across the entire single-mode bandwidth of the input rectangular waveguide. Under low power operation the detectors achieve a measured noise-equivalent-power (NEP) of about  $1.5 \times 10^{-12}$  W/ $\sqrt{\text{Hz}}$ , even without signal modulation. Such high sensitivity is expected for any zero-bias diode detector with high responsivity when there is no incident RF power; since only thermal noise can be generated under this condition. However, as the input power is increased, excess noise is generated. This noise typically has a 1/f power spectrum and is commonly known as flicker noise. Flicker noise becomes increasingly important as the input power is increased and signal modulation is generally required to achieve maximum sensitivity. The signal-to-noise of the VDI zero-bias detectors has been carefully measured as a function of input power and modulation rate. This data allows the user to understand the sensitivity of the detector under real operating conditions, and is therefore far more useful than the simple measurement of detector NEP with zero RF power, which is commonly quoted in the literature for new diode detector designs.

**Index Terms** — Terahertz detectors, zero-bias detectors, noise-equivalent power, flicker noise.

## I. INTRODUCTION

This article describes the characterization and measurement of the responsivity and noise properties of zero-bias Schottky detectors that have been developed at Virginia Diodes, Inc. The Schottky diode detector has a long history of use for the detection of power at mm- and submm-wavelengths [1]. Diode detectors can operate at ambient or cryogenic temperature and have an extremely fast response time compared with other room temperature detectors, such as Golay cells, pyroelectric detectors, or bolometers [2,3]. An important factor in considering the usefulness of all diode detectors is the excess noise sources beyond thermal and/or shot noise, such as 1/f or flicker noise. Although zero-bias diodes cannot generate significant excess noise at very low input power levels, as

the input power is increased the flicker noise also increases and eventually becomes the dominant noise mechanism. Thus, characterization of the detector requires measurement of the diode’s noise properties across the range of input power levels over which it will be used.

VDI’s Schottky diode detectors use rectangular waveguide housings and the entire circuit is optimized for operation over the full single-mode waveguide band without any mechanical tuners. Their responsivity typically ranges from about 4,000 V/W at 100 GHz to 400 V/W at 900 GHz. The primary goal of this investigation has been to characterize the sensitivity of the VDI zero-bias detectors. Thus, this paper describes measurements of the diode’s noise properties over a wide range of input power levels. The diode responsivity, NEP and signal-to-noise ratio (SNR) are presented.

## II. DIODE I-V CHARACTERISTICS

The VDI detector diodes are planar Schottky barrier diodes fabricated in a flip-chip configuration using the basic process described in [4]. This configuration, as shown in Fig. 1, allows for a low parasitic contact that is mechanically rugged and repeatable. The measured I-V of a WR-10 detector diode is shown in Fig. 2. In order to determine the theoretical voltage responsivity of the diode a least-squares curve fit was made between the measured data and the exponential Schottky diode I-V equation [5]. The measured and curve-fit data for the WR-10 diode near zero-bias are shown in Fig. 3. The least-squares curve fit parameters for this diode were determined to be  $I_{\text{sat}}=11 \mu\text{A}$ ,  $R_s=19 \Omega$ , Ideality Factor,  $\eta=1.13$ . The zero-bias junction resistance,  $dV / dI = V_o / I_{\text{sat}}$ , is 2.6 k $\Omega$ ; where  $V_o = \eta kT/q$ .

The intrinsic voltage responsivity of the diode can be determined from the diode I-V equation, as [6]

$$R_v = \left. \frac{-\frac{d^2V}{dI^2}}{\frac{dV}{dI}} \right|_{I=0} = \frac{1}{I_{\text{SAT}}} \quad (1)$$

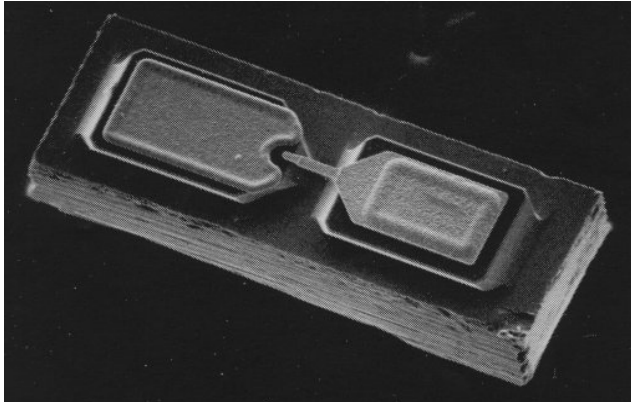


Fig. 1. Scanning electron micrograph of a planar Schottky barrier diode. Chip dimensions approximately 180x80x40  $\mu\text{m}$ .

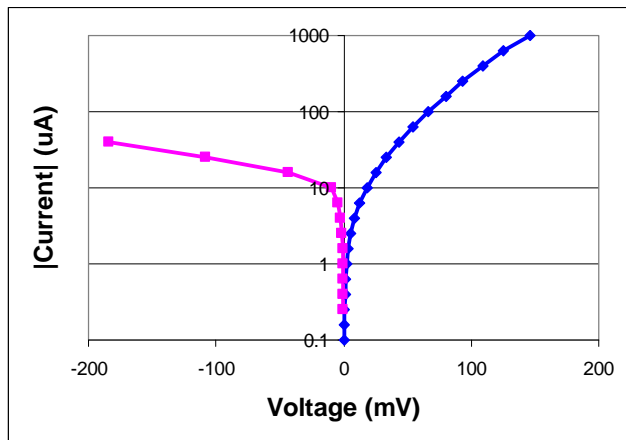


Fig. 2. The measured current-voltage characteristic of the zero-bias flip-chip WR-10 Schottky detector diode.

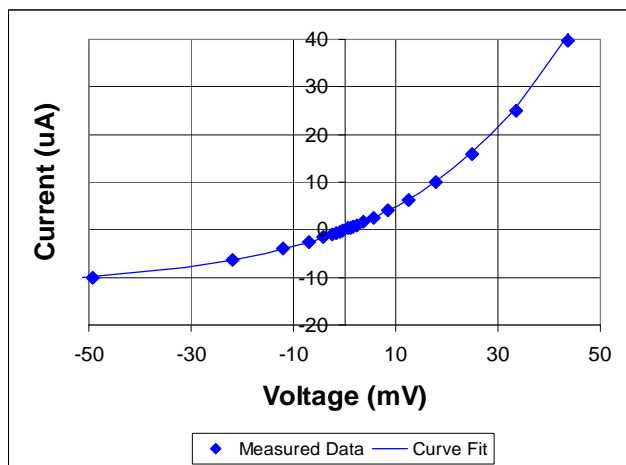


Fig. 3. Curve fit of exponential diode I-V of WR-10 detector diode to measured data near zero bias. Curve fit parameters  $I_{\text{sat}}=11 \mu\text{A}$ ,  $R_s=19 \Omega$ , Ideality,  $\eta=1.13$ .

### III. MEASUREMENTS OF DETECTOR RESPONSIVITY

Measurements over the WR-10 frequency band were made of the voltage responsivity of the detector diode discussed in the previous section. The responsivity is shown in Fig. 4. The input power to the detector was kept in the range from 3-5  $\mu\text{W}$ , which insured that the detector was operating in the square-law region. A WR-10 directional coupler was used to set the input power into the detector and to thereby eliminate the effect of standing waves on the measurement. The measured responsivity matches well with the predicted value of 6,500 V/W, indicating that the diode capacitance has only a small effect in this frequency range.

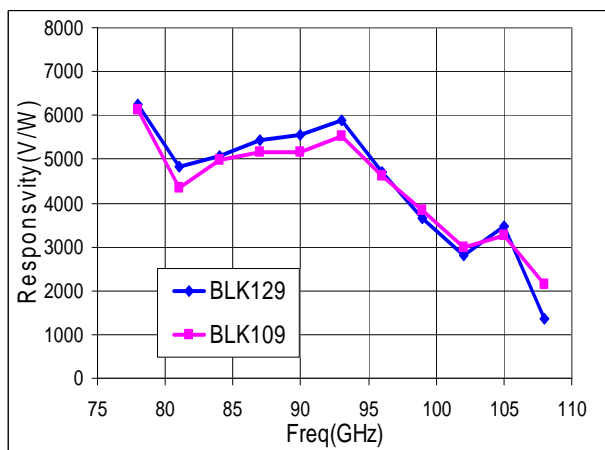


Fig. 4. Measured responsivity of two WR-10 ZBD detectors. The RF power was kept in the square-law region, and ranged from 3-5  $\mu\text{W}$  over the band.

### IV. NOISE MEASUREMENTS OF SCHOTTKY DIODES IN THE LOW SIGNAL REGIME

As a start to understanding the noise properties of these detectors, measurements were made of their zero-bias noise properties. The test configuration consisted of a low noise operational amplifier (input noise 3.2  $\text{nV}/\sqrt{\text{Hz}}$ ) with a gain of 100 followed by a Tektronix TDS744 digital oscilloscope. In order to verify the accuracy of the system, the noise properties of 1  $\text{k}\Omega$  to 10  $\text{k}\Omega$  resistors were measured, and the measurements agreed with theoretical predictions to within 10%. Next, the thermal noise of a model WR-6.5ZBD detector was measured. This detector has a measured zero-bias junction resistance of 1.8  $\text{k}\Omega$ . As shown in Fig. 5, the measured noise was



found to correspond to that of a noisy resistor with the same resistance.

When the detector is used to measure small signals, this thermal noise will be the dominant noise source. Thus, the measured noise voltage and responsivity can be used to calculate the NEP of the detector for low input power levels. The result for the WR-6.5ZBD detector, is shown in Fig. 6. The low power NEP varies from about 1.5 to 2 pW/ $\sqrt{\text{Hz}}$  across the detector band.

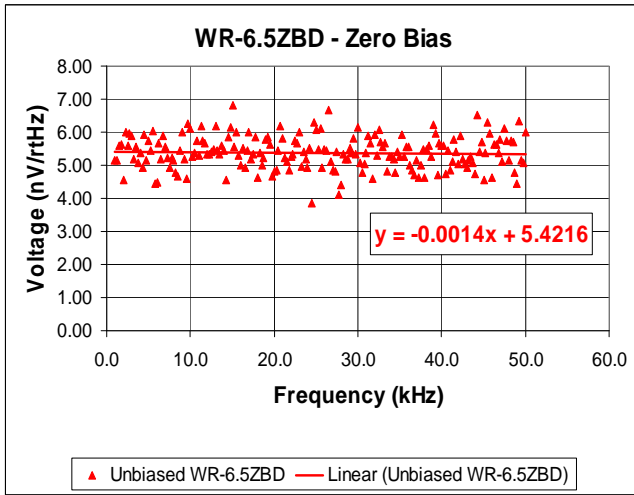


Fig. 5. The measured noise of a WR-6.5ZBD with no applied bias or RF power. The curve fit noise voltage of 5.4 nV/ $\sqrt{\text{Hz}}$  corresponds to the noise from a 1.8 k $\Omega$  resistor, which equals the measured junction resistance for this detector.

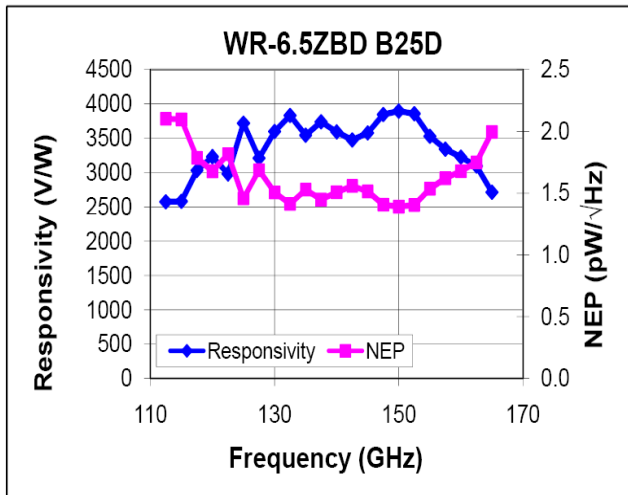


Fig. 6. The noise equivalent power of a WR-6.5ZBD calculated from the measured noise at zero-bias with no RF power and the measured responsivity as a function of frequency across the waveguide band of the detector.

## V. DYNAMIC RANGE OF SCHOTTKY DETECTORS

In order to characterize the performance of the WR-6.5ZBD under applied RF power, its noise properties were measured for varying levels of applied signal power. The measurement setup described in the previous section was used, with the addition of a DC block after the detector to avoid saturating the low-noise amplifier. The measured curves for applied power ranging from -18 dBm to -2 dBm are shown in Fig. 7. As is shown by the curve fits, the measured noise matches the expected 1/f shape.

Using the measured noise characteristics we can determine the effect of the flicker noise on the detector signal-to-noise as the applied power is increased. As shown in Fig. 7, the flicker noise factor increases roughly linearly with the applied power. Figure 8 shows the measured signal-to-noise for the WR-6.5ZBD for modulation rates ranging from 10 Hz to 100 kHz. The top curve (blue) shows the signal-to-noise for an ideal square-law device without 1/f noise and ignoring saturation effects at large signal levels. The next curve (pink) shows the effect of detector saturation, which acts to lessen the S/N improvement as the input power is increased. The three remaining curves show the actual S/N of the detector as a function of input power and modulation rate. For very low modulation rates ( $\sim 10$ Hz) the S/N saturates at rather low input powers, about -40 dBm. However, for 100kHz modulation the impact of the noise is greatly reduced resulting in improved S/N for detector operation at high signal levels.

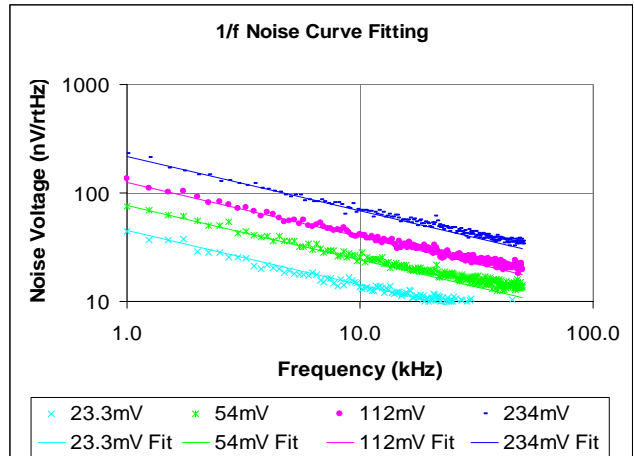


Fig. 7. The measured noise of a WR-6.5ZBD for varying levels of detected signal. The applied power levels were: -18 dBm for  $V_{\text{det}}=23$  mV, -13 dBm for  $V_{\text{det}}=54$  mV, -8 dBm for  $V_{\text{det}}=112$  mV, and -2 dBm for  $V_{\text{det}}=234$  mV.

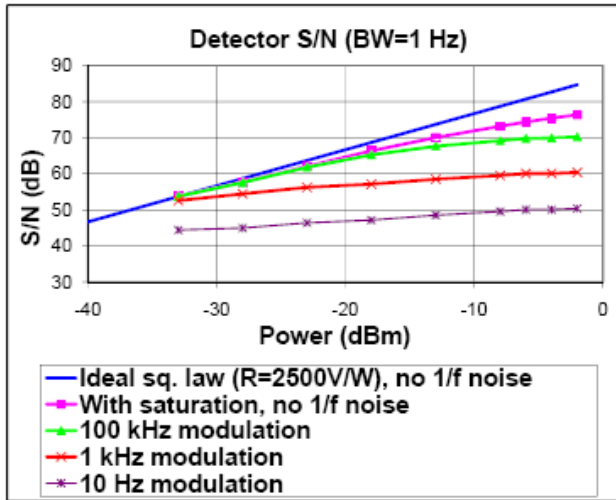


Fig. 8. The WR-6.5ZBD signal-to-noise ratio as a function of the applied signal power (-40 dBm to 0 dBm) and the signal modulation rate (100 kHz, 1 kHz, and 10 Hz). This measured data is compared to two ideal cases without excess noise, first assuming ideal square-law response and second including diode saturation effects.

## VII. CONCLUSION

Measurements of the responsivity and noise properties of VDI's zero-bias detectors have been performed. These detectors have been demonstrated to be extremely fast devices ( $\tau \ll 1$  nS) with broad operational bandwidth and high sensitivity. At small signal levels they have excellent NEP; approximately  $1.5 \text{ pW}/\sqrt{\text{Hz}}$  near 150 GHz; rising to approximately  $20 \text{ pW}/\sqrt{\text{Hz}}$  at 800 GHz. This low-signal NEP could be significantly improved by optimizing the signal coupling to the detector over a narrower frequency band. However, the detector is perhaps more useful for general applications when the coupling is optimized across the full waveguide band.

In large signal applications the flicker noise becomes increasingly significant; and thus modulation is required to achieve optimal sensitivity. The effect of diode saturation and flicker noise on the signal-to-noise ratio of the detectors, as a function of modulation, has been investigated and the results were depicted in a convenient graph.

These results have confirmed that measurements of the NEP of diode detectors at very low power levels is not sufficient to characterize their performance in the broader range of applications where higher power levels are likely to be encountered.

## ACKNOWLEDGEMENT

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