# BROADBAND CHARACTERIZATION OF A COMPACT ZERO-BIAS SCHOTTKY DIODE DETECTOR WITH A CONTINUOUS WAVE THz SYSTEM[*]

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## *Abstract*

Over the last few decades several types of Terahertz (THz) detectors have been developed to maturity, paving the way for various potential applications such as diagnostics of THz generation at particle accelerators. An important class are zero-biased Schottky diode THz detectors that are frequently applied at accelerator facilities for operation at room temperature. Zero-biased Schottky diode THz detectors are having lower noise compared to biased ones due to the absence of shot noise. Here we demonstrate the sensitivity of Schottky detectors using a commercial continuous wave photomixing THz system as source. Both, a commercially available as well as a research-grade compact quasi-optical detector with improved video bandwidth are compared from 0.05 to 1.2 THz in terms of sensitivity. At 1 THz, the research grade quasi optical detector shows 7 dB higher dynamic range than the commercial one.

## INTRODUCTION

Terahertz (THz) radiation generated either from Free Electron Lasers (FELs) or by Coherent Synchrotron Radiation (CSR) sources with high brilliance and power open doors for research and applications(low and high power) in THz domain [1]. Ultra-short pulses with picosecond length are available at several FELs have higher power compared to other table top THz sources and provide the opportunity for characterizing targets at atomic scale and beyond [2, 3]. Optical pump-probe THz (or vice versa) experiments are frequently applied to study matter and materials. These experiments are affected from time jitter as there is no natural phase locking, so that electro-optical sampling is not optimized to use in such cases. This means direct detectors have to be used. For studying the transient behavior, however, the detectors have to be sufficiently fast, with a time constant of the order of a few ps at least. Bolometers and hot-electron detectors [4] are not suitable for such studies. Also, Bolometers need to operate at cryogenic conditions which make the whole setup big, bulky and expensive. Schottky diode- [5,6] and Field Effect Transistors (FETs)-based [2, 3] are handy, easy to use, plug-play and less expensive operating costs compared to their cryogenic counterparts with reported time constants in the range of 6-20 ps [3, 5].

Continuous wave (CW) sources are such as FEL, photomixers and p-i-n diode can be used as THz sources [7] for various experiments such as spectroscopy, medical imaging, communication etc. The available Schottky diodes and FETs THz detectors can be used for these applications. Schottky diodes can rectified the signal upto the cut-off frequencies, while FETs can be used far beyond their cut-off frequencies in higher THz domain. Both are faster and sensitive compared to other counterparts available to the date. In this work, we characterize the zero-bias Schottky diode detectors: Both commercial available and modified research graded [5, 8]. The dynamic range of both are detectors is compared. This is part of the ongoing work for optimizing the Schottky diode and FETs THz detectors for applications at Particle accelerators and in future in other domains too.

## THEORY

The Schottky barrier diode consists of metal-semiconductor junction. Quasi-vertical schottky barrier diodes [9] developed by ACST GmbH has been used in both, the commercial and the research grade THz detectors. The cross section is shown in Fig. 1.

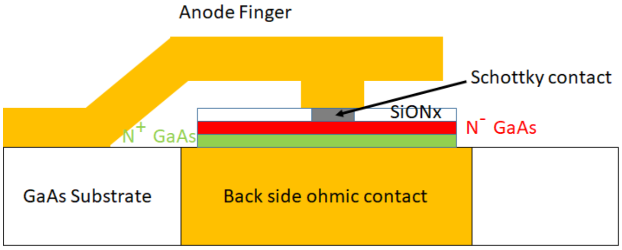

Figure 1: Cross section schematic of a qausi-vertical Schottky diode [9].

The diode is fabricated on a Gallium Arsenide (GaAs) substrate. The Anode and cathode are vertically fabricated, in contrast to the traditional horizontal contacting. This reduces the parasitic capacitance and series resistance. The quasi-vertical structure helps to keep the field distribution uniform across the anode finger and prevents current overloading when the ohmic contact is small, opposite to what' there in case of Whisker-contacted Schottky diodes. Also, quasi-vertical structures help to keep the noise level low compared to Whisker-contacted as the anode and ohmic contact are not located on the same plane, reducing the cross link of the fields. The modified Schottky diode reduces

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the heating of the device which ultimately improved the power performance. The first version of quasi-vertical type Schottky diode was developed at Technical University of Darmstadt, Germany in 2004 [10]. The back side ohmic contact provides as opportunity for flip chip mounting of the diode using up-side-up concept, instead of up-side-down as in case if both electrodes are located in the same plane. The fabricated Schottky diode is shown in Fig. 2.

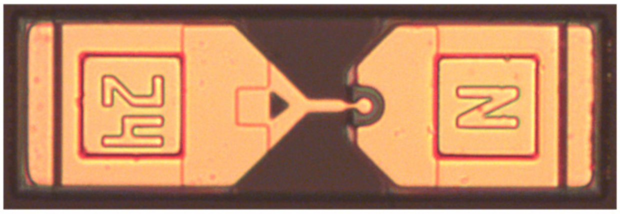

Figure 2: Fabricated quasi-vertical Schottky diode [9].

Theoretically, the majority charges (electrons) are responsible for the conduction of current in metal-semiconductor junction.

In the conduction mode, the Schottky model thermionic current is given by [11]:

$$I = I_s[\exp(\frac{q \cdot V_F}{n \cdot K \cdot T}) - 1] \tag{1}$$

where, $I_s$ is the saturation current, $q$ is electronic charge, $V_F$ is forward bias, $K$ is Boltzmann's constant, $T$ is absolute temperature. In the ideal case $n$ is equal to 1. Due to the quasi-vertical structure of Schottky diode these limitations has been rectified by improving the heat sink and field distribution uniformly over the anode finger and the ohmic contact located on the back plane. The cross link of fields between meta-semiconductor is decreased by using the quasi-vertical structure. The non-linearity of Eq. 1 is used for THz detection.

## CHARACTERIZED DEVICES

In this paper we characterized two types of packaged devices: one with lower video bandwidth (SMA connector) and a research grade detector with improved Bandwidth (K connector) as the output from the Schottky diode. In Fig. 3, the block diagram of SMA connector mounted THz detector is shown. A collimated lens with 12 mm diameter is used to couple the THz radiation and focus onto the silicon substrate mounted (of 500 µm thick) log spiral antenna coupled Schottky diode that is mounted on the back of the lens. The rectified signal is taken out from the pads of log spiral antenna and connected to the video path. The research grade detector has a video path using 25mil rogers substrate for transition from antenna contact pads to K connector. The block diagram is otherwise identical to the commercial device.

Figure 3: Block diagram of the research grade K connector-mounted THz detector.

One optimization criterion is the maximum IF frequency. The higher the video bandwidth, the shorter pulses can be detected. The commercial available one has 18 GHz of video bandwidth (limited by SMA connector), while the K mounted research graded one has 40 GHz of video bandwidth. The THz bandwidth of both is 50 GHz to 2 THz.

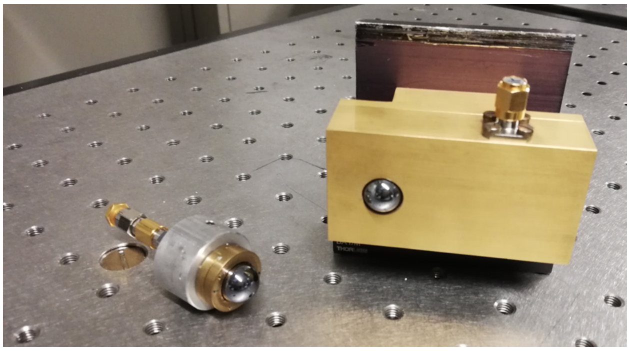

Figure 4: Left: K mounted Schottky diode THz detector, Right: SMA mounted Schottky diode THz detector.

In Fig. 4, the photo of both THz detectors is shown. A further optimization criterion was compactness: the research grade device is strongly reduced in size as compared to the commercial device. The smaller size of detector gives the flexibility for handy use at room temperature without needing much space in the experimental setup.

## EXPERIMENTAL SETUP

A commercially available Continuous wave (CW) THz photomixer source from Toptica Photonics AG was used to characterize the detectors. The experimental setup is shown in Fig. 5.

A commercial pin-diode transmitter was used as source, shown by the yellow tag in Fig. 5. Parabolic mirrors and TPX THz lenses are used to align the THz beam and focus it onto the Schottky diode receivers. This setup also helps to get rid of unwanted RF signal which sometimes can couple in through the Silicon lens at THz detector. The recified signal of the THz detector is connected to a Transimpedance amplifier (TIA) to amplify the signal with a transimpedance gain of $10^6 \frac{V}{A}$, which was read out by the lock-in amplifier afterwards. The pin-diode-based transmitter shows a strong roll-off towards 1 THz, with about 20 dB lower power at 1 THz as compared to 200 GHz.

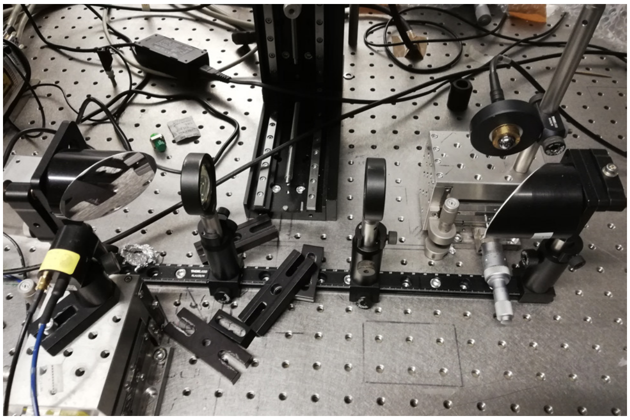

Figure 5: Experimental setup for the THz detectors characterization with Continuous Wave (CW) source.

## RESULTS AND DISCUSSIONS

The rectified signal using both detectors is shown in Fig. 6.

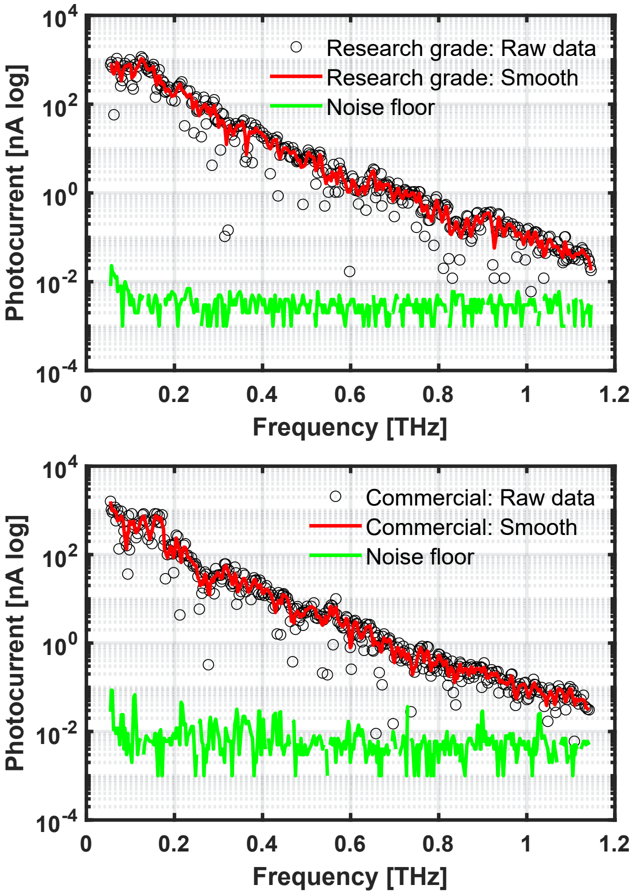

Figure 6: Top: Rectified signal from the research grade detector, Bottom: Rectified signal from the commercial detector.

The research grade (K mounted) detector features a slightly higher rectified signal over the whole frequency range compared to commercial (SMA mounted) one. Its main advantage, however, is reduced noise floor.The dynamic range (DR) is defined as follows:

$$DR\ [dB] = 20 \cdot log_{10}\left(\frac{Rectified\ signal}{Noise\ floor}\right) \qquad (2)$$

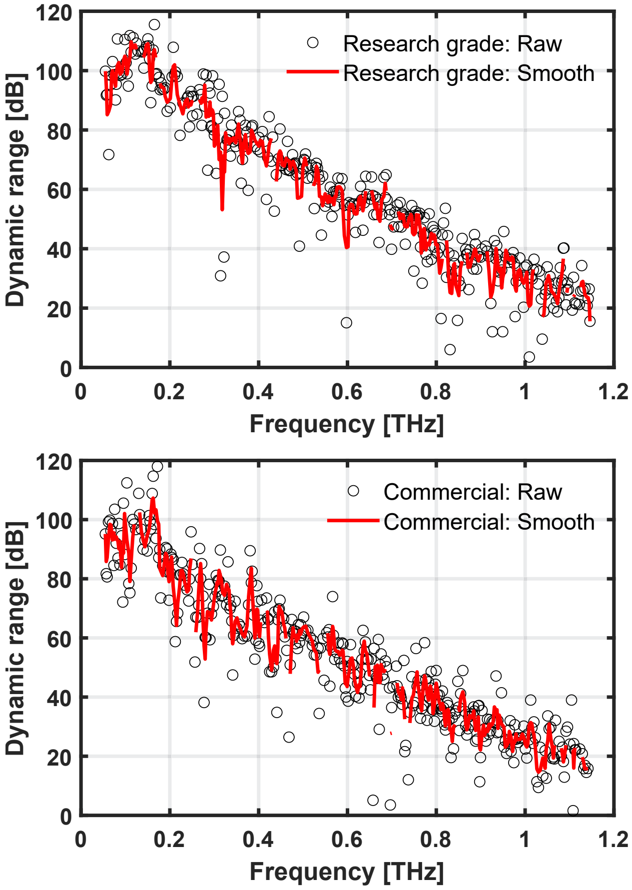

Figure 7: Top: Dynamic range of research grade detector, Bottom: Dynamic range of commercial detector.

In Fig. 7, dynamic range of both the connectors is shown. For the K connectorized device, 111 dB at 110 GHz is obtained compared to 105 dB for the SMA connectorized detector. In General in range of 50 to 180 GHz, the smoothed dynamic range just touches 100 dB fort the SMA device and slightly above 100 dB for the K-connectorized device. At 1 THz, research grade device offers 33 dB of dynamic range as compared to 26 dB by commercial one.

Phase versus frequency response for K mounted detector is shown in Fig. 8. Over the course from 0.1 THz to 1 THz, the maximum phase change is only three degrees. It is almost constant between 0.5 and 0.9 THz.

The characterized detectors in this paper along with the modified video chain detector was used to detect the pulse at FELBE HZDR, Dresden, Germany. The results were published in [5] as shown in Fig. 9. The K mounted (compact housing) research grade detector records a 16.8 ps pulse width very close to the expected pulse widht , whereas the SMA mounted (commercial) showed a severely broadened pulse with a width of 39.2 ps, proving the improved IF bandwidth of the research-grade device.

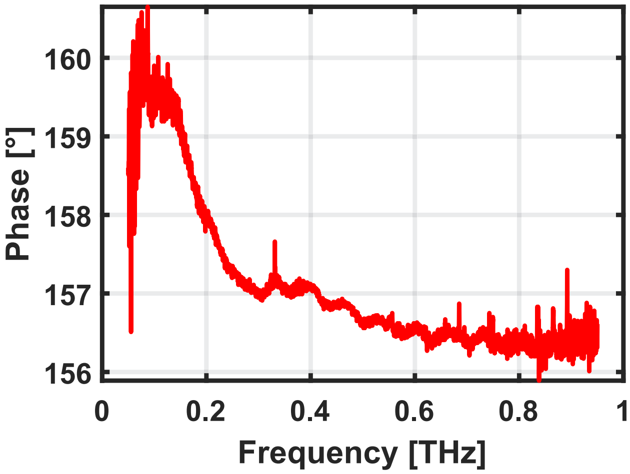

Figure 8: Phase of rectified signal from research grade detector.

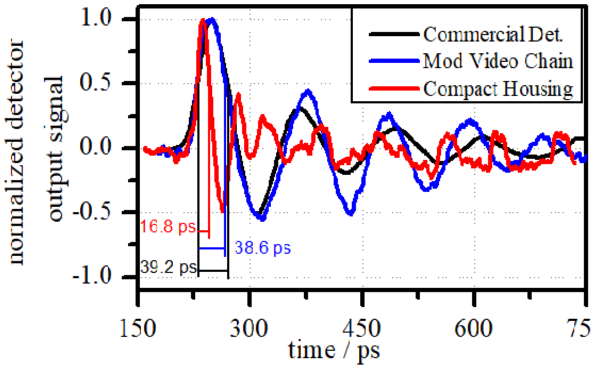

Figure 9: Detector characterization at 1.3 THz at FELBE, HZDR, ©2014 IEEE reprinted with permission from [5].

## CONCLUSIONS

In this paper, we showed the broadband characterization of commercial and research grade zero-bias Schottky diode THz detectors using a CW source. The K-connectorized device with improved IF path features a slightly higher dynamic range at 1 THz. With higher power at FELBE, we can detect much shorter pulses and higher video-bandwidth with the research grade device as compared to the commercial detector.

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