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PRELIMINARY RADIATION HARDNESS CHARACTERIZATION OF ULTRA-BROADBAND DIRECT THz DETECTORS BASED ON SCHOTTKY DIODES AND GaAs TeraFETs*

R. Yadav†,[1], F. R. Faridi, F. Bek, S. Preu, TU Darmstadt, Darmstadt, Germany
B. Scheible, A. Penirschke, Mittelhessen Univ. of Applied Sciences, Friedberg, Germany
M. Salman[1], M. Kuntzsch, J. M. Klopf, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[1]also at Mittelhessen Univ. of Applied Sciences, Friedberg, Germany

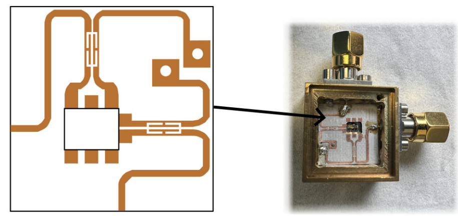
Abstract

Many currently operating and future FELs can generate radiation at megahertz repetition rates, requiring an ultra-broadband, compact, robust & fast (response time at least on a single-digit nanosecond scale) diagnostic tool. We develop ultrafast-operating terahertz detectors based on Schottky diodes and GaAs field-effect transistors (TeraFETs) that operate at room temperature. Here, we present the preliminary radiation hardness characterization of these detectors. Promising results demonstrate the ability of these detectors to be commissioned at accelerator facilities for longitudinal beam diagnostics.

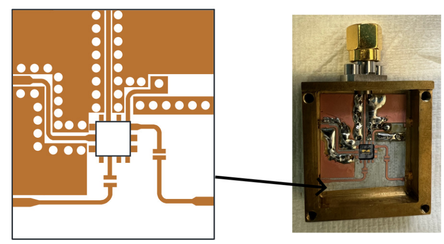
INTRODUCTION

Modern third- or fourth-generation electron-based accelerator facilities [1] require the accurate and fast characterization of THz pulses, which is crucial for optimizing FEL performance and, consequently, the beam parameters. Therefore, beam diagnostics [2] plays a vital role in machine operations, which requires the use of several instruments [3]. For longitudinal beam diagnostics at THz-generating particle accelerator facilities, conventional detectors [4] often suffer from limitations such as bandwidth restrictions, slow response times, and vulnerability to radiation damage, among others. As the majority of operating FEL facilities are capable of generating a broad THz spectrum [5], it is necessary to have a detector that can meet this ultra-broad bandwidth, along with other parameters such as fast speed, compactness, robustness, and ease of use. Also, the employed electronics are prone to various ionizing radiations [6], which can damage these electronic instruments [7]. This work presents the development of room-temperature operable terahertz (THz) detectors utilizing Schottky diodes and field-effect transistors (TeraFETs), designed to meet the stringent requirements for such applications.

This paper is divided into five sections. Section I gives the introduction to the presented work. Section II highlights the developed THz detectors, explaining their ultra-broadband THz frequency responses. The experimental setup employed for radiation hardness tests of the detectors is described in detail in section III, followed by the results & discussion presented in section IV. The conclusions and outlook of the paper are given in section V.



(a) Specimen of TeraFET packaged detector



(b) Specimen of Schottky diode packaged detector

Figure 1: Illustration of a developed (a) TeraFET and (b) Schottky-based THz detector in the packaged form.

Table 1: List of THz Detector Results Shown in this Paper

S.No	Device	Technology	Dose [Gy]
1	FET-A4	TeraFET	15.17
2	ZBSD-R4K	Schottky diode	9.09
3	HDD-K48	Schottky diode	17.95
4	PCTUD121-A1	Photoconductor	4.78

DEVELOPED THz DETECTORS

The developed THz detectors are characterized over time with respect to aging when exposed to radiation using a free-electron laser (FEL) source. This work presents only selected results. Figure 1 illustrates exemplary packaged versions of the THz detectors based on (a) TeraFET and (b) Schottky diode. The employed intermediate frequency (IF) circuit used for packaging the respective detector is shown on the left side, while the right side shows an interior view of a fully packaged detector. Similar types of packaged detectors are used for the radiation hardness characterization

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† yadav@imp.tu-darmstadt.de

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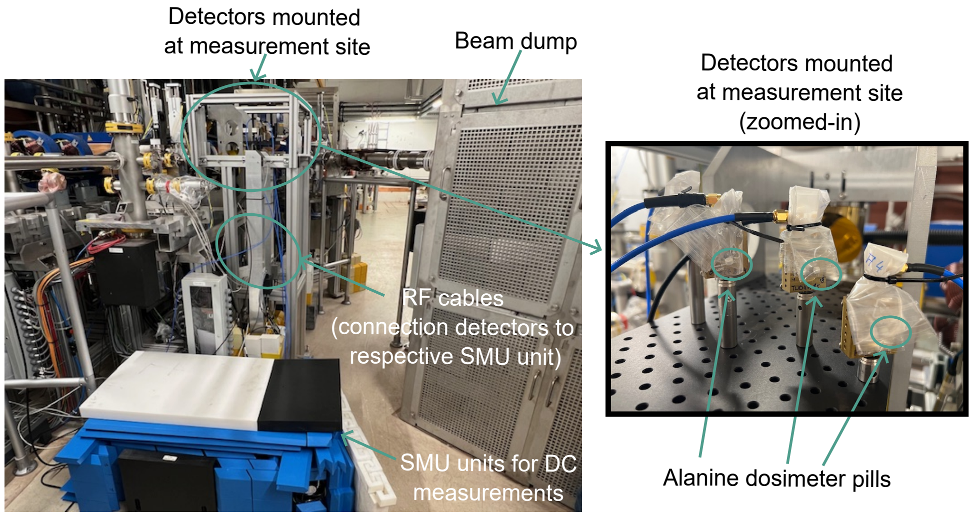

Figure 2: Image of the experimental setup employed for radiation hardness characterization of THz detectors using TELBE beamline at HZDR, Dresden, Germany.

of these THz detector technologies. The devices are contained in a brass housing for shielding. A ≈ 9 mm wide hole covered by a silicon lens permits access to the THz radiation. Table 1 shows the concise list of the THz detectors whose results are presented in this work. The doses obtained from the alanine dosimeter pills are also mentioned for the respective devices. Please note that the dose number is approximated based on the measured duration results presented in this paper. Besides TeraFETs and Schottky diodes, THz photoconductors are also investigated with respect to their radiation hardness characterization contained in a similar package as Schottkys and TeraFETs.

In previous work [8, 9], we have demonstrated ultra-broadband THz operational capabilities with a frequency coverage from below 100 GHz to 29.8 GHz for TeraFETs and up to 5.56 THz for Schottky diodes. The Schottky diode's best noise equivalent power (NEP) was 10 pW/$\sqrt{Hz}$ [8] in the range from 0.2 to 0.6 THz, making it competent for beam diagnostics and alignment applications at high-power particle accelerator facilities. The TeraFETs were not optimized with respect to responsivity but rather towards endurability and ruggedness, offering the best NEP = 2.27 nW/$\sqrt{Hz}$ at 0.5 THz [9]. In this paper, we monitor the change in device resistance over exposure time by measuring the DC current resulting from an applied bias.

EXPERIMENTAL SETUP

The developed THz detectors need to be commissioned near the beamline at particle accelerator facilities. The devices installed near the beamline are mostly exposed to high doses of varied radiation generated during or while setting up the machine operations. Thus, it is essential to test these detectors' capability to withstand exposure to the radiation environment (especially the one generated by gamma (γ) particles). Therefore, radiation hardness characterization of these detectors is carried out at the TELBE beamline of the ELBE facility located at HZDR, Dresden, Germany. Figure 2 shows the image of the experimental setup used for radiation hardness characterization of the detectors. The detectors are mounted at one of the bunch compression monitoring (BCM) stations, located near the beam dump, to expose them to the maximum amount of radiation. One detector from each of the technologies is installed: ZBSD-R4K (a zero-bias Schottky diode from ACST GmbH), HDD-K48 (a Schottky detector fabricated using the BES process at UMS), PCTUD121-A1 (a THz photoconductor fabricated in-house), and FET-A4 (an AlGaAs/GaAs TeraFET fabricated in-house). The THz detectors are connected to a source-measurement unit (SMU) located in the blue lead housing, as shown in Fig. 2, and are remotely controlled via a LAN. Three of these SMUs are placed on the floor in a housing stacked with lead blocks to protect them from harmful radiation and additionally shielded with polyethylene to protect them from neutrons. The goal is to perform DC characterization (IV measurements) of these detectors using SMUs at regular intervals during the operational beamtime schedules (during which the users are using the machine). For the precise measurement of the exposed dose, the alanine dosimeter pills (placed inside the transparent bags) are mounted on each detector, as shown in Fig. 2. These pills are sent to the manufacturer after the measurement campaign to obtain the exact dose values.

RESULTS & DISCUSSIONS

Initial measurement results are presented in Fig. 3. The DC characteristics of the detectors were monitored over 33 days. The results show the maximum current value at a defined bias voltage from each measurement taken to observe the trend of detector performance over time. The approximate dose amount from the alanine pill measurements for the respective detector is shown in Table 1. The maximum diode current (I_D) for ZBSD-R4K decreases by 18 % in the first 8

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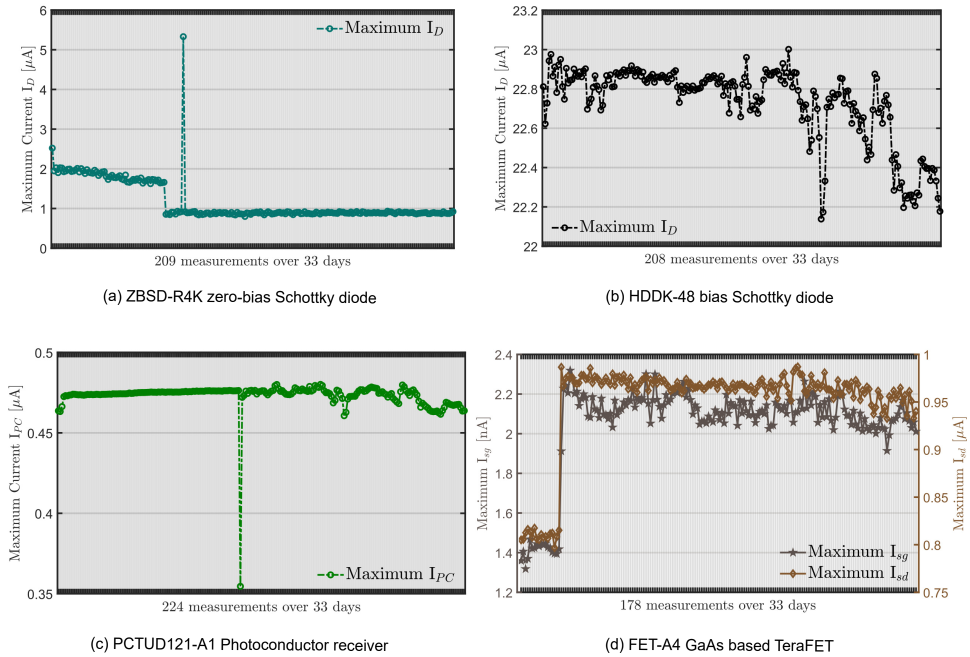

Figure 3: Maximum current measured with (a) ZBSDR4K, (b) HDDK48, (c) photoconductors, and (d) AlGaAs/GaAs TeraFET detectors over 33 days during the radiation hardness test campaign.

days, dropping from 2 µA to 1.65 µA. Subsequently, the drop observed may be attributed to a short but intense exposure to a high radiation dose, which could potentially increase the resistance of the ohmic contact. After this abrupt decline from 1.65 µA to 0.85 µA, the I_D remains almost constant. For the HDD-K48 detector, the maximum diode current I_D remains stable at approximately 22.6 ± 0.2 µA for the first 19 days, whereas for the last 14 days, it decreased by 2.76 %, from 22.8 µA to 22.17 µA. The observed change is expected to be related to the scheduled user beam time during which an experiment with high dose rates was conducted. However, this correlation needs to be verified with the dosimetry measurements. The change of only a few percent in the current allows us to conclude that the device is most likely intact. A similar trend was also observed simultaneously for the PCTUD121-A1 and FET-A4 detectors. The single peak observed in ZBSD-R4k and PCTUD121-A1 might be due to measurement error. In the case of the PCTUD121-A1 detector, the photocurrent (I_{PC}) increased from 0.46 µA to 0.47 µA during machine setup for the planned user beam time. It then remained almost constant until an event similar to HDDK48 and the TeraFETs was observed. Subsequently, the I_{PC} began to fluctuate around 0.47 µA with an amplitude of ±0.01 µA. The origin of the fluctuations is unknown and needs further study. As the device resistance hardly changed, we can conclude that the photoconductor is most likely intact. For the GaAs TeraFETs, it is insightful to observe both the source-gate current (I_{SG}, left y-axis in Fig. 3 (d)) and the source-drain current (I_{SD}, right y-axis in Fig 3 (d)). An increase is observed, with I_{SD} rising from 0.81 µA to 0.98 µA and I_{SG} rising from 1.4 nA to 2.2 nA, which could be due to higher doses during machine alignment. Subsequently, I_{SD} fluctuates around 0.96 ± 0.02 µA, and I_{SG} around 2.1 ± 0.1 nA, followed by a continuous decline trend over the last 14 days. From the DC characterization perspective, the devices remain intact, the gate is not leaking, and the source-drain resistance remains within a sensible range. For final proof of functionality, further investigation is required regarding the THz response after radiation exposure. Due to contamination, however, all detectors are still inside the beamline cave, which prohibits THz characterization at the time of submission of this article.

CONCLUSION & OUTLOOK

This work presents a radiation hardness study of room-temperature operable ultra-broadband direct THz detectors based on Schottky diodes, AlGaAs/GaAs high-electron-mobility transistors, and photoconductive mixers. The results are promising, indicating their suitability for commissioning at facilities. The monitored change in current (DC characteristics) suggests that the devices were affected by heavy irradiation; however, none of the devices appear to be dysfunctional from a DC perspective. The GaAs-based zero-bias Schottky diode and the AlGaAs/GaAs-based field-effect transistor exhibited the most significant changes in DC characteristics, which could be attributed to the comparatively small Schottky barrier in both devices (in the case of the TeraFETs) that may be modified by irradiation. The photoconductor seems least affected. However, more rigorous testing is required to understand the detector's threshold limits. Once approved by the radiation safety department, the detectors will be removed from the cave, and THz characterization will be performed to verify their functionality and the change in responsivity with respect to dose.

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