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# First characterization of innovative silicon carbide detectors for application in relative dosimetry with proton beams

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**Summary.** — Monitoring the Percentage Depth-Dose distribution (PDD) is an essential phase of beam quality control protocols in proton therapy. The scientific community is exploring innovative techniques for more precise PDD assessment, intending to apply them to high-intensity beam dosimetry. In this context, the progress made in the framework of the PRAGUE (Proton RAnGe measure Using silicon carbidE) project will be presented. The project's purpose was the development of a real-time multilayer silicon carbide (SiC) detector, able to reconstruct the PDD of 30–150 MeV proton beams over a wide intensity range ($10^6$–$10^{14}$ pps). This contribution describes the *I-V* (current *vs.* voltage) and *C-V* (capacitance *vs.* voltage) characterization of 80 SiC devices. The detectors' stability and linearity are also introduced.

## 1. – Introduction

The evaluation of the PDD is crucial in beam quality control programs with clinical proton beams, due to its correlation with the beam range and the patient's treatment plan definition. The PDD is usually measured through the ionometric approach, which, although well established, is time-consuming and exhibits a spatial resolution of about 0.1 mm. Moreover, it is not suitable for high-intensity and high-dose-rate beams, such as those required for *FLASH* Radiotherapy (FR), a new potential radiotherapy technique characterized by a dose release at ultra-high dose rates ($> 40$ Gy s$^{-1}$) associated with reduced radio-induced damage to healthy tissues [1]. The investigation into FR is still ongoing, due to the limited availability of beams with dynamic regimes adequate to

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achieve *FLASH* conditions, but also because establishing a reliable and accurate dosimetric protocol of *FLASH* beams represents a challenge. The use of non-standard beams at ultra-high dose rates disallows the direct application of the recognized dosimetric protocols (IAEA TRS-398) to *FLASH* irradiations, requiring the development of new dosimetric devices and protocols. To date, the PDD of high-intensity beam is only measured by using detection systems based on passive devices, like CR-39 and Radiochromic Films, or scintillators [2], which however feature some important disadvantages like LET or fluence dependence.

In this context, we will present the work done within the PRAGUE (Proton RAnGe measure Using silicon carbidE) project, funded by the H2020 in the framework of the MSCA-IF IV program, and by the INFN [3]. The main goal of PRAGUE was the development of a real-time SiC detector capable of reconstructing the PDD of a 30–150 MeV proton beam with both conventional (from $10^6$ pps) and high (up to $10^{14}$ pps) intensity. The detector will be composed of 60 SiC devices (active thickness 10 $\mu$m, active area $15 \cdot 15$ mm$^2$) arranged in a stack configuration; it will be able to resolve the Bragg peak with a very high longitudinal spatial resolution (around 30 $\mu$m water equivalent thickness). This contribution will provide a detailed account of the tests conducted on 80 SiC devices, which are potential candidates for the final detector assembly. The *I*-*V* and *C*-*V* profiles of these devices were examined, along with an analysis of their stability and linearity. The experimental tests were conducted at the Department of Industrial Engineering, University of Rome “Tor Vergata” (Italy).

## 2. – Materials and methods

**2**˙1. *Detectors description.* – The 80 SiC devices object of this study are $15 \cdot 15$ mm$^2$ p$^+$n planar junction purchased by the Fraunhofer company, which was responsible for the front-end processing of the chips, while the wafers were produced by the LPE$^{(R)}$ company [3]. Each device has a doping concentrations of $N_A$=$1 \cdot 10^{19}$ cm$^{-3}$ for the 0.3 $\mu$m thick p-layer and $N_D = 0.5$–$1 \cdot 10^{14}$ cm$^{-3}$ for the 10 $\mu$m thick n-layer. Finally, a substrate of 110 $\mu$m thickness with a doping concentration $N_D > 10^{18}$ cm$^{-3}$ is placed close to the active layer. The nominal depletion voltage and saturation capacitance of such devices are 4.7–9.3 V and 1.93 nF, respectively. After the electrical characterization (sect. **2**˙2), each device was bonded on a PCB board.

**2**˙2. *Electrical characterization.* – The *I*-*V* and *C*-*V* characteristics of the detectors under investigation were measured at room temperature and in air. The study of the *I*-*V* profile is crucial to determine the detector's leakage current and breakdown voltage. It can also be used to highlight the presence of sensor imperfections by analyzing the trend of the observed *I*-*V* curve. The *C*-*V* profile was analyzed to estimate the detector depletion voltage and saturation capacitance. Throughout the *I*-*V* measurements, the current generated by each detector was measured using a KEITHLEY 6517B electrometer, which also served as the voltage source. To perform the *C*-*V* acquisition, the capacitance was measured employing an LCR meter (Agilent, model 4263B) coupled with EXT Voltage Bias Fixture (Agilent, model 16065A), while the 6517B electrometer once again supplied the voltage. These measurements were performed on bare detectors, to reduce the contributions of parasitic currents and capacitances. The SiCs were contacted via needle-shaped probe electrodes, applying the voltage to the p-type SiC layer while earthing the metallic contact.

**2·3.** *Linearity and stability.* – Tests on the linearity and stability of the SiC detectors' response were carried out by irradiating the detectors in air with an X-ray beam. A copper-target X-ray tube (Ital Structures Compact 3K5 X-ray Generator) was employed as the radiation source. The distance between the X-ray tube and each detector was approximately 15 cm, ensuring uniform irradiation of their active area. The KEITHLEY 6517B was used as an amperemeter and voltage source. The detectors' response was measured as the beam current changed to examine the linearity. The stability was studied by subjecting the detectors to prolonged irradiation sessions (60 s) and evaluating the oscillations of their current response. Both characterizations were performed by applying a reverse bias voltage of 30 V to the p-type SiC layer while earthing the metallic contact.

## 3. – Results

The $I$-$V$ profile was studied in the reverse bias voltage range 0–200 V (in steps of 2.5 V) and the forward bias voltage range 0–2.5 V (in steps of 0.1 V). In fig. 1, the $I$-$V$ curves of two SiCs in the reverse bias voltage range are presented as examples.

Through this characterization, 30 of the initial 80 detectors were rejected. Their leakage current reaches values of about 1 mA at a few volts, indicating the presence of structural defects. The remaining 50 SiC devices, which exhibit a leakage current of less than 100 pA when reverse-biased up to 50 V, were subjected to further investigation.

Their $C$-$V$ profiles were analyzed in the reverse voltage range of 0–20 V, in steps of 0.25 V. The adopted capacimeter was set to operate at a full scale of 20 nF, with a sample rate of 10 kHz. The depletion voltage $V_D$ and saturation capacitance $C_S$ of each detector can be found through an approach that exploits the trend of the $1/C^2$ curve as a function of the applied bias, $V$ [4]. Ideally, when the full depletion condition is reached (when $V \geq V_D$) the trend of $1/C^2$ settles on a plateau at a constant value equal to $C_S$. The method employed involves identifying the two linear functions that best approximate the trend of $1/C^2$ when $V \leq V_D$ and $V \geq V_D$. The intersection of these two functions then yields $V_D$. The right panel of fig. 2 provides a real example of this behaviour. The $C_S$ values for the 50 SiC devices span from $C_{S,min} = 2.031 \pm 0.004$ nF to $C_{S,max} = 2.139 \pm 0.005$ nF, while $V_D$ ranges between $V_{D,min} = 2.0 \pm 0.3$ V and $V_{D,max} = 6.0 \pm 0.3$ nF.

During X-ray irradiation, the tube acceleration voltage was set to 10 kV, while the tube current was varied from 2.5 mA to 15 mA in increments of 2.5 mA to investigate the linearity of the devices. For each SiC detector, the current response was measured by setting an acquisition time of 20 s, a full scale of 200 nA, and a sampling rate of

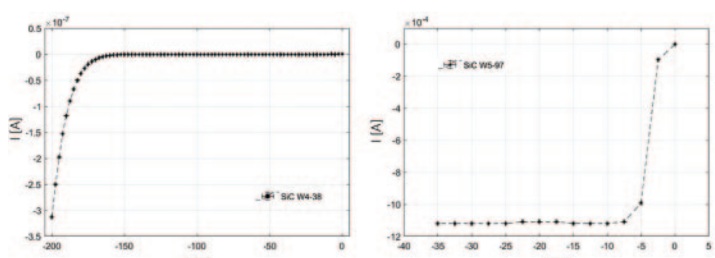


Fig. 1. – Left panel: SiC "W4-38" $I$-$V$ profile; the curve's trend follows the predicted pattern of a real junction. Right panel: SiC "W5-97" $I$-$V$ profile; the current stabilizes at $-1.1$ mA starting from $-7.5$ V. Error bars are calculated by considering the instrument's accuracy.

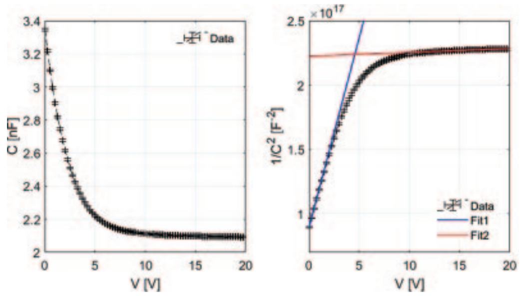


Fig. 2. – $C$-$V$ profile of SiC W4-39. Left panel: trend of capacitance $C$ *vs.* reverse applied voltage $V$. Right panel: trend of $1/C^2$ *vs.* $V$. The linear fits in the low voltage range (Fit1, $V \leq V_D$) and in the saturation region (Fit2, $V \geq V_D$) are also shown. In this case $V_D = 4.7 \pm 0.3V$ and $C_S = 2.096 \pm 0.005$ nF. Error bars are obtained by considering the accuracy of the instruments.

3 Hz. The linear trend of the SiC signals *vs.* the X-ray tube current was then studied by performing a best-fit procedure, resulting in a $r^2$ value close to one for all the detectors. To highlight any deviation from the linear trend, the percentage deviation from linearity was evaluated, finding a maximum deviation of 1.5%.

To investigate the SiC stability, the tube current and acceleration voltage were fixed to 5 mA and 10 kV, respectively. The response of the detectors was acquired for 60 s during their irradiation. To evaluate the oscillations of the current signals, a Gaussian fit on the distribution of the current values was carried out, extrapolating the average value $\mu$ (65.5–70.5 nA) and the standard deviation $\sigma$ (0.1–0.3 nA). A Chi-Square Goodness-of-Fit Test was then performed to determine whether the data comes from a normal probability distribution with parameters $\mu$ and $\sigma$. The test results always accept the null hypothesis (belonging to the hypothesized distribution) at a significance level $\alpha = 1\%$.

## 4. – Conclusion

In this work, a new generation of 80 $p^+n$ junction SiC detectors was preliminarily investigated for dosimetric applications within the PRAGUE project. Due to anomalies identified in their conductive behaviour, 30 of the 80 available detectors were rejected. The $C$-$V$ characterization enabled the evaluation of the $C_S$ and $V_D$ values for the remaining devices, revealing some discrepancies from the expected parameters. This suggests that the devices may have been manufactured with qualities differing from the anticipated specifications, a possibility that will be explored through further analysis. The detectors' linearity (within 1.5%) and stability (fluctuations within 0.5% of the mean value) were also assessed, demonstrating a high level of performance under these experimental conditions. Future work will include dosimetric characterization using conventional and high-intensity proton beams.

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