Silicon Carbide Detectors for *in vivo* Dosimetry

Giuseppe Bertuccio, Donatella Puglisi, Daniele Macera, Riccardo Di Liberto, Massimiliano Lamborizio, and Laura Mantovani

***Abstract*—Semiconductor detectors for *in vivo* dosimetry have served in recent years as an important part of quality assurance for radiotherapy. Silicon carbide (SiC) can represent a better semiconductor with respect to the more popular silicon (Si) thanks to its physical characteristics such as wide bandgap, high electron saturation velocity, lower effective atomic number, and high radiation resistance to X and gamma rays. In this article we present an investigation aimed at characterizing 4H-SiC epitaxial Schottky diodes as *in vivo* dosimeters. The electrical characterization at room temperature showed ultra low leakage current densities as low as 0.1 pA/cm^2 at 100 V bias with negligible dependence on temperature. The SiC diode was tested as radiotherapy dosimeter using 6 MV photon beams from a linear accelerator in a typical clinical setting. Collected charge as a function of exposed radiation dose were measured and compared to three standard commercially available silicon dosimeters. A sensitivity of 23 nC/Gy with linearity errors within $\pm$0.5% and time stability of 0.6% were achieved. No negligible effects on the diode I-V characteristics after irradiation were observed.**

***Index Terms*—Dosimeters, dosimetry, semiconductor radiation detectors, silicon carbide, X-ray detectors.**

I. Introduction

APPLICATION of semiconductor radiation detectors in medicine has received increasing interest during the last decade to monitor and measure entrance doses during complex treatments in radiation therapy (local or total body irradiation) and in related fields. Research on silicon pixel [1] and strip detectors [2] has resulted in an improved competitive position as compared to photomultipliers [3], film dosimetry [4] and ionizing chambers [5] due to semiconductors very small sizes, capability to integrate readout electronics, reusability, and possibility of real-time applications. Silicon diodes have been the primary semiconductor devices used as *in vivo* dosimeters because of their sensitivity to radiation at zero bias voltage, good mechanical stability, and small volume. Silicon based dosimeters, however, have low radiation hardness and exhibit a strong dependence on accumulated dose, which results in the need for pre-irradiation before use and frequent recalibration [6], [7], [8], [9]. In addition, silicon is not a tissue-equivalent material due to its high atomic number ($Z = 14$) compared to that of muscles ($Z_{\rm eff} = 7.64$) or other soft tissue, which leads to a dosimetric response strongly dependent on radiation energy [10]. There is thus interest in studying dosimeters based on alternative materials in order to achieve lower leakage currents, higher radiation hardness, lower dependence on temperature and radiation energy, and a better match to tissue properties. In this regard, wide-bandgap semiconductors such as diamond and silicon carbide have recently been proposed as good alternatives to Si-based radiation dosimeters [11], [12], [13].

Diamond is a nearly tissue-equivalent material having atomic number $Z = 6$ and is a good candidate for radiation dosimetry thanks to its high resistance to radiation damage, low energy and temperature dependence, and very low leakage currents [14]. Studies have been done in the last ten years to improve crystal quality of chemical vapor deposited (CVD) diamond [15] and recently good results with diamond-based dosimeters have been achieved [16].

Silicon carbide (SiC) is a wide bandgap semiconductor with interesting properties for developing radiation dosimeters, even if SiC is not nearly as tissue-equivalent ($Z_{\rm eff} \approx 10$) as diamond. The SiC wide bandgap (3.26 eV for 4H-SiC polytype) and the possibility to achieve high barrier rectifying junctions providing ultra low leakage current densities on the order of pA/cm^2 at $+30^\circ$C, which are more than two orders of magnitude lower than the state of the art silicon devices, are attractive properties for dosimeter development. Moreover, the high carrier saturation velocity in SiC implies high-speed response and its high crystalline quality ensures very stable response for device components. In addition, microelectronic technology enables fabrication of SiC complex layouts with sub-micrometer features.

In this paper, we present a study aimed at describing the electrical and dosimetric properties of SiC. The characteristics of a SiC dosimeter prototype were investigated and compared with three commercial silicon dosimeters.

II. Device and Technology

The devices used in this study were SiC Schottky diodes with area 5 mm^2. Fig. 1 shows a photograph of the chip and a cross-section of a diode (right side). An undoped SiC layer of 115 μm was epitaxially grown on top of a 2” 4H-SiC wafer by LPE-ETC [17]. The wafers were processed at Selex Sistemi Integrati to produce the diodes [18]. Nickel contacts were formed

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G. Bertuccio and D. Macera are with the Department of Electronics, Information and Bioengineering, Politecnico of Milano, Como 22100, Italy, and also with the National Institute of Nuclear Physics (INFN), Milano 20133, Italy (e-mail: Giuseppe.Bertuccio@polimi.it).

D. Puglisi was with the Department of Electronics, Information and Bioengineering, Politecnico of Milano, Como 22100, Italy, and is now with the Department of Physics, Chemistry and Biology, Linköping University, Linköping 58183, Sweden.

R. Di Liberto, M. Lamborizio, and L. Mantovani are with the Department of Medical Physics, IRCCS Fondazione Policlinico San Matteo, Pavia 27100, Italy (e-mail: r.diliberto@smatteo.pv.it).

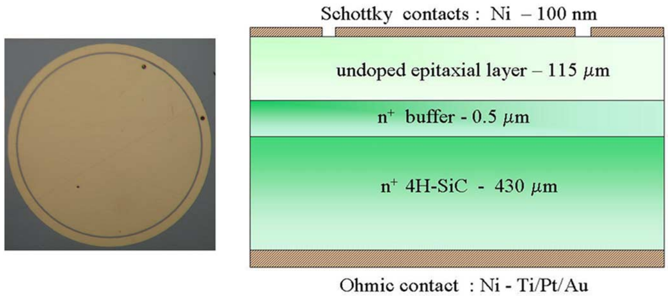

Fig. 1. Photograph and cross-section of the epitaxial 4H-SiC detector.

on the silicon front side of the SiC epitaxial layer for the formation of rectifying Schottky contacts. An anular Schottky contact served as guard ring in order to null lateral and contact edge leakage currents. The guard ring was 100 μm wide and it was positioned 20 μm from the central electrode. A Ni-Ti/Pt/Au layer was deposited on the back of the wafer in order to obtain an ohmic contact.

III. Electrical Characterization

Before testing as dosimeters the SiC diodes were characterized by means of current-voltage ($I-V$) and capacitance-voltage ($C-V$) measurements at room temperature. The results are shown and discussed in the following subsections.

A. I–V Characterization

The $I-V$ measurements were carried out on 5 mm^2 diodes in a probe station at room temperature. Particular care was devoted to the set-up in order to achieve the low-noise level required to measure currents in the femtoampere range. A sourcemeter Keithley 2410 was used to bias the device from the back contact and an electrometer Keithley 6430 was connected to the front Schottky contact. Fig. 2 shows the $I-V$ characteristics measured at $+25^\circ$C biasing the device from 0 V to 200 V. It should be noted that bias ultra low leakage currents in the femtoampere range and current densities on the order of 0.1 pA/cm^2 were measured up to 200 V. Fig. 3 shows the leakage currents measured on four samples of the 5 mm^2 area diode from the same wafer. At 200 V, three diodes had leakage currents around 10 fA, while the worse device showed a maximum current below 0.5 pA, corresponding to a current density of 10 pA/cm^2, still much lower than typical values (1 nA/cm^2) for silicon diodes.

Temperature Dependence of the Reverse Current: The temperature dependence of the diode reverse current was measured in air, placing the diode inside a thermostatic chamber. The temperature was set at $+20^\circ$C, $+30^\circ$C, $+36^\circ$C and $+40^\circ$C, and monitored by means of a thermocouple placed near the device. During the measuring time the temperature stability was $\pm 0.1^\circ$C. Fig. 4 shows the results of the measurement performed with the diode biased at 200 V. It was observed that the reverse currents stayed within a few tens of fA as the temperature was varied between $+20^\circ$C and $+40^\circ$C and did not show a monotonic trend. This behavior can be explained by considering that the measurements were performed with the diode chip in air and

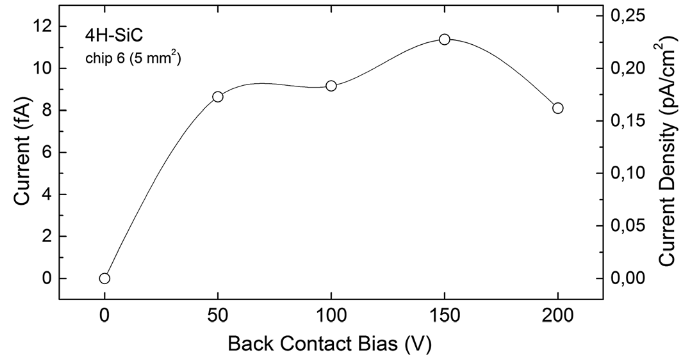

Fig. 2. Current (left axis) and current density (right axis) of the 5 mm^2 SiC Schottky diode measured at $+25^\circ$C before irradiation.

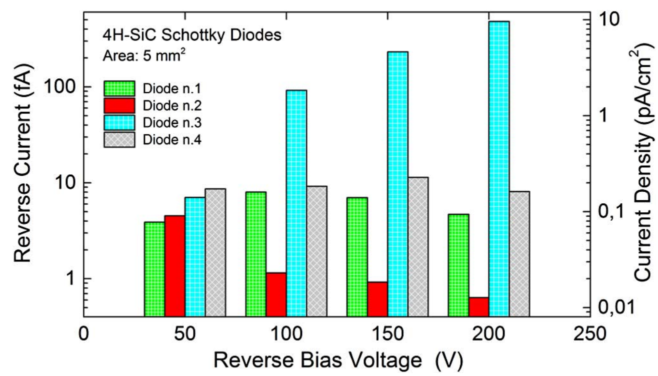

Fig. 3. Room temperature leakage current (left axis) and current density (right axis) in the voltage range 50 to 200 V measured on four 4H-SiC diodes (area 5 mm^2).

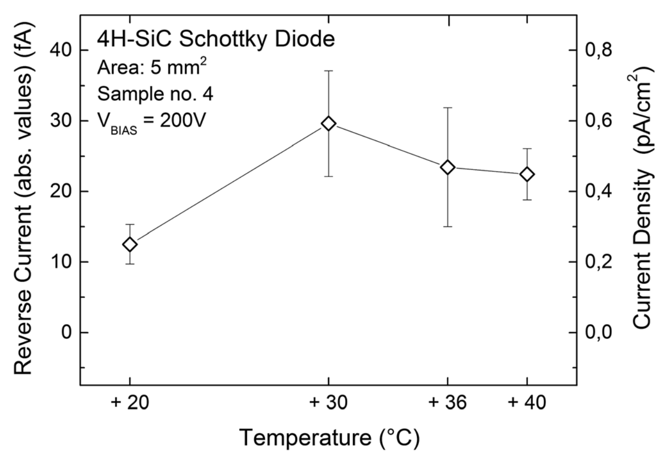

Fig. 4. Leakage current (left axis) and current density (right axis) dependence on temperature in the range of interest for radiotherapy applications.

that measurement of such ultra low leakage currents can be affected by the humidity of the environment. The observed results can be compared to those for silicon diodes of the same area, which showed currents at 20°C on the order of tens of pA (three orders of magnitude higher) which doubled for every 10°C of temperature increase. In conclusion, Fig. 4 demonstrates that leakage currents of SiC diodes are practically negligible within the temperature range of interest for dosimetry in radiotherapy.

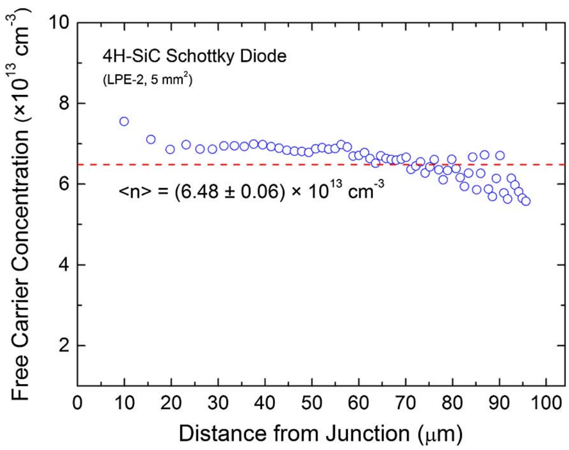

Fig. 5. Free carrier concentration profile as a function of the distance from Schottky junction. A mean value of $(6.48 \pm 0.06) \times 10^{13}$ cm^{-3} was observed.

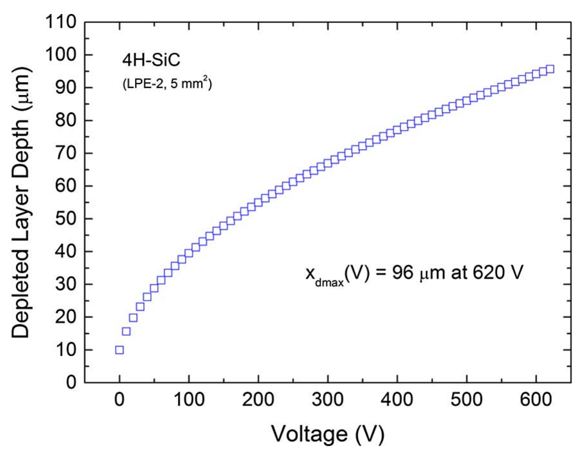

Fig. 6. Depletion layer depth as a function of the applied voltage as derived from C–V measurements.

B. C–V Characterization

Capacitance–voltage measurements up to 620 V were carried out at $+25^{\circ}$C in order to determine the doping profile of the epitaxial layer which constitutes the active region of the dosimeter. The device was placed in a test fixture Agilent 16065A connected to an Agilent 4284A Precision LCR Meter. A Keithley 2410 voltage source operating in the 4-wire connection mode was used to bias the diode and measure the applied voltage. The measurement was performed with a 100 mV AC signal at 100 kHz. The $C - V$ technique was used to determine the free carrier concentration $n(x)$ in the epitaxial layer from the slope of a $1/C^2 - V$ curve [19]. As shown in Fig. 5, the curve revealed a quite uniform $n(x)$ and a mean value of $(6.48 \pm 0.06) \times 10^{13}$ cm^{-3} was observed. According to these results, at zero bias condition the depleted layer width was about 10 μm, while a maximum depletion of 96 μm was reached at 620 V. The depleted layer thickness as a function of the applied bias voltage is shown in Fig. 6.

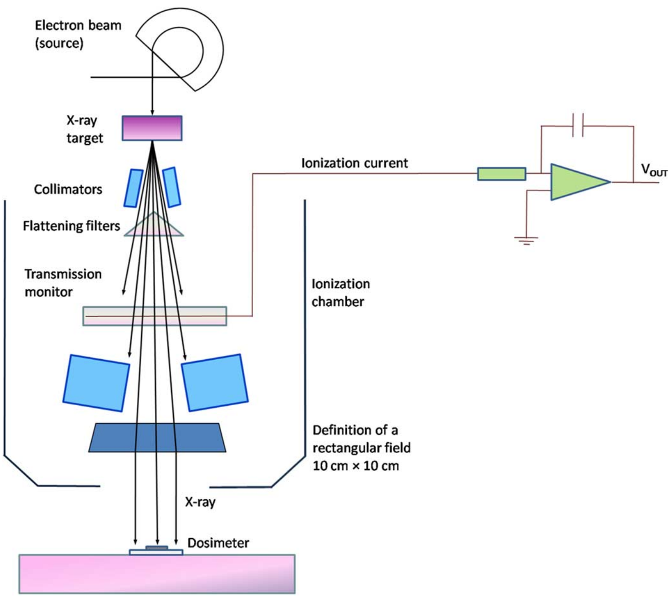

Fig. 7. Schematic of the experimental setup used for *in vivo* dosimetry. The linear accelerator used in this work produced X-rays with energies of 6 MV. The clinical photon beam was produced in the direction of the electron beam striking the X-ray target.

IV. Characterization with Radiation Therapy Equipment

A. Equipment and Experimental Setup

One of the SiC diodes was evaluated as a dosimeter. The diode was irradiated using a 6 MV photon beam from a Siemens Mevatron MX-2 linear accelerator (linac). In the linac, electrons are produced by thermionic effect, focused into a pencil beam and accelerated in straight trajectories within special vacuum structures. These accelerated electrons collide against a metal plate which results in the production of bremsstrahlung X-rays. A specific target/flattening filter combination makes the photon beam produced in the target useful for clinical applications [20]. A beam monitoring system and a beam collimation system embedded into transmission ionization chambers ensure that the radiation dose is delivered to the patient with a high degree of accuracy. In addition, biasing power supplies and readout electrometers are connected to the system. A schematic configuration of the experimental setup used in this work is shown in Fig. 7.

Irradiation was performed at a zero bias condition in the dose range 50 to 1000 Monitor Units (MU), using a constant dose rate of 200 MU/min as a single exposure. The linear accelerator was calibrated while maintaining a source-to-surface distance of 1 m, a radiation field size of 10 cm × 10 cm and using the thickness of a water equivalent material from the dosimeter to the phantom surface so that 100 MU $= 0.75$ Gy at a depth of 10 cm in water. Since the diode response changed significantly with the treatment beam setup [21], the time of use (radiation damage) [22], the radiation type and the quantity to be measured [5], it was necessary to apply appropriate correction factors to take into account the diode response as a function of source-to-surface distance, field size, diode orientation, and time of exposure.

TABLE I
MAIN FEATURES OF A 4H-SIC AND THREE COMMERCIAL SI DOSIMETERS

	SiC (this work)	SUN NUCLEAR	IBA	PTW
SEMICONDUCTOR	4H-SiC	*p*-type Si	*p*-type Si	*p*-type Si
TYPE OF DIODE OR MODEL	Schottky	1115000-2	EDP-10	T60010M
ACTIVE DETECTION AREA (mm^2)	5.0	0.64	3.14	1.0
ACTIVE DETECTION THICKNESS (μm)	8.6	30	60	2.5
LEAKAGE CURRENT DENSITY @ Room Temperature (pA/cm^2)	0.1 @ +100V	n.a.(*)	n.a.(*)	n.a.(*)
BUILDUP MATERIAL	PMMA	Brass	Stainless steel and epoxy	Lead
TOTAL BUILDUP (g/cm^2)	1.5	1.91	1.0	2.0
SENSITIVITY (nC/Gy)	23.1	31.5	30.9	9.7
LINEARITY ERROR	≤ ±0.5	≤ ±0.1	≤ ±0.1	≤ ±0.6

(∗) data not available, but typical values of leakage current densities of silicon diodes are on the order of 1 nA/cm^2.

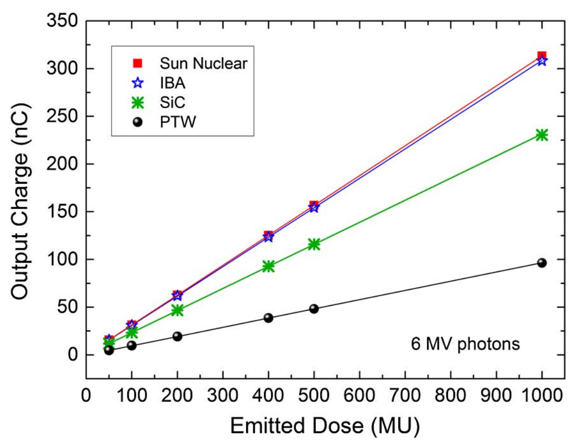

Fig. 8. Measured charge as a function of the emitted dose for the SiC diode and three standard commercial Si diodes.

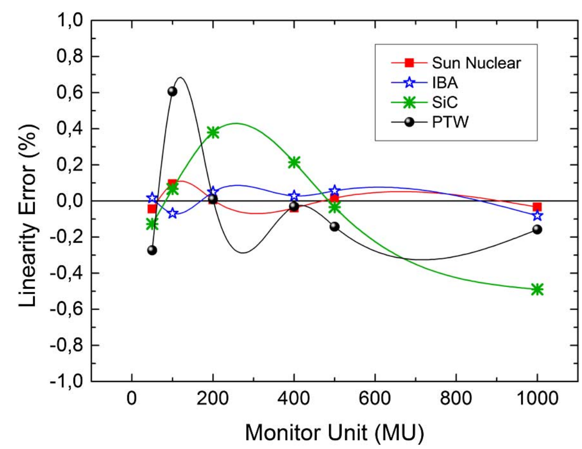

Fig. 9. Linearity error as a function of monitor unit. For the SiC dosimeter, the maximum deviation from the best fit was within $\pm 0.5\%$.

A polymethylmetacrylate (PMMA) thickness of 15 mm, which corresponds to 1.5 g/cm^2 of total buildup density, was used for the SiC dosimeter.

B. Photon Dosimetry

Three commercial silicon dosimeters from Sun Nuclear [23], IBA [24] and PTW [25] were used for calibration and comparison with the SiC diode.

The dosimetric response to X-rays was determined by measuring the collected electrical charge as a function of time using an electrometer for each diode. All diodes were biased at 0 V.

Fig. 8 shows the collected charge vs. emitted dose for the four dosimeters. The emitted dose is expressed in Monitor Unit (MU) defined as $1\text{MU} = 1$ cGy at the buildup. A linear response was observed for all the dosimeters. The slope of the linear fit gave the sensitivity S_0 of each dosimeter. $S_0 = 23$ nC/Gy was determined for SiC, which was comparable to sensitivities obtained for the commercial Si dosimeters: 32 nC/Gy for Sun Nuclear, 30 nC/Gy for IBA, and 10 nC/Gy for PTW, in agreement to the values provided by the manufacturers.

The linearity errors were determined and are shown in Fig. 9. For all dosimeters, the maximum deviation from the best fit was between $\pm 0.1\%$ and $\pm 0.6\%$. The SiC diode exhibited a linearity error lower than $\pm 0.5\%$.

The effect of different layers of buildup material on the collected charge of the SiC diode was determined. The buildup material's properties and thickness were found to be decisive in determining the dose response (expressed in collected charge). The dose response was 6.9 nC upon exposing the diode directly to the photon beam (without buildup) and it increased to 24.4 nC using a buildup of 15 mm PMMA plus a thin plastic cover on the detector. This effect can be attributed to the build-up's thickness being close to that typical for 6 MV photons (15 mm water equivalent depth). In this way, the charge balance was reached within the thickness and the signal was maximized [26].

In Table I, the main characteristics of the SiC diode and the three commercial Si dosimeters are compared.

C. Dosimeter Time-Stability

The stability of the SiC and commercial Si diodes responses were tested by repeating the measurement of the output charge at constant 100 MU (6 MV photon beams) 10 times. The buildup material of each diode is specified in Table I. All the devices were measured on simultaneously, so that eventual fluctuations of the delivered dose affected all devices equally. The total duration of the measurements was 300 seconds. The result of the experiment is shown in Fig. 10 as displacement from mean sensitivity value of each measurement. Standard deviations of the

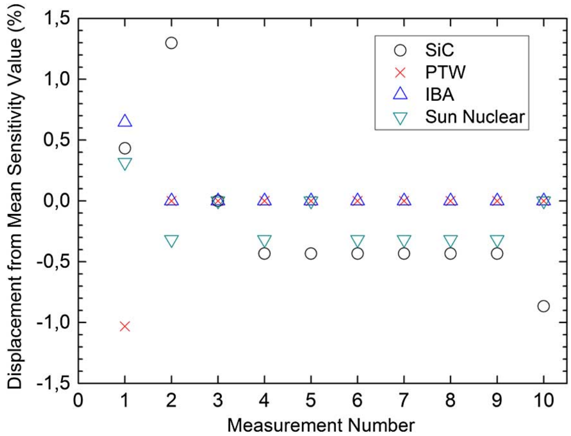

Fig. 10. Stability of the responses for the SiC and the three commercial dosimeters. A sequence of ten measurements of the output charge was done at a constant irradiation of 100 MU. The displacement from the mean sensitivity is represented in % for each measurement.

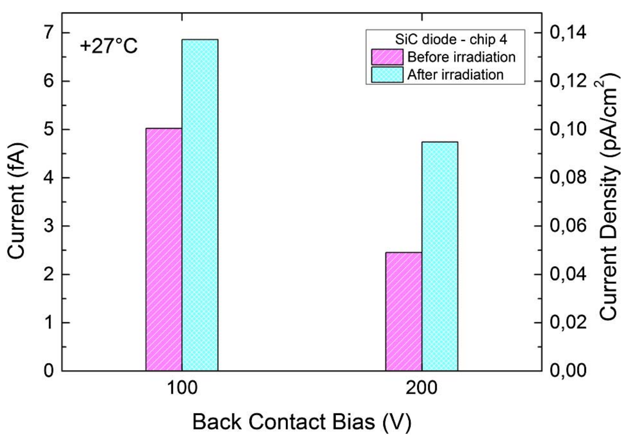

Fig. 11. Leakage currents not reverse on axis and current densities (right axis) of the SiC dosimeter at 100 V and 200 V at room temperature before and after irradiation.

measured sets equal to 0.14, 0.07, 0.06, and 0.03 nC/Gy corresponding to 0.6, 0.2, 0.2 and 0.3% for SiC, Sun Nuclear, IBA and PTW, respectively, were observed.

D. Performance of Device After Irradiation

Current–voltage characterization from 0 V to 200 V at $+27^\circ$C was performed on the SiC diode after exposure to X-ray radiation. As reported in Fig. 11, the leakage current showed an increase after irradiation but it remained below 7 fA, corresponding to 0.14 pA/cm^2 of current density, which is an extremely low value for a semiconductor diode operating at room temperature.

V. Conclusion and Perspectives

A SiC Schottky diode was tested as dosimeter under 6 MV photon beam for radiotherapy. The leakage current of the SiC diode was found to be extremely low (few femtoampere), three orders of magnitude smaller than those of silicon diodes, and almost independent of the temperature in the $+20^\circ$C to $+40^\circ$C range. Such temperature insensitivity can be very useful especially for those patients that need to be kept at a comfortable temperature with warm air blowing systems. A linear, stable and reproducible response of the charge collected as a function of entrance dose was observed. The sensitivity of the 4H-SiC dosimeter was determined to be comparable to those of commercial silicon dosimeters. Good reproducibility of the output charge was obtained during repeated measurements at constant irradiation. Moreover, no priming effects or degradation after exposure to X-rays have been observed. These results open a concrete possibility to use 4H-SiC dosimeters *in vivo* during radiotherapy treatments.

This research demonstrates the capability of SiC Schottky junctions to operate as *in vivo* dosimeters with sensitivity comparable to commercial silicon devices but with significant advantages related to much lower leakage current, lower temperature sensitivity and higher radiation hardness. Our research work constitutes the first step toward development of SiC *in vivo* dosimeters which will require extensive clinical testing before their possible commercialization. The technological steps to achieve high quality Schottky junctions are well established and the packaging required for clinical applications is expected to follow the well-established technology currently used for silicon-based dosimeters. On a cost basis, the processing to manufacture SiC Schottky junctions should be similar to fabrication of silicon diodes. A significant cost difference between the two technologies is the current higher price for SiC wafers but this must be viewed with respect to the diode cost being only a small fraction of the total cost for a dosimeter. Future work will include a study of the dependence of the SiC dosimeter response on operating temperature, energy of the photon beam and angular position with respect to the beam axis, dose rate and radiation tolerance.

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