Radiation Response of Forward Biased Float Zone and Magnetic Czochralski Silicon Detectors of Different Geometry for 1-MeV Neutron Equivalent Fluence Monitoring

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***Abstract*—Aiming at evaluating new options for radiation monitoring sensors in LHC/SLHC experiments, the radiation responses of FZ and MCz custom made silicon detectors of different geometry have been studied up to about 4×10^{14} $\mathrm{n_{eq}/cm^2}$. The radiation response of the devices under investigation is discussed in terms of material type, thickness and active area influence.**

***Index Terms*—Accelerators, p-i-n diodes, particle beams, radiation damage, radiation monitoring, semiconductor growth, silicon radiation detectors.**

I. INTRODUCTION

THE radiation environment encountered in the Large Hadron Collider (LHC) experiments at CERN [1] is completely different than the one observed in standard dosimetric applications.

In LHC experiments, the equivalent fluence (Φ_{eq}) over 10 years will cover a wide range from $10^9 - 10^{10}$ to $10^{14} - 10^{15}$ $\mathrm{n_{eq}/cm^2}$ (1-MeV equivalent neutrons per $\mathrm{cm^2}$). For the upgrade of the LHC (Super-LHC), the radiation level will be multiplied by about a factor 10 due to the increase of the cumulated luminosity towards 3000 $\mathrm{fb^{-1}}$.

Detectors and electronic devices present within this radiation field will be strongly affected by radiation damage. For this reason, the radiation field has to be precisely monitored making radiation monitoring in LHC/SLHC experiments an important issue.

In LHC experiments, the commercial OSRAM BPW34FS silicon p-i-n diode is used for monitoring high fluences [2]–[5], by injecting a constant forward readout current (I_F) of 1 mA with a pulse duration of 700 ms and by measuring the variation of the forward voltage (V_F) versus Φ_{eq}. With this readout protocol, the LHC radiation field can be monitored from 2×10^{12} $\mathrm{n_{eq}/cm^2}$ to 4×10^{14} $\mathrm{n_{eq}/cm^2}$.

In addition, in order to expand the fluence measurement range to higher fluences, another method for monitoring the diode's radiation response for Super-LHC fluences (up to few 10^{15} $\mathrm{n_{eq}/cm^2}$) is presented in [2].

However, this type of diode is not sensitive to radiation damage at low fluences ($\Phi_{\mathrm{eq}} < 2 \times 10^{12}$ $\mathrm{n_{eq}/cm^2}$). A solution already exists for monitoring low fluences, which consists on a pre-irradiation of the p-i-n diodes [5], [6], allowing to bring them immediately to their operation point (where the device starts to be sensitive to radiation damage). Using this method, the fluence measurement range can be extended, starting from about 8×10^9 $\mathrm{n_{eq}/cm^2}$, without altering the diode sensitivity for the higher fluence range [6].

Studies performed on custom made silicon p-i-n diodes have been carried out in previous works [7]–[9] and shown that the sensitivity of the devices is linked to their geometry, type and resistivity of used initial silicon material.

For instance, another type of diode which is manufactured from the Center for Medical Physics (CMRP) [8] of the University of Wollongong (UoW), Australia, is already used at CERN for monitoring low fluences. This type of device reveals a linear response with sensitivity of 1.7×10^8 $\mathrm{cm^{-2}/mV}$ when Φ_{eq} is lower than 2×10^{12} $\mathrm{n_{eq}/cm^2}$ [4].

However, with the intention to evaluate new options for radiation monitoring sensors, an investigation carried out on the radiation response of custom made devices has been performed. The variation of forward voltage versus Φ_{eq} measured at different readout current has been studied for each device under consideration in this work.

The detectors investigated during this study were made from high resistivity n-type Float Zone (FZ) and Magnetic Czochralski (MCz) silicon wafers. The geometry dependence on the detector's radiation response has also been evaluated.

This paper is organized in 5 sections. First of all, the devices and the silicon growth methods used to manufacture the devices under investigation are described. Furthermore, the measurement method is described in Section III. In addition, the effect of all the parameters which can influence the radiation response of the silicon detectors in terms of fluence measurement range and sensitivity is discussed.

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The comparison between both silicon materials (MCz and FZ) is discussed in Section IV. Finally, the influence of the silicon thickness and active area is discussed in Sections V and VI respectively.

II. Devices and Silicon Growth Methods

The devices investigated are 1000 μm and 300 μm thick (FZ and MCz) p+-n silicon detectors of very high resistivity (several $k\Omega$ cm). They have an active area of (2.5×2.5) mm^2 and (5×5) mm^2 and have been manufactured by two different research institutes: the Helsinki Institute of Physics (HIP) from Finland and the Centro National de Microelectronica (CNM) from Spain.

The manufacturing of silicon detectors used for high energy physics experiments (HEP) requires two main conditions: High resistivity and high minority carrier lifetime [10]. The main techniques for growing silicon ingots are the FZ and the Czochralski (Cz) method (see [10] and [11]). Together with the demand for a reasonable price and a homogeneous resistivity distribution, not only over a single wafer, but also over the whole ingot, FZ is the best choice of material and therefore used for detector applications nowadays, as for instance in LHC experiments.

In the research field of "Radiation hardening" and in order to performed radiation test on different materials, other silicon growth techniques have been studied. The ROSE Collaboration [12] proved that an elevated concentration of oxygen in the silicon bulk improves the radiation hardness of particle detectors with respect to the depletion voltage, when they are irradiated by charged particles [13].

From this statement, Cz and MCz silicon are being studied and characterized for HEP detectors since both have a higher concentration in oxygen than FZ silicon. This work has been mainly performed by the RD50 collaboration [14] which studies radiation hard detectors for very high luminosity colliders. A review of this work can be found in [10] and [13] and is summarized in the following.

Almost all the silicon detectors currently used in high energy physics experiments are made from silicon produced by the Float Zone growth method. This method is based on the zone melting principle and was invented by Theurer in 1962 [15]. This growth technique passes a radio frequency (RF) coil up a vertical rod of polysilicon under vacuum or in an inert gaseous atmosphere. The RF coil melts a section of the rod and any impurities are kept on the molten side of the solid/liquid phase transition as the region re-solidifies. The silicon re-solidifies as crystalline silicon. The typical oxygen concentration of FZ silicon is of the order of a few 10^{16} cm^{-3} [13].

The Magnetic Czochralski method is the same as the Czochralski (Cz) method [16], except that it is carried out within a strong horizontal and vertical magnetic field. The presence of a magnetic field during the process of MCz silicon affects the melt flow in the crucible leading to different impurity (oxygen) distribution in the ingot and therefore can modify the properties of the resultant Cz silicon which becomes MCz. During this process, the quartz crucible dissolves into the melt, giving an oxygen concentration up to the solid solubility of oxygen in Silicon.

High resistivity MCz silicon has typically an oxygen concentration of $2 - 5 \times 10^{17}$ cm^{-3}. With such a high concentration, the radiation tolerance of MCz silicon detectors is expected to be improved compared to standard FZ silicon.

Since MCz silicon has higher oxygen concentration, care has to be taken to avoid thermal donor (TD) creation during the growth process as it affects the effective doping concentration [17]. Moreover, TD generation is strongly dependent on the oxygen concentration present in the material.

There is a real motivation for studying MCz silicon as another option for particle detectors in future HEP experiments. Nevertheless its fabrication procedure is more complicated [13].

III. Measurement

Radiation studies have been performed by exposing the silicon detectors to the 24 GeV/c proton beam of the IRRAD1 facility at CERN [18]. Irradiations were carried out at about 27°C and detectors have been irradiated at fluences ranging from about 3×10^9 up to 4×10^{14} $\mathrm{n_{eq}/cm^2}$ with a fluence accuracy of $\pm 8\%$.

As silicon detectors are light sensitive, measurements have been performed in a light-tight box, using a Keithley 2410 for injecting readout currents and measuring the corresponding forward voltages.

In order to evaluate the variation of the hadron sensitivity at different readout currents, detectors have been measured at room temperature, by injecting 8 current steps: 10 μA, 100 μA, 1 mA, 5 mA, 10 mA, 15 mA, 20 mA and 25 mA, with 50 ms pulse duration. Measurements have been carried out at each irradiation step presented in this work.

The sample to sample variation could not be investigated in this study, since only one device for each silicon detector type and radiation fluence has been examined.

The samples were irradiated at about 27°C, and for that reason have undergone some annealing. However, no annealing data exist so far for silicon detectors operated in the forward direction. Nevertheless, some data exists for commercial silicon p-i-n diodes operated in forward bias as in [4] and [5], showing that the corresponding drop in signal should be less than 3% up to fluence of about 1×10^{14} $\mathrm{n_{eq}/cm^2}$.

In order to avoid room temperature annealing between and after each irradiation step, the silicon detectors were stored in a deep freezer below −20°C when not measured.

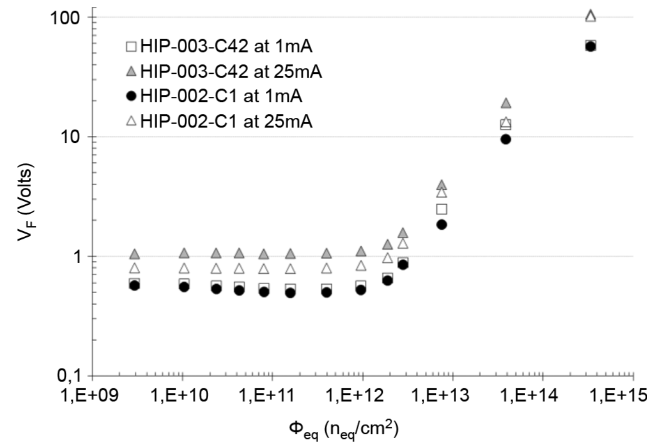
In all figures presented in this paper, for a better visibility, only few measurements performed at different readout currents are shown.

For any radiation response curves, an individual silicon detector has been measured.

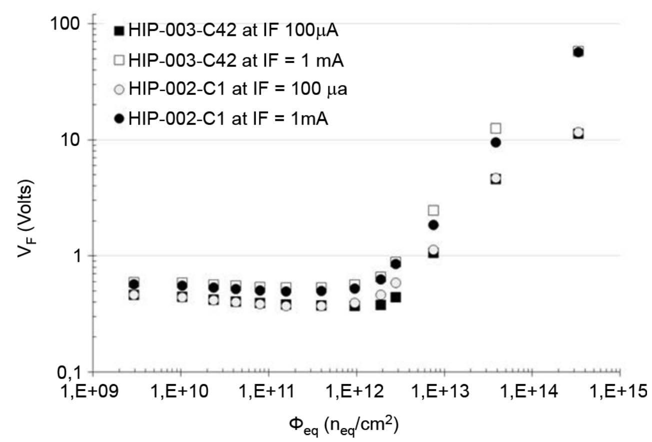
In this paper, the variation of the series resistance versus equivalent fluence has not been evaluated, since for extracting this parameter, complete I-V curves are needed [19].

IV. Comparison Between MCz and FZ Silicon Detectors

Fig. 1 shows the radiation response of the HIP-003-C42 and HIP-002-C1 silicon detectors, which are respectively MCz and FZ detectors with an identical geometry (active area of (2.5×2.5) mm^2 and thickness of 300 μm). Results for both silicon detectors operated at 1 mA and 25 mA are presented in Fig. 1(a),



(a)



(b)

Fig. 1. Radiation responses of the HIP-003-C42 (MCz) and HIP-002-C1 (FZ) after 24 GeV/c proton irradiations. The diode's forward voltages measured at (a) 1 mA and 25 mA as well as (b) 100 μA and 1 mA are plotted versus $\Phi_{\rm eq}$. Both devices have a $2.5\times 2.5\ \rm mm^2$ active area and a thickness of $300\ \mu$m.

while measurements carried out with 100 μA and 1 mA readout currents are illustrated in Fig. 1(b).

As it can be observed in this figure, both types of silicon detectors are not sensitive to radiation damage up to around $2\times 10^{12}\ \rm n_{eq}/cm^2$.

In addition, both silicon detectors start to be sensitive at the same fluence than previously observed for the BPW34FS silicon p-i-n diode [2], [4], [5], which has a similar geometry (300 μm thick diode; active area of $2.65\times 2.65\ \rm mm^2$). For this reason, one can assume that the radiation response of these types of silicon detectors should be not totally different from the one observed for the BPW34FS diode. On the other hand, the material from which the silicon detectors have been made is different and might influence their sensitivity.

For this reason, the silicon detector calibration factor (1/c) which is the inverse of the coefficient c, that links the variation of the increase of the forward voltage versus $\Phi_{\rm eq}$ (see (1)) has been evaluated for both detector types and compared to the hadron sensitivity of the BPW34FS silicon p-i-n diodes.

$$\Delta V_F = c\times \phi_{\rm eq} \tag{1}$$

TABLE I
MCZ AND FZ SILICON DETECTORS EXPERIMENTAL HADRON SENSITIVITY AT DIFFERENT READOUT CURRENTS ($\rm cm^{-2}/mV$). COMPARISON WITH THE BPW34FS HADRON SENSITIVITY

I_F	1/c (MCz)	1/c (FZ)	1/c (BPW34FS)
100 µA	8.7×10^9	8.8×10^9	1.7×10^{10}
1 mA	3.1×10^9	4.1×10^9	9.1×10^9
25 mA	2.1×10^9	2.2×10^9	6.5×10^9

For all results concerning the calibration factor presented in this paper, fits of the data are deviating at maximum 30% from the measured data points. The spread between experimental data and fits has probable origin in the errors that affects the dosimetry measurements carried out in the irradiation facility and the temperature for each measurement which varies between 21,7°C and 24,4°C. Moreover, the slight number of measurements in the linear part of the curves can also contribute to the error enhancement.

In Table I, it can then be observed that the results for the MCz and FZ materials measured at 1 mA readout current are not similar as it is the case for 100 μA and 25 mA readout current due to this uncertainty.

Results are summarized in Table I and demonstrate that the sensitivity to radiation damage for the MCz and FZ silicon detectors of identical geometry varies only slightly. Therefore, it can be concluded that the sensitivity to radiation damage of silicon diodes operated under forward bias is not considerably altered by using oxygenated silicon material.

In addition, both silicon detector sensitivities have been compared to the one of the BPW diode. Results show that their sensitivities are on the same order of magnitude. However silicon detectors are more sensitive than the commercial silicon p-i-n diode.

From experimental curves, it is possible to estimate the upper limit of the fluence measurement range, where the detector response is still linear versus fluence. For both devices, it can be observed that the variation of V_F is not linear anymore for $\Phi_{\rm eq} > 10^{14}\ \rm n_{eq}/cm^2$ (see detector's radiation responses at $I_F = 100\ \mu$A). Therefore a maximum $\Phi_{\rm eq}$ range of few $10^{14}\ \rm n_{eq}/cm^2$ has been evaluated.

At such high fluences one can consider that for these types of detectors the relaxation regime [20]–[27] is already established (as for the BPW34FS diode, see [2]), since the modification of the curve shape indicates that the device becomes ohmic-like. This effect can also be observed for thicker detectors as it is illustrated in the next sections.

V. Influence of the Detector Thickness

An investigation of the thickness influence has been carried out on two types of FZ silicon detectors with identical active area ($(2.5\times 2.5)\ \rm mm^2$) and different thicknesses.

Fig. 2 shows the variation of V_F versus $\Phi_{\rm eq}$ for 1000 μm (CNM-009-S01) and 300 μm (HIP-002-C1) thick silicon detectors. Fig. 2(a) shows the experimental results taken for both

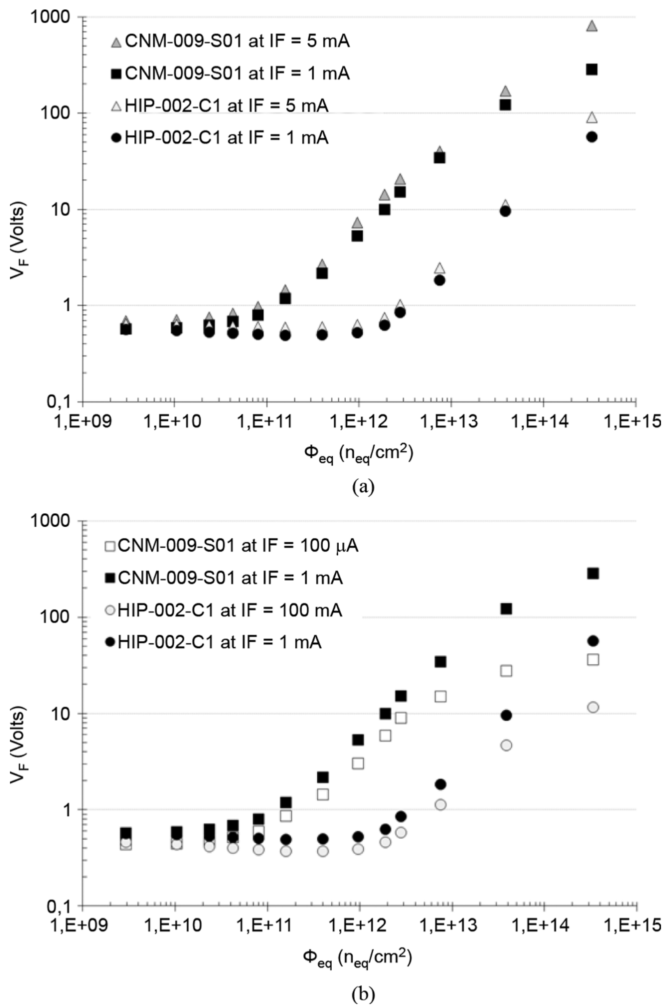


Fig. 2. Radiation responses of the HIP-002-C1 $(300\ \mu\mathrm{m})$ and CNM-009-S01 $(1000\ \mu\mathrm{m})$ after 24 GeV/c proton irradiations. The diode's forward voltages measured at (a) 1 mA and 5 mA as well as (b) $100\ \mu\mathrm{A}$ and 1 mA are plotted versus Φ_{eq}. Both devices are FZ silicon with an active area of $2.5 \times 2.5\ \mathrm{mm}^2$.

silicon detectors operated at (a) 1 mA and 5 mA as well as (b) at $100\ \mu\mathrm{A}$ and 1 mA readout currents.

It can clearly be noted that the $1000\ \mu\mathrm{m}$ thick detector starts to be sensitive to radiation damage at lower fluence $(\Phi_{\mathrm{eq}} \approx 2 \times 10^{10}\ \mathrm{n_{eq}/cm^2})$ than the $300\ \mu\mathrm{m}$ thick detector.

It has been shown in previous studies that the forward voltage of the silicon p-i-n diodes increases with radiation damages due to the degradation of the carrier lifetime and the increase of the bulk resistivity [7] and [28].

As observed and described for the $300\ \mu\mathrm{m}$ BPW34FS thick diode in [4] and [5], for $300\ \mu\mathrm{m}$ thick detectors, it can be noted that as the radiation level is increased up to $\Phi_{\mathrm{eq}} \approx 10^{12}\ \mathrm{n_{eq}/cm^2}$, V_F is slightly reduced (by tens of mV, not visible in the log plot).

This can be explained, since for such devices, the W/L (width of the detector over diffusion length) ratio is small, and V_F is dominated by the junction voltages [28].

Therefore, the decrease of the minority carrier lifetime induces a reduction of the junction voltages and thus a diminution of V_F.

TABLE II
$300\ \mu\mathrm{m}$ AND $1000\ \mu\mathrm{m}$ SILICON DETECTORS EXPERIMENTAL HADRON SENSITIVITY AT DIFFERENT READOUT CURRENTS $(\mathrm{cm^{-2}/mV})$

I_F	1/c (300 µm)	1/c (1000 µm)
100 µA	8.8×10^9	3.2×10^8
1 mA	4.1×10^9	1.9×10^8
5 mA	3.5×10^9	1.3×10^8

For both detector types, as the radiation level increases, the diffusion length is reduced to the order of W and below, inducing a positive increase of the detector sensitivity [28]. As a consequence, $1000\ \mu\mathrm{m}$ thick detectors are more sensitive to radiation damage at low fluences, since the ratio W/L starts to increase and becomes higher than 1 in contrast to $300\ \mu\mathrm{m}$ thicker detector even for lower fluences.

At high irradiation levels, the increase of the base resistivity also contributes to the total voltage drop across the diode [7] and finally dominates the voltage drop across the p-i-n diodes at very high radiation levels [7], [28].

As in the previous section, the calibration factor (1/c) has been evaluated and is presented in Table II.

The thicker detector reveals the highest sensitivity to radiation damage which is around 25 times greater than the one observed for the $300\ \mu\mathrm{m}$ thick detector.

However, the maximum Φ_{eq} measurement range observed for the $1000\ \mu\mathrm{m}$ thick detector is lower, since the forward voltage of the CNM-009-S01 silicon detector starts to saturate at an equivalent fluence of few $10^{12}\ \mathrm{n_{eq}/cm^2}$ indicating that the detector becomes ohmic-like (see [2], [20]–[27]).

VI. Influence of the Active Area

Comparison has been performed between $1000\ \mu\mathrm{m}$ thick FZ silicon detectors made with different active areas. The investigated active areas were $(5\times5)\ \mathrm{mm}^2$ and $(2.5\times2.5)\ \mathrm{mm}^2$ for the CNM-009–32 and CNM-009-S01 silicon detectors respectively.

Results are presented in Fig. 3 for both devices operated at (a) 5 mA and 1 mA, (b) 1 mA and $100\ \mu\mathrm{A}$ readout currents.

On the one hand, as discussed in previous section, the variation of the active area does not modify the fluence measurement range (where the detector response is still linear versus Φ_{eq}).

For both detector types, the radiation sensitivity starts around Φ_{eq} of about $2 \times 10^{10}\ \mathrm{n_{eq}/cm^2}$ and the shape of the forward voltage changes from a linear increase up to saturation versus Φ_{eq} around few $10^{12}\ \mathrm{n_{eq}/cm^2}$, caused by the occurrence of the ohmic-like behavior.

As for previous sections, the comparison between both detectors is based on the evaluation of their sensitivity in the linear region at different readout currents. Results are presented in Table III.

From this, it can be noted that the sensitivity (in the linear region) is increased by a factor of about 1.5 in average, when the active area is reduced by 4. This is due to two factors: i) increasing of injection current density that is derived in details in [9] and ii) pure geometrical factor W/A (width over area of the detector) which is determined by increasing of resistance

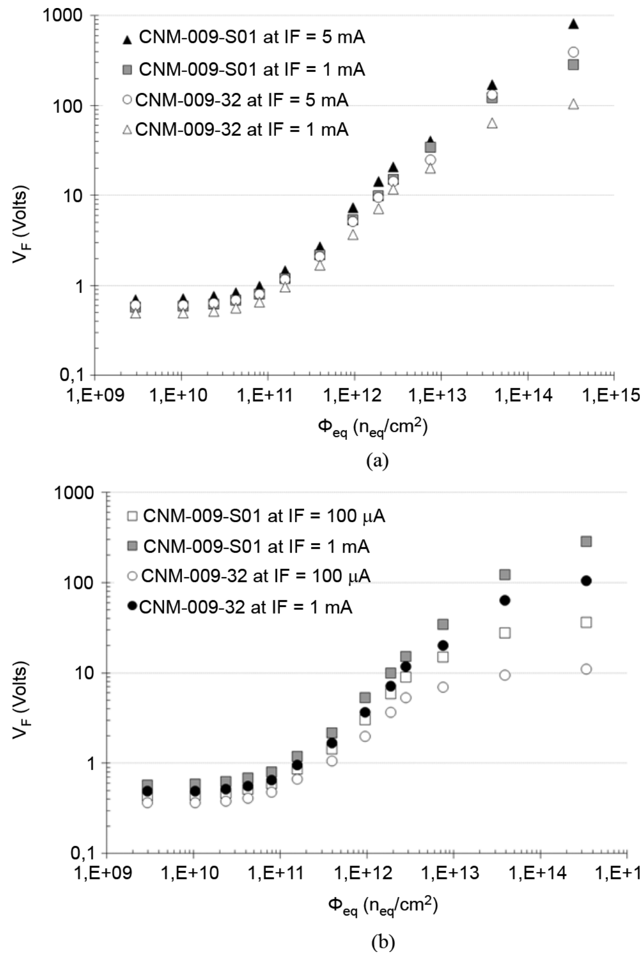


Fig. 3. Radiation responses of the CNM-009-S01 $(2.5 \times 2.5\ \mathrm{mm}^2)$ and CNM-009-32 $(5 \times 5\ \mathrm{mm}^2)$ after 24 GeV/c proton irradiations. The diode's forward voltages measured with a 50 ms readout current of (a) 1 mA and 5 mA as well as (b) 100 μA and 1 mA are plotted versus Φ_{eq}. Both devices are 1000 μm thick FZ silicon detectors.

TABLE III
$(2.5 \times 2.5)\ \mathrm{cm}^2$ AND $(5 \times 5)\ \mathrm{mm}^2$ SILICON DETECTORS EXPERIMENTAL HADRON SENSITIVITY AT DIFFERENT READOUT CURRENTS $(\mathrm{cm}^{-2}/\mathrm{mV})$

I_F	1/c ((2.5×2.5) mm²)	1/c ((5×5) mm²)
100 µA	3.2×10^8	5.7×10^8
1 mA	1.9×10^8	2.8×10^8
5 mA	1.3×10^8	2×10^8

of the diode base due to increasing of resistivity of n-Si with irradiation.

The main difference is observed in the non-linear regime (at $\Phi_{\mathrm{eq}} > 1 \times 10^{13}\ \mathrm{n_{eq}/cm^2}$). In this regime, V_F is lower for wider detector, since silicon detectors are becoming ohmic-like.

VII. CONCLUSION

With the intention of monitoring $\Phi_{\mathrm{eq}} < 2 \times 10^{12}\ \mathrm{n_{eq}/cm^2}$ and to evaluate new options for radiation monitoring sensors in LHC/SLHC experiments, several devices have been investigated.

The radiation response of silicon detectors made with different silicon materials and geometries have been evaluated from low fluences ($\Phi_{\mathrm{eq}} \approx 1 \times 10^9\ \mathrm{n_{eq}/cm^2}$) to few $10^{14}\ \mathrm{n_{eq}/cm^2}$.

The outcome of the study reveals for the first time that there is no significant difference between the radiation response of forward biased MCz (oxygenated material) and FZ silicon detectors up to a few $10^{14}\ \mathrm{n_{eq}/cm^2}$. However, data on comparison of two initial materials were presented only for 300 μm thick silicon detectors, thus further investigations on other detectors with different thicknesses are still needed to substantiate this statement.

In addition, the geometry dependence has also been investigated and shows that the main parameter which influences the silicon detector's radiation response in terms of sensitivity and fluence measurement range is the thickness as it has been previously shown in [7]–[9] and [29].

Thicker devices (1000 μm) start to be sensitive to radiation damage at lower Φ_{eq} and show a sensitivity which is around 25 times greater than the one observed for thinner detectors (300 μm). To our best knowledge, this result cannot be directly compared to previous works, since in published results, there is no comparison of the increase of the sensitivity between 300 and 1000 μm silicon p-i-n diodes with the same active area and the same initial resistivity. However, we can compare the order of magnitude of the detector sensitivity of the 1000 μm thick silicon detector with the CMRP p-i-n diode (1000 μm thick); as it is the case between 300 μm thick silicon detector and the BPW34FS diode in Table I. For 1 mA readout current, the 1000 μm thick CNM-009-S01 detector (which is the most similar than the CMRP diode in terms of geometry; base length: 1 mm and active area: $1.2\ \mathrm{mm}^2$) reveals a sensitivity of about $1.9 \times 10^8\ \mathrm{cm}^{-2}/\mathrm{mV}$. This result is in good agreement with the results published in [4] and [6], where the CMRP diode reveals a sensitivity of about $1.7 \times 10^8\ \mathrm{cm}^2/\mathrm{mV}$ at 1 mA readout current.

This result allows to state that the use of thick silicon detectors for monitoring low LHC/SLHC fluences is an option that should be considered in the future.

However, the response of this type of devices is limited to their utilization at medium and low fluences ($\Phi_{\mathrm{eq}} < 1 \times 10^{13}\ \mathrm{n_{eq}/cm^2}$), since the forward voltage does not increase linearly up to very high fluences.

Nevertheless, with the aim to characterize their radiation response in the ohmic-like regime with the approach presented in [2], a study on thick and thin silicon detector heavily irradiated (up to few $10^{15}\ \mathrm{n_{eq}/cm^2}$) is still in progress and will be addressed in a future paper.

The forward voltage for 1000 μm and 300 μm thick silicon detectors starts to increase around $2 \times 10^{10}\ \mathrm{n_{eq}/cm^2}$ and $2 \times 10^{12}\ \mathrm{n_{eq}/cm^2}$ respectively. This result is in good agreement with the results obtained for the 300 μm BPW34FS thick silicon p-i-n diode, which starts to be sensitive at Φ_{eq} of about $2 \times 10^{12}\ \mathrm{n_{eq}/cm^2}$ and in good agreement with [30] where FZ based p-i-n neutron CMRP diode was investigated.

A solution for monitoring the full LHC fluence range with custom made devices can be proposed. It consists in the use of either MCz or FZ thick silicon detectors for monitoring low fluences and thin ones for high fluences as was also demonstrated in [30] with custom made diodes for lower fluences and with 300 $\mu\mathrm{m}$ BPW34FS diodes for higher neutron fluences.

In this way, LHC/SLHC particle fluence could be monitored from low fluences ($\Phi_{\mathrm{eq}} \approx 1 \times 10^{10}\ \mathrm{n_{eq}/cm^2}$) to high fluences (few $10^{14}\ \mathrm{n_{eq}/cm^2}$). For a further expansion of the fluence measurement range, even thinner and thicker detectors could be used.

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