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Dopant concentration dependence of the response of SiC Schottky diodes to light ions ☆

M. De Napoli [a,b], F. Giacoppo [b,c], G. Raciti [a,d,*], E. Rapisarda [a,d]

[a] Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Via S. Sofia 64, I-95123 Catania, Italy
[b] Laboratori Nazionali del Sud, Via S. Sofia 62, I-95123 Catania, Italy
[c] Dipartimento di Fisica, Università degli Studi di Messina, Via Salita Sperone 31, I-98166 Messina, Italy
[d] Isituto Nazionale di Fisica Nucleare, Sezione di Catania, Via S. Sofia 64, I-95123 Catania, Italy

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ABSTRACT

The responses of Silicon Carbide (SiC) Schottky diodes of different dopant concentration to ^{12}C ions at 14.2, 28.1 and 37.6 MeV incident energies are compared. The relation between the applied reverse bias and the thickness of the depleted epitaxial region is studied for different dopant concentrations. The experimental data show that SiC diodes with lower dopant concentration need lower reverse bias to be depleted. Moreover it has been observed that the energy resolution, measured as a function of the applied reverse bias and of the ions incident energies, does not depend on the dopant concentration. The radiation damage, produced by irradiating SiC diodes of different dopant concentration with ^{16}O ions at 35.2 MeV, was evaluated by measuring the degradation of both the signal pulse-height and the energy resolution as a function of the ^{16}O fluence. Diodes having a factor 20 lower dopant concentration exhibit a radiation hardness reduced by 60%. No inversion in the signal at the breakdown fluence was observed for ^{16}O ions stopped inside the diode epitaxial region.

1. Introduction

Among the new materials convenient to be used as electronic devices and radiation detectors in very severe environments, Silicon Carbide (SiC) has been attracting attention for its interesting characteristics. This compound semiconductor has a wide bandgap (from 2.4 to 3.25 eV, depending on the SiC type [1]), a large electron saturation velocity (2×10^{7} cm/s [1]) and a high breakdown voltage. These properties promise, respectively, high temperature, high frequency and high electric fields operating conditions.

Recent work has been done to develop SiC as radiation detectors based on Schottky diode and p–n junction designs [2–4]. However, in spite of the notable development in growing, processing and producing good-quality and low-defect SiC diodes, the characterization of such devices as radiation detectors [5–10] is far from completed. SiC diodes have been already used to detect neutrons [8], X-rays [9,10] and alpha particles [5–7], showing good performances. Recently, with the aim of exploring possible applications in nuclear physics, we extended the study of the detection properties of SiC diodes also to light ions (^{12}C and ^{16}O) at energies between 5 and 18 MeV [11].

An appealing property of SiC, as well as of other wide bandgap materials such as GaAs and diamond, is their predicted radiation hardness with respect to silicon. The radiation damage on SiC diodes has been already investigated with protons, electrons and gamma rays [12–14], 300 MeV/c pions [15,16], neutrons [17], alphas, ^{12}C and heavier ions [18,19], and recently ^{16}O at 53 MeV [11], at fluences up to 10^{16} particles/cm^2, obtaining promising performances.

The main inconvenience we have found in the use of such detectors was the high bias voltage needed to deplete the epitaxial region of the diodes. However, a correlation between the depleting bias values and the dopant concentration in the epitaxial region is expected [5]. Therefore, in the present work we analyze the response of 4H–SiC Schottky diodes with different dopant concentration to ^{12}C and ^{16}O ions between 14.2 and 37.6 MeV. In particular we measure the relationship between the thickness of the depleted region and the applied reverse bias, the energy resolution, and the radiation hardness of SiC diodes with different dopant concentrations.

In Ref. [11] an inversion in the signal at a fluence of 10^{15} ions/cm^2 has been reported for a SiC diode irradiated with an ^{16}O beam at 53 MeV of incident energy. Since it was not clear whether the inversion was a consequence of the radiation damage or of the ^{16}O implantation in the SiC n^{+} substrate, we investigate

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*Corresponding author at: Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Via S. Sofia 64, I-95123 Catania, Italy. Tel.: +39 095 542 286; fax: +39 095 378 5225.
E-mail address: raciti@lns.infn.it (G. Raciti).

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this effect by irradiating the samples with an ^{16}O beam at 37.6 MeV incident energy, whose range is shorter than the thickness of the present SiC n^- epitaxial layer.

2. Experimental details

The SiC Schottky diodes have been fabricated by epitaxy onto high-purity 4H–SiC n-type substrate from the ETC-Catania [20]. The Schottky junction was realized by a 0.2 μm thick layer of Ni_2Si deposited at 600 °C on the front surface, while the ohmic contact, on the back surface, was obtained with Ni_2Si deposited at 950 °C [21,22]. The active area of each chip is $2 \times 2\,mm^2$ and the dopant nitrogen concentration and thickness of the n^+ side were $7 \times 10^{18}\,N/cm^3$ and 279 μm, respectively. Three types of SiC diodes with different nominal n^- epitaxial layer concentrations and thicknesses have been used. Their characteristics are reported in Table 1.

In particular, the SiC type c were of the same type of the ones used in our previous measurements [11].

The chips were glued on a brass foil 1 mm thick by conductive glue and single contacts between the Ni_2Si front surfaces and the individual pads of a board were realized by Al wire (2 μm thick) bonding. Two chips of each type were assembled on three different boards, for a total number of six independent detectors. The consistency of the reported results was investigated by comparing all the six detectors. The boards were set up in a scattering chamber at the Laboratori Nazionali del Sud (LNS—Catania) and operated under vacuum at 10^{-6} mbar. The active samples were irradiated with ^{12}C beam at 14.2, 28.1 and 37.6 MeV and ^{16}O beam at 35.2 MeV, accelerated by the LNS Tandem VdG [23]. The ion beams were focused 60 cm downstream with respect to the detector position in order to achieve a uniform perpendicular irradiation on a spot of about 3 mm of diameter on the SiC surface. The boards holder was moved so as to center the detectors one by one. Standard electronics was used to process the signals and set up outside the scattering chamber: preamplifiers of 45 mV/MeV gain (ORTEC 142A) and amplifiers with 0.5 μs shaping time. Data acquisition was based on CAMAC ADCs read out through a GPIB standard National Instruments interface and a data-acquisition program built in the LabView 7 framework.

3. Dopant concentration dependence of the detector response

In our previous work [11] we measured the correlation between the applied reverse bias and the thickness of the depleted epitaxial region in SiC diodes of type c. The results showed that values of bias voltage higher than 450 V are needed to fully deplete the diodes.

However the thickness (d) of the depleted layer is expected to depend on the applied reverse bias (V) through the dopant concentration (N) [24] as

$$d \approx \sqrt{\frac{2(V + V_{built\text{-}in})\varepsilon}{eN}} \tag{1}$$

Table 1
Characteristics of the three types of tested SiC diodes.

Type	Nominal dopant concentration (N/cm^3)	Thickness (μm)
a	7.6×10^{14}	37.9
b	2.0×10^{15}	43.7
c	1.5×10^{16}	21

where ε and e are the static permittivity of the material and the electron charge, respectively, and $V_{built\text{-}in}$ is the magnitude of the Schottky barrier height.

Therefore, in order to sample experimentally Eq. (1), the three types of SiC diodes with different dopant concentration were irradiated with ^{12}C ions at 14.2, 28.1 and 37.6 MeV incident energies. For each incident energy a number of energy spectra were taken over a range of reverse bias voltages from 0 to −1000 V. The latter is the maximum value that the preamplifier can tolerate.

As already observed [11], the pulse-height peak position moves towards higher channel values as the voltage increases. This behavior, common to all the presently irradiated detectors, can be described, according to Eq. (1), by the increasing thickness (d) of the active volume of the detector with increasing reverse bias voltage (V). As a result, the incident ^{12}C deposits more energy in the active region leading to detector signals with higher pulse-height. The saturation of the pulse-height is then reached when the applied reverse voltage depletes the active volume of the diode up to the range corresponding to the energy of the incoming ^{12}C ions.

The peak positions, evaluated by Gaussian fits of the energy spectra, are reported in the panels of Fig. 1, for the three SiC types, as a function of the applied reverse bias. The energy values of 13.7, 27.7 and 37.3 MeV, reported in Fig. 1 for the three ^{12}C beams, respectively, refer to the corrected incident energies in the active region of the detectors. They were evaluated by subtracting from the incident energy, the energy lost in the Ni_2Si 0.2 μm thick front layer of the diode computed by using the SRIM code [25].

By correlating the saturated peak positions to the corresponding corrected ^{12}C incident energies, we calibrated the pulse-height scale of SiC type a and b. For the low energy range the three peaks at 5.157, 5.406 and 5.805 MeV of a ^{239}Pu–^{241}Am–^{244}Cm mixed alpha source were used. An example of the calibration procedure is reported in Fig. 2 for SiC type b. On the other side, the SiC type c pulse-height scale was calibrated by using an ^{241}Am 5.48 MeV alpha source and four absorbers as in Ref. [11], since the peak-position saturation was achieved only for the ^{12}C beam at 13.7 MeV (Fig. 1, bottom panel).

All the SiC detectors show a high degree of linearity between the saturated pulse-height value and the deposited energy, as already observed in Refs. [5,6,11].

In Fig. 3 the correlation between the square-root of the applied bias at which the pulse-height of SiC a (triangles) and b (squares) saturates and the ranges of ^{12}C at 13.7, 27.7 and 37.3 MeV is shown. The range values 8.5, 19.7 and 29.1 μm of the three ^{12}C incident energies, respectively, are calculated by the SRIM code [25]. In case of SiC c we can only determine the bias required to deplete the thickness equal to the range of ^{12}C at 13.7 MeV. Indeed the thickness of 21 μm is shorter than the range of ^{12}C at 37.3 MeV, whereas the range of ^{12}C at 27.7 MeV can be reached only at voltages higher than the preamplifier limit. Therefore, in order to improve the sampling, as in Ref. [11], we correlated the applied reverse biases to the thicknesses of the depleted region evaluated by using the SRIM code [25] from the measured energy losses of the ^{12}C beam at 27.7 MeV. A good agreement between the present results (full circles) and the previously obtained ones [11] on a different SiC type c (empty circles) is found (Fig. 3). The experimental data are compared with curves calculated from Eq. (1). In the calculations the SiC static permittivity was assumed to be $\varepsilon = 9.66 \cdot \varepsilon_0$ where ε_0 is the electric constant $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m as in Ref. [26]. The magnitude of the Schottky barrier height ($V_{built-in}$), not directly measured, was assumed to be 1.5 V, which is a reasonable value for Schottky SiC diodes [27]. The best fit procedure of the experimental data gives the values of $(6.0 \pm 1.5) \times 10^{14}$, $(1.3 \pm 0.4) \times 10^{15}$ and $(5 \pm 0.5) \times 10^{15}$ atoms/cm^3 for the dopant concentrations of SiC a, b,

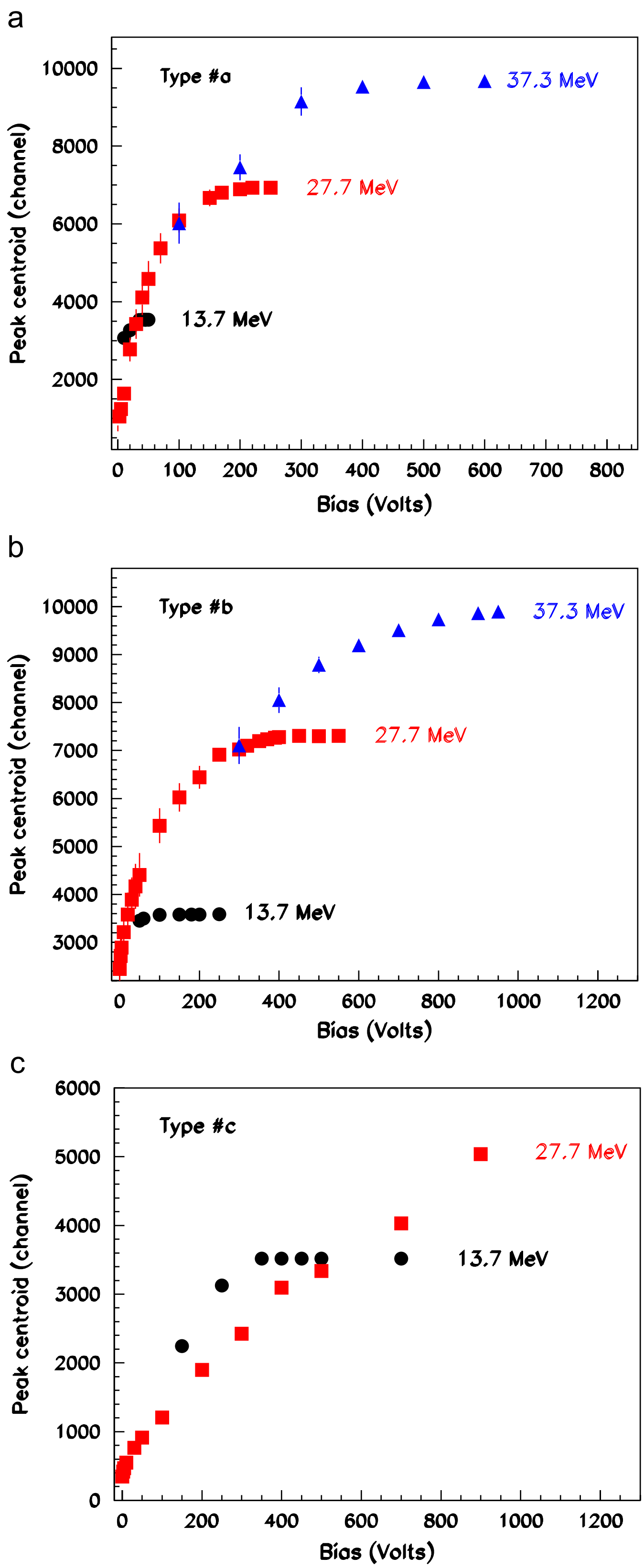

Fig. 1. (Color online) Centroid value of the energy peak of the ^{12}C at 13.7 (circles), 27.7 (squares) and 37.3 MeV (triangles) incident energies, as a function of the reverse bias applied to SiC a (top panel), b (middle panel) and c (bottom panel). Full width at half maximum of the Gaussian fits are reported as errors bars.

and c, respectively. It must be noted that, while the differences with respect to the nominal dopant concentration values could be accounted for the statistical errors, except for SiC type c, the three

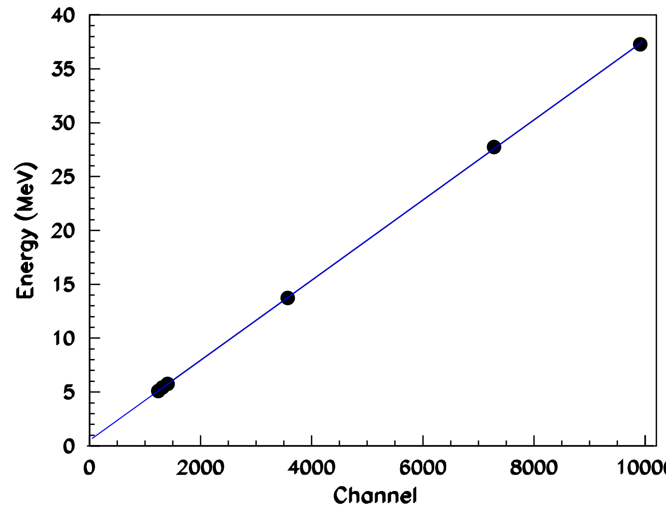

Fig. 2. (Color online) Pulse-height versus energy correlation for SiC b. Data points refer to the ^{12}C beam at 13.7, 27.7 and 37.3 MeV. The three points at lower channels correspond to the three peaks of a ^{239}Pu–^{241}Am–^{244}Cm alpha source, detected at a reverse bias value of 800 V, at which the signals are saturated.

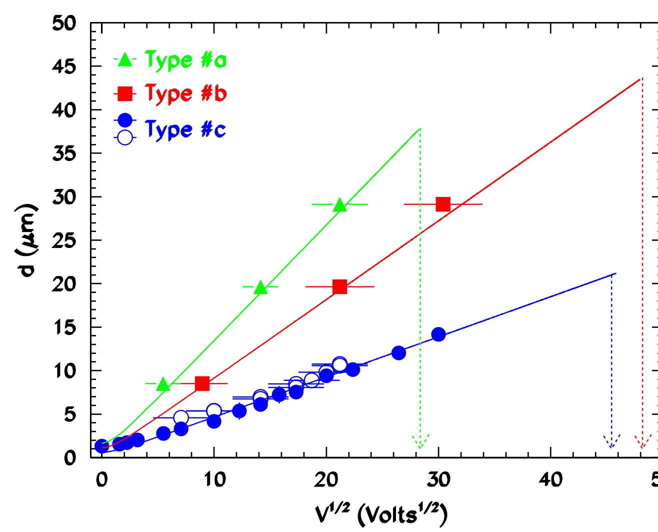

Fig. 3. (Color online) Correlation between the square-root of the applied reverse bias and the depletion layer thickness of SiC a (triangles), b (squares) and c (full circles) compared with data from Ref. [11] (empty circles). The lines are calculated from Eq. (1). Arrows indicate the square-root of the estimated bias values corresponding to fully depleted epitaxial region of the diodes.

obtained values are smaller than the nominal ones. These differences are not surprising since, as reported in Ref. [27], the dopant concentrations of various chips, originating from a common wafer subjected to a single dopant process, can vary from 4.73×10^{13} to 7.74×10^{13} atoms/cm^3. Moreover, for a fixed chip diode, some dopant profiles obtained by $C-V$ measurements show that the net dopant concentration can vary from 56% [27] up to more than an order of magnitude [19] as a function of the depth of the active layer.

Since the range of the ions used in the present measurements was smaller than the thickness of the SiC diode types a and b, we did not increase the reverse bias to the values needed to fully deplete the diodes. However, from the fitting curves of Fig. 3 these values can be evaluated as 805, 2322 and 2062 V for SiC types a–c, respectively. Although, as expected from Eq. (1), SiC diodes with lower dopant concentration require lower reverse bias values to deplete the same thickness, the values estimated to fully deplete the three type of SiC are still too high for nuclear physics applications. In Fig. 4 the relative energy resolution (FWHM of the Gaussian fit over the peak centroid) of the ^{12}C beam at 27.7 MeV, for SiC a (triangles), b (squares) and c (full circles) is shown as a function of the applied bias. Present data are compared with those of a SiC type c irradiated with ^{12}C at 17.68 MeV (empty circles) [11]. The relative energy resolution of SiC a and b largely improves by increasing the bias voltage up to the values for which the pulse-height saturation region is reached. For larger values it remains then quite constant. This trend has been already observed in Refs. [28,29]. The low resolution measured for bias values in the region where the depleted layer is smaller than the ions range could be caused both by large fluctuations in the amount of collected charge due to random recombination of minority carriers and by their longer collection time [28] that could generate a ballistic defect [30].

However, when the thickness of the depleted region is larger than the ion range, the resolution of the three SiC types is approximately the same, as shown in Fig. 5. Therefore, the different dopant concentration produces no effects on the detector energy resolution. The measured values, depending on the beam energy, range from about 5.5% down to about 1.7% as in Refs. [6,12], even though better resolutions, up to 0.34%, have been measured [31,32].

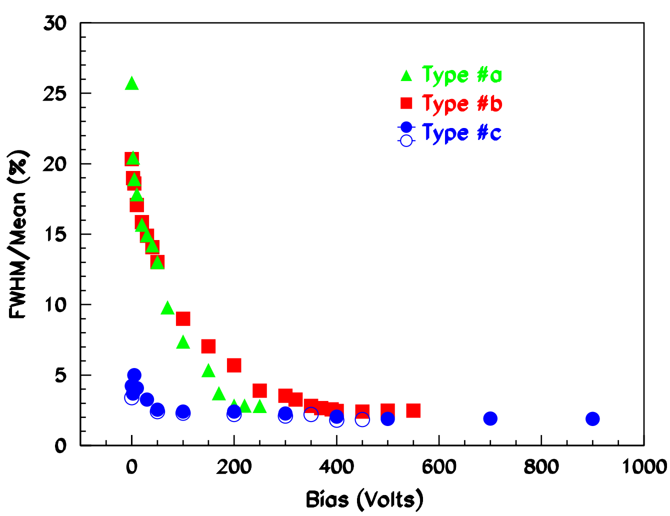

Fig. 4. (Color online) Relative energy resolution of ^{12}C at 27.7 MeV incident energy as a function of the bias applied to SiC a (triangles), b (squares) and c (full circles). Empty circles refer to relative energy resolution of ^{12}C, at 17.68 MeV incident energy, measured for SiC type c in Ref. [11].

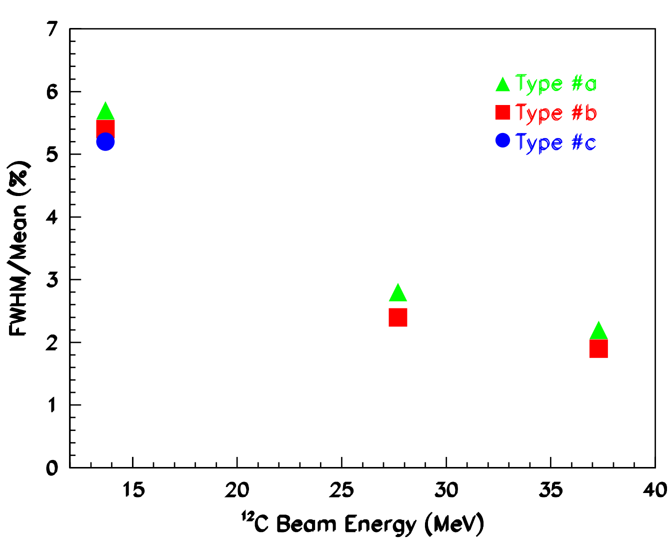

Fig. 5. (Color online) Relative energy resolution, measured at pulse-height saturation, for SiC a (triangles), b (squares) and c (circles), as a function of the beam incident energy.

4. Radiation damage

One of the most interesting properties of SiC detectors is their radiation hardness. When radiation passes through the SiC crystal the energy that goes into the creation of electro-hole pairs leads to fully reversible processes that leave no damage. On the other hand non-ionizing energy transferred to the atoms of the crystal leads to irreversible changes in the lattice. When enough of these defects, that can trap charge carriers, have been produced, charge collection is reduced.

An important task of this work was to explore the effects of a reduced dopant concentration in the radiation hardness properties of SiC detectors. SiC of types a and c were irradiated using ^{16}O ions at 35.2 MeV. Unfortunately, the two SiC b did not work during the irradiation measurements since their Al wires bonding were broken before. During the irradiation the reverse bias of SiC a and c was kept fixed at a value of 600 and 400 V, corresponding to a depletion thickness of 32.7 and 9.2 μm, respectively.

The ratio between the peak centroid of the ^{16}O energy spectrum after the irradiation (PC_{AI}) over the same peak centroid before the irradiation (PC_{BI}) is shown in Fig. 6 as a function of the ^{16}O fluence. It is evident that, by increasing the fluence, the energy peak, for both SiC a (triangles) and c (full and empty circles), moves toward lower channels, indicating an increasing incompleteness in the charge collection. A good agreement between present (full circles) and previous (empty circles) [11] results for different SiC type c is found. From Fig. 6 it can be observed that the signal amplitude of SiC type c drops to 50% at a fluence of 6.5×10^{14} ions/cm^2, whereas the one of SiC type a drops to 50% already at a fluence of 4.1×10^{14} ions/cm^2 (see lines in Fig. 6). Therefore we may conclude that for diodes with a factor 20 lower dopant concentration, the radiation hardness is reduced by 60%.

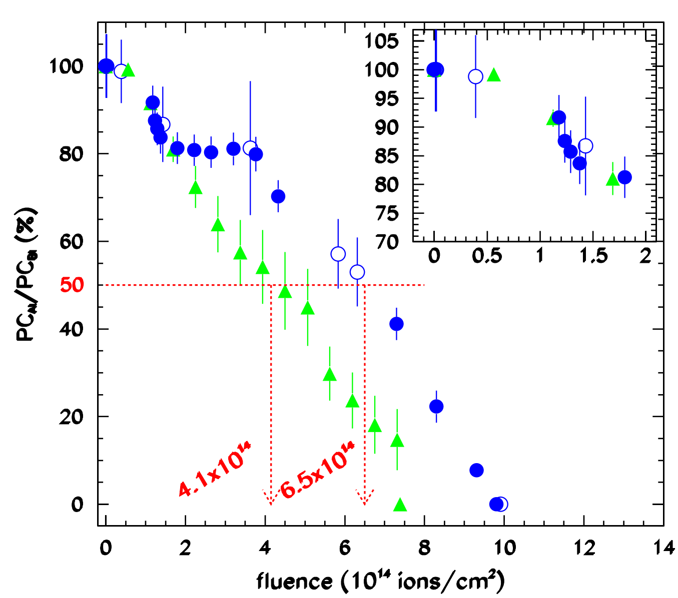

Fig. 6. (Color online) Ratio of the peak centroid channel of the ^{16}O energy spectrum after the irradiation (PC_{AI}) and before the irradiation (PC_{BI}) at increasing fluence. The present and the previous [11] data concerning SiC type c (full and empty circles, respectively) are compared with those of SiC type a (triangles).

When defects are formed inside the SiC lattice, the energy resolution of the detector is worsen due to fluctuations in the amount of charge lost. Fig. 7 shows the relation between the relative energy resolution and the ^{16}O fluence for SiC a (triangles) and c (circles). The energy resolution of SiC a degrades more than the one of SiC c for increasing fluence. Indeed, the relative energy resolution of SiC c gets 10 times worse at a fluence of 7.7×10^{14} ions/cm^2, whereas the one of SiC a worsen by the same amount already for 2.8×10^{14} ions/cm^2 (see lines in Fig. 7).

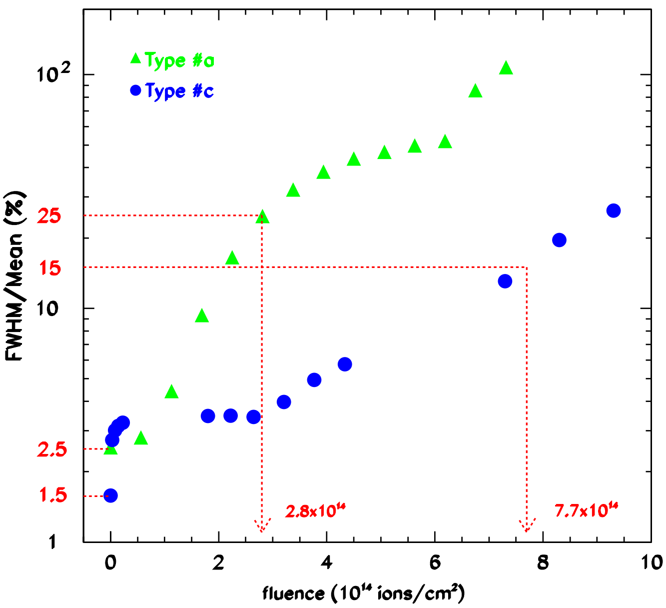

Fig. 7. (Color online) Relative energy resolution as a function of the fluence for SiC a (triangles) and c (circles).

Finally, in the previous measurements [11], we observed an inversion of the signals at the breakdown fluence (Fig. 8, top-left and bottom-left panels). In that case, SiC of type c has been irradiated with ^{16}O ions at 53 MeV of incident energy, corresponding to a range of 27.1 μm, larger than the 21 μm of the n$^-$ epitaxial layer (Fig. 9 left). As a possible explanation of the signal inversion, we therefore suggested [11] the formation of an ^{16}O layer, implanted in the n$^+$ type substrate, subdividing the 279 μm thick material in two parts with a floating ground at the ^{16}O layer.

In order to investigate such hypothesis we used ^{16}O ions with a lower incident energy so that they could be stopped in 16.3 μm, i.e. inside the n$^-$ epitaxial layer (Fig. 9 right). In particular, in case of SiC type a the range of the ^{16}O ions is inside the depleted region (32.7 μm) whereas in case of SiC type c the range exceeds the depleted region (9.2 μm), though being still inside the n$^-$ epitaxial layer.

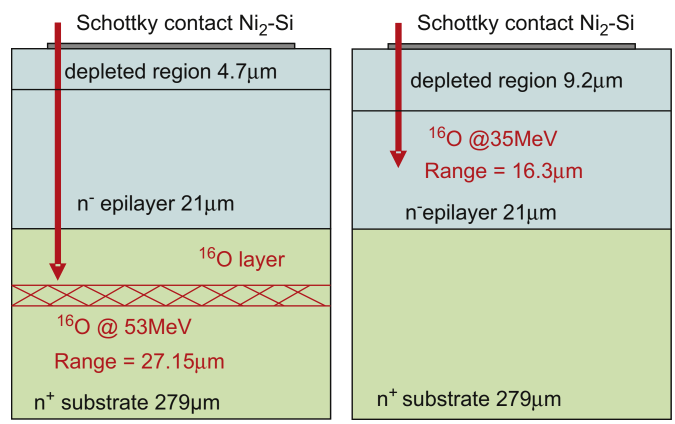

Fig. 9. (Color online) Lay-out of the ^{16}O range in the SiC diode type c irradiated with ^{16}O ions at 53 MeV in Ref. [11] (left) and in the present work (right).

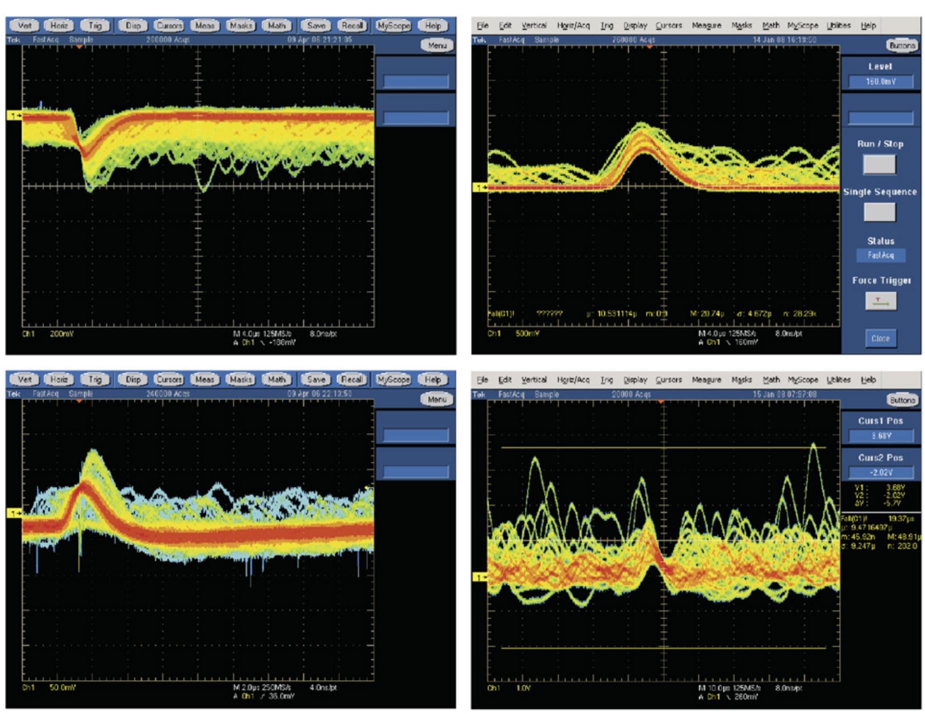

Fig. 8. (Color online) Left side: pulses from an SiC diode type c irradiated with 53 MeV ^{16}O beam [11] at the beginning of the irradiation (top-panel) and at the breakdown (bottom-panel): notice the inversion of the signal. Right side: pulses from an SiC diode of the same type c irradiated with 35.2 MeV ^{16}O beam at the beginning of the irradiation (top-panel) and at the break-down (bottom-panel).

Fig. 8 (top-right and bottom-right panels) shows that at the breakdown fluence, 7.5 and 10×10^{14} ions/cm^2, respectively, for SiC a and c, we did not observe any inversion. The different behavior with respect to the previous results supports the idea that the observed inversion was produced by the formation of an ^{16}O layer in the n$^-$ substrate rather than a consequence of the radiation damage.

5. Conclusions

In the present work the response to light ions of 4H–SiC Schottky diodes with different dopant concentration has been investigated. In particular, SiC diodes with three different dopant concentrations have been irradiated with a ^{12}C beam at 14.2, 28.1 and 37.6 MeV and a ^{16}O beam at 35.2 MeV in order to explore how the thickness of the depleted region varies for different applied reverse bias values. The collected data confirm the prediction of Eq. (1). The reverse bias voltages needed to deplete the same active volume of SiC diodes decrease at decreasing dopant concentration, but they are still too high for nuclear physics applications.

The measured energy resolution of the ions, stopped inside the depleted region, ranges from 5.5% to 1.7% at the different incident energies of the ions, but does not depend on the dopant concentration. Nevertheless, when the ions range is larger than the depleted region, the energy resolution is worse for SiC types a and b than for SiC type c. This effect strongly depends on the applied bias and could be due to the diffusion in the active region of the minority carriers produced in the unpolarized part of the detector. However, since in diodes type c the effect is negligible, we will investigate on it in the near future.

Finally, the three types of diodes were irradiated with ^{16}O ions at 35.2 MeV and the radiation hardness properties were studied by measuring the degradation of the signal as a function of the ^{16}O fluence. The present results show that SiC diodes with lower dopant concentration, suffer a faster reduction of the signal height and a larger deterioration of the energy resolution. However, a systematic collection of other experimental data is mandatory to assess the role of other possible intrinsic properties of the single chip, besides the dopant concentration, in the radiation hardness properties of SiC detectors.

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