Light ions response of silicon carbide detectors

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Abstract

Silicon carbide (SiC) Schottky diodes 21 $\mu$m thick with small surfaces and high N-dopant concentration have been used to detect alpha particles and low energy light ions. In particular $^{12}$C and $^{16}$O beams at incident energies between 5 and 18 MeV were used. The diode active-region depletion-thickness, the linearity of the response, energy resolution and signal rise-time were measured for different values of the applied reverse bias. Moreover the radiation damage on SiC diodes irradiated with 53 MeV $^{16}$O beam has been explored. The data show that SiC material is radiation harder than silicon but at least one order of magnitude less hard than epitaxial silicon diodes. An inversion in the signal was found at a fluence of $10^{15}$ ions/cm$^2$.

\textit{Key words:} SiC-Silicon Carbide, Semiconductors, Radiation Detectors, Radiation Damage

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1 Introduction

In the last years the use of electronic devices and sensors in very harsh environments at elevated temperatures, high-power, high-frequency and high radiation fields has became the subject of research and development in various fields. In particular the search for new materials, more suitable for such extreme operating conditions than the usual silicon semiconductor has received a lot of interest. Among the investigated materials, the silicon carbide (SiC) semiconductor has raised large interest and has been already used in a wide range of applications [1,2,3,4,5,6,7,8]. In particular, recent work has been done on the development of SiC radiation detectors [9,10] and on the characterization of their performances. SiC detectors were used with excellent results as neutron [11] and X-ray detectors operating at high temperatures [12]. The charged-particle response characteristics have been measured by irradiating the detectors with alpha particle sources at energies up to 5.48 MeV [13,14,15], and radiation damage effects were investigated with 24 GeV protons and gamma rays [16,17,18], 300 MeV/c pions [19], neutrons [20] and protons, alphas and $^{12}$C beams [21] at fluences up to $10^{16}$ particles/cm$^2$ [20] obtaining promising results. Indeed one of the most appealing property of the SiC, as well as of other wide bandgap materials such as GaAs and diamond, is their predicted radiation hardness with respect to Silicon. Moreover SiC diodes show low reverse current even at the very high electrical voltage applicable because

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of their higher breakdown voltage with respect to Si. Both properties make
SiC diodes suitable for the construction of specific detector arrays. The inner
tracking detectors, typically used in the high-radiation environment of particle
physics experiments, particle and ion detector arrays operating in satellites
or in the very harsh environment of laboratories producing radioactive ion-
beams would particularly benefit from the mentioned properties. In spite of
the notable development in growing, processing and producing good-quality
and low-defect SiC diodes, work to date on the use of such diodes as detectors
of particles and ions has been very limited [13,14,15,19,21]. We have therefore
studied the response signal of high-quality 4H-SiC Schottky diode to $^{12}$C and
$^{16}$O ions and to an alpha particles source at various incident energies, in order
to investigate the use of SiC detectors also in nuclear physics applications.
The main objectives of the present work are the characterization of the signal
response in term of linearity, energy resolution and rise-time as a function of
the applied reverse bias and the investigation of its degradation subsequent to
irradiation with light ions.

2 Experimental details

The Schottky diodes were fabricated by epitaxy onto high-purity 4H-SiC n-
type substrate from the ETC-Catania [22]. Figure 1 shows the layout of the
detector. The nominal n$^-$ epitaxial layer nitrogen dopant concentration and
thickness were, respectively, $1.5 \times 10^{16}$ N cm$^{-3}$ and 21 $\mu$m. The dopant concen-
tration and thickness of the n$^+$ side were respectively $7 \times 10^{18}$ N cm$^{-3}$ and 279
$\mu$m. The net doping and the thickness have been measured [22], respectively,
by C-V (Hg-probe) and FTR Biorad QS-500. The nominal defects mean value
Fig. 1. The 4H-SiC diode layout. The Schottky junction is realized by the Ni$_2$Si layer, 0.2 µm thick, deposited at 600°C on the front surface, the ohmic layer by Ni$_2$Si deposited at 950°C.

was 43 cm$^{-3}$ as measured [22] by µRaman spectroscopy with an Ar-laser at 514.5 nm.

The Schottky junction was realized by a 0.2 µm thick layer of Ni$_2$Si deposited at 600 °C on the front surface, while the ohmic contact, on the back surface, was obtained with Ni$_2$Si deposited at 950°C [23].

The active areas of the different SiC detectors were of 0.5x0.5, 1x1 and 2x2 mm$^2$ (see Fig. 2). The chips were glued on a brass foil 1 mm thick by a conductive glue and single contacts between the Ni$_2$Si front surfaces and the pads of the board shown in Figure 2 were realized by Al wire (2µm thick) bonding.

Fig. 2. Picture of the SiC detectors assembled on a board.
Two boards with respectively six and five chips 2x2 mm$^2$ of surface were assembled, for a total number of eleven independent detectors. The third board was equipped with a Si detector 300 $\mu$m thick and 3x3 cm$^2$ of surface which was used as a reference. The three 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 both 5.48 MeV alpha particles from an $^{241}$Am source and $^{12}$C and $^{16}$O beams accelerated by the LNS Tandem VdG at different energies and currents. The alpha source was set-up at a distance of 10 cm from the detector surface in order to get a near normal incidence of alpha particles on the detector. The ion beams were focused 60 cm downstream with respect to the detector position in order to achieve an uniform perpendicular irradiation in 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: preamplifiers of 45 mV/MeV gain and amplifiers with 0.5 $\mu$sec 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. Moreover the preamplifier and amplifier signals were digitalized by a Tektronix TDS 5104B digital oscilloscope.

3 Detector response

It is well known that a reverse bias must be applied in order to create in the diode a depleted region which acts as the active region for the detection of the charges produced by ionization from the incoming charged particles.

The order of magnitude of this reverse bias could be a relevant parameter for
specific applications. Therefore we measured at first the correlation between the thickness of the depleted layer and the applied bias, which is expected to follow a square-root law [24]. By using four Al absorbers of 10, 13, 14.6 and 17.3 μm thicknesses, in front of the $^{241}$Am alpha source, we scaled the incident energy from 5.48 MeV to 3.76, 3.18, 2.72 and 2.19 MeV respectively as measured by the calibrated silicon detector (see Fig. 3). Using the SRIM code [25] calculations, the ranges of the alpha particles at the four incident energies in the SiC material were evaluated to be: 10.8±0.4, 8.5±0.5, 7.0±0.6 and 5.4±0.5 μm respectively. The errors on the range thickness were evaluated by taking into account both the energy loss in the Ni$_2$Si 0.2 μm thick front layer on the detector and the FWHM (full-width at half-maximum) of the alpha spectra of Fig. 3 in order to account for the energy straggling introduced by the Al absorbers. A typical set of spectra is shown in Fig. 4 for one of the detectors used. For all the detectors the centroid position of the peak moves toward higher channels as the voltage increases. The observed shift can be described according to the increasing thickness of the active volume of the

Fig. 3. The four $^{241}$Am alpha energy spectra, measured by the Si detector with the 10, 13, 14.6 and 17.3 μm Al absorbers in front of the source. The 5.48 MeV peak is also shown for reference.
detector with increasing reverse bias voltage. As a result, the incident alphas

Fig. 4. Top: Energy spectra measured by the SiC diode at increasing bias voltage for alpha particles of 3.18 MeV incident energy. Bottom: The four alpha energy spectra (2.19, 2.72, 3.18, 3.76 MeV) measured by the SiC diode at the bias saturation values.

deposit more energy in the active region leading to detector signals with higher pulse heights. The saturation of the pulse height values 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 alpha. For a given alpha energy we then searched for the value of the applied reverse bias at which the saturation of the pulse height signals is reached (see Fig. 4-top panel).

The correlation between the evaluated range and the applied reverse voltage,
shown in Fig. 5 is nicely reproduced by a square-root law [24].

Finally, by correlating the saturated pulse height peak values and the four

![Graph](image1)

**Fig. 5.** Correlation between the square root of the applied bias and the SiC depletion layer thickness evaluated from alpha energies.

![Graph](image2)

**Fig. 6.** Energy spectra of alpha particles of 2.19 and 3.18 MeV incident energy measured in the silicon (gray) and in the SiC (black) detectors. For comparison the energy values of the SiC spectra were evaluated by using the energy calibration obtained for the silicon detector.

alpha energies (2.08, 2.62, 3.09, 3.68 MeV) corrected for the energy lost in the Ni$_2$Si 0.2 μm thick front layer of the SiC diode, we calibrated the pulse height scale. By comparing the energy peaks obtained with the SiC and the
silicon detector for the same deposited energy (see Fig. 6) we have obtained a factor of 2.1±0.3 in the charge produced by ionization, as expected from the different ionization energy values of 3.76 eV in Si and of 7.74 eV, as recently measured \[26,27\], in SiC.

To increase the explored energy range we used beams of \(^{12}\)C at 5.06 and 17.68 MeV and \(^{16}\)O at 7.3, 9.78, 12.18 and 14.21 MeV of incident energies provided by the Tandem accelerator of the LNS. The SiC diodes were operated at a reverse bias of -100V which depletes the active region of the detector up to 5.4±0.5 \(\mu\)m, wide enough to completely stop all the ions except the \(^{12}\)C at 17.68 MeV and the \(^{16}\)O at 14.21 MeV of incident energy which, according to SRIM calculation, release around 8 and 13 MeV respectively in the detector. Fig. 7 shows the energy spectra measured by the SiC diodes. The high degree of linearity observed in the correlation between the pulse height and the energy shown in Fig. 8 for SiC detectors, is consistent with previous measurements \[13,14,19\], and indicates the proportionality of the produced ionization charge to the deposited energy. Similarly to the measurements performed with the alpha source, a number of spectra were taken over a range of bias voltages, from 0 to -450 V, for the \(^{12}\)C beam at 17.68 MeV incident energy (see Fig. 7-bottom panel). We notice in Fig. 7 that no saturation has been observed in the peak centroid values, since the active region of the detector does not extend beyond the range of the \(^{12}\)C at 17.68 MeV in SiC, which is approximately 11.2 \(\mu\)m. This occurrence indicates that at the maximum applied bias voltage, -450 V, the detector is only about half depleted but, unfortunately, we could not raise the bias voltage to higher values because the electrical connections in vacuum were sparking at around -500 V. Therefore we evaluated the thickness of the depleted region by comparing SRIM calculations to the energy loss measured at different applied biases. Figure 9 shows the correlation between
Fig. 7. Top: SiC energy spectra of $^{12}\text{C}$ and $^{16}\text{O}$ beams at different energies. Bottom: $17.68$ MeV $^{12}\text{C}$ beam spectra measured at increasing negative bias voltages.

The estimated thickness of the depletion layer and the applied reverse bias for $^{12}\text{C}$ ions. We remark the good agreement with the data measured with alphas and the good linear correlation between the depletion layer thickness and the square-root of the applied bias values. From a linear fit (see Fig. 9), at zero bias voltage we estimated an active region thickness of $1.18$ $\mu$m resulting only from the Schottky contact potential, in good agreement with the result of Ref. [13].

In order to measure how the energy resolution behaves as a function of the thickness of the active region and therefore of the applied bias voltage, we analyzed the data reported in Fig. 7. A typical $^{12}\text{C}$ $17.68$ MeV response spectrum is shown in Fig. 10. The shape of the peak is well reproduced by a Gaussian function. Based on the energy calibration, the full-width at half-maximum
Fig. 8. Pulse height(channel) versus Energy plot. Data points refer to the $^{12}$C (5.06 (4.5)MeV) and $^{16}$O (7.3 (6.5), 9.78 (9.0), 12.18 (11.4) MeV) beams and to the four alpha particles energies. The energy values in parentheses are the ones corrected for the energy lost in the Ni$_2$Si 0.2 µm thick front layer on the detector. The linear correlation coefficient $R^2$ from the fit has a value of 0.998.

Fig. 9. Correlation between the square root of the applied bias and the SiC depletion layer thickness evaluated from alpha (circles) and the 17.68 MeV $^{12}$C beam (triangles) spectra. Error bars are calculated from the FWHM of the energy loss spectra of Fig. 7.

(FWHM) of the Gaussian fit to the $^{12}$C peak at 8.1 MeV (which is the energy lost in 5.4 µm by the $^{12}$C at 17.68 MeV) is 190 keV corresponding to an energy
Fig. 10. Top: $^{12}\text{C}$ at 17.68 MeV beam response of a SiC diode with an applied bias voltage of -100 Volts. The spectrum is fitted with a Gaussian function. Bottom: Relative energy resolution as a function of the applied bias voltage.

resolution of 2.3%. In the bottom panel of Fig. 10, the relative energy resolution (FWHM of the peak over the peak position), is shown as a function of the applied bias voltage. Besides an initial enhancement from 0 to -50 V, the relative resolution decreases slowly over the range of the applied bias voltages up to a value of 1.8%. The measured energy resolution values are in good agreement with the ones observed in other measurements \[14\] although larger than the recently reported SiC energy resolution value of 0.34% \[27,28\].

Moreover by storing the waveforms of the preamplifier output in the Tektronix TDS 5104B Digital Oscilloscope we analyzed the behavior of the pulses gener-
Signals from the preamplifier generated by $^{12}$C ions at 17.68 MeV incident energy for different applied bias values.

The consistency of the SiC detectors performances were investigated by testing charged-particle response of all the eleven detectors of identical configuration. All of them showed, within the error bars, the same characteristics here reported.
One of the main motivations of such study was to explore the radiation hardness properties of such SiC detectors. Five samples were irradiated using 53 MeV $^{16}$O ions provided by the Tandem at the LNS-Catania and their output signals were monitored during the irradiation time. Fig. 12 shows the peak centroid of the $^{16}$O spectrum as a function of the fluence. The applied reverse bias was kept fix at -100 V but the signals appeared to decrease in amplitude as the irradiation increased. The amplitude dropped to 50% at a fluence of $6.5 \times 10^{14}$ ions/cm$^2$ (see Fig. 12) in good agreement with results of Ref. [20,29]. At the same time, the reverse current increased by a factor of five and the noise by a factor of two (see Fig. 13). The present SiC diodes are therefore around ten times radiation harder than silicon diodes but around a factor ten less hard than thin epitaxial Si-diodes for which the charge collection efficiency drops only to about 80% at $6 \times 10^{15}$ protons/cm$^2$ at 24 GeV of incident energy [30].
Fig. 13. Pulses from a SiC diode irradiated with the 53 MeV $^{16}$O beam. Top left: beginning of irradiation. Top right: after a fluence of $3.5 \times 10^{14}$ ions/cm$^2$. Bottom left: after a fluence of $7 \times 10^{14}$ ions/cm$^2$. Bottom right: after a fluence of $10^{15}$ ions/cm$^2$: notice the inversion of the signal.

However it is not clear how to compare the damage produced by low energetic $^{12}$C or $^{16}$O ions to the damage produced by protons, neutrons, gammas or pions and which kind of defects, among the known ones, are produced during irradiation.

Finally, two different detectors were continuously observed during the irradiation up to when they break-down at a fluence of $10^{15}$ ions/cm$^2$. At this irradiation fluence we observed an inversion of the signals with respect to the non-irradiated ones (see Fig. 13 bottom-right panel). This effect seems similar to the symmetric Charge Collection Efficiency (CCE) response at both polarities mentioned in Ref. [20] at a fluence of $10^{15}$ protons/cm$^2$ and attributed to radiation damage.

Moreover, we inverted both bias and amplifier polarities and we sent on the irradiated detectors an $^{16}$O beam at 12 MeV incident energy. Since the applied reverse bias of -100 V depletes 5.4 µm of the SiC active region, we expected an energy release of 8.3 and 12 MeV in the detector from the $^{16}$O beam at 53 and
12 MeV incident energy respectively, but the pulse height of the signal was the same in both cases. Therefore we conclude that the detector was sensitive to the charged ion but not to the deposited energy.

Further analysis will be performed to understand if the observed effect is of the same nature of space-charge sign-inversion (“type inversion”), reported for Si-diodes [31,32,33]. At the moment we suggest, as possible explanation, the formation of a layer of $^{16}$O ($10^{15}$ ions/cm$^2$) at a distance of $27.2 \pm 0.4 \mu$m (which is the range of the 53 MeV $^{16}$O ions in the SiC material) from the Schottky contact, and therefore in the n$^+$ type substrate, subdividing the 300$\mu$m thick material in two parts with a floating ground at the $^{16}$O layer.

5 Conclusions

In the present work we investigated the response of SiC Schottky diodes to alphas, $^{12}$C and $^{16}$O low energetic ions in order to explore the possibility of using these detectors in nuclear physics applications in extreme environments. The signal response to the ionization produced by the low-energy ions was analyzed in terms of linearity, energy resolution, rise-time and deterioration as function of the applied reverse bias and the irradiating fluence. The latter measurements demonstrate the good quality of the SiC as a radiation hard material.

Energy resolution on the order of 3% and rise time up to 44 nsec have been measured at the maximum applied reverse bias. The amplitude of the signal drops down to 50% at a fluence of $6.5 \times 10^{14}$ ions/cm$^2$ indicating more than an order of magnitude hardness to the radiation with respect to silicon diodes. The signal inversion at a fluence of $10^{15}$ ions/cm$^2$ should be further inves-
tigated to understand if it is produced by radiation damage or by the $^{16}$O implant in the material.

The main inconvenience we have found in the use of the present detectors was the high bias voltage, needed to deplete the active region of the diode. We expect a correlation between the depleting bias values and the N doping concentration in the epitaxial region [13]. We will investigate in the near future such a correlation, being aware of the negative influence on the ionization charge production and radiation hardness of a reduced doping concentration. But reduction of the applied voltage to values far from the break down ones is a very crucial issue for future applications.

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