# Improving the radiation hardness properties of silicon detectors using oxygenated n-type and p-type silicon.

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*Abstract*

The degradation of the electrical properties of silicon detectors exposed to 24 GeV/c protons were studied using pad diodes made from different silicon materials. Standard high-grade p-type and n-type substrates and oxygenated n-type substrates have been used. The diodes were studied in term of reverse current ($I_r$) and full depletion voltage ($V_{fd}$) as a function of fluence. The oxygenated devices from different suppliers with a variety of starting materials and techniques, all show a consistent improvement of the degradation rate of $V_{fd}$ and CCE compared to un-oxygenated substrate devices.

Radiation damage of n-type detectors introduces stable defects acting as effective p-type doping and leads to the change of the conductivity type of the silicon bulk (type inversion) at a neutron equivalent fluence of a few $10^{13}$ cm$^{-2}$. The diode junction after inversion migrates from the original side to the back plane of the detector. The migration of the junction is avoided using silicon detectors with p-type substrate. Furthermore, the use of n-side readout allows a better charge collection in segmented devices operated in underdepleted mode [1]. Large area (≈ 6.4x6.4 cm$^2$) 80 µm pitch microstrip capacitively coupled detectors with polysilicon bias resistors made on p-type substrate with a n-in-p diode structure have been irradiated up to $3 \cdot 10^{14}$ cm$^{-2}$. We present results both before and after irradiation demonstrating the feasibility of using such devices at the Large Hadron Collider (LHC) at CERN.

Large area n-type capacitevely coupled detectors have also been produced with oxygenated substrate with good pre-irradiation characterstics. It is therefore anticipated that the use of oxygenated substrates combined with the n-in-p approach will allow operation of microstrip silicon detectors even above a dose of $10^{15}$ protons cm$^{-2}$.

## I. INTRODUCTION

Silicon detectors for high-energy physics applications are fabricated from high-resistivity and high purity floating-zone (FZ) silicon.

The oxygen and carbon concentrations found in this material are of the order of $10^{15}$ cm$^{-3}$. Various types of segmented detectors have been produced and used with a p-in-n diode structure.

The silicon detectors to be used in the future collider LHC at CERN will experience a severe radiation environment. The radiation introduces acceptor like defects in silicon that eventually cause increased full depletion voltage and consequent increase in the bias required for maximum charge collection.

The deterioration induced by the radiation in the characteristics of the detector depends on the starting material. The presence of high concentration of oxygen in silicon (> $10^{17}$ cm$^{-3}$) can reduce the rate of increase in the full depletion voltage of the detectors. A readily employed technique to introduce high oxygen concentration in silicon wafers via high temperature diffusion has been recently proven [2].

We studied the change of the full depletion voltage induced by the radiation of silicon detectors made with oxygenated n-type substrates compared to standard devices and to un-oxygenated p-type diodes. The advantages of using oxygenated material are evident.

Oxygenated material similar to the one used for the fabrication of these diodes has been successfully used to produce large area (6.4x6.36 cm$^2$) devices using the ATLAS barrel mask set. Total currents of ≈ 5 µA are seen at 500 V pre-irradiation. Studies are under way to investigate the properties of these more complicated devices after irradiation.

After the radiation induced conductivity type inversion, the active region will develop, as a function of the applied voltage, from the back of the detectors. The charge collection efficiency is reduced when detectors are operated underdepleted, requiring high operating voltages after irradiation. More efficient for underdepleted operation of segmented devices (microstrip detectors) is the n-in-n design [1] because the active volume after inversion develops from the strip side. The use of n-in-p design would avoid the migration of the junction and have the same advantage of n-in-n after high radiation doses. P-type substrate prototype detectors were studied in term of reverse current, full depletion voltage and interstrip capacitance before and after $3 \cdot 10^{14}$ 24 GeV/c protons cm$^{-2}$ provided by the CERN-PS facility [3].

## II. RADIATION DAMAGE ON SILICON DETECTORS

The damage due to hadron irradiation on the substrate on silicon detectors changes the electrical properties of the devices. The effects that mainly influence the operation of detectors are the increases in the leakage current, in the full depletion voltage (see for example [4]) and in the trapping rate of the charge carriers generated by an ionising particle crossing the detectors.

The increase in leakage current as a function of the fluence $\phi$ is parameterised by:

$$I_r = \alpha\phi V \quad (1)$$

where $V$ is the volume of the detector and $\alpha$ the current damage factor.

The full depletion voltage is proportional to the effective doping concentration, $N_{eff}$, whose change with fluence can be parameterised, in the case of n-type detectors, by:

$$N_{eff} = N_{eff}(0)e^{-c\phi} - \beta\phi \quad (2)$$

where , $N_{eff}(0)$ is the initial effective doping concentration, $c$ is the constant of donor removal and $\beta$ is the introduction rate of acceptor-like defects. For p-type silicon, the $\beta\phi$ factor adds to the first them of the sum, and $c$ is the constant of acceptor removal.

The inclusion of high oxygen concentration in the silicon bulk can change the effective introduction rate of acceptor-like defects, resulting in a lower value of $\beta$.

The high density of radiation induced trapping centres reduces the lifetime of the charge carriers. Part of the carriers generated by an ionising particle through the detector will undergo a trapping and de-trapping process before being collected at the electrodes, increasing the time necessary to collect all the generated charge. This causes a *ballistic deficit* in the charge collected during short integration times, which is proportional to the applied bias voltage [4].

## III. OXYGEN ENRICHED MATERIALS

High oxygen concentrations (up to a few times $10^{17}$ O atoms $cm^{-3}$) in FZ silicon wafers are obtained by high temperature diffusion [2]. Oxygen atoms from a surface source ($SiO_2$ coating of the wafer or an implanted layer of O ions) are driven at high temperature into the silicon wafer. The process is performed in an inert ($N_2$) or oxygen atmosphere. The maximum reachable concentration is the solubility of oxygen in silicon at the diffusion temperature and the O concentration depth profile depends on the diffusion time and temperature.

Square pad diodes produced by three different manufacturers using various diffusion times and temperatures have been tested. Table 1 shows the relevant parameters of the substrates and the dimension of the pad diodes. The O concentration is given at the depth of 150 µm, which corresponds to the centre of the silicon wafers used for most high-energy physics applications. All the manufacturers used a 200-300 nm thick coating of $SiO_2$ as a source for the diffusing O atoms, except one of the Micron wafers that uses a high density surface implantation of 60 keV O ions. A second control wafer has been used in each case to process identical detectors with the same condition as the O enriched wafer.

## IV. P-TYPE SUBSTRATE MICROSTRIP DETECTOR

As suggested before, the migration of the junction from the strip side to the backside of a silicon microstrip detector can be avoided using the n-in-p diode structure. This is of interest as it offers better charge collection for underdepleted microstrip detector operation.

A few 784 strip detectors, with p-in-n diode structure, 80 µm strip pitch and individual p-stop interstrip insulation have been produced and irradiated [5].

## IV. EXPERIMENTAL RESULTS

### A. Radiation induced changes in pad diodes

Table 1.
Parameters of oxygenated silicon materials

| Manufacturer | Diffusion time | Diffusion temperature (°C) | O concentration at 150 µm ($cm^{-3}$) | O source and diff. atmosphere | Diode area and thickness | Silicon wafer diameter and crystal orientation |
|---|---|---|---|---|---|---|
| Micron Semiconductor [6] | 410 hours | 1100 | ≈ 1.3 $10^{17}$ | $SiO_2$ in $N_2$ | 1 $cm^2$ 300 µm | 6” (100) |
| Micron Semiconductor | 410 hours | 1100 | ≈ 1.3 $10^{17}$ | Ion implanted layer in $N_2$ | 1 $cm^2$ 300 µm | 6” (100) |
| SINTEF [7] | 50 hours | 1150 | ≈ 2. $10^{17}$ | $SiO_2$ in $N_2$ | 0.25 $cm^2$ ≈ 300 µm | 4” (111) |
| SINTEF | 72 hours | 1150 | ≈ 2. $10^{17}$ | $SiO_2$ in $O_2$ | 0.25 $cm^2$ ≈ 300 µm | 4” (111) |
| ITME [8] | 24, 48, 72 hours | 1150 | 1.7 – 2.3 $10^{17}$ | $SiO_2$ in $N_2$ | 0.25 $cm^2$ ≈ 300 µm | 4” (111) |
| BNL [9] | 9 days | 1200 | ≈ 4 $10^{17}$ | $SiO_2$ in $N_2$ | 0.175 $cm^2$ 200 µm | 4” (111) |

The diodes were irradiated in April and July '99 with 24GeV/c protons in the CERN-PS-T7 irradiation area. They were irradiated in successive steps of fluence and measured (capacitance vs bias, CV, and reverse current vs bias, IV) after each step. Before any measurement the diodes were heated at 80 $^{o}$C for 4 minutes, in order to complete the *beneficial annealing* [10] stage and minimise the variation with time of the CV and IV characteristics.

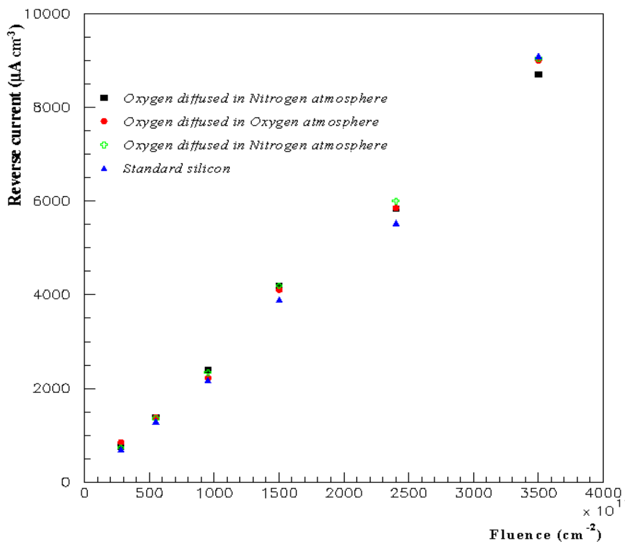


Figure 1: Reverse current versus fluence for oxygenated and un-oxygenated diodes.

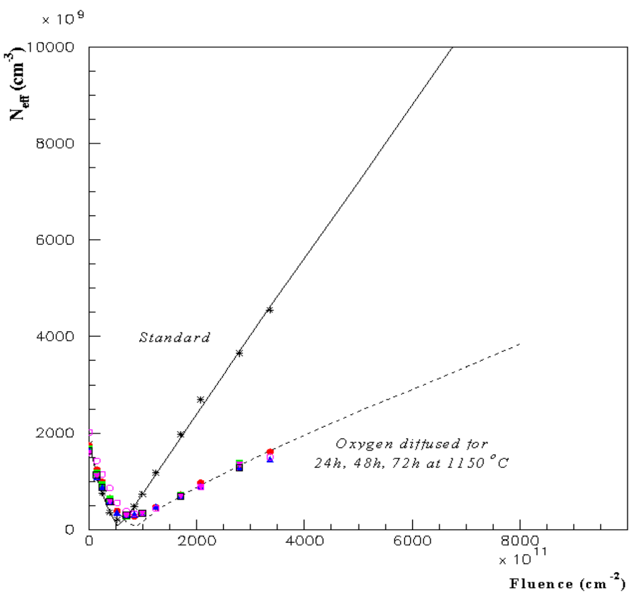


Figure 2: $N_{eff}$ as a function of fluence for un-oxygenated control diodes and oxygenated diodes with different diffusion times.

The full depletion voltage ($V_{fd}$) was evaluated from the CV curve. $N_{eff}$ was calculated using :

$$N_{eff} = \frac{2\varepsilon_{Si}}{e}\frac{V_{fd}}{w^2} \quad (3)$$

where $\varepsilon_{Si}$ is the permittivity of silicon, $e$ is the electron charge and $w$ is the detector thickness.

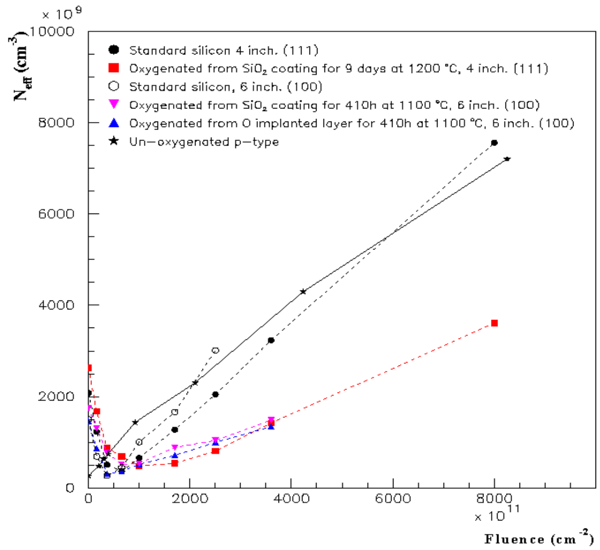


Figure 3: $N_{eff}$ as a function of fluence for un-oxygenated n-type and p-type and oxygenated n-type diodes from various sources and materials.

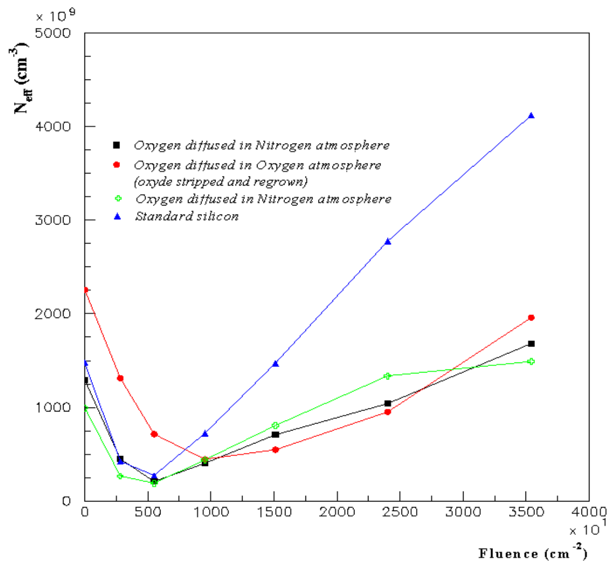


Figure 4: $N_{eff}$ as a function of fluence for un-oxygenated and oxygenated n-type diodes with oxygen diffusion in different atmospheres.

The variety of diode used includes devices processed from 4 and 6 inches wafers and (100) and (111) crystal oriented silicon. The various diffusion times and temperatures are summarised in Table 1. From Fig.1 it is evident that the increase of the reverse current with fluence is not affected by the presence of oxygen. Conversely, the change of $N_{eff}$ with fluence is strongly influenced by the presence of high oxygen concentrations in the detector bulk. Fig. 2 shows earlier results on $N_{eff}$ as a function of fluence for various diodes processed by ITME with differing diffusion times. The oxygenated devices show $N_{eff}$ after type inversion grows three times more slowly with dose than the standard, practically independent on the diffusion time. Using eq. 1, the value of $\beta$ extracted from the fit is $5\cdot10^{-3}$ cm$^{-1}$ for oxygenated and $1.7\cdot10^{-2}$ cm$^{-1}$ for standard material.

Figure 3 shows $N_{eff}$ as a function of fluence up to $8\cdot10^{-14}$ cm$^{-2}$ for n-type diodes processed by Micron and BNL and p-type diodes processed by Micron. The n-type material used by Micron is 6'' and (100) crystal oriented and by BNL is 4" and (111) crystal oriented silicon.

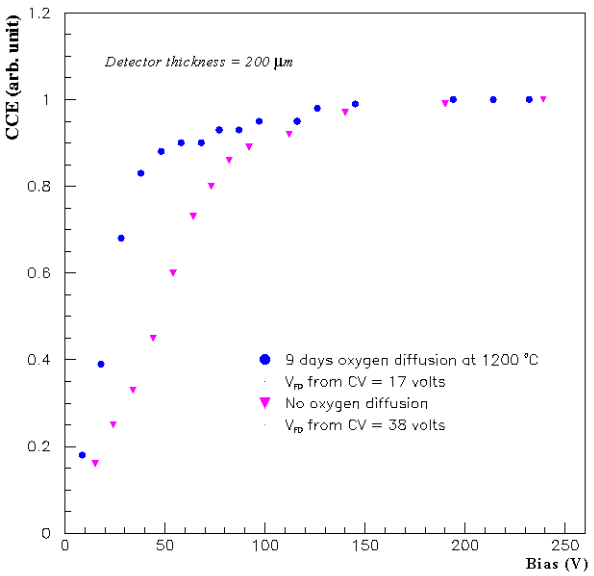


Figure 5 Charge collection efficiency for oxygenated and un-oxygenated 200µm thick diodes after $1.7\cdot10^{14}$ p cm$^{-2}$.

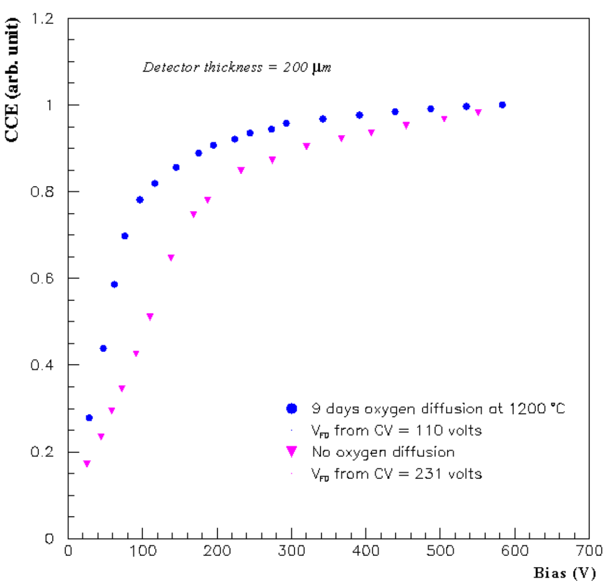


Figure 6 Charge collection efficiency for oxygenated and un-oxygenated 200µm thick diodes after $8.0\cdot10^{14}$ p cm$^{-2}$.

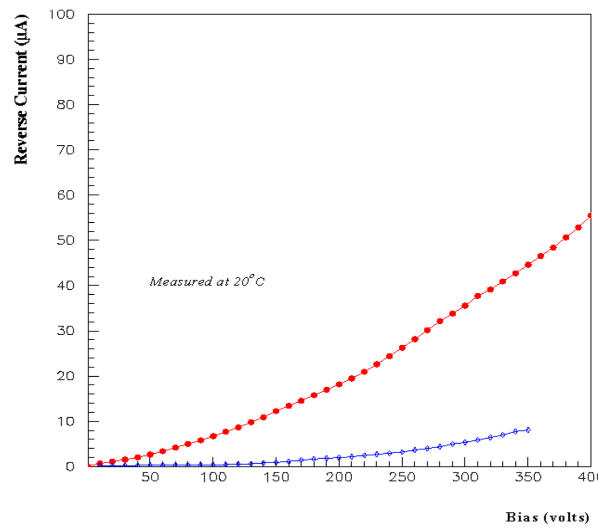


Figure 7: Pre-irradiation total currents for two p-type microstrip detectors. The full depletion voltage is ≈ 65 V.

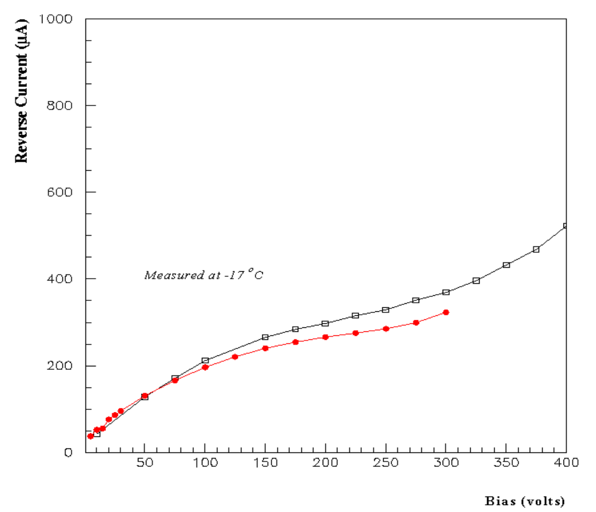


Figure 8: Total reverse currents for p-type microstrip detectors after $3\cdot10^{14}$ protons cm$^{-2}$. The full depletion voltage is ≈ 210 V.

Figure 4 shows $N_{eff}$ as a function of fluence for diodes processed by SINTEF after oxygen diffusion in $O_2$ or $N_2$ atmosphere. The results exhibited by oxygenated devices are all very similar irrespective of the difference in starting material. Also un-oxygenated p-type silicon behaves like un-oxygenated n-type silicon after conductivity type inversion.

The reduction in the $N_{eff}$ of oxygenated devices at a given dose gives corresponding improvements in the charge collection properties of detectors at low bias voltages. The charge collection studies have been carried out using short

(<5 ns FWHM) pulses of a 1060 nm wavelength laser and a fast Phillips Scientific current amplifier. The detectors were kept at –10 °C to reduce the shot noise. Figures 5 and 6 show the comparison of the charge collection efficiency for 200 µm thick detectors after $1.7{\cdot}10^{14}$ and $8.0{\cdot}10^{14}$ p cm$^{-2}$, respectively.

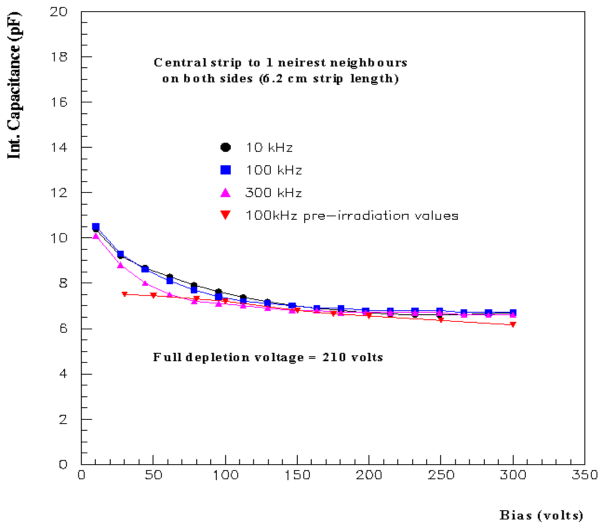


Figure 9: Capacitance of central strip to first neighbours each side. The values after irradiation are similar to the pre-irradiation value.

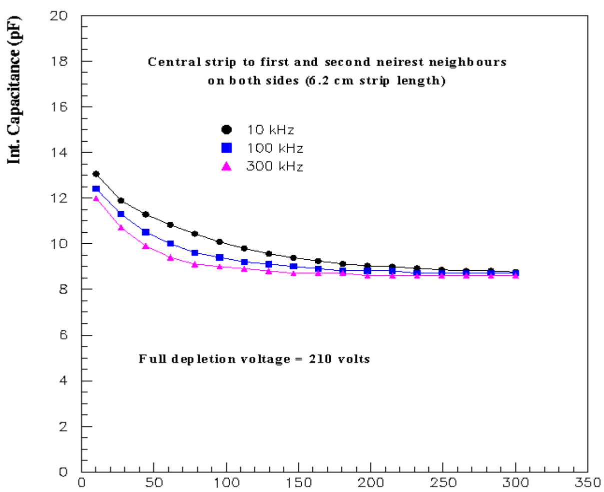


Figure 10: Capacitance of central strip to two first neighbours each side in a p-type detector after $3{\cdot}10^{14}$ protons cm$^{-2}$.

### B. *P-type detectors*

Figure 5 shows the pre-irradiation current for two microstrip p-type detectors. The depletion voltage of these devices, evaluated from CV measurements, is about 65 volts.

Figure 8 shows the total current after $3{\cdot}10^{14}$ protons cm$^{-2}$ for these detectors. Currents have been measured at –17 °C, and they are only slightly higher than the values found for standard high quality p-in-n microstrip detectors. The full depletion voltage after irradiation is about 210 volts, as determined by CV measurements.

Fig 9 then shows the capacitance of the central strip to first neighbours each side as a function of voltage. The values after irradiation are very close to the pre-irradiation measurement. Figure 10 shows the capacitance of the central strip to two neighbours each side. These values are consistent with those reported for irradiated n-in-n devices. The use of n-in-p detectors for the high dose regions at the LHC therefore looks feasible on the basis of these studies.

## IV. Conclusion

The degradation of un-oxygenated n-type and p-type diodes is very similar under proton irradiation. The presence of high oxygen concentration in the substrate allows the reduction of the damage factor of $N_{eff}$ by a factor of three compared to un-oxygenated material. It is foreseen that the benefits obtained with n-type silicon can be extended to p-type substrate using the same oxygenation technique.

Moreover, the use of p-type substrates with n-side readout of the microstrip detectors allows a further extension of the radiation tolerance of the devices, as they offer efficient operation underdepleted [1]. The feasibility of such devices has been demonstrated here.

The use of both oxygenated material and p-type substrates together, therefore looks a very promising route to a silicon detector able to survive radiation levels as high as $1{\cdot}10^{15}$ protons cm$^{-2}$.

## Acknowledgments

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