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.

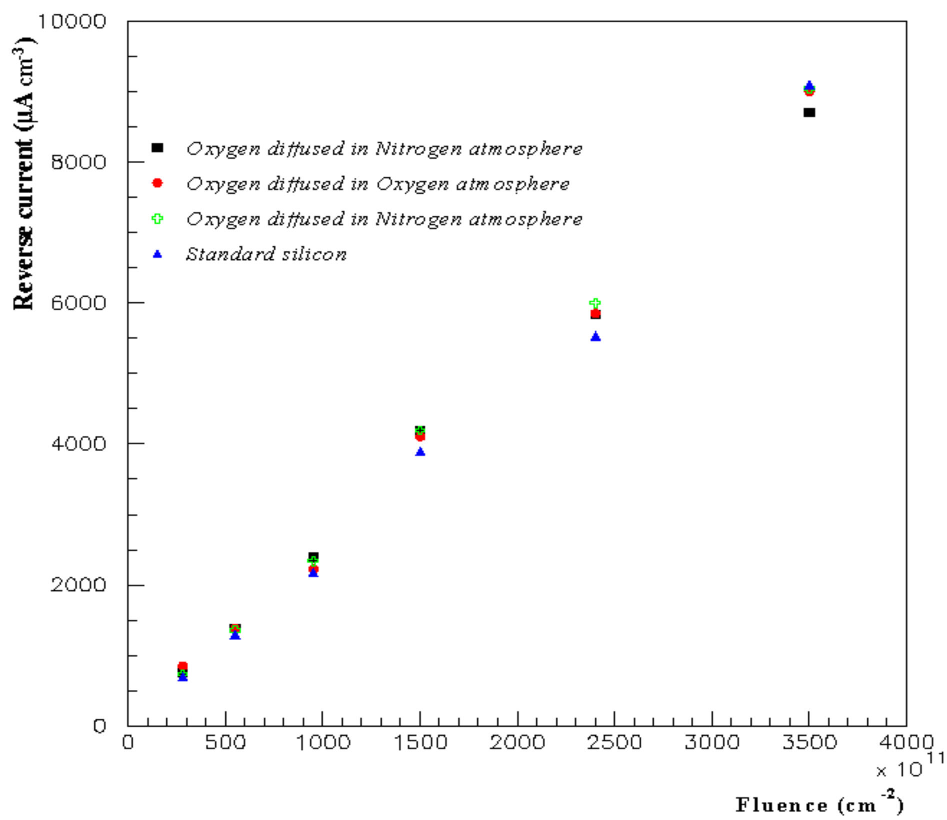
Radiation damage of n-type detectors introduces stable defects acting as effective p-type doping and leads to the change of the conductivity type of the silicon bulk (type inversion) at a neutron equivalent fluence of a few 10^{13} cm^{-2}. The diode junction after inversion migrates from the original 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. Large area ($\approx$ 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 capacitively 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 should allow operation of microstrip silicon detectors even above a dose of 10^{15} protons cm^{-2}.

Leakage current versus fluence for oxygenated and un-oxygenated silicon diodes.

The increase of the leakage current is a linear function of the fluence. The current is proportional to the concentration of radiation induced defects. The reverse volume current is measured using irradiated diodes biased above full depletion. Silicon materials with different (deliberately introduced) impurity concentrations do not show differences in the slope of the volume current with fluence. In the LHC experiments, these high currents will be reduced by cooling the detectors.

Normalised to 20 °C



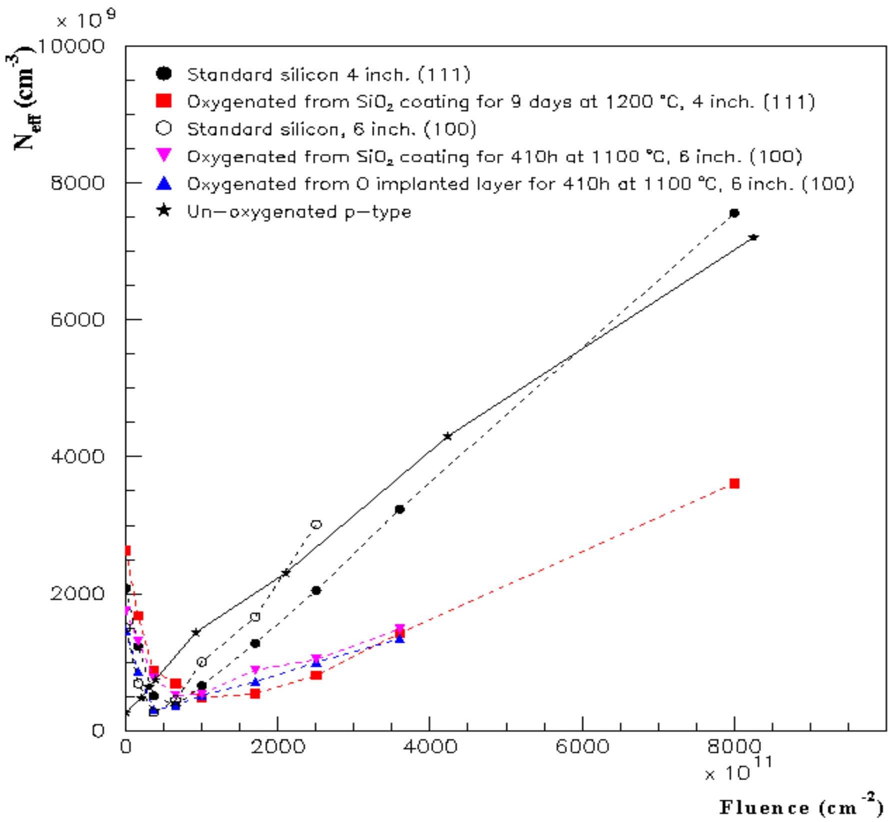
The introduction of high oxygen concentrations in the silicon bulk does not affect the increase of the leakage current with fluence

The effective doping concentration (N_{eff}) versus fluence for oxygenated and un-oxygenated silicon diodes.

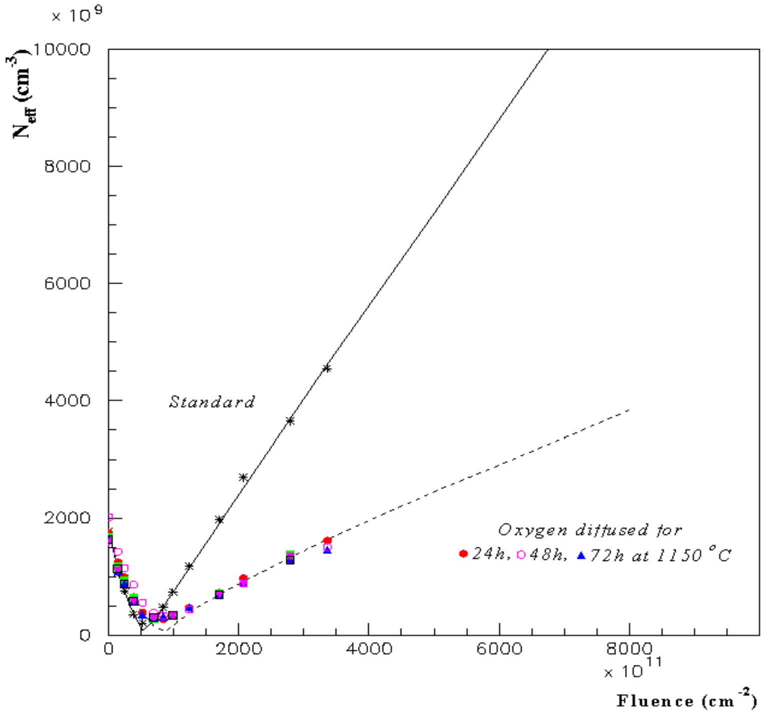
p-in-n detectors must be operated above full depletion to allow good signal/noise ratio. The full depletion voltage of silicon detectors is proportional to the effective doping concentration, which becomes more p-type as a consequence of the hadron irradiation. After heavy doses, N_{eff} is dominated by the concentration of the radiation induced p-type defects.

A high oxygen concentration ($>10^{17}$ cm^{-3}) in the silicon bulk reduces the effective introduction rate of acceptor-like defects and therefore the required detector bias after high doses.

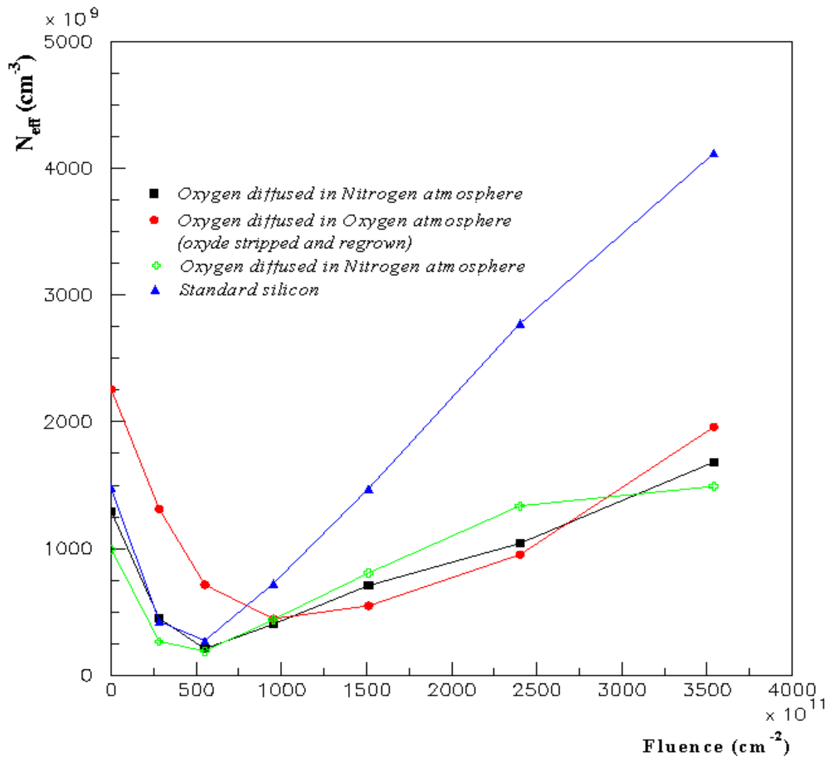
In all the following figures the diodes have been annealed at 80 ^oC for 4 minutes to just complete the beneficial annealing phase.



At high doses, N_{eff} is similar for un-oxygenated p-type or n-type starting materials, being dominated by the radiation induced defects. The oxygenated n-type silicon diodes show a substantially lower N_{eff} after high doses.

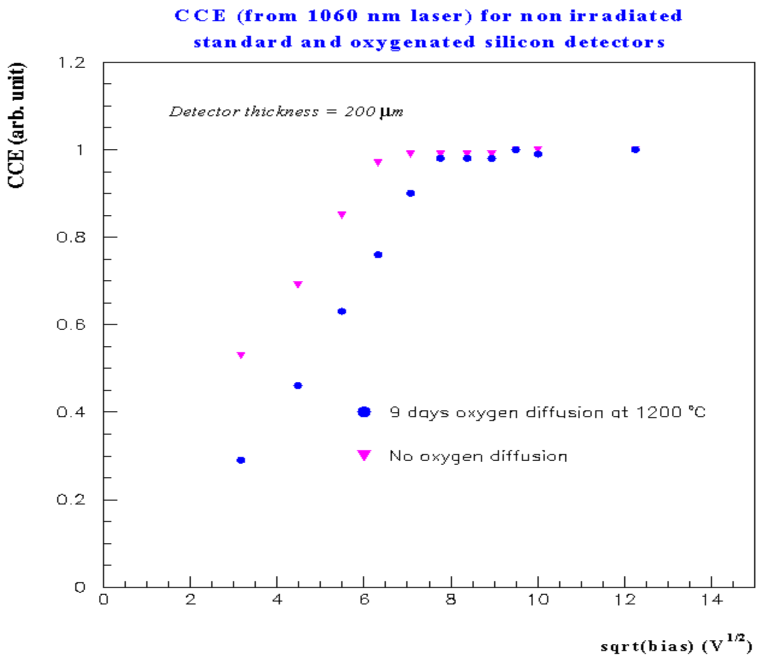


Diodes produced with silicon wafers submitted to high temperature oxygen diffusion for different times show very similar behaviours. They are here compared with diodes made from an un-oxygenated silicon wafer from the same ingot.

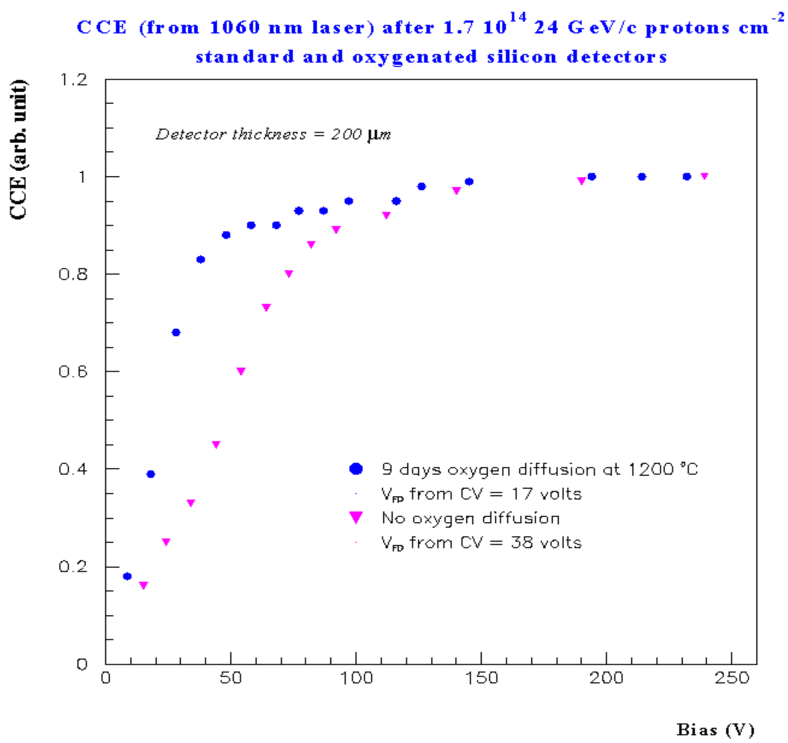


N_{eff} as a function of fluence for un-oxygenated and oxygenated n-type diodes with oxygen diffusion in different atmospheres.

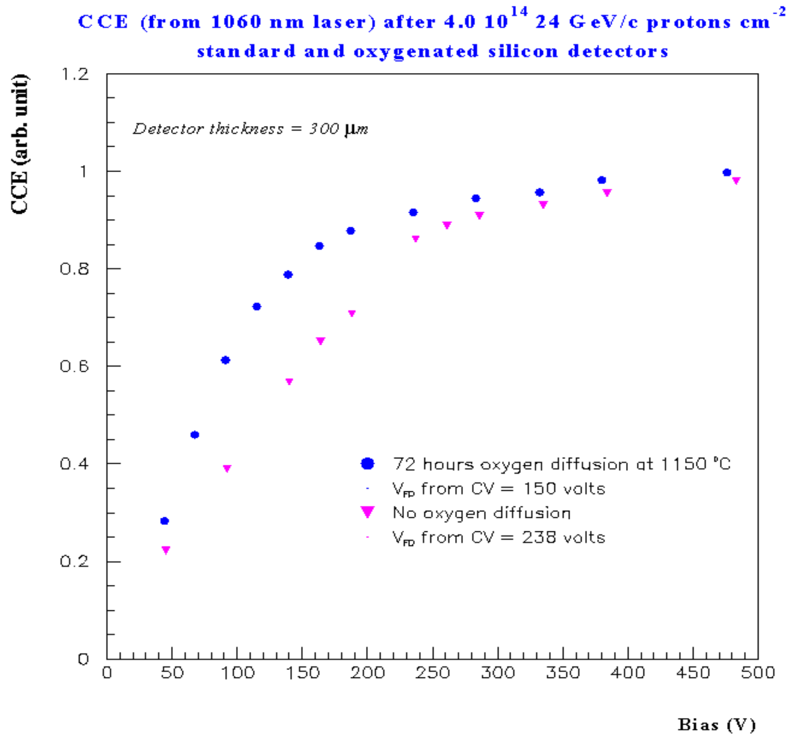
Charge collection efficiency (CCE) versus bias for oxygenated and un-oxygenated silicon diodes of different thickness before and after irradiation.

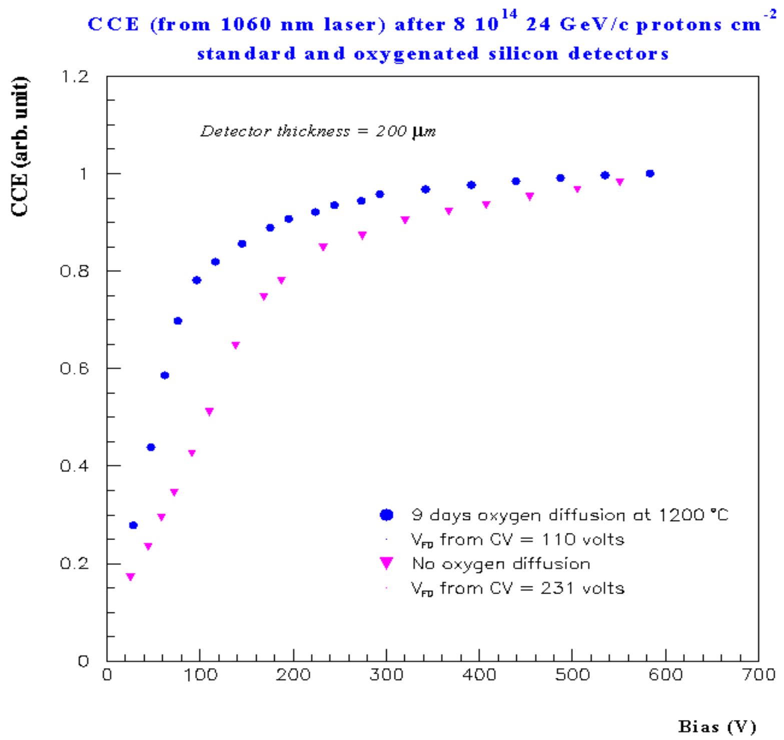


Before irradiation the collected charge increases linearly with the applied bias, to saturate at the maximum collectable charge at full depletion of the diode. The full depletion voltage (V_{FD}) depends on the initial resistivity of the silicon substrate.



After irradiation, V_{FD} is determined by the concentration of radiation induced p-type defects. The collected charge increases also above V_{FD}, because the stronger electric field reduces the effectiveness of the charge trapping due to the radiation induced defects.

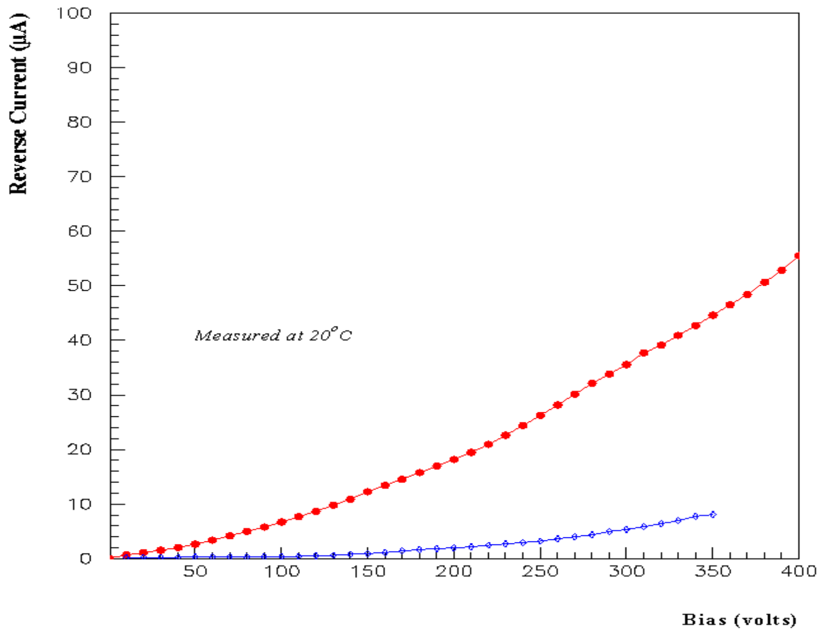




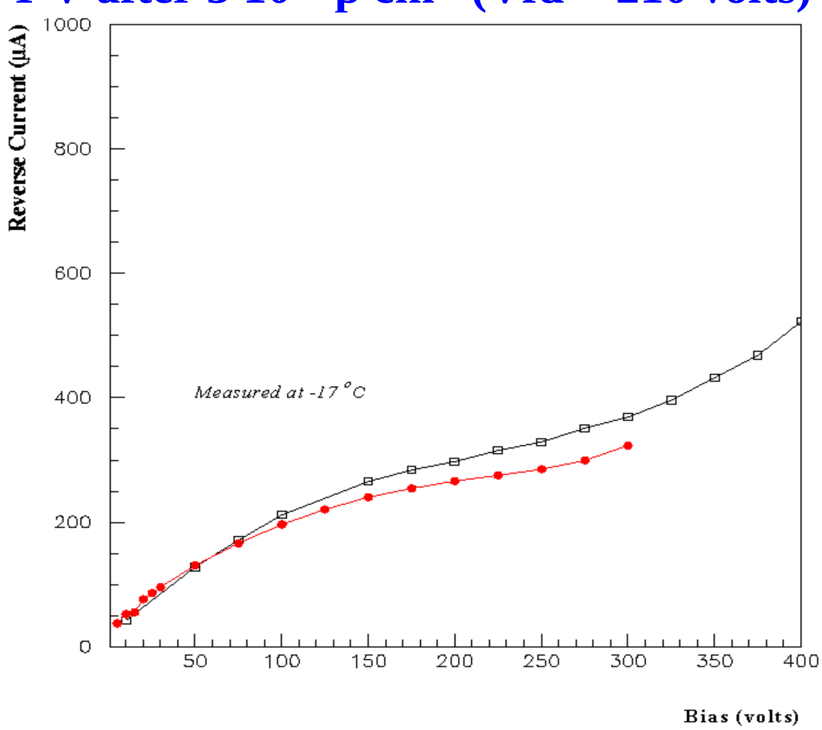
The advantages of the highly oxygenated silicon diodes are proven to be valid in term of charge collection efficiency

First results with p-type substrate microstrip detectors

Pre-irradiation I-V (Vfd = 65 volts)

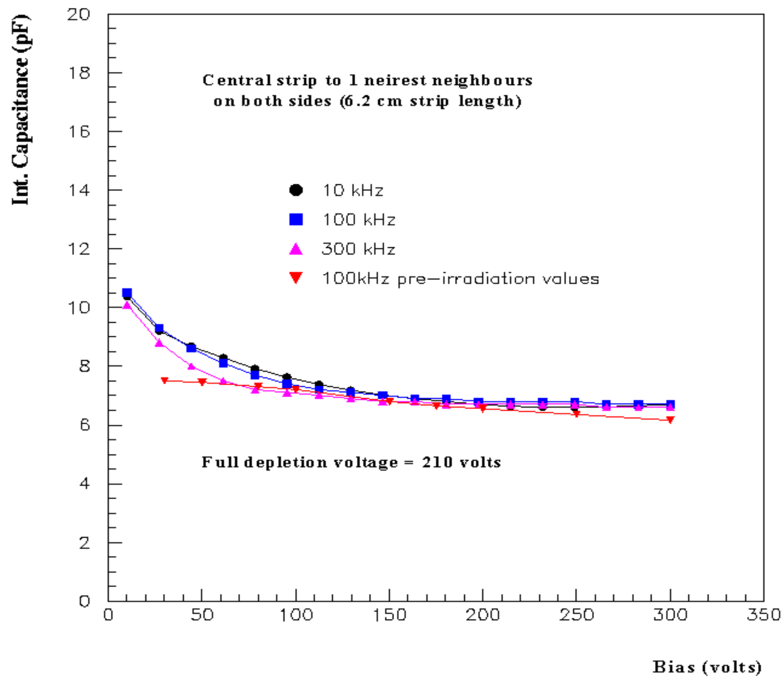


I-V after 3 10^{14} p cm^{-2} (Vfd = 210 volts)

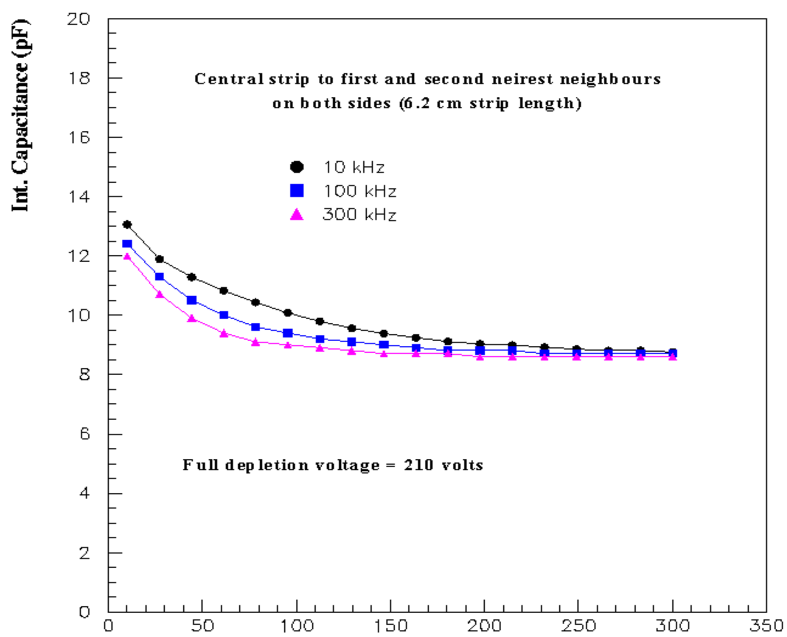


Interstrip capacitance before and after irradiation

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



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



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. 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 $1\cdot10^{15}$ protons cm^{-2}.