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Technology development of p-type microstrip detectors with radiation hard p-spray isolation

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Abstract

A technology for the fabrication of p-type microstrip silicon radiation detectors using p-spray implant isolation has been developed at CNM-IMB. The p-spray isolation has been optimized in order to withstand a gamma irradiation dose up to 50 Mrad (Si), which represents the ionization radiation dose expected in the middle region of the SCT-Atlas detector of the future Super-LHC during 10 years of operation. The best technological options for the p-spray implant were found by using a simulation software package and dedicated calibration runs. Using the optimized technology, detectors have been fabricated in the Clean Room facility of CNM-IMB, and characterized by reverse current and capacitance measurements before and after irradiation. The average full depletion voltage measured on the non-irradiated detectors was $V_{FD} = 41 \pm 3$ V, while the leakage current density for the microstrip devices at $V_{FD} + 20$ V was 400 nA/cm^2.
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1. Introduction

The quest for new radiation-hard silicon detectors has become very active in recent years due to the possible luminosity upgrade of the Large Hadron Collider (Super-LHC) at CERN [1]. The very high luminosity foreseen ($\sim 10^{35}$ cm^{-2} s^{-1}) implies that the detectors used in the upgrade of the Atlas Semiconductor Tracker will be exposed to fluences up to 10^{16} cm^{-2} 1 MeV neutron equivalent over the expected 10 years of operation. Present vertex detectors, relying on highly segmented silicon sensors, are designed to survive fast hadron fluences of about 10^{15} cm^{-2} [2]. Semiconductor detectors seem the best option for vertex sensors also in the next generation of colliders, provided that their radiation hardness is significantly improved. With the aim of developing a new reliable detector technology for the Super-LHC, the CERN RD50 collaboration "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" [3] was formed in 2002.

Silicon detectors made on n-type bulk silicon undergo spatial charge sign inversion after being irradiated with hadrons to a fluence of a few 10^{13} cm^{-2} 1 MeV neutron equivalent. After type inversion, the charge collected by these detectors at low voltages is higher when read out from the n-side than from the p-side. The migration of the junction after type inversion can be avoided by using a p-type bulk substrate and as a consequence, p-type microstrip detectors have been proposed, within the RD50 collaboration, as candidates to survive the extreme radiation conditions of the Super-LHC environment [3]. Microstrip detectors on p-type silicon present, however, the challenge of achieving a proper interstrip isolation. Since positive charge in the field oxide layer is always present and will increase when the detectors are irradiated, it makes electrons from the bulk silicon to accumulate at the silicon surface leading to a short between the strips. In order to provide the necessary interstrip isolation, the use of floating p-type zones, commonly known as p-stops, and

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surrounding the n-type strips, has been reported to show superior radiation hardness than n-type detectors, at the expense of a more complex and expensive technology. An alternative approach is the use of a p-spray blanket ion implantation to achieve the interstrip isolation.

In this paper, we present a technology for the fabrication of n-in-p microstrip detectors, which is based on the use of a p-spray isolation scheme, with the proper interstrip isolation able to survive the harsh ionizing radiation dose expected at the Super-LHC experiment. This technology has been developed by using the best technological parameters as obtained from simulation results, particularly for the ion implantation parameters of the p-spray. The evaluation of the prototype detectors has been carried out by performing the electrical characterization of the devices through the measurement of current–voltage and capacitance–voltage characteristics. This evaluation has been done not only after fabrication but also after gamma irradiation to a total dose of 50 Mrad, which is the one expected in the inner detector upgrade of Atlas [4].

2. p-type technology

One of the major technological challenges of the fabrication of n-in-p microstrip silicon detectors is to achieve a good isolation between the strips at the n-side, while ensuring the satisfactory electrical performance of the devices during all their life span. The isolation is necessary since the positive charge in the SiO_2 induces the creation of an electron accumulation layer at the oxide–silicon interface, increasing the interstrip capacitance and eventually shorting the strips together. This charge increases with the irradiation but is present even in non-irradiated oxides [5] and saturates when all traps are occupied by holes in the oxide layer.

One method to provide isolation between the strips consists on the definition of floating p-type zones, commonly known as p-stops, which surround the n-type strips. In a previous paper [6], we presented the superior radiation hardness of p-type technology, with p-stops implants, with respect to n-type detectors irradiated with 24 GeV protons. However, the p-stops have the drawback of adding a mask level to the fabrication process that increases its complexity and cost. Furthermore, the high electric fields at the edge of the p-stops have been shown to induce pre-breakdown micro-discharges which decrease the signal-to-noise ratio [7].

A technological alternative to the p-stops is the p-spray, which consists in a uniform p-type blanket implant performed on the silicon surface as shown in Fig. 1. The use of this technique does not require an extra mask as for the p-stop implant. Detectors with p-spray as isolating method have shown a better performance after irradiation than the ones fabricated with p-stops [5,8]. However, in order to ensure the strip isolation and avoid early breakdowns the p-spray implant profile has to be carefully calibrated. The need of high p-spray doses to avoid the inversion layer in the silicon surface in irradiated devices must be balanced with the decrease of the breakdown voltage (V_{BD}) and the increase of the leakage current as the p-spray implanted charge increases. The minimum p-spray dose that ensures a good isolation among the strips also at the highest irradiation doses must be used. Fig. 2 shows the simulated breakdown voltage of a p-type strip detector versus the total charge implanted with the p-spray into the silicon bulk. The simulation covers the range of implantation energy from 25 to 150 keV and the total doses from 10^{12} to $8 \times 10^{12}\,cm^{-2}$. The breakdown voltage is a function of the total implanted charge, which depends on both the energy and dose but not on the depth of the profile, at least in the range of energies and doses simulated. It is possible to observe the drastic reduction in the V_{BD} as the density of the p-spray implanted total charge increases. At a fixed bias voltage the electric field is higher when the gradient of the doping concentration at the interface between the strip and

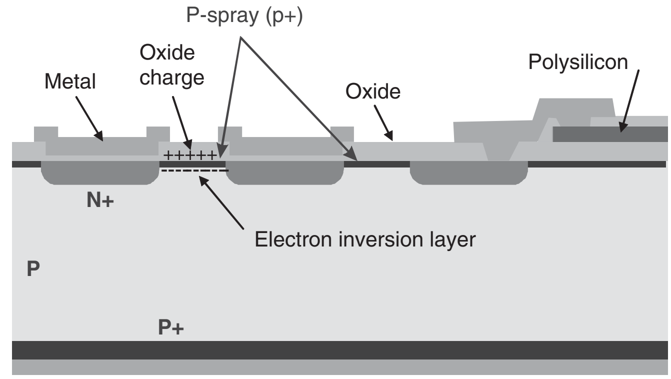

Fig. 1. Cross-section of a microstrip AC biased n-on-p detector with p-spray isolation.

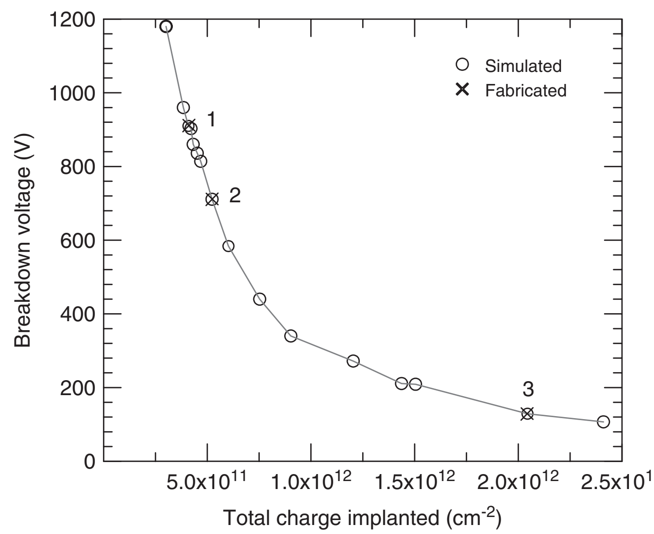

Fig. 2. Variation of the breakdown voltage as a function of the total implanted charge for the optimization of the p-spray isolation in non-irradiated detectors. Three points have been chosen for the fabrication of the strip detectors with the following parameters: (1) implant energy 45 keV and implant dose $10^{12}\,cm^{-2}$; (2) energy 150 keV and dose of $10^{12}\,cm^{-2}$; (3) energy 45 keV and dose $5 \times 10^{12}\,cm^{-2}$.

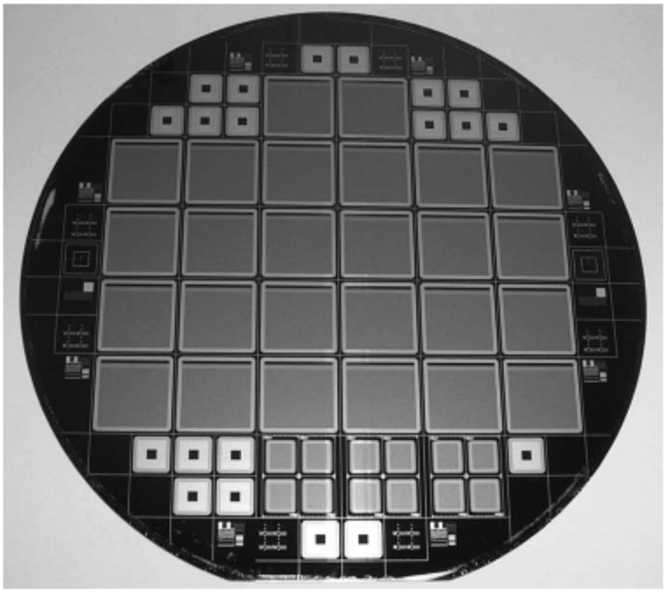

Fig. 3. Wafer processed at CNM-IMB clean room facilities. The wafer contains strip detectors, Atlas pixel detectors, pad detectors and different test structures.

the p-spray increases, leading to an early breakdown of the devices.

Various calibration runs, based on the simulation results [9], were made in order to find the best technological parameters for the p-spray implant. Fig. 3 shows an example of a wafer fabricated with a mask set designed by the CERN RD50 collaboration. This mask includes 26 microstrip baby detectors, 12 Atlas pixel detectors, 20 $5 \times 5\,\mathrm{mm}^2$ pad diodes and different test structures to measure the polysilicon resistivity and the technological parameters of the fabrication process. The strip detectors have 130 microstrips with a width of 32 μm and a pitch of 80 μm and are biased via polysilicon resistors connected to a bias ring. The strips also have an integrated metal capacitor for the capacitive coupling of the signal. The whole structure is surrounded by a multi-guard ring with field plates. The active area of the microstrip detectors is $1.06 \times 1.06\,\mathrm{cm}^2$.

3. Fabrication process

Different wafers were processed for the fabrication of the radiation detectors with p-spray isolation. Three different p-spray implantations were used for the fabrication of the devices to crosscheck the simulation results. The wafers used for the fabrication of the detectors were purchased from Siltronix and their characteristics are $\langle 1\,0\,0 \rangle$ FZ p-type, thickness of 300 ± 15 μm and nominal resistivity 30 kΩ cm, however, four-point-probe measurements on unprocessed wafers showed a resistivity of 20 ± 1 kΩ cm.

The first step in our wafer processing is an oxidation at 1100 °C in an O_2 ambient in order to grow a 200 nm of silicon oxide (SiO_2) layer. The thermal oxide is stripped off by a wet etching process. In this way, the superficial silicon layer, which could be contaminated by impurities, is removed by the wet etching process in order to minimize interface states. After the thermal oxide etching, a thin layer of oxide is thermally grown in order to implant the p-spray through it. Afterwards the wafers are oxidized again at 1100 °C in a wet oxygen atmosphere in order to grow a 800 nm layer of SiO_2. This thick layer constitutes the field isolation layer of the detectors. Then the fabrication process continues with the standard doping implantations, polysilicon deposition and metallization of the strips as in standard microstrip detectors. These steps do not change the profiles of the p-spray implants significantly since their thermal budget is negligible. The p-spray blankets were done implanting boron ions with the following parameters: ion energy 45 keV with doses of 10^{12} and $5 \times 10^{12}\,\mathrm{cm}^{-2}$, and ion energy 150 keV with a dose of $10^{12}\,\mathrm{cm}^{-2}$ which is the minimum dose available at the ion implanter at the CNM-IMB facilities assuring a uniform implantation. According to simulation, all three implant profiles are able to compensate the electron inversion layer induced at the silicon surface; therefore the natural choice would be the one with the lowest profile which assure a maximum breakdown voltage. Fig. 4 shows the p-spray profiles obtained with the fabrication and measured by the spreading resistance method.

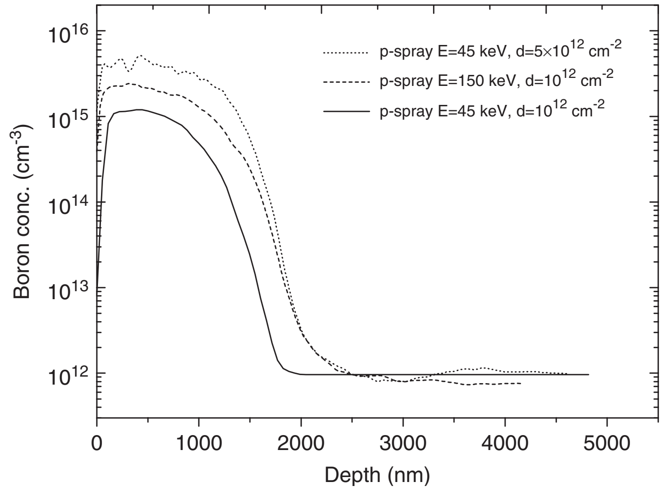

Fig. 4. Spreading resistance measurement of the three different p-spray isolations used for the fabrication of p-type detectors. In this plot, *E* stands for ion implantation energy and *d* for implanted dose.

4. Electrical characterization

A shielded probe station Karl Suss PA200 was used for the electrical probing of the detectors. The sample and contacting probes were placed in a Faraday box that provided electrical shielding and kept them dark. Two Keithley 2410 SourceMeter were used to bias simultaneously the sensible area and the guard ring of the devices and to measure the reverse current. The capacitance–voltage characteristics (*C–V*) at high voltage, up to 1000 V, were obtained with an HP 4192A Impedance Analyzer operated at 10 kHz. To separate the high voltage from the capacitance meter a special bias circuit was used. All measurements were performed at room temperature.

Fig. 5 shows the capacitance–voltage characteristics used to calculate the full depletion voltage (V_{FD}) of four different detectors under study. The standard procedure used for the extraction of V_{FD} was a crossing of two straight lines in the $\log C - \log V$ plot near the kink. The average result is $V_{FD} = 41 \pm 3$ V that corresponds to a resistivity of 21 ± 1 kΩ cm, in agreement with the value obtained with the four-point-probe. V_{FD} is independent of the p-spray used for the fabrication process.

Fig. 6 shows the current–voltage characteristics of the p-type pad detectors fabricated with the three different p-spray implants before irradiation. The curves reported are from different detectors from different wafers. The breakdown voltage (V_{BD}) decreases when increasing the total implanted dose as predicted by simulation. Table 1 shows the average V_{BD} for simple diodes fabricated with the three technologies. It can be noticed that the results of the electrical measurements are in good agreement with the simulation.

Microstrip detectors have a different current voltage characteristic than pad diodes. Figs. 7–9 show that the breakdown voltage is always in the range 100–200 V, independently on the p-spray implants used for the fabrication. This means that the junction curvature effect will cause the breakdown and not the gradient of the abrupt junction. The ends of the strips have roughly spherical corners and therefore the highest electric field, which will cause the junction breakdown.

The average leakage current of the strips and the guard rings measured at $V_{FD} + 20$ V are reported in Table 2. The leakage current of the guard ring of the detectors with the

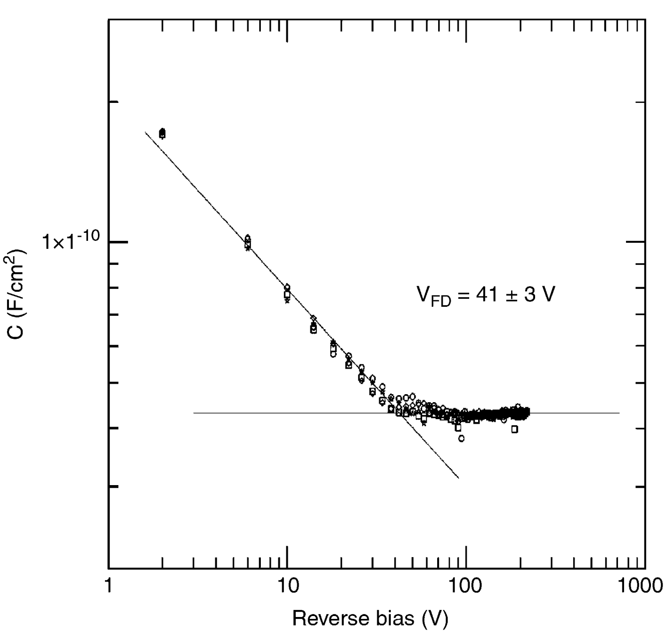

Fig. 5. Capacitance–voltage characteristics in log–log scale to estimate the full depletion voltage.

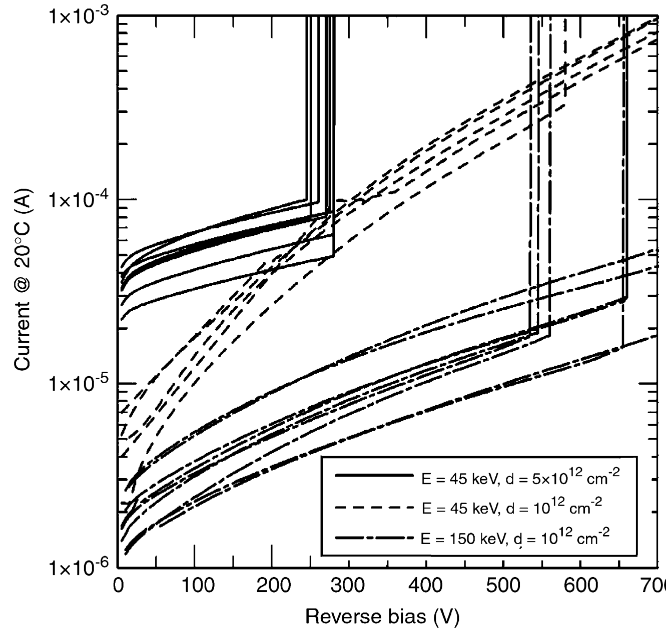

Fig. 6. Current–voltage characteristics of n-in-p pad detectors fabricated with three different p-spray implants.

Table 1
Comparison between the measured and simulated detectors breakdown voltages for the different p-spray isolations used

p-spray		V_{BD} (V) diodes	
Energy (keV)	Dose (cm^{-2})	Simulated	Measured
45	10^{12}	900	700
150	10^{12}	750	650
45	5×10^{12}	210	250

p-spray doses of 10^{12} cm^{-2} are several orders of magnitude higher that the central active area, which means that the isolation between the surface and the back plane is not adequate, there is a conducting electron channel between the guard ring and the back contact through the detector sides.

The characteristics of the detectors with the highest p-spray implanted dose (ion energy 10^{12} keV and dose 5×10^{12} cm^{-2}) show a guard ring leakage current lower than the current of the central active area. This indicates that the strips are properly isolated and the corresponding V_{BD} is high enough to allow the full depletion of the detectors before irradiation.

In order to prove the effectiveness of the p-spray isolation between the strips, some detectors were irradiated with gamma rays from a ^{60}Co source to a total silicon absorbed dose of 50 Mrad (500 kGy), which is an estimation of the total dose expected in the middle region of the future upgrade of the Atlas detector at Super-LHC. After irradiation the leakage current of the strips and the guard rings of the detectors with the lower implant doses increase significantly, reaching a value of few mA. This means that, although the detectors were properly insulated by the

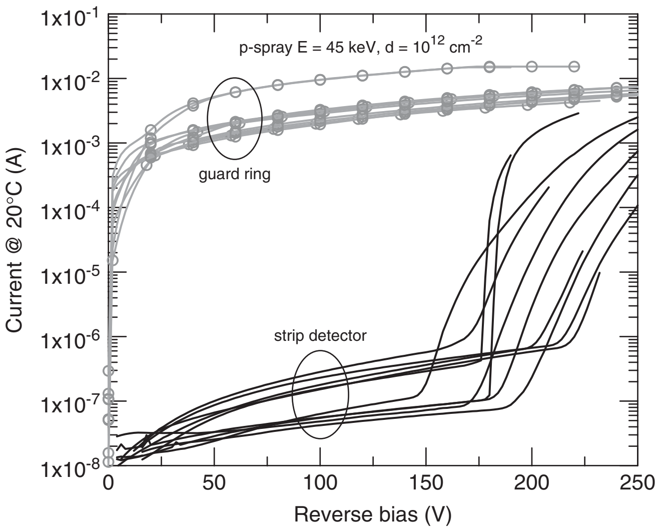

Fig. 7. Current–voltage characteristics of n-in-p strip detectors fabricated with the p-spray implant energy of 45 keV and dose of $10^{12}\,\mathrm{cm}^{-2}$.

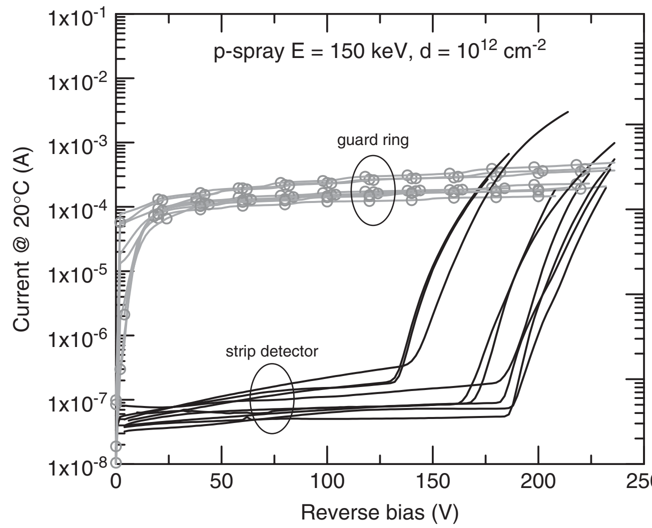

Fig. 9. Current–voltage characteristics of n-in-p strip detectors fabricated with the p-spray implant energy of 150 keV and dose of $10^{12}\,\mathrm{cm}^{-2}$.

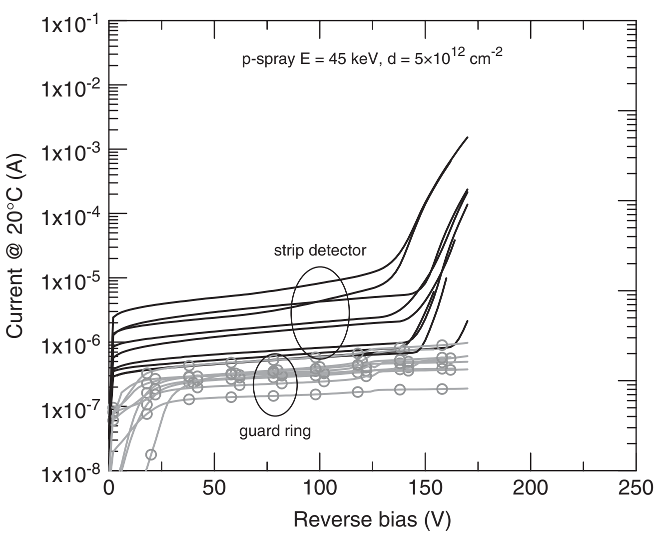

Fig. 8. Current–voltage characteristics of n-in-p strip detectors fabricated with the p-spray implant energy of 45 keV and dose of $5\times10^{12}\,\mathrm{cm}^{-2}$.

p-spray blanket before irradiation, after irradiation, the build-up of the inversion layer at the silicon oxide interface is not compensated by the p-spray implant and a current flows from the top to the bottom surface of the strip detector.

Fig. 10 shows the current–voltage characteristic of the detectors fabricated with the highest implant dose ($5\times10^{12}\,\mathrm{cm}^{-2}$) and irradiated with gamma particles. As expected the effect of the radiation is to increase the leakage current that flows through the guard ring due to the increasing of the electron concentration at the silicon/oxide interface. However, it must be noticed that the current of the strips does not change significantly, indicating that the p-spray is still adequate to guarantee a proper isolation even after the increases of the oxide charge density. Furthermore, the reverse current measurements show that the breakdown voltage of the p-spray implant with the highest dose improves after the irradiation. This

Table 2
Reverse current at 20 V over the full depletion voltage of the strip detectors fabricated with the different p-spray isolations

p-spray		Current at $V_{FD}+20\,\mathrm{V}$	
Energy (keV)	Dose (cm^{-2})	Strips	Ring
45	10^{12}	50 ± 30 nA	2 ± 1 mA
150	10^{12}	90 ± 40 nA	150 ± 40 μA
45	5×10^{12}	1.4 ± 1.1 μA	300 ± 30 nA

The currents are measured at 20 °C.

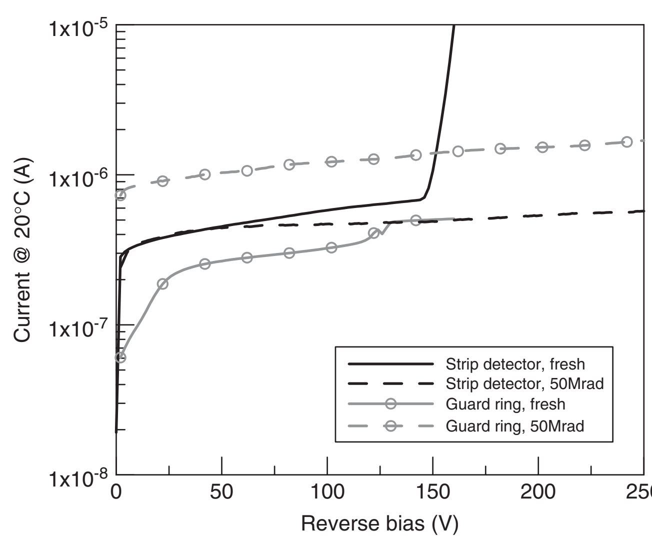

Fig. 10. Comparison of the current–voltage characteristics of irradiated and non-irradiated n-in-p strip detectors fabricated with the p-spray implant energy of 45 keV and dose of $5\times10^{12}\,\mathrm{cm}^{-2}$.

can be explained because the maximum electric field decreases with the increase of oxide charge density due to compensation of the acceptor dopants by the oxide charge. As expected, the capacitance–voltage characteristic of the strip detectors with the best p-spray isolation did not change after irradiation. The point-like defects introduced by the gamma irradiation to 50 Mrad are not enough to induce any significant change in the full depletion voltage [10].

5. Conclusions

In order to fabricate p-type strip detectors it must be proved that the isolation used to avoid the effect of the build-up of an electron layer at the silicon surface due to the trapping of positive charge into the oxide is effective after irradiation. In this work, we have presented a p-spray technology, which is able to withstand the maximum dose expected in the middle region of the Atlas inner detector upgrade experiment. Simulation was used to find the optimum balance between the need of compensating the inversion layer in the silicon surface in irradiated devices and the decrease of the breakdown voltage. According to the simulation results, microstrip detectors with different p-spray isolation implantation were fabricated and successfully tested. All devices have shown good electrical behavior and interstrips isolation before irradiation. Detectors were irradiated at the total dose expected in the middle region of the Atlas upgrade experiment, which corresponds to 50 Mrad. The p-spray obtained with the ion energy of 45 keV and with the dose of $5\times10^{12}\,\mathrm{cm}^{-2}$ has shown to be effective in providing good isolation after irradiation and a breakdown voltage higher than the full depletion voltage.

Acknowledgments

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