SMART Detector Project: recent results from the SMART experiment

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Abstract

A growing interest is recently focusing on Czochralski and Epitaxial Silicon as potentially radiation-hard materials.
We report on the processing and characterization of microstrip sensors and pad detectors produced on n- and p-type Magnetic Czochralski, Epitaxial and Float Zone silicon. The aim of this work is the development of radiation hard detectors for very high luminosity colliders. The activity is funded by INFN within the SMART project, in the framework of the RD50 Collaboration. The devices have been produced by ITC-IRST; each wafer hosts ten microstrip sensors with different geometries, several diodes and test structures.
The isolation in the strip detectors produced on p-type material has been achieved by means of a uniform p-spray implantation, with doping of $3x10^{12}$ cm^{-2} (low dose p-spray) and $5x10^{12}$ cm^{-2} (high dose p-spray).
The samples have undergone various irradiation campaigns, using 24 GeV/c protons (CERN-Geneva), 26 MeV protons (FZK-Karlsruhe) and reactor neutrons (JSI Ljubljana), up to ~10^{16} cm^{-2} 1 MeV neutrons eq. (n_{eq}/cm^2), and have been completely characterized before and after irradiation. Their radiation hardness as a function of the irradiation fluence has been established in terms of breakdown voltage, depletion voltage, leakage current, Charge Collection Efficiency and evaluating the more relevant mini-sensors parameters variation. Moreover, the time evolution of depletion voltage, leakage current and interstrip capacitance has been followed in order to study their annealing behavior and Space Charge Sign Inversion effects.

Keywords Silicon detectors; Radiation damage; microstrip detectors

1. Introduction

ATLAS and CMS, two multipurpose high energy physics experiments, are under construction at the Large Hadron Collider (LHC) at CERN. LHC is a big p-p accelerator with a beam energy of 7 TeV and a designed peak luminosity of 10^{34} $cm^{-2}s^{-1}$ [1]. The tracker detectors of both experiments have been designed to work in a very hostile radiation environment with a fast hadron fluence of $3x10^{15}$ 1 MeV-neutron-equivalent/cm^2 (n_{eq}/cm^2) expected at the minimum instrumented distance from the collision point (~4 cm). Detector technology has been developed to ensure the survival of these systems to an integrated luminosity of 500 fb^{-1}, corresponding to 10 years of LHC operation [2].

A planned upgrade of the LHC collider (SLHC project [3]) will increase both the luminosity up to a final value of 10^{35} $cm^{-2}\cdot s^{-1}$ and the beam energy up to 12.5 TeV. Tracker detectors of SLHC experiments should maintain their performance up to the maximum expected fast hadron fluence: $1.6x10^{16}$ n_{eq}/cm^2 at 4 cm from the beam line and 8 x 10^{14} n_{eq}/cm^2 at an intermediate distance of 22 cm. Silicon detectors and in particular micro-strip sensors can still be considered a viable solution in the intermediate and outer tracker regions, provided that an improvement of their radiation hardness to fluences of the order of 10^{15} n_{eq}/cm^2 can be achieved. For this purpose the activity of the SMART project, a collaboration of Italian research institutes funded by the I.N.F.N., has been focused on the development of radiation hard silicon position sensitive detectors for SLHC in the framework of CERN-RD50 collaboration [4].

Previous studies highlighted the beneficial effect in terms of radiation hardness of FZ silicon material enriched with oxygen atoms (DOFZ – Diffusion Oxygenated FZ silicon) [5]. Nowadays, with the Magnetic Czochralski (MCz) and Epitaxial growth technology it is possible to produce Si devices with an intrinsically high oxygen content and with a resistivity suitable for particle detector applications [6].

Furthermore, silicon detectors built on p-type substrates (n+ microstrip implants on p substrate i.e. n+-on-p) are a possible radiation harder solution compared to the more common p+-on-n technique, mainly for two reasons: first the p substrate, at any dose after irradiation, doesn't show type inversion, preserving the highest electrical field on the strip side, and second the n+ implants on p substrate collect electrons which have, with respect to holes, an higher mobility and a lower trapping probability, thus improving charge collection efficiency.

In this paper we report on the results achieved with test structures and microstrip detectors processed on MCz and FZ substrates (n- and p-type) heavily irradiated with protons of two different energies. Moreover, first results on thick Epitaxial devices are presented.

2. Samples and irradiation campaigns

The wafer processing has been performed by ITC-IRST (Trento, Italy) in two successive runs, using both MCz and FZ 4" silicon wafers for comparison. In the first run (RUN-I) wafers from n-type material have been processed while on the second one (RUN-II) p-type substrates have been manufactured; on both cases the same mask set has been used. For RUN-II the p-spray technique (uniform implantation) [7] is used to obtain isolation between n^+ implants with two different implantation doses, namely $3x10^{12}$ cm^{-2} (low p-spray) and $5x10^{12}$ cm^{-2} (high p-spray).

The wafers produced for RUN-I (p-on-n) on MCz substrates have a resistivity ρ>500 Ωcm, a thickness of 300 μm and <100> crystal orientation, while the ones produced on Fz materials are of type <111>, have a resistivity of around 6 KΩcm and a thickness of 300 μm. For RUN-II (n-on-p) all the wafers are of <100> type and have a substrate resistivity ≥2 KΩcm; the thickness is 300 μm for MCz substrates and 200 μm for Fz silicon.

Each wafer hosts various test structures and ten mini-sensors with equal active area (~ 0.5x5 cm^2) but with different geometry, to investigate the dependence of the detector performance on the design parameters (see Tab.1). Further details can be found in references [8,9,10]. Few identical devices on n-type 150μm thick epitaxial wafers have also been produced in a dedicated run.

μ-strip #	**Pitch**	**implant width**	**poly width**	**Al width**
S1	**50**	**15**	**10**	**23**
S2	**50**	**20**	**15**	**28**
S3	**50**	**25**	**20**	**33**
S4	**50**	**15**	**10**	**19**
S5	**50**	**15**	**10**	**27**
S6	**100**	**15**	**10**	**23**
S7	**100**	**25**	**20**	**33**
S8	**100**	**35**	**30**	**43**
S9	**100**	**25**	**20**	**37**
S10	**100**	**25**	**20**	**41**

Tab. 1. Strip parameters of the ten mini-sensors in the wafer. All the dimensions are in μm. The devices are AC-coupled and microstrips are biased through 600kΩ poly-silicon resistors.

The irradiation of the devices was performed with protons of different energies and with neutrons, in order to compare the different resulting radiation damage. The first campaign was carried out at the CERN-SPS facility with 24 GeV/c protons and at fluences up to 3×10^{15} n_{eq}/cm^2, the second one was performed at the Compact Cyclotron of the Forshungszentrum in Karlsruhe (Germany) with 26 MeV protons at fluences up to 2×10^{15} n_{eq}/cm^2 and the last one at the JSI Ljubljana with reactor neutrons, up to ~ 10^{16} n_{eq}/cm^2.

3. Pre-irradiation characterization

All the devices were completely characterized before and after irradiation, following the standard procedures defined within the RD50 Collaboration. The leakage current (I_{leak}) and the back-plane capacitance (C_{back}) measurements were performed both on diodes and on microstrip sensors in order to evaluate the breakdown performance and the depletion voltage. The strip isolation was checked by means of the interstrip capacitance (C_{int}) and the interstrip resistance (R_{int}) measurements.

Pre irradiation measurements show that all n-type devices (FZ and MCz) show high breakdown voltages (V_{bd} > 600V) and in average all the sensors have a leakage current density around J ~1.4 nA/mm^3 at 400V, well beyond their depletion voltage.

Different performance has been observed for p-type sensors that show a low breakdown voltage, in particular for sensors processed with high p-spray dose. Moreover, in detectors with larger pitch (100 µm) the breakdown is even lower than 70V (big dot curves in Fig.1). A simulation of these devices [11] has identified as responsible of the avalanche breakdown at low bias voltage the high values of the electric field, localized between the n+ implant and the p-spray layer.

A local variation of the depletion voltage (V_{dep}) in the MCz material is also measured, especially for p-type wafers, due to the non-uniform oxygen distribution that leads to a spread in the thermal donor activation in the wafer after the processing (see [10]).

For n-type microstrip sensors a typical behavior of C_{int} as a function of the bias voltage is observed, with a saturation value in over-depletion condition ranging from 0.5 to 1.2 pF/cm, in agreement with the different device geometries.

On the other hand, for p-type sensors the interstrip capacitance shows a strong variation with bias voltage (fig.2) starting from high values at low bias and slowly decreasing to a higher saturation value with respect to n-type sensors, while at the same time the interstrip resistance is increasing. The C_{int} saturation is faster in sensors processed with low p-spray sensors and for larger pitches. In addition, such behaviour is strongly influenced by the metal over-hang (Al strip wider than the n+ strip implant): the coupling between the Al strip and the p-spray layer causes an additional C_{int} contribution, that decreases as the bias voltage is increased. This effect is checked by comparing the C_{int} measurements for sensors differing only by the metal overhang extension, see

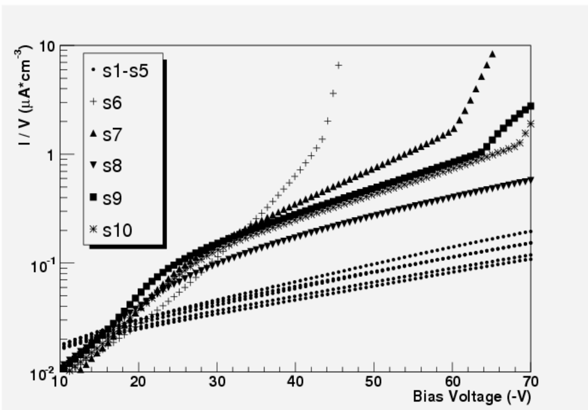

Fig. 1. Leakage Currents of MCz p-type, **high dose p-spray**, sensors measured before irradiation. Different curves refer to different geometries, big marks correspond to sensors with 100µm pitch (s6-s10)

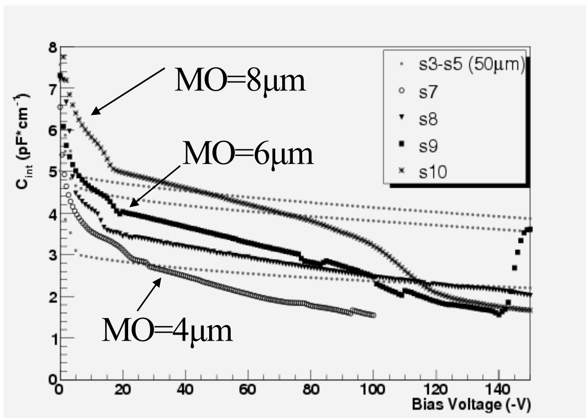

Fig.2:Interstrip capacitance of MCz p-type, **high dose p-spray**, sensors measured before irradiation. Different curves refer to different geormetries, big marks correspond to sensors with 100µm pitch (s6-s10)

fig.2 (sensors s7, s9 and s10 have increasing metal overhang MO).

The effect of the p-spray layer on the strip isolation and the relation between the p-spray dose, the MO and the interstrip capacitance are accurately described for different oxide charge densities by device simulations developed at IRST [11]; a good agreement with the experimental data is found.

The simulation results, confirmed by our observations, show that, depending on the oxide charge level and on the MO value, p-spray isolation among n^+ strip implants and optimal interstrip capacitive coupling C_{int} can be reached, in several cases, only at high bias voltage. This behaviour must be carefully followed in irradiated detectors, where it could cause problems if operation in partial depletion conditions were to be requested.

In few micro-strip sensors CCE has been also measured. The sensors have been assembled in detector units using the CMS front-end electronics and its standard DAQ system [2]. Preliminary measurement show that MCz and FZ n-type detectors have similar performance in terms of collection efficiency and signal to noise value (S/N~19) [12].

4. Post-irradiation results

Irradiated devices have been characterized at 0^oC or at -3^oC in order to limit the leakage current. All measurements have been performed immediately after irradiation and after repeated steps during the annealing phase in order to: (i) follow the radiation damage and annealing evolution on bulk current and on effective doping concentration; (ii) determine the effective irradiation fluences; (iii) study SCSI effects and estimate the inversion fluence for eventual type inversion of the different materials used (FZ, MCz).

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we have heated different groups of irradiated samples at different temperatures: 20, 60 or 80 ^oC. Moreover, by measuring I_{leak}, C_{int} and R_{int} on minisenors at different fluences and annealing time we have studied the performance of p-type irradiated sensors comparing different p spray doses, we have evaluated the impact of the geometry (metal overhang, w/p) on the noise level and leakage current value and compared MCz vs FZ performances.

With the procedure described in [14], the irradiation neutron equivalent fluences are estimated by a fit of the annealing current curves on FZ-n materials using the standard parameterisations for α(t,T) [15]. The current related damage has been evaluated for all radiation sources on n-type and p-type materials. Measurements have shown a good agreement with NIEL hypothesis and the leakage current density increase rate values are compatible with expectations: $<\alpha> \cong 4\ 10^{-17}$ A/cm [4] after 8 min of annealing at 80^oC.

Starting from the diode leakage current we have observed that n-type micro-strip detectors, of both MCz and FZ type, have good performances before and during the annealing treatment, with breakdown voltages well above their V_{dep}. The p-type detectors show an improved performance after irradiation: in the entire fluence range the breakdown voltages of the detectors with a low p-spray dose are fully comparable with the n-type sensors and are in excess of 600V, although the detectors with high dose p-spray recover completely only at irradiation fluences around $6x10^{14}$ n_{eq}/cm^2, as shown in Fig3 (the breakdown of detector irradiated at the second fluence is still at 50V). This improvement can be explained with the increase, with the irradiation dose, of the positive charge in the passivation oxide layer, which progressively depletes the p-spray starting

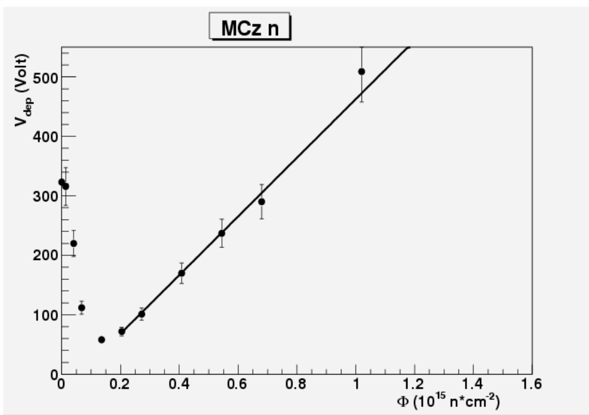

Fig. 4. Depletion voltage vs fluence for n-type MCz senosors irradiated with 26 MeV protons (see text).

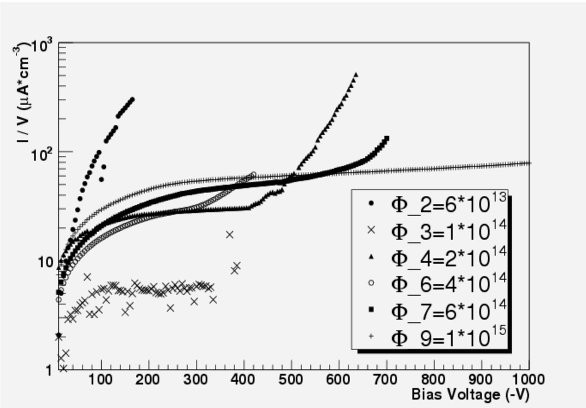

Fig. 3. Leakage Currents of **high dose p-spray** MCz p-type sensors irradiated with 26 MeV protons at different fluences (from 6×10^{13} n_{eq}/cm^2 up to 2×10^{15} n_{eq}/cm^2) The measurements are performed at 0°C and rescaled at 20°C.

from the interface bringing a 'beneficial' effect in terms of an increased breakdown voltage. This effect is also described and predicted by simulations [11].

The depletion voltage has been measured after irradiation and during the annealing at different temperatures. The annealing behavior of V_{dep} (reported in detail in [15]) shows a clear saturation beyond 200 minutes at 80 ^oC (during the reverse annealing phase) in MCz substrates of both n and p-type, while the V_{dep} values of FZ materials still increase with time.

The reduced reverse annealing growth of MCz devices would simplify damage recovery in experimental operational conditions. V_{dep} as a function of fluence is also studied after the beneficial annealing. In n-type material, FZ substrates are already type inverted at the lowest fluence, and V_{dep} increases with fluence (ϕ). On the contrary, V_{dep} values of the n-type MCz wafers show a minimum at ϕ_{min}~1.86×10^{14} n_{eq}/cm^2 (Fig.4). At the minimum the depletion voltage (and, hence, the effective doping concentration N_{eff}) is significantly different from zero, suggesting that no space charge sign inversion (SCSI) occurred, and that after the minimum the substrate is still n-type. However, while MCz devices irradiated at fluences lower than ϕ_{min} show a behavior with the annealing time typical of a not yet inverted FZ device (the beneficial annealing V_{dep} value leads toward a maximum) the annealing curves of V_{dep} for MCz devices irradiated at fluences higher than ϕ_{min} show a behavior typical of an inverted FZ device (V_{dep} measured during the beneficial annealing leads toward a minimum).

Anyway, microscopic investigation by current transients at constant temperature and Transient Current Technique (TCT) measurements have also been performed, giving a different picture: n-MCz Si diodes do not exhibit SCSI in the range 10^{14}-10^{15} n_{eq} /cm^2 [13]. Moreover, according to Thermally Stimulated Currents (TSC) analysis the deep acceptors produced by irradiation may be partially compensated by a shallow donor, which is introduced with a much higher rate in MCz than in FZ. This observation can explain a smaller introduction rate of acceptors in MCz and the fact that at 10^{15} n_{eq} cm^2 n-MCz Si is not type inverted. Preliminary simulation studies show that the minimum value of depletion voltage vs fluence and the "inverted like" annealing behavior without SCSI could be explained in terms of double junction effects [13].

In p-type substrates the V_{dep} always increases with irradiation (in fact it still remains p type at any fluence and the acceptor concentration increases with fluence). A lower V_{dep} value is measured at any time and fluences in MCz p-type material with respect to FZ ([12]).

The MCz and the FZ microstrip detectors have comparable performances in terms of the interstrip capacitance (C_{int}) after irradiation, taking into account that all crystals but n-type FZ (which is <111>) are <100> oriented. In fig.5 and fig.6 is compared the behavior of C_{int} as a function of bias voltage measured on sensors with the same geometry but

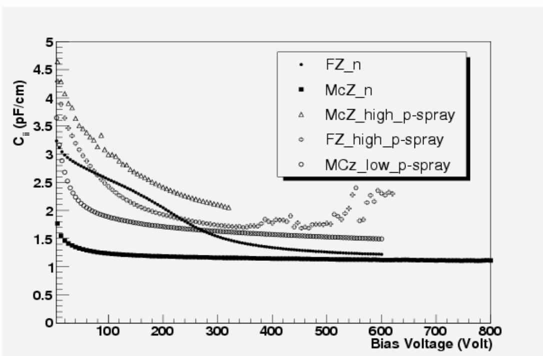

Fig. 5. C_{int} vs V_{bias} measured on different substrates irradiated with 26 MeV protons at $0,6\times10^{14}$ n_{eq} cm^{-2} (sensor geometry s1 with 50μm pitch).

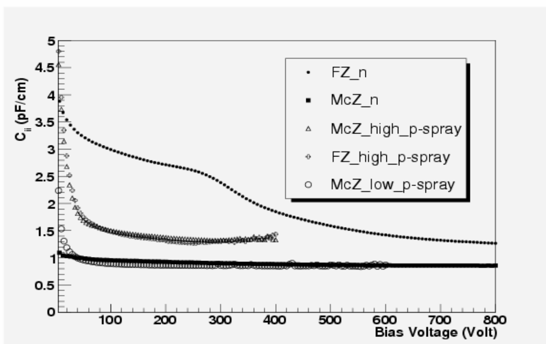

Fig. 6. C_{int} vs V_{bias} measured on different substrates irradiated with 26 MeV protons at 4×10^{14} n_{eq} cm^{-2} (sensor geometry s6 with 100μm pitch).

different materials and technological production splittings irradiated respectively at a low fluence $\phi_2 \sim 0{,}6\times10^{14}$ n_{eq}/cm^2 (sensor geometry S1, 50μm) and at a quite high one $\phi_6 \sim 4\times10^{14}$ n_{eq}/cm^2 (sensor geometry S6, 100μm). For the n-type detectors (full markers) C_{int} is not varying significantly with the fluence, with the FZ devices following the classical <111> behavior [14]. The post-irradiation value for MCz sensors, after a sharp initial decrease with V_{bias} is slightly higher and in the same range of the pre-irradiation values: 1.2-1.7 pF/cm for the detectors with a strip pitch of 50 μm and 0.5-1. pF/cm for the 100 μm pitch sensors.

For what concerns p-type detectors (empty markers), the same features observed before irradiation in the C_{int} vs V_{bias} curves are still present: interstrip capacitance decreases with V_{bias} towards a saturation value. The saturation is still faster for low p-spray isolation and for larger pitches. It can be observed that the C_{int} behavior for p-type devices improves with irradiation; in particular, low p-spray sensors show pretty comparable behavior to n-type MCz irradiated sensors since $\phi_3\sim 1\times10^{14}$ n_{eq}/cm^2 [15] while the high p-spray curves are still higher at $\phi_6 \sim 4\times10^{14}$ n_{eq}/cm^2 (Fig.6). No differences between FZ and MCz substrates is also evident (FZ and MCz high p-spray curves are quite similar). The improvement of p-type microstrip sensor performances for what concerns breakdown voltage and interstrip capacitance is also nicely predicted by device simulation [11], where it is explained in terms of oxide charge density the different p-spray dose choices.

1. Conclusions

In this work we have summarized some of the results achieved within the SMART collaboration on the characterization of heavily irradiated silicon devices. Before and after irradiation with protons up to 3×10^{15} n_{eq}/cm^2, n-type and p-type MCz Si microstrip detectors were qualified in comparison with standard FZ substrates. We have observed an improved radiation tolerance of MCz detectors with respect to standard FZ ones in terms of depletion voltage as a function of fluence and especially during the reverse annealing phase. A very good behavior has been observed in terms of interstrip capacitance after irradiation of n-type materials. Both the low breakdown voltage and the high interstrip capacitance values, observed on p-type unirradiated substrates, recover with the irradiation doses up to the maximum one investigated. Simulation studies are ongoing in order to optimize the p-spray dose and investigate other strip isolation technique (p-stop, p-spray and p-stops). These first results support the possible use of MCz n-type and p-type devices as a cost effective solution in the intermediate and outer layers of the SLHC tracker detectors.

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