Czochralski Silicon Sensors: status of development

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Abstract

Tracker systems based on silicon detectors are one of the possible choice for experiments at SLHC, the future upgrade of the LHC collider. Optimization of material and detector design are key factors to develop ultra radiation hard silicon devices. Most advanced research activity in this field identified Magnetic Czochralski (MCz) material as a candidate for the processing of such a detectors.

This paper summarizes more relevant results achieved by the CERN RD50 and SMART INFN collaborations. Recent studies on test structures and micro-strip detectors processed on MCz material n- and p-type doped, and the radiation hardness performance after heavy irradiation tests are described.

Charge collection from particles has been evaluated on diodes and micro-strip detectors and extrapolation of tracking performances up to the fluence expected at SLHC has been studied. Promising results in terms of radiation hardness parameters have been achieved.

Key words:

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1. Introduction

Tracker detectors based on Float Zone (Fz) silicon devices are now under construction for high energy physics experiments at the Large Hadron Collider (LHC)(1) (2). They have been designed to work in a hostile radiation environment to withstand a fast hadron fluence up to $3 \cdot 10^{15} cm^{-2}$ at the minimum instrumented distance from the collision point (R=4cm). The option for increasing the LHC luminosity up to $10^{35} cm^{-2} s^{-1}$ is already envisaged in order to extend the discovery potential of the machine (SuperLHC) (3). To preserve the physics potential of SLHC the tracker detectors should maintain their performance up to largest integrated luminosity.

The instantaneous luminosity increase implies higher radiation damage and high detector occupancy. Both these aspects should be taken into account to optimize the tracking detectors design to equip the future trackers.

In such experimental conditions the maximum fast hadron fluence will reach values as high as $1.6 \cdot 10^{16} cm^{-2}$ after five years of machine operation. Present technology does not guarantee the required performances in such conditions and new radiation hard material and detector design must be defined to instrument the region closest to the collision point.

Material engineering research established that

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oxygen-enriched Float Zone silicon (DOFZ) has improved radiation tolerance with respect to gamma rays and proton irradiations (4). The DOFZ devices showed to be as radiation tolerant as Fz against the neutron radiation damage.

Silicon wafers grown with Czochralski method have intrinsic higher oxygen content compared to Fz, and devices processed with this material are candidate to be radiation hard.

Oxygen concentration ([O]) on Cz material results homogeneous through the bulk and with high level. SIMS analysis (5) showed that standard achieved values are $[\mathrm{O}]=5-9\cdot 10^{17} cm^{-3}$. This concentration is much higher than the one obtained in DOFZ wafers. Moreover these values are near to the limit of oxygen solubility in silicon and this implies that the processing of devices with this material should be carefully tuned to control the Thermal Donor (TD) centers creation.

Nowadays Cz growth technique is used to build almost all existing mono-crystalline silicon wafers and ingot are produced up to 400 mm diameter. Moreover technique has been developed and improved in many aspects: incorporation of magnetic field in the crucible, technique named MCz (6) (7), thermal modeling and simulation has contributed to make available ingots and wafers detector grade for tracking particle detectors, with 1-3 KΩ cm resistivity.

Further developments of the MCz material quality are expected in the near future because of a growing interest on high resistivity material in the field of RF-IC industry and HEP research, with a probable cost reduction.

The availability of p-type MCz wafers is also appealing to increase charge collection efficiency due to the higher electron mobility and to the expected non-appearance of bulk type-inversion at heavy fluences of irradiation.

An exhaustive characterization of devices processed with MCz, of both n- and p-type doping, has been done with tests used to study global electrical properties of diodes and micro-strip. Defects and transient analysis techniques have been used to measure charge collection efficiency, electrical field profile and trap levels concentration.

This paper summarizes more relevant results achieved by recent studies with test structures and micro-strip detectors processed on n- and p-type MCz doped material, and the radiation hardness performance after heavy irradiation tests.

Most of the results presented in this paper are achieved by the CERN RD50 and the SMART INFN Italian collaborations.

2. Process and Material engineering

Wafers made of MCz material with n- and p-type bulk doping have been processed with different layouts containing pad diodes, micro-strips devices and various test structures. Institutions currently processing particle detectors on MCz wafers are: IRST (Trento, Italy), IMB-CNM (Barcelona, Spain), CiS (Germany), Helsinki Institute of Physics (Helsinki, Finland) and BNL (USA).

Process is presently done on 4 inch wafers with <100> lattice orientation, 300 μm thick, produced by Okmetic (Vantaa, Finland). Chart flow and process steps have been optimized according to the bulk doping type, to realize micro-strips devices designed for charged particle detector. Strips are AC coupled and biased through polysilicon resistors. To ensure isolation of n^+ strip implants on p-type bulk uniform p-spray surface doping has been adopted. Simulation of processed devices has been done and results provided a successful comparison with laboratory measurement (8).

Detail of process and basic performances of produced devices can be found on references (9)(10)(11)(12).

The leakage current density measured on n-type silicon diodes has values compatible with the ones currently measured for standard Fz devices. Moreover the onset of devices breakdown have good performances, allowing bias voltage applied far beyond the full depletion voltage and for some devices with stable operation up to 1000 V (13).

The spread of depletion voltage on wafer has a circular symmetry and a radial variation, at the level of 30 % similar to standard Fz material (12).

Defects analysis of processed n-type wafers has shown similar bulk properties of MCz compared with Fz ones. Spectra of defects show peaks identified with shallow levels compatible with the net doping concentration.

Most of the electrical properties of p-type devices are comparable with the ones measured on n-type devices.

Conversely p-type wafers have shown performances affected by the material properties and the process steps. Bulk resistivity measured on diodes has shown a variation with the position on the wafer. Some wafers showed also regions where type inversion of the bulk has been detected (14).

Detailed study of bulk defect levels revealed that bulk resistivity is affected by intrinsic [O] fluctuation in the material and process thermal budget.

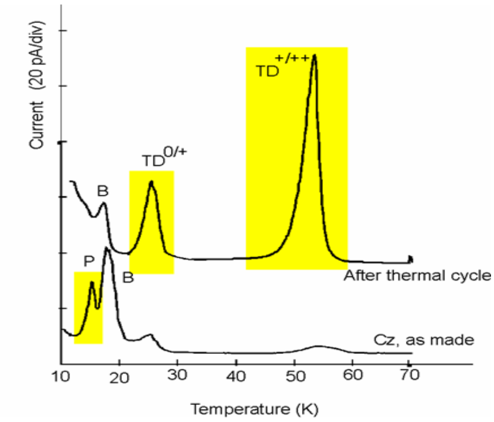

Fig. 1. Signal from TSC for a diode just after processing and after annealing treatment. Dashed region identifies peaks of Thermal Donor levels. From reference (15)

In figure 1 the TSC spectrum is reported for a device just after processing and after annealing at 420 ^{o}C for 120 minutes. Peaks corresponding to the creation of TD have been identified and further investigation showed the crucial role of thermal treatment used in the fabrication process. The TD created after annealing modify the wafer resistivity almost linearly with the annealing time at a fixed temperature.

Critical temperature range for sizable TD introduction rate has been identified between 420 ^{o}C and 650 ^{o}C, and safe processing rules for p-type material have been defined to avoid resistivity fluctuation after device fabrication (15).

3. MCz device performance

Measurements before irradiation have been executed on micro-strip detectors processed on n-type material. Experimental results showed good performances as particle detectors: measurement of Signal to Noise ratio (S/N) with minimum ionizing particle (m.i.p.) has shown values comparable to the ones of similar devices processed on Fz material.

Dedicated beam test experiments with large area ($\simeq 32cm^2$) detectors equipped with LHC-like analogue readout electronics (SCTA chips) produced S/N=23.5 $\pm$ 2.5 (16).

On p-type material strips isolation technique affects breakdown performances of micro-strip devices before irradiation. Doping of the junction side with uniform p-spray implant modifies the electric field near the strips implant border. Good performance in terms of breakdown and strip isolation has been observed exclusively for devices processed with low p-spray dose implant (i.e. $3 \cdot 10^{12} cm^{-2}$) (13). Moreover new process with improvements as the use of p-stop and moderate p-spray implants techniques are under study.

The radiation hardness of MCz material and devices has been studied comparing device performances before and after irradiation. Irradiation sources are high intensity beams of: low energy proton (26 MeV, Karlsruhe), high momentum protons (24 GeV/c, CERN SPS), low energy pions (190 MeV, PSI-Villigen) and fast nuclear reactor neutrons (TRIGA, Ljubljana). Gamma rays irradiation with ^{60}Co source has been performed too. The combination of sources used for irradiation allows to study all the components of the radiation damage and reproduces the effect of the full spectrum of radiation sources expected in the real experiment. In order to compare damage effects the expected fluences are calculated in terms of 1 MeV neutron equivalent, n_{eq}.

The current related damage has been evaluated for all radiation sources on n- and p-type materials. Measurements performed on diodes showed good agreement with NIEL hypothesis up to very high fluence $3 \cdot 10^{15} n_{eq}\, cm^{-2}$. The leakage current density increase rate values for MCz material are

compatible with Fz and literature data (10).
Results of radiation damage on effective doping concentration is reported in figures 2, 3 for devices irradiated with 26 MeV and 24 GeV/c protons.

Compared to the results obtained with the FZ and the DOFZ (4) a less pronounced change in the depletion voltage of the MCz devices is observed. On both irradiations the depletion voltage goes through a minimum, centered at $\sim 2 \cdot 10^{14} n_{eq}\, cm^{-2}$ with a small spread due to the different initial resistivity. At the minimum the depletion voltage is significantly different from zero and the effective doping concentration is not zero, pointing out that no space charge inversion sign (SCSI) occurred (17)(18). This feature is appealing for the application of this material to radiation tolerant detectors since after heavy irradiation the high field region should stay in the structured side.

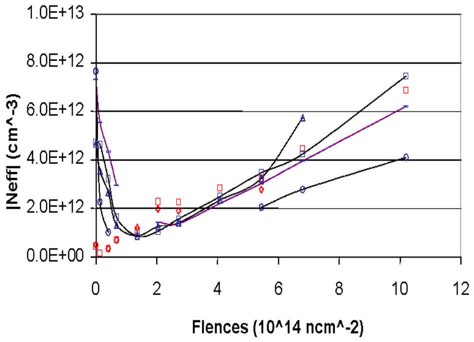

Fig. 2. Effective doping concentration for n-type MCz (full marks) and Fz (empty marks) diodes after 26 MeV protons irradiation. From reference (17)

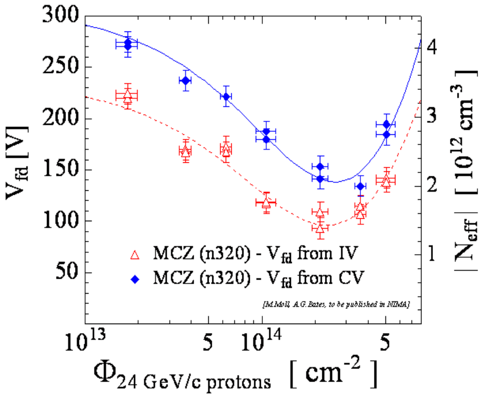

Fig. 3. Full depletion voltage and effective doping concentration for n-type MCz diodes after 24 GeV/c protons irradiation. Values are extracted from CV and IV measurements, from reference (18).

Simulation studies confirmed that this experimental results can be fairly described by the model of the double junction appearance after heavy irradiation (19). However a conclusion on type inversion is not possible from these measurements but is clarified by the TCT measurements.

The detailed study of the electric field profile inside the bulk has been performed on n-type MCz irradiated diodes using the TCT analysis (20). All the experimental results are compatible with a non uniform electric field E inside the heavily irradiated bulk. Analysis show that E can be modeled as follow: two high field regions localized to the border near the junction and the ohmic side providing the double junction, and a third one localized between the other two.

The TCT analysis of devices irradiated with 24 GeV/c protons established that up to the fluence $1.3 \cdot 10^{15} n_{eq}\, cm^{-2}$ the dominant junction is still on the p^+ side as shown in figure 4. From recent studies on devices irradiated with 26 MeV protons it can be observed instead that the dominant electric field is localized on n^+ side for fluences higher than $4.2 \cdot 10^{14} n_{eq}\, cm^{-2}$. This result is compatible with the observed one on devices irradiated with fast neutron at $5 \cdot 10^{14} n_{eq}\, cm^{-2}$ (20).

Devices processed on MCz material showed good performance on the depletion voltage measurements after annealing experiments (17). Diodes of both n- and p-type bulk material irradiated with 26 MeV protons have a better reverse annealing behavior, more effective for the n-type material, as shown in figure 5. A clear saturation of the reverse annealing beyond 200 minutes at 80 ^{o}C is observed. Conversely data of FZ materials show the expected depletion voltage increase.

The reduced reverse annealing growth of MCz material is a relevant property for a radiation hard candidate material and would simplify radiation damage recovery in experimental operational conditions.

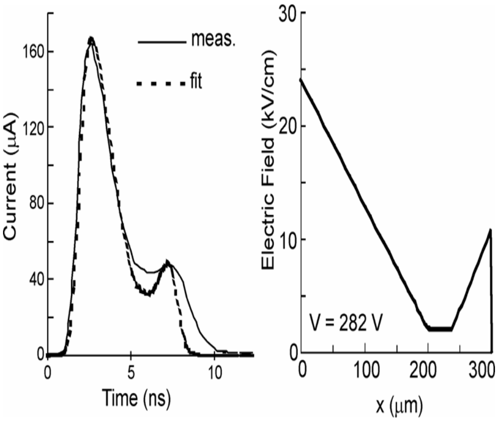

Fig. 4. TCT signal (left) and extracted electric field profile (right) for MCz diode after 24 GeV protons irradiation at $\simeq 1.3 \cdot 10^{15} n_{eq}\, cm^{-2}$. From reference (20).

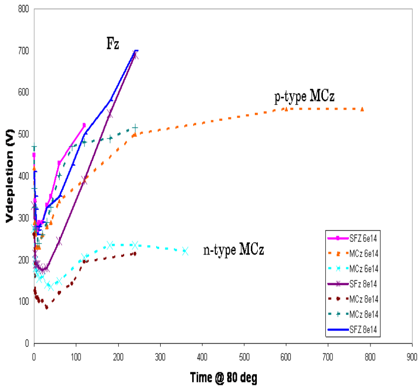

Fig. 5. Full depletion voltage for diodes irradiated wit 26 MeV protons vs. annealing time at 80 ^{o}C. From reference (17).

A detailed study of the role of shallow levels affecting the macroscopic properties of the detectors is necessary for a complete understanding of the radiation damage effects. The TSC measurements performed up to a very low temperature ($\sim$ 4.2 K) allowed to detect the shallow levels related to traditional dopant as phosphorous and boron, as well as TD defects. In Figure 6 TSC measurement results are reported in the range 10-80 K for one MCz p-on-n diode after irradiation at $4 \cdot 10^{14} n_{eq}\, cm^{-2}$ with 24 GeV protons(11).

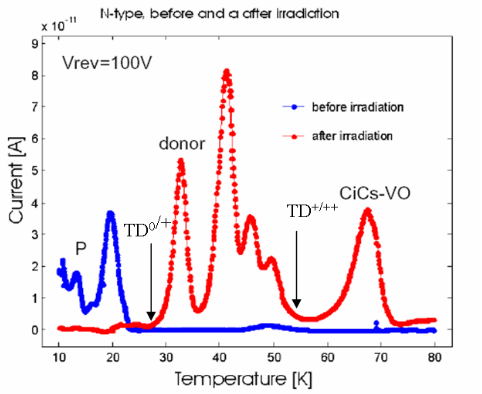

Fig. 6. TSC signal for MCz n-type diode before irradiation and after 24 GeV protons irradiation at $4 \cdot 10^{14} n_{eq}\, cm^{-2}$. From reference (11).

The arrows indicate the position where the peaks related to phosphorous and to the emissions of thermal donors TD$^{0/+}$ and TD$^{+/++}$ should be revealed. The absence of the phosphorous peak after irradiation is probably due to the radiation-induced formation of the vacancy-phosphorous complex, characterized by a deeper level at 0.42 eV. The absence of the TSC peaks related to TD indicates that irradiation does not activate these kind of defects. Peaks have been studied and identified as donor or acceptor like(11): the peak at 30 K is a shallow donor, and the group of peaks in the range 40-70K is commonly observed only after irradiation also in FZ and DOFZ. The peak at 65K is due to the superposition of C_iC_s and VO. Similar spectrum has been achieved for p-type MCz material. The same donor levels are created after irradiation and detected by TSC measurements also on standard FZ material, but the introduction rates are smaller by at least a factor 5.

The introduction rate for the donor peak has been measured on MCz material as a function of the fluence: this value is comparable with the acceptor introduction rate created by the radiation damage. In these conditions a partial compensation can occur between deep acceptors and shallow donor improving the radiation hardness of the MCz material (15).

Diodes and micro-strip detectors have been used to study the MCz material performance as particle detector after heavy irradiation. The basic measurement consists in the detection of the charge collected from a signal produced by m.i.p.

At very high fluences the Efficiency on the Charge

Collection (CCE) is affected by the partial depletion of the detector and the trapping induced by the radiation damage.

P-type material should perform better than n-type since carrier drift velocity is bigger for electrons and charge collection will be faster with a reduced effective trapping. Moreover p-type material does not type invert and electric field stays on structured junction side.

CCE measurement has been performed on diodes processed on p-type MCz material and irradiated with 26 MeV protons at fluence up to $6.8 \cdot 10^{14} n_{eq}\, cm^{-2}$ (21)

The diodes underwent through different annealing time up to 250 minutes at 80^{o}C and results are reported on figure 7. All diodes reach a saturation on the collected charge at a bias voltage compatible with the depletion voltage measured by CV technique. The charge loss at the highest measured fluences has been evaluated at the level of 25 % at depletion voltage. CCE at 90 % can be achieved increasing the bias voltage up to 700 V.

In micro-strip detectors further charge loss can be given by trapping induction on nearby strips, non efficient cluster reconstruction and readout electronics performance after heavy irradiation.

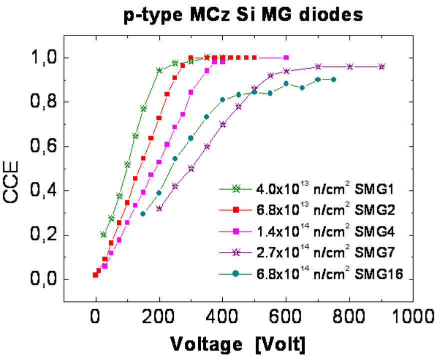

Fig. 7. CCE measured on p-type MCz diodes irradiated with 26 Mev protons. From reference (21).

To compare performance for future tracking detectors measurement are executed on micro-strip detectors equipped with a readout electronics with speed and shaping time comparable with the present LHC-like electronics.

Results achieved on micro-strip n-type detector read with 200 ns amplifier shaping time are reported in figure 8 after irradiation with 26 MeV protons at $3.3 \cdot 10^{14} n_{eq}\, cm^{-2}$. Performance of this device is good, since 90% of the total charge is collected at the depletion voltage evaluated by the CV characteristic (21).

CCE study on MCz p-type micro-strip detectors is an experimental activity going on various research groups.

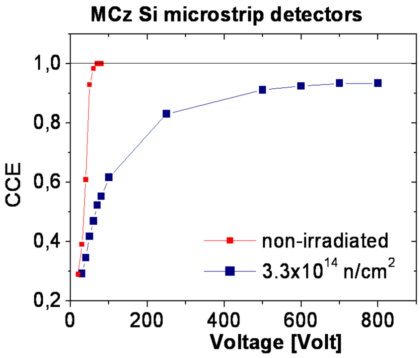

Fig. 8. CCE measured on n-type MCz micro-strip device irradiated with 26 MeV protons at $3.3 \cdot 10^{14} n_{eq}\, cm^{-2}$. From reference (21).

Available data on diodes and micro-strip detectors processed on MCz and DOFZ p-type material (22) have been used to tune a detailed simulation of CCE for MCz p-type devices (23).

After heavy irradiation at a fluence of $3.0 \cdot 10^{15} n_{eq}\, cm^{-2}$ and with a bias voltage of 800V simulation predicts that the CCE is 39%. This reduction is partially produced by the not complete depletion of the detector, 72%, while trapping decreases the charge collection by an additional 54%.

Most important parameter that defines the detector tracking performance is S/N. The simulation study has been done using a model of the LHC readout electronics, taking into account all relevant noise sources as the inter strip capacitance and the leakage current. Fig. 9 shows the S/N as a function of fluence for micro-strip device with 3 cm long strips biased with three bias voltages and at an operating temperature of 20 ^{o}C.

The choice of the optimal bias voltage is relevant only in the fluence range of $10^{15} n_{eq}\, cm^{-2}$: much below that fluence, the depletion voltage of a 300 μm thick detectors is below 400V, and much above that fluence, the trapping effects limit the depth of the effective active region. Since the charge is collected on the junction side, the active thickness can be regulated with the bias voltage while the non active detectors thickness will improve the heat conduction.

After irradiation at $3 \cdot 10^{15} n_{eq}\, cm^{-2}$ simulation predicts S/N equal to 10 a value still acceptable for optimal charged particle tracking performance.

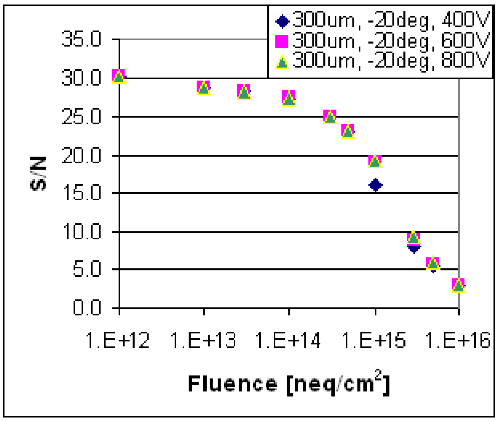

Fig. 9. Simulation results for S/N as a function of the fluence for MCz p-type micro-strip detectors. Strip length is 3 cm and detector thickness 300 μm. From reference (23)

4. Conclusion

The research activity for radiation tolerant silicon devices has produced relevant improvements in these years. Silicon material grown with MCz technique has been studied in detail. Bare material is nowadays available in large diameter ingots, and with resistivity suitable for a particle detector layout processing.

Successful production of pad devices and micro-strip detectors, processed on n- and p-type bulk has been achieved. Fabrication process rules tuned to prevent TD formation or doping change have been developed.

Performances after radiation damage have been extensively studied up to heavy irradiation fluences. MCz devices shows reverse current as standard FZ silicon, but have smaller variation on effective doping with a delayed type inversion point on n-type material. Moreover an improved long term reverse annealing has been observed for both doping type material.

Encouraging results for charged particles tracking application have been achieved before irradiation with micro-strip detectors equipped with LHC readout electronics.

First MCZ p-type silicon diodes have been tested for CCE, with promising results: 90% of the full charge is collected at $6.8 \cdot 10^{14} n_{eq}\, cm^{-2}$, and no reverse annealing effect has been detected up to that fluence.

Simulation of S/N shows good tracking performances up to $3 \cdot 10^{15} n_{eq}\, cm^{-2}$.

At present understanding MCz silicon detectors could be a cost-effective radiation hard solution for tracking systems at SLHC.

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