Silicon sensors implemented on p-type substrates for high radiation resistance application

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Abstract

Silicon based micropattern detectors are essential elements of modern high energy physics experiments. Processes based on p-type substrates are being studied for applications where extremely high radiation fluences are expected. Recent results and prototype efforts are reviewed.

Key words: Silicon micro-strip;, Silicon pixel, Radiation hardness, Charge collection efficiency
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1. Introduction

The CERN Large Hadron Collider (LHC) is poised to start operation soon and ramp up to a luminosity of 10^{34} cm^{-2}s^{-1}. To be able to cope with the high levels of radiation expected in the inner tracking devices a new technology has been developed. The so called "n-in-n" silicon micropattern detectors have replaced the conventional "p-in-n" used for decades in Si microstrip devices in subsystems exposed to the highest radiation doses. Atlas (1) and CMS (2) use this technology for their pixel inner trackers, and LHCb (3) uses this technology for their silicon strip vertex detector (VELO). In these sensors, the charge signal collecting electrodes are n^+ implants on an n-type substrate, while the p^+ implant extends throughout the back plane of the device. One of the reasons underlying this choice is the discovery of "type-inversion" (4). This results from radiation damage introducing electrically active defects in the band gap that change several sensor properties, in particular they alter the effective doping concentration N_{eff}. Its evolution as a function of the fluence is described by the equation

$$N_{eff} = N_{eff}(0)e^{-c\Phi} - \beta\Phi, \tag{1}$$

where $N_{eff}(0)$ is the initial doping concentration, c and β are empirical parameters accounting for the donor removal and the acceptor-like defect addition rates, as a function of the fluence Φ. Thus, naively, there is a value of the fluence Φ when the N_{eff} sign flips, corresponding to an effective transformation into a "p-type" equivalent substrate. Studies have shown that the more complex "double-junction" model (5; 6; 7), where the main junction is at the n^+-bulk interface, is necessary to describe the sensor properties after type-inversion. After type-inversion (8), conventional "p-in-n" devices need to be biased at full depletion in order to achieve the desired collection efficiency, while "n-in-n" devices achieve adequate performance in partially depleted mode.

An upgrade of LHC (SLHC) is being considered with a target luminosity of the order of 10^{35} cm^2s^{-1}, a factor of 10 higher than the LHC design luminosity. The corresponding increased radiation levels inspired a vigorous R&D to pursue both higher radiation hardness, to cope with the maximum levels of radiation expected at inner radii, and cost effectiveness, to enable the production of larger subsystems with increased radiation resistance.

One of the drawbacks of the "n-in-n" technology is the high field at the backplane junction in the early stages of operation of the detectors, prior to radiation damage. Because of this, "n-in-n" detectors are produced with a double-sided technology: implants in the back side include complex guard ring structures that provide a controlled voltage drop from the biasing implant to the edge of the device. Moreover, the high field region near the junction produces the quickest charge collection and thus it is desirable to have it always close to the signal collection electrode. High resistivity, detector grade p-type substrates provide a very promising solution to these limitations, as they can be implemented with single side processing and always have the junction near the collection electrode.

2. p-type technology

One of the main technological challenges in the fabrication of "n-in-p" devices is good inter-electrode isolation. This is because the positive charge in the SiO_2 oxide induces an electron accumulation layer at the oxide-Si interface that would electrically connect all the sensing elements if no isolation mechanism were introduced. This is an old problem, addressed for the first time when double-sided Si microstrip devices were introduced (9), but it is still challenging the ingenuity of device designers and foundries. The charge density in the accumulation layer increases with the radiation dose, up to a level known as the "oxide saturation charge." Interstrip isolation must guarantee a high inter-electrode resistance throughout the sensor lifetime, without adversely affecting the electrical performance of the device. Three approaches commonly used are known as p-stop, p-spray, and moderated p-spray. The p-stop method is based on p-type implants surrounding the n^+ collection electrode. "n-in-p" sensors with p-stop interstrip isolation have been shown to feature higher radiation resistance than sensors of equal geometry implemented with "n-in-n" technology (10). However p-stop implants require an additional mask, and they suffer from pre-breakdown micro-discharges that deteriorate the noise performance of the sensors implemented with this interstrip insulation. A commonly used alternative is the "p-spray" technique, where a uniform p-type blanket is implanted throughout the active surface of the device. The n^+ implants have sufficient dose to overcompensate this p-type layer in the regions where charge collection electrodes are planned. Thus the additional mask is no longer needed. In this case it is necessary to ensure that early breakdowns do not occur, and that an acceptable inter-electrode insulation is maintained throughout the detector lifetime. Thus a careful tuning of the p^+ implant dose is necessary. A hybrid solution that aims at bridging the advantages of the two methods, the so-called "moderated p-spray," is sometimes used. This solution requires an additional mask, but may ease the conflicting constraints of avoiding early breakdowns and maintaining high interstrip resistance at all radiation levels. The vast majority of the efforts has been concentrated on blanket p-spray, but different p-stop topologies, including field plate modifications (11), and moderated p-spray have been implemented. Note that due to the lower hole mobility, the depletion voltage is three times higher for p-type substrates than n-type substrates of a given resistivity.

The high energy physics community has decades of experience with detector grade n-type substrates, while the p-type option is relatively new. However, several groups are studying this technology. Both the CERN RD50 collaboration (12) and the INFN funded SMART collaboration (13) have devoted considerable resources towards a comprehensive study of the properties of a variety of sensors implemented with this technology. Sensors have been produced at research laboratories such as CNM-IMB (14), or ITC-IRST (15), as well as at industrial foundries such as Micron (16), and Hamamatsu (17). Thus a thorough understanding of the properties of these devices at different level of radiation is emerging.

3. Fabrication Details

Both diffusion oxygenated float zone (DOFZ), and magnetic Czochralski (MCz) Si wafers have been used, with a wide resistivity range and wafer thicknesses typically between 200 μm and 300 μm (11), (12), (13), (18). The availability of detector grade MCz silicon wafers is a relatively new opportunity, and recent studies (19) are very promising, MCz detectors seem to be more radiation tolerant than DOFZ detectors both with n and p type substrate. Comprehensive studies to make more systematic comparisons are under way (13).

Earlier wafers contained a large number of test structures, such as multi-guard ring diodes, MOS capacitors, and gated diodes, and a smaller number of strip or pixel detectors. Now the effort is progressing towards implementation of larger scale devices. For example, the RD50 collaboration has a set of devices being manufactured at Micron on 6 inch wafers that include strip and pixel detectors suitable for LHCb, ATLAS, and CMS upgrades. In addition, full size VELO sensors on high resistivity p-type substrates have been produced, that have been assembled into fully instrumented modules by the University of Liverpool group.

4. Performance before and after irradiation

There is a vast array of studies on the performance before and after irradiation of the detectors implemented on p-type substrates. Some examples illustrating the achievements and challenges in this process will be discussed.

Blanket p-spray isolation with lower implant dose (20) has been shown to fail to provide adequate interstrip resistance at a dose of about 50 MRad, which is the total dose expected in the middle region of the future upgrade of the Atlas detector at SLHC. A KEK group (21) reported similar findings for lower dose p-spray and p-stop implants. This group is investigating alternative isolation techniques to achieve the optimum interstrip resistance, including the use of field plates over the blocking implant.

Other operational aspects that need to be studied as a function of the radiation dose are the current versus voltage characteristic and the charge collection efficiency. It has been argued effectively (8) that the latter parameter is a much better predictor of the longevity of any given detector technology than the full depletion voltage V_{fd} extracted from a capacitance versus voltage measurement. While V_{fd} may be not practically achievable because it would induce thermal runaway in radiation damaged sensors, adequate charge collection efficiency at lower voltages may still be achieved. Figure 1 shows an example of the charge collection efficiency obtained in a 1x1 cm^2 280 μm thick microstrip detector produced by CNM-IMB using masks designed at the University of Liverpool. The charge collection measurement has been performed using a ^{106}Ru source, which has an energy deposition comparable to a minimum ionizing particles. Thus the study provides an absolute charge collection efficiency. As the noise has been shown not to depend upon the irradiation level, the signal to noise ratio scales with the charge signal, and, although it is deteriorating as a function of the radiation dose, is still acceptable at a fluence of 7×10^{15} p/cm^2, close to the expected fluence to be faced by the innermost tracking layers of ATLAS and CMS after 5 years of operation at SLHC (22).

Other radiation studies have been reported (23; 24; 25). One of the most recent is based on the measurements by a group at IFIC, Valencia, (26) of 4 microstrip detectors manufactured by CNM-IMB and irradiated with neutrons at the TRIGA Mark II reactor in Ljubljana to different fluences ranging from 10^{14} to 10^{16} n/cm^2. Figure 2 shows the current versus voltage characteristic of irradiated sensors maintained at a temperature of -30° C; a non-irradiated sensor is included for reference. Earlier micro-discharges appear at lower irradiation doses. This group investigated the charge collection properties by measuring the charged signal induced by a pulsed infrared laser (1060 nm). At the higher fluences the charge collection efficiency

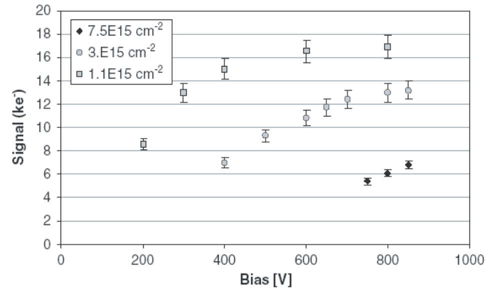

Fig. 1. Charge collection efficiency versus applied voltage, normalized to pre-irradiation value, of "n-in-p" strip detectors (vertical scale is in Ke). The radiation fluences (in p/cm^2) are shown on the left box. The detector irradiated at 3×10^{15} p/cm^2 is a standard p-type substrate, while the others are oxygen enriched. The measurements (8) have been performed at a temperature of -20/25°C.

does not reach the plateau corresponding to full depletion, and microdischarges are observed.

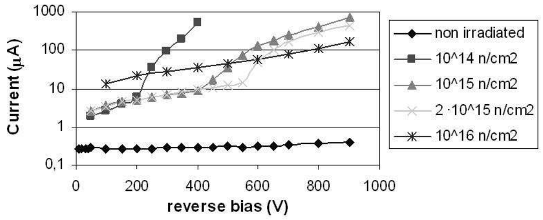

Fig. 2. Current-Voltage characteristics of "n-in-p" microstrip detectors irradiated with neutrons. The measurements (26) have been performed at a temperature of -30°C.

Figure 3 shows some interesting results reported in Ref. (24): the measured charge collection efficiency in miniature p-type strip detectors is found to be remarkably stable for very long annealing times. These data seem to contradict the expectations from the reverse annealing mechanism extensively studied in "n-in-n" detectors (27), where the effective doping concentration is shown to increase on a much shorter time scale. However, the earlier studies are largely based on full depletion voltage measurements, and they can be reconciled with these results with more complex modeling of the spatial distribution of the electric field in radiation damaged detectors.

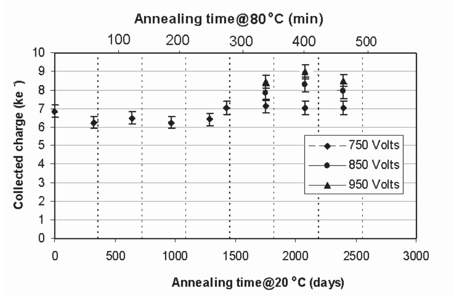

Fig. 3. Changes of the collected minimum ionizing particle signal as a function of time after irradiation for a miniature micro-strip detector irradiated up to 7.5 x 10^{15}p cm^{-2} and biased at different voltages. The detector thickness is 280 μm. The top scale corresponds to annealing time at 80°C and the bottom scale corresponds to the equivalent annealing time at 20°C (24). The measurements were performed at -20°C.

First examples of real scale p-type devices have been made. For example, 6x6 cm^2 silicon strip devices designed with ATLAS strip detector geometry implemented with n$^+$ strips implanted on different substrates have been constructed and tested (8). The LHCb-VELO group has produced full scale sensors on 300 μm thickness high resistivity p-type substrates: the depletion voltage is of the order of 100 V, while breakdown is observed at a voltage exceeding 200 V. A fully instrumented VELO module was tested in the laboratory both at the university of Liverpool and CERN, and was used in a recent beam test of 10 VELO modules.

Another large scale production of large microstrip and pixel modules on 6" wafers is under way at Micron, with masks developed by the RD50 collaboration. The VELO beam test data and laboratory and test beam characterization of the RD50 devices, before and after irradiation, will improve our understanding of the operational and system properties of detectors built with this technology.

5. Conclusions

The examples shown in this paper give some snapshots of the vibrant R&D effort to optimize processes based on p-type substrates to implement micropattern detectors. The ongoing research is making significant strides towards the development of a cost effective technology suitable for the highest radiation doses expected at SLHC.

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