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. Cost effectiveness and high radiation resistance are two important requirements for technologies to be used in inner tracking devices. Processes based on p-type substrates have very strong appeal for these applications. Recent results and prototype efforts under way are reviewed.

Key words:

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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-on-n" silicon micropattern detectors have replaced the conventional "p-on-n" used for decades in Si microstrip devices. In this approach, the charge signal collecting electrodes are implemented with 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" (1). Radiation damage introduces electrically active defects in the band gap that change several sensor properties , in particular they alter the effective doping concentration N_{eff}. The study of the N_{eff} evolution lead to the discovery of the phenomenon of "charge inversion", naively defined as a change in the N_{eff} sign (transformation into a "p-type" equivalent substrate). This effective doping concentration is described with the equation

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

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where $N(0)$ 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 radiation dose Φ. This is an effective parametrization; studies have shown that a “double-junction” model (2; 3; 4), where the main junction is at the n^+-bulk interface, provides a better description of the device properties after high radiation doses. After type inversion, “n-on-n” device achieve much better charge collection efficiency that conventional devices. Thus Atlas (5), CMS (6), and LHCb(7) use this technology for their tracking subsystems exposed to the largest radiation doses. An upgrade of LHC (sLHC) is planned to achieve a luminosity of the order of 10^{35} $\mathrm{cm}^2\mathrm{s}^{-1}$, a factor of 10 higher than the LHC design luminosity. A corresponding increase in the expected radiation doses is a natural consequence. Thus new technologies are being studied to be used in the hottest detector regions.

One of the drawbacks of the “n-on-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-on-n” detectors are produced with a double-sided technology: implants in the back side include complex guard ring structures that have the goal of providing a controlled drop of the voltage from the biasing implant to the edge of the device. Moreover, the high field region produces a quickest charge collection and thus it is desirable to have it always close to the signal collection electrode. Although many devices have been produced with the “n-on-n” technology, options that could overcome these limitations have been sought. High resistivity, detector grade p-type substrates provide a very promising solution to satisfy the radiation resistance requirements in a very cost effective manner.

2 p-type technology

One of the main technological challenges in the fabrication of “n-in-p” devices is the achievement of a 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 (8), 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 (9). 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. On the other hand, 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 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 the radiation levels. 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(10) and the INFN funded SMARTS collaboration (11) 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 (12), or ITC-IRST (13), as well as at industrial foundries such as Micron (14), and Hamamatsu (15). 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. Different isolation techniques have been used. The vast majority of the efforts has been concentrated on blanket p-spray, but different p-stop topologies, including field plate modifications (16), and moderated p-spray have been implemented.

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 (17) 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 Super-LHC. A KEK group (18) 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 (19) 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 be 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, that 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, may still be acceptable at the highest levels of radiation considered.

Other radiation studies have been reported (20; 21; 22). One of the most recent is based on the measurements by a group at IFIC, Valencia, (23) 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

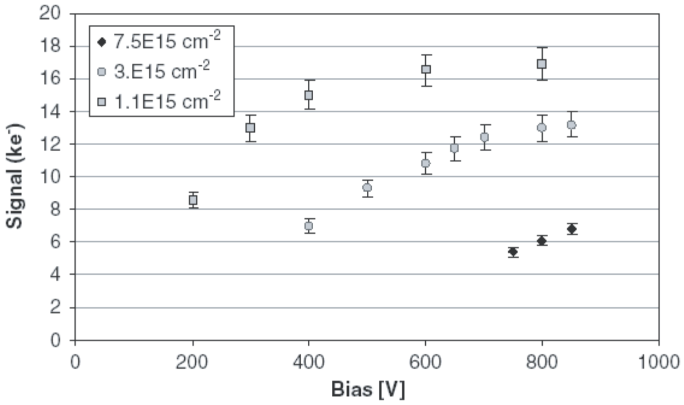

Fig. 1. Charge collection efficiency versus applied voltage, normalized to pre-irradiation value, of "n-in-p" strip detectors. The detector irradiated at 3×10^{15} pcm^{-2} is a standard p-type substrate, while the others are oxygen enriched. The measurements (19) have been performed at a temperature of -20/25°C.

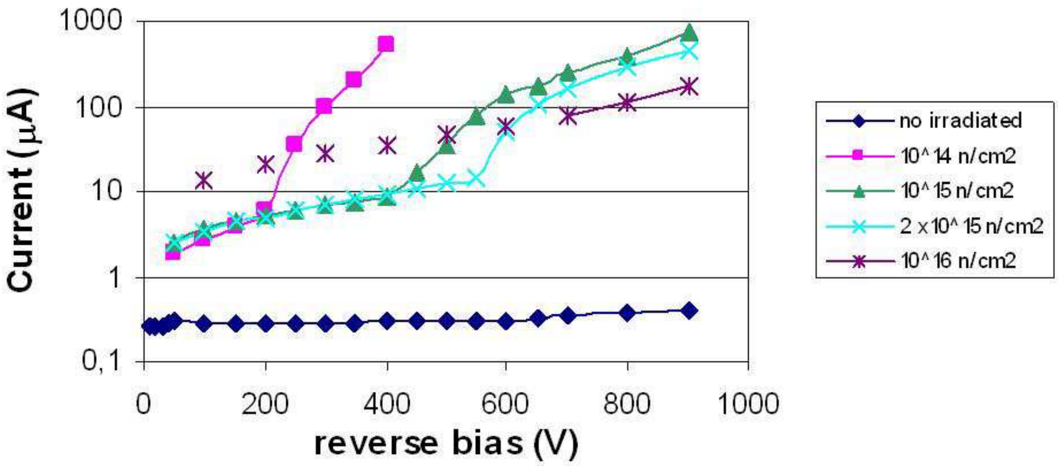

Fig. 2. Current-Voltage characteristics of "n-in-p" microstrip detectors irradiated with neutrons. The measurements(23) have been performed at a temperature of -30°C.

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

First examples of the feasibility of these detectors in real scale devices have been accomplished. 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 (19). 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 test beam run including 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 further 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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