Nuclear Instruments and Methods in Physics Research A 636 (2011) S111–S117

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Testing of surface properties pre-rad and post-rad of n-in-p silicon sensors for very high radiation environment

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ARTICLE INFO

Available online 4 June 2010

Keywords:
p-Bulk silicon
Surface damage
Charge collection
Punch-through voltage

ABSTRACT

We are developing n^+-in-p, p-bulk and n-readout, microstrip sensors as a non-inverting radiation hard silicon detector for the ATLAS Tracker Upgrade at the super LHC experiment. The surface radiation damages of the sensors fabricated by Hamamatsu Photonics are characterized on the interstrip capacitance, interstrip resistance and punch-through protection evolution. The detector should provide acceptable strip isolation, exceeding the input impedance of the signal readout chip $\sim$1 kΩ, after the integrated luminosity of 6 ab^{-1}, which is twice the luminosity goal.

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1. Introduction

The silicon microstrip detector continues to play an essential role in high-energy experiments for its ability of precision tracking. The detector at the planned Super LHC (large hadron collider) is required to remain operational up to the integrated luminosity of 3000 fb^{-1} with the instantaneous luminosity of 1×10^{35} cm^{-2} s^{-1}. In order to cope with ten-fold increase in instantaneous luminosity beyond the design value of the LHC, currently under commissioning, the ATLAS collaboration is investigating an inner tracking system based fully on semiconductor devices. The segmentation is varied in radius R, the innermost being the pixel, followed by short (2.4 cm) and long (9.7 cm) microstrip detectors. The radiation activity [1] with a

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0168-9002/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.nima.2010.04.094

safety factor of two multiplied is $(7-11)\times10^{14}$ 1 MeV $n_{eq.}/cm^2$ for the short strip (R=38 cm) and $3-6\times10^{14}$ 1 MeV n_{eq}/cm^2 for the long strip (R=85 cm) regions, where the two numbers in the parentheses are the fluence values at the central and forward regions. The charged particle contribution to the fluence is similar to the neutral at $R\sim28$ cm in the central region but decreases with R and in the forward region to typically 20% of the total. It is therefore important to investigate the damages due to both charged particles and neutrons. Both neutrons and protons displace silicon atoms via non-ionizing energy losses, which results in a bulk damage. Protons in addition ionize the atoms in their path that leads to permanent damage at the sensor surface.

The ATLAS R&D group "Development of non-inverting silicon strip detectors for the ATLAS ID upgrade" is formed to develop radiation hard tracking detectors based on the p-bulk microstrip [2] technology. Since the radiation induced impurity in silicon acts as an acceptor, the n^+-on-p device is non-inverting. This allows us to operate the sensors at partial depletion when obliged. The experience of adopting p-bulk silicon for particle tracker is limited. This is in part because additional strip isolation structure is required for individual strip signal readout to prevent mobile electrons to be accumulated between strips. The R&D group is evaluating the sensors fabricated by Hamamatsu Photonics using commercially available p-type wafers. We report the surface damage including the decrease in strip isolation and punch-through voltage evolution. The bulk damage is reported in Ref. [3].

One of the most pressing issue for n-in-p strip sensors are the interstrip characteristics before and after ionizing radiation, since the electron accumulation layer on the surface needs to be compensated for large fluences and dose levels.

Previous studies with p-type sensors, e.g. within the context of RD50, were done using p-spray to isolate the n-strips [4]. This study uses "mini-SSDs" ($\sim$1 cm long) produced by Hamamatsu Photonic (HPK) within the ATLAS upgrade program. The isolation is done with p-stops of varying geometry, p-spray and both combined with p-doses (concentration) varying from 0 up to 2×10^{13} p/cm^2.

2. Samples and irradiation

The sample sensors were fabricated using 15 cm wafers with $\langle 1\,0\,0\rangle$ crystal orientation and 320 μm thickness. The wafers we report in this paper are FZ grown (FZp wafers in Ref. [5]) having fewer defects than normal FZ wafers. The R&D group continues to evaluate other commercially available p-type wafers [5]. The strip pitch is 74.5 μm. Details of the design including strip isolation structures are described in Ref. [2]. The performance of main sensors, 97.5 mm^2, is reported elsewhere [6]. The characteristics of irradiated sensors are studied using miniature samples of 10 mm square, where there are 104 strips of 8 mm length.

The proton irradiation was performed at Cyclotron Radio Isotope Center (CYRIC) of Tohoku University. Details of irradiation facility and methods are described in Refs. [5,7]. 70-MeV protons were uniformly irradiated by scanning periodically the sample sensors. The irradiation took typically a few 10 min to a few hours depending on the fluence. The sensors were kept cooled at -10° C during irradiation and the irradiated samples were immediately stored in refrigerator to suppress any post-irradiation annealing to take place. The samples measured in Japan were glued on printed circuit board and biased at -100 V during the irradiation. The samples measured elsewhere were irradiated as bare chips with no bias applied. The fluence we refer to is in 1 MeV neutron equivalent value taking into account the NIEL factor of 1.4. The fluence uncertainty is determined by the ^{27}Al(pn) reaction cross-section, which does not exceed 10%.

3. Strip isolation structures

It is thought that n-on-p detectors are more sensitive to surface effects than p-on-n detectors. One concern is the risk that the fixed oxide charges in the Si–SiO_2 interface would lead to a conductive layer of electrons at the surface [8]. Within the project ATLAS07 for the ATLAS upgrade different structures for mini-SSDs have been produced. The different structures use the concept of preventing those damages by surface treatments, positive doped implants (p-impurities) in form of p-stop or p-spray, or combinations of both.

The p-stops are implanted to the detectors with a mask while p-spray is sprayed on over the whole sensor. Several doses and combinations of p-stop and p-spray have been applied to different sensors. Different structures to apply the p-stops have also been used, which is indicated by different zone number and seen in Fig. 1.

Detectors with zone 1 have no structure, i.e. they have only p-spray since the p-stop mask was left out. Detectors with zone 2 have individual p-stops, i.e. each strip is surrounded by p-implants in opposite to the other structures which only have a line of common p-implants between the strips. Zone 3 shares the p-stops between the strips and zone 4 has additional punch-through protection structure, which will be discussed later in the paper. Detectors with zone 5 have narrow metal, meaning the aluminum layer over the strips do not reach outside the strip itself and finally zone 6 is similar to zone 3 but with a wider strip pitch.

4. Interstrip resistance and capacitance measurements

The interstrip resistance and capacitance are important parameters used to characterize the effects of surface radiation damage of silicon strip detectors. The interstrip resistance is important for strip isolation, so that a sufficiently high interstrip resistance can prevent signal sharing between neighbors which could lead to degradation of the position resolution. The interstrip capacitance is the main contributor of noise in between strips. A properly functioning detector should thus try to minimize the interstrip capacitance in order to have a higher signal-to-noise ratio, while maximizing the interstrip resistance to minimize crosstalk between strips.

Interstrip resistance measurements were performed in a probe station. As seen in Fig. 2, the DC pad of a test strip was connected to an Agilent 4156C Precision Semiconductor Parameter Analyzer and grounded while a voltage V_2 was applied to the DC pads of two of its closest neighbors, which were also connected to the analyzer. The detectors were biased using a Keithley 2410HV Source Meter and each measurement was performed at several bias voltages ranging from 5 to 300 V. The voltage V_2 applied to the neighbor strips was varied through the parameter analyzer from -1 to 1 V in 100 mW steps. Each measurement was performed at 22° C with nitrogen gas flowing over the detector for moisture control.

The idea is that the voltage V_2 on the neighbors will induce a current I_1 through the test strip. The interstrip resistance can then be determined by

$$R_{int}=2dV_2/dI_1 \tag{1}$$

where the factor of 2 comes from the fact that two neighboring strips are used. The resulting IV curve is shown in Fig. 3.

To measure the interstrip capacitance a slightly different set-up was used. Instead of using the DC pads, the test strip and its neighbors were connected to an Agilent E4980A Precision LCR meter via the AC pads. In addition, the next two neighbors (two strips away from the test) were grounded to act as a shield from