Nuclear Instruments and Methods in Physics Research A 730 (2013) 58–61

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Signal and charge collection efficiency of n-in-p strip detectors after mixed irradiation to HL-LHC fluences

Susanne Kuehn [a,*], Thomas Barber [a], Gianluigi Casse [b], Paul Dervan [b], Adrian Driewer [c,a], Dean Forshaw [b], Torkjell Huse [b], Karl Jakobs [a], Ulrich Parzefall [a]

[a] *Institute of Physics, University of Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg, Germany*
[b] *Department of Physics, University of Liverpool, The Oliver Lodge Laboratory, Oxford Street L69 7ZE, United Kingdom*
[c] *Fraunhofer Institute for Microelectronic Circuits and Systems, Finkenstr. 61, 47057 Duisburg, Germany*

ARTICLE INFO

Available online 30 April 2013

Keywords:
Silicon particle detectors
Radiation damage
Mixed irradiation
Charge collection efficiency

ABSTRACT

For the year 2020, an upgrade of the LHC with a factor ten increase in luminosity is planned. The resulting severe radiation doses for the ATLAS tracker demand extremely radiation tolerant detectors. In this study six planar n-in-p strip sensors produced by Hamamatsu Photonics were irradiated in consecutive irradiation steps with pions of 280 Mev/*c*, protons of 25 Mev/*c* and reactor neutrons resulting in a combined fluence of up to 3×10^{15} 1 MeV neutron equivalent particles per square centimeter (n_{eq}/cm^2). This particle composition and fluence corresponds to the qualification limit specified by the ATLAS experiment for the outer pixel layers (assuming an integrated luminosity of 3000 fb^{-1}). The 320 μm thick devices are investigated using electrons from a ^{90}Sr source. After each irradiation step both charge collection efficiency and noise measurements have been performed using the ALIBAVA readout system, which is based on analogue Beetle ASICs clocked at 40 MHz.

Measurements of the signal and signal-to-noise ratio of detectors will be given after the sensors were exposed to radiation that both in fluence and composition are corresponding to the expectations for the HL-LHC trackers. Conclusions will be drawn on their operation in the ATLAS inner detector upgrade.

1. Introduction

It is foreseen to significantly increase the luminosity of the Large Hadron Collider (LHC) at CERN by upgrading it towards the HL-LHC (High Luminosity-LHC) in order to harvest the maximum physics potential of the machine. An integrated luminosity of 3000 fb^{-1} is planned to be achieved after 10–12 years of operation [1]. The resulting severe radiation doses for the ATLAS tracker demand extremely radiation tolerant tracking detectors. The inner most pixel detector layers will be exposed to fluences up to 2×10^{16} 1 MeV neutron equivalent particles per square centimeter (n_{eq}/cm^2), while for the inner strip detector region fluences of 1×10^{15} n_{eq}/cm^2 are expected [2].

The high radiation dose damages the crystal lattice of the silicon and causes a higher full depletion voltage and leakage current and degrades the collected charge due to trapping, thus reducing the signal-to-noise ratio. Several concepts are studied to cope with these disadvantages. The advantage of detectors based on p-doped bulk material is in the fact that the induced signal is dominated by electrons drifting to the readout side. Due to higher drift velocity of electrons and favorable weighting field the trapping affects less the induced charge for n-in-p than for p-in-n detectors. In addition, radiation increases trapping probabilities of electrons less than of holes [3]. And the effect of charge multiplication due to impact ionisation can occur for electrons at lower electric field strength compared to holes [4] and it has been observed in strip detectors by several groups [5,6]. A drawback of these detectors is the more complex processing since an additional inter-strip isolation has to be integrated into the design.

To cope with these demands, Hamamatsu Photonics [7] has developed a prototype series of planar n-in-p strip sensors for the upgrade of the ATLAS inner tracker. In this study a set of six mini sensors was irradiated with three different particle compositions consisting of pions, protons and neutrons. Taking into account the NIEL scaling hypothesis [8], the particle compositions are close approximations to specific radii where the particular fluence is expected (see Fig. 1). Those predictions were the results of a FLUKA simulation for the proposed ATLAS upgrade ("strawman" layout v14-2009) [9].

Results are presented on the collected charge and noise, which are measured by using electrons from a ^{90}Sr source and connecting the sensors to fast analogue readout electronics.

* Corresponding author. Tel.: +49 7612035854
E-mail address: susanne.kuehn@cern.ch (S. Kuehn).

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.04.068

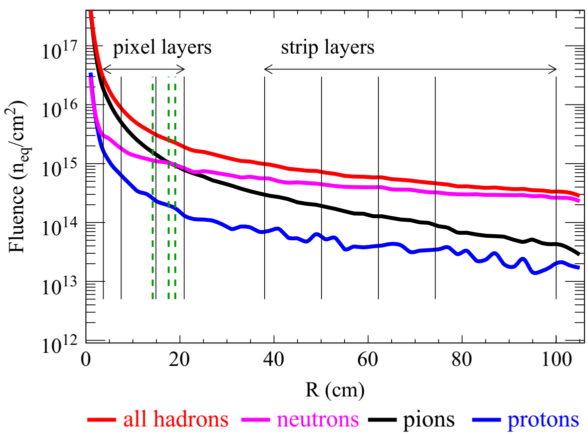

Fig. 1. Equivalent fluence for different hadron types in dependence of the distance from the interaction point for an integrated luminosity of 3000 fb^{-1}. The data is shown for z=0, a safety factor of two was applied, data from Ref. [2]. The dashed lines indicate the radii corresponding to the irradiated fluences.

The aim of this paper is to investigate the charge collection after the detectors were exposed to the mixed irradiation and to estimate the induced radiation damage.

2. Devices under test

The devices are n-in-p strip detectors from the ATLAS07-Series produced by Hamamatsu Photonics. They were produced using float zone wafers with a thickness of 320 μm. The resistivity of the substrate is approximately 6.7 kΩcm. The detectors have one p-stop structure to isolate the individual strips. Each sensor has an area of 1 cm × 1 cm, 104 strips with a length of 0.8 cm and a pitch of 74.5 μm [10]. The sensors were irradiated with different fluences and particles, namely at Paul Scherrer Institute (PSI) with 280 MeV/*c* pions, at the Karlsruhe Proton Cyclotron with 25 MeV/*c* protons and at the Jožef Stefan Institute with reactor neutrons. Detailed informations about the irradiation facilities can be found in Refs. [11–13]. The different fluences and the corresponding radii in the ATLAS inner tracker upgrade are listed in Table 1. They are a close approximation of correspondence fluence to different radii assuming an integrated luminosity of 3000 fb^{-1} and a safety factor of two.

Two sensors were irradiated for each fluence and the collected charge measurements were performed after each irradiation step. In addition, one unirradiated sensor was measured for reference. One device of the lowest fluence suffered a destructive breakdown after the proton irradiation and could not be used for further measurements. The detectors did not undergo a special annealing treatment. However, during irradiation at PSI for the highest pion dose a non-insignificant annealing time of three weeks at room temperature was required. Whereas the samples were cooled during the proton irradiation and the time of the neutron irradiation can be neglected. Besides this the sensors were kept cold (below 0 °C) and an accumulated time of approximately three days at room temperature for handling and preparation can be accounted.

3. Experimental setup

A ^{90}Sr beta source is used to perform the charge collection measurements. The readout is triggered by two scintillators behind the sensor. The electrons, contributing to the measurements, have a maximum energy of 2.3 MeV/*c* and produce charge deposits in the detector comparable to particles in the ATLAS experiment.

The data was recorded using the ALIBAVA readout system, which is based on analogue Beetle ASICs clocked at 40 MHz [14]. All strips of the sensor are connected to individual readout channels, which are calibrated using an unirradiated, well-known sensor. A gain uncertainty of approximately 6% was assumed. The measurements were performed in a freezer flushed with nitrogen, allowing the detector to be kept at a constant temperature of −20 ± 2 °C.

4. Results

Measurements were performed after each irradiation step at different bias voltages from 200 V to 1100 V. The aim is to estimate the radiation damage induced effects due to damage of crystal lattice by measuring the degradation of collected charge due to charge trapping, the increase of leakage current and the reduction of the signal-to-noise ratio.

4.1. *Charge collection*

The results of the charge collection measurements after the pion irradiation are shown in Fig. 2. The corresponding fluences are indicated by different colours. For comparison an unirradiated device is shown, too. It saturates at a voltage of approximately 200 V which indicates the full depletion voltage of the unirradiated sensor. Its leakage current is 0.02 μA at a bias voltage of 400 V and −20 °C. After irradiation no saturation but a slower increase in collected charge is visible for bias voltages above 900 V, hinting to the full depletion voltage. Whereas the full depletion voltage is expected at approximately 1000 V for a fluence of 1.4×10^{15} n_{eq}/cm^2.

Table 1
Table of different fluences applied for mixed irradiation. The first column denotes the distance from the interaction point where the corresponding particle composition is in close approximation expected in the ATLAS inner detector upgrade.

Radius (cm)	Fluence (10^{15} n_{eq}/cm^2)			
	Pions	Protons	Neutrons	Sum
19.0	0.93	0.19	0.95	2.1
17.6	1.2	0.26	1.0	2.5
14.2	1.4	0.26	1.1	2.8

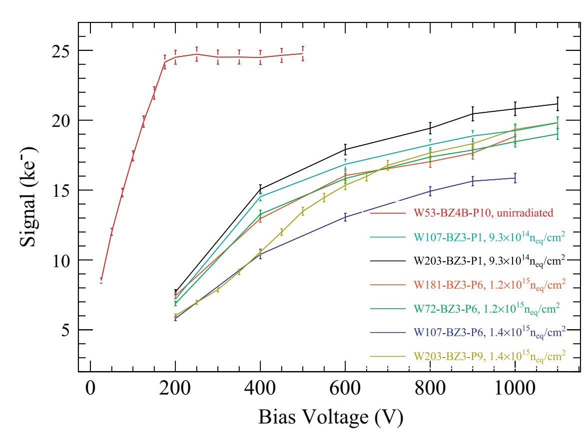

Fig. 2. Most probable charge after pion irradiation doses. The result for an unirradiated device is shown as a reference.