Nuclear Instruments and Methods in Physics Research A 612 (2010) 549–554

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

A TCT and annealing study on Magnetic Czochralski silicon detectors irradiated with neutrons and 24 GeV/c protons

Nicola Pacifico [a,*], Donato Creanza [a], Mauro de Palma [a], Norman Manna [a], Gregor Kramberger [b], Michael Moll [c]

[a] *Università degli Studi di Bari, Italy*
[b] *Jozef Stefan Institut, Ljubljana, Slovenia*
[c] *CERN, Geneva (CH), Switzerland*

ARTICLE INFO

Available online 8 August 2009

Keywords:
TCT
Annealing
MCz
Silicon detectors
RD50

ABSTRACT

Silicon diodes (pad detectors) were irradiated with 24 GeV/c protons at the CERN PS IRRAD1 facility and with neutrons at the TRIGA reactor in Ljubljana (Slovenia). The diodes were realized on Magnetic Czochralski (MCz) grown silicon, of both n- and p-type. After irradiation, an annealing study with CV measurements was performed on 24 GeV/c proton irradiated detectors, looking for hints of type inversion after irradiation and during annealing. Other pad detectors were studied using the TCT (transient current technique), to gather information about the field profile in the detector bulk and thus about the effective space charge distribution within it.

1. Introduction

Silicon detectors are currently used for the construction of the tracking systems of many High Energy Physics experiments, such as those at the Large Hadron Collider at CERN. The current generation of trackers is built using Float Zone (FZ) silicon. The FZ growing technique allows for a good crystalline purity, which results in homogeneous ingots with a very high resistivity ($10^4\,\Omega$/cm). The tracking system is nevertheless subject to high levels of radiation, up to 10^{15} fast hadrons per cm^2. The possible upgrade scenario for the LHC (super-LHC) [1] is aiming for an increase in luminosity by a factor 10, thus making the radiation damage issue a critical factor. At those levels of radiations, Float Zone silicon shows its limits, with a fast increase of the full depletion voltage and a loss in charge collection efficiency, due to the formation of deep levels in the bulk that act as trapping centers for the carriers, thus reducing the signal read at the electrodes. The leakage current also increases dramatically with irradiation, along with the power dissipation of the detector, which becomes a critical issue. The most recent studies are looking in the direction of other silicon growth techniques, such as the Magnetic Czochralski (MCz). It has been shown that high levels of oxygen (naturally present in MCz silicon) have beneficial effects in terms of radiation hardness of the detector [2].

The NIEL hypothesis [3] allows for rescaling the damage produced by different kinds of particles with different energies to a reference fluence, by means of a scaling factor k (hardness factor). The NIEL hypothesis describes correctly the proportional increase of the leakage current density with fluence for charged hadrons with different energies. The proportionality factor, called α, was found to be independent from the used silicon material with different resistivity, conduction type (n- and p-type) and oxygen content [4]. Other effects, however, like the change of the effective doping concentration and the decrease of the effective trapping times cannot be rescaled in the same fashion for all silicon materials and particle types [5,6].

It has been observed that in MCz as well as in FZ silicon detectors, irradiation with hadrons produces two different regions of space charge [7]. A region with positive space charge dominates close to the p^+ contact, while negative space charge dominates close to the n^+ contact. These two space charge regions affect the shape of the current pulse induced after generation of non-equilibrium carriers, which shows two peaks corresponding to the high fields associated with the two different space charge regions.

In the present work, p- and n-type MCz diodes irradiated with reactor neutrons and 24 GeV/c protons were studied to further investigate this *double junction* effect [8]. Where n_{eq} fluences are shown, the NIEL scaling hypothesis was used, using a scaling factor $k = 0.62$ [9].

2. Studied structures and irradiation

In this work PAD detector structures produced from MCz n- and p-type silicon were studied. The wafers were produced

* Corresponding author.
E-mail address: Nicola.Pacifico@cern.ch (N. Pacifico).

0168-9002/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2009.08.019

Table 1
Investigated structures.

Producer	Type of silicon	Active area (mm^2)	Irradiation	Experimental technique
SMART	n and p	13.7	Protons	TCT, CV/IV
HIP	n	25	Protons	CV/IV
HIP	p	25	Neutrons	TCT
Micron, CNM	n	25	Neutrons	TCT

by Okmetic Ltd. and processed by four different institutes: ITC/IRST—Trento (Italy—processing performed on behalf of the SMART collaboration), Helsinki Institute of Physics (HIP), Centro Nacional de Microelectronica (CNM, Barcelona) and Micron Semiconductors (UK). A list of the structures is shown in Table 1.

All of the diodes studied in this work were provided with an optical window on the non-ohmic contact, allowing e–h pair generation by light on this side of the detector. Some of the diodes (those processed by HIP and Micron) had a patterning on the metallization of the ohmic contact of the diode, allowing for illumination also from this side. All diodes had multiple guard rings. The innermost guard ring was connected to ground during all presented measurements.

The irradiation of the structures was performed at the CERN PS IRRAD1 facility for 24 GeV/c protons and at the Ljubljana TRIGA reactor for neutrons. The maximum irradiation fluence were, respectively, 2.4×10^{15} p/cm^2 and 8×10^{14} n/cm^2. The samples were irradiated at room temperature and stored, afterwards, at $-20\,^{\circ}$C to prevent uncontrolled annealing.

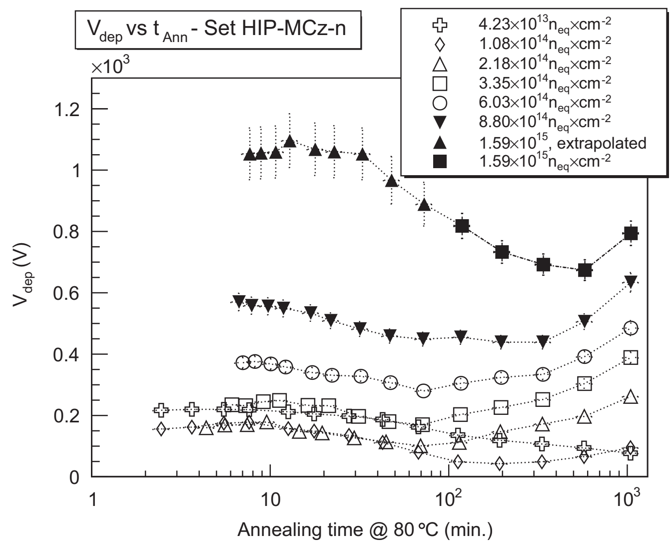

Fig. 1. V_{dep} vs. t_{ann} for the set of HIP MCz-n diodes with 24 GeV/c protons irradiation.

3. CV characterization

The CV method [3] was used to determine the depletion voltage of the diodes irradiated with 24 GeV/c protons. Studies performed on Standard Float Zone silicon [3] show that the annealing of irradiated silicon can be divided into two stages. At the beginning there is a partial removal of the negative space charge introduced by irradiation (beneficial annealing), followed by a subsequent introduction of negative space charge (long term or 'reverse' annealing). The beneficial annealing behavior of the depletion voltage allows to distinguish between n-type substrates and p-type ones. In a p-type device an introduction of negative space charge results in an increase in V_{dep} while in a n-type device the V_{dep} decreases. The annealing may be accelerated by keeping the silicon at elevated temperatures (usually 60 or 80 °C). The acceleration factor may be calculated through an Arrhenius relation [3]. In the present study annealing has been carried out by heating the samples in an oven, to a temperature of 80 °C. After annealing, the samples were always kept for at least 12 h at room temperature in a dark environment, to allow for the de-excitation of bistable levels [10].

The annealing study has been conducted on 24 GeV/c proton irradiated HIP (MCz-n) and SMART (both MCz-n and MCz-p) samples. The plot V_{dep} vs. annealing time is shown in Fig. 1 for the HIP MCz-n set and in Fig. 2 for the SMART MCz-n one. For depletion voltages above 1000 V, an extrapolation was operated for the depletion voltage, by imposing the geometrical capacitance of the detector (known). All the samples studied show an n-type annealing behavior, with V_{dep} rising slightly with beneficial annealing and then falling again with reverse annealing. All samples, with the exception of the least irradiated HIP diode, show an increase of V_{dep} after about 500 min at 80 °C indicating that the effective space charge is negative for these samples at this annealing stage.

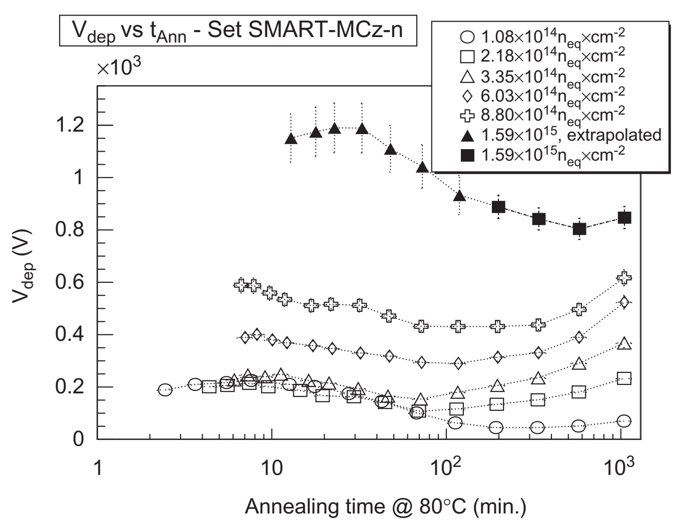

Fig. 2. V_{dep} vs. t_{ann} for the set of SMART MCz-n diodes set with 24 GeV/c protons irradiation.

The same plot is shown if Fig. 3 for SMART MCz-p samples. The annealing behavior for the three least irradiated diodes is p-type like, with V_{dep} falling during beneficial annealing and then rising back during reverse annealing. However, the most irradiated diode (1.6×10^{15} n_{eq}/cm^2) shows an n-like annealing behavior, with a curve that is comparable to those of MCz-n diodes irradiated at the same fluence. There are thus indications of dominant space charge sign inversion for MCz-p silicon from p- to n-type at this fluence.

Moreover, MCz-p devices are characterized by a sudden drop in the depletion voltage in the very first stage of annealing, which in