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Nuclear Instruments and Methods in Physics Research A 541 (2005) 202–207
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Particle detectors made of high-resistivity Czochralski silicon

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Available online 23 February 2005

Abstract

We have processed pin-diodes and strip detectors on n- and p-type high-resistivity silicon wafers grown by magnetic Czochralski method. The Czochralski silicon (Cz-Si) wafers manufactured by Okmetic Oyj have nominal resistivity of 900 Ω cm and 1.9 kΩ cm for n- and p-type, respectively. The oxygen concentration in these substrates is slightly less than typically in wafers used for integrated circuit fabrication. This is optimal for semiconductor fabrication as well as for radiation hardness. The radiation hardness of devices has been investigated with several irradiation campaigns including low- and high-energy protons, neutrons, γ-rays, lithium ions and electrons. Cz-Si was found to be more radiation hard than standard Float Zone silicon (Fz-Si) or oxygenated Fz-Si. When irradiated with protons, the full depletion voltage in Cz-Si has not exceeded its initial value of 300 V even after the fluence of $5 \times 10^{14}\,cm^{-2}$ 1-MeV eq. $n\,cm^{-2}$ that equals more than 30 years operation of strip detectors in LHC experiments.

PACS: 71.55.Cn

Keywords: Si particle detectors; Radiation hardness; Material engineering

1. Introduction

The silicon sensors used in particle tracking systems must be fully depleted at reasonably low-operating voltages. Therefore, the silicon sensors have traditionally been fabricated on wafers made by Float Zone crystal growth technique. Float Zone technique ensures high-purity and sufficiently defect-free silicon crystals that are the basic requirements for producing high-resistivity silicon substrates for detector applications. Characteristically, Fz-Si has a low oxygen concentration because of the contact-less, crucible-free crystal growth technique. Low oxygen concentration in Fz-Si can be a drawback since oxygen has

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doi:10.1016/j.nima.2005.01.057

experimentally been found to improve the radiation hardness of silicon detectors [1,2].

Radiation hardness plays an important role in the future high-energy physics experiments. For example, a possible upgrade of the CERN LHC (Large Hadron Collider) luminosity up to $10^{35}\,cm^{-2}\,s^{-1}$ has recently been proposed. This would raise the fluencies of fast hadrons up to $10^{16}\,cm^{-2}$ [3], well beyond the operational limits of present silicon detectors. Particle radiation causes irreversible crystallographic defects in the silicon material thus inducing deep-level centers that in turn result in increased detector leakage current. Additionally, the defects compensate the initial space charge of the n-type silicon created by the donor doping, which leads to elevated depletion voltages [2]. Radiation hardness of Fz-Si can be improved by applying long-term, high-temperature diffusion of oxygen. However, because of the contamination risk present in high-temperature processes, the oxygenation is difficult to implement in large scale. For example, in the future CMS (Compact Muon Solenoid) experiment at CERN LHC accelerator, the central particle trajectory tracking system, i.e. Tracker, will consist of approximately 26 000 silicon detectors with a total area of about $210\,m^2$ [4]. Furthermore, it seems to be difficult to introduce an oxygen concentration higher than 1 ppma concentration of oxygen into the silicon lattice by diffusion oxygenation process.

Recent developments in the crystal growth technology of Czochralski silicon (Cz-Si) have enabled the production of Cz-Si wafers with sufficiently high resistivity and with well-controlled, high concentration of oxygen. We have processed detectors on silicon wafers grown by magnetic Czochralski (MCz) method. The MCz method has several advantages, e.g. extending the controllable range of oxygen dissolving from the silica crucible during the crystal growth. A magnetic field can be applied in the crystal growth system in order to damp the oscillations in the melt. The applied field creates an electric current distribution and an induced magnetic field in the electrically conducting melt. This produces a Lorentz force that influences the flow and reduces the amplitude of the melt fluctuations [5].

2. Detector processing

The detectors were processed at the Microelectronics Center of Helsinki University of Technology. The starting material of the detectors was 4″ single-side-polished 300-μm-thick $\langle 1\,0\,0 \rangle$ Cz-Si wafers. The nominal resistivity of the wafers was $900\,\Omega\,cm$ and $1.9\,k\Omega\,cm$ for n- and p-type, respectively. Our detector fabrication process contains five mask levels consisting of two thermal oxidations, two ion implantations, and three sputter depositions. A detailed process description for large-area n-type strip detectors is presented in Ref. [6]. For reference purposes, Fz-Si detectors were processed on Wacker 4″ single-side-polished 300-μm-thick Fz-Si wafers with resistivity of $1.2–1.3\,k\Omega\,cm$.

The test diodes were fabricated with essentially same process parameters. However, the process steps required for the formation of bias resistors were not performed on the wafers containing test diodes. The active pad implanted area of the diodes is $5\,mm \times 5\,mm$. It is surrounded by one wide guard ring (100 μm) and 16 guard-rings (each 16-μm wide). The distance between the active area implant and the first guard ring is 10 μm. A 1-mm diameter round opening in the front metallization was left for TCT (Transient Current Technique) measurements [7].

The high-resistivity Cz-Si detectors can basically be processed into segmented or pad detectors in the same way as in the case of the traditionally used Fz-Si substrates. The essential difference between Cz-Si and Fz-Si materials is, however, the oxygen concentration. Oxygen concentration is one of the most important parameters of silicon wafers. For example, oxygen precipitates bind unwanted metallic impurities present during the processing of silicon devices [8,9]. Furthermore, stress induced during high temperature processing can lead to the formation of slip defects in the wafer. The presence of oxygen stabilizes the wafer and thus Cz-Si wafers are less prone to slip than Fz-Si wafers [10].

During the crystal growth, oxygen is dissolved into silicon from the quartz crucible. Major part of the oxygen is dissolved as silicon monoxide and is flushed away by argon gas. Furthermore, the