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Magnetic Czochralski silicon as detector material

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Abstract

The Czochralski silicon (Cz-Si) has intrinsically high oxygen concentration. Therefore Cz-Si is considered as a promising material for the tracking systems in future very high luminosity colliders. In this contribution a brief overview of the Czochralski crystal growth is given. The fabrication process issues of Cz-Si are discussed and the formation of thermal donors is especially emphasized. $N^+/p^-/p^+$ and $p^+/n^-/n^+$ detectors have been processed on magnetic Czochralski (MCz-Si) wafers. We show measurement data of AC-coupled strip detectors and single pad detectors as well as experimental results of intentional TD doping. Data of spatial homogeneity of electrical properties, full depletion voltage and leakage current, is shown and n and p-type devices are compared. Our results show that it is possible to manufacture high quality $n^+/p^-/p^+$ and $p^+/n^-/n^+$ particle detectors from high-resistivity Cz-Si.

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1. Introduction

Particle detectors made of high-resistivity silicon wafers are widely used in high-energy physics experiments. Segmented silicon detectors provide excellent spatial resolution while being cost-effective due to well-established manufacturing technology. Nevertheless, particle radiation causes irreversible crystallographic defects in silicon material deteriorating the detector performance. First, the donor doping concentration of silicon is compensated by dominantly acceptor type defects. This may cause space charge sign inversion (SCSI) in n-type silicon material, which is followed by increase of the detector full depletion voltage V_{fd}. Second, the leakage current of the detector (I_{leak}) increases linearly as a function of accumulated radiation fluence. Third, due to the trapping of charge carriers, overall charge collection efficiency (CCE) degrades [1]. The deterioration of the CCE due to the trapping of charge carriers will be the most severe obstacle for the use of silicon sensors in future very high luminosity colliders with extremely harsh radiation environment. Possible upgrade scenario of the LHC to a luminosity of $10^{35}\,cm^{-2}\,s^{-1}$, corresponding to expected total fluences of fast hadrons above $10^{16}\,cm^{-2}$ and reduced bunch-crossing interval of about 10 ns [2].

The detectors used in particle tracking systems must be fully depleted at reasonably low operating voltages. A practical limit of the operating voltage is 500 V. Detectors have traditionally been fabricated on n-type high resistivity wafers made by Float Zone (Fz-Si) crystal growth technique. The low oxygen concentration in Fz-Si is a drawback since oxygen has experimentally been found to improve the radiation hardness of silicon detectors, as demonstrated by the R&D work performed in the framework of CERN RD48 collaboration [3,4].

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. In addition to the high oxygen concentration, Cz-Si is available commercially in large quantities and many commercial detector foundries are familiar with its processing, since Cz-Si is a basic raw material of the microelectronics industry. These aspects are important when designing a future large scale tracker system.

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2. Crystal growth and material properties

In the Czochralski method, polycrystalline silicon fragments are melted inside a silica crucible. During the process, argon gas is continuously flushing the interior of the crucible and the surface of the silicon melt. Silicon single crystals are grown by slowly pulling a crystal seed up from the molten silicon, thus developing an ingot. Later, wafers are cut from the ingot.

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 [5,6]. 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 defect than Fz-Si wafers [7].

During the crystal growth the silica crucible gradually dissolves, releasing oxygen, carbon and other impurities, namely aluminum and boron, into the silicon melt. Most of the oxygen vaporizes from the melt as silicon monoxide (SiO) that is transported away by the protection gas, but the rest stays in the melt and can dissolve into the single crystal. The concentrations of interstitial oxygen and carbon impurities in the single crystal are typically $(1\text{–}10)\times10^{17}\,\text{cm}^{-3}$ and $(1\text{–}5)\times10^{16}\,\text{cm}^{-3}$, respectively. If the oxygen concentration in silicon exceeds $1\times10^{18}\,\text{cm}^{-3}$, oxygen starts to precipitate, i.e. form clusters.

The homogeneity of the material is strongly affected by the thermal gradients present in the melt crucible. The thermal gradients cause strong buoyancy-driven convection and surface-tension-driven flows at the free surfaces of the melt. These melt-convective flows are at least partially turbulent and they are largely responsible for the crystal imperfections and radially and microscopically nonuniform distributions of dopant and impurity atoms in the crystals [8]. In addition, the silicon melt is enriched by dopants and therefore the resistivity decreases as a function of the length of the ingot. For these reasons, the maximum resistivity of the standard Czochralski wafers is rather limited.

The magnetic Czochralski (MCz) method is in principle the same as the standard Czochralski crystal growth method, but the ingot is grown in a strong magnetic field, which is used to dampen the oscillations in the silicon melt. That is, the Lorentz force resulting from the applied magnetic field influences the flow and reduces the amplitude of the melt fluctuations [9,10]. In this method the concentration and the distribution of oxygen can be controlled better than in the standard CZ method, which is important for large-area detector applications. The method is today widely used in the semiconductor industry and therefore wafers grown with MCz method have become available also for the detector applications.

3. Processing of MCz-Si detectors

Pad detectors and segmented AC-coupled microstrip detectors have been processed on n and p-type MCz-Si substrates at the Microelectronics Center of Helsinki University of Technology [11,12]. The wafers are 100 mm diameter double-side-polished $300\pm2\,\mu$m-thick having $\langle 100\rangle$ crystal orientation. The nominal resistivity, measured by the four-point probe method, of the boron-doped wafers is $1800\,\Omega\,$cm, and $900\,\Omega\,$cm in phosphorous-doped wafers. The oxygen concentration of these wafers was measured by the Fourier Transformation Infrared (FTIR) spectroscopy. The measurements were done on a thick reference wafer at the Institute of Electronic Materials Technology (ITME), Warszawa, Poland. The following oxygen concentrations were measured: $4.95\times10^{17}\,\text{cm}^{-3}$ (center), $4.89\times10^{17}\,\text{cm}^{-3}$ (right), $4.93\times10^{17}\,\text{cm}^{-3}$ (left) and $4.93\times10^{17}\,\text{cm}^{-3}$ (bottom).

The process sequence is basically similar when processing MCz-Si and standard Fz-Si devices: ion implantation of the segmented side and the back plane of the wafers, implantation activation thermal treatment, processing of bias resistors and strip dielectric, contact metallization, aluminum sintering and passivation. The essential difference between MCz-Si and Fz-Si is, however, the oxygen concentration. Oxygen can form at temperatures between 400 and 600 °C complexes consisting of four or more oxygen atoms. These complexes are called thermal donors (TD) and they influence electrical properties of detectors. When processing $p^+/n/n^+$ pin-diode detectors on n-type phosphorous-doped Cz-Si substrates, the TD formation decreases the effective bulk resistivity and consequently increases V_{fd}. On the other hand, it is possible to tailor the V_{fd} of the $n^+/p^-/p^+$ device made of p-type MCz-Si wafer by deliberate introduction of TD. The ion implantations doses in our process were all $1\times10^{15}\,\text{cm}^{-2}$ while the implantation energies were 70 and 30 keV for phosphorous and boron, respectively. The thermal dry oxidations in our process were done at 1100 °C. After the oxidations, the temperature was ramped down at the rate 4 °C/min. The pullout of the wafers took place at 700 °C. Thus the wafers were cooled as fast as possible in order to avoid the temperature range 400–600 °C. All detectors were passivated by approximately 60 nm thick silicon nitride (Si_3N_4) film grown by Plasma Enhanced Chemical Vapor Deposition (PECVD) method. The deposition temperature of PECVD Si_3N_4 was 300 °C.

Figs. 1(a) and (b) show the results of the capacitance–voltage (CV) and leakage current measurement of two n-type MCz-Si strip detectors.

The bias resistors of detectors have been processed with sputtered tungsten nitride (WN_x). The reason to use WN_x instead of commonly adopted polysilicon resistor technology is twofold. First, WN_x process is very simple. The resistors do not need ion implantation and subsequent dopant activation in order to adjust resistance value. The resistance value is adjusted by controlling the film