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Characterization of proton irradiated 3D-DDTC pixel sensor prototypes fabricated at FBK

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ABSTRACT

In this paper we discuss results relevant to 3D Double-Side Double Type Column (3D-DDTC) pixel sensors fabricated at FBK (Trento, Italy) and oriented to the ATLAS upgrade. Some assemblies of these sensors featuring different columnar electrode configurations (2, 3, or 4 columns per pixel) and coupled to the ATLAS FEI3 read-out chip were irradiated up to large proton fluences and tested in laboratory with radioactive sources. In spite of the non-optimized columnar electrode overlap, sensors exhibit reasonably good charge collection properties up to an irradiation fluence of 2×10^{15} n_{eq} cm^{-2}, while requiring bias voltages in the order of 100 V. Sensor operation is further investigated by means of TCAD simulations which can effectively explain the basic mechanisms responsible for charge loss after irradiation.

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1. Introduction

The fast increase in luminosity in the modern High Energy Physics (HEP) experiments is pushing the research in the field of silicon radiation detectors to new challenging frontiers. Due to the high radiation doses foreseen for the inner tracking layers, radiation hard detectors must be designed and tested in order to provide reliable particle detection up to fluences in the order of 10^{16}1-MeV equivalent neutrons per square centimeter (n_{eq} cm^{-2}). At the same time these devices must be fast in terms of charge collection time and less power consuming than the older ones. For these reasons several R&D projects in the field of silicon radiation detectors have been launched in the past years, mostly focusing on the upgrades of the experiments at the Large Hadron Collider (LHC) at CERN, Geneva, Switzerland [1].

The main macroscopic consequences of radiation-induced defects in the detector bulk are: (i) changes in effective doping concentration, mainly with the introduction of acceptor-like defects that lead to an increase in the full depletion voltage, (ii) higher leakage currents due to the creation of generation/recombination centers, and (iii) decrease in the charge collection efficiency due to carrier trapping [2]. The overall consequence of this damage is a strong reduction in the signal-to-noise ratio that can severely reduce the tracking capabilities. To counteract these effects different strategies are possible [3]: (i) material engineering, i.e., using as a substrate either non-standard silicon (e.g., Magnetic Czochralski, epitaxial, etc.) or diamond, which are intrinsically more resistant to radiation damage; (ii) device engineering, which consists of designing detectors with geometrical configurations that allow for lower signal degradation after irradiation. One of the most promising approaches to achieve radiation hard silicon detectors is the so-called 3D-architecture proposed by Parker and collaborators in the mid 1990s [4]. In 3D detectors the electrodes have a columnar shape and are etched perpendicularly to the wafer surface, penetrating the entire sensor thickness. In this way the distance between electrodes is not bound to the thickness of the wafer (which is the case for standard planar silicon detectors) but can be optimized to suit performance requirements. Thanks to this characteristic the

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distance between the electrodes is decoupled from the active volumes thickness. As a consequence, low operating voltages (less than 10 V before irradiation, at most 200 V after irradiation), fast response times, and strong reduction of charge trapping effects after irradiation are obtained [5]. Another important feature deriving from 3D detector technology is the active edge, which consists of a trench electrode termination allowing for a good sensitivity up to a few microns away from the physical edge of the sensors. As a result a more efficient area coverage on wide surfaces and lower material budget are obtained [6]. While active edge is an intrinsic option for 3D detectors, it can also be implemented in planar sensors, although with a major process complication [7]. Besides all these advantages, 3D detectors have some disadvantages: in particular, the fabrication process is more complicated than a standard silicon detector process, the capacitance is higher and their response is not completely uniform because of the electrodes, that are not fully efficient, and of the presence of some low field regions. In order to develop 3D silicon detectors for the ATLAS upgrade the so-called ATLAS 3D sensor collaboration [8] was formed, involving many research centers and institutes from all over the world. Among the technological approaches considered for 3D fabrication, besides the original one developed at Stanford [9], there are also simplified architectural implementations. One of them, relevant to the detectors considered in this work, is the so-called 3D Double sided Double Type Column (3D-DDTC) concept, independently proposed by FBK, Trento, Italy [10] and by CNM, Barcelona, Spain [11] with the aim of reducing process complexity in view of medium volume productions. One of the main advantages of this approach is that it does not use a support wafer, thus avoiding the related steps of wafer bonding and final wafer removal. Moreover, in 3D-DDTC detectors the substrate bias can be applied from the back side, making these sensors compatible with standard planar sensors and easing the detector assembly within a tracking system. Columns are etched from both wafer sides (n^+ from the top, p^+ from the bottom) and do not pass through the entire wafer thickness, so they only partially overlap. From TCAD simulations [10], it was predicted that the performance of 3D-DDTC detectors is comparable to that of standard 3D detectors if the column overlap is a significant fraction of the wafer thickness, whereas it can be degraded if column thicknesses are not optimized, which is the case for the first prototypes fabricated at FBK and considered in this paper. Therefore, the radiation hardness should be carefully studied in order to obtain useful information for the design and technology optimization. The FBK devices were previously tested both in laboratory [12] and in beam tests at CERN in pre-irradiation conditions [13], obtaining very good results. In order to study their radiation hardness, different irradiation campaigns were conducted, and irradiated detectors were measured again in a test beam at CERN [14] and in laboratory.

In this paper we report on selected results from functional characterization with radioactive sources conducted in laboratory on these 3D-DDTC detectors. Numerical simulations are also used to gain better insight into experimental results. The paper is organized as follows: Section 2 gives a brief description of devices under test and summarizes the two proton irradiation campaigns; Section 3 describes and discusses post-irradiation measurement results also comparing them with pre-irradiation results; Section 4 reports numerical simulation results and compares them to the measurements. Conclusions follow.

2. Experimental

2.1. Sensor description

The sensors under test are 3D-DDTC detectors fabricated at FBK on 4″, 200 μm thick, p-type, FZ silicon wafers. As previously stated, in these devices columns are etched from opposite sides of the wafer and are not completely passing through the silicon bulk [9]. At the time of fabrication of these sensors (2008) the Deep Reactive Ion Etching (DRIE) equipment was not yet available at FBK so the etching of the holes was commissioned to an external company (IBS, France) and problems related to the calibration of this step led to an unseven column depth (see Fig. 1 (left)). This problem translated into a relatively small column overlap, in the order of 90 μm, which of course is not ideal and could affect the device performance, especially after irradiation. The nominal column diameter is 10 μm. The surface insulation between n^+ electrodes on the front side is achieved by combined p-spray and p-stop implants [15], whereas all ohmic columns are shorted on the back side by uniform p^+ diffusion and metal.

Devices under test are pixel detectors compatible with the FEI3 ATLAS read-out chip [16], and feature various layout options differing in the number of columns per pixel: 2E-type (two n^+ columns per pixel), 3E-type (three n^+ columns per pixel) and

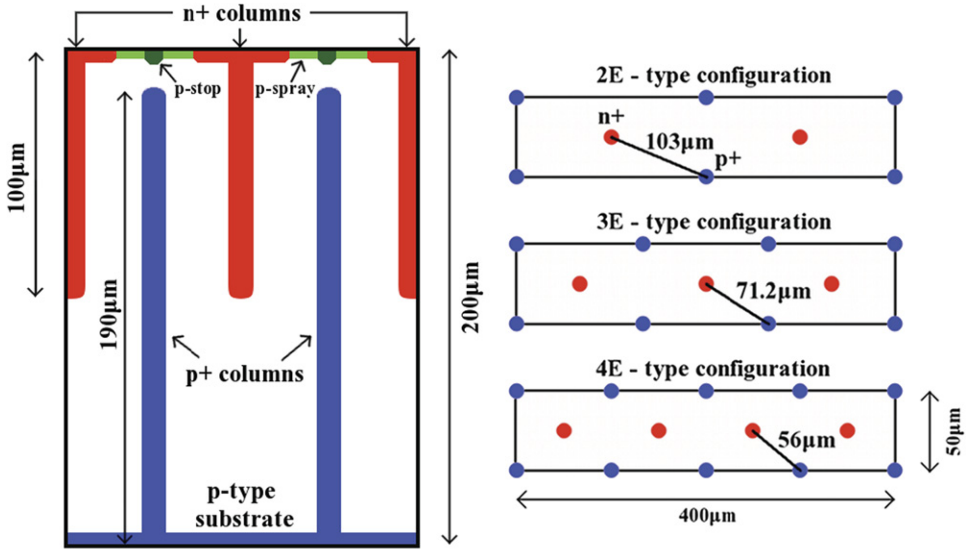

Fig. 1. (left) Schematic cross-section of the sensors and (right) different pixel configurations.

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