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Characterization of 3D and planar Si diodes with different neutron converter materials

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ABSTRACT

In this paper, we report on the characterization of silicon 3D and planar sensors, coupled with different neutron converter materials, such as ^{10}B, $^{10}B_4C$ and ^{6}LiF, with different deposition thickness. Selected results from the electrical and functional characterization of the devices are shown and comparatively discussed with the aid of SRIM and Geant4 simulations.

The limited neutron detection efficiency, on the order of $\simeq$ 1% (planar) and $\simeq$ 8% (3D) from simulations, is understood, and hints for the optimization of the devices have been derived.

1. Introduction

In the past few years, due to the shortage of ^{3}He, many interesting developments in solid-state thermal neutron detectors have been pursued (see e.g. [1] and references therein). The proposed devices typically consist of silicon P–N junctions with high aspect-ratio cavities, filled with neutron converter materials [2–7]. The shapes and dimensions of the cavities and of the gap regions (pillars) in between them are designed aiming at an overall trade-off between neutron absorption efficiency within the converter materials, absorption efficiency of the reaction products within the silicon active volume, and sensor charge collection efficiency. By doing so, the total neutron detection efficiency can be maximized: very good values have so far been reported, up to $\simeq 26\%$ [1] and $\simeq 50\%$ [5] for structures using ^{6}LiF and ^{10}B converter, respectively. Ultra thin 3D sensors with a planar converter coating are other very interesting devices proposed to minimize the γ-ray sensitivity [8–10].

Based on our experience on 3D sensors for High Energy Physics experiments [11], we have started the INFN HYDE (HYbrid DEtectors of neutrons) project. Our ultimate goal is to develop hybrid pixel detectors of thermal neutrons, compatible e.g. with read-out chips of the MEDIPIX family [12]. To this purpose, our approach to the design and the fabrication of 3D sensors is different from those already reported which are suited to diodes or strips but not to pixels. A pixellated hybrid neutron detector with good spatial and temporal resolution would be appealing for several applications in security, e.g. for detection of radioactive materials or explosives [13], medical imaging [14], forensics [15], and high energy and nuclear physics.

As a first step in this activity, we have developed a modified 3D-STC sensor structure [16] aimed at easing the deposition of different converter materials while ensuring full compatibility with a pixelated read-out chip for neutron imaging applications. As it was for the 3D-STC sensors, this first device is intended as a test vehicle allowing to develop some key process steps and to start investigating the main issues with neutron detection. From its electrical and functional characterization [17,18], deep insight into the performance and hints for the optimization have been gained.

However, given the device complexity, both in terms of topography and non-uniform charge collection behavior, the interpretation of experimental results from exposure to neutron beams was not straightforward, making it difficult to estimate the neutron detection efficiency and to compare the measured data with Geant4 simulations. To this purpose, additional experiments with planar sensors were carried out, that lend themselves to a more simple analysis and to a validation of the simulation approach for device optimization. Selected results from 3D and planar sensors are here presented and comparatively discussed.

2. Device description

The considered devices have two different structures and geometries. The schematic cross-section of planar sensors is shown in

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Fig. 1. These devices were fabricated on Float Zone, p-type substrate, 300 μm thick and with a resistivity higher than 6 k Ω cm. They have an active area of 1.71 × 1.71 mm^2, surrounded by a 100 μm wide guard ring.

The 3D sensors were fabricated on Float Zone, p-type substrates, 230 μm thick and with a very high resistivity in the range from 10 to 30 kΩcm. They consist of arrays of microstructured pixels with a pitch variable between 300 and 400 μm. A schematic cross-section is shown in Fig. 2. Each pixel features a cubic cavity with a size of 200 × 200 × 200 μm^3 etched using Deep Reactive Ion Etching (DRIE). N–P junctions are obtained with a diffusion of Phosphorus on all the sides of the cavities, whereas surface isolation between them is obtained by means of a p-spray layer. A special technology has been developed at FBK in order to have contacts to both electrode types on one side only: P-type electrodes are obtained by Boron implantation, whereas contacts to N-type cavities are obtained by means of narrow, 30 μm deep via holes filled with poly-Si. By doing so, the cavity side is completely available for the converter deposition, whereas the contact side can be used for coupling the pixels with a read-out chip. However, for these first prototypes, in order to ease the testing without need for bump-bonding, the arrays of cavities have been shorted by a metal grid to obtain diode-like devices with an active area of 25 mm^2. Additional details on the design and the technology are available in [17,18].

The neutron converters used for planar and 3D sensors are based on either ^{10}B or ^{6}Li and exploit the following neutron reactions:

$$^{10}\mathrm{B}+\mathrm{n}\begin{cases}\xrightarrow{94\%}\alpha(1.47\ \mathrm{MeV}+{}^{7}\mathrm{Li}(0.84\ \mathrm{MeV})+\gamma(0.48\ \mathrm{MeV})\\ \xrightarrow{6\%}\alpha(1.78\ \mathrm{MeV}+{}^{7}\mathrm{Li}(1.01\ \mathrm{MeV})\end{cases}$$

$$^{6}\mathrm{Li}+\mathrm{n}\longmapsto{}^{3}\mathrm{H}(2.72\ \mathrm{MeV}+\alpha(2.05\ \mathrm{MeV})$$

For planar detectors, the neutron converters were deposited by sputtering. The resulting layers are quite thin due to a non-optimized process and also because of the need to avoid mechanical stress on the surface of the detector. From measurements performed with a profilometer and also checked against SEM images (see e.g. Fig. 3), it was possible to estimate the layer thicknesses as follows:

- 486 ± 88 nm of ^{10}B and 492 ± 77 nm of $^{10}B_4C$ (both approximated in the simulations to 500 nm).
- 1.04 ± 0.15 μm of $^{10}B_4C$ (approximated in the simulations to 1 μm).

Optical inspections after sputtering treatments have shown a good adhesion of the converter materials to the silicon surface. In order to check the long term stability, the profilometer measurements have been performed both before and a few days after the experimental characterization confirming the good adhesion. From Figs. 4 to 6, it can be noticed that the area covered by the converter materials is smaller than the active area of the sensors. Since these sensors are not protected by a passivation layer, this choice was dictated by the risk of short circuits between the diode and the guard ring due to the high conductivity of the boron/boron carbide layers. Hence, a mask with a circular hole of 1 mm diameter was used to shield the sensor metal contacts from the boron deposition.

The same neutron converters used for planar sensors were deposited by sputtering also on 3D sensors, but limiting the study to the lower nominal thickness (≃ 500 nm of ^{10}B and ≃ 500 nm of $^{10}B_4C$). Since the deposition was performed on samples already attached to a PCB, in order to ease handling, the thicknesses and

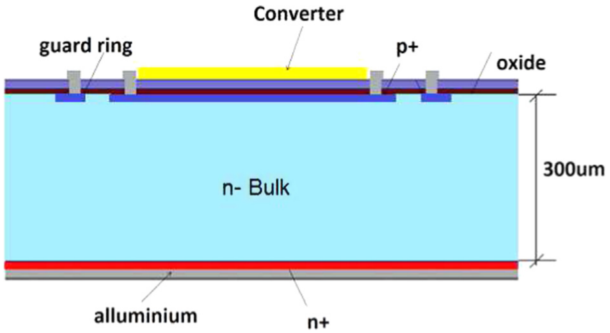

Fig. 1. Sketch of the planar sensor with sputtered converter on the top (not to scale).

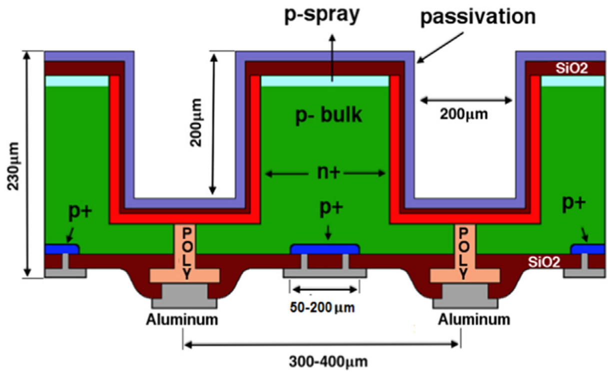

Fig. 2. Sketch of the 3D sensor (not to scale).

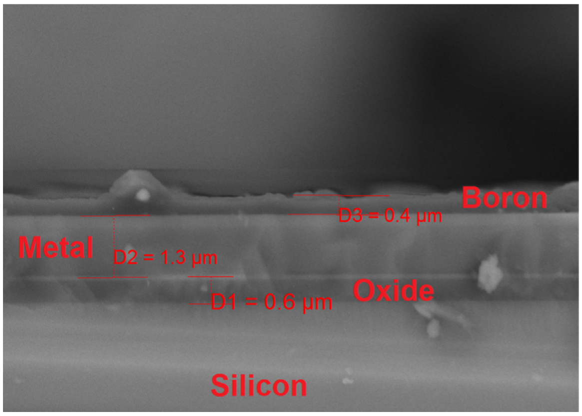

Fig. 3. A SEM micrograph of a planar sensor with ≃ 500 nm of ^{10}B sputtered on the surface.

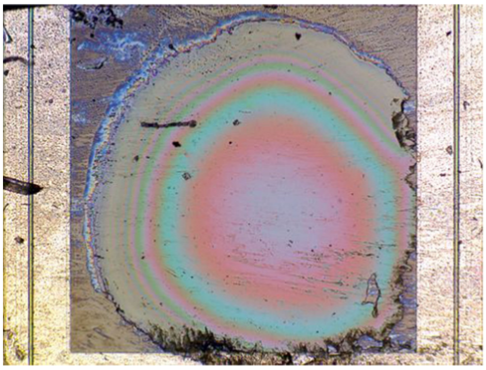

Fig. 4. An optical micrograph of ≃ 500 nm of ^{10}B sputtered on a planar sensor.