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Review of radiation damage studies on DNW CMOS MAPS

G. Traversi [a,b,*], L. Gaioni [b], A. Manazza [b,c], M. Manghisoni [a,b], L. Ratti [b,c], V. Re [a,b], S. Zucca [b,c], S. Bettarini [b,d], G. Rizzo [b,d], F. Morsani [b], L. Bosisio [b,e], I. Rashevskaya [b], V. Cindro [f]

[a] Università di Bergamo, I-24044 Dalmine, BG, Italy
[b] INFN, Istituto Nazionale di Fisica Nucleare, Italy
[c] Università di Pavia, I-27100 Pavia, Italy
[d] Università di Pisa, I-56127 Pisa, Italy
[e] Università di Trieste, I-34127 Trieste, Italy
[f] Jozef Stefan Institute, Slovenia

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ABSTRACT

Monolithic active pixel sensors fabricated in a bulk CMOS technology with no epitaxial layer and standard resistivity (10 Ω cm) substrate, featuring a deep N-well as the collecting electrode (DNW MAPS), have been exposed to $\gamma-$rays, up to a final dose of 10 Mrad (SiO_2), and to neutrons from a nuclear reactor, up to a total 1 MeV neutron equivalent fluence of about $3.7 \cdot 10^{13}$ cm^{-2}. The irradiation campaign was aimed at studying the effects of radiation on the most significant parameters of the front-end electronics and on the charge collection properties of the sensors. Device characterization has been carried out before and after irradiations. The DNW MAPS irradiated with ^{60}Co $\gamma-$rays were also subjected to high temperature annealing (100 °C for 168 h). Measurements have been performed through a number of different techniques, including electrical characterization of the front-end electronics and of DNW diodes, laser stimulation of the sensors and tests with ^{55}Fe and ^{90}Sr radioactive sources. This paper reviews the measurement results, their relation with the damage mechanisms underlying performance degradation and provides a new comparison between DNW devices and MAPS fabricated in a CMOS process with high resistivity (1 kΩ cm) epitaxial layer.

1. Introduction

CMOS Monolithic Active Pixel Sensors (MAPS) are being considered for the implementation of precise and intelligent particle trackers at future high luminosity machines such as linear colliders [1,2]. One of the main advantages of these sensors lies in the limited amount of material they add to the detector apparatus, therefore reducing multiple scattering phenomena in multilayer tracking detectors. This follows from the fact that the readout electronics is fabricated in the same substrate as the detector. They can also offer higher granularity than standard hybrid pixel detectors, thanks to their very simple readout schemes (3 transistors per pixel in the most elementary configuration). An innovative design solution for MAPS, leading to the so-called deep N-well MAPS (DNW MAPS), was proposed a few years ago in order to enable the design of MAPS with similar functionalities as hybrid pixels [3]. DNW MAPS take advantage of the properties of the triple well structure to lay out a sensor with relatively large charge collecting area read out by a classical processing chain for capacitive detectors. Depending on the experiment characteristics and on the position inside the detector, MAPS sensors may be required to withstand a total ionizing dose (TID) up to a few tens of Mrad(SiO_2) and an integrated fluence in the order of 10^{13} 1 MeV n_{eq}/cm^2. Ionizing and non-ionizing radiation effects may severely deteriorate the device performance. Both effects have been investigated with different irradiation tests and results have been published in the previous papers [4–6]. Recently, new monolithic sensors have been designed in a CMOS process, called INMAPS, featuring a quadruple well option, with a deep Pwell (DPW) layer adding to the three wells (N, P and deep N-well) available in standard CMOS processes [7,8]. The foundry provides different options for epitaxial layer resistivity (10 Ω cm, 1 kΩ cm) and thickness (5, 12 and 18 μm). 12 μm thick INMAPS sensors with high resistivity substrate were irradiated up to an integrated fluence of 10^{14} cm^{-2}. This paper provides a review of the effects of $\gamma-$rays and neutrons on the main parameters of DNW sensors. Moreover, a new comparison between DNW MAPS and INMAPS devices, showing the improved radiation hardness achieved by increasing the substrate resistivity, is also presented.

2. Effects of $\gamma-$rays on DNW MAPS performance

DNW MAPS have been fabricated in a 130 nm bulk CMOS technology without epitaxial layer. In DNW MAPS object of this

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* Corresponding author at: Università di Bergamo, I-24044 Dalmine, BG, Italy. Tel.: +39 0352052311; fax: +39 0352052077.
E-mail address: gianluca.traversi@unibg.it (G. Traversi).

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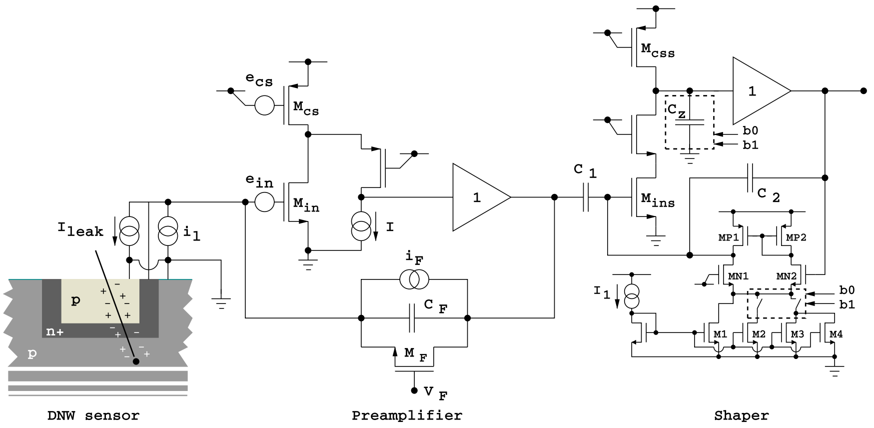

Fig. 1. Schematic diagram of the analog readout chain integrated in the deep N-well monolithic active pixel sensors. A conceptual cross-sectional view of the deep N-well sensor is also shown.

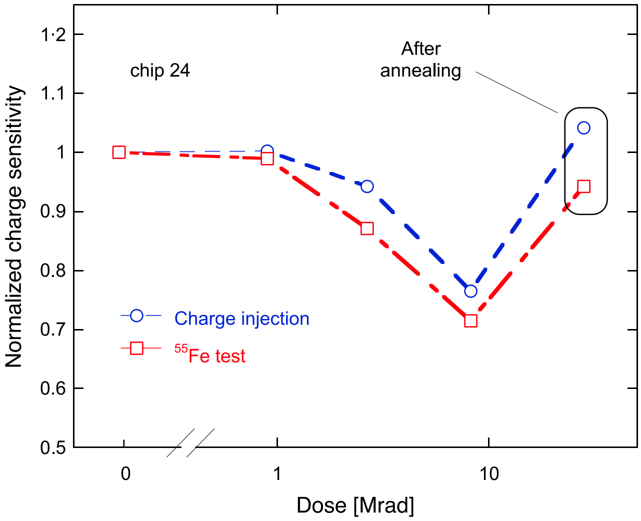

Fig. 2. Normalized (to the pre-irradiation value) charge sensitivity as a function of the absorbed dose and after the annealing step. Data are obtained through ^{55}Fe spectrum measurements and charge injection with an external pulser.

study, the sensor signal is processed by a charge sensitive amplifier and an RC-CR shaper with selectable peaking time (200 or 400 ns), as shown in Fig. 1. The DNW MAPS chip includes test structures where each pixel has a collecting electrode featuring a main body and satellite N-well diffusions (called M1), and test structures where each pixel features a T-shaped collecting electrode (called M2). More details can be found in [4,5]. Besides DNW MAPS, also single NMOS transistors and octagonal DNW diodes have been exposed to γ−rays from a ^{60}Co source up to a final dose of 9.7 Mrad (SiO$_2$). The dose rate of the ^{60}Co source was about 9.5 rad (SiO$_2$)/s. The final dose was reached through a number of intermediate irradiation steps. The devices under test were also subjected to a 100 °C annealing cycle for 168 h. All the DUTs were biased as they would be in actual applications during both the irradiation and the annealing cycle. Exposure of the DNW MAPS to ionizing radiation is responsible for a significant decrease in charge sensitivity, as shown in Fig. 2, where the normalized charge sensitivity is reported as a function of the integrated dose. The annealing cycle brings the charge sensitivity back to a state not far from its pre-irradiation conditions. Charge sensitivity was found to decrease as a results of the following mechanisms:

(1) *Threshold voltage shift in the feedback transistor of the charge preamplifier*: 130 nm N- and PMOS transistors featuring a channel width W smaller than about 1 μm were proven to undergo the so-called radiation induced narrow channel (RINC) effect, involving charge trapping in the shallow trench isolation (STI) oxides [9]. This phenomenon is likely to affect the preamplifier feedback transistor, M_F in Fig. 1 ($W = 0.18\ \mu m$, $L = 10\ \mu m$), and has been measured in single transistors, belonging to the same CMOS technology, and with the same aspect ratio, irradiated with γ−rays [4]. Therefore, change in the equivalent preamplifier feedback resistance due to threshold voltage shift in the feedback NMOSFET results in an increase of the output conductance and, in turn, in a decrease of the charge sensitivity.

(2) *Leakage current increase in the detector*: The buildup of holes in the field oxide and the creation of trapping states at the Si/SiO$_2$ interface over the PN junction may account for an increase in the surface generation current [10]. As a consequence, the leakage current is expected to be proportional to the length of the junction at the silicon surface. This was proven in DNW diodes, featuring the same structure as the MAPS collecting electrode, irradiated together with DNW MAPS [5]. The increase in the leakage current results again in an increase of the output conductance of the preamplifier feedback transistor and in a decrease of the charge sensitivity.

(3) *Change in the feedback transconductance and in the gain-bandwidth product of the shaper*: The RINC effect provides a contribution also in the shaping stage (see Fig. 1). Here, radiation induced change in the threshold voltage of the PMOS current source in the shaper input branch, M_{CCS} in Fig. 1 ($W = 0.18\ \mu m$), is responsible for a decrease in the gain-bandwidth product. A threshold voltage shift in the current source of the transconductor ($W = 0.25\ \mu m$) is also present, which, combined with the previous effect, brings about a reduction in the peak response of the analog channel.

Fig. 3 shows the equivalent noise charge (ENC) as a function of the total ionizing dose. The ENC was calculated as the ratio between the root mean square value of the noise voltage measured at the shaper output by means of a digital oscilloscope and the charge sensitivity. In the monolithic sensors under test, the main noise contribution comes from the fluctuations in the drain current of the preamplifier input device. At the available peaking times, other contributions from the preamplifier feedback network and from the detector leakage current can be safely dropped. The ENC degradation after exposure to radiation is likely to originate from low frequency noise increase in the preamplifier input device coming from parasitic lateral transistors turned on by positive charge buildup in the shallow trench isolation oxides and contributing to the overall noise [11]. Moreover, radiation induced