Computer Physics
Communications

Neutron radiation hardness of monolithic active pixel sensors for charged particle tracking

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Abstract

Monolithic Active Pixel Sensors (MAPS) for charged particle tracking consist of a novel detection technique, where the detecting element is inseparable from the readout electronics, both of them being integrated on the same substrate. As radiation hardness is mandatory for most applications, the resistance of a MAPS-detector design against irradiation is currently subject to intensive studies. Parameters such as charge-to-voltage conversion gain, pixel leakage current, noise and charge collection efficiency are being investigated as a function of integrated dose. First and second generation prototypes, MIMOSA1 and MIMOSA2, were irradiated with up to 10^{13} neutrons/cm² for this purpose. Preliminary results are presented. The charge-to-voltage conversion gain and noise were found to be almost stable and the leakage current was observed to raise moderately. On the other hand the pixel charge collected came out to be substantially affected by the highest fluencies considered.

Keywords : Monolithic active pixel sensors ; Radiation hardness; Solide state detectors; Pixel detectors; neutrons irradiation

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1. Introduction

The ability of the MAPS to provide charged particle tracking has been recently demonstrated on a series of MIMOSA (standing for Minimum Ionising MOS Active sensor) chip prototypes. The key element is the use of an n-well/p-epi diode to collect, through thermal diffusion, the charge generated by the impinging particles in the thin epitaxial layer, located underneath the readout electronics. This solution allows 100% fill factor, as required in tracking applications. First tests performed with 120 GeV/c π^- beams at CERN proved excellent detection performances. A single point resolution of 1.5µm and a detection efficiency close to 100%, resulting from a high signal-to-noise ratio of more than 30, were observed. This makes MAPS an attractive candidate for future applications in particle physics experiments.

The very high reaction rate and the beam induced radiation background expected in future experiments sets several requirements on the radiation hardness of basic detector components. This is particularly true for vertex detectors, because of their location close to the interaction point. Applications in space experiments require also hardened devices.

Radiation damage may be induced by direct ionisation due to the interaction of charged particles or energetic photons, followed – for instance – by positive charge built-up in the oxide close to the silicon interface. Interacting heavy particles (neutrons, protons and other hadrons) may also induce atom displacement in the silicon crystal lattice (bulk damage).

The expected integrated radiation dose in future high energy physics experiments may vary from some hundreds of kRads and several 10^{10}neutrons/cm² (TESLA linear collider) up to several tens of MRads and close to 10^{15} neutrons/cm² (LHC).

For modern submicron electronics, methods were found to stand such doses. In the case of a CMOS particle tracking device, an efficient charge collection from the epitaxial layer underneath the electronics has to be preserved in addition. Moreover a substantial increase of the leakage current of the charge collecting diode may have undesirable effects on the device operation (shorter saturation time, shot noise increase).

Since MAPS consist of a novel technology, very limited information exists on the sensitivity to high radiation doses. The purpose of this paper is to provide preliminary results on their tolerance to neutrons.

2. Experimental methods

2.1. Detector characteristics

Neutron radiation tolerance tests were performed with the two first generations of MAPS, fabricated in two different standard CMOS processes, having a minimum feature size of 0.6µm and 0.35µm respectively [1].

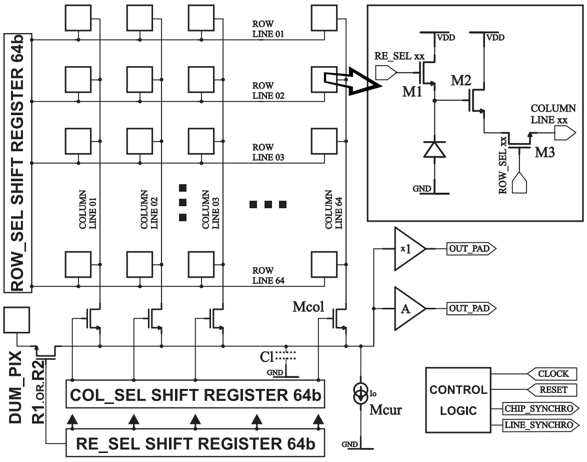

Fig. 1 : Simplified block scheme of the MIMOSA-detectors.

Both chips contain several independent arrays of active elements having slightly different design. Each array is made of 64x64 pixel elements laid down with a pitch of 20µm, uniform in both directions. The individual pixel is comprised of only 3 MOS transistors and a floating diffusion photodiode. While n-well implantation areas form the collecting diodes, the design is limited to only NMOS transistors on the pixel level, but both types of transistors are used at the chip periphery. Chips are fitted with a serial analogue readout requiring only two digital signals to operate. A schematic diagram of the MIMOSA I and II chips is presented in figure 1. Transistor M1 resets the photodiode to reverse bias. Transistor M2, combined with the current source M_{cur}, common to the entire column, is a source follower. Finally, transistor M3, combined with M_{col}, is used to address the pixel for readout. The floating diffusion of the collecting diode has to be periodically reset to remove the collected charge and to compensate the diode leakage current.

Tests were performed using chips irradiated with a wide energy spectrum of neutrons (peaked around 1MeV) at the Joint Institute for Nuclear Research (JINR) in Dubna and via the CEA-Saclay. Neutrons were chosen in order to study genuine bulk damages. Special care was taken in order to minimise the ionisation dose from the background high energy photons. Dosimetry measurements were performed, showing that the ionising dose was below 5kRad for a fluence of 10^{13}neutrons/cm².

2.2. Parameters investigated

To specify the chip radiation damage, the evolution of four main parameters was scrutinised. These were the pixel leakage current and noise, the charge collected and the gain of the readout electronics.

The chips were operated at different temperatures in a temperature stabilised dark room, which could be equipped with a ^{55}Fe X-ray source. The photons of this source create an amount of charge in the detector material similar to a minimum ionising particle.

This charge is typically spread over a cluster of neighbouring pixels, having a size of up to 5x5 pixels. To avoid overlapping hits, the mean photon flux of the source was set to about 4 hits per frame readout cycle.

2.3. Noise and collected charge spectrum

In order to measure the charge collection efficiency, the MIMOSA-chip was cooled down to 10°C and illuminated with the ^{55}Fe source. The chip readout cycle consisted of a reset and two consecutive frame readout cycles. Up to 40000 such cycles were recorded for each measurement.

To extract the charge created by the impinging photons, data were processed off-line. The cluster finding algorithm included correlated double sampling (CDS) of two consecutive frames, pedestal subtraction and common mode suppression as well as the calculation of individual pixel noise. Each pixel with a signal-to-noise ratio exceeding 5 was taken as a seed pixel and its neighbours were included into the cluster. The collected charge distributions were made for the seed pixel of each cluster as well as for the subset of 4 pixels exhibiting the largest signal.

2.4. Charge-to-voltage conversion gain

A first step of the calibration performed with the 55Fe 5.9 keV X-ray source, consisted in measuring the conversion gain. This was needed for further parameterisation, using absolute units, of the other measured parameters. Such photons interact via photoelectric effect inside the active detector volume, and generate an average number of charge carriers equal to 1640 of e/h pairs in silicon. This gives rise to a characteristic peak in the collected charge distribution. For detectors having close to 100% charge collection efficiency, the position of this peak can be directly used for measurements of the conversion gain.

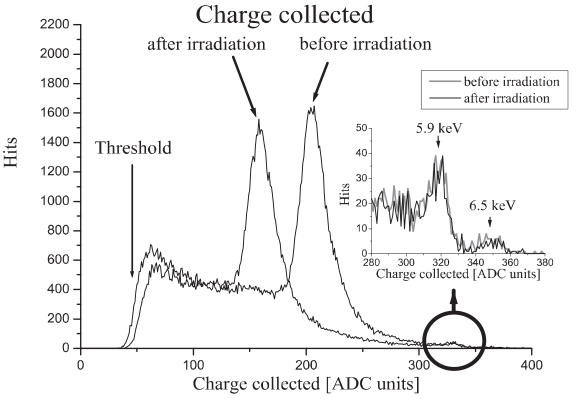

Fig. 2: Collected charge distribution of MIMOSA II illuminated with a ^{55}Fe source. The zoom shows the signal produced by 5.9 keV and 6.5keV X-rays inpinging the sensor near an n-well.

This is not the case of the present device, where the carrier transport mechanism goes mainly through thermal diffusion, and some charge losses are therefore expected. The charge is also naturally spread among several pixels. However, the assumption of a fully efficient charge collection is justified for the small sub-sample of photons converted inside the depleted volume of the collecting diode p-n junction. This explains the existence of two secondary, smaller peaks, visible on the individual pixel photon spectrum. The position of the more populated of those two particular peaks, due to a 5.9keV energy deposit, was used to measure the conversion gain.

This is illustrated in Fig. 2 which displays the charge distribution of the pixels associated to the impinging X-rays, before and after irradiation with neutrons. The small peaks above 300 ADC-units originate from photons converted nearby an n-well, whereas the two dominant peaks (located between 100 and 250 ADC-units) come from photons converted outside the neighborhood of the n-wells.
The position of these two latter peaks was used for investigating changes in the collected charge and in the charge-to-voltage conversion.

2.5. Leakage current

The leakage current was determined for each individual pixel at temperatures varied from -10°C to 40°C by steps of 10°C.

The signal sensed by non illuminated pixels is an integral of the pixel's leakage current. Therefore this current can be computed from the ratio between the signal amplitude and the frame readout time.

Each measurement was based on 160 consecutive events (an event is made of the series of frames used in a single CDS operation) to suppress random noise.

This approach is sensitive to currents down to a fraction of fA. It provides an accurate measurement of the leakage current of the charge collecting diode, provided the drain leakage current of the reset-transistor (M1) does not significantly recharge its capacity.

3. Results

The sensitivity of the MIMOSA prototypes to various neutron fluences was investigated by comparing the characteristics of irradiated chips to those of non irradiated ones. This procedure introduced a small systematic uncertainty (few %) in the comparison, reflecting the dispersion between the genuine characteristics of the individual chips and of the front-end readout cards, on which the chips were mounted.

Within the accuracy of the measurements (< 2 %), no change of the conversion gain of MIMOSA II was observed over the full range of fluences considered.

The increase of the leakage current consecutive to neutron irradiation is shown on fig. 3. The effect of neutrons on the leakage current of MIMOSA II is shown for two different designs (i.e. 1-diode and 2-diode pixels) as a function of temperature. The neutron fluence considered here amounts to 10^{13}n/cm². The leakage current was observed to increase by an order of magnitude at any of the temperatures considered and its temperature dependence was constant. The magnitude of the leakage current increase has no influence on the chip performances since the noise is dominated by other sources. This was actually verified experimentally. The results are shown in fig. 4, which displays the noise measured after CDS as a function of the fluence.

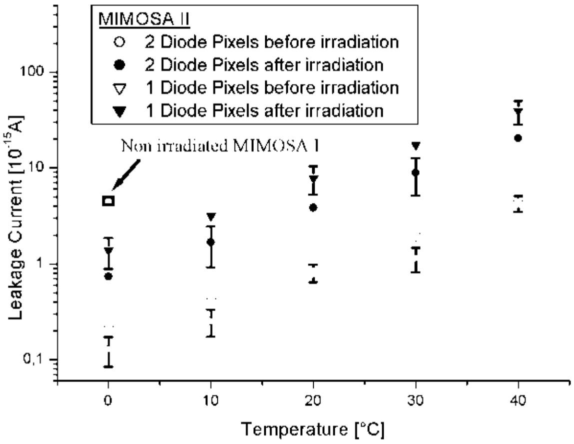

Fig. 3 : Leakage current of MIMOSA II before and after irradiation with 10^{13}n/cm² as a function of temperature. The leakage currents measured at 0°C on non-irradiated MIMOSA I chips is included for comparison. Error bars represent the pixel-to-pixel leakage current dispersions. Some of them were removed for clearity.

A similar increase in leakage current is expected for MIMOSA I. It could not be observed, being swamped by the dominating genuine leakage current of this technology.

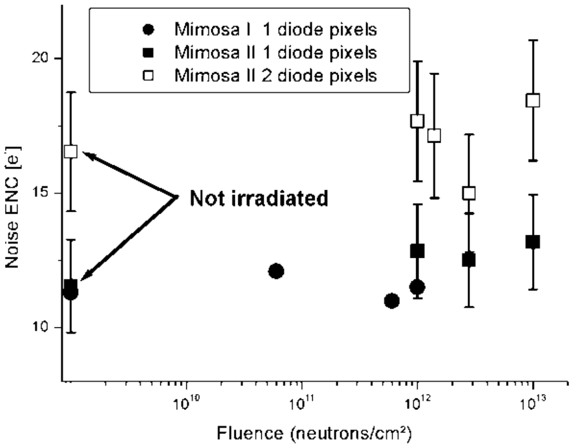

Fig. 4: Noise of MIMOSA I and II as a function of neutron fluence. Error bars represent the pixel-to-pixel noise dispersions (not available for MIMOSA I).

The sensitivity of the chips to the neutron fluence in terms of charge collection efficiency is displayed on fig. 5 for MIMOSA I and MIMOSA II. The figure represents the charge collected by groups of 4 pixels in a cluster when the chips are exposed to a ^{55}Fe source, as described in section 2.3.

One observes that MIMOSA II (resp. MIMOSA I) chips exposed to fluences of up to about 10^{12} n/cm² (resp. a few 10^{11}n/cm²) do not exhibit a significant charge loss. For higher fluences, the charge collected decreases rather smoothly: for 10^{13}n/cm², the charge collected with MIMOSA II is still of the order of 30% to 50% of the initial value, depending on the design considered. These observations suggest that the decrease of the charge collected reflects a shortening of the charge carrier's lifetime, which affects dominantly those electrons diffusing over long distances. The mean distance is indeed substantially higher for MIMOSA I, due to its relatively thick epitaxial layer (14 µm), than for MIMOSA II, for which this layer is only 4.2 µm thick. This hypothesis is also supported by the different sensitivities of chips equipped with one diode per pixel as compared to their variants equipped with two or four diodes. Though the effect is not striking, the former tend to exhibit a stronger charge loss than the latter, for a given fluence.

4. Summary and conclusion

The sensitivity of MAPS for charged particles tracking to neutron irradiation was investigated using two different prototypes with different pixel layouts.

The charge-to-voltage conversion gain was observed to remain constant up to the highest fluences considered (10^{13}n/cm²). An increase of the leakage current by an order of magnitude was measured, which did not affect significantly the pixel noise. Charge losses were observed for fluences larger than 10^{12}n/cm² or than a few 10^{11}n/cm², depending on the prototype considered. For higher fluences, a smooth decrease was found, resulting in a drop of at least 50% for 10^{13}n/cm². This drop is likely to be caused by a reduction of the minority charge carrier's lifetime in the epitaxial layer.

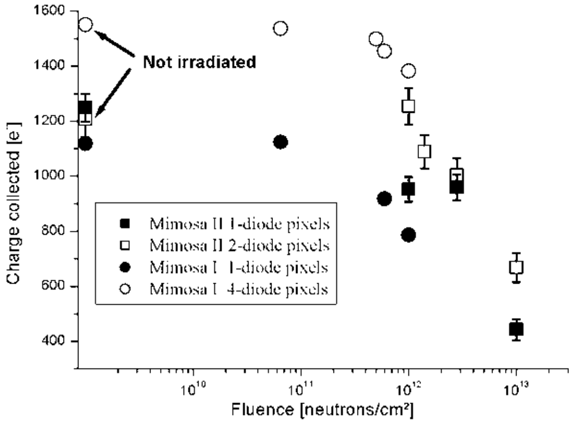

Fig. 5: Charge collected with MIMOSA I and II as a function of the neutron fluence. Error bars represent the spread of charge collection between different non irradiated MIMOSA II chips.

These results demonstrate that MAPS stand quite substantial neutron fluxes, which makes them well suited for numerous applications. Their performance is of particular interest for their use in a vertex detector at a future e^+e^- linear collider, where fluences well below 10^{11} n/cm² are expected.

Finally, one should notice that the intrinsic performances of this new technology are still being explored. The observed limits in radiation tolerance should therefore not be considered as ultimate. However, two tested devices show in the first order similar degradation, independent of a particular CMOS process used for their fabrication.

Acknowledgments

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