Radiation Hardness Study of a CMOS APS for Particle Tracking

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Abstract

A Monolithic Active Pixel Sensor (MAPS) for charged particle tracking based on a novel detector structure has been proposed. Two prototype chips were successively fabricated using 0.6 μm and 0.35 μm CMOS processes. Special radiation tolerant layout techniques were used in the second chip design. In order to study different radiation damage effects on a CMOS pixel tracker, measurements have been performed using a 30 MeV proton beam and a 10 keV X-ray generator as irradiation sources. The collected charge losses were measured after $5x10^{11}$ protons/cm^2 as well as after a moderate dose (600 kRads) of X-ray photons. An increase of a leakage current, observed as a voltage drop on the device charge collecting node, was also seen. Test results are reviewed and new tolerant structures are proposed.

I. Introduction

The ability of the APS CMOS sensors to provide charged particle tracking has been recently demonstrated [1-4]. The key element is the use of an n-well/p-epi diode to collect the charge generated by the impinging particle in the thin, epitaxial layer underneath the readout electronics. This solution allows 100% fill factor, as required in tracking application. The measured tracking performance of minimum ionising particles includes very high spatial resolution of 1.5 μm and the detection efficiency close to 100%, resulting from a high signal-to-noise ratio of more than 30. The observed excellent tracking performance makes CMOS APS an interesting candidate for future applications in Particle Physics experiments. A very high reaction rate and also beam induced radiation background expected in such environment puts several requirements on the radiation hardness of basic detector components. This is particularly true for all tracking devices, because of their location close to the reaction point. Also possible applications in space experiments require hardened devices.

Radiation damage may be induced by direct ionisation due to charged particles and high energy photons. Photon interactions are followed by positive charge built-up in the oxide close to the silicon interface. Mass particles (neutrons, protons and other hadrons) may induce bulk damages - mostly atom displacement in the silicon crystal lattice. The expected integrated radiation doses in future high energy physics application may vary from few tens of kRads and 10^{10} neutrons/cm^2 (TESLA Linear Collider) up to many MRads and close to 10^{15} neutrons/cm^2 expected at the Large Hadron Collider at CERN.

If some special layout rules are used, modern deep submicron processes may provide electronic circuits having high radiation tolerance level, up to many tens of MRads and 10^{15} neutrons/cm^2 [5,6]. However, in the case of CMOS particle tracking devices, the preservation of an efficient charge collection from the epitaxial layer underneath the electronics is required in addition. Also, an important increase of the leakage current of the charge collecting diode may have unwanted effects on the device operation (shorter saturation time, shot noise increase).

II. Proton irradiation tests

In order to study different radiation damage effects on a CMOS pixel tracker, initial measurements have been performed using a 30 MeV proton beam from the cyclotron at Karlsruhe Forshungszentrum (Germany). Two prototypes, fabricated in 0.6 μm (Mimosa I) and 0.35 μm (Mimosa II) standard CMOS processes have been tested. The latest one was designed using radiation tolerant layout rules with enclosed NMOS transistors. This solution eliminates the thick oxide at the gate ends (bird's beaks), preventing the increase of a source-drain leakage current due to the presence of a trapped positive charge created by ionising irradiation. The maximum proton fluence in this series of tests was set to $5x10^{11}$ p/cm^2. This corresponds to the ionisation dose of about 50 kRads and the atomic displacement effect (bulk damage) equivalent to 10^{12} neutrons/cm^2 (1 MeV equivalent). Under this irradiation condition the major anticipated effect on the pixel device was the minority carrier's lifetime

decrease in a slightly doped (10^{15} cm^{-3}) p-epi layer due to the bulk damage. Because the charge collection time through thermal diffusion from the undepleted epitaxial layer is relatively long (in the order of 100 ns), the minority carrier's lifetime decrease may influence the charge collection efficiency, decreasing the signal amplitude. Also, the n-well/p-epi diode leakage current may increase, due to the increase of the junction generation-recombination (G-R) currents.

Figure 1 shows a decrease of the signal amplitude (measured as a position of 5.9 keV photon peak) as a function of the proton fluence. Charge losses of up to 40% were observed after $5x10^{11}$ protons/cm^2. The related increase of the average leakage current, observed as a voltage drop for one full frame acquisition time on the device charge collecting node as a function of temperature, is shown in figure 2.

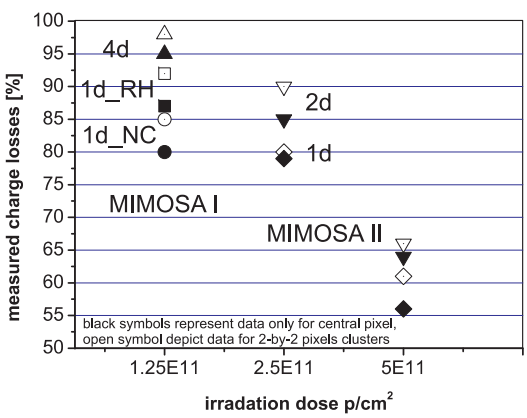


Figure 1: Measured relative charge losses after irradiation with protons for two prototype chips (Mimosa I and Mimosa II), for different pixel configuration (1, 2 and 4 diodes) implemented inside

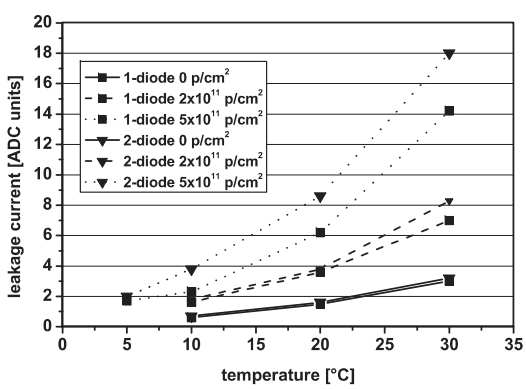


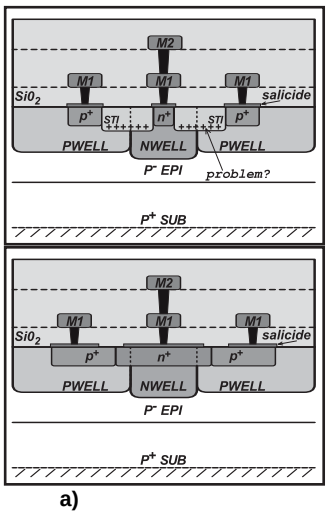
Figure 2: Increase of leakage current after irradiations with 30 MeV protons measured as a function of temperature (Mimosa II prototype).

III. Soft X-rays irradiation tests

In order to verify the hypothesis that the observed signal decrease and leakage current increase are mainly due to the bulk damage, series of irradiation tests has been performed using a 10 keV X-ray photon source. According to our knowledge the silicon bulk damage effects of such a soft X-ray photons should be negligible. Surprisingly, similar charge losses of the order of 40% have been observed after a moderate dose of 100 kRads (Mimosa I) and 600 kRads (Mimosa 2). Also, the diode leakage current increased in a very similar way by a factor of close to five. This strongly suggests that the bulk damage may not be the only mechanism to explain such an effects. It must be highlighted that other detector parameters including the pixel charge-to-voltage conversion gain remains unaffected after irradiation up to the doses mentioned before. The position of the second, photon peak attributed to the photons converted inside depleted volume near the junction [7] doesn't change after irradiation, proving that only the charge liberated deeper in the active volume is sensitive to the radiation effects.

IV. Conclusions

The collected charge losses from the epitaxial layer have been observed as an effect of both proton and soft X-ray irradiation, accompanied by the increase of a leakage (dark) current. To distinguish between ionisation and bulk damage effects, irradiation using high energy pure neutron source is under preparation. For the fluence of 10^{12} n/cm^2 (1 MeV equivalent), the ionisation dose in this case should not exceed 5 kRads. The consequence of presence of a thick oxide and shallow trench isolation structures close to the n-well/p-epi junction should be evaluated. At present the exact mechanism of observed charge loses is unknown and strong effort in terms of device simulation is required in order to understand these effects. New charge collecting diode structures, with no thick oxide around junctions, have been proposed and submitted for fabrication in 0.25 μm CMOS process (Fig.3). Test results of this devices are expected soon.



a) **b)**

Figure 3: a) Standard configuration of the N-WELL/P-EPI collecting diode with p^+ guard-ring implemented in a sub-micron process with STI; b) improved design with extended n^+ and adjacent p^+ implantation areas. The diode depicted in a) can suffer from an increase of leakage currents after ionising irradiation.

Acknowledgements

This work was possible because of a great help from Prof. Wim de Boer and his team from Karlsruhe University for the proton irradiation and from Pierre Jarron and Giovanni Anelli from CERN for the X-ray irradiation.

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