Radiation Tolerance Tests of CMOS Active Pixel Sensors used for the CMS Muon Barrel Alignment

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Abstract

Neutron and proton irradiation tests were performed to study the radiation induced alterations of COTS (Commercially available Off The Shelf) CMOS active pixel sensors at two facilities. The sensors will be used for the CMS Barrel Muon Alignment system. Results of the tests are presented in this paper.

I. INTRODUCTION

Performance of the CMS detector of the Large Hadron Collider (LHC) is affected by the position and orientation of the individual detectors. Therefore, the CMS detector has an alignment system that consists of several subsystems. One of them is the barrel and end-cap internal alignment, which measures the positions of the muon detectors with respect to the linking points [1]. This system will consist of LED light-sources, the related electronics and video cameras equipped with video-sensors (~ 800 pcs) [2].

The light sources will be attached mechanically to the muon chambers and its operation is controlled remotely. The video cameras are fixed to a rigid grid structures which positions are calibrated by a laser link system. The images from the cameras are digitised and evaluated by 36 pcs dedicated PC104 type board computers. The board computers calculate the co-ordinates of the LEDs on the images and send those values to the Supervisory Control and Data Acquisition (SCADA) workstation.

The optical and opto-electronic components have to work in a radiation environment, where the expected neutron fluence is 2.6E12 n/cm^2 and the expected proton fluence is 1E11 p/cm^2. Radiation damage induced by neutrons and protons can alter electrical and optical characteristics of the components and thus the accuracy of the whole alignment system.

II. EXPERIMENTAL TECHNIQUES

A. Image sensor

Video cameras based on the VM5402 CMOS Image Sensor have been selected and tested for surveying the alignment of the CMS Barrel Muon detector system. The VM5402 manufactured by VISION is an active pixel type image sensor with 388 x 295 pixels, each with an area of 12 x 12 μm^2. The module is suitable for applications requiring a composite video signal with minimum external circuitry [3]. The photo of the camera can be seen in figure 1.

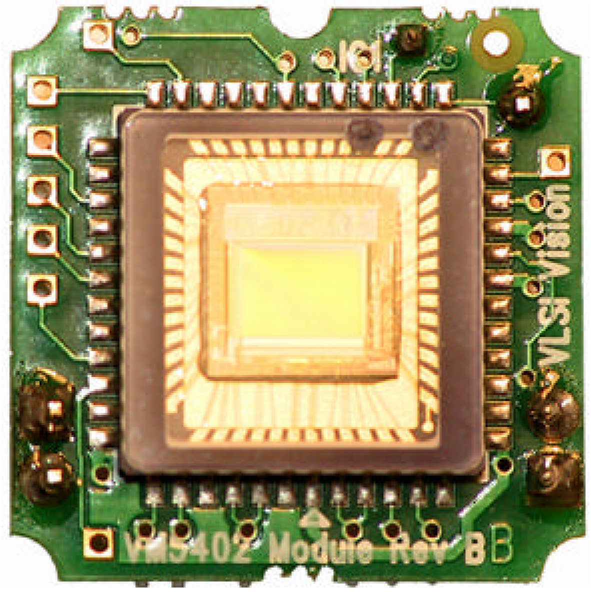

Figure 1: Video camera based on the VM5402 CMOS Image Sensor

B. Radiation facilities

Five samples of camera have been tested with 20 MeV and 95 MeV neutron and 98 MeV proton beams with fluences corresponding to the radiation environment calculations.

The 95 MeV neutron beam was produced at the Gustav Werner Cyclotron facility of the The Svedberg Laboratory (TSL) in Uppsala by 98 MeV proton beam hitting an 8 mm Li-target.

The 20 MeV neutron irradiation was done at the neutron irradiation facility at the MGC-20E cyclotron at ATOMKI, Debrecen with p(20MeV)+Be reaction [4]. Neutrons with a broad spectrum (E_n<20MeV, <E_n>=3.5MeV) were produced by bombarding a 3 mm thick target by protons.

The 98 MeV proton beam of the TSL cyclotron was broadened by a scatterer and was extracted to air[5].

C. Image recording

The video signal from the camera during irradiation was stored using a standard video recorder. In each second 50 images were recorded for off-line analysis.

III. RESULTS AND DISCUSSIONS

The recorded video images of the irradiation showed white spots and long tracks which were results of the different nuclear interactions caused by the proton and neutron irradiation. The heavy fragments from the nuclear reactions were observed as white spots in the image. The light charged particles like protons and alpha particles that follows the nuclear reactions are emitted with different energies and directions, according to the kinematics of the process. Some of these particles were emitted in the sensitive plane of the CMOS Image Sensor. They deposit their energy to the silicon and the released charge, forming the tracks, are detected by the pixels. These tracks are visible on the video image. The charge is registered along the track and the intensity value of the signal can be analysed off-line.

In figure 2 a camera image recorded during 98 MeV proton irradiation can be seen. The smaller white round spots are the result of the heavy charged particles. The largest round white spot close to the longest track is the light from the LED.

In figure 3 clearly visible the “background” created by the direct ionisation of the radiation. The greyscale level in pixels where no flash was detected increased when the beam was on. This can be explained by the effect of the direct ionisation of the protons. Majority of the protons does not make a nuclear reaction in the silicon of the image sensor, but loses a certain amount of energy by direct ionisation. The sum of these small deposited energies forms the special background structure. The products of two reactions can also be seen. In one of the reactions both the heavy fragment (large spot) and a light fragment (long track) can be seen.

The phenomena in the camera can be called a “visible Single Event Phenomena (SEU)”. Because of the analog nature of the image sensor the result of the SEU can be seen in more detail compared to a digital circuit.

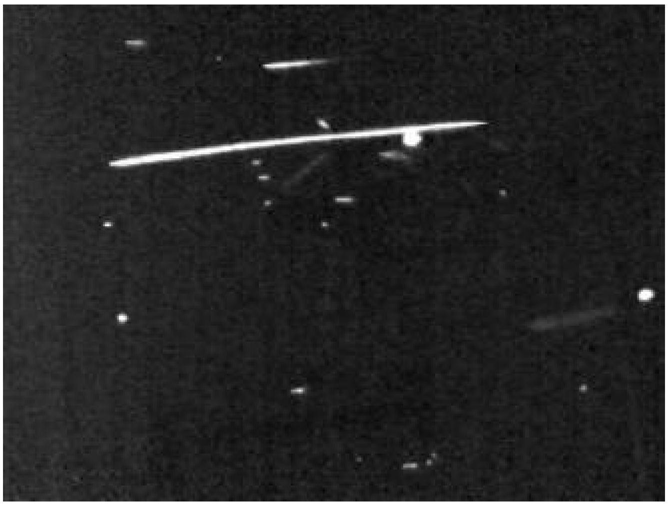

Figure 2: A typical image during 98 MeV proton irradiation.

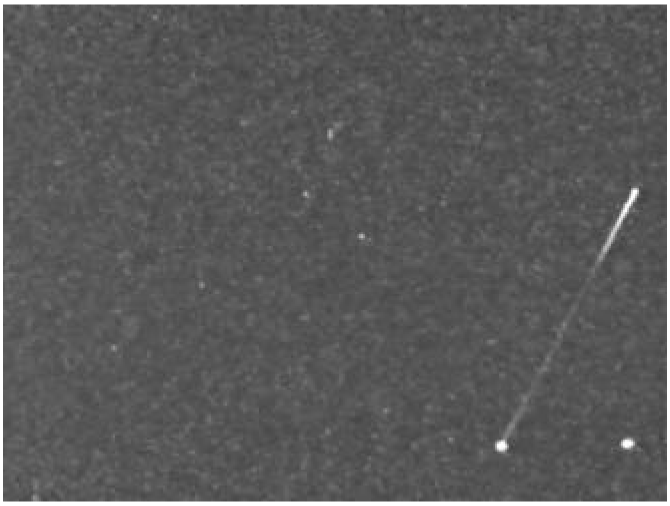

Figure 3: Image presenting the background structure caused by the irradiation.

The incident light creates proportional charges in the active pixels and this charge forms the image visible on the video monitor. In the described experiment the charges in the sensor are generated by the energy deposited by the heavy and light charged particles. Consequently the image seen on the monitor is the direct effect of the charged particles.

One possible reaction that can take place in the silicon of the image sensor is presented in figure 4. The heavy reaction product (^{25}Al) leaves on the average 2 MeV/µm. If this energy is deposited in the sensitive volume of the sensor, a spot occurs on the image. Because of the short range of the heavy fragment the deposited energy forms a round spot on the image. The range of the light fragment (α particle) is rather long, so a long track is its image. The reaction in figure 4 is a possible candidate for the reaction in figure 3 where a long track originates from a spot. The deposited energy along the track follows the Bragg curve, this is the reason why the long track becomes broader and brighter towards the end of the track (close to the edge of figure 3.).

It is obvious that a nuclear reaction caused by a proton or a neutron is a complex process. than the traditional SEU that is caused by a heavy ion. The lack of experimental information urge for investigation of the nuclear reaction processes in silicon with focus on the rare channels that produce highly ionising secondary fragments. The range of the nucleon-induced heavy secondary ions is comparable to the size of the structure in an IC. This is illustrated in the figure 4 below where one, out of many possible reactions in silicon is shown.

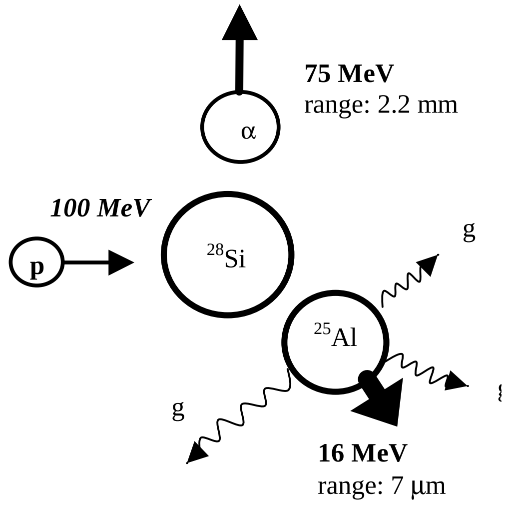

Figure 4. A schematic figure describing one of all of the possible outcomes of a proton induced nuclear reaction with ^{28}Si.

In a previous experiment [7], a silicon detector was used as an active target and particle telescopes detected light charged reaction products like p, d, t, ^{3}He and α-particles. The heaviest fragments in such nucleon-initiated reactions are responsible for the SEU's but due to their short range in silicon they could only indirectly be detected via the associated light fragment. One could compare these findings with standard SEU cross section measurements for selected memories with known circuit topology. The method and the first tests were reported recently [7]. The results obtained were compared and interpreted with Monte Carlo simulations using the GEANT code. From this exploratory experiment one can conclude that a large number of charged particles are released in the reaction and that the Monte-Carlo simulation gave, when it was applicable, a reasonable agreement with the measured data.

IV. CONCLUSION

The video cameras based on the VM5402 CMOS Image Sensor intended to be used in the CMS Muon Barrel Alignment system was studied with protons and neutrons. The observed effects caused by the radiation can be tolerated in the Barrel Muon Alignment system. However special care has to be taken during the calculation of the LED positions because the image is relatively heavily effected by the tracks and spots produced by the radiation field.

V. ACKNOWLEDGEMENT

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