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Frédéric Bernard

Sophie Petit

Sophie Courtade



IONIZING DOSES AND DISPLACEMENT DAMAGE TESTING OF COTS CMOS IMAGERS

Frédéric BERNARD⁽¹⁾, Sophie PETIT⁽¹⁾, Sophie COURTADE⁽²⁾

⁽¹⁾CNES - Centre National d'Etudes Spatiales - 18, Avenue E. Belin 31401 Toulouse cedex 9, France
Email: frederic.bernard@cnes.fr

⁽²⁾ASSYSTEM - Agence de Toulouse -13 rue Marie Louise Dissard - BP 13015- 31024 Toulouse Cedex , France

ABSTRACT

CMOS sensors begin to be a credible alternative to CCD sensors in some space missions. However, technology evolution of CMOS sensors is much faster than CCD one's. So a continuous technology evaluation is needed for CMOS imagers. Many of commercial COTS (Components Off The Shelf) CMOS sensors use organic filters, micro-lenses and non rad-hard technologies.

An evaluation of the possibilities offered by such technologies is interesting before any custom development. This can be obtained by testing commercial COTS imagers.

This article will present electro-optical performances evolution of off the shelves CMOS imagers after Ionizing Doses until 50kRad(Si) and Displacement Damage environment tests (until 10^{11} p/cm² at 50 MeV).

Dark current level and non uniformity evolutions are compared and discussed. Relative spectral response measurement and associated evolution with irradiation will also be presented and discussed.

Tests have been performed on CNES detection benches.

1. INTRODUCTION

CMOS sensors invade ground applications : mobile phones, digital still camera and so on. Constant integration and miniaturization thanks to the market oblige fabricants to be more and more imaginative and to push the limits of technologies: the use of color filters and micro-lenses is now generalized. However the use of such sensors is quite limited for space applications. For non radiometric applications CMOS COTS imagers could be interesting. The price and the technology improvement are of courses advantages. But radiation behavior of such devices could be a serious drawback.

This paper will show some results obtained on such sensors, even if they were not designed for space applications.

2. SENSORS CHOICE

Most of commercial sensors are used for webcam or digital still camera. Sensors choice is a bit difficult as we have many possibilities and as lifetime of new products is very short. Finally we decided to evaluate four different sensors, relatively representatives of elements that we were interested to test: black & white and color sensors, different technologies, and different types of pixels. Here after are the characteristics of the evaluated CMOS sensors:

Name	Techno. (μm)	Sensor Size (pixel ²)	Pixel Size (μm^2)	Power (V)	Type of Pixel	ADC Resol. (bits)	B&W / Color
A	0,25	640 x 480	5,6 x 5,6	2,5	Unknown	8	B&W
B1	0,18	640 x 480	5,6 x 5,6	3,3 & 5	3T DDS	8	B&W
B2	0,18	640 x 480	5,6 x 5,6	3,3 & 5	3T DDS	8	Bayer RGB
C	0,25	1312 x 1032	5 x 5	2,5 & 3,3	3T	12	B&W

Fig. 2-1. Characteristics of Evaluated Devices

A Bayer filter is used on B2 color sensor as shown on the photo of the chip on Fig. 2-2.

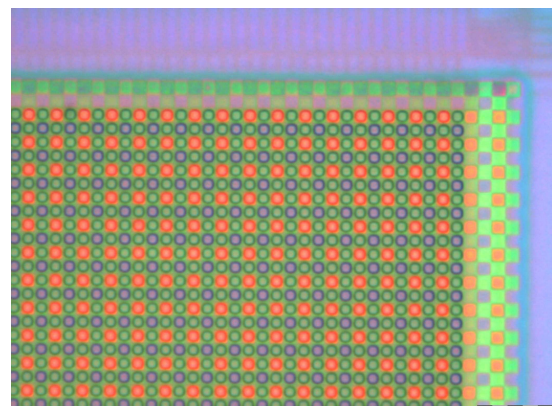


Fig 2-2 : Photo of B2 Sensor showing micro-lenses and Bayer color filter (4 colors components)

As CMOS sensors are “SoC”(System On Chip), outputs of this devices are digital : photons enter and bits come out. So we have to carefully look to what is measured and what is obtained. It is not always an easy job to go back to the raw images at pixel level.

3. ENVIRONMENT TEST PLAN

A relatively classic test plan was decided. Ionizing doses (obtained by gamma rays) have been applied by step until 15 kRad(Si) for “A” and “B” sensors and 50 kRad(Si) for the “C” sensor. The doses rates were relatively small : between 30 and 40 rad/h.

For the “C” sensor we performed measurements immediately after each dose step and 24 hours after the step to try to evaluate the proportion of non generated interface states. During this interval devices were “on” and polarized.

For annealing after doses, different protocols where used. For “A” and “C” sensors we applied a normalized 168h @ 100°C annealing. For the “B” sensors we do “isochrones” (see Fig. 3-1.) annealing until 140°C to try to identify activation energy of defects.

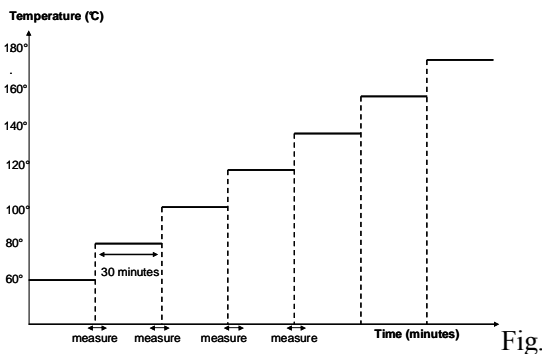


Fig. 3-1. : isochrone annealing

For the Displacement Damage test we applied on “A” and “B” sensors the following irradiations :

- 50 MeV energy protons at fluencies: 1E9p/cm², 1E10p/cm², and 1E11p/cm².
- 100 MeV energy protons at fluencies: 1E9p/cm², 1E10p/cm², and 1E11p/cm².
- 190 MeV energy protons at fluencies: 1E9p/cm², 1E10p/cm², and 1E11p/cm².

On “C” sensors, we applied :

- 30 MeV energy protons at the fluence 2E10p/cm²,
- 50 MeV energy protons at the fluence 2E10p/cm²,
- 100 MeV energy protons at the fluence 2E10p/cm².

The annealing procedure was the same as for doses.

4. TEST BENCH FACILITY

CNES test benches allows to do classical electro-optic characterizations:

- dark current mean level and dark current spatial non uniformity (DSNU),
- sensitivity, photo-response non uniformity (PRNU), fixed pattern noise (FPN), Conversion Factor, linearity and readout noise.

We can also perform spectral characterizations with a spectrometer present on the bench. This allowed us to make relative spectral response measurements and to see if spectral characteristics have shifted. The spectrum is spread in the horizontal side of the device and the response is obtained by meaning all the lines of the same column. Finally we use two lasers (532nm and 632nm) to make the spatial-spectral calibration.

The test bench is presented in Fig. 4-1.

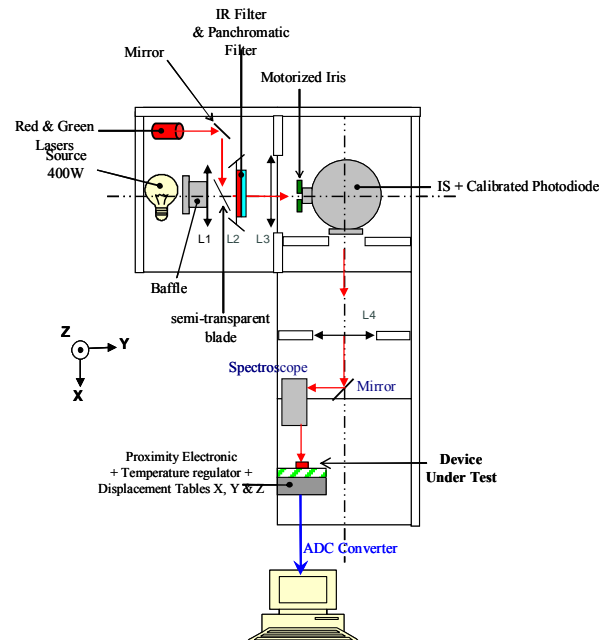


Fig. 4-1. Test Bench Description

For dark signal measurement, devices are finely regulated in temperature to minimize measurement drifts.

Every measurement is preceded by the measurement of a witness device to calibrate the test bench. So usually, electro-optical characteristics under illumination are presented after normalization to the witness.

5. IONIZING DOSES RESULTS

5.1 “A” Sensor

Results show that essentially dark current was modified (Conversion Factor is quite constant as demonstrated on Fig 5.1-3). It is to note that there is no “rebound” after annealing (see Fig. 5.1-1). This could indicate that the doses rate is small enough to reveal the interface states during the irradiation time.

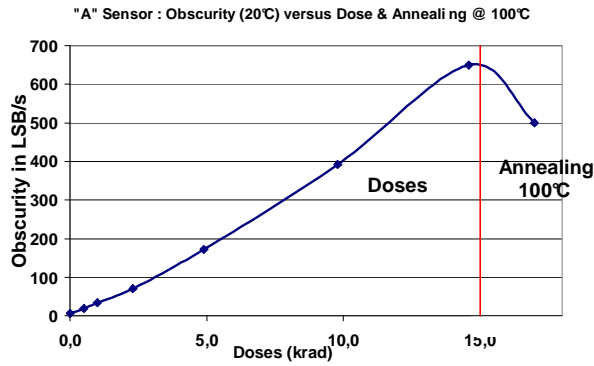


Fig. 5.1-1 : Evolution of dark current versus doses

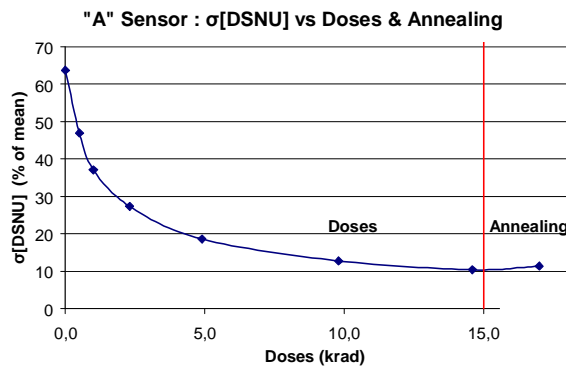


Fig. 5.1-2 : Evolution of DSNU versus doses

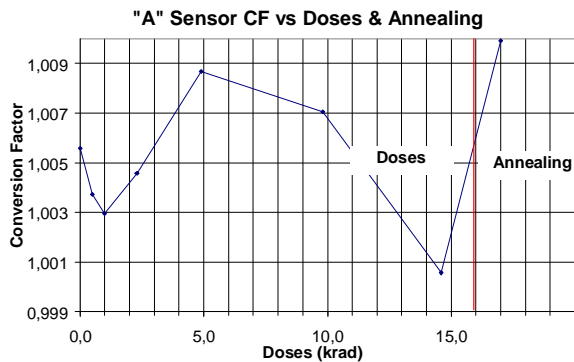


Fig. 5.1-3 : Evolution of Conversion Factor (relative to initial value) versus doses

Characteristics under illumination (sensitivity, linearity, PRNU) are similar before and after total ionizing doses. Fig.5.1-4 presents measurements of relative spectral response after irradiation.

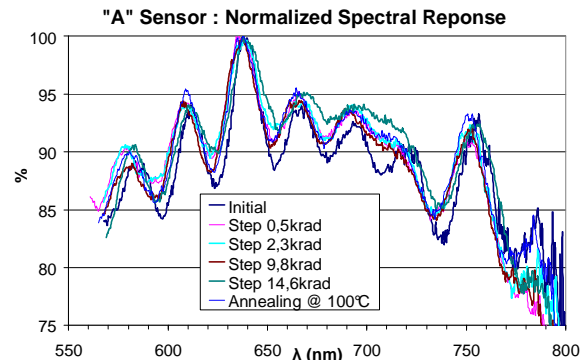


Fig 5.1-4 : Evolution of Normalized Spectral Response versus doses

5.2 "B" Sensor

As for "A" sensor, the major change occurs on dark current (Fig. 5.2-1 and 5.2-3). Annealing steps (isochrones steps) show a small rebound in the dark current curve (Fig. 5.2-2) that can be explained by the revelation of some interface states.

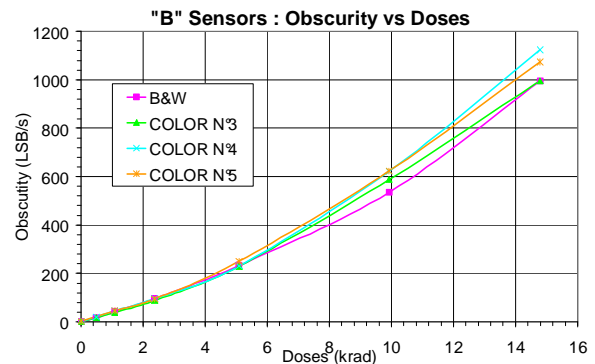


Fig. 5.2-1 : Evolution of Idark versus doses : same evolution for the B&W and the color devices

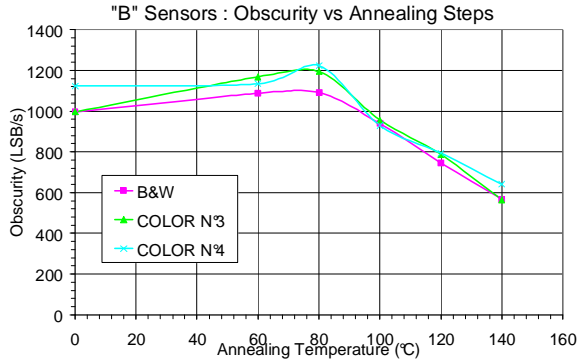


Fig. 5.2-2 : Evolution of Idark versus Annealing Steps (isochrones) : small rebounds before 100°C

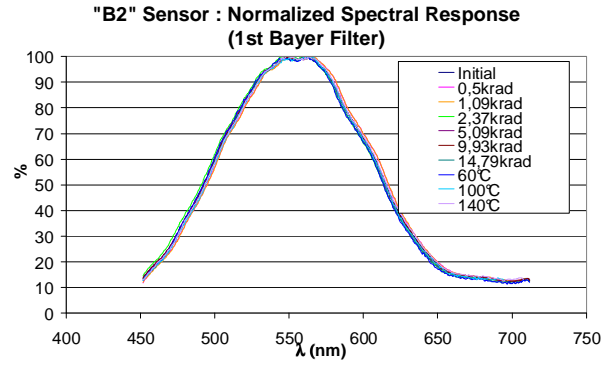


Fig. 5.2-5: Normalized Spectral Response of the 1st Bayer component versus doses

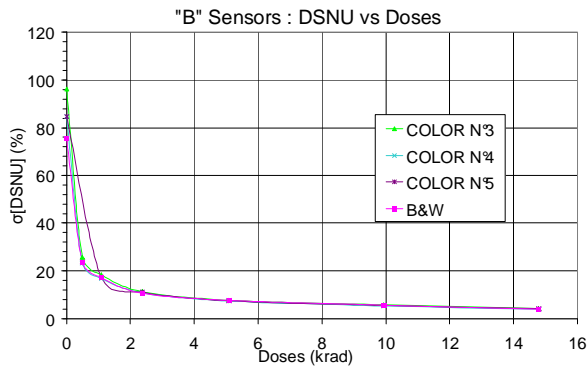


Fig. 5.2-3 : Evolution of DSNU versus doses

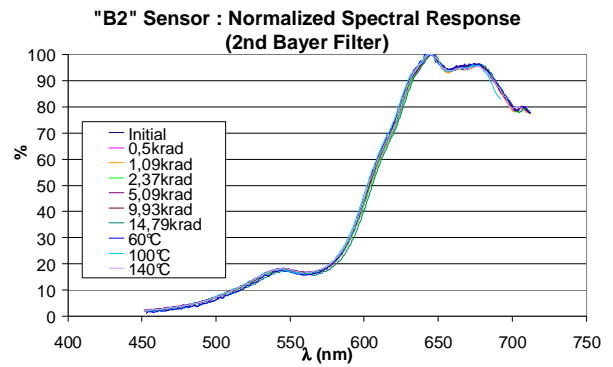


Fig. 5.2-6: Normalized Spectral Response of the 2nd Bayer component versus doses

Fig. 5.2-4 to 5.2-8 give the normalized spectral response behaviors of the B&W B1 devices and of the four colors components of B2 devices. We can note that these spectral responses are not affected by ionizing doses.

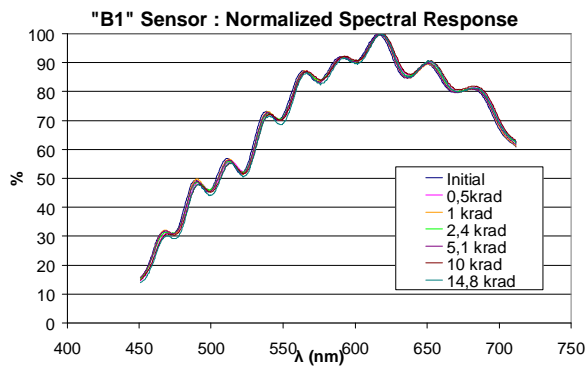


Fig. 5.2-4 : Normalized Spectral Response of B&W versus doses

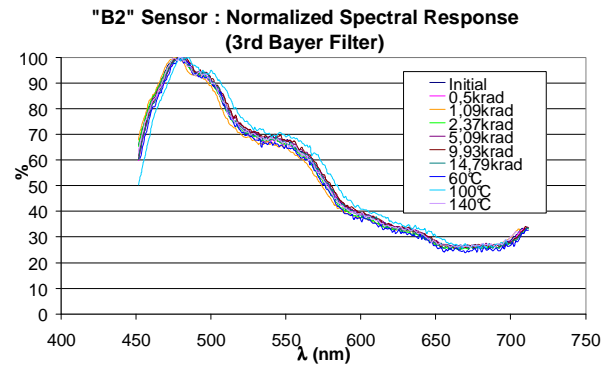


Fig. 5.2-7: Normalized Spectral Response of the 3rd Bayer component versus doses

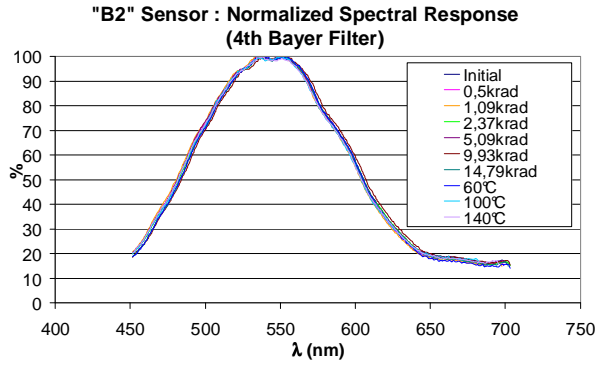


Fig. 5.2-8: Normalized Spectral Response of the 4th Bayer component versus doses

5.3 “C” Sensor

We only made measurements of dark current drift as neither illuminated electro-optical characteristics nor relative spectral response changed on “A” and “B” sensors. It is to note that – even if the results are not presented in the paper – measurements made immediately after doses steps and 24 hours (polarized) after the step are quite similar (-10%). This confirm that with relatively small doses rates, the interface states have the time to be revealed, and no rebound appear after annealing.

Annealing shows a significant curing (see Fig. 5.3-1) suggesting that the major contributor to dark signal is due to trapped charges in oxides.

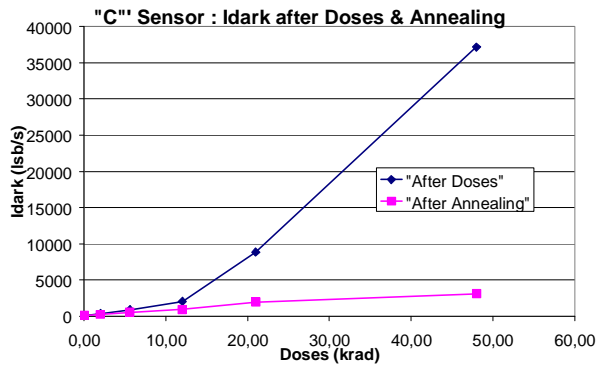


Fig. 5.3-1: dark current after doses and annealing for “C” sensor

6. DISPLACEMENT DAMAGE RESULTS

Results show that only dark signal characteristics seem to change. Electro-optical performances under illumination and relative spectral responses did not change (Fig 6-2 to Fig. 6-6) even for sensors with organic filters (B2). For these sensors we also did an isochrone annealing.

In Fig. 6-1, we can observe the mean dark current level evolution versus the NIEL. We also verify (not presented here) the linear dependency of dark current with protons fluency.

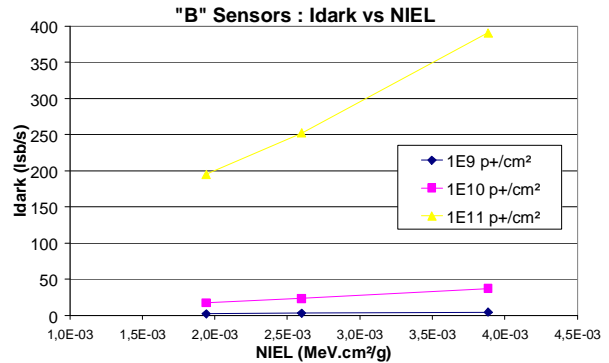


Fig. 6-1 : Evolution of dark current of “B” sensors versus NIEL

Fig. 6-2 present the normalized spectral response of the “A” (B&W) devices after protons irradiations. Fig. 6-3 to 6-5 give the normalized spectral response measured for the four colors components of “B2” colors devices. We can note that all these spectral responses are not affected by protons irradiations.

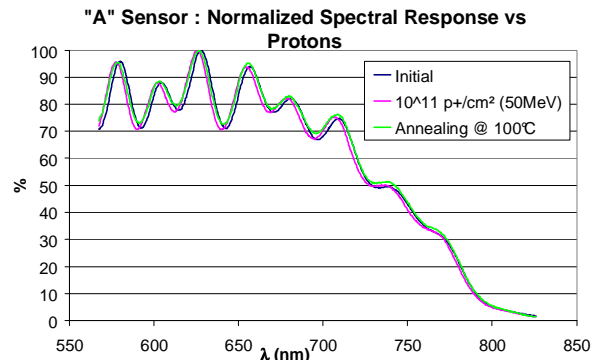


Fig. 6-2: “A” Sensor (B&W): Normalized Spectral Response after protons and annealing

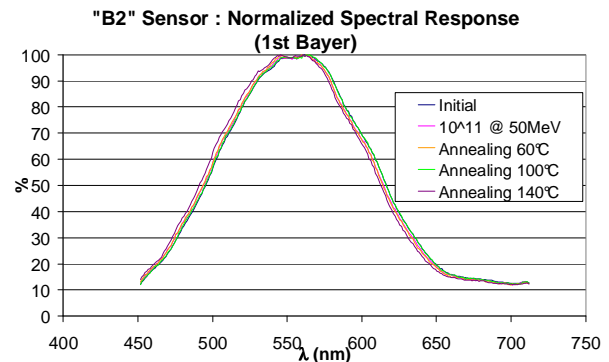


Fig. 6-3: “B2” Sensor : Normalized Spectral Response after protons and annealing

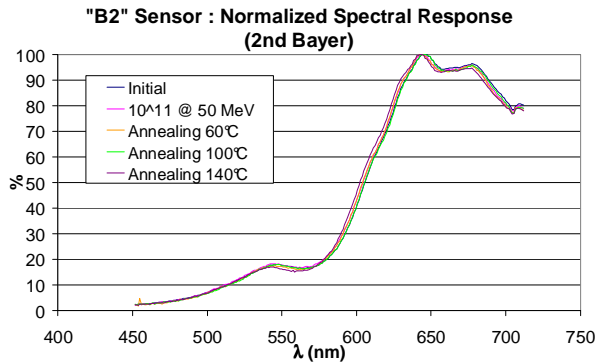


Fig. 6-4: "B2" Sensor : Normalized Spectral Response after protons and annealing

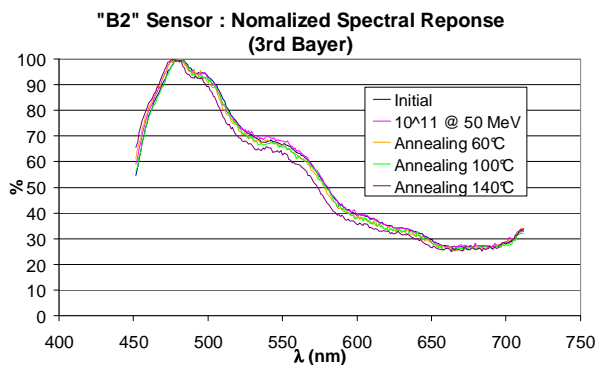


Fig. 6-5: "B2" Sensor : Normalized Spectral Response after protons and annealing

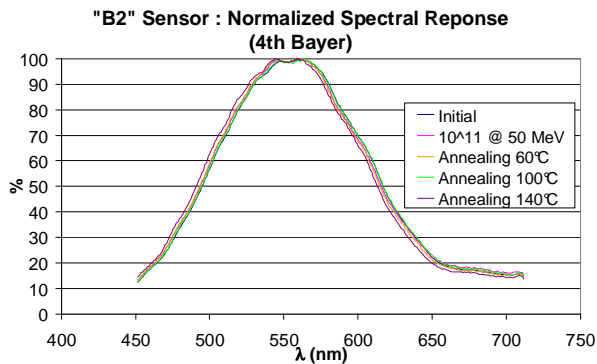


Fig. 6-6: "B2" Sensor : Normalized Spectral Response after protons and annealing

7. COMPARISON AND DISCUSSION

Total ionizing doses dark current and DSNU evolutions shows that sensors "B" and "C" are much sensible to trapped oxide charges compared to interface state as annealing allows a more or less large curing (see Fig. 7-1). We could compare mean dark current evolution of the 3 types of sensors in physical units (nA/cm²) using the conversion factor measurement. The limited

evolution of dark signal of "A" sensor seems very attractive compared to "B" and "C".

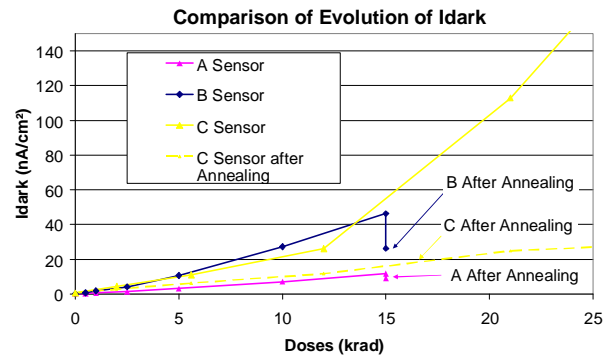


Fig. 7-1. Comparison of evolution of dark current with total ionizing doses after doses step and after annealing

We could also compare the degradation induced by ionizing doses for each type of sensor (Fig. 7-2). The evolution is around 2 nA/cm²/krad for "B" & "C" sensors at low doses. Note that "A" sensor seems to be slightly impacted compare to the others (<1 nA/cm²/krad).

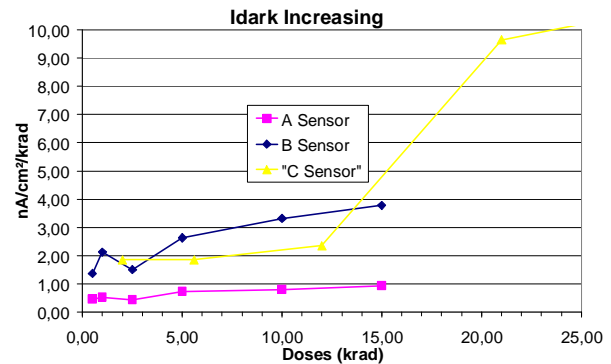


Fig. 7-2 : Evolution of dark current after doses in nA/cm²/krad for the 3 types of sensors

As the major degradation on sensors is on dark signal, it is also interesting to determine the part of the degradation caused by ionizing doses from one side and by displacement damage from the other side. If we consider Eq. 7-1, we could calculate the ionizing dose deposited by the protons, and then compare the evolution of dark signal versus the ionizing doses deposited by gamma rays and versus the ionizing doses deposited by protons (Fig. 7-3).

$$Doses (krad) = 1,6 \cdot 10^{-8} \cdot Fluency (cm^{-2}) \cdot K$$

Eq. 7-1 : Amount of doses deposited by protons. K is function of proton Energy (1,01 · 10⁻² for 10 MeV)

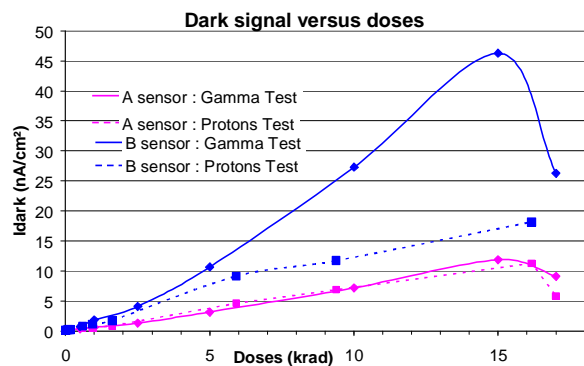


Fig. 7-3 : Comparaision of Idark versus doses for gamma rays and protons

Fig. 7-3 shows that for “A” sensor the major contributor on mean dark signal is the doses (deposited by the protons or by the gamma rays) : displacement damage are quite small (for mean current, it is not the same thing for the maximum). For the “B” sensor the (mean) dark current drift has a contribution of doses and a contribution of displacement damage.

8. CONCLUSIONS

Our evaluation gives some results on performances evolution of “recent” CMOS imagers. It shows that dark signal is sensible to total ionizing doses and displacement damage. The evolution of the dark current is probably mainly due to trapped oxide charges as a more or less huge cure is observed after annealing. Illuminated characteristics seem to be more or less “radiation proof”.

Our results confirm also that the use of organic micro-lenses or Bayer color filter is not prohibited anymore from radiations point of view. This could open the way to increase performances of CMOS imager (Sensitivity versus pixel reduction).

To complete our evaluation we also realized some “classical” evaluation lines such as latch up, Life Test and Vacuum files which are not presented in this paper. No major problems were encountered. This opens the opportunity to use commercial CMOS imagers (or micro cameras) for some low performances space applications such as appendices deployment verification, robotic vision, ...

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