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Gamma Radiation Damage Study of 0.18 μm Process CMOS Image Sensors

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A 0.18 μm process CMOS image sensor has recently been developed by e2v technologies plc. with a 0.5 megapixel imaging area consisting of 6 × 6 μm 5T pixels. The sensor is able to provide high performance in a diverse range of applications including machine vision and medical imaging, offering good low-light performance at a video rate of up to 60 fps. The CMOS sensor has desirable characteristics which make it appealing for a number of space applications. Following on from previous tests of the radiation hardness of the image sensors to proton radiation, in which the increase in dark-current and appearance of bright and RTS pixels was quantified, the sensors have now been subjected to a dose of gamma radiation. Knowledge of the performance after irradiation is important to judge suitability for space applications and radiation sensitive medical imaging applications. This knowledge will also enable image correction to mitigate the effects and allow for future CMOS devices to be designed to improve upon the findings in this paper. One device was irradiated to destruction after 120 krad(Si) while biased, and four other devices were irradiated between 5 and 20 krad(Si) while biased. This paper explores the resulting radiation damage effects on the CMOS image sensor such as increased dark current, and a central brightening effect, and discusses the implications for use of the sensor in space applications.

Keywords: CMOS, 5T, leakage current, non-uniformity, radiation damage, gamma irradiation.

1. INTRODUCTION

Since CMOS imagers are just now approaching the performance of CCDs in several realms[1], the possibility of using them to replace CCDs for certain space observation and spectrography applications is appearing. In some characteristics CMOS imagers can outperform CCDs, especially in terms of power consumption, weight, and radiation hardness, which makes them very appealing candidates for space imaging applications, especially where a radiation-hard sensor is important and power budgets are low. This work is aimed at understanding and improving the radiation hardness of the CMOS design and process used by e2v technologies plc. by characterizing the effect of ionization damage arising from a Co^{60} gamma radiation. The device irradiated was originally designed for use in machine vision applications, meaning that no specific design steps were taken to make the device radiation hard.

The solar system comprises of two different classes of radiation environment, these are the transient and non transient environments. The non-transient class comprises of trapped particles, e.g. protons and electons, held within planetary magnetic fields, for example those of the Earth and Jupiter. The transient class consists of cosmic and galactic rays and the products of solar events such as solar flares[2]. During solar events the incident particle flux can increase greatly, and planning for these events is integral to any mission with regards to radiation damage[3]. Gamma rays fall within the transient class, and thus can affect space missions at any point in time, not just during transfer within the belts, so the sensor often has to be operated whilst under continuous gamma flux and so the effects are important to investigate.

Gamma radiation causes damage to semiconductor devices primarily by creating electron-hole pairs in the gate oxide of the MOSFETs. The holes become trapped, changing the voltage required to activate the gate(increases for p-channel, and decreases for n-channel[4]), and forming traps that contribute to surface-generated leakage current. As this damage is cumulative, the total ionising dose (TID) is the important metric to compare doses in devices. This is measured depending on the absorbing material, as absorption depths are dependent on material, and for these monolithic detectors are thus measured in krad(Si). More detail on how ionising dose affects MOS devices can be found in [5], and how the dose affects individual components of the image readout process in [6]. High energy radiation such as gamma-rays can also cause single effect events, such as latch-up, which can lead to pixel failure[7].
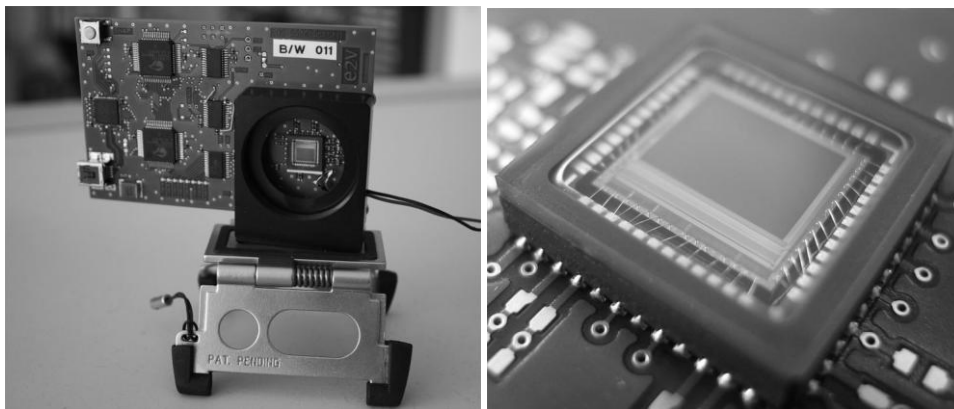
2. SETUP

Figure 1. Photographs showing the CMOS chip on demonstration board (left), and close-up of the chip (right)

The imagers used for this study are 0.5 Mpixel arrays of 5T 6×6 μm pixels, manufactured using a 0.18 μm process, and were provided by e2v technologies plc. based in Chelmsford, UK. Examples of the chip and readout boards are shown in Figure 1. The pixels have no advanced structures designed to mitigate radiation damage, so the results of this study will show a baseline of radiation hardness for the design and process used.

The off-chip USB interface is a large limiting factor on this work – until a more sophisticated readout board can be obtained, voltage shift measurements are almost impossible to obtain through the demonstration board, due to restrictions in the programmed functionality of the USB interface. Another limiting factor of these chips for the resolution of spectroscopy work is that the on-chip slope ADCs are only 8-bit, which is shown to be a limiting factor. However, the chips are capable of 60 fps, facilitating the capture of a large amount of data.
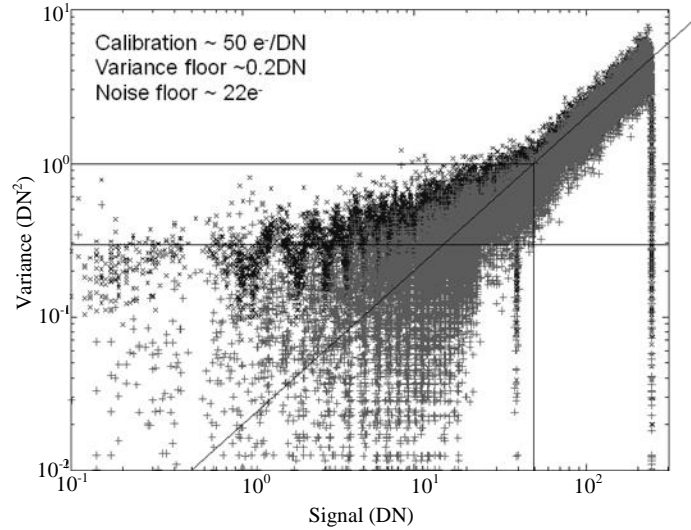

Figure 2. Typical photon transfer curve for these devices, showing full PTC (black), and PTC with read noise subtracted (grey)

Figure 2 shows a typical photon transfer plot for this range of sensors. It was obtained using a low level light source and increasing integration time. Points are plotted for each pixel. The curve indicates a calibration of 50 e$^-$.ADU^{-1}, sensor noise of 22 e$^-$ r.m.s. and a full well capacity of ~13 ke$^-$. The spread in variance at low signal levels is due to noise quantization, because of the low number of (and hence large) ADC bins.

3. DOSIMETRY

In all cases, the readout boards on the devices were shielded from damage by 3 mm thick lead sheets, often overlapping in places.

Device BW 206 was irradiated at Harwell with Co^{60} gamma radiation to a total of 450 krad(Si) at a rate of 6 krad(Si).hr^{-1} whilst biased. Communications with the device were lost after a total dose of 120 krad(Si) was deposited, a small area of the demonstration readout board was left unshielded, so damage to both the readout board and to the chip must be considered. Analysis of the possible mechanisms of this failure is discussed later in the paper.

Device BW 204 was irradiated at Harwell with Co^{60} gamma radiation to a total dose of 20.8 krad(Si) at 10.4 krad(Si).hr^{-1}, and the demonstration readout board was fully shielded. However the device had previously been irradiated to 5.5 krad(Si) of 44 MeV protons (5x10^9 10 MeV eq. protons.cm^{-2}) over half of the image area. Analysis of this device is limited to the half of the imaging area not irradiated by protons.

Three other devices were irradiated during this run, and were irradiated whilst unbiased to doses of 5.2, 10.4 and 20.8 krad(Si) respectively, but these have been unable to be analysed thus far.

All dosimetry was carried out by facility staff and errors in dosimetry are believed to be better than ±10%.
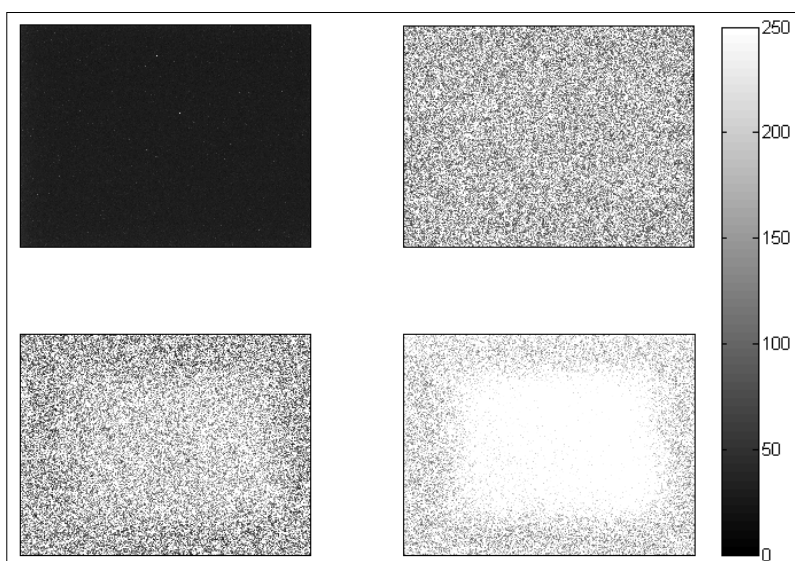
4. RESULTS

Figure 3. Still frames obtained during Co^{60} irradiation of chip BW 206 at 0 krad(Si) (no gamma flux), 0 krad(Si) (gamma flux incident), 30 krad(Si) (gamma flux incident), and 80 krad(Si) (gamma flux incident). (Top left, top right, bottom left, bottom right, respectively).

Figure 3 shows several images captured during the irradiation of chip BW 206. The gamma flux is apparent as a uniform noise across the whole sensor. As the irradiation progresses, it becomes apparent that the signal in the centre of the imaging area is increasing at a greater rate than that in the border of the imaging area, as the uniform gamma flux becomes more and more non-uniform, a similar effect is seen in some STAR-250 irradiations[8]. As the dose approaches 120 krad(Si), the device becomes completely saturated over the whole device. At this point in the irradiation, communication with the device were lost, either due to a failure of the chip, or due to failure in the un-shielded area of the readout board.
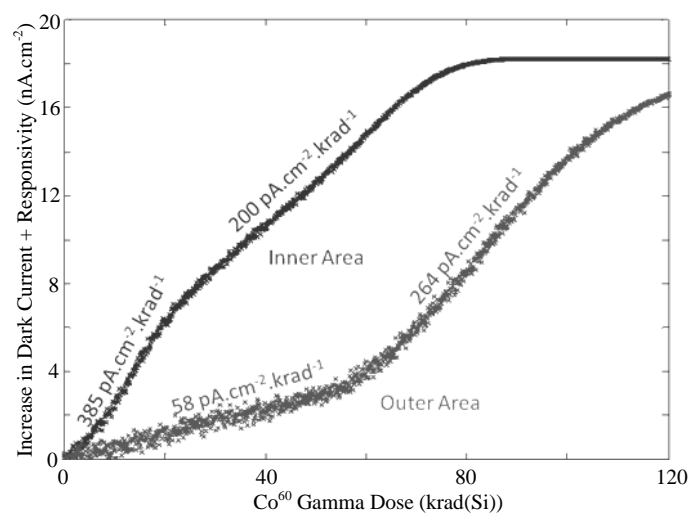

Figure 4. Measurements of the dark current for inner bright area, and outer area, during irradiation.

Figure 4 shows measurements taken at intervals of 0.1 krad(Si) during the irradiation, and plotted as an average over the inner and outer areas of the device. The inner area of the device shows a much higher increase in non-uniformity of the signal than the outer area, especially for the first 25 krad(Si). The outer area, in contrast, shows a high degree of radiation hardness up to 60 krad(Si), then begins to become damaged more quickly, equalling

or exceeding the rate of damage experienced by the inner area. The device becomes fully saturated at around 80 krad(Si) in the inner area, hence the slope returning to 0 at that point.

The quickly growing non-uniformity in the gamma flux observed in these images could be as a result of three seperate effects: a non-uniform increase in dark current, a non-uniform increase in responsivity, or a non-uniform increase in signal due to the irradiation of the unshielded area of the readout board. As the device is no longer responsive, it's very difficult to decouple these separate effects, to determine which may be the more significant cause, and to compare to other work.
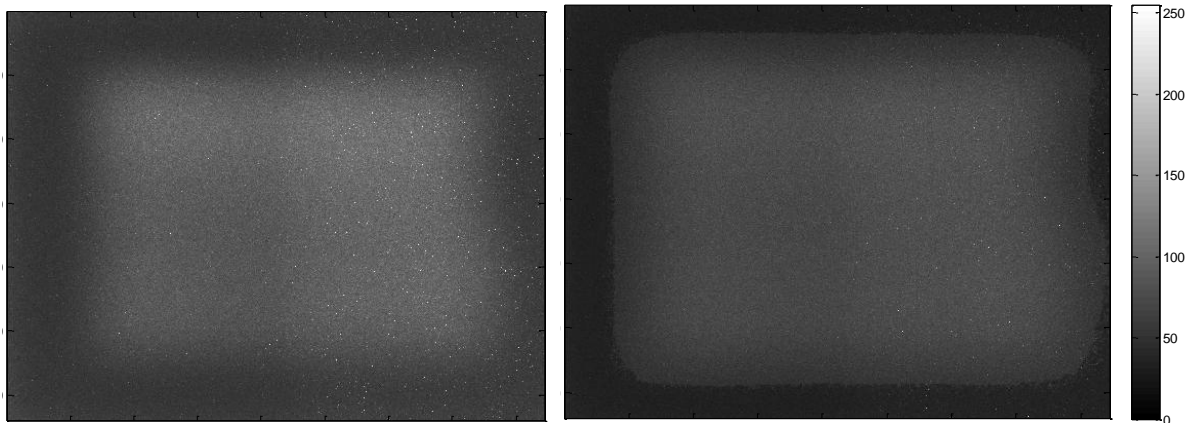

Figure 5. Dark image of chip BW 204 showing dark current non-uniformity immediately after 20 krad(Si) of irradiation (left), and after a further 6 months of annealing at room temperature (right).

Figure 5 shows the dark current pattern on a chip irradiated to 20 krad(Si) before and after 6 months of annealing at room temperature. The non-uniformity is very similar to that shown in the previous test to 120 krad(Si), and the bleeding on the right hand side of the images can be explained by prior irradiation by protons on the right hand side of the chip. It can be seen that after anneal, the dark current pattern becomes much less diffuse, and resembles glue or some similar material providing dose enhancement effects.

However, the device has been analysed for any non-uniformity of dose over the device due to underlying structure or shielding effects. No match has been found between the positioning of this dark current non-uniformity and any structural feature on the chip. As the dark current non-uniformity is central to the uniformity, and the position of the imaging area is not central to the chip (see figure 1), this suggests that the pattern of radiation damage is central to the manufacture of the imaging area, and not due to any shielding or enhancing effects. The actual reason for the enhanced dark current in the centre of the device is not understood – and is suspected to be due to the manufacture of the imaging area at the foundry level.
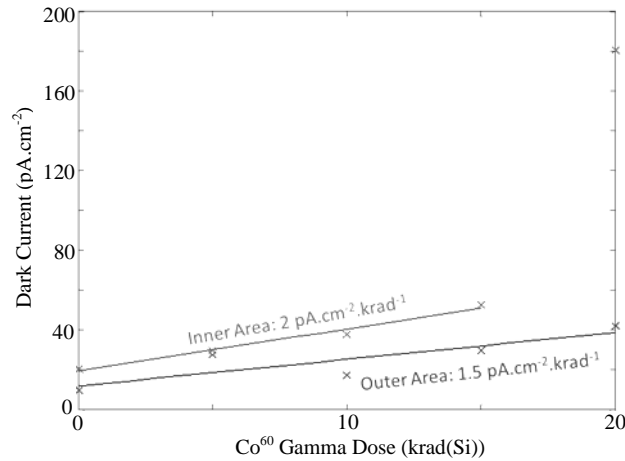
Figure 6. Plot showing average dark current with increasing radiation dose over the inner area (grey), and outer area (black)

Figure 6 shows the dark current measured at different stages during the irradiation of chip BW 204. It can be seen that much lower dark current figures are measured than were seen in Figure 4, which suggests that much of the increase in non-uniformity is due to an increase in either responsivity to the gamma radiation, or damage to the readout board. However it's also clear that the non-uniform increase in dark current is still a factor, as the inner area of the image area increases in dark current more quickly than the outer area (and shows a very large jump between 15 and 20 krad(Si)). This plot also shows the radiation hardness of CMOS technology, with even the inner area showing an increase in dark current of only 2 pA.cm^{-2}.krad(Si)$^{-1}$. We can compare this to a similar CCD not optimized for radiation hardness such as the e2v CCD57-10, which in partially inverted mode showed an increase in dark current of 30 pA.cm^{-2}.krad(Si)$^{-1[9]}$. The outer area shows an even lower measurement of 1.5 pA.cm^{-2}.krad(Si)$^{-1}$ with no sudden jump after 15 krad(Si).
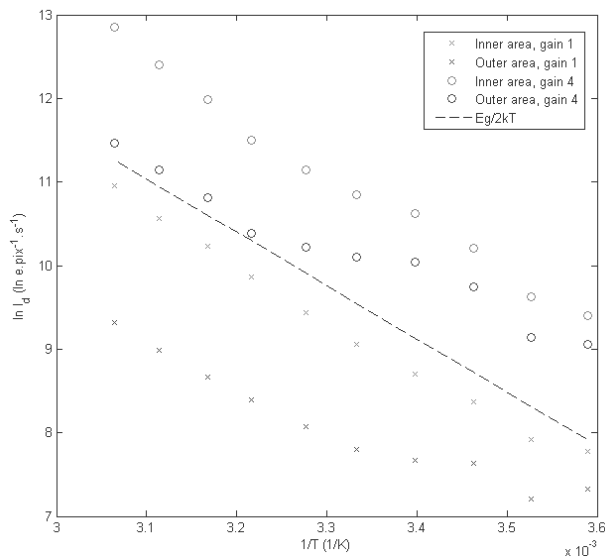

Figure 7. Shows behaviour of ln I_d against 1/T for inner and outer areas (circle and cross markers) at gains of 1 and 4 (black and grey)

Figure 7 shows that, in both regions of the imaging areas, the dark current follows the relationship:

$$I_d \propto e^{-Eg/2kT}$$

especially at high temperatures where there is more signal. The outer area shows less adherence to the trend at lower temperatures – but this could be attributed to the very low signals at low temperatures in the more

radiation hard area, thus increasing the fractional error. It does suggest that there may be a systematic effect; however it is not currently understood.

There have been recent results, that show that the dark current non-uniformity is not present on an identical device (however, back illuminated) that has been irradiated to 100 krad whilst *unbiased*[10]. This strongly suggests that the dark current non-uniformity is linked to the biased nature of the irradiation. The exact mechanisms of the central brightening are still being investigated.

5. CONCLUSIONS

Two CMOS imaging devices from e2v technologies plc. were irradiated with Co^{60} gamma radiation to 450 krad(Si) and 20.8 krad(Si). The first device stopped responding after receiving a dose of 120 krad, and showed non-uniform damage to the imaging area. The second device was then irradiated and showed the same effect present as dark current uniformity. The effect is measured and is now undergoing further investigation.

The results presented in this paper confirm the radiation-hardness of CMOS imaging devices to gamma radiation even when no specific rad-hard design has been implemented. However it has also been shown that in some cases the increase in dark current can be non-uniform for reasons not yet understood. Understanding why the outer area is more radiation hard will allow future designs to avoid exhibiting this non-uniformity and will allow production of a device showing uniform radiation hardness.

Following further design to the electrode i.e. providing a radiation-hard design will further improve the radiation hardness of these devices and make them very suitable for low-resolution, but medium radiation-hard applications, for example lunar or Martian rover navigation cameras. This application is especially appealing, as the problem of non-uniform dark current increase will not be an issue, as the device will not be operational until arrival at the lunar/Martian surface.

6. FURTHER WORK

The three devices that were irradiated unbiased are still to be analysed, due to difficulties getting them onto readout electronics. Being able to confirm that these devices show no central brightening effect will indicate that the effect is due to biasing of the chip during irradiation. Further gamma irradiations are planned to investigate possible causes of the central brightening effect, and identify possible mechanisms.

e2v technologies are producing a new generation of these devices, with a larger imaging area, smaller pixels and higher resolution ADCs, but otherwise similar architecture. This new generation should be tested for similar effects to help understand the mechanism for non-uniform dark current generation.

Two further devices have been irradiated over half of the image area with protons, and characterisation of these radiation damage effects will appear in a future paper. Work is planned to investigate single event effects in the devices due to heavy ions, and the damage caused by high energy electrons such as that in Jupiter's radiation environment. This work will help to complete the radiation damage picture of these and similar devices.

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