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Total Ionizing Dose Effects on 4-Transistor CMOS Image Sensor Pixels

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***Abstract*—This work presents a study on the degradation mechanism of 4T CMOS Image Sensors (CIS) induced by X-Rays irradiation. The degradation is mainly demonstrated by measurements of increased dark signal and dark random noise. The radiation affects the sensor's behavior differently for different reset voltages and transfer gate control, which is evaluated in detail. The basic failure mechanism is presented and it shows that the radiation induced increase of random telegraph signal noise and dark random noise is mostly originated from the Si-SiO_2 interface trap generation. Meanwhile, the charge trapping in the shallow trench isolation oxide (STI) is responsible for the post-irradiation dark signal increase as well. It is also illustrated that the post-irradiation pinned photodiode (PPD) and the transfer gate will obviously contribute to the sensor degradation as a post-irradiation dark signal and noise source.**

Keywords-4T CMOS Image Sensor; X-Rays irradiation; dark signal; dark random noise; pinned photodiode; interface trap; STI;

I. INTRODUCTION

Nowadays, the solid state imagers are playing a more and more important role in the space and medical applications, such as earth observation, satellite tracking sensor, medical imaging and so on. Even though charge coupled device (CCD) image sensors are still the preference choice in applications where high-quality imaging is required, CMOS active pixel sensors (APS) are getting a booming and promising future for their applications in a radiation environment. CMOS image sensors generally have higher radiation tolerance. A lot of studies about radiation characterization of 3-Transistor (3T) CMOS image sensors (CIS) have been carried out[1]-[3]. However, there is very few work that has been done on the radiation effects on 4T APS by now. Due to the pinned photodiode and the transfer gate transistor, the 4T APS has a different pixel architecture and operation mechanism from 3T ones, which necessitates the investigation of the radiation effects on 4T pixels[4].

In this paper, an initial insight of radiation induced degradation mechanism on 4T CIS is presented. In section III, the responses of the dark signal and dark random noise to radiation damage are described respectively in terms of the histogram shift and mean dark signal variation. Finally, some effective hardening-by-design technologies are discussed as well to improve the sensor's radiation tolerance.

II. TEST STRUCTURE AND EXPERIMENTAL DETAILS

The sensor used for the measurements in this work is fabricated in a commercially available 0.18μm technology and has integrated 150×197 pixels of 10μm pixel pitch. The sensor's output is converted from analog signals to digital ones by an off-chip 12-bit analog-to-digital converter (ADC). Correlated double sampling (CDS) is also performed to reduce the fixed pattern noise, kTC reset noise and 1/f noise. The measurements are processed with a unity analog sensor gain. As shown in Fig. 1 the schematic of a 4T APS pixel consists of a reset transistor (RST), a source follower (SF), a row selector (RS), a transfer gate (TG) and a pinned photodiode.

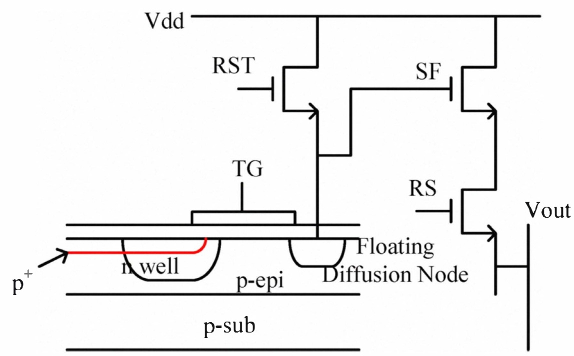

Figure 1. Schematic of a 4T APS structure

The transfer-gate transistor takes the pinned photodiode as its source region and is overlapping with the pinning layer of the PPD, where there is a high electric field distribution due to the PPD p^+ pinning layer doping profile.

The test sensors are irradiated by an X-Ray source at Philips Health Care at room temperature, reaching a total ionizing dose (TID) level of 30krad and 60krad after 2-turn radiation. During radiation the sensors are not electrically biased. The sensors are measured 3.5 days after the irradiation, while there is an extra measurement done shortly after the first radiation turn in order to characterize the effect of room temperature annealing.

III. RADIATION DEGRADATION ON 4T CMOS IMAGE SENSORS

A. Radiation Induced Dark Signal Increase

Differing from 3T pixels, the 4T pixel has a transfer gate which can disconnect the PPD from the other transistors of the pixel. Thus two types of measurements are accomplished. In one measurement the TG is on while

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in the other measurement the TG is in the off-state. This allows for separating the dark signal increase coming either only from the in-pixel MOSFETs or from the transistors plus the PPD and TG regions, respectively. Fig.2 shows the dark signal histogram with the radiation dose level of 30krad and 60krad from the sensor measurements at 360ms integration time with the transfer gate on and off.

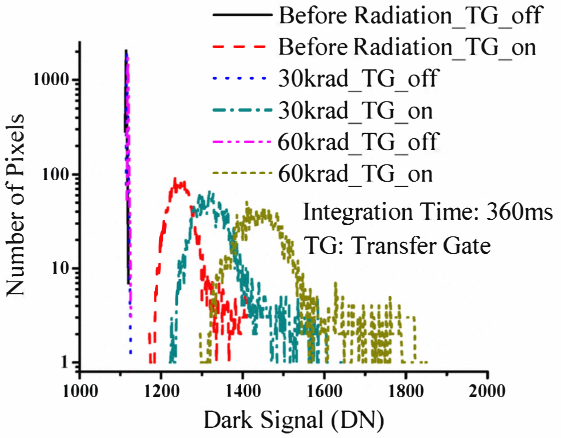

Figure 2. Dark signal histogram with radiation dose level and with the transfer gate (TG) on and off

It can be seen in Fig. 2 that when the TG is turned on from the off-state, the histogram shifts to the right side with a larger digital number (DN) and distributes wider, which is due to the dark signal increase from the PPD. After the radiation level of 30krad and 60krad, it also shows a right shift and a wider distribution of the histogram in the case of TG on and off respectively, indicating the increase of radiation induced dark signal. After the radiation, the trapped charges in the STI oxide will help to form a lateral leakage path through a parasitic field oxide transistor within one MOSFET and inter-devices, which to some extent raises the dark signal[5]. Meanwhile, the trapped charges in the STI oxide around the PPD expand its depletion region at the diode's boundaries and after the radiation damage some extra generation centers are introduced, which makes the dark signal higher as well[6][7]. As a result, the post-irradiation PPD becomes contributing to the dark signal.

However, the dark signal variations in the cases with TG off and on are obviously different. When the TG is off, the dark signal is mainly measured from the in-pixel MOSFETs, and it demonstrates a tiny post-irradiation dark signal histogram shift. Comparing with the measurements where the PPD and TG contribute to the dark signal, the influence of post-irradiation leakage current increase of in-pixel MOSFETs is relatively small on the sensor's dark signal degradation. In conclusion, the PPD has a major effect on the dark signal increase after the radiation damage.

Fig. 3 shows the mean dark signal with the increase of integration time before and after radiation. It is supposed in Fig. 3 that the mean dark signal increases linearly with the integration time of the PPD when the TG is turned on. After the radiation, the slope of the increasing dark signal is getting steeper. As mentioned previously, in the PPD the interface trap generation and the amount of generation centers in the depletion regions induced by oxide trapped charges are getting larger with the TID dose[6]. Thus, with the same integration time, the post-irradiation dark signal has a larger ascending and the slope is rising.

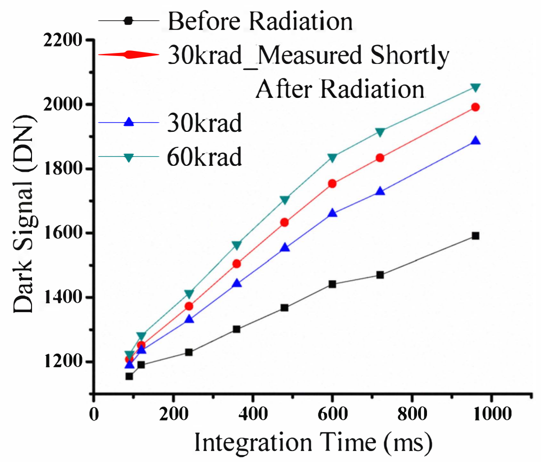

Figure 3. Mean dark signal with integration time before and after radiation

What is worth mentioning in Fig. 3 is that after 30krad, one group of data is measured shortly after radiation while the other is measured after 3.5 days at the room temperature. It can be seen that the latter shows a lower slope than the former one, which means that number of dark signal generation centers is much larger immediately after radiation and some trapped charges and generation centers can be annealed out later on[8].

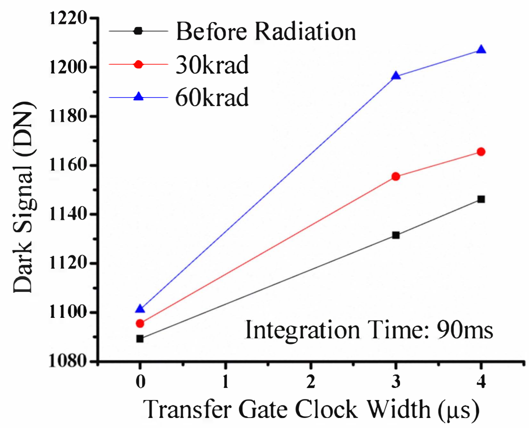

Figure 4. Mean dark signal with transfer gate clock width before and after radiation for the integration of 90ms

Fig. 4 shows the effect of the transfer gate clock width on the post-irradiation mean dark signal. The result of 0μs-width clock is measured when the TG is off while the other two are taken with the TG on having different clock width. In 4T pixels, there is a high electric field distribution at the overlapping region between the PPD and the TG, which induces impact ionization and thus becomes a dark signal source[9]. As shown in Fig. 4, with the increase of transfer gate clock width, the mean dark signal is going up. With the increase of pulse width, the electrical stress at that overlapping region is getting larger which will generate more defects and dark signals there. However, after radiation, it can be seen in Fig.4 that the relative increase of dark signal induced by the clock width extending is getting smaller with the increasing TID dose. When the TID dose level is getting higher, the dark signal increase originating from the PPD and transistors is going up and later on it becomes dominant over the dark signal induced from the electrical stress of the transfer gate clock width. Thus, the effect on the dark signal from a longer TG clock width is reduced.

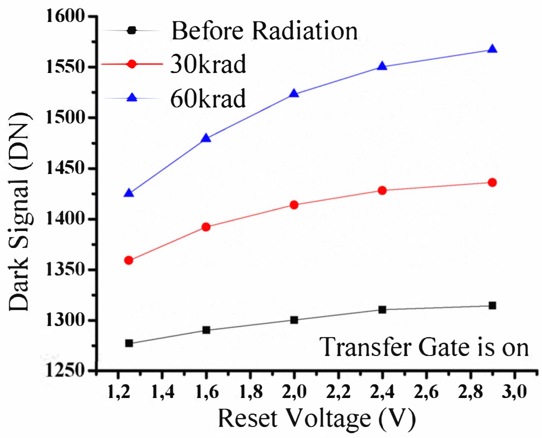

Figure 5. Mean dark signal with reset voltages before and after radiation with an integration time of 360ms

By reducing the reset voltage on the reset transistor gate, the bias point on the floating diffusion node will come down correspondently and as a result the sensor's output decreases as well[10]. Fig. 5 shows the decrease of dark signal with the declining reset voltages before and after radiation.

It can be seen in Fig. 5 that the slope of the dark signal increase with the reset voltage is going higher after 2-turn radiation and the relative variation of the mean dark signal between 2.9V and 1.25V is becoming larger as well. Based on the previous results, the pinning layer of the PPD may be damaged and its depletion region nearby the STI oxide is expanded after the radiation damage[6]. In the case of post-irradiation soft reset with 1.25V, some charges will be retained in the PPD and then the sensor's output is reduced to some extent. Therefore, in the soft-reset case, the dark signal increase with TID is lower than that of the hard-reset case, which shows a large relative-variation of the dark signal after the radiation when comparing between different reset voltages.

B. Radiation Characterization of Dark Random Noise

As mentioned previously, the ionizing radiation will introduce some trapped charges in the STI oxide together with some interface trap generation, which can be confirmed with the post-irradiation dark signal increase measured with TG on and off[7]. Moreover, the device noise performance is closely related to its interface traps, particularly for the random telegraph signal (RTS) noise[11]. In this subsection, the sensor's dark random noise will be studied to evaluate the radiation damage on the sensor from a different aspect.

When the TG is turned off, the transfer gate will exclude the noise from the TG and PPD. Then, the noise measured mainly comes from the source follower and the reset transistor. The noise of the source follower will change with its gate bias points, which can be modified by the reset voltage in the pixel[12]. Therefore, the dark random noise histogram with TG off is measured by applying different voltages on the reset gate before and after radiation. The noise histogram tail presents the RTS noise induced by interface trap generation[11].

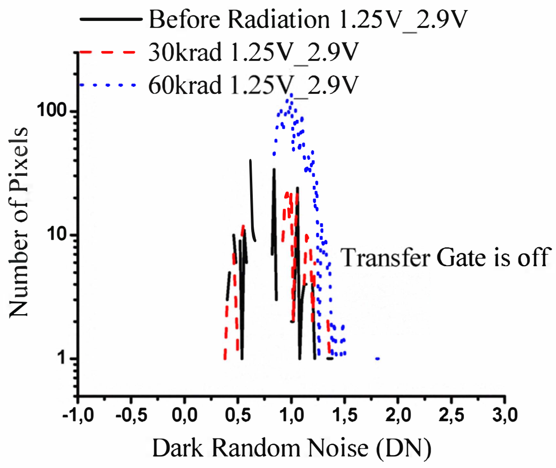

Figure 6. Histogram of dark random noise increase between measurements at the reset voltage of 1.25V and 2.9V and with the transfer gate off

Fig.6 shows the post-irradiation increase in dark random noise histogram measured with the reset voltages of 1.25V and 2.9V and with TG off. The increase of dark random noise mostly comes from the tail of the original noise histogram, therefore it mainly consists of RTS noise. It can be seen in Fig. 6 that it is shifting to the right-up side with a larger DN after radiation. Since the measurement is done with TG off, thus it demonstrates that the relative dark random noise from the source follower and the reset transistor is becoming larger, which means the increase of the interface trap generation induced by the radiation damage.

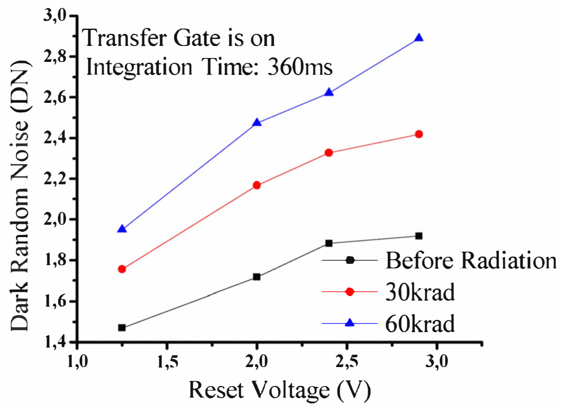

Figure 7. Mean dark random noise with reset voltages before and after radiation measured with TG on and an integration time of 360ms

However, due to the current advanced CMOS technology, the post-irradiation noise increase from the transistors in the pixel is still small. Since the PPD has a size of $53\mu m^2$ over $100\ \mu m^2$ pixel area and its pinning layer used to reduce interface traps and dark current can be damaged by the X-Rays radiation, it will become a major dark random noise source after radiation.

Fig. 7 shows the mean dark random noise increase with the reset voltage before and after radiation, which is measured with an integration time of 360ms and TG on. It can be seen firstly that the dark random noise is proportionally increasing with the reset voltage by its biasing at the floating diffusion node[12]. Furthermore, the post-irradiation PPD has some extra interface traps regenerated after the radiation. Thus, when the TG is turned on, together with the post-irradiation noise performance of the in-pixel transistors, the dark random noise of the pixel goes up rather obviously as shown in Fig. 7.

IV. CONCLUSIONS

The 4T CMOS image sensors are irradiated up to 60krad in order to evaluate the radiation induced failure mechanism on sensor's dark signal and dark random noise.

With the TG on and off, the study of post-irradiation dark signal increase from the PPD and the TG and from the in-pixel MOSFETs can be clarified. It was found that the post-irradiation dark signal increase coming from the transistor's leakage current increase is small, while the PPD and the TG are the main contributions to make the dark signal up after the radiation. It is because of the formation of a lateral leakage path through a parasitic field oxide transistor induced by the trapped charges in the STI oxide from the radiation that makes the dark signal rise to some extent. Meanwhile, these trapped charges in the STI oxide which surrounds the PPD can also expand its depletion region and have more generation centers to raise the dark signal. Moreover, the post-irradiation interface trap generation also plays a role to increase the dark signal. The high electric field distribution at the overlapping region between PPD and TG is a major dark signal source as well. The electrical stress from the TG clock width is a dominant issue to increase the dark signal before radiation while due to a large dark signal degradation from the PPD after radiation, this electrical stress induced relative dark signal variation is reduced. The reset voltages can be used to modify the sensor output, and the post-irradiation soft reset will suppress the dark signal increase a little bit.

As for the sensors' dark random noise, it is shown that the radiation induced interface trap generation in the in-pixel devices gives an increased RTS noise behavior. Furthermore, the reset voltage can also be used to modify the sensor's dark random noise and from the measurements it shows that the post-irradiation PPD becomes a noise source in the pixel as well.

In order to make CMOS image sensors more tolerant to the radiation, a p-well guard can be used to isolate the active regions from the STI oxide. Moreover, some attention can also be paid to reduce the electric field nearby the transfer gate. From the device point of view, p-channel MOSFETs can be used to replace n-channel ones in order to strengthen the radiation tolerance of the whole sensor.

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