Investigation of X-Ray Damage Effects on 4T CMOS Image Sensors

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***Abstract*—This paper presents a study on the radiation-induced trapped charges and the pixel parameter degradation of a 4T CMOS image sensor through the pixel bias voltage technique and trap-annealing. The bias voltage during the radiation has an effect on the yield of oxide trapped charges. The post-radiation shallow trapped charges can be quickly annealed at room temperature. The pixel dark random noise is recovered by annealing the positive trapped charges, while a subsequent annealing causes the pixel noise to rebound by means of the interface traps.**

Keywords-CMOS image sensor; radiation; pixel bias; trapped charges; annealing; dark random noise

I. INTRODUCTION

Radiation degradation studies on 4T CMOS image sensors are becoming increasingly popular. The 4T pixel is a promising candidate for application in space remote sensing, medical imaging, etc., because the 4T pixel presents a low dark current due to the pinned photodiode. Moreover, it is inherently radiation-tolerant due to the thin gate oxide in the CMOS technologies [1]. Ionizing-radiation induced dark current increase is always a major evaluated degradation parameter in irradiated CMOS imagers [1][2]. Most of the previous work has mainly focused on non-biased radiation. However, the effect of the pixel bias condition during radiation on the sensor degradation is very important because the sensors are mostly in working mode when applied in the harsh radiation environment. The radiation-induced trapped charges in the oxide are also highly dependent on the pixel bias conditions [3]. Moreover, the annealing of the radiated 4T imager has not been studied very well because the annealing effect highly depends on the specific fabrication process, the pixel design and the radiation setting [2][4]. Therefore, this work will present a study on the pixel bias condition effect of the 4T imager radiation degradation by analyzing the radiation-induced trapped charges and interface traps. Furthermore, the effect of post-radiation annealing of the sensor at room temperature and at 85°C is investigated as well.

II. RESULTS AND DISCUSSION

Three sensors were irradiated to 5.76krad and 8krad simultaneously by X-Rays with an average energy of 46.2keV. The dose rate was 0.32rad/s. A different bias voltage was applied to each sensor during the radiation. During the latter measurements, the temperature increased from 303K to 345K in increments of 3K. The high measurement temperature had very little influence over the annealing of the irradiated devices since the measurement time was as short as 60sec. The annealing was implemented at 85°C without electrical bias for 75 hours and for 150 hours.

Fig. 1 illustrates a 4T pixel schematic with a cross section of the pinned photodiode (PPD), the transfer gate (TG) and the reset transistor (RST). The 4T pixel is composed of a PPD, a TG, a RST, a row selector transistor (RS) and a source follower (SF). A high electric field distribution exists at the overlap region of PPD-TG, which can worsen the radiation degradation [1]. When the sensor is biased during the radiation, the positive TG pulse strengthens the generation of the surface defects in the transfer-channel under the TG and at the PPD-TG region. As a result, more surface generation current from the TG region contributes to the post-radiation pixel dark signal compared to the non-biased case. Moreover, with the pixel bias during the radiation, the charge-trapping at the lateral shallow trench isolation oxide (STI) surrounding the in-pixel MOSFETs is enhanced. The enhanced charge trapping ultimately leads to a larger pixel dark signal as well. As illustrated in Fig. 1, a larger pixel bias means a higher reset voltage on the floating diffusion node and the SF gate. Therefore, when biased during the radiation, the number of trapped charges is intensified in the lateral STI oxide around the floating diffusion node and the source follower. The details of the pixel bias condition effect during the radiation will be discussed further in the following sections.

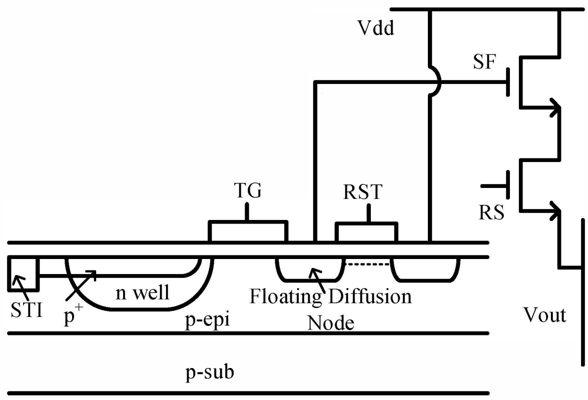

Figure 1. A 4T pixel schematic with the cross section of the PPD, the TG and the RST.

Fig. 2 shows the dark signal increasing with the radiation dose. The measurements were taken after each radiation dose increment of 0.384krad while at doses of 5.76krad and 8krad, the dark signal was measured two times, right after the radiation and after 1.5-day of room temperature annealing. During the radiation, the sensor was biased at 3V, however, during the room temperature annealing, the sensor was not electrically biased. Therefore, Fig. 2 also shows a big drop in the dark signal at the 5.76krad-dose and the 8krad-dose when measured 1.5 days after the irradiation. This drop can firstly be explained by the fact that some of the positive trapped charges are compensated by the negatively charged interface traps right after the radiation. The post-radiation interface trap generation takes place more slowly than the radiation-induced hole trapping in the STI, which follows a slower time-scale [3]. Hence, when the X-Ray radiation is finished, some of the trapped charges generated during the radiation are latterly recombined or compensated with negative interface traps. Since the number of trapped charges decreases after radiation due to the interface trap effect, the dark signal, which is induced by the post-radiation trapped charges [2], drops down when measured 1.5 days later. On the other hand, with a positive 3V-bias, most of the radiation-induced holes can hop to the Si-SiO_2 interface. That is where some trapped holes induce shallow trap levels. When settled at the room temperature for 1.5 days, some electrons from the substrate can tunnel to the radiation-induced shallow trap levels and neutralize them [3][5][6]. Thus, the post-radiation dark signal is annealed down at room temperature. For these two reasons, the drop of the dark signal at 5.76krad and 8krad is very obvious, as shown in Fig. 2.

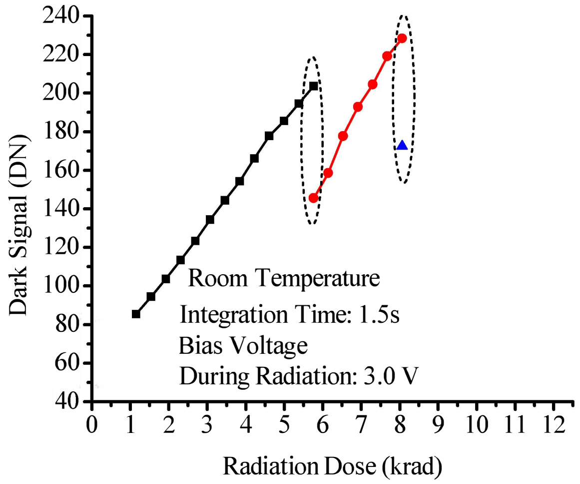

Figure 2. Dark signal versus radiation dose measured during the irradiation and 1.5 days later.

The effect of the electric field on the post-radiation trapped charges in the oxide can be investigated by measurements at different pixel bias conditions during the radiation.

Fig. 3 shows the relative increase in the post-radiation dark signal with different pixel bias voltages. Three different sensors were respectively biased with 2.4V, 3.0V and 3.3V during the radiation, while being measured after each 0.384krad radiation. The measurement time was 30sec, which is short enough to eliminate annealing effects from the measurement results. Fig. 3 shows that a smaller bias voltage induces a lower relative increase in the dark signal, while the difference between 3.0V and 3.3V is minor. The electric field distribution within the pixel is strengthened when a large bias voltage is applied. When the pixel is biased with a larger voltage and is radiated, there are more holes that can escape the initial electron-hole recombination. As a result, a larger number of holes is trapped in the same volume of oxide with a larger bias voltage [3][7]. These trapped charges not only form inter-device lateral parasitic leakage paths in the pixel but also expand the depletion regions for extra generation centers [2]. Thus, the dark signal of the sensor ultimately becomes relatively larger due to the larger number of electric-field enhanced trapped charges in the shallow trench isolation oxide caused by a larger bias voltage.

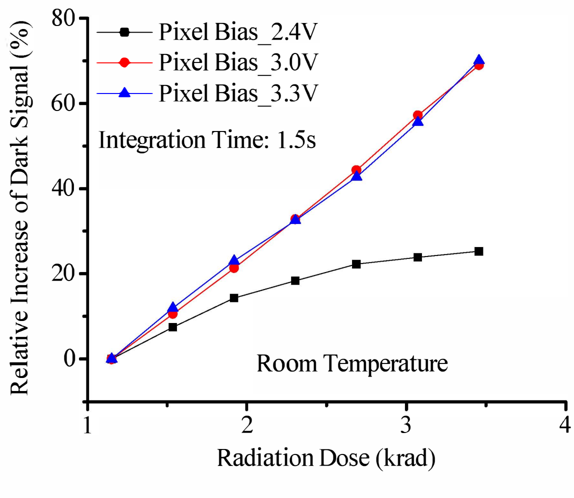

Figure 3. Pixel bias voltage effect on the relative dark signal increase with radiation doses.

Some hydrogen may be present in the oxide due to process necessity. According to [3], the radiation-induced holes can hop through the oxide, which in the meantime frees the hydrogen in the oxide to become protons. The protons then undergo a transport. When the protons reach the Si-SiO_2, they break the SiH bonds and form an interface trap. Therefore, a larger positive bias during the radiation may move more protons to the oxide interface and create more interface traps. As mentioned above, the negative interface trap can compensate the positive trapped charges, which can recover the pixel dark signal. Hence, on the one hand, a larger pixel bias can induce more trapped positive charges in the STI during the radiation. The pixel dark signal increases further due to more trapped positive charges. On the other hand, more negatively charged interface traps due to a larger bias can also greatly decrease the dark signal through the trapped charge recombination. If the aforementioned two effects take place simultaneously, a large relative increase in dark signal due to a larger bias will not be clearly observed. However, Fig. 3 still shows that during the radiation a larger bias can induce a clear, large relative increase in the dark signal. Therefore, the trapped charges generated during the radiation by a certain pixel bias, which induce the dark signal increase, are not diminished by the interface traps. Fig. 3 accordingly illustrates that the interface trap building-up does follow a slower time-scale than that of trapped charges. Moreover, during the radiation the dark signal may initially be dominated by the generation of positive trapped charges.

Table I presents a comparison of the pixel parameter degradation between a 3V-biased radiation and non-biased radiation. Clearly, the 3V pixel bias leads to a more severe degradation on the pixel dark signal and activation energy than the non-biased case according to the above discussion. The lowering of the activation energy after radiation is also a mutual impact factor for the increase in the dark signal.

TABEL I. COMPARISON OF BIAS EFFECT ON SENSOR RADIATION DEGRADATION

	5.76krad radiation-induced relative increase in dark signal	5.76krad radiation-induced decrease in activation energy
With 3V bias	143.3%	0.13eV
Without bias	79.5%	0.02eV

As discussed above, the pixel bias voltage during the radiation can affect radiation-induced trapped charges and interface trap generation, which causes the sensor activation energy and dark signal to degrade. Next, the pixel supply voltage effect on the trap level of a radiated sensor is shown. Fig. 4 shows the mean activation energy of a pixel array as a function of the pixel supply voltage before and after radiation. Here the pixel was biased with 3V during the radiation, while it was measured with 3V and 2.7V for the pixel supply voltage.

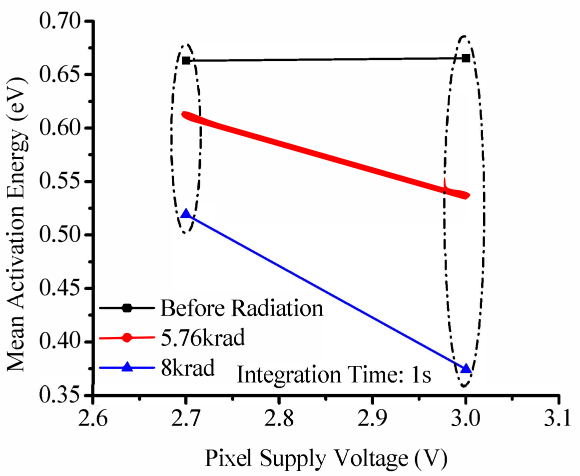

Figure 4. Mean activation energy with pixel supply voltage measured before and after radiation.

It can be seen that before radiation there is almost no change in the mean activation energy with the pixel supply voltage. However, after radiation the activation energy difference between 2.7V and 3.0V becomes larger. This difference is probably due to the increased shallow trap level generation in the band gap induced by the radiation. When a larger voltage on the pixel is applied, the band gap at the Si-SiO_2 surface bends more downwards and the energy difference between the valance band (E_V) and Fermi level (E_F) becomes larger [5]. More radiation-induced shallow defects are filled and then the dark signal increases exponentially due to the carrier density's exponential dependence on the energy difference of (E_F-E_V) [5]. As a result, the activation energy measured as a derivation from the dark current lowers with a large pixel supply voltage.

The previous study discussed the radiation-induced degradation of the sensor by the oxide trapped charge and the interface trap generation. Annealing is another tool to resolve the role of the trapped charge and interface traps in a radiated sensor.

Fig. 5 shows the annealing effect on the dark random noise of a radiated sensor after an 8krad dose. The measurement was taken after 75 hours and 150 hours, respectively, of isothermal annealing at 85^{0}C. The dark random noise histogram is analyzed here because the noise histogram tail of the sensor, as indicated in Fig. 5, refers to the 1/f noise and the RTS (Random Telegraph Signal) noise performance of the sensor. The 1/f noise in radiated MOS devices is related to the oxide trap neutralization through charge exchange and the interface trap trapping and de-trapping [6]. Meanwhile, the dark random noise of 4T imagers is deduced from the dark signal measurement. The dark signal variation of a radiated sensor is correlated with the trapped charges and interface traps in the STI oxide. Therefore, when annealing is studied for a radiated sensor, the variation in the tail of the dark random noise histogram can be used to investigate the annealing effect on the oxide trapped charges and interface traps.

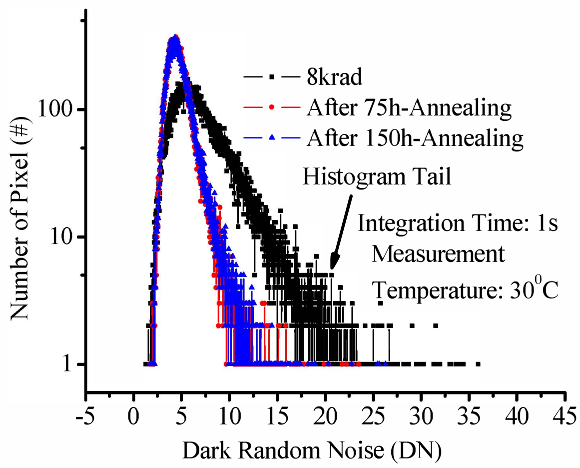

Figure 5. Annealing of the dark random noise for 75 hours and 150 hours at 85^{o}C on an irradiated sensor.

Fig. 5 shows that the tail of the dark random noise histogram shrinks and the pixel dark random noise also becomes smaller after annealing. In addition, the discrete pixels with a very large noise value between 23 DN and 35

DN have disappeared. As for a radiated sensor, the dark random noise is highly related to the oxide trapped charges [6]. Therefore, after a 75-hour annealing, many trapped charges in the oxide have been annealed out. They recombine with the electrons from the p-substrate and are neutralized through charge exchange and thermal excitation [3][6].

However, when the sensor is further annealed for another 75 hours, the histogram tail after a 150-hour annealing even shows another small increase. Some pixels with a very large dark random noise reappear. This effect can be explained as follows: most of the positive trapped charges have been annealed after a 150-hour annealing, while most of the radiation-induced interface trap still remain because the annealing temperature is low [2][3][4]. Right after radiation, part of the negative interface traps can already be compensated by the positive trapped charge near the $Si\text{-}SiO_2$ interface. However, when most of the positive trapped charges have been annealed out, the net interface trap generation increases compared to the case after a 75-hour annealing. Thus, the interface trap generation causes the dark random noise to rebound by interface trapping and de-trapping, which results in some pixels showing a large dark random noise again.

III. Summary and Conclusion

The X-Ray radiation-induced degradation on 4T CMOS imagers has been analyzed here, with regard to the sensor dark signal and the activation energy, by means of the variation in the pixel bias conditions and annealing. It has been found that a larger pixel bias voltage during radiation can lead to more severe dark signal and dark noise degradation. This is because the initial fraction of radiation-induced trapped charges in the oxide can be higher than it would be without the bias due to the larger pixel bias. A non-biased radiated sensor shows much less of a dark signal increase and less radiation-induced lowering of activation energy compared to a biased sensor. A larger pixel supply voltage for the post-radiation measurement also shows an effect on the activation energy lowering due to the band-gap bending and the corresponding shallow defects filling-induced dark signal increase. Moreover, the negative interface trap compensation and the following shallow trap neutralization through the electron tunnelling from the substrate at room temperature can quickly lower the dark signal 1.5 days after the radiation. A high temperature annealing at 85°C for 75 hours effectively removes many radiation-induced trapped charges. However, after a 150-hour annealing, the dark random noise increases again because most of the trapped charges are annealed out, after which the non-annealed interface traps try to rebound the dark random noise.

This study can provide an overview of how the 4T CMOS image sensor degradation is influenced by its working mode in a radiation environment. A lower pixel voltage can mitigate the radiation damage. An effective annealing at 85°C for 75 hours can be proposed to recover the degraded sensor, while an over-annealing may cause the sensor to degrade again.

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