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Degradation and annealing studies on gamma rays irradiated COTS PPD CISs at different dose rates

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ABSTRACT

The degradation and annealing studies on Colbalt-60 gamma-rays irradiated commercial-off-the-shelf (COTS) pinned photodiode (PPD) CMOS image sensors (CISs) at the various dose rates are presented. The irradiation experiments of COTS PPD CISs are carried out at 0.3, 3.0 and 30.0 rad(Si)/s. The COTS PPD CISs are manufactured using a standard 0.18-μm CMOS technology with four-transistor pixel PPD architecture. The behavior of the tested CISs shows a remarkable degradation after irradiation and differs in the dose rates. The dark current, dark signal non-uniformity (DSNU), random noise, saturation output, signal to noise ratio (SNR), and dynamic range (DR) versus the total ionizing dose (TID) at the various dose rates are investigated. The tendency of dark current, DSNU, and random noise increase and saturation output, SNR, and DR to decrease at 3.0 rad(Si)/s are far greater than those at 0.3 and 30.0 rad(Si)/s. The damage mechanisms caused by TID irradiation at the various dose rates are also analyzed. The annealing tests are carried out at room temperature with unbiased conditions after irradiation.

1. Introduction

CMOS image sensors (CISs) which are made in a standard very large scale integration (VLSI) technology have been used as an alternative to charge coupled devices (CCDs) in imaging and detecting for particle tracking in high-energy physics, space detector application in satellites, X-ray imaging in medicine, etc. [1–6]. Though CISs generally show a higher radiation tolerance than CCDs, CISs as well as CCDs are susceptible to the radiation damage as the total ionizing dose (TID) damage, displacement dose (DD) damage, and single event transient (SET) damage.

TID damage induces the performance degradation and even being functional failure of CISs, so this damage is still one of the most concerns of radiation effects on CISs with the development of the pixel architectures. Evans et al. have investigated the ionizing radiation effects in Monolithic CMOS active pixel sensors [7]. Goiffon et al. have presented TID versus DD damage in the CISs induced by proton radiation and dark signal increase induced by TID damage in 3 T conventional pixels and 4 T pinned photodiode (PPD) pixels of CISs [8–10]. Zujun Wang et al. have reported the degradation of 3 T CISs manufactured in 0.35-μm technology induced by TID irradiation at 0.2 and 50.0 rad(Si)/s and biased conditions [11]. Though several articles have investigated TID-induced degradation on CISs, fewer papers have focused on the dose rate effects on CISs and annealing test.

This article examines the TID radiation effects on the PPD CISs at various dose rates. The irradiation tests are carried out at the ^{60}Co γ-ray source. The CISs are manufactured in 0.18-μm process with 4 T PPD pixels. The degradation of the tested CISs induced by TID damage differs in the dose rates. The dark current, dark signal non-uniformity (DSNU), random noise, signal to noise ratio (SNR), saturation output, and dynamic range (DR) versus the TID and annealing time at the various dose rates are investigated. The degradation mechanisms of CISs induced by TID damage are also demonstrated and the annealing effects which are tested at room temperature with unbiased conditions after irradiation are also discussed.

2. Experimental details

Six COTS CISs are irradiated by ^{60}Co γ rays (at Northwest Institute of Nuclear Technology, China). The CISs have the serial number from A01 to A06, and all the samples come from the same batch. The samples are irradiated at 0.3, 3.0, and 30.0 rad(Si)/s. The dose rates are calibrated by PTW-UNIDOS before the irradiation test and then the CISs are placed in device under test (DUT). The samples are unbiased with all pins grounded during irradiation.

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0168-9002/

Table 1
TID irradiation experiment conditions and the serial number of the tested samples.

CIS number	Bias condition	Dose rate (rad(Si)/s)	Total dose (krad(Si))
A01, A02	Unbiased	30.0	150
A03, A04	Unbiased	3.0	150
A05, A06	Unbiased	0.3	150

The TID irradiation experiment conditions and the serial number of the tested samples are presented in Table 1. The CISs are measured at a CIS parameter test system within 60 min after each irradiation step. The CISs are measured at the accumulated doses of 50, 100, and 150 krad(Si) during irradiation tests. The performance of the CISs is measured pre- and post-irradiation as the European Machine Vision Association (EMVA) 1288 standard.

The annealing tests are performed at room temperature with unbiased conditions. The performance of the CISs after ^{60}Co γ rays irradiation is tested after annealing at 24 h, 48 h and 168 h. The sums of annealing time and irradiation time at 30.0 or 3.0 rad(Si)/s are also carried out to equal the irradiation time at 0.3 rad(Si)/s.

The Samples used in these experiments are made by CMOSIS. The CISs exhibit high sensitivity and low noise. The CISs are manufactured in the standard 0.18-μm CIS technology. The image arrays of the CISs consist of 648 × 488 pixels. The pixel architecture is 8 T global shutter pixel with CDS based on a 4 T PPD front end. The simplified cross section of PPD which includes the pre-metal dielectric (PMD), shallow trench isolation (STI), gate oxide, transfer gate (TG) and space charge region (SCR) is show in Fig. 1 [12]. The size of the pixel is 7.4 × 7.4 μm^2. The image sensor has a 12 bit ADC output at maximum frame rate of 300 frames/s [13].

3. Results and discussion

3.1. Dark current increase

The dark current stands for the signal response when an image sensor such as a CCD and CIS is not exposed to light, which is expressed in e/s/pixel or nA/cm^2. The main reason for the dark current are thermally induced electrons. Therefore, the dark current should increase linearly with the exposure time [14]. As the EMVA1288 standard, the dark current is given as [14]

$$\mu_d = \mu_{d0} + \mu_I t_{exp} \quad (1)$$

where μ_I is the dark current, μ_{d0} is the average number electrons without light for exposure time zero, μ_d is the average number electrons present without light, t_{exp} is the exposure time.

The dark current increase in the CIS induced by TID damage is a key issue because the dark current is very sensitive to the TID which is known to induce large dark current increase in an image

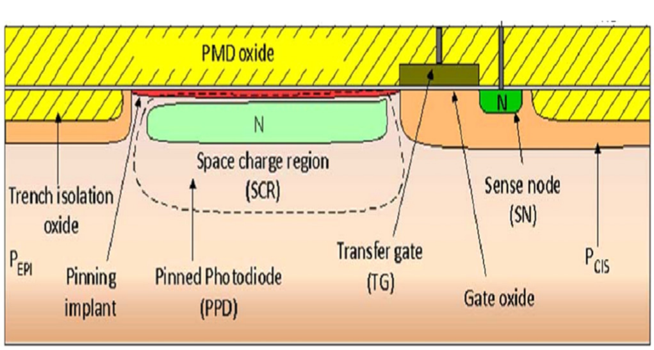

Fig. 1. The simplified PPD pixel cross section [12].

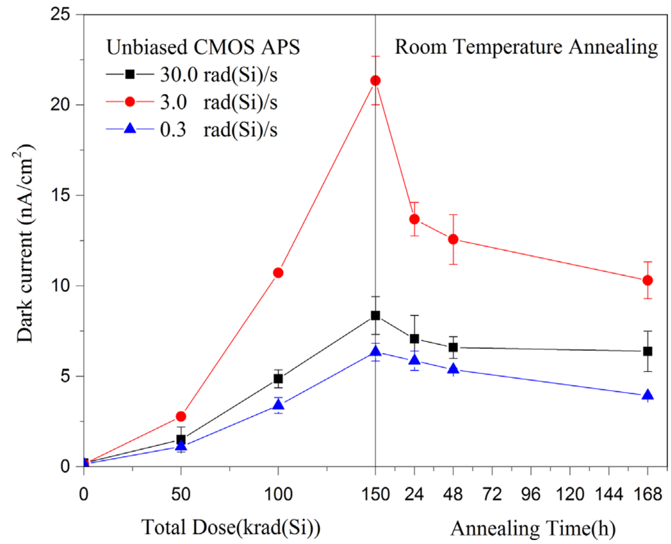

Fig. 2. Dark current versus the TID and annealing time at 0.3, 3.0 and 30.0 rad(Si)/s.

sensor. The dark currents in the CISs versus the TID and annealing time at the various dose rates are shown in Fig. 2. The dark current increases with increasing TID. The increase of dark current is caused by the trapped positive charges and the interface states induced by TID damage at the PMD, STI, TG, nitride spacer and gate oxide. Goiffon et al. have advanced two possible mechanisms of dark current increase caused by TID damage: (1) the spread of the SCR in PPD pixels to the PMD oxide induced by trapped positive charges; (2) the diffusion current contribution induced by interface states is larger than that originating neutral volume [15].

When the TID are lower than 50 krad(Si), the dark current increases slightly. However, when the TID are higher than 50 krad (Si), the dark current increases obviously. This is because the ionizing irradiation damage becomes worse with the TID accumulation. Ionizing irradiation causes an increase in the density of interfaces, which induces an increase in the dark current generation rate. At lower TID, the SCR does not extend the ambient PMD and STI, and therefore the increase of dark current caused by TID damage is very small. However, at higher TID, the SCR can extend to the ambient PMD and STI in which the trapped positive charges and interface states caused by TID damage are rich [10].

The tendency of dark current increase varies with the different dose rates as shown in Fig. 2. The tendency of dark current increase at 3.0 rad(Si)/s shows far greater than those at 0.3 and 30.0 rad(Si)/s. The dark current degradation is mainly due to the integrative actions of the interface states and the trapped positive charges in the PMD, STI, TG, nitride spacer and gate oxide. The different quantity of the generation of interface states and trapped positive charges in the PMD, STI, TG, nitride spacer and gate oxide at various dose rates may induce the tendency discrepancy.

A large amount of the trapped positive charges build up rapidly while the interface states have had insufficient time to build up at 30.0 rad(Si)/s. A substantial proportion of the trapped positive charges are neutralized while the interface states have had sufficient time to build up at 0.3 rad(Si)/s during irradiation. However, some neutralization of the trapped positive charges will take place and some buildup of interface states will also occur at 3.0 rad(Si)/s. When the irradiation experiments are carried out at a moderate dose rate such as 3.0 rad(Si)/s, both the quantity of the interface states and the trapped positive charges can induce the significant influence of the CIS performance. Thus, the dark current degradation at 3.0 rad(Si)/s shows the most severe.

Fig. 2 also illustrates the dark current versus annealing time at various dose rates. The dark current exhibits a remarkable