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Proton and Gamma Radiation Effects on a Fully Depleted Pinned Photodiode CMOS Image Sensor

Xiao Meng, Konstantin D. Stefanov, *Member, IEEE*, and Andrew D. Holland

Abstract— The radiation hardness of a fully depleted Pinned Photodiode (PPD) CMOS image sensor (CIS) has been evaluated with gamma and proton irradiations. The sensors employ an additional n-type implant in pixel which allows full depletion to be achieved by reverse biasing the substrate, and have been irradiated alongside reference devices in which the implant has been omitted. The results show no visible degradation of the sensor's radiation hardness by the additional implant. The main degraded parameters caused by ionizing radiation, from both gamma and proton irradiation, are the image lag and the surface dark current. High dark current in the sense node (SN) is identified and is found to be caused by the shallow trench isolation (STI) around the SN. The dark current increase after proton irradiation has been shown to be dominated by displacement damage induced bulk defects and the value is consistent with those from other PPD CISs in literature. The charge collection efficiency is not significantly affected by the bulk traps even after 10 MeV-equivalent proton fluence of up to 10^{12} p/cm². However, the ionizing damage from the highest proton fluence reached causes a considerable drop in the charge-to-voltage conversion factor.

Index Terms—CMOS image sensor (CIS), pinned photodiode (PPD), full depletion, radiation damage, total ionizing dose (TID), displacement damage dose (DDD).

I. INTRODUCTION

PINNED Photodiode (PPD) CMOS image sensors (CIS) are now used in a wide range of imaging applications such as Time-of-Flight (ToF) ranging, space remote sensing and particle detection, in addition to consumer imaging, owing to their excellent performance, particularly in terms of dark current and noise [1],[2]. As an attractive candidate for applications in radiation environment, especially for space applications, the PPD CIS has been extensively studied to understand their radiation hardness [3]–[6]. Among these studies, the effects of both ionizing [3],[4] and non-ionizing damage [5],[6] on PPD CISs have been investigated. Radiation

Fig. 1. Cross sectional view of the fully depleted PPD pixel design.

effects on 3T-based CISs have also been reported in earlier studies [7]–[9]. Despite the different pixel structures of PPD and 3T CISs, some of the findings from studies on 3T CISs provide valuable insights regarding their common features, such as the shallow trench isolation (STI), the region surrounding the photodiode and the transistors in the readout chain.

Despite the excellent performance of PPD CISs, they have two main limitations: low quantum efficiency (QE) at near-infrared (NIR) wavelengths and for soft X-rays due to their thin depleted region (e.g. a few micrometers), and relatively slow charge transfer time. Therefore, for applications requiring high QE and high speed, hybrid CISs [10] and fully depleted CCD [11] have been routinely used.

Recently, a new PPD CIS design that can be fully depleted by applying reverse substrate bias has been demonstrated [12],[13]. This allows very thick sensitive volumes to be depleted, and has the potential to deliver the same QE as the hybrid CISs and CCDs while maintaining the advantages of monolithic PPD CISs.

This work is intended to provide a study on the radiation hardness of this fully depleted PPD CIS. Gamma and proton irradiations have been used to examine both the ionizing and non-ionizing radiation effects on the full well capacity (FWC), charge-to-voltage conversion factor (CVF), dark current, readout noise and image lag. In addition, X-ray spectra from a ⁵⁵Fe source are used to investigate the sensor's charge

TABLE I
IRRADIATION PARAMETERS

Design variants	Irradiation	10 MeV-equivalent fluence (p/cm ²)	DDD ^a (TeV/g)	TID ^b (krad)
Ref.	Gamma	-	-	100
/DDE1	Proton	10 ¹⁰	94	3.9
/DDE2	Proton	10 ¹¹	940	39
	Proton	10 ¹²	9400	390

^aCalculated using non-ionizing energy loss (NIEL) data from [14]

^bCalculated using ionizing energy loss (IEL) data from [15]

collection behavior. In Section II, we describe the sensor design and irradiation conditions. Section III focuses on the characterization results before and after irradiation. More detailed discussions on the dark current degradation are presented in Section IV.

II. EXPERIMENTAL DETAILS

A. Sensor Design

The sensors studied here are PPD CISs designed with full depletion capability as detailed in [12] and manufactured on a commercial 180 nm CIS process [13]. Fig. 1 shows the cross section of the pixel design in which an additional deep n-type implant, named “deep depletion extension” (DDE), is added to the manufacturing process to eliminate the parasitic substrate current caused by the backside bias voltage. In order to compare the influence of the DDE on sensor’s radiation hardness, devices having the same pixel designs but without the DDE were used as reference.

B. Irradiations

Table I lists the irradiation conditions for all the tested sensors. For each irradiation, sensors with three different designs were tested. The reference device (labelled Ref.) is the design without the DDE implant. DDE1 and DDE2 are designs with DDE implants with medium and deep depths, respectively. Gamma irradiations were performed using the ⁶⁰Co cell at Brunel University, UK, for a total dose of 100 krad(Si). Proton irradiations were performed at the MC40 cyclotron facility at the University of Birmingham. Sensors were exposed to three 10 MeV-equivalent proton fluences: 10¹⁰, 10¹¹ and 10¹² protons/cm² (hereafter denoted as p/cm²). During both gamma and proton irradiations the sensors were unbiased with all pins shorted.

III. RESULTS

A. Electro-optical characteristics

This section describes the impact of irradiation on the electro-optical performance of the sensor. The FWC of the sensor can be characterized by the saturation level of the photo-response curve, where the output signal reaches its maximum as the illumination continues to increase. Another important sensor parameter, the CVF, is calculated by fitting the linear region of the mean variance curve (MVC) [16] to a straight line.

Fig. 2 presents the photo-response and the MVC obtained from a DDE1 device before and after gamma irradiation. It can be seen that the slopes of both curves remain unchanged after radiation, which means that the sensor’s linearity and CVF are

Fig. 2. Photo-response curve (a); and mean-variance curve from a gamma-irradiated DDE1 device (b), measured with light with a wavelength of 624 nm.

not affected at this radiation level. However, the output saturation level in Fig. 2(a) has clearly increased, and the peak of the variance in the MVC in Fig. 2(b) has moved towards higher signal.

Fig. 3(a) compares the change of the saturation levels after different irradiations in the three device variants. Both gamma and proton irradiations have increased the saturation level. This increase is not believed to be caused by the displacement damage dose (DDD) since gamma rays induce little displacement damage. It should also be noted that the trend of saturation level increase follows the increasing total ionizing dose (TID) of different irradiations. Since the TID is well-known to cause negative shift in the threshold voltage (V_{th}) in n-channel MOSFETs [17], the increase of the saturation level could be due to the lowering of the transistor thresholds. By probing the output signal using an oscilloscope, it was found that the maximum output signal is indeed limited by the on-chip readout circuitry. We concluded that after ionizing radiation, the V_{th} shift of the in-pixel transistors was responsible for the increase of the voltage swing of the readout chain and hence the saturation level. Similar results have been observed on a proton-irradiated PPD CIS in [18].

Fig. 3(b) shows that there is no significant change of the CVF

Fig. 3. Saturation level (a) and CVF (b) from all three sensor variants before and after irradiation.

after all irradiations, except for the 10¹² p/cm² proton fluence. The CVF reduction after the highest proton fluence could be due to degradation from either the SN capacitance or the source follower gain [19]. Results from [20] suggests that the TID-induced positive charges in the STI could form a conduction path between the SN and the surrounding n⁺ regions which increases the node capacitance, resulting in a lower CVF. Further evidence to support this hypothesis is presented in Section IV.A. Another possible cause for the CVF drop is the reduced source follower gain, because the electron mobility is known to degrade after TID due to the impeding effect from the interface traps in the channel of the MOSFETs [21],[22]. Lower carrier mobility will lead to lower transconductance g_m and hence reduced source follower gain A_V according to the following equations [23]:

$$g_m = \sqrt{2\mu_n C_{ox} (W/L) I_D} \quad (1)$$

$$A_V = g_m R_s / (1 + g_m R_s) \quad (2)$$

where μ_n is the electron mobility, C_{ox} is the oxide capacitance, I_D is the drain current, R_s is the load resistance, and W and L are the gate width and length, respectively.

Measuring the electrical transfer function (ETF) [7] of the readout chain can determine the source follower gain and the exact cause of the CVF reduction. Unfortunately, our pixel design does not allow this measurement since the drain terminals of the reset transistor and the source follower are connected. However, it should be noted that both of the two

Fig. 4. Temperature dependent mean dark current of all variants before and after different irradiations.

Fig. 5. Dark current histogram at -20 °C of a DDE1 device variant before irradiation, and after gamma and proton irradiation.

possible causes (i.e. larger SN capacitance and lower source follower gain) are degradations caused by ionization damage. In addition, it has previously been shown that the CVF of PPD CISs remains the same even after a DDD of 1.2×10⁶ TeV/g [5] which is much higher than the range studied here. These allow us to conclude that the CVF reduction is a result of the high TID from the protons rather than their DDD.

B. Dark Current

Dark current is one of the main degraded sensor parameters due to irradiation. The activation energy of the dark current is a useful indicator to the origin of the dark current. The temperature dependence of the mean dark current of the studied devices, which enables the activation energy calculation, was measured and the result is shown in Fig. 4.

For the proton-irradiated devices, the activation energy of their mean dark current is between 0.60 eV and 0.63 eV, which is close to the middle of Si bandgap, meaning that the Shockley Read Hall (SRH) recombination is the dominant mechanism responsible for the dark carrier generation [3],[6],[24]. A comparison of the DDD-induced dark current between devices studied here and other reported PPDs in literature is discussed in Section IV-B. Gamma-irradiated devices have shown very similar activation energies between 0 °C and 20 °C, but a lower value at temperatures below 0 °C. This lower activation energy

Fig. 6. Readout noise at $-40\text{ }^{\circ}\text{C}$ of three device variants measured before and after irradiation.

could be due to the field-enhanced emission (FEE) [25] possibly occurring under the transfer gate (TG) for PPD CISs [3],[6] which has been known to increase the dark current and lower the activation energy. For non-irradiated devices the dark current plateaus at about $1\text{ e}^-/\text{s}$ below $-10\text{ }^{\circ}\text{C}$. The reason for that is still unclear and requires further investigation.

The dark current histograms of a DDE1 device in Fig. 5 show significant hot pixel generation after proton irradiation, and near absence of hot pixels after gamma irradiation. This is consistent with many studies [3]-[6] and is expected.

C. Readout Noise

The readout noise was obtained from the standard deviation of the dark signal. It should be noted that the shot noise of the dark current in irradiated sensors usually dominates over the actual readout noise in the measured total noise [26]. Therefore, it is essential to reduce the dark current to its minimum before the readout noise measurement, for example by cooling. A different method possible in PPD imagers, and used in this study, is to disable the charge transfer to the SN by keeping the TG low. Fig. 6 shows the readout noise measured at $-40\text{ }^{\circ}\text{C}$, indicating no obvious degradation in all device variants in the irradiation range studied. While the readout noise in Fig. 6 differed insignificantly to that measured at $+20\text{ }^{\circ}\text{C}$, the lower temperature was chosen for the plot because it is more representative for imagers employed in scientific space missions.

D. Image Lag

In PPD CISs, photo-generated carriers collected in the PPD are not completely transferred to the SN even in non-irradiated sensors. Incomplete charge transfer happens due to several reasons: long diffusion time in the PPD, potential barrier or pocket at the PPD-TG edge, charge trapping under the TG and charge spill-back from the SN to the PPD [27], [28]. Image lag was measured as the signal in the first sensor readout in darkness following illumination at a defined level in the previous image. The contribution of the dark current is removed by subtracting the average of many images taken in darkness.

After gamma irradiation the image lag of all three device variants has increased as shown in Fig. 7(a) (note that DDE1 and DDE2 have very similar lag hence only the result from DDE1 is shown for clarity). The increased lag is most likely due

Fig. 7. Image lag comparison between the Reference and DDE1 devices before and after gamma irradiation (a); Image lag in a DDE1 device before and after proton irradiation (b).

to the potential pocket created by the positive charge induced by the TID in the TG spacer, which has been identified as the main TID-induced lag degradation in PPD CISs [4], [29]. Another obvious effect of the gamma radiation on the lag is that the signal level at which the lag abruptly increases has shifted to higher amplitudes. This shift corresponds to the increase of saturation level due to V_{th} shift as discussed in Section III-A. It can also be seen that the reference sensor has a higher lag even before irradiation. The reason for this is still not clear but is possibly due to the interaction between the DDE implant and the TG, which smooths out the potential profile at the PPD-TG edge.

Lag degradation was also observed in the proton-irradiated devices, as shown in Fig. 7(b). This is believed to be due to the ionizing damage from protons, because both the lag increase and the saturation level shifts seem to follow the TID level at different proton fluences.

E. Charge collection

Bulk defects induced by proton DDD are expected to reduce the charge collection efficiency by trapping charge in the field-free regions of the device. To study the charge collection efficiency, we observed the amplitude of the characteristic Mn-K_α X-ray peak before and after irradiation. An example of an ^{55}Fe X-ray spectrum obtained from a non-irradiated DDE1 device is shown in Fig. 8. Thanks to the low readout noise and dark current, the Mn-K_α and Mn-K_β peaks are well resolved

Fig. 8. ^{55}Fe X-ray spectrum obtained from a DDE1 device before irradiation. The backside bias applied was 0 V. The spectrum was obtained from isolated X-ray (i.e. single pixel) events.

Fig. 9. Mn- K_α peak amplitude from all three device variants before and after irradiation at 0 V backside bias.

with an FWHM resolution of about 200 eV. The characteristic Si fluorescence and escape peaks are also visible.

Fig. 9 shows the Mn- K_α peak amplitude obtained from the X-ray spectra of all three variants before and after irradiation. Gamma and proton irradiations at 100 krad, 10^{11} p/cm 2 and 10^{12} p/cm 2 show reduced peak amplitude, indicating charge loss due to bulk or ionization radiation damage effects, or both. After gamma irradiation and 10^{11} p/cm 2 proton fluence the peak amplitude has reduced by approximately 1% for all variants. This reduction can be explained by the image lag increase of about 1% at the signal level generated by Mn- K_α X-ray photons (i.e. around 1610 e $^-$) as shown in Fig. 7. Therefore, the apparent signal reduction seems to be due to the charge loss during the charge transfer process, rather than during charge collection. However, after 10^{12} p/cm 2 the peak amplitude has dropped by 13%, which is much larger than the 4% lag increase as shown in Fig. 7(b). One possible cause for this difference is the drop in the CVF at the highest proton fluence. In Fig. 3(b) we see that the TID from 10^{12} p/cm 2 protons leads to a CVF drop of around 10 %, which may well explain the large difference. Hence, the reduction of the peak amplitude is believed to be caused by the combined effect of lag increase and CVF drop by TID.

Previous studies [30], [31] have shown that the charge loss due to DDD-induced bulk traps can be reduced by increasing the depletion region and the electric field since the charge is

Fig. 10. Dark signal from a gamma-irradiated sensor as a function of the integration time. The red and black curves represent the dark signal obtained when the off-state of the reset gate voltage VRG_L is kept at 0 V and 0.5 V, respectively.

collected faster and the probability of trapping is diminished. However, applying a backside bias to the devices irradiated at 10^{12} p/cm 2 in this work did not increase the peak amplitude even when the sensor is fully depleted. This confirms that the peak amplitude reduction is the result of degradation from TID rather than lower charge collection efficiency caused by the DDD-induced bulk traps.

IV. DISCUSSION

A. Increased dark current at the sense node

The dark signal in gamma-irradiated sensors was found to increase at two different rates as the integration time increases, as shown in Fig. 10. When the integration time is longer than 400 ms, the slope of the dark signal curve suddenly increases from 455 e-/s to 55.5 ke-/s. Similar effect was observed in the proton-irradiated devices which have received high TID.

The high dark current can be explained by the spillover of dark carriers from the SN to the PPD as shown in Fig. 11. In a typical sensor operation, the charge will first collect in the PPD

Fig. 11. Illustration of the sensor operation using schematic potential diagrams (a) before and (b) after gamma irradiation. PPD is the pinned photodiode; TG is the transfer gate; SN is the sense node; RG is the reset gate and RD is the reset drain.

during the integration phase. Following that, the SN is reset through the reset transistor. Lastly, the collected charge is

Fig. 12. Simplified pixel layout and a cross section showing the exposed STI next to the sense node.

transferred from the PPD to the SN for readout. Normally, any residual carriers in the SN are drained away by resetting before readout. However, sensors exposed to high TID might have much higher dark current collecting at the SN, if the SN is near surface traps. At long integration times this high dark current can saturate the SN and spill over to the PPD. As shown in Fig. 11(b), the excess dark carriers spilled into the PPD will be transferred, subsequently read out, giving rise to the much higher observed dark current.

In order to verify this explanation, two dedicated measurements were carried out. In the first one, the low level of the reset gate voltage VRG_L was increased from 0 V to 0.5 V during integration. Fig. 10 shows that by doing that the higher dark current disappears. This is because increasing the reset gate potential partially turns on the reset transistor, which begins to act as an anti-blooming drain and removes the excess electrons before they overflow into the PPD. The second method utilized a different clock sequence in which the charge transfer from the PPD is disabled and only the SN dark current is measured instead. Fig. 10 shows that the SN dark current is nearly the same as the high dark current from the PPD at integration times above 400 ms. These two tests confirm that the higher dark current measured at long integration times originates from excess signal at the SN overflowing into the PPD. The excess signal from the SN did not influence the image lag measurements because the integration time was kept below 100 ms.

On closer examination of the pixel layout the most likely source of the high dark current at the SN was identified as the radiation-induced interface traps at the exposed edges of the STI. As shown in Fig. 12, the sense node is placed outside the p-well in order to reduce its capacitance and to increase the CVF of the sensor. The unintended effect of this design choice is that three STI edges next to the SN are not covered by a p-well. Following ionizing irradiation, large number of traps are introduced at the interface between the STI oxide and the epitaxial silicon. Large dark current is caused because the STI edge is depleted by the SN. Since the cause is understood, future radiation-hard designs can avoid this vulnerability by protecting all STI regions with a p-well at the expense of somewhat reduced CVF.

B. Dark current increase due to DDD

In Section III-B, the origin of the dark current from proton-irradiated devices is shown to be the generation-recombination (GR) centers. The exact location of the GR centers remains uncertain since they could be located either in the bulk region

Fig. 13. Mean dark current increase after different DDD. The UDF value is $K_d = 0.0887 e^- \square s^{-1} \square \mu m^{-3} \square (TeV/g)^{-1}$ which is obtained using one month annealing and measurement temperature of 20 °C.

Fig. 14. Mean dark current measured at increasing backside biases at 20 °C. The results are from DDE1 devices.

(due to DDD-induced bulk defects) or at the Si-SiO₂ interface (due to TID-induced interface traps).

The Universal Damage Factor (UDF) proposed by Srour [32] has been proved to be an effective tool to predict the DDD-induced dark current independently of particle type, energy and fluence [5], [9], [24]. However, it should be noted that because protons cause both DDD and TID, 3T pixels after proton irradiation have been shown to have higher dark current than the UDF prediction due to the extra TID-induced surface current. Proton-irradiated 4T pixels do not have this issue because the pinning implant greatly suppresses the surface current. The mean dark current increase in the studied sensors is calculated and compared with the UDF prediction in Fig. 13. The good agreement between the prediction and the experimental results implies that DDD-induced bulk defects are responsible for the dark current increase of proton-irradiated devices. This agreement also means that our PPD sensors are in line with the other reported PPD CISs with regard to their hardness to DDD.

Another method used to confirm that the proton-induced dark current originates from bulk defects is to observe the dark current dependence on the backside substrate bias. Fig. 14 shows that the dark current of a DDE1 device increases with the backside bias as the depletion region grows in depth and

includes larger number of bulk traps. This continues until around -4 V when full depletion is achieved, and no more traps are available. This behavior is observed in irradiated and non-irradiated devices because the dark current from surface states is almost fully suppressed.

V. CONCLUSION

A comprehensive characterization of the radiation hardness of a fully depleted PPD CIS is presented. Through comparison with reference sensors, the additional DDE implant applied to this sensor is shown to not affect the sensor's radiation hardness, making this design a competitive option for high radiation environments.

The increase of the dark current has been attributed mostly to bulk damage by proton irradiation and fits well with the UDF generalization. The charge collection efficiency is not affected at the highest reached fluence of 10^{12} cm^{-2} 10 MeV-equivalent protons. The increase of the image lag is consistent with buildup of positive charge caused by ionization by both gamma and proton irradiation. An additional source of surface damage at the sense node, causing high dark current and reduced CVF has been identified and fully understood. In future designs the STI region around the sense node can be fully protected by a p-well to suppress the surface current from interface states. Neutron irradiation will be carried out in the future to assess the DDD effects separately.

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