SCIENCE CHINA
Information Sciences

• HIGHLIGHT •
Special Focus on Reliability of Micro- and Nano-Electronic Devices in Harsh Environment

December 2017, Vol. 60 120402:1–120402:3
doi: 10.1007/s11432-017-9250-7

Research on proton radiation effects on CMOS image sensors with experimental and particle transport simulation methods

Yuanyuan XUE, Zujun WANG*, Minbo LIU, Baoping HE, Zhibin YAO,
Jiangkun SHENG, Wuying MA, Guantao DONG & Junshan JIN

State Key Laboratory of Intense Pulsed Irradiation Simulation and Effect, Northwest Institute of Nuclear Technology, Xi'an, 710024*, China*

Received July 15, 2017; accepted September 18, 2017; published online November 6, 2017

Citation Xue Y Y, Wang Z J, Liu M B, et al. Research on proton radiation effects on CMOS image sensors with experimental and particle transport simulation methods. Sci China Inf Sci, 2017, 60(12): 120402, doi: 10.1007/s11432-017-9250-7

Recently, complementary metal-oxide semiconductor image sensors (CISs) have become a key element of the imaging instrument and have been widely used in many scientific applications [1, 2] such as space remote sensing, medical imaging, and nuclear power plant monitoring. However, CISs used in these harsh radiation environments are susceptible to damage by particles or rays. This radiation damage includes the total ionizing dose (TID) damage, displacement dose (DD) damage, and single event transient (SET) damage. Damage by any of these would lead to image quality degradation or even functional failure. Therefore, in-deep analyses of the radiation effects on CISs are very important for the improvement of the performance of CISs under the radiation environments.

A great deal of research has been carried out to study the radiation effects on CISs in recent years. Raine et al. [3] have investigated the single DD damage effects on CISs using simulations based on Geant4. Belloir et al. [4] have reported the neutron, proton, and heavy ion radiation effects on the dark current spectroscopy of CISs. Wang et al. [5–7] have presented results on neutron and γ rays radiation effects on CISs. The TID and DD damage effects on CISs have been analyzed in detail.

Compared with the effects of gamma or neutron radiation, proton radiation effects are more complex. Not only the TID damage but also the DD damage must be included. However, only a few papers have focused on the proton radiation effects on the dark signal of CISs, specifically analyzing the damage caused by TID and DD.

In this article, the proton radiation effects on CISs are investigated. The degradation mechanisms of the dark signal induced by radiation are analyzed. Experiments with 3 and 10 MeV proton radiation are presented. In order to analyze the dark signal induced by TID and DD damage, ^{60}Co γ ray radiation experiments have also been performed. The dark signal and dark signal non-uniformity (DSNU) were measured both before and after the experiments. The Monte Carlo code Geant4 was used to simulate the proton radiation damage in the CIS. Combined with the proton radiation experiments, ^{60}Co γ ray radiation experiments, and Geant4 simulation results, the dark signal and DSNU degradation induced

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* Corresponding author (email: wangzujun@nint.ac.cn)
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by the protons with different energies and fluences were analyzed.

Mechanism. The dark current is the signal response when the CIS is not exposed to light [7]. The dark current mainly includes the bulk diffusion, surface leakage, and bulk currents [8]. Compared with the surface leakage and bulk currents, the bulk diffusion current can be neglected. Therefore, the dark current is equal to the surface leakage current plus bulk current.

TID and DD damage occurs after proton radiation. The TID and DD damage are mainly increased by the surface leakage and bulk currents, respectively. After the ^{60}Co γ rays radiation, the DD damage was neglected, and the dark current increase was mainly induced by the TID damage. As per the European Machine Vision Association (EMVA) 1288 standard, the dark signal is proportional to the dark current. Therefore, the mechanism of the dark signal was the same for the dark current.

Experiments. Two CISs (#1 and #2) were exposed to 3 and 10 MeV protons at the EN Tandem Van De Graaff accelerator in the State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China. The glass windows were taken off before the proton radiation. The flux of proton beams was 3.75×10^7 (p/cm^2·s). The proton fluence ranged from 10^{10} to 10^{11} p/cm^2. The dark signal and DSNU were measured both before and after the experiments by the evaluation board at room temperature. The CISs used in these experiments were 4 transistor (T) pinned photodiode (PPD) CISs and manufactured with the standard 0.18-μm CIS technology.

In order to analyze the radiation induced by the TID and DD damage, the ^{60}Co γ ray radiation experiments were also carried out at the Northwest Institute of Nuclear Technology. The CIS (#3) was irradiated at 50 rad(Si)/s and measured at accumulated doses of 30, 50, 100, 150 and 200 krad(Si).

Particle transport simulation. In order to analyze the dark signal and DSNU induced by the TID and DD damage, the Monte Carlo code Geant4 was used to calculate the TID and DD of the protons in the CIS. The simulation model was built according to the real pixel geometry, material and doping concentration. The pixel was modeled as a layered detector consisting of six different layers (passivation, silicon dioxide, aluminum, silicon dioxide, epitaxial and substrate). The sensitive volume of the CIS was the space charge region (SCR) and the width of SCR (W) is given as

$$W=\left\{\frac{2\varepsilon(V_{\rm bi}+V_{\rm R})}{\rm e}\left[\frac{N_{\rm a}+N_{\rm d}}{N_{\rm a}N_{\rm d}}\right]\right\}^{1/2}, \qquad (1)$$

where ε is the dielectric constant, $V_{\rm bi}$ is the built-in potential barrier, $V_{\rm R}$ is the magnitude of the applied reverse-biased voltage, e is the electron charge, $N_{\rm a}$ is the acceptor concentration, and $N_{\rm d}$ is the donor concentration. $V_{\rm R}$ is given by

$$V_{\rm R}=V_{\rm t}{\rm In}\left(\frac{N_{\rm a}N_{\rm d}}{n_{\rm i}^2}\right), \qquad (2)$$

where $V_{\rm t}=kT/{\rm e}$ is the thermal voltage, and $n_{\rm i}$ is the intrinsic carrier concentration.

The ionization and non-ionization interactions (nuclear elastic, nuclear inelastic, and Coulombic interaction) were considered in our simulation work. The DD in SCR and TID in the shallow trench isolation (STI) were simulated when the proton fluences were 1×10^{10}, 5×10^{10}, and 1×10^{11} p/cm^2 with the energies of 3 and 10 MeV.

Results. According to the ^{60}Co γ ray radiation experiments, there was threshold for the TID effects on CIS (TID$_{\rm th}$): When the TID was lower than TID$_{\rm th}$, the dark signal and DSNU were nearly not to be charged; when the TID was higher than TID$_{\rm th}$, the dark signal and DSNU increased with increasing TID. Therefore, a least-square fitting method was used to obtain the relationship between the TID and dark signal or DSNU. The TID$_{\rm th}$of the CIS was calculated, and the values of TID$_{\rm th}$ of the dark signal and DSNU were 44.6 krad(Si) and 45.6 krad(Si), respectively. The TID in the STI and DD in the SCR of CIS after 3 and 10 MeV protons radiation were calculated by Geant4. The dark signal and DSNU induced by the TID damage was then estimated. Combined with the proton radiation experiment results, the dark signal and DSNU induced by the TID and DD damage were analyzed, as shown in Table 1. The dark signal$_1$ was represent the dark signal increase induced by protons without the TID effects, and the DSNU$_1$ was represent the DSNU increase induced by protons without the TID effects.

From Table 1, one can see that after proton radiation, the dark signal and DSNU increased significantly with increasing proton fluence. The dark signal and DSNU degradation were more severe after radiation by 3 MeV protons. This is because both TID and DD of 3 MeV protons are larger than that of 10 MeV protons. When the proton fluence is 1×10^{10} p/cm^2, the TID damage has fewer effects on the dark signal. This is because the TID is lower than the TID$_{\rm th}$. However, with an increase in the fluence, the TID is larger than TID$_{\rm th}$,

Table 1 Calculated parameters

Proton energy (MeV)	Proton fluence (10^{10} p/cm^2)	TID krad(Si)	DD MeV/g	Dark signal DN	Dark signal (TID) DN	Dark signal$_1$ DN	DSNU DN	DSNU (TID) DN	DSNU$_1$ DN
3	1	23.5	2.44×10^8	121.1	0	121.1	146.2	0	146.2
3	5	117.5	1.22×10^9	551.3	183.8	367.5	310.2	10.0	300.2
3	10	235.0	2.44×10^9	1003.5	480.4	523.1	411.2	26.2	385.0
10	1	9.6	7.09×10^7	38.2	0	38.2	127.2	0	127.2
10	5	47.9	3.55×10^8	167.4	8.4	159.0	216.2	0.4	215.6
10	10	95.8	7.10×10^8	340.2	129.0	111.2	302.2	7.1	295.1

and affects the dark signal. When the CIS was irradiated by 3 and 10 MeV protons with a fluence of 1×10^{11} p/cm^2, the dark signal induced by the TID damage were 47.86% and 37.94%, respectively. Therefore, the TID damage could not be neglected when the CISs were irradiated by protons, especially when the proton energy was lower and the fluence was higher. Besides, from Table 1, one can also see that the TID damage had fewer effects on the DSNU of the CIS. Even though the CIS was irradiated with the 3 and 10 MeV protons with a fluence of 1×10^{11} p/cm^2, the DSNU induced by the TID damage were only 6.37% and 2.35%, respectively. As per the EMVA1288 standard, the DSNU is given by

$$\mu_{y,\mathrm{dark}} = \frac{1}{MN}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} y_{\mathrm{dark}}[m][n], \tag{3}$$

$$\mathrm{DSNU} = \sqrt{\frac{1}{MN-1}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left(y_{\mathrm{dark}}[m][n]-\mu_{y,\mathrm{dark}}\right)^2}, \tag{4}$$

where $\mu_{y,\mathrm{dark}}$ is the mean dark signal, M is the number of rows, and N is the number of columns of the CIS. $\mu_{y,\mathrm{dark}}[m][n]$ is the dark signal of the $[m][n]$ pixel. From (4), the DSNU represents the non-uniform distribution of the dark signal. After the ^{60}Co γ ray radiation (the TID is larger than the TID$_{\mathrm{th}}$), most of the pixels were affected by the radiation. The dark signal of each pixel is increased nearly the same. Therefore, the DSNU is not sensitive to the TID damage. Conversely, the DD damage induces many bulk defects in the sensitive volume of the CIS, which induces many dark signal spikes. The cross section, sensitive volume and proton fluence are small, so that the DD damage affects only some of the pixels, leading to a substantial increase in the DSNU.

Conclusion. In this work, we have analyzed the dark signal and DSNU of CISs induced by TID and DD damage after proton radiation. The proton radiation experiments and the ^{60}Co γ ray radiation experiments were carried out. The Monte Carlo code Genat4 was used to simulate the TID and DD of the protons in the CIS.

The dark signal and DSNU increased with increasing fluence. The dark signal and DSNU degradation were more severe after being irradiated by 3 MeV protons. After proton radiation, there was TID and DD damage in the CIS. There was a threshold of the TID effects on the CIS (TID$_{\mathrm{th}}$). The dark signal induced by TID could not be neglected especially when the proton fluence was higher or energy was lower. The DSNU induced by TID was much lower, compared with the DD damage effects. This work provided theoretical and experimental evidence for proton radiation effects on dark signals and DSNU of the CIS, and can be used to predict the degradation of the dark signal and DSNU of the CIS under complex proton radiation environments.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 11305126, 11235008) and Foundation of State Key Laboratory of China (Grant No. SKLIPR1211).

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