Analysis of proton and γ-ray radiation effects on CMOS active pixel sensors*

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Radiation effects on complementary metal–oxide–semiconductor (CMOS) active pixel sensors (APS) induced by proton and γ-ray are presented. The samples are manufactured with the standards of 0.35 μm CMOS technology. Two samples have been irradiated un-biased by 23 MeV protons with fluences of 1.43×10^{11} protons/cm^2 and 2.14×10^{11} protons/cm^2, respectively, while another sample has been exposed un-biased to 65 krad(Si) ^{60}Co γ-ray. The influences of radiation on the dark current, fixed-pattern noise under illumination, quantum efficiency, and conversion gain of the samples are investigated. The dark current, which increases drastically, is obtained by the theory based on thermal generation and the trap induced upon the irradiation. Both γ-ray and proton irradiation increase the non-uniformity of the signal, but the non-uniformity induced by protons is even worse. The degradation mechanisms of CMOS APS image sensors are analyzed, especially for the interaction induced by proton displacement damage and total ion dose (TID) damage.

Keywords: complementary metal–oxide–semiconductor (CMOS) active pixel sensor, dark current, fixed-pattern noise, quantum efficiency

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1. Introduction

Recent developments in complementary metal–oxide–semiconductor (CMOS) active pixel sensors (APS) indicate that CMOS imagers have reached or even exceeded the performance of charge-coupled devices (CCDs) in domains of low power consumption, high levels of integration, and low cost. Since CMOS APS can be used in applications with low light level (with few electrons) and extreme environment (especially for space, scientific, nuclear, medical, and military instruments applications), radiation damage of such applications becomes a primary concern.[1]

Important efforts have been made to reduce the radiation effect on CMOS APS during the last decade. It is known that that γ-ray irradiations can only induce ionization damage effects but proton irradiations induce both displacement damage and ionization damage effects.[2] Displacement damage effects are a key issue for solid state image sensors exposed to space radiation environments or used in nuclear physics experiments. Therefore, displacement damage effects on solid state image sensors are a subject of ongoing research,[3–5] particularly the degradation under illumination. Most of the previous work has been performed on devices in the dark during measurement,[6–11] which may hide some effects related to the photo-response of the devices.

In this paper, we compared the sensor performances under the radiation effects of proton and γ-ray. We studied the dark current, fixed-pattern noise under illumination (caused by the dark signal non-uniformity and photo-response non-uniformity), and conversion gain (CVG) of the sensors. The degradation mechanisms of CMOS APS image sensors were analyzed.

2. Experimental details

The device used for our test is Aptina™MT9M001 with an active imaging pixel array of 1280H×1024V. The image-sensing element has a pixel size of 5.2 μm × 5.2 μm. The typical dynamic range, the ratio of the maximum unsaturation signal to the minimum detectable signal, is 68.2 dB and the maximum signal-to-noise ratio (SNR) is 45 dB, which is dominated by the noise. The samples were manufactured with the standards of 0.35-μm CMOS technology.

The devices have been exposed to 23 MeV protons in un-biased condition with fluences of 1.43×10^{11} protons/cm^2 and 2.14×10^{11} protons/cm^2 (HI-13 tandem electrostatic ac-

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celerator at China Institute of Atomic Energy, Beijing, CNH). 23 MeV protons with fluences of 1.43×10^{11} protons/cm^2 and 2.14×10^{11} protons/cm^2 correspond to the total ionizing doses of 45 krad(Si) and 65 krad(Si), respectively. One device has been exposed un-biased to ^{60}Co γ-ray (at the Xinjiang Technical Institute of Physics & Chemistry, CAS, Urumqi, CHN) up to 65 krad(Si). All irradiations were performed at room temperature about 23 °C. The measurements were performed approximately immediately after irradiation. The irradiation conditions and devices are presented in Table 1.

Table 1. Irradiation conditions.

Device	Radiation type	Total ionizing dose/krad(Si)	Displacement damage dose/MeV·g^{-1}
#1	γ-ray	65	none
#2	proton	45	7.96×10^8
#3	proton	65	1.16×10^9

The annealing tests were carried out under the same biased conditions as the radiation tests at room temperature. The annealing temperatures are room temperature at 23 °C and high temperature at 150 °C.

An integrating sphere uniform light source was used during the measurement. The parameters of CMOS APS were measured before and after the irradiation.

3. Results and discussion

3.1. Conversion gain

Conversion gain (CVG) can be obtained by the slope of the photo transfer curve, which is a quantity to describe the process that the charge units accumulated by photo irradiance are converted into a voltage, amplified, and finally converted into a digital signal by an analog-to-digital converter (ADC). The unit of CVG is DN/e.[12] The values of CVG before and after irradiation are presented in Table 2.

Table 2. CVG (in DN/e) before and after irradiation.

Device	CVG before irradiation	CVG after irradiation
#1	0.0364	0.0373
#2	0.0368	0.0365
#3	0.0368	0.0376

From Table 2, it can be seen that CVG does not have any obvious degradation after irradiation. It is known that CVG is mainly decided by CMOS digital or analog circuits. For the CMOS APS image sensor, there is no significant degradation in MOSFET gate oxide induced by TID and almost no radiation effect on the digital or analog circuits exposed to ionizing radiation.[13] Besides, MOSFET is a majority carrier device, so it is not sensitive to the displacement damage effect.[14] Therefore, CVG does not have obvious degradation after irradiation.

3.2. Dark current

The dark signal is defined as the carriers generated in the potential wells under the pixels when no light is incident on the device. The dark signal is not constant. The main source of the dark signal is the thermally induced electrons. Therefore, the dark signal should be linearly dependent on the exposure time. Dark signal μ_d can be obtained by

$$\mu_d = \mu_I t_{exp},$$

where μ_I is the dark current given in units of e/(pixel·s).[12]

Figure 1 presents the dark current versus the total ionizing dose and annealing time at different temperatures. The experiment result shows that as the fluence of proton increases, the dark current increases rapidly and the dark current of the devices irradiated by proton is larger than that irradiated by γ-ray. As aforementioned, proton irradiations bring both displacement damage and ionization damage effects. The ionization damage effects can cause a build-up of traps at the interface (usually called Si/SiO$_2$ interface traps).[15] The displacement damage is caused by protons which collide with the silicon atoms within the crystal lattice of the detector array and create vacancy-interstitial pairs. Most of these will recombine after the collision but some will migrate through the lattice and form stable bulk traps with energy levels within the bandgap.[16] These energy states assist the electrons in the valence band to be excited to the conduction band. Therefore these traps induced by radiation increase the dark current generation rate significantly.

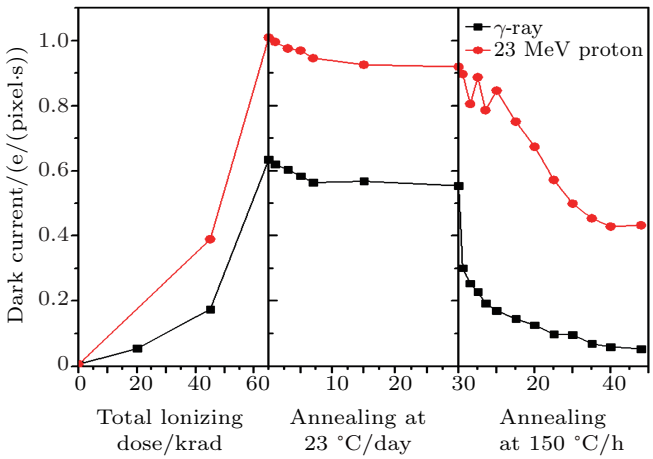


Fig. 1. The dark current versus the total ionizing dose and annealing time at different temperatures.

Figure 1 also illustrates the decrease of the dark current with annealing time at 23 °C and 150 °C. There is a slight decrease in dark current during annealing for 30 days at room temperature for both devices. A reasonable explanation may be the little decline of the interface-trap charges and the oxide-trap charges induced by the ionizing effect. The dark current

of the device irradiated by γ-ray has almost recovered completely after annealing for 50 h at 150 °C, while part recovery occurs in the device irradiated by 23 MeV proton. This corresponds to a dark current degradation mechanism.

Figure 2 shows the dark current generation mechanisms. The thermal generation stands for the dark current generation according to the conventional Shockley–Read–Hall mechanism. The minority carriers are thermally generated from the generation-recombination process in the silicon. Because the p–n junction is reverse-biased, the minority carrier concentrations in the depletion region are lower than the equilibrium concentrations. Therefore, in order to restore the system equilibrium, the recombination process can be omitted and the generation process of minority carriers is dominant.[17]

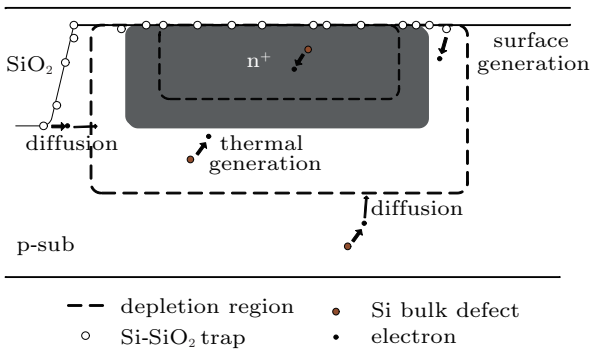


Fig. 2. Dark current generation mechanism in an n+/p-sub junction.[15]

Besides this, the ionization damage effects can also cause a build-up of trapped charge in the CMOS APS inter-electrode and gate oxide. The creation of trapped charges in the gate oxide or field oxide, which are close to the interface, broadens the width of the depletion region by changing the potential of the interface; this results in an increase of the generation process, which induces the dark current increase.[18] However, the oxide-trap charge is easy to be annealed at room temperature, while the interface traps and bulk traps are not readily annealed at room temperature.[19] Therefore, the dark current in this experiment associated with long time room temperature annealing after irradiation is mainly induced by the interface traps and bulk traps.

Since proton irradiations induce both displacement damage and ionization damage effects, the dark current induced by proton is much larger than that induced by γ-ray. The generation of bulk traps increases the dark current drastically.

3.3. Fixed-pattern noise under illumination

The fixed-pattern noise under illumination is due to the photo-response gain mismatch of different pixels (photo-response non-uniformity, PRNU) and the dark signal non-uniformity (DSNU).[16] DSNU represents the distribution of the dark signal output of each individual pixel in the whole array when no light is incident on the device.

As illustrated in Figs. 3(a) and 3(b), although both γ-ray and proton irradiation increase the non-uniformity of the signal, obviously, the proton induced non-uniformity is even worse. The histograms of the devices irradiated by proton have a broad tail extending to large signals under both illumination and dark. The relatively long tail in such distributions includes events that produce dark current much higher than the mean. The primary causes of these hot pixels are relatively uncommon inelastic interactions, in which a large amount of displacement damage is produced by a single incident silicon recoil atom.[20] Obviously, the generation of hot pixels increases the DSNU significantly.

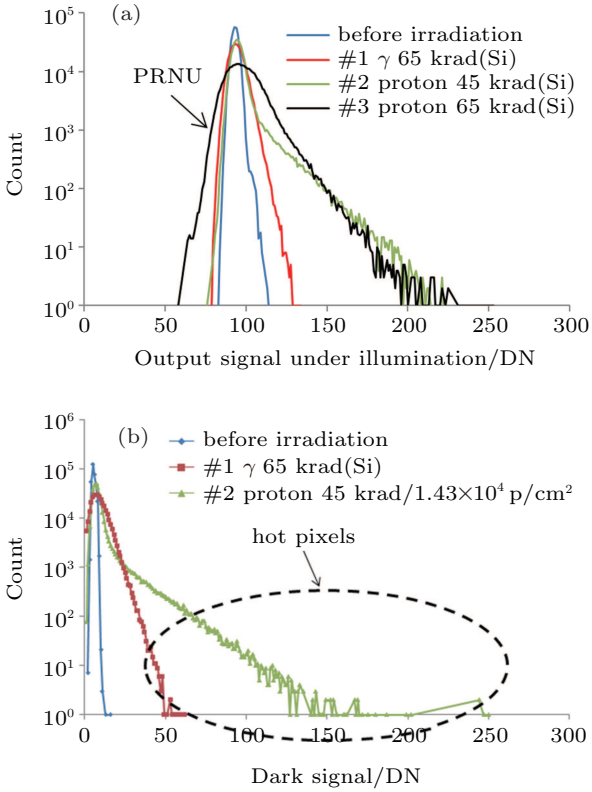


Fig. 3. (a) Histogram of output signal under illumination. (b) Histogram of dark signal.

Besides hot pixels, slight degradation of output under illumination has been observed for some pixels after irradiation, especially for those irradiated by protons. The main reason is the traps outside the depletion region in the p–n junction induced by displacement damage. The p–n junction is used to collect the photo-generated carriers, as shown in Fig. 4. In most cases, only the carriers generated within the depletion region of the p–n junction will be collected without any loss because of the existence of the build-in electrical field (V_{bi}). However, the carriers generated outside the depletion region may be recombined before diffusing to the depletion region. Therefore, the photo-electron conversion also introduces non-uniformities, which is called photo-response non-uniformity (PRNU).

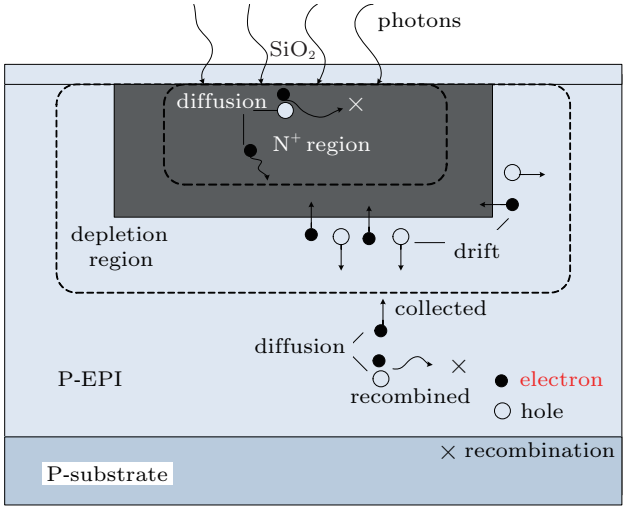


Fig. 4. Photo-generated carriers collection by a p–n junction/photodiode.[21]

As aforementioned, the displacement damage brings stable bulk traps with energy levels within the band-gap. The radiation-induced energy levels in the Si band-gap give rise to the following processes: (i) enhanced thermal generation, (ii) enhanced recombination, (iii) enhanced temporary trapping, (iv) reduced carrier concentration.[19–23] The primary effect produced by process (i) is an increase in dark current, which is induced hot pixels. Process (ii) causes effects such as reduced output. Process (iii) affects the charge collection efficiency. The photo-generated carriers may be recombined or trapped by these bulk traps before diffusing to the depletion region. As a result, bulk traps outside the depletion region induced by proton irradiation increase PRNU.

3.4. Quantum efficiency

Quantum efficiency (QE) is an important parameter of the image sensor, which indicates the ability of the sensorr to convert an incident photon of a certain wavelength into an effective electrical signal.[24]

Figures 5(a) and 5(b) present the changes of sensor 1# and 3# irradiated by γ-ray and proton, respectively. One can see that the QE has a clear drop after proton irradiation at shorter wavelengths, while there is no obvious change on QE after γ-ray. That is, the degradation of QE is caused by the displacement damage effect but not ionization damage. Incident short wavelength photons induce carrier generation near the surface and the N^+ region of the pixel where the photo-generated carriers diffusing length to the depletion region depends on the recombination lifetime. Figure 5 strongly suggests that, in some pixels, the carrier recombination lifetime reduces drastically at the N^+ region or surface of the photodiode where recombination or trapping centers increase induced proton irradiation.

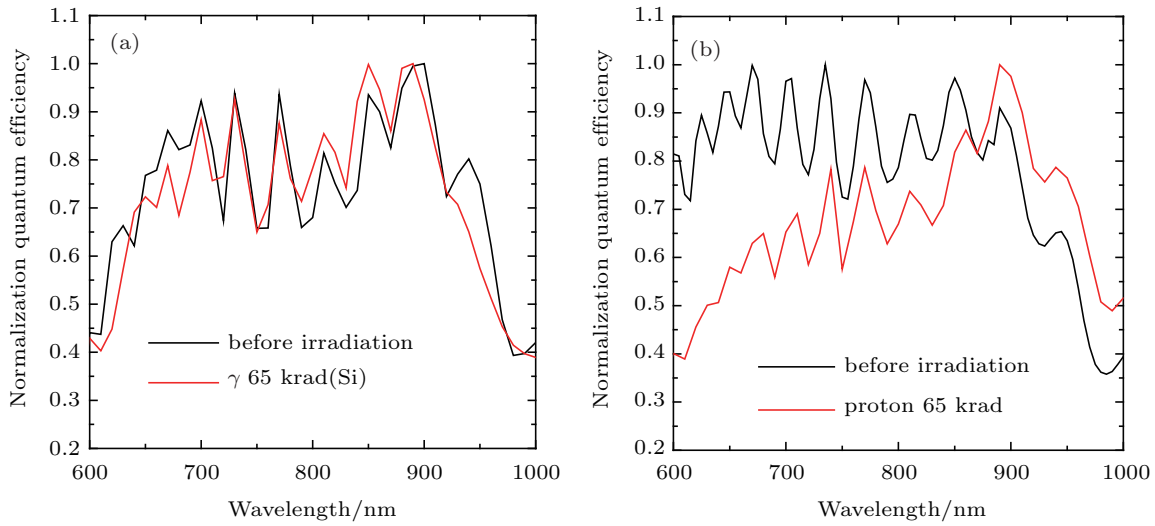


Fig. 5. (a) Sensor 1# QE before and after γ irradiation. (b) Sensor 3# QE before and after proton irradiation.

4. Conclusion

Radiation effects on CMOS APS caused by proton and γ-ray are presented. We study the dark current, FPN under illumination (caused by the dark signal non-uniformity and photoresponse non-uniformity), quantum efficiency, and conversion gain. After exposure to irradiations, all devices have a performance penalty due to the radiation damage. It is found out that the dark current induced by proton irradiation is considerable. Both γ-ray and proton irradiations increase the signal non-uniformity, but the non-uniformity induced by proton is even worse. The bulk traps induced by the displacement damage increase DSNU and PRNU and both of them make FPN under illumination worse. The degradation of QE is induced by the displacement damage effect but not ionization damage. In order to investigate the degradation in different types of CMOS APS image sensors induced by γ-ray and proton, more radiation experiments will be carried out in our future works.

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