A study of radiation effects of 9 and 12 MeV protons on Chinese CMOS image sensor degradation*

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Abstract The 9 and 12 MeV proton irradiations of the Chinese CMOS Image Sensor in the fluence range from 1×10^9 to 4×10^{10} cm^{-2}and 1×10^9 to 2×10^{12} cm^{-2} have been carried out respectively. The color pictures and dark output images are captured, and the average brightness of dark output images is calculated. The anti-irradiation fluence thresholds for 9 and 12 MeV protons are about 4×10^{10} and 2×10^{12} cm^{-2}, respectively. These can be explained by the change of the concentrations of irradiation-induced electron-hole pairs and vacancies in the various layers of CMOS image sensor calculated by the TRIM simulation program.

Key words semiconductor technology, CMOS image sensor, proton irradiation, average brightness, TRIM simulation

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1 Introduction

The complementary metal oxide semiconductor (CMOS) image sensors are used often as the key component of a high-speed camera in space application where anti-radiation, low power consumption and minimum volume are very important. So it is necessary to study how to retain the electronic devices' performance and stability in the space radiation environment where there are numerous high-energy particles and rays including protons[1] which can affect the properties of CMOS image sensors, and even disable the devices completely.

Very few papers have been published on the CMOS image sensor degradation under space environment although the design and character of radiation-hardened CMOS image sensors have been reported[2, 3]. We have studied and reported the electron, proton and gamma-ray radiation effects on a foreign CMOS image sensor[4—8].

In this paper, we report for the first time the changes of the characteristic parameters of the dark output images, the quality of color pictures captured from the Chinese CMOS image sensors and the concentrations of electron-hole pairs and vacancies produced by 9 and 12 MeV proton radiation in the various layers of CMOS image sensor calculated by the Monte Carlo code TRIM (TRansport of Ions in Matter) simulation program. A possible explanation for the changes is presented.

2 Experiments

The devices used in this experiment are the color CMOS digital image sensors made in China. The device includes an image array of 307 200 (640×480) pixels, on-pixel amplifiers, timing and control circuits, exposure detection and control, white balance detection and control, I^{2}C logical registers, analog signal processing, dual 8 bit A/D and video port as well as glass cover board, etc.

The CMOS image sensors were irradiated with 9 MeV protons from a 2×6 MV tandem accelerator in the Key Laboratory of Heavy Ion Physics (Peking University), Ministry of Education, and the irradiation of 12 MeV protons was carried out at the scanning proton beam terminal of the 13 MV tandem accelerator in China Institute of Atomic En-

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ergy. The scanned area of the irradiating protons was 30 cm×3 cm and the uniformity of the proton fluence was better than 95%. The irradiations were all performed at room temperature. The fluence range is from 1×10^9 to 4×10^{10} cm^{-2} for 9 MeV and 5×10^9 to 2×10^{12} cm^{-2} for 12 MeV. The fluence rate is 1.62×10^6 protons/(mm^2·s) for 9 MeV protons and $\sim10^9$ protons/(mm^2·s) for 12 MeV protons.

The dark output images were captured from the CMOS image sensors before and after irradiation by a computer under the dark condition. The average output brightness of dark output images were analyzed by our computer software in order to evaluate the quality of the dark output. The color pictures were captured under natural light with an 8.4 mm optical format Lens.

The characteristic parameter — the average brightness of dark output image (V_{mD}) is defined as follows[5—7]. It is the average value of gray level of each pixel (from 0 to 255) under dark conditions:

$$V_{\mathrm{mD}}=\frac{1}{N_0}\sum_{i=1}^{N_0}V_{\mathrm{iD}}\ , \tag{1}$$

where N_0 is the total pixel number of the device.

3 Results and discussion

Figures 1 and 2 show the color pictures and the dark output images captured from the CMOS image sensors irradiated by 9 and 12 MeV protons at different fluences respectively. Fig. 3 describes the changes in average brightness of the dark output images as a function of fluences.

As shown in Fig. 1, after 9 MeV proton irradiation, some color spots appear at 1×10^9 cm^{-2}; more spots and color horizontal stripes can be observed at 2.5×10^9 cm^{-2}. In addition, the pictures become a little blurry and their densities become higher with the increasing of fluence, thus making the pictures more and more blurry. At 4×10^{10} cm^{-2}, the persons' facial features are nearly hard to be identified, showing that the sensor undergoes severe performance degradation. But the quality of the pictures is very good up to 1×10^{11} cm^{-2} for the 12 MeV proton irradiation. This is coincident with the changes of the dark output images with fluence (see Fig. 2). The anti-irradiation threshold fluence of the CMOS image sensors for 12 MeV protons is about 2×10^{12} cm^{-2}, much higher than 4×10^{10} cm^{-2} for 9 MeV protons.

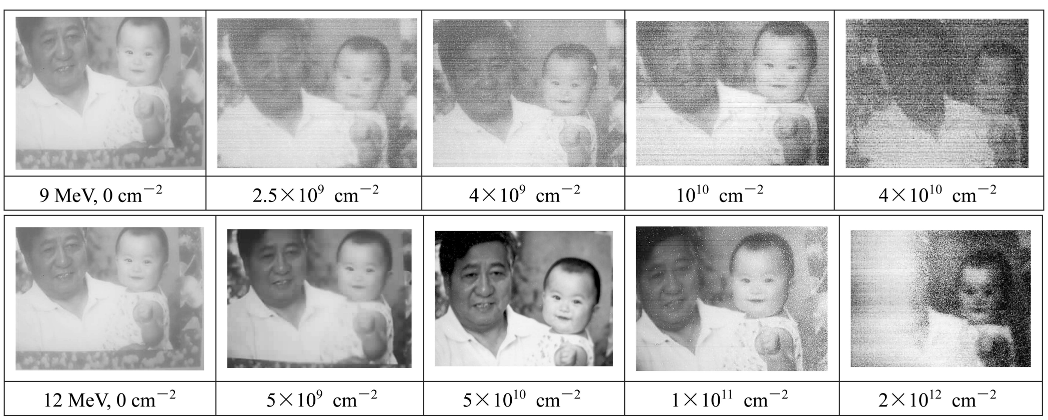

Fig. 1. Color pictures captured under natural lighting from the CMOS image sensors irradiated by 9 and 12 MeV protons at different fluences.

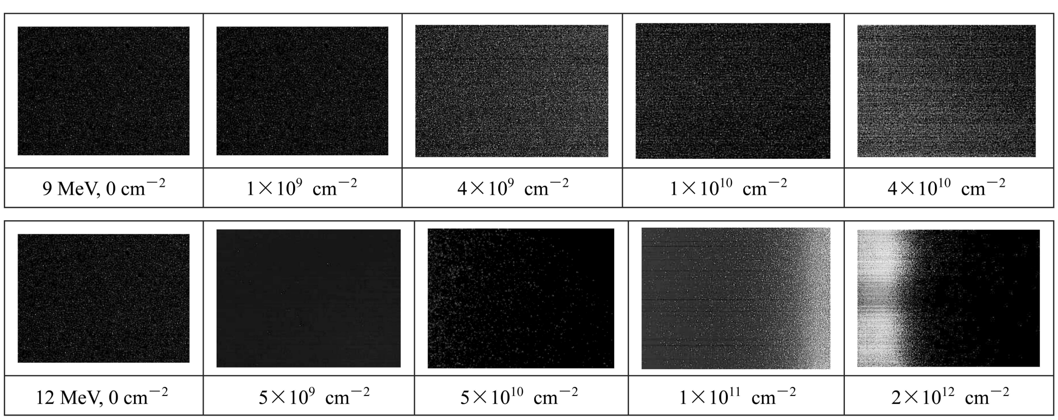

Fig. 2. Dark output images captured from CMOS image sensors irradiated by 9 and 12 MeV protons at different fluences.

As shown in Fig. 3, the average brightness for the proton irradiated image sensors increases sharply at 4×10^{9} cm^{-2} for 9 MeV protons and at 1×10^{11} cm^{-2} for 12 MeV protons. The average brightness ratio at 2×10^{12} cm^{-2} for 12 MeV protons and at 4×10^{10} cm^{-2} for 9 MeV protons is ~1.46.

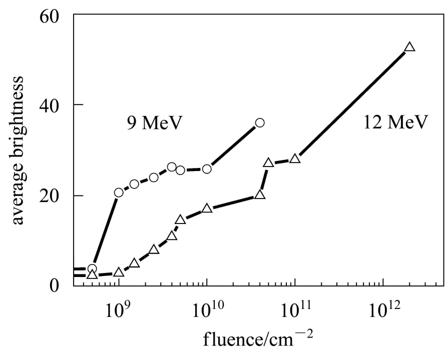

Fig. 3. Average dark output brightness of the dark output images as a function of proton energy and fluence.

The CMOS image sensor used in this experiment is a photodiode-type active pixel sensor, which integrates the photodiode arrays, image processing and control circuits on the same p-Si epitaxial layer and substrate. There is a photodiode including an N region and a p-Si epitaxial layer for a PN junction, and several transistors including a transfer transistor in each pixel. The silicon oxide surrounds the light sensitive region. Proton irradiation can induce electron-hole pairs due to the ionization effect and vacancies in the Si materials of CMOS images sensors mainly due to the collision of protons and recoils of Si atoms. When the incident photons enter a pixel, some photo-generated charges or electron-hole pairs are generated in the depletion region of the PN junction and p-Si epitaxial layer except the thermal-generated charges[9]. Under reverse bias voltage, free electrons can move into the potential well of photodiode and become the signal-producing charges during the measurement.

The concentrations of radiation-induced electron-hole pairs and vacancies in the various layers of CMOS image sensor can be calculated from the energy loss by the TRIM simulation program with proton energy and fluence. The total concentrations of electron-hole pairs and vacancies in the various layers produced by 9 and 12 MeV proton irradiations at different fluences are shown in Figs. 4 and 5. The depth is from the surface of glass cover board.

The simulation shows that the proton-induced energy deposition, which induces the electron-hole pairs, is generally 3—4 orders higher than the recoiled Si atoms-induced energy deposition. But for the production of vacancies, the energy deposition due to the recoiled Si atoms is generally 2—4 times larger than that directly due to the collisions of protons.

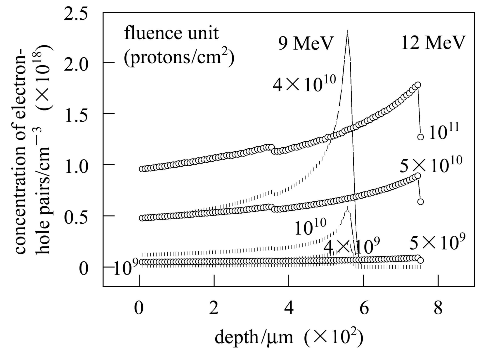

Fig. 4. The total concentrations of electron-hole pairs produced by the 9 and 12 MeV proton irradiation at different fluences in the various layers of CMOS image sensor.

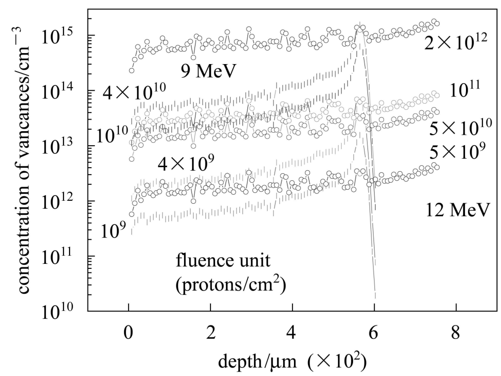

Fig. 5. The total concentrations of vacancies produced by 9 and 12 MeV proton irradiation at different fluences in the various layers of CMOS image sensor.

The CMOS image sensor can not be penetrated by 9 MeV protons, and the total concentrations of electron-hole pairs and vacancies produced in the various sensor layers of different depths change greatly; the difference of the concentrations is about 10 times. But for the 12 MeV proton irradiation, they change little. The total concentration of electron-hole pairs and vacancies produced by the 9 MeV proton irradiation is generally much higher than that by 12 MeV at the same fluence. This is due to a long project range in sensor for 12 MeV protons.

For the 9 MeV proton irradiation, the maximum total concentration of electron-hole pairs and vacancies is at 557.27 and 564.8 μm, respectively. No electron-hole pairs and vacancies are observed above 602.46 μm.

As shown in Fig. 4, the maximum total concentration of electron-hole pairs produced by 9 MeV proton irradiation is 2.3×10^{18} cm^{-3} at 4×10^{10} cm^{-2}; it is 1.78×10^{18} cm^{-3} at 1×10^{11} cm^{-2} and 3.57×10^{19} cm^{-3} at 2×10^{12} cm^{-2} for 12 MeV protons. It is much larger for 12 MeV protons than that for 9 MeV protons at the anti-irradiation threshold fluence, which has a good coincidence with the results in Fig. 3.

The radiation-induced dark current is a main factor determining the brightness of the dark output images of sensors. The change in average bulk dark current ($\Delta J_{\rm bulk}$) can be calculated[10]:

$$\Delta J_{\rm bulk} = K(n_{\rm e}E_{\rm e} + n_{\rm i}E_{\rm i}), \quad (2)$$

where K is the damage constant, n is the number of collisions and E is the average energy deposited (in MeV). The e's and I's refer to elastic and inelastic collisions respectively.

At lower proton fluence, the concentration of the radiation-induced electron-hole pairs is in the same level as that of the thermally-generated electron-hole pairs, most of their charges are used up in the transferring process, and the dark current changes little. Therefore, the average brightness has no obvious increase. While the proton fluence is higher, more radiation-induced electron-hole pairs are generated, and dark current increases quickly, the brightness of the dark output images increases quickly. If the concentration of the induced electron-hole pairs is large enough to reach or exceed the charge capacity of photodiode, the superfluous electrons may overflow from some photodiodes in all pixels and may be collected by the adjacent pixels so that the output images may become blurry at high fluence. These can induce the severe degradation of performance of the CMOS image sensors, which can explain our experimental results in Figs. 1—3.

Generally, the proton irradiation-induced vacancies in the CMOS image sensors can influence the free carrier concentrations in Si substrate and p-type epitaxial layer, specially, may act as recombination centers or electron traps as deep level defects. The concentration of vacancies in Si increases and the lifetime of the minority carriers decreases with the increasing of fluence. The recombination current increases with the concentration increasing of vacancies, therefore, with the increasing of fluence.

As shown in Fig. 5, the maximum total concentration of vacancies for 9 MeV protons at 4×10^{10} cm^{-2}, inducing severe degradation of the sensor, is just the same order as that for 12 MeV protons at 2×10^{12} cm^{-2}. Therefore, we can conclude that the influence of vacancies on the degradation of performance is a main factor for proton irradiation.

4 Summary

The difference in properties of the Chinese CMOS image sensors is very obvious for 9 and 12 MeV proton irradiations as well as different fluences. After 9 and 12 MeV proton irradiations, the persons' facial features on the color pictures are nearly hard to be identified at 4×10^{10} and 2×10^{12} cm^{-2} respectively and the dark output images become white, showing that the sensor undergoes severe performance degradation.

The TRIM program simulation shows that the proton-induced energy deposition, which induces the electron-hole pairs, is generally 3—4 orders higher than the recoiled Si atoms-induced energy deposition. But for the production of vacancies, the energy deposition due to the recoiled Si atoms is generally 2—4 times larger than that directly due to the collisions of protons. The CMOS image sensor can be penetrated by the 12 MeV protons, but can't by the 9 MeV protons. For the 9 MeV proton irradiation, the maximum total concentration of electron-hole pairs and vacancies is at 557.27 and 564.8 μm, respectively. No electron-hole pairs and vacancies are observed above 602.46 μm. But for the 12 MeV proton irradiation, it changes little. The increase of the dark current due to radiation-induced electron-hole pairs is a main factor determining the brightness of the dark output images of sensors, and the influence of vacancies on degradation of performance is a main factor for the proton irradiation.

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