Heavy Ion Irradiation Induced Single Particle Displacement Damage in 8T Global Shutter CMOS Image Sensor

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Abstract. The single particle displacement damage effects and mechanisms in 8T Global Shutter CMOS image sensors (CISs) are studied. We provide radiation effects due to 129Xe ion irradiations of 8T Global Shutter CIS by the analyses of dark current spikes and dark current non-uniformity (DCUN). The experimental results show that low fluence irradiation-induced dark current distributions in 8T global shutter CIS exhibit a clear exponential hot pixel tail that appears difficult to match with cumulative radiation effect physical models. The degradation mechanism is a high electric field distribution exists at the overlap region between gate and pinned-photodiode (PPD). The emission rate of a defect can be dramatically enhanced via a high electric field. Irradiation-induced defects are the sources of the dark electron generation and the electric field acts as an amplifier.

1. Introduction

In recent years with the inherent advantages offered by CMOS technology due to technology scaling, CISs have received much attention over the last decade, because their performance is very promising compared to charge coupled devices (CCD), e.g., low-power consumption, on chip functionality, selective read-out mechanism and the capacity to integrate advanced CMOS functions on-chip (and even inside the pixel), prompting additional interest in use of the technology for space applications. Compared with 4-Transistor (4T) rolling shutter CIS, 8T global shutter CIS not only can be create images without any motion artifact but also ensure that every pixel is exposed simultaneously at the same instant in time. Thanks to these advantages, soon after they were invented, 8T global shutter CIS is widely used in the space environment for a varied range of applications [1]. These applications include remote and near planetary imagers, X-ray satellite missions, star sensor, and stellar sensitizer, sun sensor, etc.

However, when 8T global shutter CIS is applied in space, a variety of radiation sources are encountered, which mainly consist of energetic particles. When passing through the layers of the materials that constitute a CIS, ionizing particles (such as charged particles [electrons, protons, heavy ions, etc.]) lose most of their energy by generating electron-hole pairs. This excess of charge carriers can disturb or damage CISs by inducing single-event effects (SEE) or ionizing dose effects (TID) and displacement damages dose effects (DDD). SEE occurs when the electron-hole pairs generated by a
single particle are sufficient to disturb or damage the CIS whereas TID or DDD effects are the result of the cumulative exposure to radiation. Although many papers have been devoted to the effects of radiation on rolling shutter CIS and other technology [2-7], very little is known about the sensitivity of 8T global shutter CIS to radiation. Recent studies have shown that single particle displacement damage in low fluence space conditions is the main cause of photoelectric imaging device's complex dark noise, such as dark current spikes and random telegraph signal (RTS). The damage mechanism is much more complicated than the displacement damage effect under high fluence, and the related defect generation and action process are unknown [8, 9], furthermore, such an effect is rarely researched in 8T global shutter CIS.

The aim of this work is to discusses mainly the single particle displacement damage effects and mechanisms irradiation-induced dark current spike in 8T global shutter CIS developed by CMOSIS, in order to identify and understand the weaknesses of process structure. The first part describes the experimental setup used in all the experiments, the second part discusses heavy ion irradiation induced hot pixel obtained on one device tested. The last part discusses heavy ion irradiation induced single particle displacement damage effects and the damage mechanism. These results will help improve 8T global shutter CIS designs to achieve the radiation hardness required by space applications.

2. Materials and Methods

2.1. Devices information
The sensor under test, called CMV4000, is a commercial 8T-pixel CIS designed in the 0.18μm CMOS technology using PPD pixels. The CMV4000 is a high speed CIS with 2048 by 2048 pixels (1 optical inch). The image array consists of 5.5μm×5.5μm global shutter pixels which allow exposure during read out, while performing correlated double sampling (CDS) operation. The image sensor has sixteen 10- or 12-bit digital LVDS outputs (serial). The 8T global shutter pixel schematic with cross-section of CMV4000 is presented in figure 1.

![Figure 1. 8T global shutter pixel schematic with cross-section](image)

2.2. Irradiation conditions
Table 1 describes the irradiations which were performed at room temperature. Investigations on single particle displacement damage radiation-induced dark current spike, Device-under-test (DUT) irradiation has been performed at Institute of modern physics, Chinese Academy of Sciences on the Heavy Ion Facility HIRFL. Irradiations are performed under atmospheric environment with window
glass delidded in order to provide adequate penetration of the ions through the device active layers. DUT were mounted on a custom printed-circuit-board (PCB), which were in imaging state during the experiment. A laser pattern calibrated on the beam axis is used to place the DUT in the middle of the beam. Image acquisition was carried out by CMOSIS using dedicated driving boards and acquisition system. The dark current measurements are based on several integration times, the integration times were 4.8ms, 9.6ms, 19.2ms. During image acquisition after ions beam flux, the test chamber is placed in darkness to avoid light to be captured by the sensor. In global shutter mode and use 10 bits resolution, full frame images are acquired with a frame rate of 5 image/s (around 500 images per test).

| Ion  | Accelerator | Energy (MeV) | Range (μm/Si) | LET (MeV·cm²/mg) | Flux (ions/(cm²·s)) | Fluence (ions/cm²) |
|------|-------------|--------------|---------------|------------------|---------------------|-------------------|
| Xe   | HIRFL       | 2515.5       | 95.2          | 51.05            | 2000                | 1.5×10⁶          |

3. Results

3.1. Dark current before experiment

Even without illumination, there are electron-hole pairs being generated from the photo-sensing region. Dark current is intrinsic to semiconductors and naturally occurs through the thermal generation of minority carriers. We call this source dark current because it is produced when the CIS is in...
complete darkness. The level of dark current generated determines the amount of time a potential well can exist to collect useful signal charge. This time is not very long, and therefore CIS users must deal with the dark current problem head on. In 8T global shutter CIS pixel, photodiode is covered by a P+ pinning implant. In the case of pinned-photodiode, the pinning implant’s sole purpose is to reduce the dark current by reducing the contact area between the photodiode depletion region and the surrounding oxides (shallow trench isolation, STI and premetal dielectric, PMD) [10]. Figure 2(a) shows the cross section of the photodiodes used to illustrate the dark current generation. Dark current carriers are generated through intermediate-level centers associated with imperfections or impurities within the semiconductor or at the Si-SiO$_2$ interface where near the transfer gate (TG). These states introduce energy levels into the forbidden that promote dark current by acting as “steps” in the transition of electrons and holes between the conduction and valence bands. This process is also referred to as “hopping conduction.” DCNU represents the distribution of the dark current output of each individual pixel of the whole array. The implementation of CDS on 8T global shutter CIS effectively eliminates DCNU caused by device mismatch and reset transistor. From then on, the DCNU is mainly due to pixel-level dark current. Dark current obeys the distribution would be Gaussian before ions irradiations (as shown in Figure 2(b)). Clearly dark current is a very unwanted property of 8T global shutter CIS. But, even more problematic than the dark current component of the dark current is the non-uniformity on the dark current.

Displacement damages dose effects on CIS dedicated to space applications are a subject of ongoing research. For a given displacement damages dose, the mean dark current increase induced by non-ionizing radiation in a depleted silicon volume $V_{dep}$ can be determined by using the universal damage factor [11]:

$$\Delta I_{dark} = K_{dark} \times V_{dep} \times D_d$$  \hspace{1cm} (1)

Where $K_{dark}$ the universal damage factor, $D_d$ the displacement damages dose.

3.2. Low fluence heavy ion irradiation induced single particle displacement and hot pixel

Figure 3 shows a typical dark current distribution after $^{129}$Xe ions irradiation. The histograms distributions in 8T-pixel exhibit a clear broad tail extending to large signals, which is very non-Gaussian. For $^{129}$Xe fluence presented in this figure, the displacement damage occurrence per pixel is not sufficient to impact all the pixels. For this reason, after $^{129}$Xe ions irradiation, most of the pixel dark current stays unchanged and the pixel tail represents the largest dark current spikes are an order of magnitude greater in the image, which is visually very disturbing. A dark current spike is a pixel that generates high dark current, i.e., more than the average. Those pixels that exhibit dark current spikes in the tail are called hot pixels. That leads to DCNU on a dark frame captured with a fixed integration time. Since the dark current of each individual pixel is not uniform over the complete pixel array, the induced DCNU cannot be eliminated easily. Theses heavy ion irradiation induced single particle displacement damage present a critical performance issue for 8T global shutter CISs that are used in space applications, especially when the sensors operate in long exposure time model at low light levels. When detecting weak signals, these dark current spikes of pixels that are subject to single particle displacement damage can mask the weak light signals detected by themselves or be confused with the weak light signals detected by other pixels. This will lead to a serious decline in the ability to identify targets with weak backgrounds.
Figure 3. Typical dark current distribution after 129Xe ions irradiation (a) most of the pixel dark current stays unchanged and the pixel tail represents the largest dark current spikes are an order of magnitude greater and (b) 3D stereogram of 8T global shutter pixel dark current.

Single particle displacement damages are produced by 129Xe ions, that collide with silicon atoms and displace them from their lattice sites. As a result, many vacancy interstitial pairs are formed, most of which recombine. The vacancies that survive migrate in the lattice and form stable defects [12-14]. Table 2 shows the main irradiation-induced defects and their properties in P-type Si. These defects increasing the dark current non-uniformities, by introducing individual pixels with very high dark currents (or "spikes"). Note that the data were obtained at a very low fluence of 1.5×10^6 ions/cm^2. For low earth orbits the fluence will be two or three order of magnitude higher and as a consequence the defect production cannot be circumvented by technological improvements.

| Defect type | Defect level (eV) | Charge state | Capture section (cm^2) | Annealing temperature (°C) |
|-------------|------------------|--------------|------------------------|---------------------------|
| V-O         | 0.17             | -/0          | 1×10^-14               | 350                       |
| V_2         | 0.23             | +/-          | 4×10^-16               | 300                       |
| P-V         | 0.44             | -/0          | 2×10^-15               | 150                       |

From figure 4(a), we can see the dark current distribution of different images is coincident, which indicates most of the pixels show a steady dark current spikes while fixed integration time. Dark current generated in pinned-photodiode of 8T global shutter pixel is usually the most significant component of the total dark count. If the dark current is generated in the pinned-photodiode, the dark current is expected to be proportional to the exposure time. Figure 4(b) shows the dark current of these hot pixels at the exposure times of 4.8ms, 9.6ms and 19.2ms. It can be seen that dark current spikes won't move, but their intensity will increase while increase the integration time, which suggests that the dark current is generated in the photodiode. They will be at exactly the same single-pixel location in every frame. This phenomenon indicates that this is not a random process and is caused by certain defects in 8T pixel.
4. Discussion

As mentioned above, in the case of bulk defects in the depletion region, the additional trap energy level $E_t$ introduced by the bulk defect can serve as a generation center. In CIS, these defects are mainly active in the photodiode vicinity, as pictured in figure 5. The thermal generation rate of an electron-hole pair in the depletion region can be described by the Shockley-Read-Hall statistics as [15]:

$$G(E_n) = \frac{\sigma_n \sigma_p v_{th} N_d n_i}{\exp [(E_i - E_f)/kT] + \exp [- (E_i - E_f)/kT]}$$  \hfill (2)

Where $G(E_n)$ is the net carrier generation (carriers/sec-cm$^3$), respectively, $\sigma_n$ and $\sigma_p$ are the electron and hole capture cross sections (cm$^2$), $v_{th}$ is the thermal velocity (cm/sec), $E_i$ is the intrinsic Fermi level (eV), $N_d$ is the defect density per volume (cm$^{-3}$), $E_i$ is the trap energy level (eV), $k$ is Boltzmann’s constant (J/K) and $T$ is the absolute temperature (K). As the formula (2) shows, the generation rate falls off exponentially as the defect level moves away from mid-gap in either direction. Those most effective defects whose energy level is near the intrinsic Fermi level contribute significantly to the dark current i.e., mid-band states. The band-gap in silicon is 1.12eV and so common radiation-induced defects such as the divacancy and the P-V, which have energies of ~0.44eV below the conduction band can be important, as shown in table 2, those defects were induced by heavy ion irradiation.

Figure 4. Typical dark current distribution after 129Xe ions irradiation (a) most of the pixels show a steady dark current spikes while fixed integration time and (b) dark current spikes intensity will increase while increase the integration time.

Figure 5. Illustration of the main active defects induced by displacement damage in a CIS pixel.
Although the mean bulk dark current is determined by the displacement damage dose [as shown in formula (1)], however, low fluence irradiation-induced dark current distributions in 8T global shutter CIS exhibit a clear exponential hot pixel tail that appears difficult to match with physical models and conclusion. That is why those hot pixels are exceptions where theory and experiment do not exactly track. The displacement defects generated by single particle displacement damage in 8T pixels are very complicated. They can be divided into point defects and cluster of defects. From defect behavior, they can be divided into unstable defects, stable defects, bi-stable defects and multi-states defect [13, 16-18].

The most possible mechanism to explain the appearance of dark current spikes is field enhanced emission. A strong electrical field is developed near the gate-PPD overlap due to the heavy doping profile of the pinning layer. The electric field distributed over the depletion region is high enough while induced the potential barrier sufficiently thin. Moreover, even though the PPD bulk depletion region is isolated from the surface, in order to connect this photodiode to the SF and RST MOSFETs, the P+ pinning layer has to be opened somewhere at the overlap area of gate-PPD to let the N region reach the surface. As a result, the dark current of these hot pixels is normally introduced by defects inside their photodiode depletion regions near the gate-PPD overlap, i.e. the generation rate is enhanced in the presence of an electric field because of the Poole-Frenkel effect and trap-assisted tunneling. These processes are illustrated in figure 6. The most likely tunneling path is through the smallest barrier. Thus, the carrier-tunneling usually happens through two triangular-shape barriers with a height limited by the energy band gap, as shown in figure 6. Those carriers with energies higher than this sufficiently thin barrier can directly escape from the valence band to the conduction band. The potential barrier reduction, $\Delta E$ in $eV$, induced by the Poole-Frenkel effect for thermal emission of a trap level in the band-gap, is given by:

$$\Delta E = \sqrt{\frac{qE}{\pi \varepsilon}}$$

Where $q$ is the electron charge, $E$ is the electric field, $\pi$ approximately equals to 3.14, and $\varepsilon$ is the dynamic permittivity. The Poole-Frenkel effect is a field-induced barrier lowering for the thermal emission of a carrier from a level in the band-gap. By means of intermediate traps, electrons can more easily tunnel across the band gap to contribute to the thermal generation current, which is called trap-assisted tunneling. In other words, irradiation-induced defects are the “sources” of the dark electron generation and the electric field acts as an “amplifier”.

![Energy band diagram showing the Poole-Frenkel effect and trap-assisted tunneling process](image)

**Figure 6.** Energy band diagram showing the Poole-Frenkel effect and trap-assisted tunneling process

5. Conclusions
In summary, this work dedicates to the study of degradation mechanisms of single particle displacement damage in 8T Global Shutter CIS after heavy ion irradiation at a very low fluence of $1.5 \times 10^6$ions/cm$^2$, while for low earth orbits the fluence will be two or three order of magnitude higher.
A high electric field distribution exists at the overlap region between the gate and the PPD. The emission rate of a defect can be dramatically enhanced via a high electric field. Therefore, along with point defects and cluster of defects coming from heavy ion irradiation, the existence of a high electric field inside a pixel can aggravate the radiation degradation by means of a surge in the dark current through field-enhanced emission or trap-assisted tunneling. From this perspective, the high electric field at the overlap region of gate-PPD makes the 8T pixel fragile to displacement damage in terms of a sharp increase in dark current spike by create hot pixels.

We will carry out further research in the next step about the activation energy of the dark current spikes. In this way, the radiation-induced degradation mechanism can be viewed microscopically from the macro parameter, i.e. dark current spikes.

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References
[1] Le Roch A, Virmontois C, Goiffon V, et al. Radiation Induced Defects in 8T-CMOS Global Shutter Image Sensor for Space Application [J]. IEEE Transactions on Nuclear Science, 2018; 1-1.
[2] Durnez C, Goiffon V, Virmontois C, et al. In-Depth Analysis on Radiation Induced Multi-Level Dark Current Random Telegraph Signal in Silicon Solid State Image Sensors [J]. IEEE Transactions on Nuclear Science, 2017, 64 (1): 19-26.
[3] Zhang X, Li Y D, Wen L, et al. Radiation Effects Due to 3MeV Proton Irradiations on Back-Side Illuminated CMOS Image Sensors [J]. Chinese Physics Letters, 2018 (7).
[4] Marcelot O, Goiffon V, Rizzolo S, et al. Dark Current Sharing and Cancellation Mechanisms in CMOS Image Sensors Analyzed by TCAD Simulations [J]. IEEE Transactions on Electron Devices, 2017, PP (99): 1-7.
[5] Rizzolo S, Goiffon V, Estribeau M, et al. Influence of Pixel Design on Charge Transfer Performances in CMOS Image Sensors [J]. IEEE Transactions on Electronic Devices, 2018, 65 (99).
[6] Lin-Dong Ma, Yu-Dong Li, Qi Guo, et al. Total ionizing dose effects in pinned photodiode complementary metal-oxide-semiconductor transistor active pixel sensor [J]. Chinese Physics B, 2018 (10).
[7] Lin-Dong Ma, Yu-Dong Li, Lin Wen, et al. Analysis of proton and γ-ray radiation effects on CMOS active pixel sensors [J]. Chinese Physics B, 2017, 26 (11): 264-268.
[8] Raine M, Jay A, Richard N, et al. Simulation of Single Particle Displacement Damage in Silicon – Part I: Global Approach and Primary Interaction Simulation [J]. IEEE Transactions on Nuclear Science, 2016, 64 (1): 133-140.
[9] Jay A, Hemeryck A, Richard N, et al. Simulation of Single-Particle Displacement Damage in Silicon—Part III: First Principle Characterization of Defect Properties [J]. IEEE Transactions on Nuclear Science, 2018, PP (99): 1-1.
[10] Ge X. The Design of a Global Shutter CMOS Image Sensor in 110nm Technology [D]. 2012.
[11] Srour J R, Lo D H. Universal damage factor for radiation-induced dark current in silicon devices [J]. Nuclear Science IEEE Transactions on, 2000, 47 (6): 2451-2459.
[12] Belloir J M, Goiffon V, Virmontois C, et al. Pixel pitch and particle energy influence on the dark current distribution of neutron irradiated CMOS image sensors. [J]. Optics Express,
2016, 24 (4): 4299-4315.

[13] Bogaerts J, Dierickx B, Mertens R. Enhanced dark current generation in proton-irradiated CMOS active pixel sensors [J]. *IEEE Transactions on Nuclear Science*, 2002, 49 (3): 1513-1521.

[14] Bogaert J, Dierickx B. Radiation-induced dark current increase in CMOS active pixel sensors [C]// *Photonics for Space Environments VII*. 2000.

[15] Tan J. 4T CMOS Active Pixel Sensors under Ionizing Radiation [D]. 2013.

[16] Goiffon V, Estribeau M, Magnan P. Overview of Ionizing Radiation Effects in Image Sensors Fabricated in a Deep-Submicrometer CMOS Imaging Technology [J]. *IEEE Transactions on Electron Devices*, 2009, 56 (11): 2594-2601.

[17] Goiffon V, Virmontois C, Magnan P, et al. Analysis of Total Dose-Induced Dark Current in CMOS Image Sensors From Interface State and Trapped Charge Density Measurements [J]. IEEE Transactions on Nuclear Science, 2010, 57 (6): 3087-3094.

[18] Virmontois C, Goiffon V, Corbiere F, et al. Displacement Damage Effects in Pinned Photodiode CMOS Image Sensors [J]. *IEEE Transactions on Nuclear Science*, 2013, 59 (6): 2872-2877.