Hot Pixel Generation in Active Pixel Sensors: Dosimetric and Microdosimetric response

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ABSTRACT

The dosimteric and microdosimetric response of an active pixel sensor is analyzed. The shift in dark current before and after irradiation is the metric under study. Heavy ions are seen to damage the pixel in much the same way as gamma radiation, i.e. displacement damage is minimal when considering small volume dose from heavy ions. A rate of singularly highly dosed bits, i.e. hot pixels, is calculated from the hot pixel characteristic curve. The probability of a hot pixel is seen to exhibit behavior that is not typical with other microdose effects.

INTRODUCTION

Dark current is the signal that an optical device reports in the absence of any light. Radiation increases dark current by either damaging the photonic collection site or damaging the peripheral readout circuitry, which generates leakage. Active pixel sensors are very susceptible to these effects and dark current increase due to irradiation is dominant problem in space applications of active pixel sensors [1]. Since some radiation species generate displacement damage more readily than others, the relative effect of radiation on an active pixel sensor is very complex. Protons, neutrons, and heavy ions are generally considered to cause displacement damage as well as ionization damage. Very high energy electrons will also cause displacement damage. Displacement damage reduces the charge collection efficiency of the active pixel sensor [1].

The photosensitive element of the active pixel sensor is either a phototransistor or a photo diode. The circuit of the typical 3T photodiode APS cell is illustrated in Figure 1. Light incident on the photodiode changes the current that passes through the photodiode and thus the voltage at the column output line is modulated. Radiation damage to the photodiode or any transistor will cause leakage and increase dark current [2]. Due to manufacturing and other die level variances each cell has a unique dark current, and each cell will have a response independent of the rest of the array. Therefore, the device will respond to total dose across the device and to dose on a small volume, i.e. microdose. Gamma irradiation, for example, will induce a rise in microdose across the device and each cell's response will be proportional to the response of the whole. Heavy ion irradiation, on the other hand, will induce a rise in dark current in APS cells of greater magnitude than the average increase of the device. These highly damaged cells are analogous to Single Hard Errors (SHE) in memories and are generally referred to as hot pixels. Hot pixels are very important since the false signal reported by the cell is hard to mitigate.

APS devices have been studied for a wide variety of dark current issues[1-3]. The general effects of total dose irradiation have been the most scrutinized [3]. General reliability issues that relate to dark current generation have also been investigated [3]. Charge coupled devices have been studied for hot pixel effects [4]. This study investigates the individual response of APS cells to heavy radiation and determines the amount of displacement damage that a heavy ion strike induces. This study also quantifies the event rate of hot pixels in a space environment.

THEORY

Most modern APS devices use the 3T cell shown in Figure 1. This level on integration significantly increases the number of sensitive volumes on the device that are susceptible to ion strikes. The photodiode is liable to displacement damage. The RESET and gain transistors are susceptible to ionization damage. A damaged photodiode will source more current. Damaged transistors will tend to leak more and raise dark signal. Photosensitive devices are much more sensitive to displacement damage than access transistors. This raises the question of how heavy ions will damage and therefore affect the dark current reading. Heavy ions induce displacement and ionization damage. The exact amount of damage depends on many factors including ion energy and atomic weight of the ion. For 3T APS devices, displacement-inducing radiation will change the effect of the damage when compared to ionization damage. Figure 2 depicts the affect of integration time on signal. Longer integration time allows for larger signal.

The purpose of this study is to quantify the effect that highly localized ionization and displacement damage from heavy ions. The amount and profile of ionization depends on LET, atomic weight, and energy of the ion. The magnitude of the shift in dark current, therefore, should be dependent on LET. This study determines the dependence of anomalously large shifts in dark current, i.e. hot pixels, as a function of LET and predicts the damage mechanism due to heavy ions. The APS array is expected to exhibit behavior similar to IC arrays seen in other studies [5].

PROCEDURE AND SETUP

The devices used in this study were CC256PD APS fabricated from a JPL design. The imaging array consisted of a 256 by 256 array of 3T active pixel sensors. The CMOS devices were built on a 0.6 μm process. This device is a completely digital, so the signal from each APS cell is reported digitally on the output pins. This allows for temperature compensation of dark current. The peripheral circuitry sets integration time and data is clocked out synchronously with a clock input. For this study, a PC interrogated the device using a LABVIEW based code. Figure 3 shows a standard dark image.

For this study, three types of radiation were used. Gamma radiation was obtained at the JPL Co-60 source. Crocker Nuclear Laboratory supplied the protons used in this study. Brookhaven National Laboratory provided heavy ions. Gamma and proton radiation were employed to study the total ionizing dose effects on the devices. The TID study provided a calibration to which the effect of heavy ion irradiation could be compared. This comparison is pivotal since the gamma irradiation only induces ionization damage and no displacement damage. Proton radiation, on the other hand, has a large displacement damage contribution. The ratio of ionization damage to displacement damage from proton irradiation can be changed in the device by operating the device is different bias modes. In this study, the proton irradiation occurred in biased and unbiased modes to modulate the amount of ionization damage. This approach allowed the mechanism of SEE and TID dosing effects to be identified.

For this experiment, the biased devices were irradiated while operating. Dark current measurements were taken for several modes. The flat pattern noise (FPN), the photon response non-uniformity (PRNU), and the dark current were measured. Two different integration times were also set to measure dependence on the integration time. The operating bias was set to 5 volts and the operating temperature was approximately -25 °C throughout the study.

The distribution of two dark current measurements is shown in figure 4. The abscissa of figure 4 is report as dark rate and is proportion to dark current. Both read outs occurred on the same chip at different times. The distributions are quite similar. The similarity between them is more precisely shown by the distribution of differences in dark current each APS cell reported during the two reads, which is shown in Figure 5. The distribution shown in figure 5 is narrow and symmetric, which indicates that anomalous rises in dark current will be easily seen. Also, any change in distribution parameters, e.g. variance, will also be easily identifiable.

The procedure of this test was to irradiate several devices. Half of the proton irradiations were on unbiased devices. Measurements of the FPN, PRNU, and dark current were measured between irradiation steps. Integration times of 0 and 300 ms were measured. The supply current and other CMOS parameter were monitored to ensure integrity of the read out circuitry. All irradiations occurred at normal incidence.

The dark current was measured directly from the device. The FPN yields the dark current. The FPN is the measurement from which hot pixels are measured. A hot pixel is defined as an APS cell dark current value that is six standard deviations above the mean of the current spectra. For example, in figure 5, the standard deviation is four, so any shifts in dark current over 24 units from the mean would be considered a hot pixel if an irradiation occurred between readouts. All radiation types will tend to increase the average dark current of the cells. Therefore, a highly dosed cell may look less and less like a hot pixel as the device is irradiated. So for this study, small dose levels were used and readouts were taken at each level. In this manner, the propagation of hot pixels is easily analyzed for high and low dose amounts.

RESULTS

The first section of data analyzes the dark current TID response of the devices. Figures 6, 7 and 8 plot the average dark rate of a DUT for gamma, proton, and heavy ion irradiations, respectively. Identical test protocols were followed for all three DUTs. It is obvious from comparing figure 6 and 7 that the displacement damage induced by protons affects the dark current much differently than the gamma radiation that is ionization damage only. The proton induced dark current saturates relatively quickly. The damage from gamma continues to accrue until the DUT failed. All devices were seen to fail from total dose around 100 krad(Si). Heavy ion total dosing was seen to increase in a similar fashion to gamma, implying that the damage due to heavy ions is similar to the damage caused by gamma radiation. The full paper will extend this analysis for various operational modes.

Figure 9 shows the microdosimetry aspect of an irradiation. Figure 9 shows the shift spectra, which is generated in the same way as Figure 5, before and after an irradiation. The distribution mode and average value are shifted higher. These effects are a total dose effect. Also, the distribution variance has increased, i.e. the distribution is wider, and there are many outliers. These effects are microdosimetry effects. A full treatment of the statistical microdosimetric effects will be included in the full paper. The number of hot pixels is determined by counting the number of shifts in Figure 9 with value greater than six standard deviations over the mean of the distribution. Figures 10 and 11 plot the number of hot pixels as a function of fluence for 60 MeV protons and 300 MeV Bromine ions. Both trends appear linear. Other ion types exhibit induce similar behavior in DUTs. These data will be presented and analyzed in the full paper.

The slopes of figures 10 and 11 are equivalent to the cross section of hot pixel. The cross section of different LET and energy particles can be found in this fashion. The results are plotted in Figure 12. This is the characteristic cross section curve for a hot pixel. The structure is very similar to SEU and SEL cross sections. The effects are different from previous microdose effects where SHE number is linear with LET [6]. The result of Figure 12 allows the rate of hot pixels to be calculated and a formal analysis of this will be presented in the full paper.

Several issues are obviously present concerning this approach, which will be addressed in the full paper:

1. The definition of hot pixels will be precisely developed.
2. The effect of displacement inducing heavy ions, i.e. high energy, will be investigated.
3. The TID limit of the device may limit the precision and will be investigated.

CONCLUSIONS

A microdosimetry analysis of various ion irradiations of APS cells show that the response is not completely typical with a microdosimetrical response. The number of hot pixels saturates with LET of the particle.

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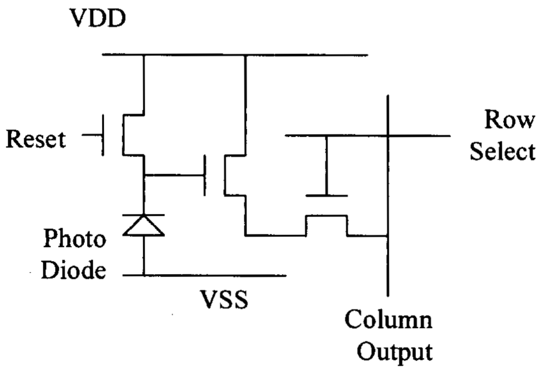

Figure 1. A photodiode based active pixel sensor.

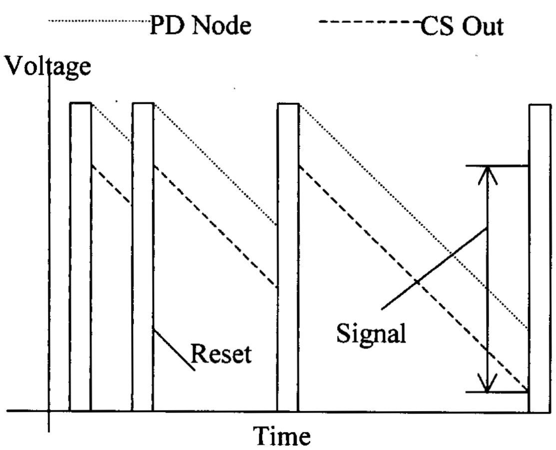

Figure 2. A timing diagram for APS signal.

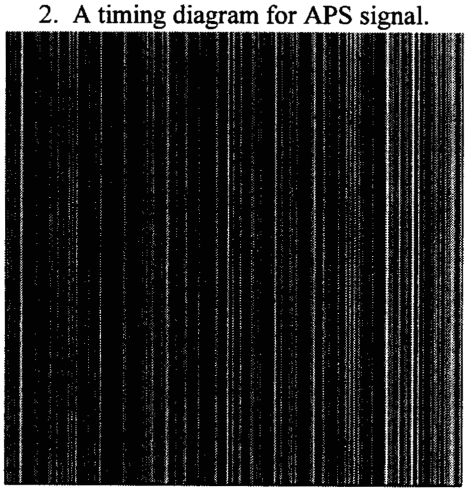

Fig. 3 A CMOS APS cell.

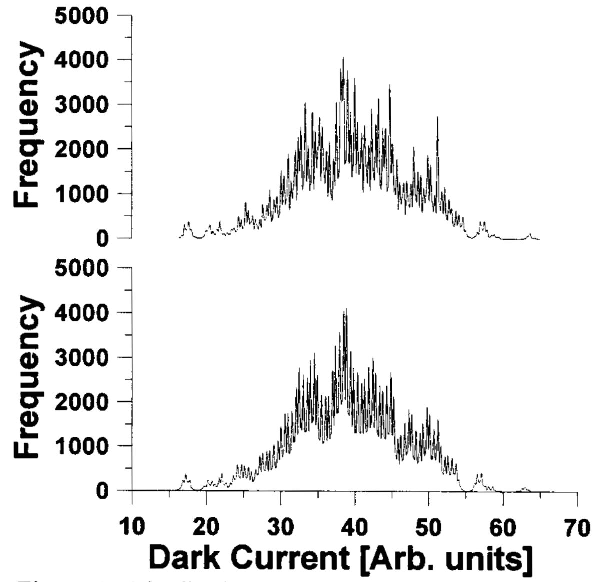

Figure 4. Distribution of dark signal across the APS.

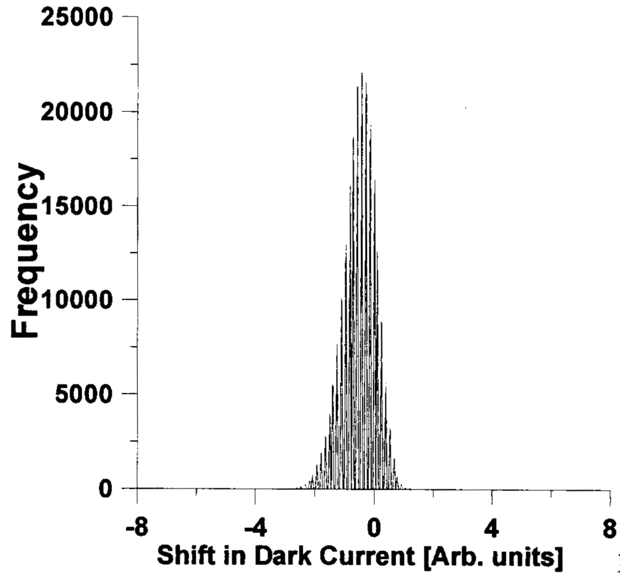

Fig. 5 Distribution of variance in a single cell.

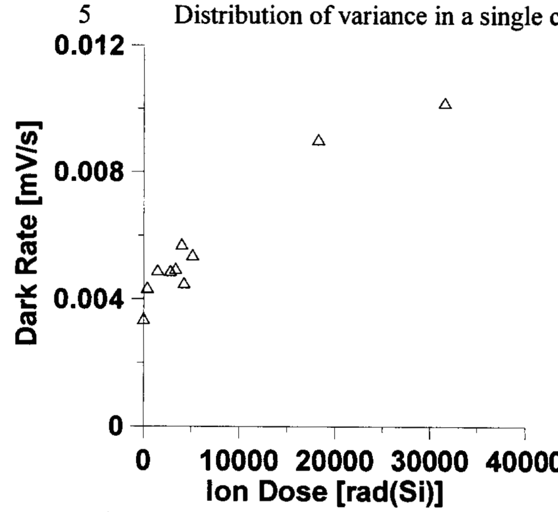

Fig. 8. Dark signal response to heavy ion total dose.

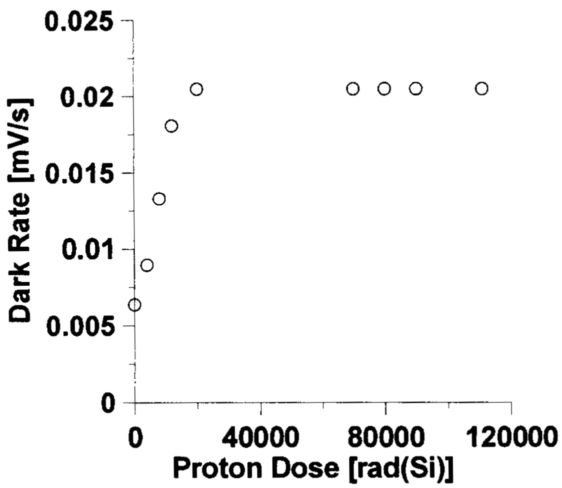

Fig. 7. Dark signal response to proton total dose.

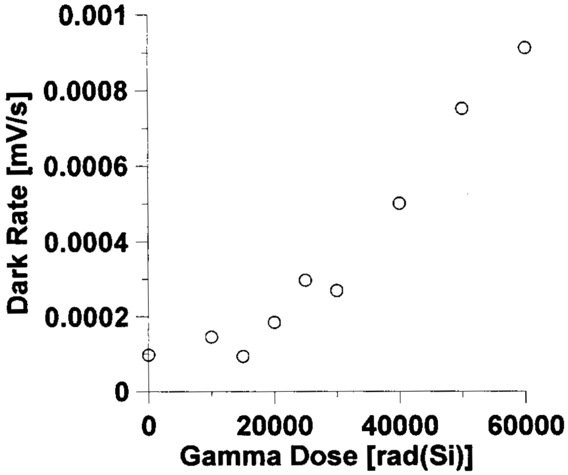

Fig. 6. Dark signal response to gamma total dose.

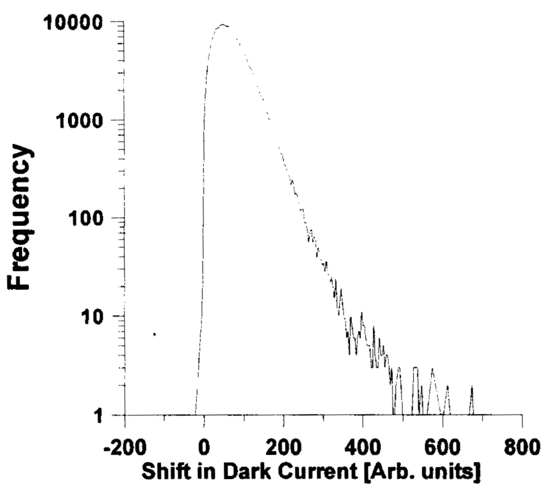

Figure 9. Shift in dark current response across the APS due to heavy ion hits.

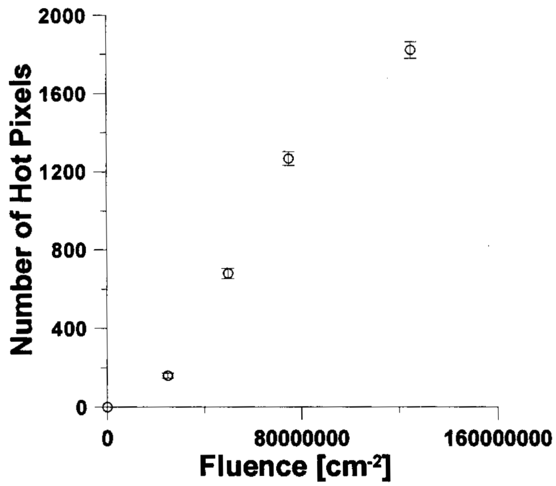

Fig. 10 Development of hot pixel as a function of dose for protons. The slope here is 1.5e-5 cm^2.

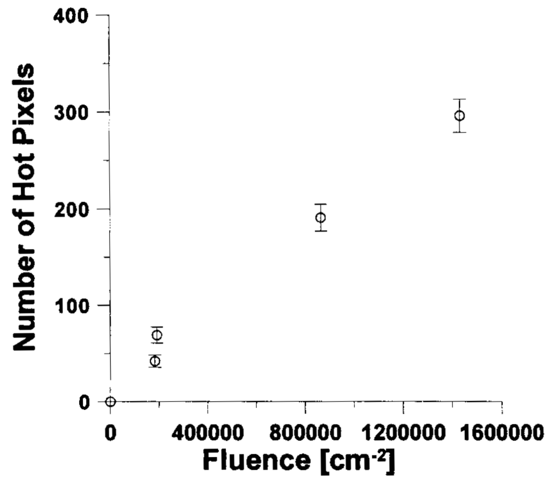

Fig. 11. Development of hot pixel as a function of dose for heavy ions. The slope here is 3.14e-4 cm^2.

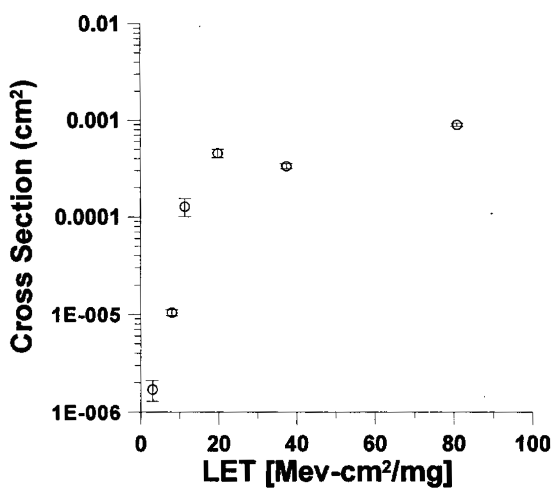

Fig. 12. Cross section of hot pixels as a function of LET.