Proton induced leakage current in CCDs

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ABSTRACT

The effect of different proton fluences on the performance of two E2V Technologies (formerly Marconi Applied Technologies, formerly EEV) CCD47-20 devices was investigated with particular emphasis given to the analysis of ‘random telegraph signal’ (RTS) generation, bright pixel generation and induced changes in base dark current level. The results show that bright pixel frequency increases as the mean energy of the proton beam is increased, and that the base dark current level after irradiation scales with the level of ionisation damage. For the RTS study, 500 pixels on one device were monitored over a twelve hour period. This data set revealed a number of distinct types of pixel charge level fluctuation and a system of classification has been devised. Previously published RTS data is discussed and reviewed in light of the new data.

Keywords: CCD, proton, leakage current, random telegraph signal, bright pixel, damage

1. INTRODUCTION

A better understanding of proton damage effects in Charge Coupled Devices (CCDs) is important for the continued use of CCDs in space based applications where the required resolution, sensitivity, operating speed, size and number of devices used in focal plane instruments is increasing. Examples of upcoming applications are the proposed XEUS[1] and GAIA[2] missions. For this study, two E2V Technologies (formerly Marconi Applied Technologies, formerly EEV) CCD47-20 devices were irradiated with protons, using the particle accelerator facilities at Birmingham University, UK, and AEA Technologies, Harwell, UK. The aim of the experiment was to see how 10 MeV equivalent proton fluences of different mean energies affected the operational characteristics of the CCD. The fluences given were representative of mission fluences expected to be received by a typical orbiting spacecraft[3].

It was expected that pixels exhibiting RTS behaviour would be generated as a result of the proton irradiations. There was an emphasis on the analysis of these pixels because the mechanism behind their behaviour and generation is not well understood. The charge levels in RTS pixels can be very high and many are clearly visible at room temperature having implications for optical uses of CCDs.

2. EXPERIMENTAL METHOD

The CCD47-20 is a three phase device and has both an image and store section, each with 1024 pixels × 1024 pixels of 13.0 μm × 13.0 μm, forming a sensitive region of 13.3 mm × 13.3 mm. The resistivity of the silicon is 20 Ωcm^{-1}, with a depletion depth of ~5 μm.

2.1 CCD 9211-5-3 irradiation

Proton beam uniformity over the target region was examined using a photodiode in pulse counting mode, with the result displayed on a spectrum analyser, before the CCD was positioned in a vacuum chamber and attached to the end of the proton beam line. Across the CCD area, the beam uniformity was found to be ±15 %. The flux reaching the photodiode in 1 minute was measured several times to calibrate the beam flux, to measure the stability of the beam and to ensure the required proton doses could be given over a suitable time scale. The error associated with the dosimetry was estimated to

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be ~20 %. Once the proton beam characteristics were determined, the target CCD was mounted in the vacuum chamber with all pins grounded to avoid potential static damage.

Two irradiations were carried out with CCD 9211-5-3 at a temperature of 22 ^{o}C. For the first irradiation, a 6.5 MeV proton beam was used to give a flux of 8.8×10^{7} protons cm^{-2}, equivalent to 1.5×10^{8} 10 MeV protons cm^{-2}, to one third of the CCD. The rest of the CCD was covered with an aluminium shield to prevent the protons damaging that part of the device. It should be noted that the store section of the CCD47-20 has its own aluminium shield, although this is not thick enough to stop the protons passing through it. The time taken to carry out the irradiation was 47 seconds.

For the second irradiation, two thirds of the CCD were shielded with aluminium while the rest of the device was irradiated through 100 µm of copper. The copper had the effect of reducing the mean energy of the protons to 2.0 MeV. The same flux of protons was given to the CCD as for the 6.5 MeV irradiation. The 10 MeV equivalent proton dose given in this case was 3.6×10^{8} protons cm^{-2}. This irradiation was carried out in 100 seconds.

For each irradiation the photodiode was positioned ~2 cm in front of the shielded section of the CCD to accurately monitor the proton flux reaching the CCD in real time. For the second irradiation, the photodiode was also covered with 100 µm of copper in order to measure the same proton flux and mean energy as that reaching the CCD (Fig. 1). The central part of the CCD remained unirradiated as a control area.

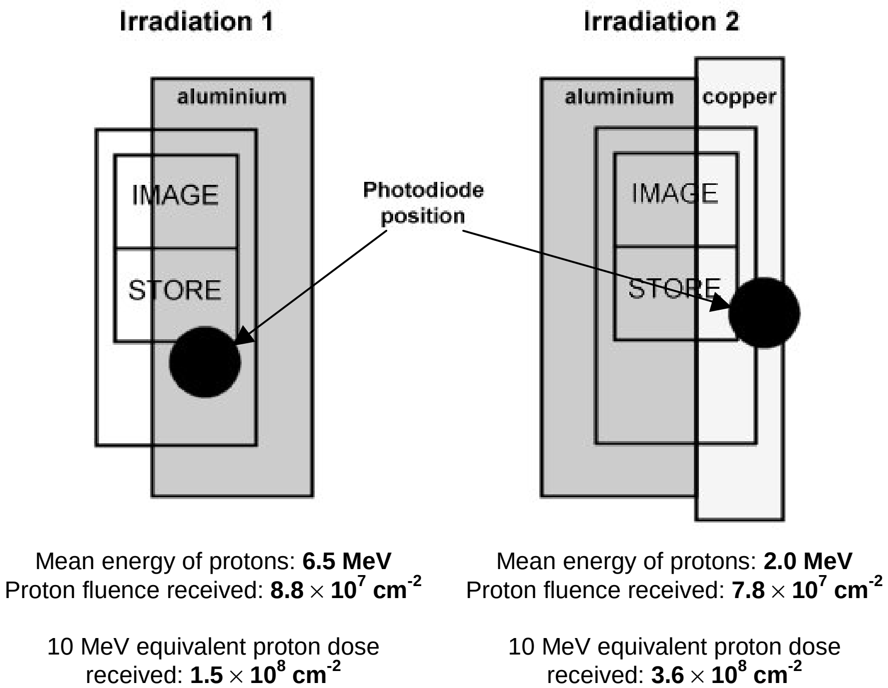


Fig. 1: This diagram shows the irradiated areas of the CCD47-20 (9211-5-3) and the dose each area received. Also shown is the position of the photodiode for each irradiation.

2.2 CCD 9211-4-4 irradiation

The dedicated proton damage beam line at the tandem accelerator facility, run by AEA Technologies in Harwell, Didcot[4], was used to irradiate CCD 9211-4-4. The CCD was mounted on a sample plate and rotated into the path of the proton beam. An aluminium shield was used to prevent protons reaching one half of the CCD, the unshielded section receiving a 10 MeV equivalent proton fluence of 3.0×10^{8} protons cm^{-2} (Fig. 2). The irradiation was carried out with all CCD pins grounded, at a temperature of 22 ^{o}C, in a time of 9 seconds. The beam profiling and dosimetry were carried out by the Harwell staff and the given dose was accurate to ~20 %.

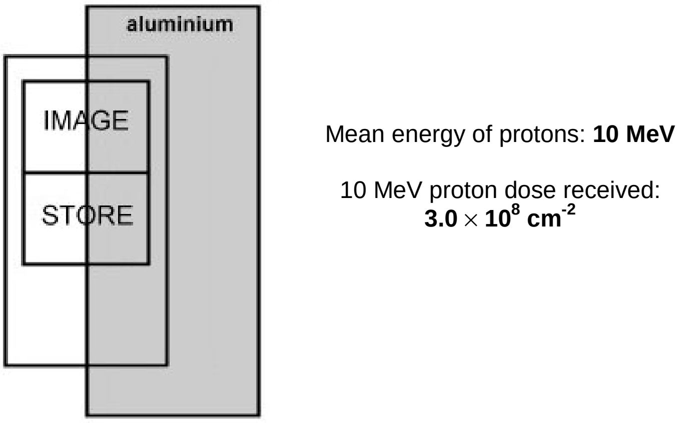


Fig. 2: This diagram shows the irradiated area of CCD47-20 (9211-4-4) and the dose received.

3. EXPERIMENTAL RESULTS

After successful completion of the proton irradiation experiments, changes in the leakage current and bright pixel populations of CCD 9211-5-3 were investigated, while the 500 brightest pixels of CCD 9211-4-4 were monitored over a 12 hour period to characterise any fluctuating pixels.

3.1 Analysis of CCD 9211-5-3

The mean dark current level increased in the areas of each CCD that were irradiated (Fig. 3). At a temperature of 24 ^{o}C, the unirradiated region in the centre of the CCD had a dark current level of ~2500 electrons, while the dark current levels for the 6.5 MeV and 2.0 MeV mean proton energy irradiations were ~4500 electrons and ~13,500 electrons respectively. The ratio of the change in dark current level from the 2.0 MeV and 6.5 MeV beams, after normalising for delivered flux, is ~6.

A large number of bright pixels were generated as a result of each irradiation. To deduce the percentage of the total number of pixels that became bright pixels after irradiation, a region of interest containing 350,000 pixels was examined in each irradiated area. The percentage of pixels with charge levels > 5σ, where σ is the rms noise in the image, above the mean background level in the 6.5 MeV and 2.0 MeV irradiated areas were 0.94 % and 0.58 % respectively. The percentage of pixels with a charge level above a particular threshold level was also investigated. The results are plotted in Figure 4, which shows the trend for both of the irradiated CCD areas.

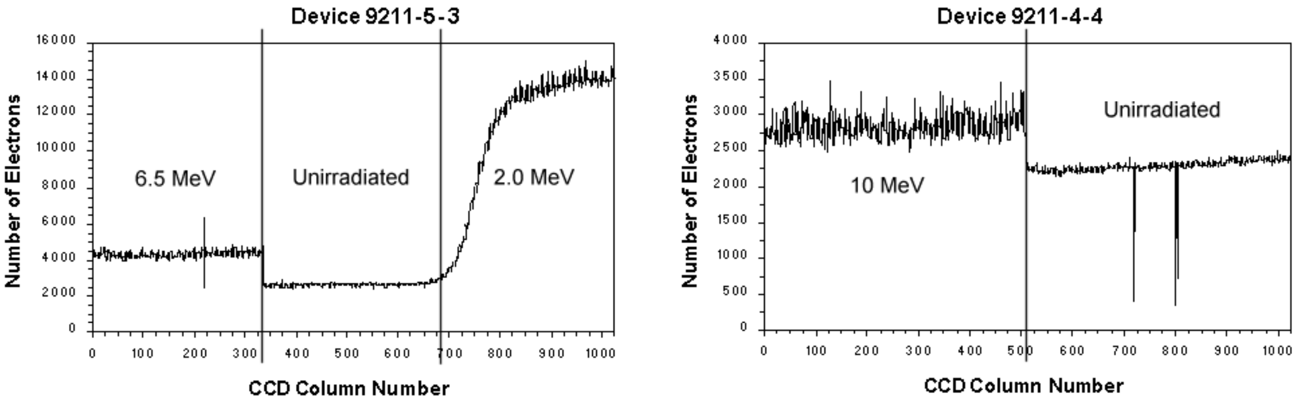


Fig. 3: Plots of the sum average of 1000 rows in the image section of each CCD showing the increase in dark current and generation of bright pixels as a result of each irradiation.

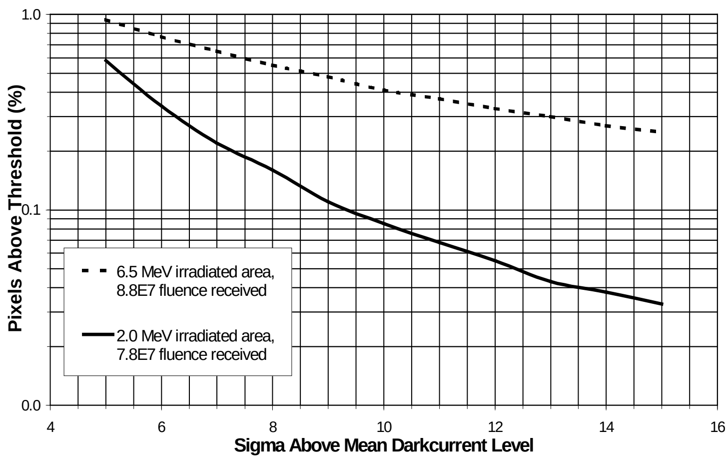


Fig. 4: The percentage of CCD pixels in each irradiated area with a charge level greater than a given threshold level above the mean background dark current.

3.2 RTS Analysis of CCD 9211-4-4

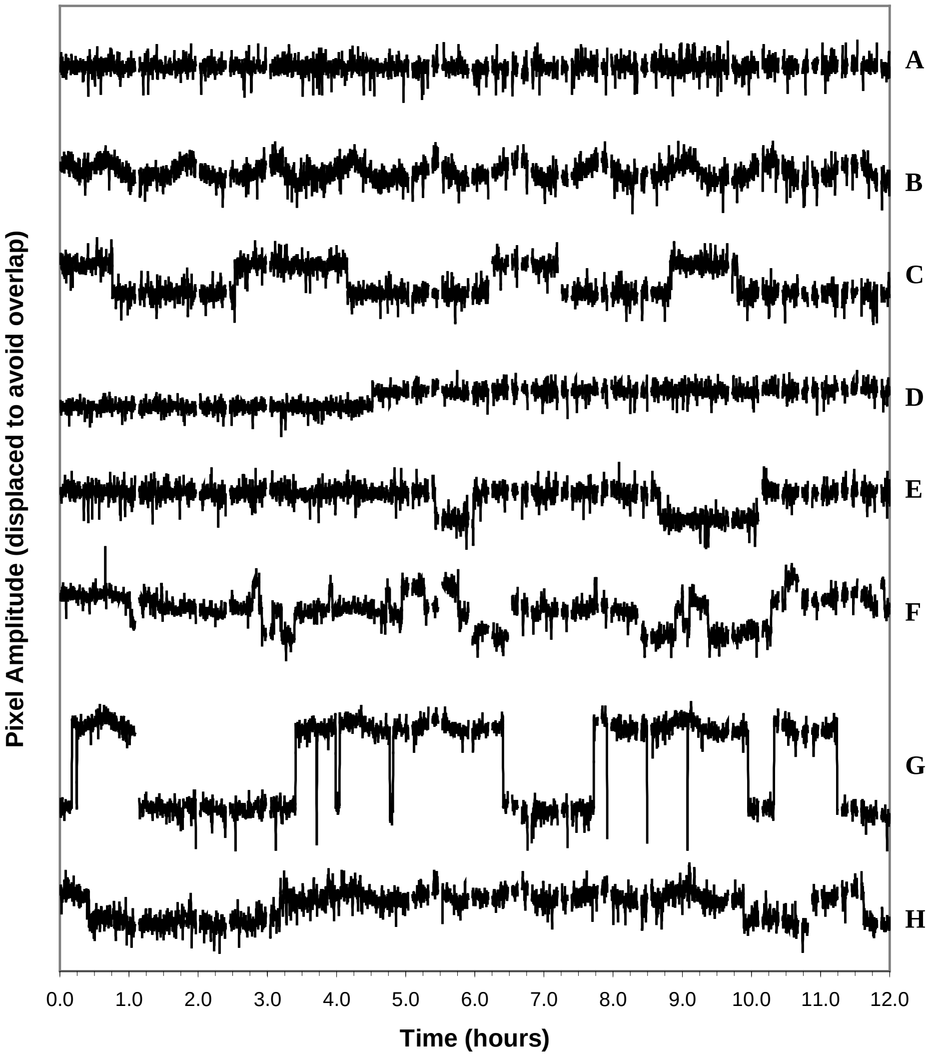
The 500 brightest pixels of the CCD were selected and monitored every 12 seconds over a period of 12 hours. The CCD was stabilised at a temperature of -10 ^{o}C while the data was collected. Using software developed for the purpose, the charge level of each pixel over the 12 hour period was investigated. Of the 500 pixels studied, 242 were found to exhibit a fluctuating charge level. A number of different types of fluctuation were observed that could be classified into one of five different categories. For each classification, the amplitude of the oscillation or transition was above 5σ of the mean pixel level of a 'Flat' reference pixel, where σ was 50 electrons, and the noise distribution was Poissonian in nature. The categories were called: Wave, Bi-Stable, Multi-Stable, Bi-Stable with Wave, and Stable. The characteristics of each are described below:

- **Wave** – The pixel amplitude varies with a sinusoidal oscillation
- **Bi-Stable** – The pixel shows sharp amplitude transitions between 2 distinct levels
- **Multi-Stable** – The pixel shows sharp amplitude transitions between more than 2 distinct levels
- **Bi-Stable with Wave** – The pixel shows sharp amplitude transitions between 2 distinct levels, while the amplitude also varies in a sinusoidal fashion
- **Flat** – The pixel shows no oscillatory nature, or transitions, that are visible above the pixel noise

Examples of each type are shown in Figure 5, spaced out to avoid overlap. Gaps in the data were caused by loss of frame synchronisation for short periods during data collection. The number of pixels in each category is shown in Table 1.

Classification	*Number of Pixels*
Stable	258
Wave	71
Bi-Stable	150
Multi-Stable	22
Bi-Stable with Wave	99

Table 1: The number of pixels exhibiting different types of fluctuation, from a total sample of 500 pixels.



A = Stable; B = Wave; C, D, E = Bi-Stable; F = Multi-Stable; G, H = Bi-Stable and Wave

Fig. 5: Examples of recorded random telegraph signals from a CCD47-20 operating at a temperature of –10 ^{o}C.

4. DISCUSSION

4.1 Ionisation and displacement damage

Ionisation damage in a CCD results in holes drifting and becoming trapped close to the silicon-oxide interface producing a ‘flat-band’ voltage shift at the interface. In addition, passage of holes through the interface creates extra interface states leading to an increase in the leakage current of the device. The change in dark current of a device after irradiation should therefore be proportional to the amount of ionisation damage caused. Using the Stopping Range of Ions in Matter (SRIM) code[5], the ratio of energy deposited per unit distance into silicon for the 6.5 MeV and 2.0 MeV proton beams used to irradiate CCD 9211-5-3 is found to be ~4. This value is comparable to the ~6 ratio of the changes in 6.5 MeV and 2.0 MeV base dark current levels observed after irradiation of the device, in reasonable agreement with the theory.

The slight difference in the ratios is due to the SRIM ratio being calculated for single proton energy values and not a spectrum of proton energies.

Previous work has shown that the number of bright pixels generated after proton irradiation scales with the amount of displacement damage, and therefore scales with the Non-Ionising Energy Loss (NIEL) function[6]. Using SRIM again, the NIEL value for the 6.5 MeV and 2.0 MeV proton energies are 1.7 and 4.6. There should therefore be a factor ~3 more bright pixels in the 2.0 MeV irradiated CCD area, compared to the 6.5 MeV irradiated CCD area. The recorded experimental data show this is not what was observed, with ~2 times more bright pixels generated in the 6.5 MeV region than the 2.0 MeV region. This ratio is for pixel amplitudes above 5σ from the mean base dark current level. Increasing the bright pixel threshold from 5σ to 15σ (Fig. 4), the bright pixel populations in both irradiated areas behave in a similar way, each obeying power law.

4.2 Fluctuating pixels

An RTS pixel is characterised by sharp transitions in amplitude with high time constants. The pixels classified as 'Bi-Stable' pixels in this study were RTS pixels exhibiting standard RTS behaviour[7], the amplitude of the pixel switching between two distinct levels. The high and low state time constants were predominantly of order several tens of minutes to hours at the –10 ^{o}C monitoring temperature. This is in agreement with previous work[8] that investigated the affect of temperature on RTS pixels, showing that the time constants increase as the temperature is lowered, the time between amplitude changes becoming many hours and even days when operating at –20 ^{o}C.

Pixels showing more than two distinct amplitude levels were also observed and classified as 'Multi-Stable' pixels. Of the RTS pixels generated after the 10 MeV proton irradiation, ~5 % were 'Multi-Stable'. This is comparable to measurements made in previous studies[9] where the fraction of generated RTS pixels exhibiting multi-stable behaviour after irradiation with different 10 MeV proton doses was found to be between ~1 % - 15 %.

No correlation between the pixel dark current pedestal level and the RTS amplitude was observed, in agreement with previous studies[8]. Pixels with high and low RTS amplitudes are observed at both high and low dark current pedestal levels.

The smooth oscillation observed in a number of pixels had a period of ~70 minutes, and was due to thermal cycling of the temperature controller. The amplitude of the oscillation increased proportionally with the mean pixel dark current level, becoming visible above the noise in all pixels with a mean dark current level above ~2200 electrons. The oscillation is not a radiation induced effect, and removing the 'Wave' classification from the collected data reveals that ~35 % of the 500 monitored pixels had generated RTS characteristics. This is in good agreement with a study involving E2V Technologies CCD02 and Hamamatsu S5466 CCDs, irradiated with electrons (^{90}Sr) and neutrons (^{252}Cf)[10], where the fraction of generated bright pixels exhibiting RTS properties was found to be 40 %.

A suggested mechanism for explaining the RTS phenomena is a change in configuration of a bi-stable, or multi-stable, defect[11, 12] located in the bulk of the CCD depletion region. The time constants measured vary from ~1 minute to > 8 hours while the measured amplitudes vary from ~250 electrons to ~850 electrons. The variation in the high and low state RTS time constants and pixel amplitudes within the same device indicate that another parameter such as the electric field strength must also be influencing the bi-stable defect. A possible explanation is that the reconfiguration of the defect involves a change in orientation of its dipole moment in relation to the surrounding electric field[7].

The RTS amplitudes observed are larger than those expected from Shockley-Read-Hall generation processes usually associated with dark current levels in CCDs. The large amplitudes could be caused by clusters of defects, where one defect has an influence on the generation rate of the surrounding defects, or by Poole-Frenkel emission. Poole-Frenkel emission is due to field-enhanced thermal excitation of trapped electrons into the conduction band. If a defect within a pixel is in a high field region, the generation rate of the defect will be higher[13].

5 CONCLUSIONS

After irradiation with protons the mean dark current level of a CCD47-20 increases proportionally with the amount of ionisation damage received. From a sample of the 500 brightest pixels generated after an irradiation of 3.0×10^{8} 10 MeV protons cm^{-2}, ~35 % exhibited RTS behaviour. Of the RTS signals generated, ~5 % showed transitions between more than 2 distinct amplitude levels. The transition amplitudes and time constants observed are comparable to previously published work, supporting the theory that configuration changes of a bi-stable, field-enhanced bulk defect are the cause of the phenomena.

Further work will involve the study of proton irradiation induced bright pixels in CCD47-20 (9211-5-3), comparing RTS pixels from both the 6.5 MeV and 2.0 MeV irradiated areas, and bright pixels present in the unirradiated part of the CCD. The time resolution of the RTS monitoring will be improved to ~10 samples per second in an attempt to reveal more structure in the data and improve on the current understanding of the phenomena.

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