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Gow, J. P. D.; Smith, P. H.; Pool, P.; Hall, D. J.; Holland, A. D. and Murray, N. J. (2015). Proton irradiation of a swept charge device at cryogenic temperature and the subsequent annealing. *Journal of Instrumentation*, 10(1), article no. C01037.

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Version: Accepted Manuscript

Link(s) to article on publisher's website:

<http://dx.doi.org/doi:10.1088/1748-0221/10/01/C01037>

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Proton Irradiation of a Swept Charge Device at Cryogenic Temperature and the Subsequent Annealing

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ABSTRACT: A number of studies have demonstrated that a room temperature proton irradiation may not be sufficient to provide an accurate estimation of the impact of the space radiation environment on detector performance. This is a result of the relationship between defect mobility and temperature, causing the performance to vary subject to the temperature history of the device from the point at which it was irradiated. Results measured using Charge Coupled Devices (CCD) irradiated at room temperature therefore tend to differ from those taken when the device was irradiated at a cryogenic temperature, more appropriate considering the operating conditions in space, impacting the prediction of in-flight performance. This paper describes the cryogenic irradiation, and subsequent annealing of an e2v technologies Swept Charge Device (SCD) CCD236 irradiated at $-35.4\text{ }^{\circ}\text{C}$ with a 10 MeV equivalent proton fluence of $5.0 \times 10^8\text{ protons.cm}^{-2}$. The CCD236 is a large area (4.4 cm^2) X-ray detector that will be flown on-board the Chandrayaan-2 and Hard X-ray Modulation Telescope spacecraft, in the Chandrayaan-2 Large Area Soft X-ray Spectrometer and the Soft X-ray Detector respectively. The SCD is readout continually in order to benefit from intrinsic dither mode clocking, leading to suppression of the surface component of the dark current and allowing the detector to be operated at warmer temperatures than a conventional CCD. The SCD is therefore an excellent choice to test and demonstrate the variation in the impact of irradiation at cryogenic temperatures in comparison to a more typical room temperature irradiation.

KEYWORDS: Proton Damage, CCD, SCD, low temperature irradiation

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1. Introduction

The reduction in performance of imaging and X-ray sensitive devices used in space, as a result of proton damage from the space radiation environment, has a large impact on technology selection and the desired operating conditions. To ensure optimum operating conditions and technology are selected it is prudent to perform a radiation damage assessment [1-4], typically starting with an assessment of the environment, followed by a characterisation of the devices available for use. The radiation damage characterisation will then allow the identification of the ideal operating conditions, where the impact of dark current, random telegraph signals and Charge Transfer Inefficiency (CTI), for example, are minimised based on the selection of temperature and readout speed. The recommendations made based on these findings impact the power (readout speed, cooling requirements) and mass requirements (shielding, increased radiator area) the detector places on the mission, often requiring a compromise to ensure budgets are not overly strained.

A typical radiation damage study irradiates multiple devices to multiple proton fluences at room temperature, with the irradiation performed at a facility with a suitable proton beam. Once the devices are returned they are cooled to an appropriate operating temperature and undergo an electro-optical characterisation to enable a recommendation on in-flight operation. However, a number of studies [5-13] have demonstrated that the post-irradiation detector performance is dependent on the temperature of the device during the irradiation and the temperature history of the device from the point at which it was irradiated. Therefore irradiations performed at room temperature may not be sufficient to demonstrate confidence in mitigation strategies as they fail to identify the impact of defect creation, as a result of annealing, before the device can be cooled for analysis. Only performing irradiations at room temperature irradiation could result in the selection of a clocking scheme susceptible to a charge trapping defect which annealed before the characterisation could be performed. The annealing of defects also complicates the identification of the often desired normalization factor to convert room temperature irradiation results into their cold equivalent.

The increased complexity of a cryogenic irradiation makes them prohibitive to perform on a large scale, comparable to that used when performing room temperature irradiations. This raises the need for a method to limit the impact of some of these issues by allowing for multiple irradiation levels to be performed on one device and a significant amount of testing to be performed at the irradiation facility within a short space of time.

This paper will discuss the proton irradiation of an e2v technologies Swept Charge Device (SCD), CCD236, performed at $-35.4\text{ }^{\circ}\text{C}$ and the subsequent change in detector performance after the device was held at room temperature for a period of 1, 7, 12, 16.5 and 82 days after the irradiation. The dark current, energy resolution and CTI are reported, and a comparison is made to a previous CCD236 irradiation performed at room temperature. The irradiation used test equipment developed for a European Space Agency (ESA) funded study into the radiation damage effects on a 1k by 4k 12 μm pixel p-channel CCD204 [14] and in the future the 4k by 4k 12 μm pixel n-channel Euclid Charge Coupled Device (CCD). The advantage of using the SCD over a conventional CCD design is that it can be operated at warmer temperatures, making it an excellent choice to test the facility by avoiding the need for extensive time cooling and heating.

2. A Brief History of Cryogenic Irradiations

Until 2003 irradiations using CCDs had only been performed at room temperature [5], however the results from the CCDs used in the Wide Field Camera (WFC) two demonstrated a fixed increase in bright defect concentrations that could not be annealed at around $20\text{ }^{\circ}\text{C}$ but also a population that could [13]. This indicated the creation of two distinct dark current generating defects, one of which required a temperature greater than $20\text{ }^{\circ}\text{C}$ to anneal. Ground based studies to investigate this affect irradiated a CCD at $-84\text{ }^{\circ}\text{C}$, the number of bright defects were then monitored as the CCD was warmed in stages up to $30\text{ }^{\circ}\text{C}$ [5-6]. The annealing of bright defects at room temperature has been identified during a number of other studies using both CCDs [9-10] and a complementary metal oxide semiconductor imaging sensors (CIS) [11]. It is interesting to note that a study performed using a CCD undergoing an electron irradiation at $-85\text{ }^{\circ}\text{C}$ monitored the devices performance for a period of 8.5 hours after the irradiation and recorded significant short term annealing of bright defects during this period of time [12].

Work performed on the CCDs used in the ESA Gaia spacecraft, for stellar astrometry, used an alpha source to perform the irradiation at $-135\text{ }^{\circ}\text{C}$ and compared the results to a device irradiated at room temperature using protons [9]. The study found the CTI to have decreased after a 26.5 hour room temperature anneal, leading to a factor of 1.5 to 2 in the uncertainty in the CTI measurements performed at room temperature. Different defects were found to anneal by different amounts leading to the recommendation that if accurate predictions to cover the full range of charge trapping defects are required, as in the case of Euclid for example, a low temperature irradiation should be performed. This study was built upon in 2010 [10] when the damage from proton irradiations performed at room temperature and $-135\text{ }^{\circ}\text{C}$ were compared, identifying a number of subtle differences in different defect concentrations impacting the CTI.

The impact of defect mobility on CTI has been investigated in detail for the CCDs used in the Chandra X-ray observatory Advanced CCD Imaging Spectrometer [7-8]. Following the exposure to low energy protons the CCDs onboard Chandra were warmed to between 20 and $30\text{ }^{\circ}\text{C}$ for a period of 8 hours, this anneal resulted in a 35% increase in CTI when measured using the onboard ^{55}Fe source [7]. Both vacancies and silicon interstitials (S_i) are highly mobile

at temperatures below -100 °C, allowing them to form stable defects with impurities in the silicon lattice leading to the formation of defects which impact the CCDs CTI. The most well-known defects which impact the operation of n-channel CCDs, the E-centre (phosphorus-vacancy), J-centre (divacancy) and A-centre (oxygen-vacancy), are stable below 150 °C and so could not be the cause of the observed change in CTI. The silicon used to fabricate the CCDs contained a significant amount of carbon, therefore during the irradiation the S_i can exchange positions with a carbon atom to create a carbon interstitial (C_i). At -100 °C C_i 's are not mobile, however at 30 °C they are now able to form metastable defects with phosphorus and carbon atoms in the lattice, forming C_i-P_s and C_i-C_s defects both of which create energy levels which could have impacted the CTI of the Chandra CCDs.

3. The Swept Charge Device (SCD)

The CCD236 is a large area (4.4 cm²) X-ray detector which is read out continually in order to benefit from intrinsic dither mode clocking, suppressing the surface component of dark current. This allows the detector to be operated at warmer temperatures than a conventional CCD, making it an excellent choice to test the facility without the need for extensive time cooling and heating the device under test. In normal operation each output sample includes samples from all “pixels” in the device, so bright defects are imperceptible, and have no deleterious effect on performance until they increase mean dark signal to a level at which it degrades spectral resolution. The column isolation of the SCD are arranged in a perpendicular structure, with 100 μm square “pixels”, leading to an effective increase in detector area during the first 120 clock doublets required to readout the entire device and producing the characteristic triangular dark current profile of a SCD. This dark current profile can demonstrate the presence of dark spikes. The two-phase pixel structure is designed to confine transferred charge to a narrow channel to minimise CTI for improved radiation hardness [15], detailed information on the operation and performance of the CCD236 can be found in [15-17]. The CCD236 will be flown on-board the Chandrayaan-2 and Hard X-ray Modulation Telescope spacecraft, in the Chandrayaan-2 Large Area Soft X-ray Spectrometer and the Soft X-ray Detector respectively.

4. Experimental Arrangement and Technique

The cryogenic irradiation test kit, illustrated in Figure 1, has been developed to measure the CTI (X-ray, Extended Pixel Edge Response (EPER) and First Pixel Edge response (FPR)), cosmetic quality and defect type and concentrations (trap pumping [18-20]) pre- and post-irradiation, and after different periods at room temperature [14]. The push-pulls allow the radiation shields to be manipulated into and out of the beam and the rotational option will allow multiple areas of the device to be irradiated. The use of an X-ray tube and rotational X-ray fluorescence (XRF) target holder enables calibration and CTI measurements to be performed at multiple energies. Two Light Emitting Diodes (LED) are included to provide the device with a flat field optical illumination for EPER, FPR and trap pumping measurements to be performed.

The CCD236 was mounted onto an aluminium cold finger attached to a two stage thermoelectric cooler with 1000 Ω platinum resistance thermometers fitted to the device package and cold finger to monitor the temperature. Temperature control to ± 0.2 °C was provided by an ILX Lightwave (Bozeman USA) LDT-5525 controller. An Oxford Instruments (Scotts Valley USA) XTF5011/75-TH X-ray tube was used to fluoresce a polished manganese target held at 45° to the incident X-ray beam to provide a controllable number of 5,898 eV

X-rays onto the SCD. Clocking and biasing were provided by an XCAM Ltd (Northampton UK). USB2REM2 camera drive box in conjunction with drive software controlled using a custom MatLab software program.

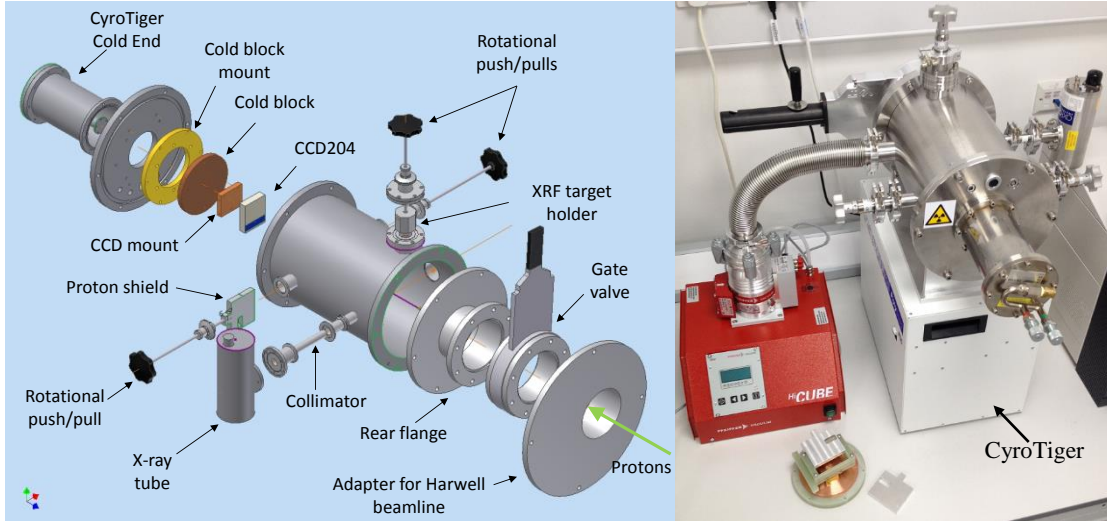


Figure 1: Schematic and photograph of the cryogenic test facility

The CCD236 was operated in two different modes, in normal mode the device was clocked continuously at a controllable readout speed, varied by changing the time allowed to perform Correlated Double Sampling (CDS) thereby reducing the bandwidth at higher readout speeds. The typical operational speed of these detectors is between 90 to 120 kHz. Faster speeds were investigated to assess the impact of reduced bandwidth when compared to radiation induced dark current and CTI, to determine an optimal operating speed when using this detectors in space. The X-ray flux was varied to provide a comparable number of X-rays incident on the device. This mode allows noise and energy resolution measurements to be made, and an estimation of the dark current to be determined based on the measured system noise with the input to the CDS card grounded. The second mode provided a small integration period prior to readout producing a triangular dark current profile. The dark current will also include a small contribution of surface dark current, however as the integration time is small it is believed that the bulk component will dominate. The profile produced is as a result of the device structure, and a similar profile is observed when a flat field illumination was provided using the LEDs.

The EPER measurement, previously untested in a SCD, relies on taking a flat field exposure, measured using a conventional CCD to be within 7% across the sensitive area of the CCD236, and measuring the amount of deferred charge in the overscan. The CTI_{EPER} is given by:

$$CTI_{EPER} = \frac{S_D(e^-)}{S_{LC}(e^-)n_t} \quad (1)$$

where $S_D(e^-)$ is the average deferred charge, $S_{LC}(e^-)$ is the charge in the last column and n_t is the number of pixel transfers [18]. The illumination was controlled to provide ~1600, 7000 and 16000 electrons in the last column. Due to the nature of SCD readout it was not expected that the results found using this method would be comparable to the same measurement performed using a CCD. This was confirmed during pre-irradiation analysis where the CTI was calculated

to be of the order $\times 10^{-3}$. If the actual pixel to pixel transfer was of the order $\times 10^{-3}$ the energy resolution measured pre-irradiation of around 130 eV would not be achievable, a CTI of $\times 10^{-6}$ is typical for a conventional CCD. Smith *et al.* [17] describe a method to determine the actual CTI in a SCD using X-rays. However this method requires a greater amount of time making it unpractical to measure CTI for this study.

4.1 CCD Irradiation and Annealing

With the equipment assembled on the end of the Synergy Health Helios-3 beamline (Harwell UK) and after the device had been held at $-35.4\text{ }^{\circ}\text{C}$ for a period of 30 minutes pre-irradiation tests were performed. The irradiation was then performed using 7.5 MeV protons at a flux of $1.1 \times 10^7\text{ protons.cm}^{-2}\text{.s}^{-1}$. Dosimetry was performed by staff at the facility and is believed to be better than 10%. The SCD was irradiated with a 10 MeV equivalent proton fluence of $5.0 \times 10^8\text{ protons.cm}^{-2}$, selected based on the SPace ENVironment Information System [21] analysis of a one year lunar orbit using the shielding assumptions made for the Chandrayaan-1 X-ray Spectrometer instrument [22]. It is not possible to re-create the space radiation environment during ground testing, therefore to account for the range of proton energies in space the Non-Ionising Energy Loss function is used as a scaling factor to provide a single energy equivalent proton fluence [23]. Upon the completion of the irradiation the post irradiation data collection was performed and the device allowed up to room temperature for return to the Open University. The test equipment was re-assembled and after a period of 24 hours the device was again cooled to $-35.4\text{ }^{\circ}\text{C}$ and the test process repeated. The analysis was then repeated after the device had been at room temperature for 7, 12, 16.5 and 82 days.

5. Results and Discussion

Pre-irradiation the device performed well across the range of readout speeds explored, shown in Figure 2, providing near Fano limited performance. Post irradiation there is a clear decrease in energy resolution as a result of radiation induced dark current and CTI. The energy resolution post irradiation between 180 to 230 kHz is comparable, therefore by operating at 180 kHz the change in energy resolution over the course of the mission would be less when compared to operating at 100 kHz, for only a small reduction pre-irradiation of around 15 eV. The impact on performance is greater at higher temperatures, for example at $0.9\text{ }^{\circ}\text{C}$ operating at 180 kHz improves the post irradiation energy resolution by around 210 eV. This is in agreement with work performed using a CCD236 irradiated at room temperature where the energy resolution was measured at 110 kHz and 175 kHz [16]. The post irradiation energy resolution is within error at the higher readout speeds, and shows a small improvement at lower readout speeds after the device was held at room temperature.

The total noise, consisting of system, read and dark noise components, as a function of readout speed is shown in Figure 3, the decrease pre-irradiation is as a result of the reduction in read noise, dark current is negligible at $-35.4\text{ }^{\circ}\text{C}$ pre-irradiation. Post irradiation there is a large increase in dark current, greater at slower readout speeds due to the increased time in which dark current can be collected, which was observed to anneal after the device had been held at room temperature. The dark current was found to anneal with the device held at room temperature following a power law, $t^{0.17}$. The same behaviour was observed when a small integration time was applied prior to the device being read out, producing the typical SCD triangular dark current profile shown in Figure 4, confirming the belief that bulk dark current is dominant. The device will now continue to be monitored before performing a $100\text{ }^{\circ}\text{C}$ anneal.

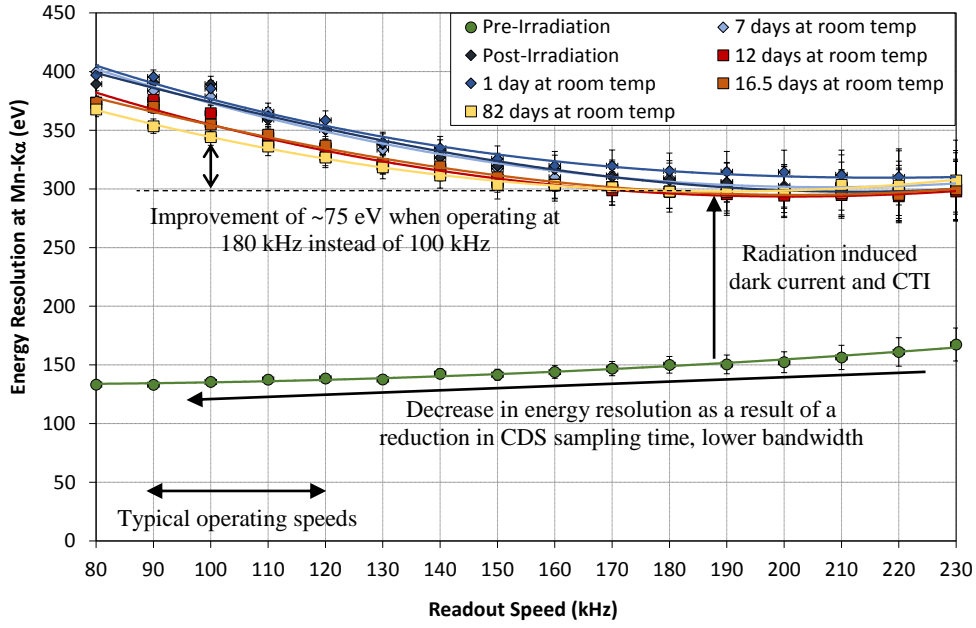


Figure 2: Energy resolution at Mn-K α as a function of readout speed at -35.4 °C

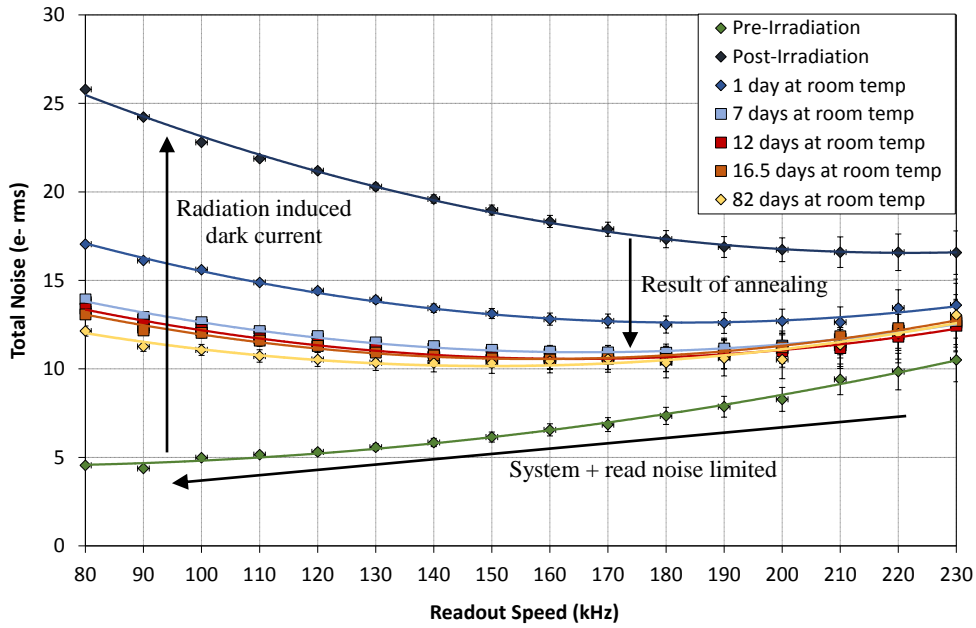


Figure 3: Total noise as a function of readout speed at -35.4 °C

The observed decrease in dark current suggests an increase in the number of defects impacting the charge transfer, without this the decrease in dark current alone should provide a significant improvement in energy resolution compared to the results shown in Figure 2. The energy resolution can be estimated by:

$$Energy\ Resolution = 2.35\omega \sqrt{F_{Si} \frac{E_y}{\omega} + \sigma_r^2 + \sigma_s^2 + \sigma_d^2 + \sigma_{CTI}^2} \quad (2)$$

where ω is the mean ionisation energy (3.65 eV) required to create an e-h pair, F_{Si} is the Fano factor (0.115), E_γ is the X-ray energy (5,898 eV), σ_r is the read noise, σ_s is the system noise, σ_d is the noise from the dark current and σ_{CTI} the noise arising from the CTI. Using the above equation to determine the noise component from CTI it was found that a large increase in CTI was required after the 1 day anneal, followed by a small decrease with time spent at room temperature up to stabilisation at 12 days. The noise component of CTI was also found to decrease as the readout speed was increased. This behaviour was confirmed by looking at the CTI_{EPER} as a function of readout speed, shown in Figure 5 where around 16000 electrons was measured in the last column. The data collected at 1600 and 7000 electrons followed a similar trend. The initial impact of the irradiation is clear by the large increase from the pre-irradiation value, as expected based on equation 2 the radiation induced increase in CTI is less as the readout speed was increased. The measured CTI_{EPER} also demonstrates reverse annealing during the initial 24 hours at room temperature, followed by a small amount of annealing accounting for the observed change in energy resolution with the device being held at room temperature.

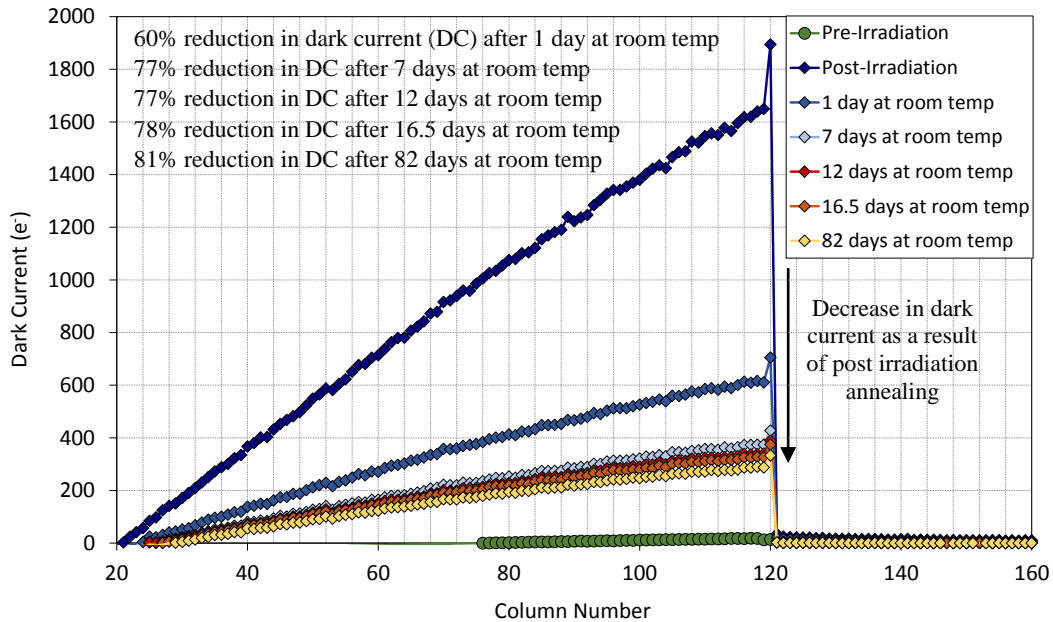


Figure 4: Triangular dark current profile with data collected at $-35.4\text{ }^\circ\text{C}$ during the room temperature anneal

Considering the time allowed for lost charge to rejoin the charge packet at different speeds there are no known trap emission times that would have a large impact CTI. The time between successive X-ray events is difficult to estimate due to the readout nature of the CCD236 where four $\sim 1\text{ cm}^2$ detector areas are combined. Based on the incident X-ray flux it would be in the range of 43 to 172 transfers between successive X-ray events. Considering this range and trap emission time constants at $-35.4\text{ }^\circ\text{C}$ both the divacancy at 0.42 eV and the stable C_i-P_s at 0.38 eV could be responsible for the observed trend at different readout speeds. The cause of the reverse annealing after 24 hours could be as a result of C_i mobility at room temperature, leading to the formation of C_i-P_s defects. The cause of the subsequent annealing is uncertain as both the divacancy and C_i-P_s are stable at this temperature. Unfortunately the readout nature of the SCD prohibits the use of techniques used to identify defects, for example trap pumping.

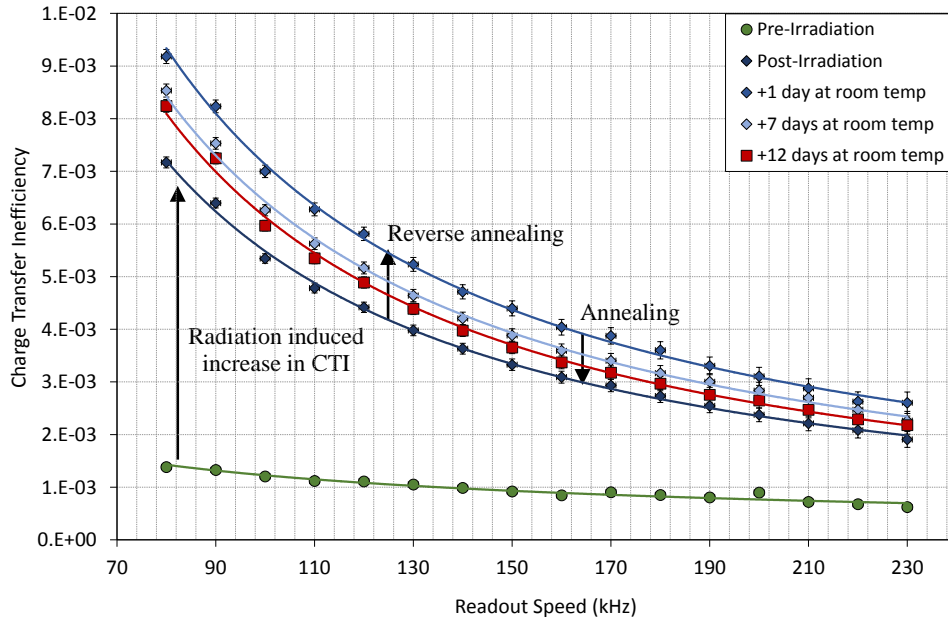


Figure 5: CTI as a function of readout speed at $-35.4\text{ }^{\circ}\text{C}$, measured with around 16000 electrons in the final column

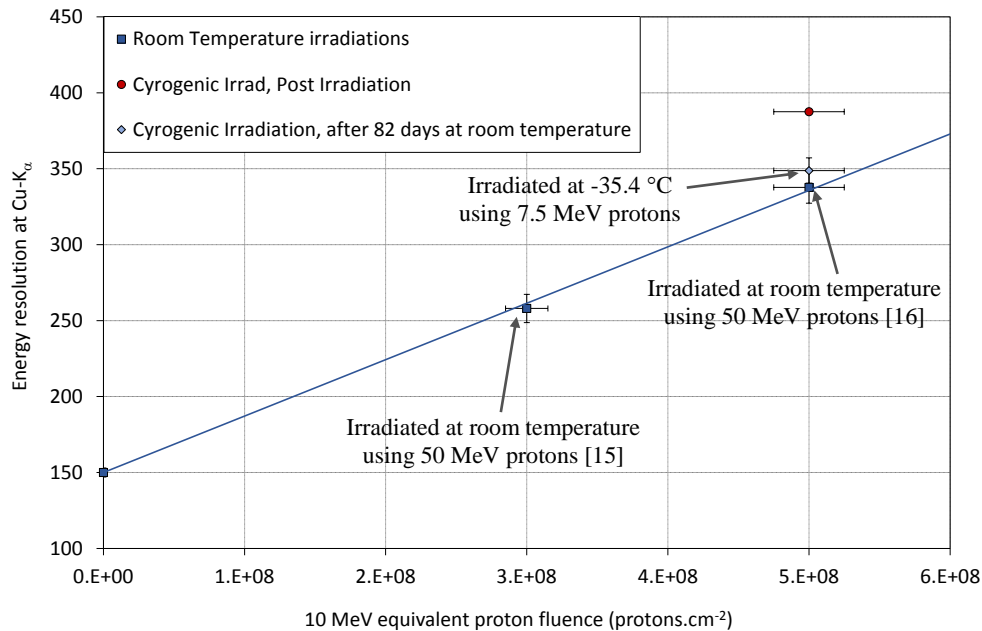


Figure 6: Energy resolution measured at Cu-K_{α} as function of proton fluence, the data point for immediately post irradiation is based on Mn-K_{α} measurements

After the device had been held at room temperature for longer than 82 days the measured energy resolution at $-30\text{ }^{\circ}\text{C}$ was found to be within error of data collected using a device irradiated at room temperature, shown in Figure 6. This is also a good demonstration of equivalent fluence as the room temperature irradiations were performed using 50 MeV protons. The data point for immediately after the irradiation in Figure 6 was estimated based on the improvement in energy resolution at Mn-K_{α} because data was not collected using the Cu-K_{α} target at this time.

6. Conclusion

Through the use of energy resolution, dark current and EPER measurements the performance of the SCD could be assessed quickly, minimising the time required at the irradiation facility. An estimation of the CTI was made using an optical illumination and the trend with readout speed was shown to compare well to the change predicted by energy resolution measurements, this demonstrates that the EPER technique is a valid method to minimise CTI in SCDs.

The room temperature annealing of the CCD236 has demonstrated the continued importance of performing cryogenic irradiations. In this case a room temperature irradiation could lead to the energy resolution at end of life being estimated to be 10% lower with the device readout under typical operating speeds. The dark current was found to anneal at room temperature, however the expected improvement in performance was almost negated by the formation of defects, possibly C_i-P_s , negatively impacting charge transfer.

The typical operating speed of an SCD is around 100 kHz, by operating the device at 180 kHz the impact of radiation induced dark current and CTI is minimised, it also provides reduced impact from annealing giving greater confidence in room temperature results. Operating at 180 kHz also provides a more gradual decrease in energy resolution over the course of a mission and improved energy resolution at mission end. Should it be possible it would be advisable to implement the option of varying the readout speed over the course of a space mission using these detectors to minimise the impact of radiation induced dark current and CTI on instrument performance.

Future tests will include devices irradiated at room temperature and monitored in the same manner as the cryogenically irradiated CCD, with a further CCD being held under cryogenic conditions continuously to monitor low temperature annealing over an extended period of time. The addition of trap pumping when using a conventional CCD will greatly increase the amount of information provided about defect formation and annealing within the silicon lattice.

Acknowledgments

The authors would like to thank Keith Jones of Synergy Health for his assistance with the irradiation and ESA for funding the development of the cryogenic irradiation test kit for use with the p-channel CCD204.

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