

HEAVY ION RADIATION TOLERANCE OF THE HWK4123 sCMOS IMAGE SENSOR FOR THE HABITABLE WORLDS OBSERVATORY

by

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M.S. THESIS

**Heavy Ion Radiation Tolerance of the HWK4123
sCMOS Image Sensor for the Habitable Worlds
Observatory**

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ABSTRACT

The Habitable Worlds Observatory (HWO) is NASA's next large flagship mission with the primary goal of observing and characterizing exoplanets that may harbor signs of life. It will assess the habitability of other worlds through direct imaging and spectroscopic measurements utilizing its coronagraph instrument. This instrument must achieve a contrast ratio of 10^{-10} . Only a few photons per hour are collected by the reflected light of exoplanets. Therefore, coronagraph instruments require highly sensitive detectors capable of resolving individual photons in order to identify signs of life within exoplanet spectra. These detectors must have low read noise, low dark current, high quantum efficiency (QE), large format pixel arrays, and high radiation tolerance spanning the visible to near infrared (NIR) wavelength range. They must also achieve a Technology Readiness Level (TRL) of 5 prior to the Mission Concept Review (MCR) towards the end of the decade. Therefore, candidate detectors must maintain these performance requirements within a relevant radiation environment expected at L2. This thesis characterizes the heavy ion radiation tolerance of one such detector, the Fairchild Imaging HWK4123 Scientific Complementary Metal-Oxide Semiconductor (sCMOS) Image Sensor. Heavy ion irradiation was performed on two HWK4123 detectors at the Michigan State University (MSU) Facility for Rare Isotope Beams (FRIB) over a surface Linear Energy Transfer (LET) range in silicon between 2.3 and 55.5 MeV cm²/mg, with fluences reaching up to 10⁷ ions/cm². Numerous non-destructive single event effects were observed during irradiation across the entire tested LET range. No notable permanent destructive single event effects were observed under irradiation. One detector accumulated a Total Ionizing Dose (TID) of 6.78 krad(Si) and a Damage Displacement Dose (DDD) of $(1.03 \pm 0.36) \times 10^8$ MeV/g(Si), resulting in an increased population of pixels with elevated dark current. These results suggest the implementation of radiation mitigation techniques for subsequent iterations of the HWK4123 detector to further reduce its susceptibility to heavy ions. Future radiation tests are required to fully characterize the radiation tolerance of the HWK4123 detector to assess its suitability for the HWO.

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DECLARATION

I, **Dylan Filosa**, declare that no part of this thesis is substantially the same as any that has been submitted for a degree or diploma at the Rochester Institute of Technology or any other University. I further declare that this work is my own. Those who have contributed scientific or other collaborative insights are fully credited in this thesis, and all prior work upon which this thesis builds is cited appropriately throughout the text. This thesis was successfully defended in Rochester, NY, USA on **8/27/26**.

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LIST OF PUBLICATIONS

The following publications were submitted as part of this research:

1. J. P. Gallagher, A. Tavana, D. Filosa, E. Alexani, S. Adler, N. Solvason and D. F. Figer, "Single-Photon Sensing CMOS Detectors for the Habitable Worlds Observatory," in *SPIE Conference 14157: X-ray, Optical, and Infrared Detectors for Astronomy XII (in press)*, Copenhagen, 2026.

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GLOSSARY OF ACRONYMS

- ADC** Analog-to-Digital Converter. 11, 13, 25, 28, 31
- ADU** Analog Digital Unit. 11, 23, 28
- BJT** bipolar-junction-transistor. 16
- BSI** Back-Side Illumination. 7, 41
- CCD** Charge Coupled Device. 7
- CDS** Correlated Double Sampling. 11, 12, 13, 36
- CfD** Center for Detectors. vii, 8, 25
- CIS** CMOS Image Sensor. viii, 9, 10, 11, 14, 17
- CML** Concept Maturity Level. 5
- CMOS** Complementary Metal-Oxide Semiconductor. 2, 3, 14, 16, 26, 36, 39, 41, 43, 44
- CMS** Correlated Multiple Sampling. ix, 36, 37, 38
- DCC** differential charge cancellation. 43
- DDD** Damage Displacement Dose. i, ix, x, 2, 6, 14, 17, 18, 19, 25, 26, 27, 35, 45, 48
- DICE** dual interlocked storage cell. 42, 43
- EAC** Exploratory Analytical Case. 5
- EMCCD** Electron Multiplying Charge-Coupled Device. 7
- FD** floating diffusion. 10, 12, 36, 37, 38
- FITS** Flexible Image Transport System. 11
- FPGA** Field Programmable Gate Array. 22, 23, 25, 36, 37, 45

FPN Fixed Pattern Noise. 13, 23

FRIB Facility for Rare Isotope Beams. i, vii, viii, 21, 22, 23, 24, 25

HabEx Habitable Exoplanet Observatory. 1, 3

HCI High Contrast Imaging. 4

HG High Gain. 10

HWO Habitable Worlds Observatory. i, 1, 2, 3, 4, 5, 6, 7, 13, 34, 35, 41, 45, 47, 48

IDL Interactive Data Language. 23, 25

JWST James Webb Space Telescope. 36, 45

LET Linear Energy Transfer. i, vii, ix, 14, 16, 17, 21, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 43, 47, 48

LG Low Gain. 10

LUVOIR Large Ultraviolet/Optical/Infrared Surveyor. 1, 3

MBE Molecular Beam Epitaxy. 41

MCR Mission Concept Review. i, 5

MKID Microwave Kinetic Inductance Detector. 7

MOSFET metal-oxide-semiconductor field-effect transistor. 13, 16

MSU Michigan State University. i, vii, viii, 21, 22, 24

NIEL non-ionizing energy loss. 19, 25

NIR near infrared. i, 4, 5, 7

PPD pinned photodiode. viii, 9, 10, 12, 27, 36, 37, 38

QE quantum efficiency. i, 1, 5, 6, 7, 9, 26, 41, 47

RIDL Rochester Imaging Detector Laboratory. vii, 8, 25, 26

RIT Rochester Institute of Technology. vii, 8, 25

RMS root-mean-square. 6

RST reset gate. 10, 12

RTN Random Telegraph Noise. 13

SAT Strategic Astrophysics Technology. 25

sCMOS Scientific Complementary Metal-Oxide Semiconductor. i, viii, 1, 7, 9, 33, 36, 45

SEB Single Event Burnout. 16, 40

SEDR Single Event Dielectric Rupture. 16

SEE Single Event Effect. 2, 14, 15, 16, 17, 23, 24, 26, 27, 31, 35, 39, 40, 41, 44, 45, 47, 48

SEFI Single Event Functional Interrupt. ix, 15, 23, 30, 31, 32, 33, 43, 44, 47, 49

SEGR Single Event Gate Rupture. 16

SEL Single Event Latchup. 16, 33, 35, 40, 41, 47

SET Single Event Transient. vii, ix, x, 15, 27, 28, 29, 30, 36, 38, 42, 43, 47, 48, 51

SETTOFF soft-error and timing-error-tolerant flip-flop. 43, 44

SEU Single Event Upset. ix, 15, 16, 23, 30, 31, 32, 33, 39, 43, 44, 47

SF source follower. 10

SiSeRo Single-electron Sensitive Readout. 7

SNR signal-to-noise ratio. 4, 36

SOI silicon-on-insulator. 40

SPAD Single Photon Avalanche Diode. 41

SPENVIS Space Environment Information System. x, 45

SPI Serial Peripheral Interface. x, 15, 23, 30, 31, 39, 41, 44, 49, 50

STI shallow trench isolation. 41

SW storage well. 9

TID Total Ionizing Dose. i, ix, x, 2, 6, 14, 17, 25, 26, 27, 35, 39, 40, 41, 43, 45, 48

TILL triple interlocked latch. 43, 44

TMR Triple Modular Redundancy. 44

TRL Technology Readiness Level. i, 5

TX1 transfer gate 1. 10, 12, 37

TX2 transfer gate 2. 10, 37

UTR Up-The-Ramp. ix, 36, 37, 38, 48

UV ultraviolet. 4, 7, 41

VRE Vegetative Red Edge. viii, 4, 5

CHAPTER 1

INTRODUCTION

The search for life on other worlds is the next great frontier of humanity. NASA's future flagship mission, the HWO, will advance our limited knowledge on this subject. This future serviceable instrument combines the goals of the Habitable Exoplanet Observatory (HabEx) and Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) missions regarding exoplanet direct imaging and spectroscopy as discussed in the Decadal Survey for Astronomy and Astrophysics 2020 [67]. Its primary goal is to identify and characterize potentially habitable exoplanets. Reflected light from these exoplanets are examined to determine its composition. Certain signatures within the atmospheric spectrum aid in the assessment of the exoplanets' habitability. However, this reflected light can be ten orders of magnitude or more fainter than its host star. Only a few photons of reflected light are received even after starlight suppression. In order to accurately identify these signatures within spectra, the HWO requires the use of single photon resolving detectors within its coronagraph instruments. These candidate detectors offer low read noise, dark current and high QE that allow for individual photons to be resolved. However, the radiation environment at L2 may degrade its performance, therefore requiring candidate detectors to exhibit radiation tolerance under expected radiation conditions at L2 [93] [89] [5] [11].

This thesis characterizes the performance of one such detector candidate, the HWK4123 sCMOS Image Sensor manufactured by Fairchild Imaging, after exposure to heavy ion radiation which span energies and fluences relevant to the radiation environment expected for the HWO at L2. Heavy ion radiation is used primarily to evaluate the detectors' susceptibility to various types of

Single Event Effect (SEE). The accumulated radiation results in TID and DDD effects, allowing for changes in detector performance to be evaluated after exposure. These results assess its radiation tolerance and suggest improvements to be made for future iterations of the detector to meet the performance requirements of the HWO. Section 2 describes the HWO, the detector and the fundamental physics behind its operation, as well as the physics of heavy ion radiation on Complementary Metal-Oxide Semiconductor (CMOS) devices. Section 3 describes the heavy ion radiation test on this detector and its performance both during and after testing. Section 4 discusses potential mitigation techniques to improve upon the radiation tolerance of the detector to meet the performance requirements of the HWO.

CHAPTER 2

DETECTOR AND RADIATION PHYSICS

Understanding the measurements that the HWO will make in its search for life will outline the necessity of the technology required to make precise measurements. A candidate detector, the HWK4123, may meet these performance requirements. However, radiation may degrade its performance. Evaluating the radiation tolerance of the HWK4123 requires an understanding of the physical mechanisms that govern its operation. This, along with the physics behind radiation effects on CMOS devices, will aid in the interpretation of results discussed in the following chapter.

2.1 The Habitable Worlds Observatory

The HWO combines the goals of the HabEx and the LUVOIR missions regarding exoplanet direct imaging and spectroscopy as discussed in the Decadal Survey for Astronomy and Astrophysics 2020 [67]. This mission is set to launch by the mid-2040s [11].

2.1.1 Exoplanet Observations

The majority of known exoplanets were discovered by the transit method, leading to the discovery of 4719 of the total 6336 known exoplanets [22]. This method requires the exoplanet to pass in front of its host star according to our line of sight. Measurements of exoplanets' radius, semi-major axis, orbital period and inclination can be derived from the dimming of the light curve as the exoplanet passes over the star. However, this method generates a significant amount of false positives, limited

by low signal-to-noise ratio (SNR), exoplanet size, small orbits, and alignment. Other significant detection methods include radial velocity and gravitational lensing [54] [38].

The HWO plans to discover exoplanets through direct imaging. This method recognizes exoplanets as an individual source of light, either by thermal emission or reflected light of its host star [54]. To achieve this, the HWO will incorporate High Contrast Imaging (HCI) by utilizing coronagraph instruments in order suppress starlight with a contrast of 10^{-10} and resolve exoplanet characteristics. Direct imaging produces higher SNR and spectral resolution than the transit method, due to the reduction of shot noise by suppressing the host starlight, and can be observed for longer periods of time [25]. The spectra of directly imaged exoplanets may reveal specular reflections, referred to as ocean glint, indicative of surface liquid water on terrestrial exoplanets during the crescent phase [23]. Direct imaging can also measure the exoplanet's orbit, phase and color. However, direct imaging is only sensitive to exoplanets with distances from host stars beyond 5 AU, and cannot directly measure mass or radius [38] [88]. According to the NASA Exoplanet Archive, there are currently 98 confirmed exoplanets detected by direct imaging [22]. The HWO plans to observe and characterize at least 25 Earth-like exoplanets [14] [36]. The habitability of icy ocean worlds in our own solar system may also be observed using the HWO, providing unique coverage in the ultraviolet (UV) [20].

Spectrographs of exoplanet atmospheres reveal its composition. Certain features within the spectrograph are indicative of a habitable world, referred to as biosignatures. Multiple biosignatures must be observed within the spectrum of an exoplanet to evaluate its habitability. For modern Earth, biosignatures include absorption features within the spectrum, such as the VRE and gaseous H_2O , O_2 , O_3 , and CO_2 between the UV and NIR wavelengths as shown in Figure 2.1. The VRE biosignature relates to surface vegetation, caused by the strong absorption of chlorophyll at red wavelengths between 660 and 700nm, as well as the reflection due to plant cell structure in the NIR [81]. Geometric albedo refers to the ratio between the reflected flux between an object and an idealized flat, white Lambert disk with a given radius and distance from a star [15]. As seen in simulated ancient Earth spectrographs, certain biosignatures vary in magnitude, as life has evolved over time, changing the composition of the atmosphere. Other biosignatures of interest to the HWO include CO , CH_4 , and NH_3 [14]. The Habitable Zone defines the range of exoplanet distances from its host star that would allow for the exoplanet with a given atmosphere to maintain surface

liquid water. Biosignatures and location are key factors that determine an exoplanets habitability. However, only a few photons of reflected light from exoplanets are received every hour. Thus, single photon resolving detectors are required for the HWO to resolve and characterize the small amount of signal received to determine the habitability of an exoplanet [79] [5].

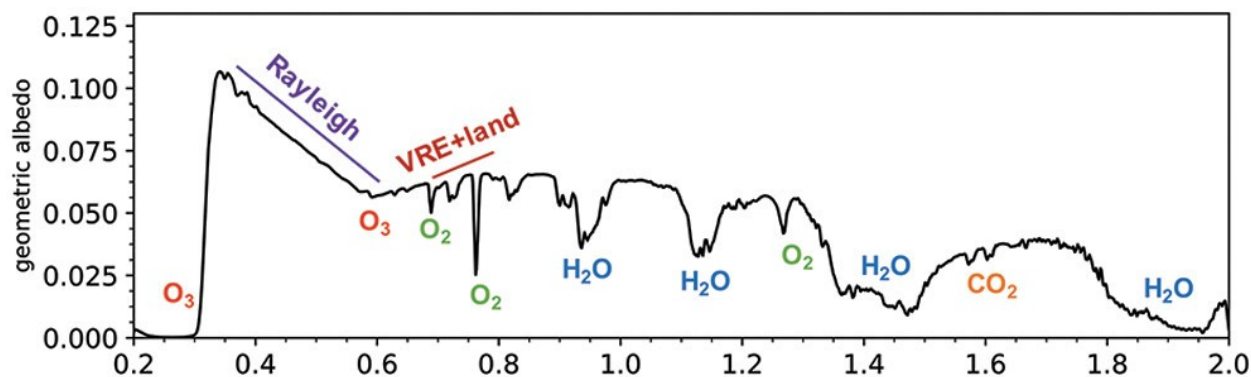


Figure 2.1: Simulated spectrum of modern Earth, with labelled biosignatures indicative of habitability for comparison to exoplanets. Also included are the locations of VRE and Rayleigh scattering [79].

2.1.2 Requirements

Two detectors are required for each channel of the coronagraph instrument for the HWO: one for direct imaging and another for spectroscopy using an integral field spectrograph. Each channel has its own set of coronagraph masks and deformable mirrors for starlight suppression. These detectors must have at least a 4K by 4K pixel array, with high QE and low read noise, covering one of or both the visible and NIR wavelengths, ranging from 0.45 to 1.70 μm . They must currently demonstrate a TRL of 3 or 4 to be considered for implementation, meaning they must have analytically or experimentally proven concepts, or have been tested in a laboratory setting and align with expected results. The HWO plans to be approved for TRL 5 before MCR within the next few years, meaning the instrument must maintain its performance in a relevant space environment. There are currently a few completed iterative architectural designs for the HWO, referred to as Exploratory Analytical Case (EAC). EAC1, 2, 3 and 5 have been finalized, while EAC 4 is still in development in preparation for Concept Maturity Level (CML) 4 [14] [36]. Candidate detectors are among the many areas of research actively being pursued during these developmental stages of the HWO.

To achieve single photon resolving capability, the candidate detector for the HWO must have a dark current less than $10^{-3} \text{ e}^-/\text{pix}/\text{s}$ for detection, $10^{-5} \text{ e}^-/\text{pix}/\text{s}$ for spectroscopy, a read noise below 0.1 e^- root-mean-square (RMS), and a peak QE above 90 %, with an average QE across the operating wavebands above 50 %. These detectors must maintain this performance in the radiation environment at L2 for a five year mission at minimum [14]. Candidate detectors must be exposed to the radiation conditions expected at L2 to determine its performance prior to implementation.

2.1.3 Radiation Environment at L2

In space, highly energetic particles are generated from a variety of sources. These particles mostly include galactic cosmic rays, solar protons, electrons and heavy ions. Although the exact origins of galactic cosmic rays remain unclear, the general consensus agrees that supernova remnants are the dominant source. Galactic cosmic rays consist primarily of protons, accounting for roughly 90 % of all cosmic rays, while electrons and heavy ions make up only 1 % each. Other potential sources include pulsar winds, microquasars, or a combination of strong stellar winds from young stars and their supernovae within superbubbles [92] [90]. Solar protons are generated by coronal mass ejections, while solar heavy ions are generated by solar flares [42] [66]. Heavy ions and protons generated within the Earth's ionosphere may become stuck within the Earth's magnetotail [10] [18] [51] [46]. All sources contribute to the performance degradation of instruments located at L2. Heavy ions are of particular interest as they deposit an immense amount of energy over a short path length through these instruments, resulting in unique radiation effects.

For one solar cycle of eleven years at L2, detectors with 1 cm of aluminum shielding would be exposed to around 3 krad(Si) of TID and 10^8 MeV/g(Si) of DDD [43]. The rate of heavy ions from the galactic background at L2 ranges from 2 to 6 ions/cm²/s, corresponding to a total fluence range of 0.69 to $2.08 \times 10^9 \text{ ions/cm}^2$ after eleven years at L2 [73]. Candidate detectors must maintain performance after a TID of 5 krad(Si) and a DDD of $7.6 \times 10^8 \text{ MeV/g(Si)}$ to demonstrate significant radiation tolerance for the HWO [45].

2.2 The HWK4123 sCMOS Image Sensor

2.2.1 Candidate Detectors

Several detectors are currently being considered as potential candidates which satisfy the needs of the HWO. Among them are Electron Multiplying Charge-Coupled Device (EMCCD), skipper Charge Coupled Device (CCD), Microwave Kinetic Inductance Detector (MKID), Single-electron Sensitive Readout (SiSeRo) CCD and sCMOS detectors. Each have their own advantages and disadvantages as summarized in Table 10 of the HWO Technology Development Plan [80]. MKIDs provide negligible read noise and dark current, however they must operate at sub-Kelvin temperatures, thus requiring cryogenic technology for optimal operation. Their pixel size is much larger compared to the other candidates, therefore limiting the number of pixels within a detector of comparable size. Skipper and SiSeRo CCDs both have high QE, low read noise and extremely low dark current. However, CCDs are more prone to permanent cumulative radiation damage compared to the other candidates, as radiation-induced traps greatly reduce the charge transfer efficiency, especially for charge furthest from the read out electronics [44] [43] [6]. sCMOS devices achieve single photon sensitivity at a fraction of the cost and are more readily available than other devices [5]. This, along with its radiation tolerance and on-chip read out architecture per pixel, make sCMOS detectors a prominent candidate for future space missions like the HWO [6].

One such sCMOS detector is the HWK4123, manufactured by Fairchild Imaging in 2020. This detector was manufactured using 65 nm Back-Side Illumination (BSI) sCMOS 3.0 technology, with a 9.4 Megapixel active pixel array in a 4100 by 2300 format, with a pixel pitch of 4.6 μm . This sensor operates across a wavelength range of 200 to 1100 nm, spanning the far UV to the NIR. Table 2.1 summarizes the relevant HWK4123 specifications [34] [35] [33]. These specifications, especially the low read noise, dark current, high QE, and large pixel format, are close to if not already satisfying the performance requirements for the HWO. The HWK4123 has already been implemented within ground-based telescopes and will be implemented for other space-based applications [76] [26] [77] [60].

HWK4123 Sensor Specifications	
Optical Format	4/3"
Active Array	4100 x 2300
Active Area	18.9 x 10.6 mm
Epitaxial Thickness	2.5 μm
Frame Rate	120 fps @ full frame rate
ADC Resolution	12 bits @ ≤ 60 fps, 11 bits @ 120 fps
Programmable Gain	LG: 1x, HG: 8x, 16x, 32x
HWK4123 Pixel Specifications	
Pixel Pitch	4.6 μm
Shutter Types	Rolling with global reset, Global
Dynamic Range	89 dB
Read Noise	0.145 e^- RMS
Dark Current	$3 \times 10^{-4} \text{e}^-/\text{pix}/\text{s}$ at 185 K
Quantum Efficiency	88 % at 485 nm
Conversion Gain	170 $\mu\text{V}/\text{e}^-$
Full Well Depth	7000 e^-

Table 2.1: HWK4123 specifications, based on the characterization of the HWK4123 at the RIDL at the CfD at RIT, as well as information adapted from [34] [35] [33] [45] [6].

2.2.2 Architecture and Read Out

The basic layout of the HWK4123 is shown in Figure 2.2. The 4100 by 2300 active pixel array is located within the center of the device. Surrounding this array are the appropriate read out and power electronics used during the normal operation of the detector.

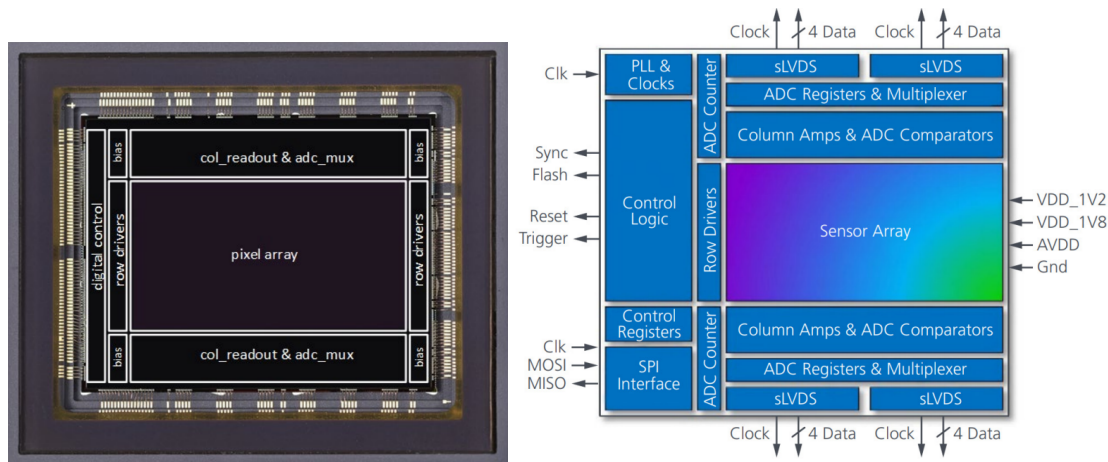


Figure 2.2: Labeled sections (left) and block diagram (right) of the HWK4123 sCMOS Image Sensor. [21] [33].

Typical CIS pixels use a reverse-bias p+np junction which collect charge, referred to as a PPD. It is comprised of impurities that are doped in such a way to efficiently collect and prevent the recombination of charge generated by an incident photon within the substrate, as shown in Figure 2.3. The n-well is placed between two p-doped regions. It contains a higher concentration of electrons, whereas the p-doped regions contain a higher concentration of holes. When these two regions come into contact, the charge carriers diffuse to balance their respective concentrations, annihilating each other. The absence of these charge carriers produces the depletion region at each border. Electrons no longer flow over the border once the electric field is high enough, caused by the increasing negative and positive ions in the p and n-doped regions respectively. Applying an external reverse-bias during reset increases the size of the depletion regions, encompassing the entire n-doped region. This region is the site of charge collection, often referred to as the storage well (SW). The top p+ layer, which resides between the n-well and the Si – SiO₂ interface, prevents generated charge from interacting with the interface, therefore minimizing the amount of traps that would increase dark current. This region has a slightly higher concentration than the bottom p-doped substrate. PPDs reduce noise, dark current, and increase QE [39] [19] [50].

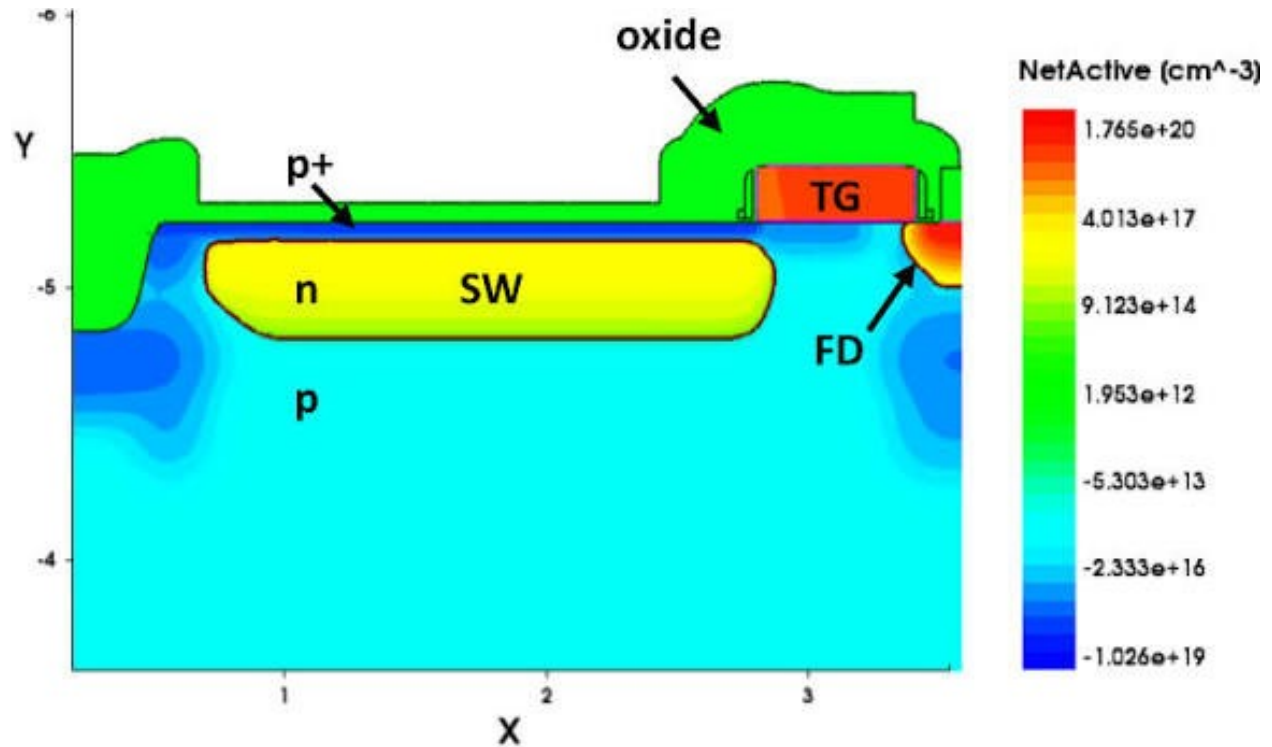


Figure 2.3: Example of a PPD within a CIS with labeled doping concentrations [39].

The PPD is incorporated within the 5T pixel architecture of the HWK4123, as shown in Figure 2.4. Charge is transferred from the PPD to the floating diffusion (FD) by transfer gate 1 (TX1). As evaluated in equation 2.1, this charge, Q , divided by the capacitance of the FD, C , determines the voltage, V . The low capacitance of the FD increases the voltage response from a single charge by hundreds of microvolts, higher than the voltage noise of the readout electronics [43]. The reset gate (RST) gate resets any charge remaining in the FD. The source follower (SF) buffers the voltage from the FD, allowing for the voltage associated with the collected charge to be read out. Finally, the row select transistor attributes each pixel to the column bus, or the bitline, for each selected row. Any unwanted charge within the PPD can be removed from each pixel by a global reset or for anti-blooming purposes through SF by turning on transfer gate 2 (TX2).

$$V = \frac{Q}{C} \quad (2.1)$$

Further down the bitline is the simplified analog signal path as shown in Figure 2.5. The column amplifier controls a programmable gain, either for a Low Gain (LG) mode of 1x gain or a High Gain (HG) mode of 8x, 16x or 32x gain. The detector can output dual-gain 11-bit data up to 120 fps,

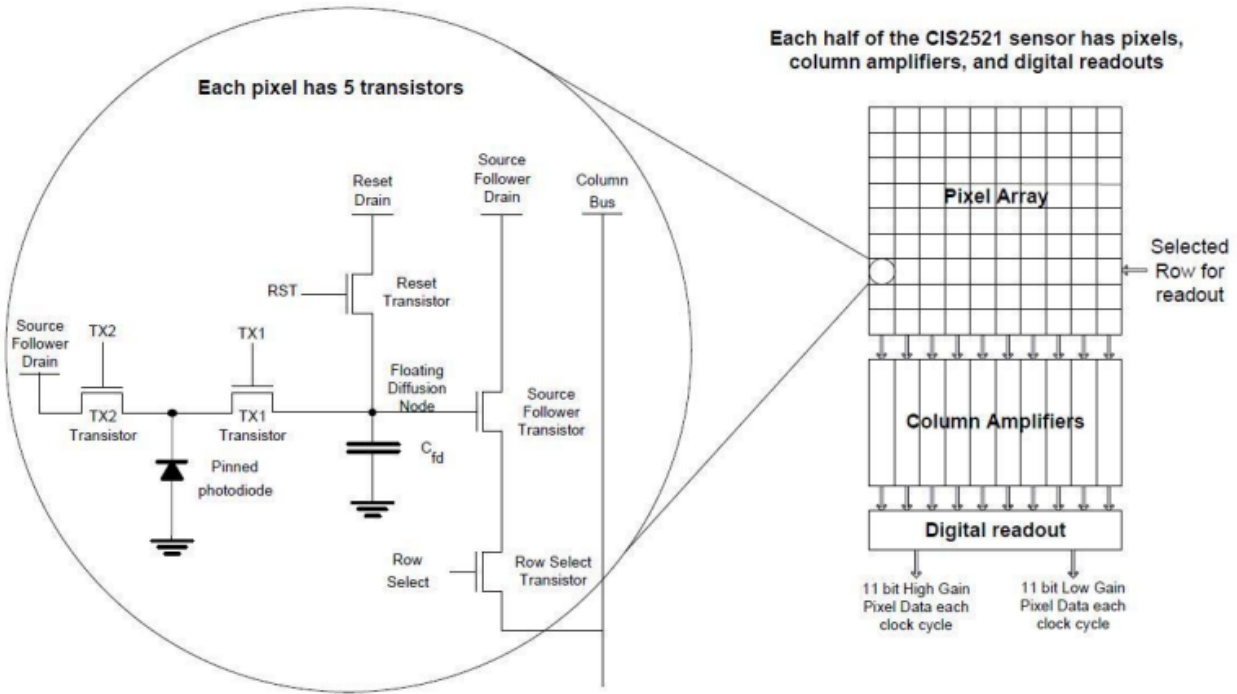


Figure 2.4: 5T pixel schematic associated with the active pixel region of the HWK4123. The 5T pixel architecture shown is based on an older Fairchild Imaging CIS, the CIS2521, which was incorporated into the HWK4123 [8].

or fixed-gain 12-bit data up to 60 fps. The gain comparator drops the gain to unity if the amplifier output exceeds v_{ref_LG} , an on-chip programmable reference voltage. The variable bandwidth stage controls the bandwidth to reduce the contribution of thermal noise, typically at higher gains, in combination with the bandwidth control within the column amplifiers. This voltage then reaches the sample and hold stage of the readout, where samples S1 and S2 are stored on capacitors prior to being converted into digital data [65] [21].

The programmable single slope Analog-to-Digital Converter (ADC) converts the analog signal determined by the voltage difference of samples S1 and S2 into a digital signal, represented as an Analog Digital Unit (ADU) within Flexible Image Transport System (FITS) images. A single-slope ADC utilizes a reference voltage ramp that increases at a fixed rate defined by a specific clock speed until it matches the input signal voltage. The comparator then fires and discontinues the clock, outputting the equivalent ADU value for that particular input voltage. For the fixed-gain 12-bit mode, the ADU range spans from 0 to 4095 ADU.

The HWK4123 utilizes Correlated Double Sampling (CDS) as its readout sampling method.

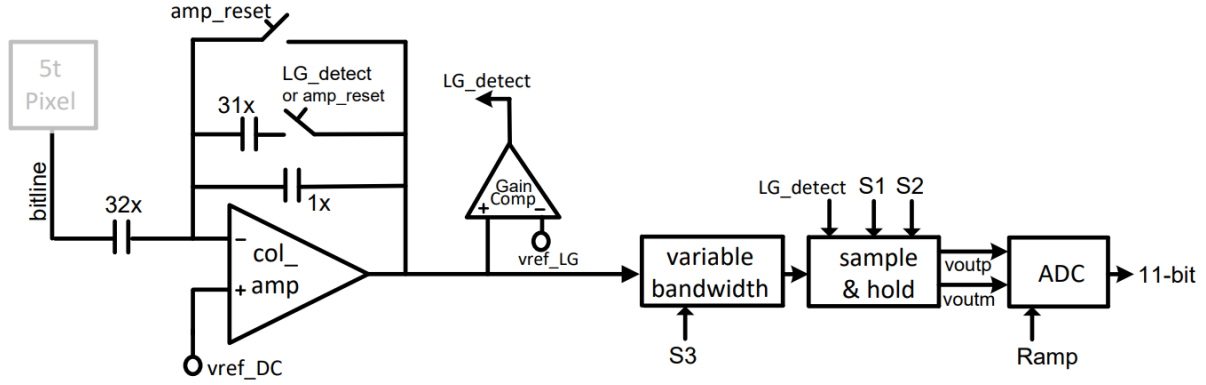


Figure 2.5: Simplified analog signal path within the HWK4123 [21].

Charge is accumulated during the integration time within the PPD when TX1 is off. The RST is then pulsed to remove any charge in the FD. A sample is then taken of the FD, referred to as the reset signal. Charge stored in the PPD is then transferred to the FD by TX1. Another sample is taken of the FD with this transferred charge, referred to as the sample signal. The signal of each pixel is then determined by the difference of the sample signal and the reset signal, represented as the charge held within S1 and S2, as shown in Figure 2.5, respectively. Both samples are taken a few microseconds apart, mitigating the effects from $1/f$ noise as the signal has little sensitivity to frequencies less than hundreds of kHz. CDS removes kTC noise from the FD [43].

2.2.3 Relevant Characterization Measurements

Two relevant detector characteristics that limit the performance of the detector are dark current and read noise. Dark current is the accumulation of charge due to thermal excitations in the absence of light. Local defects arise during fabrication that may increase the dark current for particular pixels. Other sources of dark current include radiation induced defects, thermal and surface generation. The average dark current is evaluated in equation 2.2, where P_A is the pixel area, D_{FM} is a device specific constant referred to as the dark current figure-of-merit, T is the temperature, E_{gap} is the band gap energy for silicon, and k is Boltzmann's constant. It is linear with integration time, at a rate that doubles with every 6 to 8 K increase in temperature. [56]. Dark current can be measured by taking multiple dark images across a range of integration times, evaluating the slope of the signal as a function of integration time per pixel, and computing the

median of the histogram for all pixels.

$$D_R = P_A D_{FM} T^{3/2} e^{-\frac{E_{gap}}{2kT}} \quad (2.2)$$

Read noise is a combination of various noise sources generated by the electronics of the device during read out. Included are 1/f, Johnson, kTC, Random Telegraph Noise (RTN) and ADC quantization noise. 1/f noise, or flicker noise, arises from defects between two materials, such as traps at the Si – SiO₂ interface of a metal-oxide-semiconductor field-effect transistor (MOSFET). This causes mobility charge carrier fluctuation due to scattering, as described by the Berkeley unified model [27]. This noise increases with decreasing frequency. Johnson noise, or white noise, occurs due to the thermal agitation of charged carriers, resulting in voltage uncertainty. kTC noise, or reset noise, is a specific case of Johnson noise, due to the uncertainty in the reference voltage during the reset of a MOSFET as sampled by the capacitor, caused by thermal variations in the channel resistance. This noise is suppressed by subtraction via the CDS method during read out. RTN results from the random trapping and emission of charge carriers, resulting in discrete modulation of the channel current. ADC quantization noise results from the limited integer range that rounds voltages within the resolution. [37] [56]. Read noise can be measured by taking the standard deviation across multiple short integration dark frames per pixel.

Other noise sources also limit overall detector performance. Shot noise, both from light and dark signal, results from the statistical variation in the rate at which charge is generated. Fixed Pattern Noise (FPN) arise from variation of the threshold voltage of source follower amplifiers, which control entire columns in the active pixel array [37] [56]. Quantum efficiency is the ratio between the amount of measured electrons to the amount of photons incident on the detector. All aforementioned detector characteristics degrade in radiation environments. Therefore, evaluating the effects radiation has on these characteristics will determine the suitability of the HWK4123 for the HWO.

2.3 Radiation Effects on CMOS Devices

Advancements in technology with each decade have allowed for detectors and their components to have significantly decreased in size. As a consequence, the amount of charge and capacitance required to generate unwanted effects that disrupt normal operation within these detectors has also decreased, making devices more susceptible to SEE. The scaling of CMOS devices over time changes its response to TID and DDD effects [2] [28] [91]. Therefore, evaluating the radiation tolerance of CMOS detectors is vital for consideration for future space missions.

Heavy ions generate a direct ionizing path through sensitive regions, such as p-n junctions of CIS devices, causing a variety of undesired effects. Electron-hole pairs are generated within this path, either through direct ionization from the particle itself, represented in Figure 2.6, or through indirect ionization by nuclear reactions generating secondary particles that then ionize the material. These ions transmit their energy into electrons of silicon atoms, promoting them from the valence to the conduction band. Each electron-hole pair takes 3.6 eV to generate within silicon. The number of electron-hole pairs generated in silicon is represented by equation 2.3, where ρ is the density of the material, LET is the amount of energy deposited per unit path length, E_{eh} is the energy required to generate an electron-hole pair, $\frac{dN}{dx}$ and $\frac{dP}{dx}$ are the number of electrons and holes generated per unit path length, respectively [96]. The heavy ion also creates a charge collecting funnel from the p-n junction, extending the electric field within the p-doped substrate, collecting more charge through rapid drift of electrons towards the n-doped region, while holes move towards the p-doped region. This process occurs within hundreds of picoseconds. Further collection of charge occurs afterward through diffusion, where concentrations of both electrons and holes move towards equilibrium within the sensitive region. This process occurs within hundreds of nanoseconds. The remaining uncollected electrons eventually recombine with holes. [7] [68] [52] [78].

$$\frac{dN}{dx} = \frac{dP}{dx} = \frac{\rho LET}{E_{eh}} \quad (2.3)$$

Radiation effects on these devices are broken into two categories: cumulative and single event effects. Cumulative effects depend on two kinds of dose, ionizing and non-ionizing, referred to as TID and DDD respectively. SEEs generate from individual ion interactions, resulting in either

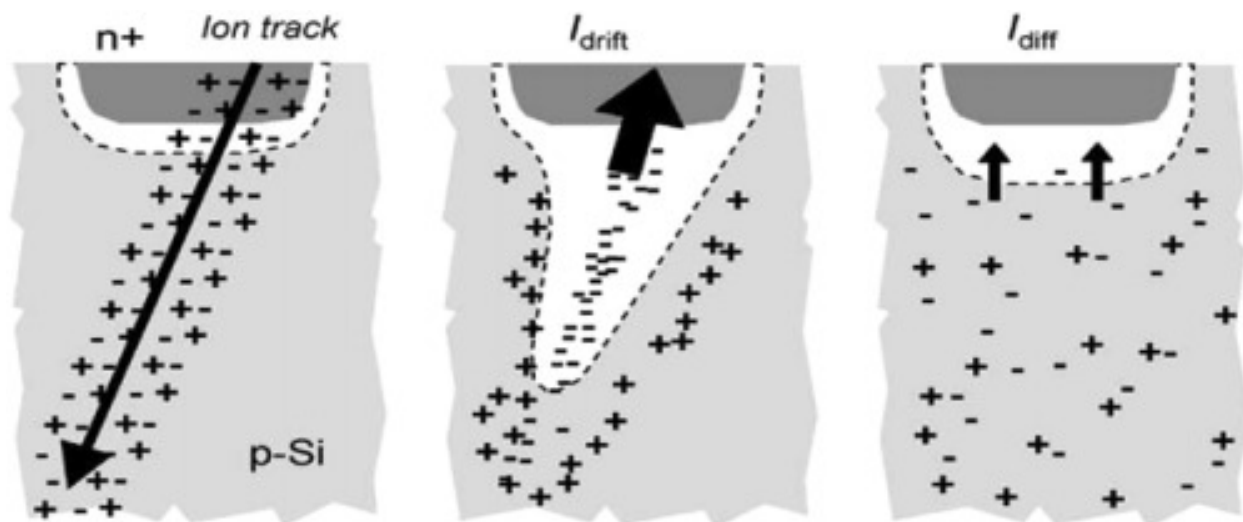


Figure 2.6: From left to right: Generation of electron-hole pairs by a heavy ion within a reverse-biased p-n junction, followed by charge collection through drift and diffusion [68].

destructive or non-destructive events.

2.3.1 SEE

SEEs comprise of non-destructive and destructive single event effects. Non-destructive effects include SET, SEU and SEFI. SETs within pixels generate temporary bright spots, and within circuits generate any transient pulse in voltage or current. SEUs and SEFIs relate to bit flips, particularly within memory circuitry, such as SPI registers. A heavy ion strike to the p-n junction of the off transistor within a cross-coupled inverter pair may generate enough charge to turn it on, therefore flipping a bit. The difference between the two is the severity of the effect caused by the bit that was flipped. For instance, a wave table timing SPI register may have flipped its least significant bit, which has not affected the normal operation of the device, therefore classifying the effect as SEU. SEFIs alter the normal operation of the device, particularly for any bit flips that involve column, row, clock, or power registers. These can either partially or completely disrupt data. In circuitry, SEFI can be identified as a small increase in nominal current that persists until reset. SEU are fixed by rewriting registers, while SEFI may require a complete reset and power cycle to restore normal operation of the device. Any defect that has occurred by non-destructive effects are recoverable either on their own or by user intervention. Within circuitry, SETs occur within combinational logic, whereas SEUs occur within sequential logic. A SET may become a

SEU if the signal is sampled by a storage element [62] [2] [52] [3].

Destructive effects generate from large amounts of deposited charge, typically from higher LET heavy ions, resulting in Single Event Latchup (SEL), Single Event Gate Rupture (SEGR), and Single Event Burnout (SEB). These events, especially if they persist, are permanent effects that will alter the normal operation of the device for the remainder of its life cycle. They have a strong temperature dependency, often increasing at higher temperatures [4]. A SEL results from a heavy ion strike on a parasitic thyristor. This activates the component, lowering the resistance between power and ground, draining high current. Excessive power remains drawn until power is removed from the circuit, otherwise causing permanent damage. SEGRs, a specific type of Single Event Dielectric Rupture (SEDR), affects the gates of a MOSFET. The electric field within the depletion region moves electrons towards the drain, while holes move towards the gate, causing a rapid increase in the gate leakage current. Equation 2.4 defines the condition for SEGR occur and undergo permanent breakdown, where E_{crit} is the critical value for the electric field, BV_{GS} is the reduced breakdown voltage across the oxide during SEGR, and T_{ox} is the oxide thickness. This increase of current may melt the gate or dielectric layers of the MOSFET. No protective methods have been developed to prevent permanent damage once SEGR has been initiated. SEBs occur at high power and voltage sites within the CMOS device, such as within a MOSFET. The electron-hole pairs generated at these sites cause collisional ionization, leading to the breakdown at the drain, leaving the parasitic bipolar-junction-transistor (BJT) on at the source. The drain-source current thus increases, leading to localized heating and potentially melting the source to drain component of the MOSFET [2] [69] [52] [68] [51].

$$E_{crit} = \frac{BV_{GS}}{T_{ox}} \quad (2.4)$$

LET is the typical unit of measurement used when reporting the amount of energy deposited onto a device per unit path length. This is used in combination with the SEE cross section in order to determine the susceptibility of the device or part. The fundamental relationship is shown in equation 2.5, normalized to the mass of the absorbing material, where ρ is the density of the material and $\frac{\partial E}{\partial x}$ is the amount of energy lost per unit path length [3]. LET changes as a function of depth within materials. For silicon, LET gradually increases, then sharply declines at its maximum

depth achieved. The surface LET refers to the LET achieved at the surface of the material, while the Bragg peak LET refers to the peak LET achieved within the material. Oftentimes, LET is reported as an effective LET, which adds a $\cos(\theta)$ factor to the denominator of equation 2.5, where θ is the incident angle of radiation.

$$LET = \frac{1}{\rho} \frac{\partial E}{\partial x} \quad (2.5)$$

The amount of charge generated within a sensitive region is evaluated in equation 2.6, where q is the elementary charge, LET is the amount of energy deposited within the material as a function of path length, ρ is the density of the material, l is the epitaxial thickness, and E_{eh} is the amount of energy required to generate an electron-hole pair. Inputting the threshold LET yields the critical charge required to generate a specific SEE [3].

$$Q = \frac{q \cdot LET \cdot \rho \cdot l}{E_{eh}} \quad (2.6)$$

2.3.2 Cumulative Effects

Opposed to SEE, cumulative effects gradually reduce the performance of CIS over time in a radiation environment. There are ionizing and non-ionizing cumulative effects, related to the amount of TID and DDD that the detector receives, respectively.

The total amount of energy deposited within the detector by ionizing particles is referred to as TID. TID effects arise within the insulating regions of the detector, such as within the gate oxide and SiO₂ layer. Approximately 17 eV of energy is required to generate electron-hole pairs within the SiO₂ layer. Electrons have a higher mobility within this region compared to holes, allowing for electrons to move more readily out of the oxide under an electric field. Differences in lattice structure at the Si – SiO₂ interface generate potential charge traps. As holes are slowly drawn towards this interface, due to their reduced mobility, they can become trapped. As TID increases, the amount of trapped charge also increases, as shown in Fig 2.7. This causes threshold voltage shifts, reduced charge carrier mobility and breakdown voltage, while increasing leakage current, dark current, random telegraph noise and 1/f noise [52] [70] [40] [86] [2]. The threshold voltage shift caused by TID is evaluated in equation 2.7, where q is the elementary charge, t_{ox} is the oxide

thickness, ΔN_{ox} is the change in the density of trapped holes within the oxide, and ϵ_{ox} is the dielectric constant of the oxide [17].

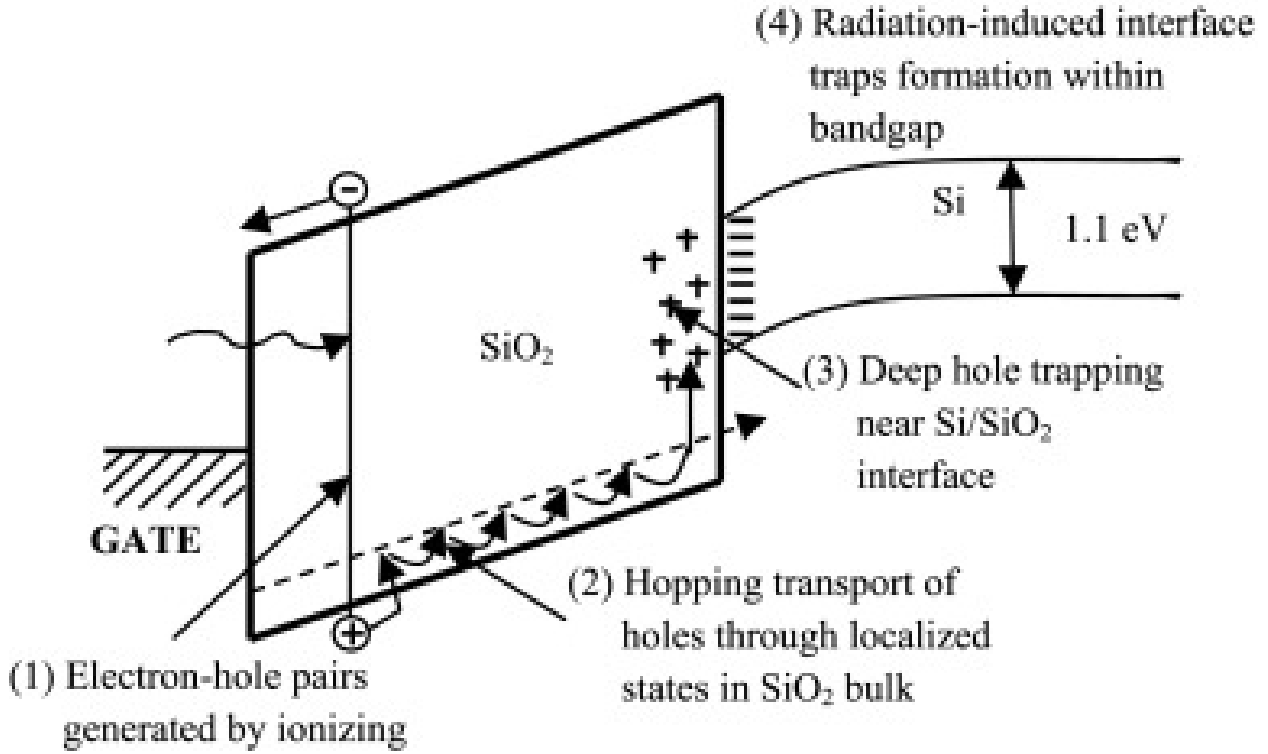


Figure 2.7: Electron-hole pair generation in SiO₂, resulting in radiation-induced trapped holes between the Si – SiO₂ interface [52].

$$\Delta V = -\frac{q t_{ox} \Delta N_{ox}}{\epsilon_{ox}} \quad (2.7)$$

The total amount of non-ionizing energy deposited within the detector by energetic particles is referred to as DDD. The amount of energy required to dislodge a silicon atom from its lattice structure into an interstitial state is 21 eV. This occurs through coulomb, nuclear elastic and nuclear inelastic scattering between energetic particles and the silicon lattice. In the simplest case, one dislodged atom, now in an interstitial state, leaves behind one vacancy state within the lattice, generating what is known as a Frenkel pair. The number of Frenkel pairs generated by heavy ions is approximated by equation 2.8, where E_{rd} is the portion of the ion energy that goes into displacements and E_d is the displacement energy threshold [87]. Frenkel pairs can create additional energy levels within the bandgap, allowing for alternate pathways to promote an electron into the

conduction band, as shown in Figure 2.8 [41]. Vacancies are found either isolated or clustered, with the latter occurring at higher particle energies inducing a cascade effect. DDD defects reduce minority charge carrier lifetime, charge mobility, charge transport, and diffusion length while increasing leakage current, dark current, and charge carrier traps [52] [70] [87].

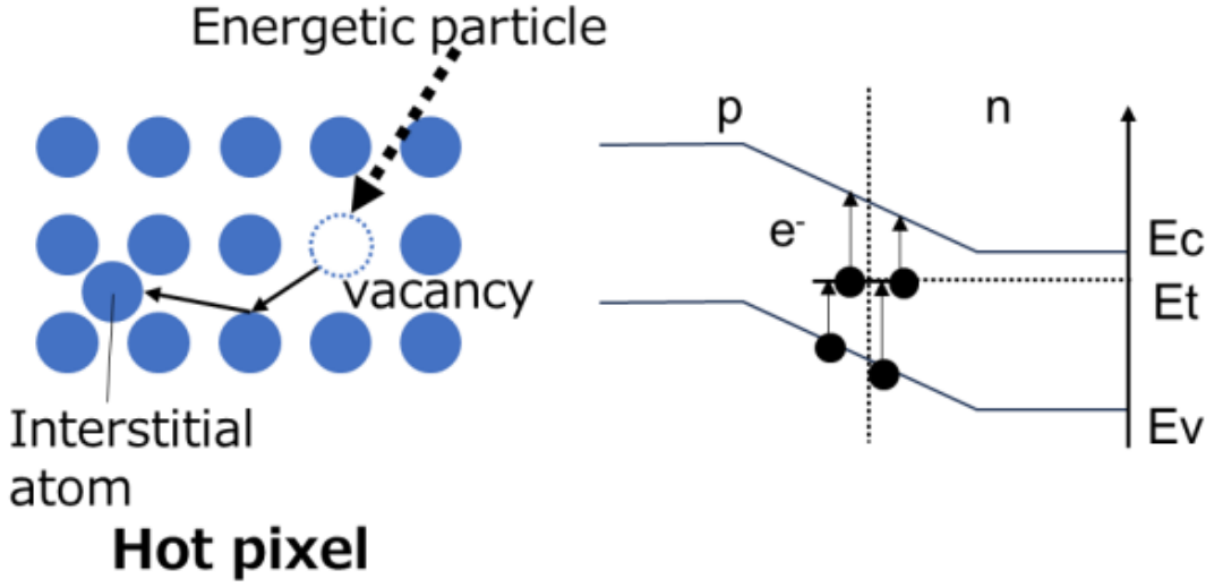


Figure 2.8: The left illustration depicts the generation of a Frenkel pair, while the right panel shows the effect this has on the bandgap from the p to n-doped substrates. The Frenkel pair introduces a new energy level, creating an easier path that requires less energy to promote an electron from the valence to the conduction band, resulting in higher dark current [41].

$$N = 0.4 \frac{E_{rd}}{E_d} \quad (2.8)$$

DDD is calculated by the product of the total fluence and non-ionizing energy loss (NIEL) per ion. NIEL is the portion of the ion's energy lost through a material that contributes to atomic displacements, evaluated in equation 2.9. $\frac{dE_{de}}{dx}$ is the displacement stopping power, N is the Avogadro constant, ρ_A and A are the density and atomic weight of the material, respectively, E and E_R are the recoil kinetic and maximum energy transferred to the recoil nucleus, respectively, E_d is the displacement threshold energy, P_k is the partition energy for the recoil nucleus, and $\frac{d\sigma(E, E_R)}{dE_R} dE_R$ is the differential cross section for any incoming particle with kinetic energy E resulting in a nuclear recoil with kinetic energy E_R [16] [85].

$$NIEL = \frac{dE_{de}}{dx} = \frac{N\rho_A}{A} \int_{E_d}^{E_R^{max}} P_k(E_R) \frac{d\sigma(E, E_R)}{dE_R} dE_R \quad (2.9)$$

CHAPTER 3

HEAVY ION RADIATION TESTING ON THE HWK4123

3.1 The MSU FRIB Facility

Heavy ion radiation testing was performed at the MSU FRIB. Two HWK4123 were irradiated: HWK4123-1453 and HWK4123-1441. Ions are generated by the electron cyclotron resonance ion source at the beginning of the beam, which are then accelerated through the K500 cyclotron. At the output beam window, this results in a range of surface LET at 30 mm in air for silicon devices between 0.9 and 83.0 MeV cm²/mg. The complete ion cocktail offered by this facility is shown in Figure 3.1. The beam operates at a 99.5% duty factor, 100 Hz repetition rate, and a 9.95 ms pulse duration [32].

19.5 MeV/u							
Ion Species	Copper Scattering Foil Width [μm]	Energy After Window [MeV/u]	Energy at 30mm Air [MeV/u]	Surface LET (Si) at 30mm Air [MeV/(mg/cm ²)]	Range (Si) at 30mm Air [μm]	Minimum Flux [pps/cm ²]	Maximum Flux [pps/cm ²]
20Ne	10	17.4	17.0	2.3	381	1.00E+02	5.00E+06
40Ar	10	16.2	15.4	7.5	241	1.00E+02	5.00E+06
59Co	5	15.8	14.7	15.3	176	1.00E+02	1.00E+06
84Kr	5	15.0	13.7	27.0	150	1.00E+02	1.00E+06
109Ag	5	13.9	12.3	43.8	118	1.00E+02	5.00E+05
129Xe	5	13.5	11.7	55.5	111	1.00E+02	5.00E+05
169Tm	5	13.4	11.7	70.0	122	1.00E+02	5.00E+05
197Au	5	13.3	11.6	83.0	122	1.00E+02	5.00E+05

35.0 MeV/u							
Ion Species	Copper Scattering Foil Width [μm]	Energy After Window [MeV/u]	Energy at 30mm Air [MeV/u]	Surface LET (Si) at 30mm Air [MeV/(mg/cm ²)]	Range (Si) at 30mm Air [μm]	Minimum Flux [pps/cm ²]	Maximum Flux [pps/cm ²]
16O	10	34	33.7	0.9	1520	1.00E+02	1.00E+07

Figure 3.1: Complete ion cocktail for the MSU FRIB KSEE facility [32].

Each HWK4123 detector was mounted in a special housing designed for exposure to radiation in air. This setup is compatible with the end station located at the output of the beam at FRIB to fully secure the system, as shown in Figure 3.2. The electronics used to power the detector and the Opal Kelly Field Programmable Gate Array (FPGA) are located behind the housing. Prior to exposure, the entire end station is moved to center the detector directly after the output beam window, which has a 30 mm air gap, minimizing the interactions between heavy ions and air. The beam angle of incidence remained the same throughout the test period, normal to the detector. An external power supply and a bias monitoring system located near the end station allowed for continuous monitoring of the detector and associated electronics for any significant changes to the operational voltage and current draw during irradiation.

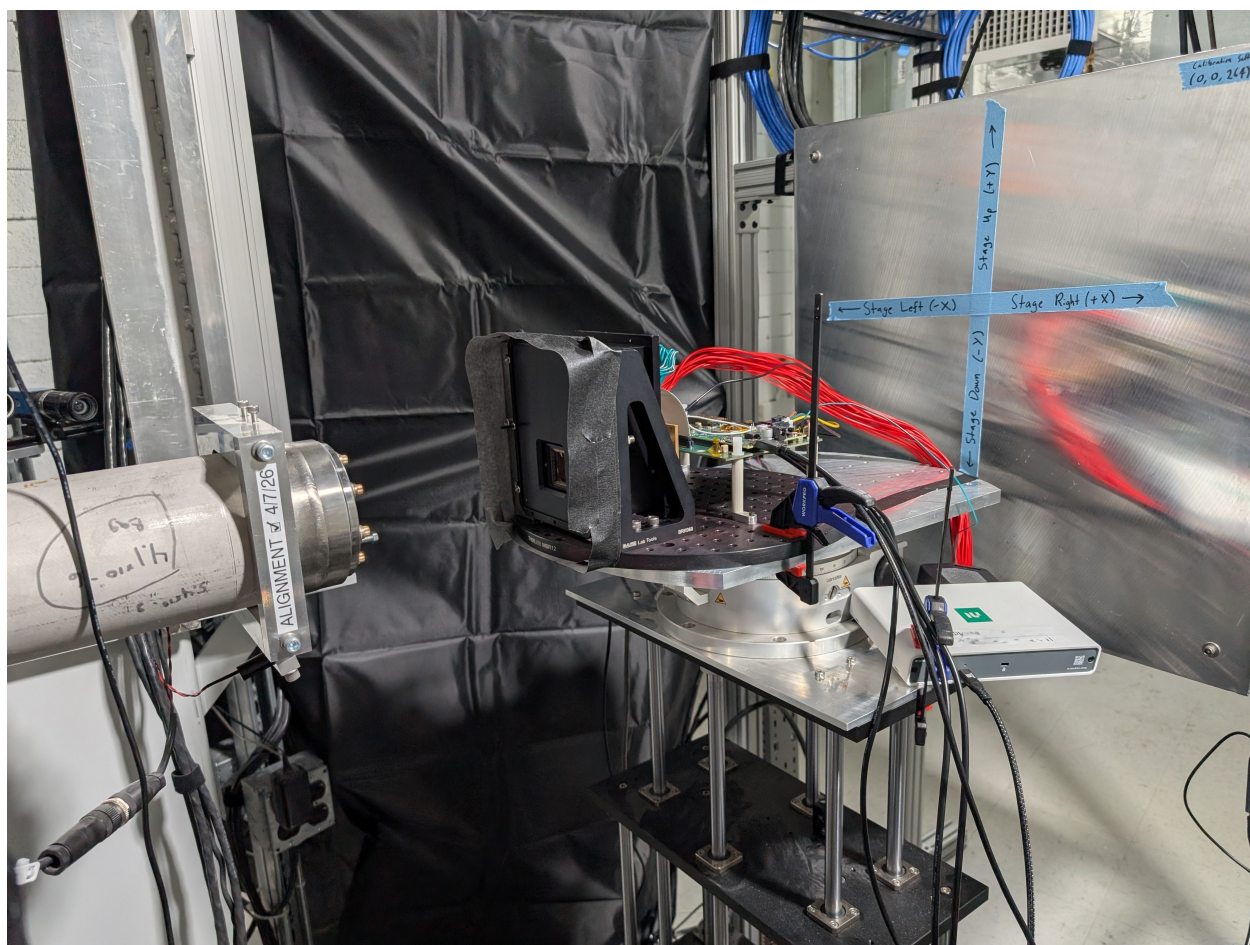


Figure 3.2: End station of the MSU FRIB KSEE beam (left gray tube), along with the HWK4123 setup (center black box) in preparation for heavy ion radiation testing. The HWK4123 is moved directly after the output of the beam window, ensuring the detector is centered with the beam prior to each exposure.

Once the beam was configured with the desired ion species and beam parameters, multiple exposure runs would capture images through Interactive Data Language (IDL) acquisition software. A single exposure run consisted of one image containing ten frames followed by one fixed pattern image containing two frames. Pattern images were injected with particular ADU values ranging from 0 to 4095 ADU from left to right, incrementing by 1 ADU per column. After each image and pattern were saved, the current SPI register values were recorded into a text file and then rewritten back to their original configuration. This preventative scrubbing technique mitigates the effects of SEU and SEFI bit flips, while also allowing for the effects seen in images to be correlated with particular SPI registers. A separate monitoring program continuously displayed basic information related to each exposure, relaying any discrepancies that would require a power cycle and reset of the system. If communication between the detector and the FPGA was lost, an alarm would trigger after 300 ms, followed by the immediate removal of power from the system, initiating a reset and power cycle. These events, referred to as "timeouts", were another cautionary step in the acquisition process to limit the duration of abnormal operation, reducing any potential destructive SEE event from persisting and causing permanent damage. In the least severe cases, these timeouts were triggered when a heavy ion strike altered a bit within a specific register which controls a flag indicating the start or end of a row of pixels while being read out. Without proper indication to the start or end of a line of data, the FPGA loses the ability to recognize when rows or frames should be read out, leading to a communication error between the detector and the FPGA.

Both HWK4123 detectors were operated at 1x gain in order to maximize the full well depth of approximately 7000 electrons. The conversion gain at 1x gain is approximately 0.5 ADU/e^- . The ADC utilized the 12-bit resolution at approximately 2.5 frames per second. Each pixel has a unique ADU offset due to FPN, with an average offset of approximately 250 ADU. The detector was operated using the rolling shutter, where the time interval between the reset and read of a particular row is the integration time, which took approximately $3.63 \times 10^{-4} \text{ s}$.

Table 3.1 summarizes the flux and fluence achieved for each ion species during the entire 16 hour testing period at FRIB for two HWK4123 detectors. Both detectors were exposed to heavy ions spanning a Bragg peak LET range between 9 and 69 $\text{MeV cm}^2/\text{mg}$. In general, higher fluxes and fluences were used for lower LET heavy ions, as timeouts occurred less frequently at lower LET. Most ions achieved a fluence of 10^7 ions/cm^2 using a flux of 10^4 ions/s/cm^2 , in order to

sufficiently observe a statistically significant amount of SEE as recommended by the radiation test standard for heavy ions [71]. For a fluence of 10^7 ions/cm², an average of approximately two ions passed through each pixel, given the pixel pitch of $4.6 \mu\text{m}$. Therefore, the average number of heavy ions that passed through each detector is approximately 8.13 ions for the HWK4123-1453 and 2.39 ions for the HWK4123-1441. No permanent damaging SEEs occurred during testing, and the bias monitoring system showed little to no increase in voltage for any of the biases.

Ion Species	Flux [ions/s/cm ²]	Fluence [ions/cm ²]	Surface LET [MeV cm ² /mg]
HWK4123-1453			
20Ne	8.89×10^3	1.19×10^7	2.3
40Ar	5.24×10^3	1.00×10^7	7.5
59Co	5.02×10^3	1.00×10^7	15.3
84Kr	1.10×10^3	5.56×10^6	27.0
129Xe	1.11×10^3	1.00×10^6	55.5
HWK4123-1441			
20Ne	1.07×10^4	1.00×10^7	2.3
129Xe	1.10×10^3	1.36×10^6	55.5

Table 3.1: Heavy ion irradiation measurements for both HWK4123 detectors used during testing at MSU FRIB. The columns from left to right are the names of the ion species used, the average measured flux, the measured fluence, and the surface LET for silicon as measured at the output beam window (30 mm of air).

3.2 The Rochester Imaging Detector Laboratory

Detector characterization before and after heavy ion radiation was performed in the RIDL in the CfD at RIT. Multiple HWK4123 detectors have been characterized in detail at this facility, funded by the Strategic Astrophysics Technology (SAT) grant (80NSSC24K0372). Thus far, this includes six individual detectors as well as two Hamamatsu ORCA-QUEST cameras, which incorporate HWK4123 detectors [47]. Various experiments are performed in a vacuum cryogenic dewar to simulate conditions relevant for a space environment. Cold electronics within the dewar control detector clocks, bias voltages and current. Warm electronics located outside the dewar include power supplies and a FPGA, using a custom hardware program. The Opal Kelly FPGA generates the detector clocks, programming the cold electronics, receiving data from the ADC. This data is then sent to a computer which deinterlaces and saves the image. Experiments are run on custom software programs using IDL. A monochromator and integrating sphere are attached to the system and can aid in the detailed characterization of detectors. Lakeshore temperature controllers maintain the temperature of the detector and system [43] [44]. Dark current and read noise measurements of both detectors were taken prior to and after irradiation to heavy ions at the RIDL. These measurements allow for the evaluation of cumulative radiation effects on detector performance.

3.3 TID and DDD Effects

As a consequence of irradiating these detectors with heavy ions, the HWK4123-1453 had accumulated a TID of 6.78 krad(Si) and a DDD of $(1.03 \pm 0.36) \times 10^8$ MeV/g(Si), while the HWK4123-1441 had accumulated 1.78 krad(Si) and a DDD of $(2.35 \pm 1.52) \times 10^7$ MeV/g(Si). The total TID was provided by the FRIB facility, whereas the DDD was calculated from the product of the total fluence and the NIEL for each ion species. The accumulated TID and DDD provide an initial characterization of the HWK4123 to cumulative radiation effects, which serves as the baseline for upcoming proton and electron radiation tests.

Figure 3.3 shows an increased population of pixels with elevated dark current in the HWK4123-1453 due to cumulative radiation effects. The detector was annealed for a few days in air at room

temperature after the heavy ion radiation test at RIDL. Although the median dark current had no significant change, a larger population of pixels exhibit higher dark current values at a detector temperature of approximately 230 K. Operating the detector at a lower temperature reduces this difference in dark current to values similar to those measured before irradiation. Another single photon resolving CMOS detector, the QISSAT1-2, reports the same general trend after exposure to 50 krad(Si) using 60 MeV protons [44]. No significant changes in read noise, QE, and electronic gain were measured after heavy ion radiation testing.

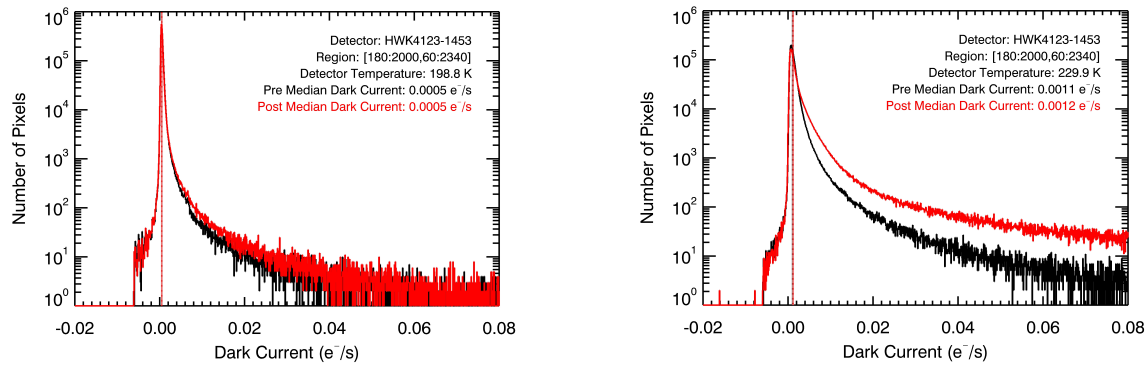


Figure 3.3: Dark current histograms of the HWK4123-1453 before and after heavy ion irradiation, represented in black and red respectively. The detector received a TID of 6.78 krad(Si) and a DDD of $(1.03 \pm 0.36) \times 10^8$ MeV/g(Si). The left and right panels are dark current measurements taken at a detector temperature of approximately 200 K and 230 K respectively.

Heavy ions can transfer enough energy to displace silicon atoms from the lattice sites permanently. DDD effects can be identified within images as individual bright pixels, referred to as hot pixels, that persist throughout each subsequent exposure. The number of hot pixels increases with both LET and accumulated DDD, as shown in Figure 3.4, which increases the overall dark current of the detector. Another HWK4123 radiation test found similar increases in the population of hot pixels, therefore resulting in a higher dark current, after irradiation of heavy ions and Co-60 gammas [51].

3.4 SEE

Numerous non-destructive SEEs were observed during heavy ion radiation testing on the two HWK4123 detectors. No permanent destructive SEEs occurred throughout the entire test period

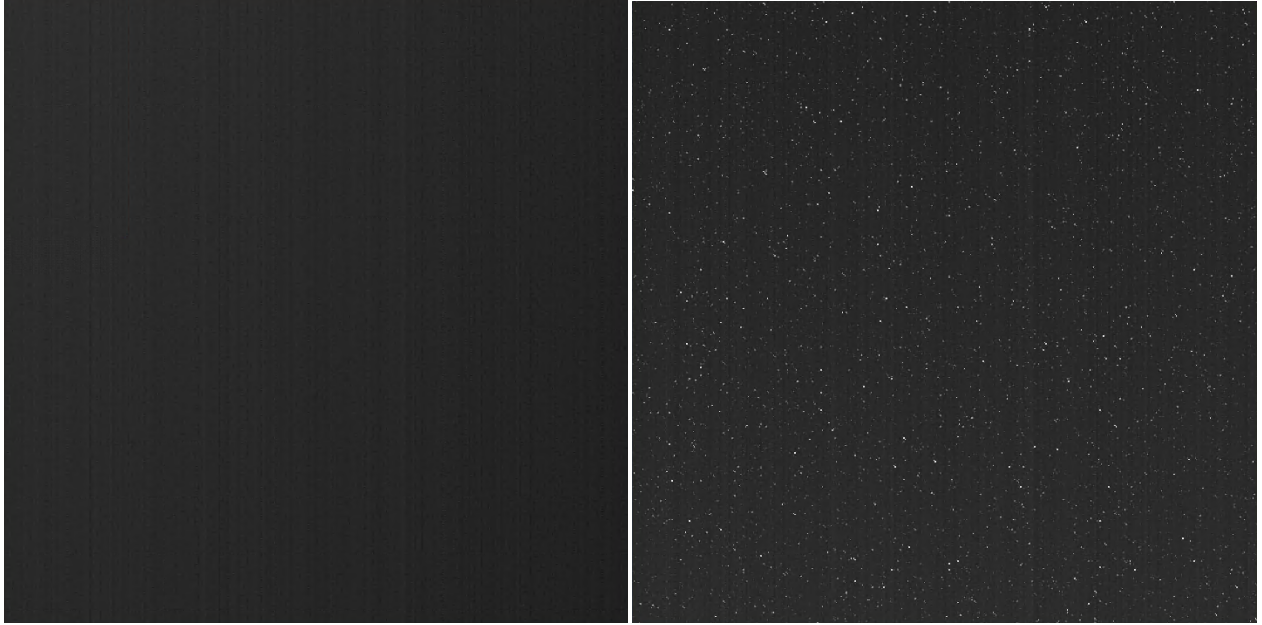


Figure 3.4: Persistent hot pixels after exposure to a TID of 6.78 krad(Si) and a DDD of $(1.03 \pm 0.36) \times 10^8 \text{ MeV/g(Si)}$ on the HWK4123-1453. The left and right panel show a 500 by 500 active pixel region of an image taken with the beam off before and after the entire irradiation test on the detector, respectively.

up to the maximum tested surface LET of $55.5 \text{ MeV cm}^2/\text{mg}$. The LET threshold for all non-destructive events is below the least energetic ion, 20Ne, at a surface LET of $2.3 \text{ MeV cm}^2/\text{mg}$, suggesting that the affected sensitive regions exist within a depth of $381 \mu\text{m}$ from the backside of the detector.

3.4.1 SET

As discussed in Chapter 2, SETs result from heavy ions striking the sensitive regions of the pixel, generating electron-hole pairs. Electrons are collected through drift and diffusion within the depletion region of the PPD, which is eventually transferred and read out within the pixel. Heavy ions generate a significant amount of charge within a single pixel, which saturates and floods into neighboring pixels. This results in a circular bright cluster of saturated pixels centered at the location of incidence. SETs are the most common type of SEE during exposure. For the purpose of this thesis, SETs refer to transient clusters seen in images under irradiation, however it is also possible to see these events by measuring small transient increases in current. The latter effect was not significantly noted based on the measurements of the bias monitoring system.

Figure 3.5 compares the relative size of SETs with surface LET for the five heavy ions used on the HWK4123-1453. In general, they increase in size with LET, with behavior similar to that of a Weibull curve. The white pixels that form the cluster are saturated at values of 4095 ADU, incorporating the 12-bit ADC output. More energetic particles impose more generated charge within a pixel, leading to more leaked charge over a larger number of neighboring pixels. Since the angle of incidence was normal to the detector, charge was distributed relatively evenly. Their shape maintains the same morphology regardless of surface LET, as long as the data was not significantly corrupted during readout. Using equation 2.6, the amount of generated charge per ion from least to most energetic is approximately 3.72×10^5 , 1.21×10^6 , 2.48×10^6 , 4.37×10^6 , and 8.98×10^6 e⁻. The collected charge shown per ion in this figure is a fraction of the total generated charge, as most electron hole pairs generated by heavy ions recombine.

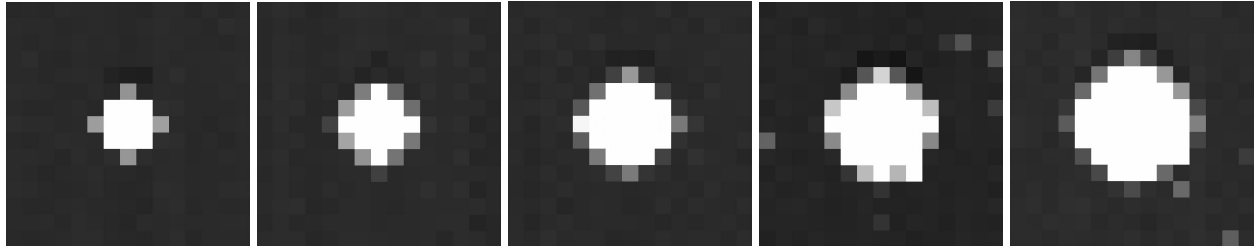


Figure 3.5: SETs increase in size with increasing surface LET. From left to right: SET seen during exposure to 20Ne, 40Ar, 59Co, 84Kr and 129Xe.

The total number of SETs seen in these images per ion is summarized in Table 3.2. Since these clusters were found in every image, the threshold surface LET for SETs is below the lowest ion, 20Ne, at 2.3 MeV cm²/mg. Clusters were identified in every frame using the find procedure of an IDL translated IRAF DAOPHOT package, designed for aperture photometry [59].

Ion Species	Surface LET [MeV cm ² /mg]	Number of SETs
HWK4123-1453		
20Ne	2.3	2.18×10^6
40Ar	7.5	1.18×10^6
59Co	15.3	1.35×10^6
84Kr	27.0	6.34×10^5
129Xe	55.5	1.38×10^5
HWK4123-1441		
20Ne	2.3	2.79×10^6
129Xe	55.5	2.11×10^5

Table 3.2: Total number of SETs identified at each ion for both detectors. From left to right, the columns are the ion species, surface LET, and total number of SETs.

Exposing each detector to 20Ne exhibited the highest abundance of clusters per image, as exposures allowed for a higher average flux around 10^4 ions/s/cm² to be used without constant timeouts. Overlapping clusters were common within these images, as well as artifacts unique to this ion. In rare cases, there exist clusters with sizes similar to those generated by a heavier ion, despite having the beam configured to irradiate 20Ne ions. In extremely rare cases, there exist streaks of SETs, as if the heavy ion had hit the pixel region of the detector at an angle, despite the detector positioned normal to the output of the beam. Both peculiar cases are shown in Figure 3.6. Proton irradiation has the capability to generate secondary particles in silicon by indirect ionization, either through elastic collisions or nuclear reactions [72]. 20Ne may have the same capability, as it is the only heavy ion lighter than silicon, has the least amount of surface LET, comparable to high surface LET protons, and has less electrons, therefore less repulsion when in close contact with silicon. In

both cases, neon may have physically collided with a silicon atom head on, causing either fusion into a heavier element with higher LET or fragmentation of the silicon nucleus, generating other energetic particles. These fragments range from smaller energetic particles like protons and alpha particles to lower LET ions. Heavy ion beams with kinetic energies on the order of tens to hundreds of MeV result in multiple heavy ion fragments after collision with different surfaces [30] [94] [95]. Displacement damage in the subsequent frame remains at the central pixel at which these particular events occurred. Indirect ionization is negligible for heavy ions, but not improbable [3].

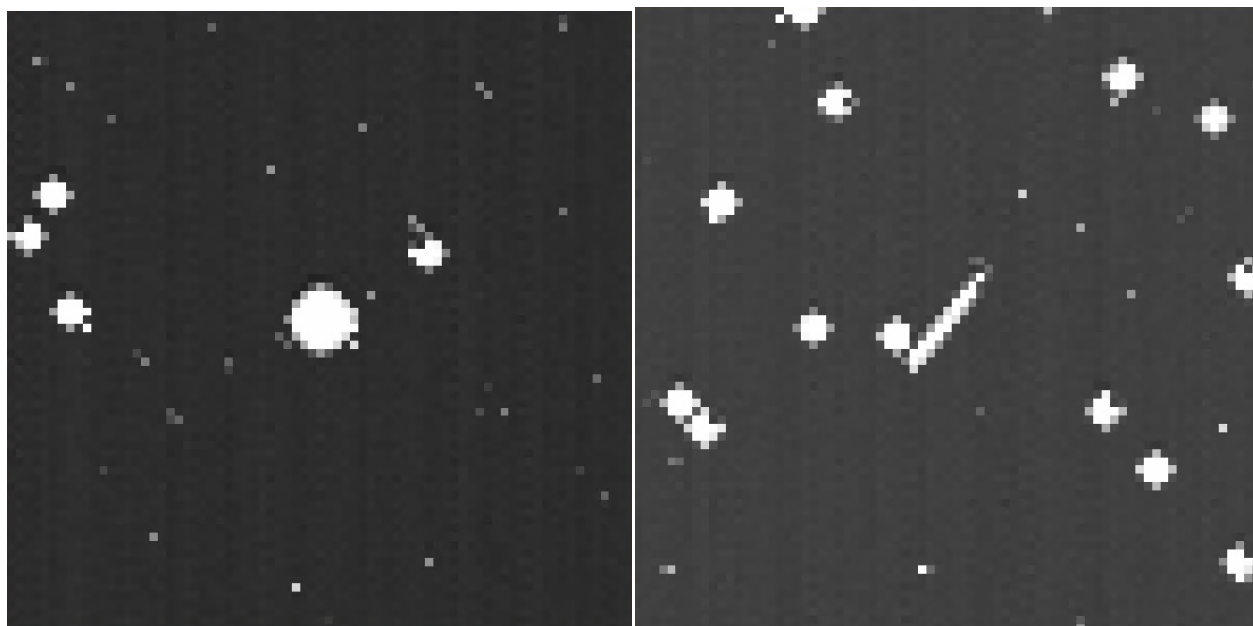


Figure 3.6: Peculiar behavior only found in ^{20}Ne images. The left panel shows a larger than expected SET for an image on HWK4123-1453, and the right panel shows a streak of saturated pixels for an image on HWK4123-1441. Both are likely results of elastic collisions and nuclear reactions of ^{20}Ne with silicon.

3.4.2 SEU and SEFI

Multiple bit flips were observed within SPI registers. At best, this had no effect on the overall operation of the device. At worst, timeouts would occur, resulting in a full reset and power cycle in order to restore normal operation. As discussed in Chapter 2, this difference in severity distinguishes the classification between SEU and SEFI. In most cases, simply rewriting the SPI registers back to their original values prior to the next exposure removed any artifacts caused by a bit flip. The total number of bit flips for all SPI registers for both detectors is shown in Figure 3.7. Approximately

200 to 550 total SEUs and 50 to 150 SEFIs had occurred during heavy ion irradiation, depending on the ion species and the total fluence achieved per ion. Almost all instances of SEU had no effect on the generation of images.

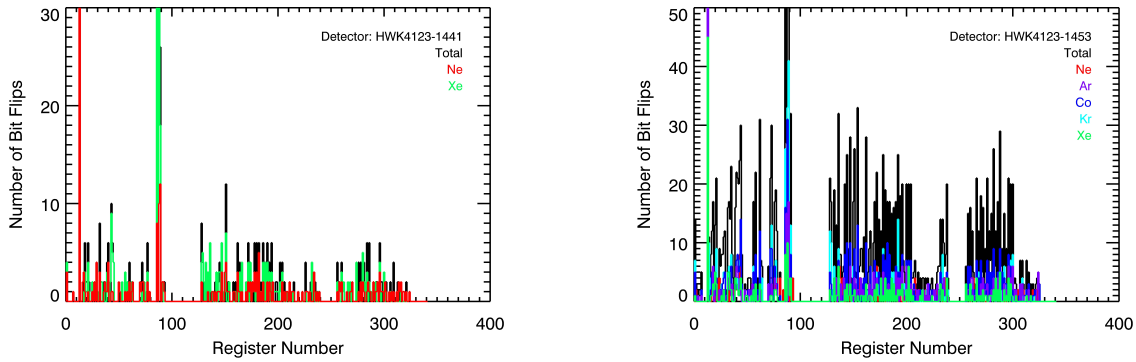


Figure 3.7: Total amount of times a bit flip occurred for each register in the HWK4123-1441 and HWK4123-1453 during heavy ion irradiation from left to right respectively. Register numbers 8 through 11 and 76 through 79 are read-only registers. As a consequence, these registers were not rewritten unless the entire system was reset, resulting in the large peaks at these locations due to repeated measurement of unchanged values.

Any partial or complete disruption of data seen within images are classified as SEFI. Affected registers include those that control column, row, clock, power, and wavetable enable SPI registers. Examples of two of the many artifacts seen in images are shown in Figure 3.8. Other image artifacts include image shifts, change to physical image size, dark backgrounds, white backgrounds, incorrect read out due to bit flips in synchronous registers, bleeding pixels, and various other unusual patterns. In rare instances, bit flips to ADCs were observed in pattern images, resulting in an increase or decrease in signal for certain pixels on the order of 2^N , where N is the bit that was flipped.

It is common to represent the susceptibility of a device or part after heavy ion radiation through a Weibull curve. These can be interpreted as the probability that a particular SEE may occur at a given LET. This probability is represented as the cross sectional area of the affected region of a device or part. Equation 3.1 defines this cross section as the total number of events that occurred over the total fluence exerted onto the device or part to generate these events. Typical units of the cross section are represented by either $\text{cm}^2/\text{device}$ or cm^2/bit .

$$\sigma = \frac{N}{\Phi} \quad (3.1)$$

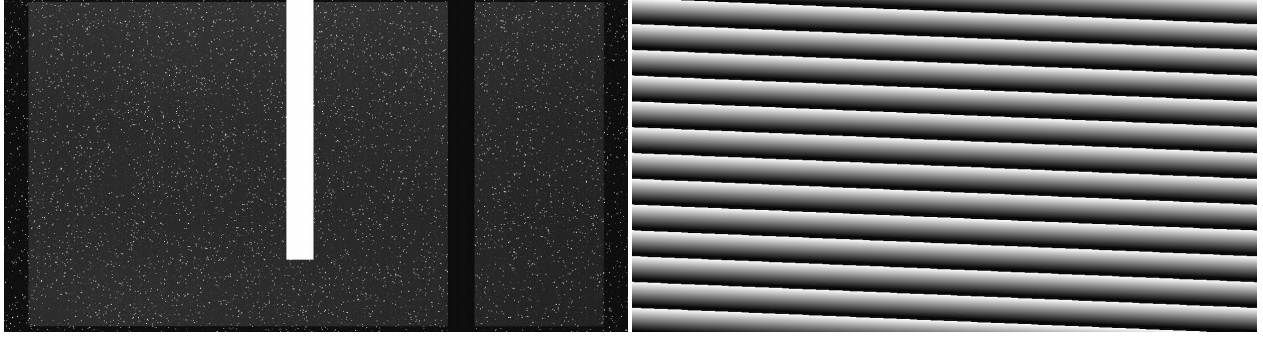


Figure 3.8: Two examples of heavy ions changing specific registers during exposure, resulting in data corruption. The left panel shows an image during a particular 84Kr exposure, in which two heavy ions hit one bit on the column power enable and column bias enable registers, generating the white and black columns respectively. The right panel shows a pattern image during a particular 129Xe exposure, which hit one bit that disabled a register that controls which horizontal region of interest to read pixels from.

The Weibull function is defined in equation 3.2. In this case, LET is the surface LET, the amount of energy imposed on the device per unit path length, while LET_0 is the threshold surface LET that defines where events begin to occur. σ_{sat} is the saturation cross-section, defining where the curve levels off. The remaining parameters W and s are fitting related, controlling the rate at which the function reaches the plateau and the slope of the function respectively [24] [2].

$$\sigma(LET) = \sigma_{sat} \left(1 - e^{\left(-\frac{LET - LET_0}{W} \right)^s} \right) \quad (3.2)$$

Figure 3.9 shows the Weibull curve for both SEUs and SEFIs experienced during heavy ion radiation testing on both detectors. The surface LET threshold for which these events began to occur is below $2.3 \text{ MeV cm}^2/\text{mg}$. SEUs and SEFIs have a saturation cross section, σ_{sat} , of approximately $2.30 \times 10^{-4} \text{ cm}^2/\text{device}$ and $6.50 \times 10^{-5} \text{ cm}^2/\text{device}$ respectively. On average, the remaining Weibull fit parameters, W and s , are $45 \text{ MeV cm}^2/\text{mg}$ and 1.0 respectively. Therefore, these events occurred exponentially, reaching roughly 67 % of the saturation cross section at $45 \text{ MeV cm}^2/\text{mg}$. That being said, these parameters are based on very few data points. More data would improve the accuracy of these fitting parameters. Another HWK4123 heavy ion radiation test also characterized SEFI susceptibility. However, the SEFI cross section they had derived is approximately 2 to 4 orders of magnitude less than what was calculated in this thesis [51].

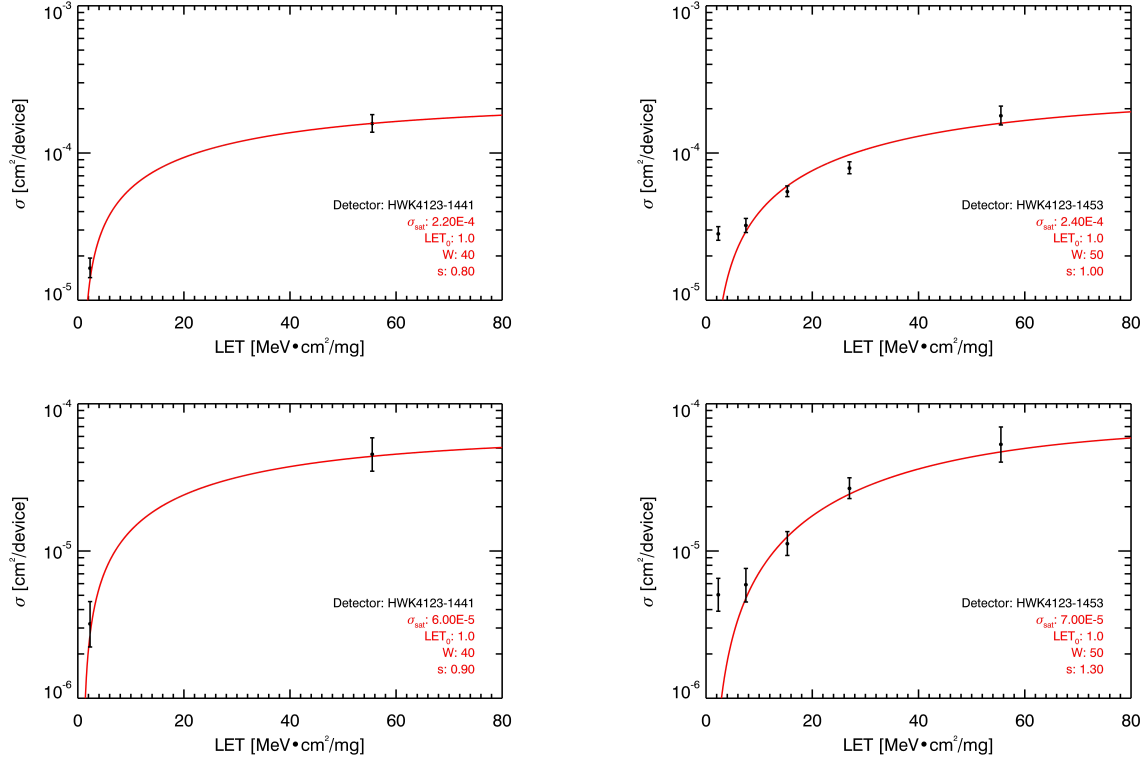


Figure 3.9: Weibull curves of SEU and SEFI susceptibility from top to bottom, for detectors HWK4123-1441 and HWK4123-1453 from left to right respectively. The four fitting parameters to each Weibull curve is shown in the legend. Error is derived from [31].

3.4.3 SEL

There were little to no notable voltage increases in the bias monitoring system throughout the entire 16 hour test period. Only four total increases in one voltage, VPTAT from 1.3 to 1.6 V, had occurred, lasting on the order of a few seconds until reverting back to its nominal voltage after a reset and power cycle of the system. These events, by definition, could be considered SEFI, however, there were no functional interrupts that disrupted the normal behavior of the detector. Therefore, these events could be considered as SEL, which if unchecked could have lead to destructive, permanent events. An example of one of these rare instances is shown in Figure 3.10.

The CIS2521, an older sCMOS detector developed by Fairchild Imaging, experienced 19 SEL between a surface LET range of approximately 16 and 30 MeV cm²/mg [84]. Another heavy ion radiation test on the HWK4123 found similar artifacts within images, with no significant increases in voltage as well [51].

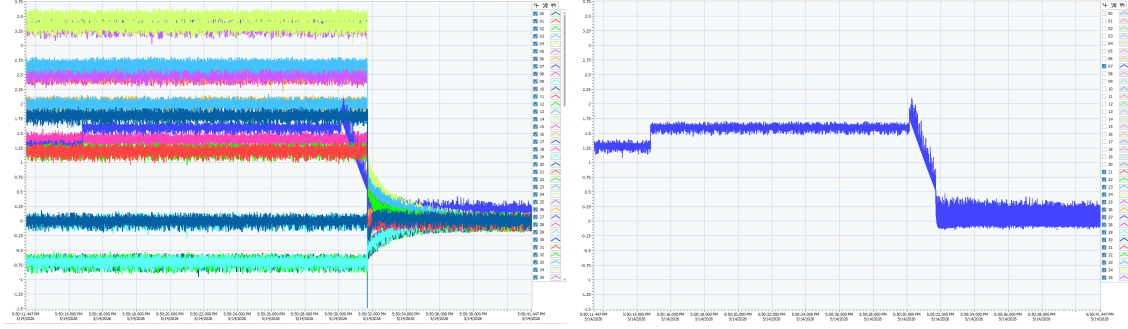


Figure 3.10: Sudden increase in VPTAT from 1.3 to 1.6 V, in comparison to other biases (left) and by itself (right). This increase occurred during a specific ^{84}Kr exposure run. The system was turned off around the 5:50:30 mark, dropping all biases to 0 V.

Since the HWK4123 remained operational throughout the entire exposure period, no permanent destructive events occurred. Therefore, the surface LET threshold must be above $55.5 \text{ MeV cm}^2/\text{mg}$, equivalent to a Bragg peak LET threshold of $69 \text{ MeV cm}^2/\text{mg}$, for the HWK4123 at room temperature normal to the incidence of radiation. Further heavy ion testing is required to accurately meet the requirements of the HWO, as they require a LET threshold above $75 \text{ MeV cm}^2/\text{mg}$ [45].

CHAPTER 4

MITIGATION TECHNIQUES

Although the HWK4123 shows promising radiation tolerance, it is not without flaw, as shown in Chapter 3. The information presented in this chapter discuss suggestions to be made in the next iteration of the HWK4123, as well as to other associated devices, to ensure optimal performance required by the HWO in its quest for life on other worlds.

To accurately characterize the tolerance of the HWK4123 to radiation, more testing must be done. The heavy ion test was performed only at room temperature, in atmosphere, at a normal incident angle. A dewar is recommended to simulate accurate space conditions during a future heavy ion test on the device, which may affect the threshold at which permanent destructive events are found, as these are temperature dependent [4]. A broader LET range would prove with greater certainty that the detector meets the SEL surface LET threshold of $75 \text{ MeV cm}^2/\text{mg}$. All SEE rates may vary with incident angle, as the heavy ion path length may increase within sensitive regions, generating more charge, causing more unwanted effects [28] [96]. Therefore, future heavy ion testing should also consider varying the incident angle of radiation. Future electron and proton testing are scheduled for the HWK4123. This will probe TID and DDD radiation effects in greater detail than through heavy ion testing alone.

Preventative measures were taken to reduce the SEE rate prior to heavy ion exposure, as discussed in Chapter 3. Certain biases were current limited to prevent the pull of dangerous current values that would result in destructive SEEs. Registers were reset after each captured image, which returned the normal operation of the device in most cases. If communication was lost with the

FPGA and was not reestablished within $300\ \mu\text{s}$, the entire system would shut off and perform a power cycle to prevent any potential destructive events from persisting and causing permanent damage.

4.1 UTR Sampling

As discussed in Chapter 2, the HWK4123 uses CDS during readout. This is typical for CMOS devices, however more readout modes exist that this detector could benefit from if correctly implemented. Infrared detectors often incorporate UTR sampling, as seen in the NIRC*am* and NIRS*pec* instruments on James Webb Space Telescope (JWST) [74] [73] [12]. Unlike CDS, UTR sampling can mitigate the effect of a cosmic ray within an image, therefore reducing SET susceptibility.

UTR sampling allows for any number of non-destructive samples to be taken per exposure, unlike CDS, which only allows two. A cosmic ray event injects signal at a specific time during integration, increasing the amount of signal at that location. Increasing the number of samples during integration allows for comparison between slopes before and after the event, recovering the expected signal, as shown in Figure 4.1. In the read noise limited case, the SNR increases with the number of samples taken per exposure using UTR sampling, until reaching a point where the $1/f$ noise dominates. UTR and Fowler sampling both reduce noise in this regime by a factor of $\sqrt{N}$, where N is the number of samples taken per exposure. UTR sampling outperforms Fowler sampling by 6 % [75] [44] [1].

The QISSAT1-2 is another sCMOS detector with similar single photon resolving capabilities to that of the HWK4123 [44]. The default sampling method this sensor incorporates uses CMS. CMS is similar in operation to CDS, however the reset and signal samples are instead sampled multiple times before and after the transfer of charge from the PPD to the FD. Both sample groups are averaged together during read out. Signal is determined by the difference between these two averaged reset and signal sample groups. While this improves the SNR of the signal, it still cannot recover the true signal in the event of a high energetic particle injecting signal during integration.

Custom hardware programming of a FPGA on the QISSAT1-2 allows for custom durations of specific wavetable registers to pulse at defined times. Clocks, which are periodic pulses with a

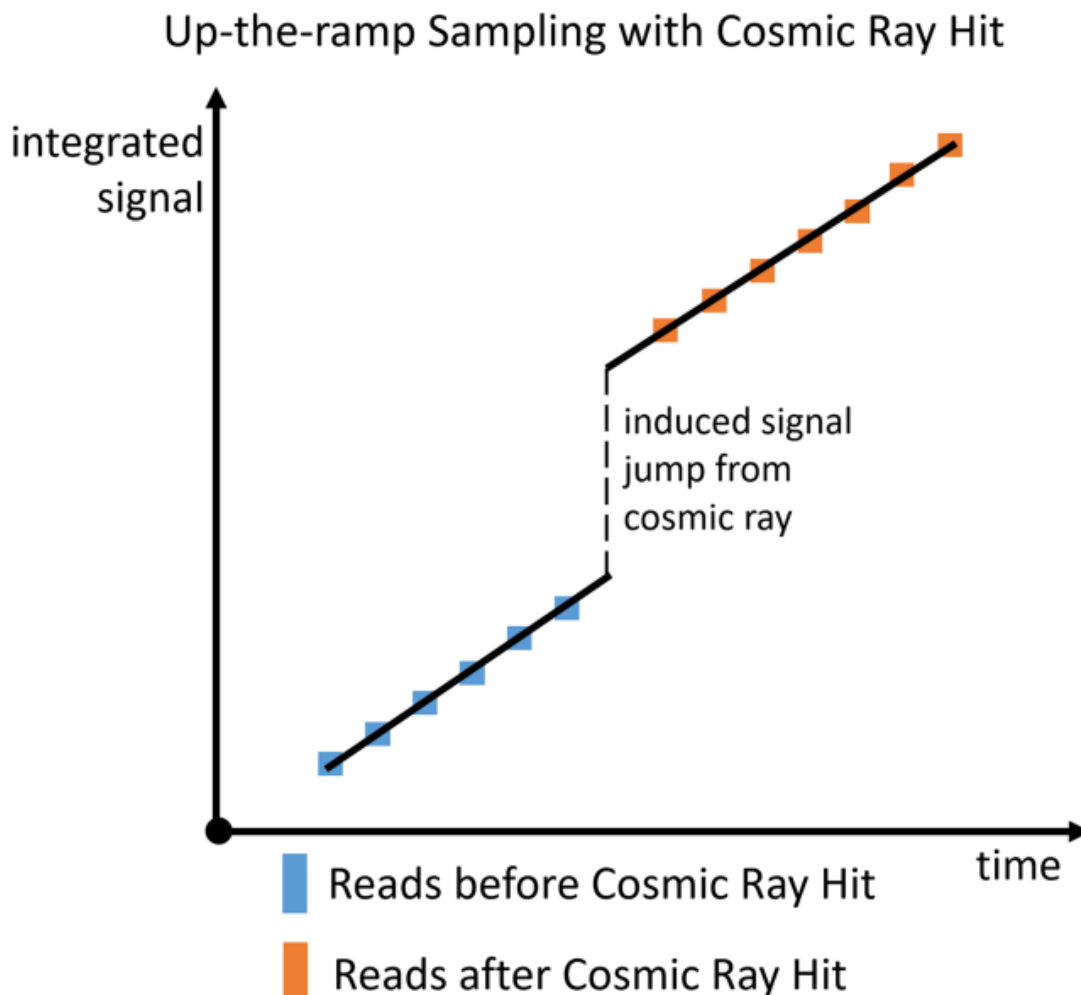


Figure 4.1: Cosmic ray injection during integration using the UTR sampling method [44].

given frequency, control when registers are enabled by assigning them to trigger at either the rising or falling edge of a clock pulse. States assign which wavetable registers to pulse for a certain amount of clock cycles. Custom wavetables hold information about the state and duration of that state, instructing the FPGA the order in which to perform certain actions during pixel read out. The difference in the actions performed by CMS and UTR sampling methods for one cycle of a wavetable for one pixel is shown in the simplified waveform timing diagram in Figure 4.2. The reset and transfer gates are triggered to empty any charge currently residing in the FD. Charge is then accumulated in the PPD until being transferred by the transfer gates. In the QISSAT1-2, the circuitry allows for two pixels in the same column to be read out at the same time, effectively becoming one large pixel, hence the two transfer gates TX1 and TX2. An optional reset is shown in

red prior to this first sample group, to ensure that the first sample group includes minimal charge in the FD. After transfer, the charge within the PPD is then sampled. Each sampling group using this specific wavetable was sampled 32 times. In the right diagram, two additional transfer and sample states are defined within the wavetable, where charge accumulates immediately after the transfer of each sample. This is effectively UTR sampling, where three signal sample states now exist per pixel as opposed to just one in CMS.

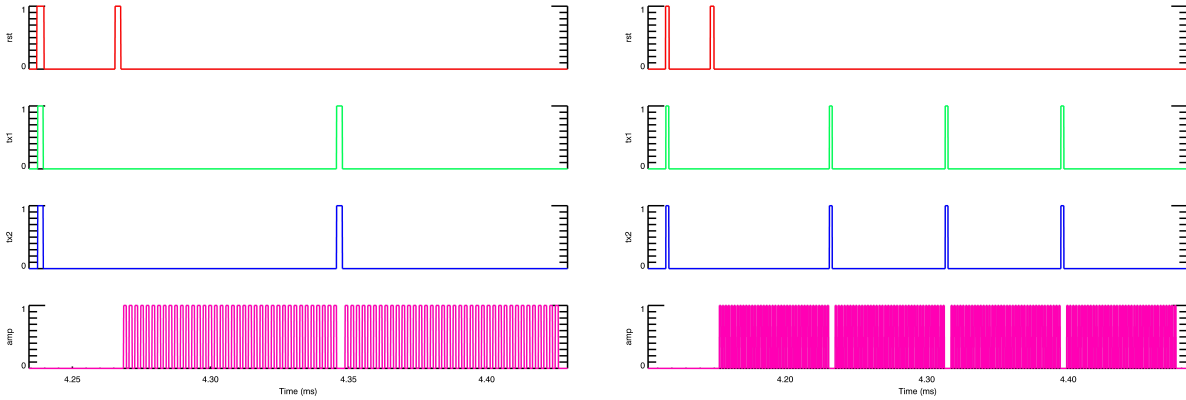


Figure 4.2: Simplified waveform diagrams of the CMS (left) and UTR (right) sampling methods on the QISSAT1-2. The time interval includes one cycle of a wavetable for one pixel. Included signals from top to bottom are the reset, transfer gates and sampling signals. Each sampling group was programmed to sample 32 times.

Once the hardware and software programs for the QISSAT1-2 had been proven to work using this new sampling method, some preliminary results were acquired. The read noise calculated between the old and new programs both achieve the same floor around $0.7 e^-$ at 32 samples per group. Therefore, implementing a different read out mode maintained the same read noise, with the added ability to now recover the signal in the event of a cosmic ray through UTR sampling.

If the HWK4123 could utilize the UTR sampling method, its susceptibility to SET would significantly decrease. The integration time per pixel would have to be on the same order or less than the amount of time it takes for charge to collect within the PPD, from hundreds of nanoseconds to hundreds of picoseconds as discussed in Chapter 2. Dividing the row time used during heavy ion testing by the number of pixels per row gives a rough estimation of 80 ns per pixel, which is already within this range. With the right integration time, enough samples can be collected during integration, mitigating the effect of SETs.

4.2 Radiation Hardening Design Choices

While the exact architecture of the HWK4123 is unknown to the public, it is possible to infer certain design choices that may improve the devices functionality in a relevant radiation environment for future iterations. A few potential architectural design choices that were made in other CMOS devices and parts that have been proven to mitigate radiation effects are discussed below. These changes are made at the design, circuit and system level.

4.2.1 Device Level

One of the simplest improvements to combat radiation effects would be to relocate important SPI registers elsewhere within the device. Heavy ions can only penetrate so far into silicon before being stopped. The furthest depth achieved during radiation testing was $381\text{ }\mu\text{m}$, achieved by the 20Ne ion. Relocating the region in which these registers are found beyond this depth would mitigate the number of SPI register bit flips, therefore allowing for a longer duration of continuous exposure without the need to reset the device. With that said, one must consider the depth of these registers at all angles. This radiation test does not account for the effect that the incident angle has on the SEE rate, which may increase due to the potential for the path length of the heavy ion strike to generate more charge within sensitive regions of the device [28] [96].

Increasing the size of transistors increases the amount of charge required to induce a SEU, as capacitance scales with size. The magnitude and duration of the SEU are reduced with increasing transistor W/L aspect ratios. $1/f$ and random telegraph noise are also suppressed at higher aspect ratios. As a consequence, they will take up more space, therefore increasing the probability of a heavy ion strike. Power consumption and delay also increase with size. One must balance the trade offs that exist when expanding the size of transistors to minimize the SEU rate [98].

Surrounding the source of transistors with the gate oxide, as shown in an edgeless transistor in Figure 4.3, can reduce the amount of charge trapped along the oxide layer, therefore mitigating effects due to TID. In regular transistors, this trapped charge induces a parasitic conductance path at the edges, resulting in current leakage between the drain and source junctions. In this configuration, hot pixel generation is reduced by 16 % [64]. Various other gate oxide shapes can improve transistor radiation tolerance. Both front and back gate edgeless transistors have a higher voltage threshold

when optimizing the shape of the gate oxide. However, these transistors are limited by their size, with a minimum W/L aspect ratio of 2.26. They can only prevent leakage current within the transistor itself, therefore, guard rings are typically used alongside edgeless transistors to prevent leakage both within and around these transistors [63] [3].

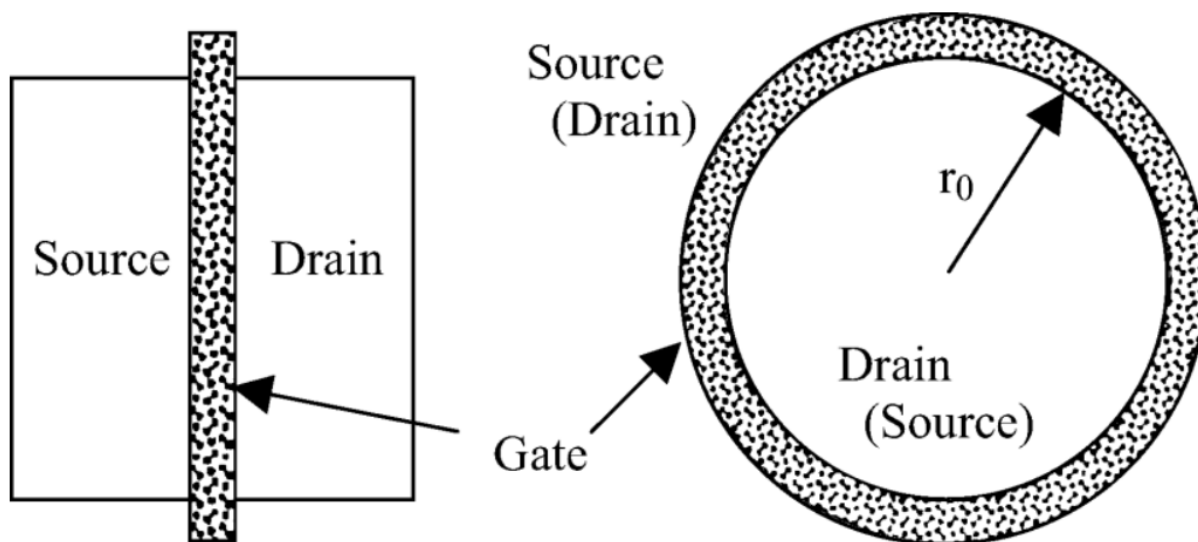


Figure 4.3: Comparison between a typical transistor (left) and an edgeless transistor (right). The gate oxide surrounds the source, improving radiation hardness to TID [64].

Adding an insulating layer, referred to as silicon-on-insulator (SOI) between the electronics and the charge collecting region of the sensor reduces the SEE rate. Less charge is collected by smaller integrated circuits built on top of thin SOI layers, resulting in a lower magnitude SEE pulse. Parasitic thyristors do not exist in these structures, therefore making them immune to SEL and SEB. However, since these integrated circuits are not connected to ground to drain excess charge, floating bipolar effects may amplify the collected charge, therefore increasing the amount of current and SEE rate. For SOI transistors, body ties may be implemented, at the cost of area, to reduce this effect by connecting to ground, allowing for excess charge to drain off the transistor instead of building up within. That being said, the effect body ties have on reducing the amount of charge within a transistor depends on the location of the heavy ion strike. SOI integrated circuits incorporate buried field oxides, therefore increasing the effects of TID by trapping charge at the Si – SiO₂ interface. This mitigation technique can improve the radiation tolerance of the device, greater than that of the regular bulk silicon design, only if floating bipolar effects are accounted for

[78] [3].

Guard rings are oppositely doped thin layers around sensitive regions. They collect excess minority charged carriers that may build up within these sensitive regions, therefore preventing SEL, reducing TID effects such as dark current. Increasing the doping concentration of the guard ring improves the radiation tolerance of the device [52] [53]. Separating the shallow trench isolation (STI), which prevents charge leakage into neighboring pixels, from the guard ring within a CMOS Single Photon Avalanche Diode (SPAD) by $0.3\text{ }\mu\text{m}$ reduces the dark current rate by 78.3 %. A guard ring implemented within 180 nm CMOS technology reported a SEL threshold above $100\text{ MeV cm}^2/\text{mg}$ [83] [29].

Molecular Beam Epitaxy (MBE) passivation adds another doping layer at the surface of the BSI technology. The internal electric field generated by this layer repels charge away from the Si – SiO₂ interface towards the collecting depletion region, therefore preventing it from being trapped. This improves tolerance to TID radiation damage, as well as significant improvements to QE, especially within the UV range. Typically, UV photons only penetrate a few nanometers within silicon, far from the depletion region, very close to the Si – SiO₂ interface. The HWK4123 only achieves a QE of around 20 % between a wavelength range of 200 and 350 nm [45]. Alternating the deposition of the silicon and dopant atoms generates a multilayer 2D-doping superlattice only a few nanometers thick. The quantum confinement of holes in this superlattice suppresses the generation and recombination of charge carriers at the Si – SiO₂ interface. This method yields a peak QE nearing 100 % [49].

The simplest solution at the device level to reduce SEE susceptibility is to relocate radiation-sensitive parts as deep as possible within the HWK4123. Of course, this cannot be applied to every sensitive region, however, if SPI registers continue to prove to be significantly susceptible to radiation, relocating may be a viable option if possible. For UV optimization, implementing MBE passivation within the HWK4123 would not only improve radiation tolerance to TID, but also extend the wavelength range in which measurements can be made. This process may promote the HWK4123 for consideration for the standalone near-UV coronagraph of the HWO [14].

4.2.2 Circuit Level

A guard gate acts as a buffer circuit. The original signal is split in two, one delayed a certain amount of time after the other. The gate is designed to float in the high impedance state if both inputs are not identical, otherwise the signal is inverted. This delay, if long enough, removes a SET pulse that has propagated through combinational logic, preventing an erroneous pulse from inverting the signal. Implementing these designs within latches only takes up to 15 % more area. However, due to the delay, the speed of the circuit is reduced. For operating frequencies of 100 MHz, speed reduction is negligible, but for frequencies of 1 GHz, the speed reduction is 33 % to eliminate longer SET pulse widths of 500 ps [9].

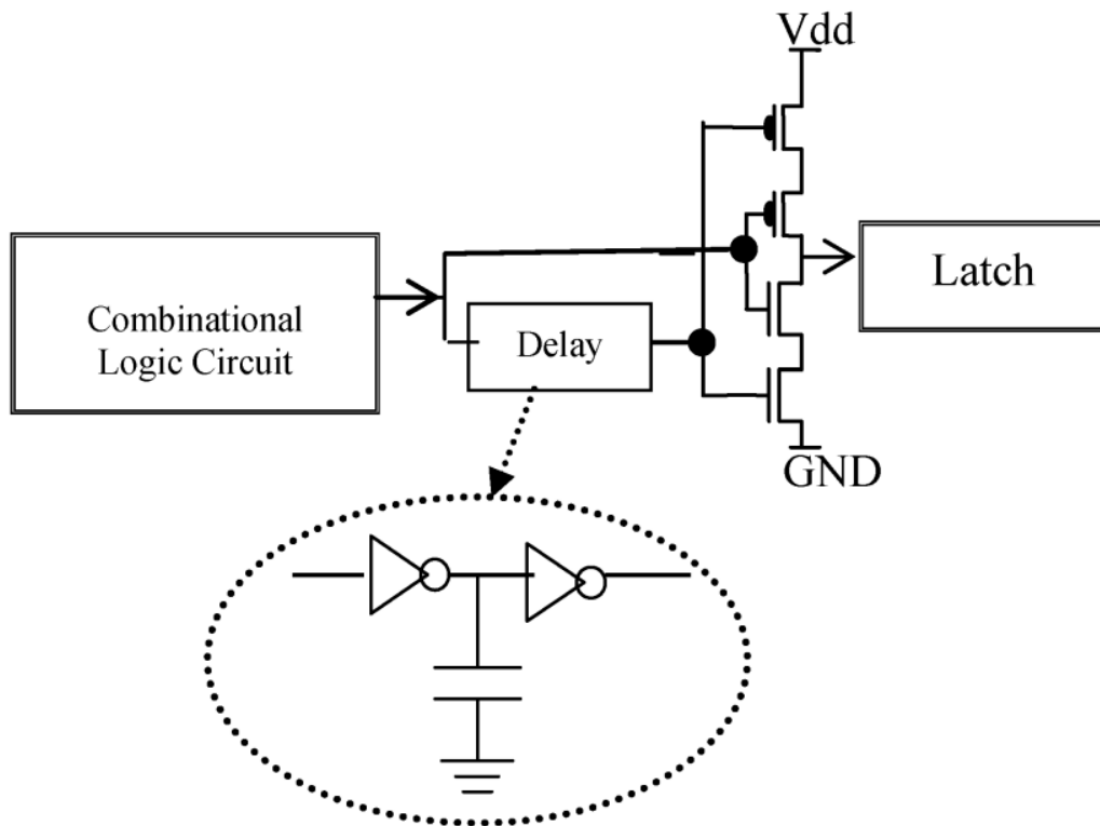


Figure 4.4: Guard gate implemented within combinational circuitry, dividing the signal in two, delaying one after the other. Long enough delays remove SET pulses [9].

The dual interlocked storage cell (DICE) is a type of radiation hardened latch, utilizing a four node redundant structure to check for the correct bit value, compared to the usual two. Two nodes hold the high logic state, while the other two hold the low logic state. If one node is affected by a

heavy ion, the other three prevent the latch from inverting the signal, therefore increasing the SEU and SEFI tolerance of the latch. However, due to the close proximity of nodes, one heavy ion may inject enough charge to affect more than one node. Implementing a guard gate to DICE prevents more than one node from being affected [9].

The triple interlocked latch (TILL) is another type of radiation hardened latch, designed for SEU and SEFI prevention. This uses triple the amount of logic gates to verify the correct value is used, whereas DICE only uses one. TILL succeeds where DICE fails, in the recovery of the correct bit value when more than one node is affected. Compared to other radiation hardened latches, TILL has the least SEU rate, at the highest threshold LET of $42 \text{ MeV cm}^2/\text{mg}$. On average, TILL is 24 % faster with a 22 % reduction in power delay product for an increase of 17 % more area [61].

Differential circuits are commonly used in analog and mixed signal design found within CMOS devices. They consist of multiple interleaved pairs of transistors. In a differential charge cancellation (DCC) layout, these pairs are arranged to minimize the distance between the sensitive drain node of both transistors, encouraging charge sharing. If a heavy ion induces a SET pulse, both nodes experience this same increase in voltage, turning it into a common-mode signal, which is then inherently rejected by the circuit's high common-mode rejection ratio. Thus, the DCC layout yields a greater immunity to SET [55] [13].

Chopper stabilization is an offset cancellation technique that can be incorporated within amplifier and reference circuits to remove radiation induced voltage shifts caused by TID. The ideal input signal is modulated to a higher frequency, the chopper frequency, by periodically reversing its polarity. This signal is then demodulated, while the offset and noise are modulated to the chopper frequency. A low-pass filter then removes this excess voltage from the signal. This method reduces radiation induced voltage shifts by 96.6 %. $1/f$ noise is reduced below the chopping frequency, when it is modulated to said frequency and filtered out, increasing the precision of the measured voltage shift. Chopper stabilization should be implemented within circuits that favor precision over speed, such as a voltage reference circuit, since this method significantly decreases speed [82].

Rewriting registers off chip to reduce the effects of SEU and SEFI was one of the precautionary measures taken during radiation testing. It is possible to implement circuitry on chip that checks and rewrites erroneous registers on the fly. One kind of self-repairing circuitry, soft-error and timing-error-tolerant flip-flop (SETTOFF), had proven to recover at worst 94 % of all bit flips.

Compared to Triple Modular Redundancy (TMR), SETTOFF uses 30 % less area and 80 % less power [62].

More sequential circuits exist than combinational ones within CMOS devices. To reduce cost, complexity, area and power consumption, focusing solely on implementing these radiation hardened techniques on sequential circuits is recommended [97]. Among all circuit level mitigation techniques, it may prove beneficial to implement circuitry which checks and rewrites SPI registers on chip within the HWK4123, as SEFI oftentimes resulted in the disruption of data during testing. If area is not a concern, implementing TILL would greatly improve upon the SEU and SEFI susceptibility of the detector.

4.2.3 System Level

TMR copies the same critical component twice, running through the same exact process at the same time. At the end, a majority voter circuit compares all three inputs, outputting the majority signal. This removes the erroneous signal caused by a SEE if only one of the three signals were affected. However, TMR triples the amount of components required with the additional smaller voter circuit, effectively tripling the power and area requirements. Thus, it should be used sparingly for vital components. TMR fails if the heavy ion induced charge within the majority voter circuit. If the SEE rate is higher than the refresh rate of the system, more than one cell may be affected, resulting in the incorrect output [58] [9] [3].

Rewriting registers off chip can either remove or reduce the effects of SEU and SEFI. This method was implemented during the radiation test, as mentioned in Chapter 3. After each image was captured, software would initiate hardware to rewrite SPI registers, regardless if they had been affected, referred to as preventative scrubbing. Corrective scrubbing rewrites registers only when an error is detected [48]. This method, while more complex, may be more beneficial for a space mission, as constantly rewriting all registers instead of checking for bit flips first costs more time.

Preventing potential destructive events from persisting by resetting the system after a certain amount of time or after a certain action has occurred reduces destructive SEE rate. This was another method that was implemented during testing, as mentioned in Chapter 3. One action that would instantly cause the system to reset and power cycle was if the system had lost connection to the

FPGA. Another preventative measure taken was to limit the current drawn by certain components to prevent any potential destructive events from permanently damaging the detector. This strategy was employed by another sCMOS image sensor by Fairchild Imaging, the CIS2521, during radiation testing. Current draw was limited to an additional 25 % compared to the nominal value [84].

Shielding the instrument with certain materials minimizes the amount of radiation damage experienced by the detector. SPENVIS is a simulation tool used to model various space radiation environments for instrument characterization [57]. SPENVIS simulations for an eleven year mission at L2 with varying aluminum shield thicknesses reveals an increasing tolerance to radiation damage with thicker shields as shown in Figure 4.5. A thickness of 4 mm blocks a significant amount of protons with energies less than 5 MeV [43] [44] [51]. For the NIRSpec instrument on JWST, roughly 20 mm of SiC and 12 mm of Mo shield its detectors from electron, proton and heavy ion radiation for particles with energies less than 100 MeV [73].

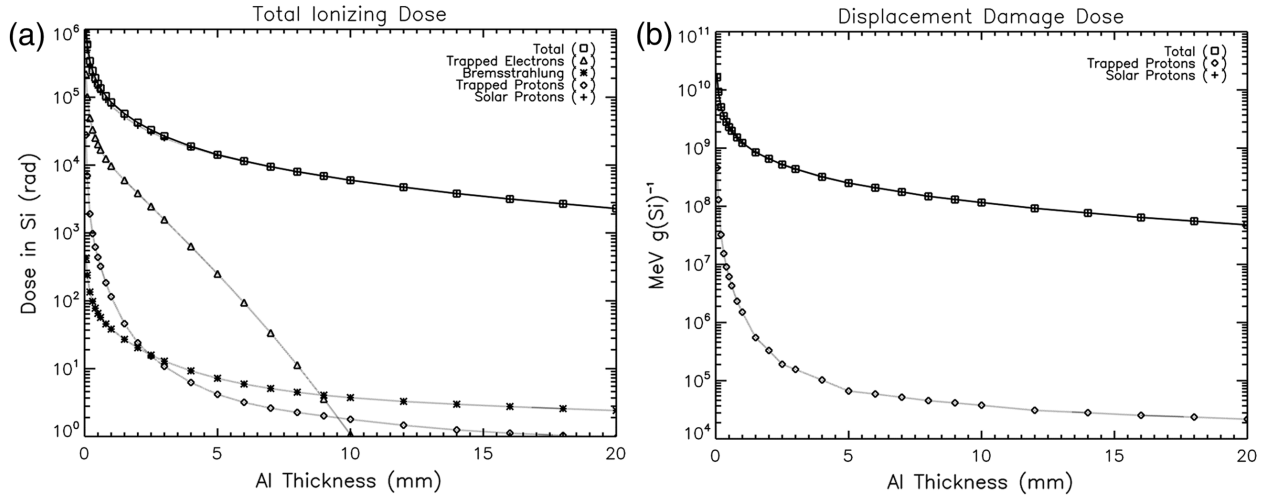


Figure 4.5: SPENVIS simulations of TID (left) and DDD (right) accumulated as a function of Aluminum shield thickness for an 11 year mission at L2 [44].

At the system level, SEE radiation tolerance of the HWK4123 may improve by the location in which it may be implemented within the coronagraph instrument. The amount of material between it and the outside of the HWO may provide enough of a barrier to block incoming radiation, as discussed for the detectors within NIRSpec on JWST. However, the simplest and most robust method to mitigate radiation effects involves various preventative measures, such as limiting current and writing programs that reset registers or the entire system depending on the SEE. Some of these methods had proven to be useful during the heavy ion radiation as discussed in Chapter 3. All

mitigation techniques of all three levels must factor the improved radiation tolerance achieved with area, power consumption, complexity, speed, precision and cost.

CHAPTER 5

CONCLUSION

The HWO is a future space mission currently in development with the main goal of observing potential habitable worlds that may harbor signs of life. The development team is actively seeking detectors capable of resolving individual photons for precise spectroscopic measurements. This requires detectors with low read noise, low dark current, high QE, large format pixel arrays, and high radiation tolerance. At its planned position at L2, radiation may degrade the ability of these detectors to maintain single photon resolving capability. The work in this thesis characterizes one such candidate detector, the HWK4123, before, during and after heavy ion irradiation to heavy ions relevant to the radiation environment expected at L2 for potential implementation within the coronagraph instruments of the HWO.

The HWK4123 was irradiated with heavy ions which span a surface LET range of 2.3 to 55.5 MeV cm²/mg, corresponding to a Bragg peak LET range of 9 to 69 MeV cm²/mg. Most heavy ions achieved the test standard fluence of 10⁷ ions/cm², resulting in a statistically significant amount of SEEs to occur. Various non-destructive SEEs were observed across the entire heavy ion range. An abundance of SETs generated within images, increasing in size with LET. Artifacts within images caused by erroneous bit flips partially or completely disrupt data. The measured cross sectional susceptibility to SEU and SEFI bit flips were on the order of 10⁻⁵ to 10⁻⁴ cm²/device and 10⁻⁶ to 10⁻⁵ cm²/device respectively. No permanent destructive SEEs occurred under irradiation. The maximum Bragg peak LET achieved was 69 MeV cm²/mg, therefore defining the lower bound SEL threshold LET required by the HWO at 75 MeV cm²/mg. Future heavy ion tests should use

a broader range of LETs to confirm this threshold. Angle and temperature dependence of SEE susceptibility was not tested for the purpose of this thesis, therefore future heavy ion radiation tests should also investigate and verify this dependency.

The HWK4123-1453 was exposed to a TID of 6.78 krad(Si), exceeding the HWO requirement of 5 krad(Si). The total accumulated DDD reached $(1.03 \pm 0.36) \times 10^8$ MeV/g(Si), which, although achieving the same order of magnitude, is less than the HWO requirement of 7.6×10^8 MeV/g(Si). The amount of hot pixels generated by radiation-induced defects within the silicon lattice increased with dose. Dark current was the only notable measurement that significantly increased after exposure, which can be reduced to expected levels by operating at lower temperatures. Therefore, the HWK4123 shows promising radiation tolerance to cumulative radiation effects. However, future proton and electron radiation tests will evaluate the radiation tolerance of the HWK4123 to cumulative effects in greater detail, as the primary purpose of this radiation test was to characterize its response to SEEs.

The HWK4123 also shows promising radiation tolerance to permanent destructive SEEs. However, non-destructive SEEs occurred frequently throughout the tested LET range. Radiation mitigation techniques should therefore be considered for future iterations of the HWK4123 to reduce its susceptibility to non-destructive SEEs. In the simplest cases, preventative measures can be taken to reduce the effects of radiation, such as through limiting current draw, utilizing different sampling methods, and resetting the device and registers after normal operation has been altered. UTR sampling can mitigate SETs seen within images. For more complex cases, this involves a redesign of the architecture within the device or the materials that surround it, to either reduce or filter out radiation-induced effects. These improvements must balance radiation tolerance with area, power consumption, complexity, speed, precision and cost.

APPENDIX A

ADDITIONAL IMAGE ARTIFACTS

These are a few more image artifacts as a result of SPI register bit flips related to SEFIs. These further demonstrate the corruption of data that may occur for the HWK4123 under heavy ion irradiation.



Figure A.1: One exposure during radiation to ^{40}Ar physically decreased the size of the pattern image. This is caused by a bit flip in the vertical region of interest SPI register, which selects which columns to read out.

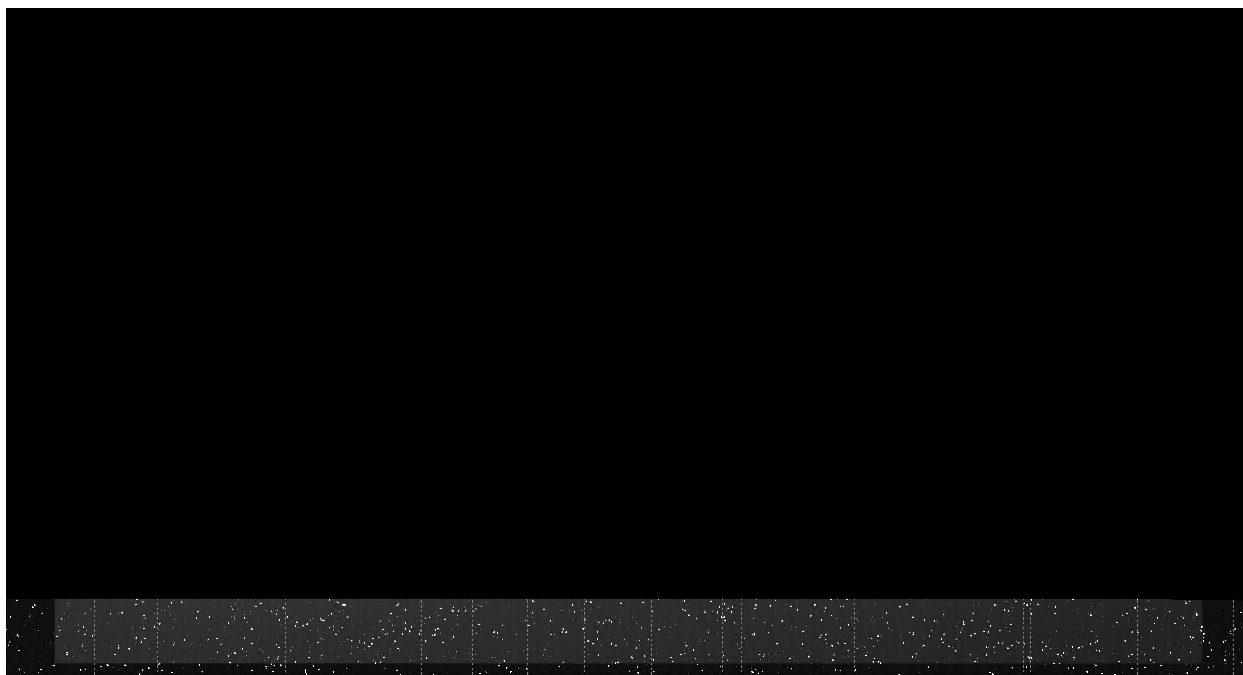


Figure A.2: One exposure during radiation to ^{59}Co caused the entire image to go dark, with pixels showing a value of 0 ADU. This is the exact frame the bit was flipped. In the remaining frames the entire image is dark. This is caused by a bit flip in the low power SPI register.

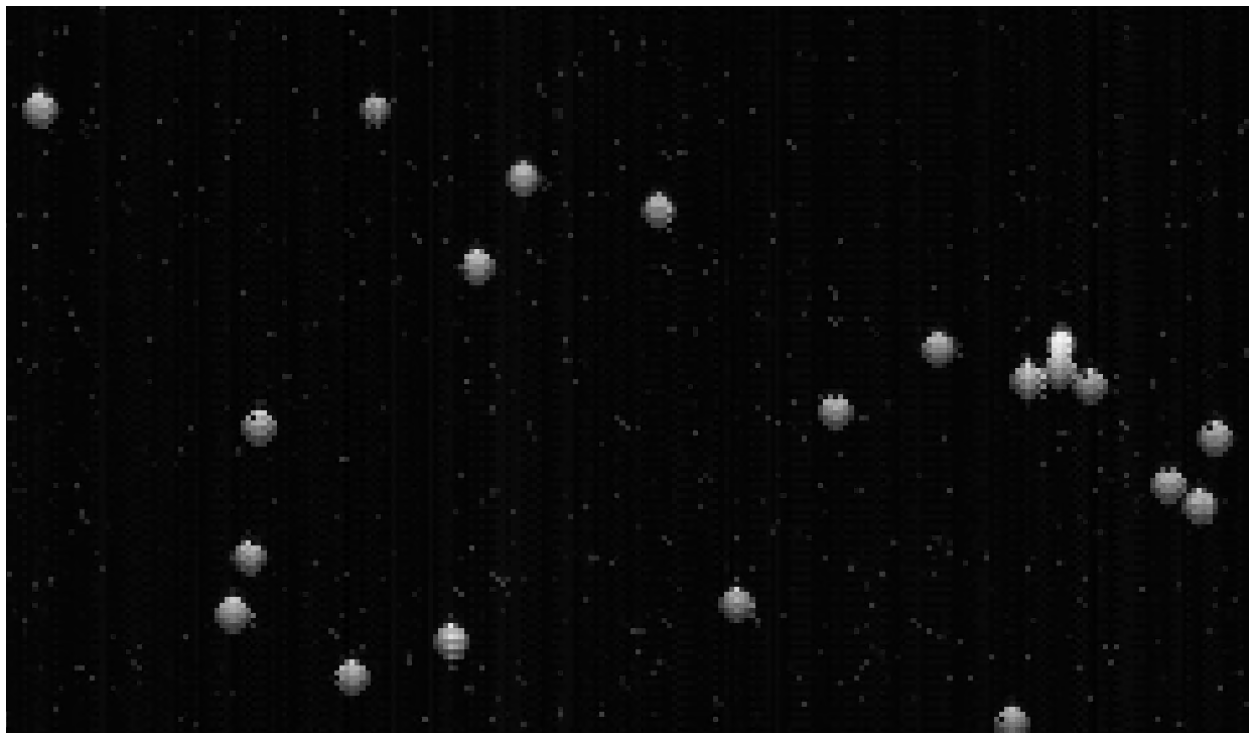


Figure A.3: Zoomed in image of one exposure during radiation to ^{84}Kr caused SETs to bleed. Other images with pixels that bled typically spanned across most of the column, unlike in this image. The exact cause is unknown, however, of the many bit flips associated with this image, one of the main configuration registers and a column bias register were affected.

APPENDIX B

READ NOISE MEASUREMENTS

These are histograms of the read noise measurements taken of the HWK4123-1453 before and after heavy ion radiation at two different temperatures. There is no significant increase shown in either of the two graphs. As discussed in Chapter 2, read noise is calculated by the standard deviation across multiple short integration dark frames per pixel. Future proton and electron radiation tests will assess the changes in read noise due to radiation effects in greater detail.

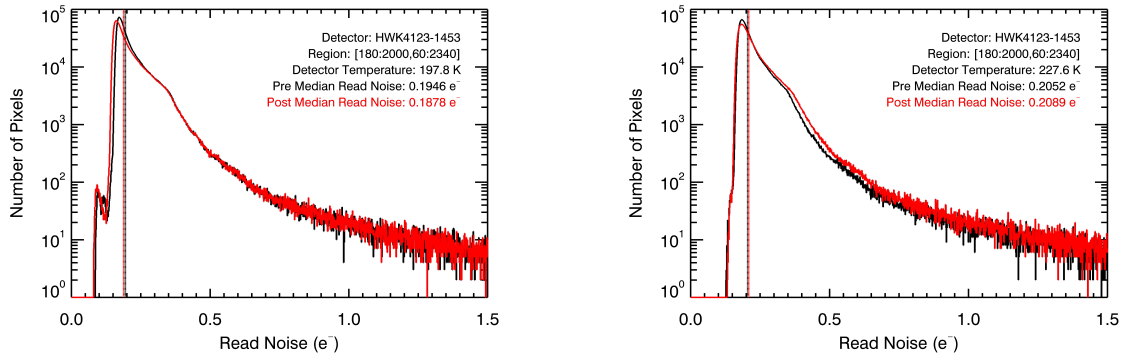


Figure B.1: Read noise histograms of the HWK4123-1453 at a detector temperature of approximately 200 K and 230 K from left to right respectively. The black curve represents read noise before the heavy ion radiation test, while the red curve represents read noise after.

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