Radiation Tolerance of HWK4123 for Space Applications

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Introduction:

It is more crucial than ever that space bound electronic components are radiation hardened as satellite missions become more varied and complex. With the advent of increasingly high-resolution space optical imaging, it is particularly critical that CMOS image sensors can tolerate the effects of various kinds of space radiation.

In this paper we provide an overview of the sources of space radiation, the effect of radiation on electronics in space, and how well Fairchild Imaging's 9.4MP, world class read noise (<0.25e- RMS) HWK4123 sCMOS sensor can tolerate operating under high-radiation environments. Typically, 65nm process semiconductors are quite susceptible to radiation issues due to their dense power rails and small transistor size, leading to latch-up. Our legacy product, the 180nm CIS2521, has a proven track record in numerous space applications over the years. In collaboration with multiple partners through various government grants, we now have quantified data that demonstrates the HWK4123's ability to operate in harsh radiation environments. Our data indicates that the sensor had some minor observed effects when exposed to 50 krad(Si) (in the form of generated bright pixels), and no catastrophic failures when undergoing heavy ion testing between 1.2-62 MeV.cm^{2}mg^{-1} and proton testing up to 105MeV.

Sources of Space Radiation:

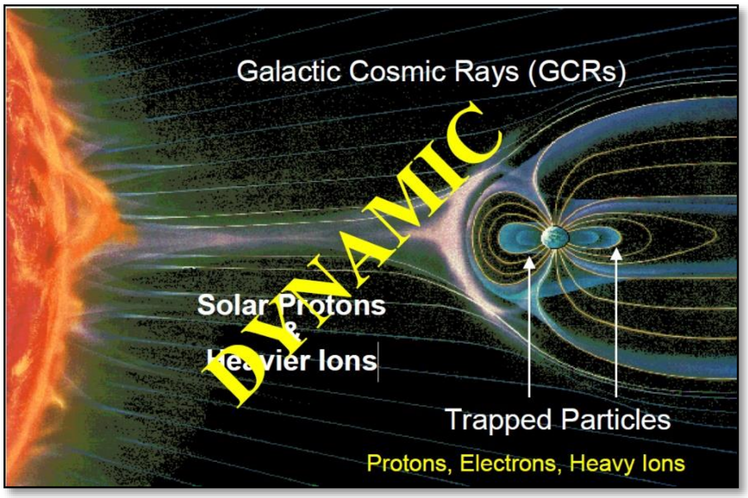


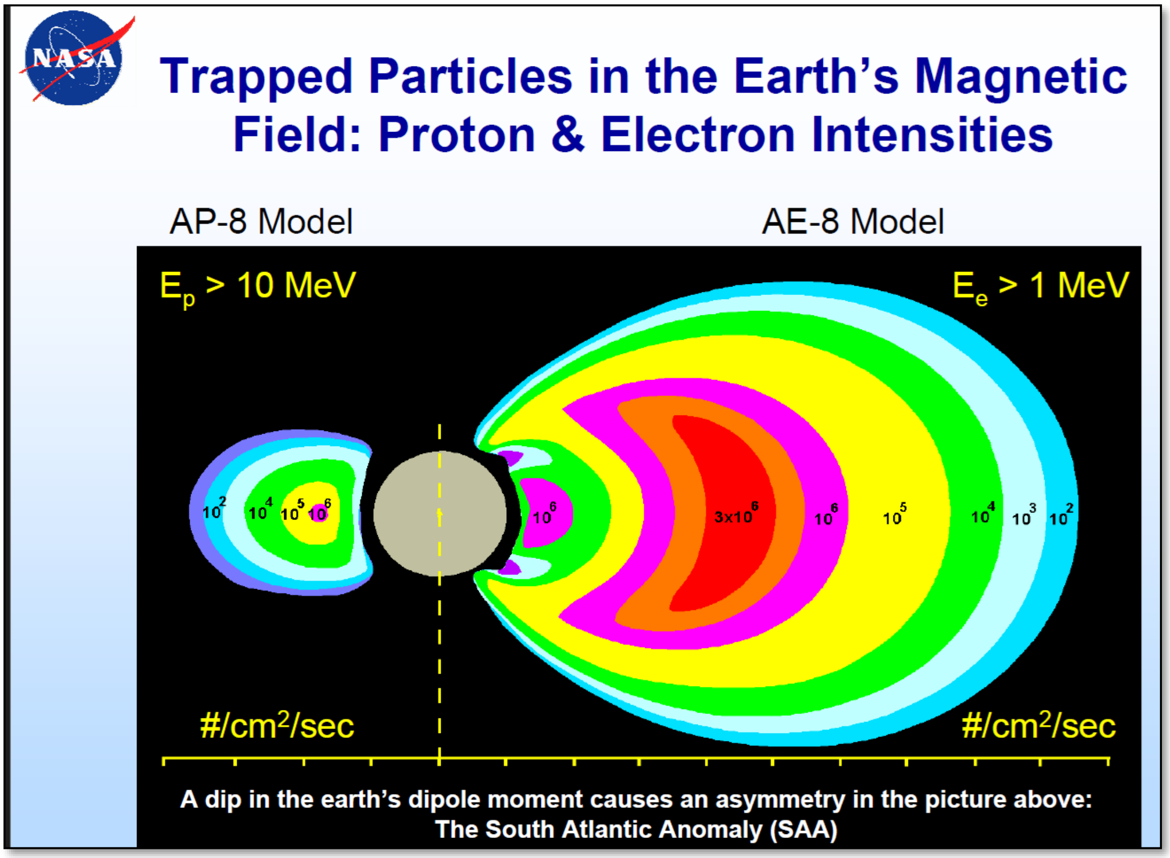
Figure 1, Credit: (NASA, 2004)

Radiation hazards come from three components of the natural space environment:

- Solar particles
  - Protons (gradual: coronal mass ejections) and heavy ions (impulsive: solar flares)
    - SEEs (Single Event Effect) and TID (Total Ionizing Dose), described in the next section

- Galactic Cosmic Rays
  - Charged particles found in free space. Origin: unknown
    - SEEs

- Trapped Particles
  - Protons, electrons, heavy ions that are present in the Earth's magnetic field
    - This includes the South Atlantic Anomaly (SAA), listed in Figure 2 below.
    - Protons are more prevalent in LEO and MEO missions
    - SEEs, TID



Trapped Particles in the Earth's Magnetic Field: Proton & Electron Intensities

AP-8 Model

AE-8 Model

$E_p > 10$ MeV

$E_e > 1$ MeV

#/cm²/sec

#/cm²/sec

A dip in the earth's dipole moment causes an asymmetry in the picture above: The South Atlantic Anomaly (SAA)

Figure 2 (NASA, 2004)

Short Term Effects of Space Radiation:

When a single charged particle passes through a semiconductor, it can cause a Single Event Effect (SEE). A SEE can cause image corruption, noisy images, or even circuit damage. Additionally, a SEE can potentially cause voltage or current spikes, leading to external hardware damage. The amount of energy that is deposited by an energized particle as it passes through the semiconductor material is known as Linear Energy Transfer (LET, dE/dX). LET in space applications is expressed in terms of MeV·cm^2/mg, which is a combination of the amount of energy lost by the particle to the material per unit path length (MeV/cm), divided by the density of the material, (mg/cm^3).

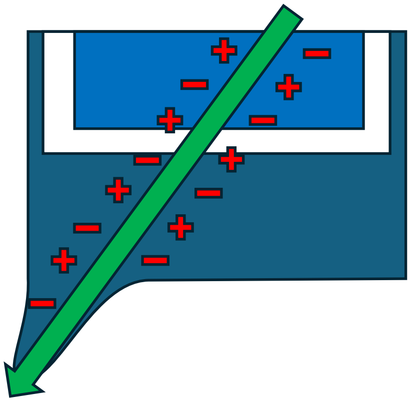


Figure 3, Example of LET effects

A common SEE that occurs in 65nm process CMOS circuits is a Single-Event Latch-up (SEL). CMOS latch-up occurs when a large current is injected into parasitic PNP and NPN bipolar transistors nested inside of the main transistor substrate, which can reverse the bias, leading to increased current draw on the external network until the device fails from thermal stress (Fairchild Semiconductor, 1989). We can see in Figure 3 that a LET is the primary source of injected current in the case of an SEL.

SEL mitigation is primarily done on the chip circuit design level; limiting current in the electronic circuit can mitigate device burnout as well. Strategies include optimized substrate resistivity and doping concentrations in wells. CMOS technology has advanced significantly in the past few decades to avoid latch-up in ground-based applications. However, without Earth's magnetic field deflecting solar winds and cosmic rays, electronics are subject to radiation levels many times higher than that of the Earth's surface. It is critical that if a sensor does experience latch-up, it can recover without damage.

Another SEE that can occur is the Single Event Functional Interrupt (SEFI). This is a soft error that generally means the sensor rests, locks up, or generates image artifacts as described in a later section. A SEFI will generate errors in a detectable way but is not permanent and is recoverable.

Short Term Effects of Space Radiation on HWK4123:

Heavy Ion Testing

Heavy ion testing is done to simulate space radiation environments in higher orbits and quantify radiation hardness for electronic components. The HWK4123 sensor was tested at the Heavy Ion Facility, which is part of the Cyclone synchrotron at UCL Louvain-la-Neuve. There were SEFIs during testing; however, there was no catastrophic failure of the device. The most severe SEFI was video streaming loss, but cycling the power was sufficient to restore operation. During operation in Low Earth Orbit, SEEs are anticipated to normally only occur during SAA passage (described in Figure 5 below), which can be circumvented by powering the camera down during SAA passage, if possible.

The ions used in testing are listed below:

Table 1: Available Ions at Heavy Ion Facility (Holland, 2025)

M/Q (mass/charge)	Ion	Energy [MeV]	Range [µm]	LET [MeV.(mg.cm-^{2})-1]
3.25	13C4+	131	269.3	1.3
3.14	22Ne7+	238	202.0	3.3
3.37	27Al8+	250	131.2	5.7
3.27	36Ar11+	353	114.0	9.9
3.31	53Cr16+	505	105.5	16.1
3.22	58Ni18+	582	100.5	20.4
3.35	84Kr25+	769	94.2	32.4
3.32	103Rh31+	957	87.3	46.1
3.54	124Xe35+	995	73.1	62.5

Proton Testing

Proton testing was conducted at Triumf in Vancouver on two HWK4123 sensors, with energy levels up to 105MeV. No tangible increase in current draw was observed, and no latch-ups were recorded. An SEU rate of approximately 2 per krad(Si) was recorded at 63MeV.

Long Term Degradation:

When a semiconductor is bombarded with radiation, the particles can cause long term damage to the crystal structure. This cumulative long term ionizing damage is called Total Ionizing Dose (TID), measured in krads (NASA, 2004). For silicon semiconductors the unit is in terms of krad(Si) to indicate that the measurement is based on the response of silicon. Over time, high energy particles colliding with transistors will knock (or displace) the atoms inside to another location, altering the lattice structure. This fundamentally changes the 5T (5 transistor) pixel of the HWK4123 sensor, and as displacement damage creates carrier generation sites, this leads to permanently increased dark current.

There may not be any immediate effect but as space missions can vary between weeks and years, it is crucial that components are chosen with mission length in mind. Proper shielding is also critical, as TID amounts are heavily affected by the thickness of the shielding material. Below is an example of TID values vs. aluminum shielding thickness.

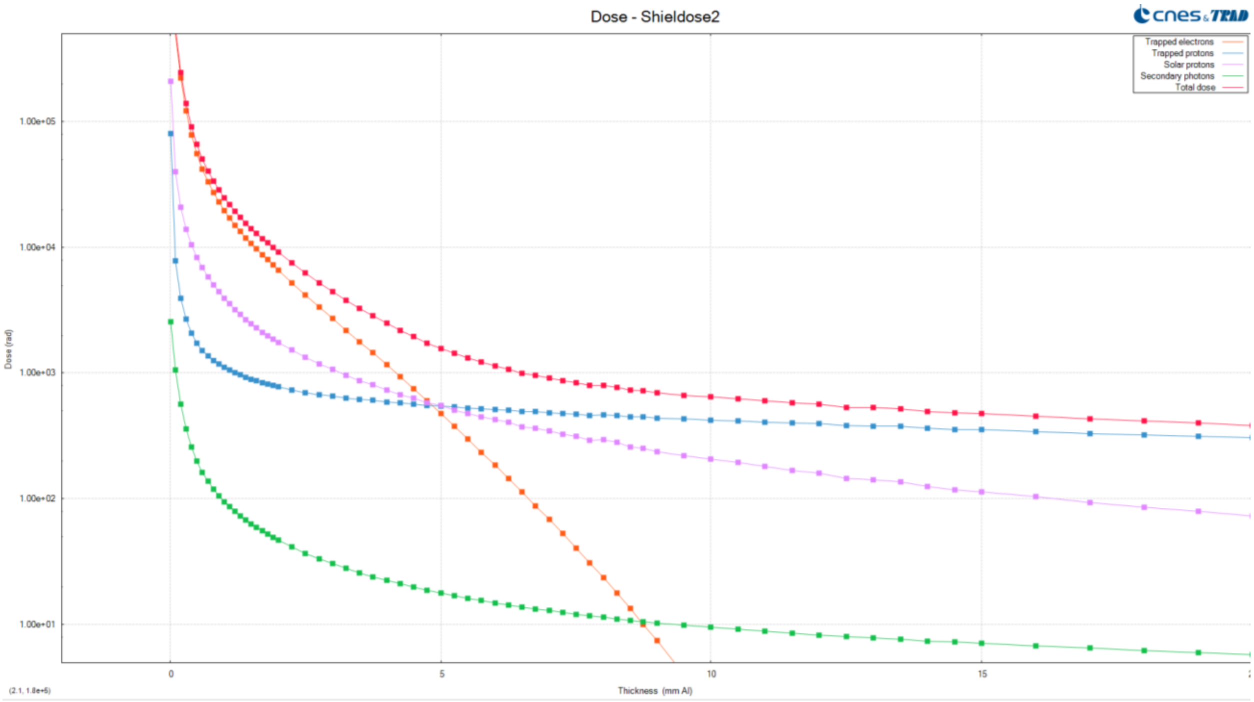


Figure 4 TID vs Shielding

TID gamma testing was conducted at the Co-60 cell operated by Amentum at the Harwell Science Campus in the UK. The irradiation was performed in 6 stages, with a total dose of 15.3krad(Si). The HWK4123 sensor experienced little change in performance during this TID irradiation process, along with rest of the payload. The mean dark current and noise appeared to increase slightly due to generation of bright pixels in the image, which is to be expected when an image sensor is bombarded with heavy protons. The actual uniform dark current was not impacted and believed to be due to pinned photodiode flushing accumulated charge.

Table 2 Irradiation Steps for Gamma Irradiation

Step	Dose rate (krad[Si]/hr) (+/-10%)	Step dose (rad[Si]) (+/-10%)	Total dose (krad[Si]) (+/-10%)
1	2.00	1.5	1.5
2	2.00	2.0	3.5
3	2.00	2.5	6.0
4	4.50	2.3	8.3
5	4.50	2.3	10.6
6	4.50	4.7	15.3

The gamma irradiations did create isolated bright pixels, but these were lower in density and intensity compared to that of energetic protons.

Radiation Effects on the HWK4123 during TID and Heavy Ion Testing:

Hot pixels are the most common form of image artifacts that occur with space radiation.

Below is a capture from the HWK4123 sensor at the start of gamma irradiation, before exposure. The sensor is at room temperature in the dark, with no column offset correction applied:

Figure 2, Credit: (Holland, 2025)

During TID testing, energetic electrons generated by the Co-60 gammas create bulk displacement effects, translating to isolated hot pixels as seen below:

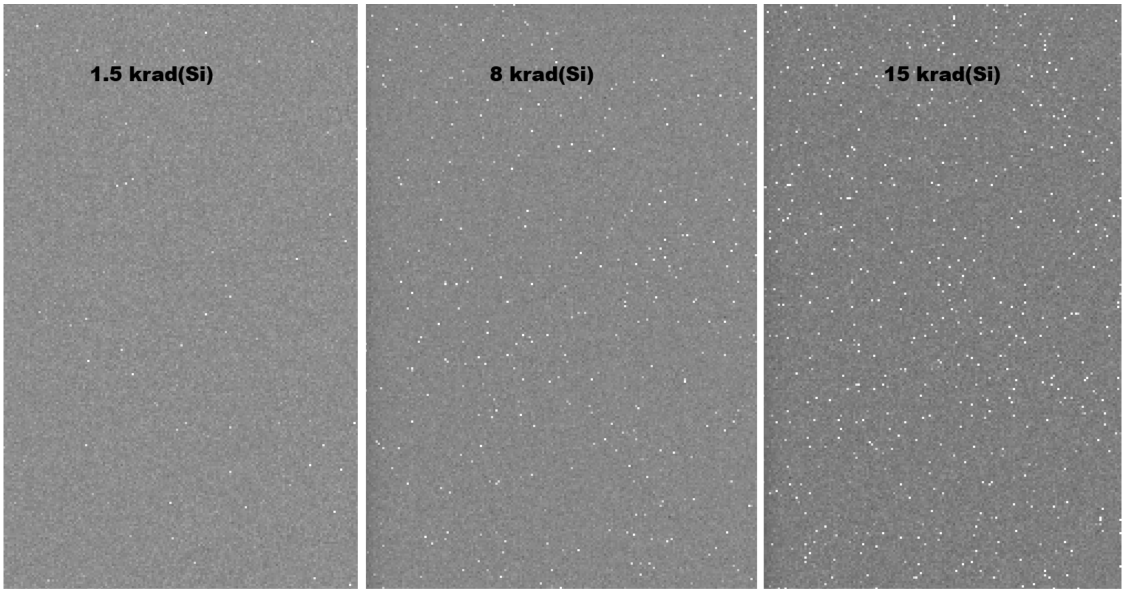


Figure 34, Credit: (Holland, 2025)

The most common artifacts that occurred during heavy ion testing were image readout freezing, baseline shifts, bright/dark lines and bars appearing in the image, and completely black images. No destructive events occurred during testing, and the sensors remained operational following the heavy ion testing, though SEFIs did require power cycling. No recorded voltage or current spikes were noted.

The SEFIs in the following table cover all the SEEs that occurred in the HWK4123 sensor, regardless of where it may have occurred in the sensor (ADCs, digital logic, pixels, etc). It is important to note that the SEFIs were not sorted by severity, and thus the recorded incidences include minor and major artifacts:

Table 3 : SEFI incidence (Holland, 2025)

LET (MeV.cm²/mg)	Ion flux (ions/cm².s)	Run time (s)	Number of SEFI	Cross section SEFI/(ion/cm²)	Ions/cm²	Cross section (cm²)
1.3	4305000	861	2	5.40E-10	3.71E+09	5.40E-10
3.3	13090000	2618	13	3.79E-10	3.43E+10	3.79E-10
5.7	5315000	1063	17	3.01E-09	5.65E+09	3.01E-09
9.9	2237000	753	10	5.94E-09	1.68E+09	5.94E-09
16.1	1800000	1800	20	6.17E-09	3.24E+09	6.17E-09
20.4	2918000	1505	13	2.96E-09	4.39E+09	2.96E-09
32.4	635000	635	20	4.96E-08	4.03E+08	4.96E-08
46.1	685000	685	20	4.26E-08	4.69E+08	4.26E-08
62.5	305000	305	17	1.83E-07	9.30E+07	1.83E-07

The bright pixels generated by the heavy ions were of overall lower intensity compared to that of TID testing. However, the total fluence was ~5000 ions/pixel, which meant that all the pixels were affected during heavy ion irradiation, leading to higher global dark current.

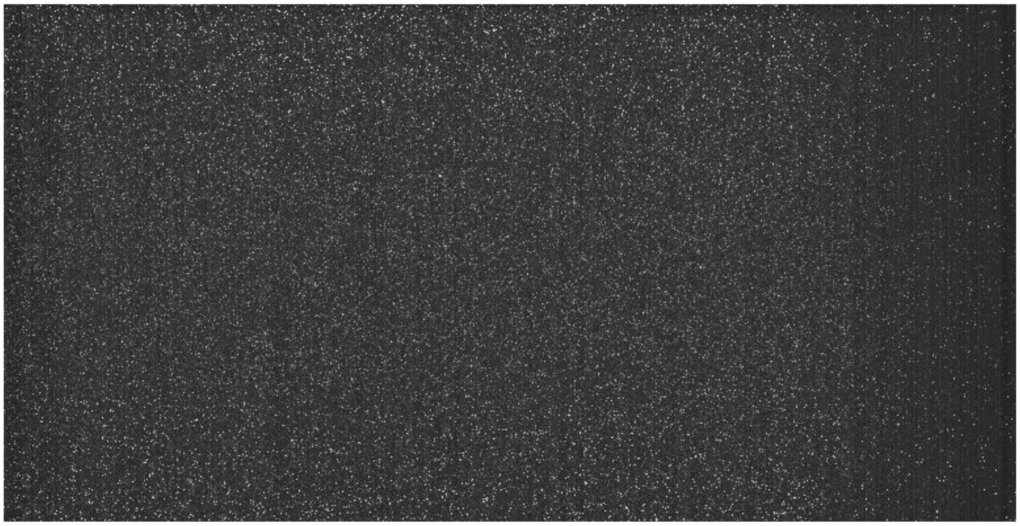


Figure 45: Dark Current Image Post-Heavy Ion Testing (Holland, 2025)

Conclusion

Radiation hardening is a crucial design consideration for any aspiring and current space mission provider. It is critical that payload integrators and manufacturers account for all points of failure when it comes to radiation tolerance.

TID testing showed that over a total dose of 15.3krad(Si) delivered over 5 hours, the HWK4123's flatband dark current did not increase after irradiations, due to the pinned photodiode's ability to dump charge. Bright pixels can be mitigated by a combination of cooling and dark frame subtraction. A typical 3-year, 600km LEO mission with 5mm aluminum shielding has a calculated TID of 0.48krad(Si), which is well below what the sensor was subjected to.

Heavy ion testing produced SEFIs of varying severity at every energy level, but more importantly did not result in any catastrophic failure of the sensor. When video streaming loss did occur, a power cycle was sufficient to recover the sensor. A cross section of functional interrupts was measured at 10^{-7} cm^2 which extended to low LET. SEFIs are anticipated to primarily occur during SAA passage, so powering down the camera system during this period is a potential mitigating action.

Proton testing produced approximately 2 registered SEUs per krad(Si) at 63MeV, demonstrating design robustness of the sensor.

Fairchild Imaging already has a proven track record of making space ready imaging sensors, and this new data proves that our HWK4123 sCMOS sensor, with the world's lowest CMOS sensor read noise, is ready to continue our legacy. As a COTS product, the HWK4123 is readily available for immediate integration into any applicable upcoming space mission.

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