TELEDYNE RAD-ICON IMAGING
A Teledyne Technologies Company

AN06: Detector Lifetime and Radiation Damage

Introduction

Hard x-rays and electronic devices don't get along. That's one possible conclusion after studying the physics of the interactions of x-ray radiation with sensitive electronics. X-ray radiation is powerful enough to seriously disrupt and even permanently damage biological tissue, so it is no surprise that complex electronic detectors can be damaged as well. An ideal detector would be sensitive enough to catch every single photon, add no noise of its own to the detected signal, and last forever without any degradation in performance. Unfortunately, such a detector doesn't exist.

In the real world of electronic sensing one can come close to achieving the first two performance criteria, and take precautions to get the most mileage towards the third. CMOS sensors in particular have high sensitivity and, as x-ray detectors, add very little noise to the signal. Digital CMOS electronics are often quoted to be "rad-hard to about 100 krad". That means a typical microchip will stop running after absorbing roughly one Joule of photon energy – not even a single calorie's worth! Fortunately for most applications, depositing energy via x-ray photons is a very slow process, and it can take a long time to dump that one calorie into a small chip.

Damage Mechanisms

The fact that a standard IC will fail after absorbing one Joule of energy is not a very good indicator of what is actually happening to the device. Changes start taking place inside the device well before it reaches the point of failure. X-rays generally interact with matter by exciting (via the Photoelectric Effect) or scattering (via the Compton Effect) electrons – at least in the energy range below one MeV. They do not affect the crystal structure or atomic order of the detector material, but they do produce a large number of free electrons, and of course positively charged ions (or holes). If the material is conductive, the electrons quickly recombine, and the equilibrium in the material is restored. However, if the material is an insulator, the energetic electrons often get ejected, leaving behind a permanent positive charge.

Integrated circuits rely on one or more insulating or dielectric layers to separate conductors and help control electric fields inside the device. Both CCDs and CMOS devices employ a thin layer of silicon dioxide (SiO_2) to separate polysilicon electrodes from the bulk silicon underneath. Charge build-up in this SiO_2 layer directly modifies the underlying electric fields, and therefore the charge transport properties of the silicon. In a CCD this means that the charge transfer becomes inefficient and the device quickly stops working. In a CMOS transistor it means that the threshold voltage of the transistor slowly shifts, until the device is either always on or completely closed off. Digital devices, as well as carefully designed analog devices, are able to tolerate moderate amounts of threshold voltage shifts, enabling them to continue to function normally until the transistors stop working and the device fails.

In a CMOS image sensor the most visible effect of radiation on device performance is seen in the dark current. Long before the transistors in such a device show any sign of change in behavior, the dark current from the photodiodes begins to increase. Modern CMOS sensors like the RadEye1 image sensor start off with extremely low dark current – on the order of 25 pA/cm^2 – so that even a strong increase in dark current will not have a significant effect for quite a while. The physical mechanism responsible for the increasing dark current is the same buildup of positive charge in the oxide layer that is described above. The charge distributions and electric fields at the perimeter of the photodiode, where the depletion region intersects with the device surface, are very sensitive to disturbances. Positive charge in the oxide layer causes electrons to accumulate underneath the surface, modifying the charge density in the depletion region and thereby increasing the leakage current across the PN junction of the diode. The dark current becomes stronger with increasing absorbed dose, until the diode eventually discharges faster than it can be read out.

Detector Lifetime

The total lifetime of a radiation imaging detector primarily depends on its usage environment. What energy spectrum does the detector see in a typical application? What is the dose rate? What is the maximum x-ray energy? Is the beam filtered or unfiltered? Are the x-rays left on continuously, or are they pulsed for individual exposures? How much use does the detector see in a typical day, week or month? And what type of objects are put in front of the detector – does the detector frequently see the unobstructed beam, or is its primary use to image thick metal plates that shield most of the radiation? Is the detector designed to hold up under radiation, or will it degrade quickly? And finally, what are the criteria for "failure"? All of these issues influence how long a detector will last in a particular environment.

Of course, many of these conditions can be summarized by counting the total dose absorbed by the detector. Yet the energy spectrum does make a difference, and a certain dose received from a tube running at 50 kVp will lead to different results than the same dose at 150 kVp. Also, it is difficult to measure or calculate the actual energy absorbed in the silicon. In practice it is easier to measure the dose rate relative to air (in rads or grays), or the exposure (in Roentgens) at the entrance window to the detector. These quantities can be adapted for different situations, provided the energy spectrum does not change significantly.

Test Conditions

Several Shad-o-Box cameras were tested under different conditions in order to determine the extent, if any, of degradation in the camera's performance with increased radiation dose. Table 1 shows the different test conditions. The standard Shad-o-Box camera was tested at 25, 45, 100 and 160 kVp. The Shad-o-Box EV shows essentially zero degradation at 25 kVp, and was tested only at 45, 100 and 160 kVp.

Table 1: Test Conditions

Peak Energy	*25 kV*	*45 kV*	*100 kV*	*160 kV*
Target	Tungsten	Tungsten	Tungsten	Tungsten
Filtration	0.5 mm Al	0.5 mm Al	none	none
Source current	1.5 mA	1 mA	100 µA	100 µA
Source-detector dist.	100 mm	100 mm	65 mm	65 mm
Dose rate	100 R/min	240 R/min	106 R/min	230 R/min

Test Criteria

The main radiation-induced effect limiting the lifetime of the Shad-o-Box cameras is the increase in dark current with cumulative exposure. None of the cameras tested failed in any other way before becoming saturated with dark current at room temperature. Of course, the saturation point can be extended by cooling the camera, or by reducing the integration time.

The test criteria that were selected are the camera dark signal (in ADU) for a 500 ms integration time, and the camera dark current (in electrons/sec). The latter can be calculated from the difference in dark signal between two images taken at different integration times; e.g. 500 ms and 1500 ms. Also measured for some cameras were the average camera gain (signal level at a fixed exposure), signal-to-noise ratio (also for a fixed exposure level), and resolution (both by monitoring a bar target image and by calculating the MTF from a straight-edge image).

Test Results

The test results are summarized in the graphs shown on the next page (Figures 1-6). Since the dark signal and current are strongly temperature-dependent (the dark current doubles approximately every 8°C), the data have been scaled to a mean camera temperature of 25°C. Typical response curves are shown for flat field signal and signal-to-noise ratio since these parameters do not vary significantly with x-ray energy. The MTF was found to be constant over both energy and total dose.

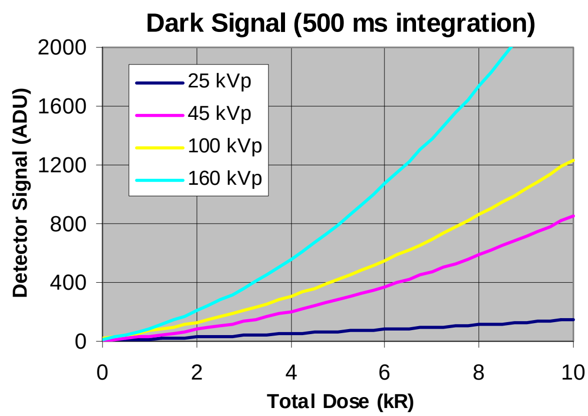

Figure 1: Standard Shad-o-Box Dark Signal

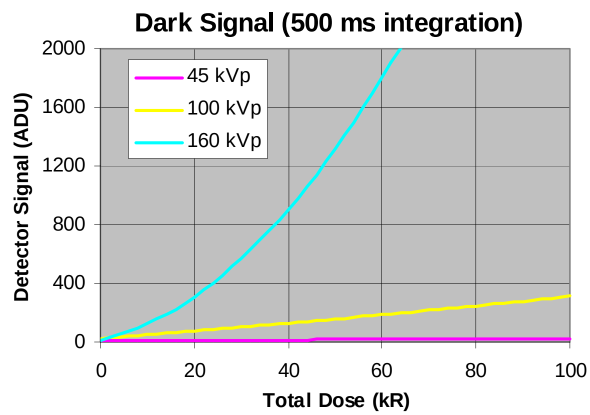

Figure 2: Shad-o-Box EV Dark Signal

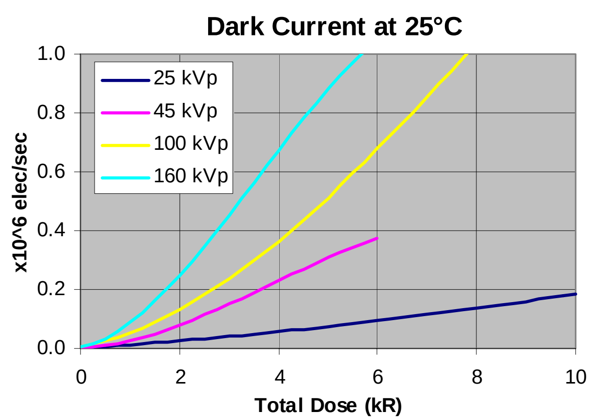

Figure 3: Standard Shad-o-Box Dark Current

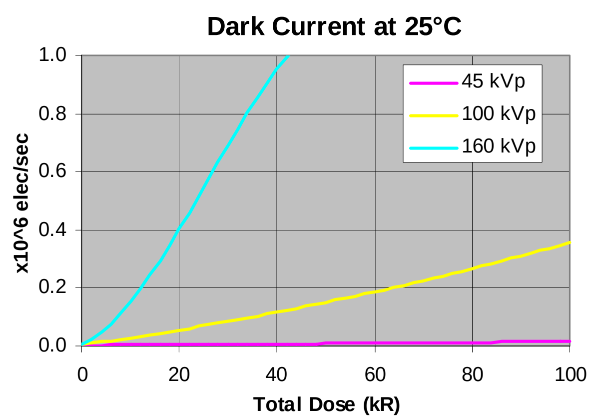

Figure 4: Shad-o-Box EV Dark Current

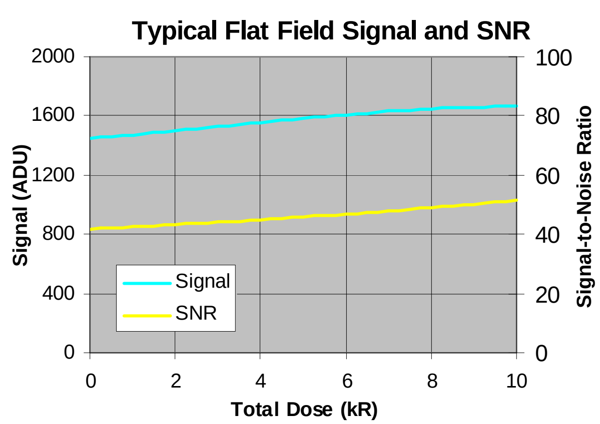

Figure 5: Standard Shad-o-Box Signal and SNR

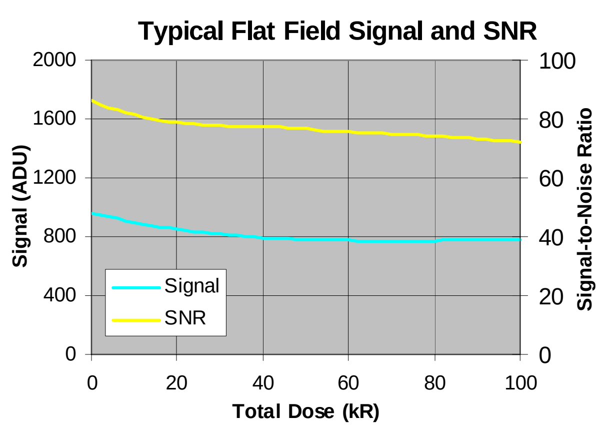

Figure 6: Shad-o-Box EV Signal and SNR

As expected, the radiation-hardened Shad-o-Box EV camera exhibits at least an order of magnitude improved radiation resistance compared to the standard Shad-o-Box. Depending on the x-ray energy, the dark current in the standard Shad-o-Box begins to consume a significant part of the total dynamic range after about 10 kR of total exposure. The Shad-o-Box EV, on the other hand, can last for several hundred kR at x-ray energies under 100 kV, and shows a usable lifetime of about 50 kR even at 160 kV. Note that the exposure for these tests was measured at the entrance window to the detector, which usually receives much less dose than the imaging object in a typical radiography setup. Cooling the camera to 0°C would extend the usable lifetime of the detector by up to an order of magnitude, just as operating it at elevated temperatures will cause it to saturate sooner. Figure 7 shows how the dark signal in the Shad-o-Box EV camera changes if the camera temperature and integration time are varied.

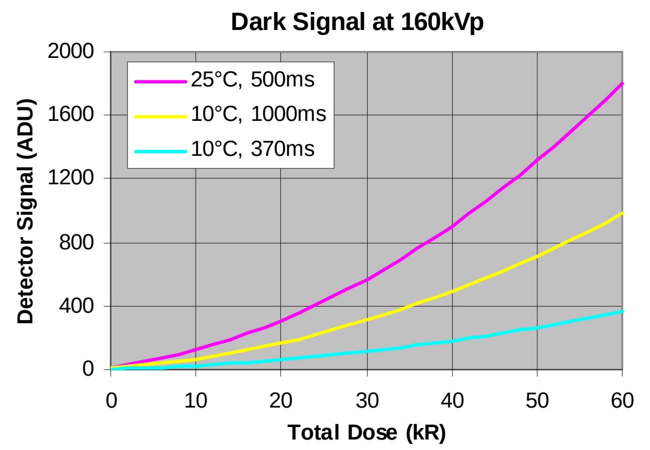

Figure 7: Shad-o-Box EV for different conditions

The plots of typical flat-field signal are essentially a measure of the change in camera gain over the lifetime of the sensor. In the standard Shad-o-Box camera the signal gain increases slightly with total exposure. In the EV version there is an equally small decrease in gain over its lifetime, with most of the change occurring over the first 20-40 kR of exposure. These changes are relatively minor compared to the gain variations within a typical sensor, and do not cause any performance degradation in the camera.

The signal-to-noise ratio graphs closely track the flat-field signal curves, as expected. The most significant thing to notice is that, even though the Shad-o-Box EV typically exhibits about 20-40% less sensitivity (in ADU/mR) than the standard Shad-o-Box camera, its signal-to-noise ratio is significantly higher. The reason for this is a reduction in directly absorbed x-rays in the silicon sensor. X-rays that are absorbed in the silicon instead of the scintillator generate large charge packets, which tend to increase the noise in the image even though they also contribute to the signal. As a result, the overall SNR for a given exposure is lower in the standard Shad-o-Box camera.

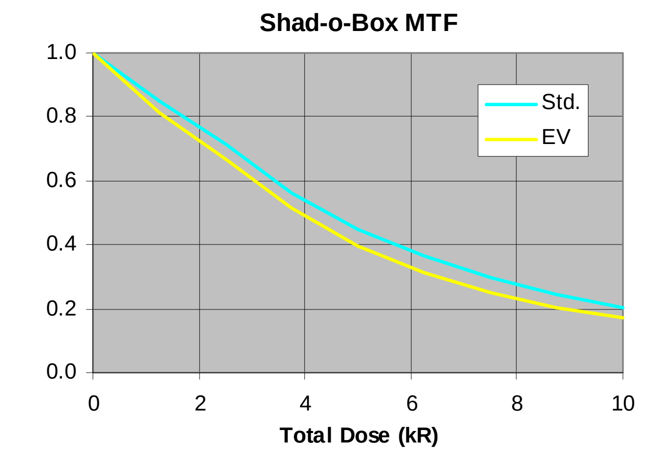

Figure 8: Typical MTF with Min-R Medium phosphor

Figure 8 shows typical MTF curves obtained for both the standard Shad-o-Box and the Shad-o-Box EV. The "slanted edge" technique was used for both measurements. There is no significant change in resolution either with respect to the x-ray energy or with total dose. (However, experimental factors such as the quality and thickness of the edge or slit used for the measurement, as well as the focus of the source and the amount of scatter present can easily cause a variation of ±5% or more in the measurement.) The Shad-o-Box EV typically has a slightly reduced MTF compared to the standard Shad-o-Box, and its resolution is likely to vary more between different parts of the image.

Conclusion

Hard x-rays and electronic devices can get along. The data presented in this application note show that electronic imaging devices can last a long time in a radiation environment. The most important thing to keep in mind is that every x-ray imaging application is unique, and what works in one situation may not be appropriate in another. Both the standard Shad-o-Box cameras and the Shad-o-Box EV series cameras perform very well in their intended application environments. In selecting which camera is appropriate, one has to first determine carefully what the energy and dose requirements are for the intended application. If long integration times are required, it may also be necessary to consider cooling the camera in order to control the dark current.

No electronic device will last forever in a high-energy radiation environment. But with the appropriate precautions, the Shad-o-Box x-ray camera can run for many years without significant degradation in performance in most application environments.