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Testing of CMOS Devices in NIF's Harsh Neutron Environment

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Testing of CMOS Devices in NIF's Harsh Neutron Environment

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ABSTRACT

Vendor supplied CMOS sensors were exposed to 14 MeV neutrons on yield shots in NIF and examined for damage. The sensors were exposed to multiple shots with a maximum fluence on one of the sensors of 4.3E11 n/cm^2. The results of post-shot testing will be presented. LLNL is investigating the suitability of CMOS imaging sensors for use in the camera of the ARIANE diagnostic which will mitigate the effects of the NIF neutron environment by dumping photoelectrons during the neutron pulse and then recording an image stored on a long persistence phosphor.

Keywords: CMOS, neutron damage, National Ignition Facility (NIF)

1. INTRODUCTION

The LLNL Target Diagnostics community has to ensure the survivability and operability of instruments in the harsh radiation and EMP environment of the NIF. Diagnostics record gated, streaked, or integrated images of phenomena. Some cameras record X-ray pinhole images directly [1,2] while others record the light output from a phosphor on the back of a streak tube or MCP [3,4]. Electronic image acquisition by electronic cameras is preferred over film because they do not have to be exchanged after every shot. However neutrons that get to an imaging sensor can generate charge in a pixel that is indistinguishable from the charge of the desired image. At high enough levels the neutron-induced charge can saturate the sensor, rendering the image useless. Also, repeated exposure from the 14 MeV neutrons produced by shots can introduce damage into imaging sensors that will also degrade images to the point that the sensor has to be replaced. NIF needs imaging sensors that can work in this environment and last for as long as possible before requiring replacement.

1.1 Dump and Read of Neutron-Induced Charge

One concept being developed by LLNL is to have an image recorded on a long decay phosphor. The imaging sensor will be put into a mode where the neutron-induced charge is "dumped". Once the neutron background has passed the imager will integrate the remaining image on the phosphor. This concept is planned for use on a high yield imaging system planned for NIF, the active readout in a neutron environment or ARIANE.[5] The X-ray pinhole image gating with a readout phosphor will acquire the desired image. Relay optics or a fiber bundle will be used to transfer the image to the camera that will reside in a shielded housing.

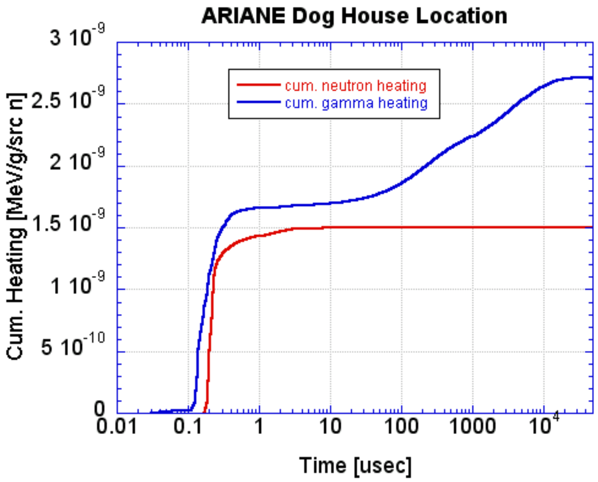


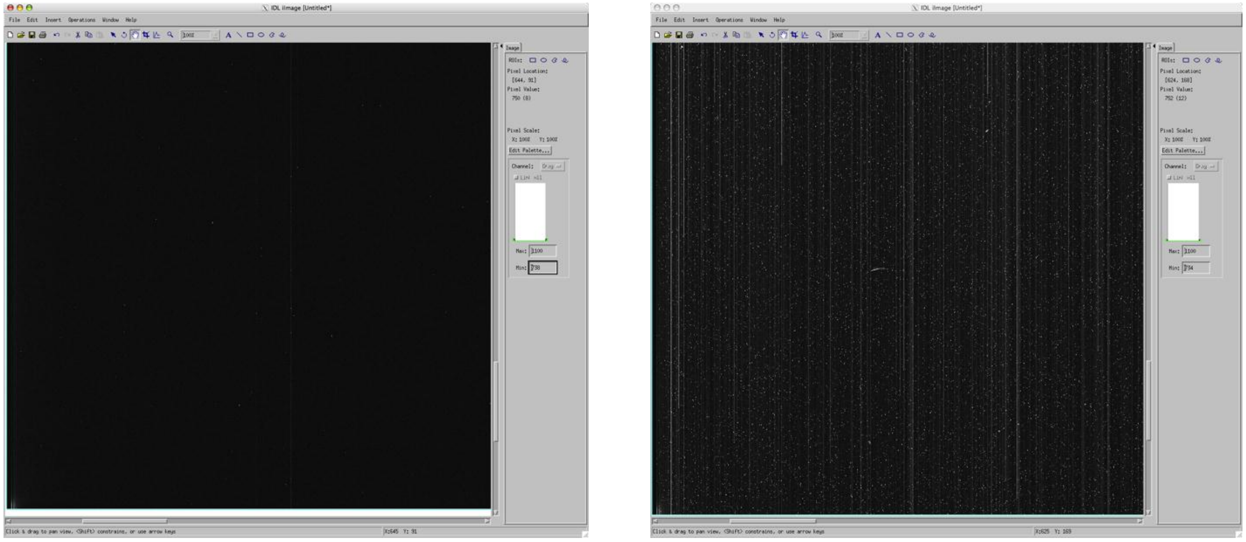
Figure 1. Calculated neutron and gamma energy deposition (normalized per 14 MeV source neutron) in Si at the ARIANE detector location (~ 10 m from target) outside of any shielding.

In order to better understand the effect on camera systems the effect of neutron induced backgrounds a modeling capability has been developed at LLNL.[6] Calculations were done on one of the design concepts for the ARIANE housing or “dog house”. As seen in figure 1, the modeling of the effects of a shot indicates that the charge will be induced by neutrons and gamma rays with most of the neutron heating and half of the gamma heating occurring in the first microsecond. An electronic camera would have to have its imaging sensor dumping charge during this time and then put it into an imaging integration mode before the phosphor decays completely.

CCD imaging sensors clear charge by clocking out the pixels. While the clock rate can be increased when the electrons in the pixels are not being digitized, a large format CCD could not be cleared effectively in ARIANE’s timeframe. Thus LLNL is investigating CMOS imagers where pixels are designed to be put into a global clear mode and then be turned on for a short period of time.

1.2 CMOS Sensor

Many of the cameras used in NIF Target Diagnostic instruments have large format CCD sensors. Experience has shown that the CCDs show an increase in damage after exposure to neutron radiation during a yield shot at NIF. Two major damage mechanisms are ionization and bulk damage [7]. Ionization damage occurs in the gate dielectric and may consist of holes trapped in the layer or interface states formed at the Si-SiO$_2$ interface. Bulk damage, also called displacement damage, occurs in the epitaxial Si layer where collisions by energetic particle can displace atoms and create defects. Ionization damage can result in flatband shift, charge trapped in the dielectric that affects bias potentials, or in surface dark current. Bulk damage degrades charge transfer efficiency, and increases dark current generation and dark current spikes. The effects have already been seen in CCD cameras used in NIF target diagnostic instruments. Figure 1 shows the increase in noise and other defects in background images before and after a 2E14 neutron yield shot.



Pixel Location: [644, 91]
Pixel Value: 750 (8)
Pixel Scale: X: 100% Y: 100%
Max: 1100
Min: 738
X:645 Y: 91

Pixel Location: [624, 168]
Pixel Value: 752 (12)
Pixel Scale: X: 100% Y: 100%
Max: 1100
Min: 734
X:625 Y: 169

Figure 2. Background images from a CCD camera in a Gated X-ray Detector (GXD) instrument before and after a neutron yield shot.

As can be seen by the streaks in the “after” image in Figure 1, a single bad pixel in a column can adversely affect every other pixel in that column due to charge transfer method used to read out a CCD. If this happens in too many columns the image will be degraded to the point the camera has to be replaced. A CMOS imaging sensor will not be susceptible to the same effect because pixels are read out directly. This feature is of interest to LLNL as it will allow an imager to be used longer before replacement.

SRI International Sarnoff has proposed using a CMOS imager technology they are developing as a solution to LLNL’s needs. Their design concept uses a mask set where a basic building block of 1k x 1k 10 mm pixels can be stitched during fabrication to create an imager with dimensions Mk x Nk where M and N are integers. A 4k x 4k imager built using this technique would adequately match the size of CCDs currently in use. However before embarking on a costly design project it was decided to start with some preliminary testing that would help us to convince ourselves that this CMOS sensor is a viable alternative.

As part of its product research and development process SRI fabricates “Sandbox” reticules with a number of prototype sensor designs. Among these are “minimal” arrays, imaging sensors of a standard size which when mounted are used to test pixel designs in a standard electronic test set [8]. LLNL purchased one of these test sets and several imagers from SRI and contracted with SRI to provide support for a study of the effect of neutron irradiation on the minimal array.

In a parallel effort SRI studied the reset circuitry in their CMOS design to determine if it would be capable of handling the neutron and gamma-induced charge in a dump and read camera. Pixels were illuminated with a pulsed LED at levels that produced photocharge similar to the amount predicted for the radiation-induced charge. The exposure resulted in charge 3 to 4 times saturation for the pixel, and it could be cleared in under 10 μsec which was determined to be suitable for ARIANE.

2. CMOS SENSOR AND TEST SET

2.1 CMOS Sensor

The minimal array selected for the test was from the Sandbox V-B run. It was a 256 x 248 array of five transistor pinned photodiode (5TPPD) 16 μm ring pixels. “Ring” refers to the sense node being in the center of the pixel with a square transfer gate surrounding it like a picture frame. While this design is different from the pixel design being developed for the Mk x Nk imager, it was decided that the area of the large ring transfer gate would make it more susceptible to neutrons and would thus present a worst-case scenario for damage. The epitaxial layer was 15 μm of 10,000 Ω-cm Si.

2.2 METS Evaluation Board

LLNL purchased a Minimal Evaluation Test Set (METS) board set from SRI and a National Instruments (NI) NI-1422 frame grabber board for computer acquisition of images. The board reads out a minimal array at a 50 kHz pixel rate. NI LabVIEW software was used to acquire and store an arbitrary number of images. The board includes an LED mounted in a housing that may be used to test the sensor under different illumination levels. This board was used for pre- and post-irradiation testing at LLNL.

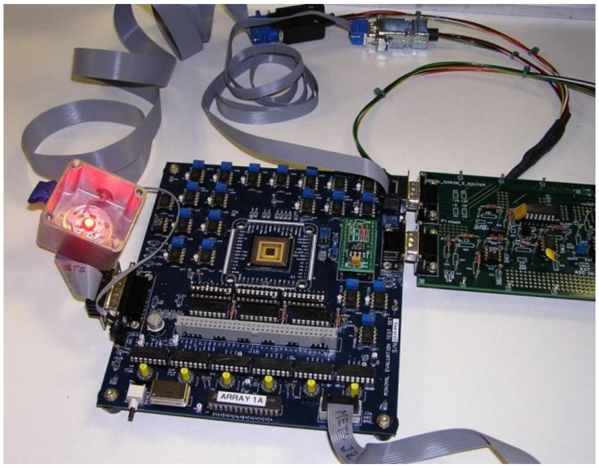


Figure 3. METS board set with a test minimal array (center). The housing with the red LED (left) can be used to illuminate the minimal array. The signal chain board (right) contains the analog-to-digital converter and interfaces to the NI-1422 frame grabber board.

3. TEST FIXTURE

3.1 Snout Fixture

In order to expose the sensors to the highest possible fluence they had to be placed as close as possible to the NIF target chamber center (TCC) where the laser beams are focused on the targets and neutrons are generated in yield shots. The target diagnostic instruments that get closest to TCC are gated pinhole imaging instruments that are placed in diagnostic instrument manipulators (DIMs) that enter the target chamber from two locations along its equator. In order to achieve the desired magnification the pinholes may need to be as close as 80 mm from TCC. The assembly that positions the pinhole is known as a "snout" and consists of a cone assembly that holds the pinhole assembly, an extension tube, and a kinematic mount that positions the snout on the front of the DIM gated imaging instrument with a high degree of precision.

Because of the complexity of experiments in the NIF and the possibility of cross-contamination of incompatible materials causing the degradation of optics or instrumentation, thorough review is done before any material is introduced into the target chamber. Any changes to the shape of an object must be reviewed for laser light and debris interactions, and anything that sees the vacuum of the target chamber must pass strict outgassing tests. Additionally any item removed from the chamber is monitored for tritium contamination from leftover fuel on yield shots.

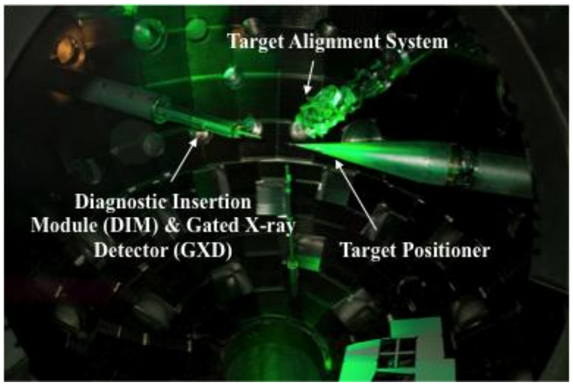


Figure 4. The interior of the NIF target chamber. The target is held at TCC by the target positioner inserted from the right. The DIM positioning the GXD instrument is on the left with the snout assembly at its tip.

As this was an add-on test the CMOS devices had to be introduced in a way that minimized their effect on other systems. The solution was to build a small aluminum enclosure that would fit within the conical pinhole holder on the snout. Installation in the conical holder was made easier by already existing mounting screw holes. An O-ring seal protected the sensor from potential tritium contamination. While it would have been preferrable to have the sensor face TCC, this could not be accomplished without interfering with the host instrument's field of view of the pinholes. Thus the sensors were positioned with one edge pointing towards TCC.

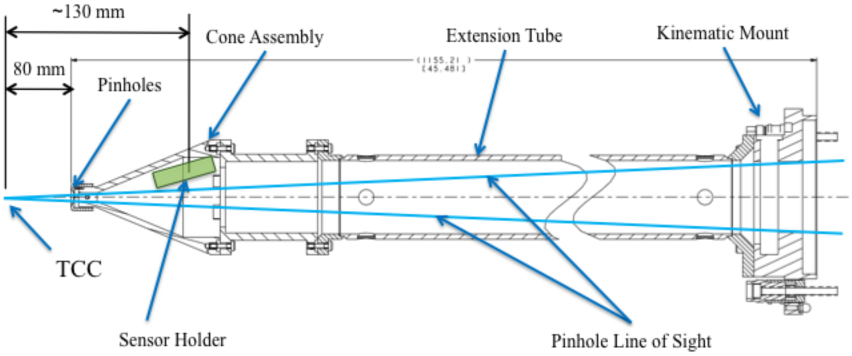


Figure 5. Position of the sensor holder (green) inside of the existing snout used on DIM-based instruments.

The process of irradiating the sensors started with them being wrapped in a layer of aluminum foil surrounded by aluminum foil tape. The foil packet was delivered to the target diagnostic factory where diagnostic components like snouts undergo final assembly and preparations for installation on diagnostics in the target chamber. The snout assembly was then transported to the NIF target bay and the snout was installed on a DIM diagnostic. Pinholes on these diagnostics are close to the target and can sustain damage, so snouts are usually replaced after every shot. After the snout was removed from the DIM diagnostic and returned to the target diagnostic factor, it was disassembled and the sensor holder removed from the cone assembly. The foil pack containing the sensor was removed from the sensor holder and released for testing of the sensor

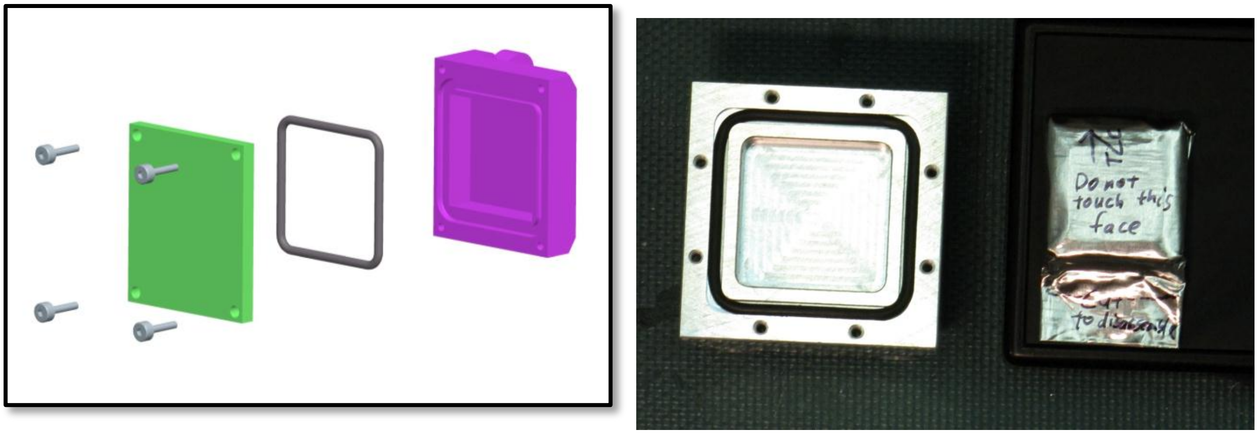


Figure 6. Left: Computer model of the sensor holder. Right: Wrapped sensor shown before insertion into a holder.

4. TEST RESULTS

Two CMOS sensors were irradiated with neutrons in the NIF target chamber during a series of yield shots in June of 2011. Each sensor was subjected to multiple shots in order to increase the total fluence seen by the sensor. Detailed modeling of the neutron flux and downscattered radiation was not available so the fluence was estimated based upon the measured neutron yield of each shot and the assumption that this was spread over $4\pi r^2$. Snouts were replaced after each shot and the turnaround time for refurbishment was longer than the days between shots. Thus two sensors were alternated to take advantage of all the shots within this period that had a significant yield.

4.1 Sensor SRI 1

The first irradiated sensor, identified as SRI-1 was exposed to neutrons on three shots with an estimated total fluence of 4.3E11 n/cm^2 or .52 krad Si.

Table 1. List of three exposures for sensor SRI-1.

	Measured Yield	$1/4\pi r^2$ Fluence
Shot 1	6.5E13 +/- 1.4E12	3.1E10 n/cm^2 @ 13 cm
Shot 3	1.9E14 +/- 4.1E12	9.0E10 n/cm^2 @ 13 cm
Shot 5	6.6E14 +/3 2.7E13	3.1E11 n/cm^2 @ 13 cm

4.2 Sensor SRI 2

The first irradiated sensor, identified as SRI-2 was also exposed to neutrons on three shots, which, by coincidence, also had an estimated total fluence of 4.3E11 n/cm^2 or .52 krad Si.

Table 2. List of three exposures for sensor SRI-2.

Date	Measured Yield	1/4πr^2 Fluence
Shot 2	2.4E14 +/- 7.9E12	1.9E10 n/cm^2 @ 31.7 cm
Shot 4	4.3E14 +/- 9.2E12	2.0E11 n/cm^2 @ 13 cm
Shot 6	4.1E14 +/- 1.1E13	1.9E11 n/cm^2 @ 13 cm

4.3 Measured Damage

Average dark and light field images were taken before and after the neutron irradiation of the sensors and compared for evidence of damage. In each case 100 images were acquired and averaged to reduce noise. Average pre shot images were subtracted from average post shot images with known bad pixels and two columns of row or edge pixels masked out. The subtracted dark images showed only a handful out of 61,436 unmasked pixels showed a 10 DN increase and only two showed an increase greater than 35 (Figure 6). Light field images were taken using the test LED built into the METS board. The subtracted light images did not show any evidence of dead pixels.

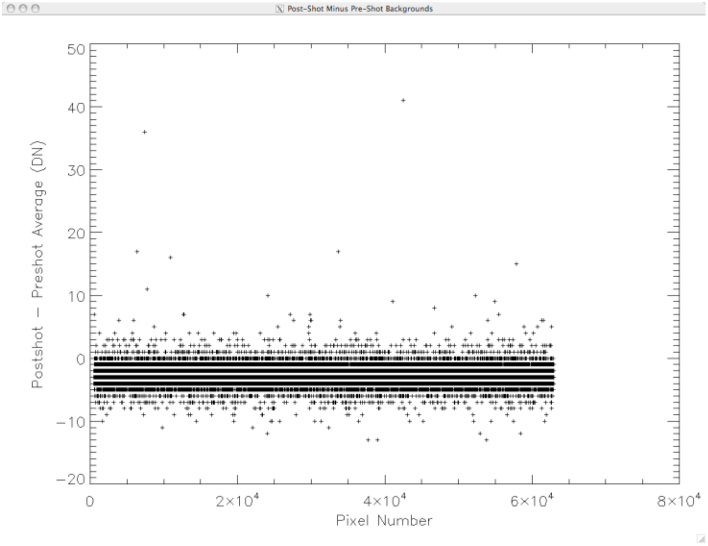


Figure 7. Plot of DN for post shot minus pre shot background images for sensor SRI 1 plotted versus the pixel number

After examination at LLNL the two sensors were returned to SRI for examination. They reported that no flat band shift was detected, no increase in read noise, no degradation of CTE, and no degradation in the dynamic range. The only effect seen was an increase in the thermal bulk dark current that they attributed to induced damage in the high resistivity (15,000 Ω-cm) silicon. Their measurements showed an increase of 3 to 5 times the dark current normally seen in that type of sensor.

5. CONCLUSIONS

CMOS sensors were subjected to 14 MeV neutrons in the NIF target chamber. Performance of the sensors before and after the exposure was compared for evidence of damage, but little was seen. The only effect appeared to be an increase in dark current. Because of limitations in placing the sensors as close to TCC as possible, they could only be irradiated in an unpowered state, as utilities to power the sensor and room for support electronics was not available. Irradiation of powered sensors would be preferred to test the susceptibility to damage mechanisms dependent upon electric fields in the sensor. The amount of irradiation was also inherently limited by the yield of the shots and the number of experiments that used the particular snout that could contain the sensor holder. This limited the irradiation seen by the sensors to an amount equal to about half of a krad Si. It would be desirable to do tests at higher fluence levels as the opportunity arises.

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