LLNL-CONF-569098

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August 3, 2012

2012 SPIE Conference
San Diego, CA, United States
August 12, 2012 through August 16, 2012

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Design and testing of a megapixel CMOS charge dump and read camera

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ABSTRACT

The National Ignition Facility requires a radiation-hardened, megapixel CMOS imaging sensor-based camera to be a direct physical and operational replacement for the CCD cameras currently used in x-ray streak cameras and gated imaging detectors. The first phase is a radiation-tolerant camera for characterization of radiation effects on the imaging sensor. This will be followed by a fully hardened version. The radiation-tolerant camera, based on the 2k by 2k CMV4000 sensor from CMOSIS Inc., has been built and optical performance was measured. Camera parts were selected to operate up to 10 krad(Si) and the camera incorporates a fast charge and dump of the sensor pixels, followed by image readout. This allows the dumping of charge due to the prompt radiation noise and then readout of the longer persistence phosphor signal from the x-ray diagnostics.

Keywords: CMOS imager, CCD camera, radiation tolerant.

1. INTRODUCTION

The National Ignition Facility uses x-ray streak cameras and gated x-ray cameras to provide spatial and time resolved images of the inertial confinement fusion implosion. Common to both diagnostics is the use of a gated microchannel plate and phosphor, coupled by a fiber optic to either a scientific grade megapixel CCD camera or film. To reduce radiation exposure to personnel and improve efficiency of data collection and analysis the preferred option would be a digital readout system.

The current primary readout system used in these NIF diagnostics is a Spectral Instruments 1000 series[1] CCD camera. The camera was designed to fit into the NIF standard diagnostic airbox cross section and image the same area as the original 35mm film pack. Due to the time integrating operation and lack of shutter, the CDD camera is sensitive to radiation at all times during the integration and readout process. Depending upon the distance from the implosion capsule, the earliest arrival time of the 14 MeV neutrons is 24 ns after the x-rays. The 14 MeV neutrons produced by the capsule interact with material creating protons, alpha particles, and gamma radiation. This radiation creates a charge in the pixel, excites the output phosphor, and creates Cherenkov radiation in the fiber optic bundle. Of those noise sources, the dominant source of background noise in the readout image is due to charge induced and detected in the CCD pixel. The background noise in the CCD will scale up with increasing neutron yields. Radiation tests at the Omega laser at LLE with a Kodak 16800 CCD[2] gave an operational limit of 10^8 n/cm^2 due to the increasing background noise. Figure 1 shows the degradation of the CCD image due to radiation induced noise[3].

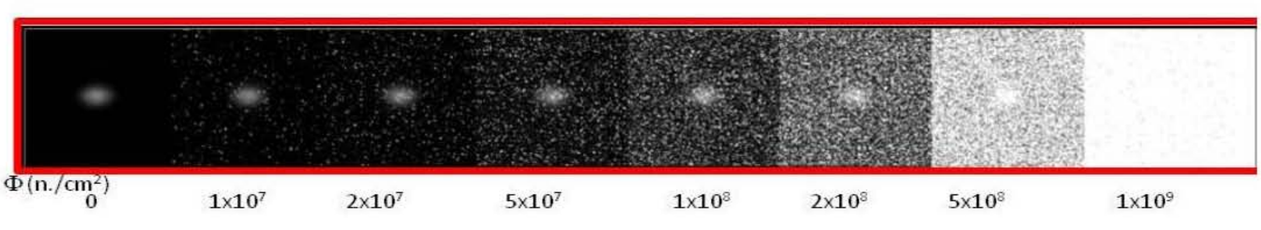

Figure 1. Noise increase on the CCD due to radiation.

One way to reduce the radiation induced background noise is to dump the charge in the pixels until the radiation due to neutrons and gamma pulses have passed. Then quickly reacquire an image of the output phosphor before the phosphor image intensity decays too low[4] as shown in figure 2. The plot is for an imaging system using P20 phosphor and a read time based on the Spectral Instruments Model 1050 camera. This method requires the image sensor to have a global reset capability: an ability to quickly dump the unwanted charge at the pixel level. In addition to increasing signal-to-noise on the output, it is important to minimize radiation effects on sensor readout and control electronics to prevent data loss during readout and mitigate long-term damage effects. These requirements are met by replacing the CCD sensor and its critical support electronics with a CMOS APD imaging sensor and its reduced set of support electronics.

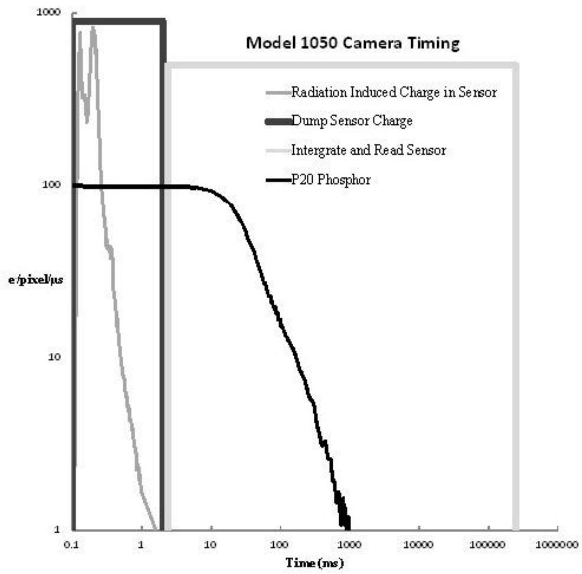

Figure 2. Plot showing timing of the charge dump due to radiation and subsequent imaging of the slower phosphor signal.

2. DESCRIPTION

Spectral Instruments built the 1050 series camera (shown in figures 3 and 4), a radiation-tolerant, fast dump camera, based on the CMOSIS CMV4000-2E5M0PN sensor[5]. For test purposes the camera has a Nikon lens mount rather than our normal fiber optic block bonded to the imager. This allows for more efficient replacement of sensors, if necessary, during the radiation testing phase. The camera uses the SI10000 camera interface and software for operation at NIF. The cameras have an optical trigger, the ability to read out an image in ≈ 250 ms over fiber optics, and operate in a thermo-electrically cooled mode down to -40C. The performance of a normal, undamaged detector should not be significantly different at room temperature when compared to -40C. However, the cooled mode is available to minimize dark current noise due to radiation damage as the device is exposed to the NIF environment.

The user has the ability to select an analog gain (between 1.0X and 1.6X) and adjust the delay between the camera trigger and acquisition of the desired image ("dump" time). The delay time is in increments of 50 ns with a range of 100 ns to 3.3 ms. The pixels are held in reset mode, removing all unwanted charge, until the specified integration delay has completed. Once the delay is complete the camera sets the pixels to integrate signal for the specified time and then reads out the data.

The electronics where chosen to provide an estimated 10krad(Si) of radiation hardness. Control and readout of the sensor is through an Actel RT3PE600L Field Programmable Gate Array (FPGA)[6] with 600,000 gates. This FPGA which is part of the radiation-tolerant RT ProASIC family experiences a 10% increase in propagation delay between 15 and 25 krad(Si). The program is stored in a 3D Plus radiation-tolerant memory which is good to 15 krad(Si).

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The CMV4000-2E5M0PN sensor has an 8-transistor (8T) architecture with a pinned photodiode fabricated in 0.18 micron CMOS process with a 5 micron EPI layer[6]. The one inch square imaging area is composed of 2048 by 2048 active pixels on a 5.5 micron pitch. The 8T design provides global shutter, global reset, and double-correlated sampling capabilities. The advantage of the global shutter is that the charge is only accumulated during exposure time. Unlike the CCDs currently used, this allows the camera to be in an environment where there is unwanted light or noise during the readout phase without causing a degradation of the output data. The pinned photodiode and the EPI layer[7] should also contribute to a reduction of the image background noise due to radiation.

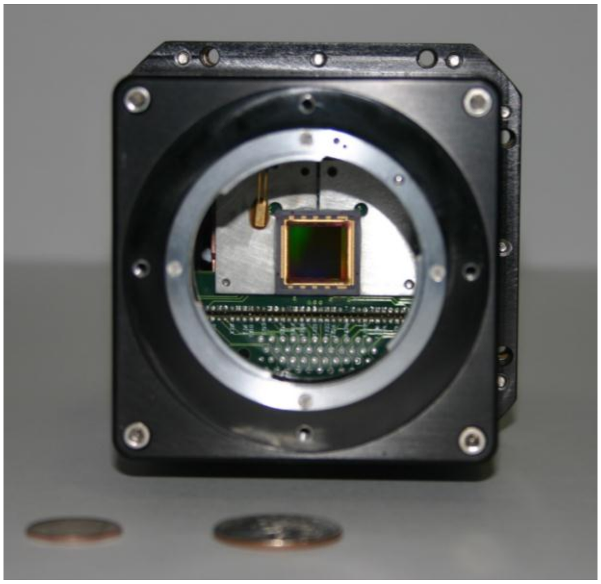

Figure 3. Front view of a Spectral Instruments Model 1050 camera showing the CMOSIS CMV4000 sensor.

Figure 4. Side view of a Spectral Instruments model 1050 camera.

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3. METHODOLGY

The radiation effects test plan consists of three steps. The first step is an optical characterization of the camera to establish a baseline. The second step will be exposure of the operating camera to the NIF radiation environment in the NIF target chamber. The final step is a repeat of the optical characterization to evaluate the effects of the radiation exposure on camera performance. For this initial test, a classic photon transfer method was used to evaluate the camera performance. From this method we can determine the camera read noise, full well signal, dynamic range, and sensitivity (camera gain constant). This camera also adds the requirements of evaluating the ability of the camera to fully dump the undesired charge and reset to acquire the desirable signal in the appropriate time scale. This will be measured by adjusting the timing of a short laser pulse through the dump region and determining the timing of this parameter and efficiency with which the undesired charge is removed.

A Gamma Scientific RS-5 Digital Light Source System[8], with calibrated DC output, was used as the source of light for these tests. Two different LED heads were available, one at 460 nm and the other at 530 nm. These two wavelengths closely duplicate the P11 and P20 phosphors commonly used on gated and streak camera systems on NIF. The RS-5 head was mounted to the FFI (Flat-Field Illuminator, also from Gamma Scientific) and a shutter assembly had been installed into the FFI for controlling light exposure time. Due to the range of the light source and the sensitivities of the cameras under test, 1.3 of ND filtering was added to the output end of the FFI. An Edmund Scientific diffuser was also installed at the output of the FFI and a fiberoptic faceplate (FOP) was used to provide coupling to the cameras under test which duplicated the typical camera use. The camera under test was mounted to the alignment stage and adjusted so that the camera's front face made direct contact with the output FOP of the illumination system. For past 1000 series cameras, this allowed for direct FOP coupling of the camera to the source. Because the 1050 camera has a lens mount with the bare sensor recessed, this positioned the sensor at 2" from the output of the source.

The camera under test acquired an image for 2 seconds, with the shutter being opened for 0.5 second, starting 0.2 seconds after the camera acquisition was initiated. Bias images (0-second, dark exposures) were acquired to determine the camera bias offset level and read noise. The camera was then illuminated with a level above full well and two images were acquired at that light intensity. The light source was reduced to the next lower intensity and two more images were acquired. This process was repeated until the light level was near the read noise level of the camera.

4. RESULTS

A 50 x 50 pixel sub-array in the overscan area of the bias images was used to determine the average bias signal (bias offset signal, S_{off}) and standard deviation (read noise, $\sigma_{R_{DN}}$).

At each illumination level, another 50 x 50 pixel sub-array (centered in the uniformly illuminated region) was used to determine the average signal. The signal levels from the two images at a given light level were averaged together and the offset level subtracted to produce the true average signal ($S_{(DN)}$) for that intensity. The first image was subtracted from the second to eliminate fixed pattern noise. The standard deviation of this same sub-array was measured and provided the shot noise for that intensity level ($\sigma_{S_{DN}}$). The resulting values were used to calculate the camera gain constant (k) for that illumination level using equation 1 below:

$$k = \frac{S_{DN}}{\left(\frac{\sigma^2_{S_{DN}}}{2}\right) - \sigma^2_{R_{DN}}} \qquad (1)$$

This process was repeated for each set of images at the various light levels. The camera gain constant values (k) from each illumination level through the linear region of the camera were averaged together to determine the average camera gain constant. This Camera Gain Constant value is a measure of the camera's sensitivity and is specified in electrons/Digital Number (e^-/DN). This factor is useful in determining the true signal level of an image in electrons.

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Table 1 shows the camera's performance specifications that are derived from this test. A unity gain comparison shows the measured full well capacity is within 2.2% of the CMOSIS specification of 13.5k electrons.

The resulting data was also plotted by converting the data to electrons, using the Camera Gain Constant, then plotting Signal vs. Noise for each light level on a log-log plot. Figure 5 shows the photon transfer curve for this camera. The point where the curve rolls off at the peak is the Full Well signal level of the camera. Read noise is defined where the plot starts to level off at the low end and would intercept the Y axis.

Another assessment of the camera performance was determined by plotting the output signal, in electrons, versus the input light input, in # of photons per pixel. Figure 6. plots this camera responsivity data. The system quantum efficiency (QE) can be derived from this plot by dividing the # of electrons out/# of photons the QE percentage. Since at visible wavelengths, 1 e^-/hole pair is generated for each photon detected. This was calculated to be approximately 50% at 530nm and 40% at 460 nm.

Table 1. Measured Camera Performance Specifications

Cam. Gain Setting	Cam. Gain Constant (e^-/DN)	Read Noise (e^-)	Full Well (e^-)	Dynamic Range
1.0X	4.6	23	13800	600
1.6X	2.6	21	9800	467

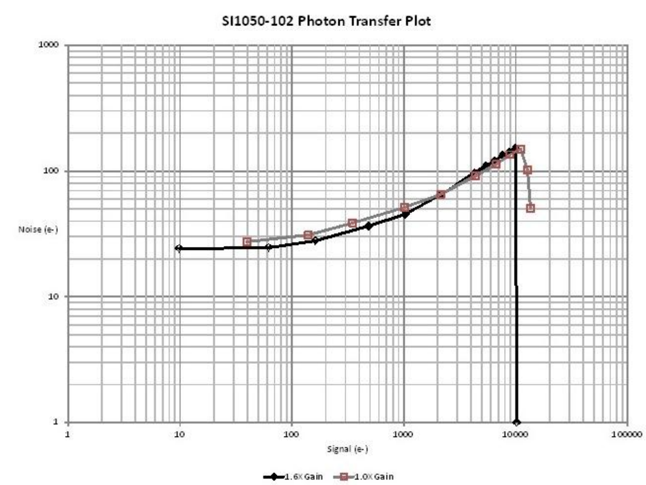

Figure 5. Photon Transfer Curve, showing the camera signal versus noise response in electrons.

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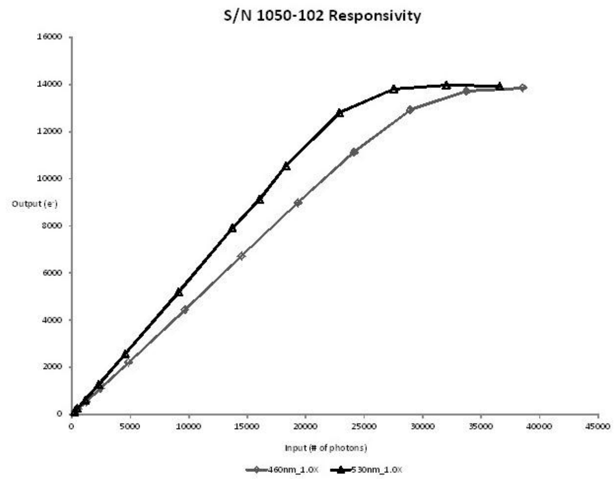

Figure 6. Responsivity Plot, showing camera output signal versus input illumination levels.

5. CONCLUSION

These results show the series 1050 CMOS-based camera can be replacement for the current 1000 series CCD-based camera. The dynamic range of 600 is more than sufficient to meet the dynamic range requirement of 300 due to the microchannel plates used in the NIF x-ray diagnsotics[9]. Additional tests will be done to determine the spatial resolution and charge dump efficiency and response time using the global shutter. The results will serve as a baseline for evaluating the camera performance as it is exposed to the NIF radiation environment. The operating software and mechanical interface allows for a virtually seamless transition from the 1000 series cameras, with regard to NIF operations. The radiation testing and subsequent optical testing will validate the performance of this camera in the required NIF environment. These results will be explored in a subsequent paper. This camera will allow NIF diagnostics to more reliably acquire data on experiments as the yields increase in the coming months and years.

ACKNOWLEDGMENTS

We wish to acknowledge Spectral Instrument's team for design and build of the first Model 1050 camera. Thanks to Travis Pond and Chris Silbernagel at National Security Technologies Livermore Operations for providing a rapid series of tests in the optical calibration lab.

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.

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