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Quantum efficiency of the CIS115 in a radiation environment

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ABSTRACT

An optical bench setup for quantum efficiency (QE) measurements across the 350 nm to 1100 nm range has been developed at the Open University's Centre for Electronic Imaging (CEI). Here we use it to measure the performance of a monolithic silicon CMOS image sensor (CIS), the CIS115. This sensor was selected for the JANUS camera, due to launch on board ESA's Jupiter ICy moons Explorer (JUICE) spacecraft in 2022. The CIS115 sensors tested here have high quantum efficiency (QE) over the optical band, due to their backside illumination and multi-layer anti-reflective coating.

Here we validate the QE measurements against manufacturer reported performance and compare the QE for unirradiated (beginning of life) and gamma-irradiated devices, indicating that no significant change in performance should be expected after a total ionizing dose (TID) of 200 krad(Si). This is important for the JANUS application, where the sensor is predicted to accumulate up to 44 krad(Si) TID. We also demonstrate that the measurement setup has excellent repeatability.

We conclude by discussing the limitations of the setup, including the key systematic error sources that have been understood and investigated. Optional improvement to the setup for reducing these errors are presented and will be considered for follow-on activities.

Keywords: CMOS image sensors, quantum efficiency, radiation damage effects, space instrumentation

1. INTRODUCTION

1.1 Background

It is important that image sensors for space missions have radiometric accuracy, in particular after they are exposed to the radiation environment during a mission's lifetime. To this end, the Open University's Centre for Electronic Imaging (CEI) has developed a cost-effective optical bench setup for quantum efficiency (QE) measurements across the 350 nm to 1100 nm range. In this article, the authors present initial room temperature QE results for the CIS115 – with two unirradiated devices and a device that had received a total ionising dose (TID) of 200 krad(Si) – and results are compared to manufacturer measurements.

The CIS115 is of interest, and has been fully space-qualified, due to its selection for use in the high-resolution JANUS camera on ESA's JUICE (Jupiter ICy moons Explorer) mission. It is a back-illuminated monolithic silicon CMOS image sensor with 3 MPixel (2000 rows $\times$ 1504 columns) of 7 μ m pitch. It is manufactured on a 0.18 μ m process and back-thinned to $\sim$ 10 μ m; this is expected to limit the QE at the longer wavelengths, but is a compromise with the expected modulation transfer function performance. The devices are coated by Teledyne e2v with their Multilayer-2 anti-reflection (AR) coating to optimise the device's QE across a wide optical wavelength range of interest to the JANUS application. Note that due to this being a greyscale sensor, it will be used in conjunction with a filter wheel to allow the selection of broad and narrow bands of wavelengths of interest to scientists, ranging between 340 nm and 1080 nm.^{1,2}

The JUICE spacecraft is planned to spend 3.5 years touring the Jovian system, during which it will be subject to significant levels of trapped radiation surrounding Jupiter. Up-to-date radiation environment and shielding models were used to predict an end-of-life (EOL) TID, with a factor of safety of 2, of 44 krad(Si).³ The radiation qualification of the sensor was carried out at the Open University's CEI, where CIS115 devices were characterised both before and after being subjected to ionising and non-ionising sources of radiation.⁴ The impact of radiation on opto-electronic properties has been studied extensively using these data, including effects on image lag⁵ and dark current³ that have been reported previously.

1.2 Quantum efficiency

QE is the percentage ratio of the number of photogenerated electrons, N_e , measured for a given number of photons, N_p – of specified energy or wavelength – incident on a detector. In this article, percentage QE is presented with respect to wavelength:

$$QE(\lambda) = \frac{N_e(\lambda)}{N_p(\lambda)} \times 100$$

The devices under test (DUTs) were back-illuminated CIS115s from the JANUS flight batch. Table 1 below details the devices used in this study, and their history. Teledyne e2v quotes the QE of back-thinned, AR-coated CIS115 devices to be 90% at 650 nm⁶, and a plot of their predicted QE values between 300 nm to 1100 nm is shown in Figure 1.

Table 1. Devices under test.

Device Serial No.	Description
15901-12-03	Unirradiated test device
15901-13-08	Used as control (i.e. unirradiated) for radiation campaigns
15901-10-03	Irradiated to TID of 200 krad(Si) at ESTEC's Co-60 facility (whilst unbiased, at room temperature)

Figure 1. Predicted QE performance of back-illuminated CIS115 (back-thinned and coated with Te2v's Multilayer-2 anti-reflective coating), reproduced from Soman *et al.*⁷

2. METHODOLOGY

2.1 Gain measurements

System gains for the three DUTs were measured using a Fe-55 source with its well-known characteristic X-ray photon energies. The values given in Table 2 were used in the calculations of the number of electrons generated by incident photons, as described later in the steps in section 2.4.

Table 2. System gains for devices under test.

Device Serial No.	Gain (DN electron ⁻¹)
15901-12-03	1.85
15901-13-08	1.84
15901-10-03	1.77

2.2 Measurement setup

The components were set up on an optical bench as shown in the flow diagram in Figure 2. The integrating sphere, lens tube containing the aperture, photodiode(s) and DUT were contained within a blacked out light path. For further stray light reduction, blackout fabric was used to cover the entire setup.

Figure 2. Measurement facility overview (*QTH: quartz tungsten halogen). Grey boxes indicate components from Bentham; red boxes are those from Thorlabs. Note this illustrates the path of photons from source to detection, and does not include links to PCs, control units, etc.

Figure 3. The 3-D printed parts encasing the portion of the PCB containing the sensor package.

A 3-D printed casing covered the PCB around the sensor package within its ZIF socket (Figure 3). The circular opening to this was centred on the package, not the sensor itself, so the setup was adjusted such that the diameter of the beam reaching the sensor resulted in no or negligible numbers of photons falling off the edge (see Figure 3a). This was checked across the wavelength range of interest.

A second 3-D printed case of the same design with photodiode #2 slotted into the opening was used to replicate the position of the DUT for reference measurements; the number of photons reaching the sensor region of interest (ROI) and the photodiode area (9.5 mm diameter) are required to match for this measurement. The shape of the photodiode active area was therefore overlaid on the image from the sensor – centred on the optical axis which is offset from the image centre, as shown in Figure 4b –and was used as the ROI for QE calculations.

Figure 4. Images from device 15901-12-03 (dark frame subtracted) at 500 nm (a) with linear colourmap and (b) with logarithmic colourmap and masking applied to only show signal within ROI.

Due to the wavelength-dependent light output or throughput of the components shown in Figure 2, as well as the variation in QE, the signal produced by the DUT was strongly wavelength-dependent. Thus, different integration times were selected for measurements at 350 nm to 1100 nm, in 50 nm steps, by finding the time required to reach a mean signal of 18,000 DN (just over a third full well capacity (FWC), i.e. $\sim 10,000$ electrons) after dark frame subtraction within the ROI. The exception was for 350 nm, which required a very long integration time (approximately 45 s) to reach this signal level; this was capped at 25 s to minimise contribution from dark current. Integration times for any wavelengths between those above were selected using linear interpolation.

2.3 Reference measurement

Photodiode #2 was set up in the optical path as described in section 2.2 for the reference measurement. Its power output was monitored (using a Thorlabs PM100USB power meter interface) until it had reached a stable value prior to starting measurements. Both photodiodes (#1 being within the integrating sphere) were zeroed at this point, while dark.

After the lamp was switched on it was allowed a warmup time to stabilise before the monochromator commenced its sweep through the wavelengths of interest. Power readings from both photodiodes were recorded simultaneously, averaging over 3000 readings (equating to ~ 1 s of integration time) at each wavelength. Both photodiodes had NIST-traceable calibration data stored within their electronics, enabling corrections for their responsivities at different wavelengths to be applied automatically. Note that although photodiode #2 was operated at a lower optical power (~ 1 nW) than the lower end of the 'optical power working range' given on its specification sheet (50 nW), no adverse effect on its performance was observed.

These data were converted to power densities ($\text{W}\cdot\text{cm}^{-2}$) using the photodiode areas; see Figure 5a for a comparison of the outputs from these, which were in turn used to calculate the throughput ratio of the focal plane vs monitoring location in the integrating sphere (photodiode #2 : photodiode #1) with respect to wavelength, shown in Figure 5b.

Figure 5. (a) Power densities measured by photodiodes during reference measurement, with estimated 2% error for PD #1 and specification sheet values for PD #2⁸; (b) corresponding throughput ratio with errors from propagation of PD #2 error only (PD #1 systematic errors cancel in N_p calculation – see section 2.4).

2.4 QE measurement

With the DUT in place, a dark warmup phase allowed the camera electronics response to become constant prior to collecting and storing dark frames (median of 10) at the integration times of interest (specified by the preliminary work carried out as described in section 2.2). A lit warmup phase followed, keeping the camera grabbing frames whilst the light source output stabilised.

Lastly, the monochromator swept through the wavelengths of interest, and the median of 10 images, grabbed at the appropriate integration times, was stored at each. The power meter reading from photodiode #1 was also recorded at each wavelength.

To calculate QE, we required the numbers of photogenerated electrons, N_e , for corresponding numbers of incident photons N_p at each wavelength, as seen in section 1.2.

To calculate N_e per cm^2 per second:

- subtract median dark frame from median lit frame;
- sum counts within ROI;
- convert value in DN to electrons using gain from corresponding Fe-55 calibration (Table 2);
- divide by number of pixels in full 9.5 mm $\varnothing$ circle (i.e. same area as PD #2);
- divide by pixel area;
- divide by total exposure time (the integration time input *plus* rolling shutter readout time of 182 ms).

To calculate N_p per cm^2 per second:

- convert photodiode #1 power measurements to power densities (in $\text{W}\cdot\text{cm}^{-2}$) by dividing by photodiode area;
- multiply by throughput ratio (calculated as described in section 2.3) to infer power density of photons at DUT;
- divide by the energy per photon for corresponding wavelengths (from $E = hc/\lambda$).

3. RESULTS

3.1 Beginning-of-life performance

Two unirradiated devices had their QE measured from 350 nm to 1100 nm in 10 nm steps to check the beginning-of-life (BOL) performance of the CIS115. The results are shown in Figure 6, with the results of QE measurements by Teledyne e2v on the five CIS115 flight models and spares (FM/FS) for comparison. The performances of the two DUT are in good agreement, despite device 15901-13-08 suffering from pieces of dust on its surface from its long history of use (see Figure 7).

A repeat measurement for device 15901-13-08 was taken at a later date, after multiple swaps of the DUT in the experimental setup in the meantime, and the QE was re-calculated using the same calibration (which itself was shown to be repeatable with measurements on 06/02/20 and 19/02/20). This confirmed repeatability of the measurement setup (Figure 8).

Figure 6. Open University optical QE measurements for two unirradiated devices shows performance matching those reported for the five FM/FS devices by Teledyne e2v.

Figure 7. (a) ROI of sample median image taken with 15901-13-08 ($\lambda = 500$ nm, $t = 0.832$ s), showing presence of dust; (b) cross section of row and column at package centre.

Figure 8. Repeat QE measurement for 15901-13-08 shows good agreement and repeatability across most of the wavelength range of interest, with measurements at the shorter wavelengths being most challenging.

3.2 QE following ionising dose

QE measurements were also made for a device irradiated to a TID of 200 krad(Si) (15901-10-03). This is over 4 times the expected EOL dose for the CIS115 on JANUS. The DUT had a faulty row which fell within the ROI used for QE calculations; however, correcting for these pixels' low signal levels by taking the average of the rows above and below had a negligible effect on the resulting QE curve (not shown).

The resulting QE data are plotted in Figure 9, with zoomed portions shown in Figure 10. Above 660 nm, the QE of the irradiated device was consistently below that of the unirradiated – although within error. It remained above the JANUS QE thresholds, however, except for the error bar at 800 nm. It is feasible that some of this difference can be accounted for by the slight differences in thickness between sensors, affecting the degree of attenuation of photons (and thus, QE) at these higher wavelengths.

At shorter wavelengths, i.e. <400 nm, there was an increase in QE observed post-irradiation. This may be attributed to the longer acquisition times required (up to 2 orders of magnitude greater than at the higher wavelengths) for these measurements, resulting in temperature increases from PCB operation and hence greater dark current. The current error analysis compensates for this to an extent, but does not take into account the higher dark current in devices subjected to TID, and this is expected to be a dominant source of error explaining the result in this short wavelength range (see section 0).

Figure 9. Comparison of unirradiated and irradiated devices (to TID of 200 krad(Si)) shows only a small difference measured between the devices across the majority of the wavelength range. The significant deviation in performance at <400 nm is likely due to excess dark current leading to overestimation of the QE in the irradiated device.

Figure 10. Comparison of unirradiated and irradiated devices (zoomed plots).

4. SOURCES OF SYSTEMATIC ERROR

4.1 Dark current

Further analysis highlighted that the temperature of the DUT, and hence dark current, increased slightly throughout the experiment thus contributing a systematic error. Dark frames used for subtractions, which were all taken prior to the lit frames, were therefore underestimating dark signal and overestimating signal collected and hence QE. This was most significant for the shortest wavelengths (<400 nm region) because their dark frames – with particularly long integration times – were collected first, when the DUT temperature was lowest.

The current error bars on QE plots incorporate a fixed value at each wavelength (± 10 DN to ± 500 DN, dependent on integration time) to describe an average variation in dark signal found by acquiring a QE dataset for a DUT (unirradiated) with dark frames taken both before and after the lit frames. However, in devices suffering from higher dark current caused by TID, the extent of this effect is likely to be exacerbated. In future work, a modified experimental setup allowing for sensor temperature monitoring and control will be implemented.

4.2 Photodiode uncertainty

Both photodiodes have an inherent measurement uncertainty; in the case of the reference photodiode (#2) these were provided in the data sheet⁸ – shown in Figure 5a – and used for error calculations. On the other hand, the uncertainties for the integrating sphere photodiode (#1) were not provided in the data sheet, so an estimate of 2% was used for the purposes of the aforementioned figure, but this contribution cancels out when multiplied by the throughput ratio in the QE calculation. The random error component for both photodiodes was minimised by averaging over 3000 readings.

4.3 Reference photodiode positioning

Ideally, the exact same optical path should be taken from the light source to both reference photodiode (#2) and the light-sensitive elements of the DUT. It was calculated that the former was approximately 2 mm further from light source than the latter, constrained by the setup and photodiode package not allowing for any shortening of this distance. The difference in incident flux was expected to be negligible, however, since the light from the pinhole aperture was quasi-parallel, as observed under tests using additional displacements of up to 4 mm.

The error in the reference photodiode (#2) position in the image plane was assumed to be negligible, as the only different component used to couple this to the pinhole aperture was a matching 3-D printed case, manufactured using the same equipment. Testing the effect of a conservative tolerance level of ± 0.6 mm by displacement of a spot image within the ROI found a <0.1% fall in mean signal.

In the calculation of N_e described in section 2.4, the region off the CIS115 edge that fell within the circular ROI was essentially counted as contributing zero electrons, potentially resulting in an underestimate of QE. Presuming a symmetrically illuminated spot, an average of 0.2% and maximum of 0.6% of signal was found to be lost off-edge, as expected due to majority of flux being at the centre of the ROI (see Figure 4**Error! Reference source not found.**(b)) – therefore this effect was deemed to be negligible.

4.4 Other error contributions

It was noted that the calibration of the reference photodiode (#2) may not have been carried out in the same configuration as when taking the measurements for QE calculations here (using a spot instead of flat-field illumination), so there may be some uncertainty introduced when the automatic scaling for responsivity at different wavelengths is carried out.

Image lag in the DUTs was also considered, as the mean signal output was $\sim 10,000$ e^- across wavelengths (except for the shortest wavelengths, with approximately half the signal), i.e. where lag starts to be observed.⁵ But due to the system being in equilibrium, with frames being continuously read out, no lag effects on measurements were expected.

5. SUMMARY AND FUTURE WORK

QE measurements were successfully performed on unirradiated and irradiated (to TID of 200 krad(Si)) back-illuminated CIS115 devices. The QE measurement setup allowed for repeatable measurements and the results from unirradiated devices matched those measured previously by Teledyne e2v.

No significant change in QE was observed as a result of TID, as values remained mostly within error of the unirradiated devices; pre- and post-irradiation QE measurements are required to rule out whether any change is due to differences between devices (e.g. thickness). Larger QE values measured at the shortest wavelengths after TID are likely affected by the increase in dark current by heating during longer integration times combined with the greater dark current expected after TID. These factors need to be accounted for in future work for more reliable results by adapting the setup to allow for temperature control of the DUT. Replacing the bulb of the light source in order to increase its power will also help by reducing the integration times required at extreme wavelengths.

Another dominant source of error is any systematic error in the photodiode #2 readings. Because QE is a comparative measurement rather than absolute, the results obtained are only as good as the error in this reference standard allows. Reduction of this error could be achieved through bespoke calibration of the photodiode against a radiometric standard, or through the replacement of this photodiode with an alternative off-the-shelf item that comes with an improved calibration. In addition, the option to remove the neutral density filter within the current photodiode will be investigated. to avoid additional scatter and boost the optical power to within specifications.

Further experiments taking the above into account are planned to better ascertain the behaviour of QE following TID.

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