The X-ray Quantum Efficiency Measurement of High Resistivity CCDs

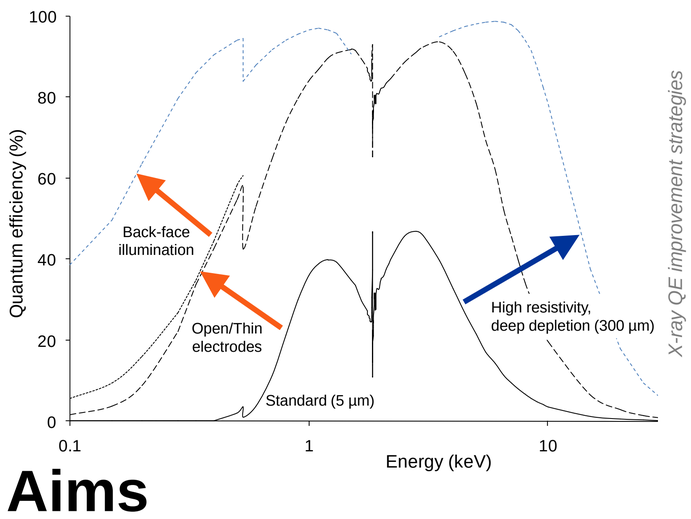
N. J. Murray[a/b], A. D. Holland[b], D. R. Smith[a], J. P. Gow[a], P. J. Pool[c], D. J. Burt[c]

[a]Imaging for Space and Terrestrial Applications, School of Engineering & Design, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK
[b]e2v centre for electronic imaging, Planetary and Space Science Research Institute, Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
[c]e2v technologies plc, Waterhouse Lane, Chelmsford, Essex, CM1 2QU, UK

Introduction

The quantum efficiency (QE) of a CCD is the fraction of incident photons that it samples.

The X-ray sensitivity of a CCD is evaluated by measuring the quantum efficiency (QE) at a range of incident photon energies. This is practically achieved by measuring the relative difference in flux measurements between the CCD and a calibrated reference detector when illuminated by the same X-ray source. (The calibration of the reference detector allows the absolute QE to be determined for the CCD) Ensuring an identical source illumination for both the CCD and reference detector is not possible to achieve practically as both CCD and reference detector cannot occupy the same position at the same time. The three popular methods for making QE measurements however, all require some spatial or temporal displacement between the CCD and reference detector measurements and are described in this paper. Typically such designs can require a large amount of laboratory space, can be complicated and expensive to build or impose mechanical constraints, limiting the type of reference detector employed.

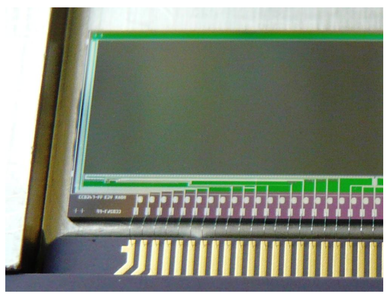


The X-ray QE of a front illuminated CCD is highly dependent on photon energy due to the transmission of photons through the different layers of surface structures that comprise the CCD. Low energy (soft) X-ray photons (<0.5 keV) have less than a 10% probability of reaching the active silicon with standard electrode structures. Open or thin electrode designs, such as the EPIC-MOS (CCD22 - open electrode) and CCD66 (thin electrode), have been manufactured to improve this detection efficiency to ~50%. This is achieved by reducing the thickness of the 'dead' layers of silicon dioxide, polysilicon and silicon nitride the photons must traverse to reach the active silicon. Back illumination can achieve far greater (3) soft X-ray QE, although the overall thickness of the device must reduced to fully deplete the device. Higher energy photons (>5 keV) suffer the converse problem. They have a lower probability of being absorbed within the depleted region of the silicon, due to their energy being high enough to pass through the depleted region into the bulk, or completely through the device. Electron-hole pairs that are created beyond the depleted region will become diffuse and may only be partially collected and sampled by the CCD pixel structure, yielding an undeterminable incident photon energy for the event that was generated, resulting in a reduced QE.

Aims

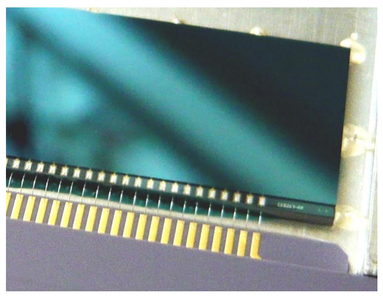
- This paper presents different methods used for taking X-ray QE measurements of CCDs and discusses their advantages and limitations.
- This paper presents the design of the X-ray QE facility that was developed.
- This paper presents X-ray QE measurements for the three different CCDs described below, in the energy range 1 keV to 20 keV to an error of 10%.

Devices Measured



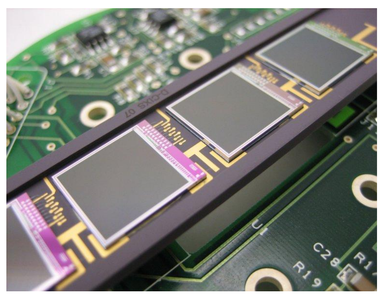
High Resistivity CCD247-FI

- 2nd Generation high-rho CCD
- Front-face illuminated
- 2108 512 13.5 µm imaging area
- n-Channel
- ~8 kΩ cm bulk silicon
- ~300 µm depletion



High Resistivity CCD217-BI

- 1st Generation high-rho CCD
- Back-face illuminated
- 2108 512 13.5 µm imaging area
- n-Channel
- ~8 kΩ cm bulk silicon
- ~100 µm depletion



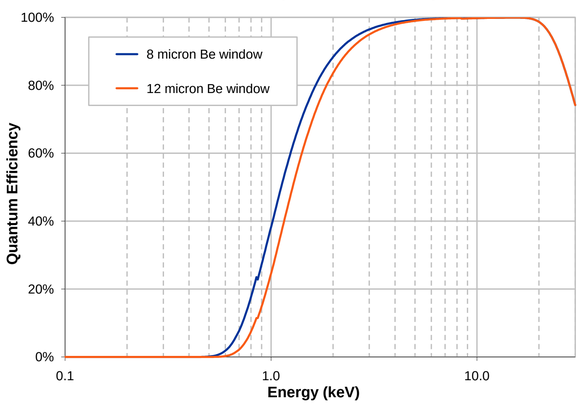
Swept-Charge Device CCD54-FI

- 1st Generation SCD
- Front-face illuminated
- 1.1 cm² collecting area
- n-Channel
- ~50 µm epitaxial silicon
- ~40 µm depletion

The QE Facility

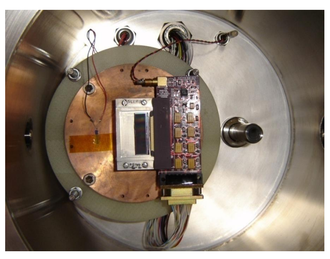
In order to measure the increased high energy X-ray QE sensitivity of deep depletion CCDs, such as the CCD247-FI, a reference detector with a high QE was required. The reference detector chosen was a lithium drifted silicon crystal (SiLi) with a collecting area of 30 mm² that was depleted to ~4.5 mm by applying a 500 V bias across the crystal, allowing X-ray photons in the energy range 5 keV to 20 keV to be sampled with a QE of approximately 100%. The QE of the SiLi detector is modelled taking into account X-ray photon absorption in the beryllium entrance window and nickel electrode contact. The beryllium entrance window is used to filter out the optical wavelengths and has a thickness of between 8 µm and 12 µm. The uncertainty of the Be window thickness has negligible impact on the QE measurements taken for photon energies greater than 5 keV. The nickel electrode covering the entire crystal surface is used to apply the high bias potential to drive the depletion and has a thickness of ~8 nm, although the exact thickness is unknown. Even though the Ni-K absorption edge is within the energy range of interest, the error imposed by the uncertainty of the thickness is negligible due to its relatively small size. The modelled QE for the SiLi detector with both 8 µm and 12 µm beryllium entrance windows. The true QE of the SiLi detector therefore lies somewhere between these two curves.

Modelled SiLi Quantum Efficiency

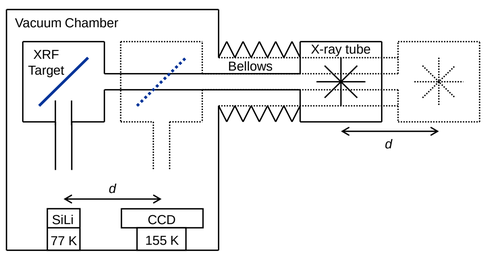


SiLi Detector

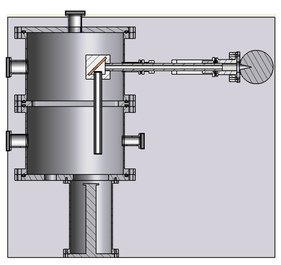
The SiLi crystal must be cooled during operation to suppress dark current; this is achieved by thermal conduction with liquid nitrogen that is stored in the insulated white tank. The liquid nitrogen tank prohibits the SiLi detector from being translatable and was therefore permanently fixed onto a custom made vacuum flange with the CCD assembly mounted next to it. The internal face of this flange that is sealed within the vacuum chamber during operation and is shown below left.



CCD and SiLi Entrance Window



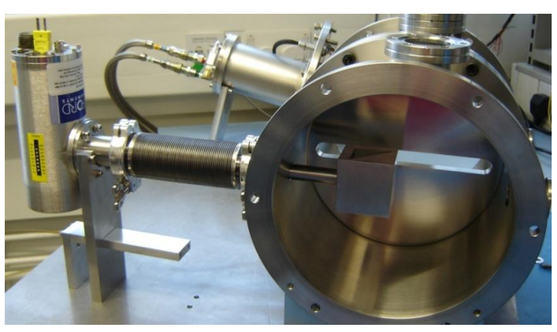
Translatable X-ray Source Plan



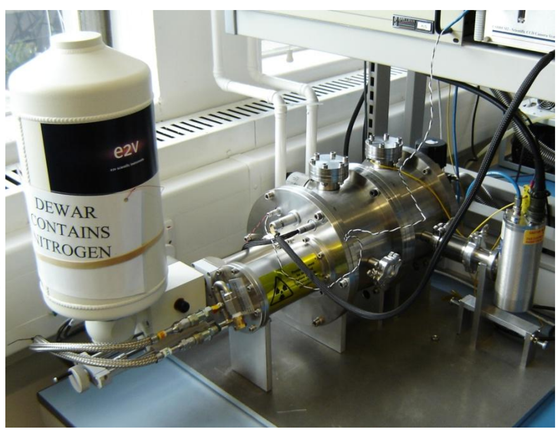
X-ray QE Facility Section View

Due to the mechanical constraints of cooling both the SiLi detector and the CCD, it was not possible to translate them between an X-ray beam during the experiment. It was therefore decided to move the X-ray beam between fixed detectors to ensure identical spatial displacement with minimal temporal disruption between flux measurements, a bellows is used to maintain the vacuum. The fluorescence target material of the movable X-ray source can be substituted between experiments to acquire data for QE measurements at different photon energies.

The development of the QE test facility is shown in the surrounding figures and will be described in detail in the paper, followed by a presentation of QE measurements taken for a CCD247-FI, CCD217-BI and swept-charge device CCD54-FI.



XRF Target Box



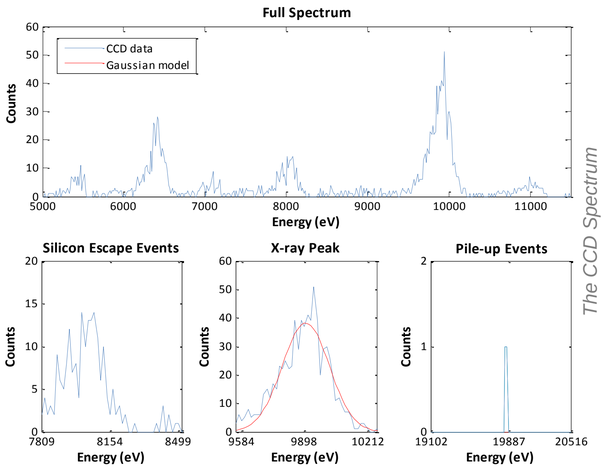
The CCD X-ray QE Facility

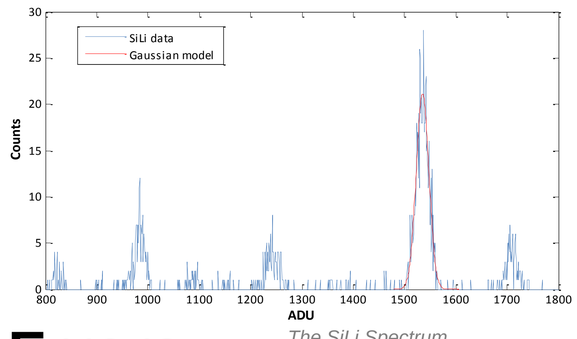
Method

Characteristic X-rays were collimated into a 50 mm² spot that could be translated across the horizontal plane of the CCD imaging surface and the SiLi entrance window. Alignment of the beam to the SiLi was checked by exposing a piece of Gaphchromic film placed over the beryllium entrance window for ½ hour. Adjustments were made to the external depth stop screws to ensure the collimated beam was directly aligned to the SiLi entrance window. Precise alignment of the CCD was not necessary as the imaging area was large in comparison to the collimated beam and the beam area could be 'windowed' during processing.

The X-ray source was initially aligned to the CCD and clamped into place. The clamp was necessary to prevent the atmospheric pressure from constricting the bellows and pulling the X-ray source out of alignment with the CCD. Images were acquired in continuous, full-frame mode (TDI), with zero additional integration between rows/frames. This allowed the collimated 50 mm² X-ray exposure to be 'effectively' distributed across the vertical axis of the imaging area, reducing the probability of pile-up events. The integration period of the CCD image was calculated by multiplying the row readout time, including the parallel transfer time for the next row into the readout register, by the number of rows in the image. After acquisition of the CCD image, the X-ray source was immediately repositioned to align with the SiLi detector entrance window, taking approximately 5 seconds. A corresponding SiLi spectrum was then acquired for the X-ray beam for the same integration period as the CCD image. A number of CCD images and corresponding SiLi spectrums were obtained to increase the photon statistics for each of the X-ray energies measured.

The CCD image was read into a two-dimensional Matlab array. Pixel values were put into a histogram and plotted as a spectrum. The energy scale was then obtained by calibration to the background distribution and a known X-ray peak, typically the Fe-Kα (6,403 eV) peak prevalent in all acquisitions due to fluorescence from the collimator. A background threshold was set to 6σ to facilitate the event recognition algorithms. Each event pattern was then processed to count each event type and then summed into the equivalent isolated (1 1) event. A second histogram of the CCD image was then produced for the isolated events only; this was used to select the 3σ boundaries of the photon energy of interest. The cumulative count between these two boundaries was then found to determine the detected X-ray flux at that energy. The silicon escape and pile-up peak energies were also calculated to 3σ and added to this count where possible. The total photon count in the CCD image at the selected energy was then normalised into counts/sec/cm².





The SiLi Spectrum

The spectral data acquired from the SiLi was then imported into another Matlab array. Similar operations were performed to establish the total photon count at the same energy selected for the CCD image. However the energy calibration was slightly different as there is no background peak in the spectrum due to the discrimination of the SiLi output processing electronics. Two known X-ray peaks were used to make the energy calibration. Total counts in the SiLi spectrum for the energy selected were again normalised into counts/second/cm².

Finally the calculated flux at the CCD was then divided by that obtained from the corresponding SiLi spectrum to calculate the relative QE. This was then multiplied by the modelled SiLi QE at that energy to determine an absolute CCD QE for the selected energy.

Errors

Photon statistics – Approximately 600 X-ray photons in the peak were required for the Gaussian fitting algorithm. For some of the elements the fluorescence yield was too low to acquire enough data.

Output flux – The output from the X-ray tube was measured to have a variation in flux of 4.6% in steady state operation, the tube was given ~2 hours to reach a steady state before measurements were made. A number of repeat measurements were made between detectors to also minimise the effect.

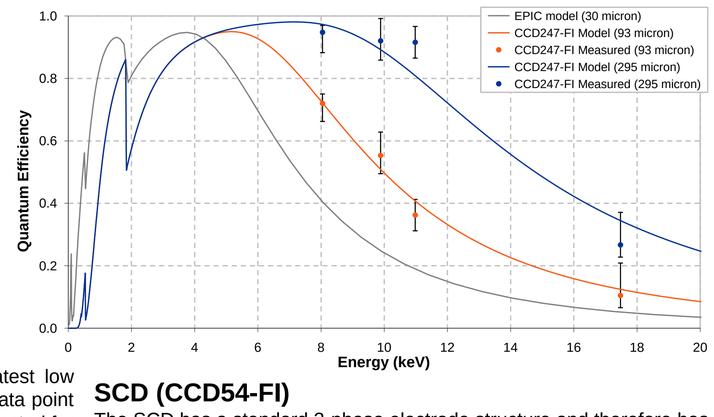
Filter transmission - The uncertainty of the low energy QE for SiLi detector due to the thickness of the beryllium window would have an effect on QE measurements made between 0 keV to 5 keV. This is estimated based on the two extremes of the window thickness, for a given energy.

Counting - For some energies, silicon escape events could not be included in the total count, where such energies conflicted with the characteristic lines of other elements in the X-ray source. This could potentially contribute a positive error of 5%, due to the K-shell fluorescence yield of a silicon atom, however as the error will be the same for the SiLi, the effect is negligible.

Results

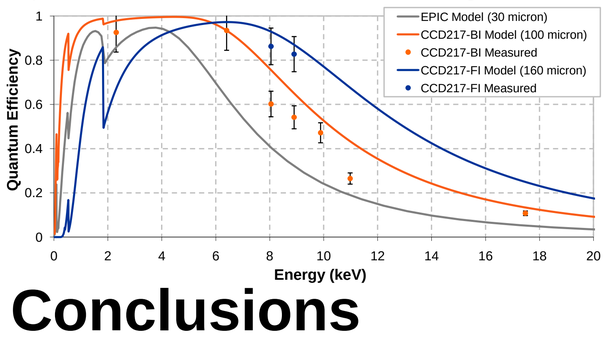
CCD247-FI

The measured QE data points for the CCD247-FI agree with the models for depletion depths of 93 µm and 295 µm to within the estimated error of 9.6%. The extra thickness of depletion that is achievable with high resistivity devices, such as the CCD247, allows adequate photon statistics to measure the QE at Mo-Kα (17,478 eV). Only high energy (>8 keV) measurements have been taken at this time as the front-face illuminated device has not been optimised for low energy performance.



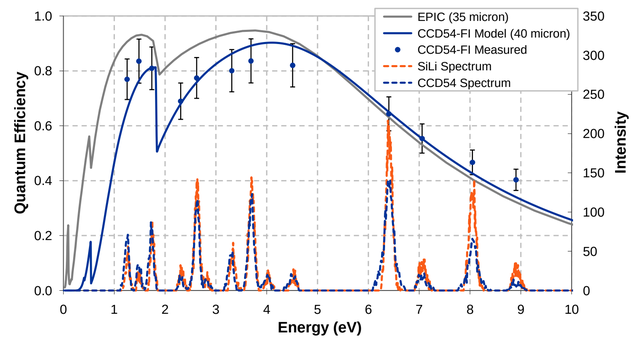
CCD217-BI & CCD217-FI

The back-face illuminated CCD217 should have the greatest low energy QE of all the devices and this is supported by the data point at 2,308 eV. Nearly all of the data points are lower than expected for both the back and front-face illuminated device. This was attributed to the low responsivity of these 1st generation high-rho devices, that impacts on the event reconstruction, under-calculating the flux.



SCD (CCD54-FI)

The SCD has a standard 3-phase electrode structure and therefore has reduced QE in comparison to the EPIC-MOS device. Having a slightly thicker depletion region, the QE measurements for the SCD support a theoretical depletion depth of ~40 µm. Results were obtained at -40˚C.



Conclusions

Quantum efficiency measurements of X-ray photons were taken about the centre of the CCD imaging areas using the QE facility developed to within a maximum error of 9.6% (<10% was desired).

Data points were plotted alongside the modelled QE curve for the CCD247 that was assumed to have been fabricated on 8 kΩ cm bulk p-type silicon. Due to the similarity between the data points and the model, a device **depletion** of 93 µm and **295 µm** is believed for the **CCD247-FI**, when substrate potentials of 0 V and -100 V are applied respectively.

The CCD247-FI shows an improvement in QE for the higher energies (>4 keV), with an increase of ~70% at 10 keV compared to that of the EPIC-MOS devices onboard XMM-Newton, demonstrating the suitability of high-resistivity bulk silicon technology in future CCD based X-ray missions.

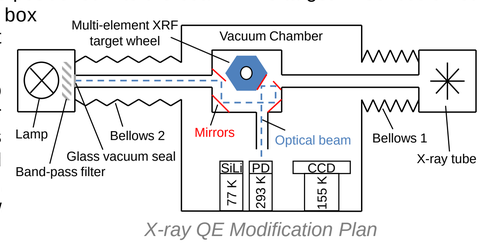
Future Work

The facility could be adapted to measure the QE of future devices in the MOS CCD development programme for XEUS/IXO. This would include extending the energy range of calibration lines,

particularly to lower energies down to carbon/oxygen (277/525 eV) using low energy electron gun and monochromator as the source of X-ray photons. This will enable the QE of thin and open electrode technologies to be evaluated.

The experimental downtime (~3.5 hours), experienced whilst changing the XRF target, could be significantly reduced by replacing the target box with one that includes a rotational target wheel, allowing multiple XRF targets to be positioned into the beam. The target wheel could not be rotated by a traditional vacuum feed-through due to the translation of the target box assembly during operation. Therefore, a stepper motor unit would be required to sit inside the target box and rotate the wheel between samples when required.

By including a rotational target wheel, the QE facility could be further enhanced to allow for optical QE measurements. This could be achieved by including a mirror surface on the target wheel that would reflect light onto the detectors from a band-pass light filtered source entering the vacuum chamber from the opposite port to that used for the X-ray beam. A second reference detector, such as calibrated photodiode (PD), would be required to take the relative flux measurements, as the beryllium window blocks the optical wavelengths.



X-ray QE Modification Plan

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Imaging for Space and Terrestrial Applications Group
School of Engineering & Design, Brunel University, UB8 3PH, UK
neil.murray@brunel.ac.uk