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ABSTRACT

The focal plane array of the Euclid VIS instrument comprises 36 large area, back-illuminated, red-enhanced CCD detectors (designated CCD 273). These CCDs were specified by the Euclid VIS instrument team in close collaboration with ESA and e2v technologies. Prototypes were fabricated and tested through an ESA pre-development activity and the contract to qualify and manufacture flight CCDs is now underway. This paper describes the CCD requirements, the design (and design drivers) for the CCD and package, the current status of the CCD production programme and a summary of key performance measurements.

Keywords: CCD, Euclid, optical astronomy, cosmology

1. INTRODUCTION

Due for launch in 2020, ESA's Euclid mission[1] will study the geometry of the Universe by measuring the distribution of dark matter and dark energy with unprecedented accuracy. The satellite will be placed 1.5 million km from Earth in a halo orbit around L2 (the Sun-Earth second Lagrangian point). It will use a 1.2m Korsch telescope[2] to measure the shape and redshift of galaxies to z=2 (about 10 billion years of cosmological evolution). Euclid will survey most of the extragalactic sky, combining two observational techniques: measurement of Weak Gravitational Lensing (WL) and measurement of galaxy clustering and hence Baryonic Acoustic Oscillations (BAO).

The Weak Lensing measurement comprises a systematic survey of galaxy distortion caused by gravitational light deflection and modified by the expansion of the Universe. In order to conduct these measurements, Euclid will carry a large format visible imager called the VIS instrument[3,4]. VIS will image in a single *R+I+Z* band from 550-900 nm over a field of view of ~0.5 deg^2, reaching a magnitude of V=24.5 (10sigma). Analysis of VIS data will measure the effect of Weak Lensing on nearly 1.5 billion galaxies over 15000 deg^2, from which cosmological models may be constrained. VIS will also provide a legacy dataset of unprecedented spatial resolution over most of the extra-Galactic sky.

The focal plane of the Euclid VIS instrument requires an array of optical detectors. CCDs were selected early in the study phase, thanks to their extensive heritage and suitability for astronomy applications. The requirement specifications for the CCD-273 were developed by the Euclid VIS instrument team, ESA and e2v technologies. This CCD report is given from an ESA perspective. A previous Euclid CCD overview was presented to SPIE in 2012 by e2v technologies[5].

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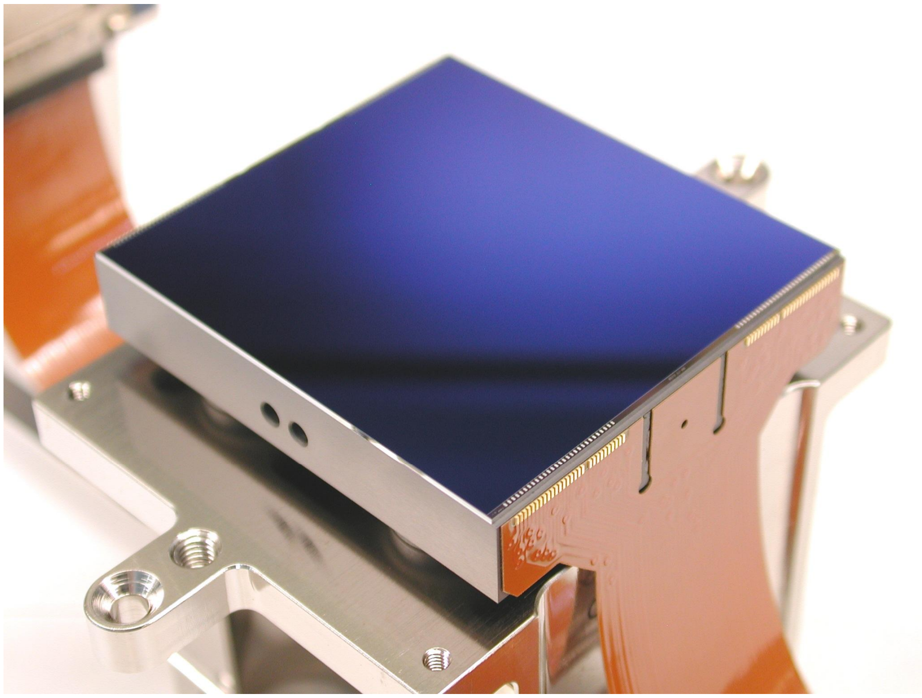

Figure 1-1 The Euclid VIS CCD. Note the two flex-circuits are bonded to the sides of the silicon carbide (SiC) package allowing the CCDs to be butted on four sides in the VIS focal plane.

2. KEY CCD REQUIREMENTS

2.1 Geometrical Requirements and Design

The Euclid VIS focal plane will contain 36 CCD detectors arranged in 6 rows with 6 CCDs in each row. Each CCD is designed to be "four sides butt-able" and in order to avoid large gaps between active areas, they are full-frame devices (no storage region for frame transfer). They are sawn in order to minimize the dead area around each device and packaged with readout flex-circuits mounted perpendicular to the optical surface, a configuration which necessitates wire-bonding onto the ends of the flex-circuit tracks (see Figure 1-1). This method has already been applied successfully for Gaia[11] and several subsequent e2v CCDs.

The pixel size is 12.0x12.0 µm (to sample the Euclid PSF correctly). The CCD has 4096 (H) x 4132 (V) light sensitive pixels allowing two square devices to be fabricated on each 6 inch wafer. This was considered the optimum size taking into account yield, number of readout nodes, uniformity, readout time, noise and CTI. Figure 2-1 indicates the dimensions of the VIS CCD in the image plane.

The CCD has a split image section and two split serial registers, dividing the active area into four equal quadrants. In the baseline operating mode, the parallel and serial clocks will transfer the signal to 4 readout nodes in the corners of the CCD. This is a simple means of reducing the readout time by a factor of four with respect to using a single output node. It has a secondary advantage of reducing the distance over which electrons must be transferred, and hence reducing the effects of Charge Transfer Inefficiency (CTI). It would be possible to implement (many) more readout nodes in order to reduce the readout time and distance much more significantly. However, this had to be weighed against the advantages of low noise, uniformity and simplified calibration which are the inherent benefits of a CCD with few output amplifiers. The CCD has 51 pre-scan pixels at each output node allowing the output amplifiers to be positioned so that the width of the sawn CCD is minimized.

Euclid VIS images will never be binned so neither parallel summing registers nor serial summing wells have been incorporated.

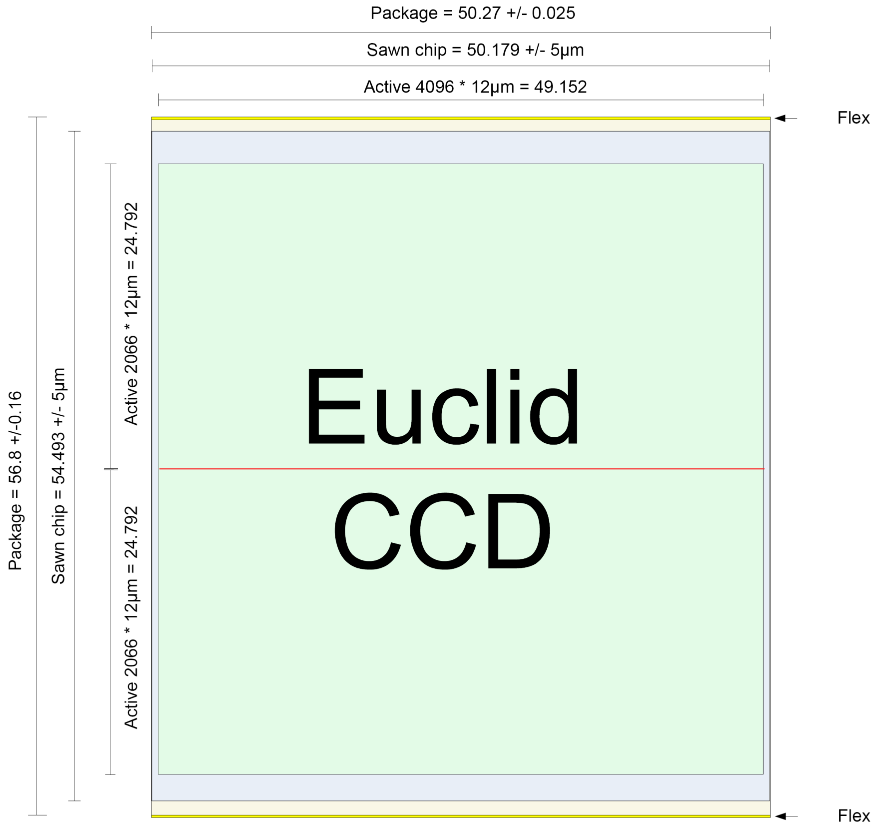

Figure 2-1 Schematic indicating the dimensions of the imaging area, the sawn CCD and the overall package including the thickness of the bonded flex circuits

The CCD packaging and mounting concept is broadly based on that employed in the Gaia programme. However, the precise CCD height and flatness requirements are driven by the telescope depth of focus. This is tighter for Euclid than for Gaia leading to challenging requirements on the CCD: The optical surface of the CCD shall be fully included between two parallel planes separated by a maximum distance of 20µm (+/- 10µm relative to the CCD mean plane); The nominal height (H) of the mean plane relative to the mounting plane shall be 13.97mm +/- 0.035mm. In order to prevent cracking of the silicon carbide (SiC) CCD package, it is also necessary to place a requirement on the mounting plane flatness across the three feet (or lands) of the CCD package. Namely: The peak-to-peak flatness shall be better than 5 µm across the three CCD lands. In order to achieve all of these requirements simultaneously, it has been necessary to adopt a mounting scheme which does not require shimming in order to achieve alignment but which relies upon careful control of the inherent SiC package flatness and the CCD to package glue line.

The total mass of the CCD assembly (i.e. Si, package, studs, stud fasteners, flex circuits and connectors) is less than 94g.

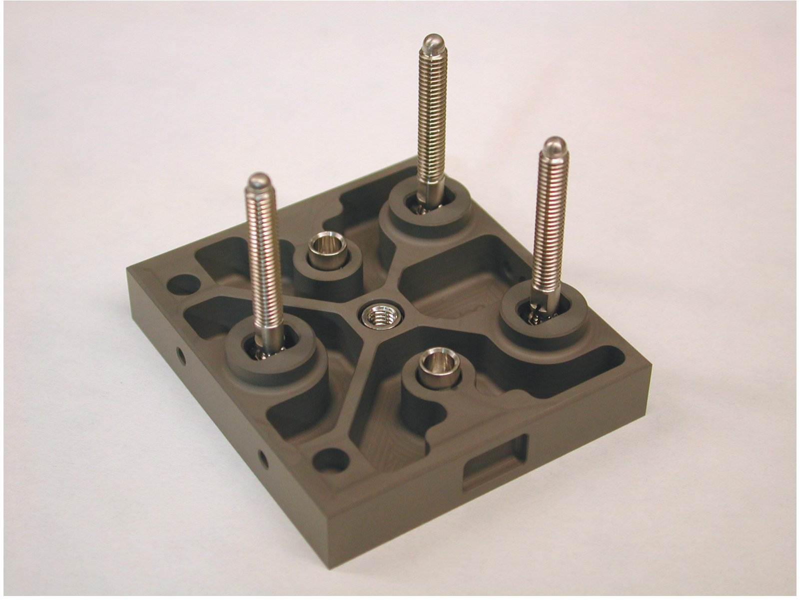

Figure 2-2 A view of the underside of the silicon carbide (SiC) package. Note that unlike Gaia, there are no shims since the flatness of the machined SiC surfaces is good enough to meet alignment requirements without shimming.

2.2 Electro-Optical Requirements and Design

Table 2-1 VIS CCD wavelength dependent requirements on Quantum Efficiency (QE), Modulation Transfer Function (MTF) and Photo-Response Non-Uniformity (PRNU)

Wavelength (nm)	Minimum Q.E Requirement	Minimum MTF (at Nyquist)	Maximum PRNU (1σ)
550	0.83	0.30	2%
650	0.83		
750	0.83	0.35	2%
850	0.70		
900	0.49	0.40	2%

CCD QE requirements flow down from the required overall VIS instrument response which is enhanced for observing very faint, red-shifted galaxies. In order to obtain high QE at longer wavelengths, high resistivity (1500Ωcm/50µm) epitaxial silicon is used (also referred to as 'deep depletion' material). The CCD is back-thinned to the nominal depletion depth of 40µm (to optimize MTF) and a red enhanced hafnium oxide anti-reflection coating is applied. The requirements shown in Table 2-1 are the final agreed values following negotiation with e2v technologies, taking into account the expected yield of suitable CCDs as well as performance. In addition to the in-band values (shown), out-of-band QE must also be considered. This should be low since the PSF is wavelength dependent and out-of-band photons will degrade ellipticity measurements. In practice, the CCD QE drops quickly below 350nm and above 1000nm making it difficult to measure. e2v has not been given out-of-band requirements for the maximum allowed QE, but this will be characterized by the Euclid consortium as part of performance assessment and calibration.

The PSF shape and FWHM are critical for Euclid. One contribution to the overall FWHM is charge spreading in the CCD and ideally, the Euclid Consortium would like to place FWHM requirements on the CCD. However, e2v does not have a standard test to measure the FWHM due to charge spreading in the CCD. Instead, the Modulation Transfer Function (MTF) is measured using a well-established “knife edge” method. The MTF requirements in Table 2-1 have been calculated by the Euclid Consortium according to the allowed contribution of the CCD to the overall PSF FWHM. Charge spreading and hence FWHM and MTF, are signal level dependent. The MTF values will be measured (for acceptance) at a nominal level of 0.3 to 0.5 times Full Well Capacity (FWC). They will also be measured (for information) at a signal level of 0.8 times FWC.

The VIS instrument requires sufficient dynamic range in order to observe very faint galaxies and relatively bright calibration stars in the same image. Given the noise and integration time, this defines an image area Full Well Capacity (FWC) requirement of 175,000 e-. The Full Well Capacity is said to be reached when either: The linearity requirement is no longer met or; The Beginning of Life Charge Transfer Efficiency (CTE) requirement is no longer met. In order to achieve a high FWC with a relatively small 12x12μm pixel size, there is no Supplementary Buried Channel and no Anti-Blooming Drain. Furthermore, the image area employs 4-phase pixels (4μm, 2μm, 4μm, 2μm) allowing half of the pixel area to remain depleted during transfers as opposed to one third in a 3-phase device.

Although there is no binning requirement for Euclid, it is normal practice to ensure that the serial register pixels have a higher FWC than the image section pixels in order to avoid design traps. This is achieved by widening the register channel width, resulting in rectangular 12x20μm serial register pixels. The serial register employs 3-phase clocks so that electrons may be moved towards the readout node at either end of the register or the register may be split and readout through both nodes simultaneously (the default operating mode). The estimated register FWC under a single ‘ON’ electrode is approximately 300ke- with 7 volt clocks. Also unlike Gaia, the Euclid serial registers include a gate controlled parallel dump capability to a separately biased drain. This allows the serial registers to be emptied quickly without having to clock the electrons through the output node. This drain also provides isolation from spurious peripheral charge generated at the top and bottom of the device.

End of Life cosmetic defect requirements (after proton and gamma irradiation) correspond to a maximum 1% loss of effective area allocated to the CCD at system level. This allows for a total of 150,000 lost pixels or 40 lost columns per CCD. The cosmetic quality of the CCDs should be much better than this, with a Beginning of Life acceptance requirement of no more than 1500 dead pixels or 8 dead columns per CCD.

CTI will cause signal loss and deferred charge (smearing). These effects will distort the galaxy and calibration star images. The observed distortion will be highly dynamic and will vary as a function of radiation damage, distance from the output node, signal level, recent charge history (trap occupancy) etc. Calibrating these distortions will be complicated and it is important to ensure that the effects are minimized. This means that good CTE is required from the CCDs at Beginning of Life. In addition, it is essential to know that the required performance can still be achieved at End of Life, following reduction in CTE due to radiation damage. However, there are only limited steps that can be taken to improve CTE. In the absence of design errors (design traps) and assuming that the CCD is clocked correctly (with sufficient clock overlaps for instance), the inherent CTE at Beginning of Life is determined by the readout speed and the temperature. For this reason, the CTE acceptance requirements simply correspond to values typical of high grade devices produced by e2v. Similarly, the End of Life, post irradiation CTE (Lot Acceptance Testing) requirements correspond to typical values following a total 10MeV equivalent non-ionizing radiation dose of $5x10^9$ protons/cm^2 (see Section 2.4).

Table 2-2 gives the CTE requirement values negotiated and agreed with e2v technologies for acceptance of CCD Flight Models. These correspond to the CTE measured using a standard test with X-rays in darkness. It should be noted that the CTE values obtained during e2v acceptance testing (using X-rays) do not directly indicate the charge loss and distortion that will be observed in real Euclid optical images. This is because real Euclid images will consist of faint galaxies, stars and cosmic rays with a significant optical background. This is very different from X-ray point sources in darkness. In particular, the optical background across the CCD will keep a large fraction of slow traps filled and hence inactive.

Characterization, correction and calibration of CTE effects in Euclid data is a major activity for the Euclid Scientific Consortium. The science objectives require the ellipticity of galaxies to be known to an accuracy of 1.1e-4[12,13]. Different trap species contribute to this requirement in different ways: most charge loss is due to un-suppressed slow traps whilst most smearing is caused by species with characteristic release times similar to the clock speed[14]. CCD testing is now being conducted with more realistic, “Euclid-like” images[8,9] to support detailed modeling[7,9,15,16,17] and confirm that the science requirements can be met using CCDs with the nominal (X-ray) CTE values given in Table 2-2 (following post-processing to correct and remove CTE trailing[18,19,20]).

Table 2-2 Charge Transfer Efficiency (CTE) requirements on the VIS CCD at Beginning of Life (BoL) and following irradiation with a 10MeV equivalent non-ionizing radiation dose of 5×10^9 protons/cm^2.

Direction	**Minimum CTE at BoL**	**Minimum CTE post irradiation**	**Unit**	**Comments**
Parallel	99.9995	99.9945	%	Measured using Fe^{55}
Serial	99.9995	99.996	%	Measured using Fe^{55}

Because Euclid is a survey mission, the CCDs will be exposed to bright stars on a regular basis. This will result in signals thousands of times greater than the Full Well Capacity. Excess charges should spill along the columns such that bright sources do not cause the loss of unnecessarily large fractions of the image area. The loss of area will be assessed by e2v in order to demonstrate the following requirement: When a single pixel is exposed to an integrated signal of 7.25×10^8 electrons (3600 x Full Well Capacity), the area of the CCD lost (that is, not available for imaging at full performance) shall be 45 columns wide or less (centred on the column containing the saturated pixel).

In addition to considering the area lost to bright sources, without active steps in operation of the CCD, saturated pixels in one exposure are expected to cause a “memory effect”. i.e. latent charge is expected to be released in subsequent exposures, damaging the performance unacceptably. This results in a temporal bright star requirement on the CCD: A saturated signal of 3600 x FWC (per pixel) over an area of at least 5x5 pixels in the image area shall not leave a latent signal in any pixel greater than 10e- above the background in the following 500 second exposure. In order to reduce latency effects, it is proposed to invert the image section clocks for (not more than) 1 second in between exposures. This condition may be employed in order to meet the requirement. Apart from this “reset” operation, the CCD will be operated non-inverted (non-AIMO or non-MPP) in order to maximize Full Well Capacity. Dark current is negligible at the Euclid operating temperature. A nominal requirement of less than 2 e-/pix/hr has been agreed in order to identify defective CCDs. This value is easily achieved in Non-Inverted Mode Operation (NIMO).

2.3 Electrical Requirements and Design

Table 2-3 Key electrical requirements on the Euclid VIS CCD.

Electrical Requirement	**Value**	**Note**
Maximum Read-out Noise	3.6 e- rms	70 kpix/s
Responsivity	6.5 to 8.5 μV/e-	
Maximum flat band voltage shift	0.1 V/krad	following exposure to ionizing radiation
Maximum static power dissipation	52 mW	with all 4 ports powered
Maximum dynamic power dissipation	60 mW	with all 4 ports simultaneously at 70 kpix/s
Maximum integral non-linearity	4 %	measured between 250 electrons (TBC) and FWC

The key electrical requirements for the Euclid VIS CCD are summarized in Table 2-3. These acceptance values are typical of e2v scientific devices since the output circuit is an existing design with heritage from Gaia and other astronomical applications. Hence, the operation and performance of the VIS instrument have been derived using these established characteristics as a starting point.

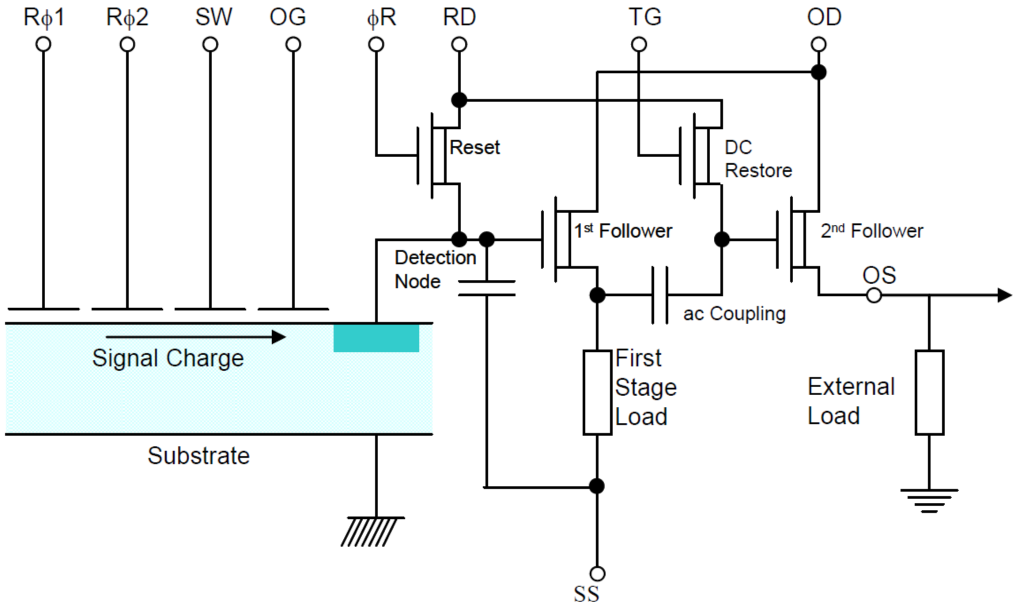

Figure 2-3 Output amplifier or readout node of the Euclid VIS CCD. Note the Summing Well replaces the final Rϕ3 electrode and hence in normal operation is also tied to the clock phase timing of Rϕ3

The output amplifier employed for Euclid is tailored for un-binned operation with a high-responsivity, low-noise amplifier matched to the dynamic range. It is based on a standard e2v circuit for low noise scientific applications (See Figure 2-3). Minor modifications have been applied to widen the reset transistor and the channel across the output gate. These changes are applied for deep depletion devices where narrow channels are known to cause higher threshold voltages compared with devices fabricated on standard resistivity silicon. The wider channel causes a small increase in capacitance at the detection node and consequently influences the Charge to Voltage conversion Factor (CVF).

All electrical connections between the CCD and the Read Out Electronics (ROEs) are made via flexi-cables terminated with 37 pin micro-D connectors fabricated using low-outgassing space compatible materials.

2.4 Environmental Requirements and Design

The VIS CCD procurement was started well in advance of selecting the Euclid Payload and Prime Contractors and even before final selection of the Soyuz launch vehicle. Therefore, VIS environmental requirements within the Payload Module had not been formally agreed at that time. The CCD mechanical requirements are based upon MIL standards, modified according to experience of similar instruments. The resulting CCD qualification requirement for vibration is ±12mm displacements from 5 to 32Hz and 50g accelerations from 32 to 2000Hz all in x, y and z. The requirement on shock is 500g with a 1.0ms pulse.

Thermal requirements have been negotiated according to the expected thermal environment during the lifetime of the instrument, but also according to the existing limitations of the CCD and package technology. For example, the survival temperature of the CCDs had to be raised from 120K to 140K within the overall payload thermal design. This is due to a limitation of the adhesive attaching the flex circuit to the SiC package. The requirement on non-operating temperature range (from manufacture to End of Life) is 140K to 358K. The requirement on operating temperature range (from manufacture to End of Life) is 150K to 308K.

Radiation environment requirements were established during the study phase. Values were adopted which should be achievable with realistic shielding and which should allow Euclid to meet the final scientific performance at end of mission i.e. the CCD shall be qualified for a total Cobalt 60 ionizing radiation dose of 10kRad(Si) and the CCD shall be qualified for a total 10MeV equivalent non-ionizing radiation dose of 5×10^9 protons/cm^2. These values have then been given to the Payload Prime Contractor (with margins) as requirements on CCD radiation shielding.

In order to reduce the effect of ionizing radiation damage, the VIS CCD employs 'thin oxide' technology. The magnitude of the threshold voltage shift following ionizing radiation damage is related to the dielectric thickness. For the standard e2v dielectric thickness, the flat-band-voltage shift is approximately 200mV/kRad, whilst for the thin dielectric process, the shift is approximately 45mV/kRad. Note that the thin dielectric process also offers low voltage operation for lower power dissipation.

In recent years, many scientific CCDs for space applications have incorporated a charge injection structure which allows a bright line (or multiple lines) of charge to be introduced (normally at the top of the image section). This charge is then read through the entire CCD and has the effect of filling slow traps and rendering them inactive for a period of time (until they release their electrons). Since the VIS instrument observes using long integration times of 565 seconds, the optical background in each image will be in the range of 60 to 120 electrons/pixel. This optical background has the effect of keeping slow traps filled so that a charge injection structure will give little additional benefit for trap suppression. However, charge injection lines can also be valuable for characterizing radiation damage by measuring the electrons lost from the front of a series of injected lines (first pixel response), and by characterizing the charge released behind a series of injected lines (deferred charge trails). For this reason, a charge injection structure has been included in the VIS CCD. Because the CCD has readout registers at both ends, the injection structure is placed across the middle of the image section (See red line in Figure 2-1). It is referred to as a split frame charge injection structure.

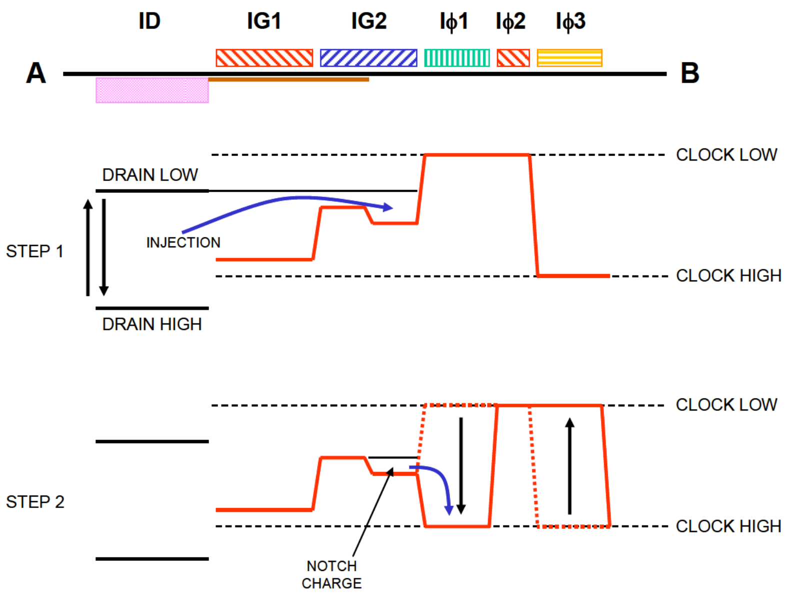

Figure 2-4 The charge injection structure may be operated in several ways. This schematic indicates a method for injecting a relatively small amount of charge defined by the capacity of an implanted “notch”.

Early injection structures could only inject very high signals and offered no control over the signal level. For Euclid, a “notched” charge injection structure has been incorporated offering the possibility to inject relatively low signal levels (between 2000 and 10000 electrons) with a spatial uniformity better than 50% peak to peak across the device. The charge injection structure comprises 2 gates and a drain. The whole structure occupies a strip 48µm wide (equivalent to 4 pixels wide) across the entire width of the CCD.

Fixed Charge Injection starts with the voltages on Iφ1 and Iφ2 at image clock low levels; The voltage on IG1 at image clock high; The drain voltage at its high value; and IG2 at a mid-clock voltage level. ‘STEP1’ in Figure 2-4 depicts that the voltage on the injection drain is then pulsed from its high value to a low value and back again.

While the drain voltage is low, electrons can move freely under IG1 and IG2. When the drain voltage returns to its high state, the electrons flow back out leaving only a fixed quantity of charge held by the “notch” which is defined by an implant under IG2. ‘STEP 2’ in Figure 2-4 shows this fixed quantity of charge advancing into the image section as the image clocks cycle. Note that for this mode of “notched” charge injection, gates IG1 and IG2 are left static. These gates may be used for more conventional charge injection of high but relatively uncontrolled signal levels.

CCDs for space astronomy (e.g. Gaia and XMM) have generally included a Supplementary Buried Channel which causes electrons to pass through a smaller cross-section of silicon and encounter fewer traps. However, with a pixel size of just 12µm there is little (if any) benefit to including this channel in Euclid CCDs. Furthermore, an SBC would reduce the FWC and could potentially introduce design traps.

Euclid will operate at L2 and the CCD technology is broadly the same as the Gaia CCDs (especially the Gaia red-enhanced photometry and spectroscopy CCDs). The operating mode is different, but lessons may be learned from analysis of Gaia CCDs operating in the L2 radiation environment[6]. However, it is important to note that Gaia was launched after solar maximum, when solar activity is decreasing. Euclid is currently scheduled to be launched before solar maximum when the radiation environment is likely to be significantly worse.

3. CURRENT STATUS OF THE CCD PRODUCTION PROGRAMME

The Euclid CCDs are being procured by ESA as Customer Furnished Items (CFI) to be delivered directly to the VIS Instrument Team within the Euclid consortium. There are several reasons for this. The CCDs constitute a significant fraction of the overall cost of the VIS instrument. This cost could not be easily handled by an individual group within the Euclid Consortium, which depends on grants from national funding agencies and is not structured to place such a large contract with industry in any one country. In addition, detectors often fall on the critical path of instruments and telescopes. By taking responsibility for the CCD procurement, ESA were able to place the flight contract with e2v as soon as Euclid was approved and even ran a CCD pre-development for several years before Euclid was selected.

The flight CCD contract kicked off at the beginning of 2012. The programme comprises two phases. Phase 1 is the CCD qualification phase which also includes the production of Structural Thermal Models (STM) and Engineering Models (EM). Phase 2 is the flight CCD production phase including acceptance testing and the production of further EM CCDs from the flight batches. The whole programme is summarized schematically in Figure 3-1. Note that this contract followed an extensive pre-development activity during the Euclid study phase. The CCD design was well established and the current contract does not include design activities, but started with preparation for CCD production immediately.

At present, 27 of 66 Structural Thermal Model CCDs have been delivered. The STMs are required in four batches with four different build standards, to be used in various structural, thermal and optical alignment tests at focal plane and VIS instrument level. The first batches of flight-like CCDs have been fabricated at wafer level, back-thinned and packaged, and the first CCDs are ready for electro-optical testing following a recent successful Test Readiness Review (TRR). CCDs from these batches will be selected for qualification testing and for delivery to the Euclid Consortium as Engineering Models (EM).

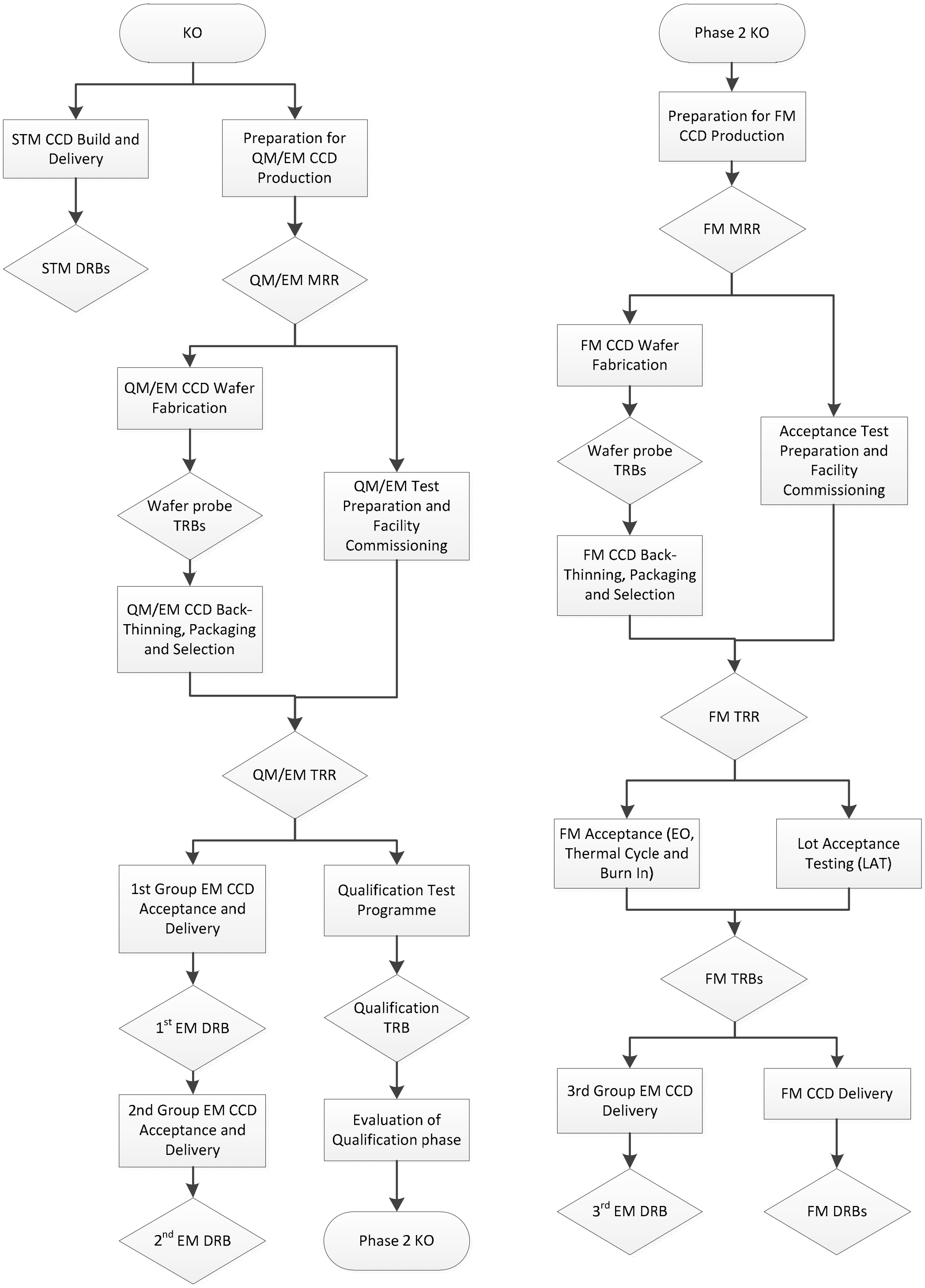

Figure 3-1 Overview of the Euclid VIS CCD programme taken from a work package summary in the original ESA Statement of Work.

4. STATUS OF CCD PERFORMANCE ASSESSMENT

Initial testing of Euclid CCDs has been conducted by e2v and by members of the Euclid CCD Working Group at MSSL, ESTEC and the Open University. Euclid CCD performance is addressed elsewhere[7,8,9,10]. We only note here that testing generally demonstrates performance meeting or exceeding requirements. For example, readout noise of 2.5e- has been measured at 70kHz compared with a requirement of 3.6e-. Parallel CTE values of 99.9999% and serial CTE values of 99.9996% have been measured using X-rays compared with a requirement of 99.9995% in both the parallel and serial direction. Similarly, Figure 4-1 indicates that QE exceeds the requirements by as much as 10%. However, the measurements at e2v and ESTEC differ by approximately 3%. Random errors are small so the calibration of the QE test facilities will be checked.

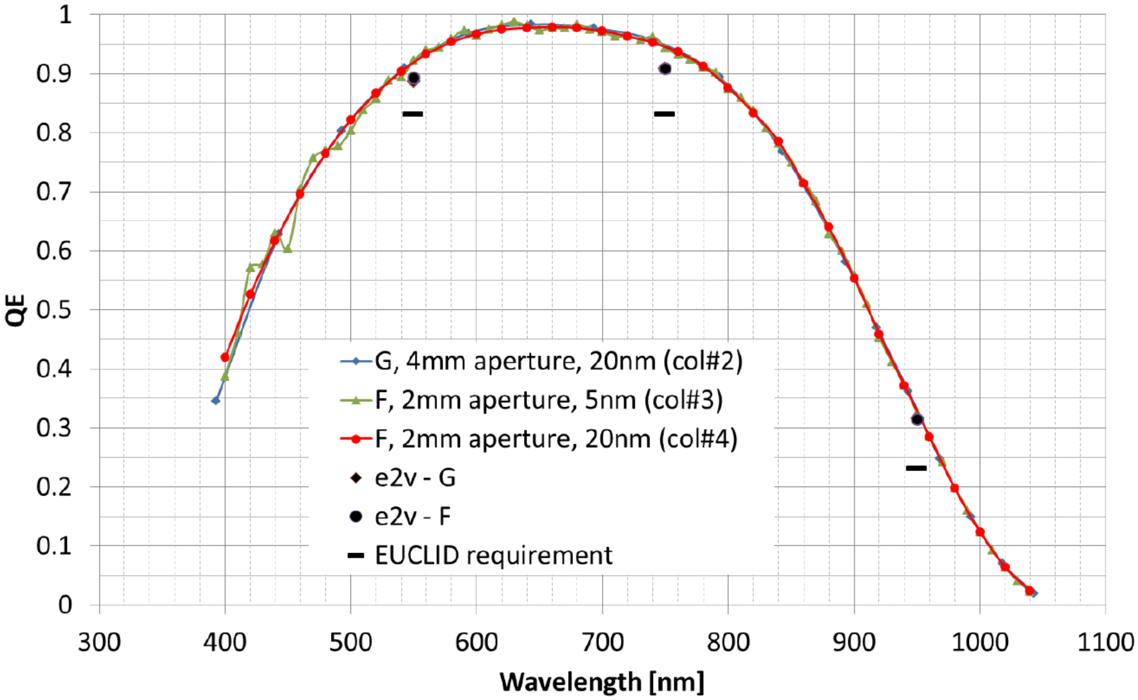

Figure 4-1 An example of Quantum Efficiency measurements made at ESTEC. Three requirement values are indicated together with three measurements by e2v at those values. The small but systematic difference between e2v and ESTEC measurements needs to be understood.

SUMMARY

Requirement specifications for the Euclid VIS CCDs have been derived from a flow-down of Euclid science, telescope and VIS instrument requirements. However, CCD technology has a very significant heritage and in many respects, the Euclid VIS channel has been designed using the expected CCD performance as a starting point. For this reason, it has been possible to start CCD design and prototype development even before Euclid was selected and long before mission and payload prime contractors were in place. The flight CCD contract was negotiated as soon as Euclid was selected, approximately half of the STM CCDs have been delivered, the first EM and QM CCDs have been fabricated and these are currently being packaged. Test facilities have been commissioned and the first electro-optical testing of EM/QM CCDs is just beginning. So far, the performance of the Euclid VIS CCDs appears to be in line with expectations and requirements.

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