Requirements, developments and challenges for CCD and CMOS image sensors for space applications

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1. Introduction

Space optical instruments have largely been based on CCDs, particularly for high-performance scientific applications. CCDs still exhibit the best combination of large size, low noise, large charge-handling capacity, spectral response, QE and dark-signal uniformity. They however suffer from delicate clocking conditions, degradation by smear during transfer, lack of additional integrated functions (e.g. windowing, ADC) and a limited supplier base. An evolution is taking place with CCDs gradually being replaced by CMOS-based devices for applications that are not requiring the utmost performance (e.g. star trackers, imagers) because of their specific features and operation advantages. The current challenge is the development of CMOS imagers that would rival CCDs in terms of radiometric performance in space environment.

This paper gives a user's perspective of the main types of requirements for optical detectors in the "silicon range" (250 – 1000 nm) for space applications and illustrates the various developments conducted under ESA's funding.

2. High-end applications of CCDs in space

CCDs have been the workhorses of optical sensors in satellites since the 1970's. Starting with linear arrays for Earth Observation, their use generalized to high-end astronomy missions, see for example the Hubble Space Telescope[1].

Although there are many specific cases, one can make a distinction between two main types of applications:

- Observation of faint sources, generally on a dim background are typical of astronomy observatories and are characterized by a *low flux* of photons. Medium to long integration times, very small noises are required.
- Observation of spatial and spectral variations of brighter scenes are typical of Earth or planetary observation, with *high fluxes* of photons. Short integration times, large charge handling capacity are required but also limited noise (large dynamic range) as very small changes need often to be discriminated.

A recent example of low-flux application is the astrometry GAIA mission, which is based on a large array (fig.1) of 106 close-butted e2v 91-72 CCDs, operated at -110 C [2].

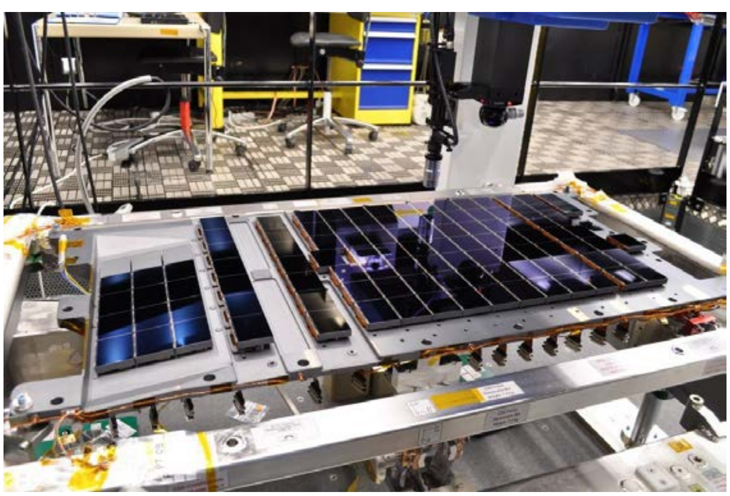

Fig. 1 GAIA focal plane and CCD 91-72 (courtesy of Astrium SAS and e2v)

Each of them has 1966 by 4500 pixels, with pixel dimensions of 30 µm by 10 µm, respectively. Astrometry measurements naturally benefits from the unique capability of CCDs to perform time-domain-integration (TDI) by synchronising the charge transfers with the transit of star images on the CCD assembly. As the accuracy of the star positioning critically depends on the knowledge of the system point-spread function, degradation of the CCD response in space radiation environment has been extensively analysed [2]. The performance of the CCD depends on the specific operation mode and read-out frequencies, with read-out noise measured on FPA lower than 11e- a833kHz and 3 e- at 64 kHz. For a full-well capacity of about 350000 e-, this performance corresponds to dynamic ranges of 90 and 101 dB, respectively.

A recent example of high-flux application can be found in the spectrometer developed for the GMES Sentinel-4 mission, to be flown on Meteosat-Third-Generation (MTG) [3]. The instrument will monitor air quality using two spectrometers in the ranges 305-500 nm (UV-VIS) and 750-775 nm (NIR). The CCDs are optimised for each spectrometer but have been designed together to ensure communality of design. A prototype of the UV-VIS CCD has been made by e2v, with an architecture illustrated in fig.2.

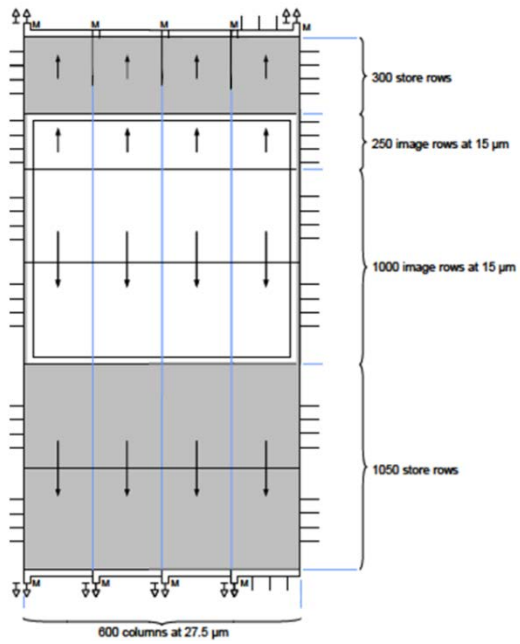

Fig. 2 CCD274 prototype (courtesy of e2v)

The device is a thinned, non-inverted, four-phase, split frame-transfer CCD sensor comprising two image sections focusing on ultraviolet and visible light respectively. The two sections are independently clocked in opposite directions, to minimise smear effects due to the much larger signal in the visible section. The extra 50 rows in the store sections are used to keep the top line of charges in the store well away from the shield edge and for estimation of smear signal. The CCD has met its performance requirements, with particularly a readout noise of 15e- in a bandwidth of 4.3 MHz for a FWC in excess of 1.4 Me- at the 1% non-linearity limit (dynamic range 100 dB).

The CCD has been purposely chosen to be non-inverted and will be operated at 215 K. This ensures optimum mitigation of the degradations due to collision damage in the bulk of the device. The measurement of atmospheric trace gas (e.g. NO_2, O_3) is based on the detection of small absorption features in a continuum spectrum. It is very important to ensure negligible RTS noise, high CTE and low-level of image lag. Gamma and proton irradiations have been performed to demonstrate that charge transfer inefficiency remains lower that a few 10^{-5} per transfer.

3. CMOS detectors as event trackers

CMOS detectors were mainly introduced in space as sensors for star trackers. Indeed the flexibility and ease of implementation provided by (multiple) windowing, non-destructive read-out and on-chip ADC make CMOS-based sensors very appealing for such applications. As it a building block for various implementations and is space-qualified according to generic specifications, resistance to high levels of radiation is of paramount importance, leading to the development of specific rad-hard pixel layouts. One such device is HAS2 [4], which has become one of the industry standards. It features 1000x1000 pixels of 18 μm pitch, a 12-bit internal ADC and its performance is kept up to an ionising dose of 42 krads, with functionality up to 300 krads. An upgraded version (HAS3) is under development with a 1280x1280 format, 11-μm pitch, 24 LVDS outputs and global and rolling shutter. The electro-optical performance of HAS2 illustrate the different in radiometric performance with CCDs. The typical 1% linear range of 50ke-, associated with a read-out noise of 50-75 e- (at a pixel rate of 5 MHz) corresponds to a dynamic range of 60 dB. Front-side illumination also limits quantum efficiency to 45 %.

A demonstrator has been made of a detector fully using unique on-chip processing capabilities for detection on lightning events from geostationary orbit [5]. The 256x256 front-illuminated demonstrator featured in-pixel detection of events, comparison with neighbours and previous frame and fast on-chip localization of events. However the steps to make a larger back-illuminated flight model were deemed too large for a risk-limited development and the Lightning Imager instrument [6] on MTG will use a more classical approach based on a back-side illuminated 1000x1170 pixel, 24-μm pitch, detector with internal 12-bit ADCs providing 60 LVDS outputs operating up to 250 MHz.

4. CMOS detectors for radiometrically critical applications

CMOS arrays are already regularly flying, up to geostationary orbit [7]. The very large focal plane of the Sentinel-2 Multi-Spectral Imager, made of 12 staggered arrays operated at +20 C, each made of 12 rows of 2596/1298 detectors with 7.5/15 μm pitch respectively, is representative of current capabilities [8].

The introduction of CMOS sensors for high-end scientific and application missions is however slowed down by the performance requirements that are often driving designs not fully consistent with the mainstream developments for larger markets in consumer cameras, automotive, medical and surveillance applications. Requirements for large charge handling capacity and high dynamic ranges, extended spectral response in UV, high QE, well-controlled radiation resistance lead to large-size detectors with large pixels and complex circuitry. The scant availability of foundry processes to sustain these developments is a particular stumbling block. The common reliance of “fab-less” suppliers on many external service providers offers considerable flexibility but also a certain fragility of the supply chain, contrary to the traditional integration of processes with CCD manufacturers.

Over the last 10 years, the European Space Agency has been developing, with industrial partners, CMOS imagers aimed at replacing CCDs in space-science and Earth observation applications. “High-flux” applications, for Earth Observation or planetary sciences, call for devices with typical format of 1k x 1k pixels or more, CHC of 0.5-1 Me-, read-out noise < 50 e- (10-20 e- as goal), stare (integrate-while-read) operation, BSI and frame rates of 10 Hz or larger. “Low-flux” requirements for astronomy applications are similar, with however a lower CHC of 50-100 ke- for a read-out noise < 5e- and lower frame rate. In all cases, one aims at “zero defect”, excellent uniformity (2-3%) and minimization and good characterization of degradations due to typical radiation levels of long-duration space missions.

Initial ESA-funded developments led by IMEC [9,10] focused on a design that can be used either as a monolithic, global shutter, back-side illuminated CMOS imager and as a ROIC for hybrid detectors. Considerable efforts have been devoted to the optimization of all aspects of the process to meet performance requirements. The two variants achieve a dynamic range of about 75 dB, with a CHC of 350 ke for the monolithic version and 950 ke and later 1.75 Me- for the hybrid version. Excellent crosstalk performance was reached using isolation trenches on the hybrid device. In both cases, mastering the back-surface treatments to achieve best possible QE represented a challenge.

Current activities include:

- The development by CMOSIS of a back-side illuminated, global shutter 1024x1024 pixel (20-mm pitch) array, with target noise of 25 e- (with in-pixel CDS) for a CHC of 400 ke-. Dual gains are implemented to achieve this level of performance. Manufacturing of thin back-side illuminated devices is based on engineered SOI substrates. A redesign is being performed to optimise various aspects of the circuitry and remove some artefacts

- The realization, with CMOSIS as prime contractor and design house, of two “high-flux” 512x512 demonstrators featuring back-illumination, global-shutter, dual gain and in pixel-CDS. Target requirements are a CHC > 500 ke-, for a read-out noise < 50 e-. The demonstrators are made with IMEC 130 nm and ESPROS 150 nm and feature only technological processes located in Europe.

- a similar activity for “low-flux” applications (same format, tentatively CHC > 50 ke, read-out noise < 5e) to be started in the 2nd half of 2013. The objective is also to promote European-only technologies, in particular a foundry not used in the “high-flux” activity mentioned above.

5. The unexpected competition

The introduction of CMOS detectors in space missions goes in parallel with the use of hybrid infra-red detectors, particularly those using HgCdTe arrays. Hybrid detectors using Si photodiode arrays are particularly attractive as they can benefit from the IR heritage and use the advantages related to the separate optimisation of the photodetection and read-out functions [9,10]. The possibility to extend the spectral response of HgdTe to UV by removing the substrate[11] however allows using the same detector and the same electronics in hyperspectral imagers covering the spectral range 400-2500 nm using two spectrometers, as in the PRISMA satellite[12]. The price to pay is a lower operating temperature (around 150K) which can be afforded if such a cooling capability already exists for the SWIR channel and a somewhat higher level of defects.

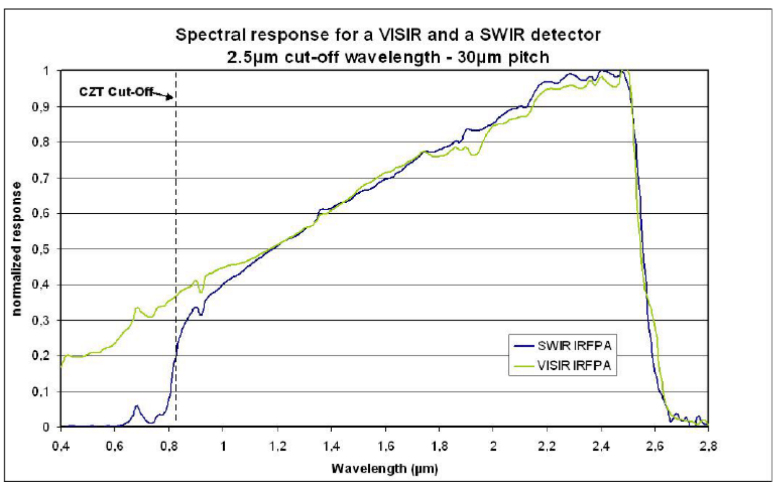

Fig. 3 Spectral responsivity of thinned and unthinned HgCdTe (Ref.11)

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