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Modern UV detectors for small aperture space mission to study comets

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Abstract. A small dedicated UV telescope with a modern detector can obtain a lot of new information to study comets in the UV range, which is inaccessible for ground telescopes. We discuss the latest trends in UV-optimized CMOS and CCD detectors that can improve the efficiency of a small aperture (20 cm) space burn UV telescope. The improvements of classical CCD are moving toward improving quantum efficiency in UV, development of the new anti-reflection coatings and multilayer UV filters with enhanced red leak suppression. CMOS with a very small pixel (3-5 μm) of more than 20 Mpixel format allows to improve sampling and to increase the price/performance ratio of a small aperture telescope.

Key words: UV detectors – CCD – CMOS – comets

1. Introduction

For a long time the efficiency (total transmittance or effective area) of a space telescope in UV was low because of low quantum efficiency of detectors, losses on reflective coatings on the mirrors, absence of anti-reflecting coating for UV lenses, problems with fabrication of large and complicated UV lenses and red leak of UV filters.

The progress in detector and multiplayer filter technologies makes it possible to significantly improve the efficiency of UV telescopes, especially in the near-UV range. Nowadays it has become possible to design a small aperture UV telescope with a total throughput of the system similar to the optical range. For a decade after the completion of the HST, the hopes of astrophysicists are associated with the World Space Observatory - Ultraviolet (WSO-UV) Project, which is scheduled to launch in 2025 (Sachkov et al., 2020, 2019). With the help of the project tools, most of the tasks in the field of ultraviolet studies of comets (Sachkov, 2016; Sachkov et al., 2018) and exoplanets (Fossati et al., 2014) will be effectively solved.

The UV detector with anti-reflective coating and (possibly) with directly deposited UV filters is the key element of the telescope. The design of a new UV wide field telescope should be carried out in parallel with the design of a large format detector and filters.

In this paper we discuss a possible approach to select the UV detector for a small aperture space borne UV telescope to study comets in UV.

2. General requirements for the detector and trade-off between CCD and CMOS

The baseline detector requirements to study comets in UV are as follows:

- image format of no less than 4000×4000 pixels;
- pixel size of 5-10 μm;
- spectral range: FUV and NUV with the best possible sensitivity, with no strict requirements for optical sensitivity;
- red leak suppression of UV filters better and E-5 (target);
- reasonable dynamic range (higher than 5000 in a single frame);
- ability to operate with local over illumination;
- low afterglow;
- very low readout noise (target is 1...2 e^- RMS) to operate with UV filters that lead to a very low background. It is also required to improve image co-adding;
- low dark current (less than 0.01 e^- pixel^{-1} s^{-1}) to operate with exposures of up to a few minutes;
- electronic shutter;
- high radiation tolerance.

Currently, the CMOS detector technology has demonstrated the following characteristics:

- readout noise of less than 3 e^-RMS, some detectors demonstrate a 1 e^- RMS readout noise level in high gain mode with limited dynamic range;
- lag (loss of charge during readout) of less than 2 e^-;
- geometric dimensions of up to 5-7 cm;
- pixels of various sizes down to a few microns are available, however scientific grade sensors with reasonable performance have a pixel size larger than 5 μm;
- quantum efficiency of a back illuminated CMOS with anti-reflective coating has been raised up to 90% in a visible range, which is comparable to the best CCD;

– CMOS back illumination technology demonstrates similar behavior to the CCD technology in terms of quantum efficiency and back surface treatment, therefore, most probably in the future UV optimized CMOS with UV anti-reflective coatings will reach the same quantum efficiency in NUV and FUV ranges as CCD has.

The CCD detector technology has shown the following parameters:

– readout noise of about $3\,e^-$ RMS at low speed;

– large dynamic range, up to 18 bit ADC;

– charge transfer inefficiency for a long space mission is an issue, especially when operated with a low background which is the case for UV observations, in the worst-case scenario charge loses can rise up to 10 electrons;

– geometric dimensions of up to 9 cm;

– frame transfer CCD provides electronic shutter functionality, but with doubled chip area;

– pixel size of 10...20 μm for scientific grade CCD;

– quantum efficiency of back illuminated CCD with coating in NUV can reach 80%;

– technology to improve CCD quantum efficiency in FUV up to 50% was demonstrated;

– series of UV missions demonstrate maturity of the CCD technology.

The main advantages and disadvantages of CMOS versus CCD as a detector for a small aperture UV telescope to observe comets are as follows.

Advantages of CMOS over CCD:

– lower readout noise;

– higher readout speed;

– smaller pixel size;

– electronic shutter (global, roller).

Disadvantages of CMOS over CCD:

– slightly lower quantum efficiency for very small pixel size detectors;

– lower dynamic range;

– pixel-to-pixel variations of photo-electrical parameters;

– to achieve a full dynamic range, many CMOS need to take 2 images with low and high gain modes, which cause additional photometric errors;

– CMOS detectors still have limited heritage in space scientific application, especially in UV range;

– impossibility to achieve extremely (less than $0.01\,\mathrm{e^-\,pixel^{-1}\,s^{-1}}$) low dark current even with deep cooling.

3. Quantum efficiency in UV

Observation in UV with CMOS and CCD detectors faces two challenges, low quantum efficiency in UV and the red leak of UV filters.

In the ultraviolet spectral range, the short absorption lengths (below 10 nm) and high reflectance of the silicon strongly affect the quantum efficiency.

In the USA (NASA Jet Propulsion Laboratory), a surface passivation technology by boron atoms (delta-doped) was developed Hoenk et al. (2014). The technology of surface growth using a molecular beam on the back surface of a CCD, CMOS or photodiode with control accuracy up to the atomic level is used. Afterwards, the ALD (atomic layer deposition) technology is used to apply a multilayer anti-reflection coating on the detector. The combination of these two technologies makes it possible to build a CCD or CMOS detector with a high quantum efficiency in the range of 100-300 nm. Delta-doped technology provides a high internal quantum efficiency and the additional anti-reflection coating reduces light loss on reflection. It is shown Nikzad et al. (2012), that it is possible to design simple coatings using different materials to achieve >50% of quantum efficiency in different parts of the UV range: MgF_2 of 13 nm thickness for 130-160 nm range, Al_2O_3 of 16 nm thickness for 160-200 nm, Al_2O_3 of 23 nm thickness for 200-230 nm, HfO_2 of 23 nm thickness for 230-280 nm.

Alternatively, Teledyne e2v has developed the proprietary processes to improve the UV quantum efficiency Heymes et al. (2020). To improve internal quantum efficiency, the shallow p+ implantation is used to permit the thinning of the backside potential well of a CCD chip. Two different levels are available: basic with a 40 nm ±10 nm thick p+ layer and enhanced which uses an extra etching process to thin the p+ layer. For the enhanced process, the quantum efficiency without coating is about 10-15% in FUV range.

The second step is reducing the reflectivity of the back-surface by using an anti-reflective coating designed for targeted wavelengths. For example, for the WUVS project Teledyne e2v developed a special gradient anti-reflection coating for 180-310 nm range matched with a spectrograph dispersion Shugarov et al. (2014). According to the test results, this coating improves the quantum efficiency up to 4 times in comparison with the uncoated CCD in 250-300 nm range Shugarov et al. (2021a).

One of the prospect examples of using a CMOS detector to operate in the near UV range is the Ultraviolet Transient Astronomical Satellite (ULTRA-SAT) Asif (2021) that is currently in a preliminary design phase. The wide field UV space telescope has a $200\,\mathrm{deg}^2$ field of view and the mosaic of four back-side illuminated UV optimized CMOS sensors has a sensitive area of 90×90 mm (89.8 Megapixel). The CMOS sensors are designed and produced by Tower Semiconductor Ltd and Analog Value Ltd. (AV) in Israel. The photo sensitive area of a single chip is 45.011×45.011 mm (4738×4738 pixels) with a pixel size of $9.5\,\mu$m, well capacity is $140\,\mathrm{ke}^-$ and 16-21 ke^- in low and high gain modes, dark current is $< 0.026\,\mathrm{e}^-\,\mathrm{s}^{-1}$ at 200 K, readout noise with rolling shutter is $< 3.5\,\mathrm{e}^-$ RMS and a readout time of < 20 s.

The key feature of the detector is high quantum efficiency in NUV.

Firstly, the back-illuminated CMOS sensor has high-K dielectric coating to improve internal quantum efficiency in UV. This coating acts similar to the delta doping technology from JPL.

Secondly, an optimized anti-reflection coating is applied. Different anti-reflective coatings were tested to find a balance between transmittance and red leak suppression. According to current test results Bastian-Querner et al. (2021), the average quantum efficiency of 60% (corrected for quantum yield) in the range of 220-280 nm can be achieved.

4. Field of view, angular resolution and image co-adding

Digital co-adding is especially important for a small aperture telescope without a large mosaic. It is the only way for a small telescope to improve sensitivity, to achieve best possible angular resolution and to map extended objects such as comets in different filters.

For each project the telescope field of view and detector pixel scale should be selected in order to find a balance between angular resolution, field of view and observation rate according to scientific tasks.

Because of a limited amount of comets, for a dedicated project to observe comets in UV the observing rate is not a priority. To study comets in UV and to compete with other ground based and space borne telescopes, the angular resolution should have priority over a single frame field of view, because of the possibility to construct a mosaic image using many observations.

The angular resolution should be better than 0.5 arcsec and the telescope field of view large enough to utilize a 20-50 Mpixel class detector.

Image co-adding helps to improve the dynamic range of a CMOS detector that may have only 12-14 bit ADC. Image co-adding is especially important for a small pixel size CMOS with a limited pixel well capacity. Image co-adding with a high gain mode may be considered instead of using a CMOS dual gain readout to improve the photometric accuracy, if a detector with $1\,\mathrm{e}^-$RMS noise will be available.

Fixed filters directly deposited on a detector is a good choice for a small size telescope to simplify the design and to reduce the cost, as well as to improve the red leak suppression. Fixed filters are another argument to use image co-adding technique.

The main negative point of co-adding is extra consuming of observing time.

5. Small pixel size CMOS

In the last few years it has become possible to manufacture an active pixel with a size of 3-5 μm with reasonable well capacity of tens of thousands of electrons, low noise and high quantum efficiency.

In high gain mode some CMOS has a readout noise as low as 1 e^- RMS, thus a dynamic range of such small pixels can be more than 5000:1, that is enough for scientific application and even can compete with some classic CCD.

The combination of a telescope with high image quality and CMOS with a small pixel allows to build a wide field telescope with an improved price/performance ratio.

The CMOS cost is not as high as the telescope and evidently much lower than the whole mission cost. Therefore, it is better to chose the detector that is slightly larger than the telescope's field of view, e.g. to put the round telescope field of view inside the square detector with a small margin at the detector's edge.

Using small pixel size CMOS it is possible to increase the field of view of the telescope while maintaining sampling without increasing the cost of the focal unit. The other option is to improve the spatial resolution by having better sampling.

Designing and manufacturing of the moderate field of view telescope with enhanced image quality in order to operate with a small pixel detector is complicated and expensive, however modern technologies of optics manufacturing will probably keep the telescope cost at a reasonable level.

As an example, the 151 Mpixel CMOS IMX411BSI has format of $14{\times}10$ k ($54{\times}40$ mm) and a pixel size of 3.76 μm. Unfortunately, this promising sensor most probably will not have a UV-enhanced option.

Another example is a modern CMOS GSPRINT4521 with a global shutter, photosensitive area of $23{\times}18.4$ mm, pixel size of 4.5 μm, pixel capacity of 30000 e^- and reading noise of 3 e^- RMS. UV-optimized GPEXEL sensors with special treatments of the back side of the silicon wafer demonstrated reasonable quantum efficiency without anti-reflection coating Shugarov et al. (2021b). We hope that multilayer UV coating, similar to the DORADO project, can be applied for GPIXEL's back illuminated CMOS.

6. UV filters to observe comets

Red leak is one of the main problem to design UV filters for silicon-based detectors.

For the near-UV range the best multilayer filters provide acceptable suppression of the optical component, however for the far-UV range the photometric correction of the observed data is required in most cases.

In the DORADO project it is proposed to use a multilayer dielectric filter on the CCD surface Singer et al. (2021). The operation band pass is 180-230 nm and suppression of the optical component is about E-5. It was demonstrated that directly deposited filter on CCD provides twice better suppression than the HST WFC3 common standalone multilayer filters.

To observe comets in UV, we suggest putting at least 4 multilayer filters directly on the detector: three for the UV range (FUV, NUV1, NUV2) and one standard V filter to correct the long-pass transmission of UV filters, e.g. for red leak calibration. The presence of several optical filters will expand the scientific capabilities of the mission.

Directly deposited filters help to avoid additional mechanical filter change mechanism.

7. Conclusion

A promising way to build an effective small aperture moderate price UV telescope to observe comets in UV is to combine the following approaches and technologies:

- to design a telescope with a UV lens field corrector to provide better than 0.5 arcsec resolution with a 5 μm pixel size detector;
- to use small pixel size CMOS of a 20-50 Mpixel format to improve angular resolution and data capacity;
- to look for a 1 e^- RMS noise CMOS detector to improve image co-adding and to utilize the advantage of a low sky background in UV;
- to look for the possibility to deposit several different UV-optimized coatings (probably of different materials) on the detector;
- to look for the possibility to deposit several UV filters with good red leak suppression on the detector.

A combination of a small aperture high angular resolution telescope and CMOS with a small pixel will allow to design a system with better price/performance ratio than before. The CMOS detector, which is not sensitive to local overexposure and has a large dynamic range, will allow to achieve a very high S/N ratio when adding a large number of frames of the comet's nucleus and tail.

The presence of a bright comet nucleus will not affect the telescope's ability to observe a weak tail.

A dedicated 20 cm aperture UV-optimized telescope with modern UV optimized detector and filters will allow to perform a detailed study of comets in the UV range, which is inaccessible for ground telescopes.

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