# An Overview of Modern CMOS and CCD Detectors for Wide Field Telescopes

A. Shugarov

Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia
shugarov@inasan.ru

**Abstract.** Improvement of classical CCD technology moves in the direction of increasing parallelism, building 4-sided buttable devices, and improving IR sensitivity. Large format scientific CMOS (GSENSE6060) of the 6×6 k (60×60 mm) and 9×9 k (90×90 mm) format, as well as CMOS with a very small pixel (3-5 $\mu m$) of more than 100 Mpixel, have some benefits in readout speed and noise in comparison with classical CCD. The first CMOS mosaic with 10x 3-side buttable CMOS was built for TAOS II project. The experimental curved CMOS based on commercially available CMV20000 with acceptable characteristics being demonstrated.

**Keywords:** instrumentations: detectors

DOI:10.26119/978-5-6045062-0-2_2020_171

## 1 Progress with CCD Detectors

CCD technology approaches theoretical limitation, however, in recent years there have been several changes. The first trend, the development of 4-side buttable CCD aim to achieve a fill factor of CCD mosaic >90%.

The second direction is to increase the readout speed of the CCD by increasing the number of output amplifiers up to 8-16 units. As an example, CCD250-82 developed for LSST project has a 4×4 k format, 16 amplifiers and a readout time of 2 s with 5 $e^-$ rms noise, which is close to that of modern CMOS sensors.

Another recent advance in CCD technology is the production of a CCD on ultra-thick substrates, which together with a multi-layer anti-reflection coating, allow for excellent quantum efficiency (75% at a wavelength of 1 $\mu m$) that is close to the red limit of Si. One of the problems of such sensors on a thick substrate is increasing the probability of electron diffusion toward a neighbouring pixel, it was solved by electric potential in the thickness of silicon by applying a relatively high voltage to the back side of the substrate.

Since small bodies in the solar system are observed in reflected light, the near-IR range is preferable for wide field survey telescopes. The appearance of a CCD with very high sensitivity in the IR region allows us to begin designing wide field systems with maximum transmission shifted from the visible region to the region of 500-1000 nm.

For the CCD250-82 version on an ultra-thick substrate, using a multi-layer coating optimised for both the IR and UV regions, a quantum efficiency of >80% is achieved in the range of 370-940 nm, a level of moderate sensitivity (>30%) is achieved in the range of 320-1020 nm. This is challenge to design the wide field telescope with very wide spectral range of about 350-1000 nm, but it will increase the sensitivity of a telescope in survey mode, when detector used without a filter. These improvements also promise the ability to upgrade older telescopes, through increased efficiency of the detector.

## 2 Progress with CMOS Detectors

CMOS detectors were previously unable to compete with large-format scientific grade CCD detectors and mosaics. The appearance of larger (40-60 mm) and relatively inexpensive CMOS allowed the use CMOS on wide field telescopes for a medium size aperture (40-80 cm). The new largest CMOS detector with a format of 8904×9178 pixels (89×92 mm) and a 10 $\mu$ pixel size from the Chinese company GPIXEL is a promising solution for 1 m class telescope. The internal ADCs provide a 16 bit equivalent resolution, while the pixel full well is 90000 $e^-$, and the quantum efficiency at 550 nm surpasses 90%. The first samples of this new CMOS are expected in 2020 and probably will be used in the mosaic of the Chinese ground based WFST telescope with an aperture of 2.5 m, field of view of 3° (9x CMOS), and CSST Space telescope.

The world's first 3-side buttable scientific CMOS, designed to build a large mosaic focal plane is CIS113, it has 1920×4608 pixel format, 16 $\mu m$ pixel size. A distinctive feature of the CIS113 CMOS is the optimisation of the chip architecture to keep 3 sides free of electronic circuits and the absence of an analog-to-digital converter on the chip. The external high-resolution ADC can be used, similar to classic CCDs, allows for reduced operating temperatures due to heat dissipation on the CMOS, which is important for cryogenically cooled mosaics best suited to astronomical observation.

The negative side of the CIS113 features described above is the lower reading speed in full-frame mode (2 Hz), which, however, together with the electronic shutter, is sufficient for most practical astronomy tasks. The chip enables random access to pixels, that is the key feature of the TAOS II project. The mosaic of 10x CIS113 (9×9 k pixels, 150×150 mm) to conduct simultaneous photometry of 10,000 stars at a frequency of 20 Hz over the whole 1.7° field of view for a 1.3 m aperture telescope. It is impossible to do it with traditional CCD mosaics.

In last decade, the only way to cross the 50 MPixel threshold was to build a mosaic CCD detector, which raised the cost of both the camera itself and the focal unit in comparison to compact cameras with a thermoelectric cooler. In recent years it has become possible to produce a CMOS with pixel size of 3-5 $\mu m$, which has a sufficient capacity (tens of thousands of electrons), low noise, and a high quantum efficiency. The dynamic range raises up to a ratio of more than 5000:1, which is enough for survey telescopes.

As an example, the 151 Mpixel CMOS IMX411BSI has format of 14×10 k (54×40 mm) and a pixel size of 3.76 $\mu m$. The pixel capacity is 50 ke$^-$, the noise is 3 e$^-$ rms, the built-in ADC has 16-bit resolution. GPIXEL is able to manufacture a single chip CMOS within the 400 Mpixel class with a 20×20 k (90×90 mm) format and 4.6 $\mu m$ pixel size.

The cost of a CMOS is typically proportional to its area, not pixel size. Thus, a CMOS with a smaller pixel is characterised by a lower cost per pixel. These sensors allow us to begin the production of wide field telescopes with apertures of 0.2-1 m with a data capacity of 100-400 Mpixel per frame. It is possible to enlarge the field of view of the telescope, improve sampling and/or optical resolution while maintaining field of view. In both cases, a more advanced optical scheme is required.

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

Curved CMOS can be used to build small aperture ultra-wide field telescopes with single chip detector, as well as to build large curved mosaic detectors for medium and large aperture telescopes.

CEA-LETI, in collaboration with CNRS-LAM, successfully carried out experiments on the manufacture of convex and concave CMOS chips using the commercially available CMV20000 of 5120×3840 format, 6.4 $\mu m$ pixel. The photosensitive element (CMOS chip) was removed from the case, then, after thinning the substrate, was pasted on a curved substrate, after which the curved chip was inserted back into the standard case, the electrodes were then re-wired. Thus, the experimental CMOS is fully compatible with the original in terms of mechanical and electrical interfaces but features the curved surface. Both convex and concave CMOS with a radius of curvature of 150 mm were produced, the measured characteristics being similar to the original flat sensor.

*Acknowledgements.* The research funded by RFBR, Project No. 19-29-11013.