Application of sCMOS

in space debris measurement

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Abstract:

The technology of the scientific grade complementary metal oxide semiconductors (sCMOS) has been rapidly developed. Due to its high frame rate and low noise, sCMOS has an advantage for observing of space debris. We introduce the application of sCMOS to the measurements of space debris, and compare it to the charge-coupled device (CCD).

Introduction:

High temporal and spatial resolution and high accuracy are the pursuit of optical surveys for space debris. The detector, as a key factor for performance of optical surveys, always utilizes a CCD camera. However, due to the rapid development of CMOS technology, especially the lithography and process control in fabrication, CMOS has shown its advantage of the small size of pixel, high frame rate and low noise for high temporal and spatial resolution. The first generation scientific CMOS (sCMOS) camera made by Andor Technology [@] has been applied in space debris measurement.

Requirement of Photon detector for SD:

For space debris measurement, the main specifications of the detector, that we care about, are listed below:

- quantum efficiency(QE)
- image area
- pixel size
- fill factor
- read noise
- read speed

- full well
- dark current
- photo response non uniformity(PRNU)
- linearity

Detector Selection

If we classify the detector by electronic architecture, there are two types, CCD and CMOS. Simply speaking, the feature of the CCD's architecture is serial, CMOS's is parallel. We could induce that, parallel means high read speed, but take the risk of high noise at the same time.

In the scientific market, CMOS performance has generally been worse than CCDs due to a reputation of unacceptably high read noise and dark current, lower fill factors, and greater non-uniformity. Thanks to the technology improvement, recently, scientific CMOS (sCMOS) has been designed to overcome the drawbacks of traditional CMOS, and it is comparable to CCD in the scientific market.

QE

From the curve, we can see that, quantum efficiency of sCMOS is about 60 percent, and front-illuminate CCD is about 50 percent. Back-illuminated CCD could reach about 90 percent. So, quantum efficiency of sCMOS is lower than the typical value of Back-illuminated CCD, and is higher than that of Front-illuminated CCD.

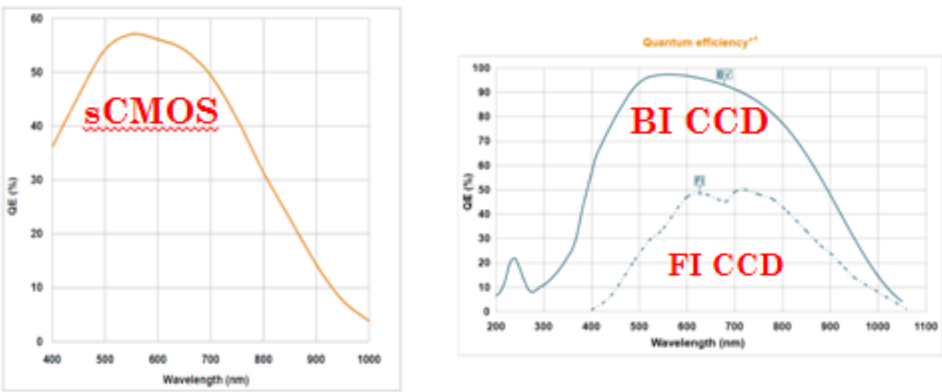

Fig 1:QE of sCMOS and CCD(BI&FI)

Pixel & Full depth

Secondly, let us see the pixel and full depth. The pixel size of sCMOS (left in **Fig 2**) is six point five by six point five micro-meter, much smaller than typical size of the CCD (right in **Fig 2**)， which is about twelve micro-meter, which means higher spatial resolution. Accordingly, small size is accompanied with lower full depth to some extent. When we see bright stars, it is easily to be saturated. So it would limit the measurement of the bright signal.

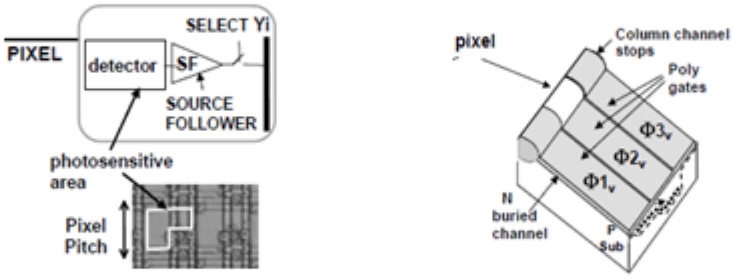

Fig2: Pixel of sCMOS and CCD

Fill factor

Then let us argue about another important parameter correlated to the pixel, the fill factor, which is the proportion of active area of pixel. We could see it from Fig 3, the left one is the CCD, the middle one is the CMOS. So, lower fill factor is the inevitable drawback of sCMOS, due to its architecture. To improve it, we could use micro-lens to focus. Let us see right part. The micro-lens could improve the fill factor a lot. For sCMOS, the fill factor is more than ninety percent, however, it is still lower than the CCD. The CCD's fill factor could reach nearly one hundred percent.

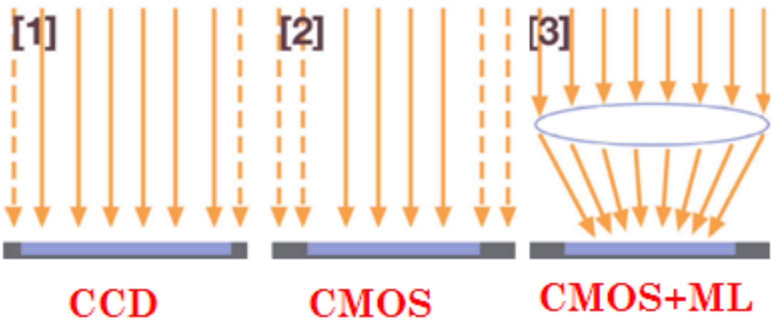

Fig3: Fill factor of sCMOS and CCD

Cross talk of sCMOS

CMOS use micro lens to improve the fill factor, it works very well. However, micro lens would introduce another problem, Cross-talk between adjacent pixels. So, for sCMOS, Cross-talk is not just an electrical effect as with the CCD. When the incident ray of micro-lens is off-axis, the ray would run into a neighbor pixel. Cross talk could be optimized by optic design, the method could be an air gap， light guide, metal-mirror, and so on. We can see that, the cross-talk could be decreased, but could not be eliminated. And it would be more serious when the off-axis angle is larger. The Cross-talk effect would limit the off-axis angle of ML, and focal ratio (not too fast).

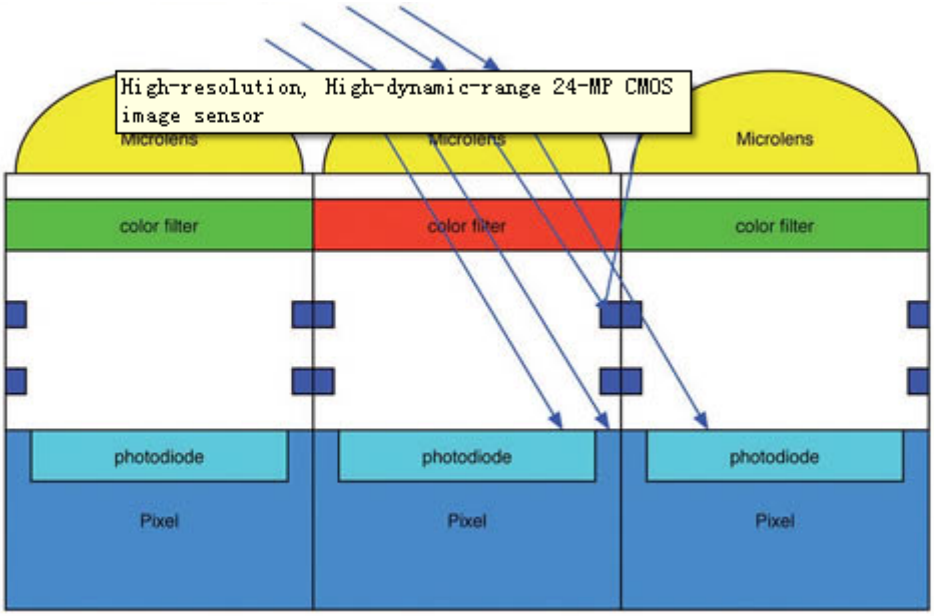

Fig4: Cross talk effect of sCMOS

Read speed and Noise

Our requirement for the detector is fast speed with low noise at the same time. For the CCD, read speed and noise is a compromise pair of specifications. Fast speed means high noise. To get low noise, you have to accept slower speed. EMCCD introduced EM gain to decrease the read noise floor relatively. It could reach both fast read speed and low read noise. But, EM gain could introduce additional noise, multiplicative noise, we use a noise factor to describe it. The additional noise would limit the ability for the measurement of a bright signal.

For sCMOS, the compromise between speed and noise disappeared. We know that, parallel architecture means fast speed. Thanks to the improvement of lithography and process control in the fabrication these years, sCMOS could reach low read noise with fast speed at the same time. It means that, we could get high sensitivity and high temporal resolution at the same time. And, the noise is so low that sCMOS could reach a high dynamic range, although the full depth is lower.

PRNU

The PRNU, Pixel Response Non-Uniformity, is one drawback of CMOS, because of its parallel architecture. It is difficult to overcome. Thanks to lithography and process control in fabrication, the PRNU could be decreased a lot. sCMOS's non-uniformity could reach a level of one percent. It is a little larger than CCD, but it is comparable. The linearity is the important parameter to describe how well is the detector response to differences of the intensity of the signal. High linearity is a requirement of detectors. Both CCD and sCMOS are well enough in the valid range. sCMOS could reach 99.9%, which is a little superior to CCD.

Shutter

Another component of the detector is the shutter. It is used to control the exposure time. In the CCD, the shutter is a mechanical structure. So for the operation time we need to be consider: the shutter effect would occur when the shutter is opening or closing, and the shutter can easily fail for mechanical reasons. For the sCMOS, the shutter is electronic. So there is no shutter effect, and the malfunction rate would decrease a lot. But, the electronic shutter is difficult to be suitable for a large image area.

Dark current

Dark current is an important parameter for a long time exposure. It is proportional to the temperature. sCMOS introduced semiconductor cooling technology, and it could be cooled to minus forty degrees. The dark current (see Fig 5) could reach 0.03 electron per pixel per second, which is comparable to CCD.

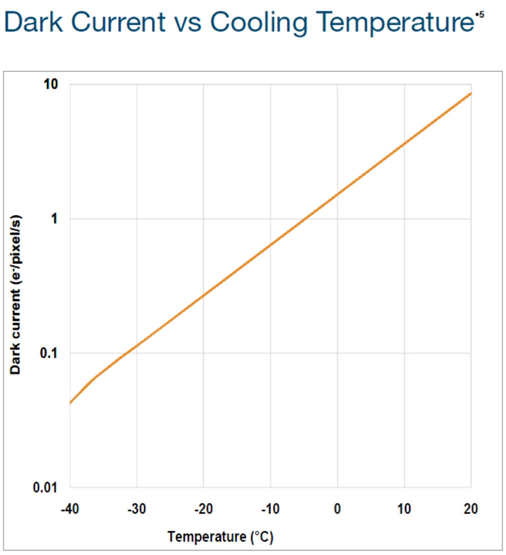

Fig5: Dark current of sCMOS

sCMOS VS CCD

Table 1 shows the main specifications of sCMOS and the comparison with a CCD.

Table 1: Performance of sCMOS (Andor Neo sCMOS)

Parameter	Performance	VS CCD
quantum efficiency(QE)	57%@570nm	lower than back illuminated CCD
image area	16.6mm×14mm	comparable to CCD
pixel size	6.5μm	smaller than CCD
fill factor	>90%	less than CCD (usually 100%)
read noise	$1e^-$@100Mhz $1.4\ e^-$@280Mhz	less than normal CCD, comparable to EMCCD
read speed	100/280Mhz	much faster than CCD
full well	$29400e^-$	less than CCD
dark current	$0.03e^-$/pixel/sec(-40℃)	lower than normal CCD, comparable to EMCCD
photo response non uniformity	1%	comparable to CCD
linearity	99.9%	a little superior to CCD
shutter	electronic	eliminate the shutter effect and reduce the malfunction rate of CCD(mechanical)

From Table 1, we could conclude that the sCMOS has its advantage of small pixel size to get high spatial resolution and fast read speed with lower read noise to get high temporal resolution. However, its lower fill factor would influence the photometric accuracy, and its lower QE would limit the performance of faint source's measurement. Its lower full well would limit the dynamic range.

In conclusion, sCMOS has its advantages and disadvantages of optical measurements. It needs to be applied in observations to verify its performance.

Application

We use a 25cm (f/3.6) telescope, with sCMOS camera, to observe stars to measure its photometric accuracy, which is shown in Fig 6.

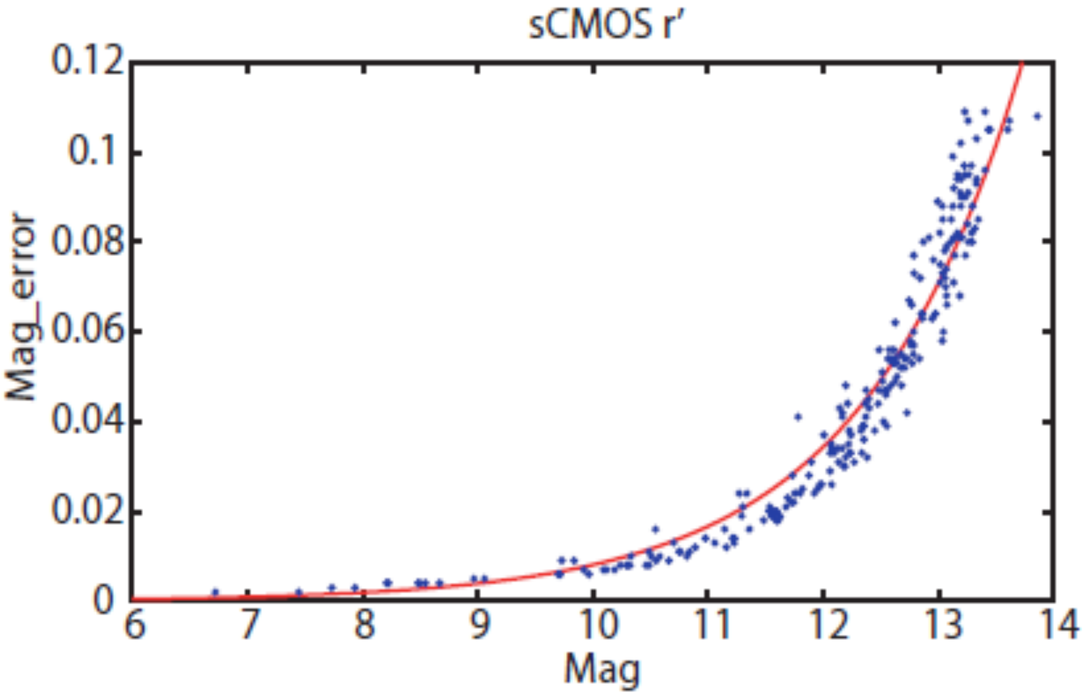

Fig 6: the magnitudes and photometric accuracies of stars by sCMOS camera

Also, we acquire the image of space debris to check performance of sCMOS (shown in Fig 7).

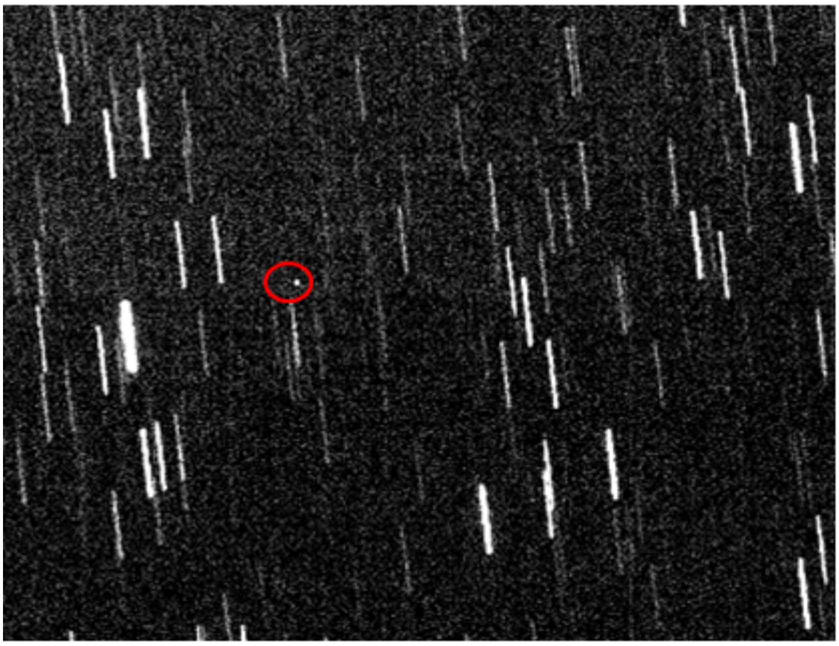

Fig 7: image of space debris acquired by sCMOS camera

Conclusion

For the space debris measurement by sCMOS, we could acquire high temporal and spatial resolution, with photometric accuracy comparable to CCD. It would be widely applied in space debris measurement in the near future.

Reference

Evaluation of a scientific CMOS camera for astronomical observations, Research in Astron. Astrophys. **2013** Vol. **13** No. **5**, 615–628 , Peng Qiu, Yong-Na Mao, Xiao-Meng Lu, E Xiang and Xiao-Jun Jiang, 2013 Vol. 13 No. 5, 615–628