Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting
August 23–26 & August 30–September 1, 2021

CONTEMPORARY OPTICAL SURVEILLANCE TECHNOLOGIES

J. Garner
Oak Ridge National Laboratory

K. Jenkins
Pacific Northwest National Laboratory

J. Hite
Oak Ridge National Laboratory

G. Westphal
Oak Ridge National Laboratory

A. Moore
Pacific Northwest National Laboratory

J. Benz
Pacific Northwest National Laboratory

J. Cree
Pacific Northwest National Laboratory

M. MacDougall
Pacific Northwest National Laboratory

N. Moore
Pacific Northwest National Laboratory

N. Smith
Pacific Northwest National Laboratory

ABSTRACT

This paper will discuss recent advances in digital imaging technologies that may be applicable for International Atomic Energy Agency (IAEA) safeguards. This paper describes CCD and CMOS sensors and techniques to improve their low light performance. This paper also introduces alternatives to visible light imaging, such as infrared (IR) cameras and time-of-flight sensors and briefly presents some of the other technologies the ORNL team investigated.

INTRODUCTION

Beginning in fiscal year 2020, Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) conducted a preliminary evaluation of candidate imaging technologies that might supplement the current surveillance systems employed for international safeguards or be considered for future surveillance systems. This paper focuses on an introduction to CCD and CMOS sensors for visible light imaging and techniques to optimize low-light performance.

SILICON SENSOR USE CASES AND IMPROVEMENTS

Modern digital visible light imaging sensors typically consist of an array of photosensitive pixels arranged on silicon in a rectangular grid. Incoming photons are converted into electrons using the photoelectric effect. The sensors are categorized as either charge-coupled devices (CCDs) or complementary metal-oxide semiconductor (CMOS) sensors.

CCD SENSORS

CCD pixels are based on a semiconductor capacitor, which accumulates charge proportional to the incoming light. The accumulated charge is transferred sequentially along a row or column of adjacent pixels and into a shift register that feeds into a common amplifier for readout, hence the name *charge-coupled*. Because the charge from each pixel uses a single amplifier and readout, the gain for each pixel is very uniform, but the frame rate can be slow. Figure 1 provides a high-level schematic demonstrating the key components of a CCD sensor. In comparison, Figure 2 provides a high level schematic demonstrating the key components of a CMOS sensor.

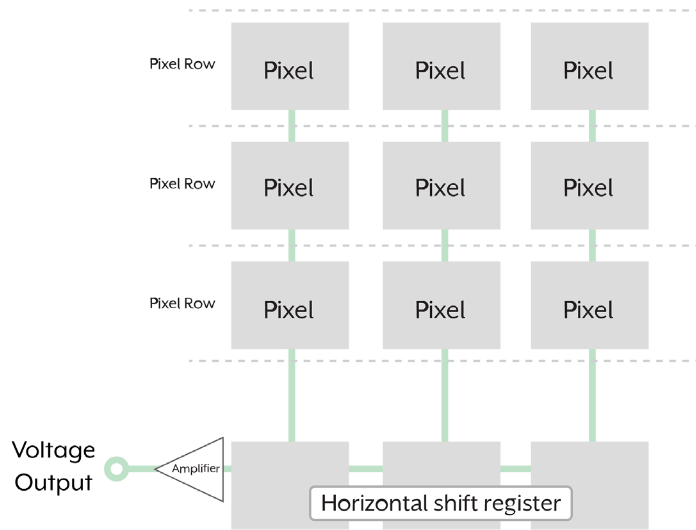

Figure 1. Pixel matrix in a CCD sensor.[1]

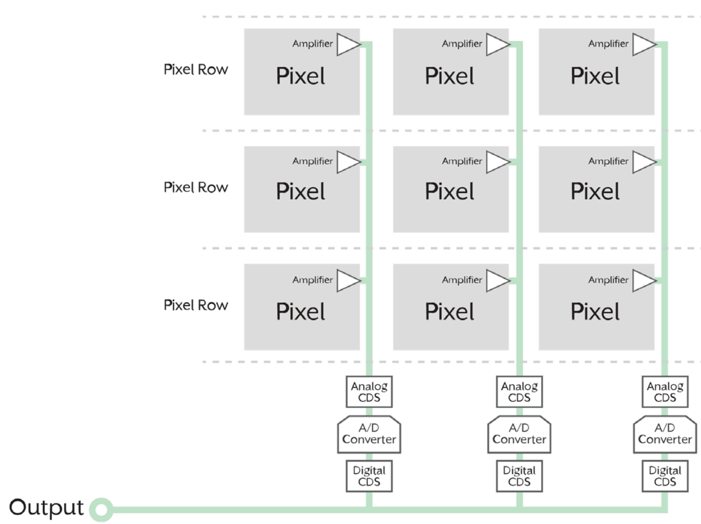

Figure 2. Pixel matrix in a CMOS sensor.[2]

There are several approaches for transferring the charge from pixels to amplifier in CCD sensors. As shown in Figure 3, interline transfer CCDs placed shift registers between pixels. Charge was shifted through the registered sequentially until the charge from each pixel was output. This is the most common type of CCD sensor and was popularized by Sony. Natively interline transfer CCDs have a fill factor of only about 30% which means only 30% of incoming light reaches the photodiode substrate and the remainder is blocked by non-photodiode components. The fill factor can be improved to over 90% with

[1] Reprinted with permission from LUCID Vision Labs. Source: https://d1d1c1tnh6i0t6.cloudfront.net/wp-content/uploads/2017/08/Conventional-CCD-Sensor-3.svg extracted from [1].
[2] Reprinted with permission from LUCID Vision Labs. Source: https://d1d1c1tnh6i0t6.cloudfront.net/wp-content/uploads/2016/09/Conventional-CMOS-Sensor-2.svg extracted from [1].

microlenses[3]. A frame readout CCD, as shown in Figure 4, shifts the charge through other pixels until it reaches the shift register. This type of sensor may have a 90% fill factor without microlenses but readout is typically very slow, and the pixels are still active during readout making it essential to use a strobed light source or mechanical shutter to avoid incidental light during readout. Frame transfer CCDs, as shown in Figure 5, shift the charge from all pixels to a frame store, and then the image is read out from the frame store. Fill factors of about 90% are possible, but the sensors are generally expensive because of the increased chip size.

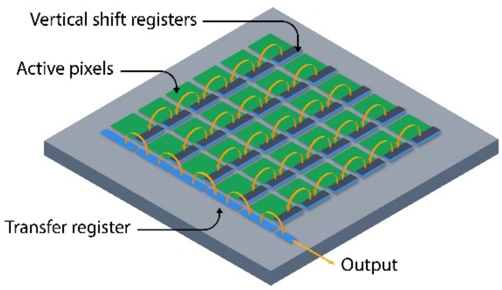

Figure 3. Interline transfer CCD[4]

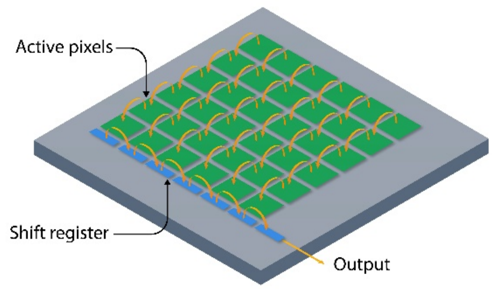

Figure 4. Frame readout CCD[4]

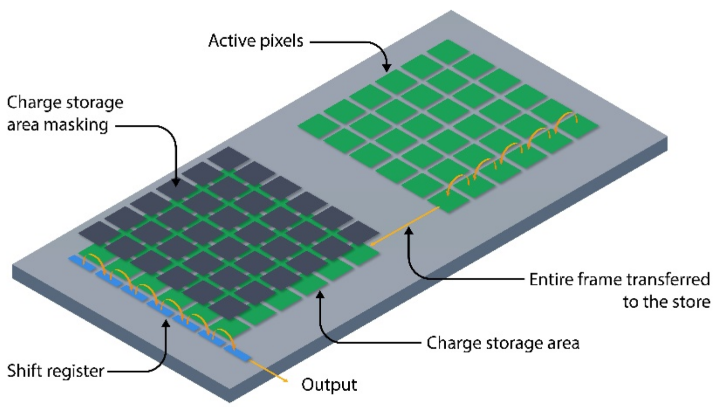

Figure 5. Frame transfer CCD[4]

Modern CMOS technologies and fabrication techniques have allowed CMOS sensors to surpass CCDs in price and performance for most applications; however, CCDs continue to outperform CMOS sensors for product stability, dynamic range, near IR performance, pixel binning, electron multiplication and some radiation tolerance applications [3]. Product stability may be particularly important for international safeguards applications given the extended development and deployment lifecycle of safeguards surveillance equipment. CMOS detectors are typically manufactured in commercial semiconductor foundries that produce many different types of CMOS devices. These CMOS production processes are constantly evolving resulting in process and design changes that can affect things such as radiation tolerance. While some of the largest manufactures ceased producing CCDs (e.g., Sony, OnSemi formerly Kodak), several vertically integrated fabricators continue to produce CCD sensors that offer longer term stability and availability for longer term projects [3, 4].

[3] Microlenses can focus incoming light onto the photodiode surface instead of allowing it to fall on the non-photosensitive areas of the device. Figure 6 and Figure 7 show a microlens in reference to the photosensitive photodiode area of each pixel. For more information see: https://hamamatsu.magnet.fsu.edu/articles/microlensarray.html
[4] Original work of Adam Malin inspired by [2].

CMOS Sensors

Pixels in a CMOS sensor are typically constructed of a photodiode and transistors. Since each pixel has its own amplifying transistor, readout can be performed directly instead of using the sequential charge transfer procedure used in a CCD. CMOS sensors are also known as *active pixel sensors* because each pixel has its own amplifier. Figure 2 provides a high-level schematic demonstrating the key components of a CMOS sensor.

CMOS SENSOR IMPROVEMENTS

CMOS sensors are generally composed of photosensitive array of photodiodes located on a silicon wafer substrate, which also contains the readout circuitry. As shown in Figure 6, the traditional approach (front side illuminated [FSI]) assembles the wiring and other components on top of the photosensitive element. This results in lower quantum efficiencies[5] as some light is blocked by the nonsensitive components. The complexities of wiring and other components that may block incident light form the photosensitive photodiode are more obvious in the schematic shown in Figure 7.

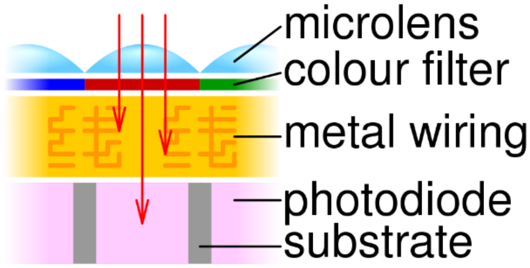

Figure 6. Side view of FSI sensor design.[6]

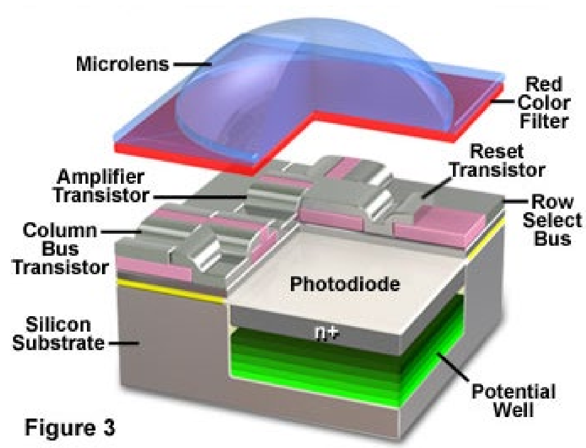

Figure 7. Traditional CMOS sensors include transistors and wiring that reduce the fill factor and quantum efficiency.[7]

As shown in Figure 8, manufacturers like Sony have drastically improved CMOS sensors over time. At least in the case of Sony, early CMOS sensors used aluminum wiring between the active components in each pixel. Sony's second generation sensors switched to copper traces, and its third generation switched to thinner copper and transistors. These changes resulted in better low light sensitivity especially for shorter wavelengths in the blue and green portion of the spectrum because the photons had a lower chance of being reflected off the metal wiring or dissipated in the transistor region thus improving their chance of reaching the pixel wells and being detected. As shown in Figure 9, the quantum efficiency of FSI CCD and CMOS sensors is limited, typically on the order of 50%. Sony and other vendors began introducing back side illuminated (BSI) sensors in fifth generation sensors around 2009 [5, 6]. As shown in Figure 8,

---

[5] *Quantum efficiency* refers to a sensor's spectral response to incident light. The fill factor refers to the amount of incident light that impinges on the photosensitive area, but quantum efficiency also accounts for a sensor's ability to convert the incident light into a signal.

[6] Reprinted with permission from https://en.wikipedia.org/wiki/Back-illuminated_sensor#/media/File:Comparison_backside_illumination.svg

[7] Reprinted with permission from MolecularExpressions.com at Florida State University Research Foundation Source: https://micro.magnet.fsu.edu/primer/digitalimaging/images/cmos/cmoschipsfigure3.jpg extracted from https://micro.magnet.fsu.edu/primer/digitalimaging/cmosimagesensors.html

BSI sensors position the wiring and other components below the photosensitive area such that incoming light shines directly onto the photosensitive layer, resulting in significantly higher typical quantum efficiencies. BSI CCD and CMOS sensors can achieve much greater quantum efficiencies than FSI sensors as shown in Figure 9. In fact, modern BSI CMOS sensors can reach quantum efficiencies in excess of 90%, which means they perform better in low light conditions and that they are generally preferable for surveillance applications [4]. However, FSI sensors are much easier and cheaper to manufacture than BSI sensors.

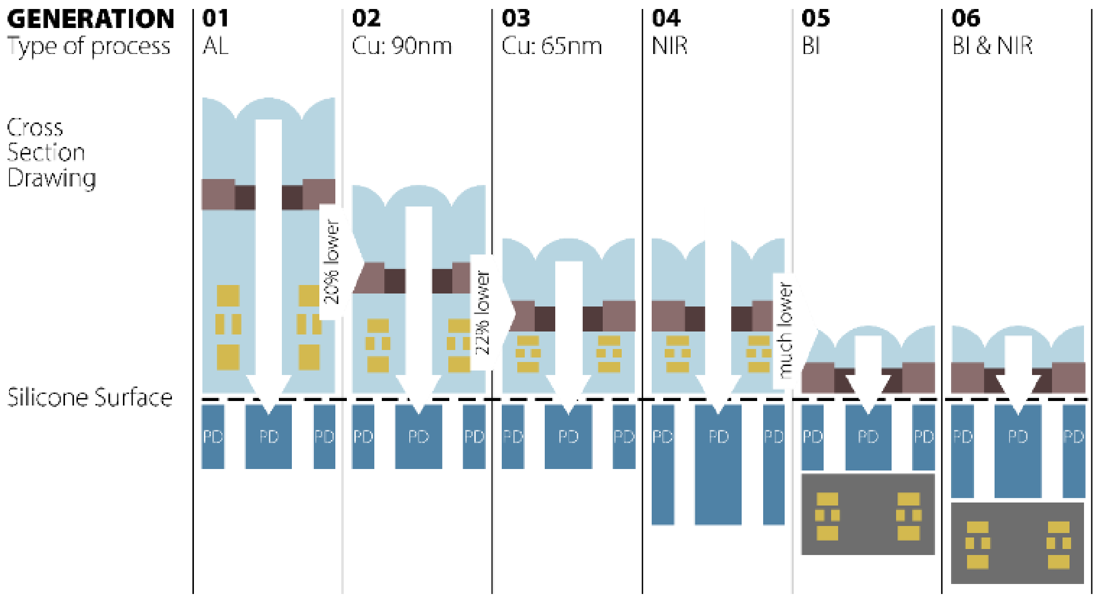

Figure 8. CMOS sensors have improved over time, with improvements from using thinner components with FSI, and more recently using BSI to improve quantum efficiency.[8]

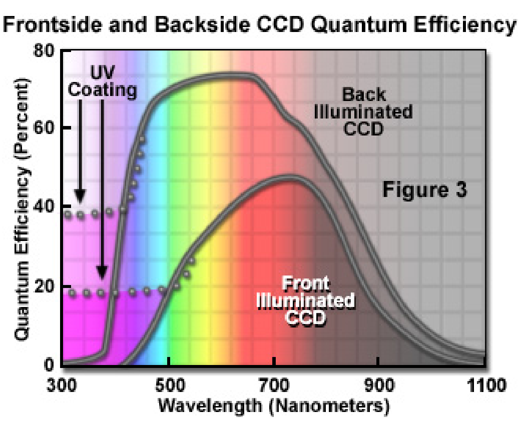

Figure 9. Quantum efficiency of a back-illuminated CCD versus a front-illuminated CCD.[9]

[8] Image credit: Original work of Adam Malin inspired by https://www.framos.com/en/news/what-is-sony-s-exmor-technology-anyway

[9] Reprinted with permission from MolecularExpressions.com at Florida State University Research Foundation Source: https://micro.magnet.fsu.edu/primer/digitalimaging/concepts/images/quantumefficiencyfigure3.jpg extracted from https://hamamatsu.magnet.fsu.edu/articles/quantumefficiency.html

CMOS GLOBAL SHUTTER

CMOS sensors historically had a *rolling shutter* where each row of pixels was sequentially reset, exposed, then readout before proceeding to the next row (Figure 10). Adjacent rows are exposed at slightly different times, which could lead to image distortion as shown with the helicopter blades in Figure 11 when capturing fast-moving objects. The rolling shutter also posed difficulties when synchronizing exposure with an external light source (e.g., a flash) [3]. Recently global shutter CMOS sensors have become more widely available, but it is still common to see rolling shutters used with CMOS sensors because of reduced complexity in the readout electronics [2]. Global shutter CMOS sensors do not suffer from the temporal distortion issues and are better suited to capture fast moving scenes.

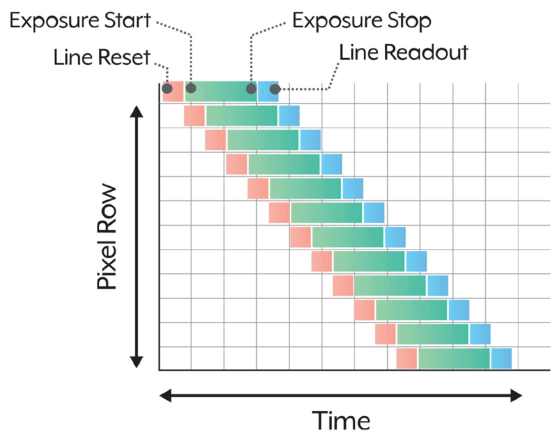

Figure 10. Pixel exposure sequence in a rolling shutter.[10]

Figure 11. Example of rolling shutter temporal distortion in an image of helicopter blades.[11]

BETTER LOW LIGHT PERFORMANCE

Although modern CMOS image sensors can have a quantum efficiency of close to 90%, this may be insufficient for some applications. This section will describe several techniques to improve images when a high quantum efficiency is not enough.

Several approaches could be used to improve performance in low light environments. One of the simplest is to increase the exposure time. For scenes that change slowly, the rate photons reach the sensor or individual pixels only changes gradually, so a longer exposure allows more photons to reach each pixel which can result in better low light images. However, images could be blurry if the camera vibrates during exposure or if an object moves through the scene quickly.

A monochrome sensor will likely capture better low light images than the color version of the sensor. As shown in Figure 12, image sensors provide color images by adding a Bayer filter above the photosensitive pixels. The Bayer filter makes pixels preferentially more sensitive to some portions of the spectrum by blocking other portions of the spectrum, at the cost of reducing the overall quantum efficiency. As shown in Figure 13, for a monochrome sensor the quantum efficiency of every pixel is maximized; however, with a color imager using a Bayer filter, 25% of the pixels are preferentially sensitive to blue and IR light,

---

[10] Reprinted with permission from LUCID Vision Labs. Source: https://d1d1c1tnh6i0t6.cloudfront.net/wp-content/uploads/2017/08/rolling-shutter-timing.svg extracted from [1].
[11] Reprinted with permission from Wikimedia. Source: https://en.wikipedia.org/wiki/Rolling_shutter#/media/File:Jamtlands_Flyg_EC120B_Colibri.JPG

50% of the pixels are preferentially sensitive to green and IR light and the remaining 25% of pixels are preferentially sensitive to red and IR light.

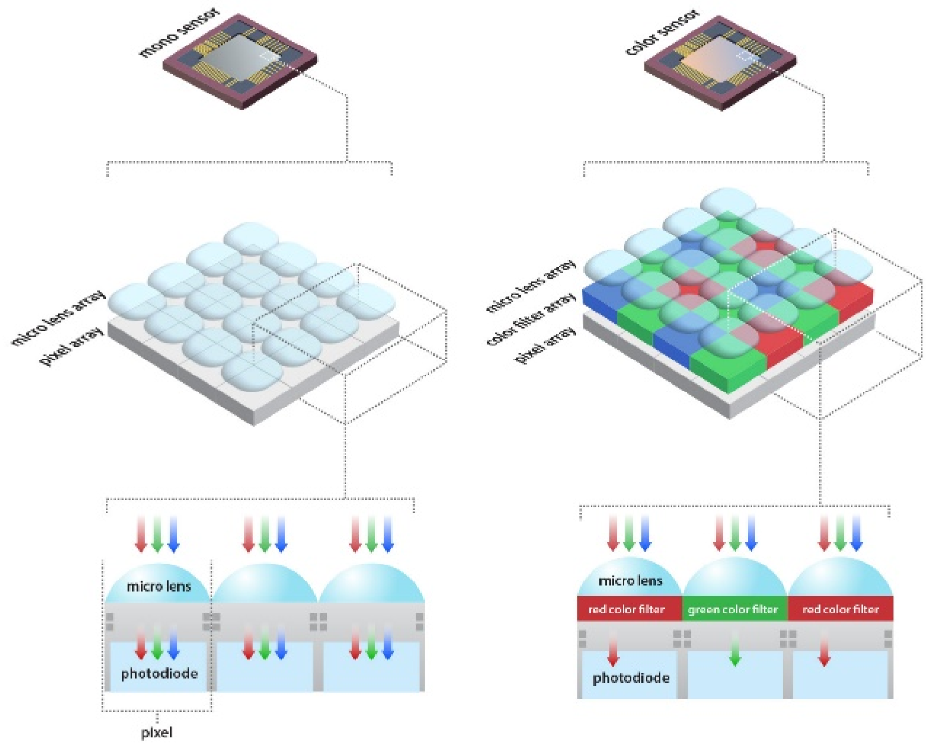

Figure 12. Comparison of monochrome sensor (*left*) to color sensor with Bayer filter (*right*).[12]

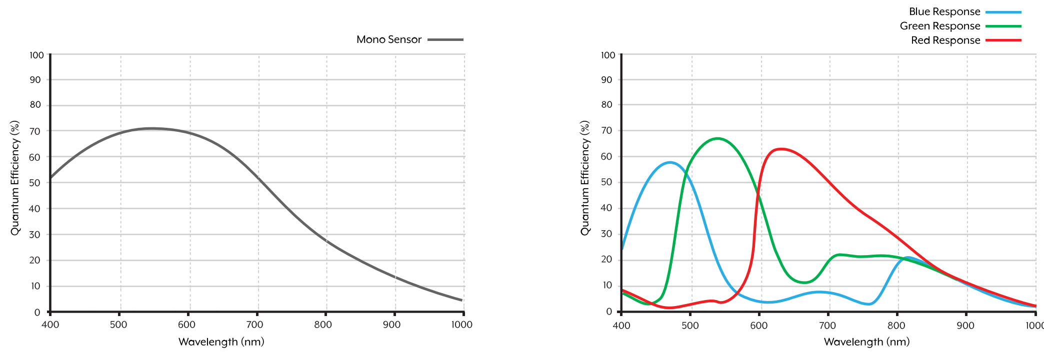

Figure 13. Spectral response of monochrome pixels compared to the same sensor with a Bayer filter.[13]

CCDs and CMOS sensors inherently suffer from several sources of noise which reduce the detectable contrast in images. One source of noise is read noise which results from the analog to digital conversion process. Binning, or combining the signal from several pixels, can improve performance in low light environments by reducing the effects of read noise. Some CCDs can be configured such that charge from adjacent pixels is combined before it is converted to a digital signal. For example, if a CCD sensor has a signal of three electrons (e-) per pixel and a read noise of 3e-, the signal-to-noise ratio would be 3/3 = 1.

[12] Reprinted with permission from LUCID Vision Labs. Source: https://d1d1c1tnh6i0t6.cloudfront.net/wp-content/uploads/2017/08/color-vs-mono-sensor-bayer-pattern-1.jpg extracted from [1].

[13] Reprinted with permission from Lucid. Source: https://d1d1c1tnh6i0t6.cloudfront.net/wp-content/uploads/2017/08/Mono-Color-Spectral-Response-charts-2.svg extracted from [1]

If the signal from four adjacent pixels were combined and then digitized, the signal would improve to 4 × 3e = 12 e-, yet the noise would remain 3 e-, resulting in a signal-to-noise ratio of 12 e- / 3 e- = 4. So, the signal-to-noise ratio would be four times better if the pixels are binned together. Of course, this improved signal to noise ratio comes at the cost of poorer spatial resolution because the signal from the four pixels is now read as a single super pixel. To bin the same four pixels after they had been digitized with a CMOS detector would result in the same 12 e- signal, but the noise would accumulate as the square root of the sum of the read noise (i.e., $\sqrt{4 \times 3\, e-} = 6\, e-$). So the signal-to-noise ratio binning on a CMOS would improve from 1 to 12 e- / 6 e- = 2, which is only half as good as the improved signal-to-noise ratio of binning on the CCD [6]. Figure 14 illustrates binning on a CCD sensor compared to Figure 15 which illustrates binning on a CMOS sensor. In these figures, photons are shown as yellow circles are converted to photoelectrons shown as green circles in each pixel shown as grey rectangles. For a CCD sensor, the photoelectrons are passed through the shift registers shown as blue rectangles before being combined with read noise electrons shown as gray circles. For the CMOS sensor the digitized signal is shown as red arrows being combined. Because the CMOS sensor digitizes the signal

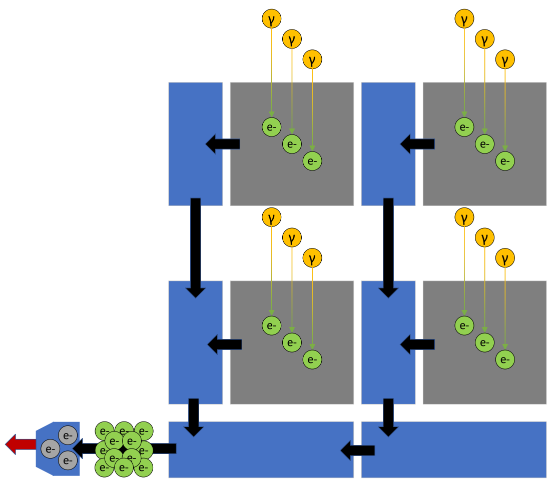

Figure 14. Passive pixel nature of CCD sensor retains benefits of binning signal from multiple pixels.[14]

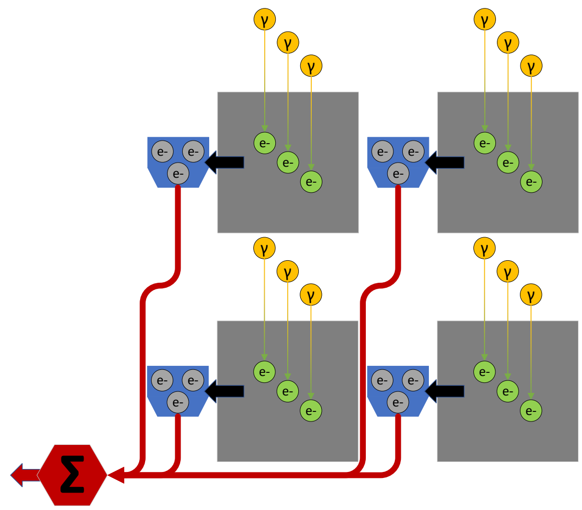

Figure 15. Active pixel nature of CMOS sensor minimizes benefits of binning pixels together for low light applications.[15]

A more exotic approach for low light scenes involves the use of electron-multiplying CCDs (EMCCDs). EMCCDs, as depicted in Figure 16, compared to a traditional CCD, as depicted in Figure 1 and Figure 14, include an electron multiplication register. By using an increased voltage (up to 50 V), secondary electrons are generated via impact-ionization along the multiplication register to achieve gains of up to 1000×. This approach allows single-photon detection. Single-photon detection may also be possible with single photon avalanche diode (SPAD) image sensors, which are more similar to an active pixel or CMOS sensors. Canon has released a 1-MP SPAD sensor, which performs the avalanche multiplication at each pixel as shown in Figure 17[7].

[14] Original work of Jim Garner
[15] Original work of Jim Garner

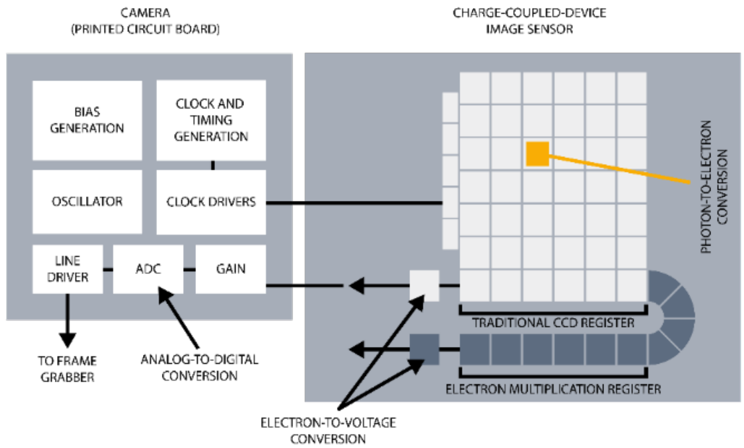

Figure 16. The signal from an EMCCD can pass through an electron multiplication register.[16]

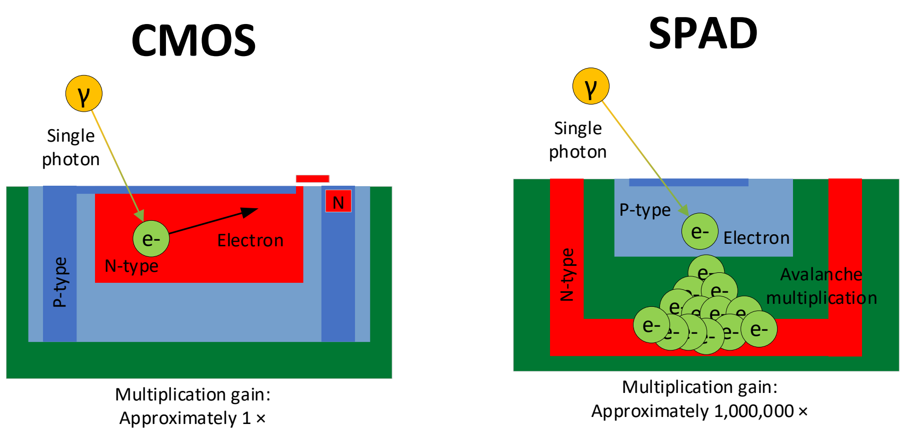

Figure 17. SPAD image sensor uses a high reverse bias for electron multiplication at each pixel.[17]

OTHER RELEVANT IMAGING TOPICS

As described above there are several approaches for better imaging in scenes with low visible light, but one surveillance approach may be to use other portions of the electromagnetic (EM) spectrum. For scenes with radiant heat sources, infrared (IR) cameras might provide a good alternative to relying on facility lighting. For example, spent fuel dry storage casks will likely emit heat during medium-term storage and the view from an IR camera may resemble the artist's conceptual view shown in Figure 18. There are several types of sensors that provide IR imagery. A summary of some of those methods is included in [8]. That reference also describes:

- multispectral imaging to fuse images from different portions of the EM spectrum for an improved image
- use of time-of-flight sensors to acquire depth information about a scene,
- enabling machine learning at the camera to process scene information more efficiently and potentially reduce transmission and data storage requirements,

[16] Original work of Adam Malin inspired by https://camera.hamamatsu.com/blobs/1328783831778?ssbinary=true extracted from https://camera.hamamatsu.com/jp/en/technical_guides/visual_guide/index.html

[17] Original work of Jim Garner inspired by: https://global.canon/en/news/img/2020/p20200624b.jpg extracted from https://global.canon/en/news/2020/20200624.html

- leveraging board level camera components to enable more cost-effective custom camera solutions,
- technical approaches used in low light astronomy cameras to reduce noise and improve low light performance, and
- approaches employed to improve the radiation tolerance of camera systems deployed in the nuclear industry.

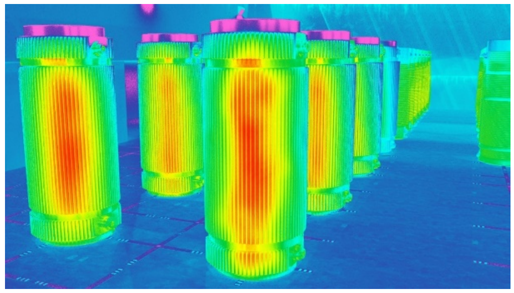

Figure 18. Conceptual view of cask storage area from an IR camera.[18]

CONCLUSIONS

International safeguards relies on surveillance to maintain continuity of knowledge between inspections. This paper described several recent advances in image sensor technology that may dramatically improve the quality of images in low light environments. This paper also introduced more exotic solutions such as EMCCD or SPAD sensors, which may enable even single photon imaging. Although visible light imaging has improved in recent years, other portions of the electromagnetic spectrum could also be used in lieu of or to supplement visible light imaging. For most surveillance applications a BSI CMOS sensor is sufficient, but CCDs offer some unique benefits including long term product stability which may be applicable for international safeguards.

ACKNOWLEDGMENTS

The work presented in this paper was funded by the US Department of Energy's National Nuclear Security Administration, Office of International Nuclear Safeguards.

REFERENCES

[1] *Introduction to Image Sensors | LUCID Vision Labs.* [Online]. Available: https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/. (accessed: Sep. 29, 2020).

[2] *The Future is Bright for CCD Sensors.* [Online]. Available: https://www.teledyneimaging.com/media/1299/2020-01-22_e2v_the-future-is-bright-for-ccd-sensors_web.pdf.

[3] *OnSemi, Product Discontinuance Notification* (accessed: Jul. 14, 2021).

[4] *Sony Debuts World's First Digital Still Cameras with Back-Illuminated 'Exmor R' CMOS Sensor Technology.* [Online]. Available: https://www.sony.com/content/sony/en/en_us/SCA/company-news/press-releases/sony-electronics/2009/sony-debuts-worlds-first-digital-still-cameras-with-backilluminated-exmor-r-cmos-sensor-technology.html. (accessed: Jul. 26, 2021).

[5] Darren Bessette, *What is Sony's Exmor Technology Anyway?* [Online]. Available: https://www.framos.com/en/news/what-is-sony-s-exmor-technology-anyway. (accessed: Sep. 16, 2020).

[6] *Canon Global, Canon Develops World's First 1-megapixel SPAD Image Sensor | Canon Global.* [Online]. Available: https://global.canon/en/news/2020/20200624.html. (accessed: Jul. 26, 2021).

[7] J. Garner et al., *International Safeguards Camera Technology Considerations: Part II*. ORNL/SPR-2021/2036, Oak Ridge National Laboratory, Oak Ridge, TN, Aug. 2021.

[18] Image credit: Original work of Adam Malin of ORNL.