CCD versus CMOS: **Which is Better?**

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The Charge Coupled Device (known as a CCD) has dominated astronomy and consumer electronics for nearly five decades. But that is changing. Today, the Complementary Metal Oxide Semiconductor Active Pixel Sensor (CMOS APS, also known as CMOS) has matured to the point where it is replacing CCD detectors in all but the most specialized applications.

So which sensor is best for your needs? This ebook provides an overview of CCD and CMOS APS sensors—including how both types work, and a side-by-side comparison of features and advantages to help you make your decision.

First, A Brief History Lesson

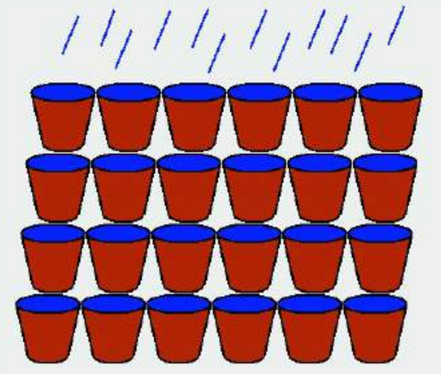
Invented in 1969, the Nobel prize-winning CCD became a mature technology after about 20 years. CCD cameras gained wide acceptance for still imaging, video, and photometric measurements, replacing the previous generations of bulky vacuum tube equipment. The Hubble Space Telescope, launched in 1990, famously uses CCD technology to produce its stunning vistas and science data. On the home front, consumers bought CCD-based handheld camcorders to record family life, and businesses used them for security cameras and inspection equipment.

In the mid-1980s, CMOS Active Pixel sensors were produced as a low-cost alternative to the dominant CCD technology. First proposed in 1968 by Peter Noble at Plessey in the UK, these sensors were updated in the early 2000s to use the now-standard CMOS transistor technology.

Early CMOS was only used in low-performance applications. However, with the advent of smartphones, security cameras and car safety systems, manufacturers were able to drive the development of low-cost CMOS at multi-million-unit volumes—driving prices down, and driving performance and innovation up. By 2007, CMOS had achieved market parity with CCD sensors, and by 2019 the first sensors capable of surpassing CCD performance appeared.

How Both Sensor Types Work

Camera sensors use picture elements known as “pixels” to detect light. A common analogy when talking about pixels is to imagine an array of buckets collecting rainwater. You could determine the shape and density of the cloud overhead by how much water ends up in each bucket.



CMOS and CCD both use arrays of silicon pixels (“buckets”) to detect light. When a photon of light hits a silicon atom, it knocks an electron into a higher energy state. This frees the electron to move through the material. It is now referred to as a photoelectron (“rain drop”).

The big difference happens when you read out the sensor.

CCD

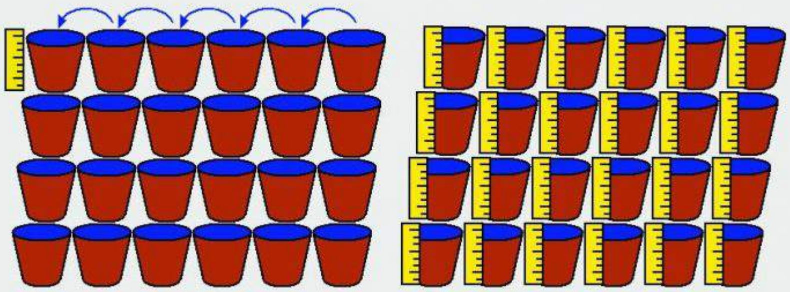
In a CCD, special electrodes attract and repel electrons, shuffling them out one-by-one to a corner of the chip. Using the analogy above, water is poured from one bucket to the next, like an old-fashioned fire brigade, until it reaches a corner of the array where it is measured. In a real sensor, a couple of on-board transistors make this measurement by converting the number of electrons from a pixel into a voltage. It then goes to some electronics outside of the sensor, which include an analog-to-digital converter. The result is a number for each pixel, describing how much light was detected. Since all the pixels are measured by the exact same electronics, CCD cameras can be made very consistent and accurate.

CCD sensors are built using either NMOS or PMOS technology, which was popular in the 1970s but is rarely used today for other semiconductor devices.

CMOS

Most modern electronics are built using Complementary Metal Oxide Semiconductor (CMOS) technology, which is a combination of NMOS and PMOS. By using CMOS, it is much easier to build complex electronics right into the sensor itself. This can be a major cost and space savings, especially for a miniaturized cell phone camera.

In a CMOS detector, there are transistors at every single pixel. They convert the signal to a voltage, which connects via internal wires to some complex on-board electronics. Typical CMOS sensors have one or two analog-to-digital converters for each column in the sensor. Instead of a couple of transistors on board, there can be millions.



CCD sensors have one readout in corner, while CMOS sensors have readout at each pixel.

Readout

By incorporating all these electronics into the sensor, the chip itself is made much more complex, but the camera is greatly simplified.

CCD sensors only have one, two, or sometimes four readouts—potentially one in each corner. CMOS sensors have thousands. This means that CMOS cameras can read out incredibly fast, even 100x faster than a comparable CCD. For long-exposure applications this is not so important—but it is especially important for video cameras.

These thousands of readouts in a CMOS sensor have a huge speed advantage, but there is a high price to be paid in terms of amplifier glow and pattern noise. CCD users have seen a little glow in the corners of the sensor; early users of CMOS sensors were overwhelmed by the glow and long exposure problems of these new sensors.

Side-by-Side Comparison

In the last few years, the best CMOS sensors are finally approaching or even exceeding CCD performance levels, but not in every aspect. This table compares CCD to the highest-performing CMOS sensors available today.

As you can see on the following pages, CCDs still have some significant advantages for high-performance, low light level imaging—although these advantages are slowly being chipped away at by new CMOS technology:

Parameter	CCD	Scientific CMOS	Winner
Availability	Some major CCD sensor lines are becoming obsolete. Very expensive specialty sensors made by companies like Teledyne e2v are here for the foreseeable future.	Companies are making major investments, and the technology has been improving rapidly. New sensors appear all the time.	CMOS is the future for most applications. CCD will continue to serve specialty niches such as scientific instruments.
Cost *Both the sensor and the camera itself*	Large CCD sensors are expensive, and external analog and digital camera electronics are complex.	Large CMOS sensors are similarly expensive. Analog electronics are eliminated but digital electronics are more complex.	For simple cameras, CMOS is much cheaper. For cooled low-light imaging cameras, there is little to no difference.
Sensitivity (Quantum Efficiency)	60-95%, though high QE sensors are very expensive.	75-95%	CMOS provides more bang for your buck.
Speed *Readout in megapixels per second (MPS)*	1 to 40 MPS	100 to 400 MPS	CMOS
Read Noise *How much noise in electrons is produced at each pixel when the sensor is read*	5-10 electrons for standard CCDs, 1 electron for more complex electron multiplying devices (EMCCD).	1-3 electrons is common for modern CMOS sensors, and this continues to improve.	CMOS or EMCCD
Cooling	High cooling is relatively easily achieved.	Sensors generate a large amount of heat and cannot operate at extreme cold temperatures.	CCD
Electronic Shutter	Interline and frame transfer sensors only.	Rolling shutter is less complex but pixels expose at different times; global shutter is more expensive.	No major advantage of one over the other.
Mechanical Shutter	Required for full-frame sensors; very helpful for image calibration.	Very helpful for image calibration.	No major advantage of one over the other.

Parameter	CCD	Scientific CMOS	Winner
Pixel Size	3 to 25 microns	2 to 9 microns	Larger pixels are a better match for long focal length telescopes. Most CMOS sensors have small pixels, but some larger pixel models are appearing.
Well Depth *How many electrons can each pixel hold—very important for photometry*	40,000 to 200,000	30,000 to 75,000. Can be mitigated via stacking given low read noise.	CCD, but stacking can give CMOS the advantage.
Analog-to-Digital (A/D) Converter Bits	16 bits	Usually 12; some chips now use dual gain to create 16-bit images but with some pitfalls. 14- and 16-bit sensors are becoming available.	CCD
Binning *Combining pixels for sensitivity or resolution matching*	Easily achieved at an analog level with zero added noise, with extremely high binning levels possible.	On-chip analog binning is extremely limited; most available sensors can only perform 2×1.	CCD
Amp Glow *On-board electronics create some light via LED effect*	Easily mitigated by powering down readout transistors.	This is a bigger problem with CMOS, since there can be millions of on-board transistors.	CCD, though CMOS has improved substantially.
Infrared Imaging	Deep depletion sensors can achieve high QE at 650 to 1000 nm.	Currently not possible with CMOS sensors based on silicon.	CCD
Fixed Pattern Noise	Occasional hot columns, easily mitigated.	Fixed pattern noise can be a significant problem, but technology is improving rapidly.	No major advantage with newer sensors.
Calibration *How "clean" an image can be created*	Techniques for CCDs are well-established and effective.	Can be more complex, e.g. HDR modes, lack of overscan data; techniques are still being perfected.	CCD

Which Sensor is Right For You?

If you need to detect extremely faint light sources, you will require either hour-long exposures or very high binning factors to achieve sufficient signal-to-noise ratio. For these applications, CCD sensors have a massive advantage over the newer CMOS technology—they have far less “amp glow” and have far better analog binning capabilities. CMOS sensors simply don’t work in these applications.

So why, then, are major companies switching to CMOS now? The reality is that most (non-scientific) imaging applications require video or short exposures. In those situations, CMOS is superior in both cost and performance. This has undermined the economic proposition for manufacturing CCD sensors in volume.

As a result, ON Semiconductor discontinued the former Kodak / Truesense devices in 2019. But this is not the end of CCD technology. Certain Sony CCD sensors will be available until 2026. For high-end astronomy and spectroscopy markets, companies like Teledyne e2v will continue to manufacture extreme-performance CCD sensors for years to come.

Serious astronomical applications such as photometry and spectroscopy or life sciences applications such as bioluminescence and fluorescence will continue to need CCD technology for the near term. Less demanding imaging or those needing higher speed imaging will all switch to CMOS sensors.

The technology, and the imaging market in general, continues to change rapidly. As such, it is likely that the state-of-the-art in CMOS will soon be used in ever more applications.

To meet your needs for today and tomorrow, Diffraction Limited’s SBIG® line of cameras includes both high-performance CCD and modern CMOS APS sensors.

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