CCD Vs. CMOS or Exmor CMOS: Which Image Sensor Is Better and Why?

1 Introduction

Much has been written about the relative advantages of CMOS versus CCD sensors. It seems that the debate has continued on for as long as most people can remember with no definitive conclusion in sight. It is not surprising that a definitive answer is elusive, since the topic is not static. Technologies and markets evolve, affecting not only what is technically feasible, but also what is commercially viable. Imager applications are varied, with different and changing requirements. Some applications are best served by CMOS sensor, some by CCDs. In this article, we will attempt to add some clarity to the discussion by examining the different situations, explaining some of the lesser known technical trade-offs, and introducing cost considerations into the picture.

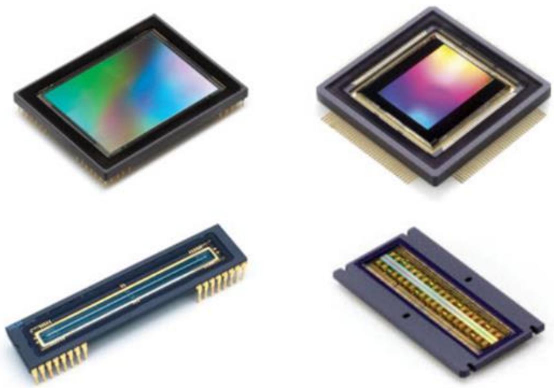


Fig. 1 CCD (left) and CMOS (right) image sensors

2 In the Beginning...

CCDs and CMOS imagers were both invented in the late 1960s and 1970s.

CCD became dominant, primarily because they gave far superior images with the fabrication technology available.

CCD (charge coupled device) and CMOS (complementary metal oxide semiconductor) image sensors are two different technologies for capturing images digitally. Each has unique strengths and weaknesses giving advantages in different applications.

Fig.2 Comparative pictures of CCD image and CMOS image

Though both the sensors work on the same principle, there are differences in their functioning. Before we start with the discussion, here is a comparative picture taken from cameras that use CCD image sensor and CMOS image sensor. You can spot the difference for yourself!

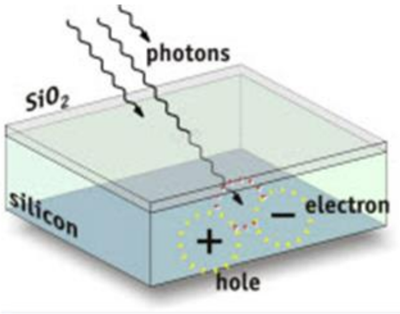


Fig.3 Photoelectric Effect

CCD and CMOS imagers both depend on the photoelectric effect as shown in Fig.3 to create electrical signal from light. Both types of imagers convert light into electric charge and process it into electronic signals.

In a CCD sensor, each cell acts as an analog device. The light that falls on the sensor is stored as an electrical charge in the photo sensors. An additional circuitry converts this electrical charge into digital information. This unit electrical charge is considered to be one pixel when the digital information is read.

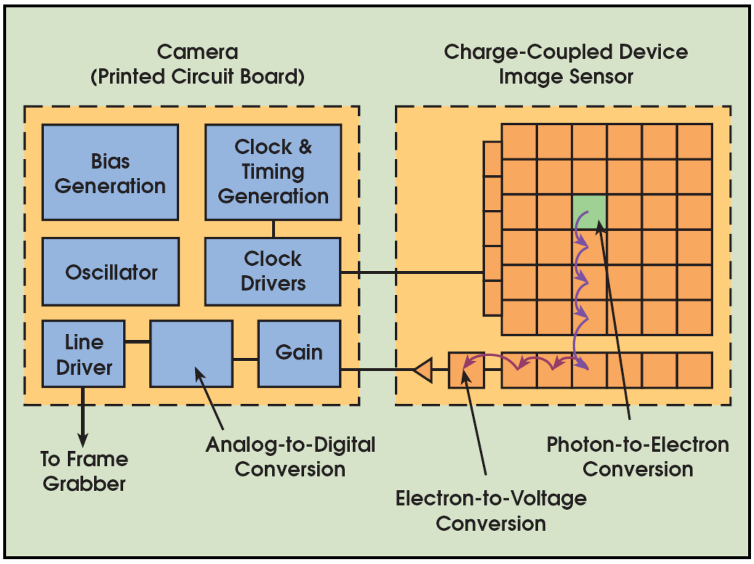


Fig.4: Transfer Principle of CCD sensor, On a CCD, most functions take place on the camera's printed circuit board. If the application's demands change, a designer can change the electronics without redesigning the imager.

In a CMOS sensor, each pixel has its own charge-to-voltage conversion. So, when the light strikes the chip, the electrical charge is converted to a prefixed voltage value, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. These other functions increase the design complexity and reduce the area available for light capture. With each pixel doing its own conversion, uniformity is lower, but it is also massively parallel, allowing high total bandwidth for high speed.

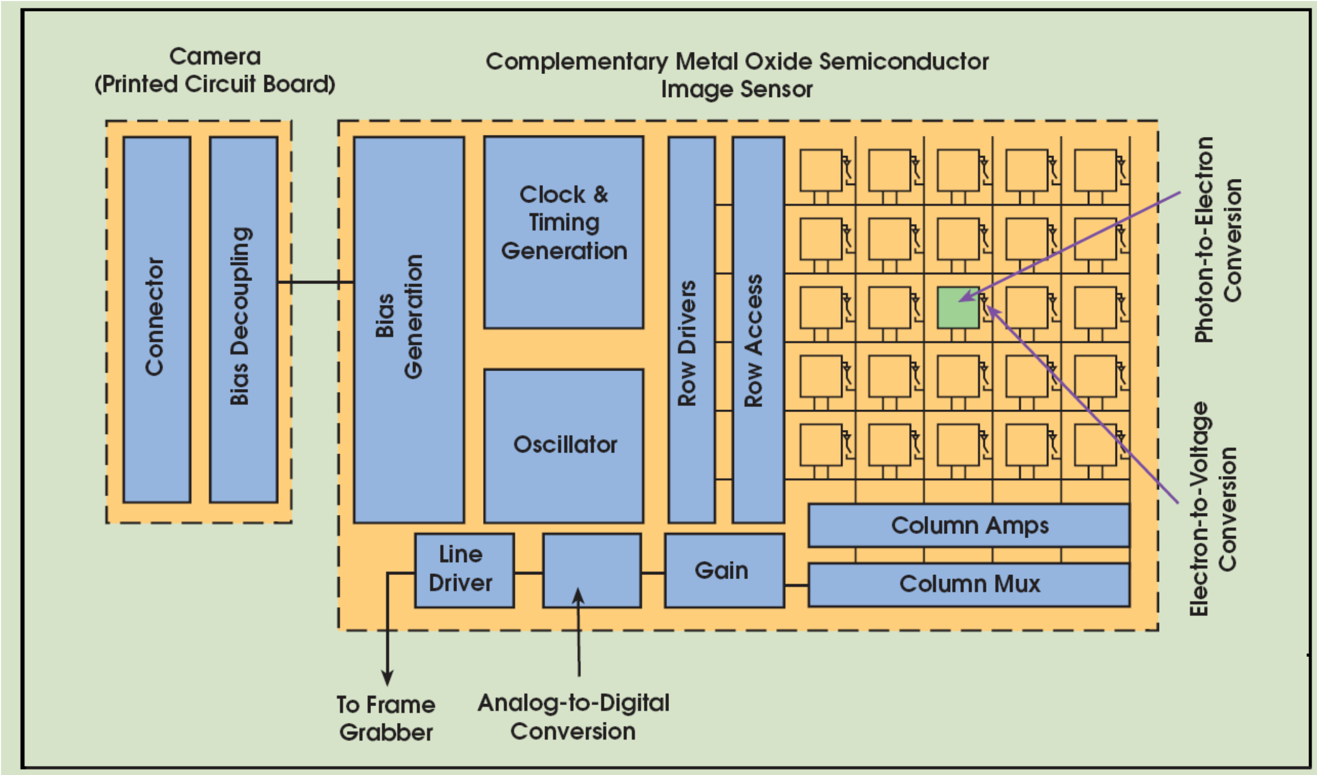


Fig. 5 Principle of CMOS Sensor: A CMOS imager converts charge to voltage at the pixel, and most functions are integrated into the chip. This makes imager functions less flexible but, for applications in rugged environments, a CMOS camera can be more reliable.

CMOS image sensors required more uniformity and smaller features than silicon wafer foundries could deliver at the time. Not until the 1990s did lithography develop to the point that designers could begin making a case for CMOS imagers again. Renewed interest in CMOS was based on **expectations of lowered power consumption, camera-on-a-chip integration, and lowered fabrication costs from the reuse of mainstream logic and memory device fabrication**. Achieving these benefits in practice while simultaneously delivering high image quality has taken far more time, money, and process adaptation than original projections suggested, but CMOS imagers have joined CCDs as mainstream, mature technology.

The most important point to consider while looking at image sensors is the clarity of the images. Images should be free from any distortions. Mentioned below are a few other factors that differentiate the CCD and CMOS sensors.

3 CCD vs. Conventional CMOS Sensor

3.1 Construction

CCD chips record the pixels (when light strikes) on the chip and then send these pixels one after the other, thus the time taken for sending the pixels for one image increases. Also, due to constant fetching and sending actions, the chip uses a lot of energy.

In case of CMOS chips, the sensors themselves have a lot of inbuilt circuitry, which enables reading of the pixels at the photo sensor level itself. This data is transmitted all at once. So, there is no time lag, and also, less energy is utilized due to this action.

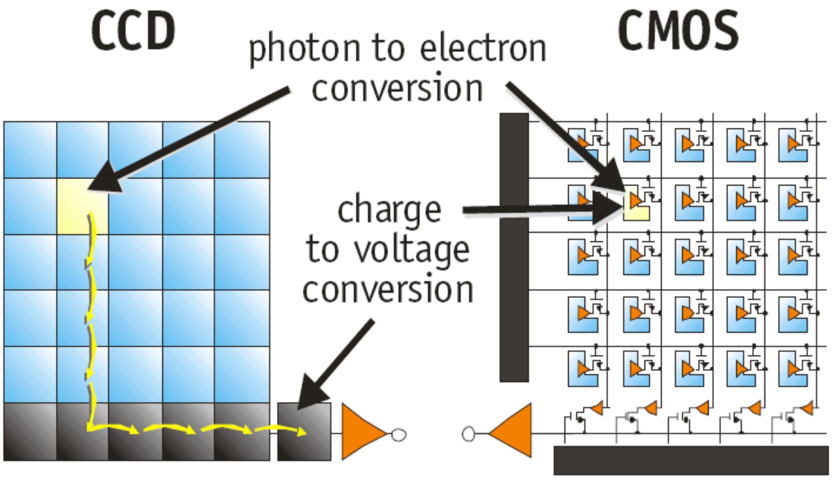


Fig.6. CCDs move photo generated charge from pixel to pixel and convert it to voltage at an output node; CMOS imagers convert charge to voltage inside each pixel.

3.2 Light Sensitivity

CCD sensors work effectively in low light conditions because of **higher fill factor**. The pixels are first recorded on the chip and then they are transmitted. Hence, the image will be enhanced. But due to constant transmission of data, the efficiency of the sensor reduces.

In CMOS, there are a lot of sensors that are cluttered on the chip. Thus, the light sensitivity reduces as there are a number of circuits through which the light needs to penetrate (**lower fill factor**). Thus, such an image can be of low quality. However, due to the presence of small circuits on the chip, the image is boosted at every stage. Hence, even though the original image may be low in quality, the output image will be a better one.

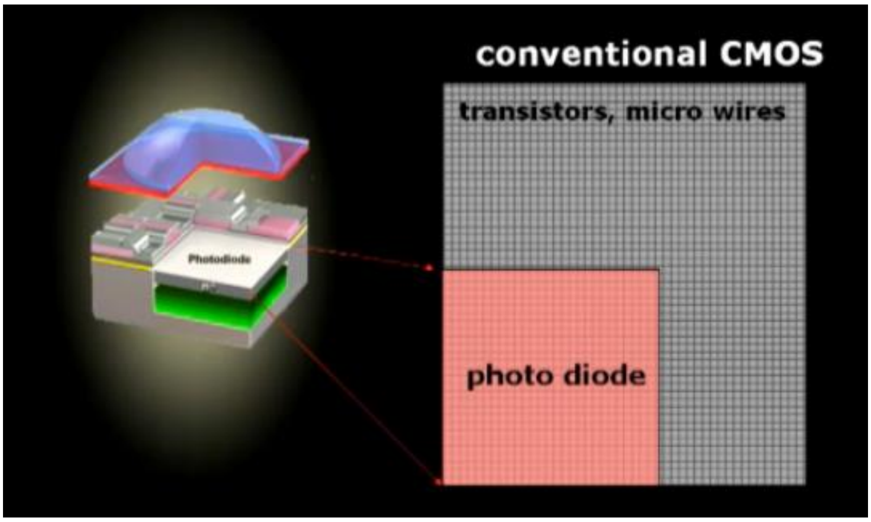


Fig. 7 Fill factor of CMOS sensor

3.3 Power

As mentioned earlier, CCD sensors have constant fetch-transfer cycles. Thus, the power consumed by the chip is huge.

However, CMOS sensors convert the data into digital form and send this data, all in one go, thus consuming very little power.

3.4 Vertical Streaking or Vertical Smear

When the CCD sensor-based cameras are used in live or video mode, they exhibit vertical streaking. In such images, a vertical bright line is created. As there are a lot of analog sensors present in a row, the current that overflows one of the sensors, leaks to the entire row, thus creating a vertical line. However, in other modes, CCD sensors do not have such characteristics.

There is no such problem in CMOS sensors as each circuit is perfectly isolated from the rest of the circuits on the chip.

Fig. 8 Vertical streaking (Left)

3.5 Biasing and clocking

CMOS imagers have a clear edge in this regard. They generally operate with a single bias voltage and clock level. Nonstandard biases are generated on-chip with charge pump circuitry isolated from the user unless there is some noise leakage. CCDs typically require a few higher-voltage biases, but clocking has been simplified in modern devices that operate with low-voltage clocks.

3.6 Shuttering

The ability to start and stop exposure arbitrarily. It is a standard feature of virtually all consumer and most industrial CCDs, especially interline transfer devices, and is particularly important in machine vision applications. CCDs can deliver superior electronic shuttering, with little fill-factor compromise, even in small-pixel image sensors.

Implementing uniform electronic shuttering in CMOS imagers requires a number of transistors in each pixel. In line-scan CMOS imagers, electronic shuttering does not compromise fill factor because shutter transistors can be placed adjacent to the active area of each pixel. In area scan (matrix) imagers, uniform electronic shuttering comes at the expense of fill factor because the opaque shutter transistors must be placed in what would otherwise be an optically sensitive area of each pixel. CMOS matrix sensor designers have dealt with this challenge in two ways:

A nonuniform shutter, called a rolling shutter, exposes different lines of an array at different times. It reduces the number of in-pixel transistors, improving fill factor. This is sometimes acceptable for consumer imaging, but in higher-performance applications, object motion manifests as a distorted image.

A uniform synchronous shutter, sometimes called a nonrolling shutter, exposes all pixels of the array at the same time. Object motion stops with no distortion, but this approach consumes pixel area because it requires extra transistors in each pixel. Users must choose between low fill factor and small pixels on a small, less-expensive image sensor, or large pixels with much higher fill factor on a larger, more costly image sensor.

CMOS sensors have a rolling shutter wherein all parts of a frame are not captured at a time. Each part of the frame is captured separately, and then, all these parts are displayed at once. This may induce a time lag in frames, and the images may wobble or suffer from skew. However, the high-end CMOS cameras have more efficient sensors.

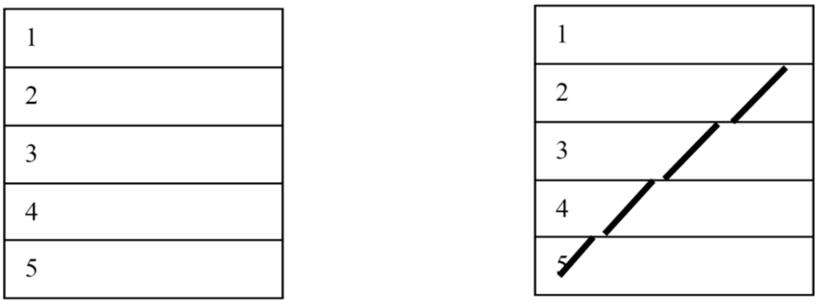


Fig.9 Imaging sensor with only 5 lines of resolution using rolling shutter readout.

In this example we read line 1 completely before line 2 is read and so forth. A line consists of many pixels. Typical line times, depending on the frame rate and sensor architecture, can be several hundred microseconds.

When reading line 1 out, lines 2, 3, 4 & 5 are being exposed. Line 1 will start being exposed again after it is completely readout. Therefore, a fast moving object within one frame time could have discontinuities due to the "rolling exposure".

3.7 Image Quality

CCD sensors have better uniformity as the same electronic generates the value for each pixel. Only a few transistors are involved and thus can generate lower noise. lower noise levels because its layout allows more pixels to be made on its surface. Hence, the colors of the images that are captured are more vibrant. This improves the image quality.

On the other hand, CMOS sensors, due to their layout, each circuit have their own characteristics, which generate fixed pattern noise in the image. Several transistors with individual differences generate higher noise.

3.8 Windowing Function

One unique capability of CMOS technology is the ability to read out a portion of the image sensor. This allows elevated frame or line rates for small regions of interest. This is an enabling capability for CMOS imagers in some applications, such as high-temporal-precision object tracking in a subregion of an image.

CCDs generally have limited abilities in windowing.

3.9 Speed;

Speed is an area in which CMOS arguably has the advantage over CCDs because all camera functions can be placed on the image sensor.

With one die, signal and power trace distances can be shorter, with less inductance, capacitance and propagation delays. To date, though, CMOS imagers have established only modest advantages in this regard, largely because of early focus on consumer applications that do not demand notably high speeds compared with the CCD's industrial, scientific and medical applications.

3.10 System design

Good electronics around the CCD is necessary to get good images. Electronic affects the image quality directly.

For CMOS sensor，digitization is done in the CMOS-chip itself. You need less and easier components around. Image quality is mainly influenced by the chip.

3.11 Cost Considerations

Leverage, volume, yield, and the number of devices per wafer all affect cost. So far, we have focused on the performance differences between CMOS and CCD imagers. It would be naive to assume that business decisions are based on performance trade-offs alone. What matters more to many business decision-makers is value, or the performance received for the price paid.

The cost picture can be complicated, so we will focus only on a few important points.

First, leverage is key. At the risk of stating the obvious, imagers that are already on the market will cost much less than a full custom imager, regardless of whether it is a CMOS or a CCD imager. If customization is necessary, unless the change is minor, it is generally cheaper to develop a custom CCD than it is to develop a custom CMOS imager. CMOS imager development is generally more expensive because CMOS uses more expensive deep submicron masks. There is also much more circuitry to design in a CMOS device. As a result, even in applications where a custom CMOS imager clearly has better performance, the value proposition can still favor a custom CCD.

Secondly, volume matters. Although the cost to develop a new CMOS imager is higher, CMOS imagers that can leverage from larger economies of scale will have lower unit cost. With high volumes, a low unit cost can be financially more important than a low development cost.

Third, supply security is important. It is very costly to be left with a product that is designed around an imager that is discontinued. In spite of a better value proposition, it may be wiser to choose the company which is best able to produce the imager – CMOS or CCD – long term.

3.12 Feature and Performance Comparison of CCD and Conventional CMOS Sensor

3.12.1 Performance Comparison of CCD and Conventional CMOS

Feature	CCD	Conventional CMOS
Signal out of pixel	Electron packet	Voltage
Signal out of chip	Voltage (analog)	Bits (digital)
Signal out of camera	Bits (digital)	Bits (digital)
Fill factor	High	Moderate
Amplifier mismatch	N/A	Moderate
System Noise	Low	Moderate
System Complexity	High	Low
Sensor Complexity	Low	High
Camera components	Sensor + multiple support chips + lens	Sensor + lens possible, but additional support chips common
Relative R&D cost	Lower	Higher
Relative system cost	Depends on Application	Depends on Application

3.12.2 Feature Comparison of CCD and Conventional CMOS

Performance	CCD	Conventional CMOS
Responsivity	Moderate	Slightly better
Dynamic Range	High	Moderate
Uniformity	High	Low to Moderate
Uniform Shuttering	Fast, common	Poor
Uniformity	High	Low to Moderate
Speed	Moderate to High	Higher
Windowing	Limited	Extensive
Anti blooming	High to none	High

4 Conventional CMOS vs Sony Exmor CMOS Sensor

In the conventional microscope field and astronomy field, Aptina and Omnivision CMOS sensors are widely used because their complete product line (from 0.3MP to 18MP) and their competitive price. But they have many well-known defects comparing with CCD sensor as follows:

- Much noise
- Low sensitivity
- Slow frame speed
- Normally rolling shutter

In the recent years, Sony has invested much on CMOS sensors called Exmor or Exmor R CMOS sensors due to the development of the mobile cellphone market, surveillance market and vehicle related market. They have excellent performance by now.

4.1 What are Exmor and Exmor R CMOS sensors?

Exmor is the name of a technology Sony implemented on some of their CMOS image sensors. It performs on-chip analogue/digital signal conversion and two-step noise reduction in parallel on each column of the

CMOS sensor.

Exmor R is a back-illuminated version of Sony's CMOS image sensor. Exmor R was announced by Sony on 11 June 2008 and was the world's first mass-produced implementation of the back-illuminated sensor technology. Sony claims that Exmor R is approximately twice as sensitive as a normal front illuminated sensor. This active pixel sensor is found in several Sony mobile phones and cameras as well as Apple's iPhone 4S, 5,5S, 6 and 6 plus. The Exmor R sensor allows the camera of the smartphone to capture high definition movies and still image in low lit areas.

Originally, Exmor R was limited to smaller sensors for camcorders, compact cameras and mobile phones, but the Sony ILCE-7RM2 full-frame camera introduced on the 10 June 2015 features an Exmor R sensor as well. Sony has already decided to stop the CCD production. since Sony has full confidence that their CMOS sensor will be as good as or even better than their CCD sensor.

(http://image-sensors-world.blogspot.com/2015/02/sony-to-discontinue-entire-ccd-products.html)

ToupTek has developed new cameras by selecting some of the best sensors from the Sony Latest sensor product line. They use Exmor & Exmor R technology and have the following feature:

4.2 Low Noise and High Sensitivity

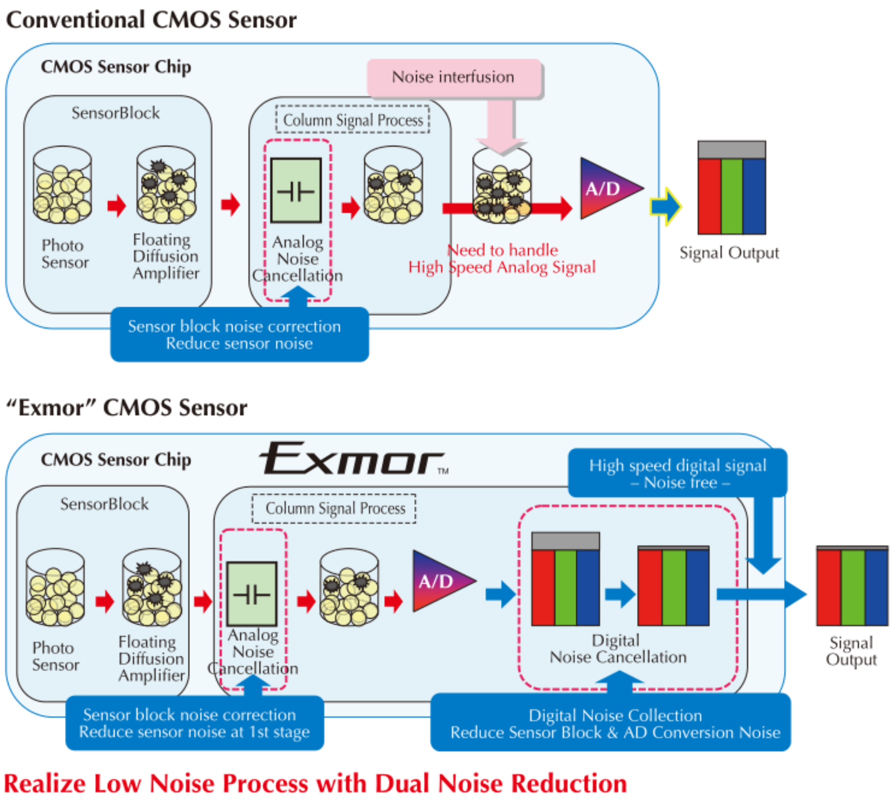


Fig.10 Conventional CMOS and Exmor CMOS

1. As you can see from the above diagram, the "Exmor" sensor has 2 noise reduction process including analogue noise reduction and digital noise reduction while the conventional one has only analogue noise reduction.

2. Even the smallest amount of signal noise can have a negative impact on a photo. Noise is introduced into an image if defects are present in the silicon from which the pixel is made. By minimizing the occurrence of defects and

contamination, and by shielding areas that are vulnerable to defects, Sony has decreased the amount of noise that may be possible in other sensors.

3. Sony enhanced sensitivity of the CMOS sensor by modifying the transistor array and layout, and by making the photodiode as large as possible and creating a system that increases the accuracy of light that is guided to the photodiode.

4.3 Back-illuminated, High Sensitivity and no CRA Related Defects（” Exmor R”）

Sony further improved the capabilities of the CMOS sensor by developing a back- illuminated structure, with the aim of creating a camera capable of taking exceptional photographs even by candlelight. "Exmor R" is approximately twice as sensitive as a conventional front- illuminated CMOS sensor and also features low noise. In a back-illuminated CMOS sensor, light is directed onto the silicon substrate from behind, allowing light to be used with a level of efficiency not possible with conventional front- illuminated pixel structures. Photographers can now create smooth, high-quality images in low light settings, including night scenes.

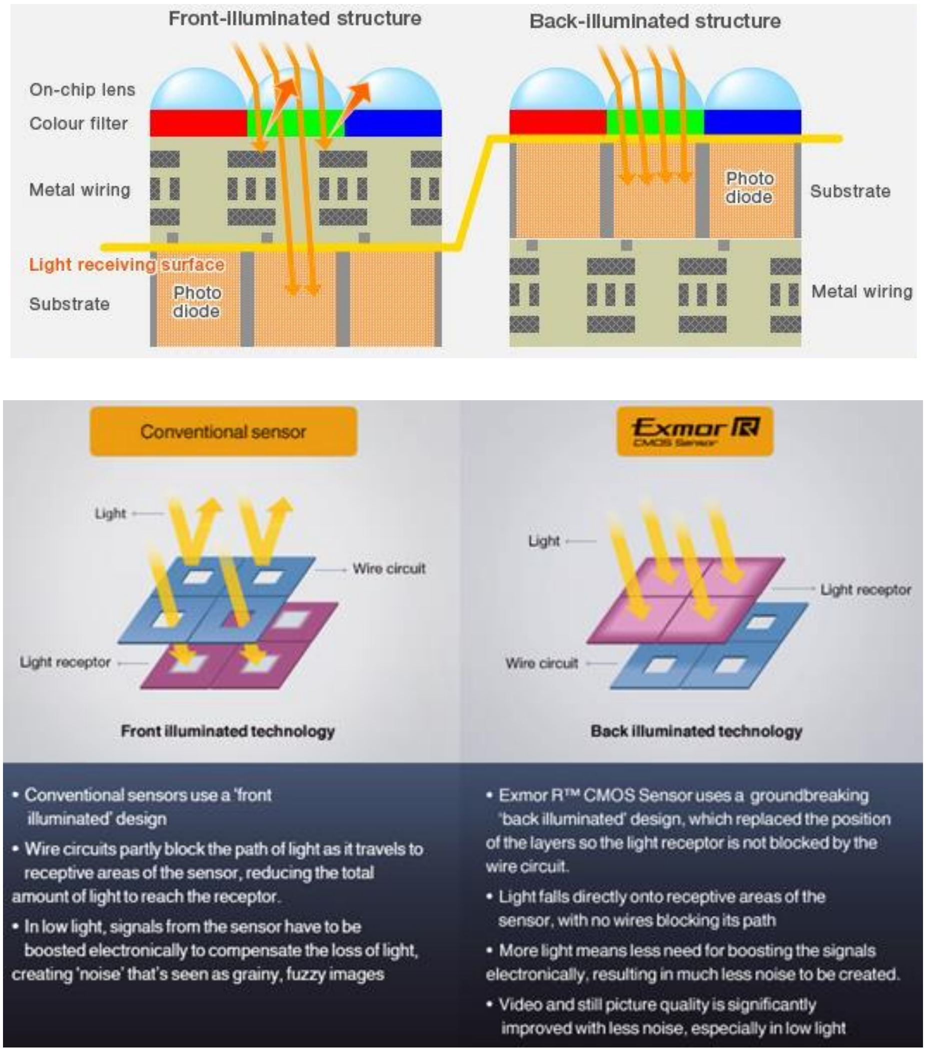
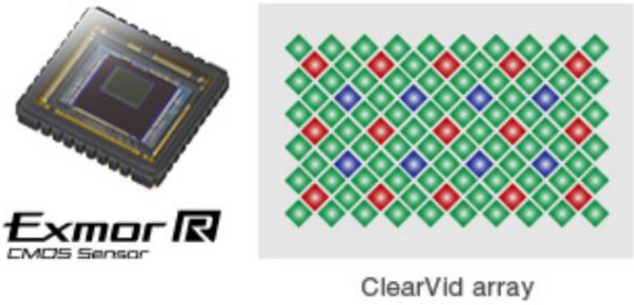


Fig.11 Conventional CMOS and Exmor R CMOS sensors

Fig.12 Two sample pictures taken with a front-illuminated camera structure (left) compared to back-illuminated camera structure (right). Sample images taken under low light conditions (30 lux).The CRA related problem (background not uniform) does not exist anymore.

4.4 Fast Frame Speed

The key to increased speed can be found in parallel signal processing. CMOS sensors have analog-digital (A/D) conversion circuits that convert analog pixel signals into digital signals. Speed is increased by arranging thousands of these circuits in a horizontal array and allowing them to operate simultaneously. The A/D conversion circuits used in Sony's CMOS sensors have important characteristics, including the reduced size of the analog circuits in which noise is created, and automatic noise cancellation. This circuit design enables noise reduction to be combined with enhanced speed.



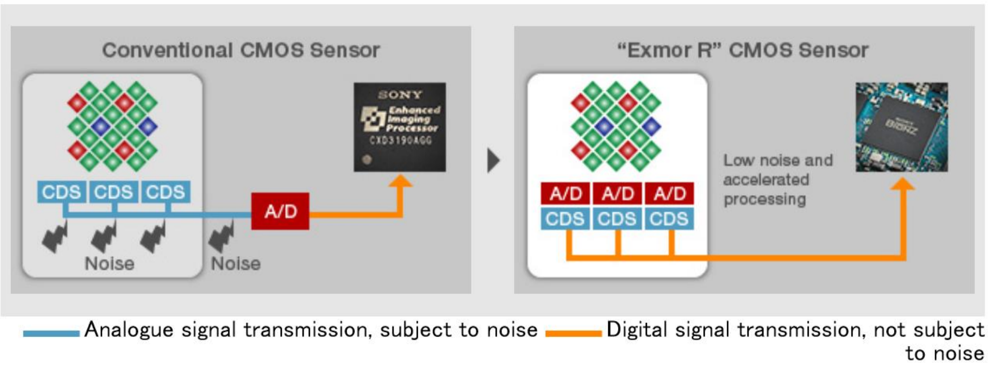


Fig. 13 Signal transmission of Conventional CMOS and Exmor R CMOS sensor

The latest Sony sensors can support fast frame speed and USB3.0 could help it to achieve their best performance. This is the reason why ToupTek develop new cameras based on USB3.0. Besides, USB3.0 helps the camera to transfer video on 12/14bit.

4.5 Global Shutter (Some Sensors)

The conventional CMOS use the rolling shutter while CCD use global shutter. Now some Sony “Exmor” and “Exmor R” sensors use global shutter which make the CMOS sensor more like a CCD, such as IMX174, IMX302.

4.6 Good Continuity

In the near future, Sony will develop and provide better sensors and this will enrich ToupTek E3 and G3 family products.

4.7 Feature and Performance Comparison Conventional CMOS and Exmor CMOS

4.7.1 Feature Comparison

Feature	CMOS	Exmor R CMOS
Signal out of pixel	Voltage	Voltage
Signal out of chip	Bits (digital)	Bits (digital)
Signal out of camera	Bits (digital)	Bits (digital)
Fill factor	Moderate	High
Amplifier mismatch	Moderate	Moderate
System Noise	Moderate	Low
System Complexity	Low	Low
Sensor Complexity	High	Higher
Camera components	Sensor + lens possible, but additional support chips common	Sensor + lens possible, but additional support chips common
Relative R&D cost	Higher	Higher
Relative system cost	Depends on Application	Depends on Application

4.7.2 Performance Comparison

Performance	Conventional CMOS	Exmor CMOS
Responsivity	Slightly better	Much better
Dynamic Range	Moderate	Higher
Uniformity	Low to Moderate	Higher
Uniform Shuttering	Poor	Fast, common
Uniformity	Low to Moderate	High
Speed	Higher	Higher
Windowing	Extensive	Extensive

5 New Product with Sony “Exmor” and “Exmor R” sensor

Based on Sony “Exmor” and “Exmor R” CMOS sensors, ToupTek developed two series cameras, which includes E3 series camera and G3 series camera. Both of them can be used for microscope application and astronomy application. You just need to specify the mounting interface when ordering. They can replace CCD camera on many occasions while they are much more cost-effective. A comparison table of sensitivity will be provided at the end.

1) E3CMOS Camera

E3CMOS Series is ToupTek USB3.0 Camera using the latest Sony “Exmor” and “Exmor R” CMOS cameras. It is perfect for fluorescence microscope application, astronomy application and other dark field environment application, as well as bright field applications. The E3 family now includes:

Order Code	Sensor & Size(mm)	Pixel(μm)	G Sensitivity Dark Signal	FPS/Resolution	Binning	Exposure
E3CMOS12000KPA **EP112000A**	12M/IMX226(C) 1/1.7“(9.33mm)	1.85x1.85	280mv with 1/30s 0.1mv with 1/30s	7.1@4000x3000 30@2048x1080	1x1, 2x2	0.244~2000ms
E3CMOS06300KPA **EP106300A**	6.3M/IMX178(C) 1/1.8“ (8.92mm)	2.4x2.4	425mv with 1/30s 0.15mv with 1/30s	15@3072 x2048 26@1536 x 1024	1x1, 2x2	0.244~2000ms
E3CMOS03100KPB **EP103100B**	3.1M/IMX123(C) 1/2.8“ (6.46mm)	2.5x2.5	600mv with 1/30s 0.15mv with 1/30s	25@2048x1536 30@1920x1080	1x1	0.244~2000ms
E3CMOS02300KPA **EP102300A**	2.3M/IMX185(C) 1/1.9“ (8.58mm)	3.75x3.75	1120mv with 1/30s 0.15mv with 1/30s	38@1920x1200 66@960x600	1x1, 2x2	0.244~2000ms
E3CMOS02300KPB **EP102300B**	2.3M/IMX302(C,GS) 1/1.2“ (13.4mm)	5.86x5.86	1016mv with 1/30s 0.15mv with 1/30s	30@1920x1200	1x1	0.244~2000ms

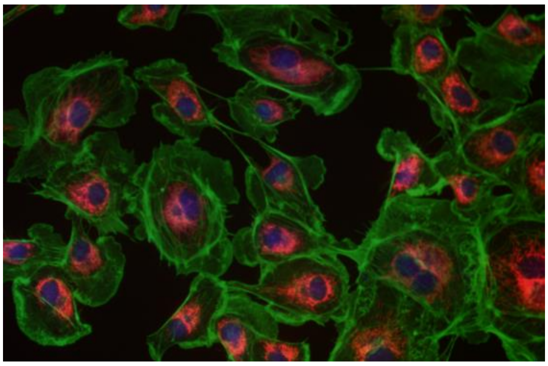


Fig.14 E3CMOS02300KPA sample picture

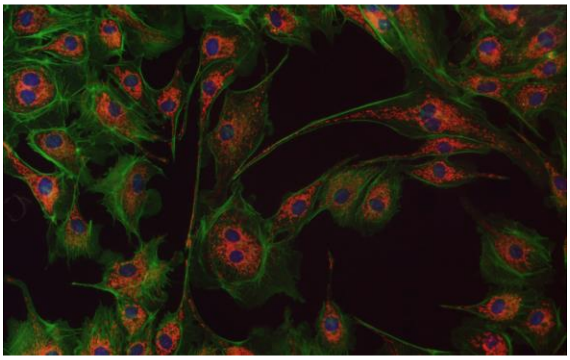


Fig.15 E3CMOS06300KPA sample picture

2) G3CMOS Camera

G3CMOS Series is USB3.0 Camera with ASCOM ST4 guiding port and electric fan for cooling using the latest Sony "Exmor" and "Exmor R" CMOS sensors. It is perfect for astronomy application and other low lit environment application. The G3 family now includes:

Order Code	Sensor & Size(mm)	Pixel(μm)	G Sensitivity Dark Signal	FPS/Resolution	Binning	Exposure
G3CMOS06300KPA GP106300A	6.3M/IMX178(C) 1/1.8" (8.92mm)	2.4x2.4	425mv with 1/30s 0.15mv with 1/30s	15@3072 x2048 26@1536 x 1024	1x1, 2x2	0.1ms~3600s
G3CMOS02300KPA GP102300A	2.3M/IMX185(C) 1/1.9" (8.58mm)	3.75x3.75	1120mv with 1/30s 0.15mv with 1/30s	38@1920x1200 66@960x600	1x1, 2x2	0.1ms~3600s
G3CMOS02300KPB GP102300B	2.3M/IMX302(C,GS) 1/1.2" (13.4mm)	5.86x5.86	1016mv with 1/30s 0.15mv with 1/30s	30@1920x1200	1x1	0.1ms~3600s

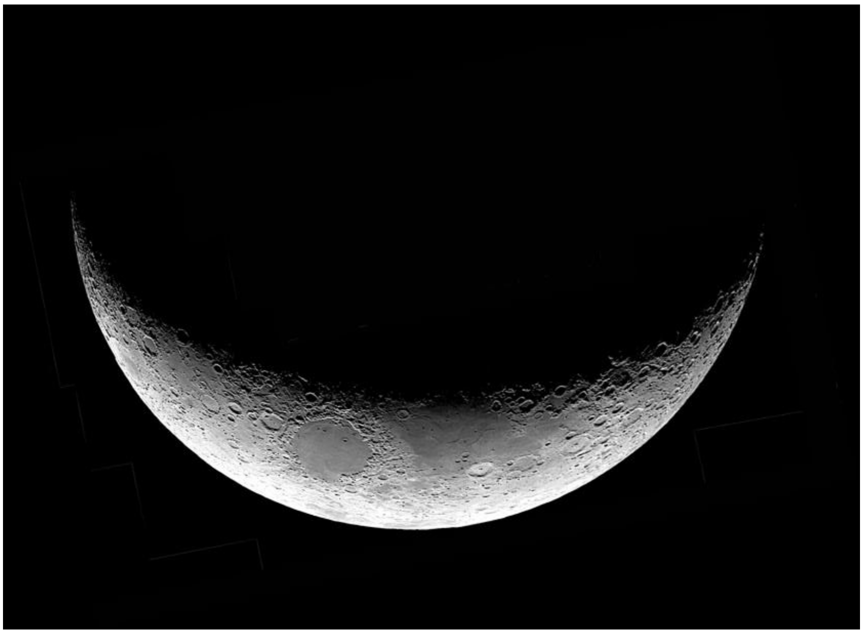


Fig.15 G3CMOS02300KPA sample picture