An image sensor is the device in an electronic camera that converts the optical image presented by the lens into an electrical signal. Since the late 1960s, when the basic principles of semiconductor image sensors were invented, various types of imaging devices have been proposed. Charge Coupled Device (CCD) image sensors long dominated professional and broadcast cameras and camcorders. Recently, Complementary Metal Oxide Semiconductor (CMOS) image sensors have started to appear in professional cameras.

The choice of CMOS or CCD sensors has sparked intense interest and raised important questions. What is the difference between CCD and CMOS? How do the two types of sensors operate? What technologies do they employ? How do the two sensor types compare? And what are the likely prospects for future development? As the world's leading manufacturer of semiconductor image sensors – and a technology leader in both CCD and CMOS sensors – Sony is in a unique position to answer these questions. We hope this paper will deepen your knowledge of image sensors and become a useful resource.
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Chapter 5  Into the Future
Chapter 1  Sony and Image Sensor Development

1-1  Sony and the CCD

Almost from the time the Charge Coupled Device (CCD) was invented, Sony became its most vigorous advocate and most passionate developer. In our view, CCDs had the potential to be vastly smaller, lighter and lower in power consumption than the vacuum tube imagers used in television cameras. CCDs promised to be relatively free from such chronic picture artifacts as lag and burn-in. CCDs would not suffer from the physical fragility of large glass tubes or the sensitivity to shock, vibration and electromagnetic radiation. Finally, CCDs promised a new level of stability and freedom from the painstaking periodic alignment of tubes. For Sony, CCDs potentially spelled not merely the end of camera vacuum tubes, but also the beginning of a new era of electronic imaging that might challenge the supremacy of film photography.

Spurred on by this sweeping vision, Sony persisted in CCD semiconductor development at a time when others abandoned the technology as too difficult to commercialize. After nine long years of development, Sony introduced the company’s first commercial CCDs in 1979, and went on to develop CCDs for broadcasting, professional video, consumer video, medical applications, machine vision and security cameras. The CCD market later gained even more momentum with the worldwide boom in professional and consumer digital photography. Today, Sony is the number one manufacturer of high performance image sensors.

1-2  Sony and CMOS

Over the decades, the CCD has enjoyed marked quality advantages over the rival Complementary Metal Oxide Semiconductor (CMOS) technology. These have included superior signal-to-noise ratio, sensitivity, and freedom from geometric distortion. For years, CCDs were preferred where image quality was paramount, while CMOS sensors were used in applications like PC cameras and camera phones, where the priorities were low power consumption and a high degree of on-chip integration.

Several developments enabled CMOS technology to narrow the gap. In particular, the shift from passive-pixel to active-pixel technology helped CMOS sensors to achieve competitive quality. Today, Sony-manufactured CMOS sensors are featured on several leading digital single lens reflex (D-SLR) still cameras, including our own α (alpha) DSLR-A700. And Sony CMOS sensors are now available on a number of Sony broadcast, professional and consumer video camcorders.
Chapter 2 Image Sensor Basics

There are two basic types of image sensors: CCD and CMOS. Both use large arrays of thousands (sometimes millions) of photosites, commonly called pixels. And both types carry out the same steps.

1. Light-to-charge conversion
   In the photo-sensitive area of each pixel, light directed from the camera lens is converted into electrons that collect in a semiconductor "bucket."

2. Charge accumulation
   As more light enters, more electrons come into the bucket.

3. Transfer
   The signal must move out of the photo-sensitive area of the chip, and eventually off the chip itself.

4. Charge-to-voltage conversion
   The accumulated charge must be output as a voltage signal.

5. Amplification
   The result of charge-to-voltage conversion is a very weak voltage that must be made strong before it can be handed off to the camera circuitry.

Both CCD and CMOS sensors perform all of these steps. However, they differ as to where and in what sequence these steps occur.

CCD sensors move the buckets of charge off the photo sensitive areas, as shown in the diagram below. These buckets of charge are then passed through vertical and horizontal shift registers. The shift registers act as bucket brigades, sequentially handing charge from one semiconductor bucket to the next.

CMOS image sensors immediately convert the bucket of charge into voltage before it leaves each pixel. Modern CMOS sensors also include an amplifier for each pixel. After amplification, the voltage output of the pixel is transferred via a micro-wire to the output of the chip.

Difference between Mechanisms of CCD and CMOS Image Sensors

CCD and CMOS sensors perform the same steps, but at different locations, and in a different sequence.
Let's take a closer look at how the CCD image sensor works.

1. A CCD image sensor can have thousands or even millions of pixels (labeled "a" in the illustration). Each pixel has a photo sensor (b) that converts incoming light into electrons. The photo sensor acts like a bucket. It accumulates electron charge in the same way that a bucket stores water.

2. A vertical shift register (c) is situated between the columns of photo sensors. This vertical shift register consists of multiple semiconductor buckets in a vertical line. This shift register is literally a "charge coupled device," from which the CCD image sensor gets it name.

3. During the vertical sync interval, all the charges accumulated in all the photo sensors are simultaneously transferred into the adjacent vertical shift register CCDs. The photo sensor is like a dam, holding back a reservoir of electrons. The transfer is like the floodgates of multiple dams opening at the same time, and the water of all these dams draining at the same time.
Chapter 2  Image Sensor Basics

4. The timing of the charge transfer to the vertical CCD depends on the frame or field rate of the camera. For example, at a rate of 60 fields per second, the accumulated charge will be transferred to the vertical CCD every 1/60 second. It is as if the floodgates of all the dams open and drain water at an interval of 1/60 second.

5. Each charge is shifted down the vertical CCD in bucket-brigade fashion. The timing of the transfers is the same as the line-scanning frequency of the camera. With a 525-scanning-line camera operating at 60 interlaced fields per second, the charges are transferred at intervals of 1/15,750 second.

6. The vertical CCDs all transfer charges into another CCD positioned horizontally across the bottom of the image sensing area. This is the horizontal shift register (d).

7. During the horizontal sync interval, all the charges are shifted in bucket-brigade fashion across the horizontal CCD and into the amplifier (x).

8. Since the charges transferred from the horizontal CCD are very small, an amplifier is needed both to convert the charges to voltage and to make this voltage stronger. This amplified output goes to the camera’s signal processor.

Charge Transfer by CCD in a Bucket-brigade Fashion

CCD image sensors get their name from the vertical and horizontal shift registers, which are Charge Coupled Devices that act as bucket brigades.
In comparison to CCDs, modern CMOS sensors have a distinctly different structure.

1. As with CCDs, a CMOS image sensor can have millions of pixels (a). In modern CMOS sensors, each pixel consists of a photo sensor (b), an amplifier (y), and a pixel-select switch (e).

2. As in a CCD, the CMOS pixel's photo sensor (b) converts light into electrons. The photo sensor again acts like a bucket, accumulating electron charges the same way that a bucket stores water.
3. Since the charge accumulated in the photo sensor is too small to transfer through micro wires, the charge is first converted to a voltage and amplified right at the pixel. Active-pixel CMOS image sensors can have millions of amplifiers, one per pixel. (For a detailed description of CMOS amplifiers, please refer to section 2.3.)

4. Any individual CMOS micro-wire can carry voltage from only one pixel at a time, as controlled by the pixel-select switch. This is different from the operation of a CCD image sensor, in which the charges of all pixels are transferred simultaneously into their respective vertical shift registers, and all these charges simultaneously move down the vertical shift registers.

5. In addition to the pixel-select switch, the column-select switch and the column circuit are also used to control the output of amplified voltages. To output a video signal, all the switches on the CMOS chip act in a precise sequence.

5.1. First, all the pixel-select switches on a given row are turned ON. This action outputs the amplified voltages of each pixel to their respective column circuit, where they are processed into signal voltages and temporarily stored.

5.2. Then, column-select switches are turned ON from left to right. In this way, signal voltages of each pixel in the same row are output in order.

5.3. By repeating this operation for all rows from the top to the bottom in order, signal voltages of all pixels can be output from the top-left corner to the bottom-right corner of the image sensor.

6. These signal voltages are output to the signal processor of the camera.

2-3 Active-pixel CMOS Amplifiers

The first CMOS image sensors had no amplifiers at the pixels to convert the accumulated charges into strong voltages. These early CMOS sensors depended on a single amplifier, positioned at the output. Unfortunately, the micro-wire connecting a pixel to the output amplifier needed to be quite long, in the range of several millimeters. The relatively weak voltage produced from a small amount of charge accumulated in the photo sensor was significantly reduced when output through the long wire. These "passive-pixel" CMOS sensors had lower sensitivity than CCD image sensors, which had an amplifier immediately at the output of the horizontal CCD.

As a result, these early CMOS designs were not as widely used as CCDs. This problem was not overcome until engineers began to put amplifiers right into each pixel. The photo sensor is connected to the amplifier's gate by a micro-wire just a few micrometers in length. As a result, the output of the photo sensor can be applied to the amplifier with minimal loss. This was the concept behind active-pixel CMOS. The active-pixel CMOS amplifier works as follows:
Chapter 2  Image Sensor Basics

Voltage Generated on Surface of Photo Sensor – Like the Rising Water Level of a Bucket

Fig. A When Charge is NOT Accumulated in Photo Sensor

Fig. B When Charge is Accumulated in Photo Sensor

NOTE: The downward direction indicates a high voltage. Conversely, the upward direction indicates a high negative potential, since the charge has a negative electrical value.

1. As charge accumulates in the CMOS photo sensor, the voltage generated on the sensor's surface decreases proportionately. Once again, the charge in the photo sensor is like water in a bucket. As shown in Figure A, when no charge has accumulated, the photo sensor is like a bucket that is almost empty, meaning a high voltage is generated on the sensor's surface.

   As shown in Figure B, when a charge has accumulated, the voltage on the photo sensor's surface decreases proportionately, like the water level rising in proportion to the amount of water being poured into a bucket. These two surface voltages are output through a signal wire.

2. The difference between these two surface voltages becomes the pixel output. This process of taking two samples and detecting the difference is called Correlated Double Sampling (CDS). (For more information on CDS, please turn to sections 3-7 and 3-8.)

3. As we have seen, the signal voltage produced directly on the photo sensor's surface is significantly reduced when it is output through the long signal wire. There is a need to amplify this voltage right on the pixel by using a large amount of current originated from the power supply unit of a camera.

4. Amplifiers are electronic circuits (transistors) that produce an output signal proportional to the input signal, but much stronger, due to the large current from the power supply unit. An amplifier behaves like a floodgate, the height of the gate being determined by the surface voltage from the photo sensor, coming in from the right in Figure C. Continuing with the analogy, 'water' (current) from the power supply voltage enters the amplifier through the 'canal' at the top of Figure C. The 'water' level in Figure C represents the voltage V1, generated in the amplifier when no charge is accumulated in the photo sensor. The water level is low, meaning that the voltage is high.
Figure D shows the voltage $V_2$, generated in the amplifier when a charge is accumulated in the photo sensor. The water level is high, meaning that the voltage is low. These amplified voltages are sent via micro-wire to the column circuit, where the output signal voltage is produced by subtracting $V_2$ from $V_1$.

Signal Voltage Generated by Amplifier—Like a Floodgate that Controls the Water Level of a Canal

- Fig. C When Charge is NOT Accumulated in Photo Sensor
- Fig. D When Charge is Accumulated in Photo Sensor

Here again, the downward direction indicates a high voltage. Conversely, the upward direction indicates a high negative potential, since the charge has a negative electrical value.

5. By this process, the active-pixel CMOS design can convert a small amount of charge in the photo sensor to a voltage, amplify it, and output it to the column circuit through the long signal wire.

These operations can be summarized as follows:

1. When incident light on the photo sensor is strong, the charge accumulated in the photo sensor is large.
2. When the accumulated charge is large, the decrease of the voltage generated on the photo sensor’s surface is large.
3. When the decrease of the surface voltage is large, the decrease of the amplified voltage is large.
4. When the decrease of the amplified voltage is large, the signal voltage created by the column circuit is large.
The principle of amplification of a CCD image sensor is the same as that of a CMOS image sensor. However, where active-pixel CMOS image sensors use thousands or millions of amplifiers, one per pixel, the classic CCD image sensor uses a single amplifier, located at the output of the horizontal shift register CCD. Here’s how it works.

1. From the horizontal shift register CCD, the charge enters a storage region called the “floating diffusion” (see diagram below). This has the same semiconductor structure as a photo sensor.

2. The voltage at the surface of the floating diffusion varies in proportion to the accumulated charge. A short micro wire (just a few micrometers long) connects this voltage to the gate of the amplifier.

3. The voltage generated on the surface of the floating diffusion controls the gate of the amplifier. When a charge is transferred to the floating diffusion, the voltage generated on its surface decreases in proportion to the amount of charge. And the gate voltage of the amplifier decreases in proportion.

4. Since the CCD does not have a column circuit, the CCD outputs the resulting voltage to the camera’s signal processing ICs.

To prepare for each packet of charge, the floating diffusion is first drained of the previous charge. Called reset, this draining process can never be perfect. Even after reset, some charge always remains in the floating diffusion storage region. This remaining charge represents noise that can potentially degrade the picture quality. To suppress this noise, modern CCD cameras use the same Correlated Double Sampling technique mentioned above for CMOS sensors. While CMOS sensors perform Correlated Double Sampling in the column circuit, CCD cameras typically perform Correlated Double Sampling in the signal processing IC, rather than in the image sensor itself. (For a detailed description of Correlated Double Sampling, please turn to section 3-7.)
Chapter 3  Image Sensor Improvements

Both CCD and CMOS image sensors have benefited from decades of improvement and refinement. In many cases, new pixel structures initially developed for CCDs have also been applied to CMOS image sensors. This has played a major role in bringing CMOS picture quality up to the level of CCD image sensors. Continuing improvements in sensor technology and refinements in semiconductor fabrication have also enabled sensor manufacturers to deliver higher and higher imaging performance from smaller and smaller pixels. Thanks to these improvements, contemporary image sensors can deliver extremely high performance in full 1920 x 1080 pixel high definition.

Comparison of Pixel Sizes of CCDs Used in Sony Cameras

Sony’s first CCD broadcast camera, the BVP-5, had a pixel roughly nine times the size of the modern-day HDW-F900R pixel. But thanks to technology improvements, the pixel on the right performs better.

3-1  Buried Photodiode

HAD CCD

A familiar concern in electronic circuitry is noise. Image sensor noise randomly changes pixel values in ways unrelated to the original image. In a noisy image, pixels that should be all the same tone are randomly lighter or darker. One major source of noise is the unprotected photo-sensitive areas. When the photo sensor surface is exposed, unwanted free electrons can randomly strike the surface, adding to the accumulated signal charge. In addition, if a signal electron rises up to the surface of the photo sensor, it can exit, causing an unwanted reduction in signal charge. This not only generates noise, but can also reduce the level of the output signal.

By means of another analogy, the charge in the photo sensor is like alcohol in an open beaker. The alcohol can become contaminated by dust from the air. The alcohol can also evaporate into the air, reducing the overall amount.
Chapter 3  Image Sensor Improvements

Conventional photodiodes (left) enable signal change electrons to escape and free electrons to enter. Sony’s HAD CCD uses a Hole Accumulated Layer (HAL) to cover the photodiode and block these problems.

To solve this problem, Sony buried the sensor under a thin strip called the Hole Accumulated Layer (HAL). The HAL acts like a lid on our beaker of alcohol. Because it prevents electrons from passing, the HAL eliminates the interfusion of free electrons and the disappearance of signal charge. Introduced in 1984, Sony’s first sensors adopting the buried photodiode were called Hole Accumulated Diode (HAD) CCDs.

3-2 HAD CMOS Image Sensor

Like a CCD image sensor, a CMOS image sensor can also produce significantly better picture quality by adopting the buried-type photodiode. However, if a conventional CMOS image sensor were to use the buried-type photodiode, the Hole Accumulated Layer would prevent any voltage from being generated on the photo sensor’s surface. Such a sensor would not work!

Sony found the solution by creating an entirely new CMOS structure. For image sensing, the photodiode is buried under a Hole Accumulated Layer. Next to this, Sony added a floating diffusion to each pixel. This is the same structure that enables amplification in CCD image sensors. The photodiode empties its charge into the floating diffusion, which is protected from light. Then the floating diffusion stores the charge and generates a surface voltage to drive the amplifier.
Chapter 3  Image Sensor Improvements

HAD-type CMOS Image Sensor

Cross section of one pixel in a HAD type CMOS image sensor. From left to right, you can see the buried photodiode under the HAL, the floating diffusion and the amplifier.

3-3  On-chip Microlenses

Hyper HAD™, Super HAD™ CCDs

One critical measure of image sensor performance is sensitivity, the ability to see in the dark. For maximum sensitivity, incoming light is precious. Unfortunately, the surfaces of both CCD and CMOS image sensors alternate between light sensitive areas (where incoming light is put to work) and non-sensing areas (where incoming light is wasted). Eliminating this waste would dramatically improve sensitivity. This required a method to direct light away from the non-sensing areas and concentrate light on the sensitive areas.

On-chip Lens
Chapter 3  Image Sensor Improvements

The answer was microscopically small lenses, manufactured as an integral part of the semiconductor process and aligned above each photodiode. These microlenses converge and direct more light onto each photo sensor. Working in combination with Sony’s HAD buried diode technology, this significantly increases CCD sensitivity.

The result was introduced in 1997 as the Hyper HAD CCD (for broadcast cameras) and the Super HAD CCD (for non-broadcast cameras).

Vertical Smear

![Image of vertical smear reduction](image)

CCD smear from image highlights (left) is dramatically reduced by on-chip lenses (right). (Sample photos for illustration purposes.)

The on-chip lenses also play a significant role in reducing vertical smear, an image artifact in CCD sensors. Vertical smear is often caused by incoming light leaking directly into the vertical shift register CCD. By concentrating light on the image sensing areas only, vertical smear is dramatically reduced.

Sony has also applied this on-chip microlens technology to CMOS image sensors.

3-4  Improved Microlenses

Power HAD™ CCDs

Over the years, Sony refined the microlens manufacturing process, minimizing the gaps between lenses. This increased low-light sensitivity further still. These improved microlenses were introduced starting in 1998 as the Power HAD CCDs (for broadcast cameras).
Chapter 3  Image Sensor Improvements

Comparison between Hyper HAD and Power HAD CCDs

Reduced gaps between the microlenses extend sensitivity further still.

3-5 Internal Lenses

Power HAD EX™, Exwave HAD™ CCDs

Sony kept refining the microlens technology, developing a technique for introducing a second lens between the main microlens and the photo shielding film. By using this bi-convex lens shape, Sony was able to make the microlens even more powerful and more effective at collecting incident light, boosting sensitivity further still. In addition, thinner insulation film inside the image sensor cut down on the opportunity for stray light reflections. This reduces vertical smear to a bare minimum. These improvements were introduced in non-broadcast cameras in 1998 as the Exwave HAD CCD and in broadcast cameras in 2000 as the Power HAD EX CCD.

Comparison between Power HAD and Power HAD EX CCDs

In the Power HAD EX CCD, an internal lens improves sensitivity while a thinner insulation film minimizes smear.
Chapter 3  Image Sensor Improvements

3-6 Column Analog-to-Digital Converter

One of the advantages of CMOS image sensors is that many common integrated circuits are also based on CMOS technology. So it is easier to build additional functions into the image sensor chip. In this way, CMOS image sensors often include on-board analog-to-digital converters (ADCs).

The conventional method of CMOS analog-to-digital conversion maintains the signal in analog form in horizontal micro-wires that run across the bottom of the sensor. Unfortunately, these analog signals are exposed to high frequency switching noise that can degrade picture quality.

Conventional CMOS Sensor

![Diagram of CMOS sensor with labels and connections]
Sensor engineers can overcome this problem by building analog-to-digital converters (ADCs) into each column of the sensor. For example, a sensor with 1920 (H) x 1080 (V) active pixels would have 1920 A/D converters right on the chip. This arrangement helps to suppress noise because digital signals have always been far more noise-resistant than analog. In analog systems, it is often impossible to distinguish between the desired signal and unwanted noise. In contrast, as long as a digital system can successfully distinguish between a 1 and a 0, random noise is completely ignored.

By placing ADCs so close to each photosite, these sensors significantly reduce the signal's exposure to noise. In addition, by dividing the work among so many ADCs, the operating frequency of the ADCs is substantially reduced. This also helps to maintain a clean, low-noise output signal.
Chapter 3  Image Sensor Improvements

3-7 Correlated Double Sampling

Active-pixel CMOS sensors use a “reset switch” in each pixel to drain the accumulated charge of the previous video field, in preparation for the next video field. Unfortunately, the draining process is not perfect. Some electrons will always remain in the image sensing area. These electrons represent switching noise, which can become part of the video signal. Even worse, this noise is of the “fixed pattern” type. Unlike conventional video noise, which has a random behavior, fixed pattern noise creates a permanent, unwanted texture that can be especially visible in dark scenes. Modern CMOS sensors combat fixed pattern noise with Correlated Double Sampling.

It is to support Correlated Double Sampling that active-pixel CMOS image sensors conduct charge-to-voltage conversion twice for every pixel (as we saw in section 2-3). Both of these voltages are also amplified. Correlated Double Sampling can effectively suppress noise by literally subtracting the amplified voltage containing only noise from the amplified voltage containing both noise and the desired signal.

Sony CMOS cameras use HAD CMOS technology, in which each pixel incorporates a floating diffusion. In these sensors, Correlated Double Sampling works in the following sequence:

1. The reset switch drains the floating diffusion of the old accumulated charge that was used for the previous video field.
2. The amplifier converts the charge left in the floating diffusion, which represents only noise, into a voltage.
3. The accumulated charge in the photo sensor (during the active field exposure) transfers into the floating diffusion area.
4. The amplifier converts the second charge in the floating diffusion, which represents signal mixed with noise, into a second voltage.
5. The column circuit subtracts the noise-only voltage from the signal-mixed-with-noise voltage to produces an output voltage. As a result, fixed pattern noise can be effectively suppressed.

As we’ve seen in section 2-4, CCD amplifiers also require reset switching at the floating diffusion and are also prone to reset noise. For this reason, CCD cameras also suppress reset noise with Correlated Double Sampling. But unlike CMOS designs, the typical CCD camera performs Correlated Double Sampling in the associated signal processing IC, rather than the image sensor itself.

3-8 Digital Correlated Double Sampling

Exmor™ CMOS Sensor

We’ve seen that pixel-by-pixel variation can lead to fixed pattern noise. And we’ve seen that Correlated Double Sampling (CDS) can control this noise. However, inconsistency among the column circuits themselves can still permit column-by-column variations, which can produce vertical fixed pattern noise. Sony engineers recently introduced an approach to deal with this: the Exmor image sensor.
Chapter 3  Image Sensor Improvements

The conventional column ADC design performs the following steps:
1. The pixel outputs the amplified noise voltage.
2. The pixel outputs the amplified signal-with-noise voltage.
3. The column circuit subtracts the noise voltage from the signal-with-noise voltage to create the output voltage.
4. The column ADC converts the output voltage to digital.

In contrast, the Exmor circuit performs the following steps:
1. The pixel outputs the amplified noise voltage.
2. The column ADC converts the noise voltage to digital.
3. The pixel outputs the amplified signal-with-noise voltage.
4. The column ADC converts the signal-with-noise voltage to digital.
5. The column ADC subtracts the digital noise value from the digital signal-with-noise value to create the digital output value.

Digital CDS used in Exmor CMOS sensor

In this way, the Exmor design performs Correlated Double Sampling in the digital domain. Consistency from column to column is far higher and vertical fixed pattern noise is far lower than in the conventional Correlated Double Sampling technique.
Chapter 3   Image Sensor Improvements

3-9 Pixel Interpolation

ClearVid CMOS Sensor™

With any given sensor technology, there is a tradeoff between pixel size and pixel quality. Larger pixels mean better sensitivity, dynamic range and signal-to-noise ratio. Smaller pixels mean higher resolution. Sony's ClearVid CMOS Sensor is a way to overcome this tradeoff. Typical image sensors provide a one-to-one relationship of image sensor photosites to camera pixels. In this way, a 1920 x 1080 camera image usually requires a 1920 x 1080 sensor – slightly over 2 million photosites. In contrast, a ClearVid CMOS Sensor can achieve almost the same resolution using only half the number of pixels. Using half the pixels means that the photosites can be twice as large, for improved sensitivity, dynamic range and signal-to-noise ratio.

Photosite Layout of the ClearVid CMOS Sensor

The ClearVid CMOS Sensor uses a diamond-pattern photosite layout, rotated 45 degrees from the usual vertical columns and horizontal rows. The system generates actual pixel values and interpolated pixel values.

In the ClearVid CMOS Sensor, the pixels are turned 45 degrees to form a diamond sampling pattern, instead of the usual vertical and horizontal grid. Half the pixel information is supplied directly from the CMOS photosites. The other half of the pixel information is interpolated with very high quality, based on information drawn from four adjacent photosites. This interpolation occurs outside the image sensor, in Sony’s Enhanced Imaging Processor™ large-scale integrated circuit. The end result? Very high spatial resolution combined with very high performance in sensitivity, dynamic range and signal-to-noise.
It is tempting to make sweeping statements about the comparative advantages of CMOS and CCD image sensors. But sweeping generalizations are often misleading when it comes to practical comparisons of real-world products. In addition, many commonly-held beliefs about image sensors that were true at one time, have since had to be reexamined by advancing technology. And the comparisons we offer here are subject to change as both CCD and CMOS technologies continue to develop.

4-1 Noise

For decades, CCDs had a clear advantage because they produced lower noise. However, improvements in CMOS technology including the buried photodiode have effectively closed this gap. Now both technologies are capable of clean, low-noise imagery.

4-2 Vertical Smear

In the early days of CCDs, bright picture highlights were often subject to vertical smear: unwanted streaks above and below. Smear is caused in the vertical shift register CCDs. While the role of the vertical CCD is to transfer charges, it has the same construction as the photo sensors. This means the vertical CCD is capable of converting stray light into additional, unwanted charge. So as long as light leaks into the vertical CCD, it generates smear.

In contrast, CMOS image sensors are immune to vertical smear, because the CMOS image sensor uses a signal wire to transfer voltage. Even if light hits the signal wire, it has no effect.

Several landmarks of CCD sensor design have all but eliminated smear. First, on-chip microlenses concentrated light on the photo sensors, reducing stray light substantially. Second, Sony Power HAD EX CCDs reduced the thickness of the insulation layer, cutting stray light further still. These advancements have reduced smear to negligible levels, as low as -140 dB (typical). Today, both CCD and CMOS technologies routinely produce smear-free images.

4-3 Power Supply

All image sensors depend on DC power supply voltage from the camera. CCD image sensors require several voltages to transfer charges in bucket-brigade fashion. In addition, operating the entire CCD requires relatively high voltages (typically 7 to 10 V), resulting in high power consumption. On the other hand, operating any given CMOS amplifier and select switch requires only a single power source with a relatively low voltage (typically 3.3 to 5.3 V).

As a result, CMOS sensors have lower power consumption. This not only helps extend the battery life of portable cameras, but also makes for a smaller, simpler power supply and reduces the requirements for image sensor cooling. This gives CMOS image sensors an advantage for smaller, lighter cameras.
High definition image sensors can have six times the number of pixels of standard definition sensors. New camera capabilities like overcranking and 1080/60P, 1080/50P, 720/60P and 720/50P require faster frame rates than traditional video. Higher pixel counts and faster frame rates both place stringent new requirements on image sensor processing speed. Here, CMOS image sensors can offer advantages.

One way to achieve high speed is to divide the work into multiple channels. In this way, the sensor can accommodate more pixels because the load on any single channel can be reduced. On the vertical axis, both sensor types provide multiple channels. The CCD provides multiple vertical shift register CCDs. CMOS provides multiple vertical micro wires and column circuits.

Creating multiple outputs in a CCD (left) requires an increase in complexity and cost. Multiple outputs on a CMOS sensor (right) requires only small, easy-to-manufacture micro wires.

The difference is creating horizontal channels. CMOS sensors can easily be designed to accommodate multiple horizontal channels, executed as ultra-fine micro wires. High-resolution CCD image sensors also have multiple horizontal channels, but creating these channels in a CCD is more complex. It requires additional horizontal shift register CCDs, which occupy more space and add to manufacturing complexity. In this way, the CMOS image sensor can offer an advantage where fast processing of high pixel counts is a priority. This is the primary reason why CMOS is often the sensor of choice for digital single-lens reflex cameras (D-SLRs).

High pixel counts and high frame rates can also tax the ability of amplifiers to keep up. Here again, the work can be managed by dividing the load among multiple amplifiers. And here again, CMOS sensors can have an advantage.
Chapter 4  Image Sensors Compared

Most standard definition CCD image sensors have only a single amplifier situated after the horizontal shift register CCD. This lone amplifier processes signals from every pixel. High definition CCD image sensors can incorporate multiple high-speed amplifiers, requiring multiple horizontal shift register CCDs. As we've seen, this extracts a penalty in complexity.

In contrast, active-pixel CMOS image sensors are free from these penalties. In this CMOS design, there is a separate amplifier for each pixel, so amplifier speed is not a concern.

4-5  Systemization

Typical integrated circuits use the same Metal Oxide Semiconductor (MOS) substrate as CMOS image sensors. This makes it relatively easy to add functions to the CMOS chip, such as column analog-to-digital converters. At even higher levels of systemization, CMOS technology lends itself to camera-on-chip and system-on-chip integration.

4-6  Geometric Distortion

In CCD image capture, all the pixels are synchronized. They all start accumulating charge at the same time, and they all transfer their charges simultaneously. As we've seen, CMOS sensors operate according to a different principle. CMOS sensors accumulate charges and read them out one line at a time. This can create geometric distortion when there is relative motion between the camera and the subject. For example, if a car speeds through the frame, the timing delays inherent in CMOS line-by-line readout make the car appear to lean backwards. The distortion can also appear when the subject is still but the camera moves. Experienced video shooters often test this phenomenon by rapidly panning the camera back and forth past the legs of a table. A distorted image will show "wobbly legs."

Image Distortion with CMOS Camera

Fortunately, human vision is not particularly sensitive to detail in moving objects. So this image distortion is not a major issue in most program production. However, for high-end television and movie production, where images are closely scrutinized, this image distortion can be a serious problem.
Chapter 5  Into the Future

Sony is the world leader in semiconductor image sensors and a leader in both CMOS and CCD technology. In this way, Sony is well positioned to understand the advantages of each technology – and to cherry-pick the best technology for each application. When existing chips cannot meet our camera goals, we can create all-new sensors. And when important new image sensor technologies emerge, we can create new cameras to take advantage of the higher performance levels.

At the current state of development, CMOS and CCD sensors both deserve a place in broadcast and professional video cameras. CMOS is particularly outstanding where issues of power consumption, systemization and processing speed are most important. And CCDs excel where the images will be subjected to the most critical evaluation.