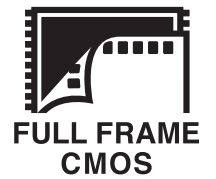
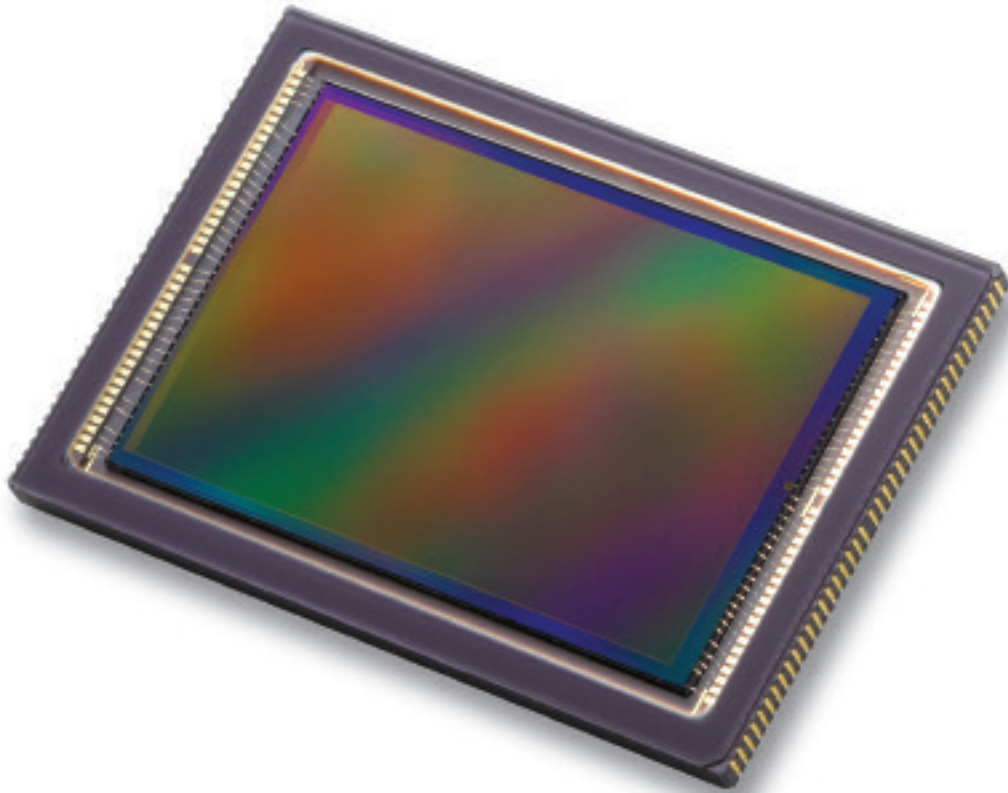


**Canon**



**WHITE PAPER**



**CANON'S FULL-FRAME  
CMOS SENSORS:**

**THE FINEST TOOLS  
FOR DIGITAL  
PHOTOGRAPHY**

<b>Table of Contents</b>	<b>I. INTRODUCTION</b>	<b>3</b>
	<b>II. WHAT IS “FULL-FRAME”?</b>	<b>4</b>
	<b>III. WHAT ARE THE ADVANTAGES OF FULL-FRAME SENSORS?</b>	<b>5</b>
	Image quality considerations	5
	Focal length conversion factors	7
	Full-frame vs. APS-C, some other considerations	10
	<b>IV. THE ECONOMICS OF IMAGE SENSORS</b>	<b>11</b>
	Wafers and sensors	11
	<b>V. WHY CMOS?</b>	<b>13</b>
	CCD	13
	CMOS	14
	Power consumption issues	15
	Speed issues	16
	Noise issues	17
	<b>VI. CANON’S UNIQUE R&amp;D SYNERGY</b>	<b>20</b>
	Other differences between CMOS and CCD image sensors	21
	Summing up for now	23
	<b>VII. SOME HISTORY</b>	<b>24</b>
	Getting to here	24
	Steppers and scanners	26
	<b>VIII. CONCLUSION</b>	<b>30</b>

# I. INTRODUCTION

Canon currently makes five extraordinary EOS DSLR (Digital Single Lens Reflex) cameras of which two, the EOS-1Ds Mark II and the EOS 5D, incorporate full-frame CMOS (Complementary Metal Oxide Semiconductor) image sensors. Today, these cameras are unique in format and unequalled in performance. This paper will discuss what is meant by “full-frame sensor,” why full-frame sensors are the finest all-around tools of digital photography, why CMOS is superior to CCD (Charge-Coupled Device) for DSLR cameras, and how it came to pass that the evolution of a host of associated technologies – and some courageous and insightful business decisions – positioned Canon to stand alone as the only manufacturer of 35mm format digital cameras with full-frame image sensors today (as of August 1st, 2006).



## II. WHAT IS “FULL-FRAME” ?

Early in the 20th century, in the search for a more portable camera format, 35mm movie film was adapted for use in still cameras. At first, there was no standard frame size, but eventually, the industry settled on 36 x 24mm. Great rangefinder systems were developed by Leitz (Leica) and Zeiss (Contax), Canon and Nikon, among others. In the latter half of the century, professional 35mm photography was dominated by SLR systems developed by Canon and Nikon. An immense array of lenses was a powerful component of these systems. When the first DSLR cameras reached professionals and consumers in the late 1990s and early 2000s, their image sensors were not as large as the standard 35mm frame, causing some consternation. Photographers started pressing camera manufacturers to offer 36 x 24mm image sensors.

Medium format 120/220 film is 6cm wide. The smallest common image sizes on this film are 60 x 60mm (2 1/4 inches) and 60 x 45mm (2 1/4 x 1 5/8 inches). Excellent, if relatively limited, lens systems have been developed for these formats. While some vendors are calling their very expensive 49 x 36.7mm image sensors “full-frame,” they are not, at least in terms of medium format. This isn't to say that there are no true full-frame medium format sensors available. For the record, and as a matter of interest to tech-heads, Fairchild Imaging's CCD 486 has a 61.44 x 61.44mm image area and 16 megapixels. It is included in liquid-cooled format with the Peregrine 486 (extreme sensitivity under low light conditions) and Condor 486 (X-ray and electron imaging) scientific cameras. It is offered separately in three grades and in frontside and backside illuminated configurations. The cheapest (frontside, grade 3) is \$16,000; the priciest is \$95,000 for a backside-illuminated grade 1.

Fairchild's CCD 595, for “advanced scientific, space and aerial reconnaissance applications,” has a rather spectacular 81 megapixels on its 80.64 x 80.64mm image area. The sensor alone, sans camera or associated electronics, costs approximately \$100,000, depending upon packaging and application. The point of mentioning this exotica here is to frame the discussion of, and to establish the cost of, advanced sensor technology and to give a clearer sense of Canon's position in the marketplace. This paper will demonstrate the excellence and the value of Canon's full-frame technology as seen in the context of both less expensive and more expensive units.

# III. WHAT ARE THE ADVANTAGES OF FULL-FRAME SENSORS?

## Image quality considerations

Regardless of format, full-frame sensors are all about image quality. The most obvious advantage of full-frame sensors is the ability to combine high resolution with large pixel sizes. Compare two sensors with the same number of pixels, one a full-frame unit and one smaller. The pixels of the full-frame sensor are larger. Each larger pixel has a greater surface area available for gathering light. More light collected means less amplification needs to be applied to the output signal of each pixel for the purposes of readout and image processing. Less is better here because magnifying low-level signals inevitably entails picking up and increasing noise that will then have to be removed as thoroughly as possible in a later step.

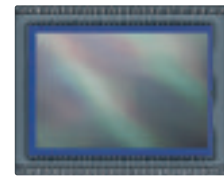
## Sensor size



35mm full-frame sensor:  
approx. 36 x 24mm



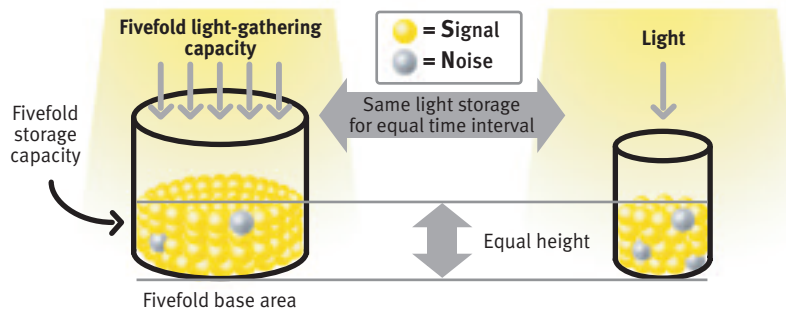
APS-H size sensor:  
approx. 29 x 19mm



APS-C size sensor:  
approx. 22 x 15mm

From the diagram below, one can see that bigger pixels offer higher sensitivity because they can gather more light in less time than smaller pixels. The diagram also shows that larger pixels are less inclined to light overflow or spillover because of their greater capacity, improving dynamic range. Finally, for a given quantity of noise, more light gathered means a higher signal-to-noise ratio and increased optical signal purity.

**If base area is 5 times the average, then light-gathering and storage capacities also are fivefold.**



Note: The proportion of yellow to grey is the S/N ratio.

In the extreme case of low-light photography and ISO ratings of 800 and above, high signal-to-noise ratios give full-frame sensors a great advantage. In bright light with low ISO settings, the abundant charge storage of Canon's large CMOS pixels avoids oversaturation.

Larger pixels help full-frame sensors to produce a higher dynamic range and finer tonal gradations than their smaller brethren. Insufficient dynamic range for a given situation means values at their respective ends of the exposure curve will be compressed, showing little separation or variation, or worse, they will be entirely featureless. These unwelcome events are called, respectively, “blowout” and “black-crush.” Here are two difficult subjects rendered correctly:



*Camera: EOS-1Ds Mark II  
Lens: EF 85mm f/1.8 USM  
Shutter speed: 1/400 sec.  
Aperture value: f/7.1  
ISO speed: 100*



*Camera: EOS-1Ds Mark II  
Lens: EF 17-40mm f/4L USM  
Shutter speed: 1/6 sec.  
Aperture value: f/11  
ISO speed: 100*

In the case of low light, fast movement and vivid color, smaller sensors often produce visual noise at the requisite ISO speeds of 1000 and greater. By creating less noise to begin with and by relying less on signal boosting and artificial noise reduction, Canon’s full-frame CMOS sensors have the sensitivity and control to deliver beautiful color in indoor sporting events.

Well-designed big pixels also avoid false colors, eliminate unnatural tonal jumps and produce smoother and more subtle gradations of color:



*Camera: EOS 5D  
Lens: EF 200mm f/2.8L II USM  
Shutter speed: 1/6400 sec.  
Aperture value: f/2.8  
ISO speed: 3200  
White balance: Auto*



*Camera: EOS 5D  
Lens: EF 17-40mm f/4L USM  
Shutter speed: 1/160 sec.  
Aperture value: f/11  
ISO speed: 100*

Canon's full-frame sensors have reached another image quality milestone as well. Their gradations and dynamic range are now the equal of the best positive films, and their resolution and lack of grain are superior. No smaller sensor has achieved this level of performance.



With 35mm film



With 35mm full-frame sensor

### Resolution



With 35mm film



With 35mm full-frame sensor

### Grainy image



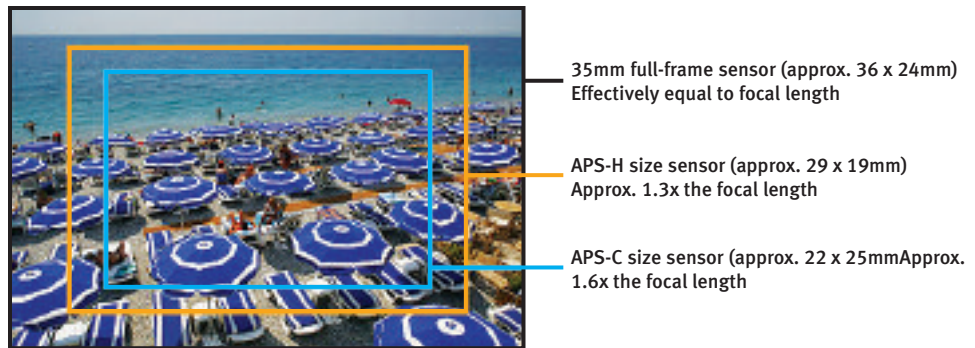
With 35mm film



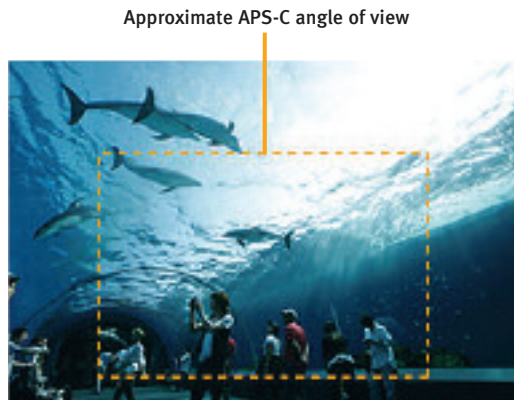
With 35mm full-frame sensor

### Focal length conversion factors

Something photographers discovered with early DSLR cameras was variously called a lens magnification factor or correction factor or focal length conversion factor. On every 35mm format digital camera with a sensor smaller than 36 x 24mm, lenses originally designed for 35mm cameras act as if their focal lengths are longer than their original specification. The arithmetic goes like this: an APS-C sensor is approximately 22 x 15mm. Its diagonal is about 26.6mm. An APS-H sensor (found exclusively in the Canon EOS-1D, -1D Mark II and -1D Mark II N – more on this later) is about 29 x 19mm, so its diagonal is roughly 34.7mm. The diagonal of a full 35mm frame is about 43.3mm. Dividing 43.3 by 26.6 gives a lens conversion factor of 1.6x for APS-C; dividing 43.3 by 34.7 gives a lens conversion factor of 1.3x for APS-H. Lenses of 20mm, 50mm and 300mm will become, functionally, 32mm, 80mm and 480mm respectively for APS-C. The original lenses will now have the field-of-view, or angle-of-view, of 1.6 times longer lenses. With the APS-H sensor, the changes are less pronounced: 300 to 390, 50 to 65 and 20 to 26mm. Here is a diagram showing the relative differences:



For a sports or wildlife photographer whose tools of the trade are principally long lenses, the use of an APS-C DSLR provides the advantage of “longer” telephoto lenses that are smaller, lighter and more affordable yet have the same effective maximum apertures as telephoto lenses on a full-frame camera. These benefits are less pronounced at standard focal lengths, but are still significant occasionally. Wide-angle lenses are another story, though. Until the recent advent of very wide angle rectilinear zooms such as the Canon EF-S 10–22mm f/3.5–4.5 USM, it was very expensive, if not impossible, to achieve high image quality with wide-angle coverage at an affordable price with an APS-C DSLR camera. This diagram shows how freedom from focal length conversion factors is a big advantage for full-frame sensors when a situation requires a wide angle lens:



With 35mm full-frame sensor

Fisheye lenses afford the most extreme wide angle perspectives. With an APS-C sensor, though, much of the effect can be lost:

**Canon’s full-frame CMOS sensor enables the wide-angle and intense perspective of this lens.**



With APS-C size sensor



With 35mm full-frame sensor



One of the most appealing characteristics of full-frame sensors is that they allow every lens to have its own original, as-designed optical signature, something which is lost with the change of coverage and the elimination of a substantial part of the cone of light that the lens projects rearward. For example, the aesthetic properties of the out-of-focus component of an image, sometimes called “bokeh” and seen most often as background blur, are a key design parameter of Canon EF lenses. Spherical and chromatic aberration and diaphragm configuration are all part of the equation. (Canon’s manufacturing equipment tool division has custom-designed a robotic machine with ceramic arms, motors and substrates that assembles aperture blades with incredible nanomotion precision.) Although bokeh is purely subjective and cannot be quantified, professional portrait photographers, in particular, know good bokeh when they see it. It is characterized by soft and beautifully blended backgrounds, free of blotchiness, blobbiness or sharp edges (on anything, but especially twigs, tree limbs and light sources). Sophisticated photographers know that the out-of-focus parts of an image are critical to its overall effect.

When a lens designed to image on a full-frame field is used with a smaller sensor, changes occur. If a person switched from full-frame to APS-C while using the same lens, he or she would have to back up (if possible) to maintain the size of the subject in the finder, or, one could say, the crop. With a greater subject-camera distance, depth-of-field would now increase if the aperture remains constant. Background blur and subject-background relief would be reduced. This effect can be seen in these two images: Background blur and subject-background relief would be reduced. This effect can be seen in these two images:



*With APS-C size sensor*



*With 35mm full-frame sensor*

With the flower kept the same size, look at the softness of the stem on the right as well as the background. The difference is considerable and favors the full-frame sensor heavily.

Here are two more examples of appealing background blur created with full-frame sensor Canon cameras:



Camera: EOS-1D Mark II n  
Lens: EF 300mm f/2.8L IS USM  
Shutter speed: 1/200 sec.  
Aperture value: f/3.2  
ISO speed: 100



Camera: EOS 5D  
Lens: EF 100mm f/2.8 Macro USM  
Shutter speed: 1.6 sec.  
Aperture value: f/8  
ISO speed: 100

### **Full-frame vs. APS-C, some other considerations**

For any comparison of full-frame and APS-C sensors in which image quality is paramount, full-frame wins, hands down. For low light, bright light, vivid colors, subtle colors, any focal length or film speed, full-frame is the champion. Still, there's more to photography than image quality. For example, smaller sensors mean smaller mirrors, smaller mirror boxes, smaller pentaprisms, indeed, smaller cameras, and lighter ones, too. Smaller sensors can be covered by smaller and lighter lenses. Smaller cameras are easier to carry. Consumers think about this, and pros spend lots of time mulling it over, too. Consider the difference in weight of two camera bags, one with two EOS-1 Series bodies, a few EF lenses and a Speedlite, and a bag with two EOS 30D cameras, an equal number of EF-S lenses and that Speedlite. Add a rolling case with computer stuff, chargers, cables and some clothing and then drag the whole pile through airports, on and off planes, in and out of taxis, rental cars and hotel rooms for a few years. Your back will know the difference.

All those big pieces in a full-frame camera have their own benefits, though. Anyone who has become accustomed to the dark and somewhat small viewfinder images of APS-C cameras will never forget his or her first look through an EOS 5D's finder. Some people are so startled that they almost drop the camera. The mirror, focusing screen and pentaprism are all scaled for a sensor whose area is 2.6 times larger than APS-C (864mm<sup>2</sup> vs. 330mm<sup>2</sup>) components. The EOS 5D's finder can be at least 1 1/3 stops brighter than an APS-C finder constructed of identical materials when viewed through the same lens. The view is big, bright and immediate; detail is clear and crisp. Forget eyestrain. It's a different world in there.

With all these benefits, it's only natural to wonder why all DSLR cameras aren't full-frame. Ultimately, the issue is money. Research, development, manufacturing and distribution costs are all independent of camera size, so a smaller camera will not cost appreciably less than a larger one for any of these reasons. The end cost difference between small mirrors, mirror boxes, chassis and so forth, and larger ones is not that great. The difference is the sensor.

# IV. THE ECONOMICS OF IMAGE SENSORS

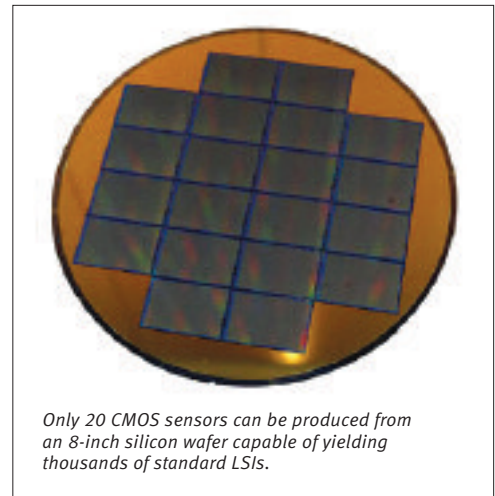
Image sensors contain millions of individual light-sensitive devices called photodiodes. Sensor design begins when a group of engineers draws up an individual photodiode, consisting not only of a light sensitive portion but also supporting circuitry and a physical housing. This design is duplicated millions of times using a CAD (Computer-Aided Design) process. The resulting photodiodes are electronically linked to each other and arranged in a grid pattern to form a circuit. An image of the circuit pattern is projected onto a silicon wafer at a very high rate of reduction by means of a semiconductor manufacturing tool called a mask aligner or stepper.

## Wafers and sensors

Thin disks of silicon called “wafers” are used as the raw material of semiconductor manufacturing. Depending upon its composition, (for example, high-resistivity silicon wafers have much greater electrical field depth -- and broader spectral response -- than low-resistivity wafers) an 8" diameter wafer could cost as much as \$450 to \$500, \$1,000 or even \$5,000. After several hundred process steps, perhaps between 400 and 600 (including, for example, thin film deposition, lithography, photoresist coating and alignment, exposure, developing, etching and cleaning), one has a wafer covered with sensors. If the sensors are APS-C size, there are about 200 of them on the wafer, depending on layout and the design of the periphery of each sensor. For APS-H, there are about 46 or so. Full-frame sensors? Just 20.

Consider, too, that an 8" silicon wafer usually yields 1000 to 2000 LSI (Large-Scale Integrated) circuits. If, say, 20 areas have defects, such as dust or scratches, up to 1980 usable chips remain. With 20 large sensors on a wafer, each sensor is an easy “target.” Damage anywhere ruins the whole sensor. 20 randomly distributed dust and scratch marks could ruin the whole batch. This means that the handling of full-frame sensors during manufacture needs to be obsessively precise, and therefore they are more expensive.

Of course, there is more to this topic. For example, the circuit pattern of a full-frame sensor is too large to be projected on the silicon wafer all at once; it requires three separate exposures (See page 53). This means that the number of masks and exposure processes is tripled. For now, appreciate that a full-frame sensor costs not three or four times, but ten, twenty or more times as much as an APS-C sensor. Here,



then, is the greatest disadvantage of full-frame sensors and the greatest advantage of small sensors. Regardless of future technological developments, cameras with full-frame sensors will always cost much more than cameras with smaller sensors. That's why the EOS Digital Rebel XT, EOS 20D and EOS 30D are such excellent values, and it is also why the EOS 5D and the EOS-1Ds Mark II must come with a substantial price differential. (Interestingly, the APS-H sensor of the EOS-1D Mark II N is the largest size that can be imaged in one shot onto a wafer. Extended through the whole sensor production process, the difference in price between the 1D Mark II N and the 1Ds Mark II can be readily understood.) Each camera's position in the marketplace is clear. There are many photographers for whom image quality is the most important thing, even as they have serious concerns about portability, practicality and expense. For them, no other manufacturer currently offers a wider selection of solutions than Canon.

# V. WHY CMOS?

**CCD** The CCD (Charge-Coupled Device) was invented in 1969 by two researchers at Bell Labs in Murray Hill, N.J., Willard S. Boyle and George E. Smith. (In 2006, they shared the \$500,000 Charles Stark Draper Prize for engineers whose achievements have made a significant impact on society, awarded by the National Academy of Engineering.) In the CCD, incoming photons strike a matrix of photodiodes that convert light energy into electrons that are stored briefly in a charge potential well before being transferred out along registers to an amplifier. Originally, CCDs were expected to become a new kind of memory device. Although this development path was not fruitful, the sensitivity of CCDs to light recommended them for imaging applications. Light, the visible part of the electromagnetic spectrum, stretches from approximately 400 to 700nm (nanometers or  $0.4\mu\text{m}$  to  $0.7\mu\text{m}$ ). Silicon responds to wavelengths below 1100nm ( $1.1\mu\text{m}$ ), a highly serendipitous coincidence.

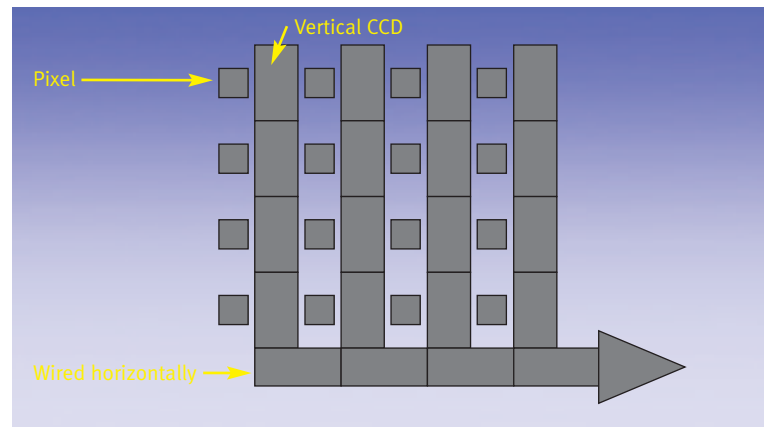
Photodiodes are, in fact, semiconductors, the most basic of which is a pn pair made up of a p-type and an n-type semiconductor. If a plus electrode (anode) is attached to the p-type side, and a minus electrode (cathode) is attached to the n-type side of the pn pair, and electric current is then passed through this circuit, current flows through the semiconductor. This is known as forward bias. If one creates a reversed circuit by attaching a plus electrode to the n-type side and a minus electrode to the p-type side of the pn pair, then electrical current will be unable to flow. This is known as reverse bias. Photodiodes possess this reverse bias structure. The main difference from standard semiconductors is the way in which they accumulate electrical charge in direct proportion to the amount of light that strikes them, an attribute critical to their use in imaging.

Photodiodes are designed to enable light to strike them on their p-type sides. When light strikes this side, electrons and holes are created (electron-hole charge pairs) within the semiconductor in a photoelectric effect. Depending upon their wavelengths, photons are absorbed at different depths in the silicon. Short wavelengths striking the photodiode are absorbed by the p-type layer, and the electrons created as a result are attracted to the n-type layer. Long wavelengths reach the n-type layer, and the holes created as a result in the n-type layer are attracted to the p-type layer. So, holes gather on the p-type side, which accumulates positive charge, while electrons gather on the n-type side, which accumulates negative charge. Because the circuit is reverse-biased, the electrical charges generated are unable to flow.

The brighter the light that hits the photodiode, the greater the electrical charge that will accumulate within it. This accumulation of electrical charge at the junction of the pn pair when light strikes is known as a photovoltaic effect.

## How an Interline Transfer CCD Works

One pixel's electrical charge is transferred to the next row in a bucket relay and it is also moved horizontally. The converter at the end converts it into a voltage signal.



Advantages: **Proven record of technologies and commercialization, low noise high S/N.**

Disadvantages: **High power consumption, higher speed difficult, on-chip peripheral circuits difficult.**

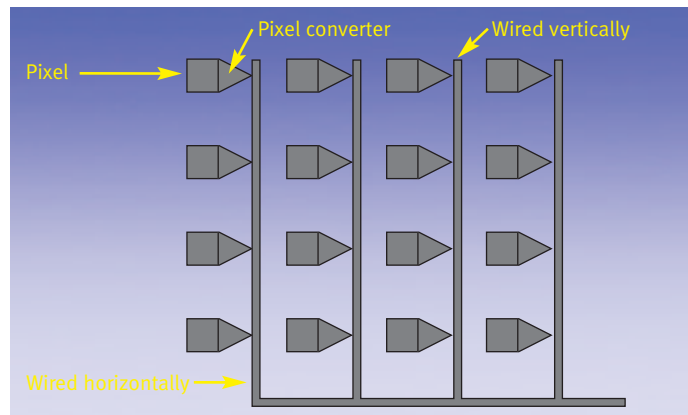
CCDs are comprised of photodiodes and polysilicon gate mechanisms for transferring the charges accumulating within the photodiodes to the edge of the CCD. The CCD photodiodes are arranged in an X,Y checkerboard of rows and columns. Charge transfer regions are arranged in columns next to each row of photodiodes. The charges themselves cannot be read as electrical signals and need to be transferred across the CCD to the edge, where they are converted into voltage, one row at a time. By applying a series of pulses, the charges accumulated at each photodiode are relayed in succession, much like buckets of water in a bucket line, down the rows of photodiodes to the edge. The “charge-coupled” part of a CCD refers to the way charges are moved through gates from one photodiode to the next. This sequential method of signal processing is inherently slower than the simultaneous processing performed by CMOS sensors.

CCDs require the application of differing voltages in several places for two, three or four phase clocking signals, clock levels and bias. This increases power consumption considerably, makes system integration difficult, enlarges components and increases costs.

**CMOS** Like CCDs, CMOS sensors are semiconductor light sensors. They have much the same structure as the CMOS memory chips used in computers, microprocessors and ASICs (Application Specific Integrated Circuits). Whereas memory chips use rows and rows of transistors to record data, CMOS sensors contain rows of photodiodes coupled with individual amplifiers to increase the electrical signal from the photodiodes.

## How a CMOS Image Sensor works

Each pixel has a converter to convert the charge to voltage to be read.



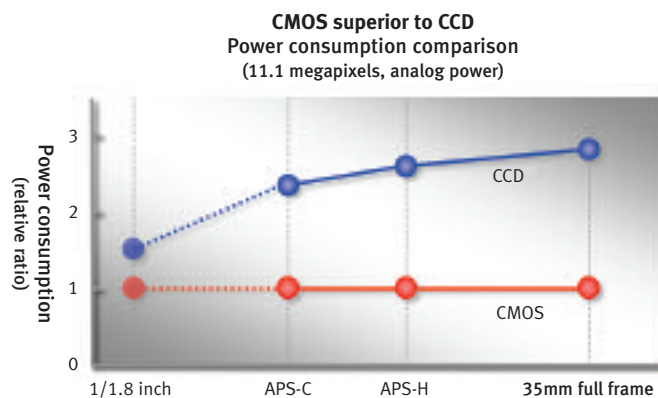
Advantages: **Low power consumption, faster speed is easy, on-chip peripheral circuits possible.**

Disadvantages: **Irregular pixels and random noise.**

## Power consumption issues

Transferring voltage requires almost no power compared to transferring a charge, which must move mass. So even with a larger CMOS sensor, power consumption does not change as long as the number of channels is not increased. CCDs, on the other hand, transfer output charges "as is," consuming power for the horizontal reading. The bigger CCDs are, the more power they consume. Making them faster also requires more power. A Canon in-house comparison of CCD and CMOS power consumption found that with the very small sensor in point-and-shoot digital cameras, the CCD consumes 50% more power than CMOS. In the case of an APS-C size sensor, used in DSLR cameras such as the EOS Digital Rebel XT, EOS 20D and 30D, the CCD consumes more than twice as much power. With full-frame 35mm sensors, CCDs consume about three times more power as a baseline. Under certain circumstances, the difference can be up to 100 times more power consumed by a CCD sensor than by a CMOS sensor of similar size and pixel density.

## Save power with CMOS



Larger sizes consume more power

➡ The larger the size, the larger the difference between CCD and CMOS.

➡ **CMOS better for large sensors**

More power creates more heat and noise. CCDs also have increased power consumption at longer shutter speeds; more electricity flowing means, again, heat and noise problems. Scientific cameras with CCD sensors solve all these problems with massive power supplies and liquid or thermoelectric cooling, entailing commensurate cost, complexity and weight penalties. In consumer cameras, the lower power consumption of CMOS sensors means battery packs can be much smaller, cameras lighter and recharge times shorter. Batteries can maintain their working voltages for much longer.

### The difference between CMOS and CCD

**High-speed, multiple channels**

**Canon's current CMOS is even faster!**

- Improved screen compositing performance with multi-channel reading (spatial frequency)
- With the same internal operation frequency, the reading speed is twice as fast!

**➔ When it comes to speed, CMOS wins hands down.**

- Faster internal operating frequency
- Multi-channel

**➔ Reading speed is faster!**

**Speed issues** Because CMOS sensors have a converter at each photodiode to transform the charge to voltage, each row of photodiodes can be read separately, and multiple channels of sensor data can be read out simultaneously at high speed.

	<b>CMOS Sensor</b>	<b>CCD (Charge Coupled Device)</b>
<b>Electrical charge reading</b>	<p style="text-align: center;">Pixel Converter Wired vertically Wired horizontally</p>	<p style="text-align: center;">Vertical CCD Horizontal CCD</p>
	The signal is amplified at each pixel, then read in turn. Peripheral circuits possible.	The signal is read in a bucket relay, system and amplified at the end.
<b>Advantages</b>	Low power consumption, faster speed is easy, on-chip peripheral circuits possible.	Proven record of technologies and commercialization. - Simplified sensor - Low noise, high S/N
<b>Disadvantages</b>	Much noise - Irregular pixels - Random noise occurs <div style="border: 2px solid red; border-radius: 50%; padding: 5px; display: inline-block; color: white; font-weight: bold;">Problem solved by Canon!</div>	High power consumption, faster speed difficult, on-chip peripheral circuits difficult

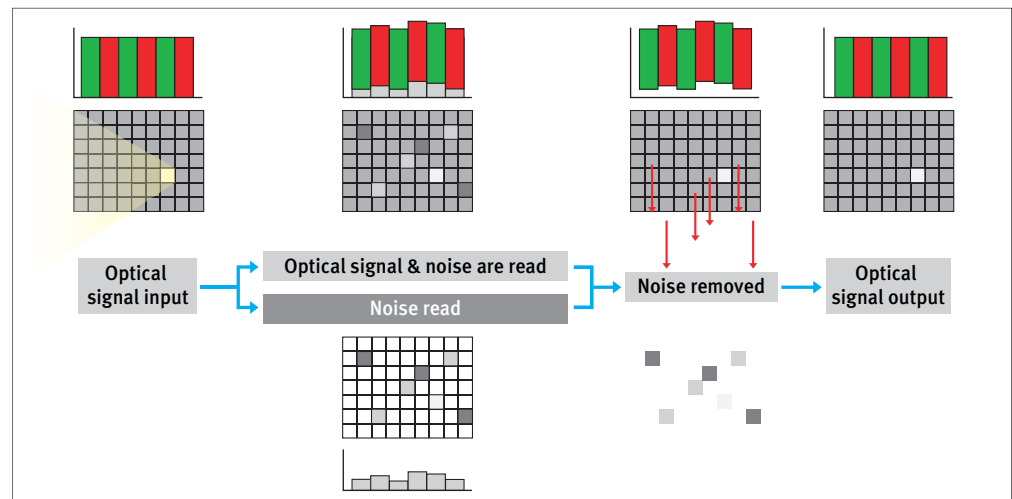
In the full-frame, 16.7 megapixel EOS-1Ds Mark II and the APS-H, 8.2 megapixel EOS-1D Mark II N, eight data channels are read simultaneously, a key to their remarkable combination of high resolution and high performance. In contrast, a CCD can be divided easily into left and right halves for two channels to be read separately. However, having more than two channels is difficult. Since the reading time cannot be shortened, faster speed is hard to attain.



**Noise issues** CMOS sensors generally have the disadvantage of generating more electrical noise than CCDs, which can result in poor image quality. There are unavoidable fluctuations in the performance of the millions of photodiodes and amplifiers incorporated into a CMOS sensor, and the tiny differences in performance result in noise in the output image. To overcome this problem, Canon developed on-chip technology to record the noise of each pixel before exposure, and automatically subtract such noise from the image when it is created. The incorporation of noise reduction enables the reading of a noise-free signal. This on-chip circuitry can be added only to CMOS sensors, not CCDs, because of the differences in the way the two are manufactured.

Canon has also altered the conventional three-transistor architecture of CMOS pixels (a photodiode, a MOSFET pixel amplifier and a reset switch for initializing optical charge), which are adversely affected by reset noise (called kTC noise, where  $k$  = Boltzmann's constant,  $T$  = operating temperature and  $C$  = total capacitance appearing at the input node of the amplifier transistor) caused when the sense-node capacitor is reset. To counteract this noise, Canon has added a fourth transistor that acts as a transfer gate. Kodak has designed four-transistor CMOS pixels in their own proprietary configuration, while Nikon's LBCAST sensors are 3-T.

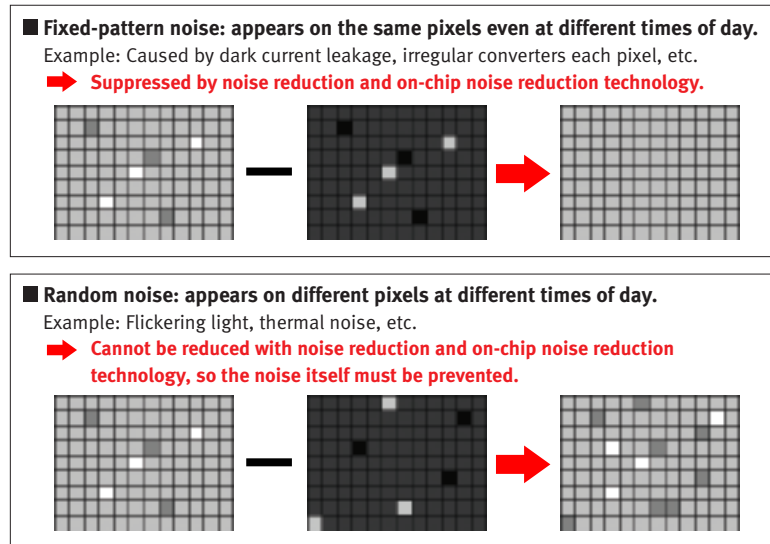
#### On-chip noise reduction technology



There are two types of noise that affect the image quality. One is called fixed-pattern noise, caused by dark current leakage, irregular pixel converters and the like. It appears on the same pixels at different times when images are taken. It can be suppressed with noise reduction and on-chip noise reduction technology. The main approach is CDS (Correlated Double Sampling), having one light signal read by two circuits. First, only the noise is read. Next, it is read in combination with the light signal. When the noise component is subtracted from the combined signal, the fixed-pattern noise can be eliminated. Canon's four-transistor technology is crucial in this process.

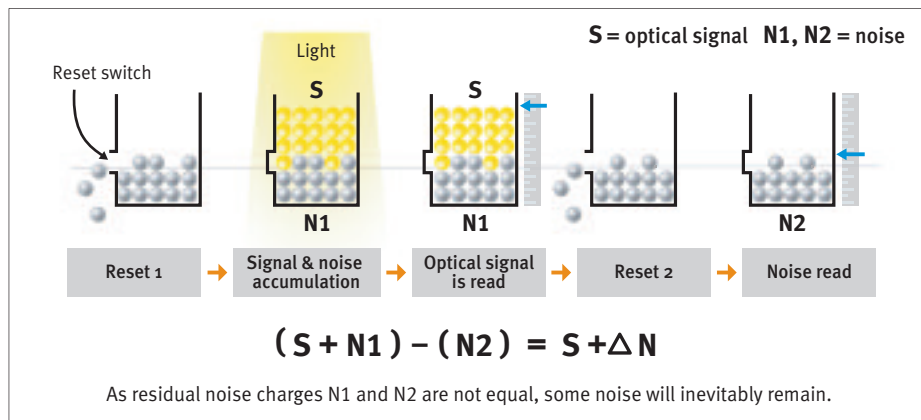
The other type of noise is called random noise, which appears on different pixels at different times. It is caused by flickering light or thermal effects. The noise reduction method used for fixed-pattern noise cannot be used to suppress random noise.

## The difference between fixed-pattern and random noise



Older approaches to random noise removal proved inadequate because the photodiode was reset incompletely after it was read. Imagine a valve that divides water between two water tanks. When the valve opens, the water does not know which tank to go to, so the amount of water becomes irregular over time. When the valve is opened and closed the first time, the new light charge (S) is accumulated and read as (S + N1) although it is unknown how much charge (N1) is in the bucket. When the valve is again opened, closed and reset, the noise charge (N2) is read and subtracted. This method cannot eliminate the noise charge (random noise) that varies each time the valve is opened and closed.

## Previous functionality



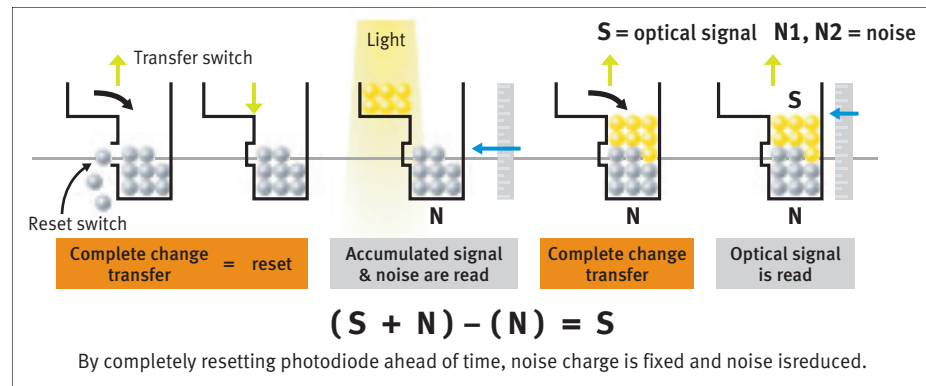
Canon's highly effective method for random noise suppression is called complete electronic charge transfer, or complete charge transfer technology. Canon designed the photodiode and the signal reader independently to ensure that the sensor resets the photodiodes that store electrical charges. By first transferring the residual discharge — light and noise signals — left in a photodiode to the corresponding signal reader, the Canon sensor resets the diode while reading and

holding the initial noise data. After the optical signal and noise data have been read together, the initial noise data is used to remove the remaining noise from the photodiode and suppress random noise, leaving a nice, clean signal.

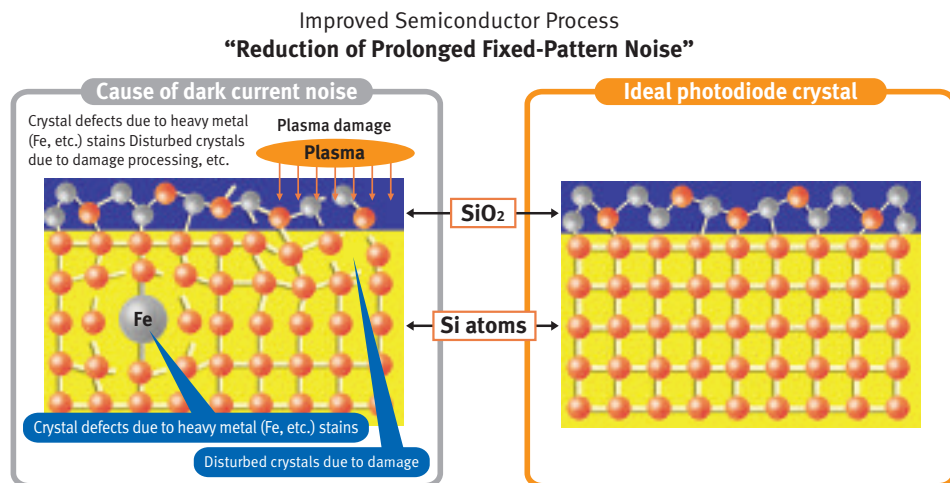
In the second diagram, the noise charge (N) is held while the light charge (S) accumulates in a different bucket. After the noise charge (N) is read, it is completely transferred from the bucket holding the light charge to the bucket holding the noise charge. The noise charge is then added together and read as (S+N). When it is subtracted, the noise charge (random noise) is eliminated.

Random noise normally increases with fast signal processing, so Canon has also developed unique technology that amplifies signals according to the sensitivity level generated just as they are read. Signals with high S/N ratios are then sent to a high-speed amplifier. With this assistance, low-noise sensors can function well in shooting situations requiring high ISO speeds and long exposures.

### Canon functionality



Dark current noise is caused by dirty substances, defective crystals due to plasma damage and other anomalies in the semiconductor manufacturing process. Sharing R&D information between divisions has enabled the development of solutions to these problems and has resulted in the improvement of Canon CMOS sensors.



**Revamped semiconductor process greatly reduces dark current noise!!**

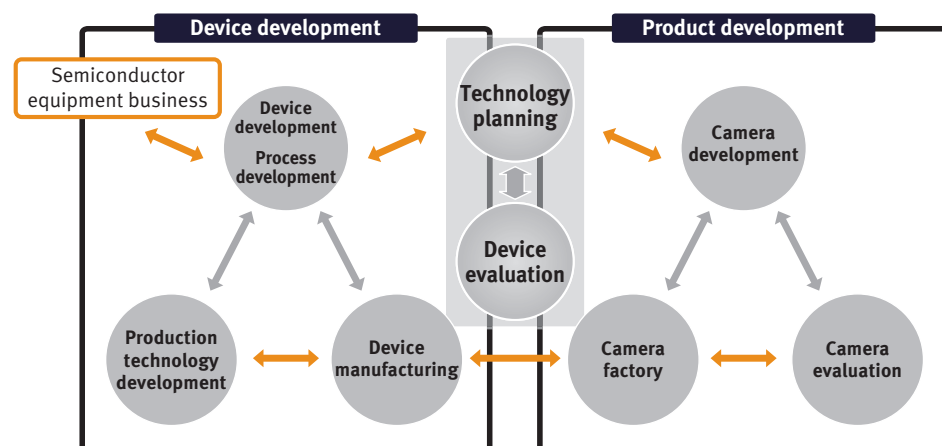
# VI. CANON'S UNIQUE R&D SYNERGY

Canon's strong background in semiconductor manufacturing equipment is one component in a corporate structure that has made Canon unique in the way its divisions work with each other on design, manufacturing and process development. For example, corporate optics research and semiconductor R&D shared a building, so scientists could talk and use common tools. Recently, each needed more space; now, they are next door to each other.

A signature feature of Canon's corporate structure is its multiple sets of R&D groups. At the top is a cutting-edge group that is not associated with products, just science. The middle group is also not exactly a product team. It searches for ways to commercialize technologies developed, discovered or invented by the first group, figures out what needs to be done to make connections and acts as a hub, sharing its knowledge with many in-house constituencies. Third is the product group that finalizes designs for the market. Even here, though, there is sharing across divisions. The camera people, for example, work with semiconductor people, not by themselves. They collaborate to determine what to make and how to make it. The knowledge they develop can be applied to other products, can filter back to mid-level R&D and can be used as the basis for custom designs.

Competitors, who have to go to third parties for important components such as imaging sensors and image processors, lose all these synergies because close information exchange is rare when technology secrets aren't shared readily. Should camera manufacturers design their own sensors and then go out looking for a fab, or semiconductor foundry, to make them? Should they buy something already developed by a third party? Who will resolve the electronic interface issues or pixel-level optical problems? Will it even be people who understand cameras and photography?

**The development and manufacturing system**

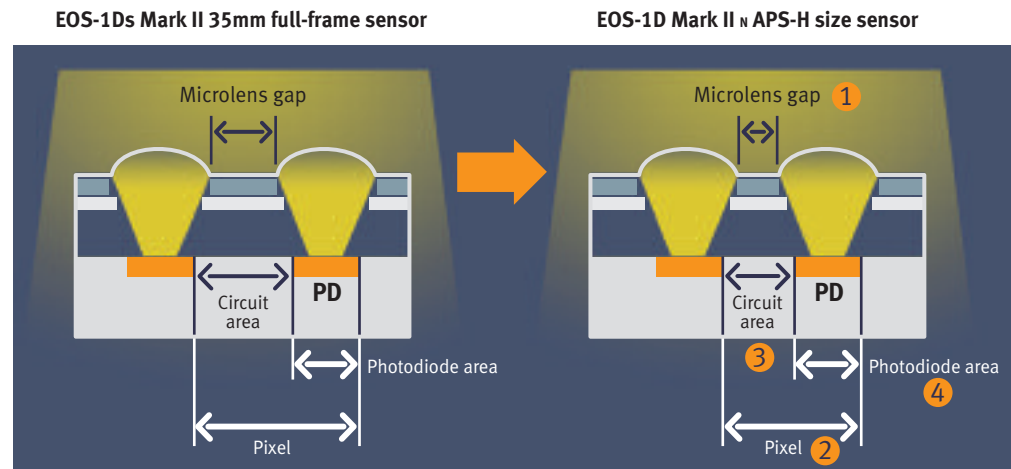


### Other differences between CMOS and CCD image sensors

It is widely mentioned that CCD photodiode surfaces are completely light sensitive, so their “fill factor” is said to be 100%. CMOS photodiodes have transistors near the surface, so they are not completely light sensitive and their fill factors are typically less. However, the shift registers between the rows of photodiodes on CCDs are masked and not light sensitive. On CMOS sensors, the metallic overlay of interconnects is not light sensitive either. The fact is that the degree to which an entire sensor either is or is not light sensitive is a matter of varying architecture and clever engineering.

For example, sophisticated new microlenses with tiny gaps between them appreciably increase the efficiency of Canon CMOS sensor light gathering. Convex microlenses are arrayed on the CMOS sensor surface with each lens matched to a single pixel. By shrinking the gaps between these minute lenses, Canon has enhanced the sensor’s light-gathering efficiency despite increased pixel density, resulting in the expansion of signal output range at high ISO speeds.

### On-Chip microlens



Reducing Microlens gap ① increases light-gathering efficiency.

➔ **Signal output range expanded in high ISOs.**

By decreasing both pixel size ② and circuit area ③, photodiode area ④ was kept constant. Therefore, the same amount of light can be gathered as on previous sensors.

➔ **Signal output range expanded in low ISOs.**

One often reads that the optimization of the CCD manufacturing process to speed charge transfer and improve image quality has made it difficult to integrate electronics onto the sensor, meaning that CCD manufacture is specialized while CMOS manufacture can take place in a standard semiconductor foundry. However, the high quality and low noise that are the hallmarks of Canon’s CMOS sensors are obtained by altering the manufacturing process to maximize color response at specific wavelengths and to reduce dark currents. Canon’s DSLR sensors have little in common with the commodity grade CMOS sensors found in cell phones or the cameras of other manufacturers. Additionally, conventional CMOS fabrication plants that manufacture ICs do not have the post-production infrastructure to handle imaging devices: clean rooms, flat-glass handling equipment and specialized packaging machinery. Suitably configured for high-end sensor manufacture, a CMOS fab is closely focused on its mission, even though it can always turn out some immaculate logic chips when necessary.

As an illustration of appropriate care, examine the picture of a Canon shipping container for exposure devices. It has double-layer air suspension to eliminate vibration, an accelerometer to check for shock and temperature and air pressure recorders to track weather events that might endanger stable precision.



*With double-layer air suspension to protect exposure devices from vibration, the ride in Canon's special shipping trailer is purported to be quite comfortable.*

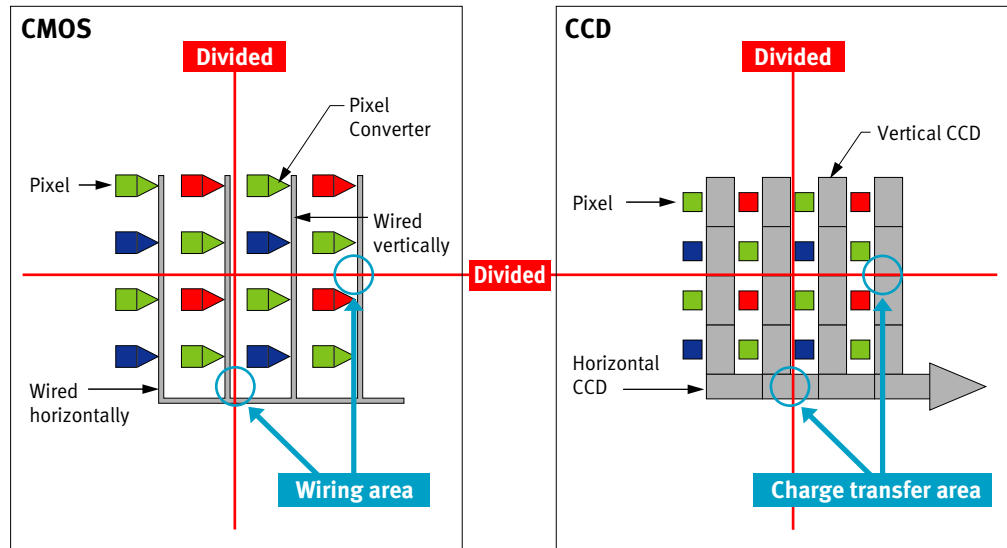
It is very difficult to produce a full-frame CCD sensor. The largest stepper/scanner image field today is 26mm tall by 33mm wide. This means all full-frame sensors must be made with multiple exposures, typically three for every imaging step in the manufacturing process. With CCDs, the electrical charge captured by the pixel is converted to voltage by only one converter. Horizontal and vertical electrical charge transfer paths are necessary over the entire CCD. The charge transfer paths must allow the charge to flow smoothly, like a gutter for rainwater. If there is any flaw or bump along the connecting seams, called an electron trap, the flow might clog up or spill out. Dividing up a CCD to match seams both horizontally and vertically requires unusually high precision, so fabricating a large CCD sensor is a painstaking process and potentially extremely expensive. This begins to explain why those Fairchild sensors mentioned earlier cost so much.

By comparison, because CMOS sensors convert photons to electrical charge to voltage at each pixel, the wiring just has to be electronically connected when aligning multiple exposures on a wafer. This is the key reason that Canon has been able to design and manufacture full-frame sensors for the EOS-1Ds, EOS-1Ds Mark II and EOS 5D. "Just," of course, is a funny word in this context. The 11.1-megapixel sensor in the EOS-1Ds had 200m circuits. The question here is not whether full-frame CCD sensors can be produced; the question is, primarily, how much such a sensor and camera would cost, and secondarily, whether a reasonably portable camera with acceptable run time could satisfy the power requirements of such a sensor. Against this, the CMOS sensor is ideally suited to the production of full-frame, 35mm format DSLR cameras that have superb performance, great practicality and portability, extensive system compatibility and very reasonable cost -- bargains, actually -- when compared with the alternatives.

## CMOS makes 35mm size easy

### Objective

Making a large sensor that exceeds the exposure limit of the micro pattern exposure machine for CMOS fabrication.



### Successful technology

Adjoining exposure semiconductor fabrication process incorporated

### Summing up for now

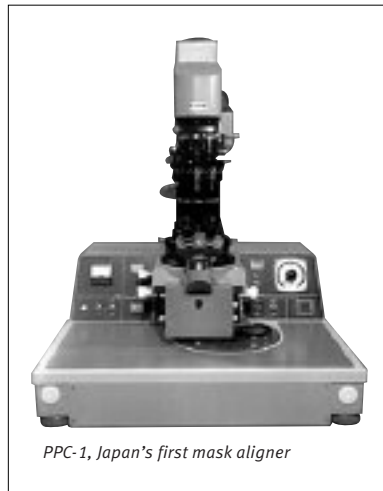
At this stage in the development of optical sensors, it seems likely that both CCD and CMOS technology will coexist peacefully for a long time.

- Although CCDs produce less noise than CMOS sensors, both types must rely on sophisticated noise reduction strategies to perform high-quality imaging.
- CMOS sensors use much less power than CCDs – the bigger the sensor, the bigger the difference – thus CMOS sensors extend battery life, require smaller batteries and make CMOS well-suited to use in cameras that need to be transported practically rather than mounted on studio stands or the noses of reconnaissance aircraft.
- CMOS sensors are initially less costly to produce than CCDs, but professional quality components must be made in specialized facilities.
- CMOS sensors use active pixels and multichannel readout to deliver their signals faster than CCDs. Multiple channels also allow low operation frequencies, suppressing noise even at high speeds. The higher the resolution of the sensor, the more pronounced the difference becomes. For example, the Canon EOS-1Ds Mark II has a 16.7 megapixel sensor yet fires consistently at 4 frames-per-second.
- CMOS manufacturing techniques permit on-chip integration of circuitry with intra-pixel amplification and on-chip noise reduction, boosting performance and minimizing outboard control electronics.
- CMOS technology lends itself to step and repeat, adjoining exposure and “stitching” during manufacture, enabling Canon to make the only full-frame 35mm format sensors on the market today.

## VII. SOME HISTORY

### Getting to here

Canon and Nikon have now competed with each other for about seven decades. Nikon is the older company of the two: It started operations in 1917, whereas the company that eventually became Canon did not appear until the early 1930s. It is probably not well known that the first Canon camera on the market, the Hansa-Canon of 1936, used Nikkor lenses. In 1945, Precision Optical Industry Co. Ltd. (the original official name of Canon) started making its own lenses, branded Serenar. Over the years, the two companies developed extensive expertise in the science and manufacture of precision optics. When Fairchild in the United States in 1959 pioneered



integrated circuit manufacturing, it was natural that Canon and Nikon would enter the field. Canon began development of an ultra-high resolution lens for IC production in 1965. It needed to have several times more resolving power than the photographic lenses of the day, as well as much closer manufacturing tolerances. The U 100mm f/2.8 lens was finished in 1967, establishing Canon in the high resolution lens field. Their first complete product, announced in 1970, was the PPC-1 semiconductor photographic etcher (mask aligner) with a U 170mm lens, an alignment microscope and alignment mechanism.

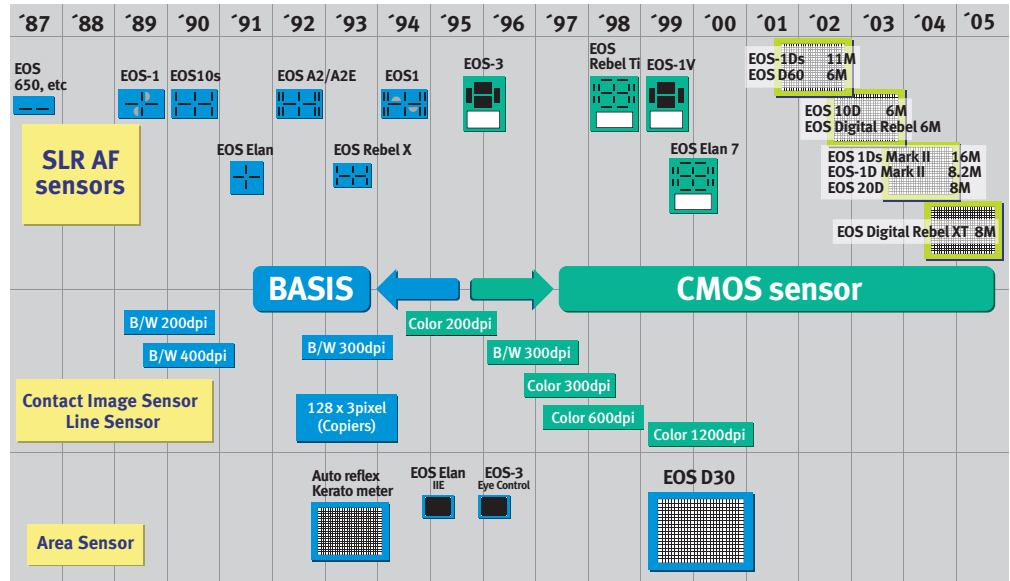
The PLA-500FA mask aligner, introduced in 1978, featured a laser-based automatic alignment system. Nikon began development of its SR-1 Step-and-Repeat System in 1976 and completed the work in 1978. In 1980, they offered the first stepper made in Japan, model NSR-1010G. Throughout the 1980s, they expanded the range and added wafer inspection and handling equipment. Canon's first stepper, the FPA-1500FA, was introduced in 1984.

In 1985, when Canon was developing its first autofocus camera, the EOS 650 (introduced March 1987), it took the bold step of choosing to manufacture the AF sensor itself, rather than purchasing an outsourced unit. It was a simple, single-line CMOS sensor with on-pixel amplification, called the BASIS (BAsis-Stored Image Sensor). The amplification-type solid-state imaging sensor had been invented by Canon scientist (and now Managing Director), Nobuyoshi Tanaka, who championed its application for sensors in Canon's SLR cameras, using technology Canon had originated as part of its semiconductor manufacturing equipment business. Tanaka picked Yoshio Nakamura to lead the BASIS development team that created the world's first CMOS AF sensor.



## History of Canon Sensors

Canon's sensor development technology ahead of its time



CMOS sensor technology soon found its way into other Canon products, including the sensor used for Eye Controlled AF in the EOS A2E (also known as the EOS 5) and EOS-3 film cameras. In addition to an eye control area sensor, the EOS-3 of 1998 had three more Canon-made sensors, the 21-zone AE sensor, the TTL flash metering sensor and the CMOS area AF sensor.

Early on, Canon realized several important things: that the age of digital cameras would probably come soon, that a Canon-produced CMOS sensor could also be used as an imaging sensor in a digital camera and, significantly, that Canon's other businesses would provide new market opportunities for the technologies they were about to develop, offsetting some of the risks they were about to take.

The EOS D30 digital SLR camera featuring Canon's very first CMOS imaging sensor with 3.1 megapixels was introduced in 2000. This camera was remarkable for its relatively affordable \$3,000 price (pro DSLR cameras with lower resolution were selling for as much as \$18,000 just a few years earlier) as well as its excellent image quality and handling characteristics.

In 2002, Canon created a major event in the history of photography with the introduction of the EOS-1Ds, an 11.1 megapixel professional DSLR with a full-frame CMOS sensor, developed and manufactured entirely by Canon. Unlike practically every DSLR that preceded it, the EOS-1Ds had a full-frame, 36 x 24mm, CMOS sensor. Canon's CMOS sensor technology was also used in the EOS-1Ds for both its 21-zone evaluative metering sensor and the Area AF sensor.

When Canon made the decision to manufacture its own sensors in 1985, they were already a major manufacturer of business equipment: black & white and color copiers, laser and inkjet printers, billing machines, calculators and fax machines, as well as broadcast television products, audio equipment, refractometers and industrial equipment for in-house applications. While some managers must have

been concerned about the level of investment required for assuming the entire responsibility for research and development of sensors and their manufacture, there were clearly people at Canon who were saying, “We could use these sensors we produce for autofocus and exposure control in cameras; we could use them in our flatbed scanners and multifunction printers; they’d be valuable throughout the paper path and elsewhere in our laser printers and copiers, and then we could apply the technology to the print heads of our inkjet printers.”

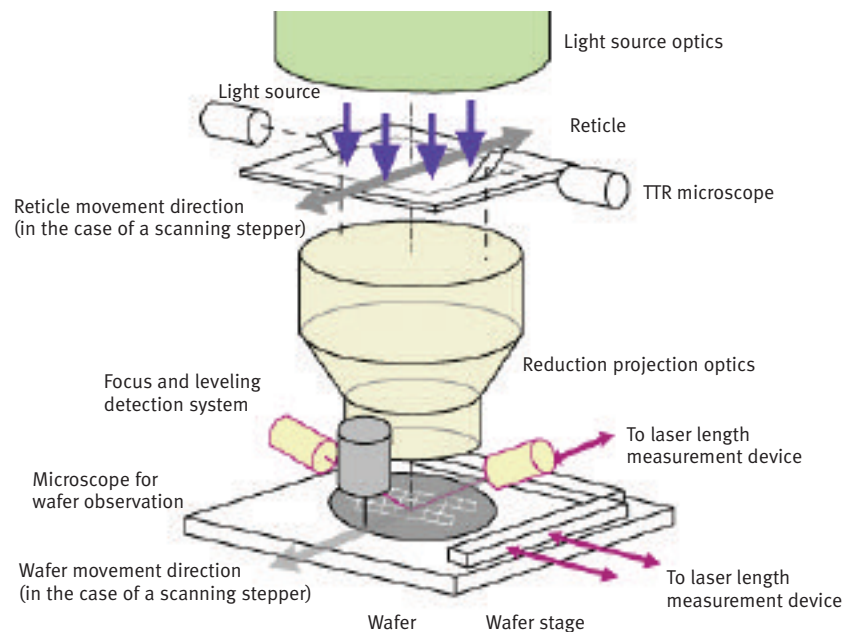
### Steppers and Scanners

Whether making AF chips, CCDs or CMOS sensors, semiconductor fabrication techniques are used. There are two kinds of machines that make semiconductors. The older and simpler is called a stepper.



Canon FPA-5500iZa stepper  
Approximate dimensions:  
7.5 x 11.1 x 8.5 ft. (W x D x H)

This is a Canon FPA-5500iZa stepper (sometimes called a “scan-field stepper”). It is often used to make the color filter layer for CCD and CMOS sensors, as well as less-critical process layers on many devices. It is, approximately, a \$5-million machine.



The light source of machines like this is often a laser, although the larger features of image sensors can be projected with the 365nm wavelength output of a short-arc mercury lamp rather than the 248nm and 193nm wavelengths of deep-ultraviolet lasers. The reticles can be thought of as glass plate negatives (5 times enlarged)

that are projected onto the silicon wafer below, but, looking at one, it would be hard to guess what it is. The image on the reticle side is a highly convoluted version of what is wanted. Many extra features are added because much information is lost in a low pass filter. Optical proximity correction, and often extreme exaggeration, is used to modify shapes to compensate for properties of the lithography process, such as the way different wavelengths function with great magnification and nanometer level imaging. Some features on the wafer will be smaller than the wavelength of the light that imaged them. In the trade, reticles are often called “artwork.” A set of perhaps 20 to 40 quartz reticles, worth several million dollars, needs to be perfected before a sensor is ready to be manufactured.

The lens looks pretty large in the diagram. Lenses in high-end machines today can run 5 feet tall and 2 1/2 feet in diameter and weigh several hundred kilograms. They are designed using absolute cutting-edge knowledge of glass, glass manufacturing, optics and physics. The image from the reticle is projected (and reduced) onto the 200–300mm silicon wafer at the bottom of the diagram. The machine is called a stepper because, after each small area exposure, the wafer stage moves a step for the next shot. Each time the wafer is exposed, it is then processed. Some of these steps include dry and wet etching, baking, encapsulation, epitaxy (growth of a single-crystal thick silicon layer on the front of a wafer), masking and coating.

In 1965, Gordon Moore, co-founder of Intel, observed that the number of transistors on an integrated circuit would double every year. The prediction/law has been re-interpreted variously to say that data density or computing power per unit cost will double every 18 or 24 months. The prediction has approximately held good for 40 years now and is generally estimated to have another two decades, at least, to run. In order to make circuits with smaller and smaller elements and keep up with Moore’s Law, regarded as a necessity in the marketplace, there is a constant search for new glass, new light sources, new liquids in which to immerse the wafer during exposure and much more.

Currently, 90 nanometer (feature size) machines are common; 65nm units are coming; 45nm scanners should be along in 3 years, and the research roadblocks are at the 30nm level with lots of attention given to anyone who can squeeze down to 29.9nm, however tentatively. ArF (Argon Fluoride) excimer laser immersion is hot now; EUV (Extreme UltraViolet) is probably next. Lens numerical apertures get bigger and bigger. To handle these geometries, advanced semiconductors are made on scanners, or stepper-scanners, rather than steppers. (The best old steppers made it to about 15nm.) The general idea remains the same, but in a scanner, both the reticle and the wafer move. The reticle moves 4 times as fast as the wafer going the opposite way, and the wafer moves as fast as 500 millimeters-per-second. More burn time means more reliability but less production, so speed needs to be evaluated in the context of throughput and productivity. (A goal might be, say, 100 wafers-per-hour.) The image is projected in a rectangular slit 7 or 8mm tall by 26mm wide. The laser pulses and is adjusted 4000 times per second. Each completed movement yields an image 33 x 26mm, big, but not big enough to make a full-frame sensor in one pass.

## Scanner: Semiconductor exposure equipment

### Reticle Stage

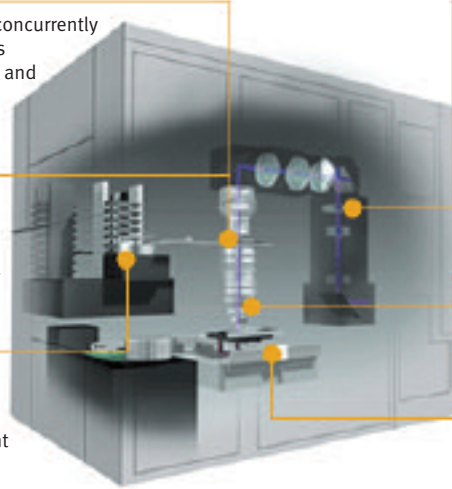
Holds reticles and moving concurrently with the wafer stage, moves continuously at high speed and with ultraprecision during the production process.

### Reticle

Source image that is scaled down by the lens and projected onto the surface of the silicon wafer.

### Reticle Changer

Supplies reticles for each stage of the production process from image projection and development to final processing.



### Light Source

Uses excimer laser beams at an extremely low wavelength (i-ray, KrF/ArF, excimer laser, etc.)

Light	Wavelength
i-ray	385nm
KrF excimer laser	248nm
ArF excimer laser	193nm
F2	157nm

### Lens

Out of the most important components in semiconductor exposure equipment, requires far more precision than a camera lens

### Wafer Stage

Moves rapidly and with ultraprecision while holding the silicon wafer

A scanner represents a considerable expense to its purchaser, perhaps \$30–40 million. With about 20 systems installed, imagine what a whole fab is worth. Worse, says Canon semiconductor guru Philip Ware, a fab is a “wasting asset,” which means the minute you buy it, you have to begin the dual processes of maintaining and upgrading it. As an aside, if it’s difficult to keep up as a user of this equipment, imagine the resources necessary to stay on the cutting edge if you are a manufacturer. No wonder there are only three major players in this field. Akiyoshi Suzuki, Canon nanotechnology specialist and fellow of the International Society for Optical Engineering, kids that he sometimes envies architects because their work remains for others to see, at least for a while.

Currently, there are at least 40 suppliers of CMOS sensor products. (There is probably an equal number of CCD manufacturers.) Micron claims to be the biggest, having grown in part through its purchase of Photobit in 2002. OmniVision and MagnaChip are big as well. Add Canon (which does not sell its CMOS sensors separately), Avago, Cypress, Eastman Kodak, STMicroelectronics, Toshiba, Samsung and Sony. In recent years, Cypress bought FillFactory and SmaL Camera Technologies; Eastman Kodak bought National Semiconductor’s imaging chip business; MagnaChip is acquiring IC Media.

There are two different business models: companies who design and manufacture the sensors, called IDMs, for integrated device manufacturers and “fabless” companies who design sensors and then go to foundries to have them made. A good argument can be made on either side. IDMs control their products completely and maximize quality, performance, production levels and costs as they wish at each step in the design and manufacturing process. They have that “wasting asset” to contend with, though. Sony, Samsung, Toshiba – and Canon – all have internal customer bases. The fabless companies think they’re better off unencumbered and free to chase technology and wring economies from subcontractors. All the consolidation means many companies are finding the market too competitive.

Unique is an overused word; things which are not even out of the ordinary are called unique every day. In major respects, however, Canon is unique and stands alone. It is the only company in the world that makes semiconductor manufacturing equipment, uses its own equipment to actually manufacture semiconductors (including those beautiful full-frame CMOS sensors), and then consistently and exclusively puts those sensors into its own cameras. This is total control and total synergy at the highest level. The risks taken in 1985 have paid off.

Semiconductor manufacturing at Canon provides a technical foundation for the design, development and production of the creations it sells, such as office equipment, still and video cameras, projectors, displays and display optical systems, X-ray digital cameras, tonometers (that test for glaucoma with an air puff), broadcast television lenses, remote-controlled pan-tilt systems, advanced scientific telescope lenses, rotary encoders, mirror projection aligners, steppers and scanners, software-based equipment operating systems, ecologically sound production systems and much more. The incredibly precise tools used to make these things, and the tools used to maintain that equipment, come from Canon's unique manufacturing equipment tool division, tightly linked to semiconductor-machine production R&D, that devises and makes tools of unprecedented accuracy. Canon does not sell these tools.

# VIII. CONCLUSION

Canon CMOS sensors and, in particular, Canon full-frame CMOS sensors, must be seen as the extraordinary result of many kinds of expertise that Canon has developed since the 1930s. In recognizing the enormous image quality advantages Canon's full-frame CMOS sensors enjoy, one cannot help but respect and admire Canon's ability to produce these sensors in concert with two cameras whose remarkable performance and value leads the entire DSLR segment, the EOS-1Ds Mark II and the EOS 5D.