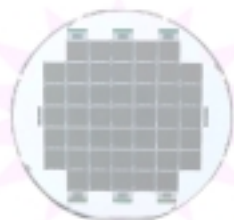


Kodak CMOS Image Sensors



A White Paper on Kodak's Leading Technology and Market Position



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Summary

Kodak is a leading supplier of CCD (Charge Coupled Device) image sensors and has recently introduced CMOS (Complementary Metal Oxide Semiconductor) image sensors. Each of these technologies has strengths and weaknesses and there is currently much confusion about the merits of each. This paper describes the basic differences between the technologies, characterizes the current state of the industry, explains Kodak's position in the industry and its vision for the future of CMOS imager technology.

In short, Kodak currently offers leading-edge CMOS imaging technology that is used in both high performance and low-cost applications. CMOS imaging technology will enable whole new classes of mobile imaging products because of its ability to integrate additional electronics on-chip, its low power and low cost. These are billion dollar market opportunities and Kodak will provide image information solutions consisting of image sensors, support electronics and optics. Kodak will focus on its superior image quality sensors to provide the best visual solution at competitive prices.



CMOS Enables New Applications

CMOS image sensor technology is just starting to enter the market now. Will it displace CCD technology? Opinions differ, but Kodak feels the biggest opportunities for CMOS imagers are in new product categories made possible by the features of CMOS sensors. The key features that will enable this emergence include the much lower power usage of CMOS imagers, the ability to integrate additional circuitry on-chip and lower system cost. Such features play perfectly to advanced mobile products that can now add imaging capabilities for the first time.

Figure 1 shows the migration of imaging technology. As can be seen, there are already two branches: the high-performance, low-volume branch and the low-cost, high-volume branch. In the high-performance branch are applications such as motion analysis, medical imaging, astronomy and low-end professional still cameras. Such applications will continue to be dominated by CCD technology, but CMOS technology will find market share too, especially for lower cost or more portable versions of these products. This is exactly where Kodak's "Extended Performance" CMOS imagers are targeted.

The other branch is where most of the CMOS activity will be. Here, in many applications CCD sensors will be replaced with CMOS sensors. These could include some security applications, biometric and consumer digital cameras.

But the majority of growth is expected to come from new products enabled by CMOS imaging technology. This will

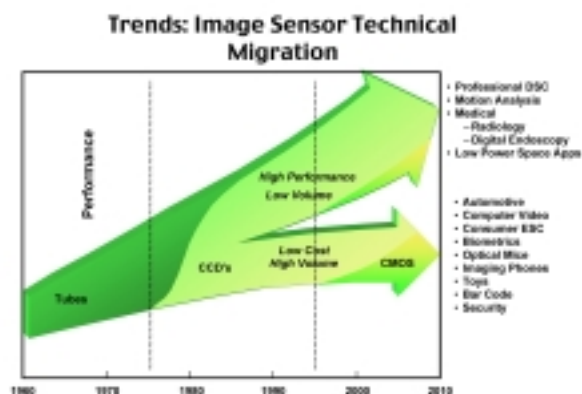


Figure 1

include automotive, computer video, optical mice, imaging phones, toys, bar code readers and a host of hybrid products that can now include imaging. Such products will be mass produced consumer products that require millions of CMOS imagers.

How Are CMOS Imagers Different Than CCD Imagers?

Both CMOS and CCD imagers are fabricated in a silicon foundry using similar equipment. But much of the similarities end there. Alternative manufacturing processes and device architectures make the imagers quite different, and therefore, better suited for varying applications.

CCD technology was developed in the 1970's and 1980's specifically for imaging applications. CCD technology and fabrication processes were optimized to build an image sensor with the best possible optical properties and image quality. The technology continues to improve and is still the choice in applications where image quality is the primary requirement or market share factor.



A CCD is composed of pixels, or picture elements, which are arranged in an X-Y matrix consisting of rows and columns. Each pixel, in turn, is composed of a photodiode and an adjacent charge holding region, which is shielded from light. The photodiode converts light (photons) into charge (electrons). The number of electrons collected is proportional to the light intensity. Typically, light is collected over the entire imager simultaneously and then transferred to the adjacent charge transfer cells within the columns.

Next, the charge must be readout. To do this, a row of data including signal from one pixel in each of the columns is moved to a separate horizontal charge transfer register. Charge packets for a given row are readout serially and sensed by a charge to voltage conversion and amplifier section (see Figure 2). The next row of data is then clocked into the horizontal transfer register. This is repeated until all rows are readout and an image can be displayed.

This architecture produces a low noise, high-performance imager, but it has trade-offs in terms of the manufacturing process. For example, CCD process technologies have been optimized to improve image quality, but in so doing, these processes are now unsuitable for efficient integration of other electronics onto the silicon. To operate a CCD also requires that one applies several clock signals, clock levels, and bias voltages, complicating system integration and increasing power consumption, system bulk and cost.

A CMOS imager, on the other hand, is made with standard silicon processes in high-volume foundries. Peripheral electronics, such as digital logic, clock drivers, or analog-to-digital converters, can be readily integrated with the same

fabrication process—a big potential advantage. CMOS imagers will also directly benefit from the progression of mainstream semiconductor technology, leveraging the move to smaller design rules and the ability to scale the technology to high volumes and resolutions.

To achieve these benefits, the CMOS imager architecture is arranged more like a memory cell or a flat-panel display. Each pixel contains a photodiode that converts light to electrons, a charge-to-voltage conversion section, a reset and select transistor and an amplifier section. Overlaying the entire imager is a grid of metal interconnects to apply timing and readout signals, and an array of column output signal interconnects. The column lines connect to a set of decode and readout (multiplexing) electronics that are arranged

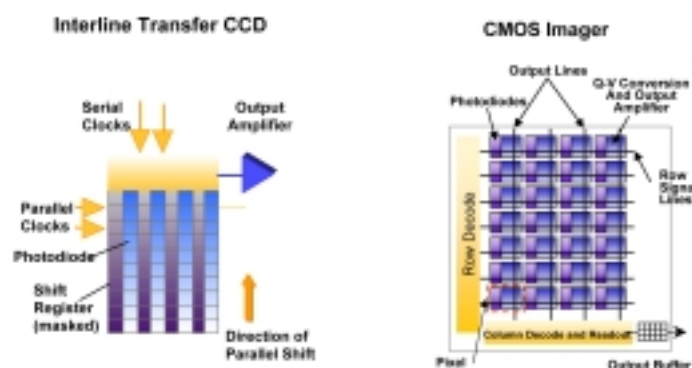


Figure 2
CMOS and CCD Sensor Architectures

per column outside of the pixel array. This architecture allows the pixel signals from the entire array, from sub-sections or even a single pixel to be readout by a simple X-Y addressing technique. This is something a CCD can't do.



CCD	CMOS
Smallest Pixel Size	Single 3.3-5 V Supply
Lowest Fixed Pattern Noise	Low Power Consumption
Low Dark Current	X-Y Addressing and Sub-sampling
~100% Fill Factor for Full-Frame CCD	Smallest System Size
Established Technology/Market Base	Easy Integration of Circuitry
Highest Sensitivity	Lower Cost
Electronic Shutter without Artifacts	

Table 1
Comparison of CCD and CMOS Image Sensor Features

There are many variations on both CCD and CMOS architectures but the basic characteristics and differences between the two technologies remain the same. Table 1 summarizes some of the main differences between CMOS over CCD imagers. These characteristics can be used to guide designers and users in determining which sensor technology is best for their application.

The State of CMOS Technology

If CMOS imager technology has all of these benefits over CCD technology, why hasn't it completely displaced it by now? There are a number of reasons; some are technical or performance related, and others are related more with the growing maturity of the technology. CCDs have been mass produced for over 25 years whereas CMOS technology has only just begun the mass production phase. Rapid adoption was also hindered because some companies over-promised the capabilities of CMOS sensors. When they finally delivered imagers, they disappointed customers and users because of poor imaging performance and poor image quality.

Alternatively, Kodak chose to develop the CMOS technology to the point where it could deliver quality images before commercially introducing products. Since Kodak also makes a full line of high performance CCD imagers, CMOS development was greatly aided by the expertise gained from 25 years of CCD process development and manufacturing. While it is true that standard CMOS manufacturing lines and equipment can be used to make imagers, low-noise, good-quality imagers require that the process be modified to achieve these results.

For example, a standard CMOS logic process normally seeks to have a shallow epi layer thickness to mitigate CMOS latch-up. For an imager, this can lead to low response in the red portion of the spectrum. Shallow, heavily doped junctions enable dense short gate length devices—a desirable feature in CMOS logic but a cause of low green response and high dark currents in CMOS imagers. These and numerous other process trade-offs must be understood and optimized to achieve the best possible performance—something Kodak has learned to do from its CCD manufacturing experience.



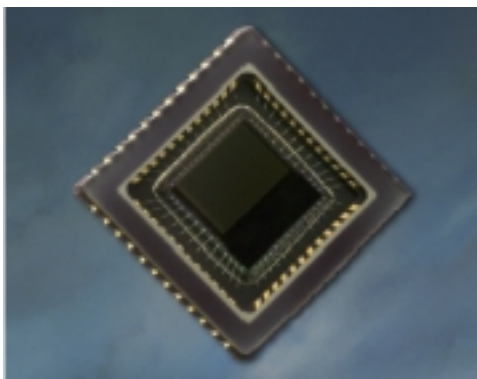


Figure 3
Kodak's KAC-0310 Image Sensor

Consider Kodak's KAC-0310 Image Sensor as an example of the current state-of-the-art (see Figure 3). This device features a sensor with 640 x 480 active elements with row and column decode electronics. But there is also additional logic integrated onto the same CMOS chip that makes the device a monolithic image capture and processing engine. This includes a timing and control section enabling programmable windowing, sub-sampling and readout modes, a frame rate clamp (FRC) for black level calibration, digitally programmable amplifiers for white balance and gain control, a 10-bit analog-to-digital conversion (ADC) section and post-ADC digital logic processing (see Figure 4). This mixed-signal imager can output VGA images at 60 frames per second and consumes less than 200 mW while running off a single 3.3 Volt supply. A similar CCD imager consumes about 500 mW and requires more physical volume due to the support chips and multiple supply voltages.

Such devices demonstrate a key difference from CCD technology; the ability to integrate additional logic and achieve a camera-on-a-chip. This allows the consolidation of multiple discrete logic and mixed signal ICs into a single device, thus reducing the size, part count, power consumption and cost of the imaging solution.

Bridging the CCD / CMOS Performance Gap

Many CMOS imagers do not perform at the same level as CCD imagers. Most notably, CMOS imagers can have high fixed-pattern noise, low sensitivity to light, high dark current, focal plane shutter effects and some difficulty scaling to smaller pixel sizes. This is in part due to the architecture of CMOS devices, as well as their relatively infant state of manufacturing. However, there has been steady progress in solving these issues, particularly at Kodak.

For example, Kodak has patented a CMOS imager architecture that includes a 'pinned photodiode' detector element, along with a proprietary transfer gate structure and reduced dark current processes. Clever circuit designs have been implemented for both noise reduction and as a means to circumvent alternatives that require more difficult process adjustments. Reducing dark current, for example, helps lower the overall sensor noise resulting in higher camera signal-to-noise levels and wider dynamic range.



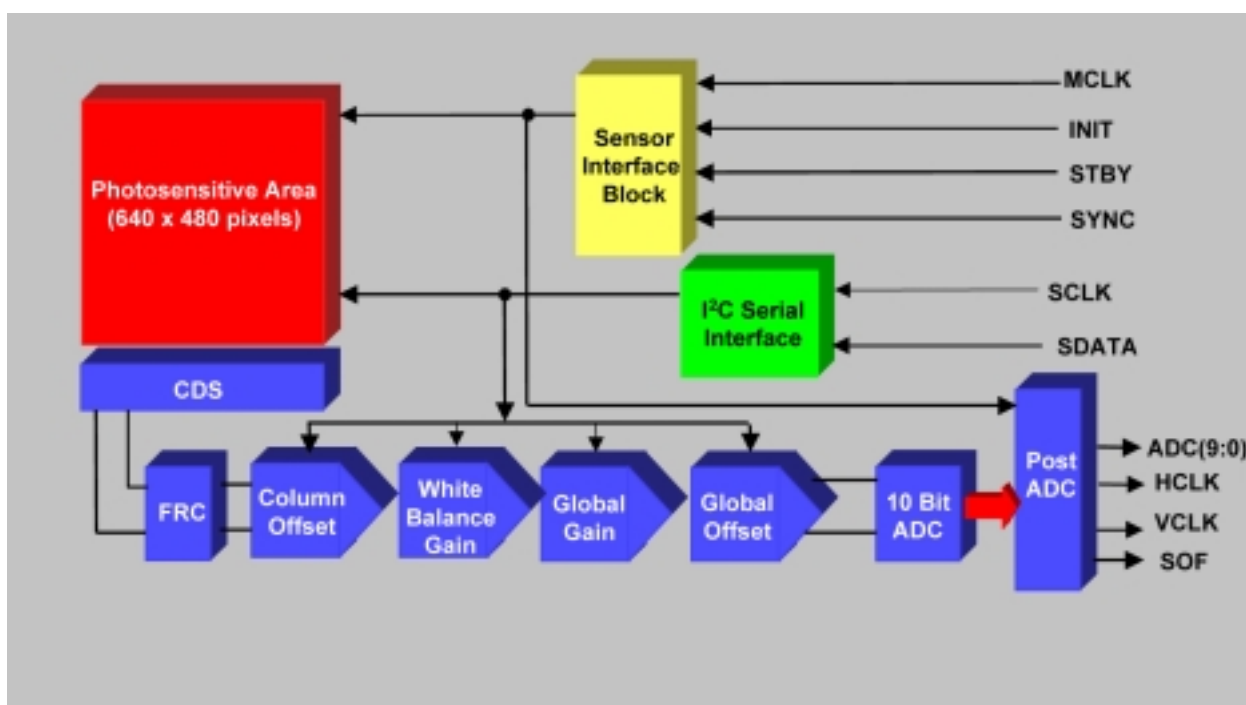


Figure 4
Simplified Block Diagram of KAC-0310 CMOS Image Sensor

Obtaining uniform photo-response across an entire array is also critical and this is achieved by applying Kodak's CCD expertise and experience to the CMOS process and circuit design. But these changes must also be consistent with the fabrication of mixed-signal logic in order to produce a camera-on-a-chip. Understanding these complex trade-offs between process parameters, imager performance, mixed signal logic, cost and system complexity is precisely where Kodak has focused major development efforts. As a result, Kodak has now filed numerous patents related to CMOS technology, with many issued so far, establishing a leadership position in the field.

Let's consider how superior CMOS specs can affect camera performance. For example, camera makers like to have cameras that can capture low noise images in all types of conditions, from dimly lit rooms to bright outdoor areas. Digital cameras typically perform the worst in dimly lit scenes. To improve the image quality or signal to noise for dimly lit conditions requires a sensor with wide dynamic range.

This translates into a sensor with high quantum efficiency (sensitivity), large electron storage capacity, low dark current, and low noise. These sensor attributes are critical to achieve good low light performance. Camera makers also desire a sensor that can capture scenes with both dimly and highly illuminated regions without blooming or loss of detail in the bright areas, and with detail and low noise in the dark areas. This requires a sensor with wide dynamic range for good signal to noise and detail in the dark regions, and wide intra-scene dynamic range to retain the details in the bright regions. These two types of dynamic range have different sensor requirements. Most CMOS sensor specification sheets today are providing the intra-scene dynamic range number as the dynamic range specification. High intra-scene dynamic range is desirable but is not sufficient to provide good image quality for dimly lit scenes (see sidebar). The number on the Kodak spec sheet is true dynamic range. Kodak CMOS sensors will provide excellent true dynamic range and intra-scene dynamic range. (see sidebar).

On Kodak's KAC-0310 1/3" optical format VGA Image Sensor, the sensitivity at 550



nm is an impressive 90,000 electrons/mcs (meter-candle-second) without the use of microlenses. Kodak offers CMOS images with integral microlens arrays. This matrix of tiny lens elements fits right over each pixel to help collect more light and focus it onto the photodiode. This increases sensitivity to 137,000 electrons/mcs. Other CMOS sensor vendors state this in Volts/mcs. This can be misleading since the number of volts per mcs contains the gain of converting electrons to volts and any voltage gain in the system. Since the signal is captured as electrons, the important thing to know is how many signal electrons are produced per mcs. A sensor can provide a large number of volts per mcs by adding voltage gain in the signal path. Since the voltage gain is applied to signal as well as noise, one can have a large number of volts per mcs without having a large SNR. Noise levels (dark current normalized to the entire pixel area) are a low 0.2 na/cm². Other CMOS vendors may quote as low a number, but they may not be normalizing the dark current to the smaller photodiode area, but instead, to the larger pixel area. If this is not explicitly stated, it can make the dark current performance appear better than it really is.

Capture of fast moving objects is also desirable. This requires a rapid shutter and fast responding CMOS sensors. Kodak sensors feature patented global shutter operation with zero image lag. Other CMOS sensors have only a 'rolling-shutter' which can lead to image blur or artifacts from AC illumination.

Another area where Kodak has a competitive advantage is in color science and image processing technology. Extensive experience in making integral color filter arrays for CCD-based professional cameras and applications has been applied to the manufacture of CMOS sensors also.

Kodak also plans to introduce "Extended- Performance" versions of their CMOS image sensors. Such devices will feature wider intra-scene dynamic range, efficient on-chip color processing, and other features.

Most importantly, CMOS technology is poised to follow the evolution of traditional high-volume silicon technology pushing toward smaller and smaller design rules. This allows Kodak to migrate production of CMOS imagers from lines using 0.6 micron design rules, to next-generation lines utilizing 0.35 and 0.25 micron design rules. These advanced devices will allow the pixel size to shrink to about half their current size within the next few years. As a result, many more pixels will be packed onto standard ¼", ⅓" and ½" imager formats.

Debuting in November 2000, for example, will be a 1280 x 1024 (SXGA) resolution CMOS image sensor in a ½" format, the KAC-1310. This device increases pixel densities and will offer a wide, true dynamic range of 60 dB—performance rivaling many CCD imagers.

Why Kodak?

Kodak will be a major player in the emerging CMOS imager market just as they are in the CCD imager market, and they will supply CMOS sensors and imaging engine solutions for all market segments. The company will focus on supplying high-quality image solutions at competitive prices. With similar experience in the CCD market, Kodak can offer a wide range of competitive advantages in this market.

Consider system integration. Kodak has already introduced a VGA imager with a high level of complementary electronic functional integration. This can be extended to include RAM/ROM, microprocessor or DSP cores and even system interfaces. With Kodak's in-house optical expertise, the addition of optical elements to form complete imaging solutions is possible too.



Kodak will provide such solutions or work with customers on shared solutions. Such imaging engine systems allow Kodak to deliver information, not just images — a key competitive advantage.

Kodak's CMOS technology is at the peak of its class. These sensors offer high sensitivity, low light level performance, wide dynamic range, low noise, global shutter operation and on-chip color processing. Further, Kodak has sophisticated automated optical testing capabilities with defect detection and mapping capabilities. All of this is meant to insure that high quality sensors are delivered to specification as well as on-time. The bottom line is that whether one is looking for a CCD or CMOS solution, Kodak offers superior image quality at competitive prices.

Intra-Scene vs. True Dynamic Range

Image sensor manufacturers will often refer to the "dynamic range" of their product. There are two types of dynamic range; true dynamic range (DR) and intra-scene dynamic range (IDR). Most CMOS sensor manufacturers provide a number without explaining which of the two types it is.

True dynamic range is a measure of the sensor's maximum number of signal electrons compared to its total dark temporal RMS noise level. The total dark noise includes dark current shot noise, pixel read noise, and temporal noise of any signal processing circuits that are integrated in the signal readout path. It does not include photon shot noise, however. The maximum number of signal electrons is the charge capacity of the pixel minus the average number of dark current electrons collected for a specific integration time. DR is reported in dB and a higher value means a greater ratio of the sensor's maximum number of signal electrons to its total dark noise. For example, if the ratio is 1000:1 this will be a DR of 60dB.

Intra-scene dynamic range (IDR) refers to the range of illumination levels within a single scene that imager sensor can provide details about. This is a measure of the sensor's maximum calculable or extrapolated signal level, compared to its total dark temporal RMS noise level. A good way to illustrate this is to consider a sensor that takes two pictures of the same scene. The first picture features a long integration time while the second uses a short integration time.

The picture with the long integration time will provide good details in the dark regions of the scene but the bright regions may not show good details since too many electrons may have overpowered, or saturated the pixel. Alternatively, the picture with the short integration time will provide good details in the bright areas (because the pixels did not saturate), but now, there are not enough photons captured to provide good details in the darker regions of the scene.

The good news is that signal processing electronics can be used to blend these two images to provide an image that offers good details in both the dark and bright regions of the scene. This is the intra-scene dynamic range. A sensor can have high IDR without having low noise or high DR.

Consider two different scenes where DR and IDR are important. If the scene is outdoors there may be a wide range of illumination from shadowed areas to reflections of the sun off of the water. Here, high IDR is important to capture details of both the bright and dark areas. However, high DR is not needed since even the darkest parts of the scene will have enough photons to generate good signal-to-noise ratios even with a short integration time.

On the other hand, if the scene is a birthday party with candles in a dim room, then a wide DR is more important. While the candles create enough photons for good signal-to-noise levels, the dimly lit room does not, thus requiring a sensor with high sensitivity and low noise and low dark current. A wide IDR sensor with lower sensitivity and higher noise and dark current could integrate over a long time period. However this will produce high noise, and limited signal range in the dark regions if the electrons generated from dark current are comparable to the photo-generated electrons. Saturation for the candles if the dynamic range is not high enough. High IDR is not sufficient in this case; wide DR is required to produce a low noise, high quality image.

