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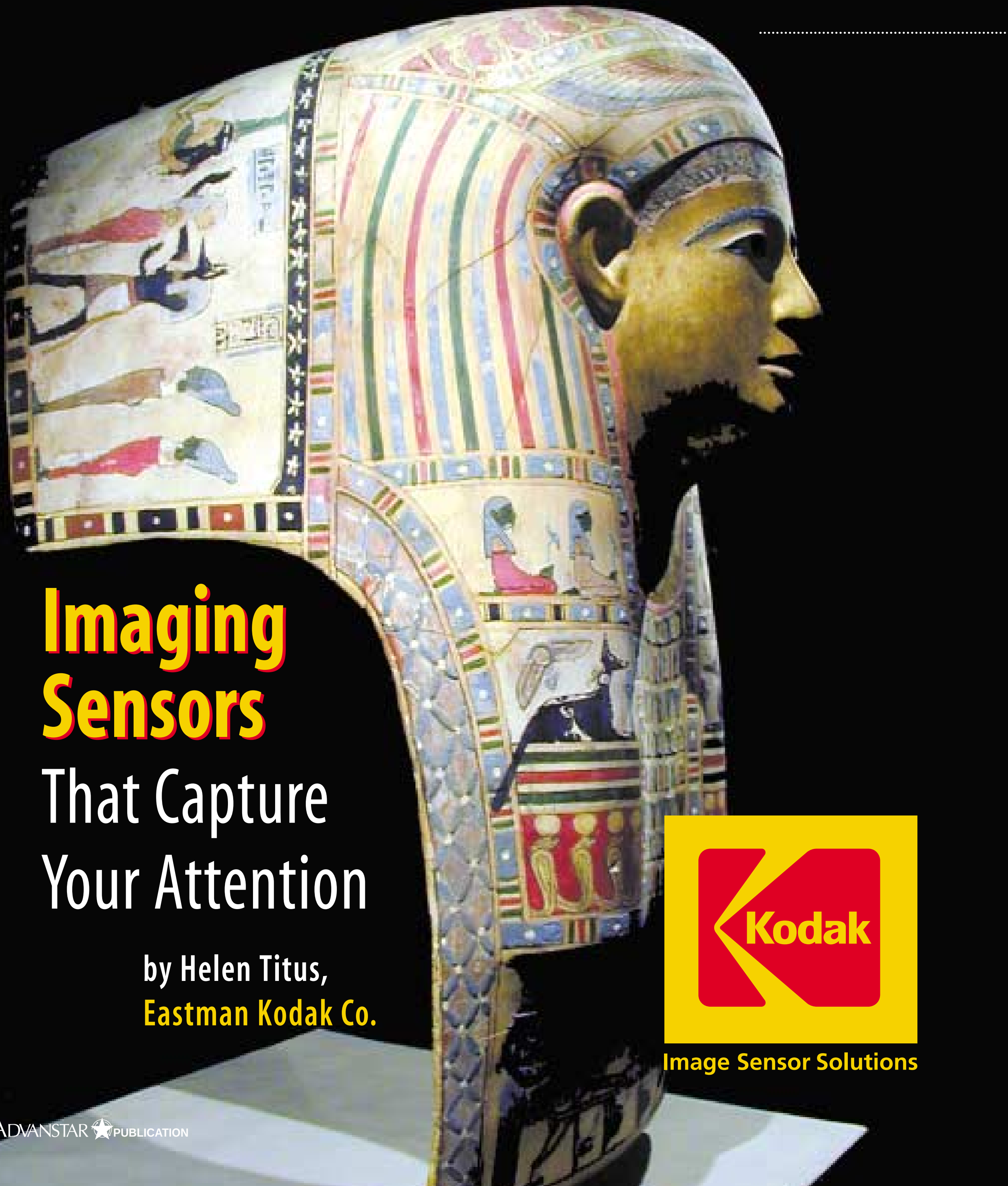

Imaging Sensors That Capture Your Attention

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Imaging Sensors
That Capture Your Attention

Ready to revolutionize the market, CMOS technology enables you to add imaging capabilities to products you never thought possible.

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Image Sensor Solutions

The mainstay of image capture for the last 25 years has been the CCD (charge coupled device) image sensor, but CMOS (complementary metal oxide semiconductor) devices have seen rapidly increasing success. Each of these technologies has its strengths and weaknesses, and there is much confusion about the merits of each. Now CMOS technology is poised for rapid growth in a wide variety of new products, especially mobile imaging products.

New Applications

Figure 1 shows a high-level view of the migration of image sensor technology. The high-performance, low-volume branch encompasses such applications as motion analysis, medical imaging, astronomy, and low-end professional still cameras. CCD technology will continue to dominate these and similar applications, but CMOS sensors will capture a market share. For example, Kodak's extended-performance CMOS sensors are targeted at lower cost or more portable versions of these imaging products.

The low-cost, high-volume branch is where most of the CMOS action will be. Here, in many applications (e.g., security applications, bar code readers, and consumer digital cameras), CMOS sensors will replace CCD devices. The majority of growth, however, is expected to come from new products enabled by CMOS imaging technology, such as automotive, computer video, optical mice, imaging phones, toys, biometrics, and a host of hybrid products. CMOS technology is appealing to developers of these products, because of its:

- Low power consumption
- Ability to integrate timing, control, and other signal processing circuitry on chip
- Single supply and master clock operation

CMOS's key features allow smaller system size and lower system cost, making the sensors well matched to advanced mobile products in need of imaging capabilities. These products will be mass consumer products that require millions of CMOS imagers.

Both CMOS and CCD imagers are manufactured

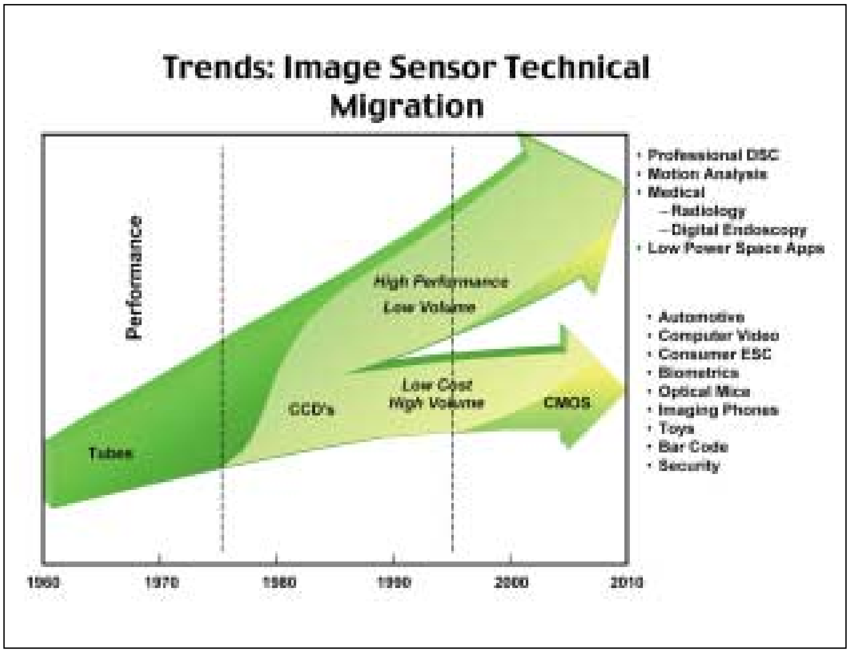

Figure 1. This graph shows the trend in image sensor migration of CCD and CMOS devices for various market applications. CCDs will continue to dominate in high-performance, low-volume segments, such as professional digital still cameras, machine vision, medical, and scientific applications. But CMOS will emerge the winner in low-cost, high-volume applications, particularly where low power consumption and small system size are key.

in silicon wafer fabs using similar equipment, but the similarities end there. Alternative manufacturing processes, individual device architectures, and unique materials make the imagers quite different and therefore better suited for different applications.

The CCD Approach

CCD technology was developed for imaging applications, and its fabrication processes were optimized to build an image sensor with the best possible optical properties and image quality. Continually improving CCD technology 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, arranged in an X,Y matrix consisting of rows and columns. Each pixel, in turn, is composed of a photodiode and an adjacent charge transfer region, which is shielded from light. Adjacent charge transfer regions are arranged in a column to form a vertical charge transfer register. 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 in the columns.

Next, the charge must be read out. To do this, one row of data, including signals from one pixel in each of the columns, is transferred from the vertical charge transfer register to a separate horizontal charge transfer register. The charge packets for a given row are then read out 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. The process is repeated until all rows are read out and an image can be displayed.

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

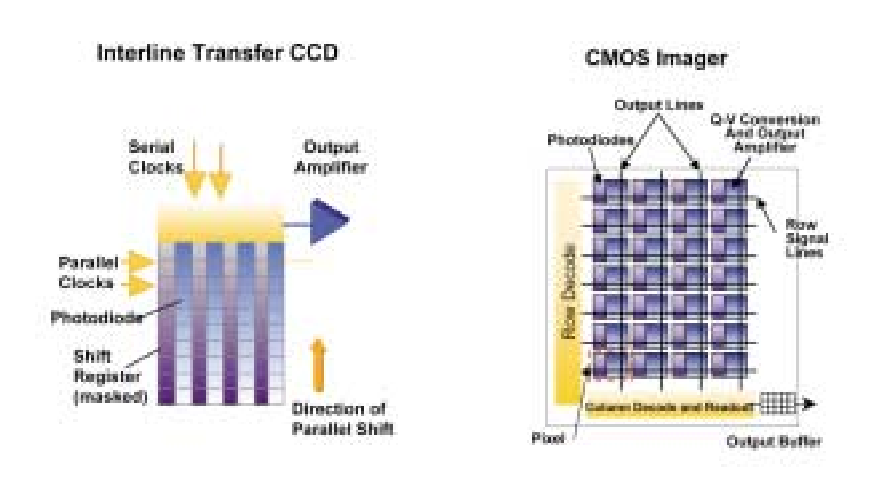

Figure 2. This illustration compares a typical interline transfer CCD architecture with a typical CMOS imager architecture. The CCD must read out each row of pixels serially. But a CMOS imager is X,Y addressable, so each pixel can be read out independently, making windowing or subsampling of the image possible.

The CMOS Difference

CMOS imagers, on the other hand, are made with standard CMOS silicon processes in high-volume wafer fabs that produce ICs, such as microprocessors, microcontrollers, and DSPs. Therefore, the CMOS's pixel array can be formed on the same device with standard electronics, such as digital logic, clock drivers, or A/D converters—a big advantage over the CCD processes. CMOS imagers can use the high-volume infrastructure of the semiconductor industry and will directly benefit from the progression of mainstream semiconductor technology, taking advantage of 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, which converts light to electrons; charge-to-voltage conversion section; reset and select transistor; and amplifier section.

Overlaying the entire pixel array is a grid of metal interconnects, which applies timing and readout signals, and an output signal metal interconnect for each column. The column output signal is connected to a set of decode and readout electronics, which are arranged for each column outside the pixel array. This architecture allows the pixel signals from the entire array, from subsections to individual pixels, to be read by a simple X,Y addressing technique—impossible with a CCD.

There are many variations on CCD and CMOS imager architectures, but the basic characteristics and differences between the two technologies remain the same. To help you decide which sensor technology is best for your applications, Table 1 (page 28) summarizes some of the main differences between the two technologies.

TABLE 1

Comparison of CCD and CMOS Image Sensor Features

CCD	CMOS
Smallest pixel size	Single power supply
Lowest noise	Single master clock
Lowest dark current	Low power consumption
~100% fill factor for full-frame CCD	X,Y addressing and subsampling
Established technology market base	Smallest system size
Highest sensitivity	Easy integration of circuitry
Electronic shutter without artifacts	

The State of CMOS Technology

If CMOS imager technology has all these benefits over CCD technology, why hasn't CMOS displaced CCD by now? There are a number of reasons; some are technical or performance related, and others are related more to the growing maturity of the technology. CCDs have been mass produced for more than 25 years; CMOS technology has only just begun the mass production phase. Rapid adoption of CMOS was also hindered because some companies overpromised the capabilities of the sensors.

Although it's true that standard CMOS manufacturing lines and equipment can be used to make CMOS imagers, low-noise, good-quality imagers require that the process be modified to achieve the best results. For example, a standard CMOS logic process for mitigating CMOS latchup can lead to low red response for an imager. Similarly, the process for creating dense, short-gate-length CMOS logic chips causes high dark currents and low green response in an imaging device. These and other process trade-offs must be understood and optimized to achieve the best possible performance.

Consider Kodak's KAC-0310 image sensor as an example. This device features a sensor with 640 × 480 active elements, with row and column decode electronics. The company has integrated additional logic on the same CMOS chip, which makes the device a monolithic image capture and processing engine. Shown in Figure 3, the additional logic includes:

- A timing and control section, enabling programmable windowing, subsampling, and readout modes
- A frame rate clamp (FRC) for black level calibration
- Digitally programmable amplifiers for white balance and gain control
- A 10-bit A/D converter
- Post-A/D conversion digital logic processing

This mixed-signal imager can output VGA images at 60 frames per second and consumes <200 mW while running off a 3.3 V supply. A similar CCD imager consumes about 500 mW and requires more physical volume because of the support chips and multiple supply voltages.

Devices such as the KAC-0310 demonstrate a key difference between CMOS and

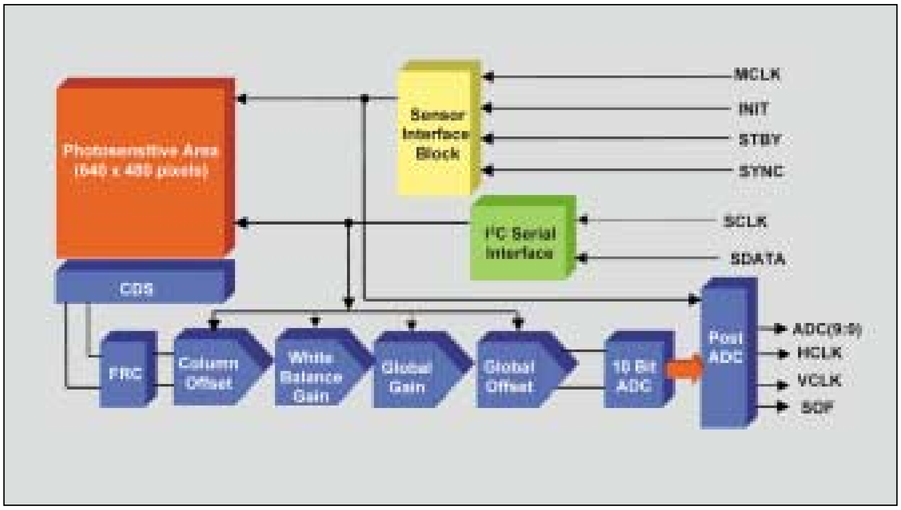

Figure 3. The block diagram of the KODAK KAC-0310 image sensor illustrates the features available on chip. These include a correlated double sampler (CDS), a frame rate clamp (FRC), an A/D converter (ADC), and post A/D conversion digital logic (Post ADC).

True Dynamic Range vs. Intrascene Dynamic Range

Image sensor manufacturers often refer to the dynamic range of their product, but there are two types of dynamic range. Most CMOS sensor manufacturers provide a number without explaining whether it is the true dynamic range or the intrascene dynamic range.

True dynamic range (DR) measures the sensor's maximum number of signal electrons compared with its total dark temporal rms noise level. The total dark noise includes dark current shot noise, pixel read noise, and temporal noise of signal processing circuits 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, the DR is 60 dB.

Intrascene dynamic range (IDR) refers to the range of illumination levels in a scene about which the imager sensor can provide details. This is a measure of the sensor's maximum calculable or extrapolated signal level compared with its total dark temporal rms noise level.

To better understand, consider a sensor that takes two pictures of the same scene. The first picture features a long integration time, and 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 because too many electrons may have overpowered, or saturated, the pixel. Alternately, the picture with the short integration time will provide good details in the bright areas (because the pixels did not saturate), but now there aren't 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 with good details in both the dark and the bright regions of the scene. This is the intrascene dynamic range. A sensor can have high IDR without having low noise or high DR.

Consider two scenes where DR and IDR are important. An outdoors scene may have a wide range of illumination from shadowed areas to reflections of the sun off of water. Here, high IDR is important to capture details of both the bright and dark areas. High DR is not needed, however, because even the darkest parts of the scene will have enough photons to generate good SNR, 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 SNR levels, the dimly lit room doesn't, thus requiring a sensor with either a long integration time (to capture enough photons) or high sensitivity and low noise. But integrating over a long time period can lead to saturation for the candles if the dynamic range is not high enough. High IDR is not sufficient in this case. □

CCD technology: the ability to integrate additional logic and achieve a camera on a chip. CMOS allows the consolidation of multiple discrete-logic and mixed-signal ICs in one device, reducing the size, part count, power consumption, and cost of the imaging solution.

Most important, CMOS technology is poised to follow the evolution of traditional high-volume silicon technology, pushing toward smaller and smaller design rules. This allows manufacturers to migrate production of CMOS imagers from lines using 0.6 micron design rules, to next-generation lines using 0.35 and 0.25 micron design rules. These advanced devices will allow the pixel size to shrink to about half their current size in the next few years. As a result, many more pixels will be packed onto standard $^1/_4$ in., $^1/_3$ in., and $^1/_2$ in. imager formats. For example, Kodak's KAC-1310 CMOS sensor features 1280 × 1024 (SXGA) resolution in a $^1/_2$ in. format, increases pixel densities, and offers a wide, true dynamic range of 60 dB, which is on par with most CCD imagers.

Evaluating Specifications

Many CMOS imagers don't 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 the CMOS device, as well as the lack of focus on problems that are key to providing good image quality but that do not affect the cost or performance of CMOS ICs. However, there has been steady progress in solving these issues recently.

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

Obtaining a uniform photo-response across an entire array is also critical, and this can be achieved by applying CCD expertise and experience to the CMOS process and circuit design. But these changes must also be consistent with the fabrication of mixed-signal circuits to produce a camera on a chip. Understanding these complex tradeoffs between process parameters, imager performance, mixed signal circuits, cost, and system complexity is critical to achieving an optimally designed and manufactured sensor.

Camera makers and users 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 areas. To improve the image quality or SNR for dimly lit conditions, you need a sensor with a wide dynamic range. This translates into a sensor with high quantum efficiency (sensitivity), large electron storage capacity, low dark current, and low noise.

Also desirable is a sensor that can capture scenes containing both dimly lit 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 a wide dynamic range for good SNR and detail in the dark regions, and wide intrascene dynamic range to retain the details in the bright regions.

These two types of dynamic range have different sensor requirements. Most CMOS sensor spec sheets provide the intrascene dynamic range number as the dynamic range specification. High intrascene dynamic range is desirable but is not sufficient to provide good image quality for dimly lit scenes (see the sidebar "True Dynamic Range vs. Intrascene Dynamic Range").

When examining the sensitivity specification of a sensor, be careful to understand how the measurement was made. Some suppliers specify this parameter in V/mcs (meter-candle-second), but others prefer electrons/mcs. The V/mcs measurement can be misleading because the number includes the gain of converting electrons to volts and any voltage gain in the system. Because 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 V/mcs by adding voltage gain in the signal path. Because the voltage gain is applied to the signal as well as the noise, you can have a large number of V/mcs without having a large SNR.

Also be sure to note how the noise level of the sensor is calculated. Some manufacturers will normalize the measurement to the area of the photodiode, and others will normalize to the entire pixel area. Normalizing to the photodiode area tends to produce a bigger number. Make sure you do an apples to apples comparison because low-noise performance is critical for good low-light operation. Some sensors can also feature integrated 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 can double the sensitivity of the sensor.

Capture of fast moving objects is also desirable. This requires a rapid shutter and a fast-responding CMOS sensor. Sensors with a global shutter operation and zero image lag perform better than ones that offer only a rolling-shutter, which can lead to image blur or artifacts from AC illumination.

Don't forget about the color science and image processing technology included with the sensor either. Look for suppliers who have extensive experience in making integral color filter arrays and image processing algorithms for CCD-based professional cameras and applications. These can be applied directly or easily modified for CMOS sensors. ■

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