New Scientific CMOS Cameras with Back-Illuminated Technology

Low-Light, Time-Resolved Imaging and Spectroscopy Applications Get New Boost

Overview

Low-light scientific cameras are behind many revolutionary discoveries, ranging from quantum imaging to astronomy. For more than five decades, CCD cameras and their variants — electron-multiplying CCD (EMCCD) and intensified CCD (ICCD) cameras — have provided the single-photon sensitivity and moderate frame rates required for scientific imaging and spectroscopy applications. More recently, scientific CMOS (sCMOS) cameras that are capable of achieving low read noise and higher frame rates have become an alternative to CCD cameras in several applications. However, the first generations of these sCMOS devices fall short on sensitivity owing to their front-illuminated architecture, which imposes a fundamental limit on their quantum efficiency (i.e., the fraction of incident photons detected in each pixel).

Aided by the latest CMOS fabrication technology, sCMOS devices can finally be created with a back-illuminated sensor architecture. As a result, sCMOS sensors are now capable of CCD-like quantum efficiency (>95%) and dynamic range without compromising the low read noise and high frame rates for which they are known. The latest generation of sCMOS cameras, such as the KURO™ from Princeton Instruments, take full advantage of this back-illuminated sensor technology to provide a significant improvement over previous-generation, front-illuminated sCMOS cameras.

Back-illuminated sCMOS camera technology is a serious contender as an optical detector for myriad applications, including hyperspectral imaging, astronomy, cold-atom imaging, quantum imaging, fluorescence spectroscopy, and high-speed spectroscopy. This technical note will present the salient features and performance characteristics of the new technology.

Back-Illuminated Architecture

Back-illuminated technology has been available for scientific CCD detectors for many years. Due to their higher sensitivity over a broader spectral region (deep-UV to near-IR), back-illuminated detectors are preferred over front-illuminated detectors for ultra-low-light applications ranging from astronomy to Raman spectroscopy to biological imaging. The difference between front-illuminated and back-illuminated sensors is apparent at a glance. Front-illuminated sensors are reflective in appearance because most of the incident light is reflected back to the viewer, whereas back-illuminated sensors are visibly darker owing to their absorption of most of the incident light (see Figure 1).

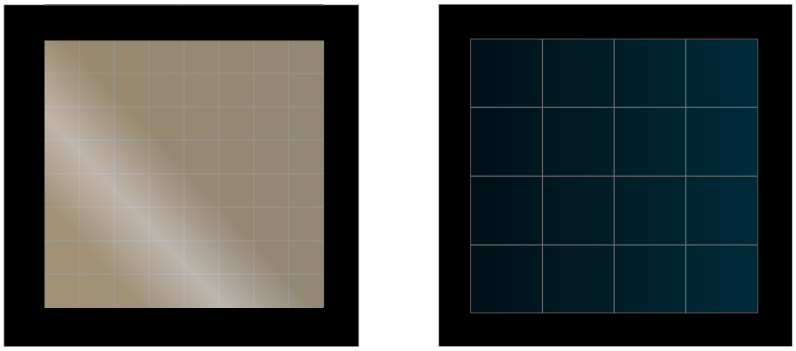


Figure 1.
Typical front-illuminated CCD / sCMOS sensors (left) are reflective in appearance whereas back-illuminated sensors (right) appear dark.

The KURO features a back-illuminated sensor architecture just like that of the most sensitive CCD detectors available. Back-illuminated technology allows this new sCMOS camera system to deliver >95% quantum efficiency and 100% fill factor (see Figure 2).

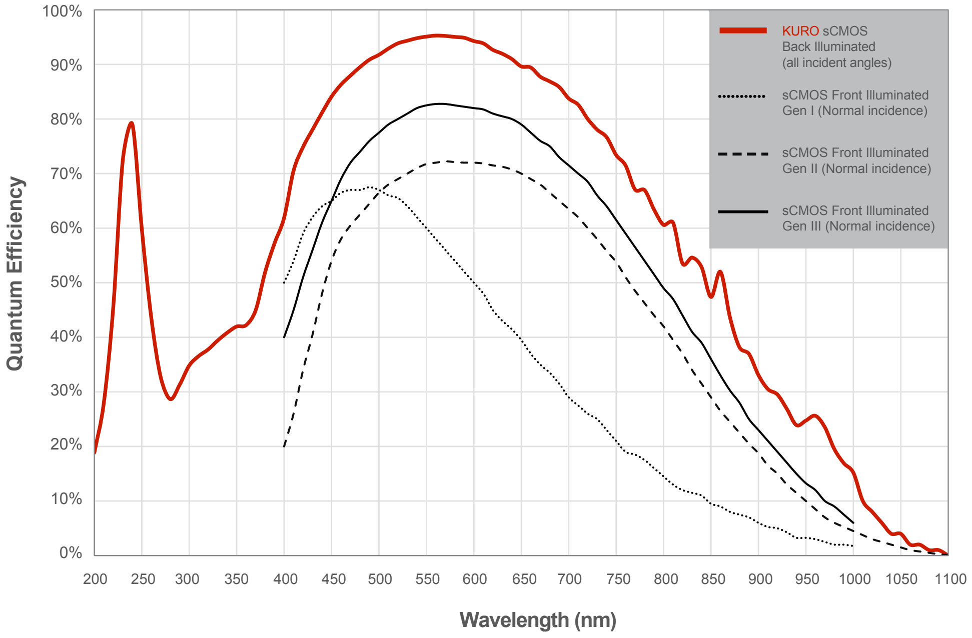
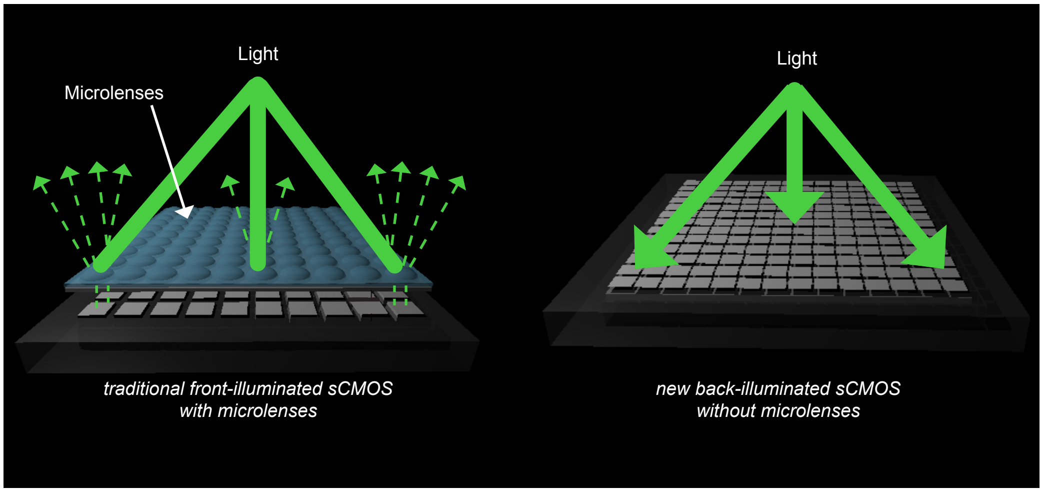


Figure 2.
Back-illuminated sCMOS technology provides higher quantum efficiency than front-illuminated sCMOS sensors across a broad spectral range, including the UV.

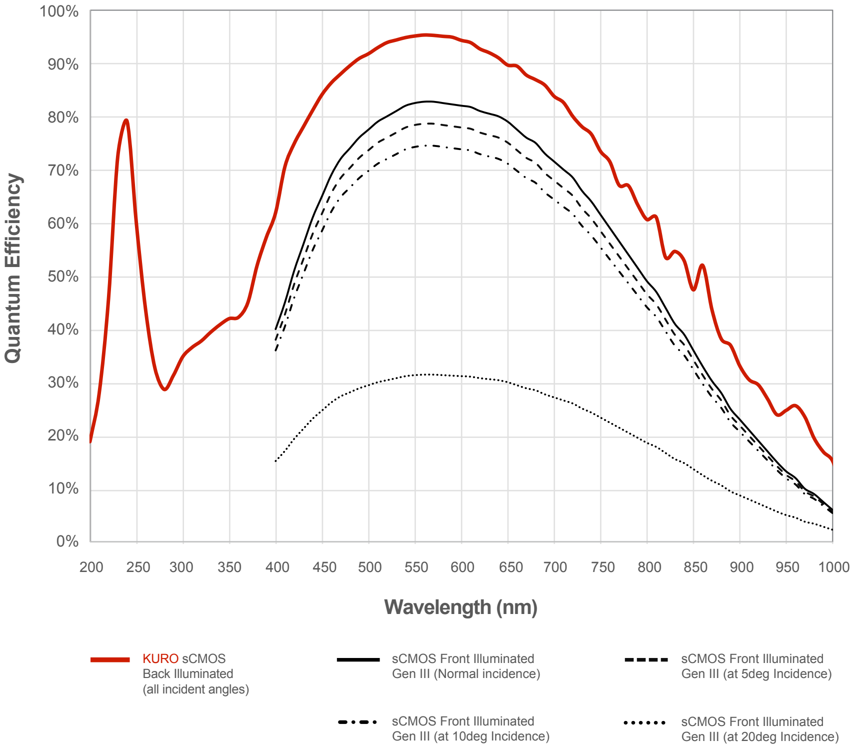
Since front-illuminated sCMOS sensors have readout/conversion circuitry inside each pixel, only a portion of each pixel is sensitive to light. This portion is referred to as the “fill factor” of the pixel. Most front-illuminated sCMOS sensors have microlenses on top of each pixel to refocus the incoming light into the photosensitive part of the pixel and increase the effective fill factor (see Figure 3). Although microlenses help improve the light-collection efficiency of a front-illuminated sensor, they also carry certain drawbacks that limit the performance of most of these sCMOS cameras. Note that unlike front-illuminated sCMOS sensors, which claim ~80% peak quantum efficiency, back-illuminated sCMOS sensors do not use any microlenses.

Figure 3.
The typical front-illuminated sCMOS sensor architecture (left) relies on the use of microlenses. Back-illuminated sCMOS sensors (right) do not utilize microlenses.



Unfortunately, microlenses are most efficient only when the incident angle of light is normal to the sensor surface (see Figure 4). If light enters the sensor at any other angle, as is the case for most scientific imaging and spectroscopy applications, the efficacy of microlenses degrades considerably — especially at wider entrance angles ("high NA" in microscopy parlance). While this quantum efficiency vs. incident angle relationship is not widely published in camera or sensor manufacturers' literature, the degradation is a real cause for concern when ultra-low-light performance is required. Even though the layout of microlenses has been improved by various CMOS manufacturers, the angular dependency of photo-response causes non-uniformity, especially at the edges of the sensor.

Figure 4.
Front-illuminated sCMOS sensors often rely on microlenses, which significantly degrade quantum efficiency when light is incident at any angle other than normal to the sensor surface. New back-illuminated sCMOS sensors do not exhibit this performance limitation.



In addition, these microlenses are typically made of plastic-like materials that transmit very poorly, or not at all, in the UV range (below 400 nm). The lack of microlenses in a back-illuminated sCMOS sensor's architecture translates to outstanding response in the UV range (see Figures 2 and 4).

High Frame Rates and Low Read Noise

Back-illuminated sCMOS cameras, such as the KURO, offer very high frame rates, up to 82 fps at full 1200 x 1200 resolution, with an exceptionally low 1.3 e- rms (median) read noise. The KURO camera is capable of delivering hundreds of frames per second with reduced resolution (see Table 1). And though sCMOS sensors typically do not support on-chip binning, they do allow "off-chip" software binning after frame acquisition.

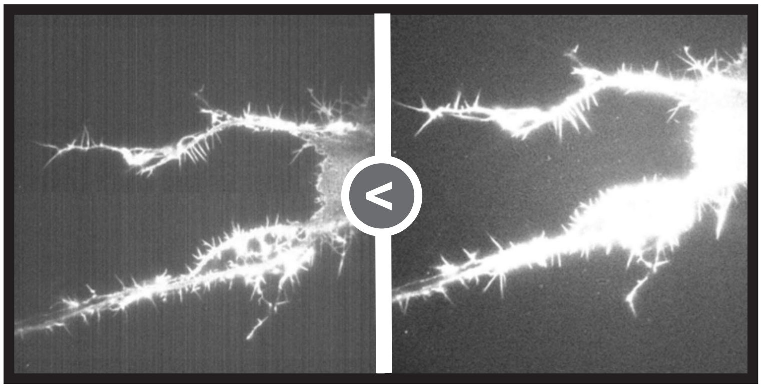
Table 1.
Low read noise and high frame rates make the new back-illuminated sCMOS camera ideal for high-speed spectroscopy applications.

Resolution	Frame rate: fps (12 bit / 16 bit)
1200 x 1200	82 / 41
1200 x 512	192 / 96
1200 x 256	384 / 192
1200 x 128	768 / 384
1200 x 64	1536 / 768
1200 x 32	3072 / 1536

It is worth noting that the 11 μm^2 pixel pitch of the new back-illuminated sCMOS sensor captures 2.8x more photons than other sCMOS sensors. Each pixel can also handle a large full well of 80,000 electrons, allowing excellent dynamic range (61,500:1 or 95 dB).

Reduced Fixed-Pattern Noise

The KURO back-illuminated camera uses the latest sCMOS fabrication technology along with optimized electronics. As a result, it has a significantly better noise profile than any front-illuminated sCMOS camera (see Figure 5).


100 frame average of front-illuminated sCMOS camera

back-illuminated sCMOS camera

Figure 5.
Fixed-pattern noise: front-illuminated sCMOS sensor (left) vs. back-illuminated sCMOS sensor (right).

Sensor Comparison

Table 2 provides a convenient summary of several key specifications and performance capabilities associated with front-illuminated sCMOS and recently introduced back-illuminated sCMOS sensors.

Table 2.
Comparison of front-illuminated sCMOS and back-illuminated sCMOS sensors.

Feature/Spec	Front-illuminated sCMOS	Back-illuminated sCMOS
Microlenses used	Yes	No
Peak QE	~65% – 80% (at normal incidence)	>95% (at all incident angles)
Pixel fill factor	60% – 70% typical	100%
Wavelength range	400 – 1000 nm	<200 – 1100 nm
Fixed-pattern noise	High	Low
UV (<400 nm) sensitivity	No	Yes (up to 75% QE in 200 –400 nm region)

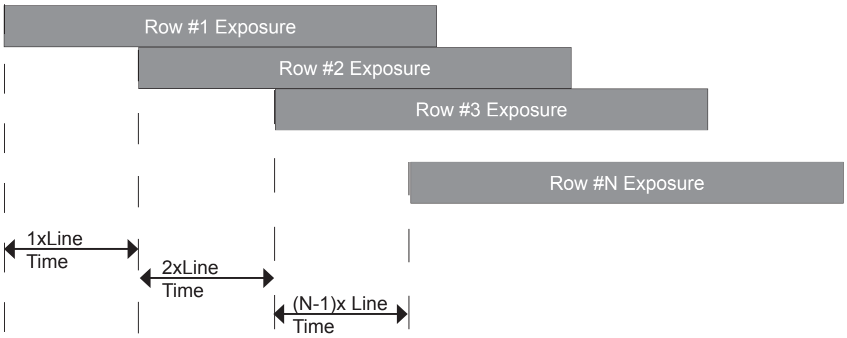
Readout Modes: Rolling and Global Shutter

One of the key features of CMOS sensors is the availability of rolling electronic shutter mode. This is distinct from global shutter or “snapshot” mode, which exposes all pixels at the same time. Global shutter is preferred when the object needs to be “frozen” in time; however, this mode typically causes the read noise to increase by as much as 1.5 to 2x compared to rolling shutter mode while decreasing the frame rate by 2x.

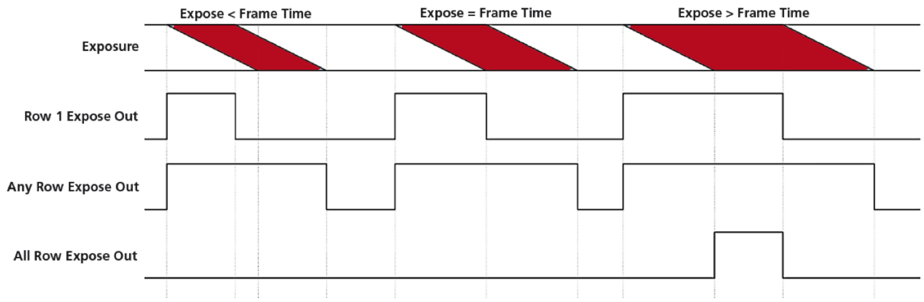
In rolling shutter mode, the first row of the sensor is exposed first, the second row is exposed after one line read time, and so forth. In other words, the last row of the sensor is exposed at “(N-1) x line time” after the first row. This may cause image artifacts when looking at high-speed events that occur significantly faster than the frame rate, but most scientific applications can work with rolling shutter mode as long as the frame rate is sufficiently high. Global shutter mode, on the other hand, is preferred for industrial imaging applications in which the objects under inspection are moving at a rapid pace.

Advanced camera designs, such as that of the KURO, offer a way to trigger external light sources/shutters so as to create a “pseudo” global shutter mode. To do so, the camera simply outputs a TTL signal that goes high when “all” the pixels are exposing. This will, in effect, cause the pixels to take a snapshot of the event when it is illuminated. Figure 6 presents timing diagrams for the KURO camera’s rolling shutter and “pseudo” global shutter modes.

Figure 6.
Timing diagrams for rolling shutter and "pseudo" global shutter modes.



Row #	Exposure Start time	Exposure End time
1	TO	TO+EXP TIME (user entered value)
2	TO+(1xLINE TIME)	TO+(1xLINE TIME)+EXP TIME
3	TO+	
N	TO+(N-1 * LINE TIME)	TO+(N-1xLINE TIME)+EXP TIME



Which Sensor Technology: CCD, EMCCD, ICCD, or Back-Illuminated sCMOS?

Scientists and engineers should carefully consider which sensor technology is best suited to their application. In general, for imaging or spectroscopy applications that require extended integration times (seconds to hours), CCD or EMCCD cameras are still preferred. This is also true for spectroscopy applications that require on-chip binning. Meanwhile, for time-resolved applications that require ultrafast gating, intensified cameras (ICCD or *em*ICCD) are the best choice. Back-illuminated sCMOS cameras provide the sensitivity and frame rates needed for all other applications with relatively short integration times (less than 10 seconds). Table 3 summarizes several key features of these sensor technologies and offers some general recommendations for different applications.

Table 3.

Comparison of sensor features with application recommendations.

Feature/Spec	Back-Illuminated CCD	Back-Illuminated EMCCD	ICCD	Back-Illuminated sCMOS
Peak QE	~95%	~95%	~50% (photocathode QE)	~95%
Read noise	~2 – 4 e- rms	<1 e- rms (with EM gain)	<1 e- rms (with intensifier gain)	<2 e- rms (<1.5 e- rms median)
Frame rate at full resolution	~5 fps	~30 fps – 60 fps	~10 fps – 30 fps	~40 fps – 80 fps
Frame rate at reduced resolution	>5,000 fps (in kinetics mode)	>10,000 fps (in kinetics/crop modes)	>1,000 fps	>3,000 fps
Gating	No	No	Yes (<500 psec)	No
On-chip binning	Yes	Yes	Yes	No
Typical applications	Astronomy, Raman spectroscopy with requirement for long integration times (msec to hours)	High-frame-rate, single-photon-sensitive applications with relatively short integration times (μsec to msec)	Gated (psec to μsec exposures), time-resolved imaging and spectroscopy	High frame rates with moderate integration times (<10 sec) in low-light applications such as adaptive optics, ion imaging, hyperspectral imaging, etc.

Camera Ecosystem

Important as the advantages of back-illuminated sCMOS technology are, so too is the ability to fully leverage the inherent benefits of this new sensor type. Designed for operation within the Princeton Instruments LightField® software ecosystem, the KURO is easy to control and can be integrated quickly in myriad imaging and spectroscopy experiments. Camera integration for use with MathWorks' MATLAB® and National Instruments' LabVIEW® is also fast and simple. A full suite of input-output TTL signals is provided as well, making it easy to synchronize camera operation with external events or light sources.

Online Resources

For more information about back-illuminated scientific CMOS cameras for ultra-low-light imaging and spectroscopy, please visit: **www.princetoninstruments.com**