Princeton Instruments

APPLICATION NOTE

Next-generation, performance-enhancing EMCCD technology

A primer on eXcelon™ 3 technology

eXcelon3 is a breakthrough technology that provides the best EMCCD performance available on the market

Primer contents:

Introduction

Since their invention in 1969, charge-coupled devices (CCDs) have been used to detect the faint light from items as nearby as cells under a microscope to those as far away as stellar objects at the edge of the known universe. Over the past four decades, low-light CCD cameras have facilitated some of the biggest breakthroughs in both the life sciences and the physical sciences. Salient features that have contributed to the remarkable track record of these detectors include greater than 90% peak quantum efficiency (QE), very low read noise of 2 e- rms or less, 100% fill factor, and excellent charge-transfer efficiency.

About twelve years ago, a variant of CCDs known as electron-multiplying CCDs (EMCCDs) was developed. In addition to the features noted above, EMCCDs are able to achieve sub-electron read noise at high frame rates, allowing single-photon detection. Thus, CCD and EMCCD cameras are commonly the instruments of choice for scientific applications ranging from steady-state astronomical imaging to dynamic single-molecule imaging, and from widefield imaging to spectroscopy.

This paper provides a basic overview of the advantages and disadvantages of EMCCDs and introduces a new sensor technology, eXcelon3, that mitigates some of their inherent limitations. Those who are mainly interested in learning about a novel way to obtain enhanced low-light CCD (i.e., non-EMCCD) performance can refer to the Princeton Instruments technical note on eXcelon technology.

Types of EMCCDs

In a traditional front-illuminated EMCCD, light passes through the polysilicon gates that define a charge well at each pixel (see Figure 1). While the gates transmit a number of the incident photons to the EMCCD's photoconversion layer, they also reflect and absorb a fraction of photons, thereby preventing some light from reaching the pixel's photosensitive region. As a result, front-illuminated devices typically offer only about 50% QE (i.e., the fraction of incident photons contributing to the signal).

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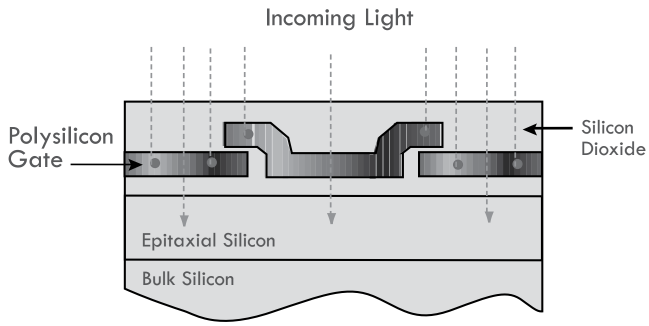
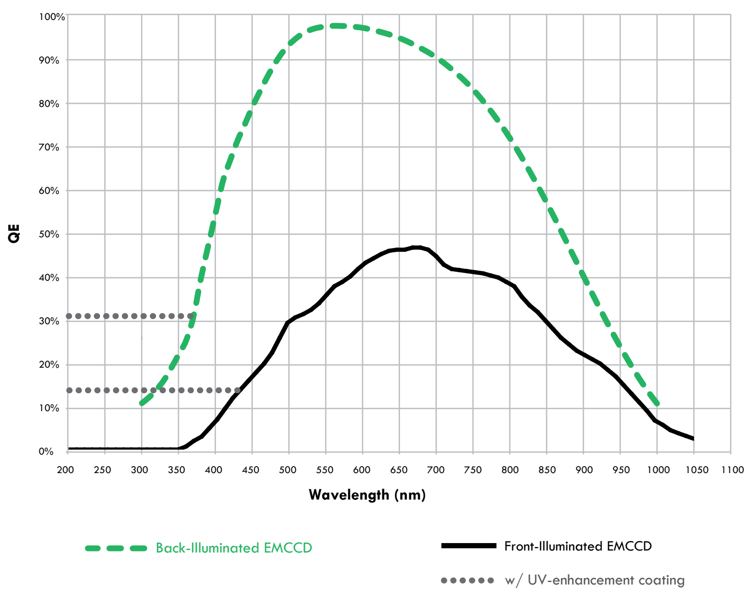
Technology	Sensor type	Architecture
eXcelon3	Back-illuminated EMCCD	Custom thinned
eXcelon	Back-illuminated CCD	Thinned or deep depletion

Figure 1.
Cross-section of a traditional front-illuminated EMCCD. Light passes through the polysilicon gates in order to reach the device's photoconversion layer.



To improve QE, devices can be uniformly thinned via acid-etching techniques to attain approximately 10 to 15 µm thickness so that an image can be focused directly onto the photosensitive area of the EMCCD (i.e., the depletion region), where there is no gate structure. Compared to front-illuminated EMCCDs, these thinned back-illuminated devices have a higher QE (>90%) across the visible spectrum. (See Figure 2.)

Figure 2.
Typical QE of traditional front-illuminated EMCCDs and standard thinned back-illuminated EMCCDs. Dotted lines on the left represent QE in UV region with UV-enhancement coating.



All EMCCDs employ on-chip amplification of photoelectrons to boost signals above the read noise of the sensor (see Figure 3). As a result, EMCCD cameras can achieve sub-electron read noise even at video rates or higher. Not surprisingly, these cameras have become very popular for a variety of ultra-low-light, high-frame-rate applications, including time-resolved astronomy and single-molecule fluorescence imaging (see Figure 4).

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Figure 3.
EMCCDs amplify electrons in an extended serial register through a process called impact ionization before they reach the output amplifier and subsequent electronics. The main benefit of the technology, therefore, is a far better signal-to-noise ratio for signals below the read noise.

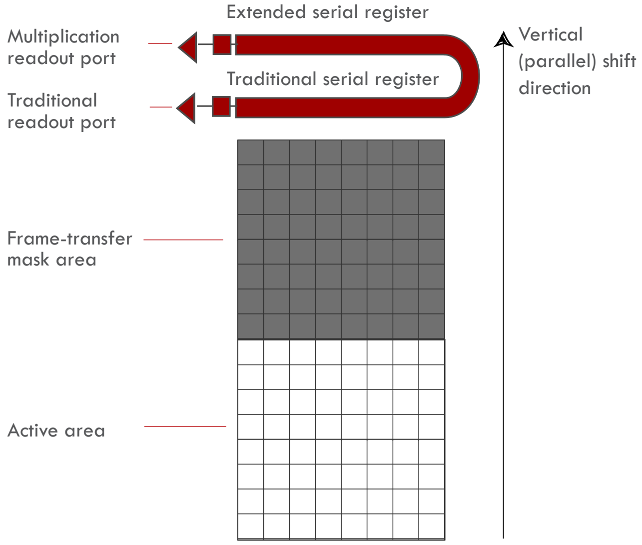
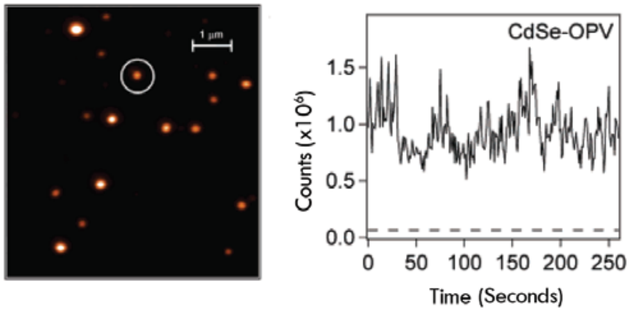


Figure 4.
Single-particle fluorescence image acquired using an EMCCD camera (left) with fluorescence time trace (right) of the circled nanostructure.[1]



Due to material processing and manufacturing complexities, EMCCDs are unable to realize deep-depletion technology (which allows longer-wavelength photons to interact within the photosensitive area of the EMCCD as opposed to merely penetrating it) commercially at this time. Unfortunately, for applications requiring NIR sensitivity and low etaloning (see Appendix A), this imposes significant limitations. Front-illuminated EMCCDs, for instance, offer etalon-free imaging, but have 2x to 3x lower sensitivity than their back-illuminated counterparts. Conversely, back-illuminated EMCCDs suffer from etaloning in the NIR, though they have higher QE in this region.

Advantages and disadvantages

Table 1 briefly summarizes the main advantages and disadvantages of the aforementioned technologies in relation to low-light imaging and spectroscopy applications. Overall, front-illuminated EMCCDs are relatively inexpensive, but provide lower sensitivity (refer to Figure 2). In the NIR, they have 2x to 3x lower QE than back-illuminated EMCCDs. It is worth noting, however, that front-illuminated EMCCDs may be preferable for certain high-light-level NIR applications, as they do not suffer from etaloning.

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Technology	Sensitivity range* (nm)	Peak QE wavelength (nm)	Peak QE**	Etaloning reduction/fringe suppression in NIR	Dark current
Front-illuminated EMCCDs	200 to 1100	700	47%	Excellent	1x
Standard back-illuminated EMCCDs	<200 to 1100	550	97%	Poor	1x (with AIMO)
NEW eXcelon3 back-illuminated EMCCDs	<200 to 1100	650	95%	Very good	1x

*Sensitivity range with special UV coating that extends UV sensitivity
**Typical data at +25°C

Table 1. Main advantages and disadvantages of various sensor technologies.

New eXcelon3 technology for EMCCDs

Until now, researchers whose applications require low-light broadband photon detection had but one choice when utilizing an EMCCD camera, that is, standard thinned back-illuminated technology. Although such EMCCD cameras are capable of delivering extremely high sensitivity, their performance is nonetheless compromised to a certain extent by the limitations described in the preceding section. Recently, Princeton Instruments developed EMCCDs (and associated cameras) that minimize and even eliminate some of these hindrances.

While the precise details regarding this new technology are beyond the scope of this primer and cannot be revealed for intellectual property reasons, the benefits of eXcelon3 can be explained via comparative measurements.

New eXcelon3 sensors are based on a custom back-illuminated architecture and provide three significant advantages over other EMCCD technologies:

- **Best possible QE and fringe suppression**
- **As much as 70% reduction in etaloning (i.e., peak-to-peak fringe amplitudes)**
- **Outstanding QE improvement — up to 3x increase in the UV and 1.3x increase in the NIR**

First, consider the sensitivity of eXcelon3 technology. Figure 5 shows that eXcelon3 back-illuminated EMCCDs provide higher sensitivity below 475 nm and above 625 nm than standard thinned back-illuminated EMCCDs. The small drop in the green region can generally be tolerated, especially taking into account the other benefits that this technology offers. For the broadest wavelength sensitivity, the new sensors are also available with UV-enhancement coatings. The relative gain in QE using eXcelon3 technology is plotted in Figure 6.

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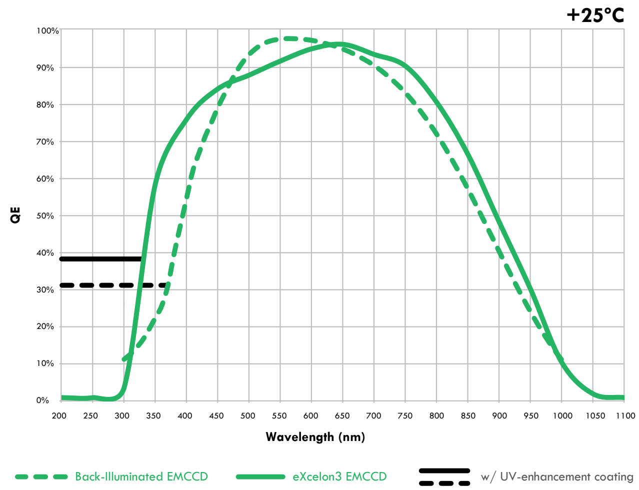


Figure 5.
Typical QE of eXcelon3 back-illuminated EMCCDs and standard thinned back-illuminated EMCCDs. Solid/dashed black lines on the left represent enhanced QE in UV region with optional UV-enhancement coatings.*

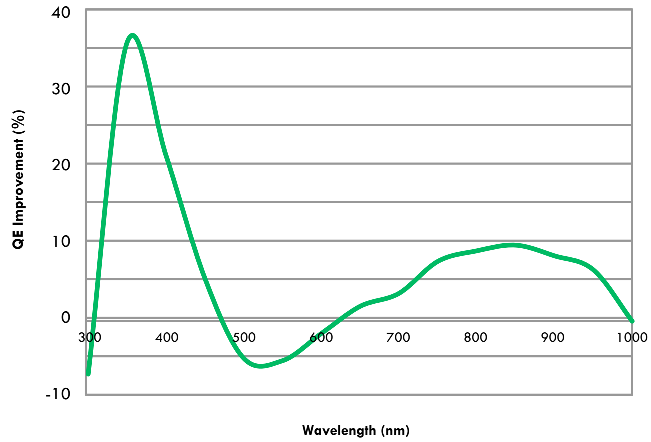


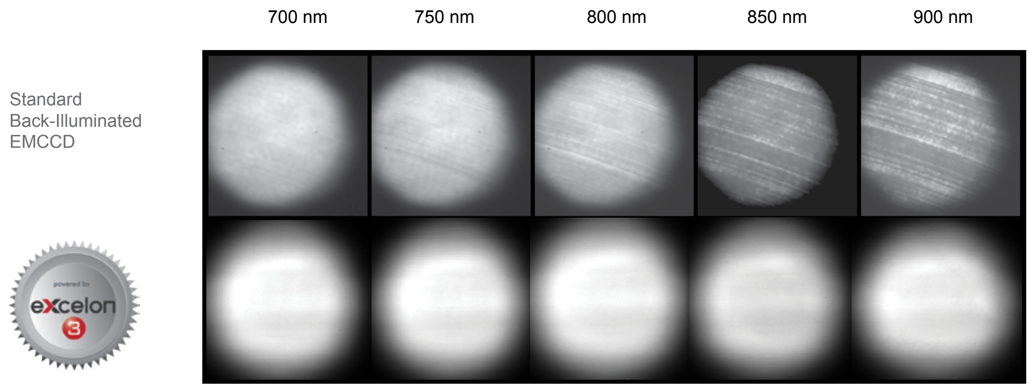
Figure 6.
The improvement in QE provided by eXcelon3 back-illuminated EMCCDs relative to standard thinned back-illuminated EMCCDs.

Another key eXcelon3 advantage is the new technology's lower etaloning in the NIR. Figure 7 presents a series of images showing the etaloning performance of cameras utilizing standard thinned back-illuminated EMCCDs and eXcelon3 back-illuminated EMCCDs.

Finally, eXcelon3 technology has similar dark current to the AIMO (Advanced Inverted Mode Operation) utilized by standard thinned back-illuminated EMCCDs. This is 100x lower than that of the NIMO (Non-Inverted Mode Operation) employed by back-illuminated deep-depletion CCDs. Low dark current is an important consideration, especially in spectroscopy, where signal is integrated over many minutes and binned over several rows.

** Data shown for imaging-format eXcelon3 EMCCDs. Similar improvements are seen for spectroscopy-format eXcelon EMCCDs. Refer to www.princetoninstruments.com/products/excelon for details.*

Figure 7.
Etaloning in the NIR for standard thinned back-illuminated EMCCD cameras and eXcelon3 back-illuminated EMCCD cameras.



Comparison: eXcelon3 vs. less-advanced EMCCD designs

Princeton Instruments' exclusive eXcelon3 EMCCD technology is the result of years of dedicated R&D. This custom technology represents an intelligent and comprehensive approach to EMCCD performance improvement. From the time Princeton Instruments first introduced its original eXcelon technology to the market, however, several other manufacturers have touted their own design enhancements, claiming to provide similar improved performance. In truth, their relatively simplistic approaches (e.g., mere utilization of AR coatings) provide camera users with only modest gains. Princeton Instruments' eXcelon3, on the other hand, is a true breakthrough technology that delivers readily appreciable benefits. Figures 8 and 9, for instance, show that eXcelon3-enabled cameras offer far less etaloning than cameras that rely on less-sophisticated EMCCD designs.

Both figures compare etaloning performance at the critical NIR wavelengths from 700 to 900 nm. A broadband light source coupled to a monochromator acts as an illuminator. The data presented is a series of images taken at 1 nm increments that shows the onset of etaloning around 700 nm in the less-advanced designs. From the data, it can also be appreciated that due to the spatial and temporal variation of etaloning, it is very difficult to correct for this phenomenon during post-processing. In contrast, Princeton Instruments ProEM+ cameras with eXcelon3 significantly reduce etaloning throughout the NIR region.

Figure 8.
Improvement in etaloning of eXcelon3 back-illuminated EMCCDs (right) over less-sophisticated back-illuminated EMCCD designs (left). To watch this video online, please visit www.princetoninstruments.com/products/excelon.

Figure 9.
Reduction in etaloning provided by eXcelon3 back-illuminated EMCCDs (right) compared to less-sophisticated back-illuminated EMCCD designs (left). Cross-sectional data of magnified images from Figure 8 at various wavelengths. To watch this video online, please visit www.princetoninstruments.com/products/excelon.

Figure 8.

Figure 9.

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Ways to further improve sensitivity

While sensor technology is an important determiner of camera system sensitivity and signal-to-noise ratio in a given experiment, factors such as optical window throughput are also important.

To maximize light throughput, Princeton Instruments uses a highly advanced single-window vacuum design (see Figure 10). This means the vacuum window is the only optical surface encountered by incident photons before they reach the EMCCD detection surface. Although the design is the best available, each uncoated optical surface of the vacuum window can still have 3 to 4% transmission loss, or a total loss of 6 to 8%. For light-starved imaging applications, this loss can result in a significant reduction of signal-to noise ratio. Moreover, any light reflected inside the system can lead to glare and fringing, especially when used with coherent illumination. The solution is to apply anti-reflective (AR) coatings on the window in the optical path, which reduces total losses to below 1% and sometimes even to less than 0.5%. For applications utilizing extremely coherent light sources, a wedge window may also be required to eliminate glare and fringing.

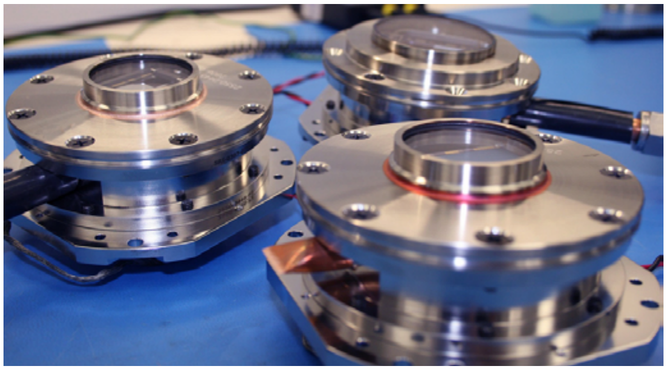

Figure 10.
A single vacuum window with optimized anti-reflective coating ensures maximum light throughput. Furthermore, a brazed metal-to-glass interface provides long-term vacuum seal integrity, as opposed to the degradation associated with traditional epoxy.

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Princeton Instruments cameras are designed with a single window made of high-grade fused silica/quartz/MgF_2 that acts as a vacuum viewport. Any shipping-protection windows on the EMCCD are removed prior to installing it in the vacuum chamber. The vacuum window, which is brazed (a high-temperature fusion process at the molecular level) to the vacuum chamber, can be customized with single- or multiple-layer AR coatings to match the wavelength of interest (see Figure 11). It should be noted that AR coatings typically provide the best performance when they are tuned for a narrow wavelength range. Since they may have poorer transmission outside their optimum wavelength range, care must be taken before choosing an AR coating.

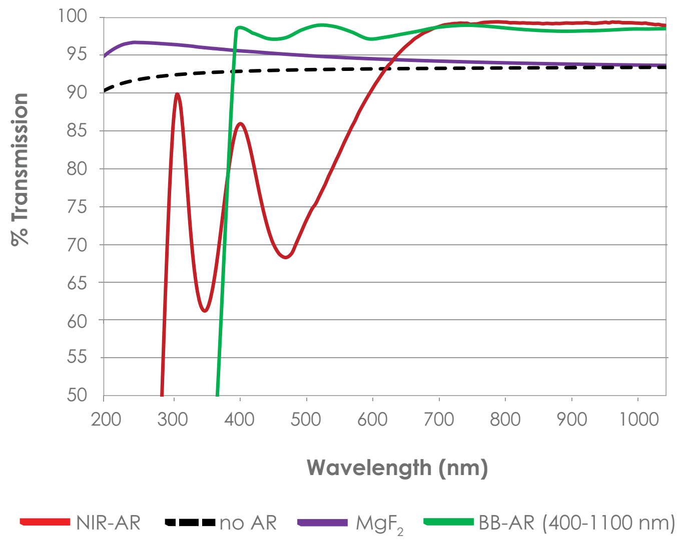

Figure 11.
Princeton Instruments offers a choice of multiple-layer coating options on the vacuum window.

Conclusions

Developed by Princeton Instruments, new eXcelon3 EMCCD technology provides higher sensitivity (over a broad wavelength range) as well as lower etaloning than standard thinned back-illuminated EMCCDs. For most imaging and spectroscopy applications in which standard thinned back-illuminated EMCCDs are commonly utilized, such as single-molecule fluorescence, FRET, luminescence, kinetics, BEC imaging, Raman spectroscopy, and astronomy, eXcelon3 now offers researchers superior performance (see Figure 12).

Acknowledgment

[1]N.I. Hammer, K.T. Early, K. Sill, M.Y. Odoi, T. Emrick, and M.D. Barnes, "Coverage-mediated suppression of blinking in solid state quantum dot-conjugated organic composite nanostructures," Journal of Physical Chemistry B, 110, 14167, (2006). Copyright © 2006 American Chemical Society.

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Choosing the Right Camera

Figure 12.
Technology and application summary. Next-generation eXcelon3 technology is available in Princeton Instruments EMCCD cameras. Novel eXcelon technology from Princeton Instruments is available for select back-illuminated CCD cameras with thinned and deep-depletion sensor architectures.

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Appendix A: Etaloning in the NIR

Standard thinned back-illuminated EMCCDs are solid-state imaging devices that have been etched to 10 to 15 µm thickness in order to collect light through the back surface. As a result of this modification, no light is lost via absorption and reflection by the polysilicon gate structure; these EMCCDs have more than twice the QE of their front-illuminated counterparts. An unfortunate side effect of this process is that the devices become semi-transparent in the NIR. Reflections between the parallel front and back surfaces of these EMCCDs cause them to act as partial etalons. This etalon-like behavior leads to unwanted fringes of constructive and destructive interference, which artificially modulate a spectrum. The extent of modulation can be significant (more than 20%) and the spectral spacing of fringes (typically 5 nm) is close enough to make them troublesome for almost all NIR spectroscopy.

An etalon is a thin, flat transparent optical element with two highly reflective surfaces that form a resonant optical cavity. Only wavelengths that fit an exact integer number of times between the surfaces can be sustained in this cavity. Because of this property, etalons can be used as comb filters, passing just a series of uniformly spaced wavelengths. In an imperfect etalon, the reflectance of the surfaces becomes less than 100% and the spectral characteristics soften from a spiky comb to a smooth set of fringes. Absorption between the surfaces also worsens the quality of the resonant cavity, which is measured by cavity finesse (see Figures A-1, A-2, and A-3).

Thus, the three factors that determine the shape and character of an etalon are **d,** the distance between the two surfaces; **λ,** the wavelength of the light; and **Q,** the finesse of the cavity, as shown in the following equation (where **I** is intensity):

$$I = \frac{I_{\mathrm{max}}}{1+(2Q/\pi)^2 \sin^2(2\pi d/\lambda)}$$

(Equation adapted from B. Saleh and M. Teich, Fundamentals of Photonics, John Wiley & Sons, New York, 1991)

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Figure A-1.
Example of spectral etaloning showing the variation in intensity (vertical axis) with wavelength.

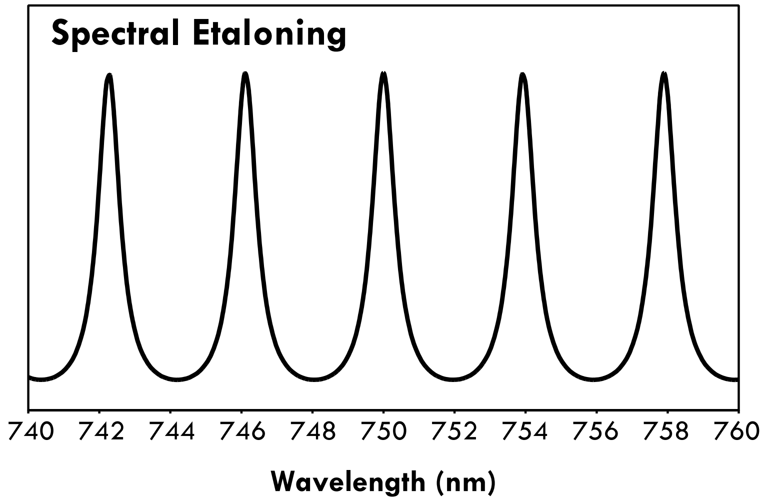


Figure A-2.
Example of spatial etaloning showing the variation in intensity (vertical axis) with thickness.

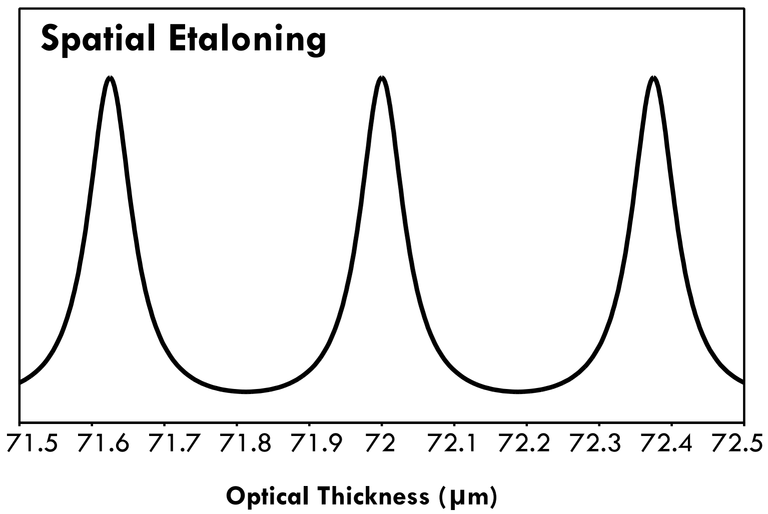
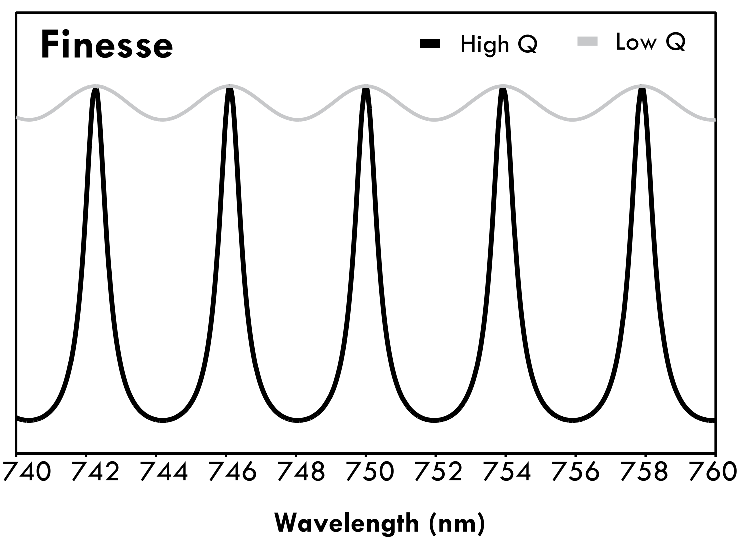


Figure A-3.
Example of etaloning showing the effects of finesse (Q) on the quality of the etalon.



At NIR wavelengths, the silicon of which EMCCDs are made becomes increasingly transparent, causing the QE to decline in the red. The back surface, where light enters an EMCCD in the back-illuminated configuration, is typically AR coated. These coatings are not perfect, however, and their effectiveness varies by wavelength. Most EMCCD back-surface AR coatings are not optimized for the NIR.

For example, the reflection from the back surface of an EMCCD that is optimized for ultraviolet (UV) response is worse in the NIR than that from an EMCCD whose AR coating is optimized for longer wavelengths.

Once light has passed through the body of an EMCCD and is about to reach the polysilicon electrodes, it encounters a sandwich of layers that generally includes silicon dioxide (refractive index 1.5). This sizeable discontinuity from the refractive index of silicon (which is 4) produces a large reflection back into the EMCCD. At wavelengths where silicon is transparent enough that light can traverse the thickness of the EMCCD several times, light bounces back and forth between the two surfaces. This increases the effective path length in the silicon (enhancing the QE) and also sets up a standing wave pattern. Amplitude is lost at both reflective surfaces and by absorption in the body of the silicon. However, at longer wavelengths, sufficient amplitude survives to cause significant constructive or destructive interference.

While silicon is usually thought of as opaque, it must be remembered that a standard back-illuminated EMCCD is typically only 10 to 15 µm thick (less than a thousandth of an inch). A layer this thin can transmit a significant fraction of NIR light. For example, a back-illuminated EMCCD that is 15 µm thick (mechanically) would have the effective optical thickness of about 60 µm (since the refractive index of silicon in this wavelength range is 4). Thus, the roundtrip optical path length between the surfaces is approximately 120 µm. At 750 nm, this would be 160 wavelengths. Therefore, there would be constructive interference at 750 nm. This pattern of interference would continue to repeat with intervals of about 5 nm.

In addition to the spectral source of etaloning, in a thinned EMCCD there can also be spatial etaloning. The spatial pattern arises from the incidence of monochromatic light on an etalon whose thickness is not perfectly constant. A small variation in thickness can change the local properties from constructive to destructive interference. The change required is only a half-wavelength in the roundtrip path length. Since the index of silicon is 4, the change in EMCCD mechanical thickness required to produce this optical effect is only about 1/16 of a wavelength, or 0.05 µm at a wavelength of 800 nm. This effect can actually be used to visualize how uniform the thickness of an EMCCD is. If an EMCCD had perfectly uniform thickness, the modulation due to spatial etaloning at a given wavelength would disappear. All pixels would have the same degree of constructive or destructive interference at a given wavelength.

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In most imaging applications with standard thinned back-illuminated EMCCDs, spatial etaloning is not evident because the applications are at shorter wavelengths, where the silicon absorption damps out the etalon effect. In addition, many applications use light that is spectrally broad enough to span (and average out) several etalon-fringe cycles. The latter requires only a spectral bandwidth of a few nanometers. In a spectrometer, by comparison, the light on any one column of pixels is very narrow spectrally, typically less than 0.1 nm. Thus, this spectral bandwidth is much less than the period of etalon cycles (~5 nm). As a result, spatial etaloning is quite evident when viewing an image of a uniform spectrum (e.g., tungsten bulb) in the NIR (see Figure A-4).
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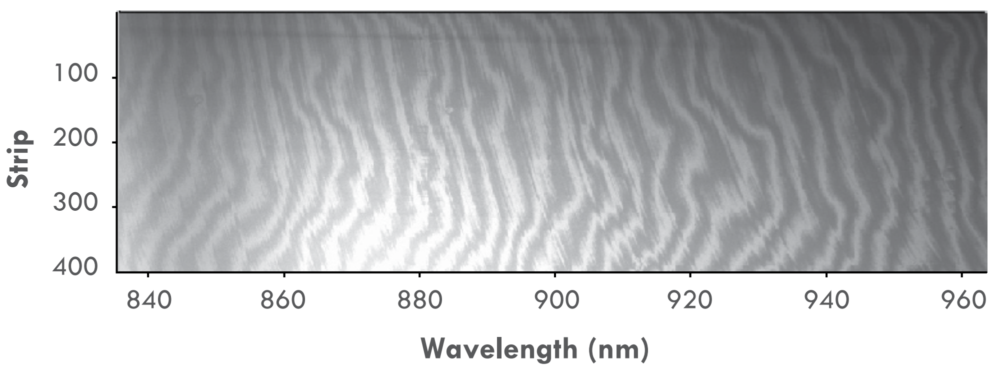
Figure A-4.
Image from a back-illuminated EMCCD camera showing combined spectroscopic and spatial etaloning.



Spectroscopic etaloning is related to, but different from, spatial etaloning. It derives from the fact that in a spectrometer the wavelength of light varies across the EMCCD. Thus, even if a back-illuminated EMCCD was available with absolutely uniform thickness, it would still show fringes due to this etalon effect. The fringes in this case are due to the variation of the wavelength, not the thickness. As a result, when a spectrum is dispersed across a back-illuminated EMCCD, the characteristic comb pattern will be superimposed on the normal response.

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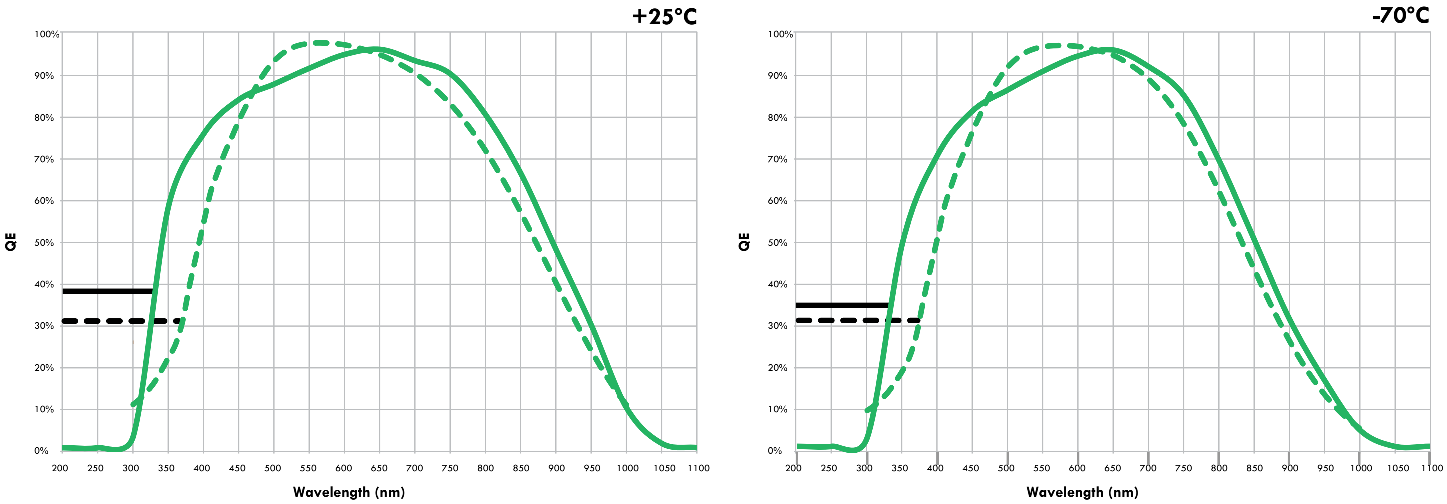
Appendix B: Effect of cooling on QE

In addition to the sensor technology type and factors such as optical window throughput, cooling the detector has an effect on QE. Typically, cooling decreases long-wavelength coverage due to a change in electron mobility and effective path lengths. Figure B-1 presents a theoretical estimate of QE as various sensors are cooled.



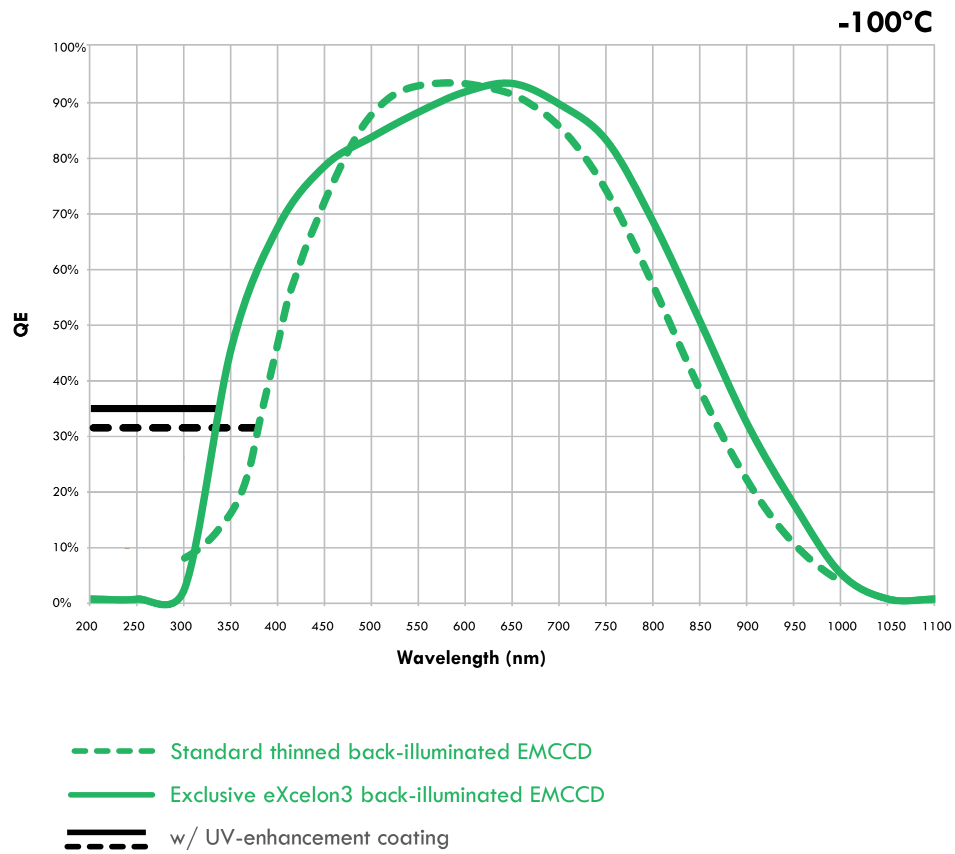


Figure B-1.
QE for various types of back-illuminated EMCCDs at +25°C, -70°C, and -100°C. Solid/dashed black lines on the left represent QE in UV region with optional UV-enhancement coatings.

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