New-generation CCD/EMCCD technology
A review of eXcelon™ technology

eXcelon

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 ten 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 various types of low-light CCDs/EMCCDs and introduces a new sensor technology, eXcelon, that promises to mitigate some of their inherent limitations.

Contents:

Types of CCDs and EMCCDs

Scientific-grade CCDs afford researchers a number of distinct technologies from which to choose. Primary CCD types include front-illuminated CCDs, standard thinned back-illuminated CCDs, and standard back-illuminated deep-depletion CCDs.

In a traditional front-illuminated CCD, 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 CCD'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).
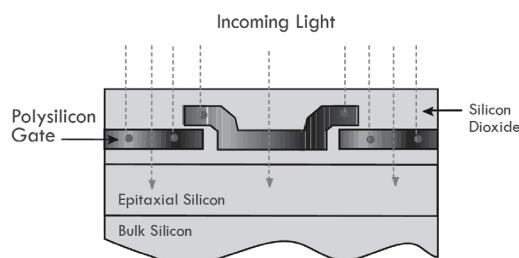

Figure 1. *Cross-section of a traditional front-illuminated CCD. Light passes through the polysilicon gates in order to reach the device's photoconversion layer.*

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 CCD (i.e., the depletion region), where there is no gate structure. Compared to front-illuminated CCDs, these thinned back-illuminated devices have a higher QE (>90%) across the visible spectrum. To further improve QE, especially for near-infrared (NIR) imaging and x-ray applications, a bias voltage can be applied to a layer of high-resistivity silicon ranging from 50 to 300 μm thickness in order to produce a "deeper" depletion region (i.e., active photosensitive area). This architecture allows longer-wavelength photons to interact within the layer as opposed to merely penetrating it, ultimately helping to increase QE (see Figure 2).
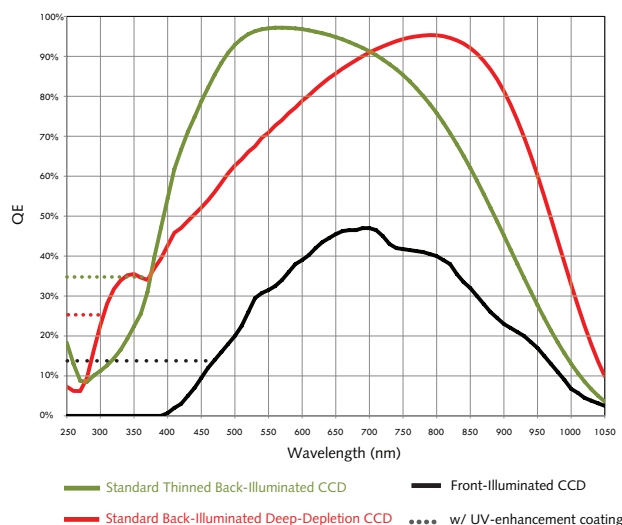
Figure 2. *Typical QE of traditional front-illuminated CCDs, standard thinned back-illuminated CCDs, and standard back-illuminated deep-depletion CCDs. Dotted lines on the left represent QE in UV region with UV-enhancement coating.*

Electron-multiplying CCDs, meanwhile, are a relatively recent innovation that employ on-chip amplification of photoelectrons to boost signals above the read noise of the sensor (see Figure 3).
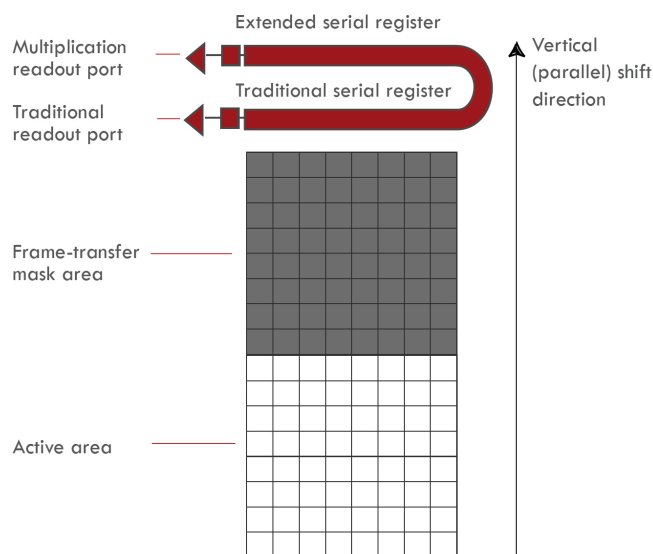

Figure 3. *EMCCDs amplify electrons in an extended serial register through a process called impact ionization before they reach the output amplifier and subsequent electronics. The main benefit of the technology, therefore, is a far better signal-to-noise ratio for signals below the read noise.*

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).
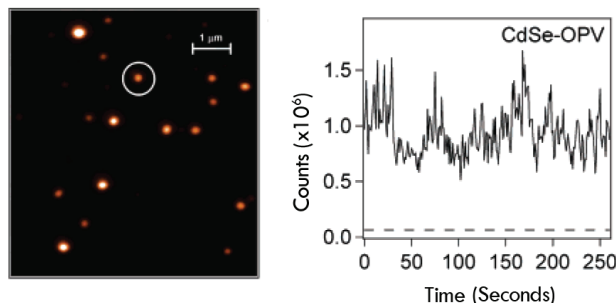

Figure 4. *Single-particle fluorescence image acquired using an EMCCD camera (left) with fluorescence time trace (right) of the circled nanostructure.[1]*

Due to material processing and manufacturing complexities, EMCCDs are unable to realize deep-depletion technology 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 CCDs are relatively inexpensive, but provide lower sensitivity (refer to Figure 2). In the NIR, they have 2x to 3x lower QE than back-illuminated CCDs. It is worth noting, however, that front-illuminated CCDs may be preferable for certain high-light-level NIR applications, as they do not suffer from etaloning.

In addition to the deep-depletion technology on the market today, there have been several designs calling for fully depleted sensors featuring silicon that is 100 to 300 μm thick. Such devices promise to provide further improvement in NIR sensitivity, but have yet to be made available on a large commercial scale.

Technology	Sensitivity range* (nm)	Peak QE wavelength (nm)	Peak QE**	Etaloning reduction/ fringe suppression in NIR	Dark current
Front-illuminated sensors	200 to 1100	700	47%***	Excellent	1x
Back-illuminated sensors	<200 to 1100	550	97%	Poor	1x (with AIMO)
Back-illuminated deep-depletion sensors	<200 to 1100	800	95%	Very good to excellent	50 to 100x
New eXcelon back-illuminated sensors	<200 to 1100	700	98%	Very good	1x
New eXcelon back-illuminated deep-depletion sensors	<200 to 1100	800 to 850	98%	Excellent	50 to 100x

   *   Sensitivity range with special UV coating that extends UV sensitivity

 **   Typical data at +25°C

***   Virtual-phase front-illuminated sensors may provide higher QE (albeit still far lower than back-illuminated sensors)

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

New eXcelon Technology

Until recently, researchers whose applications require low-light broadband photon detection had to choose between cameras that utilize either standard thinned back-illuminated or standard back-illuminated deep-depletion technologies. Although both of these options 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, Photometrics and Princeton Instruments have worked with e2v, a leading CCD/EMCCD manufacturer, to develop a new generation of sensors (and associated cameras) that will minimize and even eliminate some of these hindrances.

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

New eXcelon sensors are based on a standard back-illuminated architecture and provide three significant advantages over the other technologies under discussion:

- Higher sensitivity across broader wavelength range (than standard thinned back-illuminated CCDs and standard back-illuminated deep-depletion CCDs)
- Lower etaloning (than standard thinned back-illuminated CCDs and standard back-illuminated deep-depletion CCDs)
- Lower dark current (similar to standard thinned back-illuminated CCDs and standard back-illuminated deep-depletion CCDs)

eXcelon CCD Technology

First, consider the sensitivity of the new technology. Figure 5A shows that eXcelon back-illuminated CCDs provide higher sensitivity below 500 nm and above 625 nm than standard thinned back-illuminated sensors. For the broadest wavelength sensitivity, the new sensors are also available with UV-enhancement coatings. The relative gain in QE using eXcelon technology is plotted in Figure 5B, which estimates a 10 to 12% maximum increase.
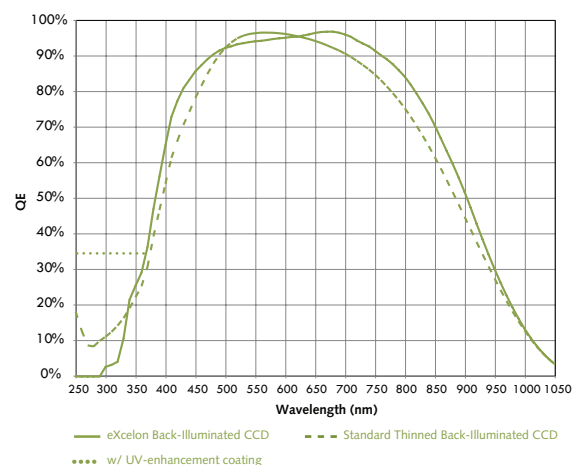

— eXcelon Back-Illuminated CCD   – – – Standard Thinned Back-Illuminated CCD
•••• w/ UV-enhancement coating

Figure 5A. *Typical QE of new eXcelon back-illuminated CCDs and standard thinned back-illuminated CCDs. Dotted line on the left represents enhanced QE in UV region with optional UV-enhancement coating.*
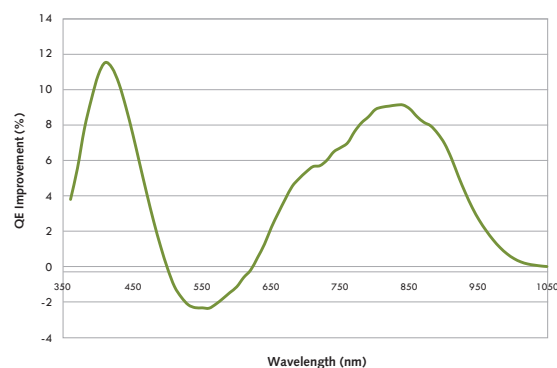

Figure 5B. *The improvement in QE provided by eXcelon back-illuminated CCDs relative to standard back-illuminated CCDs.*

Similar data was acquired to compare the sensitivity of standard back-illuminated EMCCD to the new eXelon back-illuminated EMCCD. Figure 6A shows that eXcelon back-illuminated EMCCDs provide higher sensitivity below 475 nm and above 680 nm than standard thinned back-illuminated EMCCD sensors. The small (7 to 10%) drop in the green region can generally be tolerated, especially taking into account the extra quantum yield provided by dyes commonly used in these wavelengths, and considering 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 eXcelon technology is plotted in Figure 6B, which estimates a >40% maximum increase.
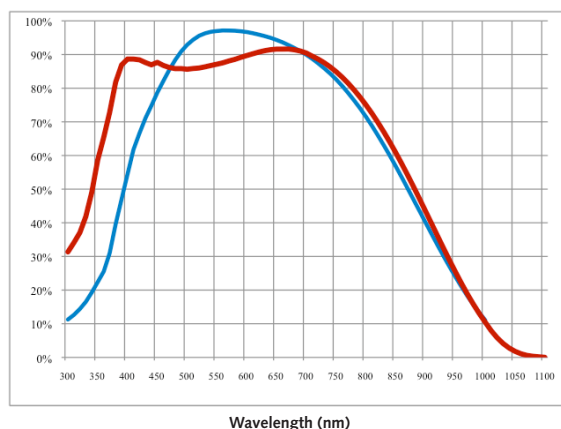

Figure 7. *Etaloning in the NIR for standard thinned back-illuminated CCD cameras, eXcelon back-illuminated CCD cameras, and standard back-illuminated deep-depletion CCD cameras.*

Figure 6A. *Typical QE of new eXcelon back-illuminated EMCCDs and standard thinned back-illuminated EMCCDs. Dotted line on the left represents enhanced QE in UV region with optional UV-enhancement coating.*
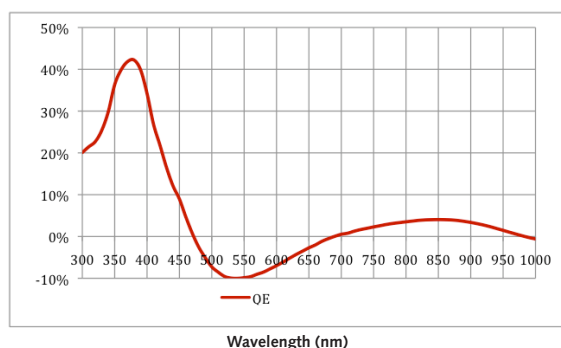

Figure 6B. *The improvement in QE provided by eXcelon back Illuminated EMCCD's relative to standard back illuminated EMCCD's.*

Figure 8. *Improvement in etaloning in eXcelon back-illuminated CCD cameras (right) over standard thinned back-illuminated CCD cameras (left). Cross-sectional data of magnified images from Figure 7 taken with a 900 nm monochromatic light source.*

Another key eXcelon advantage is the new technology's significantly lower etaloning in the NIR. Figure 7 presents a series of images showing the etaloning performance of cameras utilizing standard thinned back-illuminated CCDs, eXcelon back-illuminated CCDs, and standard back-illuminated deep-depletion CCDs. Figure 8 also shows that eXcelon-enabled cameras offer far less etaloning than cameras configured with a standard thinned back-illuminated sensor.
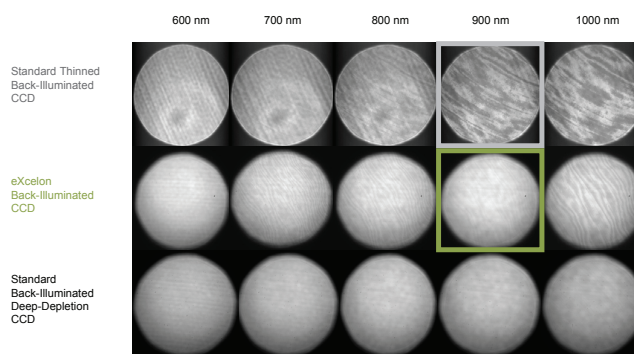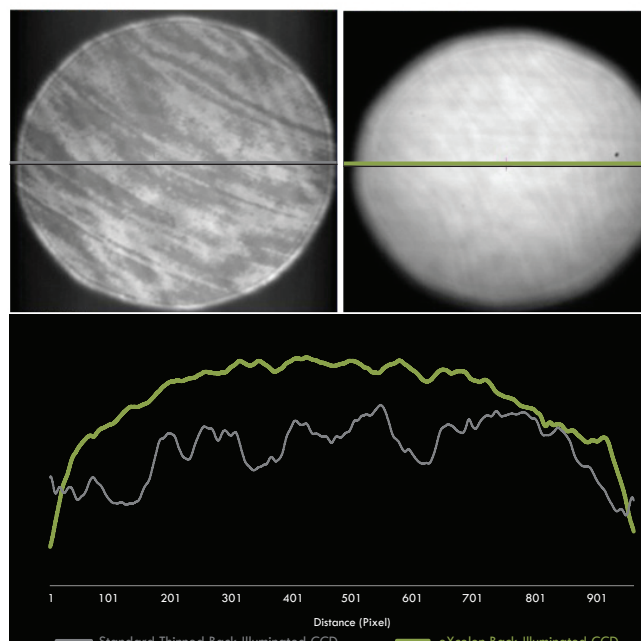
Finally, since original eXcelon technology is based on a standard thinned back-illuminated architecture, it has similar dark current (i.e., 100x lower than that of standard back-illuminated deep-depletion CCDs). In other words, standard back-illuminated deep-depletion CCDs require deeper cooling to achieve similar dark noise performance as that of eXcelon detectors. This is an important consideration, especially in spectroscopy, where signal is integrated over many minutes and binned over several rows.

eXcelon EMCCD Technology

Similar gains in performance can be realized using eXcelon back-illuminated EMCCDs in low-noise camera designs. Figure 9 shows the improvement in etaloning in eXcelon back-illuminated EMCCDs over standard back-illuminated EMCCDs. It is clear to see that eXcelon technology significantly reduces problematic etaloning in the NIR.
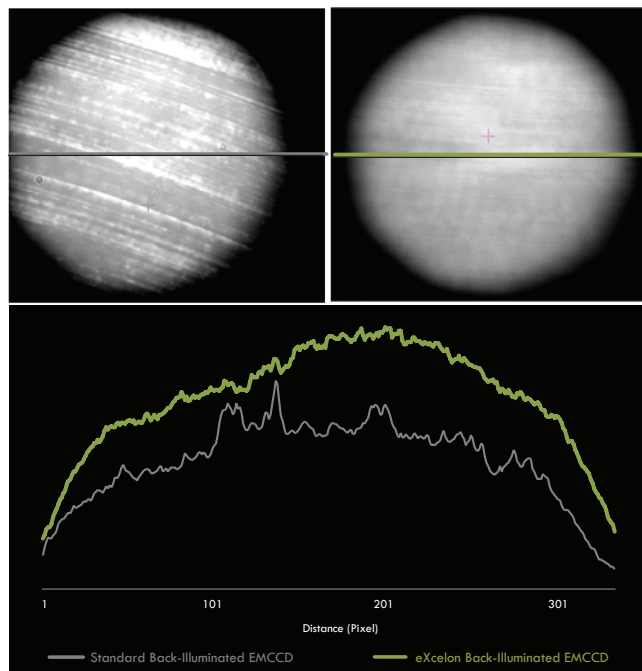

Figure 9. *Etaloning for standard back-illuminated EMCCD cameras (left) and eXcelon back-illuminated EMCCD cameras (right). Cross-sectional data of images taken at 850 nm.*

High Performance Vacuum Design

Photometrics cameras are designed with a single window made of high-grade transmission glass that acts as a vacuum viewport. Any shipping protection windows on the CCD or 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 (Figure 10.)
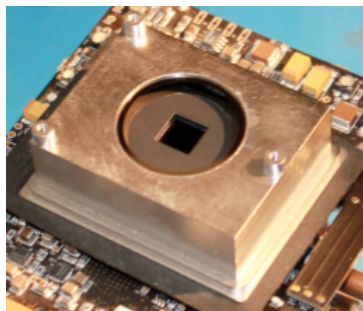

Figure 10. *A single vacuum window with optimized anti-reflective coating ensures maximum light throughput. Furthermore, a brazed metal-to-glass interface provides long-term vacuum seal integrity, as opposed to the degradation associated with traditional epoxy.*

Conclusions

Developed jointly by Photometrics, Princeton Instruments and e2v, new eXcelon back-illuminated sensor technology provides higher sensitivity (over a broad wavelength range) as well as lower etaloning than standard back-illuminated sensor technology. For most applications in which standard thinned back-illuminated sensors are commonly utilized, eXcelon now offers researchers superior performance.

For applications that require extremely high sensitivity and the lowest etaloning in the NIR, new eXcelon back-illuminated deep-depletion sensors are the best choice. However, to keep dark noise at a minimum, these detectors must be cooled. For spectroscopy applications such as Raman, either deep thermoelectric cooling or liquid nitrogen cooling is recommended.

Front-illuminated sensors, meanwhile, remain a highly cost-effective option, as long as substantially lower QE is acceptable to the user.

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.

Appendix A: Etaloning in the NIR

Standard thinned back-illuminated CCDs 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 CCDs 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 CCDs 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):

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

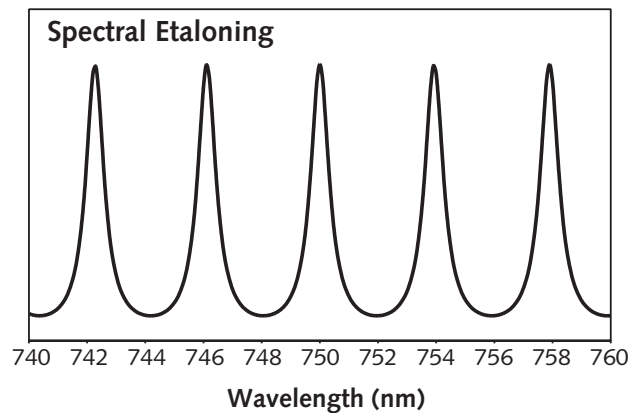(Equation adapted from B. Saleh and M. Teich, *Fundamentals of Photonics*, John Wiley & Sons, New York, 1991)

Spectral Etaloning

Wavelength (nm)

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

Spatial Etaloning

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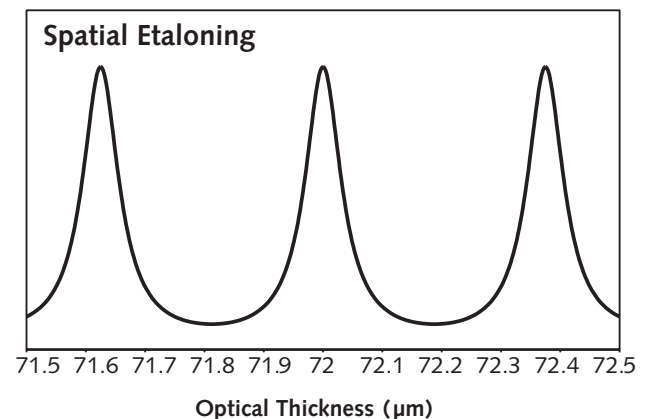
Figure A-2. *Example of spatial etaloning showing the variation in intensity (vertical axis) with thickness.*
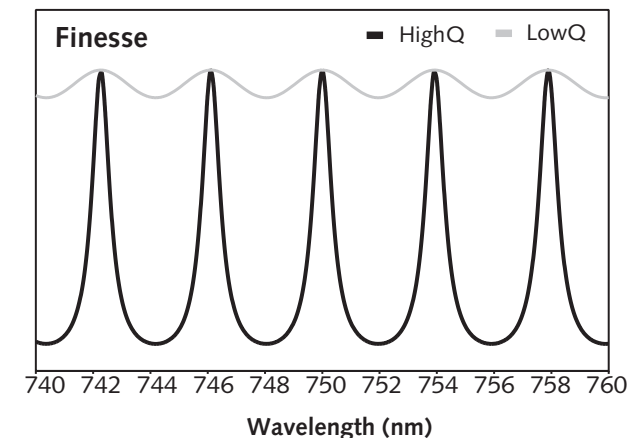

Finesse ▬ HighQ ▬ LowQ

Wavelength (nm)

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 CCDs are made becomes increasingly transparent, causing the QE to decline in the red. The back surface, where light enters a CCD in the back-illuminated configuration, is typically AR coated. These coatings are not perfect, however, and their effectiveness varies by wavelength. Most CCD back-surface AR coatings are not optimized for the NIR.

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

Once light has passed through the body of a CCD 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 CCD. At wavelengths where silicon is transparent enough that light can traverse the thickness of the CCD 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 CCD 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 CCD 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 CCD 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 CCD 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 a CCD is. If a CCD 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.

In most imaging applications with standard thinned back-illuminated CCDs, 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).
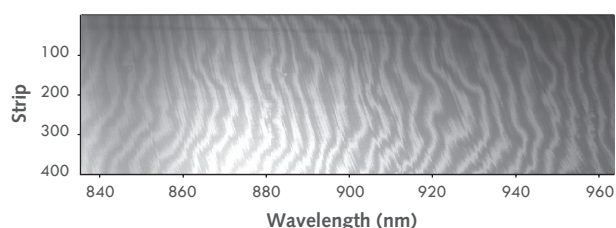

Figure A-4. *Image from a back-illuminated CCD camera showing combined spectroscopic and spatial etaloning.*

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 CCD. Thus, even if a back-illuminated CCD 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 CCD, the characteristic comb pattern will be superimposed on the normal response.

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.
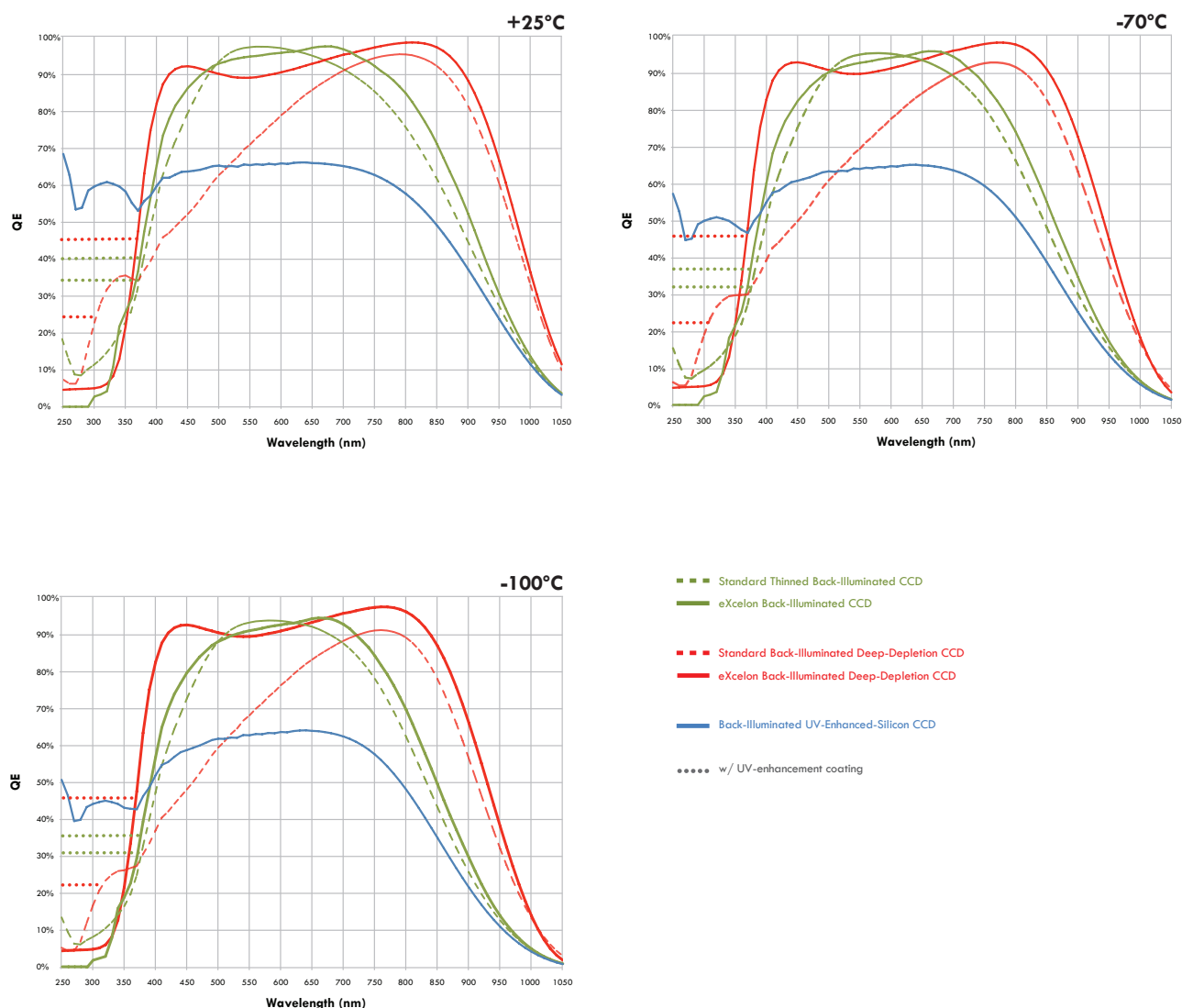

Figure B-1. *QE for various types of back-illuminated CCDs at +25°C, -70°C, and -100°C. Dotted lines on the left represent QE in UV region with optional UV-enhancement coating.*