Memo Title:	**CCD Sensor Selection Guide**
Memo Number:	**0007**
Revision No. / Date:	**1.0**
Date:	**8-Sep-2009**

The CCDsp Scientific camera is available for a variety of different sensors that cover a broad spectrum of applications. In order to help the user choose a sensor perfect for their application, this document explores some of the different kind of CCD sensors, their advantages/disadvantages and some important factors that drive the selection of a sensor for an application.

When selecting a sensor for an application the following parameters should be considered:

1. Spectral range of interest – This term refers to the region of the electromagnetic spectrum in which the CCD should be most sensitive, for example: visible, near infrared, ultraviolet, etc.

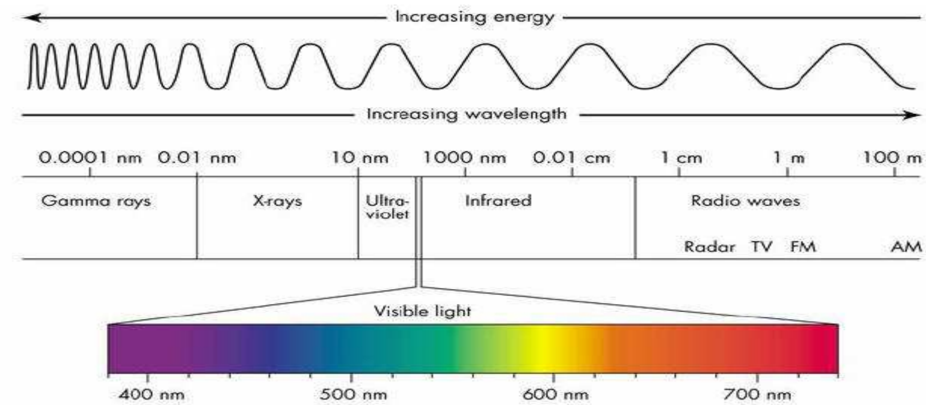

Figure 1: Electromagnetic spectrum – emphasis on visible spectrum of light. (Image obtained from [6])

2. Amount of available light: In applications with very low levels of incident light, detecting the actual signal is of importance and a challenge. Such applications require longer exposures and hence need CCD sensors where noise due to dark current is minimal.

3. Quantum Efficiency (QE) – Quantum efficiency is the measure of the sensitivity of an image sensor to input illumination. It is defined as the proportion of incident photons which generate signal charge, and is normally expressed as a percentage. It is wavelength dependent. [9].

4. Pixel Size – Pixel size dictates the size of the light sensitive elements in a CCD sensor. This is again an application specific parameter and is primarily dependent on the optics of the system.

5. Active Area (Number of Pixels) – Different applications require a different active number of pixels. This is application specific and would be governed by factors like aperture of the lens and focal length of interest.

6. Dynamic Range (SNR) – The dynamic range of a CCD device is the ratio of the maximum achievable signal and the total camera noise. Higher the dynamic range the better the overall system performance. Dynamic range can be expressed in decibels (dB), or simply as a ratio.

   Dynamic range (ratio) = N_{SAT} / N_{Noise}
   or
   SNR (dB) = $20 \log(N_{SAT} / N_{Noise})$

   N_{SAT} = Full well capacity of the sensor.
   N_{Noise} = Total camera noise, i.e. dark noise, readout noise and shot noise.

   As dynamic range performance improves the dimmest intensities of an image can be measured more accurately [7].

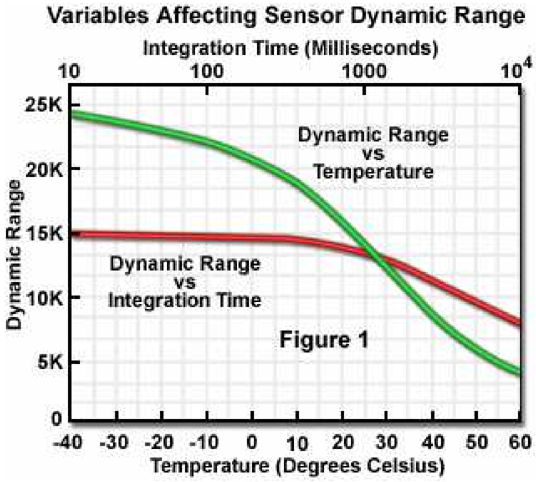

Figure 2: Dynamic range performance versus temperature and integration time [7].

   It can be seen from the figure above that dynamic range is higher at lower temperatures. This can be explained due to the fact that dark current and shot noise due to dark current is reduced in CCDs with cooling. The total camera noise is inversely proportional to the dynamic range, hence it is also important to have camera electronics that are quiet.

   Longer integration times don't affect the dynamic range up to a certain point, but eventually longer integration times will contribute to reduced dynamic range. This is because longer integration times means the system noise will have a higher dark noise contribution.

7. Etaloning –This is a phenomenon that degrades the performance of thinned, back-illuminated CCDs. The effect is caused by light waves passing through the CCD and reflected at the rear surface, producing interference fringes when they interact with incoming waves [8]. Silicon tends to become very transparent in the near IR spectrum and in back thinned CCDs, the proximity of the front and back surfaces allow these interference patterns to appear. As the thickness of CCDs increase, more light absorption occurs, reducing the etaloning. Etaloning appears as intensity variations as a function of position on the CCD. Typically etaloning is only an issue in spectroscopy applications, since the diffraction grating forces the light at each point along the CCD to be essentially monochromatic.

The following section will show the quantum efficiency curves for the various different types of sensors and discuss what kind of applications they are a good fit for based on some of the selection parameters listed above.

CCD Types

Front Illuminated

Though front illuminated sensors have low quantum efficiency they do not experience any significant etaloning effects and have low dark current generation (

Table 1). Front illuminated sensors also offer a good balance between cost and quantum efficiency. They are ideal for use in applications with high level of incident light.

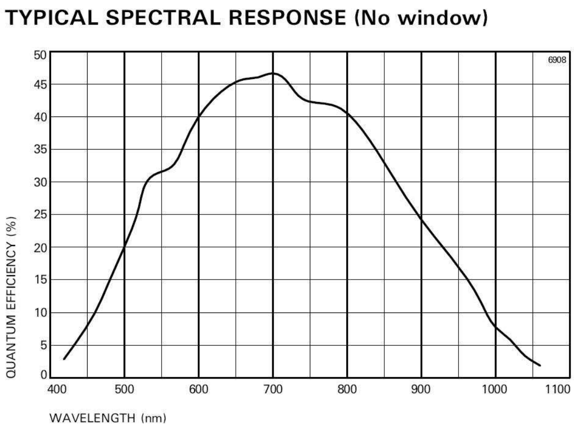

Figure 3: Typical Spectral Response for Front Illuminated sensor. (Image obtained from [3]).

Back Illuminated

Back illuminated sensors have the best quantum efficiency, but they suffer from etaloning effects in the NIR wavelengths. Due to the manufacturing process of back illuminated sensors they are generally very expensive and are used mostly when quantum efficiency is very important for the application. These sensors are ideal for low-light visible applications.

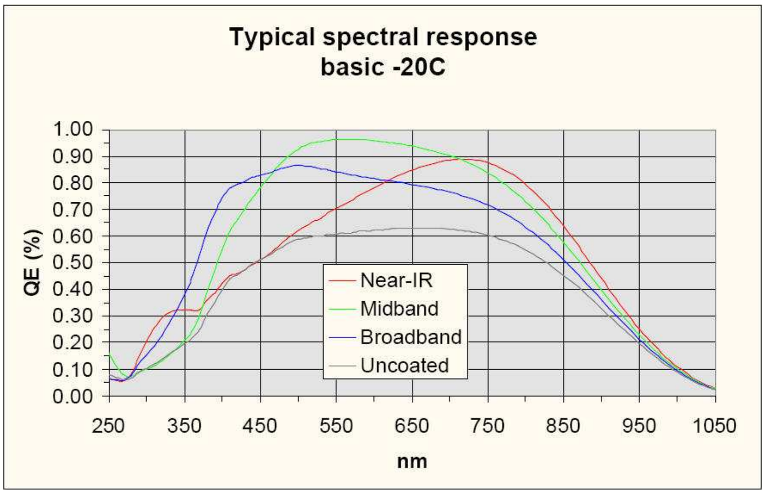

Figure 4: Typical QE Curve. (Image obtained from [2]).

Open Electrode

Open electrode sensors are front illuminated devices with sensitivity into the UV range. They are an alternative to back illuminated sensors where UV sensitivity is needed. These devices can also be an attractive alternative to deep depletion devices for the NIR range, since their quantum efficiency in the NIR is similar to deep depletion devices, but they have much lower dark current.

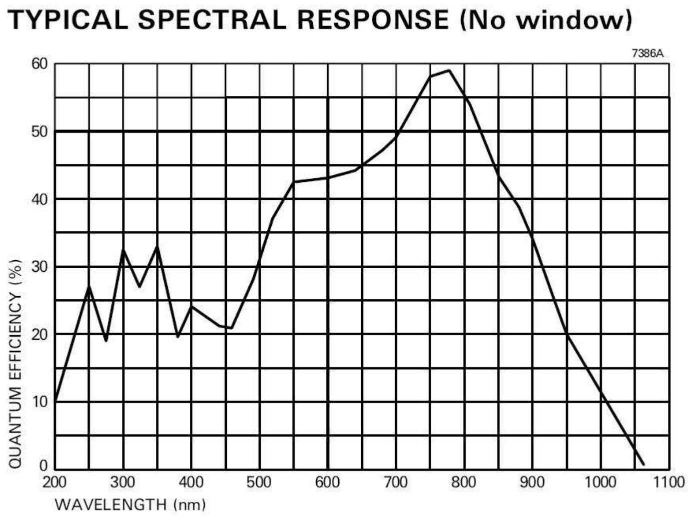

Figure 5: Typical Spectral Response for Open Electrode sensor. (Image obtained from [4]).

Deep Depletion

Deep depletion sensors have deeper pixel wells and collect more IR generated photons. Deep depletion sensors are used when IR sensitivity is critical, but they generate higher dark current and need good cooling options. Deep depletion devices have the added benefit of not suffering from etaloning effect.

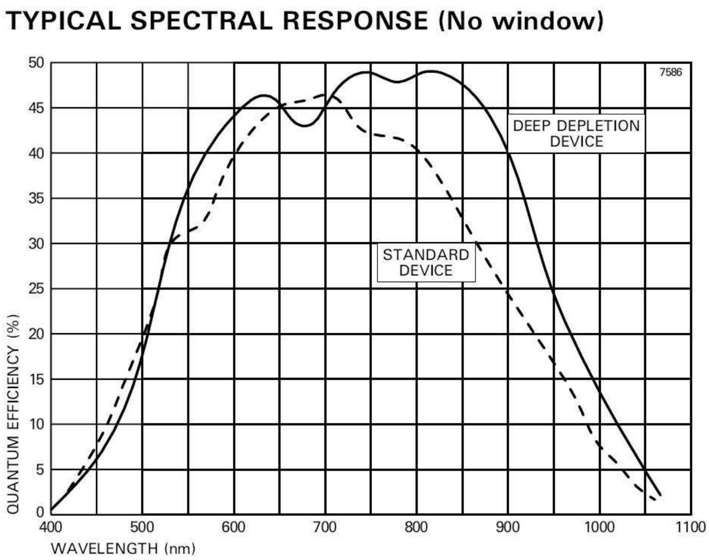

Figure 6: Typical Spectral Response for Deep Depletion sensors. (Image obtained from [5]).

Sensitivity and Dynamic Range

Having high quantum efficiency isn't everything, but it sure helps!

The peak quantum efficiency of the sensors discussed above range from 45% to 95%, but depending on the wavelength of interest, usable quantum efficiency can be 20 % or lower. Sometimes a sensor with lower quantum efficiency and lower dark current can be better than a sensor with high quantum efficiency, e.g. using a front illuminated sensor over a deep depletion sensor for NIR applications.

Conventional wisdom is that deep depletion devices are better at near IR, but look at the comparison below!

Sensor	QE @ 950nm	Dark Current @ -30 °C
Deep Depletion	25 %	500 ē/pixel/second
Front Illuminated	17%	0.2 ē/pixel/second
Back Illuminated	32 %	1 ē/pixel/second

Table 1: Comparison between quantum efficiency and Dark current for different CCD sensors. (Data obtained from [5],[3],[1]).

For an exposure of more than a second or two, the signal quality from the front illuminated sensor will be better than a deep depletion sensor. A front illuminated sensor would be a better and cheaper option in this case if the quantum efficiency is good enough for the application. A deep depletion sensor would provide higher quantum efficiency, but is more expensive and would require better cooling options to reduce the added noise to the signal due to high dark current. However, if better cooling is available, using a deep depletion sensor would be provide better performance.

The back illuminated sensor has better quantum efficiency and dark current than both the deep depletion sensor and front illuminated sensor, but this comes at a significantly higher cost. Also at NIR wavelengths back illuminated sensors may suffer from etaloning. So, again the best choice of the sensor for the application would be dictated by the amount of available light, spectral range of interest, required quantum efficiency and cost.

Sensor Type Selection

	Spec Range	Dark Current	Cost	QE @ 800nm	QE @ 500nm	NIR Etaloning	Low Light
OE	UV	low	mid	55%	30%	N/A	good
BI	VIS	low	high	80%	93%	yes	good
FI	VIS/NIR	low	low	40%	20%	no	poor
DD	NIR	high	high	48%	18%	no	very poor
BIDD	NIR	high	very high	80%	90%	no	good
InGaAs	IR	very high	very high	N/A	N/A	N/A	good

Table 2: Sensor Characteristics Summary.

CCDsp Camera Offerings

CCDsp Camera Model	TE Cooled	Sensor #	Sensor Type	Size (µm)	Active Area		Active Pixels	
					H (mm)	V (mm)	H (mm)	V (mm)
Hamamatsu								
CCDspH7031-0906	Single	S7031-0906	BI	24x24	12.288	1.392	512	58
CCDspH7031-0907	Single	S7031-0907	BI	24x24	12.288	2.928	512	122
CCDspH7031-0908	Single	S7031-0908	BI	24x24	24.576	6.000	512	250
CCDspH7031-1006	Single	S7031-1006	BI	24x24	24.576	1.392	1024	58
CCDspH7031-1007	Single	S7031-1007	BI	24x24	24.576	2.928	1024	122
CCDspH7031-1008	Single	S7031-1008	BI	24x24	24.576	6.00	1024	250
e2V								
CCDspE3011-BI	Three	30-11 BI	BI	26.0x26	26.6	6.70	1024	256
CCDspE3011-BI DD	Three	30-11 BI DD	BI, DD	26.0x26	26.6	6.70	1024	256
CCDspE3011-FI	Three	30-11 FI	FI	26.0x26	26.6	6.70	1024	256
CCDspE30-11 FI OE	Three	30-11 FI OE	FI, OE	26.0x26	26.6	6.70	1024	256
CCDspE30-11 FI DD	Three	30-11 FI DD	FI, DD	26.0x26	26.6	6.70	1024	256

Table 2: CCDsp Scientific Camera offerings.

Note: The table above just lists some of the scientific cameras CCDsp Platform offer. Please visit the website at http://www.criticallink.com//products/ccdsp/ccdssp-hamamatsu/ for more options.

References

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[5] e2V technologies,"CCD30-11 Deep Depletion Sensor High Performance CCD Sensor ," 2006, Available: http://www.e2v.com/assets/media/files/documents/imaging-space-and-scientific-sensors/03-30-11(2).pdf [Accessed: September 15, 2009].

[6] "Light", Available: https://www.msu.edu/~zeluffjo/light.html [Accessed: September 18, 2009].

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[8] Photonics Dictionary, Available: http://www.photonics.com/directory/dictionary/lookup.asp?url=lookup&entrynum=1732&letter=e, [Accessed: September 28, 2009].

[9] e2V technologies,"CCD Sensors Technical Note Glossary of Terms ," Available: http://www.e2v.com/assets/media/files/documents/imaging-space-and-scientific-sensors/Papers/ccdtn106.pdf [Accessed: September 28, 2009].