Digital Camera Fundamentals

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In the last few years, light measurement has evolved from a dependence on traditional emulsion-based film photomicrography, to one where electronic images are the media of choice. The imaging recording device is one of the most critical components in many experiments so understanding the process of how the light images are recorded and the choices available can enhance the quality of the light measurement data. In this guide we aim to provide an understanding of the basics of light detection and also help select a suitable detector for specific applications. High performance digital cameras can be defined by a number of variables. Each of these variables is discussed in detail in subsequent sections but a brief description is included here for convenience.

Scientific Camera Types

Scientific Digital cameras come in 4 primary types based on the sensor technology they use and these are: CCD's, EMCCD's, CMOS and ICCD cameras. The different cameras and their various architectures have inherent strengths and weaknesses and these are covered in this section.

CCD Sensor Formats

The most common scientific camera, the Charge Coupled Device camera (CCD), comes with three fundamental architectures and these are Full Frame, Frame Transfer and Interline format. The different architectures and their inherent strengths and weaknesses and are covered in this section.

Spectral Response

The spectral response of a camera refers to the detected signal response as a function of the wavelength of light. This parameter is often expressed in terms of the Quantum Efficiency (hereinafter in this document referred to as QE), a measure of the detector's ability to produce an electronic charge as a percentage of the total number of incident photons that are detected. The fundamental factors which affect spectral response are covered in this section.

Camera Sensitivity & Noise

The sensitivity of a camera is the minimum light signal that can be detected and by convention we equate that to light level falling on the camera that produces a signal just equal to the camera's noise. Hence the noise of a camera sets an ultimate limit on the camera sensitivity. Digital cameras are therefore often compared using their noise figures and noise derives from a variety of sources principally:

- Read Noise: inherent output amplifier noise
- Dark Noise: thermally induced noise arising from the camera in the absence of light (can be reduced by lowering the operating temperature)
- Shot Noise (Light Signal): noise arising out of the stochastic nature of the photon flux itself

It is often overlooked that the light signal has its own inherent noise component (also know as Shot Noise) which is equal to the square root of the signal. Another noise source which is often overlooked is the excess noise that arises from the cameras response to light signal, which is known as the Noise Factor.

Dynamic Range

Dynamic Range is a measure of the maximum and minimum intensities that can be simultaneously detected in the same field of view. It is often calculated as the maximum signal that can be accumulated, divided by the minimum signal which in turn equates to the noise associated with reading the minimum signal. It is commonly expressed either as the number of bits required to digitize the associated signals or on the decibel scale.

Blooming & Anti-blooming

A camera's ability to cope with large signals is important in some applications. When a CCD camera saturates it does so with a characteristic vertical streak pattern, called Blooming. In this section the effect is explained and how it can be compensated for.

Signal/Noise Ratio

A camera's signal-to-noise ratio (commonly abbreviated S/N or SNR) is the comparison measurement of the incoming light signal versus the various inherent or generated noise levels, and is a measure of the variation of a signal that indicates the confidence with which the magnitude of the signal can be estimated.

Spatial Resolution

Digital cameras have finite minimum regions of detection (commonly known as Pixels) that set a limit on the Spatial Resolution of a camera. However the spatial resolution is affected by other factors such as the quality of the lens or imaging system. The limiting spatial resolution is commonly determined from the minimum separation required for discrimination between two high contrast objects, e.g. white points or lines on a black background. Contrast is an important factor in resolution as high contrast objects (e.g. black and white lines) are more readily resolved than low contrast objects (e.g. adjacent gray lines). The contrast and resolution performance of a camera can be incorporated into a single specification called the Modulation Transfer Function (MTF).

Frame Rate

The Frame Rate of a digital camera is the fastest rate at which subsequent images can be recorded and saved. Digital cameras can readout sub sections of the image or bin pixels together to achieve faster readout rates, therefore typically two frame rates are defined, i.e. one is a full frame readout rate and the other is the fastest possible readout rate.

Blemishes & Non-uniformities

Cameras to some degree all exhibit blemishes which affect the reproduction of the light signal. This is due to several variables, i.e.:

- Gain variations across the sensor
- Regional differences in noise

EMCCD Cameras

EMCCD cameras are relatively new types of cameras which allow high sensitivity measurements to be taken at high frame rates. The operation and properties of these cameras are outlined.

ICCD Cameras

Intensified CCD cameras combine an image intensifier and a CCD camera and are inherently low light cameras. In addition the image intensifier has useful properties which allow the camera to have very short exposure times. The operation and properties of these cameras are outlined in this section.

CCD, EMCCD & ICCD Camera Comparisons

In this section a detailed comparison between CCD, EMCCD and ICCD cameras is shown and the applications suited to each camera is highlighted.

Scientific Digital Cameras

The principal forms of high performance digital camera include:

- The popular Charge-Coupled Device (CCD) Camera
- The Electron Multiplying Charge Coupled Device (EMCCD) Camera
- The Complementary-Metal-Oxide-Semiconductor (CMOS) detector camera
- The Image Intensified CCD Camera (ICCD)

In the first three detectors, a silicon diode photosensor (often called a Pixel) is coupled to a charge storage region that is, in turn, connected to an amplifier that reads out the quantity of accumulated charge. Incident photons generate electronic charges, which are stored in the charge storage region.

If the incident photons have sufficient energy and they are absorbed in the depletion region they liberate a electron which can be detected as a charge. The transmission and absorption properties of the silicon then define the spectral response of the detector and this is explained further on QE in a later section.

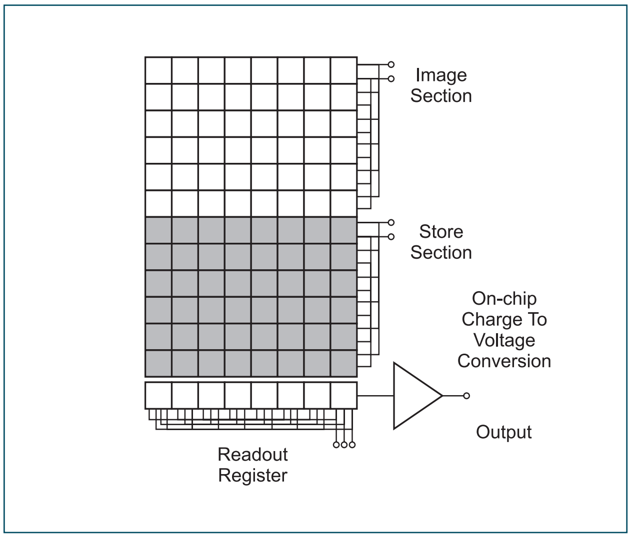


Figure 1: Typical CCD Structure

In a CCD, there is typically only one amplifier at the corner of the entire array and the stored charge is sequentially transferred through the parallel registers to a linear serial register, then to an output node adjacent to the read-out amplifier. CCD sensors were first developed in the late 60's and the technology is relatively mature now. CCD performance has pushed the boundaries in the efficiency of light detection and in reducing the noise from either dark signal or amplifier readout.

One weakness of a CCD is the fact that the CCD is essentially a serial readout device and low noise performance is only achieved at the expense of slow readout speeds. CMOS cameras can achieve high frame rates with moderate sensitivity.

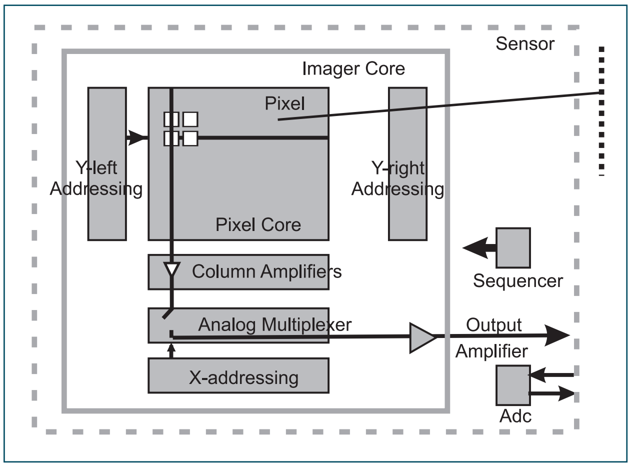


Figure 2 - CMOS Structure

In CMOS detectors, each individual photosensor or more typically each column of photosensors has an amplifier associated with it. A row of pixels can be readout in parallel with the row selected by an addressing register or an individual pixel can be selected by column multiplexer. A CMOS device is essentially a parallel readout device and therefore can achieve higher readout speeds particularly required by imaging applications. CMOS detector technology however still needs considerable development to compete against CCD for performance in scientific applications. To achieve the parallel readout the CMOS amplifier uses multiple amplifiers, each with its own gain, linearity and noise performance variation. Compensating for the variations in the current state of the art CMOS devices is difficult over a wide range of illumination levels and to the accuracy required by scientific applications. High speed readout with high sensitivity can be achieved by EMCCD cameras.

The EMCCD has essentially the same structure as a CCD with the addition of a very important feature. The stored charge is transferred through the parallel registers to a linear register as before but now prior to being readout at the output node the charge is shifted through an additional register, the multiplication register in which the charge is amplified. A signal can therefore be amplified above the readout noise of the amplifier and hence an EMCCD can have a higher sensitivity than a CCD.

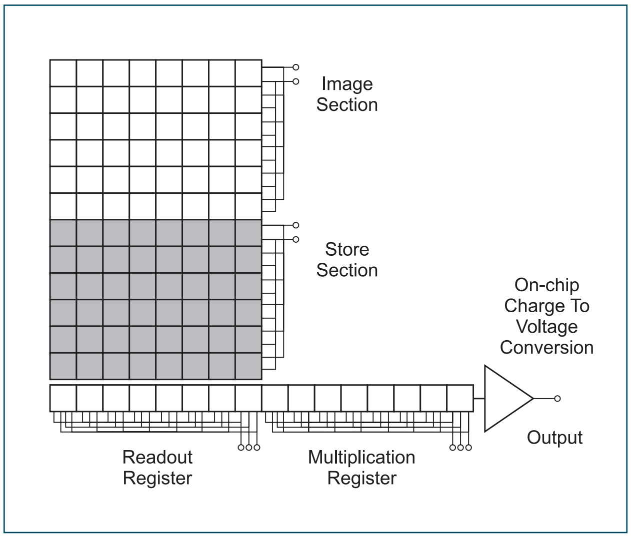


Figure 3 - EMCCD Structure

EMCCDS use similar structures to CCD's and are similarly restrained in the minimum exposure time they can achieve. Intensified CCD Cameras can achieve ultra short exposure times.

In the Image Intensifier a photosensitive surface (Photocathode) captures incident photons and generates electronic charges that are sensed and amplified.

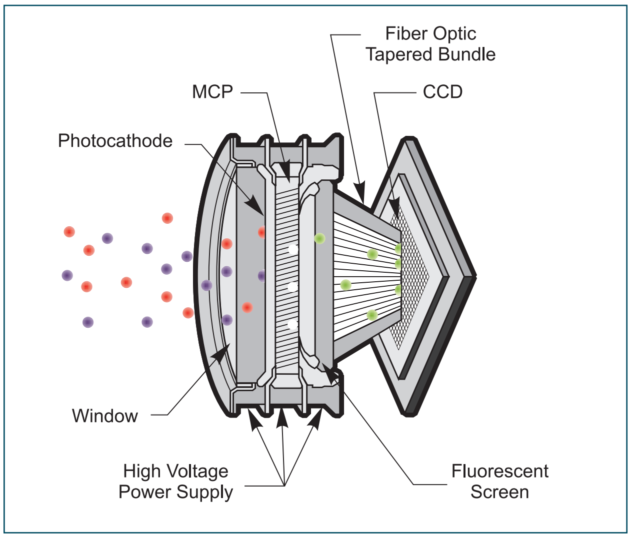


Figure 4 - ICCD Structure

The photocathode is similar in nature to the photosensitive region of a Photomultiplier tubes (PMTs) that are widely used in confocal microscopes and spectrometers. When photons fall on a photocathode they utilize the energy of the incident photons to release electrons. The liberated electrons are then accelerated toward an electron multiplier composed of a series of angled tubes known as the Micro-Channel Plate. Under the accelerating potential of a high voltage, the incident electrons gain sufficient energy to knock off additional electrons and hence amplifies the original signal. This signal can then be detected in several ways, either by direct detection using a CCD (also called a EBCCD Electron Bombardment Charge Coupled Device) or indirectly by using a phosphor and CCD.

The ICCD can achieve short exposure times by using a pulsed gate voltage between the photocathode and MCP. By applying a small positive voltage, electrons liberated by the photocathode can be suppressed and hence not detected. By switching the voltage to a negative voltage, electrons from the photocathode are accelerated across the gap to the MCP where they can be amplified and detected. By applying a suitable short voltage pulse the intensifier can therefore be effectively turned on and off in sub nanosecond intervals.

ICCD cameras find uses in applications where short exposure times or gating is required such as LIBs or combustion research.

CCD cameras are the camera of choice for most scientific applications which require sensitivity or dynamic range. The sheer range of CCD sensor options offers the prospect to select a sensor of the best overall characteristics for applications ranging from astronomy to spectroscopy. CCD technology is relatively mature while CMOS technology still needs major development to compete with CCD's in scientific applications.

An EMCCD camera works best in applications when a high sensitivity needs to be coupled with high speed such as fluorescent microscopy or ultra fast spectroscopy. EMCCD is relatively new technology and there is still a relatively limited range of sensor formats currently available. In coming years these sensors are expected to get faster with increasing numbers of formats becoming available.

Hybrid sensors which combine CCD and CMOS technologies can potentially deliver performance superior to either CCD or CMOS bulk detectors. They look the better long term option but there is still a considerable amount of development required before they can be commercially viable. In particular to overcome the issues associated with compensating for the variation of the multiple amplifiers.

Many of the principals that apply to CCD's also apply to other camera formats. In the following section we will cover the characteristics of the CCD and then cover in more detail EMCCD's and ICCD's in later sections and highlight how their characteristics differ.

CCD Sensor Architectures

The CCD architectures commonly used for high performance cameras are described below:

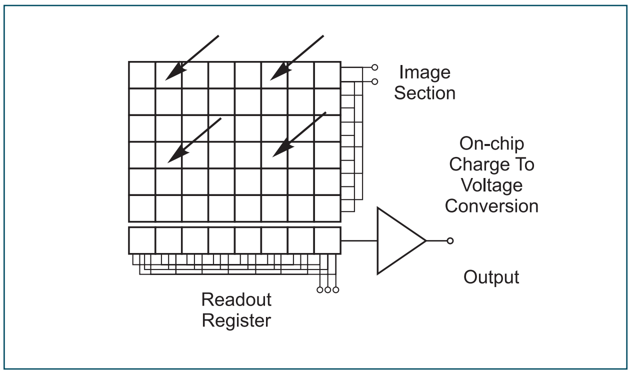


Figure 5 - Typical full frame CCD sensor format

The full frame CCD is the simplest form of sensor in which incoming photons fall on the full light sensitive sensor array. To readout the sensor the accumulated charge must then be shifted vertically row by row into the serial output register and for each row the readout register must be shifted horizontally to readout each individual pixel. This is known as "Progressive Scan" readout. A disadvantage of full frame is charge smearing caused by light falling on the sensor whilst accumulated charge signal is being transferred to the readout register. To avoid this, devices sometimes utilise a mechanical shutter to cover the sensor during the readout process. However, mechanical shutters have lifetime issues and are relatively slow. Shutters are not needed however in spectrographic operations or when a pulsed light source is used. Full frame CCD's are typically the most sensitive CCD's available and can work efficiently in many different illumination situations.

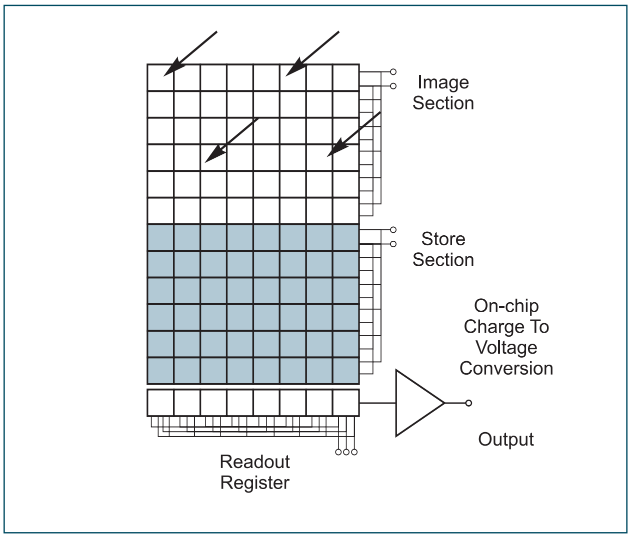


Figure 6 - Typical frame transfer CCD sensor format

The frame-transfer CCD uses a two-part sensor in which one-half of the parallel array is used as a storage region and is protected from light by a light-tight mask. Incoming photons are allowed to fall on the uncovered portion of the array and the accumulated charge is then rapidly shifted (in the order of milliseconds) into the masked storage region for charge transfer to the serial output register. While the signal is being integrated on the light-sensitive portion of the sensor, the stored charge is read out.

Frame transfer devices have typically faster frame rates than full frames devices and have the advantage of a high duty cycle i.e. the sensor is always collecting light. A disadvantage of this architecture is the charge smearing during the transfer from the light-sensitive to the masked regions of the CCD, although they are significantly better than full frame devices. The frame transfer CCD has the sensitivity of the full frame device but are typically more expensive due to the larger sensor size needed to accommodate the frame storage region.

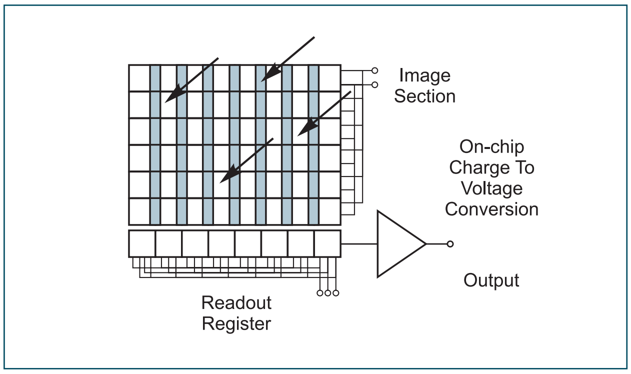


Figure 7 - Typical interline CCD sensor format

The interline-transfer CCD incorporates charge transfer channels called Interline Masks (see Figure 7 above). These are immediately adjacent to each photodiode so that the accumulated charge can be rapidly shifted into the channels after image acquisition has been completed. The very rapid image acquisition virtually eliminates image smear. Altering the voltages at the photodiode so that the generated charges are injected into the substrate, rather than shifted to the transfer channels, can electronically shutter interline-transfer CCDs.

Interline devices have the disadvantage that the interline mask effectively reduces the light sensitive area of the sensor. This can be partially compensated by the use of microlens arrays to increase the photodiode fill factor. The compensation usually works best for parallel light illumination but for some applications which need wide angle illumination (small F/# number) the sensitivity is significantly compromised.

Spectral Response (Quantum Efficiency)

The Spectral Response (or QE) of the CCD is governed by the ability of the photons to be absorbed in the Depletion Region of the detector. It is only in the depletion region that photons are converted into electronic charges and subsequently can be held by the electric fields which form the pixel. The charge held in the depletion region is then transferred and measured. To highlight the spectral response effects lets examine the cross-section of a typical CCD detector shown in Figure 8:

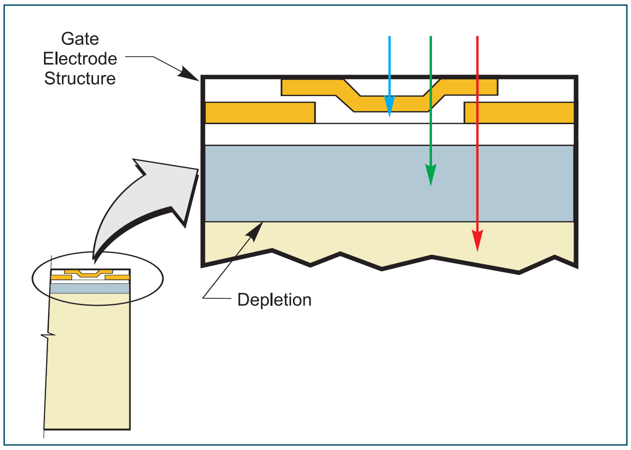


Figure 8 - CCD cross section showing depletion region

Photons falling on the CCD must first transverse the region dominated by the gate electrodes by which the applied clocking voltages create the electric fields that form the boundary of the depletion region and shift charge through the CCD.

The gate structures can absorb or reflect all wavelengths to some extent and as a result reduce the spectral response below the theoretical maximum of 1 electron charge generated per one photon (in the case of visible light). The shorter wavelengths (blue light) are particularly absorbing and below ~350nm they absorb all the photons before they can be detected in the depleted region. Photons with longer wavelengths (i.e. red photons) have a low probability of absorption by the silicon and can pass through the depletion region without being detected and hence reduce the red sensitivity of the device. Photons with wavelengths greater than 1.1µm do not have enough energy to create a free electron charge and so they cannot be detected with Silicon CCD's.

The various absorption effects combine to define the spectral sensitivity of the CCD. The spectral sensitivity is typically expressed as a QE Curve, in which the probability to detect a photon of a particular wavelength is expressed as a percentage. So for example if one in every 10 photons is detected this is expressed as a QE of 10%. The curve for a typical CCD is shown in Figure 9.

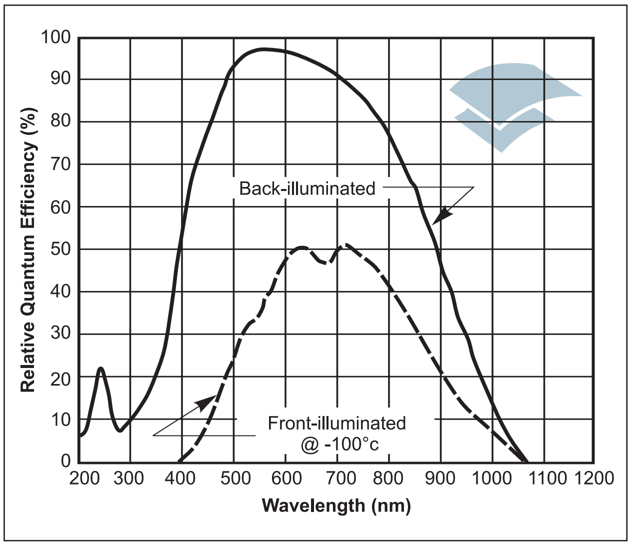


Figure 9 - QE Curves

The losses due to the gate electrode structure can be completely eliminated in the Back-Illuminated CCD. In this design, light falls onto the back of the CCD in a region where the bulk of the silicon has been thinned by etching until it is transparent (a thickness corresponding to about 10-15 microns).

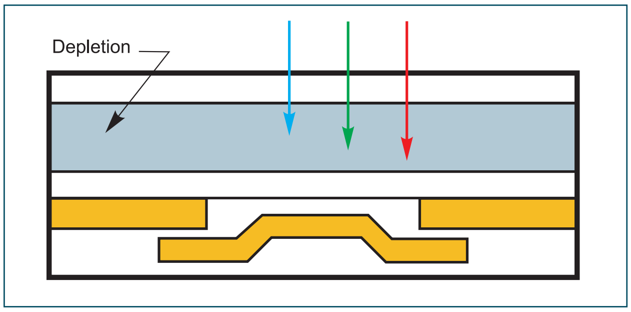
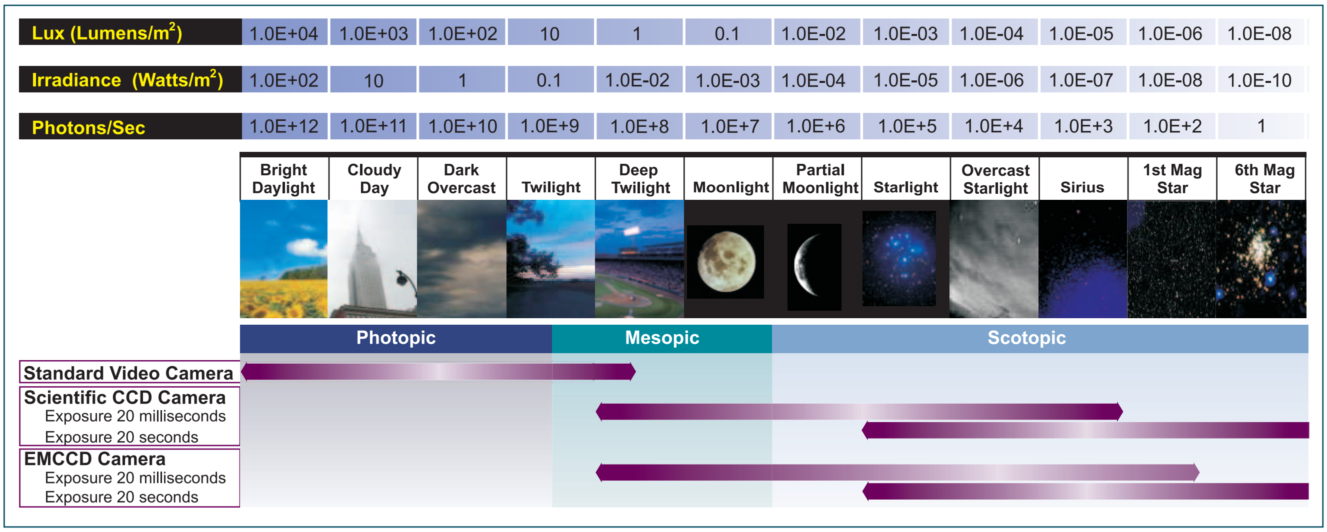


Figure 10 - Back illuminated CCD cross section

Back-thinning results in a delicate, relatively expensive sensor that, to date, has only been employed in high-end scientific-grade CCD cameras. Numerous attempts have been made to increase sensitivity more cost effectively by decreasing the absorption of the gate electrodes. The more successful attempts have included using less obstructive gate electrodes structures such as Open Electrode or Virtual Phase Technology (proprietary technology of Texas Instruments) or using more transparent gate electrode materials such as Indium Tin Oxide in the Kodak™ Blue Plus™ technology.

Camera Sensitivity & Noise



	Bright Daylight	Cloudy Day	Dark Overcast	Twilight	Deep Twilight	Moonlight	Partial Moonlight	Starlight	Overcast Starlight	Sirius	1st Mag Star	6th Mag Star
Lux (Lumens/m^2)	1.0E+04	1.0E+03	1.0E+02	10	1	0.1	1.0E-02	1.0E-03	1.0E-04	1.0E-05	1.0E-06	1.0E-08
Irradiance (Watts/m^2)	1.0E+02	10	1	0.1	1.0E-02	1.0E-03	1.0E-04	1.0E-05	1.0E-06	1.0E-07	1.0E-08	1.0E-10
Photons/Sec	1.0E+12	1.0E+11	1.0E+10	1.0E+9	1.0E+8	1.0E+7	1.0E+6	1.0E+5	1.0E+4	1.0E+3	1.0E+2	1

Figure 11 - Relative sensitivity of scientific cameras to the human eye

The sensitivity of a camera is typically expressed in either the number of photons or in a measure of photon flux which can be related to human observations, called the Lux. A Lux is a measure of illumination which has a value of 1 Lumen per square meter. The Lumen is a photometric equivalent of a Watt which is weighted to match the eye response of the "standard observer".

The sensitivity of the human eye varies at different wavelengths and this has an implication of the number of photons equivalent to a given photometric quantity. The conversion to photons in the table above assumes the light is monochromatic yellowish green light with a wavelength of 555nm which is at the peak of the sensitivity of the human eye. For a given minimum sensitivity in lumens the number of photons varies, for example, see below a table showing the minimum light levels discernable by a typical human observer in the various measures.

Human Observer-sensitivity

Wavelength	Photons per second	Radiometric Measure Watts	Photometric Measure Lumens
450	213	9.40E-17	2.44E-15
555	10	3.58E-18	2.44E-15
650	110	3.36E-17	2.46E-15

The details of photometry (which takes into consideration the human perception of light intensity) versus radiometry which is the absolute measure of light intensity are covered in a later section.

If a given light signal induces a signal on the camera below the readout noise of the camera it cannot be detected so the total noise of the camera is a useful way to define the sensitivity of the camera.

The noise measured by a digital camera comes from a number of sources which will be covered in detail in a later section. Here we will concentrate predominately on the three main sources and they are:

- Sensor readout noise
- Thermal noise
- The noise from the signal itself: photon noise

The total camera noise is the sum, in quadrature, (i.e. the square root is taken of the sum of the various square of the noises) is calculated as shown here:

$$\delta_{total} = \sqrt{\delta^2_{readout} + \delta^2_{dark} + \delta^2_{signal}}$$

The readout noise is an inherent property of the sensor and except for EMCCD cameras, which will be covered in a later section, is usually the limit on sensitivity for most cameras. The readout noise is a combination of noise sources, which originate from the process of amplifying and converting the photoelectrons created into a voltage. Over the years readout noise has improved but fundamentally the faster the readout of the camera, the higher the noise due to the increasing bandwidth required. Low noise CCD's in the past have typically employed very low readout speeds and hence they are often known as Slow Scan CCD's.

The second source of noise is the dark noise that arises from thermally generated charges in the silicon sensor. Recent improvements in CCD design have greatly diminished dark noise to negligible levels and reduced their contribution to total read-out noise to less than 10 electrons per pixel at room temperatures. For the ultimate sensitivity cooling the CCD to temperatures ~-100°C is still required.

Some room temperature cameras may have such a low dark signal that it can be ignored for integration periods of a second or less. Cooling further reduces the dark signal and permits much longer integration periods, up to several hours, without significant dark charge accumulation. The noise arising from the dark charge is given by Poisson statistics as the square root of the charge arising form the thermal effects, i.e.:

$$\delta_{\text{dark}} = \sqrt{N_{\text{dark}}}$$

The incoming photons have an inherent noise ∂_{signal} known as photon Shot noise. If we consider the effects of a number of photons P which would generate in a pixel with QE D_{QE} a signal of N_e electrons they will have a noise as defined by Poisson statistics shown here:

$$\delta_{\text{signal}} = \sqrt{D_{QE} P}$$

If we look at the chart in Figure 12 below we can see the results of a practical example by calculating the sensitivity – and hence noise – of a DW436 camera for increasing exposure from 1 second to 1000 seconds when the camera is cooled to either –65°C or –25°C.

From specification sheets we can see the Readout noise = 7.5e^- @ 1MHz and the Dark Current at -65°C = 0.003 e^-/pixel/second and at –25°C is 1e^-/pixel/second.

As can be seen above the higher dark current at –25°C starts to increase the overall noise with exposures of 10 seconds or more. When cooled to –65°C the dark current has negligible effect for exposures less than 1,000 seconds.

A note of caution: the noise calculated is an average and actual measurements will have peak-to-peak values typically 5 times higher than the average noise. In subsequent sections you will see that to detect a signal with a reasonably high level of confidence the signal must typically greater than the read noise squared!

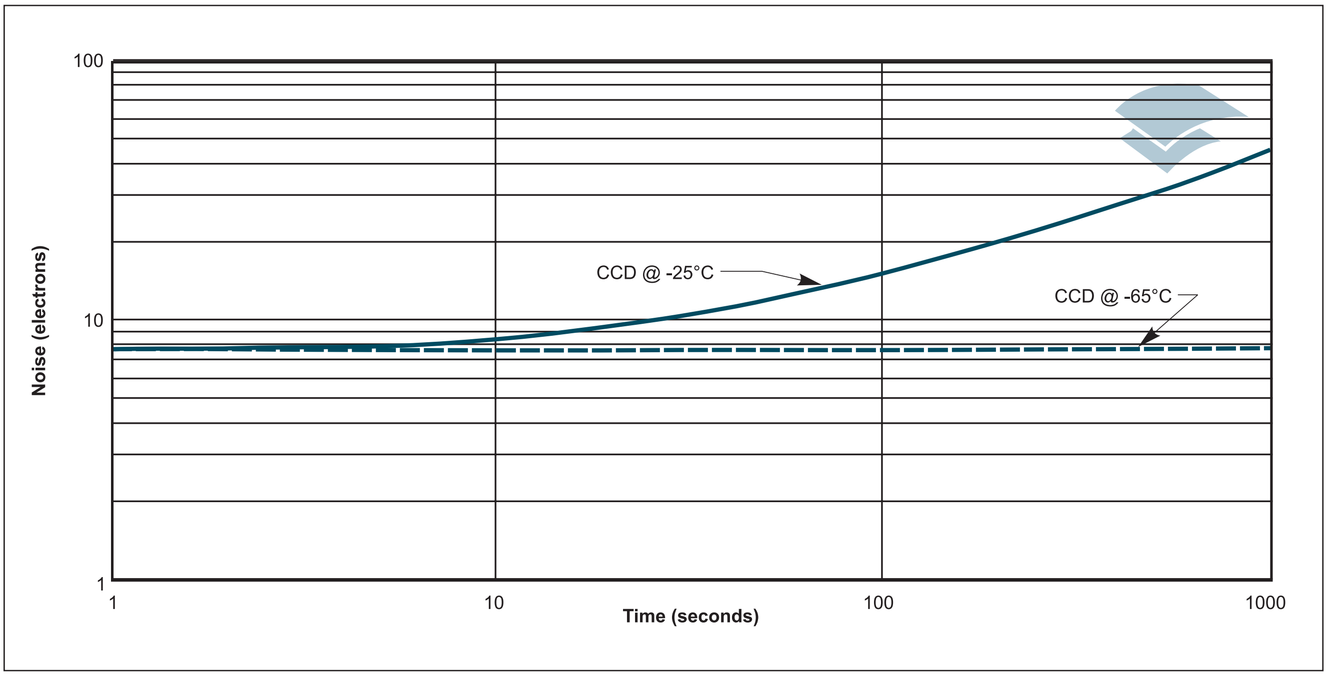


Figure 12 - Noise versus exposure time

Dynamic range & Full Well Capacity

The dynamic range of a CCD is typically defined as the full-well capacity divided by the camera noise and relates to the ability of a camera to record simultaneously very low light signals alongside bright signals. The ratio is often expressed in decibels which is calculated as 20log (Full well capacity/read noise) or in the equivalent number of A/D units required to digitise the signal.

The full well capacity is the largest charge a pixel can hold before saturation which results in degradation of the signal. When the charge in a pixel exceeds the saturation level, the charge starts to fill adjacent pixels a process known as Blooming. The camera also starts to deviate from a linear response and hence compromises the quantitative performance of the camera. Larger pixels have lower spatial resolution but their greater well capacity offers higher dynamic range which can be important for some applications. The table below shows the full well capacity and dynamic range of a small selection of cameras.

Blooming and Anti-blooming

Blooming occurs when the charge in a pixel exceeds the saturation level and the charge starts to fill adjacent pixels. Typically CCD sensors are designed to allow easy vertical shifting of the charge but potential barriers are created to reduce flow into horizontal pixels. Hence the excess charge will preferentially flow into the nearest vertical neighbours. Blooming therefore produces a characteristic vertical streak, e.g. see Figure 13.

Blooming can be a nuisance when a strong signal can obscure data from a weak signal of interest especially on an image with a high dynamic range. Blooming is usually less of an issue in spectroscopy applications when the CCD is aligned to be in the same orientation as the spectrograph slit. Any excess charge is due to light from the same wavelength and the blooming only serves to effectively increase the system dynamic range.

Some sensors are designed with structures built into them which limits blooming, anti-blooming structures. Anti-blooming structures bleed off any excess charge before they can overflow the pixel and thereby stop blooming. Anti-blooming structures can reduce the effective quantum efficiency and introduce non linearity into the sensor. Therefore anti-blooming sensors are not recommended for applications requiring very low light or high accuracy measurements.

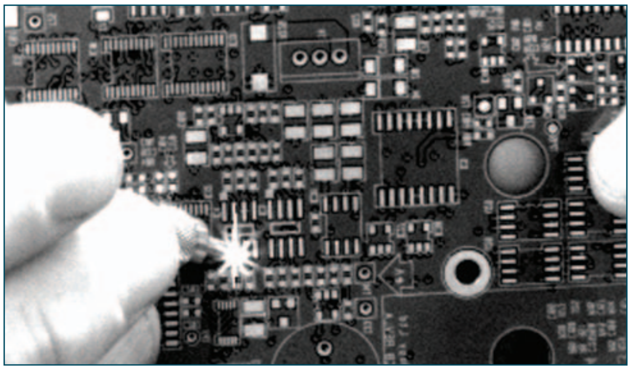


Figure 13 - Image showing Anti-blooming

As an alternative to using anti-blooming sensors an image can be acquired using accumulation mode. Accumulation mode allows successive scans of shorter exposures to be summed to achieve effectively an exposure which is longer by the number of accumulations acquired. If each of the accumulations has light just below the saturation point to be summed the dynamic range of the accumulated signal is also increased by the number of accumulations.

Full Well Capacity & Dynamic Range of Various Cameras

Camera	Pixel Size µm²	Full Well Capacity	Read noise e-	Dynamic range	Decibels db	Bits	Notes
DU-885K-VP	8 x 8	40,000	20	2,000	66	11	EM Amplifier with no Gain
DL-658M-TIL	10 x 10	35,000	12	2,917	69	12	EM amplifier with No Gain
DU-897-CSO-BV	16 x 16	200,000	7	28,571	89	15	Conventional amplifier @ 1MHz
DU920N-BV	26 x 26	510,000	4	127,500	102	17	33KHz Readout speed

Signal-to-Noise ratio

A related measurement to sensitivity and noise is the signal to noise ratio. Lets consider the theoretical prediction of signal to noise for a typical camera. If we assume we have a number of photons P falling on a camera pixel with a Quantum Efficiency D_{QE} this will generate a signal of N_e electrons as below.

$$N_e = D_{QE} P$$

The incoming photons have an inherent noise ∂_{signal} known as photon Shot noise and as the photons follow Poisson statistics this is the given below:

$$\delta_{signal} = \sqrt{D_{QE} P}$$

The other noise sources are: $\partial_{readout}$ is the readout noise, ∂_{dark} is the noise resulting from thermally generated electrons (so called dark signal), and ∂_{signal} is the noise generated by the photon signal. Putting these terms together we can then generate an expression for the signal to noise ratio for a typical camera.

$$\frac{S}{N} = \frac{D_{QE} P}{\sqrt{(\delta^2_{dark} + \delta^2_{signal} + \delta^2_{readout})}}$$

Substituting for the expressions for Noise we can see the equation for signal to noise is as follows;

$$\frac{S}{N} = \frac{D_{QE} P}{\sqrt{D_{QE} P + N_{dark} + \delta^2_{readout}}}$$

The thermal noise component N_{dark} is a function of temperature and exposure time and in the limit where the exposure time is very short and the CCD is cooled to a low temperature this term is negligible. We have also neglected other factors that affect the signal to noise especially of EMCCD and ICCD cameras. These will be covered in more detail in a later section.

The plot for the signal to noise ratio for a typical back illuminated CCD camera versus for an ideal detector is shown in Figure 14. In this plot we have taken the example when the readout noise of the CCD is $10e^-$ and the QE is 93%.

It can be seen by manipulation of the equation that the signal-to-noise ratio approaches that of an ideal detector in the situation when:

$$D_{QE} P \geq \delta^2_{readout}$$

which can be rearranged thus:

$$P \geq \frac{\delta^2_{readout}}{D_{QE}}$$

To achieve good signal to noise performance for a camera with a readout noise of $10e^-$, the photons per pixel P must therefore be greater than the read noise squared or ~100 electrons for this particular example.

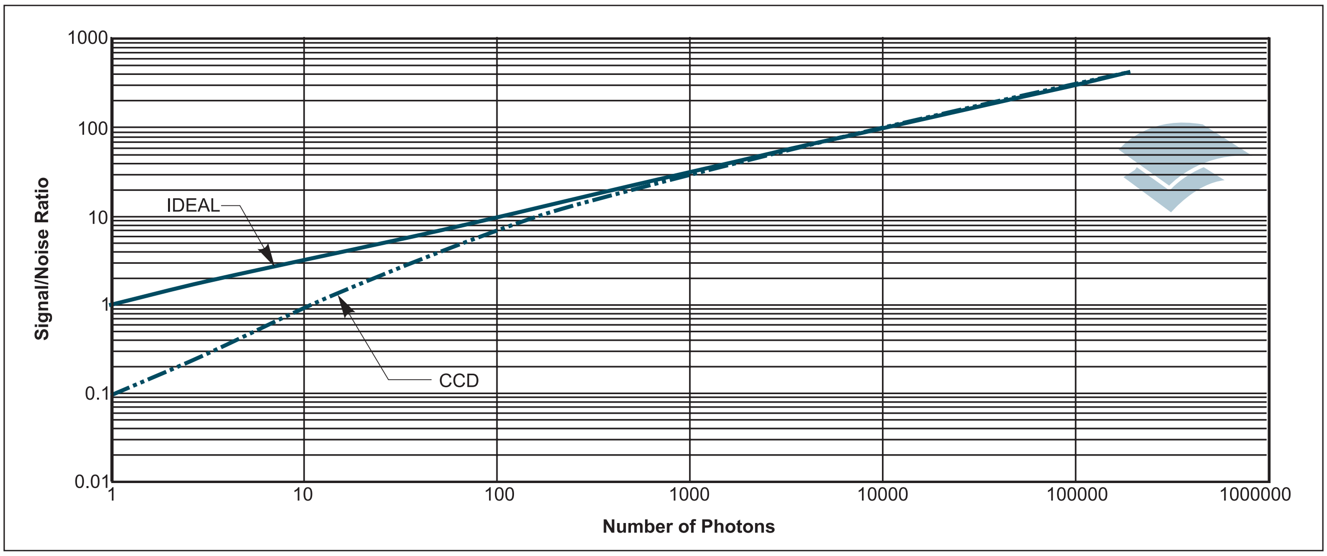


Figure 14 Signal to Noise ratio versus light flux in Photons

Spatial Resolution

The resolution of a CCD is a function of the number of pixels and their size relative to the projected image. CCD arrays of over 1,000 x 1,000 sensors (1 Mega-pixel) are now commonplace in scientific-grade cameras. The trend in cameras is for the sensor size to decrease, and cameras with pixels as small as 4 x 4 microns are currently available in the consumer market. Before we consider the most appropriate pixel size of a particular application it is important to consider the relative size of projected image to the pixel size to obtain a satisfactory reproduction of the image.

Consider a projected image of a circular object that has a diameter smaller than a pixel. If the image falls directly in the centre of a pixel then the camera will reproduce the object as a square of 1 pixel. Even if the object is imaged onto the vertices of 4 pixels the object will still be reproduced as a square, only dimmer – not a faithful reproduction. If the diameter of the projected image is equivalent to one or even two pixel diagonals the image reproduction is still not a faithful reproduction of the object and critically varies on whether the centre of the image projection falls on either the centre of a pixel or at the vertex of pixels.

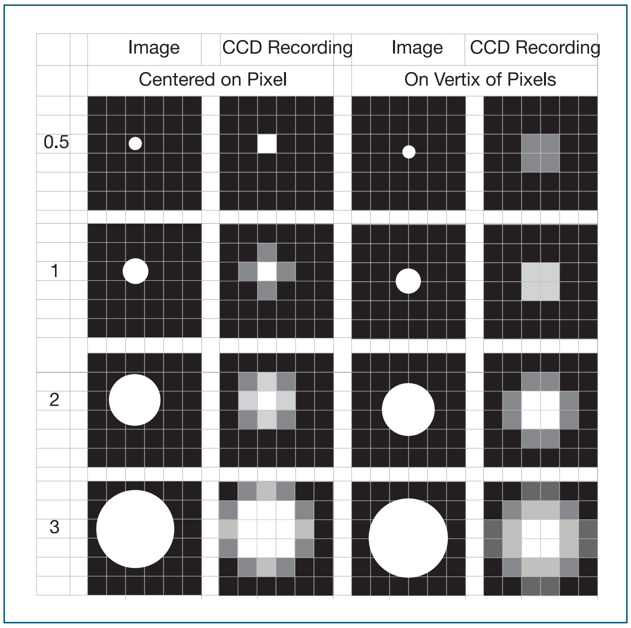


Figure 15 - CCD Output patterns

It is only when the object image covers three pixels do we start to obtain an image that is more faithfully reproduced, and clearly represents a circular object. The quality of the image is also now independent of where the object image is centred, at a pixel center or at the vertex of pixels. Nyquist's theorem, which states that the frequency of the digital sample should be twice that of the analog frequency, is typically cited to recommend a "sampling rate" of 2 pixels relative to the object image size. The Nyquist theorem deals with 2-dimensional signals such as audio and electrical signals and it is unsuitable for an image, which has three dimensions of intensity versus *x* and *y* spatial dimensions.

In addition to the discrete pixels, other factors such as the quality of the imaging system and camera noise all limit the accurate reproduction of an object. The resolution and performance of a camera within an optical system can be characterized by a quantity known as the modulation transfer function (MTF), which is a measurement of the camera and optical system's ability to transfer contrast from the specimen to the intermediate image plane at a specific resolution. Computation of the MTF is a mechanism that is often utilized by optical manufacturers to incorporate resolution and contrast data into a single specification. This concept is derived from standard conventions utilized in electrical engineering that relate the degree of modulation of an output signal to a function of the signal frequency.

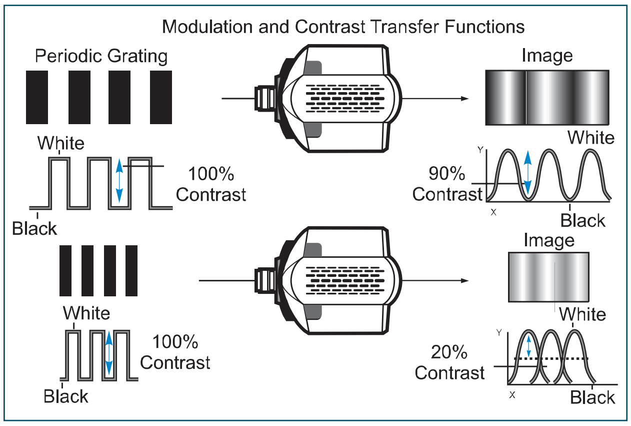


Figure 16 - Measurement of MTF

A typical MTF curve for a CCD camera with a 10x10 and 20x20 micron pixels is shown in figure 17. The spatial frequency of sine waves projected onto the sensor surface is plotted on the abscissa and the resultant modulation percentage on the ordinate. The limiting resolution is normally defined as the 3 percent modulation level.

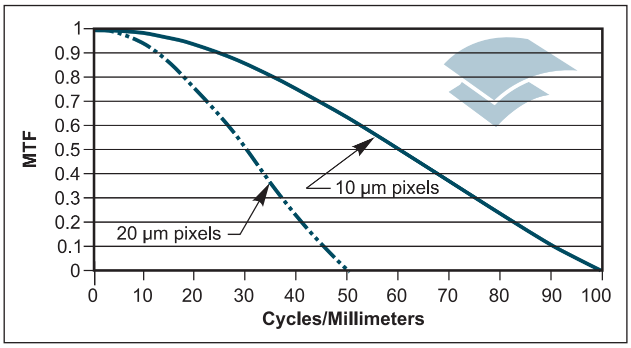


Figure 17 - MTF for CCD

Adequate resolution of an object can only be achieved if at least two samples are made for each resolvable unit (many investigators prefer three samples per resolvable unit to ensure sufficient sampling). In the case of the epi-fluorescence microscope, the resolvable unit from the Abbe diffraction limit at a wavelength of 550 nanometers using a 1.25 numerical aperture lens is 0.27 microns. If a 100x objective is employed, the projected size of a diffraction-limited spot on the face of the CCD would be 27 microns. A sensor size of 13 x 13 micron pixels would just allow the optical and electronic resolution to be matched, with a 9 x 9 micron pixel preferred. Although small sensors in a CCD improve spatial resolution, they also limit the dynamic range of the device.

Binning

CCD's are very versatile devices and their readout pattern can be manipulated to achieve various effects. One of the most common effects is Binning. Binning allows charges from adjacent pixels to be combined and this can offer benefits in faster readout speeds and improved signal to noise ratios albeit at the expense of reduced spatial resolution.

To understand the process, lets us compare the process of single pixel readout versus 2 x 2 binning shown. If we consider a spot of light evenly illuminates the four pixels of our miniature CCD. The CCD has a light sensitive region of just four pixels and a readout register depicted in blue at the bottom of the CCD. The light signal induces a charge of 20 electrons in each of the four pixels as shown by their shading and the numbers in the bottom right hand corner of the pixel.

The light falls evenly on the four pixels and creates a charge of 20e in each of the four pixels.

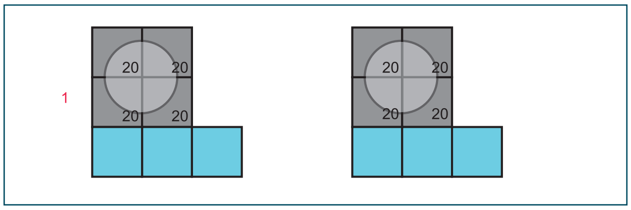


Figure 18

The first operation is to shift the charge down one row. The charge from the lowest pixels gets shifted into the readout register.

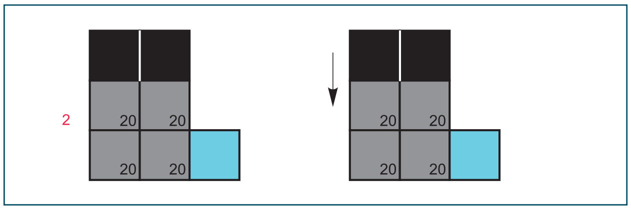


Figure 19

For single pixel readout, the charge in the readout register is shifted to the right and into the readout amplifier. In the binning operation the charge is shifted down again and the charge from the second row is added to the first row in the readout register.

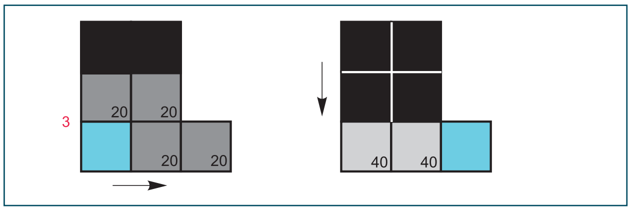


Figure 20

For single pixel readout, the first pixel is readout while the readout register is shifted again to shift the charge in the second pixel into the readout amplifier. In the binning operation the summed charge from the two right pixels is shifted into the readout amplifier.

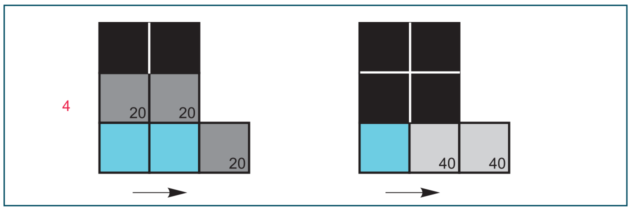


Figure 21

In the single pixel readout, the next row is shifted vertically into the readout register. In the binning operation the readout register is shifted again to sum the charge from the 4 pixels in the readout amplifier before being readout.

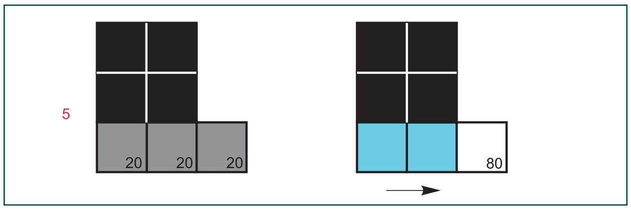


Figure 22

In the single pixel readout mode, the readout register is shifted to the right again to readout the next pixel. Binned operation is now complete.

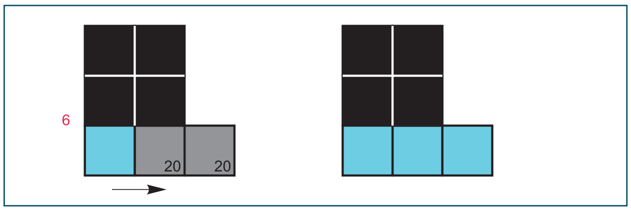


Figure 23

In the single pixel readout the readout register is shifted to the right again to readout the final pixel.

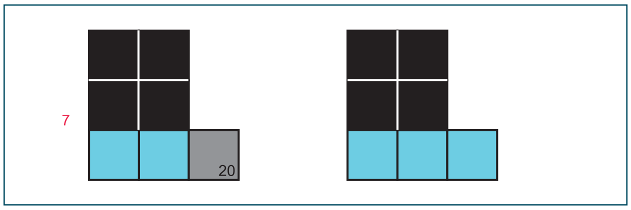


Figure 24

It is important to highlight the main differences in the two readout schemes. In the first we achieve the full spatial resolution the sensor offers. In the Binned example we have reduced the 4 pixel pattern to a single pixel and hence lost spatial resolution. However the binned operation takes less steps to readout the sensor and hence is faster. Typically binning 2x2 is twice as fast; this is achieved by having to shift the readout register only every 2 vertical shifts. If we were binning 3x 3 or 4x4 on a CCD then the readout would be respectively 3 and 4 times faster. The binned example also highlights how binning improves signal to noise ratio. If we assume our CCD has a readout noise of 10e then in the single pixel example each pixel is readout with a noise of 10e hence we achieve a signal to noise ratio of 2:1 (20e/10e). Even if we subsequently sum the four pixels in a computer after readout, the signal-to-noise ratio becomes 4:1. In adding the four pixels we sum the signal (4 times 20e i.e. 80e) and the noise is added in quadrature i.e. square root of the sum of the noises squared (square root of 4 times 10 squared i.e. 20e). In the binned example there is no noise until the signal is readout by the amplifier so the signal to noise ratio is 8:1(80e/10e) i.e. twice as good as the single pixel readout mode.

One of the most common applications of binning is in spectroscopy. In spectroscopic CCD systems, a spectral line is typically an image of the slit formed on the CCD. The image of the slit will typically have a high aspect ratio, i.e. very long and thin and orientated perpendicular to the readout register. The signal from a single spectral line can now be binned to achieve the best signal to noise ratio without any deterioration in spectral resolution.

Frame Rates

The frame rate of a camera is the fastest rate at which an image or spectra can be continuously recorded and saved. Frame rates are governed principally by the number of pixels and the pixel readout rate but other factors such as whether a sub array is used, whether there is binning and at which vertical shift clock speeds are also factors. In image mode the frame rate is measured using full frame readout with all the individual pixels readout at normal operating clocking speeds. In spectral mode the frame rate is measured with a fully vertically binned pattern and normal operating clock speeds.

Frame Rates of Various Cameras

Camera	Frame Rate Standard	Frame Rate Maximum	Comments
DU401A-BV	81.0	97.0	Spectral Mode
DU970N-BV	427.0	1,500	Spectral Mode
DH720-18F-63	166.0	950	Imaging Mode
DU-885-CSO-VP	31.5	200	Imaging Mode
DU-897-CSO-BV	32.0	106	Imaging Mode
DW436-BV	0.2	10	Imaging Mode

Camera Blemishes and Non-uniformities

All cameras to some degree exhibit blemishes which impair the faithful reproduction of the light signal. The primary source of the blemishes is the sensor itself and here are some of the blemishes that occur.

Black Pixels

Black pixels are regions of the sensor typically pixels or small clusters of pixels which have significantly lower response than their neighbors (less than 75% the response of the average pixel). They are typically formed due to contamination on the sensor surface or embedded in the sensor. The effect of Black pixels can be removed by taking a flat fielding reference or by post processing interpolation to mitigate their effects. Black pixels are rarely a major issue unless they extend to many pixels.

Hot Pixels

Hot pixels have a much higher dark current than their neighbors (50 times higher than specifciation). They typically have a different temperature response than the bulk of the sensor and so can appear to differing amounts at different temperatures. They are usually due to contamination embedded in the sensor. The effect of Hot pixels, unless they are particularly large, can usually be removed by taking a background

Column Defects

A combination of blemishes may adversely affect a column. A column defect may due to some of the following:

- A total of more than 30 black pixels or hot pixels
- Hot Column:- a column which has a dark current greater than 2 times specification
- Black Column:- a column which has saturation less than 90% of the average column
- A trap:- see next section

Traps

Traps are peculiar to CCD's, they usually only occur in a single pixel and they can be caused by contaminants getting into the CCD during the production process or by the effects of radiation on the CCD structure. They act by becoming temporary holders of charge. As charge is shifted though a trap, the trap holds onto a portion of the charge (the trap size), while the trap is filled subsequent charge transfers are unaffected. The charge in the trap slowly dissipates until it is refilled by new charge created by illumination or by new charge being shifted through the pixel. Traps can be any size even down to a single electron charge trap but they are usually only noticeable when their size is greater than 200 electrons. Traps are identified by analyzing their impact on an illuminated CCD at a mixture of high and low light levels. The dynamic nature of the traps is difficult to model and therefore they are difficult to compensate for. Severe traps can be overcome by providing an initial light illumination to fill the traps before the proper exposure is required but this adversely affects the signal to noise.

Andor Camera Grades

Andor grades our standard cameras with the following definitions. Within the active image area which is defined as central area ignoring the 2.5% of the pixels around the edge of the sensor the following blemishes are allowed. Some large area or specialist sensors have their own definition as agreed by the sensors manufacturer and their grading is defined in their specification sheets.

Blemish Specifications for CCD Cameras

Blemishes	Grade A	Grade B	Comments
Black pixels	≤ 80	≤ 160	Per million pixels
Hot Pixels	≤ 60	≤ 120	Per million pixels
Black Columns	≤ 1	≤ 4	Per thousand columns
Hot Columns	≤ 1	≤ 4	Per thousand columns
Traps	≤ 4	≤ 8	Per million pixels

EMCCD Cameras

EMCCD technology, sometimes known as 'on-chip multiplication', is an innovation first introduced to the digital scientific imaging community by Andor Technology in 2001, with the launch of our dedicated, high-end iXon platform of ultra-sensitive cameras. Essentially, the EMCCD is an image sensor that is capable of detecting single photon events without an image intensifier, achievable by way of a unique electron multiplying structure built into the chip.

EMCCD cameras overcome a fundamental physical constraint to deliver high sensitivity with high speed. Traditional CCD cameras offered high sensitivity, with readout noises in single figure <10e^- but at the expense of slow readout. Hence they were often referred to as 'slow scan' cameras. The fundamental constraint came from the CCD charge amplifier. To have high speed operation the bandwidth of the charge amplifier needs to be as wide as possible but it is a fundamental principal that the noise scales with the bandwidth of the amplifier hence higher speed amplifiers have higher noise. Slow scan CCD's have relatively low bandwidth and hence can only be read out at modest speeds typically less than 1MHz. EMCCD cameras avoid this constraint by amplifying the charge signal before the charge amplifier and hence maintain unprecedented sensitivity at high speeds. By amplifying the signal the readout noise is effectively by passed and readout noise no longer is a limit on sensitivity.

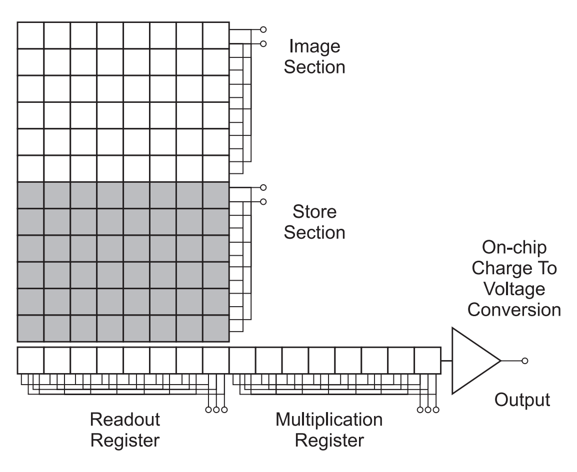


Figure 25 - EMCCD structure

Most EMCCDs utilise a Frame Transfer CCD structure shown in Figure 25. Frame Transfer CCDs feature two areas – the sensor area which captures the image and the storage area, where the image is stored prior to readout. The storage area is normally identical in size to the sensor area and is covered with an opaque mask, normally made of aluminium. During an acquisition, the sensor area is exposed to light and an image is captured – this image is then automatically shifted downwards behind the masked region of the chip, and then read out. While this is happening the sensor area is again exposed and the next image is acquired. The aluminium mask therefore acts like an electronic shutter. To readout the sensor the charge is shifted out through the readout register and through the multiplication register where amplification occurs prior to readout by the charge amplifier.

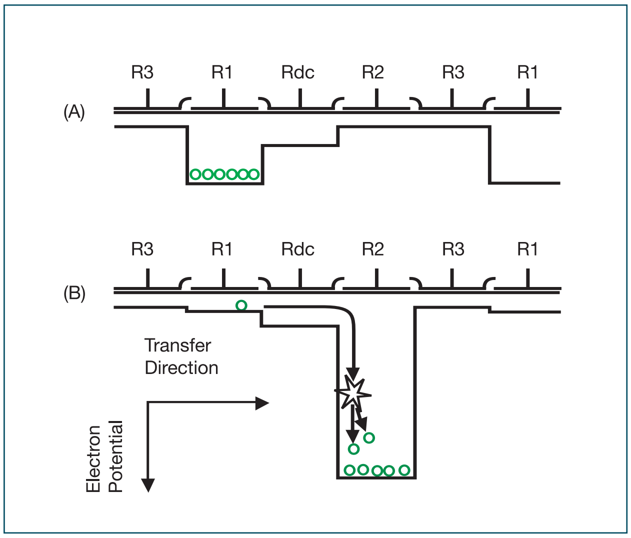


Figure 26 - Gain register operation

The amplification occurs in the multiplication register through the scheme highlighted in Figure 26 above. The multiplication register contains many hundreds of cells and the amplification process occurs in each cell by harnessing a process which occurs naturally in CCD's known as Clock-Induced Charge or Spurious Charge. Clock-induced charge has traditionally been considered a source of noise and something to minimise but not in EMCCD's. When clocking the charge through a register there is a very tiny but finite probability that the charges being clocked can create additional charges by a process known as 'impact ionization'. Impact ionization occurs when a charge has sufficient energy to create another electron-hole pair and hence a free electron charge in the conduction band can create another charge. Hence amplification occurs. To make this process viable EMCCD's tailor the process in two ways. Firstly the probability of any one charge creating a secondary electron is increased by giving the initial electron charge more energy by clocking the charge with a higher voltage. Secondly the EMCCD is designed with hundreds of cells in which impact ionization can occur and although the probability of amplification or multiplication in any one cell is small over the register of cells the probability is very high and gains of up to thousands can be achieved.

The probability of charge multiplication varies with temperature – the lower the temperature the higher the probability and hence gains of the EMCCD. This probability also increases with increasing voltage applied to the multiplication register. By adjusting the temperature and voltage applied to the sensor the EMCCD camera can achieve gains from practically unity with voltages ~20V to thousands by applying voltages of 25–50V depending on the sensor.

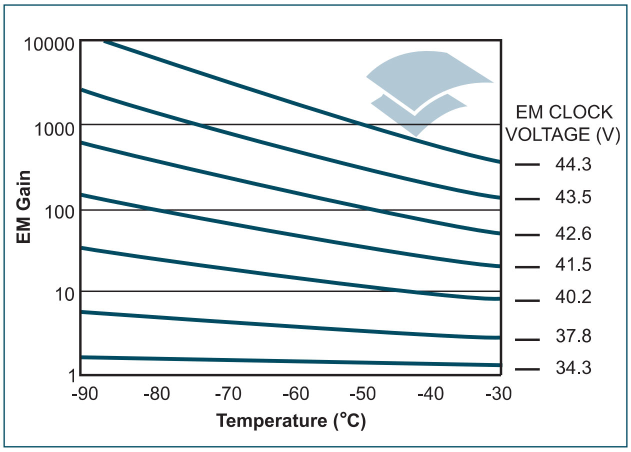


Figure 27 - EM Gain versus voltage

Noise and sensitivity of an EMCCD

EMCCD cameras basically come in the same varieties as regular CCD's so they share the same properties and Quantum Efficiencies. They also share the same noise issues of CCD's with one additional complication. The amplification process adds additional noise which must be taken into consideration and results in a Noise Factor greater than 1. The details of this noise is covered in a later section.

Dynamic Range of an EMCCD

The EMCCD gain also complicates the dynamic range of the camera, as shown in Figure 28:

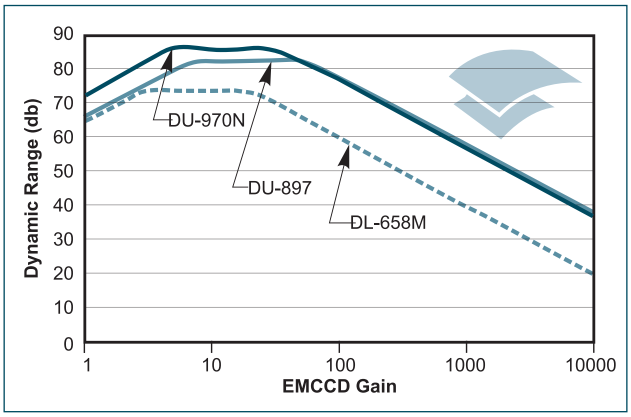


Figure 28 - Dynamic range versus EM Gain

Initially as the EM Gain is applied the dynamic range increases. The EM Gain reduces the effective read noise but the higher well capacity in the EM Gain register can accommodate the amplified signal. When the EM Gain register can no longer accommodate the amplified full well capacity of a pixel the dynamic range flattens. When the gain is sufficient to reduce the noise below single photon levels the dynamic range then falls off.

Noise Factor and Photon Counting

The exact gain a charge entering the gain register of an EMCCD sensor is impossible to know as the processes which give rise to the gain are stochastic. We can however calculate the probability distribution of output charges for a given input charge. In Figure 29 below the probability of obtaining a distinct output charge for various input charges is plotted for a typical EM register set to a gain of 500.

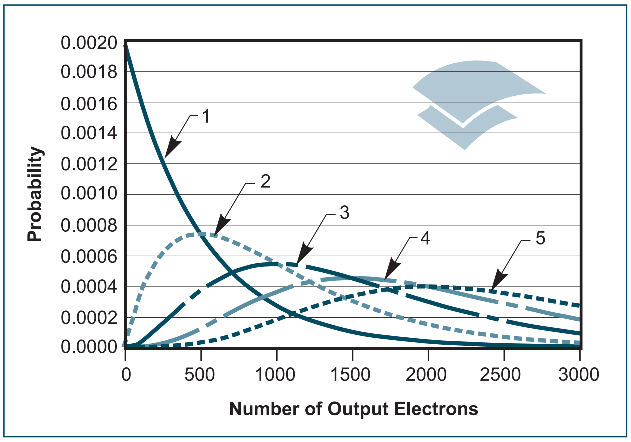


Figure 29 - Probability of a given output charge

If we measure an output signal of 1,000 electrons you can see from Figure 29 that there is a reasonable probability that this signal could have resulted from either an input signal of 1, 2, 3, 4 or even 5 electrons. At high gains (>30) this uncertainty introduces an additional noise component which is dependent on the input signal hences acts like a Noise Factor of the EM amplifier. The details of how the Noise Factor affects the signal to noise are described in a later section.

In the limit of when there is less than 1electron falling on a pixel in a single exposure the EMCCD can be used in Photon counting mode. In this mode a threshold is set above the ordinary amplifier readout and all events are counted as single photons. In this mode with a suitable high gain a high fraction of the incident photons (>90%) can be counted without being affected by the Noise factor effect.

Intensified CCD Cameras

Andor first introduced an Intensified CCD (ICCD) cameras into its range in 1995. Indeed Andor was the first company to offer a fully integrated ICCD which included a high performance delay generator, a high voltage gating unit and camera unit all built into the ICCD camera.

ICCD Structure

Intensified CCD's are also cameras which can exploit gain to overcome the read noise limit but also have the added feature of being able to achieve very fast gate times. The gating and amplification occurs in the image intensifier tube. Image intensifiers were initially developed for night vision applications by the Military but increasingly their development is been driven by scientific applications. The Image intensifier tube is an evacuated tube which comprises the Photocathode, Microchannel plate (MCP) and a Phosphor screen. The properties of these determine the performance of the device.

The photocathode is coated on the inside surface of the input window and it captures the incident image: see Figure 30. When a photon of the image strikes the photocathode, a photoelectron is emitted, which is then drawn towards the MCP by an electric field. The MCP is a thin disc (about 1mm thick) which is a honeycomb of glass channels typically 6-10 µm, each with a resistive coating. A high potential is applied across the MCP, enabling the photoelectron to accelerate down one of the channels in the disc. When the photoelectron has sufficient energy, it dislodges secondary electrons from the channel walls. These electrons in turn undergo acceleration which results in a cloud of electrons exiting the MCP. Gains in excess of 10,000 can readily be achieved. The degree of electron multiplication depends on the gain voltage applied across the MCP which can be controlled in the camera.

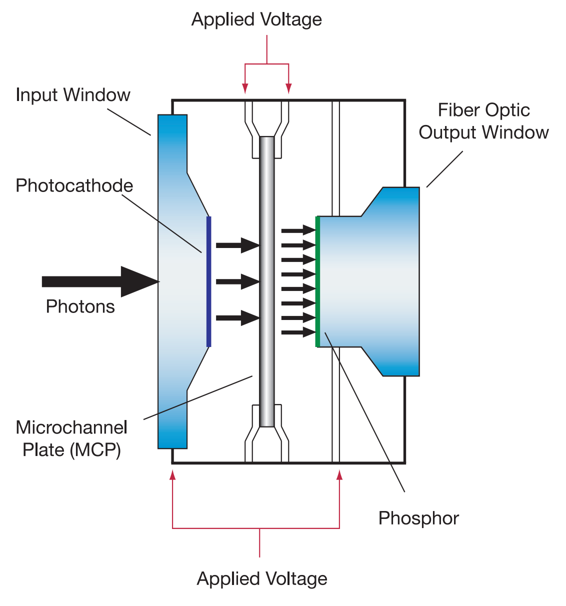


Figure 30 - Image Intensifier Structure

The output of the image intensifier is coupled to the CCD typically by a fiber optic coupler: see Figure 31. Fiber-coupled systems are physically compact with low optical distortion levels. The high efficiency fibre optic coupling means that the image intensifier can be operated at lower gains, and this in turn results in better dynamic range performance from the image intensifier (better than 15 bit). An alternative coupling method is to use a lens between the output of the image intensifier and the CCD – a 'lens-coupled ICCD'. This has the advantage of allowing the image intensifier to be removed, thus enabling the CCD to be used alone for unintensified applications. With a suitably high quality image intensifier, the lens coupled arrangement can also produce a better quality image as the fibre-to-fibre variations and blemishes are removed from the system. Disadvantages of lens coupled systems are larger physical size, lower coupling efficiencies and increased scatter.

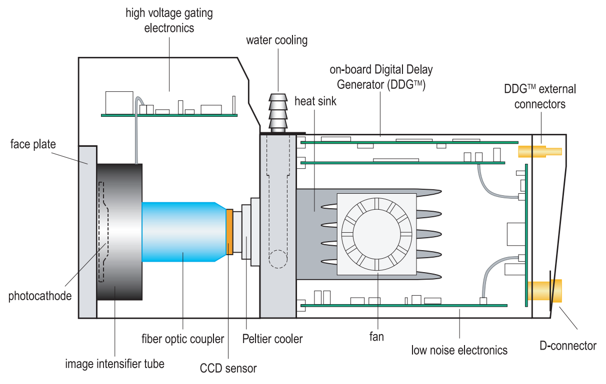


Figure 31 - Schematic of ICCD

Specialist power supplies are needed to operate the Image intensifier. To achieve fast Gating a high voltage pulser must be used which can pulse 200V pulses with sub-nanosecond rise and fall times. To set the gain of the MCP a stable voltage must be applied typically in the range of 600 to 900 volts. To achieve good sharp images the phosphor voltage must be typically 4kV - 8kV depending on the phosphor and tube type.

Spectral response of an ICCD

The spectral response of an ICCD is primarily determined by the photocathode material used in Image Intensifier. There are a number of intensifiers routinely used in the scientific applications and they have been classified in relation to the Military classifications that originally developed them. The early intensifiers were classified as Gen I intensifiers.

Gen I intensifiers used a different construction which didn't use a MCP and are no longer in regular use. Gen II intensifiers use Bi or Multi Alkali Photocathodes and include an MCP. Gen III intensifiers are now replacing Gen II intensifiers for most military purposes and use a semiconductor photocathode. Gen III filmless photocathodes are a more recent development which Andor brought to the market. Gen II and Gen III intensifiers have useful properties for scientific imaging or spectroscopy and are therefore offered by Andor. Their relative properties are highlighted below.

Gen II Intensifier Spectral response

A Gen II intensifier incorporates a Bi or Multi Alkali photocathode which are the same materials used in the photocathodes of Photomultiplier tubes. Gen II photocathodes are typically applied to a quartz window which allows the photocathode response to extend into the UV (~180nm). The quartz window can be substituted for a Magnesium Fluoride window to provide response into the VUV (~120nm). The mix and thickness of the photocathode can be 'tuned' to optimise the wavelength response in different regions. Andor offers three standard Gen II options, the 'W' intensifier which is optimized for the visible wavelength region, the 'WR' intensifier which is optimized for the near infrared region and the 'UW' option which is optimized for the Ultraviolet region.

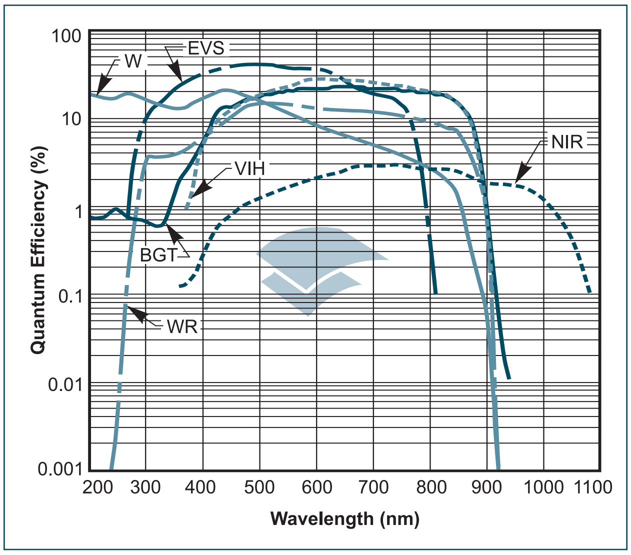


Figure 32 - Gen II Quantum Efficiencies

Gen III Filmed and Filmless Intensifier Spectral Response

A Gen III intensifier incorporates a semiconductor photocathode which is made from Gallium Arsenide (GaAs). The photocathode is only available on a glass window which limits the spectral response to wavelengths greater than the 350nm. The Gen III intensifier provides good spectral response from the visible to the near infrared.

The Gen III intensifier photocathode is prone to being poisoned by impurities in the image intensifier tube. This was particularly a problem when used in the harsh conditions needed by the Military. To protect the photocathode a thin coating of Aluminium is put down over the input to the MCP. This layer prevents impurity ions being accelerated back from the MCP damaging the photocathode and hence this lengthens the lifetime of the image intensifier. The protection layer has a drawback however as it presents a barrier to the photoelectrons emerging from the photocathode, which must be overcome. To penetrate the barrier the photoelectrons must be accelerated by a much higher electric field, typically of the order of 1000V, as opposed to the 200V required for a Gen II tube. There are two consequences of this protection layer, first it increases the Noise Factor arising from the amplification process and hence limits signal to noise ratio. Secondly the higher voltages place a bigger burden on the gating circuitry to achieve short gate times so gate times are typically 2 to 3 times slower than a Gen II intensifier.

A Gen III filmless intensifier also incorporates a semiconductor photocathode which is made from Gallium Arsenide (GaAs) but typically the photocathode material is doped to 'tune' the response to particular wavelength ranges. The photocathode is also available on wide wavelength response glass to allow more blue response. As the name suggests the filmless Gen III is really a Gen III without the MCP protection layer. With the improvement in production processes and for the scientific market lifetime Gen III lifetime is no longer an issue. Removing the protection layer eliminates the issues with higher Noise Factor and slower gating times. Andor offers two standard Gen III filmless intensifiers, one which is tuned more to cover the visible and near infrared region VIH (360-910nm) and another which is tuned to cover the visible band with more blue response HVS (270-740nm).

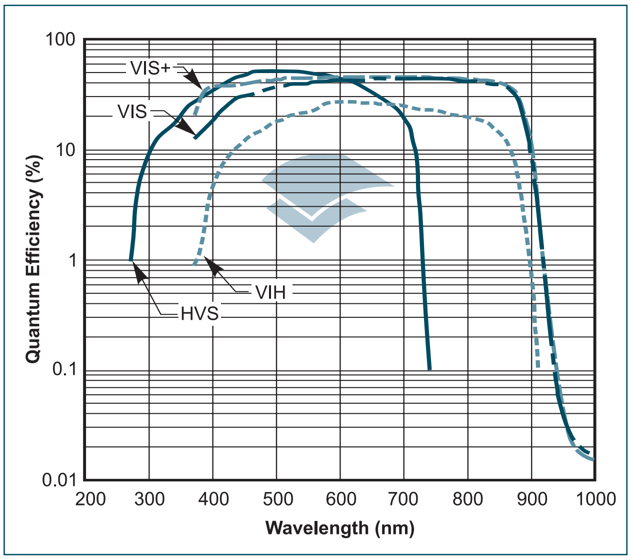


Figure 33 - Gen III Quantum Efficiencies

Noise and Sensitivity of an ICCD

The noise and hence sensitivity of the ICCD is also governed by the Image Intensifier. The image intensifier amplifies the signal so that the CCD section of the camera no longer dominates the noise of the camera. Hence an ICCD can be viewed as a camera with effectively no read noise. There is still a dark current component which originates from thermally generated charge in the photocathode and as this occurs before the amplification stage, it will also get amplified. The dark current in image intensifiers was traditionally called the Equivalent Back Ground Illumination (normally abbreviated to EBI). The dark current is generally not an issue when using short gate times. A more thorough analysis of noise and signal to noise ratio for all cameras in contained in a following section.

Gating Times

A real advantage ICCD's have over EMCCD's and CCD's is their optical shuttering properties. The Image Intensifier can be operated as a very fast optical switch, capturing an optical signal in billionths of a second.

By applying a negative voltage, typically -150V to -200V for a Gen II Intensifier, between the photocathode and MCP, photoelectrons generated in the photocathode are swept out of the photocathode, across the gap and into the MCP for amplification. The intensifier is therefore gated on. By applying a small positive voltage, typically 50V, the photoelectrons cannot cross the gap and no signal is seen. The intensifier is therefore gated off. The minimum time taken to gate the intensifier from being off to on and then off again is called the Minimum Gate time. The Minimum Gate time depends on a number of factors but principally on the structure of the Photocathode and the electronic gating circuitry.

Gen III filmless can be gated in times less than 2 nanoseconds (ns). Gen III filmed as stated before are typically longer ~5ns. Gen II photocathodes are also usually slower typically 50ns but by applying a thin metal underlay gating times of less than 2 nanoseconds are also possible. Applying the underlay will sacrifice some of the QE properties of the photocathode. Gen II and filmless Gen III intensifiers can also be gated in sub nanosecond timescales with special Gater units.

The Intensifier can be repetitively gated at rates of up to 50KHz for standard operation or up to 500KHz for specially requested cameras. Although the CCD section of the camera cannot be readout at this rate, there are advantages in operating the optical gating independently. A repetitive signal can be sampled and the output of the intensifier summed on the CCD to integrate up a larger signal that otherwise may not be visible.

Dynamic Range

The dynamic range of the ICCD is governed by the CCD section and varies with the Gain of the ICCD. A higher dynamic range CCD used in the ICCD will result in a higher dynamic range ICCD camera. See below for typical measurements.

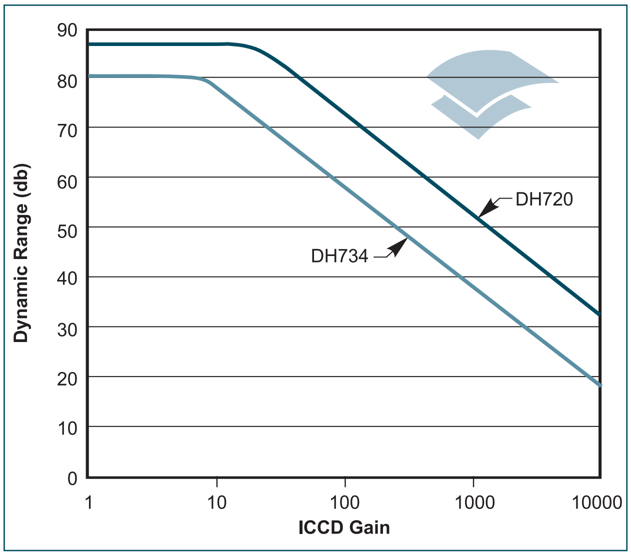


Figure 34 - ICCD Dynamic range versus Gain

On this graph you can see the dynamic range of the CCD determines the initial dynamic range of the ICCD camera. As the gain increases the smaller signals that can be accommodated is compensated by the lower read noise to keep the dynamic range constant. When the read noise drops below a single photon level the dynamic range of the ICCD starts dropping as the gain increases further.

Frame Rates

The frame rates of an ICCD are governed by the CCD specifications, especially the number of pixels and pixel readout rate. See the table below:

ICCD Frame Rates

Camera	Frame Rate Standard	Frame Rate Maximum	Comments
DH720	166.0	950	Spectral Mode
DH734	1.0	200	Imaging Mode

One point of note here is that you have to be careful on the choice of phosphor used for high frame operation. The standard phosphor on an Image Intensifier used for ICCD's is called a P43 type. This phosphor emits in the green which is optimal to be detected by a CCD. However the phosphor is relatively long lived. If electrons hit the phosphor in an instant light emisson occurs from the phosphor for a considerable time afterwards. The light emisson decays in a non-exponential manner so after 2ms it decays to 10% of its initial level and after 20ms it decays to less than 1.0%. If we are using a high frame rate operation which is reading out 50 frames/second 1% of the signal from the first frame will appear in the second and so on. To remove this time integration effect it is better to use a fast phosphor. Andor recommends a P46 phosphor for this operation. A P46 phosphor has a lifetime of 200ns for the light level to decay to 10% of its value and 2µs to decay to 1.0% of its initial level and hence will reduce the overlapping effect in fast frame readout. The light emission of the P46 phosphor is not as well optimized to the CCD readout but this can be overcome by using a higher gain on the Image intensifier.

Noise Factor & Photon Counting

As with the case of an EMCCD it is impossible to know the exact gain a charge entering the MCP of an ICCD will receive as the processes which give rise to the gain are stochastic. The uncertainty of the gain process gives rise to a noise component which scales with input signal a Noise factor. The Noise Factor of a Gen II or filmless Gen III intensifier typically ranges from 1.6 to 2.2 and 3.5 to 4.2 for a filmed Gen III intensifier.

In the limit of when there is less than 1electron falling on a pixel in a single exposure the ICCD can also be used in Photon counting mode. In this mode a threshold is set above the ordinary amplifier readout and all events are counted as single photons. In this mode with a suitable high gain a high fraction of the incident photons (>90%) can be counted without being affected by the Noise factor effect.

Resolution

ICCD cameras have lower resolution than CCD cameras the main reason is again the Image Intensifier. See Figure 35 below. In the image intensifier the MCP and phosphor both make a major contribution to degrading the MTF that a bare CCD would have. Recent developments in finer phosphor deposition, reducing gaps and reducing the bore of the Microchannel plates has resulted in much better performance but typically resolution is limited to less than 60 line pairs/mm.

See Andor's range of ICCD cameras in the Andor iStar product section.

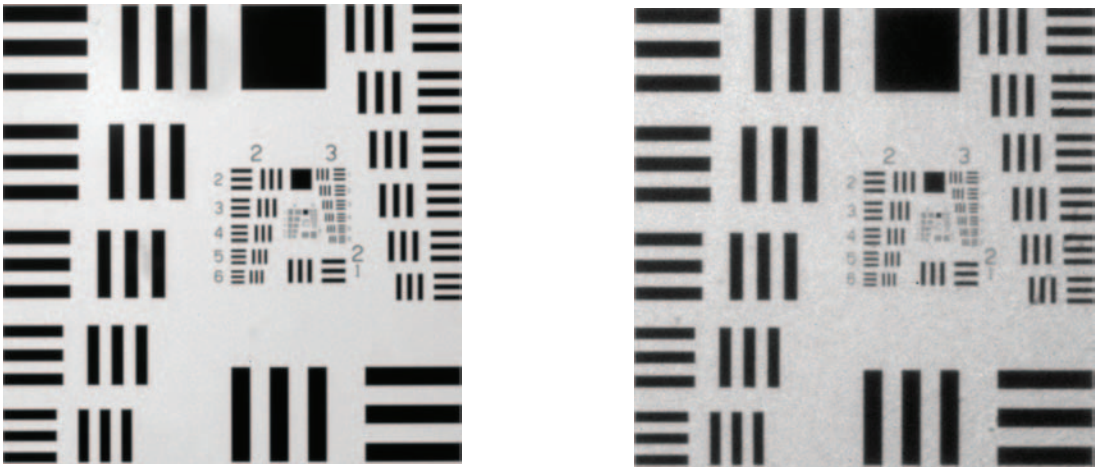


Figure 35 - Images of a US airforce resolution chart using a CCD on the left versus an ICCD camera on the right

CCD, EMCCD and ICCD Camera Comparisons

In order to make a more detailed comparison between CCD, EMCCD and ICCD cameras we need expand the analysis of the signal to noise equation covered in an earlier section to include more effects.

The two primary effects to be included are:

- Spurious noise (also called Clock Induced Charge)
- Noise Factor (also called Amplification noise)

The first additional component is the Spurious Noise or Clock Induced Charge which originates from within the CCD camera. When charge is shifted pixel to pixel towards the output amplifier there is a very small but finite probability that charges can knock off additional charges by a process called impact ionization. These unwanted charges have the effect of generating an additional noise component. The effect is present in all CCD's but in a good camera design the effect is usually minimized and can then only be seen in exceptional circumstances, for example when binning a very large number of pixels. In a CCD or an ICCD the noise component is so low it typically is hidden by the readout noise or dark current components. In an EMCCD however, spurious charges that occur in the image section are amplified by the EMCCD gain register and therefore are very detectable. Incidentally the EMCCD gain register works by effectively harnessing the same effect of impact ionization that creates the spurious charges. The Spurious Noise can be represented by a charge component that occurs every camera readout cycle.

$$\delta \mathrm{cic}$$

The second noise component originates from the amplification process and is represented by the Noise factor. In any amplification process when a signal is amplified, the input noise is also amplified. However the amplification can add additional noise and this noise must be taken into consideration. The noise is typically represented by a factor called the Noise Factor which represents the additional noise over the noise expected from the amplification process. If our camera amplifies our signal by a gain of M we can define our Noise Factor (F) by the following expression;

$$F^2 = \frac{\delta^2_{out}}{M^2\,\delta^2_{input}}$$

The noise factor equals the ratio of the Output Noise of the amplifier over the Gain M and input noise factor of 1. An ideal amplifier would therefore have a noise factor of 1

If we now consider our equation for the Signal to noise, with P photons falling on a pixel in our camera with a quantum efficiency DQE and a Gain M. The signal output from our camera is electrons would be:

$$S = M \bullet D_{QE} \bullet P$$

The total camera noise is the sum in quadrature of the various noise sources, i.e. the square root of the sum of the noises squared. Therefore the total Noise is as follows;

$$\mathrm{Noise} = \delta_{total} = \sqrt{\delta^2_{readout} + F^2 \cdot M^2 \cdot (\delta^2_{dark} + \delta^2_{signal} + \delta^2_{cic})}$$

Note the Dark current noise, the Light Signal noise and Clock Induced Charge noise are all amplified and hence their noise is amplified by the Gain M and we also have to take into consideration the additional amplifier noise by multiplying by the Noise Factor F. You can see this equation originates from a rearrangement of the equation for Noise factor above.

Substituting for Photon noise, the resulting equation for Signal to noise is as follows;

$$\frac{S}{N} = \frac{M \cdot D_{QE} \cdot P}{\sqrt{F^2 \cdot M^2 (D_{QE} \cdot P + \delta^2_{dark} + \delta^2_{cic}) + \delta^2_{readout}}}$$

This can be more readily appreciated by dividing the equation throughout by M.

$$\frac{S}{N} = \frac{D_{QE} \cdot P}{\sqrt{F^2 \cdot (D_{QE} \cdot P + \delta^2_{dark} + \delta^2_{cic}) + \frac{\delta^2_{readout}}{M^2}}}$$

If we examine the theoretical signal to noise ratios for various cameras using this equation we can appreciate the comparisons between the cameras. The parameters we have used are as follows;

	Ideal	CCD	EMCCD	ICCD
Quantum Efficiency (DQE)	100%	93%	93%	50%
Readout Noise	0	10	60	20
Gain	1	1	1,000	1,000
Spurious Noise	0	0.05	0.05	0
Dark noise	0	0.001	0.001	0.001
Noise Factor	1	1	1.41	1.6

Note the Noise Factor for an EMCCD is 1.41 which is exactly the theoretical predictions of an ideal gain register with a stochastic gain process as used in the EMCCD. The Noise factor for a Filmless Gen III ICCD has been measured as 1.6 which is better than their filmed counterparts who have a Noise factor of 3.52.

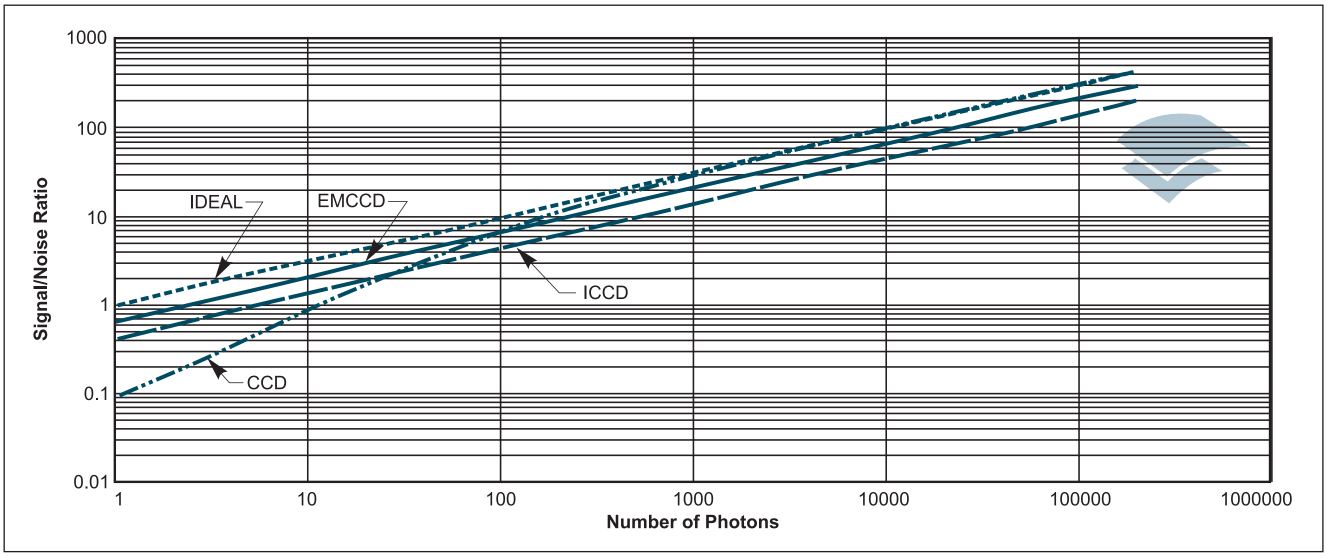


Figure 36 - Signal//Noise ratio comparison for CCD, EMCCD and ICCD

The results are displayed in Figure 36. As you can see in the limit of low photon signals and low signal to noise ratios the gain of the EMCCD and the ICCD have the higher sensitivity and can achieve detection (S/N>1) at light levels less than 10 photons per pixel. As the readout of the EMCCD and ICCD can also be significantly faster this means that a signal can be detected up to 10-100 times faster with an EMCCD or an ICCD than a slow scan CCD. In integrating mode the EMCCD out performs the ICCD with the higher quantum efficiency and the lower Noise factor. At higher signal to noise ratios and with more photons of light the CCD starts to outperform the EMCCD and ICCD. The near perfect noise factor of 1 and with the ultimate in quantum efficiency the CCD starts to rapidly approach the performance of the ideal detector. The EMCCD can of course be switch into a regular CCD by lowering the Gain to unity and reading out slowly to achieve the similar performance.

In the limit of very low signals where there is less than 1 photon per pixel per readout the EMCCD and ICCD can be used in the photon counting mode unlike the CCD. The higher quantum efficiency usually enables the EMCCD to outperform the ICCD but in some circumstances the ICCD can outperform the EMCCD if the ICCD intensifier has lower EBI than the Clock induced charge noise of an un-optimized EMCCD.

In the limit of very low signals you can see the CCD's S/N suffers due to the fixed Readout noise component and this continues until the photon flux level is greater than the readout noise squared. The EMCCD and ICCD work well for low light levels as the Gain effectively removes all the read out noise component of the noise.

Gain Aging Effects

A note of caution the gain components in an ICCD and an EMCCD i.e. the MCP and the EM register suffer from gain aging effects. For a given applied voltage to the gain components you would expect the gain to remain constant. However the gain components suffer from parasitic effects which lower their gain as a function of the total charge extracted from them. Therefore if you measure the gain over a period of time at a fixed voltage and temperature the gain will fall off and the fall off will be more pronounced the more extracted charge that passes though the gain component. The gain is not lost however and a certain gain can be recovered by simply increasing the voltage in the gain component to compensate for the aging effect. Ultimately the gain components can be damaged by excessive voltage so they do have an ultimate lifetime. To minimize the effects of gain aging it is desirable not to have the gain turned up when the device is not recording signal and to use the gain sparingly i.e. set the gain to give you sufficient sensitivity and not to use the gain at the maximum level needlessly. Please refer to the more detailed notes in your manual on gain aging effects.

Intensified CCD's also suffer from an additional aging effect due to the poisoning of the photocathode. The photocathode gets damaged by contaminates in the image intensifier tube and this damage is accelerated when the tube is gated on. Improving production techniques has reduced the level of contaminates and hence increased the tube lifetime. The damage is not recoverable so again it is good practice to keep the gain turned down when it is not required and minimise the light falling on the photocathode.

System considerations

In selecting a digital camera there are other parameters that should be assessed to ensure the camera can offer the best possible performance in the widest range of applications. These include:

- Sensor readout optimization options
- Cooling options
- Synchronization signals
- Computer interfacing options

Sensor readout Optimization

To allow the camera to be optimized for the widest range of applications it is important to have options for the camera readout and these include:

- Sensor Preamp options
- Variable pixel speed options
- Variable vertical shift speed options
- Binning and sub image options

These options and the reason for their selection are explained in the following sections.

Sensor Preamp options

A CCD sensor can have a much larger dynamic range than can be faithfully reproduced with the current A/D converters and signal processing circuitry currently available in digital cameras. To access the range of signals from the smallest to the largest and to optimize the camera performance it is necessary to allow different pre-amplifier gains. Let's take the example of one sensor and it various options to appreciate the issues and see how using different pre-amp gains allows us to make the best choices.

If we consider the DU920N-BV spectroscopy camera the sensor has a readout noise <4e^-. A single pixel has a full well capacity of 500Ke^- and if we bin the sensor it has an effective full well capacity of 1,000Ke^-. The single pixel dynamic range is 125,000 to 1 and the binned dynamic range is 250,000 to 1. A camera with a 16bit analog to digital converter (ADC) has only 65536 different levels so we are immediately in a dilemma. The ADC cannot cover the full dynamic range of the CCD. If we set the gain of the pre-amplifier of the camera to be 4e^- then noise will be approximately 1 count but the ADC will saturate at ~262Ke^-. If we set the gain of the pre amplifier of the camera to be ~16e^- then ADC will then saturate at ~1,000Ke^- but now the lowest level of signals will be lost within a single ADC count.

The limited range of the ADC effectively creates a new noise source. The ADC produces discrete output levels and a range of analog inputs can produce the same output. If we consider the quantization noise that arises from the imperfect transformation of analog signals to a digital signals by the ADC the uncertainty of error produces an effective noise given by:

$$\delta_{ADC} = \frac{N_{well}}{2^n\sqrt{12}}$$

Where N_{well} is the effective full well capacity of a pixel in electrons and n is the number of bits of the ADC. If we add this noise in quadrature with the noise floor of 4e^- we can see this limits the dynamic range of the system.

You can immediately see that unless the gain of the preamp is set sufficiently high the noise from the ADC significantly increases the overall system noise. To achieve the highest sensitivity or lowest noise it is important to have a preamplifier setting which allows the ADC noise to be negligible. This can be achieved by setting a gain where the read noise is much less than 1 count of the A/D (half in the case above). The next logical point to set the gain is optimize the ADC to match the full well of a single pixel i.e. the highest count level equates to the full well depth. The third logical setting of the preamplifier gain is to match the highest ADC count to the full well depth of the readout register (typically 2 times the single pixel depth). This level allows the highest signal to noise ratio.

Pre-amplifier Gain Settings

Gain	Saturation	ADC Noise	Total Noise	Comments
2e^-/ADC	~130,000	0.6	4.0	Highest sensitivity
8e^-/ADC	~524,000	2.3	4.6	Best S/N ratio for single pixel
16e^-/ADC	~1,000,000	4.4	5.9	Best S/N ratio for binned pixels

Variable Horizontal Readout Rate options

The Horizontal Readout Rate defines the rate at which pixels are read from the shift register. The faster the Horizontal Readout Rate the higher the frame rate that can be achieved. The ability to change the pixel readout speed is important to achieve the maximum flexibility of camera operation. Slower readout typically allows lower read noise but at the expense of slower frame rates. Depending on the camera there may be several possible readout rates available.

Variable Vertical shift options

The Vertical shift speed is the time taken to shift a vertical row on the CCD. The ability to vary the vertical shift speed is important for several reasons. It is possible using the different vertical speeds to better synchronise the frame rates to external events such as a confocal spinning disc. Faster vertical shift speeds also have benefits in lower clock induced charge especially for EMCCD's. A drawback with faster vertical shift speeds is that the charge transfer efficiency is reduced. This is particularly important for bright signals as a pixel with a large signal is likely to leave a significant charge behind which results in degraded spatial resolution.

You may select a Vertical Shift Speed (the speed with which charge is moved down the CCD-chip prior to readout) from a drop-down list box on the CCD Setup Acquisition dialog Box. The speed is actually given as the time in microseconds taken to vertically shift one line, i.e. shorter times = higher speed.

Slower vertical clocks ensure better change transfer efficiency but results in a slower maximum frame rate and possibility higher well depth. To improve the transfer efficiency the clocking voltage can be increased using the Vertical Clock Voltage Amplitude setting. However, the higher the voltage, the higher the clock-induced charge. The user must make a measured judgement as to which setting work best for their situation. At vertical clocks of 4us or longer the "Normal" voltage setting should be suitable.

Binning and sub image options

Increasing the frame rates can only be achieved by effectively reducing the total number of pixels to be read out. There are two principal ways of achieving higher frame rates, either by binning or by sub image or cropped mode readout.

Binning is the process whereby charge from a group of pixels can be summed together. In addition to achieving faster frame rates this increases the signal to noise ratio but it also degrades the image resolution as the summed pixel act as one large super pixel. Adding pixels together before reading them out reduces the numbers of pixels.

Sub image or cropped mode is the process whereby a portion of the active image is readout out or cropped and the surrounding extraneous image is discarded. The sub image region can be any smaller rectangular region of the sensor and the smaller the sub region the less pixels to be readout and consequently the faster the frame rates.

It is possible to also combine the techniques of using a sub region and binning them to achieve even faster frame rates. Another way to achieve ultra fast frame rates is to use a special form of crop mode called Isolated crop mode to further speed up the frame rates in special circumstances. If only the bottom left corner of the sensor is illuminated the rest of the sensor can be ignored and the as the sub image closest to the readout register is readout the camera does not need to discard the rest of the image prior to reading out the sub image again. This saves time and speeds the cropped mode up even faster.

Cooling Options

Cooling the sensor reduces noise and this is very important for high sensitivity measurements. The camera performance improves with reducing temperature not just due to lower dark current but also due to reduced effects from blemishes. Cooling the sensor much lower than –100ºC is of limited benefit and below –120ºC many sensors no longer operate.

Cooing can be achieved by either using proprietary thermoelectric coolers or Joule Thompson Coolers such as the Cyrotiger. Historically cooling of sensors has been accomplished with liquid nitrogen (LN2). The use of LN2 as a coolant is, at best, inconvenient. Maintenance, operating cost, availability at remote locations, and the hazardous nature of the material all combine to limit the practicality of a LN2-cooled device.

The ability to operate the cooling at different temperatures is useful. At times when the highest sensitivity is required setting the temperature to the lowest possible is best. To operate the sensor for the best long term stability and lowest drift setting the temperature should be set at approximately three quarters of the lowest temperature possible. To operate the sensor at the most efficient power setting the sensor should be set to approximately half the minimum temperature.

To cool the sensor it must be operated in a vacuum. To efficiently cool it, the sensor should be the coldest component in the camera, unfortunately that means if the sensor is not in a very good vacuum the sensor now becomes the surface of choice for condensates such as moisture and hydrocarbons. Condensates degrade the sensor and damage its performance, particularly its quantum efficiency. Andor has developed its proprietary UltraVac™ enclosure to ensure the highest vacuum possible and one that remains for a minimum of 5 years guaranteed.

Our cameras are produced in our production facility in Belfast which boasts a Class 10,000 clean room, which is essential for building high quality, permanent vacuum systems - this means fewer than 10,000 particles of less than 0.5µm dimension per cubic meter.

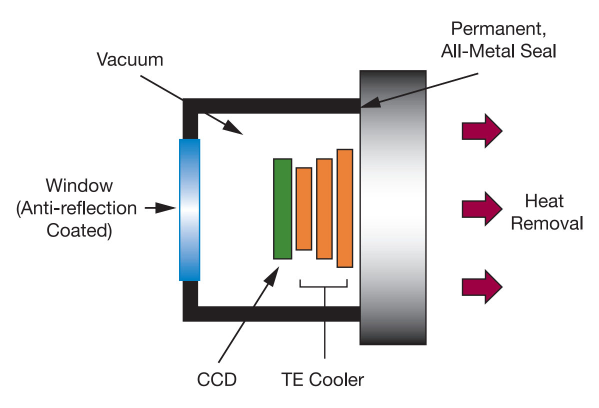


Figure 37 UltraVac metal hermetic vacuum sealing

Andor's innovative vacuum seal design means that only one window is required in front of the sensor enabling maximum photon throughput. This design is suited to high-end CCD cameras for operation in photon-starved conditions. An anti-reflection coating is also an option to further enhance performance and a MgF2 window is available for operation down to 120nm.

We all know that it is more complicated than that. Pixel size needs to be taken into consideration, reduced dark current is the true goal, and even that will differ for sensors and manufacturers, however it is worth looking at different cooling options so that we can best configure our system solution.

In cooling the sensor it should be appreciated that the TE cooler removes heat from the sensor and now this heat energy must be removed from the camera to allow the camera to retain the sensor at the appropriate temperature. This can be achieved by either using air or water to remove the excess heat from the camera.

Using air is a good and effective method of removing heat from your CCD.

Positive points of Air cooling:

- Convenient - not reliant on any extra power or equipment
- None of the problems or dangers associated with liquid nitrogen
- None of the problems concerning the use of cooling water below the ambient dew point

Negative points of Air Cooling:

- Detector design becomes large and bulky
- Power requirements will be greatly increased
- Vibrations from the fan could compromise measurements

Water is also a good and effective way to remove excess heat. The water acts as a medium to remove the heat from inside the camera head and the excess heat can then subsequently be transferred to air cooling. Water can come from any source of clean water such as the tap or from a water circulator.

Positive points of using a water circulator

- This is a compact and effective cooling aid.
- Once the water has been added to a circulator – no mains water supply is required making the unit very portable.
- Condensation is not usually an issue.

Negative points of using a water circulator:

- Addition of another piece of equipment to the system set-up

Water can also come from a water chiller. Water chillers can be used in a wider range of temperatures to achieve the best possible cooling performance. The chiller sets a reliable body temperature of the camera which reduces drift An issue to be aware of however is that the temperature of the cooling water must not be below the dew point of the ambient atmosphere. For example, in a room at 25°C with 40% humidity the dew point is 8.5°C so cooling with 10°C water is fine. If you used water below 8.5°C then moisture will start to condense onto the electronics in the head and this can lead to serious damage.

Synchronization Options

It is often necessary to coordinate the reading of a camera with external hardware. Examples of external hardware are Acoustic Optical switched laser source or be as simple as mechanical shutter. Andor cameras have several mechanisms to allow this to happen.

First the camera can be internally triggered i.e. the cameras acts as the master and sends out signals to allow other hardware be aware it is taking a scan. When running the camera sends a TTL pulse out on the 'FIRE' signal connector.

The Camera can be operated as a slave device and be externally triggered. In this case the camera waits for a TTL signal on the EXT TRIG connector before taking an exposure.

Computer Interface Options

Cameras or for that matter PCs by themselves aren't especially useful. The value comes from being able to connect them and then using their respective properties to do so much more. Cameras can capture the images and the PC's can convert these images into real information, both for qualitative and quantitative analysis. We will review here the various interfaces that can be used to connect a camera to a PC.

- PCI
- USB
- Firewire 1394
- Ethernet

USB 2.0

The original version of the Universal Serial Bus, known as USB 1.1, started appearing about in 2000. USB ports are now universal on new Windows and Macintosh computers. USB 1.1 moves data back and forth as fast as 12 megabits per second (Mbps). That's more than enough for many devices, but some such as scanners, camcorders, external hard drives and external CD drives benefit greatly from more speed. So an industry group called the USB Implementers Forum defined the USB 2 .0 as a second-generation standard. USB 2 .0 is 40 times faster than its predecessor and is capable of moving data at a 480 Mbps.

FireWire 1394

The Firewire interface was developed by Apple Computers in the mid 1990's and was adopted by the an independent trade association called the 1394 Trade Association after the IEEE 1394 computer interface standard. The other major backer is Sony, using the i.Link name. Firewire can be operated as a synchronous device which allows high speed bandwidth for short periods of time. Recently introduced with 1394, data can now be transferred as fast as 800 Mbps, faster than USB 2 .0 Apple and Sony put 1394 ports on all their computers; a few other manufacturers, notably Compaq, put 1394 on a few high-end models but the interface is not used as widely as USB 2 . 0.

PCI Interface

The PCI (Peripheral Component Interconnect) bus was first introduced by Intel in 1991 to replace the ISA/EISA bus. The bus is not hot pluggable and involves opening the computer to obtain access to the slots.. It was later taken over by the PCI Special Interest Group (PCI-SIG) who revised the protocol in 1993. The bus offers a total available bandwidth of 1Gigabit/s but this is shared between slots which mean that high demand devices can quickly saturate the bandwidth. In 1997 this problem was partially alleviated by implementation of a separate AGP slot (Accelerated Graphics Port) with dedicated bandwidth. Other steps were also taken at the chip level along with integrated components, which helped to extend PCI's viability. However, with the advent of SATA, RAID, Gigabyte Ethernet and other high-demand devices, a new architecture is required. The PCI bus is expected to be phased out in 2006 to make way for the PCI Express bus.

PCI Express Interface

PCI Express (PCIe)is a scalable I/O (Input/Output) serial bus technology set to replace parallel PCI bus which came standard on motherboards manufactured from the late 90's. In the latter part of 2005 PCI Express slots began appearing alongside standard slots, starting a gradual transition.

PCI Express has several advantages, not only to the user but to manufacturers. It can be implemented as a unifying I/O structure for desktops, mobiles, servers and workstations, and it's cheaper than PCI or AGP to implement at the board level. This keeps costs low for the consumer. It is also designed to be compatible with existing Operating Systems and PCI device drivers.

PCI Express is a point-to-point connection, meaning it does not share bandwidth but communicates directly with devices via a switch that directs data flow. It also allows for hot swapping or hot plugging and consumes less power than PCI.

The initial rollout of PCI-Express provides three consumer flavors: x1, x2, and x16. The number represents the number of lanes: x1 has 1 lane; x2 has 2 lanes, and so on. Each lane is bi-directional and consists of 4 pins. Lanes have a delivery transfer rate of 2 GBs in each direction for a total of 500 GBs, per lane.

PCIe Bandwidth

PCIe	Lanes	Pins	MB/ps	Purpose
x1	1	4	4 GBs	Device
x2	2	8	8 GBs	Device
x16	16	64	64 GBs	Graphics Card

The 16-lane (x16) slot replaces the AGP for PCIe graphics cards, while the x1 and x2 slots will be used for devices. As graphic demands increase, x32 and x64 slots will be realized, and future versions of PCIe are expected to drastically increase lane data rates.

PCI-X

PCI Express is not to be confused with PCI-X, used in the server market. PCI-X improves on standard PCI bus to deliver a maximum bandwidth of 1GBs. PCIe has been developed for the server market as well, initially with the x4, x8 and x12 formats reserved. This far exceeds PCI-X capability.

Ethernet

Ethernet was originally developed by Xerox Corporation to connect computers to printers. Ethernet uses a bus or star topology to connect computers and peripherals and supports data transfer rates of 10 MBs. The Ethernet specification served as the basis for the IEEE 802.3 standard, which specifies the physical and lower software layers. It is one of the most widely implemented LAN standards. A newer version of Ethernet, called 100Base-T, supports data transfer rates of 100 Mbps and the latest version, Gigabit Ethernet supports data rates of 1 gigabit (1,000 megabits) per second.