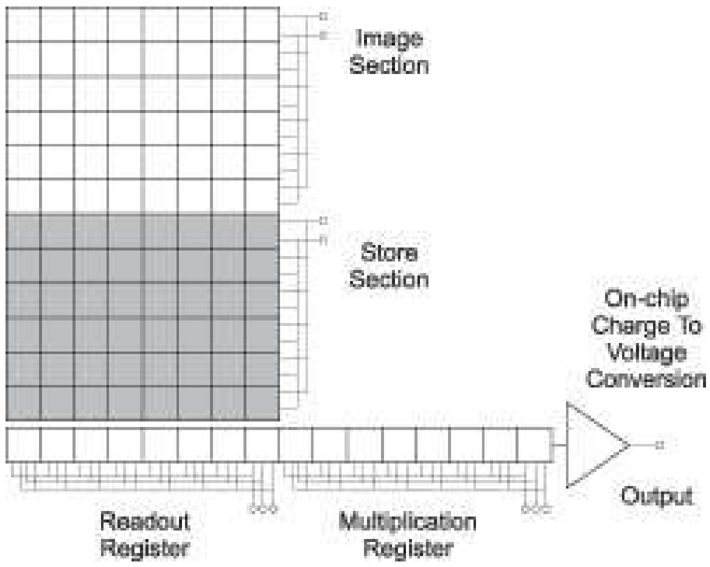
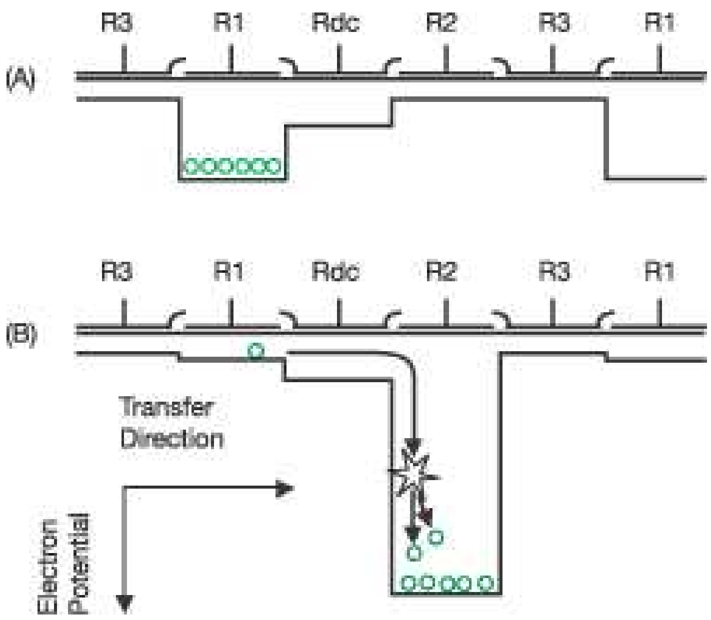
Electron Multiplying CCD Cameras

The technology behind EMCCDs

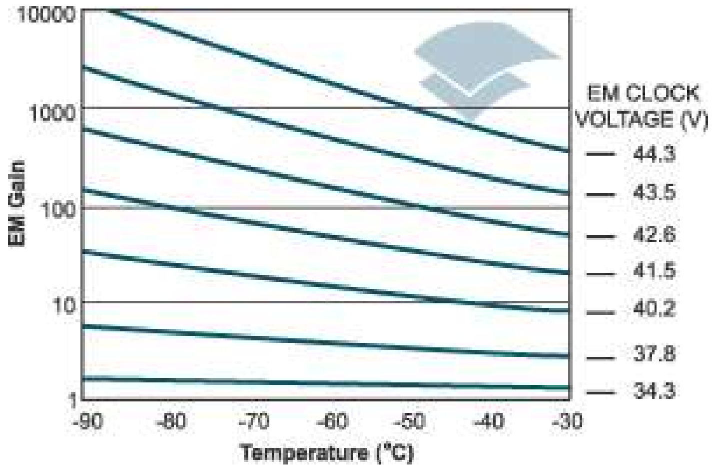


EMCCD technology, sometimes known as 'on-chip multiplication', is an innovation first introduced to the digital scientific imaging community by Andor Technology in 2001, with the launch of our dedicated, high-end iXon EMCCD Camera platform of ultra-sensitive cameras. Essentially, the EMCCD is an image 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 principle 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.



Most EMCCDs utilise a Frame Transfer CCD structure shown in the diagram to the right. Frame Transfer CCDs feature two areas – the sensor area which captures the image and the storage area, where the image is stored prior to read out. 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.

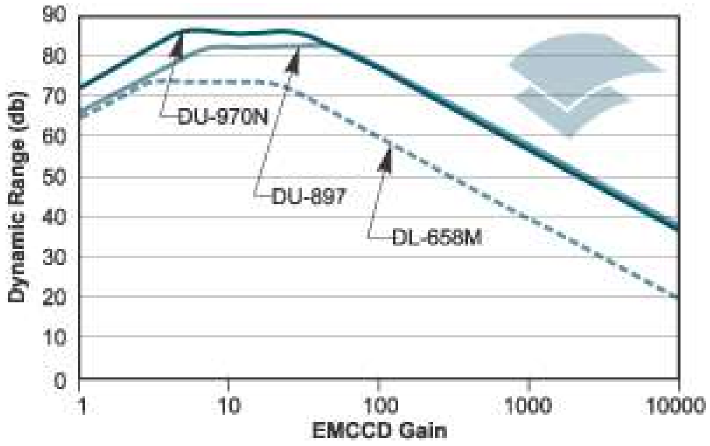


The amplification occurs in the multiplication register through the scheme highlighted in the second diagram on the right. The multiplication register contains many hundreds of cells and the amplification process occurs in each cell by harnessing a process which occurs naturally in CCD's known as Clock-Induced 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.

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.

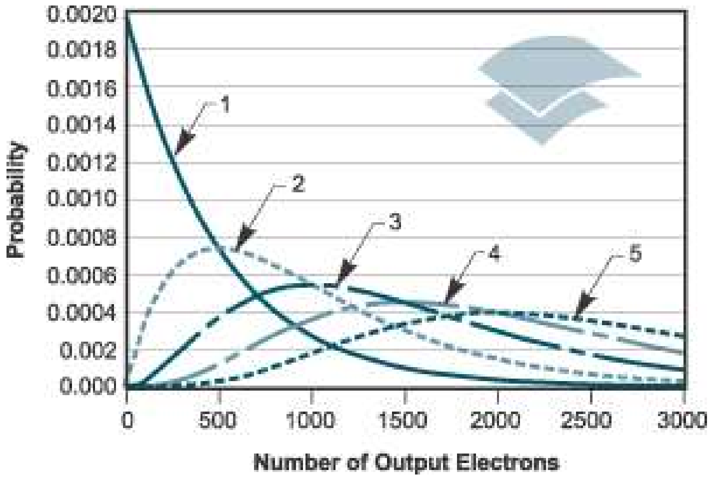
The EMCCD gain also complicates the dynamic range of the camera, as shown here.

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.



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 5 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

If we measure an output signal of 1,000 electrons you can see from the diagram opposite 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 and hence 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.