Electron Multiplying Charge-Coupled Devices

The Electron Multiplying Charge-Coupled Device (EMCCD) was introduced by Andor Technology Plc. in 2000. As a new solution to low light imaging needs, the EMCCD quickly found its way into many applications spanning all disciplines of science and engineering.

Introduction:

The EMCCD is a modified Charge-Coupled Device (CCD). CCDs were invented at Bell Laboratories in 1969 as a method of semiconductor memory. By allowing a charge to move across the surface of a semiconductor, a CCD will serially pass pixel information to its output channel. The charge generated by each pixel is proportional to the amount of light absorbed by the pixel.
Several parameters of a CCD are measured to report the performance of the CCD. Each is used to characterize the CCD and allows the engineer or scientist to decide which CCD is most applicable to their particular need.

There are several challenges met with low light imaging. First, the random noise primarily caused by thermal energy in a sensor (called dark current) limits the sensitivity of the sensor. Another source of noise is called “read noise”. Read noise is generated by the movement of charges across the semiconductor. Dark current and
read noise forms what is called a “noise floor”, where a low-intensity input signal can be lost in the inherent noise. Several modifications to CCD imagery have been developed to reduce signal loss in low light imaging, each technology having a unique solution to the challenges.

**EMCCD Technology:**

Electron Multiplication of the CCD image is performed directly on the CCD chip itself. Rather than using an image-intensifier (like Intensified CCDs), this allows the EMCCD package to be smaller and more compact than other low-light imaging solutions.

The portion of the chip that performs electron multiplication is called the High Voltage Electron Multiplying Register. A CCD will absorb photons (light) from the scene it is regarding and convert the photon energy into free electrons. The CCD carries charge from one pixel to the next by passing electrons from the originating pixel through the device to the output amplifier. Since the more electrons in a pixel represent a higher intensity output at that particular pixel on an output monitor, increasing the number of electrons will result in amplifying the original scene.
Increasing the number of electrons is done using a concept called Impact Ionization. Here, by increasing the voltage used to transfer a charge from one pixel to the next, electrons have enough energy to “collide” with electrons in the material – freeing more electrons.

The voltage required to move electrons from one pixel to the next is roughly 40-60V, so the voltage required to generate electron multiplication must be significantly higher. (Specific voltages were not published, possibly because of proprietary reasons) The impact ionization is the heart of the electron multiplying portion of the EMCCD, it is important to note that its effect is probabilistic. The probability ($P$) of getting $n$ output electrons from $m$ input electrons given a mean register gain of $g$ can be described as:

$$P(n) = \frac{(n - m + 1)^{m-1}}{(m - 1)! \left( g - 1 + \frac{1}{m} \right)^m} \exp \left( - \frac{n - m + 1}{g - 1 + \frac{1}{m}} \right) \text{ if } n \geq m$$
For each pixel shift in the electron multiplying register, there is only a 1.5% to 2% probability that one electron will generate a second electron. However, there are over 500 shifts in the register, resulting in a gain of: $g = (1 + P)^R$, where $g$ is the gain, $P$ is the probability of multiplication and $R$ is the number of shifts in the register. Assuming a 2% probability, one electron can generate almost 20,000 electrons after 500 shifts.

**Advantages and Disadvantages:**

There are many advantages to the EMCCD over its competing technologies. First, its smaller packaging requirements make it a clear option over ICCDs that require an intensifier be placed in front of the CCD. There is a quantum-efficiency benefit as well, since there are less optics between the scene and the sensor. The EMCCD has more flexibility, as the High Voltage Electron Multiplying Shift Register can be turned off through software – resulting in normal CCD operation. Finally, according to Andor, the EMCCD technology is cheaper than the ICCD.

There is no restriction to monochrome imaging, as with ICCD technology (the intensifier removes color information), assuming that
sufficient pixel resolution and filters can be put in place. However, it is important to note that color filters would significantly reduce the quantum efficiency of the device, and most likely would not be preferred in low-light applications.

There are two major disadvantages to EMCCD technology. First, it is not possible to quickly gate the device, limiting its high speed resolution. ICCD technology is able to gate in picosecond ranges, while EMCCD technology is only as fast as microsecond gating. The other disadvantage is Multiplying noise. Since the multiplication is probabilistic, there cannot be an exact gain measurement that is uniform for each pixel. This noise is reduced by assuming either a pixel has – or does not have an electron. (During extreme low-light situations where single photon sensitivity is needed) In this case, amplification only happens to the pixels that have a charge, and not to pixels containing no charge.

Which is Better EMCCD or ICCD?

The preference of the EMCCD over the ICCD is one of application. The EMCCD is certainly a better choice for quantum efficiency (better than 90% at 570nm) over the ICCD. The ICCD’s
faster gating time allows its application towards high-speed low-light imaging. The EMCCD is cheaper and has a longer life-span when compared to the ICCD.

It is interesting to note that the developers of EMCCD technology, Andor, have manufactured ICCD technology for years. They continue to develop and market both technologies. One would clearly expect a superior technology to replace another, so the assumption must be made that the two competing technologies lack a clear advantage over each other.
Bibliography


“Electron Multiplying Charge Coupled Device”
<http://www.emccd.com>