Electron Multiplying CCD Technology: The new ICCD

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ABSTRACT

A novel CCD has been commercially produced by Marconi Applied Technology, UK under the trade name of L3Vision, and by Texas Instruments, USA under the trade name Impactron, both of which incorporate an all solid-state electron multiplying structure based on the Impact Ionisation phenomenon in silicon. This technology combines the single photon detection sensitivity of ICCDs with the inherent advantages of CCDs. Here we compare the electron multiplying CCD (EMCCD) with scientific ICCDs. In particular we look at the effect of the Excess Noise Factors on the respective S/N performances. We compare QEs, spatial resolution, darksignal, EBI and Clock Induced Charge (CIC), with the latter two as the ultimate limitations on sensitivity. We conclude that the electron multiplying CCD is a credible alternative to ICCDs in all non-gated applications.

Keywords: Electron Multiplying CCD, L3Vision, Impactron, Impact Ionisation, EMCCD, ICCD, Low Light Level.

1. INTRODUCTION

Marconi Applied Technology (UK) has developed a new CCD architecture[1] that unites the sensitivity of an ICCD, or an EB-CCD, with the inherent advantages of a CCD. This technology is sold under the trade name L3Vision, and is covered by a patent (EP 0 866 501 A1). Presently three CCD formats are commercially available under the part numbers CCD60, CCD65, and CCD87 with more formats, including back illuminated versions, due in the near future. Similar technology and relevant patents (US 4912536 Mar. 27, 1990 and 5337340 Aug. 9, 1994) have also been developed by Texas Instruments, TX under the trade name Impactron[2], but devices arrived too late to be included in this present study (results will be published in a future paper). Consequently, the results presented here are based on the Marconi CCD65 and CCD67 devices incorporated into the Andor Technology iXon range of scientific cameras, sold under the trade name EMCCD (Electron Multiplying CCD).

The principle of operation of the all solid state electron multiplying CCDs has been covered elsewhere[1-6] and the purpose of this paper is to compare this new technology with existing Intensified CCDs (ICCDs). While we are primarily interested in scientific applications the results will be more widely applicable. The ICCDs used here are based on thermoelectric cooled scientific CCDs which are directly fiber optically coupled to proximity focused intensifiers. The intensifiers have a high resolution with 64 lp/mm, use both GenII and GenIII type photocathodes and incorporate fast phosphors. Long lifetime phosphors are not compatible with most scientific measurements as they can give time integration at high frame rates. The high speed gating ability of the ICCDs is not considered here since EMCCDs cannot compete in those kinds of applications, therefore the data presented assumes that the photocathode QEs are optimised for best QE and not gating speed (principally they will not have any metal underlay that would otherwise compromise QE). The areas of comparison are Resolution, Noise factor, Quantum Efficiency, EBI/Darksignal, and Clocking Induced Charge (CIC), also referred to as Spurious Charge.

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Low-Light-Level and Real-Time Imaging Systems, Components, and Applications,
C. Bruce Johnson, Divyendu Sinha, Phillip A. Laplante, Editors, Proceedings of SPIE
Vol. 4796 (2003) © 2003 SPIE · 0277-786X/03/$15.00

2. SPATIAL RESOLUTION

A CCD has good resolution that is largely determined by the pixel size (which can be down to 6µm), and it is only compromised by photons which are absorbed near the boundary between pixels because these have a probability of going into either pixel. ICCDs have a number of phenomena which affect the resolution, but steady improvements in phosphors and MCPs of modern devices result in better than 64 lp/mm, which corresponds to a FWHM spot size of about 25µm. Now this cannot match the resolution of the 16µm square pixel size of the Marconi CCD87 chip or the 7.4µm square pixel size of the Texas Instruments TC253 chip, but it is still often assumed that when the spot size for the tube matches the pixel size of the CCD then the resolution is no longer limited by the tube. However the FWHM does not tell the whole story because it does not account for the long tail in the spot profile. Proper comparisons require MTF curves, but Figure 1 and 2 are a more visual presentation of the effect on resolution. Figure 1 shows the average resultant pixel distribution of single electron events recorded at high gains for both an EMCCD and a 64 lp/mm ICCD with comparable pixel sizes. For the ICCD, about 50% of the resultant signal from a single event is spread into neighbouring pixels, this has a considerable spatial averaging compared to the EMCCD and must be taken into account in subsequent measurements (see Sections 3 and 7 below). Figure 2 shows sub-regions from two full resolution images, one taken with the EMCCD and the other with the ICCD, the pixel sizes are clearly seen as well as the difference in resolutions.

3. NOISE FACTOR

The noise factors for the different detector types arise because of loss mechanisms (if any) that may exist and as a result of the statistics of the electron multiplication process, whether that occurs inside the silicon crystal lattice for the EMCCD or the channel of the MCP in the case of the ICCD.
Signal to Noise (S/N) measurements were made for both the EMCCD and ICCD by repeated measurements of a uniformly illuminated area on each detector for several different gains. Here the gains refer to the electron multiplication gains; for the ICCD this means the ratio of photoelectrons from the photocathode to photoelectrons in the CCD, and for the EMCCD it means the ratio of electrons going into the multiplication register to the number at the output node. Some of the results are shown in Figure 3 and 4 as plots of the S/N versus Signal for the EMCCD and a Gen II based ICCD respectively. The data points are the S/N of a single pixel down to an average signal level of 1 photoelectron per pixel. The lines are based on theory which takes into account signal shot noise and readout noise of the CCD, therefore the deviation of the data points from the lines is a measure of the noise factor. The theory curves for the ICCD also take into account the spatial smoothing indicated earlier, this has to be done because the measurement made for any one pixel actually gets about 50% of its signal from the surrounding pixels.
For the EMCCD a gain of X1 means no electron multiplication, it is operating like a standard CCD, and the data points lie on the theory line indicating a noise factor of unity, just as would be expected for any standard CCD since they do not have any significant loss mechanisms or statistics. As the gain is increased the statistics of the multiplication process begin to add noise and the noise factor increases. Simple theory for the electron multiplication process[3] has indicated a noise figure of 1.4, even at high gains, but various measurements by ourselves and others[2,5] have consistently found lower values, some as low as 1.2. The data of Figure 3 gives an average of 1.3.
Looking at the ICCD, the opposite trend is observed, as the gain is increased the noise factor improves. This is because image intensifiers have been designed primarily for operation at maximum gain, to lower the gain the MCP voltage is lowered, but operating the MCP at low voltages increases the loss mechanism in both the photoelectron capture and the multiplication process and hence increases the noise factor. This leads to a little appreciated phenomenon with modern ICCD systems, namely that the already high sensitivity of modern scientific CCDs, combined with the efficient optical coupling (fiber optic) of the intensifier output, causes the CCD to saturate even in modest light levels. To prevent this, ICCD users will reduce the MCP voltage, not realising that this has the effect of degrading the S/N of the signal.
However, when operated at appropriately high MCP voltages, the ICCD data, not all shown here, confirms the already well-known noise factors for ICCDs, the better of these are summarised in Table 1 along with those for the EMCCD. The noise factor for filmless Gen III could not be measured because none were available at the time, but since they are the same construction as a Gen II it is reasonable to assume they will have a similar noise factor.

Detector type	Noise Factor
Gen II	1.6
Gen III filmed	2
Gen III filmless	1.6
EMCCD	1.3
CCD	1

Table 1. Noise factors for the Electron Multiplying CCD and ICCDs based on various intensifier types.

The larger noise factor for the filmed Gen III compared to either the Gen II or filmless Gen III arises because the film adds an extra loss mechanism for electrons arriving at the input of the MCP.
It may seem strange that a multiplication process that adds noise is used to detect small signals but it must be remembered that these small signals would otherwise be lost in the electronic noise of the CCD output amplifier (readout noise). This also means that if the signal is not so small (is shot noise limited i.e. not being lost in the readout noise) then using an image intensifier or using the electron multiplier in an EMCCD does indeed degrade the S/N. The EMCCD has an advantage here, because its gain can be turned on and off it can be optimally operated in both low light level and bright level conditions.

4. QUANTUM EFFICIENCY

Figure 5 shows a representable selection of QEs for various photocathodes and CCD variants. The two Gen II photocathodes, Wide response (W) and Wide with enhanced Red response (WR), are assumed to have no metal underlay that would otherwise reduce QE, underlays are only relevant to achieving fast photocathode gating. Only front illuminated EMCCDs are presently available and two curves are shown with and without UV phosphor coating, however back illuminated EMCCDs are presently in fabrication and four curves are included to illustrate the expected options and their respective performances.
QE is an easy concept to understand in itself, and it is equally easy to use QE curves to compare the performance between different CCDs, say, assuming all other factors are equal. The same applies for comparing different Gen II photocathodes and separately comparing Gen III photocathodes. But for comparing between these different technologies, CCD, EMCCD, Gen II ICCD, and Gen III ICCD, QE on its own will be misleading. The QE of a photocathode is just that, the probability of a photon producing a photoelectron, but it does not tell you the probability of detecting that photon, which is what actually matters. To do that all other loss mechanisms and statistical noise sources must be taken into account, in other words it must include the noise factor. This is done by correcting the QE to give the Effective QE for the different technologies, using

$$\text{Effective QE} = \text{QE}/(N_f)^2 \qquad \text{Equation 1}$$

Where Nf is the noise factor. Figures 6 and 7 show the QEs of Figure 5 converted to Effective QEs, two separate graphs are used for clarity, Figure 6 assumes filmed Gen IIIs and Figure 7 assumes filmless Gen IIIs. These graphs are a fair comparison of detection performance <u>for all signal levels</u> for all three technologies (EMCCD, Gen II ICCD, and Gen III ICCD) because they all have electron multiplication which allow any signal to be multiplied above the readout noise from their CCD amplifiers. The QE curves for standard CCDs (or EMCCDs with their multiplication turned off) are not shown in Figure 6 or 7, since they would show the best QEs of all, it would not be a correct comparison because their readout noise cannot properly be taken into account (however it would be fair for higher signal levels that are shot noise limited). It is clear from Figure 6 and 7 that the EMCCD, particularly the back illuminated versions, wins out in raw detectability.

5. EBI, DARKSIGNAL AND CLOCKING INDUCED CHARGE

Darksignal or darkcurrent for the EMCCD is just the same as in a conventional CCD and can be reduced by cooling. Traditionally, when judging the optimum operating temperature to eliminate the darksignal of a CCD, a temperature at which the darksignal shot noise is comfortably below the readout noise is selected (taking into account the desired exposure time), further cooling provides no real benefit. For the EMCCD, however, where there can be essentially no readout noise and single electron events can be detected, we would ideally want no darksignal. This does not mean that more extensive cooling is needed to see the benefits of the electron multiplier, rather that yet more sensitivity through yet longer exposures (should the application allow this) can be obtained with further cooling than usual. But any darksignal that is still remaining will be multiplied up along with the signal, this is different from the case of the CCD chip darksignal in an ICCD system where the signal is multiplied above the darksignal, just as it is multiplied above the readout noise. Therefore, in general the EMCCD will need better cooling than the CCD chip in an ICCD system. Fortunately, CCD chips can be readily mounted on a TE cooler in a vacuum and efficiently cooled to effectively eliminate darksignal for all but long exposures, this is now routine for most scientific CCD systems.

Therefore, it is the EBI (resulting from the photocathode of the tube) of the ICCD that we need to compare to the darksignal of the EMCCD. Cooling can also reduce the EBI of the photocathode, however in practice this is more difficult than for a CCD chip on its own. Cooling an image intensifier which is fiber optically coupled to a CCD chip is much less practical. Also the decrease of EBI with temperature is much less favourable compared to the darksignal decrease with temperature for a CCD. For the above-mentioned reasons, darksignal is less of a limitation for an EMCCD than EBI is for a ICCD. In practice the more limiting factor for an EMCCD is Clocking Induced Charge.

Impact Ionisation can occur even under normal clocking in any CCD, but when properly set-up it is very small; only one in 100 transfers or so will produce an electron. This phenomenon is referred to as Clocking Induced Charge (CIC), or Spurious Charge, and in the EMCCD there is extra CIC generated in the electron multiplication register at high gain. To keep clock induced charge to a minimum, careful attention has to be paid to the clock amplitudes and edges. CIC is usually lost in the CCD readout noise in even the lowest noise conventional CCDs, however for the EMCCD at high gain, even individual electrons can be seen as sharp spikes in the image and any CIC will become visible. The effect is similar to EBI in an ICCD, but unlike EBI, it is independent of exposure (and will actually increase slightly with lower temperatures[5,7,8]).

No equivalent phenomenon exists in ICCDs and this charge will set the absolute limit on the sensitivity of the EMCCD. However, this should not be over-stated; Figure 8 illustrates the CIC and how it would trade off against the EBI of the ICCD for different exposure times. The line for the EMCCD includes the fixed CIC component plus the residual darksignal at the stated temperature. For the ICCD there is only EBI therefore the lines all start from zero and linearly increase with exposure. Several lines are shown because EBI varies greatly, not just between different photocathode types but even from tube to tube for the same type. Therefore the lines shown can only be indicative. There is a general trend of EBI increasing with increased red response and some of these quickly overtake the CIC of the EMCCD. Whether CIC will be a problem will depend on the particular measurement, for example in the NIR, only the EMCCD has usable QE but at other wavelengths and where your signal may only be one or two photoelectons then it may be more of a limitation.

6. MULTIPLICATION REGISTER CTE

This is another phenomenon unique to EMCCDs, which occurs as the signal charge is being multiplied (as it transfers through the electron multiplication register). As this signal charge packet grows above about 50k to 100k electrons per pixel it begins to experience Charge Transfer Efficiency (CTE) problems. A small amount of the charge gets left behind in each transfer and appears in the image as low level horizontal streaking from any bright feature in the image. Again this effect should not be overstated as it only occurs at high gain and relatively high signals, a combination where high gain may not be required anyway, but it may limit the effective dynamic range of some measurements.

7. COMPARISON

It should be clear by now that EMCCDs have great attributes compared to ICCDs, QE, resolution, and image quality. But there is the CIC and CTE to consider. By choosing a suitable type of measurement at a particular wavelength, exposure time and signal level, we can make either the EMCCD or the ICCD look best. To figure out which will be most suitable for your application will require consideration of all the parameters discussed above. Therefore to end this paper, it was decided to perform just one comparison between the two technologies. We have chosen a measurement and setting so that both technologies should deliver similar results according to the data presented in this paper. Two movie sequences[9] were taken, one with the EMCCD and one with the ICCD, both with similar pixel sizes. A wavelength was chosen so that both had the same Effective QE (therefore matching QE and noise factor), an exposure was chosen so that the number of EBI events matched the number of CIC and darksignal events and a suitably low signal level was chosen so that these would be seen. Single frames from the movie sequences are shown in Figure 9, the white areas are approximately 3 photoelectrons per pixel on average for both detectors. The top image is the EMCCD and the bottom image is the ICCD, and on the surface of it, the ICCD image looks better. But because ICCDs have been the most commonly used low light level imaging systems to date, we have become accustomed to the subtle smoothing effects of image intensifiers and we are not comparing like with like. The middle image is the EMCCD smoothed using the point spread data of Figure 1, and now we see that both give very comparable results, as we would expect. BUT, the top image is the better data because it is a truer representation of reality, so when you evaluate this new technology in your application, bare in mind that you may be seeing your data in stark resolution for the first time. If your measurements are movie sequence types, such as live cell imaging or single molecule detection, then there is a further effect to be aware of when making a comparison, which is temporal smoothing from a slow decay phosphor. As was mentioned earlier, all the measurements presented in this paper use ICCDs that have fast decay phosphors, but slow decay phosphors are still used in many other ICCDs and these will give a false impression of better image quality. These smoothing effects may not always be considered negative as they can sometimes help to visualise what is being measured (e.g. in surveillance application), but these effects can be implemented in software for the EMCCD data.

8. CONCLUSIONS

It is clear that electron multiplying CCDs are a credible alternative to ICCDs. Whether ICCDs will remain pre-eminent or will be displaced by EMCCDs will depend on what further developments take place. The EMCCD technology is new and developments are relatively certain. Already being a CCD, it has clear advantages in QE, so it will have the best raw detectability and it is difficult to see intensifiers overtaking this soon. It also has the advantages of better resolution and the absence of image artefacts, such as halo and chicken wire. Its weaknesses are the CIC and the multiplication register CTE at high gains and signal level, although they do not apply in all situations and both will probably prove amenable to improvements in future developments.

We must stress that we are only dealing with the scientific applications that presently require ICCDs; this is neither the major market nor the largest technology driver for intensifiers. Image intensifiers have seen steady improvements and there is no reason to think that this will not continue, and it is likely that both technologies will co-exist for many more years. Predicting future trends in technology is foolhardy at best, but probably one of the biggest reasons that the EMCCD technology has a secure future is that it is an all solid state solution and is produced using standard silicon fabrication techniques. While there are development costs to be recouped and further developments will also need to be financed as the technology matures, Electron Multiplying CCDs are inherently inexpensive and amenable to mass production and in the longer term this may be decisive.

REFERENCES

1) P. Jerram et al, "*The LLLCCD: Low Light Imaging without the need for an Intensifier*", SPIE **Vol 4306**, 2001.

2) J. Hynecek, *"Impactron – A New Solid State Image Intensifier"*, IEEE Trans. on Electron Devices, **Vol. 48**, No. 10, Oct. 2001.

3) C. D. Mackay et al, "*Sub-Electron Read Noise at MHz Pixel Rates*", http://www.marconitech.com/ccds/l3vision/technology.php.

4) S. H. Spencer and N. J. Catlett, "*Low Light Level Solid State TV Imaging*", March 2000, http://www.marconitech.com/ccds/l3vision/technology.php

5) D. J. Denvir and E.Conroy, *"Electron Multiplying CCD Technology: Application to Ultrasensitive Detection of Biomolecules"*, January 2001, Photonics West, Biomedical Optics (BiOS)

6) E. J. Harris et al, "*Evaluation of a Novel CCD Camera for Dose Reduction in Digital Radiography*", http://www.marconitech.com/ccds/l3vision/technology.php

7) C. R. Crowell and S. M. Sze, "*Temperature Dependence of Avalanche Multiplication in Semiconductors*", Applied Physics Letters, **Vol 9**, No 6, Sept 1966.

8) Y. Okuto and C. R. Crowell, Phys. Rev. B, **Vol. 6**, pp.3076, 1992.

9) www.andor-tech.com

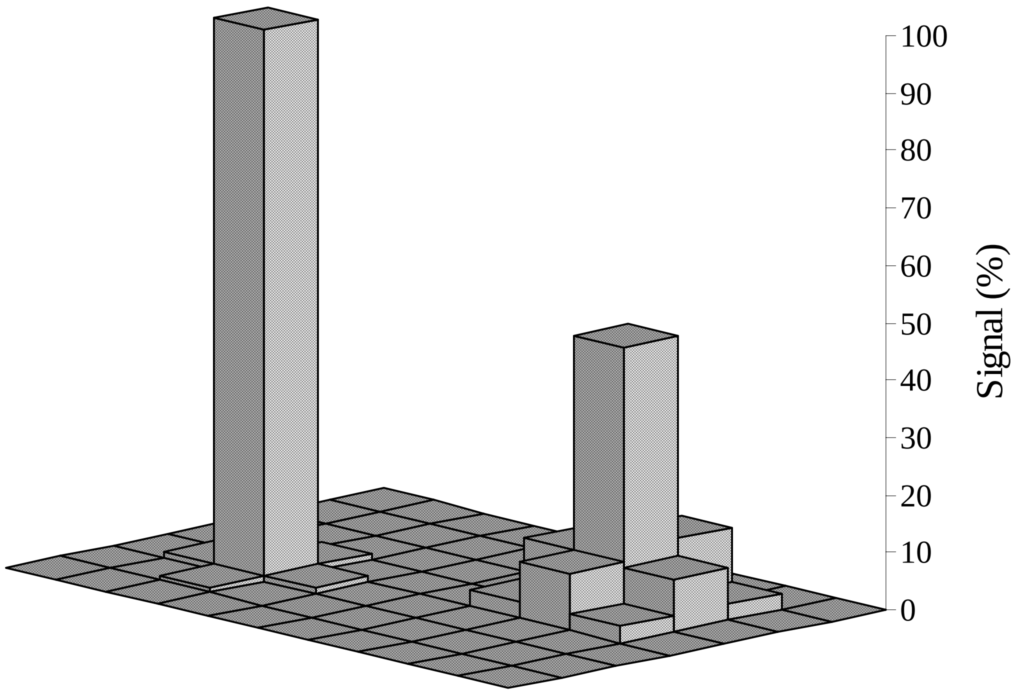

Figure 1. Point spread distribution for single events on EMCCD (left) and ICCD (right).

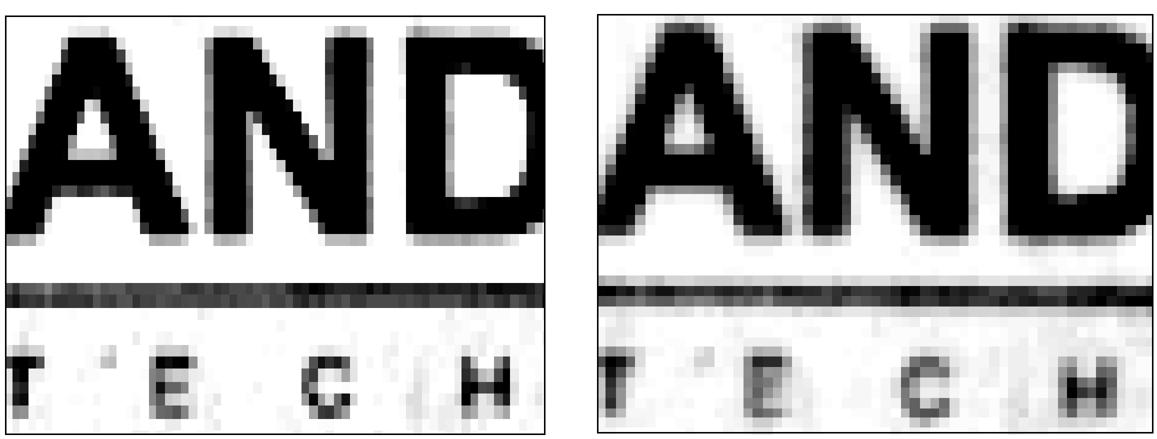

Figure 2. The effect of charge spreading on spatial resolution for EMCCD (left) and ICCD (right).

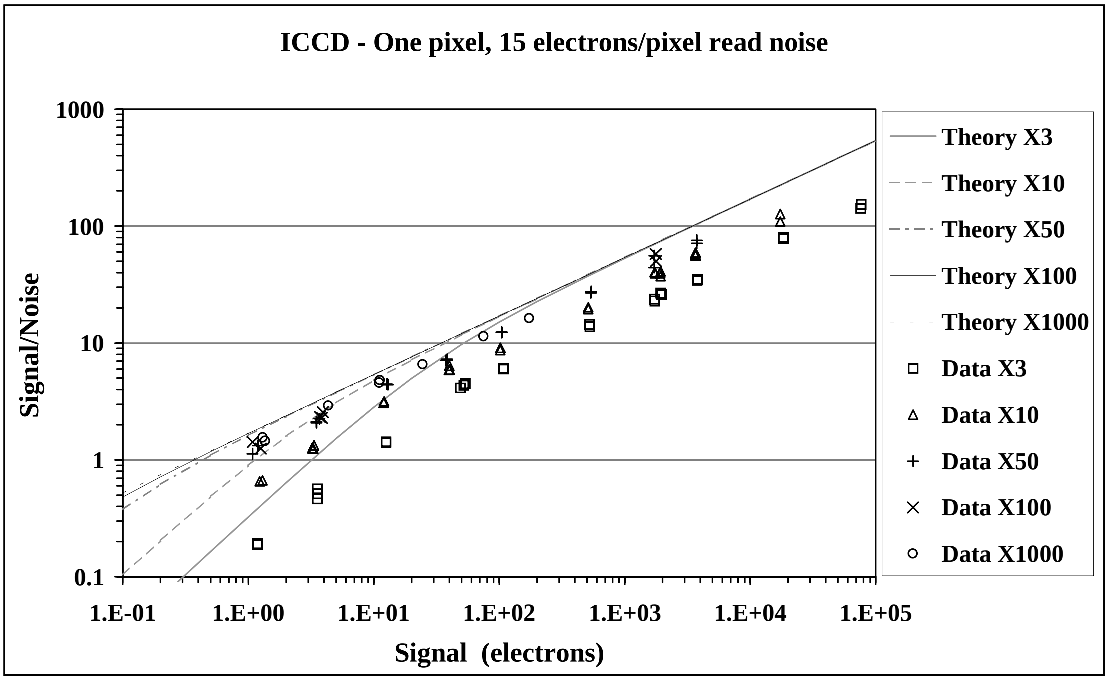

Figure 3. Expected and measured single pixel performance for ICCD at different gains assuming 15 electrons read noise.

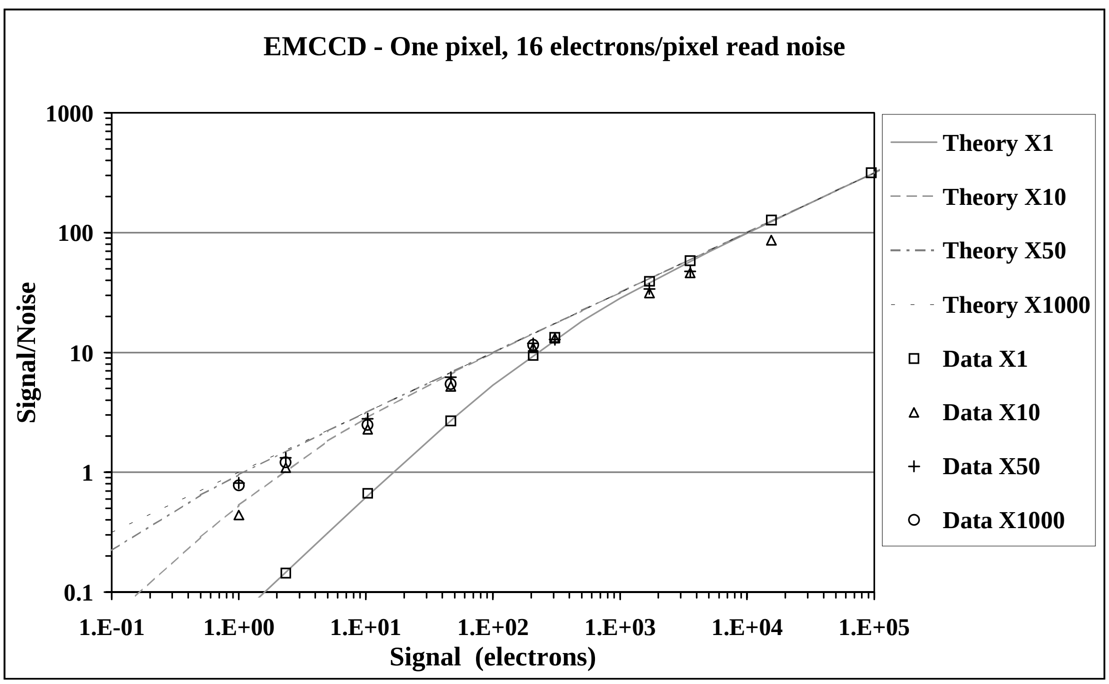

Figure 4. Expected and measured single pixel performance for EMCCD at different gains assuming 16 electrons read noise.

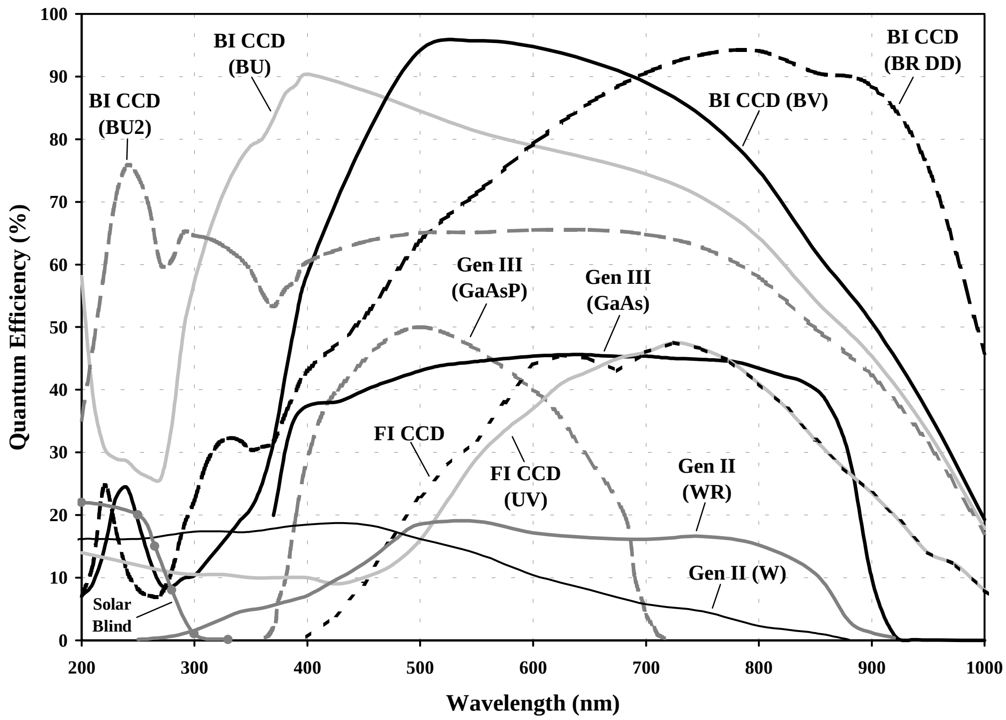

Figure 5. Quantum Efficiencies of BI (Back Illuminated) and FI (Front Illuminated) CCDs without electron multiplication, and Gen II and Gen III photocathodes.

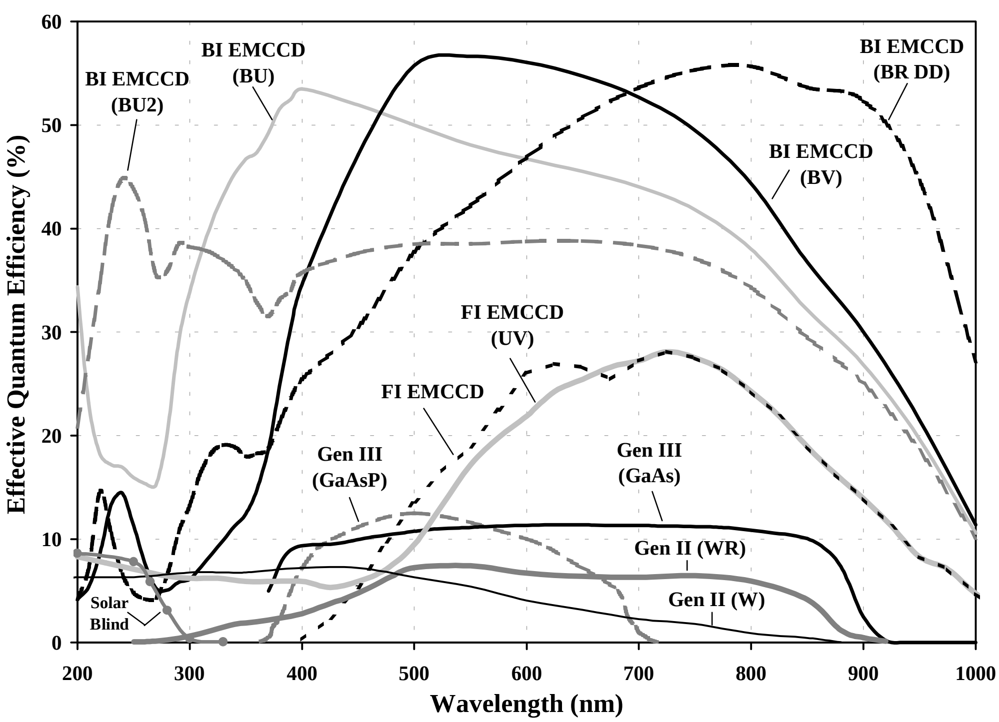

Figure 6. Effective Quantum Efficiencies (i.e taking into account the noise factors associated with electron multiplication) of BI (Back Illuminated) and FI (Front Illuminated) EMCCDs and Gen II and filmed Gen III based ICCDs.

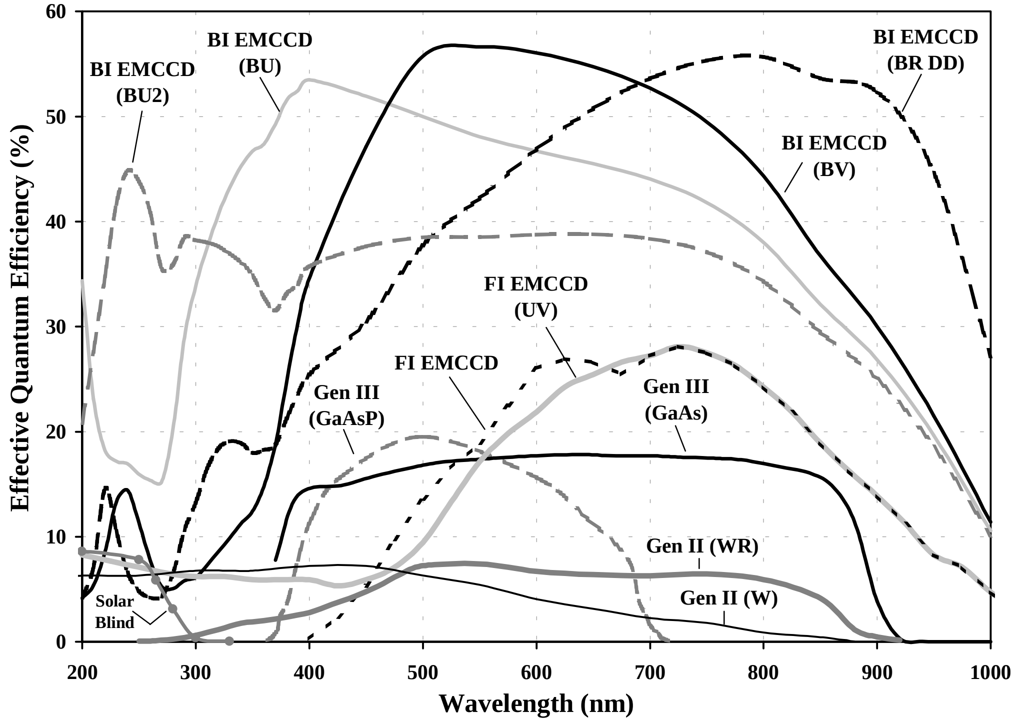

Figure 7. Effective Quantum Efficiencies (i.e taking into account the noise factors associated with electron multiplication) of BI (Back Illuminated) and FI (Front Illuminated) EMCCDs and Gen II and filmless Gen III based ICCDs.

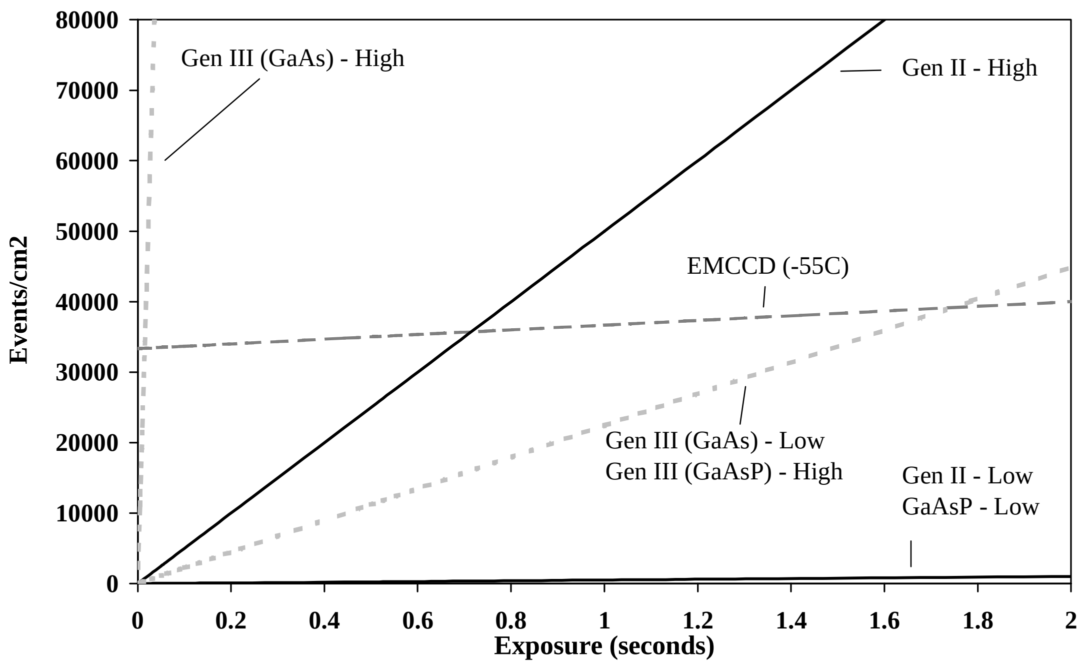

Figure 8. Typical events/cm^2 versus exposure time for the EMCCD (temperature -55^{o}C) and Gen II and Gen III ICCDs.

Figure 9. The top image is the EMCCD and the bottom image is the ICCD, the middle image is the EMCCD spatially smoothed using data of Figure 1. The average signal level of the white areas are approximately three electrons/pixel for all 3 images and gains for both systems were approximately X1800 each.