Understanding Electron Multiplying Gain

Raptor Photonics
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Electron Multiplying CCD (EMCCD) cameras, such as the Falcon III, can be used to detect very weak signals, which would otherwise be lost within the noise floor of the camera. Using a conventional CCD to detect these very weak signals, usually requires both long exposure times (to integrate a detectable amount of signal) and slow readout rates (to minimize the read noise). However, EMCCD cameras can detect these same signals using much shorter exposure times and higher readout rates. This is done by applying EM gain to the signal before it reaches the output amplifier of the CCD sensor, effectively reducing the read noise of the sensor by a factor equal to the amount of gain applied.

Producing EM Gain

EMCCDs have an additional register (the multiplication register) located between the horizontal readout register and the output amplifier which are present on conventional CCDs. Charge from the image area is transferred through the readout register into the multiplication register where the amplification occurs. Gain is achieved by impact ionization, a stochastic process which produces secondary electrons as the charge is shifted through the pixels of the multiplication register. A specific pixel structure within this register enables higher voltages to be used during the transfer of charge from one pixel to the next. This high voltage (typically a few tens of volts) results in a finite probability of secondary electrons being produced during each transfer. These secondary electrons, combined with the original charge in the pixel, are transferred through the remainder of the multiplication register, undergoing further amplification during each subsequent pixel transfer. The total gain is the ratio of the amount of charge in a pixel at the end of the multiplication register to the amount of charge contained by that pixel just before the start of the multiplication register.

The probability (P) of generating a secondary electron during an individual transfer is quite low (typically less than 2%) even when using relatively high transfer voltages. Therefore, in order to achieve a useful amount of total gain, the charge must undergo many transfers, which is achieved by having many pixels within the multiplication register. The total gain (G) produced is related to the number of transfers, i.e. the number of pixels (N) in the multiplication register, via the relation:

$$G = (1 + P)^N$$

Under normal operating conditions P is usually within the range 0.001 to 0.016 and N is typically between 500 and 600, enabling a wide range of total gain values to be produced.

For example, if N = 577 and P = 0.008 then:

$$G = (1 + 0.008)^{577} \approx 99$$

Whereas if P where to increase slightly, to say 0.016, then:

$$G = (1 + 0.016)^{577} \approx 9500$$

As these examples demonstrate, the total gain is strongly dependent upon the probability of generating secondary electrons, which in turn is a function of both the electric field strength (related to the applied clock voltage) and the temperature of the CCD silicon in which the transfers are occurring.

Controlling the Amount of EM Gain

The total gain produced within an EMCCD is dependent upon the number of transfers (N) and the probability (P) of secondary electrons being produced, as stated above. The number of transfers, N, is specified by the number of pixels in the multiplication register and is therefore predetermined by the CCD sensor manufacturer. However, camera manufacturers can provide the customer with some control over the value of P by enabling the adjustment of both the transfer clock voltage and the CCD temperature.

The amplitude of the transfer clock voltage controls the electric field experienced by the charge during each transfer, which is when the impact ionization occurs. Higher amplitudes result in a higher probability of secondary electrons being produced. The Falcon III software commands allow the user to adjust the amplitude of the clock voltage via a 12-bit (0 – 4095) digital-to-analog (DAC) converter, thereby controlling the total gain produced. The relationship between the clock voltage and the total gain produced is exponential and typically DAC values up to approximately 3000 produce minimal gain (<10×). At higher DAC settings, the gain ramps exponentially and small changes in the DAC value equate to significant changes in gain.

Decreasing the sensor temperature actually increases the probability of secondary electrons being produced during transfers. Therefore, higher gain can be achieved using a specified clock voltage or conversely a lower clock voltage can be used to attain the required level of gain. The Falcon III camera has a high performance integrated cooling system which enables sensor temperatures down to -70°C to be reached. Under these conditions, high gain values can be achieved using relatively low amplitude clock voltages.

The precise amount of gain produced within a sensor is very strongly dependent on both the clock amplitude and CCD temperature. However, the characteristics of individual devices will change over time due to 'gain ageing' which is discussed later in this document. Raptor Photonics EMCCD cameras, such as the Falcon III, do not attempt to offer the user controls labelled as 'real' or 'actual' gain based on semi-empirical approximations, as the reported values will not be accurate 100% of the time.

Optimum Level of EM Gain

The fundamental use of EM gain is to amplify the signal before it reaches the output amplifier, so that the readout noise of the camera effectively becomes negligible (compared to the amplified signal). An EM gain level in the region of 3 to 5 times the read noise is usually sufficient to achieve this.

The Falcon III camera has a typical read noise value of 70e- rms with the EM gain OFF (i.e. unity gain) at 40MHz readout. Therefore, applying EM gain in the region of 250× will easily overcome the noise floor of the camera and make the effective read noise (n_{eff}) << 1e- rms, as shown below:

$$n_{eff} = \frac{\textit{read noise with EM Gain OFF}}{\textit{EM Gain}} = \frac{70}{250} = 0.28\ e^{-}\,rms$$

In some instances, such as true photon counting applications, the user may wish to increase the EM gain to an even higher level than that shown in the illustration above. EM gain levels of approximately 1000× are sufficient for these types of applications but increasing the EM gain further than this typically starts to have a negative impact on the imaging performance and lifetime of the sensor.

Impact of Excessive Gain

There are two main effects which occur when images are acquired with excessively high EM gain:

1) Decrease in Dynamic Range

The intra-scene dynamic range (DR) of an imaging system is defined at the ratio of the brightest detectable signal (B) to the weakest detectable signal (W).

$$DR = \frac{B}{W}$$

In a conventional CCD the full well capacity of the image area pixels determines the limit of the brightest detectable signal (ignoring on-chip binning for simplicity). However, when using an EMCCD with high EM gain values, the brightest detectable signal is set by the maximum amount of charge (CEM) which can be transferred through the multiplication register. This register is designed to have a full well capacity which is higher than the image pixels so that some (small) level of EM gain can be applied to bright signals before encountering saturation effects.

At high EM gain (G) settings the charge (C) at the output of the multiplication register is related to the signal (S) by:

$$C = G \times S$$

The brightest detectable signal at high EM gain values is defined by the condition C = CEM. From the above equation stated for the charge (C) at the multiplication register, we can define the maximum amount of charge (CEM) as:

$$C_{EM} = G \times S$$

$$C_{EM} = G \times B$$

Re-arranging this equation and substituting for B, gives the relationship between dynamic range and EM gain (under high gain conditions):

$$DR = \frac{B}{W} = \frac{\frac{C_{EM}}{G}}{W}$$

The weakest detectable signal under these conditions will be one photon, which gives a minimum detectable signal, W = 1 (photo)-electron. Specifying CEM in electrons and substituting for W, simplifies the above relationship to:

$$DR = \frac{\frac{C_{EM}}{G}}{W} = \frac{\frac{C_{EM}}{G}}{1} = \frac{C_{EM}}{G}$$

Therefore, to maximize the dynamic range of the system, the EM gain should ideally be adjusted to just achieve a minimum detectable signal equivalent to 1 electron. Increasing the EM gain above this level decreases the dynamic range of the system, as the brightest detectable signal is being reduced while the minimum detectable signal remains unchanged at the limit of 1 photon.

2) Gain Ageing

A secondary effect of using excessive EM gain is accelerated ageing of the sensor, caused by a permanent change or reduction in the electric field experienced by charge being transferred through the multiplication register. This ageing manifests as a decrease in the EM gain produced for a given clock voltage amplitude and CCD temperature. The rate of ageing is related to both the applied clock voltage amplitude and the amount of charge which passes through the multiplication register. Higher voltages and higher amounts of charge result in faster ageing of the sensor. The sensor used in the Falcon III has the lowest voltage clock amplitude required to produce EM gain of all commercially available sensors presently available.

Summary

- EMCCDs are the most sensitive solid state imaging devices for low light detection in the VUV to NIR wavelength range.
- EMCCDs deliver many of the benefits of a conventional CCD detector, such as low dark current and excellent image uniformity, but with the additional benefits of sensitivity down to single photon detection and increased frame rates.
- The impact ionization process used to produce EM gain is strongly dependent on voltage clock amplitudes, sensor temperature and sensor history.
- The actual amount of EM gain applied cannot be accurately defined by semi-empirical approximations, particularly over extended periods of usage. In some cases, the actual and reported values of the "real" or "linear" gain can very quickly deviate from one another.
- The best rule of thumb for using EMCCDs is to use just enough EM gain to bring the detected signal out of the camera noise floor.
- Excessive EM gain will reduce the systems intra-scene dynamic range and possibly result in accelerated ageing of the EMCCD sensor.
- The sensor used in the Falcon III has the lowest voltage clock amplitude required to produce EM gain of all commercially available sensors presently available.
- Optimization of EM gain usage and care to avoid excessive charge transfer through the multiplication register will provide an extremely sensitive camera system capable of many years operation.

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