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Low-Light Technical Note 2
The Use of Multiplication Gain in L3Vision™ Electron Multiplying CCD Sensors

INTRODUCTION

e2v technologies L3Vision™ Electron Multiplying Charge Coupled Devices (EMCCDs) use a novel charge multiplication technique to facilitate gain in the charge domain and enable performance with an equivalent output noise of less than 1 e^- at pixel rates of over 11 MHz. Thus the sensors are excellently suited for scientific imaging where the illumination is limited, or for TV applications at very low light levels.

This Technical Note discusses the different sources of noise in an L3Vision™ EMCCD, and explains how to determine the optimum multiplication gain for a particular application.

SOURCES OF NOISE IN AN L3Vision™ EMCCD

There are four significant sources of noise on the output of an L3Vision™ EMCCD: photon shot noise on the detected signal, dark signal, readout noise and noise resulting from the multiplication gain process.

Photon Shot Noise

A detected signal of S_0 photons has a photon shot noise of $\sqrt{S_0}$ photons. The photon shot noise derives from the fundamental quantum nature of light, and constitutes the theoretical noise limitation of any low-light level imaging application.

Dark Signal

Dark signal is the name given to the thermally generated charge detected as spurious signal. A dark signal of S_D on an image contributes a noise of $\sqrt{S_D}$ to the detected signal.

The total dark signal S_D consists of two components, the thermal dark signal D and the clock-induced charge (CIC) C, so that:

$$S_D = Dt + C \qquad (1)$$

where t is the integration time being employed.

The thermal dark signal has the standard temperature dependence for conventional CCDs, typically being given by:

$$D = 3.3 \times 10^6 T^2 e^{-9080/T} \text{ nA/cm}^2 \qquad (2)$$

for operation in inverted mode, and by:

$$D = 122 T^3 e^{-6400/T} \text{ nA/cm}^2 \qquad (3)$$

for operation in non-inverted mode.

The CIC is a function of the clock amplitude, clock edge speeds and rate of parallel transfer. CIC is only weakly temperature dependent and is typically 0.1 e^-/pixel/frame for operation in inverted mode and 0.003 e^-/pixel/frame for operation in non-inverted mode at −55 °C.

Readout Noise

The readout noise, N_a, is the contribution of noise due to the CCD output amplifier and the subsequent camera processing electronics. The readout noise increases with increasing readout rate. For a conventional CCD, the readout noise is generally the dominant noise component, particularly when operating at fast readout rates.

Noise from the Multiplication Gain

When multiplication gain is employed, there is an additional contribution to the noise due to the stochastic nature of the charge multiplication process. The excess noise factor, F, is defined as the input referred noise with gain divided by the input referred noise without gain, under conditions of zero readout noise.

If in the multiplication process each signal electron is assumed to behave independently of all the other signal electrons, it can be shown that, for large multiplication gain[1]:

$$F = \sqrt{2/(1 + \alpha)} \qquad (4)$$

where α is the probability of multiplication gain per stage. Since the L3Vision™ EMCCDs have typically 500 - 600 multiplication gain stages, $\alpha \ll 1$, and this gives $F = \sqrt{2}$.

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Total Noise

The basis of the EMCCD technology is that by applying a significantly large multiplication gain, the readout noise contribution to the total noise can be effectively eliminated.

If a multiplication gain of G is employed, the total detected noise S_N, referenced to the image area, is given by:

$$S_N = \sqrt{S_D F^2 + S_0 F^2 + (N_a{}^2/G^2)} \qquad (5)$$

It can be seen that by setting the multiplication gain G to a sufficiently large value, the readout noise is effectively eliminated.

The dark signal S_D may also be reduced to negligible levels by sufficient cooling of the device. Under these circumstances the noise is reduced to within a factor F of the theoretical quantum limit.

OPTIMISATION OF CCD MULTIPLICATION GAIN: WORKED EXAMPLES FOR TYPICAL APPLICATIONS

It is important to use the correct multiplication gain for a given application to optimise the device performance. Using too low a multiplication gain will fail to eliminate the system readout noise entirely. Using too high a multiplication gain will reduce the peak signal that can be detected, and may also make the system unnecessarily sensitive to small changes in the R∅2HV bias level.

The correct multiplication gain to use in a given application can be derived by considering equation (5). The following examples show how equation (5) may be used to calculate the optimum multiplication gain in typical applications of EMCCDs.

Example 1: TV Surveillance Imaging at Starlight Illumination

Consider an application where a scene is imaged at starlight illumination, in real time. An antibloomed CCD65 operating at 625-line TV rate with an f/1.4 lens could be used, operating in a camera system where the total readout noise = 200 e^-, and where cooling is used to maintain the sensor at T = 20 °C.

At T = 20 °C, the typical sensor dark signal is 290 e^-/pixel/s. For operation in 625 line TV mode, this equates to 6 e^-/pixel/frame, $= S_D$. Starlight Illumination through an f/1.4 lens gives a detected signal of approximately 12 e^-/pixel/frame, $= S_0$. Calculating the first two terms in the square root of equation (5), $S_D F^2 + S_0 F^2 = 2 \times 6 + 2 \times 12 = 36\ e^-$. Successful effective elimination of the readout noise thus requires G to be set so that $N_a{}^2/G^2 \ll 36$. Choosing to set up so that $N_a{}^2/G^2 = 3$, G should therefore be $\sim 115^*$.

Note that under these conditions, the peak signal that can be detected in the image area, without saturating the device output, is given by the gain register charge handling capacity (typically 800 ke^-) divided by the multiplication gain, in this case giving typically 7 ke^-/pixel/frame.

Example 2: TV Surveillance Imaging at Overcast Starlight Illumination

Consider next an application where a scene is imaged at overcast starlight illumination, in real time. Again, an antibloomed 625-line TV-rate CCD65 with an f/1.4 lens could be used, again operating in a camera system where the total readout noise = 200 e^-, but in this case use cooling to maintain the sensor at T = 0 °C.

The calculation proceeds in a similar way to Example 1. At T = 0 °C, the typical sensor dark signal is 40 e^-/pixel/s. This equates to 0.8 e^-/pixel/frame, $= S_D$. Overcast starlight illumination through an f/1.4 lens gives a detected signal of approximately 1.2 e^-/pixel/frame, $= S_0$. So in this case, $S_D F^2 + S_0 F^2 = 2 \times 0.8 + 2 \times 1.2 = 4\ e^-$. In this case, choose to set up so that $N_a{}^2/G^2 = 0.4$, and thus G should be $\sim 316^*$.

Under these conditions, the peak signal that can be detected in the image area, without saturating the device output, is typically 800 ke^-/316, $\sim$2.5 ke^-.

* Additional gain will be required to produce a useful contrast on the TV monitor. This may be a combination of CCD and off-chip gain.

Example 3: Slow-scan Imaging at Low Light Levels

Consider now a scientific imaging application where the incident radiation intensity is 6×10^{-9} W/m^2 and is of wavelength λ = 700 nm. This time, a CCD87, integrating for 1 second and reading out at 1 MHz could be used, in a camera system with a total readout noise of 50 e^-, with the sensor cooled to operate at T = −40 °C.

In this case, the incident radiation gives a mean incident signal of 5.4 photons/pixel/s. At λ = 700 nm, a front-illuminated device has a quantum efficiency of approximately 43%. Therefore, integration for 1 second gives a mean detected signal, S_0, of 2.3 e^-/pixel/frame. Operating in inverted mode at T = −40 °C, the dark signal, S_D, is approximately 0.03 e^-. In addition, there is a fixed dark signal associated with readout of approximately 0.1 e^-/pixel/frame, giving a total of 0.13 e^-/pixel/frame. So $S_D F^2 + S_0 F^2 = 2 \times 0.13 + 2 \times 2.3 = 4.9\ e^-$.

If the readout noise was reduced to a level approximately 1% of the other contributions to the noise, then $N_a{}^2/G^2 = 0.05$. Therefore, setting G to $\sim$225 effectively eliminates the readout noise. Note that, in this application, the readout noise and dark signal noise are then very small in comparison to the fundamental quantum shot noise.

Example 4: Photon Counting

Finally, consider an application where photon counting is required. Again a CCD87 could be used, in this case operating at T = −55 °C, with an integration time of 1 second, readout at 1 MHz and a total system readout noise of 50 e^-.

Operating at T = −55 °C, the dark signal is dominated by the readout component of 0.1 e^-/pixel/frame. Therefore G needs to be sufficiently large so that the readout dark signal is dominant over the amplifier readout noise. Setting $N_a^2/G^2 = 0.005$, G is calculated at ~700. In practice, G may be set to 1000 since for a photon counting application, the reduction in the peak detectable signal is unlikely to be of any consequence.

Thus by effectively eliminating the readout noise, the noise floor consists of the readout dark signal component, of typically 0.1 e^-/pixel/frame. Thus a spurious 'photon' is detected in only 1 out of every 10 pixels typically, making photon counting achievable with the EMCCD technology.

SUMMARY

The EMCCD technology enables the ultimate in low-light imaging performance by the use of sufficient multiplication gain. The optimum multiplication gain to use in any given application depends on the light level, the system readout noise and the sensor temperature.

FURTHER INFORMATION

For further information and technical support, please contact e2v technologies.

REFERENCES

1. "The Noise Performance of Electron Multiplying Charge Coupled Devices",
   accepted for publication by the IEEE Transactions on Electron Devices, December 2002.
   Robbins and Hadwen.