

Single Photon Imaging using a CCD and Electron Multiplication

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Summary

This article presents an overview of low light imaging using charge-coupled devices. Emphasis is placed on electron multiplication technology, which is incorporated within the current sensors of choice for many demanding applications requiring high performance imaging down to the single photon level.

Introduction

CCDs have been with us for 40 years and throughout this time significant advances in the manufacturing, architecture and performance have been made. One such advance has been the introduction of the electron multiplying CCD, the EMCCD, which has been commercially available for almost 10 years. The technology has developed and matured to the point where it is the current technology of choice for a diverse range of demanding low light imaging/sensing applications such as single molecular imaging in the life sciences and atmospheric monitoring from space. These applications tend to have the requirements of high quantum efficiency, sub electron readout noise and relatively high data/frame rates.

Discussion

Noise is the factor that limits the ultimate sensitivity of a device. The main sources of noise to be considered are the shot noise on the photon generated signal, shot noise on the background and noise introduced by the signal readout.

The shot noise on the signal can be minimised by ensuring the maximum number of photons reach the sensor (optical design, pixel size, fill factor etc) and that once at the sensor, the photons are converted to signal electrons as efficiently as possible. Front face devices have a quantum efficiency of around 40% in the visible typically and the use of open electrodes and virtual phase devices can increase this to around 60%. For the ultimate efficiency back illumination is required. Quantum efficiencies of greater than 95% are achievable in commercial back-thinned devices, with useful response extending well into the vacuum ultraviolet. Imaging of the infrared is limited by the band-gap of silicon, but current developments in the use of thick, high resistivity silicon have demonstrated a quantum efficiency as high as 60% at 1 μm , whilst preserving good point spread function.

Background signal also adds shot noise. Background signal can come from a variety of sources but at room temperature is usually dominated by the thermal generation of electron-hole pairs and is reduced significantly by cooling. An additional source of background, especially relevant at low temperatures and very low signal levels, is the clock-induced charge or spurious charge, and originates from the electron-hole pairs generated by the impact ionisation of holes as they drift through high field regions of the device during clocking. This can be minimised by careful device design and the

optimisation of the clocking schemes employed. For high performance scientific sensors running in MPP mode (IMO) a typical figure of better than 0.0001 electrons per transfer can be obtained. This can be reduced appreciably by depleting the Si/SiO₂ interface but greater cooling will be necessary.

The conversion of signal electrons to a useful potential is a noisy process and is dependent on the design of the output amplifier and the pixel rate required. Amplifiers designed for scientific applications can achieve excellent noise figures down to ~1.5 r.m.s. electrons. These require very low readout rates and a 2kx2k device would take several minutes to readout through a single amplifier. Multiple amplifiers can be used to reduce the readout time whilst maintaining the noise performance. An extreme case of this is the column parallel CCD where one amplifier is used for each column.

The noise from low noise scientific type amplifiers is still too high for a true, single photon imaging capability. However, amplifying the signal whilst still in the charge domain, before the charge to voltage conversion process, effectively eliminates this noise source. This is realised in the EMCCD where, prior to reaching the charge to voltage amplifier, the signal charge passes through a number of multiplication stages. At each stage the multiplication is achieved by allowing the signal to drift through an electric field high enough to generate an impact ionisation event with a probability of about 1.4%. 500 multiplication stages give a total gain of 1000x, independent of the readout rate. Thus single electron (single photon) events can be observed over the noise of the amplifier, even at video frame rates and above.

For the ultimate sensitivity, therefore, back-illumination technology is combined with electron multiplication and devices are cooled to suppress dark signal. Devices are available off the shelf but some applications have very specific requirements and demand a custom design. One such device is the EMCCD employed within the adaptive optics systems for professional astronomical telescopes used to correct for the effects of atmospheric turbulence. Single photon imaging capability is needed to centroid projected spots to the required accuracy. This, together with the need to sample at least 240x240 pixels at a frame rate of 1.5 kHz, makes the application ideally suited to back-illuminated EMCCD technology.

Another example requiring a custom design is for the space-borne observation of aerosols within the atmosphere. A prototype EMCCD sensor for a Light Detection and Ranging (LIDAR) instrument has been developed as part of an ESA study into instrumentation for future earth observation missions. The basic requirement was for a detector to measure the variation in brightness of a small spot of light with a sampling window of less than 1 μ s. Despite its single photon sensitivity the detector also had to be tolerant of very large signals arising from specular reflections.

Conclusion

The optimisation of the CCD for high sensitivity has been reviewed and an overview of EMCCD technology presented. The combination of the very high quantum efficiency of back illumination with electron multiplication leads to extremely sensitive devices capable of efficient single photon imaging at high frame rates.