On-chip Multiplication Gain

Technology Introduction

Traditional low-light-level imaging systems face a fundamental challenge when they are required to capture events at high frame rates. Because the read noise of CCDs increases with the pixel readout rate, the read noise sets the detection limit of these devices for low-light-level work.[1]

In order to overcome this limitation, it is frequently necessary to amplify the signal itself above the read noise. Currently, image intensifiers are often employed for this purpose.[2] For example, ICCD camera systems offer a proven solution for single-molecule fluorescence (SMF), a live-cell imaging application that demands very high detector sensitivity as well as readout rates equal to and beyond those associated with video. However, while vast improvements have been made to these vacuum devices in terms of sensitivity and resolution over the years, they still suffer from a few disadvantages, including susceptibility to damage under high-light-level conditions and a relatively high cost of manufacture.

Recently, though, CCD manufacturers have introduced novel, high-sensitivity CCDs that have been designed specifically to address the challenges of ultra-low-light imaging applications — without the use of external image intensifiers. The new detectors utilize revolutionary "on-chip multiplication gain" technology to multiply photon-generated charge above the readout noise, even at supravideo frame rates.

This special, signal-boosting process occurs before the charge reaches the on-chip amplifier, effectively reducing the CCD read noise by the gain factor, which typically falls between 1 and 1000. The primary benefit of the technology, therefore, is a far better signal-to-noise ratio for signal levels below the CCD read-noise floor.

Technology Summary

On-chip Multiplication Gain

The principal difference between a charge-multiplying CCD and a standard CCD is the presence of an extended serial register in the new device (see **Figure 1**). Note that since the on-chip multiplication gain takes place after photons have been detected in the device's active area, it is possible to adapt the new technology to all current CCD architectures (i.e., back-illuminated CCDs, interline-transfer CCDs, etc.).

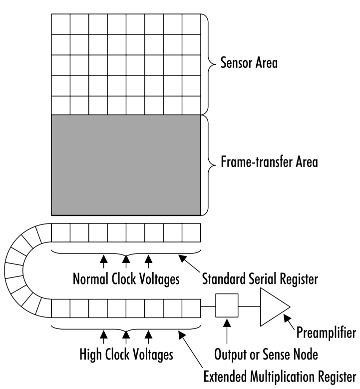

Figure 1. *Depiction of an electron-multiplying CCD. The example shown here is a frame-transfer device.*

Electrons are accelerated from pixel to pixel in the extra portion of the register (also known as a *multiplication register*) by applying higher-than-typical CCD clock voltages (up to 40 V). The higher voltage causes secondary electrons to be generated by impact ionization. The on-chip multiplication gain can be controlled by increasing or decreasing the clock voltages (gain is exponentially proportional to the voltage).

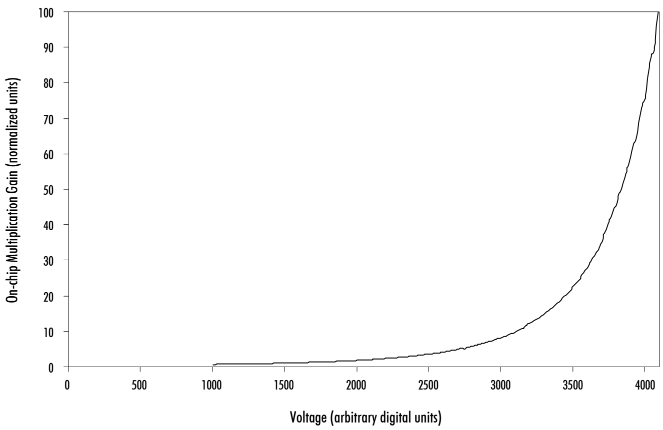

Figure 2. Gain vs. Voltage

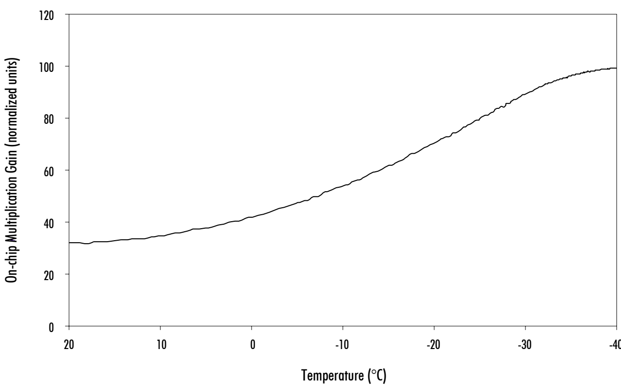

Figure 3. Gain vs. Temperature

As mentioned earlier, the gain factor achieved through the process can be as high as 1000x. In fact, the on-chip multiplication gain is actually a complex function of the probability of secondary-electron generation and the number of pixels in the multiplication register. Mathematically, it is given by

$$G = (1+g)^N,$$

where N is the number of pixels in the multiplication register and g is the probability of generating a secondary electron in a single stage, typically 0.012. Although the probability is low, the total gain can be quite high, owing to a large number (N) of pixels in the multiplication register. As a typical example, a CCD with $N=400$ produces an on-chip multiplication gain (G) of 118.

The probability of secondary-electron generation, g, is dependent on the voltage levels of the serial clock and the temperature of the CCD. Therefore, the total on-chip multiplication gain (G) has a complex exponential relationship with the voltage, temperature, and number of stages. **Figure 2** clearly illustrates that the "last few volts" of the applied voltage result in a large increase in the on-chip multiplication gain. In practice, the level of voltage is commonly mapped to a high-resolution DAC (digital-to-analog converter) and controlled through software.

CCD Cooling

Another factor that influences on-chip multiplication gain is the CCD temperature. Simply put, the colder the temperature, the more likely it is for a primary electron to generate a secondary electron in the silicon, resulting in higher gain (see **Figure 3**). Studies show a threefold to fourfold improvement in the on-chip multiplication gain due to detector cooling. This strong performance dependency underscores the importance of choosing the optimum CCD temperature and preventing it from fluctuating with the environment.

Of course, cooling also reduces the dark current (charge generated by thermal excitation in the absence of light) that is generated in each pixel. Minimizing the dark current is particularly important because this undesirable charge is multiplied along with the useful, photon-generated charge in the extended register.

Noise Factor

On-chip multiplication gain is a probabilistic phenomenon, which means that there is a statistical deviation in the gain (often, the reported on-chip multiplication gain is an ensemble average). The deviation or uncertainty in on-chip multiplication gain, which is related to the pulse-height distribution found in various scientific literature, introduces some amount of additional system noise, quantified by "noise factor"(F). To date, this noise factor has been measured to be between 1.0 and 1.4. While preliminary studies indicate that the noise factor is constant at moderate gain levels, it does increase substantially at extremely high gain levels. This fact warrants the judicious use of on-chip multiplication gain.

The following equation summarizes the total noise generated in a CCD with on-chip multiplication gain. (For simplicity's sake, dark current is ignored. If the detector is not cooled, this contribution must be introduced into the calculation.)

$$\sigma_{Total} = \sqrt{(S^*F) + (\sigma_R/G)^2}$$

where σ_{Total} = Total noise introduced into the system
S = Number of photon-generated electrons (signal)
F = Additional noise factor
σ_R = Read noise of the detector
G = On-chip multiplication gain

The term σ_R/G is the effective read noise of the detector as a result of the on-chip multiplication gain.

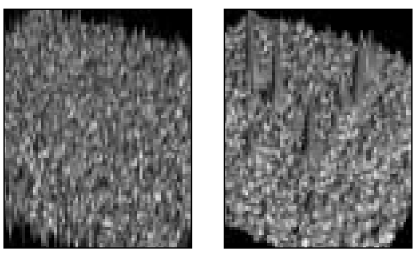

Figure 4. Single molecules of perylene diimide in polymethylmethacrylate gel. Fluorescence emission acquired using a Photometrics Cascade camera with "on-chip multiplication gain" off (left) and on (right). SMF images courtesy of Kallie Willets and Stefanie Nishimura, W.E. Moerner Lab, Department of Chemistry, Stanford University.

Technology Comparison

Much of the sensitivity advantage offered by traditional, cooled CCD cameras comes from their ability to integrate signal on the chip prior to readout — and thereby only incur read noise once during measurement. Hence, for the long exposures required in many low-light-level applications, frame rates for these cameras are low.

However, the extremely low read noise attainable with on-chip multiplication gain allows images to be acquired by running the new devices at "live" frame rates, with the individual frames being added together in the host computer. This ability greatly improves the utility of the new detectors for low-light-level work.

The net result is that the new devices boast the sensitivity of intensified and electron-bombardment CCDs, but don't carry the risk of potential damage to external image-intensifier hardware. And because no photocathode or phosphor is involved, the spatial resolution provided is as high as that offered by standard CCD imagers with the same array and pixel size.

When properly integrated in a high-performance digital camera platform, the new CCDs provide researchers an excellent choice for nongated, low-light-level applications that require video (or supravideo) frame rates and excellent spatial resolution. Examples of such applications are SMF, intracellular ion imaging, and biological fluid flow measurements (see **Figure 4**). When the new detectors are deeply cooled, with the on-chip multiplication gain sufficiently higher than the read noise and a low photon-arrival rate, even photon counting should be possible without image-intensifier hardware.

[1] Roper Scientific technical note #4 — Low Noise: An Integral Part of High-Performance CCD (HCCD) Camera Systems

[2] Roper Scientific technical note #11 — Introduction to Image Intensifiers for Scientific Imaging

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