*The LLLCCD : Low Light Imaging without the need for an intensifier

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ABSTRACT

A new CCD sensor technology has been developed by Marconi Applied Technologies (Chelmsford, UK) which effectively reduces read-out noise to less than one electron rms[1,2,3]. A single Low Light Level CCD (LLLCCD) can operate over a wide range of read-out rates from TV to slow-scan and give superior performance to that available from either intensified or slow-scan CCD sensors.

Keywords : CCD, Low Light, Photon counting, Dynamic range

1. INTRODUCTION

The technological drive for CCDs used in scientific imaging applications has been towards the detection of ever smaller signals at increasing pixel rates. In order to form images at low photon flux, all of the noise components within the CCD must be minimised and the signal maximised, i.e. essentially by achieving high quantum efficiency. This paper is primarily concerned with noise reduction, but quantum efficiency will also be discussed.

The two main sources of temporal noise in a CCD are amplifier noise and shot noise associated with the thermally generated "dark signal". Amplifier noise can be reduced by minimising the output node capacitance. State-of-the-art amplifiers have the capacitance as small as 10 fF and achieve noise with a floor value of less than 2 electrons at very low read-out rates, rising to tens of electrons at MHz rates. The dark signal can be reduced by use of inverted mode operation (IMO), also called multi-phase pinned (MPP), and/or by cooling.

The new device structure utilises an amplifier of conventional design but applies gain to the signal charge prior to the output node. This effectively reduces the magnitude of the amplifier noise, which can now be less than 1 electron at MHz rates. In operation, a trade-off can be made between dynamic range and pixel rate and, under low flux density conditions, photon counting is possible.

2. LLLCCD Technology

2.1 LLLCCD Architecture and Function

The architecture of a frame transfer device designed using the new LLLCCD technology is shown in figure 1. The image, store and read-out register are of conventional design, but there is an extended section of "gain" register between the normal serial register and the final detection node. The design of the gain register is as shown schematically in figure 2. Two of the phases (Ø1 and Ø3) are clocked with normal amplitude drive pulses (typically 10 volts), whereas the drive pulses of the third phase (Ø2) are of

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a much higher amplitude (typically 40-50 volts). Before each Ø2 electrode is another electrode (Ødc) held at a low d.c. voltage (typically 2 volts). The large potential difference between Ødc and Ø2 gives rise to a high electric field in the underlying silicon such that electrons transferred from Ø1 to Ø2 during the normal clocking sequence can experience avalanche multiplication, which thereby increases the number of electrons in the charge packet, i.e. gain. Although the mean gain per stage (R) is generally small, typically 0.01, over the large number of stages of a typical read-out register the total gain, given by:

$$G = (1+R)^n$$

can be usefully high, e.g. 145 with n = 500. Adjustment of the gain is possible with fine control of the high amplitude clock pulse. The gain register generally has the same number of elements as the normal serial register such that its inclusion simply results in a one-line delay in the read-out sequence.

These gain figures are not fixed, as with a conventional amplifier, but are essentially mean values arising from the combination of numerous statistical events. For input of N electrons per element to the gain register the gain fluctuations may be expressed as causing an input-referred fluctuation of $\sqrt{N}$ electrons. Hence, if the input signal has associated shot noise of $\sqrt{N}$ electrons, the effective input-referred noise with gain becomes $\sqrt{(2N)}$. The total input-referred noise equivalent signal (NES) in darkness is therefore given by:

$$NES = \sqrt{(2N_d + N_a^2/G^2)} \quad \text{electrons rms}$$

where N_d is the mean dark signal in electrons per element and N_a is the amplifier noise in electrons rms.

Achieving highest performance therefore requires both minimal dark signal and G larger than N_a.

The maximum gain per stage, as set by the onset of excess noise, is found to be about 0.015.

Figure 1 Frame transfer LLLCCD

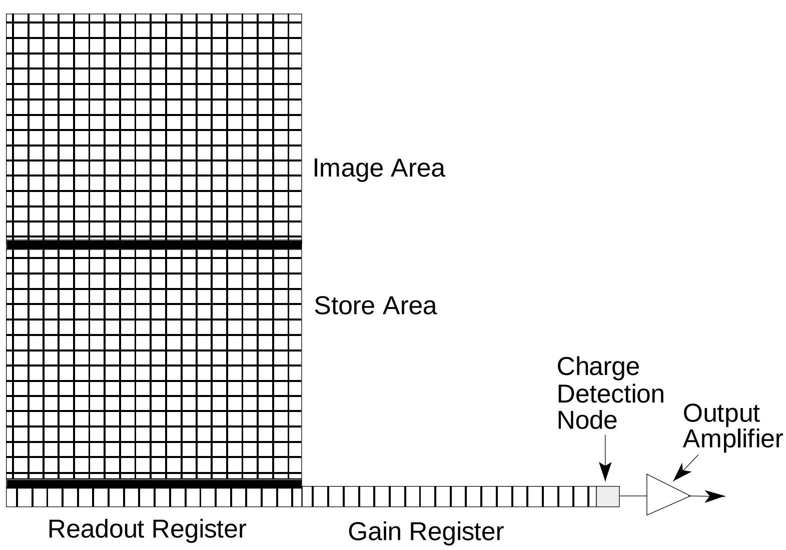
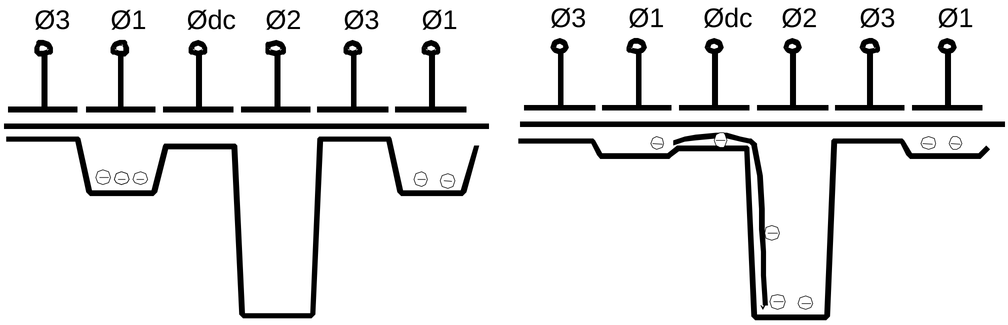


Figure 2



It may be noted that a previous implementation of a CCD with avalanche gain[4] suffered from excessive spurious charge generation, largely caused by the use of virtual-phase electrode technology. The current Marconi devices are of more-conventional electrode technology and do not suffer from this problem. The previous implementation also achieved gain in all sections of the device, giving rise to the problem of noticeable spatial variations. The LLLCCD technology pipelines all charge through the same gain structure, thereby avoiding the spatial variations of gain.

It should be noted that avalanche gain shows a strong temperature dependence[5]

2.2 LLLCCD : CCD65

The CCD65 is the first commercial device to use LLLCCD technology. It comprises a nominally 1-inch format TV frame-transfer device with interlace, IMO/MPP and shielded-drain antiblooming capability. There are 576 elements per line, and read-out at approximately 11 MHz is required for TV rate operation. The full-well capacity is about 100k electrons per pixel.

The detection node capacitance is 65 fF and the associated reset noise is about 100 electrons rms. At lower read-out frequencies (i.e. not related to TV rates) correlated double sampling (CDS) can be used to suppress the reset component giving noise with a low-frequency floor value of about 4 electrons rms, rising to about 10 electrons rms at 1 MHz. At the 11 MHz TV rate the noise with CDS is about 35 electrons rms, and it can be preferable to use simpler non-CDS circuitry and accept the higher reset-dominated noise of 100 electrons rms.

3. Dark Signal

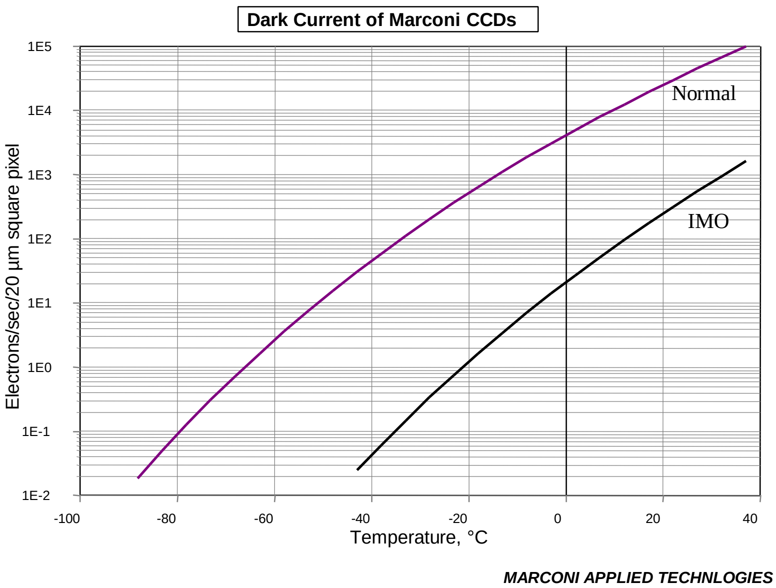
The dark signal can comprise both thermally-generated and transfer-induced components**.**

3.1 Thermally-generated dark signal

The thermal generation of dark signal in CCDs is well understood. Expressed as a current the dark signal at 20°C is typically 1nA/cm^2 for standard devices or 10pA/cm^2 for IMO/MPP devices. This dark signal reduces rapidly with temperature in the manner shown in figure 3. When using the new LLLCCD technology the dark current will need to be reduced further than is necessary with a standard CCD since, in a sparse signal situation, every electron is potentially significant. The actual temperature required will clearly depend on the integration time and application. For example, for a TV application where a dark signal level of an electron per pixel per frame can be accepted, the operating temperature for an IMO/MPP device would need to be about 10°C, but for a scientific application where longer integration times are required to detect sufficient photons, then dark charge of <0.1 electron per pixel could be necessary and the temperature will need to be reduced accordingly.

With the very low mean dark charge requirement for LLLCCD, dark signal non-uniformity is not generally significant.

Figure 3 CCD Dark Current



3.2 Transfer Induced Charge

Parallel clock transitions, particularly those with fast edges, are known to produce spurious charge by avalanche multiplication of holes in the column isolation regions. For most of Marconi's devices this effect is normally negligible, although it may be significant in IMO/MPP devices operated with multiple line binning, as is often practised in spectroscopy. With the new LLLCCD devices being operated at very low temperatures to reduce the thermal generation, clock induced charge can become the dominant noise source as the generation mechanism is largely temperature independent. There are two approaches that can be taken to address this problem. For the highest performance requirements it will normally be preferable to use non-IMO/MPP devices (as the transfer-induced charge in these tends to be at very much lower levels) and to operate at a lower temperatures. If operation is required at temperatures which make IMO/MPP devices essential, then these should be manufactured for operation with reduced clock voltage swing (as this minimises the surface fields causing the charge generation), which has the consequence of reducing the full well capacity.

4 Performance

4.1 Dynamic Range

As the gain G is increased, the effective read noise decreases with a consequent increase in dynamic range. This direct relationship continues until either :

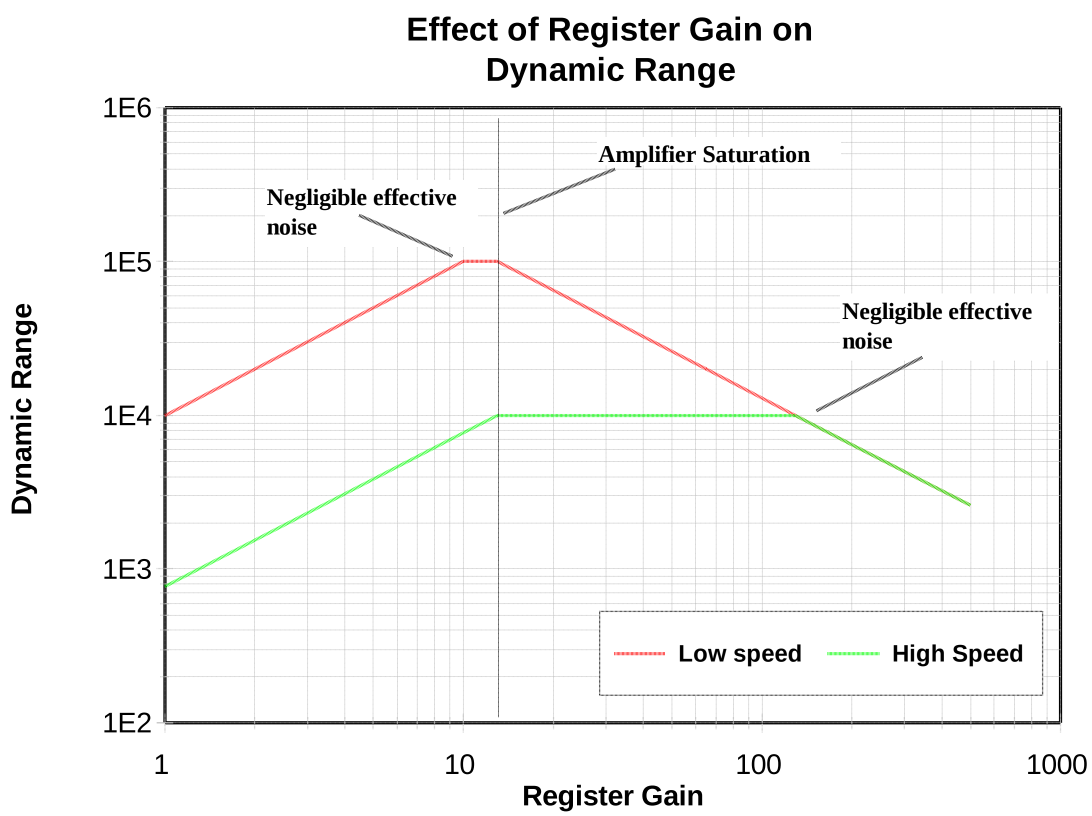
1. Read noise becomes negligible.
2. The "pixel full well with applied gain" exceeds the charge handling capacity of the output circuit

After the first of either of these conditions is achieved, dynamic range stays approximately constant until the gain is sufficient to reach the other condition. When both of these conditions apply, further gain increase restricts the number of detectable image electrons, so dynamic range falls.

This can be illustrated with reference to CCD65. The output circuit can handle about 1.3M electrons. Hence, with a pixel full well of 100k electrons, a gain of 13 will be sufficient to saturate the output.

Operating at high pixel rate without CDS, the gain will need to be set at least 100 to reduce the amplifier noise to below 1 electron, so the output will saturate before reaching the pixel full well. However, at lower pixel rates, say 1 MHz, the gain may now be set at only 10 to similarly reduce the amplifier noise. Under this condition the pixel could saturate before the output. These two conditions are shown in Fig 4

Figure 4

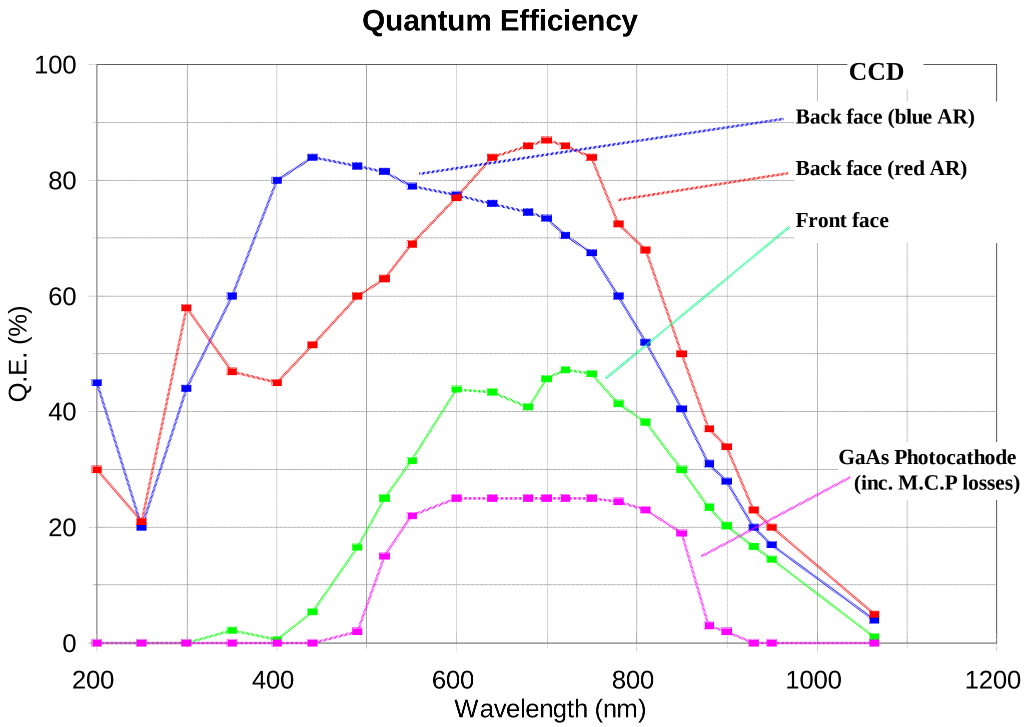


4.2 **Quantum efficiency**

As noted earlier, the ability to perform useful imaging at low photon flux levels requires both the reduction of all noise components and a high probability that a photon will be converted to a signal electron, i.e. high quantum efficiency. In this context, it should be noted that in an image intensifier with a channel plate, the photo-cathode quantum efficiency must be multiplied by the open area ratio of the channel plate to give a "useful quantum efficiency". The open area ratio of the CCD65 is 100%

Taking this into account, Fig 5 shows typical quantum efficiencies for image intensifiers and CCDs. It can be seen that a current front-illuminated CCD compares well with an intensifier and that back-illumination, as may be available with LLLCCD technology in the near future, can give significant improvements. The back-illuminated devices can have anti-reflection coatings optimised for the red or blue regions of the spectrum, as indicated.

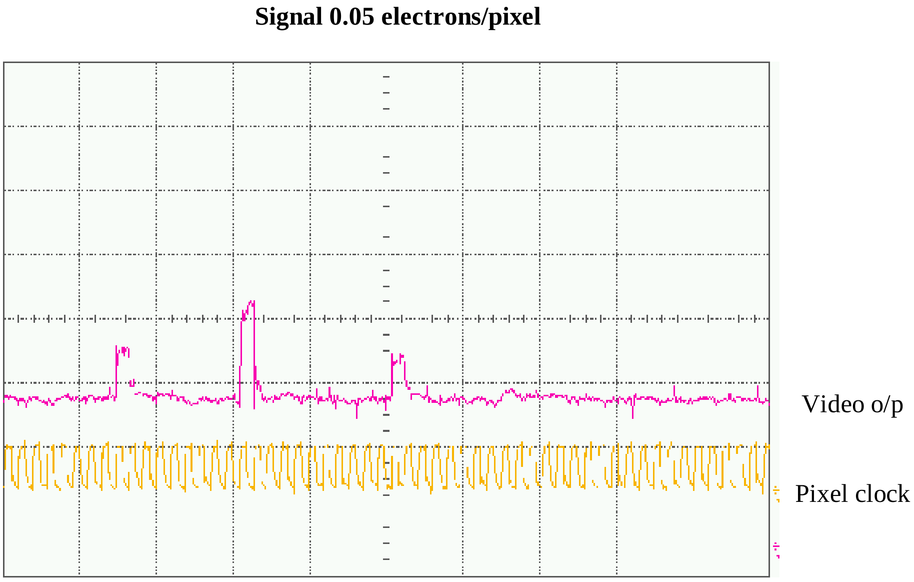
Figure 5



4.3 Photon Counting

The gain uncertainty described in section 2.1, (which is also present in intensifier systems) makes it impossible to determine from the output signal the exact number of signal electrons originally transferred from the pixel. Consequently photon counting is only possible with LLLCCD technology if the photon flux is of a sufficiently low density that no more than one electron is generated in any pixel during the integration period. Then, with the chip at low temperature to eliminate dark charge and the gain set at a suitable level with respect to the amplifier read noise, all output signals above a threshold may be counted as photon events. For normal imaging, the gain may be adjusted to give best dynamic range, as described earlier, but for photon counting gain can be set at >1000 to give best discrimination from amplifier noise. To illustrate this figure 6 shows raw video output at 11MHz with a mean signal of 0.05 electrons/pixel. The gain is set at about 1000, making single electron events large compared with the output circuit read noise of 100 electrons.

Figure 6 Single electron events



5 LLLCCD CCD Images

Figures 7a,7b,7c[6] are X-ray images of a: assorted objects, b: mobile ‘phone, c: human pelvis and lumbar vertebrae. These images are single frames from a video recording taken by lens coupling a CCD65 camera to a scintillator screen and demonstrate the low noise, uniform background available from these devices.

Figure 7a

Figure 7b

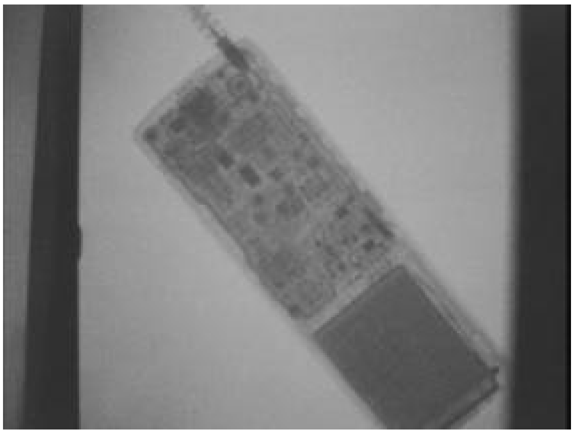
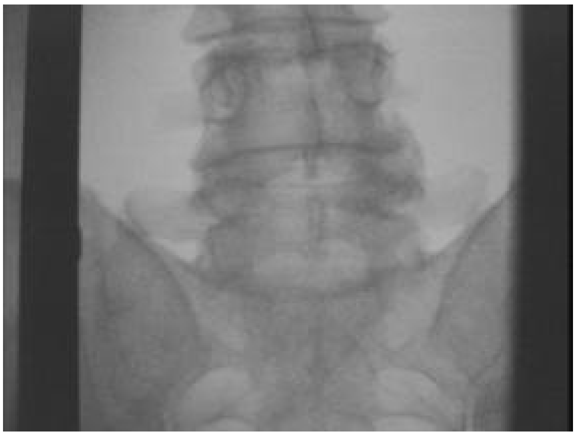


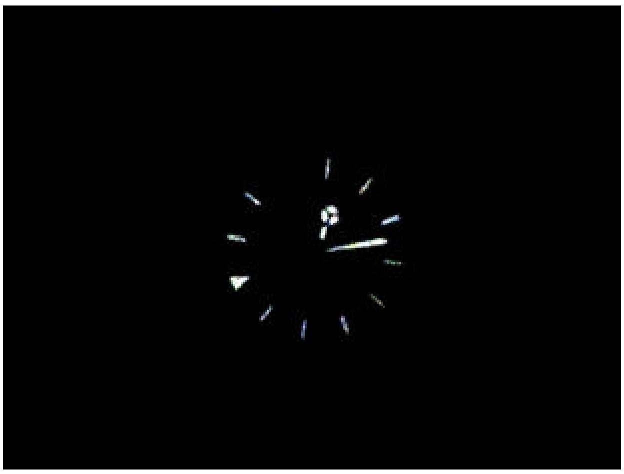
Figure 7c



Figures 8a and 8b are frames from video recordings of a luminescent watch. The image in Figure 8a was obtained using a “Super Gen II” image intensifier coupled to a CCD. This shows typical background ion scintillation and, though optimally focussed, displays an un-sharp image. The image from the CCD65 recording, in Figure 8b (taken 5 minutes earlier) has no visible background noise and gives a sharp image, as expected from direct CCD imaging .

Figure 8a

Figure 8b



6. Summary

The structure and characteristics of the new LLLCCD have been introduced. Early measurements support predictions of sub-electron read-out noise at up to high pixel rates, with the ability to discriminate single electron signals at >10MHz. The device is therefore capable of providing useful performance at the very low light levels where previously either intensified or slow-scan sensors were used.

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