A 30 fps 1920 x 1080 pixel Electron Multiplying CCD Image Sensor with Per-Pixel Switchable Gain

C. Parks, S. Kosman, E. Nelson, N. Roberts, and S. Yaniga
ON Semiconductor
1964 Lake Ave, Rochester, NY 14615 USA
christopher.parks@onsemi.com

***Abstract*—The dynamic range of an Electron Multiplying Charge Coupled Device (EMCCD) is increased by switching charge packets between the EMCCD output and a nonmultiplying output. The decision over the switching of a charge packet is based on data from a nondestructive floating gate amplifier. The image sensor is capable of imaging scenes with signals ranging from 1 e to 20 ke with a noise floor less than 1 e. An EMCCD gain of 20 at clock amplitude of 14.7 V has 0.7 e noise. The nonmultiplying portions of the CCD are compatible with standard 3.3 V CMOS logic.**

I. Introduction

Electron multiplying CCD (EMCCD) image sensors have existed for more than 20 years[1, 2], but they have difficulty with dynamic range. While they can have less than one electron noise, the maximum signal is limited by the charge capacity of the EMCCD. With a charge capacity of 100 ke and a gain of 100, the maximum input signal is 1000 e. Thus the dynamic range is only 60 db. The signal to noise ratio of the image is also reduced by the EMCCD excess noise factor.[3, 4] The EMCCD increases the photon shot noise by a factor of 1.4. A new image sensor with an EMCCD has been developed to overcome these limitations.

II. Image Sensor Architecture

A diagram of the image sensor output architecture is shown in Fig. 1. The 1920 x 1080 imaging pixels are divided up into four quadrants. Each quadrant transfers charge packets towards its respective corner of the image sensor. Each vertical CCD (VCCD) and horizontal CCD (HCCD) has reversible charge transfer capability so all pixels may be read out of one, two, or four corners of the image sensor.

Fig. 2 shows the output amplifier detail of each quadrant of the image sensor. The HCCD under the pixel array transfers charge packets to a nondestructive floating gate amplifier. The floating gate amplifier is used to determine the size of a charge packet before it reaches the EMCCD. If the charge packet is too large, it will bloom the EMCCD. In that case the timing of the charge switch is changed to route the charge packet to a floating diffusion output amplifier with no EMCCD gain. The charge switch routes the charge packet to the EMCCD if the charge packet is small enough to pass through the EMCCD without blooming.

The combination of the floating gate amplifier and charge switch allows the full dynamic range of the pixel to be utilized without prior knowledge of the image scene content. The EMCCD can always be set for maximum gain, minimum noise without concern for blooming. Any charge packet from 1e to 20ke may be measured with a

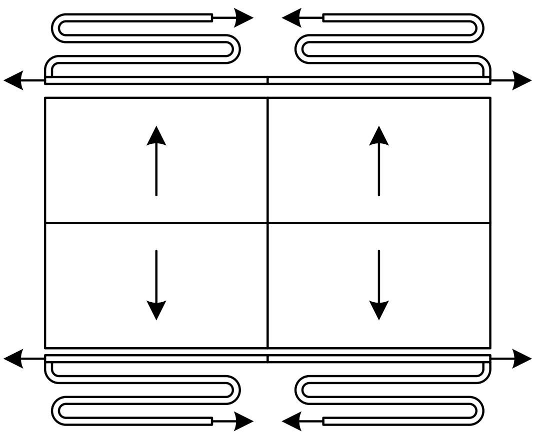

Fig. 1 The image sensor output architecture.

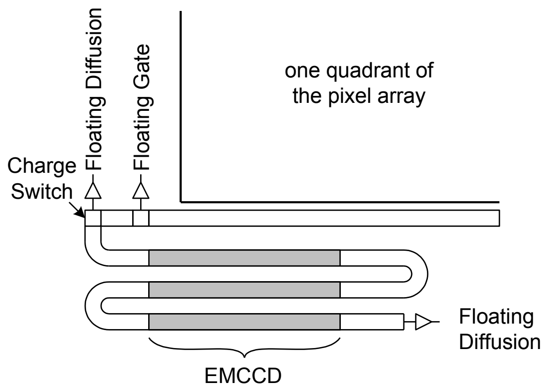

Fig. 2. The output amplifiers and EMCCD in each quadrant of the image sensor.

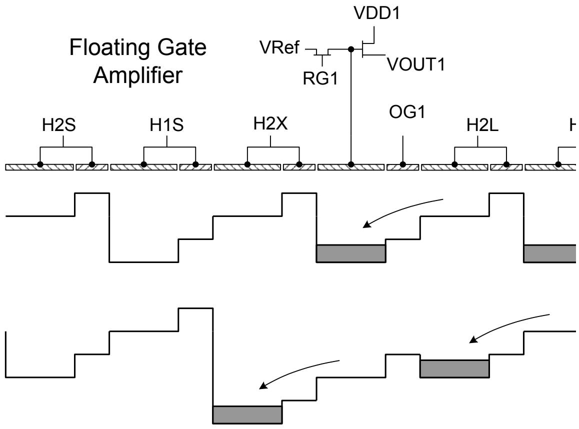

Fig. 3 Charge transfer through the floating gate amplifier.

noise floor of 0.7 e. Also, large signal charge packets are not routed through the EMCCD so they do not have the signal to noise ratio degraded by the EMCCD excess noise factor.

III. Floating Gate Amplifier

The floating gate amplifier shown in Fig. 3 has a charge to voltage conversion gain of 6.2 μV/e and a noise floor of 60 e. The HCCD gate voltages H1S, H2S, H2L, and RG1 are CMOS logic compatible at 0.0 to 3.3 V. The H2X gate requires 6.0 V amplitude to pull charge out from the floating gate. There is a reset transistor, RG1, attached to the floating gate to establish its DC offset to an internally generated voltage VRef. The RG1 gate is clocked high to hold the floating gate at a constant voltage while the H2X gate pulls charge out of the floating gate.

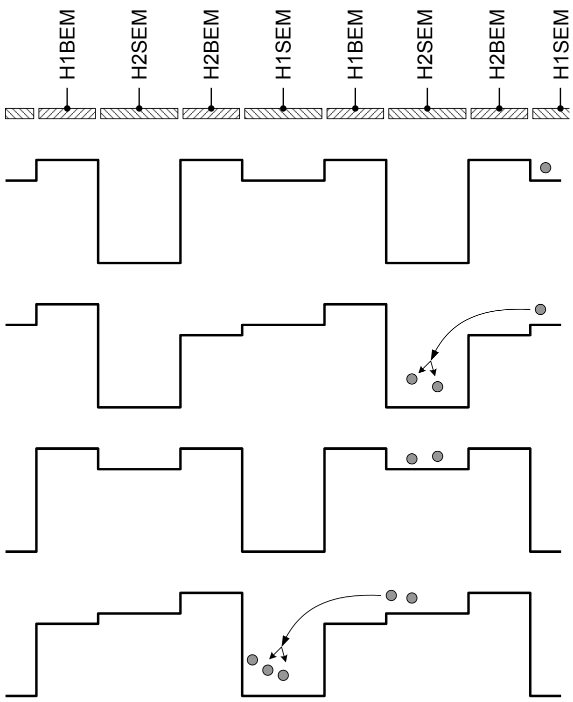

Fig. 4 The charge multiplication process in the EMCCD.

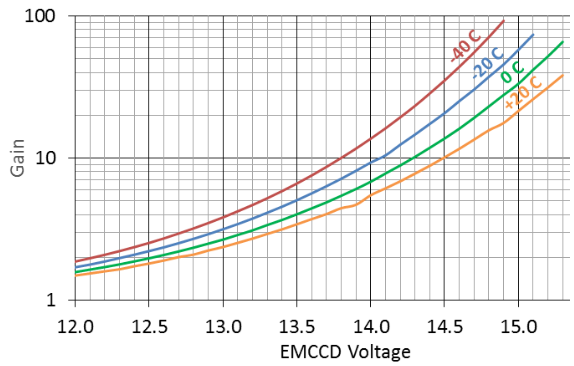

Fig. 5 The EMCCD gain vs. the high level voltage of the charge multiplying gates. The differenet curves are for temperatures from -40 C to +20C.

The DC voltage OG1 is generated internally on the image sensor.

The floating gate amplifier is only used as a threshold detector, not an imaging amplifier. A threshold of about 3 times the noise, 180 e, is the optimal threshold for switching charge between the EMCCD and the floating diffusion output with no multiplication.

IV. EMCCD

The EMCCD structure is shown in Fig. 4. The barrier gates H1BEM and H2BEM are 0 to 5 V clocks which hold back charge in the H1SEM or H2SEM charge multiplying gates. When the next gate has reached is maximum voltage the barrier gate is lowered to allow charge to pass through the high electric field to the next charge multiplying gate. The charge multiplying gates are clocked with a low level of 0 V and a high level ranging from 13 to 15 V. The amount of charge multiplication gain is determined by the high level voltage of the charge multiplying gate as shown in Fig 5.

There are 1,800 charge multiplying transfers in the EMCCD. The EMCCD is sized to only hold a maximum of 20 ke and does not have an overflow drain. It is not necessary to construct a large charge capacity EMCCD or overflow drain because the floating gate amplifier and charge switch prevent oversized charge packets from entering the EMCCD. Keeping the EMCCD small reduces the gate capacitance for less power and lowers the chance of spurious charge generation.

Fig. 6 shows the effective noise of the EMCCD (noise/gain) vs. gain. The noise for just the EMCCD was measured by directing the charge switch to not allow any charge to enter the EMCCD. The noise is also plotted when dark signal from the pixel array is allowed to enter the EMCCD. For the noise measurement the temperature was lowered to -40 C to eliminate dark current and the VCCD will also operate with a 4 V amplitude to eliminate VCCD spurious charge.

The effective noise of the EMCCD goes well below 0.1 e and shows no sign of spurious charge generation within the EMCCD. The effective noise of the pixel array reaches a minimum of 0.45 e. It has been determined that

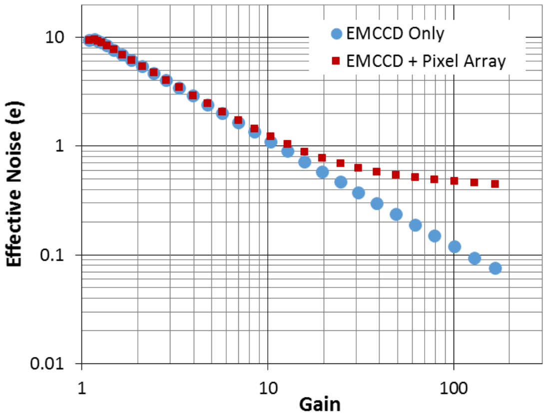

Fig. 6 The effective noise vs. EMCCD gain for just the EMCCD and the EMCCD + pixel dark signal. The temperature was -40 C.

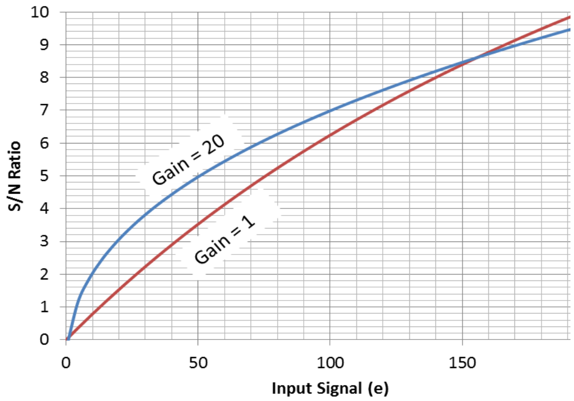

Fig. 8 The signal to noise ratio vs. signal with and without EMCCD gain

this limit is predominantly from output amplifier hot electron luminescence photons (amplifier glow) reflecting off the substrate backside and being converted to electrons in the photodiodes and VCCD during the 1/30 s image readout time. For long integrations the output amplifier power is turned off to eliminate the amplifier glow. Integrations as long as 12 hours have be done with no visible amplifier glow in the image.

The recommended operating gain for the EMCCD is 20 because higher gains provide little improvement. A gain of 20 still has a noise level less than 1 e.

In Fig. 7 the EMCCD gain was set to be 20 when the input signal is 180 e. The gain is plotted vs. input signal from 0 to 300 e. The gain is not constant so there is a small nonlinearity in the output signal vs. input signal. The gain increases with signal because when charge fills up the gate behind the barriers H1BEM or H2BEM the channel potential decreases. Then as the barrier is lowered the first electrons in the charge packet to spill over the barrier experience a higher electric field than do the last electrons in the charge packet.

The signal to noise ratio (S/N) with and without gain is shown in Fig. 8. The S/N of the EMCCD is larger than the output with no gain from 0 to 160 e. Above 160 e the photon shot noise and the excess noise factor of the EMCCD dominate over the output amplifier read noise. Therefore use of the EMCCD above 160 e degrades the image quality. With the recommended gain of 20 and a maximum recommended input signal of 180 e the maximum output signal of the EMCCD will be 3,600 e.

The full linearity curve from 1 e to 20 ke must be pieced together from the pixels that were and were not passed through the EMCCD. To piece together the two outputs, the nonmultiplied output needs to be digitally multiplied by the EMCCD gain to match pixels that passed through the EMCCD. Fig. 9 shows the full combined linearity curve with the nonlinear deviation from a straight line.

The operating temperature of the image sensor must be lowered. To obtain noise levels below 1 e there must be less than 1 e of dark signal in the image. Fig. 10 shows the image sensor dark signal vs. temperature. The three curves correspond to the number of outputs used to read out the image. The quad output curve has the lowest dark signal because the image is read out in 33 ms where the single output curve the image is read out in 110 ms. The dominant source of dark signal is from the VCCD. The VCCD dark signal is typically 100 times larger than the photodiode dark signal.

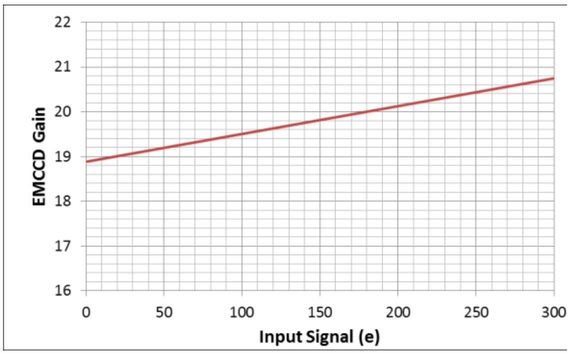

Fig. 7 The EMCCD gain vs. input signal.

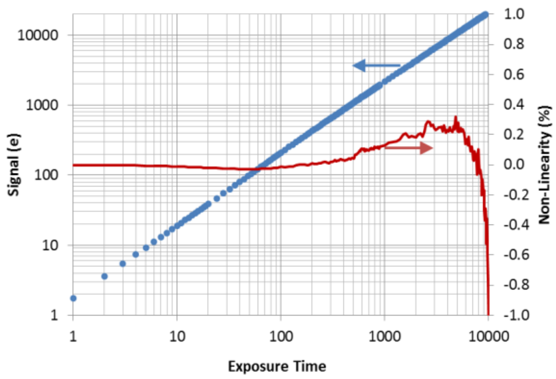

Fig. 9 The linearity plot after the EMCCD and nonmultiplied outputs have been combined.

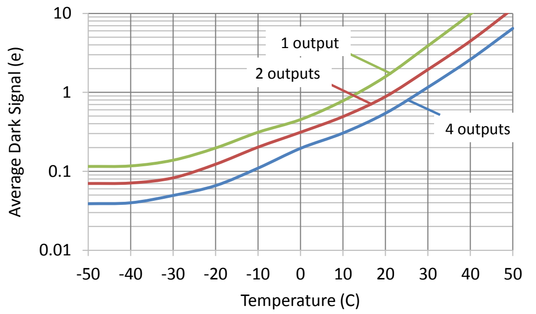

Fig. 10 The average dark signal vs temperature for 1, 2, and 4 outputs.

V. Reliability

Gain stability has always been a concern with EMCCD's[5]. The gain stability reliability testing of the EMCCD is in progress. As of this writing, a series of cameras operating 28 EMCCD's have been operating for 40 to 80 days. Fig. 11 shows how the EMCCD clock voltage to maintain a gain of 20 changes with time. One camera has no illumination, just dark signal at a temperature of 20 C. There is no measurable drift with no illumination.

The worst recommended operating condition is where every pixel in the image is continuously illuminated to 200 e. The current prediction is a 6 year lifetime. End of life is defined as a 1.5 V drift of the EMCCD clock voltage. After a drift of 1.5 V it is expected that the higher voltage may begin to accelerate the aging process through oxide dielectric breakdown. Actual usage is expected to have an average signal in the EMCCD much less than 200 e and a lifetime longer than 6 years. By achieving <1e- noise with moderate gains (20x), gain aging effects are reduced as a result of reasonable clock voltages (< 15V).

When exceeding the recommended signal level in the EMCCD the lifetime shortens. With an input of 500 e the predicted lifetime shortens to 3.5 years.

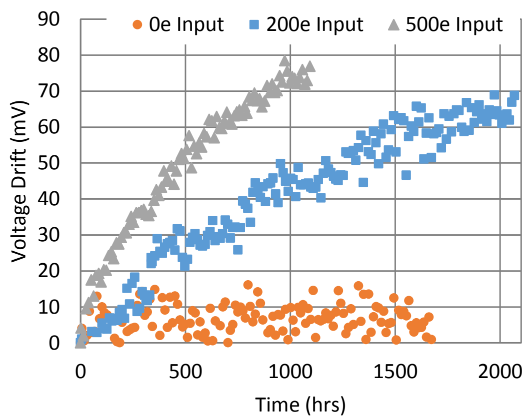

Fig. 11 The drift in the voltage needed to maintain a gain of 20 vs. time. The operating temperature is +20 C.

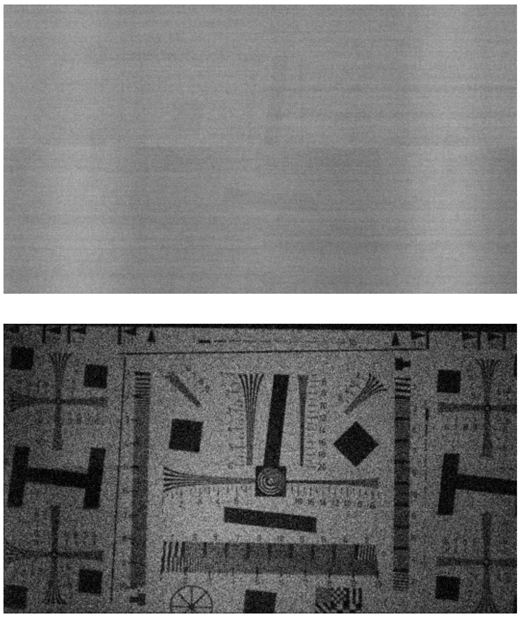

Fig. 12 top: an image with no EMCCD gain, bottom: the same image with an EMCCD gain of 30. The bright regions of the image have an average signal of 2e.

VI. Conclusion

We have successfully fabricated an EMCCD with an intrascene dynamic range of 86 db and a noise floor less than 1 e. Fig. 12 shows comparison images of the same scene acquired with and without the EMCCD.

VII. Acknowledgements

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VIII. References

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