0.3e- Read Noise @30fps 9.5Mpixel CMOS Image Sensor for Scientific Applications Requiring Photon Counting

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Introduction

Photon Counting has become very useful in the applications of Quantum Computing and confirmation of Quantum Entanglement. These scientific applications demand ever higher frame rates and quantum efficiencies, with noise values still low enough to allow photon counting. Photomultiplier tubes and single photon avalanche photodetectors (SPADs) can be used to detect photons. However, a limitation of these devices is that they don't allow for multiple photon detection. Generally, a read noise below 0.3e- is required to obtain single photon resolution, as shown in Figure 1. In this paper we show that Fairchild Imaging's HWK4123 9.5Mpixel CMOS image sensor (2308 x 4108) is capable of read noise below 0.3e-, at speeds up to 30fps. The HWK4123 was introduced a few years ago showing 0.5e- read noise (RMS) at room temperature at a readout rate of 120fps [1].

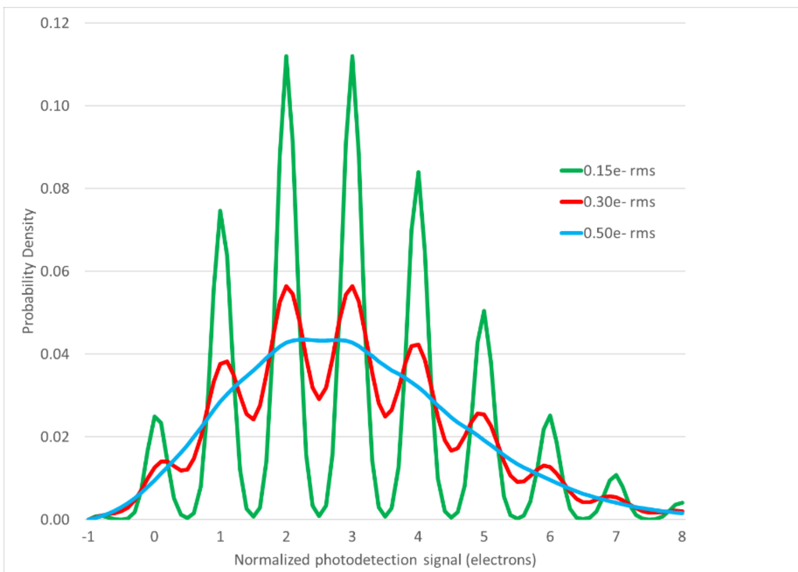

Figure 1: Photon # resolution, lambda=3, for 3 different read noises

Frame rate	temperature	read noise (RMS)
120fps	25C	0.40e-
30fps	25C	0.31e-
30fps	-12C	0.28e-
5fps	-12C	0.23e-

Table 1: 4123 noise vs frame rate

We have improved it. While increasing the original linear Full Well of 7,000e- up to 7,500e-, optimizing improvements have also allowed the HWK4123 to now achieve 0.28e- RMS read noise @30fps (@-12C) and 0.23e- read noise @5fps (@-12C). The latest optimization brings the room temperature noise down to 0.30e- at 30fps, and 0.40e- at 120fps. See Table 1. Figure 4 shows the read noise distribution of the 5fps @-12C measurement, with statistical peak at 0.18e- and median of 0.21e-.

[1] Kwang B Cho and B. Johnson, "0.5e- rms Read Noise CMOS Image Sensors…for Night Vision Application," 2023 International Image Sensor Workshop, R7.5

The sensor is fabricated in a 65nm backside (BSI) process, and with improved surface features to raise peak Quantum Efficiency (QE) from the initially report 87%, to the now measured > 90%. See Figure 2. We have also added new features: 12-bit ADC Rolling Shutter operation with a max frame rate of 76fps; and Global Shutter 50fps operation with a read noise of 2.6e-. Shutter efficiency of 99.9% was measured in Global Shutter mode.

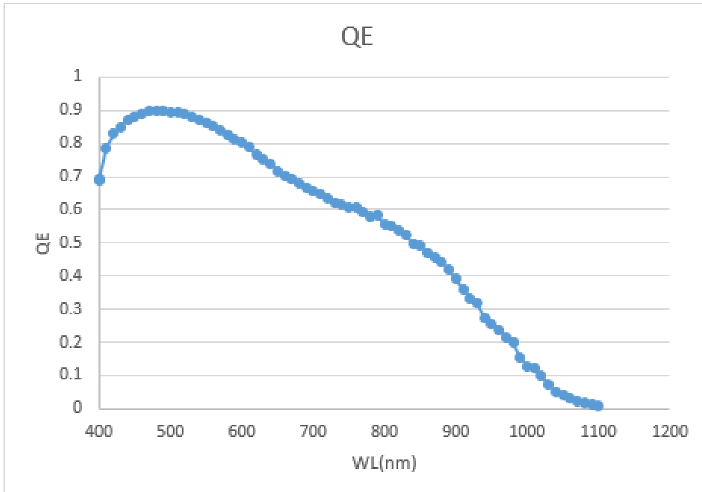

Figure 2: Quantum Efficiency, peak 90.1% @480nm

Photon Resolution

Below, we show the results of 12-bit mode image captures from a single pixel. For the histogram dataset in Figure 3, 135,000 frames at 5fps were captured at -12C with conversion set to around 30DN/e-.

For this, we chose a pixel with read noise of 0.19e- RMS at +25C and 0.13e- at -12C and plotted the distribution of pixel response. Illumination averaged around 2.1e-/pixel per frame. A Poisson distribution characteristic of photon-counting is observed, with highest peak centered at the DN value corresponding to 2e-.

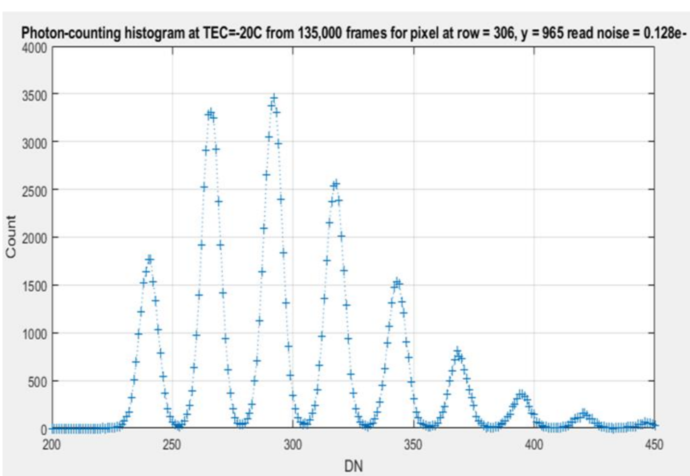

Figure 3: 12-bit photon resolution at -12C.

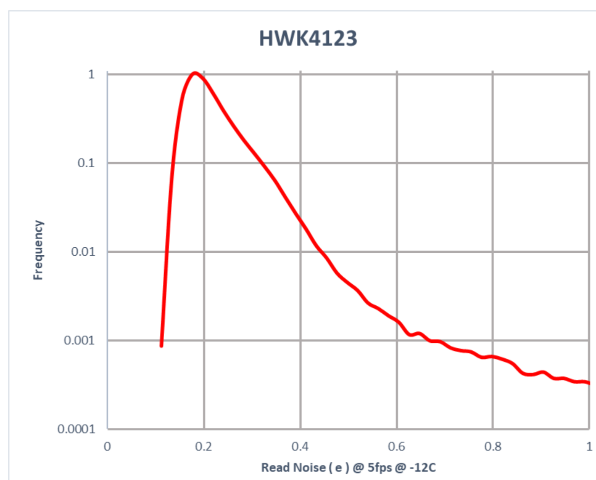

Figure 4: Read Noise distribution @5fps at -12C

In Figure 4, a histogram of the HWK4123 read noise taken from a 1000x1000 pixel area is shown. The peak of that distribution is 0.176e- (taken at 5fps and -12C), and the median is 0.205e while the reported and measured

RMS value[2] is 0.23e-. The HWK4123 pixel conversion gain is approximately 165uV/e-. Other photon counting sensors, such as J. Ma et al[3] use a conversion gain of greater than 300uV/e- to achieve low read noise (0.31e- median with a single sampling cycle). However, our customer requirement of 7,500e- full-well limited the conversion gain that we could use. Further, our speed requirements only allowed for a single correlated value sampling per pixel.

Consideration of photodiode dark current, PD DC, is also important at sub-micron read noise levels. Our camera includes a TEC for temperature control, and Figure 5 shows the PD dark current for chip temperatures between -12C and +54C.

	4123	
TEC	DC (e)	Chip Temp(C)
-20	0.02	-11.7
-10	0.06	-2.2
0	0.12	7.4
10	0.29	16.6
20	0.72	25.5
30	2.31	35.4
40	7.95	44.0
50	28.70	54.4

Figure 5: Photodiode dark current (e-/sec) at various junction temperatures.

At the lowest frame rates (e.g. 5fps), the floating diffusion (FD) conversion node could hold charge for more than 80us during each row's readout, so FD dark current had to be minimized as well. Fortunately, the HWK4123's Global Shutter mode uses the FD node for global pixel value storage allowing for easy measurement of the FD dark current. Photomask changes around the FD node were employed to minimize the FD DC.

Bandwidth control

Figure 6 shows the HWK4123 simplified analog signal path that includes the pixel, column amplifier, gain comparator, variable bandwidth buffer, sample and hold capacitors, and Analog to Digital Convertor (ADC) module. The column amplifier has two gain modes: a programmable high gain mode of up to 32x and a low gain mode of 1x. The gain comparator is used to automatically drop the gain to unity if the amplifier output exceeds vref_LG, an on-chip programmable reference voltage. The full well capacity is limited by the voltage swing at the floating diffusion node in low gain (1x) mode with a linear full well capacity of 7500e-.

Careful control of the column amplifier bandwidth facilitates minimum thermal noise contribution in high gain mode. For operation at 120fps, the bandwidth can be set to obtain an average read noise of 0.4e- rms. For lower frame rates, the variable bandwidth can be squeezed down as low as 4.2kHz in order to minimize thermal noise. Note that this variable bandwidth can be controlled dynamically (between 230KHz and 4KHz), so that the slew rate is not compromised.

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[2] In our RMS noise measures, the calculation is $N_{rms} = sqrt[mean(temporal\ variances)]$ Note: this is not a mean or median of the individual pixel read noise temporal RMS values, which would be generally lower.

[3] J.Ma, Zhang, et al, "A 0.19e- rms Read Noise 16.7Mpixel Stacked Quanta Image Sensor…", IEEE Electron Device Letters (Vol 42, Issue 6, June 2021)

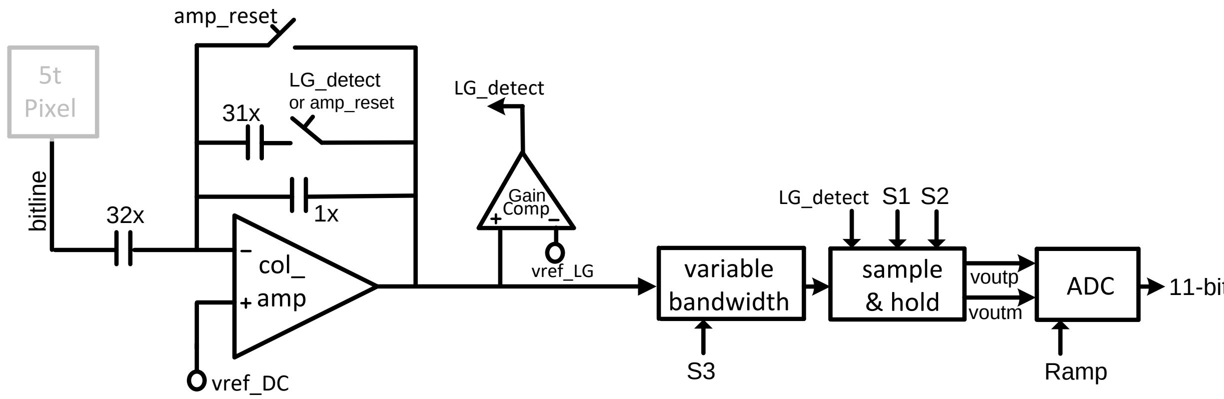

Figure 6: Simplified Analog Signal Path

Analog to Digital Conversion

The HWK4123 can provide dual-gain 11-bit data at up to 120fps, or fixed-gain 12-bit data at up to 76fps. The single-slope ADC ramp is programmable. Normally, the 11-bit high-gain 32x data would have a conversion factor of 7.8DN/electron, and the 12-bit high-gain data to have a conversion factor 15DN/e-. But, by reducing the ADC ramp height, the 12-bit conversion factor can be taken up to 30DN/e-. However, in this later state, the full-well achievable would be one half that with a nominal ADC ramp height.

Global Shutter operation

The HWK4123 can also now be run in Global Shutter mode, operating at 50fps, using a combination of two 100fps frames. Read noise of 2.6e- is measured at a fixed gain of 11x at room temperature. GS integration and readout can be triggered internally or through an External Trigger pin. Using internal triggering, the integration time can be as low as one row-time, or 8us. Shutter efficiency of 99.9% was measured. The full-well is reduced to 4.7Ke- from the 7.5Ke- seen in Rolling Shutter.

Summary

Changes to the optical layers, settings, and control waveforms have allowed improvements in the HWK4123 to achieve photon-counting sensitivity at speeds up to 30fps. Quantum efficiency was raised to greater than 90%, while full-well capacity was also improved by 7%. Two new modes of operation were introduced: 12-bit resolution with fixed-gain, and Global Shutter mode.

References

[1] Kwang B Cho and B. Johnson, "0.5e- rms Read Noise CMOS Image Sensors…for Night Vision Application," 2023 International Image Sensor Workshop, R7.5

[2] J.Ma, Zhang, et al, "A 0.19e- rms Read Noise 16.7Mpixel Stacked Quanta Image Sensor…", IEEE Electron Device Letters (Vol 42, Issue 6, June 2021)