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

Steve Mims, Kwang Bo Cho, Shabnam Ansari, Hung Do, Khai Nguyen, William Tian, Angel Lopez, Son Vo
Fairchild Imaging, Inc. | smims@fcimg.com, 408-433-2593 | 1841 Zanker Road, Suite 50, San Jose, CA 95112 USA

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.

frame rate	junction 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

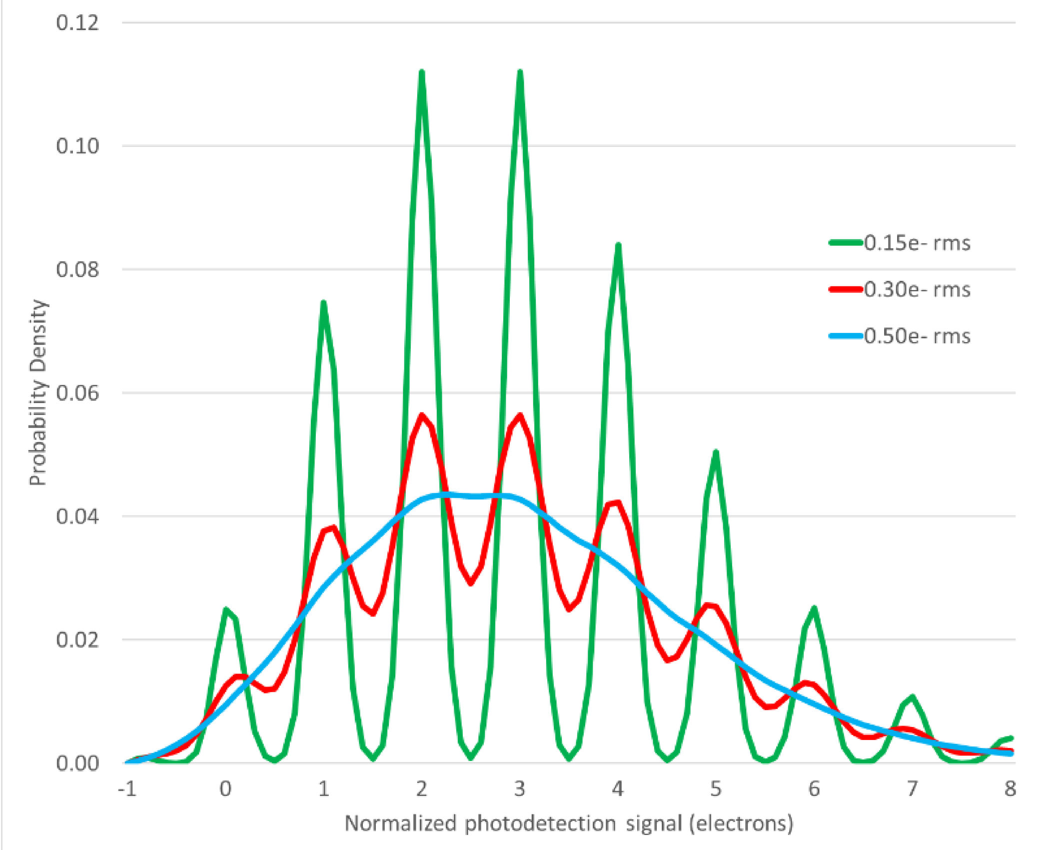

Figure 1: Photon # resolution, lambda=3, for 3 different read noises

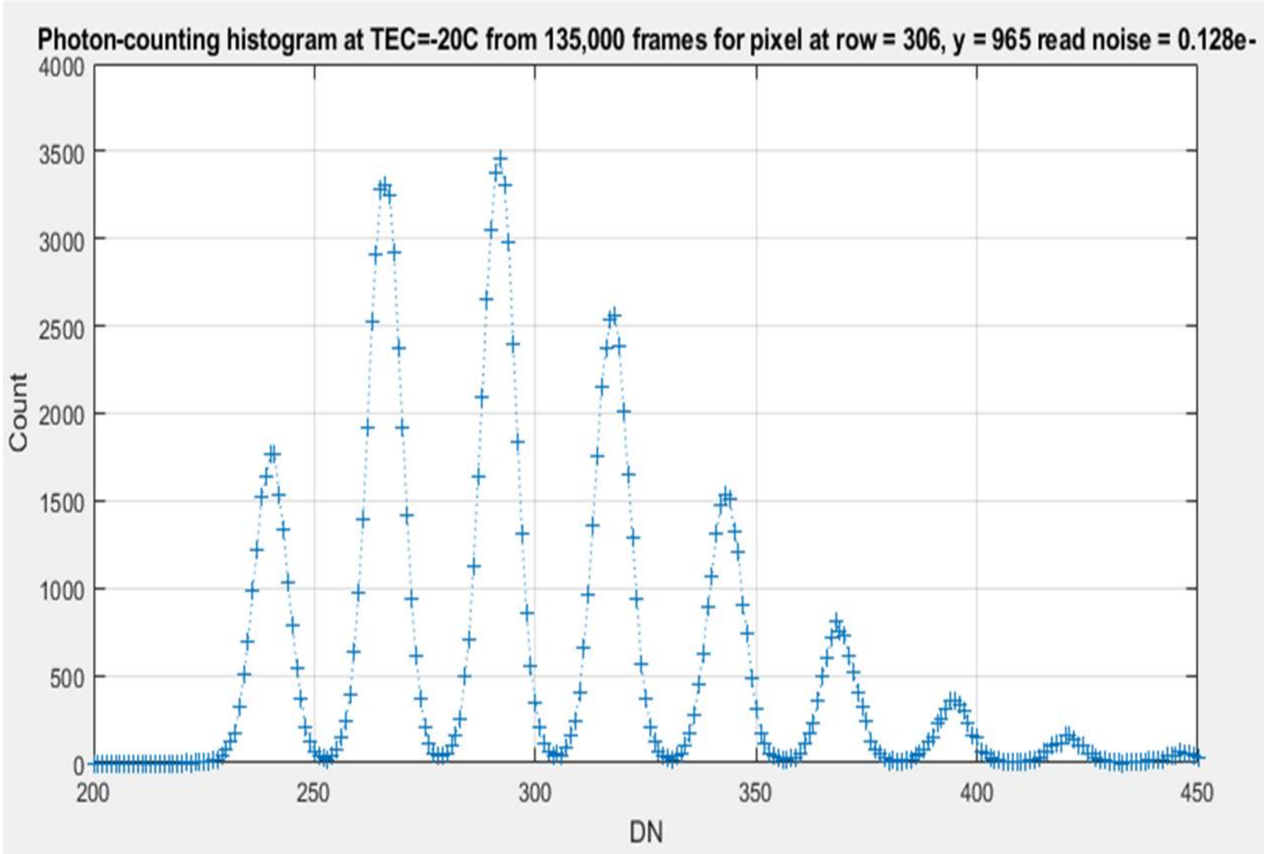

Figure 3: 12-bit photon resolution at -12C.

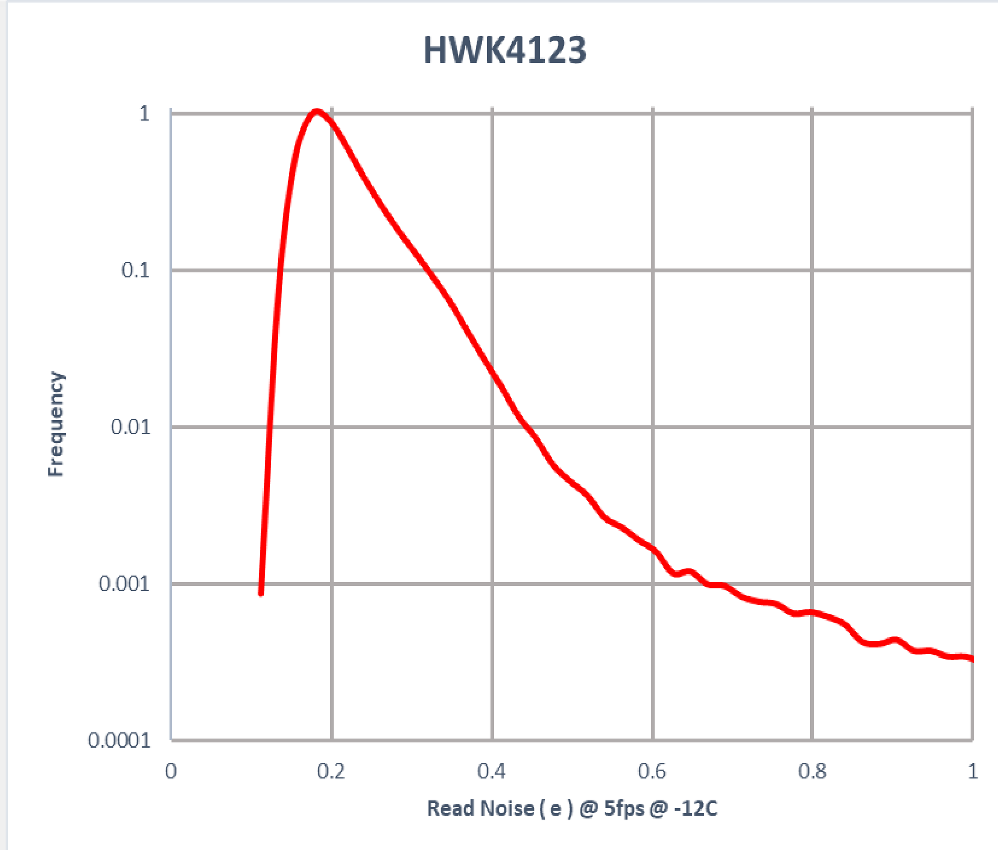

Figure 4: Read Noise distribution @5fps at -12C

Improvement: 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-**. 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.

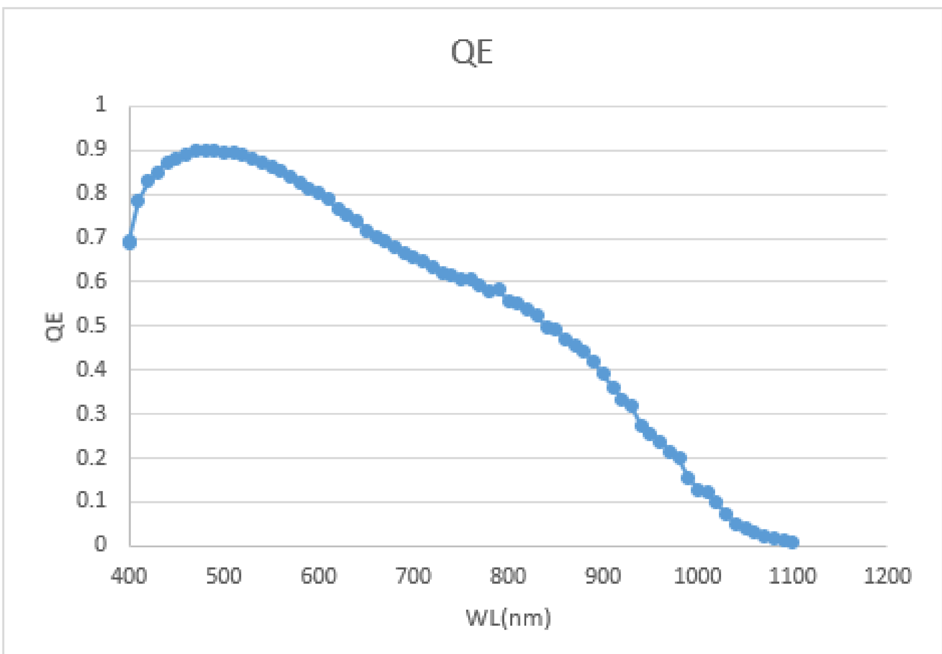

Figure 2: Quantum Efficiency, peak 90.1% @480nm

	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) vs temperature

Photon Resolution: 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 is 0.23e-. **Recently a customer reported measurement of 0.166e- RMS @5fps over their ROI, with their camera TEC set to -66C.** The HWK4123 pixel conversion gain is approximately 165uV/e-. Other photon counting sensors, such as J. Ma et al 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. 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.

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.

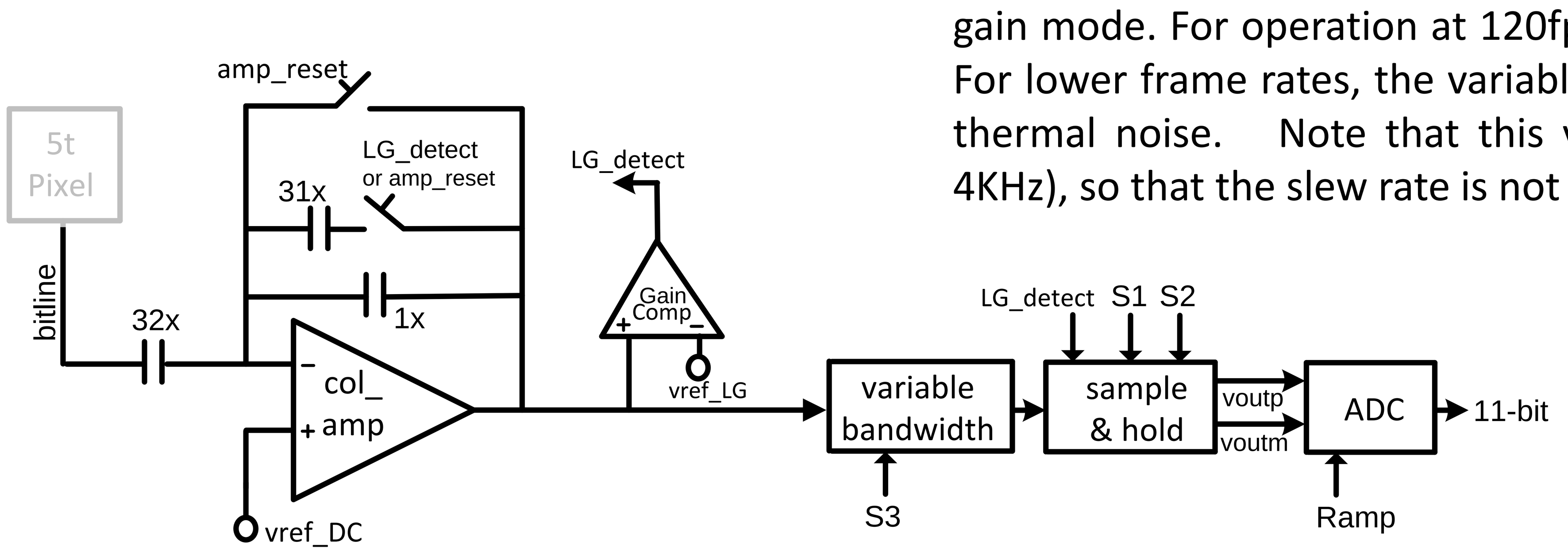

Figure 6: Simplified Analog Signal Path

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.