A Method for Estimating Quantum Efficiency for CMOS Image Sensors

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ABSTRACT

The standard method for measuring QE for a CCD sensor is not adequate for CMOS APS since it does not take into consideration the random offset, gain variations, and nonlinearity introduced by the APS readout circuits. The paper presents a new method to accurately estimate QE of an APS. Instead of varying illumination as in the CCD method, illumination is kept constant and the pixel output is continuously observed — sampling at regular intervals. This makes it possible to eliminate random offset. The experiment is repeated multiple times to obtain good estimates of the pixel output mean and variance at each sample time. The sensor response is approximated by a piecewise linear function and using the Poisson statistics of shot noise (which are also used in the CCD method) gain, charge and read noise are estimated for each line segment. This procedure is repeated at no illumination so that dark charge may be estimated and subtracted from the total charge estimates. The method can also be used to estimate readout noise and gain FPN. Results from 64×64 pixel APS test structures implemented in a 0.35 um CMOS process are reported. Using 6 different chips and 16 pixels per chip QE=0.37, gain FPN=2%, dark charge=832e-, and readout noise= 40e-, are estimated.

Keywords: Quantum efficiency, CMOS image sensors, gain FPN

1. INTRODUCTION

Quantum efficiency (QE) is the fraction of photon flux that contributes to the photocurrent in a photodetector or a pixel. Increasing QE improves sensor signal to noise ratio and dynamic range. Because QE is a complex function of the photodetector type (photodiode, phototransistor, photogate, etc.), the process technology, and the physical layout, in general it cannot be determined analytically or using simulation. Instead, it must be measured.

The standard method for measuring QE for a CCD image sensor, e.g. Janesick et al.,[1] cannot be used for CMOS active pixel sensors (APS) because the sensor output response as a function of the photogenerated charge for CCDs and CMOS APS are very different. In a CCD sensor the output response can be expressed as a linear function of the photogenerated charge plus readout noise assuming constant gain across the pixels. The constant gain is justified by the fact that in a typical CCD all pixels share the same output amplifier. As a result, differences between pixel responses are primarily due to differences in their photodetector characteristics, which are usually very small. In contrast, the output response for a CMOS APS can exhibit significant nonlinearity,[2] and pixel to pixel gain and offset variations, due to the presence of the column and pixel amplifiers which are not shared by all pixels.[3]

To measure QE of a CMOS photodetector, we proposed a single pixel test structure.[4] We designed the test structure to have highly linear response and very low noise, and added calibration circuits to accurately estimate the gain. Unfortunately, this test structure cannot be used to determine QE for an APS, since the structure of an APS pixel and our single pixel test structure are quite different.

In this paper we describe a method for measuring the QE of a CMOS APS. Like Janesick's method, we rely on the Poisson statistics of integrated shot noise to estimate the gain. But we also account for the CMOS APS output response nonlinearity, pixel to pixel gain and offset variations, and readout noise. We describe our method in the next section. In Section 3 we present results obtained from the 64×64 test structures.[4] The results are from a 0.35μm implementation of the test structures. Results from multiple pixels, and from multiple chips are presented. We also show how these results may be used to determine gain fixed pattern noise (FPN).[5]

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2. THEORY

A typical CMOS APS uses a time-sampled read out approach. After a certain integration time, pixel values are read out one row at a time, and then reset to a predetermined value. Our QE measurement method uses a different approach. The pixel outputs are continuously observed and externally sampled at regular time intervals during photocharge integration. Using this method the effect of amplifier offsets can be eliminated, and the nonlinearity of the APS response can be approximated by a piecewise linear response.

To estimate QE for an APS, we measure the output voltage under a uniform light field. We perform N independent experiments and measure a sample path consisting of M temporal output samples for each. We denote the samples by $V_{i,j}$, $i = 1, \ldots, N$ and $j = 1, \ldots, M$. Even under constant illumination, the sensor output response is a nonlinear function of time. We approximate the response using a piecewise linear model consisting of $K \geq 1$ segments. For each set of voltage output samples $V_{i,j}$, $j = 1, \ldots, M$, the first segment ranges from $j = j_0 = 1$ to j_1, the second from $j = j_1$ to j_2, and the last from j_{K-1} to $j_K = M$. The number of segments K is chosen by investigating several output sample paths and choosing a K which is large enough to provide a good fit, but small enough that the number of samples per segment is sufficient for data analysis. The pixel output within segment s, $0 \leq s \leq K-1$ is given by:

$$V_{i,j} = g_s Q_{i,j} + U_{s,i} + Z_{i,j}, \tag{1}$$

where g_s is the gain from the pixel to the sensor output of segment s measured in volts/electron, $Q_{i,j}$ is the charge, in electrons, collected at the jth sample time (of path i), $U_{s,i}$ is the offset of path i in segment s and is assumed to be random with unknown mean and variance. The charge $Q_{i,j}$ is the sum of the photogenerated charge $Q^l_{i,j}$ and leakage or dark charge $Q^d_{i,j}$. $Z_{i,j}$ is the readout noise which is assumed to be independent and identically distributed for all i and j, with zero mean and unknown variance σ^2_Z. The readout noise is also assumed to be independent of the charge samples $Q_{i,j}$, and the offsets $U_{s,i}$. Note that the gain g_s can vary from pixel to pixel. The following discussion will consider the output from a fixed pixel. Later we show how the estimated pixel gains may be used to estimate the gain FPN.

To eliminate the offset we normalize with respect to the first sample in each segment to obtain,

$$X_{s,i,(j-j_s)} = g_s(Q_{i,j} - Q_{i,j_s}) + Z_{i,j} - Z_{i,j_s}, \tag{2}$$

where $j = j_s + 1, \ldots, j_{s+1}$.

The charge increments $Q_{i,j} - Q_{i,j_s}$ are samples from a Poisson process and thus are Poisson random variables with mean and variance of $\mu^l(j-j_s)\tau + \mu^d(j-j_s)\tau$, μ^l is the average photocurrent, μ^d is the average dark current, and τ is time interval between two consecutive samples. Thus, the mean and variance of the sample $X_{s,i,(j-j_s)}$ are given by:

$$E[X_{s,i,(j-j_s)}] = g_s(\mu^l + \mu^d)(j-j_s)\tau \text{ and} \tag{3}$$

$$Var[X_{s,i,(j-j_s)}] = g_s^2(\mu^l + \mu^d)(j-j_s)\tau + 2\sigma^2_Z, \tag{4}$$

respectively.

To estimate QE we first compute the sample means and variances

$$\overline{X_{s,j}} = \frac{1}{N}\sum_{i=1}^{N} X_{s,i,j}, \text{ and} \tag{5}$$

$$\overline{\sigma^2_{s,j}} = \frac{1}{N-1}\sum_{i=1}^{N}\left(X^2_{s,i,j} - \overline{X_{s,j}}^2\right), \tag{6}$$

where $j = 1, \ldots, j_{s+1} - j_s$.

We then find the least squares estimates

$$\mathbf{P_s} = \begin{bmatrix} \overline{2\sigma^2_Z} \\ g_s\overline{(\mu^l + \mu^d)\tau} \\ g_s^2\overline{(\mu^l + \mu^d)\tau} \end{bmatrix}, \tag{7}$$

using

$$\mathbf{P_s} = (\mathbf{A_s}^T\mathbf{A_s})^{-1}\mathbf{A_s}^T\mathbf{Y_s}, \tag{8}$$

where

$$\mathbf{A_s} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 2 & 0 \\ 0 & 3 & 0 \\ \vdots & \vdots & \vdots \\ 0 & (j_{s+1}-j_s) & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 2 \\ 1 & 0 & 3 \\ \vdots & \vdots & \vdots \\ 1 & 0 & (j_{s+1}-j_s) \end{bmatrix}, \text{ and } \quad \mathbf{Y_s} = \begin{bmatrix} \overline{X_{s,1}} \\ \overline{X_{s,2}} \\ \overline{X_{s,3}} \\ \vdots \\ \overline{X_{s,(j_{s+1}-j_s)}} \\ \overline{\sigma^2_{s,1}} \\ \overline{\sigma^2_{s,2}} \\ \overline{\sigma^2_{s,3}} \\ \vdots \\ \overline{\sigma^2_{s,(j_{s+1}-j_s)}} \end{bmatrix}. \tag{9}$$

The charge collected in segment s is estimated by

$$\overline{Q^l_s} = \frac{\left(g_s\overline{(\mu^l+\mu^d)\tau}\right)^2}{\left(g_s^2\overline{(\mu^l+\mu^d)\tau}\right)}(j_{s+1}-j_s). \tag{10}$$

The same set of measurements and analysis is repeated at no illumination to obtain an estimate of the dark charge in segment s

$$\overline{Q^d_s} = \frac{\left(g_s\overline{(\mu^d)\tau}\right)^2}{\left(g_s^2\overline{(\mu^d)\tau}\right)}(j_{s+1}-j_s). \tag{11}$$

We define QE at a specific wavelength λ as the ratio of the photogenerated charge (in electrons) collected by the pixel to the number of photons incident on the entire pixel area. We assume that QE is a constant for a process run. Thus any variation in output responses are attributed to random noise or FPN. To estimate QE, we first estimate η^p, the estimate of QE based only on the outputs from pixel p, and then average it over p. The QE estimate based on pixel p output is given by

$$\overline{\eta^p} = \frac{\sum_{s=0}^{K-1}(\overline{Q^l_s} - \overline{Q^d_s})}{F \times T}, \tag{12}$$

where F is the number of photons incident on the pixel per second and T is the integration time. The QE estimate assuming W pixels is given by

$$\overline{\eta} = \frac{1}{W}\sum_{p=1}^{W}\overline{\eta^p}, \tag{13}$$

The estimate of QE can be used to estimate the gains of the pixels in each segment s. Let $\overline{X^p_{s,(j_{s+1}-j_s)}}$ be the mean output value of pixel p in segment s at the last sample $(j_{s+1}-j_s)$, then

$$\overline{g^p_s} = \frac{\overline{X^p_{s,(j_{s+1}-j_s)}}}{\overline{\eta}F(j_{s+1}-j_s)\tau}. \tag{14}$$

Gain FPN is the pixel to pixel gain variation within the same sensor chip. We define it, for each segment s, as the standard deviation $\overline{\sigma_{g_s}}$ of the gain

$$\overline{\sigma^2_{g_s}} = \frac{1}{W-1}\sum_{p=1}^{W}\left(\overline{g^p_s} - \frac{1}{W}\sum_{p=1}^{W}\overline{g^p_s}\right)^2. \tag{15}$$

3. RESULTS

In this section we present measured QE and gain FPN results from our 64×64 pixel APS sensor[4] fabricated in a 0.35μm digital CMOS process. A summary of the main sensor characteristics are provided in Table 1.

Technology	0.35 μm, 4-layer metal 1-layer poly, nwell CMOS
Number of Pixels	64×64
Pixel Area	14μm×14μm
Transistors per pixel	3
Fill Factor	29%
Photodetector	nwell/psub diode
Pixel Interconnect	Metal1 and Poly

Table 1. 64×64 APS Test Structure Characteristics

The setup used to measure QE is shown in Figure 1. It consists of a DC light source, a monochromator, an integrating sphere, and a calibrated photodiode. Each measurement is performed by irradiating the sensor with a monochromatic source through an integrating sphere. The pixels in the array are reset before each measurement. The output samples from each row of pixels are then measured. Each pixel output is sampled every $\tau = 400\mu$s to obtain $M = 240$ sample. The sensor output is amplified using a very low noise amplifier and then quantized using a 16-bit ADC. The experiment is repeated $N = 2048$ times for each pixel. A total of $W = 96$ pixels from 6 different chips were measured. Afer collecting the measurements from each chip, a calibrated photodiode is placed in the same position as the chip and the incident photon flux is measured. We made sure that the distance between the sensor and the exit port of the integrating sphere was at least five times the diameter of the integrating sphere's exit port to minimize photon flux measurement error.

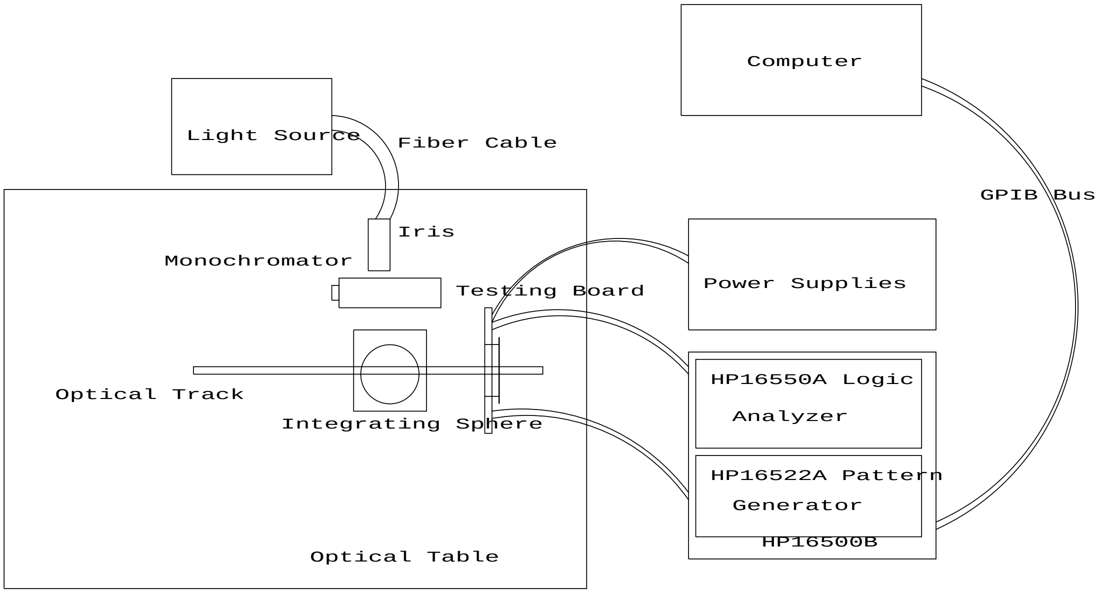

Figure 1. QE Measurement Setup

The output of a typical pixel irradiated with 1.76×10^{12} photons/(s×cm^2) at $\lambda = 600$nm is shown in Figure 2. We used $K = 3$ linear segments to approximate the response. The first segment consisted of 80 samples, while the second and third consisted of 81 samples each. The APS output mean and variance as a function of time are shown in Figures 3 and 4 respectively.

A histogram of the QE estimates from the 96 measured pixels is shown in Figure 5. The estimated QE for the process run at $\lambda = 600$nm is 0.37 electrons/photon and the estimated standard deviation is 0.028 electrons/photon. Using a gaussian error model with a confidence interval of 95% corresponding error in the QE measurement is ±15%. The estimated QE results from each chip are presented in Table 2.

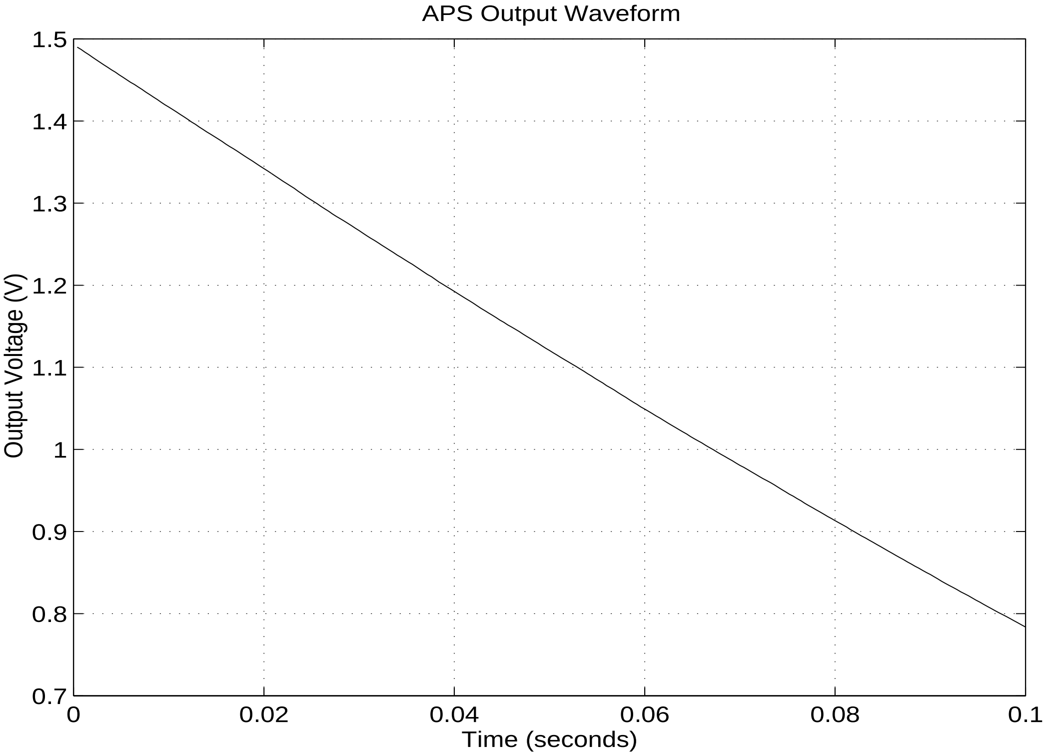

Figure 2. APS output waveform

	chip1	chip2	chip3	chip4	chip5	chip6	all chips
Mean	0.388	0.389	0.389	0.391	0.348	0.335	0.373
STD	0.020	0.015	0.015	0.015	0.017	0.014	0.028

Table 2. Estimated chip QE in electrons/photon. “All chips” refers to statistics from all measured pixels.

The estimated chip gain and gain FPN are presented in Table 3. The gain FPN for a chip is approximately 2% of the mean value of the gain. The QE number used in computing gain FPN is the average over all 6 chips.

In addition to estimating QE, gain, and gain FPN we can also use our measurements to estimate the dark charge collected by the sensor and the sensor readout noise. We estimated the average dark charge collected during the 96ms integration period (at 22°C) to be 832 electrons and its standard deviation to be 177 electrons. The estimated dark charge corresponds to approximately 0.05% of full well. Table 4 shows the estimated dark charge and the standard deviations for the 6 chips. The average chip readout noise σ_n is estimated to be 200μV at the output of the sensor. This corresponds to approximately 40 electrons of noise at the pixel. Note that our readout noise estimate does not measure the KTC noise caused by reseting the pixel.

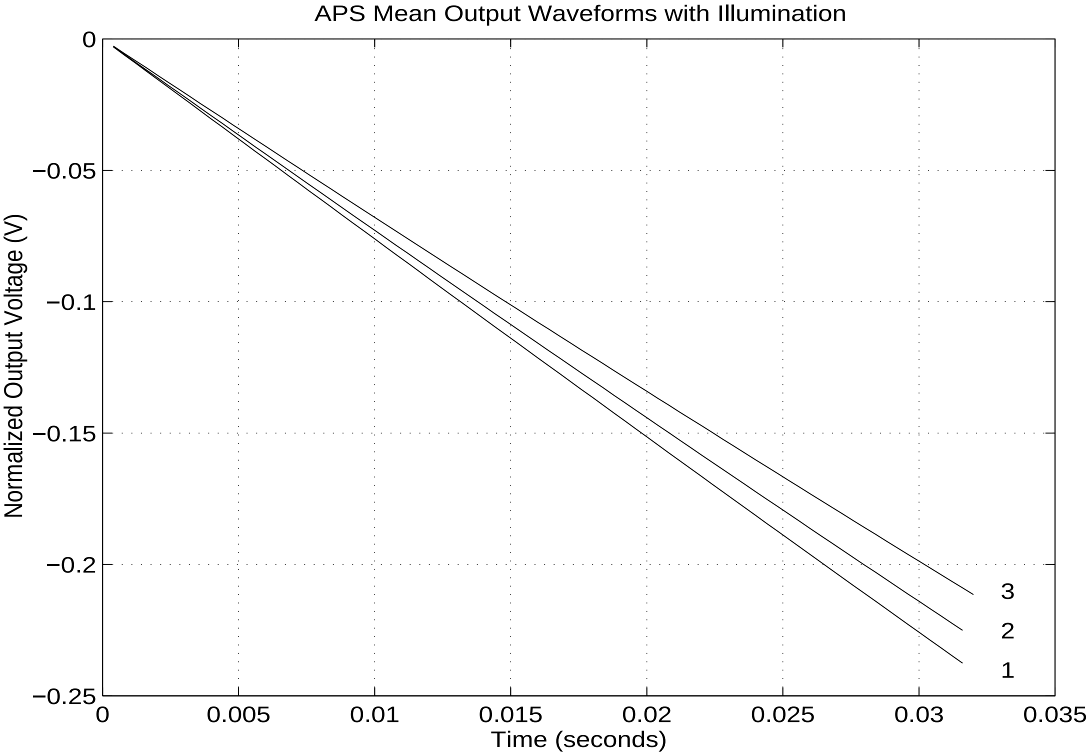

Figure 3. APS output mean as a function of time for segments 1, 2, and 3.

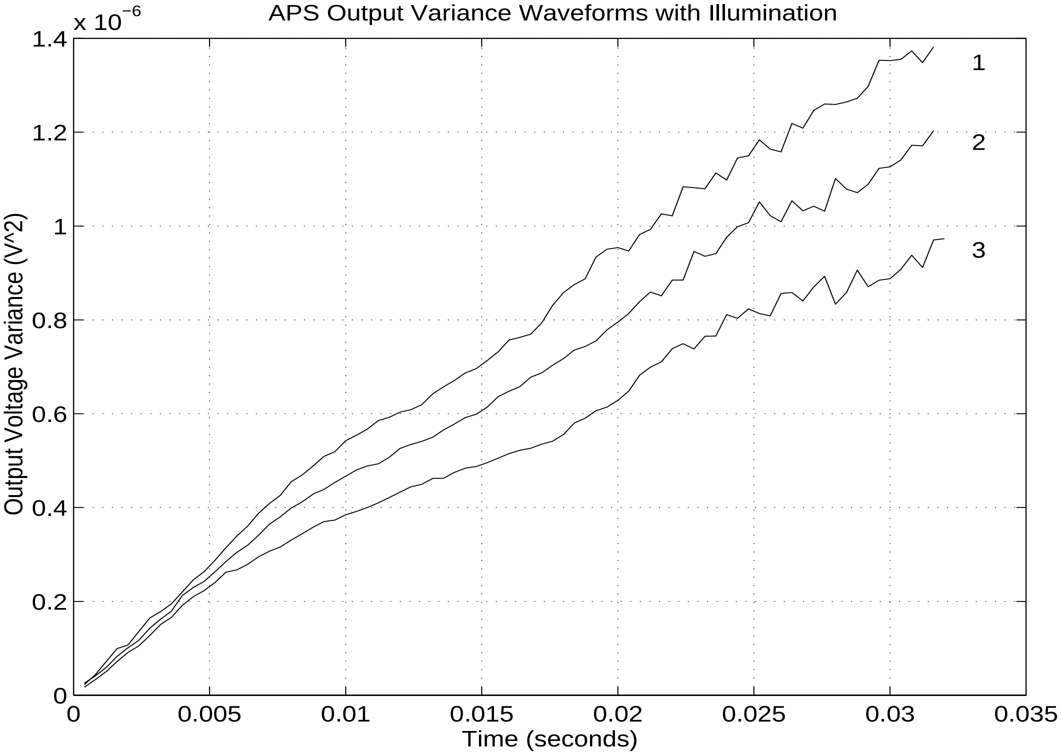

Figure 4. APS output variance as a function of time for segments 1, 2, and 3.

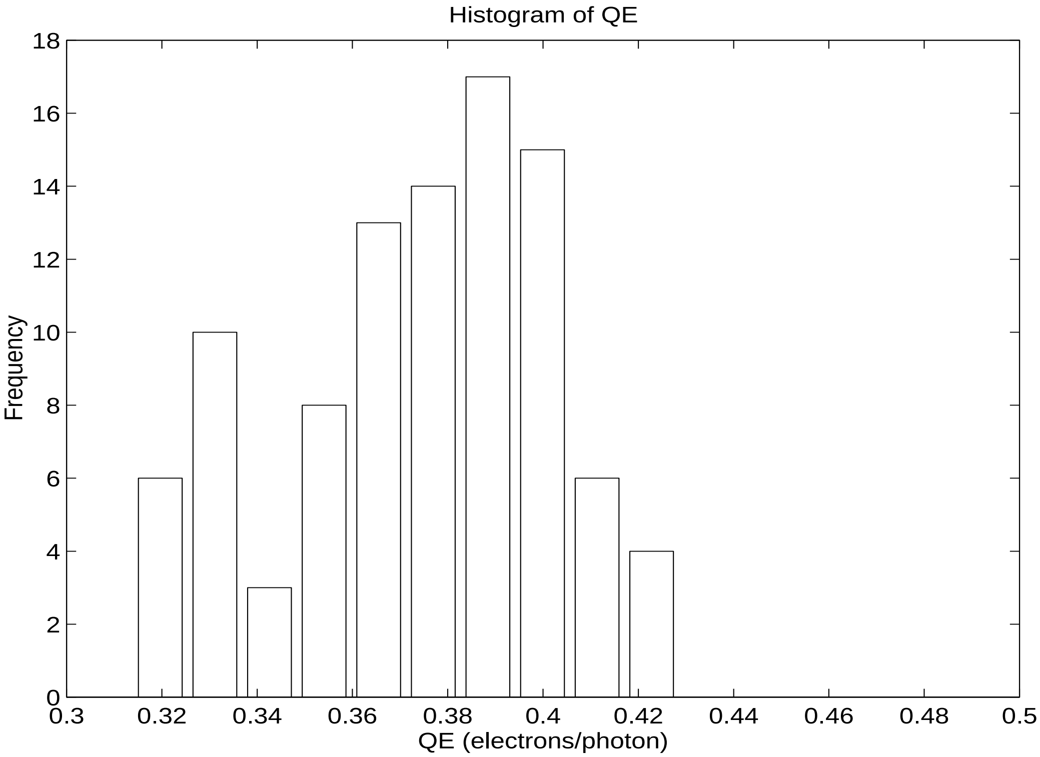

Figure 5. Histogram of measured QE for 96 pixels. The QE sample mean is 0.37 and standard deviation is 0.028.

segment	statistic	chip1	chip2	chip3	chip4	chip5	chip6	all chips
1	Mean	5.53	5.61	5.64	5.72	5.02	5.05	5.43
1	STD	0.10	0.10	0.11	0.10	0.10	0.08	0.30
2	Mean	5.23	5.33	5.38	5.45	4.78	4.83	5.17
2	STD	0.09	0.09	0.10	0.10	0.09	0.08	0.28
3	Mean	4.85	4.97	5.01	5.09	4.47	4.55	4.82
3	STD	0.08	0.09	0.10	0.09	0.09	0.07	0.25

Table 3. Estimated gain and gain FPN in μV/electron. "all chips" refers to statistics from all measured pixels.

statistic	chip1	chip2	chip3	chip4	chip5	chip6	all chips
Mean	849	764	910	817	887	765	832
STD	133	132	235	142	216	145	177

Table 4. Estimated dark charge in electrons. The dark charge was collected over a 96ms integration period at 22°C.

4. CONCLUSIONS

We described a new technique for estimating QE, gain, gain FPN, dark charge, and readout noise for CMOS APS. Our method is similar to Janesick's method in that it relies on the Poisson statistics of shot noise, but it also takes into consideration the nonlinearity of the APS response, gain variation, offsets, and readout noise. We provided a least squares method for estimating the gain and QE and demonstrated that the estimators have low error.

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