Charge Transfer Noise in Image Sensors

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***Abstract*— Charge transfer noise often limits the performance of image sensors when read noise is reduced to below 2e- RMS. Therefore, understanding the source or sources of charge transfer noise and how they can be reduced is essential for the design of ultra low noise image sensors. In this paper we analyze charge transfer noise in a 4T CMOS image sensor using a simple 1-D model.**

We investigate incomplete charge transfer noise and determine that it is not a significant source of transfer noise in 4T CMOS image sensor. Therefore, we conclude that the most probable source of transfer noise in 4T CMOS image sensors is charge trapping and detrapping at the Si–SiO2 interface during the charge transfer process. We propose a model for analyzing this noise based on a random sum of random telegraph signals. Finally we analyze this model and discuss how it can be verified.

I. Introduction

READ noise sets the fundamental detection limit for image sensors. Process improvements in modern image sensors have reduced reset noise and source follower noise to levels where other sources are starting to dominate. Specifically, charge transfer noise often limits the performance of image sensors when read noise is reduced to below 2e- RMS. Therefore, understanding the source of charge transfer noise and how it can be reduced is essential for the design of ultra low noise image sensors.

Charge transfer noise was first rigorously investigated in surface channel CCDs in the early 1980s by Omura and Owanda [1]. They derive the charge noise generated by surface trapping and detrapping while signal charge is moved from the photogate pixel to the output amplifier. Their model matches measured results for sensors with a large number of charge transfer stages and a large number of traps. Unfortunately, their results break down for cases when the number of charge transfers and or traps is small. Incomplete charge transfer noise has been reported in CMOS photogate sensors [2], CMOS pinned photodiode sensors [3] and hybrid CCD/CMOS image sensors [4].

In this paper we analyze charge transfer noise in a 4T APS using a 1-D model. This same model can be used for analyzing charge transfer noise in the final stage of a CCD or a hybrid CCD/CMOS image sensor. The remainder of this paper is organized as follows: Section II presents a 1-D model for analyzing charge transfer noise. The following section presents a detailed analysis of the 1-D model, and derives a closed form solution for the charge transfer noise power and its spectrum. The final section provides summary conclusions.

II. Transfer Noise Model

In this section we develop a simple model for charge transfer noise in 4T CMOS image sensors. A typical 4T CMOS image sensor pixel is shown in Figure 1. There are at least two possible causes for transfer noise, the first is incomplete charge transfer between the pinned photodiode and the floating diffusion node, and the second is charge trapping and detrapping at the Si–SiO2 interface [1]. Incomplete charge transfer results in variations in thermionic emission and or quantum mechanical tunneling from either a potential barrier or a potential pocket between the pinned photodiode and the floating diffusion node. Charge trapping also causes variation in the charge collected on the floating diffusion node.

In order to determine if incomplete charge transfer is a source of noise in 4T CMOS image sensors, we will estimate the average time required to empty charge from a small potential barrier or a small potential pocket within the pinned photodiode (see Figure 2). We will assume that thermionic emission is the dominant source of electron transport from the potential pocket to the floating diffusion node. In addition, we will assume that at $t = 0$ the potential pocket is filled with

[1] It is also possible that charge trapping occurs in the bulk, but typically the density of bulk traps is very low in modern CMOS processes.

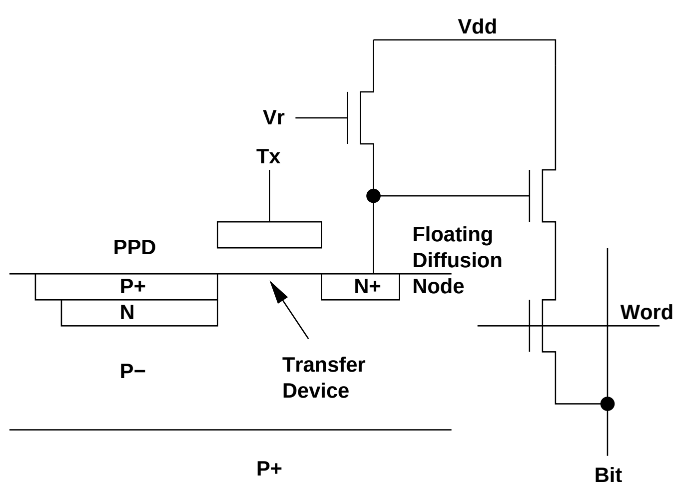

Fig. 1. 4T APS Pixel

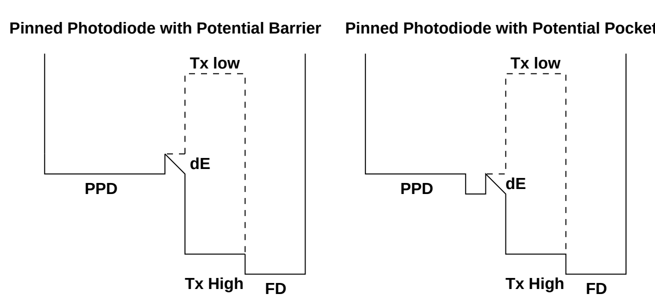

Fig. 2. Pinned Photodiode Energy Diagram

electrons. The probability of an electron being emitted from the potential pocket during a small time interval dt is equal to the probability that a given electron has enough energy to jump over the barrier times the probability that the same electron is close enough to the barrier to jump over, times the number of electrons inside the potential well, i.e.

$$P_r(N+1, t+dt|N, t) = \frac{1}{1+e^{-\frac{q^2N^2}{k\theta c_{pd}}}} \frac{(N_0 - N)v_{th}dt}{2l_{pd}}, \quad (1)$$

where N is the number of electrons emitted from the potential pocket at time t, N_0 is the number of electrons in the potential pocket at $t = 0$, v_{th} is the thermal velocity of electrons in the potential pocket at thermal equilibrium, l_{pd} is the length of the photodiode, q is the charge of an electron, k is Boltzmann's constant, θ is absolute temperature, and c_{pd} is the pinned photodiode capacitance. Note that dt can be made small enough such that the probability of emitting more than one electron during dt is vanishingly small. Equation 1 assumes that the location of each electron is uniformly distributed within the potential well, and that each electron is traveling to either the left or right with velocity v_{th}. When an electron hits the potential barrier it either bounces off the barrier or jumps over it. The probability of an electron bouncing off the barrier or jumping over it is determined by the Fermi-Dirac distribution, where the difference between the Fermi level and the barrier is assumed to be

$$\Delta E = \frac{q^2N^2}{k\theta c_{pd}}. \quad (2)$$

If we assume that electrons are independently emitted from the potential well with an exponential waiting time then using Equation 1 it can be shown that the probability density function of the emission time of the Nth electron, T_N, is

$$f(t_N|N) = \frac{1}{\tau_N} e^{-\frac{t_N}{\tau_N}}, \quad (3)$$

where t_N is the time between the emission of the Nth and $N+1$th electron, and

$$\tau_N = \frac{1}{1+e^{-\frac{q^2N^2}{k\theta c_{pd}}}} \frac{(N_0 - N)v_{th}}{2l_{pd}}. \quad (4)$$

The time to emit all N_0 electrons from the potential pocket is

$$T_{emission} = \sum_{i=1}^{N_0} T_i. \quad (5)$$

Therefore the average emission time is

$$\begin{aligned} E[T_{emission}] &= \textstyle\sum_{i=1}^{N_0} E[T_i] \\ &= \textstyle\sum_{i=1}^{N_0} \tau_i, \end{aligned} \quad (6)$$

and the variance of the emission time is

$$\begin{aligned} \sigma^2_{T_{emission}} &= \textstyle\sum_{i=1}^{N_0} (E[T_i^2] - E[T_i]^2) \\ &= \textstyle\sum_{i=1}^{N_0} \tau_i^2. \end{aligned} \quad (7)$$

Assuming that $N_0 = 100e-$, $v_{th} = 1.33 \times 10^5$m/s, $l_{pd} = 10\mu$m, $\theta = 300$K, and $c_{pd} = 4$fF, then $E[T_{emission}] = 0.821$ns and $\sigma_{T_{emission}} = 0.193$ns. Clearly the emission time of this process is much faster than the typical charge transfer time in a 4T CMOS image sensor, i.e. approximately 1μs. Therefore, even if our example is off by one or two orders of magnitude, due to the 1-D approximation, incomplete charge transfer is not a significant source of charge transfer noise. If lag in the pinned photodiode is very large this analysis should be reconsidered. Additional information on thermionic-emission from potential wells is discussed by Kawai [5] and Janesick [6].

Charge trapping and detrapping at the Si–SiO2 interface is likely the dominate source of charge transfer noise in 4T CMOS image sensors. Specifically, as charge is transferred from the pinned photodiode to the floating diffusion node it comes in contact with the Si–SiO2 interface near the floating diffusion node. In addition, while the transfer gate voltage is held high electrons from the floating diffusion can interact with surface traps in the transfer channel. Both of these mechanisms enable charge trapping and or detrapping during charge transfer. We propose the following random telegraph based model to analyze charge fluctuations at the floating diffusion node while the transfer gate is high. The number of electrons added or subtracted to the floating diffusion node at time $t \geq 0$ is

$$Y(t) = \sum_{i=1}^{N} Z_i(t), \quad (8)$$

where i is the trap index, and N is the number of traps in the transfer channel. Each trap is either full or empty at time t and its initial state is unknown. The number of electrons added or subtracted to the floating diffusion node at time $t \geq 0$ by trap i is

$$Z_i(t) = X_i(t) + B_i, \quad (9)$$

where $X_i(t)$ is a random telegraph signal (RTS) with unit amplitude, and B_i is a random variable with $P_r(B = 1/2) = 1/2$ and $P_r(B = -1/2) = 1/2$. B_is are determined at $t = 0$ and stay constant for $t > 0$. B_is are assumed to be uncorrelated. Therefore $Z_i(t)$ toggles between 0 and 1 or 0 and -1 depending on the value of B_i. Moreover, if $B_i = 1/2$ then $Z_i(t)$ toggles between 0 and 1 representing a trap that contained an electron at $t = 0$. If $B_i = -1/2$ then $Z_i(t)$ toggles between 0 and -1 representing a trap that was empty at $t = 0$. By definition, we assume that each trap can only hold one electron[2]. The number of traps in the channel N is a random variable with mean μ_N and variance σ_N^2. Each RTS $X_i(t)$ has a Poisson distributed transition probability, i.e. the probability of m transitions in t seconds is

$$P_r(m, t) = \frac{(\nu t)^m e^{-\nu t}}{m!} \quad t \geq 0 \quad m \geq 0, \quad (10)$$

where ν is the characteristic transition frequency. We also assume that RTSs are uncorrelated, and that the average emission and capture times are equal for each RTS[3]. Figure 3 shows a typical waveform for $X_i(t)$. The characteristic transition frequency ν is a random variable with the following

[2]This may not always be a good approximation but it simplifies the mathematics in this paper.

[3]The average emission and capture times for each trap are not stationary, they are a function of the channel potential, but we will neglect this in our analysis.

distribution

$$f_\nu(\nu) = \frac{1}{\nu \ln(\frac{\nu_2}{\nu_1})} \quad \nu_1 \le \nu \le \nu_2 \tag{11}$$

where ν_1 is the lowest transition frequency of any trap and ν_2 is the highest transition frequency of any trap. $f_\nu(\nu)$ is derived assuming that traps are uniformly distributed as a function of depth into the SiO2 [7]. Note that this assumption it typically used to explain 1/f noise in surface channel MOSFETs. We assume that N and ν are independent random variables.

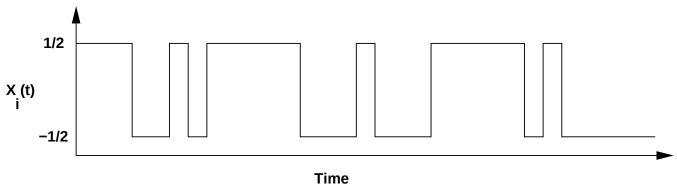

Fig. 3. RTS Waveform

III. Transfer Noise Analysis

In this section we analyze the model developed in Section II. In order to derive the autocorrelation function of $Y(t)$ we need to determine the statistics of its components. By definition a symmetric RTS, with Poisson distributed transition times and a fixed transition frequency ν, has a mean value of zero, i.e.

$$E[X_i(t)|\nu] = 0, \tag{12}$$

and an autocorrelation function

$$E[X_i(t)X_i(t+\tau)|\nu] = \frac{1}{4}e^{-2\nu|\tau|}. \tag{13}$$

Note that this shows that $X_i(t)$ is wide sense stationary and therefore $Y(t)$ will also be wide sense stationary. Since RTSs are assumed to be uncorrelated

$$E[X_i(t_1)X_j(t_2)|\nu] = 0 \quad i \ne j. \tag{14}$$

It can then be shown that

$$E[Z_i(t)|\nu] = 0, \tag{15}$$

$$E[Z_i(t)Z_i(t+\tau)|\nu] = \frac{1}{4}e^{-2\nu|\tau|}, \tag{16}$$

and

$$E[Z_i(t_1)Z_j(t_2)|\nu] = 0 \quad i \ne j. \tag{17}$$

Now we are ready to determine the average value of $Y(t)$ given ν, i.e.

$$E[E[Y(t)|N,\nu]] = 0. \tag{18}$$

The autocorrelation function of $Y(t)$ given N and ν, i.e. the autocorrelation function of $Y(t)$ with a known number of traps with a fixed trapping frequency ν, is

$$\begin{aligned} E[Y(t)Y(t+\tau)|N,\nu] &= E[(\textstyle\sum_{i=1}^{N} Z_i(t))\times \\ &\quad (\textstyle\sum_{j=1}^{N} Z_j(t+\tau))|N,\nu] \\ &= NE[Z_i(t)Z_i(t+\tau)|\nu]+ \\ &\quad N(N-1)E[Z_i(t)Z_j(t+\tau)|\nu]. \end{aligned} \tag{19}$$

Taking the expectation of $E[Y(t)Y(t+\tau)|N,\nu]$ with respect to N we find

$$\begin{aligned} R_{YY|\nu}(\tau) &= E[Y(t)Y(t+\tau)|\nu] \\ &= \tfrac{1}{4}\mu_N e^{-2\nu|\tau|}. \end{aligned} \tag{20}$$

Since $Y(t)$ is wide sense stationary the two sided power spectral density is defined as the Fourier transform of the autocorrelation function $R_{YY|\nu}(\tau)$, i.e.

$$\begin{aligned} S_{YY|\nu}(f) &= \textstyle\int_{-\infty}^{\infty} R_{YY|\nu}(\tau)e^{-2\pi jf\tau}d\tau \\ &= \frac{\mu_N}{4}\frac{\frac{1}{\nu}}{1+(\frac{\pi f}{\nu})^2} \quad -\infty \le f \le \infty. \end{aligned} \tag{21}$$

This shows that $Y(t)$ given ν has a Lorentzian spectrum as expected for this model. Taking the expectation of $S_{YY|\nu}(f)$ over ν we find

$$\begin{aligned} E[S_{YY|\nu}(f)] &= \frac{\mu_N}{4}\int_{\nu_1}^{\nu_2}\frac{\nu}{\nu^2+(\pi f)^2}f_\nu(\nu)d\nu \\ &= \frac{\mu_N}{4\ln(\frac{\nu_2}{\nu_1})}\int_{\nu_1}^{\nu_2}\frac{1}{\nu^2+(\pi f)^2}d\nu \\ &= \frac{\mu_N}{4\ln(\frac{\nu_2}{\nu_1})}\frac{tan^{-1}(\frac{\nu_2}{\pi f})-tan^{-1}(\frac{\nu_1}{\pi f})}{\pi f}. \end{aligned} \tag{22}$$

This shows that the noise power spectrum of $Y(t)$ has an inverse frequency dependence between ν_1 and ν_2. Again this is expected based on our trap frequency distribution $f_\nu(\nu)$. This model can be verified by first measuring the power spectrum of a single pixel while the transfer gate is high, and then measuring the spectrum of the same pixel with the transfer gate low. The difference of the two power spectrums is the power spectrum of the charge transfer noise. If the transfer device has a large number of traps then equation 22 should predict the measured transfer noise power spectral density, but if the number of traps is close to one then equation 21 should predict the measured transfer noise power spectral density. If neither equation matches the measured transfer noise power spectral density, then this model is not valid for predicting charge transfer noise! Figures 4 and 5 show the power spectral densities predicted by equations 21 and 22 respectively. Figure 4 assumes $\mu_N = 1$ and $\nu = 10000$ transition/sec, and Figure 5 assumes $\mu_N = 10$, $\nu_1 = 10$ transitions/sec and $\nu_2 = 10^7$ transitions/sec.

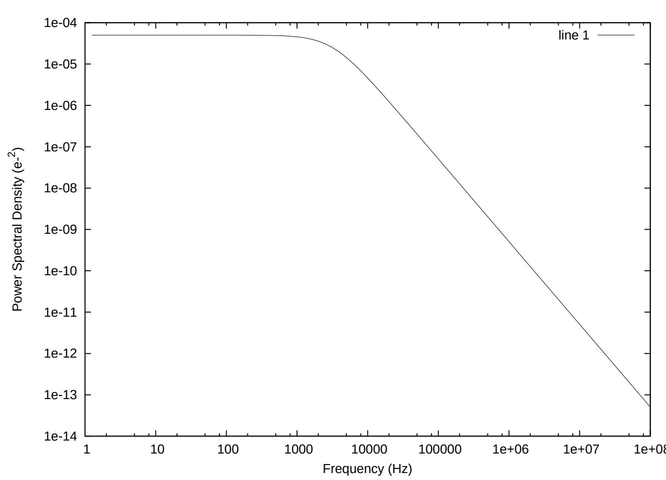

Fig. 4. Lorentzian Noise Spectrum Predicted by Equation 21

In most applications 4T CMOS image sensors with pinned photodiodes use correlated double sampling (CDS) to measure the charge transferred from the pinned photodiode to the floating diffusion node. Therefore, we define

$$A(t) = Y(t) - Y(0) \quad t \geq 0 \tag{23}$$

to estimate the charge transfer noise power after CDS. A typical waveform of $A(t)$ is shown in Figure 6. It can be shown that

$$E[A(t)] = 0, \tag{24}$$

and

$$\begin{aligned} E[A(t)^2|\nu] &= E[(Y(t) - Y(0))^2] \\ &= 2E[Y(0)^2 - Y(0)Y(t)] \\ &= \tfrac{1}{2}\mu_N(1 - e^{-2\nu t}). \end{aligned} \tag{25}$$

Taking the expectation of $E[A(t)^2|\nu]$ with respect to ν we find

$$\begin{aligned} E[A(t)^2] &= \tfrac{\mu_N}{2}\textstyle\int_{\nu_1}^{\nu_2}(1 - e^{-2\nu t}) f_\nu(\nu) d\nu \\ &= \tfrac{\mu_N}{2\ln(\frac{\nu_2}{\nu_1})}\textstyle\int_{\nu_1}^{\nu_2}(1 - e^{-2\nu t})\frac{1}{\nu} d\nu \\ &= -\tfrac{\mu_N}{2\ln(\frac{\nu_2}{\nu_1})}\textstyle\sum_{i=1}^{\infty}\frac{(-2\nu_2 t)^i - (-2\nu_1 t)^i}{i(i!)}. \end{aligned} \tag{26}$$

Figure 7 shows the variance of $A(t)$, i.e. $E[A(t)^2]$, as a function of time assuming that $\mu_N = 10, \nu_1 = 10$ transitions/s, and $\nu_2 = 1e7$ transitions/s. For small values of t

$$E[A(t)^2] \approx \mu_N \frac{t(\nu_2 - \nu_1)}{\ln(\frac{\nu_2}{\nu_1})}. \tag{27}$$

This implies that charge should be transferred from the pinned photodiode to the floating diffusion node as quickly as possible, i.e. the transfer gate should be pulsed high for as short a period of time as necessary to transfer all of the charge in the pinned photodiode. Clearly there is a trade off between image lag, incomplete charge transfer, and transfer noise in a 4T APS.

IV. Conclusion

We have presented a theoretical framework for understanding and modeling charge transfer noise in CMOS, CCD and hybrid CCD/CMOS image sensors. Further work is still required to validate this model using both simulated and measured data.

References

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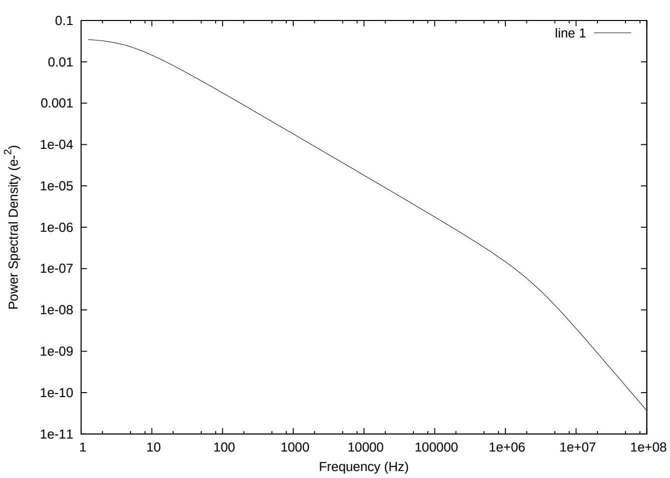

Fig. 5. 1/f Noise Spectrum Predicted by Equation 22

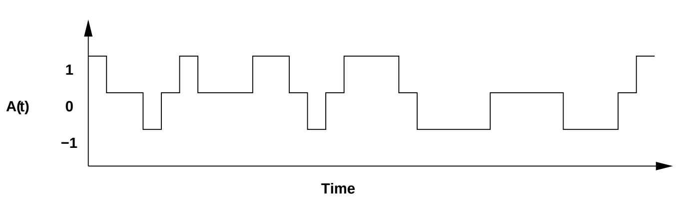

Fig. 6. Typical $A(t)$ Waveform

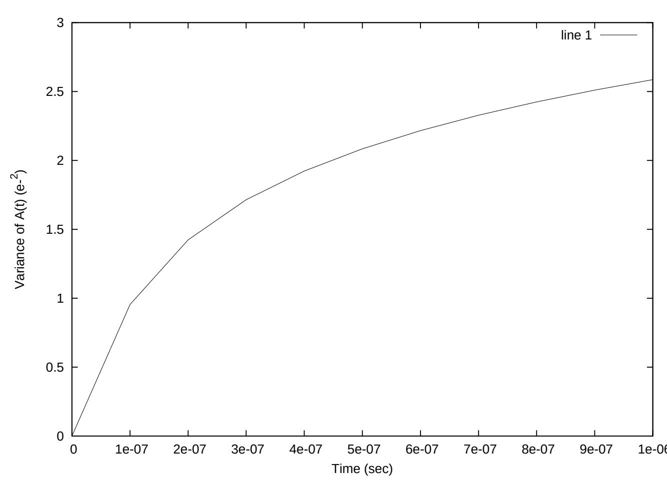

Fig. 7. Variance of $A(t)$ as a function of time