Noise in a CMOS digital pixel sensor*

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Abstract: Based on the study of noise performance in CMOS digital pixel sensor (DPS), a mathematical model of noise is established with the pulse-width-modulation (PWM) principle. Compared with traditional CMOS image sensors, the integration time is different and A/D conversion is implemented in each PWM DPS pixel. Then, the quantitative calculating formula of system noise is derived. It is found that dark current shot noise is the dominant noise source in low light region while photodiode shot noise becomes significantly important in the bright region. In this model, photodiode shot noise does not vary with luminance, but dark current shot noise does. According to increasing photodiode capacitance and the comparator's reference voltage or optimizing the mismatch in the comparator, the total noise can be reduced. These results serve as a guideline for the design of PWM DPS.

Key words: CMOS image sensor; digital pixel sensor; random noise; pattern noise

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1. Introduction

The impact of CMOS technology scaling on analog integrated circuits has become increasingly significant in recent years, so it is difficult to maintain the advantages of high performance in CMOS active pixel sensors (APS)[1]. However, it is possible to design low-noise CMOS digital pixel sensors (DPS) with technology scaling. There are obvious advantages for DPS[2]. Using pixel-level ADC in DPS not only reduces the required design in analog circuits, but also improves its system performance, particularly in terms of noise[3, 4]. In addition to pixel-level A/D conversion in voltage mode[5−7], present researches mainly focus on DPS based on pulse width modulation (PWM) in time domain. In PWM DPS, the photocurrent information could be converted into time measurement[8] and the data also could be compressed and stored in pixel level[9, 10].

However, noise still limits the system performance of DPS severely and the analysis results of noise in APS[11−13] could not be applied to DPS. The noise sources and their impact on DPS must be studied. Thus, measures can be taken to reduce noise in DPS. In this paper, noise characteristic of PWM DPS is analyzed and its mathematical noise model is established, in which the different components and effects of noise between DPS and APS are compared. Also, the method of optimizing circuit design to suppress noise is presented.

2. Architecture and scheme of the PWM DPS

Figure 1(a) shows the functional diagram of a DPS pixel implementing the PWM scheme. It consists of a photodiode, a reset transistor, a comparator (shown in Fig. 1(b)) and an n-bit memory. Firstly, the voltage at node PD (V_{PD}) is reset to V_{rst} to initiate an integration cycle. After the reset, the photodiode will be linearly discharged by the photocurrent at a rate proportional to the light intensity. V_{PD} is given by

$$V(t) = V_{rst} - \frac{I_{ph}t}{C_{PD}}, \tag{1}$$

where I_{ph} is the photocurrent and C_{PD} is the capacitance at node PD. As V_{PD} varies, the comparator continuously compares V_{PD} with a reference voltage V_{ref}. When the threshold is reached, the comparator outputs a pulse signal and thus the pixel value is converted to the pulse width, which is expressed by the integration time t_{int}:

$$t_{int} = \frac{(V_{rst} - V_{ref})C_{PD}}{I_{ph}}. \tag{2}$$

I_{ph} is different in different conditions of incident light and therefore the integration time of these pixels is also different. In other word, the exposure time, inversely proportional to I_{ph}, is recorded to tell the photo information from all the pixels. Figure 1(c) illustrates the scheme. Suppose that there are two pixels with the photocurrent I_{ph1} and I_{ph2}, and the corresponding integration time is t_1 and t_2:

$$\frac{t_1}{t_2} = \frac{I_{ph2}}{I_{ph1}}. \tag{3}$$

The precision of time measurement is severely limited by the noise in the PWM DPS pixel. Although several noise sources introduced by complicated analog circuits are eliminated, noise characteristic in PWM DPS is quite different from that in traditional CMOS image sensors and the factors that affect the noise characteristic are also different.

3. Analysis of random noise and pattern noise

It's required that the integration time of each pixel should be precisely recorded, but noise limits the accuracy. When the image is reconstructed, errors caused by noise will affect the image quality. There are two types of noise, random noise and pattern noise, in PWM DPS.

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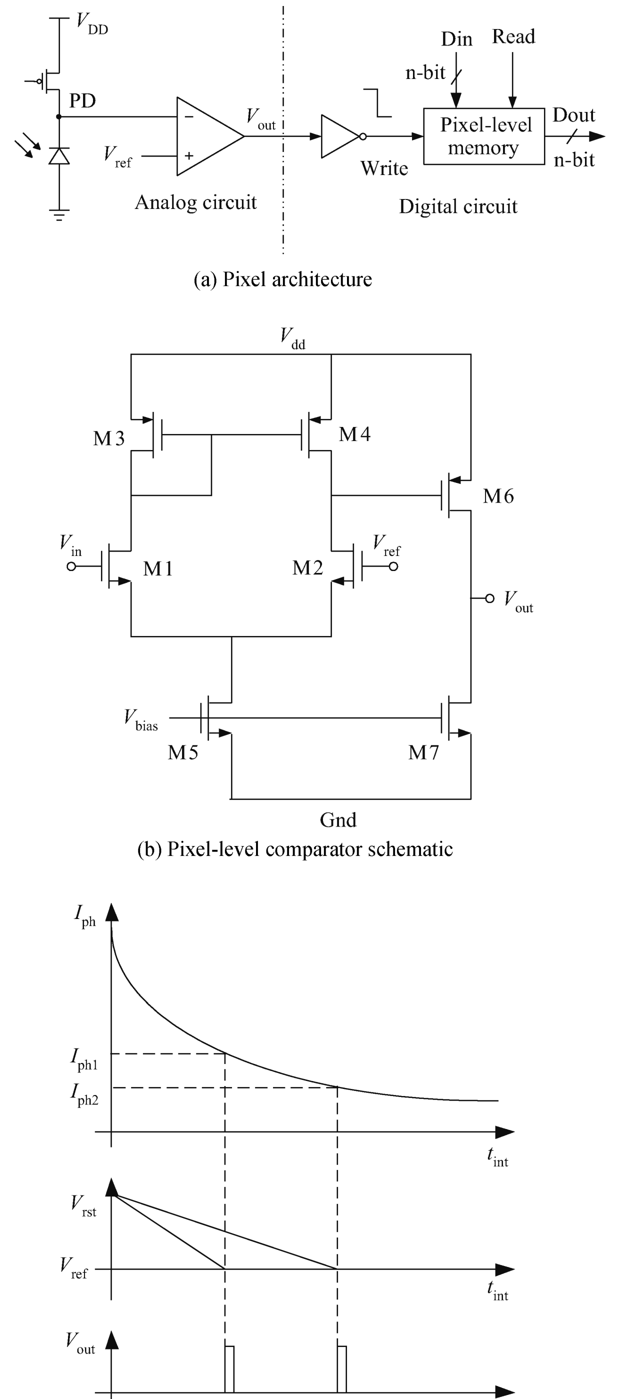

(a) Pixel architecture

(b) Pixel-level comparator schematic

(c) Operational principle of PWM DPS

Fig. 1. Architecture and principle of PWM DPS.

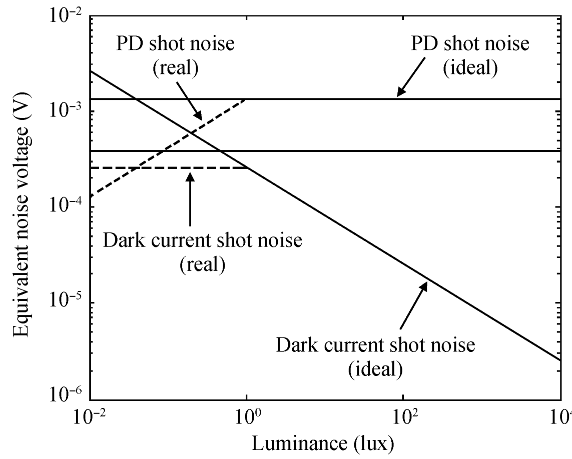

Fig. 2. Relationship between illumination and shot noise in PWM DPS.

3.1. Random noise

Random noise is one of the limiting factors in DPS. It varies with time and is not constant from frame to frame. Compared to an APS pixel, random noise in DPS does not compose source follower noise, column amplifier noise and readout noise, because of its simple structure and pixel-level A/D conversion. Only reset noise and shot noise are the components of random noise in PWM DPS.

3.1.1. Shot noise

Shot noise arises from the random generation of carriers through pn junction. On one hand, the random generation of electron–hole pairs causes the photoelectron shot noise, which is given by

$$v_{\mathrm{ph}} = \frac{\sqrt{q I_{\mathrm{ph}} t_{\mathrm{int}}}}{C_{\mathrm{PD}}}. \tag{4}$$

On the other hand, thermal generation within the depletion region leads to the dark current shot noise. It is expressed as

$$v_{\mathrm{dk}} = \frac{\sqrt{q I_{\mathrm{dk}} t_{\mathrm{int}}}}{C_{\mathrm{PD}}}. \tag{5}$$

I_{dk} is the dark current. So the total shot noise is

$$v_{\mathrm{shot}} = \sqrt{v_{\mathrm{ph}}^2 + v_{\mathrm{dk}}^2} = \frac{\sqrt{q(I_{\mathrm{ph}} + I_{\mathrm{dk}}) t_{\mathrm{int}}}}{C_{\mathrm{PD}}}. \tag{6}$$

Shot noise is related to the photocurrent, dark current, integration time and the capacitance at node PD. When the integration time is constant, like the scheme in CMOS APS, the photocurrent shot noise is proportional to illumination and the dark current shot noise is constant. It shows that the dark current shot noise has nothing to do with the incident light condition, but the photocurrent shot noise changes with the incident light condition. However, each pixel has its own integration time in PWM DPS. Considering this condition, the expression of shot noise becomes different. From Eq. (2), it can be calculated as

$$I_{\mathrm{ph}} t_{\mathrm{int}} = (V_{\mathrm{rst}} - V_{\mathrm{ref}}) C_{\mathrm{PD}}. \tag{7}$$

According to Eq. (2), Equations (4) and (5) can be also expressed as

$$v_{\mathrm{ph}} = \sqrt{\frac{q(V_{\mathrm{rst}} - V_{\mathrm{ref}})}{C_{\mathrm{PD}}}}, \tag{8}$$

$$v_{\mathrm{dk}} = \sqrt{\frac{q(V_{\mathrm{rst}} - V_{\mathrm{ref}})}{C_{\mathrm{PD}}} \frac{I_{\mathrm{dk}}}{I_{\mathrm{ph}}}}. \tag{9}$$

Thus, Equation (6) can be expressed in another form:

$$v_{\rm shot}=\sqrt{\frac{q(V_{\rm rst}-V_{\rm ref})}{C_{\rm PD}}\left(1+\frac{I_{\rm dk}}{I_{\rm ph}}\right)}. \quad (10)$$

As long as $V_{\rm PD}$ can drop to $V_{\rm ref}$, $v_{\rm ph}$ is constant which is independent of $I_{\rm ph}$ and $t_{\rm int}$ while $v_{\rm dk}$ is decreasing with $I_{\rm ph}$ increases. The results are quite different from those in CMOS APS, as shown in Fig. 2 (solid lines).

The longest integration time hasn't been considered in the ideal condition. Time measurement in the actual DPS system will be limited. There are the longest operational cycle and thus the maximum integration time $t_{\rm int,\,max}$, corresponding to the minimum illumination $L_{\rm min}$. During the measurable scope, shot noise's variation still meets Eq. (8) and (9). If $t_{\rm int}>t_{\rm int,\,max}$, the effective integration time is $t_{\rm int,\,max}$. So

$$v_{\rm ph}=\frac{\sqrt{qI_{\rm ph}t_{\rm int}}}{C_{\rm PD}}=\sqrt{\frac{qL(V_{\rm rst}-V_{\rm ref})}{C_{\rm PD}L_{\rm min}}}, \quad (11)$$

$$v_{\rm dk}=\frac{\sqrt{qI_{\rm dk}t_{\rm int}}}{C_{\rm PD}}=\alpha\sqrt{\frac{q(V_{\rm rst}-V_{\rm ref})}{C_{\rm PD}L_{\rm min}}}, \quad (12)$$

where α is constant. As the incident light intensity ($L<L_{\rm min}$) decreases, $v_{\rm ph}$ decreases and $v_{\rm dk}$ remains constant. Dashed lines in Fig. 2 show this situation.

3.1.2. Reset noise

When the pixel is reset through the reset transistor, the resistance of the MOSFET channel results in thermal noise. Reset noise is also known as kTC noise, expressed by

$$v_{\rm rst}=\sqrt{\frac{kT}{C_{\rm PD}}}, \quad (13)$$

where k is Boltzmann's constant ($k=1.38\times10^{-23}$ J/K) and T is the temperature in Kelvin.

3.2. Pattern noise

Pattern noise does not change significantly from frame to frame and is called spatial noise. It is essentially independent of time, but associated with the signal. Pattern noise is divided into two components, fixed pattern noise (FPN) and photo-response non-uniformity (PRNU). PRNU is ignored in this section because of its little effect on image quality.

Fixed pattern noise is measured in the absence of illumination. FPN is fixed in a given pixel. As a whole, FPN is different from pixel to pixel. FPN in CMOS APS consists of pixel FPN caused by the mismatch of pixel and column FPN caused by the mismatch of column readout circuit. Pixel FPN sources from the source follower in a pixel. Column FPN is mainly from the column amplifier offset. DPS eliminates these sources of noise on the root. Only pixel FPN exists in it. Meanwhile, there is a comparator in each DPS pixel and thus comparator offset is the most important component. The integration time including the effect of input offset voltage $V_{\rm os}$ is given by

$$t'_{\rm int}=\frac{(V_{\rm rst}+V_{\rm os}-V_{\rm ref})C_{\rm PD}}{I_{\rm ph}}. \quad (14)$$

Table 1. Relationship between the integration time and its error.

L (lux)	$\Delta t_{\rm int}$ (μs)	$t_{\rm int}$ (μs)
10^0	9496.5	949654.4
10^4	0.9497	94.9654

Then the error introduced by comparator offset is expressed as

$$\Delta t_{\rm int}=t'_{\rm int}-t_{\rm int}=\frac{V_{\rm os}C_{\rm PD}}{I_{\rm ph}}. \quad (15)$$

With the increase of light intensity, the error that introduced into the integration time decreases. Assuming $V_{\rm os}=3$ mV, Table 1 shows the errors and the corresponding integration time in different level of illumination. The error will put a significant impact on the accuracy of the overall system.

The offset voltage of comparator is mainly determined by the threshold voltage offset $\Delta V_{\rm TH}$ and the W/L offset $\Delta(W/L)$ of the transistors. Assuming W/L and $V_{\rm TH}$ are the ideal values, so the actual values are

$$(W/L)_{\rm i}=W/L+\Delta(W/L)_{\rm i}, \quad (16)$$

$$V_{\rm THi}=V_{\rm TH}+\Delta V_{\rm THi}. \quad (17)$$

$\Delta V_{\rm TH}$ is given by

$$\Delta V_{\rm TH}=\frac{A_{\rm VTH}}{\sqrt{WL}}, \quad (18)$$

where $A_{\rm VTH}$ is a process-specific parameter. Thus the offset of the comparator is expressed by

$$V_{\rm os}=(V_{\rm GS1,2}-V_{\rm TH1,2})\frac{\Delta(W/L)_2-\Delta(W/L)_1}{2(W/L)_{1,2}}+(\Delta V_{\rm TH1}-\Delta V_{\rm TH2})+\frac{g_{\rm m3,4}}{g_{\rm m1,2}}\left[(V_{\rm GS3,4}-V_{\rm TH3,4})\times\frac{\Delta(W/L)_4-\Delta(W/L)_3}{2(W/L)_{3,4}}+(\Delta V_{\rm TH3}-\Delta V_{\rm TH4})\right]. \quad (19)$$

The input offset voltage depends on the circuit bias condition. The mismatch of device dimension offset impacts much more on the offset as the overdrive voltage increases. The threshold voltage offset is directly added to the input. Since the offset in the second stage is divided by the gain firstly and then added, the total offset voltage is due to the offset in the differential stage.

4. DPS system noise and methods of its suppression

DPS reduces thermal noise and flicker noise caused by analog circuits, especially the readout circuits, so that noise characteristics have been greatly improved, as shown in Table 2. Since reset noise, shot noise and pixel FPN are the components of noise in PWM DPS, the total noise is expressed as

$$v_{\rm tot}=\sqrt{v_{\rm ph}^2+v_{\rm dk}^2+v_{\rm rst}^2+v_{\rm FPN}^2}. \quad (20)$$

Table 2. Noise in APS and DPS.

Name	APS	DPS
Rest noise	√	√
Shot noise	√	√
Pixel/Column amplifier noise	√	
Readout noise	√	
Pixel FPN	√	√
Column FPN	√	

Table 3. Calculation of random noise.

Name	Equivalent noise voltage
v_{rst}	0.3742 mV
v_{ph}	1.2759 mV
v_{dk}	0.2546 μV, I_{ph} = 8.94 nA
	80.4973 μV, I_{ph} = 89.4 fA

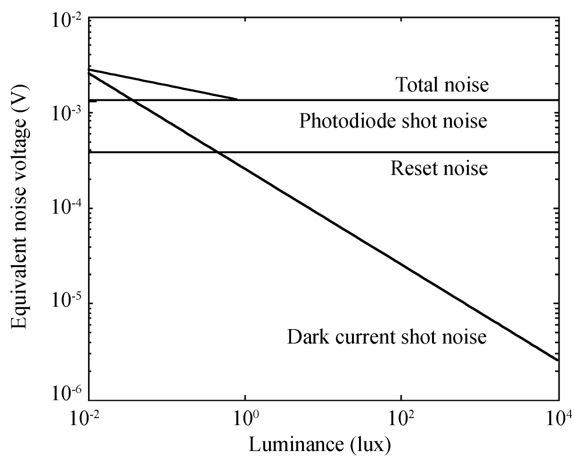

Fig. 3. Temporal noise as a function of illumination.

N+/Pwell diodes with the area of 6 × 6 μm^2 from GSMC 0.13 μm CMOS process are used as photodiodes. The capacitance at node PD is about 29.8 fF. The reset voltage is 1.2 V and the reference voltage of comparator is 0.9 V in the design. Assume that mean dark current is 1 nA/cm^2 and the temperature is 300 K. According to the equations that have been derived in the paper, each kind of the noise can be calculated in volts as shown in Table 3. Various sources of noise and the total noise (FPN is not included) in volts are shown in Fig. 3.

In the APS noise model, reset noise is the dominant noise source in the low light region while photodiode shot noise becomes more and more important as the light intensity increases. In addition, dark current shot noise is not related to the luminance. However, in this model, dark current shot noise varies with the luminance. It is the most important source when the light intensity is low. As illumination level increases, it decreases dramatically while photodiode shot noise becomes the dominant noise source. It is also considered that photodiode shot noise is not affected by illumination because of the influence of various integration times on it.

Temporal noise with the variable parameters C_{PD} and V_{ref} is drawn in Fig. 4. To improve the noise characteristic of PWM DPS, it is suggested that: (1) The capacitance at node PD should be increased, according to increasing the photosensitive area of the photodiode to improve fill factor. But it

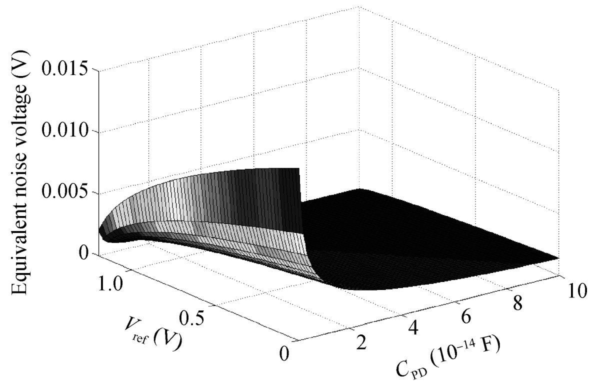

Fig. 4. Temporal noise as a function of C_{PD} and V_{ref}.

would increase the error introduced by the comparator offset. So there is a compromise between them. (2) The comparator reference voltage should be selected carefully. The higher it is, the smaller shot noise is. (3) In order to reduce the mismatch and thus to reduce pixel FPN, the size of the MOSFETs in the comparator input stage can be larger. But this will increase the pixel area as well. (4) It is of great benefit to keep the overdrive voltage of the transistors in the differential input stage small. Because it can effectively suppress the mismatch caused by the device dimensions and reduce pixel FPN.

5. Conclusion

Noise severely constraints the accuracy of the time measurement and the quality of the image. In contrast to noise analysis in CMOS APS, the noise characteristic of DPS based on a PWM scheme has been studied in this paper. Reset noise, shot noise and pixel FPN are the noise sources in PWM DPS. The mathematical model of noise in PWM DPS, which is quite different from that in APS, is established. It shows that dark current shot noise is the dominant noise source in low light region while photodiode shot noise become significantly important in bright region. Moreover, dark current shot noise has nothing to do with the incident light condition, but the photocurrent shot noise does not. In order to suppress the noise in PWM DPS, it is advised to increase photodiode capacitance and the comparator's reference voltage or optimize the mismatch in the comparator. The results serve as a guideline for PWM DPS design.

References

[1] Wong H P. CMOS image sensors-recent advances and device scaling considerations. International Electron Devices Meeting, Technical Digest, Washington DC: IEEE Press, 1997: 201

[2] Gamal E, Eltoukhy A. CMOS image sensors. IEEE Circuits and Devices Magazine, 2005, 21(3): 6

[3] Ni J H, Huang Q Y. CMOS image sensor and its development trend. OME Information, 2008: 33

[4] Gamal A E. Trends in CMOS image sensor technology and design. International Electron Devices Meeting, Technical Digest, San Francisco: IEEE Press, 2002: 805

[5] Yang D, Fowler B, Gamal A E. A Nyquist-rate pixel- level ADC for CMOS image sensors. IEEE J Solid-State Circuits, 1999, 34(3): 348

[6] Kleinfelder S, Lim S H, Liu X Q, et al. A 10000 frames/s CMOS digital pixel sensor. IEEE J Solid-State Circuits, 2001, 36(12): 2049

[7] Rhee J, Joo Y. Wide dynamic range CMOS image sensor with pixel level ADC. Electron Lett, 2003, 39(4): 360

[8] Bermak A. A CMOS imager with PFM/PWM based analog-to-digital converter. IEEE International Symposium on Circuits and Systems, Phoenix: IEEE Press, 2002: 53

[9] Zhang M, Bermark A. A compact digital pixel sensor architecture using predictive coding scheme. IEEE Sensors Conference, Lecce, 2008: 961

[10] Zhang M, Bermark A. Compressive acquisition CMOS image sensor: from the algorithm to hardware implementation. IEEE Trans VLSI Syst, 2010, 18(3): 490

[11] Tian H, Fowler B, Gammal A E. Analysis of temporal noise in CMOS photodiode active pixel sensor. IEEE J Solid-State Circuits, 2001, 36(1): 92

[12] Brouk I, Nemirovsky A, Nemirovsky Y. Analysis of noise in CMOS image sensor. IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems, Tel-Aviv: IEEE Press, 2008: 1

[13] Kawai N, Kawahito S. Measurement of low-noise column readout circuits for CMOS image sensors. IEEE Trans Electron Devices, 2006, 53(7): 1737