A Wide Dynamic Range CMOS Image Sensor with Integration of Short-Exposure-Time Signals

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1 Introduction

A wide dynamic range image sensor is required in the fields of automobiles, security systems, digital still camera and cameras for industrial purposes. There are two major requirements for high-quality wide-dynamic-range image sensors. One is to keep high SNR in whole illumination range. The other is low noise characteristic in low illumination level. Numerous methods to expand dynamic range of the CMOS image sensor is reported. These include (1)measurement of time to reach a threshold using a counter and a comparator placed in a pixel[1], (2)measurement of the number of saturation times in a pixel in one frame period[2], (3)use of logarithmic characteristics of MOS transistors[3, 4, 5, 6], (4)capturing 2 or more images of different exposure time[7, 8, 9, 10], (5) varying the level of reset gate during integration[11], (6)capturing 2 images in two photo conversion regions which have different conversion gain[12], (7)collecting blooming electrons on floating diffusion[13].

Some of the methods for wide dynamic range CMOS imagers can only be used for active pixel circuits in which the reset(kTC) noise is not canceled. Dual exposure method is well known for expanding dynamic range, where the technique is first introduced in CCD image sensors. The problem is the SNR dip at the boundary of high illumination and low illumination region if the linear response is extended to high illumination region using short-exposure-time signal. A multiple exposure method can reduce the SNR dip effectively. However, the conventional multiple exposure method requires a large size on-chip frame memory.

In this paper, we propose a method to expand the dynamic range using multiple different time exposures and the integration of short exposure time signals. In the proposed method, any type of active pixel sensors can be used. Therefore, the dynamic range can also be expanded to low illumination side if a low-noise active pixel sensor technology with a pinned photo diode is used. The integration of short-exposure time signal helps to reduce the SNR dip, keeping relatively high SNR for whole range of illumination. The prototype wide dynamic range CMOS image sensor with VGA format is designed using 0.25μm, single-polysilicon, 4-metal CMOS process technology.

2 Principle of dynamic range expansion

In a wide dynamic range image sensor using a dual exposure method, DR is given by

$$DR = 20 \log \frac{I_{max}}{I_{min}} \text{[dB]} \tag{1}$$

where I_{max} and I_{min} are the maximum and the minimum photo current that can be handled in the pixel. I_{max} and I_{min} are given by

$$I_{max} = Q_{max}/T_S \tag{2}$$

and

$$I_{min} = Q_{min}/T_L \tag{3}$$

where Q_{max} is the maximum signal charge that can be handled in the pixel, Q_{min} the minimum signal charge that is determined by the noise level, T_S the short exposure time and T_L the long exposure time. Therefore, the dynamic range is given by

$$DR = 20 \log \frac{Q_{max}}{Q_{min}} \frac{T_L}{T_S} = 20 \log \frac{Q_{max}}{Q_{min}} \frac{(T_F - T_S)}{T_S} \text{[dB]} \tag{4}$$

where T_F is the frame period, that is shared by the two exposures,i.e., $T_F = T_L + T_S$. The dynamic range can be extended by a factor of T_L/T_S. For example, the dynamic range is expanded by 42dB with $T_S = T_F/128$.

As described later, the combination of two exposure times cause a large SNR dip at the boundary of two different exposures if the linear response is extended to high illumination region using short-exposure-time signals. If the photo

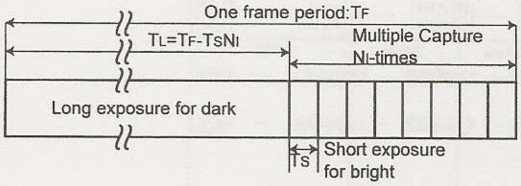

Figure 1: Timing chart for one frame period.

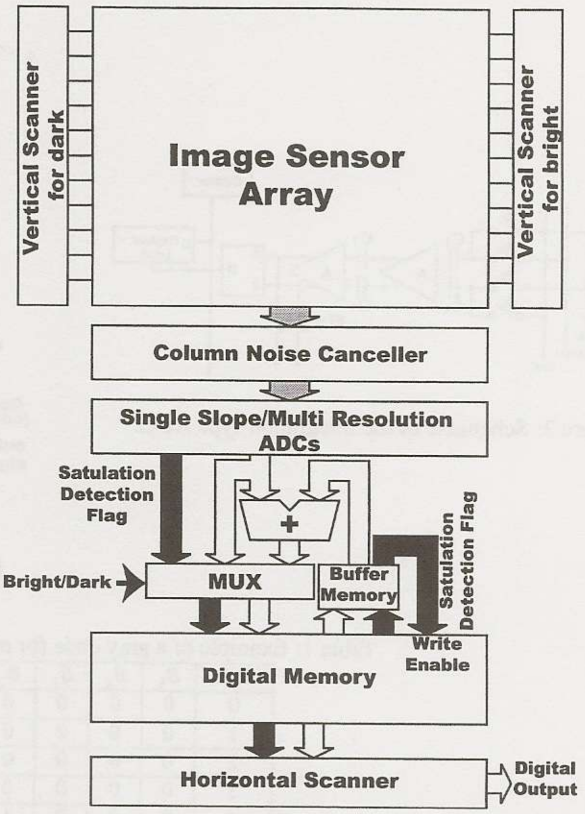

Figure 2: Block diagram of the proposed wide dynamic range CMOS image sensor.

current exceeds Q_{max}/T_L, the output is switched to the short exposure-time signal. Therefore, at the boundary, the signal charge is reduced to $Q_{max}(T_S/T_L)$ from Q_{max}. If the SNR is determined by the ratio of the signal of each exposure level and the noise charge due to shot noise, the SNR dip, ΔSNR, is given by

$$\Delta\mathrm{SNR} = 10\log_{10}(T_S/T_L) \tag{5}$$

For example, $\Delta\mathrm{SNR} = 21\mathrm{dB}$ for $T_S = T_F/128$.

In order to reduce the SNR dip, we introduce a method with a long exposure for low light level signal and multiple short exposures for high light level signals as shown in Figure 1. The signals of short exposures are integrated outside of the pixel array. In this case, the frame period is shared by the long exposure and multiple short exposures, i.e.,

$$T_F = T_L + N_I \times T_S \tag{6}$$

where N_I is the number of short exposures. The dynamic range of this method is given by

$$DR = 20\log_{10}\frac{Q_{max}}{Q_{min}}\frac{T_F - N_I \times T_S}{T_S}[\mathrm{dB}] \tag{7}$$

The dynamic range is expanded by a factor of 41.6dB with $T_S = T_F/128$ and $N_I = 8$. The SNR dip is given by

$$\Delta\mathrm{SNR} = 10log_{10}(N_I \times T_S/T_L) \tag{8}$$

For example, $\Delta\mathrm{SNR} = 11.7\mathrm{dB}$ for $T_S = T_F/128$ and $N_I = 8$.

3 Wide dynamic range image sensor

The block diagram of the proposed wide dynamic range CMOS image sensor is shown in Figure 2. It consists of a pixel array, column parallel read-out circuits for noise cancellation, a multi-resolution integration-type analog-to-digital converter(ADC), digital accumulator ,digital memory array, timing controller, horizontal scanner and vertical scanners.

As the column noise canceler, a switched-capacitor amplifier is used.

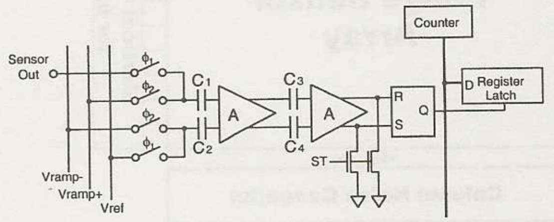

Figure 3: Schematic of the integration-type ADC.

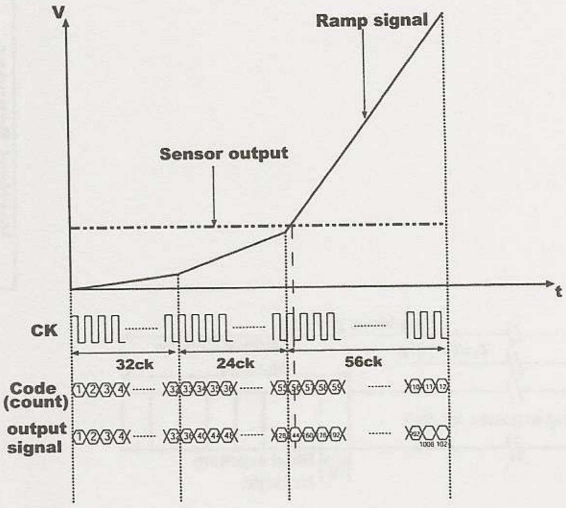

Figure 4: Waveform of the ramp signal generator.

Table 1: Example of a gray code for multiple resolution(5b).

Code	B_5	B_4	B_3	B_2	B_1	B_0
0	0	0	0	0	0	0
1	0	0	0	0	0	1
2	0	0	0	0	1	1
3	0	0	0	0	1	0
4	0	0	0	1	1	0
5	0	0	0	1	1	1
6	0	0	0	1	0	1
7	0	0	0	1	0	0
8	0	0	1	1	0	0
10	0	0	1	1	1	0
12	0	0	1	0	1	0
14	0	0	1	0	0	0
16	0	1	1	0	0	0
20	0	1	1	1	0	0
24	0	1	0	1	0	0
28	0	1	0	0	0	0
OF	1	1	0	0	0	0

3.1 Multiple-resolution ADC

Noise canceled analog signals are converted to digital signals in column parallel ADCs. To read out the long and the short accumulation time signals for multiple times and to keep high SNR, a high-resolution high-speed ADC is necessary. An integration-type single-slope ADC using a comparator array, a register array and a ramp signal generator is useful for a high-resolution column-parallel ADC of digital CMOS image sensors. However, the long conversion time of the integration-type ADC is not suitable for our purpose. In order to reduce the conversion time while keeping high SNR, a multiple-slope integration-type ADC is developed. The schematic diagram of the ADC is shown in Figure 3. The waveform of the ramp signal generator is shown in Figure 4. In this ADC, the long exposure signal is converted to 10-bit full resolution digital code. The short exposure signals are converted to multiple-resolution digital code where a high resolution(10b LSB), a middle resolution(8b) and a low resolution(6b) are applied to a small, middle and large signals, respectively.

To meet this A/D conversion characteristic, a modified Gray code counter is used. Table.1 show the conversion table of the modified Gray code as an example. In this case, the resolution is 5 bits for 0 through 8, 4bits for code 8 through 16, and 3bits for 16 through 32. In the 10b modified Gray code counter actually used for the designed image sensor, the resolution is 10bits for 0 through 32, 8bits for 32 through 128 and 6bits for 128 through 1024. The total number of counting is reduced to 112 from 1024.

3.2 Digital integration and a digital memory

The digitized short-accumulation-time signals are integrated at the buffer memory to reduce the SNR dip at a boundary of the long and the short exposures.

Since the readouts of multiple short-exposure-time signals to be integrated can be done in a short time slot, the buffer memory size for the integration can be small enough. The buffer memory size C_{BM} is given by

$$C_{BM} = C_{FM} N_I \frac{T_S}{T_F} \tag{9}$$

where C_{FM} is the frame memory size. For example,$C_{BM} = C_{FM}/16$ for $T_S = T_F/128$ and $N_I = 8$. Therefore, the buffer memory can be easily integrated on the the CMOS image sensor chip.

In order to reduce the readout rate from the image sensor chip, the long exposure signals are once stored in the buffer memory. If the long exposure signal exceeds the maximum level that can be handled, the A/D converter generates a saturation flag which indicates whether the pixel is saturated or not. In the readout phase of the short exposure signal, the saturation flag of the long exposure signal of the corresponding pixel is read out from the buffer memory. If the flag is "1", the content of the buffer memory is replaced by the short exposure signal. This process is performed on pixel-by-pixel basis. When the integration of the short-exposure-time signals is completed, the data stored in the buffer memory are read out. The data are either of the long exposure signal or of the integrated short-exposure signals. Therefore, a one-bit code to indicate that the data are for long or short exposures is also read out simultaneously.

3.3 Prototype wide dynamic range CMOS image sensor

A prototype wide dynamic range CMOS image sensor which has outputs of a long exposure signal and 3 short exposure signals is designed. The digital integrator and digital memory is not integrated on this particular prototype sensor. A layout is shown in Figure 5. This prototype sensor is designed using 0.25μm, single-polysilicon, 4-metal CMOS image sensor technology. A sensor array has 664×486 pixels. The pixel size is $10\mu m \times 10\mu m$ and the die size is $8.5mm \times 10mm$. The prototype sensor has 40bits parallel output consisting of a 10-bit long exposure signal and $3\times$10-bit short exposure signals.

4 SNR definition of multiple exposure wide dynamic range image sensors

In general, the signal-to-noise ratio(SNR) of wide dynamic range image sensors has been defined as the ratio of the signal amplitude and the noise in each illumination level[14]. However, this does not always reflect the actual influence of the noise when we monitor the wide-dynamic-range image on a display.

In this paper, another definition of the SNR of wide dynamic range image sensors is introduced from the viewpoints of the SNR monitored on a display.

In most wide dynamic range camera applications, a better contrast image is required in dark region than bright region. The photo conversion curve is defined as shown in Figure 6.

In Figure 6, X_L and X_F are the maximum illumination levels for the long and the short exposures, respectively, and Y_L and Y_F are output levels corresponding to X_L and X_F, respectively. In this case, the linear response in the low illumination region is extended to a brighter region by using the short exposure signal. X_C and Y_C corresponds to the bending point of the piecewise linear transfer curve. Two parameters, A_L and A_C are defined as

$$A_L = \frac{Y_L}{Y_F}, A_C = \frac{X_C}{X_L} = \frac{Y_C}{Y_L} \tag{10}$$

The SNR is defined by the ratio of the maximum signal amplitude and the noise amplitude in each piecewise linear region. In the low and the high illumination regions, the maximum signal amplitudes are Y_C and $Y_F - Y_C$,respectively. The calculated SNR as a function of the photo current with A_c as a parameter is shown Figure 7 in the simple dual exposure method. In this calculation, T_F/T_S is 128, A_L is 1/8, the read noise is 7 electrons, the conversion gain is 32μV/electron, the full scale of ADC is 1.2V and the resolution of the ADC is 10bits. The resulting photo conversion characteristic is shown in Figure 8. From this result, the SNR dip around the boundary region depends on the choice of A_C. The SNR dip is 20 dB. The SNR in the low illumination region is increased by a factor of $20\log A_c$ dB.

Figure 9 shows the SNR as a function of the photo current in the case of the proposed method using the integration of short exposure time signals. The integration of the short exposure signals is effective in reducing the SNR dip and in improving the SNR of high illumination region. The SNR dip is reduced by a factor of $10\log N_I$ dB. Figure 10 shows a zoom-up view of the photo conversion characteristics around the range of X_L to X_C. The resolution of gray-scale code is improved by the integration of short exposure signals.

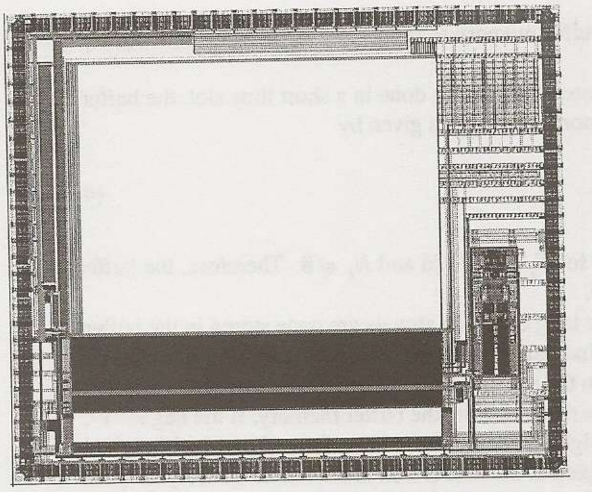

Figure 5: Layout of the prototype wide dynamic range CMOS image sensor.

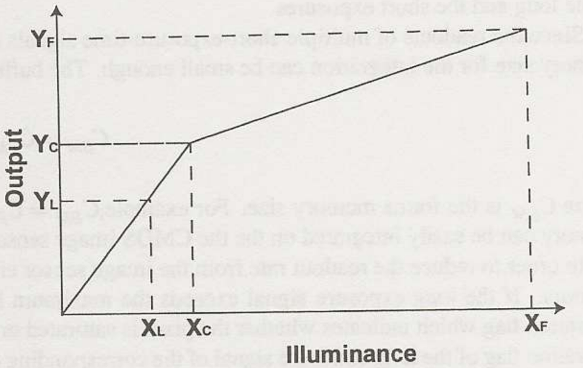

Figure 6: Photo conversion curve of wide dynamic range camera.

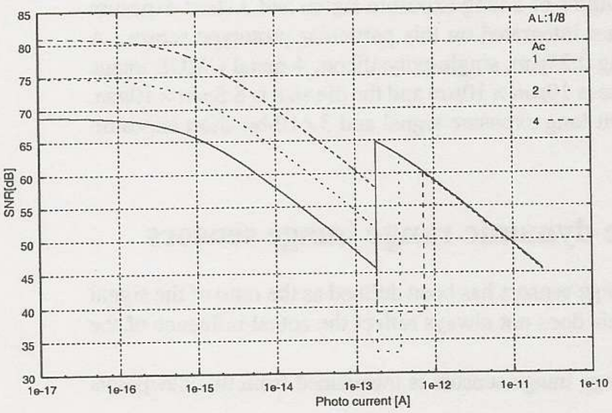

Figure 7: SNR curve versus photo current with A_c as a parameter.

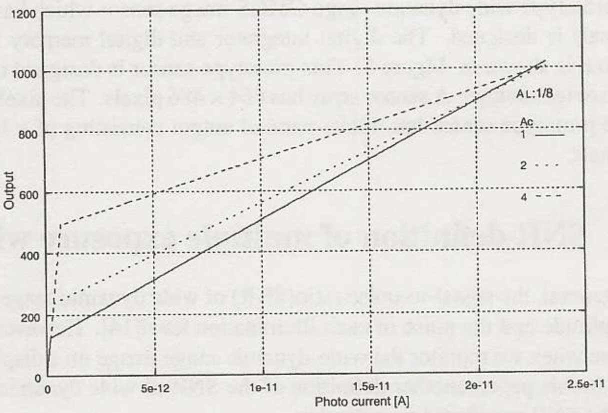

Figure 8: Photo conversion characteristic versus photo current with A_c as a parameter.

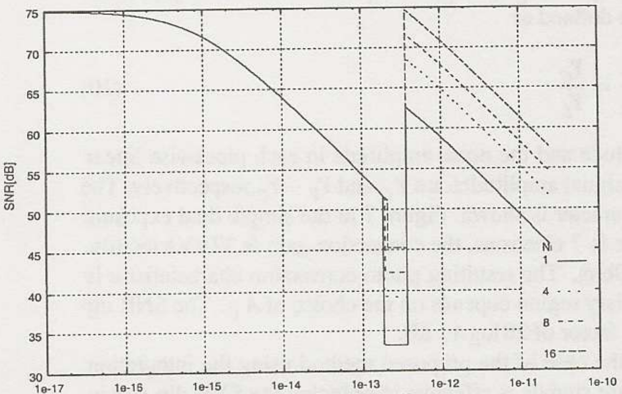

Figure 9: Comparison of SNR versus photo current with N_I as a parameter.

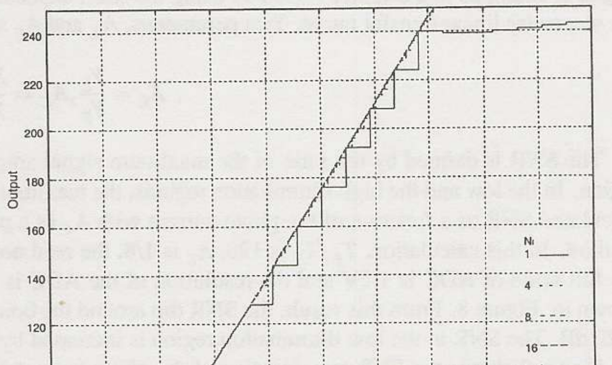

Figure 10: Comparison of output code versus photo current with N_I as parameter.

5 conclusions

This paper presents a method of wide dynamic range imaging. The digital integration of short exposure signals is effective in the wide dynamic range CMOS image sensor with high image quality over a wide illumination range. In the low illumination level, the use of a low-noise pixel device can improve the SNR, resulting the expansion of the dynamic range to low illumination side. The SNR dip at the boundary of low and high illumination regions can be effectively reduced using the digital integration method.

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