Wide dynamic range CMOS image sensor with in-pixel double-exposure and synthesis*

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Abstract: A wide-dynamic-range CMOS image sensor (CIS) based on synthesis of a long-time and a short-time exposure signal in the floating diffusion (FD) of a five-transistor active pixel is proposed. With optimized pixel operation, the response curve is compressed and a wide dynamic range image is obtained. A prototype wide-dynamic-range CMOS image sensor was developed with a 0.18 μm CIS process. With the double exposure time 2.4 ms and 70 ns, the dynamic range of the proposed sensor is 80 dB with 30 frames per second (fps). The proposed CMOS image sensor meets the demands of applications in security surveillance systems.

Key words: CMOS image sensor; double exposure; dynamic range; five-transistor active pixel
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1. Introduction

With the development of security surveillance systems, an image senor with a wide dynamic range is required. However, the dynamic range of conventional CMOS image sensors is lower than 60 dB[1], and thus cannot capture a scene consisting of both bright and dark regions without losing details. In order to expand the dynamic range of CMOS image sensors, some methods have been reported: logarithmic sensor response[2], using a lateral overflow integration capacitor[3], conditional reset[4] and so on. But these methods are at the cost of the complexity of the pixel. The conventional double exposure[5, 6] or multiple exposure[7] technology captures two or more images in different time periods and synthesizes them in a large size memory.

Yamada[8] indicated that a feedback loop circuit could be incorporated in each pixel so that multiple signals with different exposure periods were synthesized in the pixel and the dynamic range of the CMOS image sensor was enlarged. However, the feedback loop circuit made the pixel complex. In this paper, an optimized method to synthesize double or multiple exposure signals of CMOS image sensors is proposed. With the pixel operation, the double exposure signals are stored and synthesized in the floating diffusion node of the pixel. A wide dynamic range image is obtained without extra transistors in the pixel or memories on chip.

2. Pixel basic operation

Figure 1 shows a brief schematic of the sensor including pixel arrays, pixel driver, row decoder, reference and bias, column-parallel readout and processing module, and digital output module. Figure 2 is a pixel structure diagram. The five-transistor active pixel employs a pinned photodiode (PPD). M1 is the reset transistor with the control signal RST at its gate terminal. M2 is the transfer gate with the control signal TCK at its gate terminal. M3 is the amplifier transistor (source follower). M4 is the row selection transistor with the control signal SEL at its gate terminal. M5 is the global reset transistor with the pixel reset signal PR at its gate terminal.

The five-transistor pixel is operated in the global shutter mode, and the operation process is as follows: First, the signal PR is high to clear all the PD nodes. After that, the signal PR is low and the exposure begins. When the exposure finishes, the signal TCK is changed from low to high and the photoelectrons at PD are fully transferred to FD. When the signal TCK becomes low, one exposure period is finished. The exposure period is from the negative edge of PR to the negative edge of TCK. The double sampling technology is used to read out the illumination signal and the reset signal.

The five-transistor active pixel has many advantages: (1) The global shutter operation ensures that the exposure and readout operations are parallel with high frame rate, so it is suitable for high speed surveillance systems; (2) In the double exposure operation, the FD node is used for storing and synthesizing the illumination signals. PR resets all of the PD

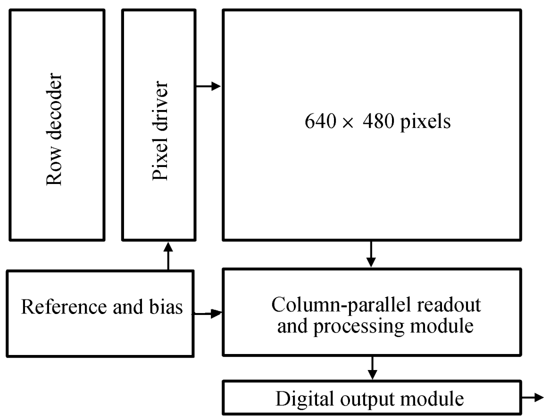

Fig. 1. Schematic of the sensor.

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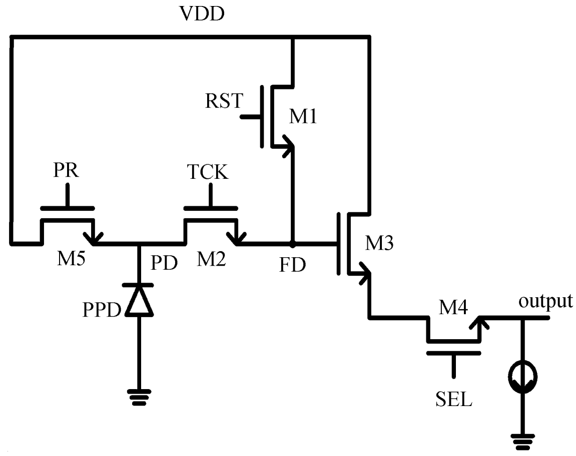

Fig. 2. Pixel structure diagram.

nodes to start the next exposure period, and the FD node saves the previous exposure signal. So it is easy to realize the double exposure operation. (3) M5 works as anti-blooming to limit the well capacity of PD.

3. Wide dynamic range operation

Figure 3 shows the timing diagram of the wide dynamic range operation. To make sure that read operation and long exposure operation are parallel, the long exposure T_1 is first and the short exposure T_2 is second. After the double exposure, the read operation works row by row. Figure 4 shows that through the design of the pixel drive circuit, the low level signal PR and the high level signal TCK are adjustable voltage signals. The adjustable signal PR prevents the excess photoelectrons at PD from flowing to the adjacent pixels. The voltage of the low level PR signal is above 0 V so that the barrier of M5 is lower than M2, and the excess photoelectrons flow to VDD through M5 during the exposure period. The adjustable signal TCK produces a barrier from PD to FD, so in the short exposure period, for the two adjacent pixels with high illumination close to each other, the number of photoelectrons exceeding the barrier to FD is different, and the details of the bright region are captured.

Figure 4 is the potential diagram of the double exposure operation:

(a) PR resets PD and the long exposure period begins.

(b) When the long exposure finishes, the information on the dark regions is captured and for the high illumination regions the well capacity of PD is full.

(c) The control signal TCK changes from low to high, but lower than VDD. The excess photoelectrons exceed the barrier from PD to FD.

(d) TCK is low and the long exposure signal is stored in FD. For high illumination, the quantity of overflow photoelectrons is the same.

(e) PR resets PD again and the short exposure period begins.

(f) When the short exposure finishes, for the high illumination regions the well capacity of PD is not full and the quantity of integration photoelectrons is different.

(g) TCK is high and lower than VDD, and for high illumination, the quantity of overflow photoelectrons is different. The long exposure signal and the short exposure signal synthesize at FD.

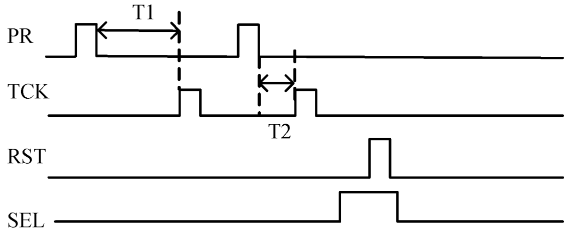

Fig. 3. Timing diagram.

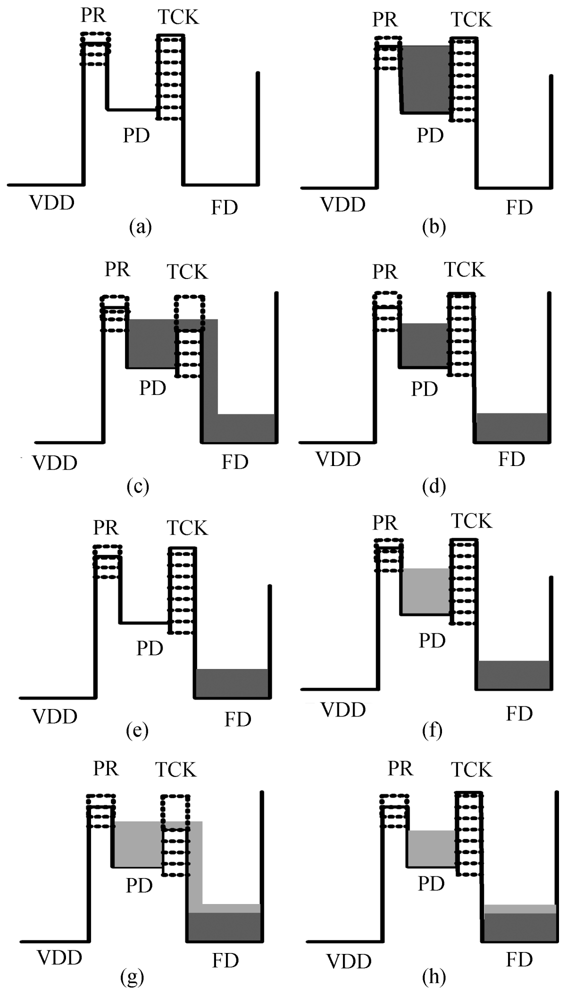

Fig. 4. Potential diagram of the double exposure operation.

(h) TCK is low and the synthesized signal is read out. In the double exposure period, the low level signal PR is adjustable.

To optimize the double exposure, the method to choose the high level signal TCK and the low level signal PR are discussed as follows. For example, the high level amplitudes of TCK are the same and the low level amplitudes of PR are the same in the double exposure operation.

3.1. Voltage level of the control signal

Suppose the full well capacity of PD is $q_{\max}$ neglecting the dark current. In the double exposure operation, the time period of the long exposure is T_1, and that of the short exposure is

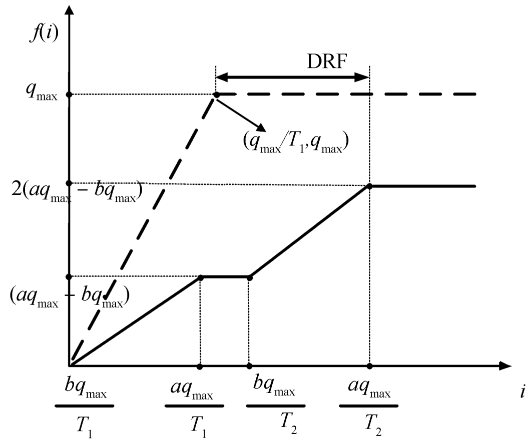

Fig. 5. $f(i)$ versus i curve.

T_2. The low level signal PR reduces the well capacity of PD to aq_{max} ($0 < a < 1$), and there is a barrier from PD to FD due to the high level signal TCK so that the excess photoelectrons at PD overflow to FD. Suppose the amount of photoelectrons remaining in PD is bq_{max} ($0 < b < 1$). From theoretical analysis, Equation (1) is the relationship formula between $f(i)$ and i, and the corresponding curves are shown in Fig. 5.

$$f(i) = \begin{cases} 0, \quad i < \dfrac{bq_{max}}{T_1}, \\ iT_1 - bq_{max}, \quad \dfrac{bq_{max}}{T_1} \leqslant i < \dfrac{aq_{max}}{T_1}, \\ aq_{max} - bq_{max}, \quad \dfrac{aq_{max}}{T_1} \leqslant i < \dfrac{bq_{max}}{T_2}, \\ aq_{max} + iT_2 - 2bq_{max}, \quad \dfrac{bq_{max}}{T_2} \leqslant i < \dfrac{aq_{max}}{T_2}, \\ 2(aq_{max} - bq_{max}), \quad i \geqslant \dfrac{aq_{max}}{T_2}. \end{cases} \tag{1}$$

According to the curve, the maximum non-saturating input signal in the conventional exposure operation is

$$i_{max} = q_{max}/T_1, \tag{2}$$

and the maximum non-saturating input signal in the proposed double exposure operation is

$$i'_{max} = aq_{max}/T_2, \tag{3}$$

so the dynamic range enhancement factor (DRF) is

$$\text{DRF} = 20\lg(i'_{max}/i_{max}) = 20\lg a \cdot T_1/T_2. \tag{4}$$

It can be shown that as a or T_1/T_2 increases, DRF increases.

Suppose the full well capacity of FD is q_{FDmax}, ($q_{max} < q_{FDmax}$). So the total maximum photoelectrons at FD are

$$2(aq_{max} - bq_{max}) \leqslant q_{max} \leqslant q_{FDmax}, \quad a - b \leqslant 0.5. \tag{5}$$

When the illumination signal is transferred from PD to FD, the right potential barrier is lower than the left for M2. So

$$a > b \quad \text{and} \quad a - 0.5 \leqslant b < a. \tag{6}$$

To capture the details of the darker regions, the value of b takes a smaller value.

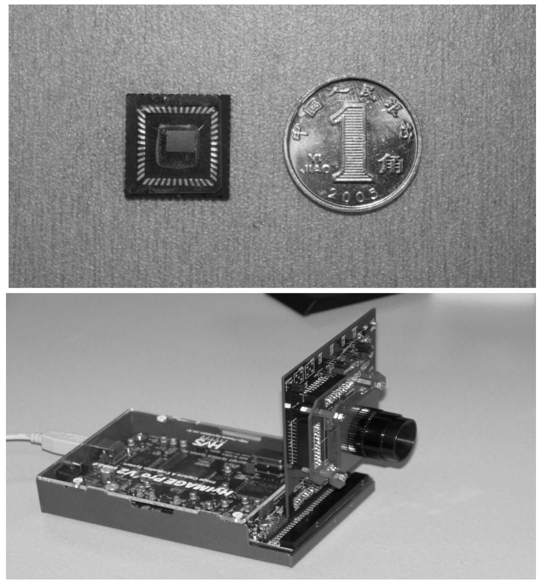

Fig. 6. Chip and capture system.

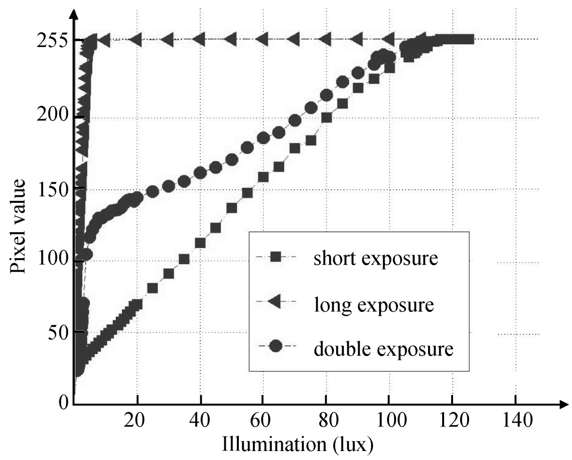

Fig. 7. Response curve.

3.2. Exposure time

In the double exposure operation, the dark details are captured during the long exposure period; the bright details are captured during the short exposure period. Suppose that in the conventional exposure operation, the dark areas of the scene can be captured in t_1, the bright details can be captured in t_2,

$$i_{max}t_2 = q_{max}. \tag{7}$$

In order to capture a scene consisting of both bright and dark regions without losing details, the exposure times T_1 and T_2 of the proposed double exposure should meet some conditions. To exceed the barrier from PD to FD, the long exposure time increases.

$$T_1 = t_1 + bq_{max}/i_{max} = t_1 + bt_2. \tag{8}$$

To prevent the photoelectrons spilling over, the total photoelectrons at FD,

$$(aq_{max}/i_{max} - bq_{max}/i_{max}) + (T_2 - bq_{max}/i_{max}) = t_2. \tag{9}$$

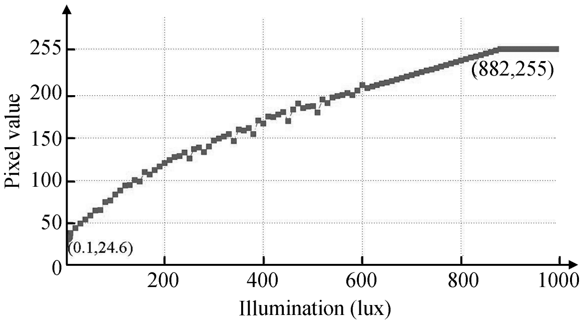

Fig. 8. Dynamic range.

Table 1. Exposure parameters.

Characteristic	Value
First exposure time	2.4 ms
Second exposure time	70 ns
High level of TCK	84 mV
Low level of PR	0.3 V
Frame frequency	30 fps
Dynamic range	80 dB

So

$$T_2 = (2b - a + 1)t_2. \tag{10}$$

Above all, in the double exposure operation, the voltage level of the control signal PR and TCK should be taken into consideration. The exposure time also needs to be considered according to the scene information and the degree of the pixel saturation.

4. Measurement results

The proposed double exposure operation and the drive circuit have been employed in a prototype CMOS image sensor. This sensor was fabricated based on a 0.18 μm CIS process. Figure 6 shows the chip and the capture system. Figure 7 shows the test response curves. The triangle curve is the response of long exposure in the conventional exposure operation; the square curve is the response of short exposure in the conventional exposure operation; the round curve in the middle is the response of the proposed in-pixel double exposure and synthesis operation. Figure 8 is the response curve under the conditions listed in Table 1, and the maximum dynamic range achieved is 80 dB. Figure 9 shows the images which are captured in the conventional exposure operation and the proposed double exposure operation. Figure 9(a) is the short-time-exposure image of the conventional operation. The region outside the window is clear, whereas the inside is almost at the black level and the details are lost. Figure 9(b) is the long-time-exposure image of the conventional operation. The bright region outside the window shows flashing highlights due to the pixel saturation, while the region inside the window is captured clearly. Figure 9(c) is the image of the proposed double-exposure and synthesis operation. The regions outside and inside the window are both captured.

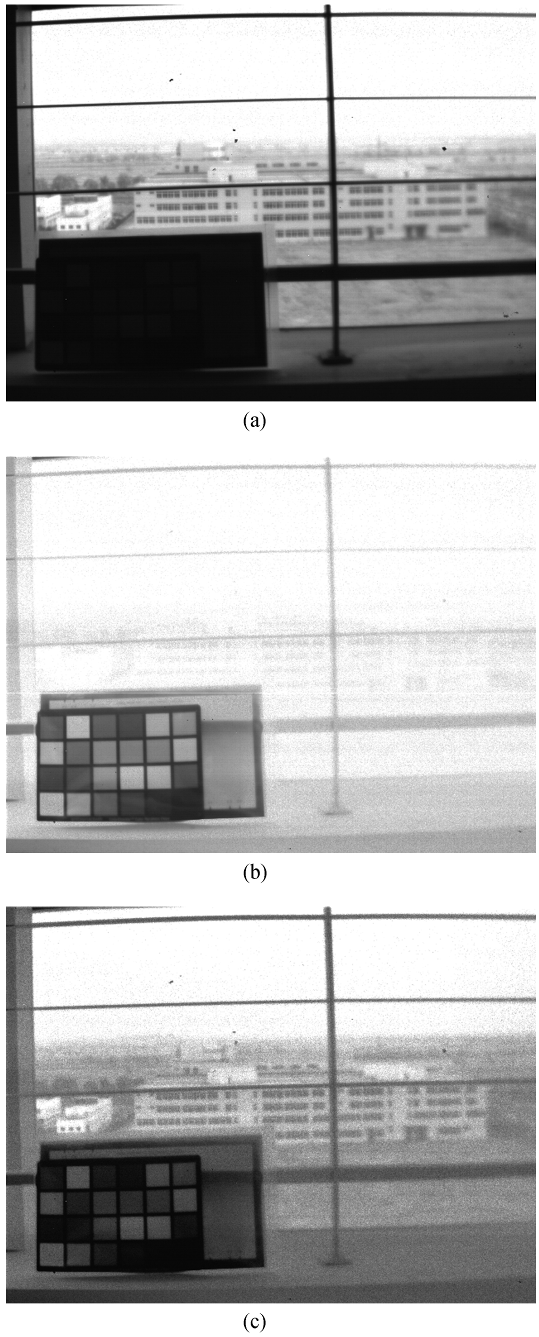

Fig. 9. Sample images. (a) Short-time-exposure image. (b) Long-time-exposure image. (c) The proposed wide dynamic range CIS.

5. Conclusion

A CMOS image sensor with in-pixel double-exposure and synthesis has been presented. Through optimizing the synthesis methods in the aspects of the exposure time and the voltage level of the control signal, the response curve of the CMOS image sensor is compressed and the dynamic range is enhanced to 80 dB.

References

[1] Hara K, Kubo H, Kimura M, et al. A linear-logarithmic CMOS sensor with offset calibration using an injected charge signal. ISSCC, 2005: 354

[2] Kavadias S, Dierickx B, Scheffer D, et al. A logarithmic response CMOS image sensor with on-chip calibration. IEEE J Solid-State Circuits, 2000, 35: 1148

[3] Akahane N, Sugawa S. Improvement of a 100-dB dynamic range CMOS image sensor using a lateral overflow integration capacitor. IEEE J Solid-State Circuits, 2006, 41: 851

[4] Yang S H, Cho K R. High dynamic range CMOS image sensor with conditional reset. IEEE Custom Integrated Circuit Conference, 2002: 265

[5] Yadid-Pecht O, Fossum E R. Wide intrascene dynamic range CMOS APS using dual sampling. IEEE Trans Electron Devices, 1997, 44: 1721

[6] Lin B R, Huang S Y, Lai C H, et al. A high dynamic range CMOS image sensor design based on two-frame composition. Proceedings IEEE International SOC Conference, 2003: 389

[7] Sasaki M, Mase M, Kawahito S, et al. A wide-dynamic-range CMOS image sensor based on multiple short exposure time readout with multiple resolution column parallel ADC. IEEE J Sensors, 2007, 7: 151

[8] Yamada T, Kasuga S, Murata T, et al. A 140 dB dynamic range MOS image sensor with in-pixel multiple-exposure synthesis. ISSCC, 2008