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Temperature Compensation Scheme for Logarithmic CMOS Image Sensor

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ABSTRACT

In this paper, we present a temperature compensation method for logarithmic CMOS image sensors. As Bandgap technique, the compensation circuit generates V_{PTAT1} and V_{PTAT2} voltages to compensate temperature variation of the sensor output signal voltage (Out-AC-Signal) which we call V_{CTAT1} and output reference voltage (V_{Ref-ph}) which we call V_{CTAT2}. The proposed method is divided into three stages. At first, we copy the photocurrent in order to store it in the V_{PTAT1} circuit generator. Second, we use a pixel structure with improved output voltage swing. It has an output voltage swing two times larger than the standard logarithmic pixel. Third, we add a third column amplifier branch dedicated to V_{PTAT1} circuit generator. With this method, we obtain a good temperature stability of the sensor response in the temperature range from -30 to 125°C without changing the sensor operation and we conserve all the same sensor response characteristics.

I. INTRODUCTION

CMOS image sensors are used in various industrial applications: military, surveillance, etc [1]. The logarithmic sensors have the advantage of providing a great dynamic range (DR), about 120dB [2]. E.g. in automobile safety or monitoring that require greater dynamic range to detect details at the same time in highlights and shadows of a scene. These sensors are often exposed to large temperature variations. E.g. in automotive applications, the temperature may vary from -30 to 125°C.

A. Logarithmic CMOS image sensor

Standard logarithmic pixel is composed of one photodiode and three or four PMOS transistors [2] (Fig.1(a)). These sensors have a continuous operating curve (Fig.1(c)) which provides an output voltage logarithmically dependent from the photocurrent value. The pixels transient operation is shown in Fig.1(d). Note that, in order to avoid Fixed Pattern Noise (FPN) problem, this sensor extract two informations: The photogenerated output voltage (Out-AC-Signal) and a reference voltage (V_{Ref-ph}) by applying a voltage vcal=0V for the transistor M4 (Fig.2) [2]. The transistor M1 operates in subthreshold mode. It is used

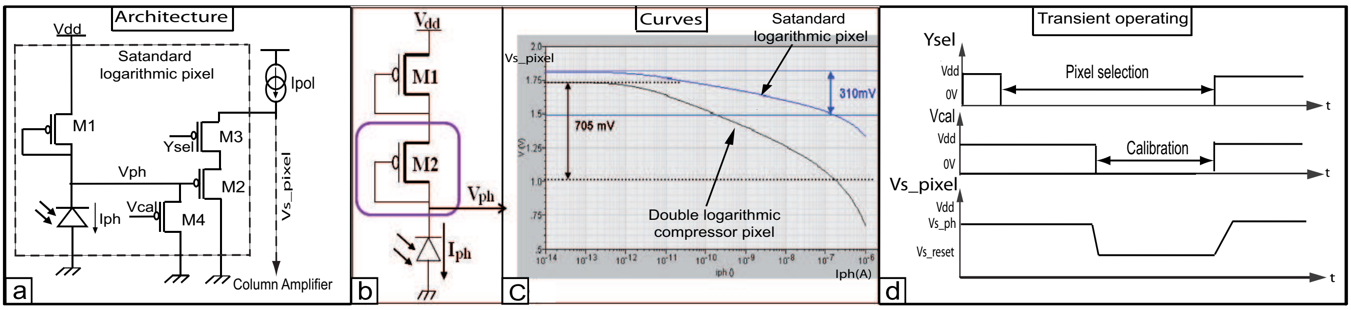

Fig. 1. Logarithmic CMOS Image Sensor [2]: a) 4T Pixel Schematic; b) pixel with double logarithmic compressor; c) DC simulation result of the typical and the improved one; c) Transient characteristic of the pixel

to create an output voltage that is a logarithmic function of the photocurrent (Fig.1). Equation (1) shows the relationship of the output voltage $V_{s-pixel}$ with the photocurrent I_{ph}.

$$V_{s-pixel} = V_{ph} + V_{th2} = \left[V_{dd} - nU_t ln\left(\frac{I_{ph}}{I_0}\right)\right] + V_{th2} \quad (1)$$

Where drain source voltage V_{ds} of the transistor M3 turned on is neglected. V_{th2} is the threshold voltage of M2. Parameters n and I_0 are process dependent, n value is between 1 and 2. U_t is the thermal voltage (Ut=kT/q).

B. Output voltage swing improvement

To improve the output voltage swing of the standard logarithmic pixel, we referred to the architecture presented by [3] and enhanced by [4]. The basic principle of this pixel is to insert a second diode connected transistor (M2 in Fig.1(b)), operating in sub-threshold region, as a second logarithmic compressor, between the photodiode and the first transistor. So we obtain a new relation between the pixel output voltage and the photocurrent (equation (2)).

$$V_{ph} = V_{dd} - n(n+1)U_t ln\left(\frac{I_{ph}}{I_0}\right) \tag{2}$$

The improvement made by this method is due to the multiplication of the logarithmic slope of the curve by the factor: n+1$\approx$ 2. (Fig.1(c)) gives the result of the DC simulation that compares the two output voltage swings.

The main contribution of this work is the improvement of the robustness of logarithmic sensors, making them less sensitive to temperature variations without changing the sensor operation. We also conserve the sensors main characteristics.

Up till now, no integrated solution of this shortcoming has been proposed. There is one analog method known as CMOS Bandgap Voltage Reference [5], which provides an output DC voltage (or current) insensitive to temperature. Researchers also use Bandgap operation to do temperature compensation in many circuits such as in CMOS DRAM [6], but never for CMOS image sensor.

The paper is structured as follows; In Section 2 the results of the temperature effect on logarithmic sensor are presented and discussed. Section 3 introduces the proposed solution and the results are presented in section 4. Conclusion and future work are given in the last section.

II. Temperature effect on logarithmic CMOS image sensor

The temperature effect on the overall logarithmic CMOS image sensor (Fig.2) is illustrated in Fig.3.

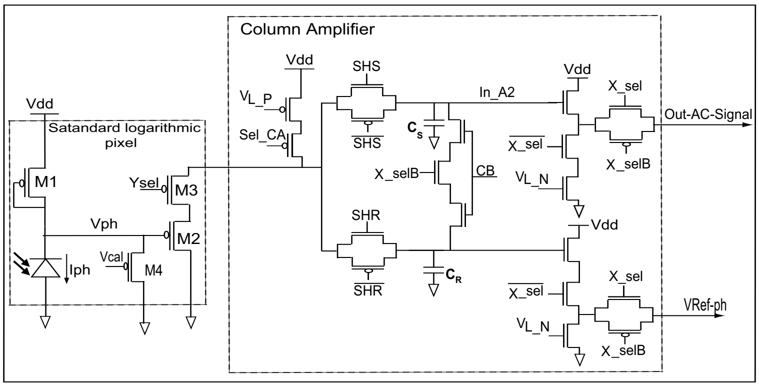

Fig. 2. Logarithmic 4T Pixel and Column Amplifier Schematic Diagram proposed by [2]

Fig.3 shows that the sensor output voltage is strongly affected by temperature: Around 200mV to 300mV deviation for a temperature range of 155°C. Its values increase with temperature differently for each photocurrent I_{ph} (Fig.3). We also observe two different types of variation : an offset deviation and a slope variation. According to Fig.3(a) and Fig.3(b), the dynamic range increases for high temperature but it decreases for low temperatures.

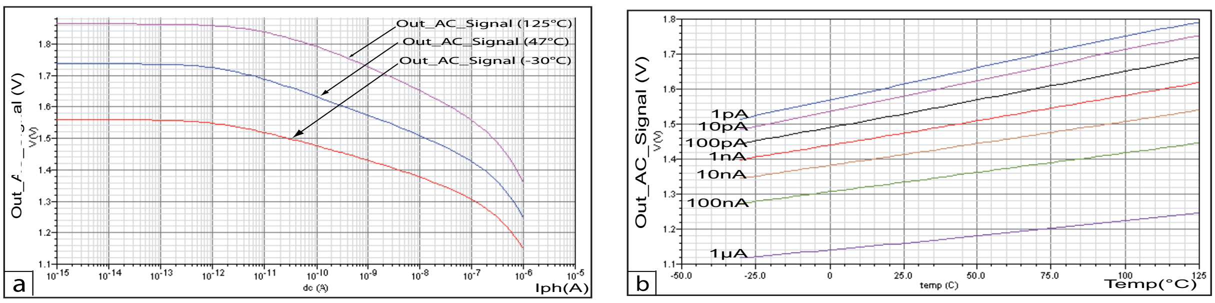

Fig. 3. a) Out-AC-Signal Variation with Photocurrent (I_{ph}) for Several Values of Temperature (-30°C, 47°C and 125°C), b) Out-AC-Signal Variation with Temperature (from -30°C to 125°C) for Several Values of I_{ph} (Fig.3(a))

Note that, the sensor output reference voltage (V_{Ref-ph}) has a constant temperature variation because it does not depend on the pixel photocurrent I_{ph}.

Besides, in [1] it was demonstrated that the photodiode dark current has a large variation especially for high temperatures, its value is almost doubled every 6 to 8°C. The noise also increases with temperature. As a conclusion, the sensor cannot work correctly in a wide range of temperature values without temperature compensation.

III. Proposed solution

The proposed solution is inspired from Bandgap [5] which is based on adding two voltages, V_{CTAT} and V_{PTAT}. These voltages have equal but contradictory temperature variations in order to obtain a compensated voltage V_{COMP} insensitive to temperature variation. So, in this method we compensate the temperature variation of sensor response V_{CTAT} by a V_{PTAT} which is generated by V_{PTAT} circuit generator (Fig.4(a)). Note that, the compensated voltage V_{COMP} could be written as

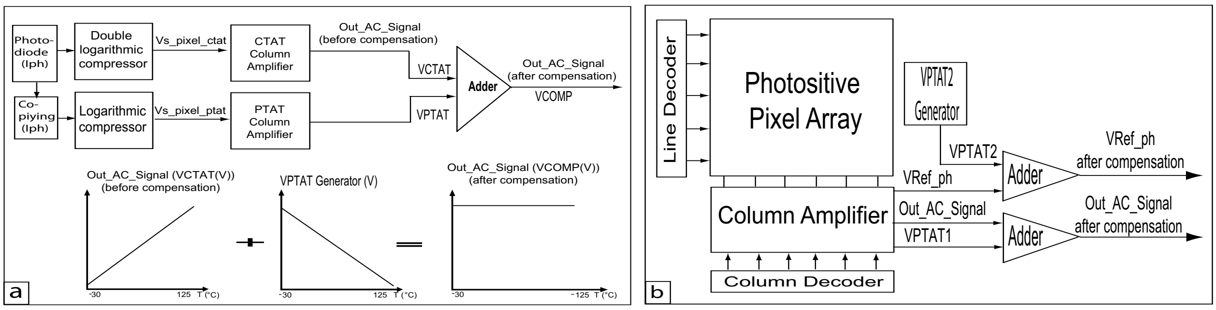

Fig. 4. a) The Temperature Compensation Method Diagram, b) The Temperature Compensation Global System Schematic Diagram

V_{COMP}=V_{CTAT}+V_{PTAT}(Fig.4(a)). But, as presented in section 2, the temperature variation of the sensor response V_{CTAT} is very different from one photocurrent to another. Thus, to achieve a good temperature compensation, we must have a V_{PTAT} voltage generator circuit that depends on the temperature variation and the photogenerated current as is the case for the sensor output response V_{CTAT}. So, the solution is to take into account the photocurrent value in the V_{PTAT} voltage generator circuit, via the M5 and M6 PMOS transistors (Fig.5) for copying the photocurrent value. Equation (3) is obtained with this structure:

$$V_{SM6} = (n-1)V_{dd} + nU_t ln\left(\frac{I_{ph}}{I_0}\right) \tag{3}$$

To obtain a good temperature compensation, it is necessary to have the same but opposite temperature sensitivity slope (generated by the M6 transistor (Fig.5)) between the both voltages V_{CTAT1} and V_{PTAT1}. Equation (3) provides an opposite temperature sensitivity in relation with the output of the pixel. This implies that the same architecture of the sensor readout scheme (pixel follower amplifier and column amplifier) should be used. As said in section 2, Out-AC-Signal and V_{Ref-ph} have two different types of temperature variations. This is why we use two V_{PTAT} circuits generator for each of them (Fig.5). We call Out-AC-Signal voltage the V_{CTAT1}, the V_{Ref-ph} voltage the V_{CTAT2} and their compensation voltages V_{PTAT1} and V_{PTAT2} respectively. As specified before, the V_{Ref-ph} voltage does not depend on the photocurrent, thus it is not necessary to take into account the photocurrent in the V_{PTAT2} generator circuit (Fig.5) At the end, we sum the two voltages, V_{CTAT1}

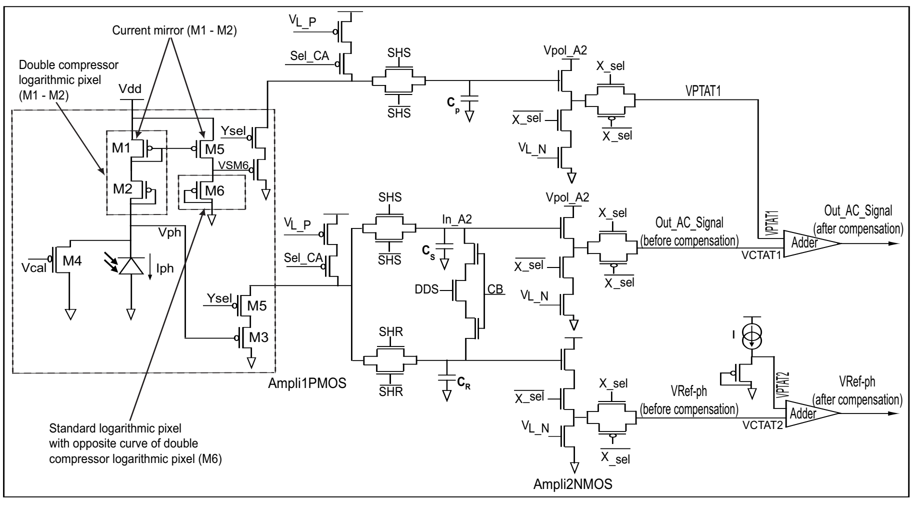

Fig. 5. The Temperature Compensation System Transistor Schematic Diagram

and V_{PTAT1}, and we obtain a signal with an output voltage swing close to the one of standard logarithmic pixel (equation (4)). This is why we use the output voltage swing improvement for V_{CTAT1} and the voltage swing of normal logarithmic pixel for V_{PTAT1}.

$$V_{ph} + V_{SM6} = n \left[V_{dd} - nU_t ln \left(\frac{I_{ph}}{I_0} \right) \right] \tag{4}$$

The final schematic diagram is shown in Fig.4(b). Note that only one circuit of V_{PTAT2} generator is needed for doing a temperature compensation of the V_{Ref-ph} of all the pixels of the image sensor.

IV. Results and discussion

By using this method, we succeed to have a good temperature compensation from -30 to 125°C for logarithmic sensor (Fig.6(a) and (b)). Fig.6(a) shows the three curves of the output voltage (Out-AC-Signal) obtained with -30°C, 47°C and 125°C before and after compensation, the corresponding curves from V_{PTAT1} are also shown. By looking at these results, we obtained after compensation, very similar output voltage curves in the temperature range from -30 to 125°C. Moreover, the

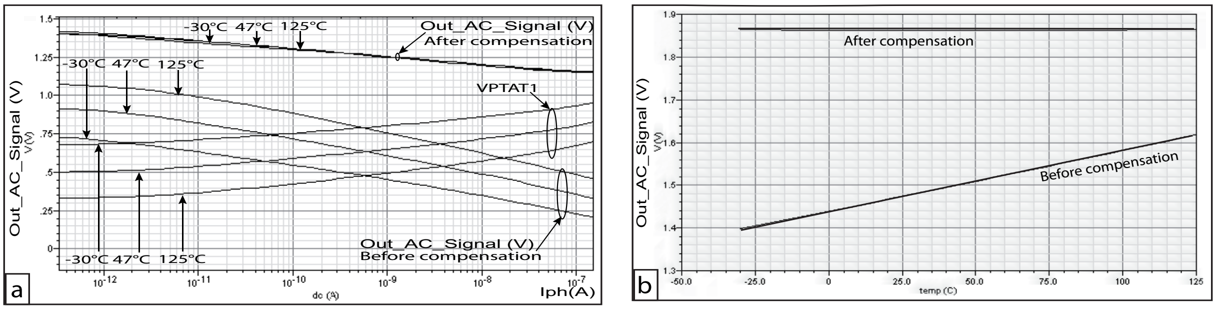

Fig. 6. a) Results Obtained With The Compensation Scheme, b) Compensated and Non Compensated Out-AC-Signal Curves for I_{ph}=1nA (Fig.3)

sensor response curve characteristics of standard logarithmic sensor are the same before and after compensation. Except that after compensation, the sensor response is insensitive to temperature variation. As conclusion, a good temperature compensation for the sensor responses is obtained without changing the operation of the sensor. In addition, we conserve almost all characteristics of the standard sensor responses like input DR ($\approx 120dB$) and the output voltage swing ($\approx 310mV$). Fig.6(b) shows the DC simulation of two sensor output voltage curves (Out-AC-Signal) before and after compensation optimized for I_{ph}=1nA. Furthermore, we get less than 2mV of variation at the output voltage from -30 to 125°C for I_{ph}=1nA instead of 260mV before compensation. On the other hand, we obtain maximum temperature variation less than 10mV for the rest of the photoccurent values. We have reduced the output voltage temperature variation of the sensor at least 90% and at most 98% for all the photocurrent values. For the output (V_{Ref-ph}), a good temperature compensation is obtained and we reduce the temperature effect by 98%. The advantage of this temperature compensated 9T pixel is that it preserves the same response characteristics of a basic FPN compensated logarithmic sensor, for this we add a seconde reference branche for the PTAT column amplifier.

V. Conclusions and future work

A temperature compensation system dedicated to CMOS logarithmic image sensor has been presented. After an overview of this sensor, temperature effect results have been shown. This paper also shows that the output voltage of this sensor varies strongly and linearly with temperature and it depends on the photocurrent. A temperature compensation method is described with its three stages, and the associated results. Through this method, we have reduced strongly the total variation of the initial output voltages temperature variation and we have a good temperature stability of the responses (Out-AC-Signal and V_{Ref-ph}). The advantage of this method is that it conserves the same sensor response characteristics like the high sensor DR. Only one circuit to compensate all the reference voltages V_{Ref-ph} of the sensor is used.

VI. Acknowledgment

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