Temperature Compensation Method for Logarithmic CMOS Vision Sensor Using CMOS Voltage Reference Bandgap Technique

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***Abstract*—A temperature compensation method for logarithmic CMOS vision sensor is presented in this paper. This method is inspired from CMOS Bandgap Voltage Reference technique. The proposed method uses simple circuits located in the column amplifier. As systems using Bandgap technique, our circuits generate V_{PTAT1} and V_{PTAT2} voltages to compensate temperature variation of the sensor output signal voltage (Out-AC-Signal voltage) which we call V_{CTAT1} and output reference voltage (V_{Ref-ph} voltage) which we call V_{CTAT2}. With this method, a good temperature stability of the sensor response in the temperature range from -30°C to 125°C is obtained. The great advantage of this method that we obtain a good temperature compensation for the output voltages and it conserves all pixel characteristics like fill factor and the photositive pixel array area. This method has been verified via Cadence simulation in a $0.35\mu m$ CMOS technology. This method and the complete circuit have also been presented with the associated results.**

I. Introduction

CMOS image sensors find widespread use in various industrial applications including: military, surveillance, medical, etc [1]. In these applications, CMOS image sensors are often exposed to large temperature variations. E.g. in automotive applications inside and outside the vehicle the temperature may vary from -30°C to 125°C.

CMOS visions sensors capture light information and convert it into an analogue or digital electrical signal [2]. There are two kinds of CMOS vision sensors: The "logarithmic" sensors and the "standard" integration sensors. This work is focused on the logarithmic sensors as shown in Fig.1. The logarithmic sensors pixel is composed of one photodiode and three or four PMOS transistors [3], as illustrated in Fig.1(a). These logarithmic sensors has the advantage of providing a great dynamic range (DR), about 120dB [3] instead of 60-70dB for a standard integration CMOS sensor or 80dB for a CCD sensor. These sensors have a continuous operating curve shown in Fig.1(b). The Transient operating of the pixel is shown in Fig.1(c) [3].

Note that, in order to avoid Fixed Pattern Noise (FPN) problem, this sensor extract two informations: The photogenerated output voltage called Out-AC-Signal and a reference voltage called V_{Ref-ph} see Fig.2 [3].

A diode-connected MOS transistor operating in subthreshold mode (M1) is used to create an output voltage that is a logarithmic function of the photocurrent (Fig.1). Equation

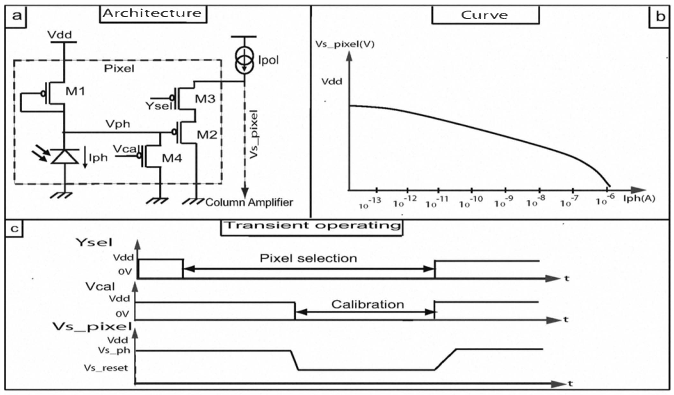

Fig. 1. Logarithmic CMOS Image Sensor: a) 4T Pixel Schematic; b) Logarithmic phototransduction curve; c) Transient characteristic of the pixel

(1) shows the logarithmic relationship of the output voltage $V_{s-pixel}$ with the photocurrent I_{ph}.

$$V_{s-pixel} = V_{ph} + V_{t2} = \left[V_{dd} - nU_t ln\left(\frac{I_{ph}}{I_0}\right) \right] + V_{t2} \quad (1)$$

Where the drain source voltage V_{ds} of the transistor M3 turned on is neglected. The V_{t2} is the threshold voltage of M2. Parameters n and I_0 are process dependent. Parameter n value is between 1 and 2. U_t is the thermal voltage (Ut=kT/q).

The main contribution of the work, presented in this paper, is the improvement of the robustness of logarithmic CMOS image sensors, making them less sensitive to temperature variations without changing the sensor operation. This method conserves the sensors main characteristics like the dynamic range. Another advantage of this method that it conserves the pixel array surface and it needs only a little area in column amplifier for doing the temperature compensation.

Until now, there is one analogue method, which provides an output DC voltage or current insensitive to temperature variations. This method is called CMOS Bandgap Voltage Reference for CMOS technology [4]. CMOS Bandgap Voltage Reference technique is very interesting, but it is optimized to provide fixed output voltage. In the other hand, researchers also use Bandgap Voltage Reference operation to do temperature compensation in many circuits as in CMOS Dynamic Random Access Memory (DRAM) [5], but never for CMOS image sensor. As a result, our compensation method is inspired from Bandgap Voltage Reference technique.

The paper is structured as follows; Section 2 discusses the influence of temperature on the main MOS transistor parameters like: mobility μ_n, threshold voltage V_{th}, and I_{DS} current. In Section 3 the results of temperature effect on the logarithmic CMOS image sensor are discussed. Section 4 introduces the proposed solution, which use the operation of the CMOS Bandgap Voltage Reference technique. In the same section, we explain how this compensation method works. Afterward, simulations results are presented and discussed. Finally, conclusion and future work are given in the last section.

II. The Effects of Temperature on MOS Transistor Parameters

In MOS transistor temperature influences on two essential parameters, threshold voltage V_{th} and electrons mobility μ_n [6], [7].

A. Threshold voltage V_{th}

Threshold voltage V_{th} varies approximately $-2mV/°C$ [8], [9] as is modelled in equation (2):

$$V_{th} = V_{th_0} - [a \times (T - T_0)] \quad (2)$$

V_{th_0}= 0,7V is the initial threshold voltage. a is a process parameter with $a = 2.3mV/°C$ in $0.35\mu m$ CMOS technology. T is the environmental temperature. T_0 is the room temperature 27°C.

B. The mobility factor μ_n

In fact, mobility μ_n decreases with temperature as shown in equation (3):

$$\mu_n(T) = \mu_0[(T - T_0)^{BEX}] \quad (3)$$

With μ_0 = 660 $[cm^2/V.S]$ for NMOS transistor, and 210 $[cm^2/V.S]$ for PMOS transistor. $BEX \approx -1,5$ is a negative temperature exponent for the mobility in $0.35\mu m$ CMOS technology.

C. The drain current I_{DS}

Equation (4) gives the drain current evolution in saturation region:

$$I_{DS} = (\frac{\mu_n C_{ox}}{2})(\frac{W}{L})[(V_{GS} - V_T)^2] \quad (4)$$

As mentioned above, mobility μ_n decreases with increasing temperature. Therefore, the drain current I_{DS} decreases with increasing temperature. However, threshold voltage V_{th} decreases with temperature and from equation (4) I_{DS} increases with decreasing V_{th}. From this, we find two opposing trends. Finally, we deduce that at larger values of I_{DS}, I_{DS} decreases with the increasing temperature. Namely, the decrease in μ_n is more influential than the decrease in V_{th}. On the other hand, at lower values, the I_{DS} increases with increasing temperature. Namely, the decrease in V_{th} is more influential than the decrease in μ_n. However, at a certain value of I_{DS}, both influence of μ_n and V_{th}, cancel each others and I_{DS} current is insensitive to temperature variation [6], [7], [10].

III. Impact of Temperature on the Logarithmic CMOS Image Sensor

The temperature effect on the overall logarithmic CMOS image sensor is shown in this section and is illustrated in Fig.2.

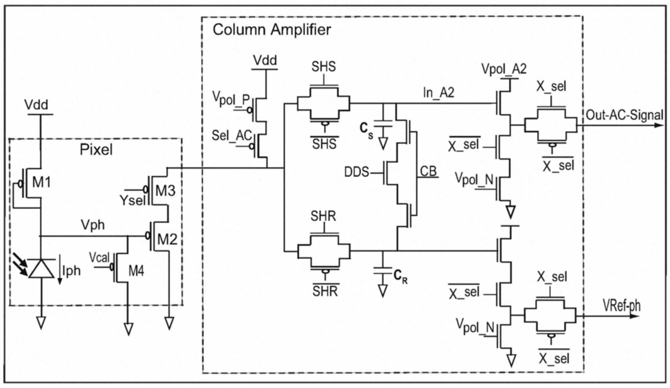

Fig. 2. Logarithmic 4T Pixel and Column Amplifier Schematic Diagram proposed by [3]

Fig.3 shows that the output voltage of logarithmic CMOS image sensor 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} as shown in Fig.3. We also observe two different types of variation: an offset deviation and a slope variation.

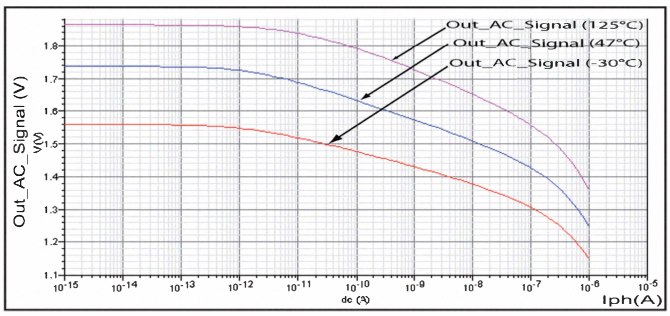

Fig. 3. Out-AC-Signal Variation with Photocurrent (I_{ph}) for Several Values of Temperature (-30°C, 47°C and 125°C)

In addition, Fig.4 illustrates that the output voltage increases linearly with temperature for all photocurrent values. According to Fig.3 and Fig.4, the dynamic range increases for high temperatures but it decreases for low temperatures.

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,

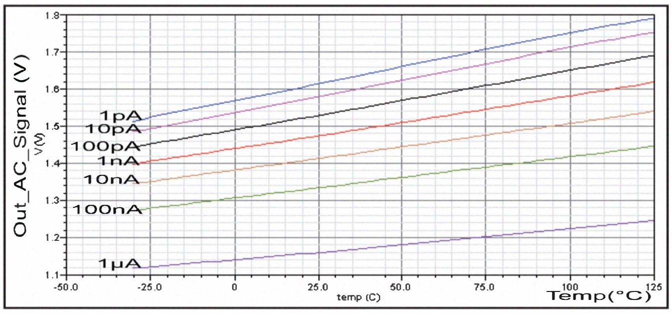

Fig. 4. Out-AC-Signal Variation with Temperature (from -30°C to 125°C) for Several Values of I_{ph} (Fig. 3)

its value is almost doubled every 6 to 8°C. The noise in the sensor also increases with temperature [1].

As a conclusion, the logarithmic CMOS image sensor cannot work correctly in a wide range of temperature values without temperature compensation.

IV. Proposed Solution

Our temperature compensation method is inspired from the Bandgap Voltage Reference technique 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, with this method we compensate the temperature variation of logarithmic CMOS image sensor response V_{CTAT} voltage by a V_{PTAT} voltage which is generated by V_{PTAT} circuit generator (Fig.5). The aim of this compensation is to get a sensor response insensitive to temperature variation.

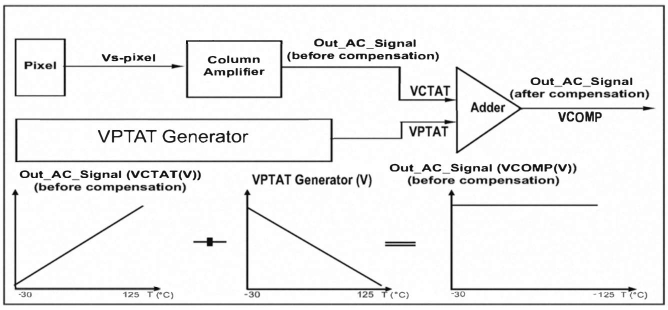

Fig. 5. Our Temperature Compensation Method Diagram

Note that, the compensated voltage V_{COMP} could be written as V_{COMP}=V_{CTAT}+V_{PTAT} as indicated in Fig.5. The compensation method operation is also shown in this figure.

We precise that, the same method is applied for V_{Ref-ph} voltage. As indicated before, in section 3, the temperature variation of Out-AC-Signal and V_{Ref-ph} is not the same, for this we use two V_{PTAT} circuits generator as shown in Fig.6. To be clear, 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. The transistor schematic of the global circuit is detailed in Fig.6.

The difficulty of this compensation method is to get output voltages insensitive to temperature variation without change

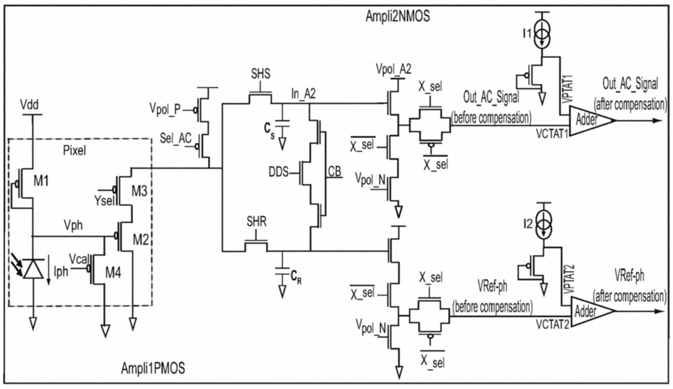

Fig. 6. Our Temperature Compensation System Schematic Diagram

the operating of the sensor. For this the two circuits shown in Fig.6 are used. This two circuits provide two voltages V_{PTAT1} and V_{PTAT2} that have the same but opposite temperature sensitivity for each output voltages V_{CTAT1} and V_{CTAT2} respectively.

The great advantage of this method that only two circuits of V_{PTAT1} and V_{PTAT2} generator are needed for doing a temperature compensation for the output voltages of all the pixels of the image sensor. Analogue adders are placed close to the column amplifier row and receive all column amplifiers outputs: Out-AC-Signal and V_{Ref-ph}, via the column decoder selection and V_{PTAT1} and V_{PTAT2} from the V_{PTAT1} and V_{PTAT2} generator circuits. The final schematic diagram is shown in Fig.7.

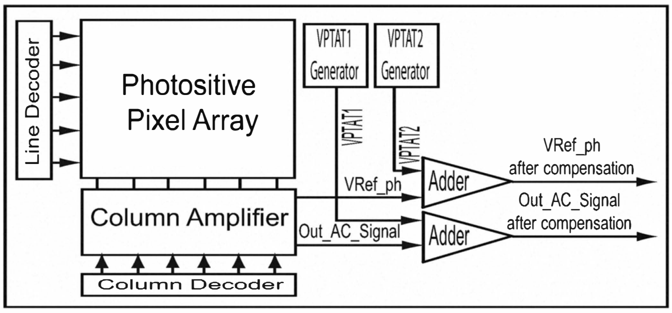

Fig. 7. Our Temperature Compensation Global System Schematic Diagram

V. Results and Discussion

By using this method, we succeeded to have a temperature compensation from -30°C to 125°C for logarithmic CMOS vision sensor as shown in Fig.8 and Fig.9.

Fig.8 shows the three curves of the sensor output voltage (Out-AC-Signal) obtained with -30°C, 47°C and 125°C temperature values 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°C to 125°C.

the only difference that we have, is a shift in the voltage output curve by 500mV up. This shift changes nothing in the

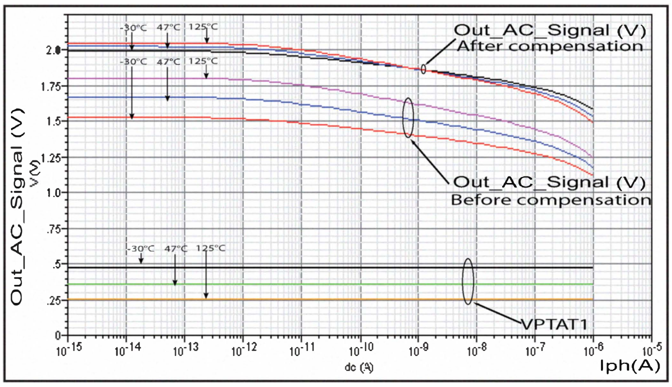

Fig. 8. Results Obtained With Our Compensation Scheme

sensor operation.

Fig.9 shows the two curves of sensor output voltage Out-AC-Signal obtained without and with compensation scheme optimized for I_{ph}=1nA. We conclude clearly that after compensation we obtained an output voltage curve that is insensitive to temperature variation.

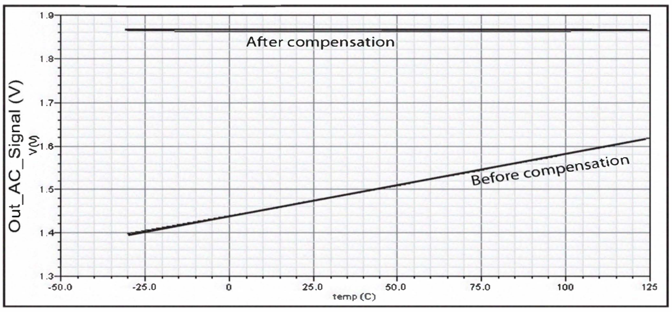

Fig. 9. Compensated and Non Compensated Out-AC-Signal Curves for I_{ph}=1nA (Fig. 3)

Furthermore, we get a good temperature compensation, less than 1mV of the output voltage temperature variation from -30°C to 125°C for I_{ph}=1nA instead of 200mV. However, when we move from this value we compensate less than in 1nA. Despite variations in slope, the compensation is well and we obtain less than 16mV from 45°C to 125°C instead of 110mV, and less than 25mV from 45°C to -30°C instead of 165mV for I_{ph}=1pA. As conclusion, the output voltage variation of the sensor is reduced at most by 96% and at least by 78%. Note that, the values obtained above are the temperature variation of the difference between the two output voltages Out-AC-Signal and V_{Ref-ph} from -30°C to 125°C.

Therefore, with this temperature compensation method, a response sensor insensitive to temperature variation is obtained. The main advantage of this method is that it conserves all characteristics of the logarithmic CMOS vision sensor, like dynamic range and pixel silicon area.

Concerning the sensor output reference voltage (V_{Ref-ph}) a good temperature compensation is obtained and the temperature variation is reduced by 92%. The reason of this, that the V_{Ref-ph} voltage it not depends with the photocurrent I_{ph} as is the cas with the Out-AC-Signal voltage.

VI. Conclusions and Future Work

A temperature compensation system dedicated to CMOS logarithmic image sensor has been presented. After an overview of logarithmic CMOS image sensor, the temperature effects on MOS transistor parameters like mobility μ_n, threshold voltage V_{th} and drain current I_{DS} are introduced. Temperature effect results on logarithmic CMOS image sensor have been shown. We have been shown that the output voltage of the logarithmic CMOS image sensor varies strongly and linearly with temperature and it depends with photocurrent. A temperature compensation method is described and the associated results are shown. Through this compensation method, we have reduced strongly the temperature variation of the output voltages and we have a good temperature stability of the responses sensor (Out-AC-Signal and V_{Ref-ph}). The main advantage of this method is that it conserves the same sensor response characteristics like the high sensor dynamic range. In addition, it conserves pixel array silicon area and only two circuits to compensate all the output voltages Out-AC-Signal and V_{Ref-ph} of the sensor are used. Future works consist of designing a prototype of CMOS imager, which includes this temperature compensation scheme and the adaptation of this method for a standard integration pixel scheme.

VII. Acknowledgment

We would like to thank the VisImalogic project, and the "Pôle de compétivité" Minalogic which funds this research work.

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