A Low-Power Supply-Insensitive Temperature Sensor in 90nm CMOS Process

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***Abstract*—A low power and low voltage temperature sensor with power supply voltage insensitive improvement is presented in this paper. Compared to the conventional four-transistor temperature sensor, which has the power supply voltage sensitive problem, the linearity error of the proposed structure is reduced. The proposed temperature sensor is designed in TSMC 90nm 1P9M process and the nominal power supply voltage is 1V. The simulation results show that the linearity error of the proposed circuit is 0.29 ℃ and power consumption is 29μw. The linearity errors are 0.99℃ and 2.8 ℃ under the 10% variation of the power supply voltage.**

I. Introduction

On-chip temperature sensors play an important role in measurement and consumer electronics, such as monitoring the temperature in processors. Integrated temperature monitors can provide a way to avoid the increasing temperatures of chip destroying devices and reduce the lifetime. Recently, more and more researches focus on low chip area, low power consumption, low temperature errors, and low power supply headroom problems. [1]-[4]

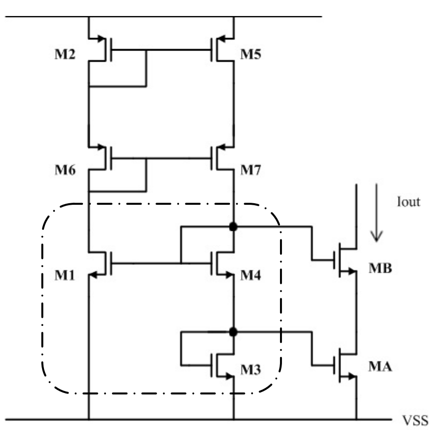

Figure 1. The three-transistor structure, current output temperature sensor. [5]

The temperature sensor shown in Figure 1 is a threshold voltage reference cell which is the three-transistor structure presented in reference [5]. The three-transistor temperature sensor has good linear characteristics which are designed under power supply voltage 1.8V or more.[5] However, the linearity of three-transistor temperature sensor will be worse in the CMOS process down to 90nm and 1V power supply. Due to no enough headroom, the transistors will work in the subthreshold region and increase the temperature errors will be increased.

II. Conventional Temperature sensor and proposed Temperature sensor

In this section, both of the conventional and the proposed temperature sensors are described. The objects in on-chip temperature sensors are to achieve extremely small area, low power consumption, and highly accurate in the specifications of power supply voltage variations over the designing temperature range.

A. The conventional temperature sensor

Reference [6] introduced the four-transistor temperature sensor, shown in Figure 2 which is designed in 90nm processes. An additional transistor M0 works in saturation region is added to improve the linearity of temperature sensor. This completed structure includes four-transistor temperature sensor, an error amplifier, and a current mirror on the top, shown in Figure3. Compare the three-transistor temperature sensor, the four-transistor temperature sensor change the operating points to make the designing output voltage in strong inversion region instead of in subthreshold region in deep submicron technologies.

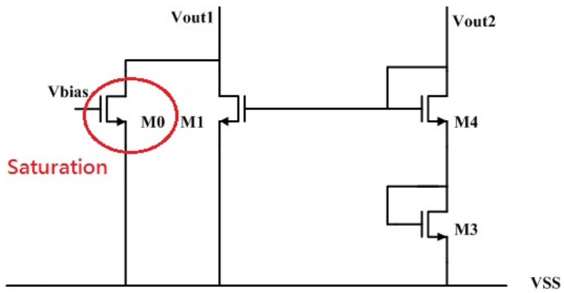

Figure 2. The conventional four-transistor, voltage output temperature sensor. [6]

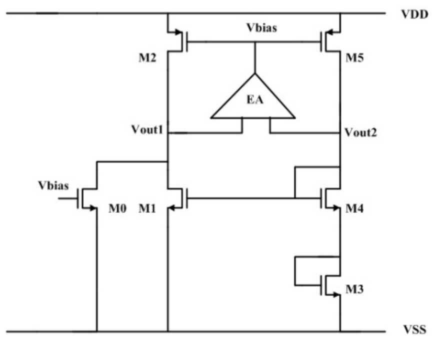

Figure 3. The conventional four-transistor temperature sensor with the bias circuit. [6]

The conventional four-transistor structure improve the poor linearity when the process down to 90nm and 1V of power supply voltage[6]. Nevertheless, there are drawbacks in the conventional four-transistor temperature sensor with the bias circuit. First, using an error amplifier in the bias circuit will occupy large area and increase the power consumption. Second, using the output voltage of an error amplifier in this structure to be the bias voltage of M0 will cause the power supply voltage sensitive problem. In order to compare the power supply voltage influence in the conventional four-transistor temperature sensor with the bias circuit and the proposed four-transistor temperature sensor with the improved bias circuit, the sensitivity of Vout2 with respect to power supply voltage in the conventional circuit can be calculated simply without considering r_{ds} effect and it is given by equation (1).

$$\frac{V_{out2}}{V_{DD}} = \frac{g_{m5}\left(\frac{1}{g_{m3}}+\frac{1}{g_{m4}}\right)\left(1-A_{EA}\frac{g_{m2}}{g_{m2}+A_{EA}g_{m0}}\right)}{1-A_{EA}g_{m5}\left(\frac{1}{g_{m3}}+\frac{1}{g_{m4}}\right)\left(1+\frac{g_{m1}-A_{EA}g_{m0}}{g_{m2}+A_{EA}g_{mo}}\right)} \tag{1}$$

When the $g_m = \theta\sqrt{I_D}$, γ is the current ratio of M_0 and I_{out1}, and the gain of the error amplifier A_{EA} is pretty high, it follows that the sensitivity S_{VDD}^{Vout2} can be expressed as

$$S_{VDD}^{Vout2} = \frac{2\theta_5}{\theta_3}\left(1-\frac{\theta_5}{\theta_0\sqrt{\gamma}}\right) \tag{2}$$

B. The proposed temperature sensor

Since there are drawbacks of the conventional four-transistor temperature sensor with the bias circuit, shown in Figure 3, the improvements of this structure are necessary. The proposed four-transistor temperature sensor, shown in Figure 4, removes the error amplifier and reduces the sensitive problem of power supply voltage.

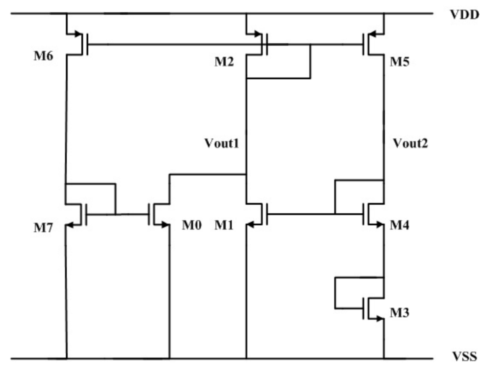

Figure 4. The proposed four-transistor temperature sensor with the improved bias circuit.

In this circuit, M0~M7 work in saturation region. Five equations (3) – (6) describe the operation of the proposed circuit.

$$I_{D,M0} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_0 (V_{GS0} - V_{tn0})^2 \tag{3}$$

$$I_{D,M1} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1 (V_{GS1} - V_{tn1})^2 \tag{4}$$

$$I_{D,M4} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_4 (V_{GS4} - V_{tn4})^2 \tag{5}$$

$$I_{D,M4} = I_{D,M0} + I_{D,M1} \tag{6}$$

In order to compare the power supply voltage influence in the conventional four-transistor temperature sensor and the proposed four-transistor temperature sensor with the improved bias circuit, the sensitivity of Vout2 with respect to power supply voltage in the proposed circuit can be calculated simply with considering r_{ds} effect and it is given by equation (7).

$$\frac{V_{out2}}{V_{DD}} = \frac{2\lambda[(-\theta_0\theta_6)\sqrt{xyI_D}+(\theta_0\theta_5)\sqrt{xy^2I_D}+(\theta_5\theta_7)\sqrt{x^2yI_D}+(\theta_5\theta_7)\sqrt{(1-x)^2yI_D}+(\theta_1\theta_7)\sqrt{(1-x)yI_D}]}{-\theta_0\theta_3\theta_6\sqrt{xy}+\theta_1\theta_3\theta_7\sqrt{(1-x)y}-2\theta_1\theta_5\theta_7\sqrt{(1-x)y}} \tag{7}$$

Where $g_m = \theta\sqrt{I_D}$, the term x is the current ratio of $I_{D,M0}$ and I_{out1}, and y is the current ratio of $I_{D,M7}$ and I_{out1}. The small sensitivity can be achieved by adjusting these terms properly. Without considering r_{ds} effect, V_{out2} is not dependent upon power supply voltage. Compared with sensitivity equation (2), the power supply sensitivity of the proposed temperature sensor can be reduced.

III. SIMULATION RESULTS

The two circuits are designed in TSMC 90nm 1P9M process. The simulation results of the conventional four-transistor temperature sensor under the same device sizes that reference [6] presented Table I, are shown in Figure 5 and Figure 6. Simulations of the proposed four-transistor temperature sensor are presented and, shown in Figure 7, Figure 8, Figure 9, and Figure 10.

Table I. The device sizes of the conventional four-transistor temperature sensor provided by [6].

	M_0	M_1	M_3	M_4
$(\frac{W}{L})$	$\frac{0.6\mu m}{2.8\mu m}$	$\frac{0.2\mu m}{2.8\mu m}$	$\frac{3.5\mu m}{0.14\mu m}\times 4$	$\frac{3.5\mu m}{0.14\mu m}\times 4$

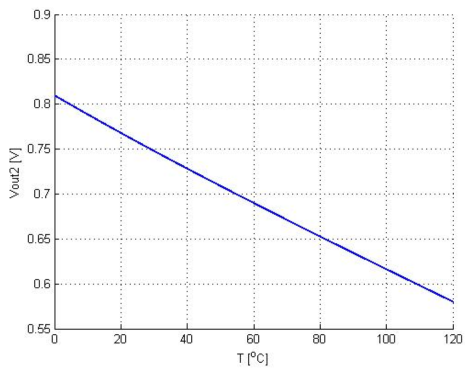

Figure 5. Simulation results of the output voltage from 0°C to 120 °C of the conventional four-transistor temperature sensor.

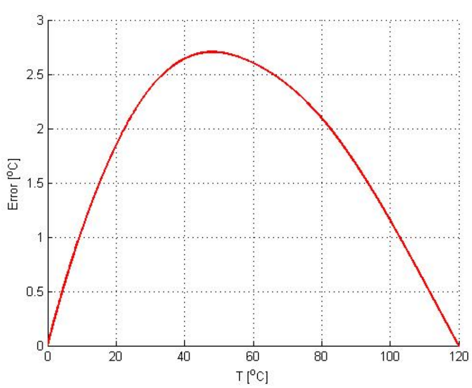

Figure 6. Simulation results of the temperature error from 0°C to 120°C of the conventional four-transistor temperature sensor.

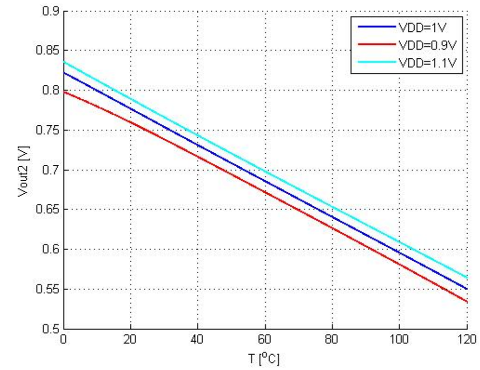

Figure 7. Simulation results of the output voltage from 0°C to 120°Cunder the nominal power supply voltage $V_{DD} = 1V$, and the 10% variation of normal power supply voltage $V_{DD} = 1.1V$, $V_{DD} = 0.9V$ in the proposed four-transistor temperature sensor with the improved bias circuit.

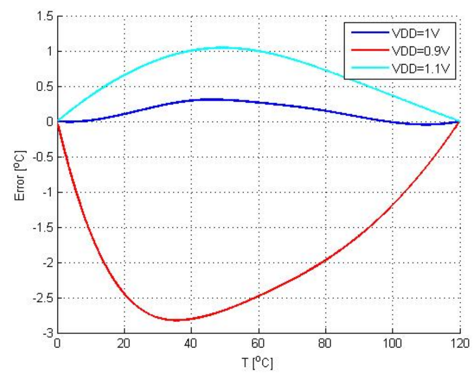

Figure 8. Simulation results of the temperature error from 0°C to 120°C under the nominal power supply voltage $V_{DD} = 1V$, and the 10% variation of normal power supply voltage $V_{DD} = 1.1V$, $V_{DD} = 0.9V$ in the proposed four-transistor temperature sensor with the improved bias circuit.

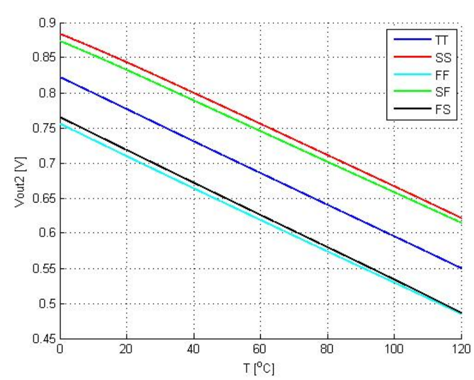

Figure 9. Simulation results of the output voltage from 0°C to 120°Cunder the nominal power supply voltage $V_{DD} = 1V$ and process variations in

the proposed four-transistor temperature sensor with the improved bias circuit.

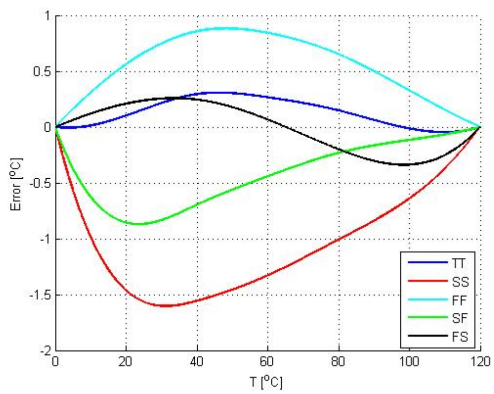

Figure 10. Simulation results of the temperature error from 0℃ to 120℃ under the nominal power supply voltage $V_{DD} = 1V$ and process variations in the proposed four-transistor temperature sensor with the improved bias circuit.

IV. CONCULSION

In this paper, the four-transistor temperature sensor with improved bias circuit is presented. The designing circuit is in TSMC 90nm process, and the power supply voltage is from 0.9V to 1.1V under the temperature range of 120℃. Simulation results of the proposed circuit show the worst case of nonlinear temperature error is 0.29 ℃ under normal power supply voltage 1V, 0.99℃ under power supply voltage 1.1V, and 2.8 ℃ under power supply voltage 0.9V. The power consumption is about 29µW under the typical condition.

REFERENCES

[1] Chen Zhao; Jun He; Sheng-Huang Lee; Peterson, K.; Geiger, R.; Degang Chen, "Linear vt-based temperature sensors with low process sensitivity and improved power supply headroom," Circuits and S ystems (ISCAS), 2011 IEEE International Symposium on , vol., no., pp.2553,2556, 15-18 May 2011

[2] Ueno, Ken, Tetsuya Asai, and Yoshihito Amemiya. "Low-power temperature-to-frequency converter consisting of subthreshold CMOS circuits for integrated smart temperature sensors." Sensors and Actuators A: Physical 165.1 , pp.132-137, 2011

[3] Zhou Shenghua; Wu Nanjian, "A novel ultra low power temperature sensor for UHF RFID tag chip," Solid-State Circuits Conference, 2007. ASSCC '07. IEEE Asian , vol., no., pp.464,467, 12-14 Nov. 2007

[4] Yu-Shiang Lin; Sylvester, D; Blaauw, D, "An ultra low power 1V, 220nW temperature sensor for passive wireless applications," Custom Integrated Circuits Conference, 2008. CICC 2008. IEEE , vol., no., pp.507,510, 21-24 Sept. 2008

[5] Szekely, V.; Marta, C.; Kohari, Z.; Rencz, M., "CMOS sensors for on-line thermal monitoring of VLSI circuits," Very Large Scale Integration (VLSI) Systems, IEEE Transactions on , vol.5, no.3, pp.270,276, Sept. 1997

[6] Sasaki, M.; Ikeda, M.; Asada, K., "A Temperature Sensor With an Inaccuracy of -1/+0.8 ℃ Using 90-nm 1-V CMOS for Online Thermal Monitoring of VLSI Circuits," Semiconductor Manufacturing, IEEE Transactions on , vol.21, no.2, pp.201,208, May 2008