CMOS integrated sensor circuit for temperature measurement based on 50 nm technology

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Published in The Journal of Engineering; Received on 25th August 2017; Accepted on 13th October 2017

Abstract: A fully-integrated complementary metal–oxide semiconductor sensor using NPN transistors for temperature measurement is presented. The main purpose of the device is to monitor the temperature for implanted integrated circuits and to ensure the safe operation by monitoring the temperature on-chip. This study adopted a behavioural simulator that uses LTSPICE for a temperature sensor for performing the rapid and accurate simulation. It is advantageous in 50 nm technique to design the circuits. The integrated sensor circuit consists of a bias circuit, an operational amplifier, and a thermal module. A high sensitivity of 5.9 mV/°C in the output voltage circuit has been measured, the linear dependence of voltage drop across the bipolar junction transistor on temperature, in a range from −30 to 125°C, has been used for thermal sensing.

1 Introduction

In recent years, complementary metal–oxide semiconductor (CMOS) has widely been used in sensors circuits design. In 2016, Mansoor et al. [1] designed a silicon on insulator CMOS multi-sensor microelectromechanical systems chip, which can simultaneously measure temperature, pressure and flow rate. In 2017, Wen-Sheng et al. [2] have proposed a dark current suppression technique for a light detector in a variable-temperature system. The advantages of CMOS temperature sensors include small size, low cost, high performance and easy mass-production. In many industrial applications, temperature sensors operate over a wide temperature range from −30 to 125°C [3].

Both bipolar and metal–oxide semiconductor (MOS) transistors are generally used to implement on-chip sensors, e.g. temperature sensors [4]. In the bipolar transistors, the base-emitter voltage and the saturation current are used for extraction of the basic signals. And in the case of the MOS transistors, the basic signals are derived from the threshold voltage and mobility. However, most of the circuits of temperature sensors are used by bipolar transistors because the temperature characteristics of the bipolar transistor show better than MOS transistor [5].

In this paper, the design has focused on sensing temperature parameters, which are interested in by scientists and researchers working in the field of chip design. The main design of the circuits is discussed, which includes short-channel bias circuit, operational amplifier circuit, thermal sensing circuits, diagram simulation, data processing and parameters calculation.

2 Design of the temperature sensor

Fig. 1 illustrates the schematic structure of the temperature sensor circuits. The sensor circuits made up of a current mirror source, a couple of bipolar junction transistors and a resistance. $Q_1$ and $Q_2$ are the two NPN bipolar transistors. $I_1$ and $I_2$ are the collector currents of $Q_1$ and $Q_2$, provided by the constant current source, respectively. The voltage on the resistance $R$ is the voltage difference between the $V_{BE1}$ and $V_{BE2}$. The relationship [6] between voltage and current is given as

$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{KT}{q} \ln \frac{I_1}{I_2} \gamma$$  \hspace{1cm} (1)

$$\Delta V_{BE} = \frac{KT}{q} \ln \frac{I_1}{I_2}$$  \hspace{1cm} (2)

where $K$ is the Boltzmann constant and $q$ is the electronic charge. $T$ is the absolute temperature. $\gamma$ is the emitter area ratio of $Q_1$ and $Q_2$. When $\gamma = 1$ (2) works. According to (1) and (2), when the temperature increases, the voltage of basic-emitter decreases, so the sensor can put the temperature signals into voltage signals. This paper follows the principle of the circuits design.

In order to provide bias for the amplifier circuits, the bias circuit is divided into start-up circuit, beta multiplier circuit, and the reference bias electric three parts. A start-up circuit is integrated to guarantee the circuit settles at the right operating point. Liu et al. [7] the beta multiplication circuit can be used to realise the resistor on the source side of the MOS, meanwhile, it can also calculate the data of the current. According to Fig. 2, the relationship between $V_{GS1}$ and $V_{GS2}$ is presented as

$$V_{GS1} = V_{GS2} + I_{REF} \cdot R_1, \quad V_{GS1} > V_{GS2}$$  \hspace{1cm} (3)

To meet (3), the bigger $W_2/L_2$ is chosen for the $\beta_2$ of $M2$. Then the required current $I_{REF}$ could be obtained only with a small grid-source voltage. The relationship between voltage and current is given as [8]

$$V_{GS} = \sqrt{\frac{2I_{D}}{B}} + V_{THN}$$  \hspace{1cm} (4)

$$\beta_1 = K \cdot P \frac{W_1}{L_1}, \quad \beta_2 = K \cdot P \frac{W_2}{L_2}$$  \hspace{1cm} (5)

$$\beta_3 = K \cdot \beta_1$$  \hspace{1cm} (6)

$$I_{REF} = \frac{2}{R^2 P \cdot M1} \left(1 - \frac{1}{\sqrt{K}}\right)^2$$  \hspace{1cm} (7)

In beta multiplication circuit reference voltage source, the gate voltage of $M1$ is always related to temperature. Through the spice simulation, the results show that the temperature change is $\sim 60$ mV/100°C [9].

The short-channel bias circuit consists of the beta multiplier circuit and the reference circuit. According to the (8)–(15), the circuit parameters are calculated. In the short-channel bias circuits
The module of the operational amplifier gain of a differential amplifier, which depends on the product of transconductance $g_m$ and output resistance $R_f$, is given by (19).

$$A_{OLDC} = A_1 \cdot A_2 = g_{m1} \cdot (r_{on} \parallel r_{op}) \cdot g_{m2} \cdot r_{op}$$  

$$A_1 = g_{m1} \cdot R_1, \quad A_2 = g_{m2} \cdot R_2$$  

$$R_1 = r_{on} \parallel r_{op} = 111 \, k\Omega$$  

$$R_2 = r_{on} \parallel r_{gain} \approx r_{op} = 333 \, k\Omega$$  

$$g_{m1} = g_{m2} = g_{m2} = \frac{150 \, \mu A}{V}$$

The circuits contain an output buffer realised by C1. The output resistance $r_{op}$ of the amplifier is $333 \, k\Omega$. If a buffer is added to the output of the secondary amplifier, the circuits will get a suitable gain and a good power supply rejection ratio. Although this process might lead to the secondary gain reduce, the circuit could still get a more reasonable overall gain due to the first level circuit gain is larger.

In the first stage circuit, the differential amplifier gain is 500. The secondary amplifier uses a topology structure; its gain depends on its driving load resistance. If there is no load connected to the other output, then gain as follows:

$$A_2 = -10 \cdot (g_{m2} + g_{m1}) \cdot \frac{r_{op} \parallel r_{on}}{10} = -31.6$$  

$$A_{OLDC} = A_1 \cdot A_2 = 15,800 \quad (22)$$

Finally, the overall operational amplifier gain is 84 dB.

As shown in Fig. 4, the structure of the thermal sensor consists of several parts. Q1 and Q2 are two NPN bipolar transistors $v_p$ and $v_n$ are the input terminals of the operational amplifier, M30 is a common-source amplifier. So as to get higher precision, M30 plays an important role in the circuit. The node of the output is the simulation test point; it also is the output terminal of whole circuit, the difference between gate-source voltage $V_{GS}$ and threshold voltage $V_{THN}$ is the grid overdrive voltage $V_{OVN}$. Grid overdrive voltage is an important parameter, which is in direct proportion to the MOS inversion frequency $f_s$. In order to realise higher operational speed, both the leakage current $I_D$ and the transconductance $g_m$ are related to the wide of MOS. The detailed short-channel bias circuit is omitted due to the length of the letter.

$$V_{OVN} = V_{GS} - V_{THN} \neq V_{DS,Sat}$$  

$$V_{OVN} = 70 \, mV \rightarrow V_{GS} = 350 \, mV$$  

$$f_s = \frac{g_m}{2\pi C_{gs}} \propto \frac{V_{OVN}}{L}$$  

$$I_D = V_{sat} \cdot C_{ox} \cdot W \cdot (V_{GS} - V_{THN} - V_{DS,sat})$$  

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = v_{sat} \cdot C_{ox} \cdot W$$  

$$I_D = 10 \, \mu A$$  

$$g_m = 150 \, \mu A/V$$  

$$\frac{W}{L_N} = \frac{25}{\Gamma}, \quad \frac{W}{L_P} = \frac{50}{\Gamma}$$

![Fig. 1 Schematic of temperature sensor](image1)

![Fig. 2 Beta multiplication circuit](image2)

![Fig. 3 Operational amplifier](image3)
circuits. According to the simulation data, the fitted curve was shown in Fig. 4. Dots and lines represent the original data and fitted curve, respectively.

The relationship between output voltage $V$ and temperature $T$ is fitted as

$$V = -0.0059T + 3.8973 \quad (24)$$

The temperature coefficient is 5.9 mV/°C, which means when every 1°C temperature changed, the voltage will change 5.9 mV.

3 Conclusion

A fully-integrated CMOS temperature sensor that can sense a temperature change has been successfully simulated in 50 nm technology. The main design software is LTspice and Matlab. Due to the 50 nm technology, the area of application circuits is saved, power consumption is reduced, and the operating speed is increased. The sensitivity of temperature sensors is $5.9 \text{ mV/°C}$ in the tested range from $-30$ up to $125^\circ \text{C}$. The design could be implanted in integrated circuits to monitor the on-chip temperature, and to ensure the safe of the chip.

4 Acknowledgments

This work was partly supported by the Natural Science Foundation of Liaoning province, China (no. 2014020020).

5 References

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