ISSN 1009－3095 Journal of Zhejiang University SCIENCE V.3, No.5, P.553－558, Nov.－Dec., 2002
http://www.periodicals.com.cn; http://www.zju.edu.cn/English
http://www.zjupress.com; http://lib.zju.edu.cn/eindex.htm; jzu_s@mail.hz.zj.cn

A novel voltage output integrated circuit temperature sensor*

WU Xiao-bo(吴晓波)†, ZHAO Meng-lian(赵梦恋)[1], FANG Zhi-gang(方志刚)[2],
YAN Xiao-lang(严晓浪)[1]

([1] *Institute of Very Large Scale Integrated Circuit Design, Zhejiang University, Hangzhou 310027, China*)
([2] *Department of Information and Electronics, Zhejiang University, Hangzhou 310027, China*)

†E-mail: wuxb@vlsi.zju.edu.cn

Received Nov. 12, 2001; revision accepted May 6, 2002

Abstract: The novel integrated circuit (IC) temperature sensor presented in this paper works similarly as a two-terminal Zener, has breakdown voltage directly proportional to Kelvin temperature at 10 mV/℃, with typical error of less than ±1.0℃ over a temperature range from −50℃ to +125℃. In addition to all the features that conventional IC temperature sensors have, the new device also has very low static power dissipation (0.5 mW), low output impedance (less than 1Ω), excellent stability, high reproducibility, and high precision. The sensor's circuit design and layout are discussed in detail. Applications of the sensor include almost any type of temperature sensing over the range of −50℃ − +125℃. The low impedance and linear output of the device make interfacing the readout or control circuitry especially easy. Due to the excellent performance and low cost of this sensor, more applications of the sensor over wide temperature range are expected.

Key words: Temperature sensing, IC (integrated circuit) sensor, Thermal matching
Document code: A **CLC number:** TN431.1

INTRODUCTION

Compared with conventional temperature sensors like thermocouples, RTDs (Resistance Temperature Detector) and thermistors, the integrated circuit temperature sensors (IC temperature sensor) have some outstanding advantages such as excellent linearity, high sensitivity and flexibility. In addition, they are usually easy to use and suitable for mass production. Therefore IC temperature sensors have been highly regarded by many international giants like Analog Devices, National Semiconductor and NEC since they first appeared in the late 20th century. And a lot of efforts have been put into their development thereafter.

Driven by developments of personal computer, PDA (Personal Digital Assistor) products and automotive applications in recent years, the design and manufacture of IC temperature sensors progress rapidly, applications have been found in more related fields, while the total annual revenue of the industry has exceeded US $ 300 million.

The novel IC temperature sensor developed by the authors and presented, in addition to all the advantages mentioned above, has excellent insensitivity to variations of power supply and load. The very simple temperature sensing circuitry is one of many reasons for its successful application in fields such as scientific instruments, industrial equipment, multi-point temperature monitor system, consumer products and medical monitors.

CIRCUIT DESIGN

The basic circuit of the developed temperature sensor is shown in Fig. 1.

The transistors Q_1 and Q_2 (whose emitter area ratio is r), their collector resistors R_{C1}, R_{C2} ($R_{C1} = R_{C2}$) and a constant current source I_E constitute a differential amplifier. A deep nega-

---

* Project (No. 991106204) supported by Science and Technology Committee of Zhejiang Province, China

tive feedback loop that consists of an error amplifier A, transistors Q_3, Q_4 and some resistors constrains the currents I_{C1} and I_{C2} to be equal:

$$I_{C1} = I_{C2} = \frac{1}{2} I_E$$

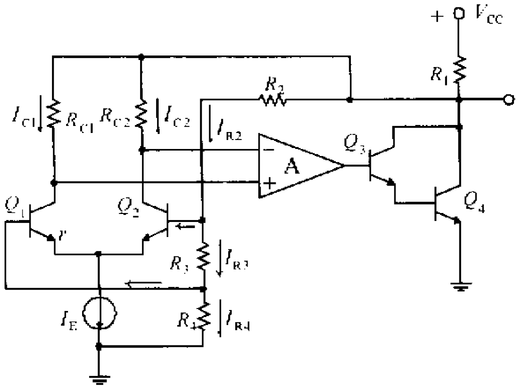

Fig. 1 Basic circuit of the temperature sensor

The temperature sensitive parameter of interest is the difference between the V_{BE} of Q_1 and Q_2. This can be easily derived from the relation between base-emitter voltage and emitter current density:

$$\Delta V_{BE} = V_{BE2} - V_{BE1} = \frac{kT}{q} \ln r$$

Where k is Boltzmann's constant, T is Kelvin temperature, and q is the electron charge.

The voltage difference ΔV_{BE} is proportional to Kelvin temperature. It is the basis of the whole circuit.

From Fig. 1 the following can be derived:

The current flowing through R_3 is

$$I_{R_3} = \frac{\Delta V_{BE}}{R_3}$$

The current flowing through R_2 is

$$I_{R_2} = \frac{\Delta V_{BE}}{R_3} + \frac{1}{\beta} I_{C_2} = \frac{\Delta V_{BE}}{R_3} + \frac{1}{2\beta} I_E$$

And the current flowing through R_4 is

$$I_{R_4} = \frac{\Delta V_{BE}}{R_3} - \frac{1}{\beta} I_{C_1} = \frac{\Delta V_{BE}}{R_3} - \frac{1}{2\beta} I_E$$

Thus, the output voltage V_0 amounts to:

$$V_0 = I_{R_2} R_2 + \Delta V_{BE} + I_{R4} R_4 =$$

$$\left(\frac{\Delta V_{BE}}{R_3} + \frac{1}{2\beta} I_E\right) R_2 \Delta V_{BE} +$$

$$\left(\frac{\Delta V_{BE}}{R_3} - \frac{1}{2\beta} I_E\right) R_4$$

If β is large enough and I_E is small enough to ensure that $\frac{1}{2\beta} I_E$ is much smaller than $\frac{\Delta V_{BE}}{R_3}$, as a good approximation, V_0 would be:

$$V_0 = \left(1 + \frac{R_2 + R_4}{R_3}\right) \cdot \Delta V_{BE} =$$

$$\frac{R_2 + R_3 + R_4}{R_3} \cdot \frac{kT}{q} \ln r$$

In other words, when the circuit parameters including r, R_2, R_3 and R_4 have been chosen, the output voltage V_0 is a function of Kelvin temperature T. Moreover, if the ratio of $(R_2 + R_3 + R_4)/R_3$ is independent of temperature, the output voltage V_0 would be well linear with Kelvin temperature.

Fig. 2 is the schematic of the new temperature sensor circuit based on Fig. 1. As described above, the core of this circuit is a differential amplifier consisting of a pair of transistors Q_1 and Q_2 with unequal emitter areas. By choosing their emitter area ratio r as well as the resistance ratio of R_1, R_2 and R_3, a steady reference voltage of 2.5V at room temperature is obtainable, which is proportional to Kelvin temperature at a scale factor of 10 mV/℃.

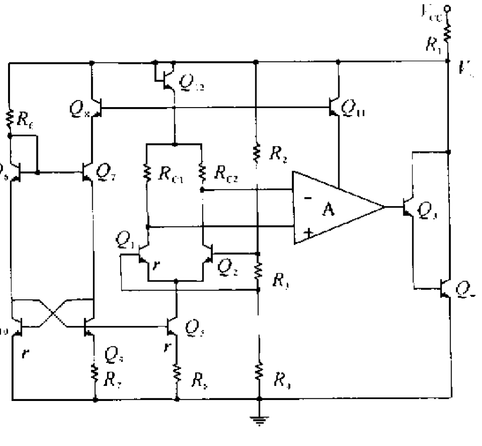

Fig. 2 The schematic of the sensor

Transistor Q_5, together with Q_6, Q_7, Q_9 and Q_{10}, constitutes a precision constant current source that acts as the emitter current source of the differential amplifier to raise its common mode rejection ratio(CMRR)and improve its stability.

Note that the transistor Q_{12} is introduced as an active load to substitute for a large passive load (usually, a diffused resistor)which always occupies much more area on a chip. It is well known that reducing chip area is of great benefit to minimizing its thermal lag and thus to speed up its thermal response. Moreover, the smaller chip area will be beneficial to its yield in production.

There are still two other important points that should to be mentioned:

1. Proper static current setting of the differential amplifier and its matching with the current flowing through the R_2, R_3 and R_4. The discussion above shows that it will determine its available operating temperature range and influence its linearity and power consumption that affects its thermal stability directly.

2. Choosing the emitter area ratios of the transistor pairs. Several transistor pairs with unequal emitter area are used in the thermal-sensitive core as well as the error amplifier and the constant current source. It should be noted that these ratios would influence the output level, sensitivity and stability of the sensor.

As a result, the linearity of the circuit over the desired temperature range is kept within ± 0.5 − 1.0%; The dynamic impedance is less than 1 Ω; and the power dissipation is reduced to about 0.5 mW. The circuit was modified subsequently and simulated repetitively and optimized to the greatest extent.

LAYOUT

In this device, the layout and structure design has the same importance as the circuit design.

As a temperature sensor, the device must be able to work in a wide temperature range from − 50℃ to + 125℃. Namely, it should be capable of withstanding the heat and cold operating extremes of silicon devices.

To improve the high temperature performance of the circuit, a special structure is introduced for each transistor with its base shorted to collector like Q_6, Q_{12} and so on(so called diode-connected transistor), which is widely used in IC sensors, references, operational amplifiers and many other analog ICs. While working at high temperature, a key problem for such a transistor is how to avoid saturation. As an example, an NPN transistor Q_6 is considered. Because it is an IC transistor, most of its collector resistance is in the epitaxial layer between the buried layer and the surface collector contact. This resistance is expressed as two separate resistors R_1 and R_2 in Fig. 3. In a usual diode-connected transistor the collector has contact with the base only, which is marked as B, C in Fig. 3(a), and no other additional contact. Fig. 3(b) shows its equivalent circuit. In this case R_1 does not have current flowing through it; the collector current IC flows through R_2, so that at high temperature both I_C

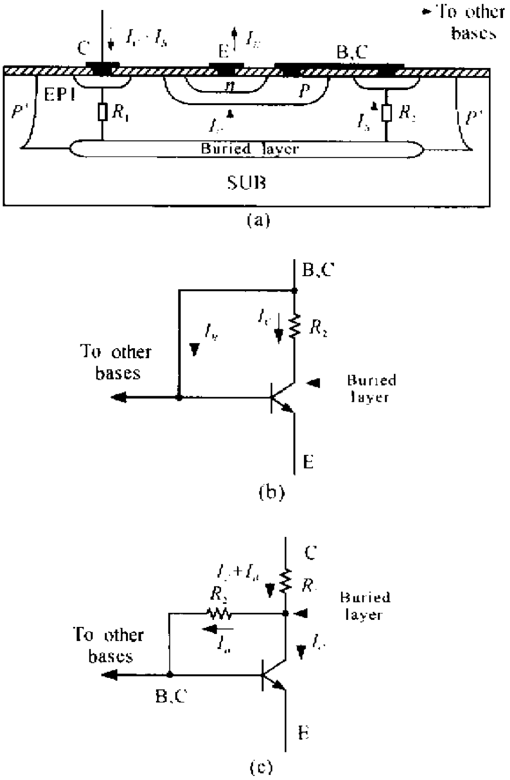

Fig. 3 Cross-section of Q_6 and its equivalent circuits
(a) Cross-section of Q_6; (b) The equivalent circuit of a usual transistor; (c) The equivalent circuit of Q
E: Emitter B: Base C: Collector

and R_2 increase with temperature to produce a large voltage drop across R_2 and results in saturation of the transistor. In this sensor, as show in Figs. 3(a) and (c), by making two surface contacts C and B, C on opposite ends of each diode-connected transistor, the current flowing through R_2 is substituted by I_B. Since I_B is much smaller than I_C, it produces negligible voltage drop V_{CB}. Therefore the voltage of the buried layer is maintained near its base voltage over the whole operating temperature range; and the transistor is not saturated even at very high temperature.

On the other hand, when the sensor is operating at low temperature, the gain loss of transistors will bring about abnormal operation of the device. It becomes serious especially when the multi-emitter transistors are adopted in the circuit; because a multi-emitter transistor is basically n unit transistors in parallel with each of them carrying only $1/n$ of the total emitter current. It is well known that the smaller the operating current is, the more serious the transistor gain loss is, owing to so-called small current effect. It results in degeneration of the circuit performance; to avoid which, a special full aluminum layer covering is utilized for both surface base-collector and base-emitter junctions and the particular tiny circle emitter patterns are introduced. The small current gain is thus raised successfully and excellent performance of such transistors is obtained down to −50℃. Note that under this condition the emitter current of each unit transistor has decreased to less than sub-microampere level.

As a result, good linearity of the output voltage over a wide temperature range is achieved.

Fig. 4 is the outline of the layout.

Note that almost all resistors are placed in the area R; and that transistors Q_3, Q_4 and Q_{12} are located in a common isolated island.

It is natural that as a thermally sensitive device, thermal matching among the components of this circuit is significant. Therefore the heat∈ flux distribution and the thermal equilibrium on the chip have been carefully treated. For instance, to reduce the heating effect, the crucial temperature sensing transistor pair Q_1, Q_2 and the main power-consuming transistor Q_4, which can be considered as a heat source, are located at the opposite ends of the chip. And all key transistors (or transistor pairs) such as Q_1 and Q_2, Q_5 and Q_{10}, Q_8 and Q_{11} are arranged symmetrically around the thermal centerline of the chip to ensure heat balance during circuit operation.

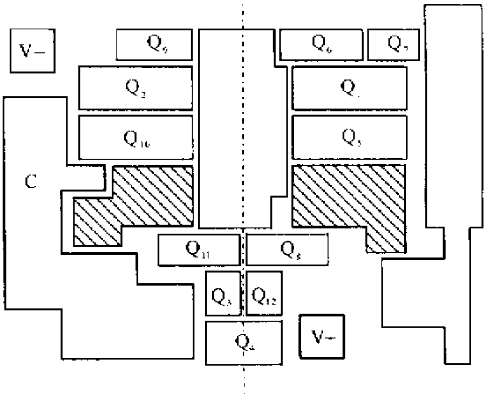

Fig. 4 Kayout if the sensor

▨ Amplifier A

Fig. 5 shows a particular symmetrical layout design of the transistor pair Q_1 and Q_2 that have emitter area ratio of 1∶10. To improve the symmetry of this pair, the so-called dummy emitters structure is introduced. Consider the structure of Fig. 5, Q_1 has ten circle emitters within a rectangle base. Q_2 is made in the same way with only one emitter and nine dummy emitters. It results in excellent symmetry in the environment and minimizing the electrical and thermal mismatching. Therefore, both electrical and thermal performances of the circuit are improved. As mentioned above, the area of the chip must be minimized as much as possible to reduce its thermal lag. It is also helpful to package miniaturization and enhances the product yield.

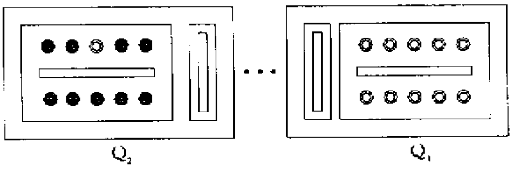

Fig. 5 Transistor pair Q_1, Q_2 with dummy emitters

● Dummy

In fact, the chip minimization depends largely on the circuit's passive components like high resistance resistor and MOS capacitor as they usually occupy much area on a chip. Accurate ion implant technology is used to reduce the resistor area while precision is maintained with chip area of less than 0.64 mm^2.

In addition， the control of the resistance ratio and its temperature drift has been effectively achieved. It results in good uniformity of products， which is of key importance to mass production.

In the design of lateral PNP transistors， efforts are put into striking a balance between their high gain and high output impedance to improve the stability of the circuit while keeping its low dynamic impedance as a Zener-like device.

As a result， the device has linear V vs. T characteristics over the whole desired temperature range. High accuracy is obtained with this device.

EXPERIMENTAL RESULTS AND DISCUSSION

The sensor is made by 1μm standard bipolar technology. The base resistor is 180Ω/sq. (square resistance). In order to reduce the resistor area， precision ion-implant resistors of 3000 Ω/sq. are used.

The I-V characteristic of the developed IC temperature sensor is shown in Fig. 6.

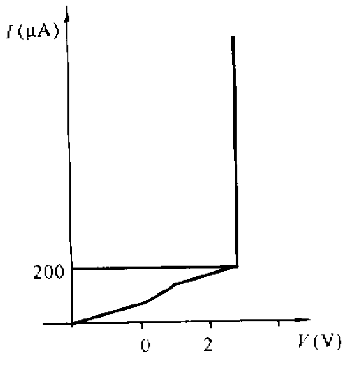

Fig. 6 I-V characteristics of the temperature sensor

The I-V characteristics show that the output impedance of the sensor is very low and indicate that this sensor has excellent insensitivity to variations of power supply.

The measured V_0-T plot of some samples over a −50℃ to +125℃ temperature range is shown in Fig. 7. The plot indicates that the sensors have a high V vs. T sensitivity and good linearity.

Application of the least square method to the test data showed that the device's performance is linear within ±0.3−0.6 % F.S(Full Scale) between −30℃ and +125℃， which is equivalent to temperature spread of ±0.5−1.0℃. The operating temperature range can also be extended to the range of −50℃ to +125℃ while the linearity is kept within ±1.0 % F.S.

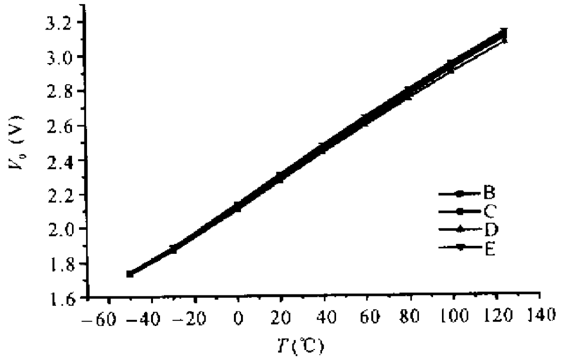

Fig. 7 The V_0-T plot of some samples over temperature range from −50℃ to +125℃

Some specifications of the device measured by the Zhejiang Institute of Metrology are listed below.

As listed in Table 1， the output impedance of the IC temperature sensor has been reduced to less than 1Ω.

Table 1 Specifications of the device

Parameter	Typical value
Sensitivity	10.0 mV/℃
Linearity	
(−30 − +125℃)	±0.3−0.6%F•S
(−50 − +125℃)	±0.3−1.0%F•S
Static power dissipation at 27℃	<0.50 mW
Output impedance	0.50−0.80Ω
Temperature resolution	0.1℃

Table 1 also shows that the static power dissipation at 27℃ is less than 0.5 mW. It is much lower than that of usual current output and even lower than that of most voltage output sensors. Note that the low static power dissipation is very important for sensors to reduce their self-heating effect so as to improve their accuracy. This is an outstanding advantage of the device, which has been proved by many users.

In addition, the reproducibility of the sensor is good. According to the measurements lasting 120 hours and repeated at intervals of 12 hours, the error of its output voltage is less than 1mV. Converted into temperature, it is equivalent to 0.1℃.

The results of 720 hours round-the-clock testing indicated that the drift of the output voltage was less than 2 mV, which is equivalent to temperature drift of 0.2℃. It shows the long-term stability of this device is fairly good.

CONCLUSIONS

A novel precision IC temperature sensor with its breakdown voltage directly proportional to Kelvin temperature is introduced in this paper. Its sensing mechanism is based on the temperature performance of bipolar transistors. Besides good linearity, easy reproducibility, and high sensitivity, the device has low output impedance and very low power dissipation, which results in excellent stability and anti-interference ability. Moreover, it makes interfacing the readout or control circuitry especially easy.

Owing to its excellent performances and low cost, its wide application is expected.

ACKNOWLEDGMENT

The authors wish to express their appreciation to Prof. Zhu Shusheng, Prof. Yuan Zhenfeng, Prof. Lu Pinzhen and Prof. Chen Kailiang for their helpful discussions in the course of this work.

References

Amador, R., Polanco, A., 1998. Technological compensation circuit for accurate temperature sensor. *Sensors and Actuators*, A**69**: 172 – 177.

Amador, R., Polanco, A., Nagy, A., 1999. The spread of η and V go and its influence on the sensitivity of a bipolar IC Celsius sensor. *Sensors and Actuators*, A**77**: 9 – 13.

Behzad, R., 2001. Design of Analog CMOS Integrated Circuits. McGraw-Hill Higher Education, New York.

Bianchi, R.A., Karam, J.M., Courtois, B., Nadal, R., Pressecq, F., Sifflet, S., 2000. CMOS-compatible temperature sensor with digital output for wide temperature range applications. *Microelectronics Journal*, **31**: 803 – 810.

Meijer, G. C. M., 1980. An IC temperature transducer with an intrinsic reference. *IEEE Journal of Solid-State Circuits*, SC-**15**(3): 370 – 373.

Montane, E., Bota, S. A., Samitier, J., 1998. A compact temperature sensor for a 1.0μm CMOS technology using lateral p-n-p transistors: *Microelectronics Journal*, **29**: 277 – 281.

Moore, B. D., 1999. Tradeoffs in selecting IC temperature sensors. *Microprocessors and Microsystems*. **23**: 181 – 184.

Pease, R. A., 1984. A new Fahrenheit temperature sensor. *IEEE Journal of Solid-State Circuits*. SC-**19**(6): 971 – 977.

Tsividis, Y. P., 1980. Accurate analysis of temperature effects in IC-VBE characteristics with application to bandgap reference sources. *IEEE Journal of Solid-State Circuits*, SC-**15**(6): 1076 – 1083.

Wang, G., Meijer, G. C. M., 2000. The temperature characteristics of bipolar transistors fabricated in CMOS technology. *Sensors and Actuators*, A**87**: 81 – 89.