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A Novel Built-in CMOS Temperature Sensor for VLSI Circuits*

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Abstract: A novel temperature sensor is developed and presented especially for the purpose of on-line thermal monitoring of VLSI chips. This sensor requires very small silicon area and low power consumption, and the simulation results show that its accuracy is in the order of 0.8℃. The proposed sensor can be easily implemented using regular CMOS process technologies, and can be easily integrated to any VLSI circuits to increase their reliability.

Key words: temperature sensor; thermal testability; frequency-output

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1 Introduction

Due to the advances in the fabrication process field of integrated circuits, the component density and the overall power dissipation of the high-performance VLSI chips increase continuously. At the beginning of this century, the power dissipated in a single chip has exceeded 100W, and tightly packed chip assemblies as the multichip modules can even dissipate thousands watts. Therefore, the thermal state of integrated circuits has been always a great problem concerned and is considered as a bottleneck in increasing the integration of electronic systems.

To overcome this problem, many researchers developed low-power design techniques for VLSI systems[1,2]. In order to avoid thermal damages, continuous thermal monitoring should be applied during both the production reliability testing and the field operation. An efficient way is to build temperature sensors into all VLSI chips, with the appropriate circuitry providing easy read-out. In some earlier works[3,4], the researchers used the parasitic, lateral or substrate bipolar transistors, which can be realized in most of the CMOS processes, as thermal sensors. These are usually PTAT sensors. The weakness of these sensors is that the bipolar structures are not well characterized in a MOS process. Thus, although they can provide a satisfiect solution for a given process, the circuits can not be regarded as a general CMOS approach and can not be widely used.

2 Problem formulation

There are various temperature sensors suitable for thermal state verification of integrated circuit microstructures such as thermoresistors, pn junctions, and the exploitation of the weak-inver-

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sion of MOS transistors. Our objective is to convert the temperature to an oscillating signal to make it compatible to digital circuit design method and facilitate the evaluation of the temperature sensed. A temperature sensor based on a ring-oscillator is introduced in Ref. [5], this cell guarantees a accuracy of 3℃ that is marginally acceptable as a chip temperature sensor but the silicon area required is rather big. A MOS temperature controlled oscillator is used as a sensor to monitor the thermal state of microelectronic structures in Ref. [6]. However, this sensor requires about 10 to 15mW power to drive the thermal delay line and the dissipater transistor.

To overcome these inconveniences, we think that the temperature sensors to be used as built-in units for VLSI circuits on-line thermal monitoring should meet some special requirements as follows:

(1) Nearly linearity in a temperature range (usually 0~ 100℃);

(2) Low power consumption (no more than 1mW);

(3) Simple structure and small silicon area (usually no more than 40 transistors);

(4) Easy read-out results with favorably digital output signal (e.g., the frequency of a square wave which carries the temperature information);

(5) Easy (one-point) calibration;

(6) High accuracy (in the order of 2℃ or less);

(7) Compatibility with the present CMOS process;

Considering the given requirements, we present a new built-in temperature sensor meeting all the above requirements.

3 Built-in thermal monitoring sensor

Our new temperature sensor is a voltage-controlled relaxation oscillator-based temperature sensor shown in Fig. 1. The circuit consists of two parts, a voltage-output sensor and a relaxation oscillator.

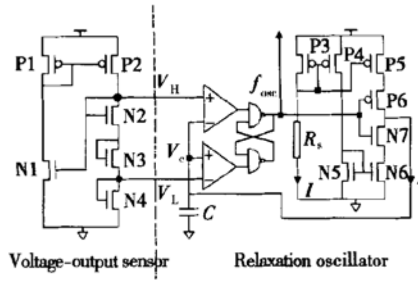

Fig. 1 Temperature sensor designed based on a voltage-controlled relaxation oscillator

3.1 Voltage-output sensor

Our voltage-output sensor circuit exploits the temperature dependence of the most important parameter of the MOS transistor, namely, the threshold voltage (V_T). The threshold voltage has a negative temperature coefficient as

$$V_T(T) = V_T(T_0) + a(T - T_0) \qquad (1)$$

where a is the temperature coefficient with a typical value of -1.8mV/K in CMOS 0.35μm 5V technology; $V_T(T_0)$ is the value of the threshold voltage at temperature T_0.

As shown in Fig. 1, the voltage output sensor is a threshold voltage reference cell. The p-channel transistors P1, P2 constitute a current mirror. The current of transistor N1 is mirrored to transistors N2, N3, and N4. The voltage drop on these transistors is fed back to the gate of N1. For easy calculating, we choose a same size of the transistors N2, N3, and N4 ($\beta_{N2}= \beta_{N3}= \beta_{N4}$), and we choose appropriate size of the other transistors to ensure that the transistors P1, P2, N1, N2, N3, and N4 are all in the state of saturation. Then the output voltages of this sensor are in direct proportion to the threshold voltage and linear with temperature and their values are

$$V_H = V_T\left(1 + \frac{2\lambda_{P12}}{\lambda_{P12} - 3\lambda_{N12}}\right) = k_1 V_T \qquad (2)$$

$$V_L = V_T\left(1 + \frac{2\lambda_{N12}}{\lambda_{P12} - 3\lambda_{N12}}\right) = k_2 V_T \qquad (3)$$

where λ_{N12} is determined by the ratio between the gate sizes of the n-channel transistor N1 and N2, and λ_{P12} is the ratio of the gate sizes of the p-channel transistor P1 and P2.

$$\lambda_{N12} = \sqrt{\frac{W_{N1}/L_{N1}}{W_{N2}/L_{N2}}} \quad (4)$$

$$\lambda_{P12} = \sqrt{\frac{W_{P1}/L_{P1}}{W_{P2}/L_{P2}}} \quad (5)$$

By adjusting the sizes of the transistors, we found λ_{P12} should be bigger than three times of λ_{N12}, when the transistors P1, P2, N1, N2, N3, and N4 are all in the state of saturation.

The advantages of this circuit arrangement are the simplicity and the stable output. An important feature is that the output voltages of V_H and V_L are practically independent of the supply voltage (V_{DD}).

3.2 Voltage-controlled relaxation oscillator

The quick interfacing of the analogue, current-output sensor with the digital environment is not a simple task. To overcome this problem we use a voltage-controlled relaxation oscillator as the voltage-frequency converter. The output signal of this converter is a square-wave, the frequency of which carries the temperature information. This frequency can be easily turned into a digital number by counting the square-wave pulses in a prescribed time window.

As shown in Fig. 1, the current of the resistor is mirrored using the transistors P3, P4, P5, N5, N6 to provide the same source and sink currents to charge and discharge the capacitor C. Assuming the initial value of the f_{osc} is logic 0, then the transistor P6 is on and the transistor N7 is off causing the capacitor C to be charged using the source current I until V_c exceeds the upper threshold V_H. When this occurs, the output latch toggles and the logic value of f_{osc} becomes logic 1, which in turn makes the transistor P6 off and the transistor N7 on. This makes the capacitor C to be discharged by the sink current until the capacitor voltage falls below a lower threshold V_L at which time the entire cycle repeats. Neglecting the delay of the comparators, latch and transistors P6 and N7, the oscillation cycle time should be:

$$T_{osc} = \frac{2C(V_H - V_L)}{I} = \frac{2C(k_1 - k_2)V_T}{I} \quad (6)$$

The current I is given by:

$$I = (V_{DD} - V_{gsp3})/R_s \quad (7)$$

As the current is small and the W/L ratio of the transistor P3 is chosen to be big in this design, the V_{gsp3} can be approximated to the threshold voltage of the transistor P1 and therefore the current can be approximated by

$$I = (V_{DD} - V_T)/R_s \quad (8)$$

And the temperature dependence of the resistor R_s is

$$R_s(T) = R_s(T_0)(1 + k\Delta T) \quad (9)$$

where k is the temperature coefficient of the resistor, with typical value $k = 255\times10^{-6}/℃$ for polysilicon sheet resistor in the CMOS 0.35μm 5V technology.

Therefore, the oscillation cycle time is found to be

$$T_{osc} = \frac{2C(k_1 - k_2)V_T R_s}{V_{DD} - V_T}$$
$$= \frac{2C(k_1 - k_2)(V_{T0} + a\Delta T)R_s(T_0)(1 + k\Delta T)}{(V_{DD} - V_{T0})\left(1 - \frac{a}{V_{DD} - V_{T0}}\Delta T\right)}$$
$$\approx \text{const} \times \left\{1 + \left[k + \frac{aV_{DD}}{(V_{DD} - V_{T0})V_{T0}}\right]\Delta T\right\}$$
$$= \text{const} \times (1 + \beta\Delta T) \quad (10)$$

This equation implies that the cycle time of the relaxation oscillator is nearly linear with temperature, and then the frequency of the oscillator is

$$f_{osc} \propto \frac{1}{1 + \beta\Delta T} \quad (11)$$

4 Simulation results and discussion

The simulation result of the voltage-output thermal sensor is illustrated in Fig. 2, and the variation of the relaxation oscillator-based sensor oscillation cycle time and frequency versus the chip temperature is shown in Fig. 3.

To evaluate a build-in thermal sensor, there are three important characteristics: accuracy, silicon area (transistor number), and power dissipa-

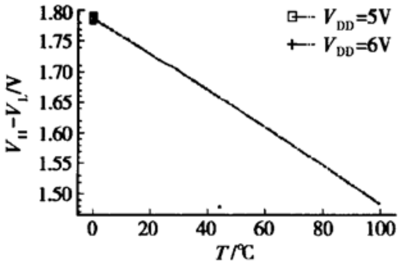

Fig. 2　Output voltage versus temperature diagram for the voltage-output sensor

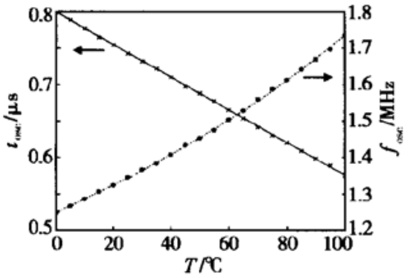

Fig. 3　Oscillation frequency and cycle time of the relaxation oscillator-based sensor

tion. The characteristics of our voltage-controlled relaxation oscillator-based sensor is shown in Table 1.

Table 1　Summary of important characteristics of the developed temperature sensor

Characteristic	Value
Accuracy	0.8℃
Transistor number	34
Power dissipation	0.15mW
Nominal frequency	1.3MHz

5　Conclusion

In this paper, a practical and efficient built-in temperature sensor for thermal monitoring of the integrated circuits is introduced. The main advantages of the presented chip temperature sensors are low silicon area, low power dissipation, digital output in form of oscillation frequency, high accuracy, and easily implemented using regular CMOS process technologies. Therefore, this sensor can be easily integrated to any VLSI circuits to increase circuits′ reliability.

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一种新型的集成电路片上 CMOS 温度传感器*

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摘要: 介绍了一种可以用于片上温度监控的 CMOS 温度传感器, 该传感器具有面积小、功耗低、精度高、易于实现等优点, 可以比较容易地集成到芯片上实现温度监测功能.

关键词: 温度传感器; 热可测性; 频率输出

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