A process-insensitive thermal protection circuit

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Abstract: A novel process-insensitive thermal protection structure has been developed. This circuit contains several sub-circuits such as band-gap reference, reference output buffer, resistance voltage divider branch, and hysteresis circuit. By using reference buffer, the precise reference voltage from band-gap reference is delivered to resistance voltage divider branch and is divided precisely. Then the threshold temperatures of this protection circuit can be set by this precise voltage, unaffected by process variation and mismatch. A hysteresis circuit is also used here to prevent thermal oscillation. This circuit is fabricated in TSMC 0.18 μm CMOS technology, and occupies about 3×10^4 μm^2 chip area.

Key words: thermal protection; precise threshold temperature; process variation insensitive; mismatch insensitive
DOI: 10.1088/1674-4926/32/7/075013 **EEACC:** 1205; 2570D

1. Introduction

Thermal protection is frequently required by some integrated circuits and devices, such as power amplifier and voltage sources or regulators, to prevent damage caused by overheating[1], because operation of these power components may easily cause dangerous self-heating[2].

There are several ways to realize a thermal protection circuit, but in most structures realized in the CMOS process, the methods to predetermine the threshold temperature can be simplified to one structure, as shown in Fig. 1[3].

In this structure, V_A has a negative temperature coefficient, and V_B, which is set by I_2 and R, can be seen as constant. V_A is higher than V_B under normal operation.

When the temperature gets high enough, V_A becomes lower than V_B. Then the output level of the comparator reverses. Usually, that means that the bias circuit of the main circuit will be shut down, and the heating part of the circuit will be shut down accordingly. Then self-heating of the circuit can be stopped and the chip can be protected.

The temperature at which V_B becomes lower than V_A is called the threshold temperature. Obviously, it is set by I_2 and R. But, as we all know, it is very difficult to make a resistor that has a precise resistance in a modern IC process. On the other hand, due to process variation, the current I_2 is often not precise too. This makes the threshold temperature deviate from the predetermined temperature. Figure 2 shows the output voltage waveform of the circuit above, versus temperature.

Obviously, the threshold temperatures under different process corner are very different. Two threshold temperatures deviate largely from those predetermined. That is to say, in the worst cases, the protection circuit cannot protect the chip from over-heating, or prevent the chip from working at normal temperature.

2. Circuit design

In this paper, a process-insensitive thermal protection circuit is proposed. This circuit can provide a control signal at the precise predetermined temperature, and it does not occupy a large chip area.

Figure 3 shows the main circuit of the proposed thermal protection circuit. It consists of a band-gap reference output buffer, a temperature sensor branch, a resistance voltage divider branch, a comparator, an output waveform shaping circuit, and a hysteresis circuit. In this figure, triangles DA1 and DA2 stand for double-input-single-output differential ampli-

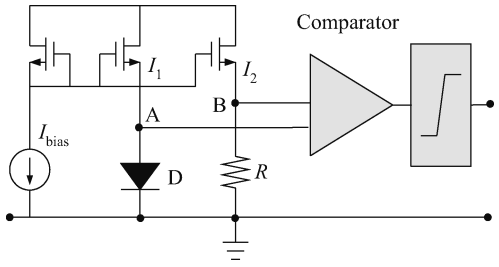

Fig. 1. Traditional CMOS thermal protection circuit.

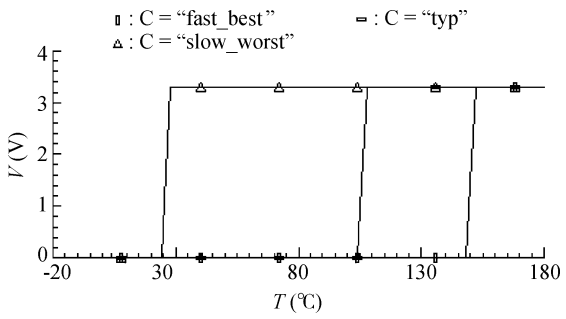

Fig. 2. Corner simulation of a traditional structure.

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Received 30 December 2010, revised manuscript received 2 March 2011

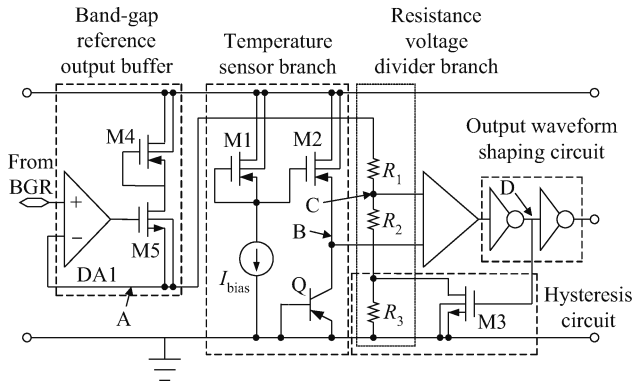

Fig. 3. Main circuit of proposed circuit.

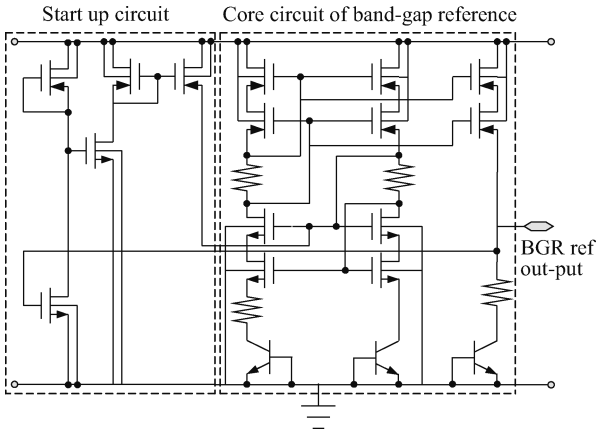

Fig. 4. Band-gap reference circuit used in this work.

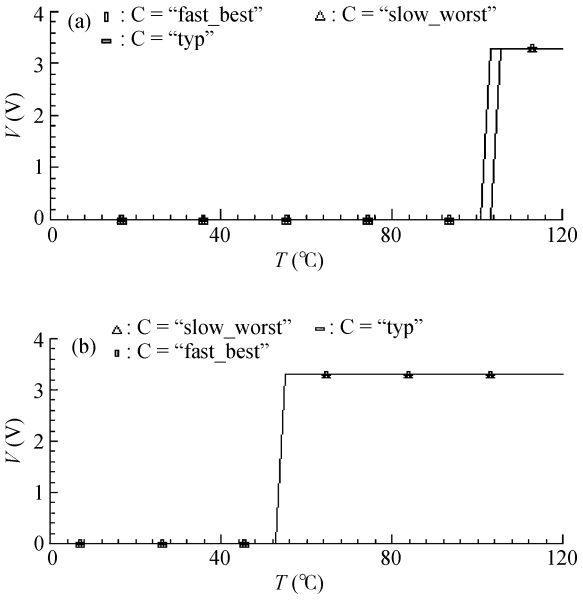

Fig. 5. Corner simulation of (a) warming process and (b) cooling process.

fiers, so that the figure can be simplified. The two inverters, which constitute the output waveform shaping circuit, are also simplified for the same reason.

The band-gap reference output buffer includes a differential amplifier, a PMOSFET M4 and a NMOSFET M5[4, 5]. It is important to note that M5 is used as a source follower, and constitutes a unity gain negative feedback structure, together with the amplifier. This structure forces the node A to have a voltage equal to the input voltage of DA1 (namely, the output of the band-gap reference), and provides a very high input impedance. This impedance is so high that it can hardly make any impact on the output voltage of the band-gap reference, which is connected to the positive input of DA1. PMOS M4 provides working current for M5.

The voltage of node A is provided to the resistance voltage divider branch, and divided by the branch. M3 works as a switch, and is open under normal operation of the chip. Then, the voltage of node C is determined by the proportion of R_1 and R_2,

$$V_{\rm C} = \frac{R_2}{R_1 + R_2} V_{\rm A}. \tag{1}$$

In the modern IC process, it is easy to get precise proportions of resistances. Hence, as the output voltage of the band-gap reference is also precise, the voltage of node C can be very precise.

PNP transistor Q, whose base and emitter are both connected to the ground of the circuit, can be seen as a diode connecting node B and ground. As the cathode of the diode is connected to the ground, when it is working, the diode is always forward-biased. According to semiconductor theory, the voltage of node B has a negative temperature coefficient[6]. Under the chip's normal operation, the voltage of node B is higher than that of node C, and as temperature increases, the voltage of node B decreases. The temperature at which $V_{\rm B}$ becomes lower than $V_{\rm C}$ is defined as the threshold temperature $T_{\rm th}$. At this temperature, the output voltage level of the comparator (DA2) reverses. This reversing of voltage is shaped by the output waveform shaping circuit, and becomes a digital control signal (0 and 1), which can be provided to the bias circuit, and shut it down, so that the whole chip can be protected.

The proposed circuit also contains a hysteresis circuit. During the process of the temperature increase to the $T_{\rm th}$ from normal operation, node D is logic 1, therefore switch M3 is open, and R_3 is shortened. Once the working temperature gets higher than $T_{\rm th}$, the voltage level of node D become logic 0, M3 is closed, and $V_{\rm C}$ becomes higher,

$$V_{\rm C}' = \frac{R_2 + R_3}{R_1 + R_2 + R_3} V_{\rm A}. \tag{2}$$

Then, unless the temperature falls below another temperature $T_{\rm th}'$, which is much lower than $T_{\rm th}$, the output of the comparator will not be changed. In this way, the chip can be protected from frequently opening and closing, which is caused by the thermal oscillation near $T_{\rm th}$.

Figure 4 shows the schematic of the band-gap reference used in this work. By using this structure[7], the mismatch of the reference can be controlled under a very low level. However, any other BGR structure that has appropriate output voltage can also be used here.

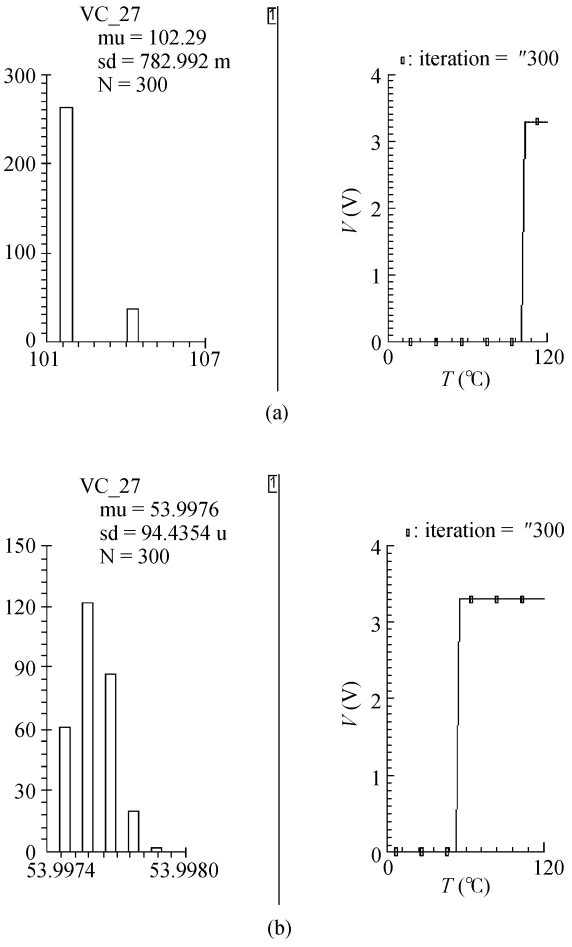

Fig. 6. Monte Carlo analysis of (a) $T_{\rm th}$ and (b) $T_{\rm th}'$.

3. Simulation and experimental results

Figure 5 shows the corner simulations of the warming and cooling processes. Figure 6 shows the Monte Carlo analysis result of these processes. These simulations prove the robustness of the proposed circuit.

Figure 7 is the photograph of a LDO chip that contains the thermal protection circuit proposed (highlighted by the black box). Area 1 is the band-gap reference, and area 2 is the main circuit of the proposed thermal protection circuit. As the band-gap reference is the essential part of an LDO chip, the thermal protection circuit only occupies another chip area of about 3×10^4 μm^2. Table 1 shows the tabulated measured $T_{\rm th}$ and $T_{\rm th}'$ of the circuits.

According to statistical knowledge, the standard deviations of $T_{\rm th}$ and $T_{\rm th}$' can be calculated by

$$S = \sqrt{S^2} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - X)^2}. \qquad (3)$$

Then we can get the experimental results of the two standard deviations as $S_{T_{\rm th}} = 1.354$, $S_{T_{\rm th}'} = 0.8494$.

These data show that the measured results are dispersed from the predetermined threshold temperature. These dispersions are not only caused by process variation and mismatch but also by measurement errors.

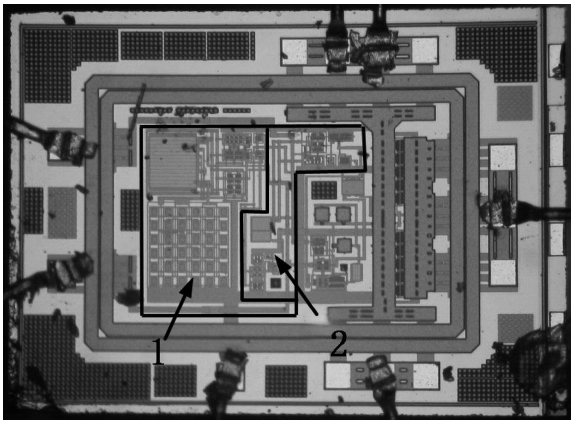

Fig. 7. Photograph of this work.

Table 1. The measured threshold temperature $T_{\rm th}$ and $T_{\rm th}'$.

Number	$T_{\rm th}$	$T_{\rm th}$'
1	101.5	53.5
2	102.9	55.1
3	105.2	54.4
4	103.1	54.8
5	102.9	55.3
6	103.7	54.6
7	101.8	53.3
8	103.2	53.5

4. Conclusion

A new structure of thermal protection circuit has been proposed in this paper. By using a band-gap reference and its output buffer, and a resistance voltage divider branch, the threshold temperature can be set precisely, and its robustness is proved by the measured $T_{\rm th}$ and $T_{\rm th}'$.

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