# A STAND-ALONE LOW-POWER DIGITAL TEMPERATURE SENSOR FOR IC MONITORING

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***ABSTRACT***

*In this paper, we propose an ultra-low power stand-alone temperature sensor for IC monitoring. The temperature sensor integrates a bandgap voltage reference, a current reference that generate the required biasing of the circuit. The temperature is sensed through the VBE (PTAT) of a bipolar transistor. The high accuracy of the temperature sensor is not an issue for our application since the sensor is used for IC monitoring i.e. for thermal shut-down and short-circuit protection requirements. The sensor outputs a 4 bits binary word that is proportional to the IC temperature. This digital information can be processed by a microprocessor/DSP to take the convenient decision such that shutdown. The main contribution of this work is to present a low-power temperature integrating the different functionalities without any additional external circuit. This can be an interesting solution for IP providers to use such stand-alone circuit within the SoC i.e. just plug-and-play. To the known of the author, it is the first time that a complete technical solution is presented. The circuit was implemented using XFAB 180nm technology and the verifications was performed using Cadence tool.*

***KEYWORDS***

*SoC, IC design, Stand-alone temperature sensor, IC monitoring, IC design-for-test*

## 1. INTRODUCTION

The temperature monitoring is becoming an essential and necessary unit in different applications like power management system, temperature management, hot spot detection in multi core system, thermal testing, and IC monitoring. The uprising of on-chip temperature sensing is mainly due to rapid development of process technology. As a result, these embedded sensors usually feature small area, low power consumption and digital output, to achieve minimum cost. In the state of the art, different temperature sensors have been proposed with high accuracy and low-power [1][2][3][4][5]. In our application, the aim of integrating such sensors is to detect short-circuits or any abnormal behavior that may occur on-chip. In addition, we are especially interested by developing "stand-alone and autonomous temperature monitor". By this, we mean an independent product that can be integrated in any chip without any additional requirements such as bias voltage, bias current, reference voltage, etc. Thus, such monitor can be adapted with different types of IC i.e. analog, RF, digital, or a complete SoC (System-On-Chip) without any additional resources from the IC except the power supply. At the layout level, obviously the optimal placement of the different sensing devices will depend on the location of the critical blocks with high power consumption that are specific in each chip.

To the knowledge of the author, such low-power complete solution, with low area overhead that integrates voltage and current references, bias generator, etc, and highly recommended by the industry have not been presented in the literature. Sections II and III describe the system level approach and the architecture of the monitor respectively. Section IV present the design of the different blocks and the simulation results are presented in section V. Section VI concludes the paper.

## 2. System Level Approach

Our approach consists of developing a sensor that can monitor different parts in the SoC i.e. RF systems, Analog front-ends, digital/logic parts as shown in Fig. 1. To implement such approach, the Sensing Device (SD) that is responsible to monitor and track the temperature variation and convert the physical information into electrical signal must be as simple as possible with very low-area overhead since it will be plugged in different locations on chip. The places that must be chosen are in general the blocks and/or devices with high power dissipation. Examples include the power amplifiers in RF systems, the power stage in power regulators, the hot spots within the microprocessors.

## 3. Temperature Monitor Architecture

In this section, we will detail the building blocks of the temperature monitor. The stand-alone monitor that we propose is shown in Fig. 2. There are two main blocks.

- The sensing devices of the monitor that will be placed in different locations on-chip i.e. close to the block that dissipate high-power
- The core of the monitor that is formed by: a) the bandgap voltage reference with the voltage divider that generates different bias voltages, b) the current reference that generates the required bias currents, c) the comparators that output the digital bits and d) the analog multiplexer that switches between the different SDs.

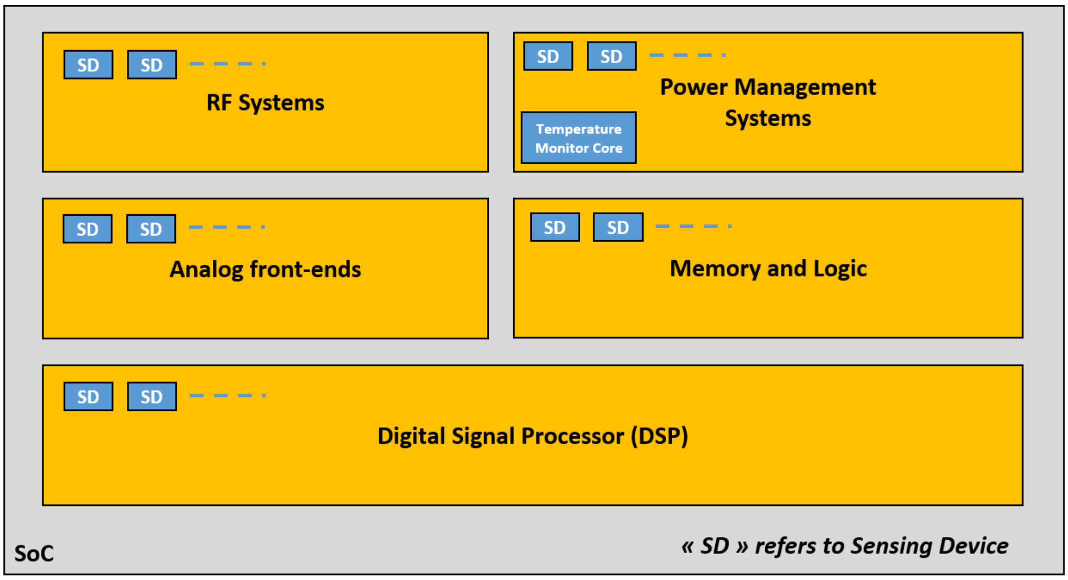


Fig. 1. System level approach

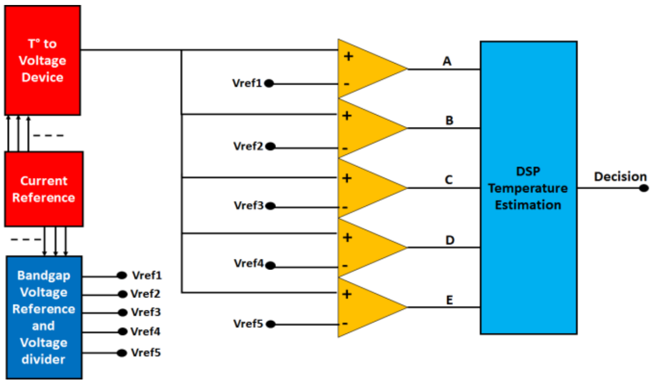


Fig. 2. Architecture of the stand-alone temperature monitor

To understand the principle of operation, suppose that we have a single SD where the SD output is a voltage that varies inversely proportional to the temperature e.g. from ~ 600 mV @ -40°C to ~ 250 mV @ 125°C. Now, we cut the voltage range in different intervals and we fix a limit to each interval. Obviously, each voltage interval corresponds to a temperature interval and the voltage limit corresponds to a temperature value. Depending on the comparators output, the processor estimates the temperature range as detailed in table 1:

Table 1 Temperature sensor output dependinng on the temperature range

| | |
|---|---|
| -40°C < T < 0 °C | ABCD = 0000 |
| 0 °C < T < 40 °C | ABCD = 1000 |
| 40 °C < T < 80 °C | ABCD = 1100 |
| 80 °C < T <120 °C | ABCD = 1110 |
| T > 120°C | ABCD = 1111 |

## 4. TEMPERATURE MONITOR DESIGN

### 4.1. SENSING DEVICE (SD)

As a simple SD, the bipolar transistor can be applied to generate the basic signal for temperature monitor using the base-emitter voltage and the saturation current. The MOS transistor can be used to extract the same information using the threshold voltage and the mobility. It appears that the base-emitter voltage and saturation current of the bipolar transistors show better temperature characteristics [1].

When the bipolar transistor operates in the active region, it generates a base-emitter voltage that is directly proportional to the absolute temperature (PTAT) via the thermal voltage $V_T = kT/q$. The $V_{BE}$ voltage varies linearly with the temperature, thus by comparing the $V_{BE}$ to different references voltages with very high accuracy over worst cases process, voltage and temperature conditions, we can deduce the temperature range of the place where the bipolar transistor is plugged. Finally, such SD meets our requirements in terms of simplicity and silicon area overhead. Simply, one can place the PNP bipolar and connect its emitter to the bias current branch of the current reference.

Here, we must stress a point that there are no specific constraints at the layout level on the connection between the current reference and the bipolar transistor, the bias current is in the order of few nA, therefore the IR drop is negligible.

### 4.2. BAND GAP VOLTAGE REFERENCE

The Band gap Voltage Reference shown in figure 3 is an analog circuit that generates an output voltage with high accuracy over process, power supply voltage, and temperature (PVT) variations. As already mentioned, such accurate reference voltage is required to make the comparison with the base-emitter voltage $V_{BE}$ that tracks the temperature variation. To generate a quantity that remains constant with temperature, we postulate that if two quantities having opposite temperature coefficients (TCs) are added with proper weighting, the result displays a zero TC. For example, if we have two reference voltage $V_1$ and $V_2$ that vary in opposite directions with temperature, we choose $\alpha_1$ and $\alpha_2$ such that $(\alpha_1 * \partial V_1/\partial T) + (\alpha_2 * \partial V_2/\partial T) = 0$, obtaining a reference voltage, $V_{REF} = \alpha_1 V_1 + \alpha_1 V_2$, with zero TC [1]. Again, based on various device parameters in semiconductor technologies, the characteristics of the bipolar transistor can provide positive and negative TCs. The study of the bandgap architecture shows that the output voltage is fixed by the parameters of the silicon technology, in general around 1.25 V [1].

$$V_{REF} \approx V_{BE} + V_T \ln n \tag{1}$$

where “n” is the number of bipolar transistor in the right branch in figure 3. Now, this voltage $V_{REF}$ is called bandgap reference. To understand the origin of this terminology, let us write the voltage output voltage as shown in [1]:

$$\frac{\partial V_{REF}}{\partial T} = \frac{\partial V_{BE}}{\partial T} + \frac{V_T}{T} \ln n \tag{2}$$

So, to obtain, $\partial V_{REF}/\partial T = 0$, we must size the circuit such that:

$$\frac{V_{BE} - (4+m)V_T - E_g/q}{T} = -\frac{V_T}{T} \ln n \tag{3}$$

The reader can refer to [1] for more details on the bandgap reference analysis.

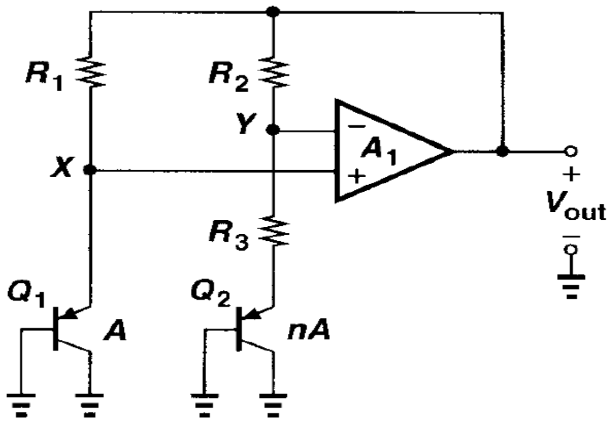


Fig. 3. Bandgap Voltage Reference [1]

In our application, the main concern is to develop a voltage reference with: a) a very low-power consumption i.e. less than 1 µA. The main critical block is the operational amplifier that must be designed such that the stability is achieved with the lower capacitance value. To this end, we have implemented a single stage amplifier with a single low frequency pole at the output. The circuit is shown in Fig. 4. Given that, there is no strong constraint related to the noise, the power consumption of the amplifier was fixed to 400 nA. In addition, we fix a maximum current consumption of 500 nA to the resistor network (R1, R2, R3) and the voltage divider that generates the different bias voltages.

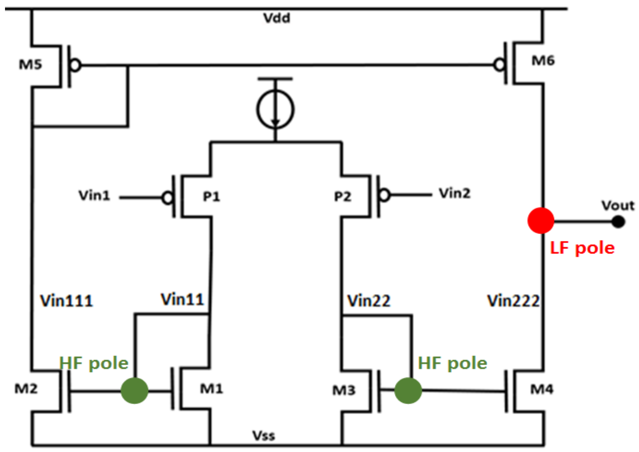


Fig. 4. Operational Amplifier of the bandgap voltage reference

Special care has been taken when we sized the differential pair and the current mirrors to reduce the inaccuracy due to the mismatch between transistors. The length of the different transistors has been fixed to L= 2 µm to decrease the mismatch.
A voltage divider is connected at the output of the reference circuit to generate the different reference voltages that will be compared to the base-emitter voltage as shown in Fig. 2. The size of the resistors was selected for a maximum current of 500 nA i.e. 1.2V / 500nA equal to 2.4 MΩ.

### 4.3 SUPPLY INDEPENDENT CURRENT REFERENCE

The temperature monitor must also include its own current reference (Fig. 5) that is required to bias the bandgap voltage reference, the comparators and the sensing devices. Obviously, the current reference must be supply independent, otherwise the current will vary with the power supply as shown in equation 4.

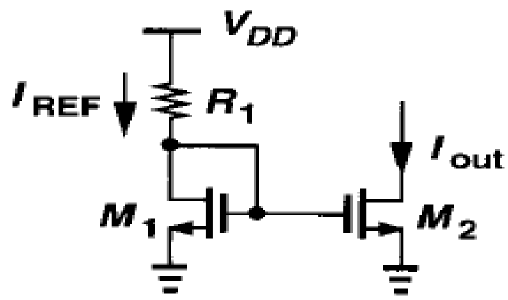


Fig. 5. Current reference using simple resistor [1]

$$\Delta Iout = \frac{\Delta VDD}{R1+\frac{1}{gm1}} \times \frac{(\frac{W}{L})2}{(\frac{W}{L})1} \quad (4)$$

To obtain a less sensitive solution, we postulate that the circuit must bias itself, i.e., $I_{REF}$ must be somehow derived from $I_{out}$. The idea is that if $I_{out}$ is to be ultimately independent on $V_{DD}$, then $I_{REF}$ can be a replica of $I_{out}$.

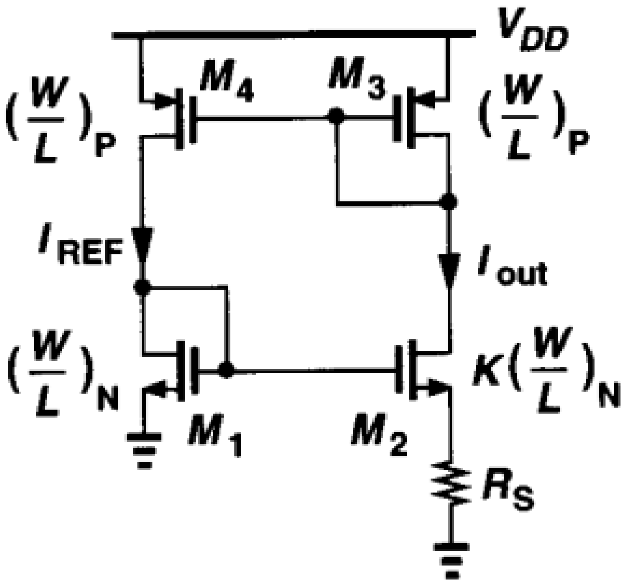


Fig. 6. Supply Independent Current Reference [1]

Fig. 6 illustrates an implementation of supply independent current source [1] where $M_3$ and $M_4$ copy $I_{out}$, thereby defining $I_{REF}$. In essence, $I_{REF}$ is 'bootstrapped' to $I_{out}$. With the sizes chosen here, we have ($I_{out} = K.\ I_{REF}$) if the channel-length modulation is neglected. Note that, since each diode-connected device feeds from a current source, $I_{out}$ and $I_{REF}$ are relatively independent of $V_{DD}$. From [1]:

$$Iout = \frac{2}{\mu n.Cox\left(\frac{W}{L}\right)N} \cdot \frac{1}{Rs^2}\left(1 - \frac{1}{\sqrt{k}}\right)^2$$

Long channels are used for all transistors in the circuit since such circuit exhibits little supply dependency if channel-length modulation is negligible.

### 4.4 COMPARATORS

Fig. 7 presents the design of the comparator. There is no specific requirement in terms of speed thus the comparator was designed to meet the minimum power consumption < 100 nA.

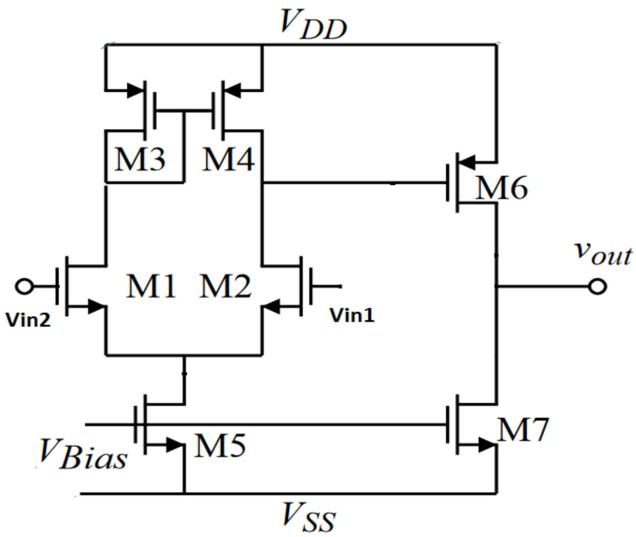


Fig. 7. Comparator Design [1]

## 5. SIMULATIONS RESULTS

The architecture shown in figure 2 was implemented at transistor level using the 0.18 µm from XFAB technology. The power consumption of the circuit is less than 7 uA where the bandgap voltages consumes 4 uA, the voltage divider connected on the bandgap voltage output consumes 500 nA, the comparators consume 2 uA (each comparator consumes 400 nA), the current reference consumes 100 nA. Figure 8 shows the simulation of the variation of the sensor output VBE with the temperature. The sensing device output i.e. the bipolar, varies linearly with the temperature. Figure 9 shows the variation of reference output voltage with the temperature. The results show a high accuracy of the reference output with the temperature variation.

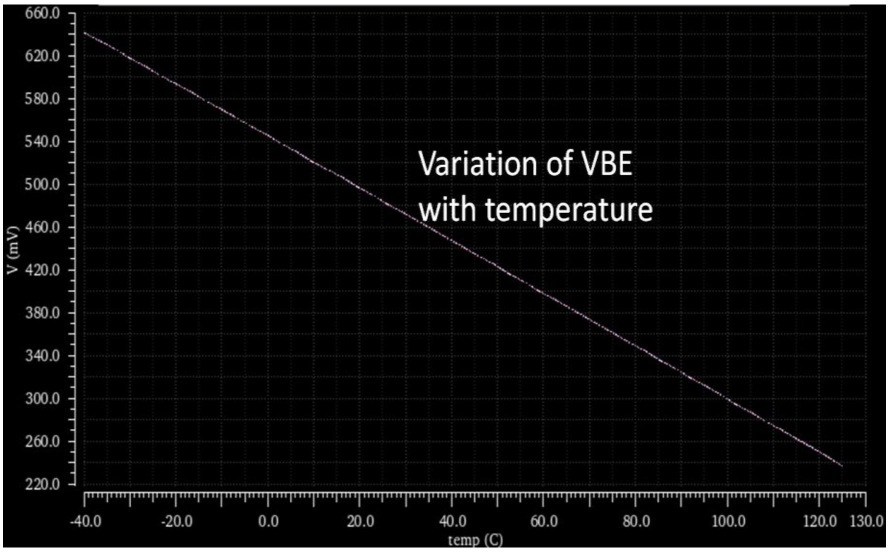


Fig. 8. Variation of the sensing device output with the temperature

The different references voltages of the comparators (Vref1 to Vref5, see figure 2) are generated from the voltage divider that is connected on the bandgap reference output.

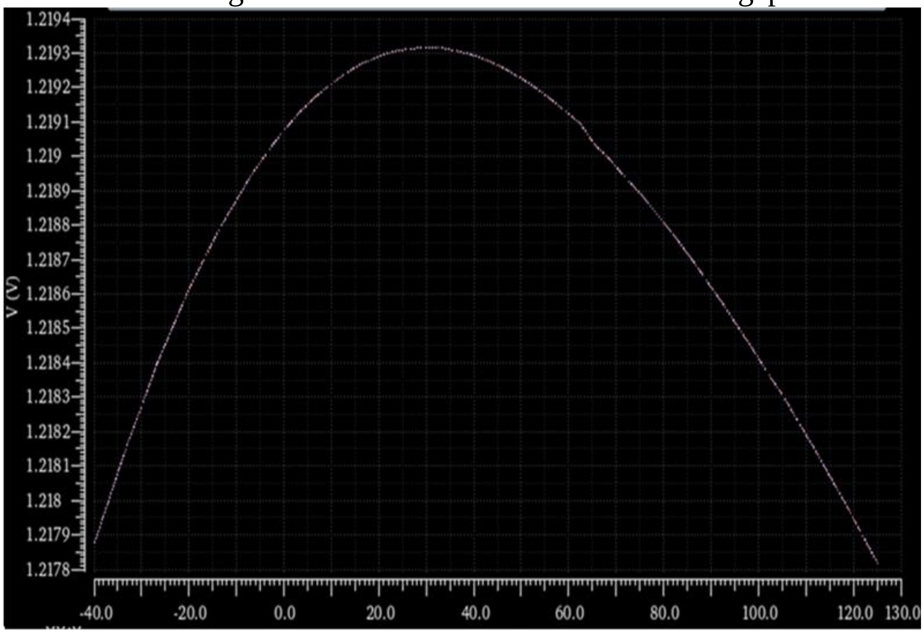


Fig. 9. Bandgap voltage reference output variation with the temperature

Figure 10 shows the comparators digital outputs for different temperature range. The results shown in this figure correlate with the table 1. The on-chip processor can process these outputs and make the decision based on the applications constraints.

## 6. CONCLUSIONS

In this paper, we have presented a stand-alone temperature sensor that integrates the bandgap voltage reference and the current reference that generate the required biasing of the circuit. The sensor outputs a 4 bits binary word that is proportional to the IC temperature. This digital information can be processed by a microprocessor/DSP to take the convenient decision such that shutdown.

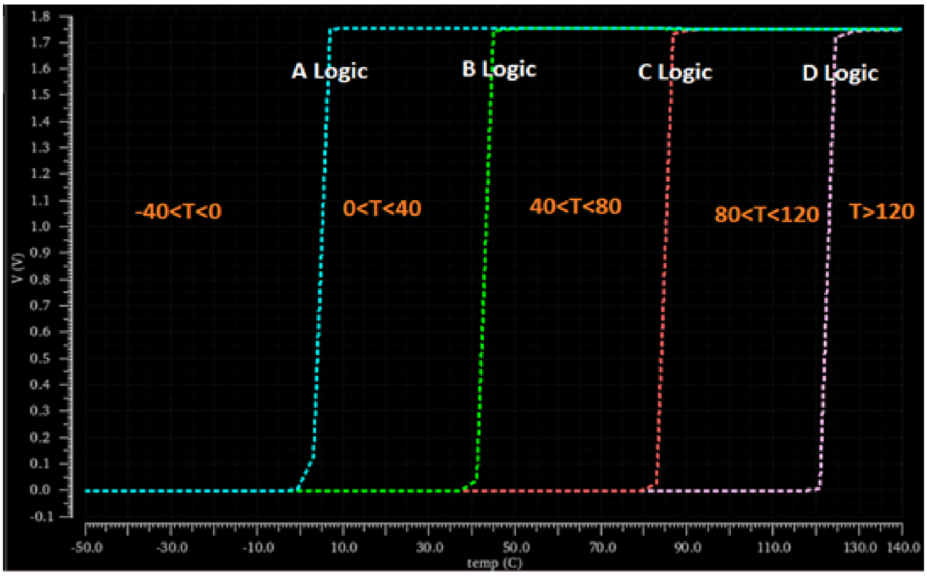


Fig. 10. Comparators outputs depending in terms of the chip temperature

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