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CMOS based thermal detector for processor

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Article Info	ABSTRACT
	This project proposed a design of low power CMOS-based thermal detector which can detect the temperature of processor such as in Central Processing Unit. By re-designing temperature detector circuit using CMOS technology, the reduction in power consumption and area size of the thermal detector can be obtained. In this paper, the design of thermal detector consists of temperature sensing core, amplifier, and Analog to Digital Converter (ADC), respectively. The sensor was designed using 0.13 μm CMOS technology and operates by sensing the temperature of processor and produced a digital output value. The temperature detection range was setup between 0 °C to 80 °C with 10 °C resolution. The temperature detector was capable to show temperature readings in binary value. It consumed an average power of 558.2 μW and a space occupancy of 0.0118 mm².

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1. INTRODUCTION

Temperature sensor is commonly used for various kind of application such as in measurement, instrumentation, and control system [1-4]. Most of processors nowadays are easily overheated due to high usage of softwares and applications. Overheating of processor can cause system malfunction [5] and damage to the processor. Unfortunately, there is no warning showed when this problem happened. The damaged processor has to be replaced and it is quite costly to the user. Due to the high-power usage of the processor, it is even challenging to add-on the thermal sensor into the processor [6]. For an on-chip temperature sensors, it must be compatible with the technology available in the process, maintain a small area, has good accuracy with low power consumption over standard process variations and over typical supply voltage variations [1, 4, 6-7].

The Complementary Metal Oxide Semiconductor (CMOS) based thermal detector has been widely used because of the low power sensor characteristic. There are other different types of temperature sensors such as the Bipolar Junction Transistor (BJT) [7-9], graphene-based Field Effect Transistor (GFET) temperature sensor [10], resistor-based thermal sensor [11], and diode based temperature sensor [12-13]. In this project, the CMOS-based temperature sensor was selected because it consumes less power as compared to other types of temperature sensor. Nowadays, the minimum CMOS based thermal detector with ADC is needed to consume at least around 650 μW [14]. By re-designing and lowering the number of transistors in the circuit, the power consumption of the CMOS based thermal detector can be reduced. In this paper, a low power consumption CMOS based thermal detector is designed using low power reduction techniques [15]. On the other hand, the circuit was designed to achieve small space occupancy and developed using Cadence software. The CMOS based thermal detector was aimed for the detection of temperature from

0 °C to 80 °C; as the best performance of processor is within 27 °C (room temperature) to 60 °C [16]. The design parameter was optimized based on the objective to implement the sensor circuit for the detection of temperature in processor.

2. CIRCUIT BLOCK DIAGRAM

A temperature sensor is a device that provides the temperature measurement in electrical signal for example in the voltage form. The changes of the temperature cause the output voltage that produced by the temperature sensor to either increases or decreases. The electrical signal was then converted into digital form so that it can be shown in the other devices. Temperature sensors are easily produced with semiconductor processing technology by using the temperature characteristics of the PN junction [2-3]. The basic block diagram of CMOS based thermal detector is shown in Figure 1. The circuit design consist of a temperature sensing core, amplifier, and analogue to digital converter (ADC) sub-circuit.
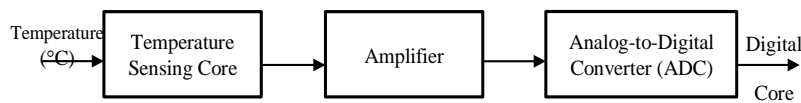

Figure 1. Basic block diagram of temperature sensor

3. RESEARCH METHOD

The sub-circuit for each block diagram in Figure 1 was designed in Cadence® custom/analog/RF using 0.13μm CMOS technology, which took the advantages of P- and N- channel of transistor device. The average value of power consumption for the whole circuit was measured by using the Analog Design Environment (ADE). The analysis of power consumption and space occupied space by the thermal detector was performed and compared with the performance of thermal detector circuit in previous work [4-5, 13-16].

3.1. Temperature Sensing Core

The temperature sensing circuit was developed based on self-stabilized feedback architecture [17]. A threshold-voltage, V_T based is adapted where the circuit expresses temperature information as an output voltage. Figure 2(a) illustrates the current source circuit used in the design, which sets the threshold voltage. The current source sub-circuit is functioned as a self-biasing circuit that generates current which not affected by the voltage source. The current mirror circuit is formed by transistors M3 and M4. These transistors sizes determine the relationship between currents I_1 and I_2 of this current mirror circuit.
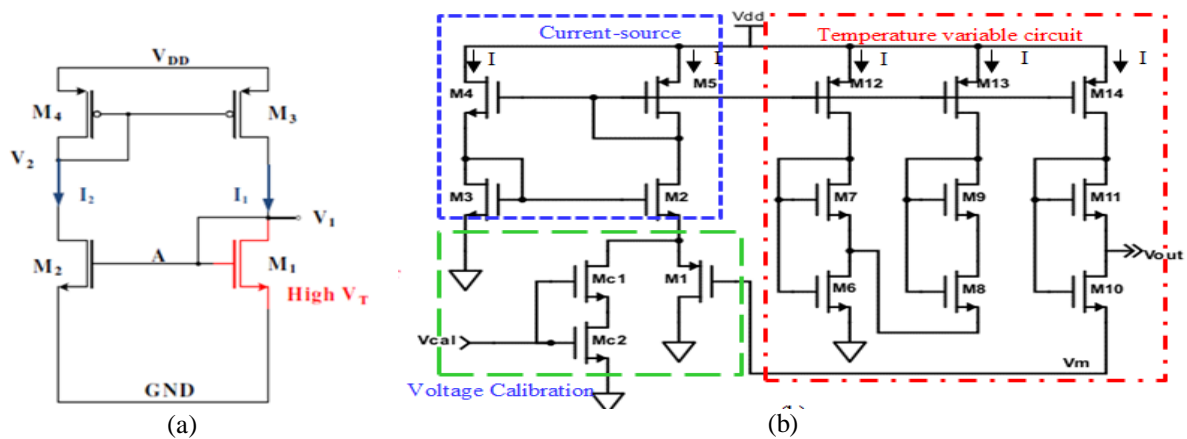

Figure 2. Schematic for (a) Current source circuit and (b) Temperature detector circuit

The circuit can be designed to operate with different current mirror gains and the mirror gain is a degree of freedom in the design space for these circuits [7]. The V_T-based temperature sensors can be

described using the standard square-law device model. However, the channel length modulation effects is neglected. The design variables $\left\{\frac{W_1}{L_1}, \frac{W_2}{L_2}, \frac{W_3}{L_3}, \frac{W_4}{L_4}\right\}$ is obtained from (1) [18].

$$\begin{cases} \frac{1}{2}\mu_n C_{ox} \left(\frac{W}{L}\right)_1 \left(V_1 - V_{T_1}\right)^2 = I_1 \\ \frac{1}{2}\mu_p C_{ox} \left(\frac{W}{L}\right)_3 \left(V_{DD} - V_2 - |V_{T_3}|\right)^2 = I_1 \\ \frac{1}{2}\mu_n C_{ox} \left(\frac{W}{L}\right)_2 \left(V_1 - V_{T_2}\right)^2 = I_2 \\ \frac{1}{2}\mu_p C_{ox} \left(\frac{W}{L}\right)_4 \left(V_{DD} - V_2 - |V_{T_4}|\right)^2 = I_2 \end{cases} \tag{1}$$

The proposed temperature detector circuit is presented in Figure 2(b) which combines a current source circuit, temperature variable circuit, and voltage calibration circuit. The sensing circuit is combined with a flash ADC to perform the digital conversion. Table 1 tabulates the transistors size.

Table 1. Transistors Size in for Temperature Sensing Core

Transistor	No.of Fingers	Width/Length (µm/µm)
M1	1	1.5/20
M2	10	3/3
M3	4	3/3
M6, M8, M10	1	1/3
M7	3	3/3
M9	4	3/3
M11	28	3/3
M4, M5 M12, M13, M14	1	3/10
MC1, MC2	1	1/20

3.2. Amplifier Circuit

A basic amplifier circuit operates like an inverter [1, 14]. It inverts the input voltage from high voltage to lower voltage and vice versa. The amplifier circuit in this work was design with a single PMOS and NMOS transistor. With the input voltage connected to the gate of NMOS transistor, while the gate of PMOS transistor connected to the output voltage, it acts as an op-amp that amplifies the voltage. A common-source configuration was used in the circuit design.

3.3. Analog to Digital Converter

The most common types of ADC that are available in the market are the flash ADC, the successive approximation register (SAR) ADC and Sigma-delta ADC [19-21]. The flash ADC [22-23] uses comparator to compare the voltage differences between the input voltage and reference voltage. It has great conversion speed compared to SAR and Sigma-delta ADC. However, it consumes a lot of space since it requires many logic gates and voltage comparators [23]. Flash ADC is mostly used in conversion that required less than 8-bit digital output. A SAR ADC [20] only requires one comparator and counting logic to perform the conversion. SAR ADC is normally used in which the value of output digital bits is not perfectly 2^N, where N is the number of bit [11]. The basic block diagram of a flash ADC applied in the design is shown in Figure 3.
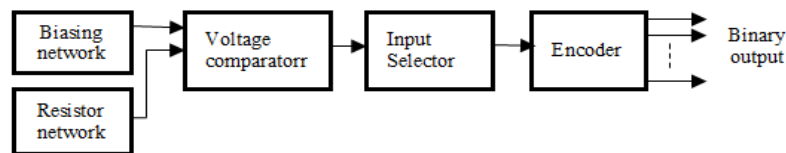

Figure 3. Block diagram of Flash ADC

The ADC block operates by comparing the input voltage with reference voltage. The output is shown in a digital form. All the output of the voltage comparators were sent to the selector circuit which determine whether the voltage obtained is within the specified range. The binary output of temperature readings were extracted using encoder circuit (OR gates).

4.   RESULTS AND ANALYSIS
4.1. Temperature Sensing Core Output
The input voltage for the temperature sensing core circuit is fixed at 1.2V. This is to make sure that the output voltage of the temperature sensing core is adequate to be used as the main input voltages for amplifier and ADC block. The length (L) of all the transistors is in the range of 3 - 20 μm. These transistor sizes were considered as to obtain a high resistance for better detection of temperature [17]. In practical, the temperature sensing core can be calibrated by measuring the die temperature (after fabrication) at a reference point. The temperature sensing core circuit occupies a space area of 0.00289 mm² (or 120.9 μm x 23.9μm) and consumes an average power of 1.045 μW. The gate-source voltage shows an exponential relationship with the drain current in the temperature variable sub-circuit as seen in Figure 4.

The output voltage was obtained by adding the gate-source voltage of the upper part transistors of the temperature sub-circuit and subtracting the voltage of the lower part transistors. This temperature sensing core was able to sense temperature in the range of -260 °C to 170 °C. The temperature values were calibrated from 0 to 1.2 V. At temperature -260 °C, the corresponding voltage was about 0.05 V. Then, the voltage increased exponentially up to 170 °C. Above this temperature value, the output voltage dropped drastically. This behavior was anticipated as V_T is a temperature dependant parameter [19]. Thus, nonlinearity of the output voltage with respect to temperature is dominated by the 2nd order temperature effects. The drastic falling trend above 170 °C might also introduced through the nonideal output conductance parameters in the transistor [18].
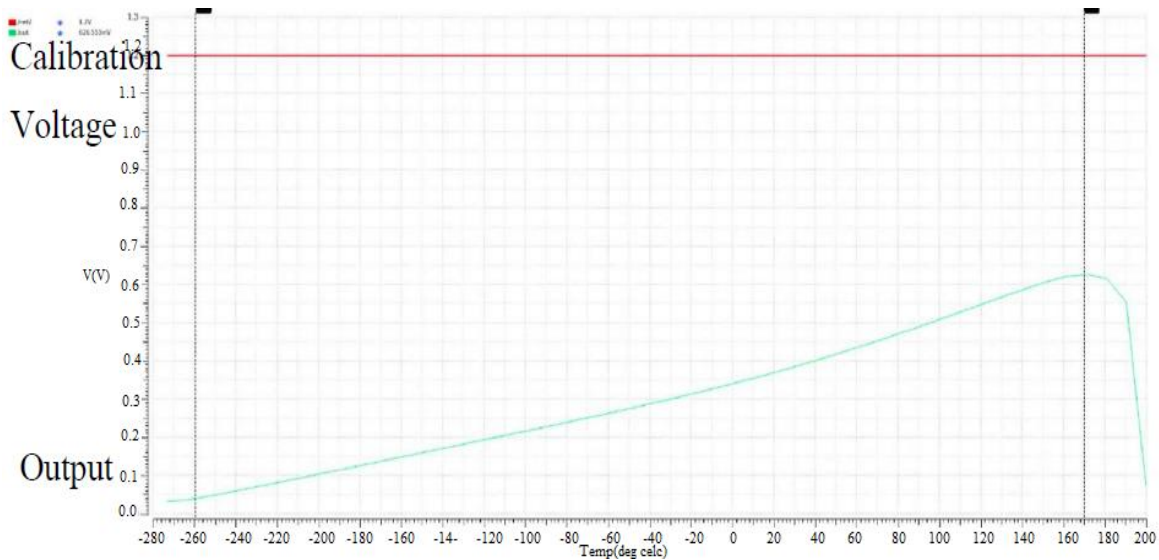

Figure 4. ADE of temperature sensing core

4.2. Amplifier Output
Figure 5 shows the output of the amplifier where the input is connected to the output of temperature sensing core. Therefore, amplifier circuit received a voltage input which represents the temperature values. The output voltage of the amplifier was about 744 mV (at 0 °C) and 450 mV (80 °C), respectively. However, these readings were opposite the trend of the incoming input voltage obtained from the temperature sensing core, 341 mV and 471 mV, respectively. This shows that the input voltage was inverted.

The output in Figure 5 was expected as the inverting amplifier amplifies and inverts the input signal. At 0 °C, the input voltage was set as 340 mV (obtained from temperature core circuit). The input voltage was proportionally increased about 10 mV with every 5°C temperature value until it reached 470 mV at 0 °C. The output voltage was amplified about double the input voltage at low temperature and reduced as the temperature increased to 80 °C. The amplification gain (A_V) was achieved by setup earlier made with transistor length parameter. The maximum output voltage was achieved by considering (2) [17].
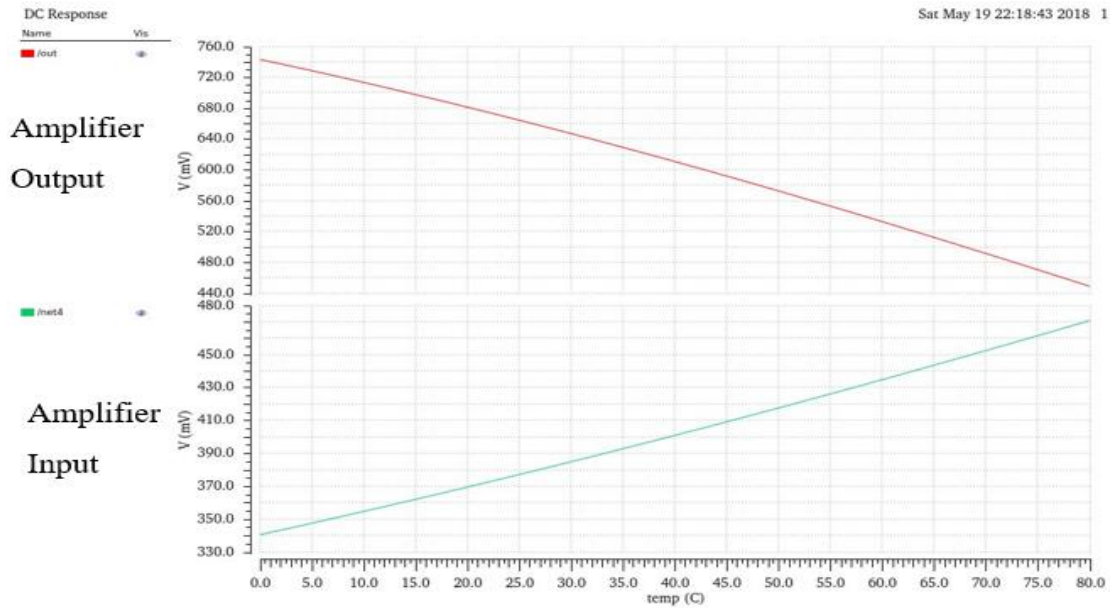
$$v_{OUT}(max) \cong V_{DD} - |V_T| \tag{2}$$

Figure 5. ADE of the amplifier connected to temperature sensing core

4.3. Analog to Digital Converter (ADC)
4.3.1 Resistor Network

The resistor network in for ADC block in Figure 3 acta as an important role in providing reference voltages to the voltage comparators; which is compared with the input voltage. By having the output voltages and corresponding temperature based on temperature sensing output in Figure 5, the calculation of resistor values and corresponding voltages can be done according to (3) [19].

$$V_{ref} = \frac{R_a}{R_b + R_a} \times V_{in} \tag{3}$$

where V_{ref} is the reference voltage, R_a is the total resistor value after the reference voltage, R_b is the total resistor value before the reference voltage, and V_{in} is the input voltage of set at 1.2V. The resistor value and corresponding voltage is shown in the Table 2.

Table 2. Resistor Value and Corresponding Voltage

Resistor	Resistor Value (kΩ)	Corresponding Voltage after resistor network (V)
R1	17.654	0.899
R2	8.239	0.759
R3	1.766	0.729
R4	2.059	0.694
R5	2.260	0.655
R6	2.560	0.612
R7	2.654	0.566
R8	2.353	0.526
R9	2.654	0.481
R10	28.241	0.000
R_{total}	70.440	

4.3.2 Voltage Comparator

A voltage comparator circuit is sub-unit of a flash ADC circuit. It is used to compare the input voltage with the reference voltage (obtained from the resistor network). When the input voltage is higher than the reference voltage by approximately 400 mV, the voltage comparator gives an output of 40.8 mV. If the reference voltage is higher than the input voltage, the output voltage of 1.17 V is obtained. These results were plotted in Figure 6. If the $+ V_P$, the input of the comparator is at a greater potential than the $-V_N$ input, the output of the comparator is a logic 1. If the + input of comparator is at a potential less than the – input, the output of the comparator is at logic 0.
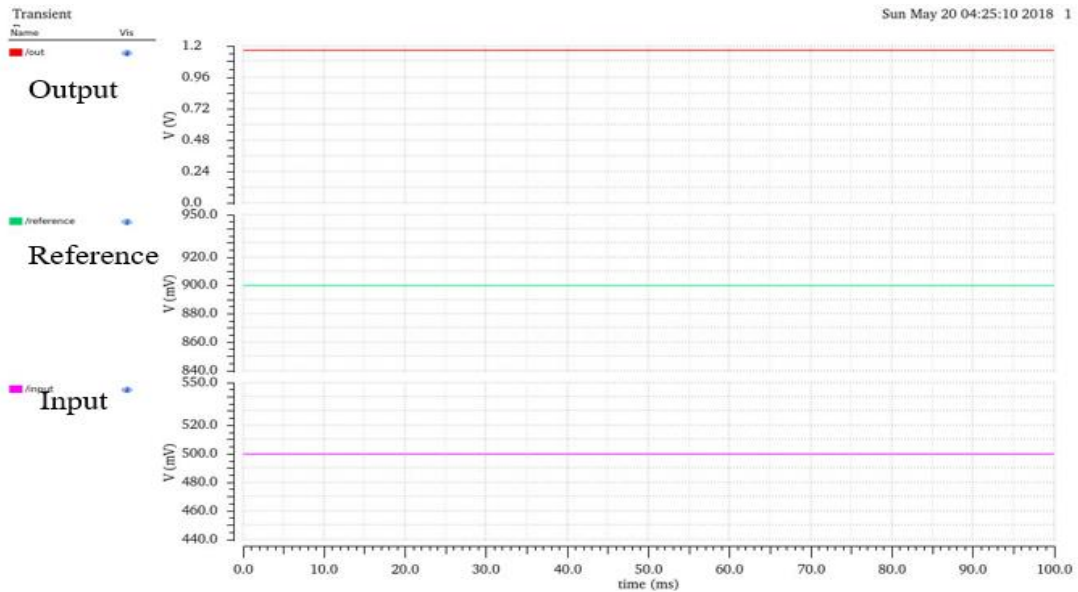
Figure 6. Output of Voltage Comparator when $V_{in} < V_{ref}$

4.3.3 Digital Encoder Circuit

The digital encoder circuit is developed using OR gates and implemented to combine the output from input selector circuit in order to show the binary output of the temperature detector. For the ADC circuit, a few different input OR gates were used, e.g., 2-input, 3-input, 5-input OR gate, etc. All those OR gates are designed to show the digital binary output of the ADC. The 2-input OR gate is used to show the *b6* bit, the 3-input OR gate was to show the *b5* bit, the 5-input OR gate was to show the *b4* bit, and another three 4-input OR gate was to show the output *b3*, *b2* and *b1* bit. By combining the resistors, voltage comparator, XOR gates, and the OR gates, a full flash ADC circuit is developed.

4.4. Complete Circuit

After each block of the temperature sensing core, amplifier, and ADC circuit components have been designed, simulated, and verified; these blocks were combined to form the complete temperature detector circuit. This temperature detector circuit is capable to represent the temperature value 0 °C to 80 °C as a 7 bit binary output as shown in Figure 7. Bit b6 is the most significant bit (MSB). This conversion was made possible with the ADC circuit. Figure 8 shows the overall circuit layout. Table 3 tabulates the results of temperature value and the binary output at a resolution of 10 °C.
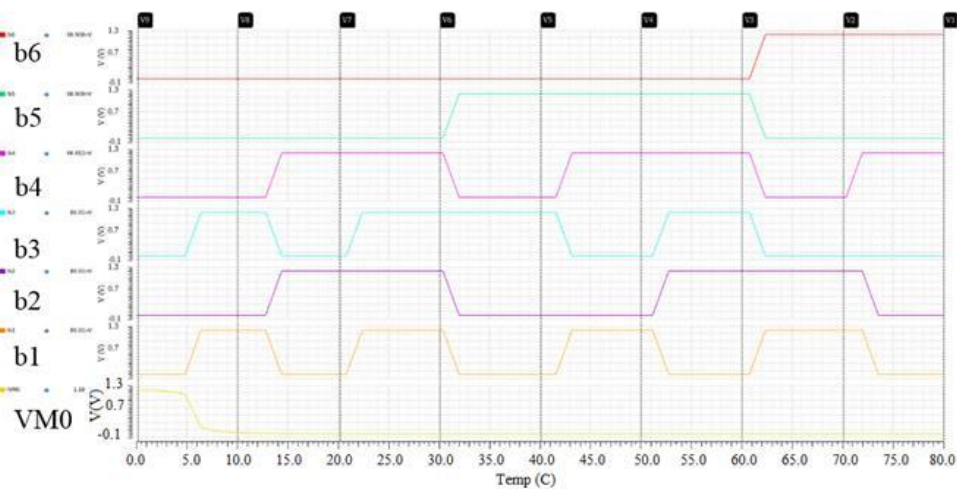

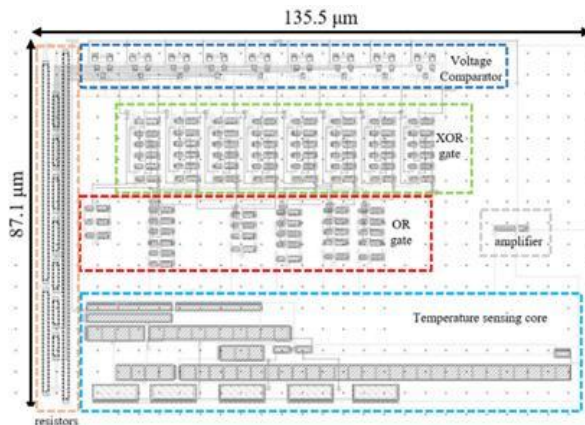Figure 7. Binary Output View of ADC circuit

Figure 8. Layout View of Full Temperature Detector
(135.5 μm x 87.1 μm)

Table 3. Output of ADC Corresponding to Temperature

Temperature (°C)	Binary Output of ADC						
	b6	b5	b4	b3	b2	b1	VM
0	0	0	0	0	0	0	1
10	0	0	0	1	0	1	0
20	0	0	1	0	1	0	0
30	0	0	1	1	1	1	0
40	0	1	0	1	0	0	0
50	0	1	1	0	0	1	0
60	0	1	1	1	1	0	0
70	1	0	0	0	1	1	0
80	1	0	1	0	0	0	0

5. CONCLUSION

Overall, the temperature detector to detect the temperature range from 0 °C to 80 °C with the resolution of 10 °C has been successfully designed. The temperature detector also has a low power consumption of 558.2 μW with space occupancy of 0.0118 mm². The power dissipation is expected to be higher than other previous work [14, 17, 23-25]. This is due to the existing of flash ADC that contains nine units of voltage comparators (about 60 μW each). On the plus side, this temperature detector design is capable to show the temperature in binary value which not offered in most of other works in [23-4, 6]. Compared to the CMOS temperature sensor with built-in ADC [14], this work has lower power consumption by 14 % with a reduction of about 91.8 μW. For more accurate temperature reading, the resolution of the temperature detector can be increased by modifying the voltage comparator design to be more precised in comparing voltage. However, the complexity of circuit is also predictable due to additional of gates operation and layout size increases.

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