A CMOS-Based Ultra-Wide Range Temperature Sensor for Quantum Computing Circuits in 65nm CMOS

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***Abstract* - In this paper, an ultra-wide range CMOS temperature sensor is designed for applications in cryogenic and room temperature environments, particularly targeting quantum computing systems where control circuits are integrated into the cryogenic domain. A beta multiplier structure is employed as the sensing element to generate a temperature-proportional current. By leveraging the temperature coefficient (TC) of MOSFET mobility and resistor characteristics, the sensor ensures a stable TC. The generated current serves as the bias for a relaxation oscillator, which facilitates temperature-to-frequency conversion. The relaxation oscillator operates with a lower TC than the beta multiplier, with its frequency variation determined by the bias current. The resulting frequency is then digitized using a 16-bit counter. The sensor is designed to operate over a temperature range of -270°C to 30°C. Simulation results indicate that the oscillator produces 20.6 KHz at -250°C with a TC of 0.75 KHz/°C.**

***Keywords*—CMOS, temperature sensor, cryogenic, relaxation-oscillator.**

I. INTRODUCTION

Temperature sensors are widely used in various applications requiring precise thermal monitoring. In integrated circuits, they are often embedded to enable real-time temperature-dependent control. While conventional temperature sensors are designed to operate in the room temperature range, they become ineffective in cryogenic environments [1],[2],[3],[4],[5].

Quantum computing systems, which rely on the precise qubit control, were initially implemented with room-temperature control circuits as shown in Fig. 1. However, as these systems evolved, it became evident that the long interconnect cables required to link room-temperature electronics with cryogenic qubits introduced significant challenges. High parasitic resistance, increased power dissipation, and unwanted noise from cabling severely impacted system stability and efficiency [6]. To mitigate these issues, the industry has shifted towards integrating more of the control circuitry directly into the cryogenic environment. Even though integrated control circuits are designed to operate at cryogenic temperatures, their electrical characteristics, such as threshold voltage, mobility, and leakage current, can still vary significantly with temperature. These variations can impact timing accuracy and analog performance. Therefore, precise on-chip temperature monitoring remains essential to ensure stable operation and dynamic compensation in cryogenic control systems. This transition necessitates the development of circuits, including temperature sensors, that function reliably at cryogenic temperatures, typically around 4 K.

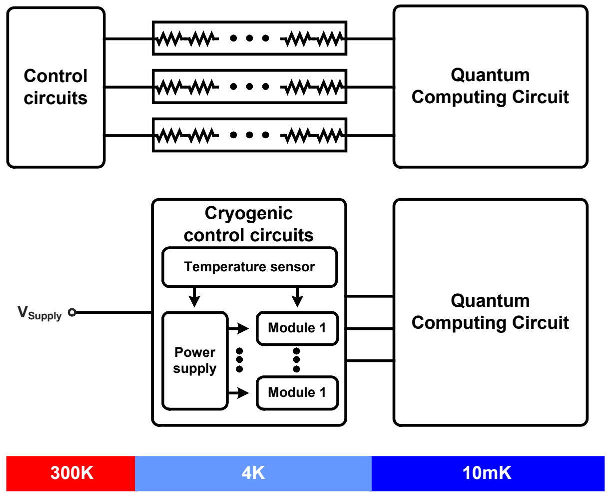

Fig. 1. Quantum computing system.

Temperature sensing within the cryogenic environment is essential for ensuring the stable operation of quantum computing systems. The electrical characteristics of MOSFETs and passive components change significantly at low temperatures, affecting circuit behavior and necessitating precise temperature monitoring. Conventional temperature sensors [1],[2],[3] based on bipolar junction transistors (BJTs) fail under such conditions due to their unreliable operation at cryogenic temperatures. Previous research has explored CMOS-based temperature sensors [1],[2],[3], but these solutions often require complex reference circuits that are unsuitable for extreme cryogenic environments.

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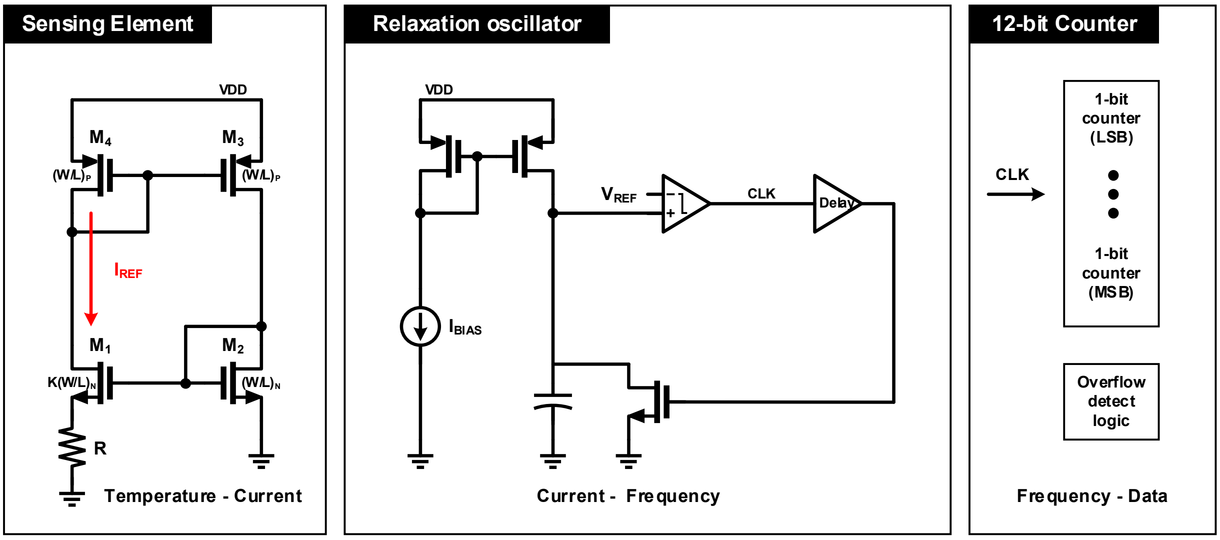

Fig. 2. Complement architecture of proposed temperature sensor.

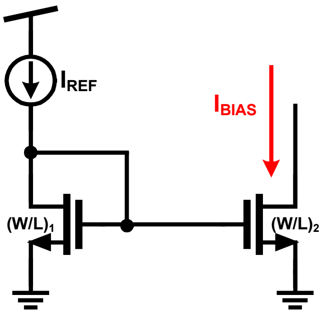

Fig. 3. Current mirror circuit.

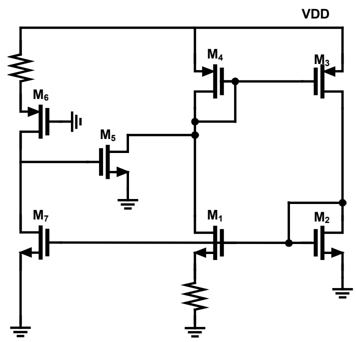

Fig. 4. Start-up circuit for beta multiplier.

This paper proposes a CMOS-based temperature sensor that employs a beta-multiplier sensing element and a relaxation oscillator for temperature-to-frequency conversion. Through MOSFET behavior analysis and simulation, we demonstrate a stable, wide-range cryogenic temperature sensor designed to support the growing demand for cryogenic-compatible control circuits.

II. PROPOSED TEMPERATURE SENSOR

The proposed temperature sensor consists of three stages: temperature-to-current conversion, current-to-frequency conversion, and frequency-to-digital signal conversion. In the temperature-to-current conversion stage, a current proportional to temperature is generated. This current can either be proportional to absolute temperature (PTAT) or complementary to absolute temperature (CTAT). Regardless of whether PTAT or CTAT is used, the temperature coefficient should remain constant. In the subsequent current-to-frequency and frequency-to-digital signal conversion stages, the objective is to design a temperature-independent circuit with a low TC, ideally close to zero, to ensure that the signal remains unaffected by temperature variations. Ultimately, this ensures that the digital signal output is directly proportional to temperature. As shown in Fig. 2, the temperature sensor is implemented using circuits optimized for each stage of conversion.

A. Temperature to Current Conversion

To convert temperature information into a digital signal, a sensing element is required to first transform temperature variations into current or voltage. In this paper, we adopt a beta-multiplier-based sensing element to convert temperature variations into a proportional current, as illustrated in Fig. 2. The sensing element is designed to achieve a linear temperature-to-current conversion within a specific range while maintaining a constant temperature coefficient. The output current of the beta multiplier is given by Equation (1):

$$I_{REF} = \frac{2}{\mu_n C_{ox}(W/L)_N} * \frac{1}{R^2} * \left(1 - \frac{1}{\sqrt{K}}\right)^2 \qquad (1)$$

Where Cox, W, L, and K are constant parameters that do not affect the TC. Therefore, the TC of I_{REF} is determined solely by the TC of the NMOS mobility μ_n and the resistor R. As expressed in Equation (2), R7 has a temperature-dependent coefficient α, allowing its value to vary proportionally with temperature.

$$R = R_{ref}[1 + \alpha(T - T_{ref})] \qquad (2)$$

When incorporating the temperature dependency, the temperature coefficient (TC) of the reference current can be approximated as Equation (3):

$$TCI_{REF} \approx -2\alpha - \frac{1.5}{T_{REF}} \qquad (3)$$

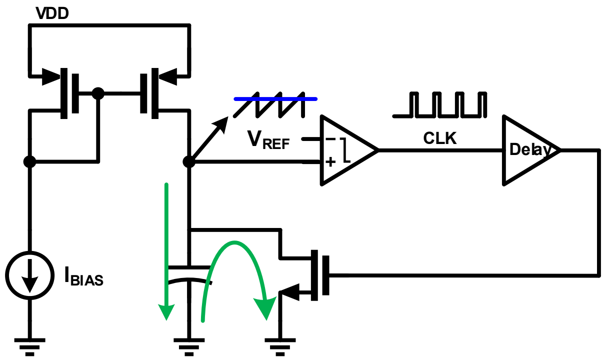

Fig. 5. Proposed relaxation oscillator.

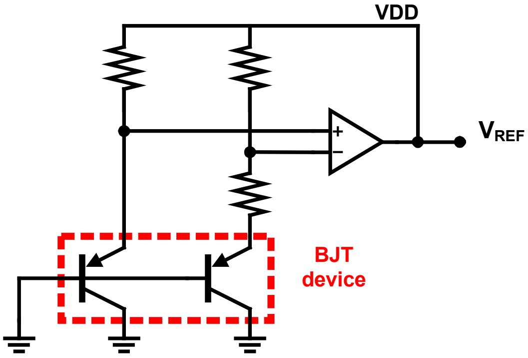

Fig. 6. Conventional bandgap reference circuit

As shown in Equation (3), the temperature coefficient of I_{REF} is primarily determined by the resistor's temperature coefficient α. When α exhibits a CTAT behavior (i.e., the resistance increases with temperature), the resulting I_{REF} shows a PTAT characteristic. In this work, this CTAT-like resistor is used in a beta-multiplier circuit to generate a PTAT current. This PTAT current is then mirrored through a current mirror circuit to bias the oscillator, as illustrated in Fig. 3. The resulting bias current, I_{BIAS}, is defined by Equation (4) :

$$I_{BIAS} = \frac{(W/L)_2}{(W/L)_1} * I_{REF} \qquad (4)$$

which does not contain the TC term except I_{REF}. Therefore, the TC of the I_{BIAS} is only affected by the TC of the I_{REF}. The generated current I_{BIAS} biases the oscillator.

However, the beta multiplier may fail to operate under certain initial conditions. If the initial conditions result in zero current flow, additional control signals are required to initiate operation. Given the limited number of interconnects available in cryogenic environments, an internal start-up circuit is necessary. In a scenario where the PMOS gate is initially high and the NMOS gate is low, no current is generated. To address this issue, a current path is established through transistor M5 (Fig. 4), ensuring the proper initialization of the gate voltages. The current path through M5 is controlled via additional transistors M6 and M7, which enable or disable the path as needed. During normal beta multiplier operation, M5 is turned off, and current continues to flow through the M6 and M7 path. To minimize leakage current, a high-resistance resistor is employed in the start-up circuit.

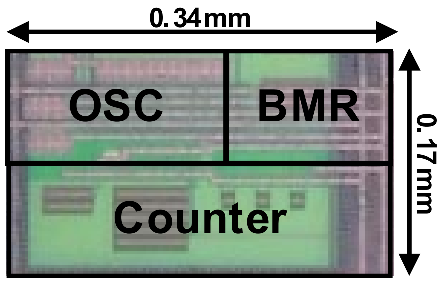

Fig. 7. Die micrograph.

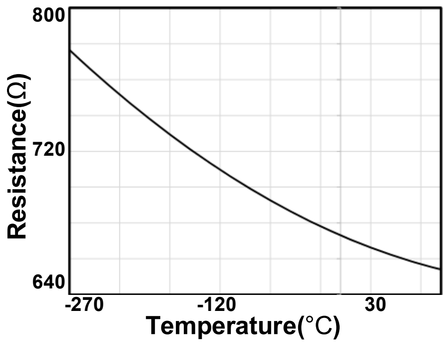

Fig. 8. TC of resistor at beta multiplier (simulation).

B. Current to Frequency Conversion

The current-to-frequency conversion in the proposed temperature sensor is performed using a relaxation Oscillator, which converts the sensed current into a frequency signal. As shown in Fig. 5, the relaxation oscillator operates based on the charging and discharging of a capacitor, which is driven by the current generated from the sensing element. The capacitor voltage exhibits a ramp waveform, where the charging and discharging rates vary according to the input current.

This ramp signal is continuously compared to a fixed external reference voltage (V_{REF}) by a comparator, which generates a periodic clock signal (CLK) when the voltage reaches a defined threshold. The frequency of this clock signal is determined by the rate of charge and discharge of the capacitor, which is controlled by the input bias current I_{IN}. Since I_{IN} increases with temperature due to its PTAT characteristic, the oscillator frequency also increases accordingly. The relationship between frequency and current is expressed as Equation (5):

$$f_{OSC} = \frac{I_{IN}}{C * \Delta V} \qquad (5)$$

where I_{IN} is the PTAT bias current, C is the capacitor value, and ΔV is the ramp peak voltage, both of which are designed to be temperature independent. In the proposed circuit, the delay introduced by the delay stage does not affect the oscillation frequency, but rather modulates the duty cycle of the output signal. The frequency is solely determined by the capacitor charging time, which depends on the PTAT bias current. Therefore, Equation (5) accurately models the oscillation frequency without needing to incorporate the delay time.

TABLE I. Comparison with previous published CMOS temperature sensors.

Parameter	This work	[7]	[2]	[3]	[4]
Process	65nm	130nm	65nm	0.16μm	65nm
Chip area (mm^2)	**0.058**	-	0.1	0.16	0.2
Sensing range(°C)	**-250 ~ 30**	-180 ~ 0	-70 ~ 125	-55 ~ 125	-40 ~ 130
Supply Voltage (V)	**1.2**	1.2 -1.3	1.2 - 1.3	1.5 - 2	1.5
Current consumption	**6.9μA**	-	8.3μA	4.6μA	0.5μA
Power Consumption	**8.28μW**	1μW	9.96μW	6.9μW	0.75μW
Based device	**CMOS**	CMOS	BJT	BJT	CMOS

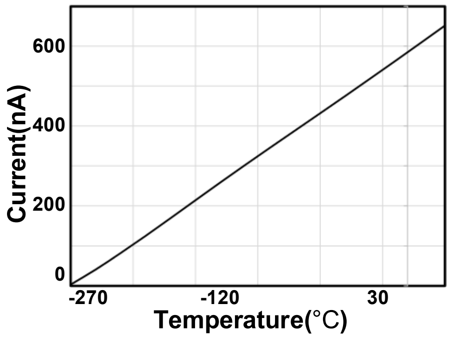

Fig. 9. Generated I_{REF} at beta multiplier (simulation).

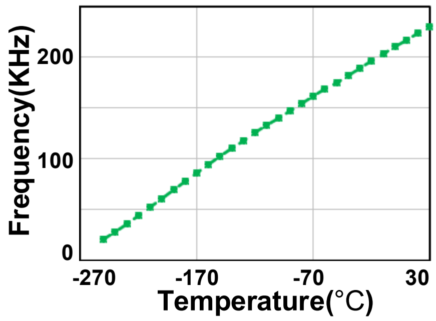

Fig. 10. Frequency-Temperature plot of relaxation oscillator (simulation).

To ensure temperature stability, both the reference voltage (V_{REF}) and the bias current used in the comparator must exhibit a zero-temperature coefficient, making them independent of temperature variations. Conventional bandgap reference circuits, which rely on bipolar junction transistor (BJT) devices, are not suitable for cryogenic operation due to the unpredictable behavior of BJTs at extremely low temperatures (Fig. 6). Instead, an MOSFET-based alternative temperature-stable reference circuit is required to maintain accurate oscillation characteristics in the cryogenic region.

The output frequency generated by the relaxation oscillator is fed into a 12-bit digital counter, which counts the number of oscillation cycles within a fixed reference time window. Since the oscillation frequency is proportional to temperature, the resulting count value provides a direct digital representation of the sensed temperature.

III. SIMULATION RESULTS

The proposed wide-range cryogenic temperature sensor was implemented using the TSMC 65nm process (Fig. 7). The core cell size of the temperature sensor, including the sensing element, relaxation oscillator, and the 12-bit on-chip digital counter, is 0.058 mm². The design was simulated over a temperature range of -250°C to 30°C (24K to 300K), covering the cryogenic region up to room temperature. Fig. 8 shows the resistance variation with temperature. Based on the curve, the resistor exhibits a TC of approximately –595ppm/°C, indicating a CTAT behavior. Using this resistor, the beta multiplier achieves a reference current I_{REF} of 3.3nA at -270°C (Fig. 9). The generated PTAT current is used to bias the current-controlled relaxation oscillator, producing a temperature-dependent frequency. The resulting frequency exhibits a temperature coefficient of 0.75 kHz/°C (Fig. 10), confirming a PTAT frequency characteristic. Table I summarizes the performance of the proposed temperature sensor and provides a comparison with previous temperature sensors.

IV. CONCLUSION

This paper was conducted after identifying the characteristics of the devices through cryogenic region simulations. Based on the analyzed device behavior, a beta-multiplier-based sensing element with a well-defined temperature coefficient was designed. The overall circuit architecture consists of a sensing element incorporating a beta multiplier and a current mirror, an oscillator controlled by bias current, and a digital counter for frequency measurement. The current generated by the sensing element, determined by the resistor characteristics and device parameters, is 3.3nA at a cryogenic temperature of -270°C. This current is used as the bias current for the oscillator via a current mirror. As the generated current increases linearly with temperature, the oscillator frequency also varies linearly with temperature. The resulting frequency is 20.6 kHz at -250°C, with a TC of 0.75 kHz/°C. The proposed temperature sensor is expected to significantly reduce interconnect complexity, enhance system stability, minimize circuit size, and improve cost efficiency in wide-temperature-range applications.

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