A CMOS On-Chip Temperature Sensor with -0.21℃/ 0.17℃ Inaccuracy from -20℃ to 100℃

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***Abstract*— An accurate, small, low-power CMOS temperature sensor for on-chip thermal monitoring is proposed. The temperature sensor utilizes the temperature characteristics of the threshold voltage of a MOS transistor to sense temperature and is quite linear over the in temperature range (-20°C, 100°C).**

The threshold-based temperature sensors were designed in the ON Semiconductor 1P6M (Single Poly, 6 Metal) 180nm process with a 1.8V supply voltage. The die area of this circuit is only 14.8μm×22.2μm. It has low power consumption of about 1.026μW at a 1% duty cycle. Measurement results show that a batch of 5 temperature sensors have a nonlinear error bounded of -0.21°C to +0.17°C with a one-point calibration and batch slope/curvature correction over the target operating temperature range (-20°C, 100°C).

Key Words: Temperature Sensor, Bias Generator, Reference Generator, Threshold Extraction

I. INTRODUCTION

In modem VLSI design, temperature monitoring has been of considerable importance for many technology nodes. With the trend continuing for more complexity, increased speed, and higher levels of integration, high-performance on-chip thermal monitoring is becoming increasingly important. On-chip thermal monitoring has also become an integral part of the power management of most integrated circuits.

Essentially, the temperature dependence of circuit or device parameter is used to build integrated temperature sensor. And the temperature information will be expressed as a current, a voltage, or as period or frequency. Two of these parameters have proven useful for generating output voltages that vary linearly with temperature. One is the thermal voltage, $V_t=kT/q$, that appears in the exponent of the diode equation which can be used to provide an output voltage that is proportional to absolute temperature (PTAT) by taking the difference between the two diode voltages, ΔV_d, when the junctions are biased with fixed-ratio currents. The other is the threshold voltage of a MOS transistor which has nearly linear temperature dependence. Circuits that express the threshold voltage at the output can also serve as temperature sensors.

Traditionally, integrated temperature monitors have been based upon the PTAT voltage generated from circuits that provide the ΔV_d but when designed in high-volume bulk CMOS processes, the ΔV_d is usually obtained from the difference in base-emitter voltage of two parasitic diode connected vertical pnp transistors. Some of the more recent ΔV_d based temperature sensors are discussed in [1] ~ [2]. However, area and power consumed by the pn-junctions are not attractive for on-chip applications and the performance of ΔV_d -based sensors appears to be seriously degraded in fine-feature processes because of degradations in the performance of the parasitic vertical pnp transistors [7].

Self-biased V_{DD}-insensitive bias generator circuits that express the threshold voltage at the output have been used recently to build threshold voltage based (V_{TH}-based) temperature sensors [3] ,[4]. These temperature sensors can be designed with very small silicon area and low power consumption. Simulation results in [3] based upon a standard temperature-dependent threshold voltage model for the inverse-Wildar temperature sensor predict 0.15°**C** accuracy with a two-point temperature calibration over a practical temperature range of [-20°**C**, 100°**C**]. In this standard model, the threshold voltage change with temperature is perfectly linear and the very small simulated nonlinearity can be attributed to circuit limitations in expressing the threshold voltage at the output due to the finite output impedance of the MOS transistors. Although the simulated temperature errors attributable to the finite output conductance are very small, model errors in the temperature-dependent threshold model due to higher-order temperature dependence of the threshold voltage are of potential concern and experimental verification is necessary to predict the effects of these errors.

In this work, theoretical and experimental results are presented for a threshold voltage based temperature sensor designed to operate over a wide temperature range using the V_{DD}-independent self-stabilized inverse-Wildar architecture. Section II is comprised of an analytical characterization of the temperature sensor along with a discussion of simulation results. Experimental results are presented in Section III. In Section IV, conclusion is made.

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II. THRESHOLD VOLTAGE AND VT BASED TEMPERATURE SENSOR

A. *Threshold Voltage Temperature Model*

The temperature dependence of the threshold voltage incorporated in the BSIM 4 model, given in (1), is nearly linear with respect to temperature [5].

$$V_{tn}(T) = V_{tn0} + (KT1 + \frac{KT1L}{L_{eff}} + KT2 \cdot V_{bseff}) \cdot (\frac{T}{T_{NOM}} - 1) \tag{1}$$

In this model, T is the absolute temperature in K. Parameters KT1, KT1L, and KT2 are constants, T_{NOM} is equal to 300K, L_{eff} is the effective length, and V_{bseff} is the effective bulk to source voltage. If the bulk terminal of the device is connected to the source, a small circuit-dependent temperature nonlinearity that could be contributed by V_{bs} vanishes. Ideally, a V_{TH}-based temperature sensor has an output voltage that is proportional to V_{TH} where the proportionality constant is not temperature dependent. Consequently, the output voltage of a V_{TH}-based sensor inherits the linear dependence on absolute temperature of (1).

However, in reality the threshold voltage is not perfect linear with temperature. Though in a different process, V_{TH} models derived in [6] show modest temperature nonlinearity and measured results show even more nonlinearity though the overall nonlinearity is still very small. Consequently, V_{TH}-based temperature sensors will also inherit the small nonlinearity inherent in V_{TH}. This nonlinearity will degrade performance of the temperature sensor if uncorrected but, if more accuracy is needed, its effects can be reduced with batch curvature calibration.

B. *V_{TH} based Temperature Sensor*

The five-transistor self-stabilized Inverse Widlar temperature sensor discussed in [3] appears in Fig. 1.

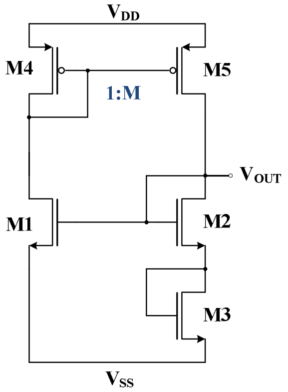

Fig. 1 Schematic of proposed temperature sensor

A start-up circuit is necessary to eliminate an undesired stable operating point but is not shown, because it does not affect the basic temperature-dependent properties of this circuit. The output V_{OUT} is ideally proportional to the n-channel threshold voltage. An analytical expression for V_{OUT}, based upon the square-law device model that "faithfully" predicts the dependence of V_{OUT} on threshold voltage is given by.

$$V_{out} = \frac{V_{tn1} \cdot (1 + \sqrt{\frac{(W/L)_2}{(W/L)_3}}) - V_{tn2} \cdot \sqrt{\frac{(W/L)_2}{M \cdot (W/L)_1}} - V_{tn3} \cdot \sqrt{\frac{(W/L)_2}{M \cdot (W/L)_1}}}{1 + \sqrt{\frac{(W/L)_2}{(W/L)_3}} - \sqrt{\frac{(W/L)_2}{M \cdot (W/L)_1}}} \tag{5}$$

M is the current mirror gain. The linear dependence on threshold voltage and the independence of supply voltage V_{DD} is apparent in this expression.

This temperature sensor has been designed in a 1P6M ONC18 CMOS process. Simulation results for the output voltage V_{OUT} are shown in Fig.2 (a) over the temperature range [-20°C, 100°C] and over the process corners that are typically designated as TT, FF and SS. This temperature sensor has a nominal sensitivity of -1.12mV/°C and is quite linear over all process corners. Fig.2 (b) shows that the maximum INL temperature error over process corners throughout the 120°C range is about 0.4°C. Due to process variations, the voltage level changes but the offset temperature error can be corrected with a single-point calibration. This will be discussed along with the measurement results in the next section.

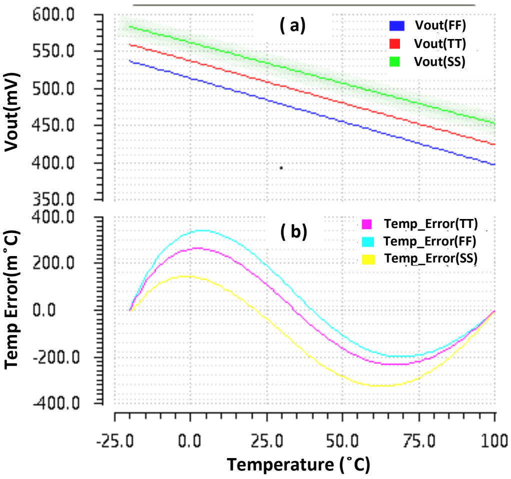

Fig. 2 Simulation Results of inverse-Widlar temperature sensor V_{OUT} and INL temperature errors over corners

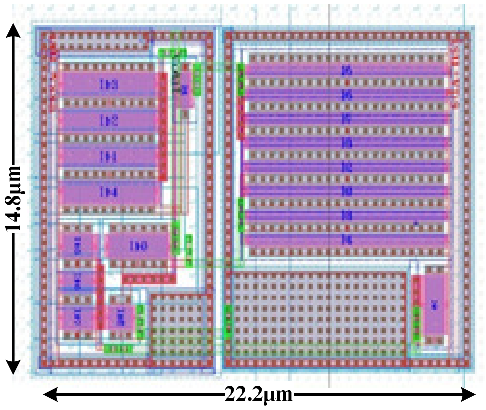

Fig. 3 The Layout of proposed circuit

The layout of the temperature sensor, exclusive of bonding pads, is shown in Fig.3. The area of the sensor is 328.56 μm^2. The nominal power consumption is 103μW with a nominal supply voltage of 1.8V.

III. MEASUREMENT RESULTS

Five temperature sensor chips were tested by making temperature measurements with a 6 digit multi-meter from -20°C to 100°C with 10°C per step using a Fluke 7103 micro-bath. Temperature in the micro-bath was measured with T100-250-18 Platinum Resistance Thermometers with a maximum error of 0.03°C.

Fig. 4 shows the measured output voltages from the five temperature sensors. Different voltage levels reflect the shifts from the nominal threshold voltage. The level shifts due to process variations can be removed with a single-point temperature calibration.

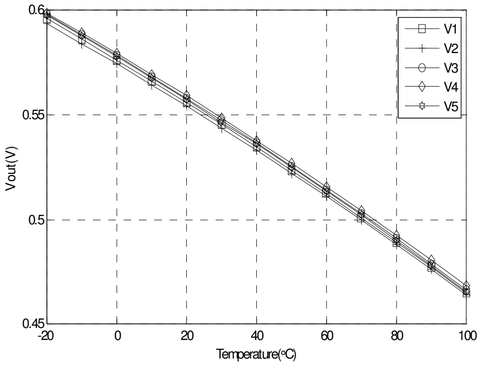

Fig. 4 V_{OUT} Measurement results of proposed temperature sensor

Fig.5 shows the measured nonlinearity using an end-point fit-line for the five devices is about ±1.9°C. Compared to the simulation results in Fig.2, the measured temperature nonlinear error is about 5 times worse than predicted. The major reason for the anticipated discrepancy between the measured and simulated results is the absence of a higher-order term in the temperature dependent vender-supplied model of the threshold voltage as discussed in Section II.

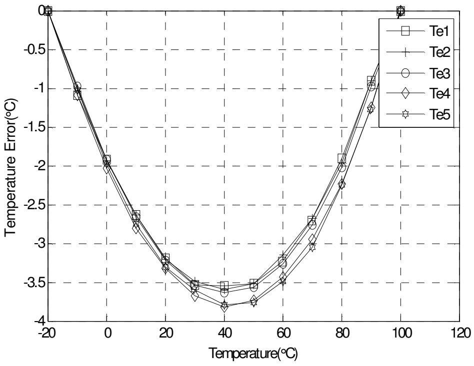

Fig. 5 INL temperature error of proposed temperature sensor

The outputs of all five chips were calibrated at a single temperature of 40°C using a simple level-shift. The single-point calibrated results are shown in Fig. 6. The calibrated temperature sensors provide good accuracy and linearity over the target operating range. The temperature error from the fit line is a common measure of the linearity performance of the sensor. The fit-line temperature error of this sensor is shown in Fig. 7. This shows an INL for the five sensors of approximately ±2.3°C.

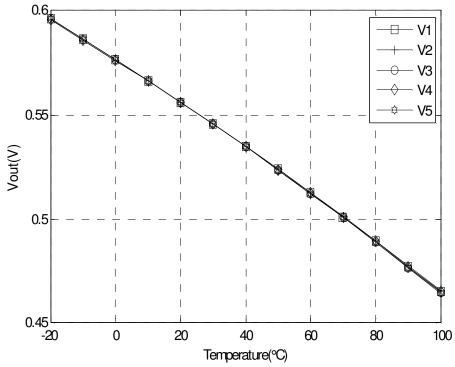

Fig. 6 V_{OUT} Measurement results of proposed temperature sensor with one point calibration

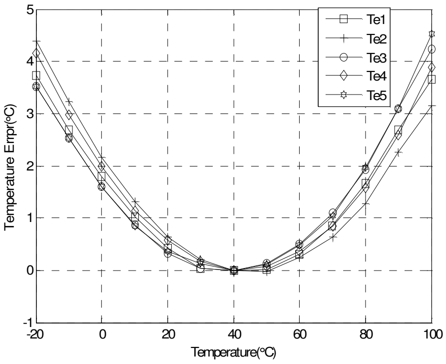

Fig. 7 V_{OUT} temperature error of proposed temperature sensor with one point and slope calibration

A batch slope/curvature error correction was also implemented. In this case, the average slope and the average curvature from all 5 chips in the batch were calculated from the measured slope and curvature and this correction was then applied to all 5 chips. The residual error is shown in Fig.8. Compared with the single-point calibration results, the accuracy is improved from [-2.25°C, 2.25°C] to [-0.21°C, 0.17°C]. This accuracy exceeds that of most published results.

To measure noise performance of the proposed temperature sensor, one of the temperature sensors was measured continuously for 12.5 hours with the test temperature being maintained at 105℃ throughout the test. In this test, samples were made of the temperature sensor output at the rate of one sample per second. The measured results are shown in Fig.9. It can be seen that the measurement noise voltage is within the [-0.2mV, 0.1mV] band which corresponds to a temperature error of [-0.16℃, 0.08℃].

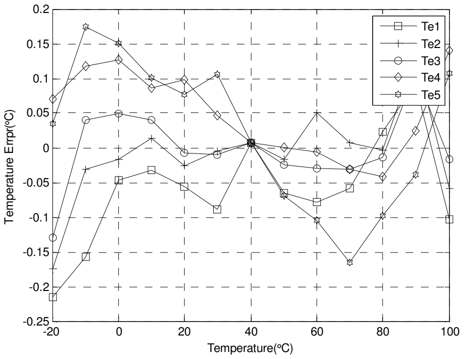

Fig. 8 V_{OUT} temperature error of proposed temperature sensor with one point and slope/curvature calibration

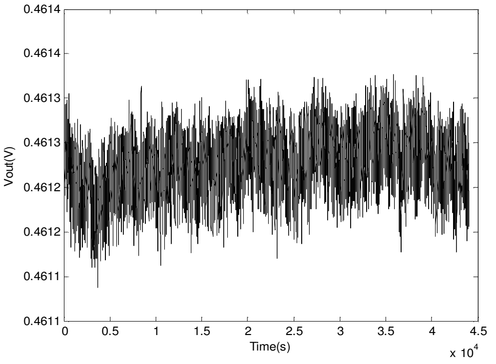

Fig. 9 V_{OUT} noise performance measurement results

The output voltage variation of the proposed temperature sensor due to power supply variations was also measured. The results are shown in the Fig.10. The V_{OUT} variation is around 0.6mV, when V_{DD} changes by 20mV. If this level of supply voltage variation is present, the 0.6V V_{OUT} variation would introduce a temperature error of about 0.53°C. The effects of supply voltage variation can be nearly eliminated by either regulating the supply voltage or by adding cascading to key devices in the temperature sensor of Fig. 1.

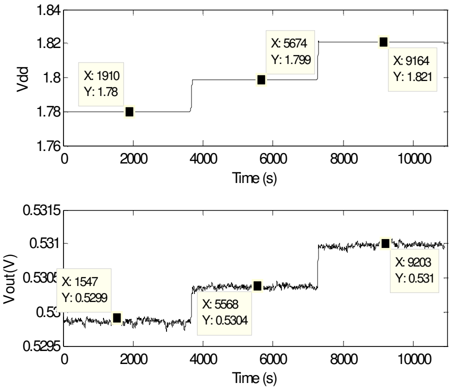

Fig.10 V_{OUT} variance due to V_{DD} changes

In the Table 1, a performance comparison between the proposed V_{TH}-based temperature sensor and some other recent works on temperature sensors is made. The circuit designed in this work has achieved better measurement accuracy with smaller area and lower power consumption.

TABLE I. COMPARISION WITH OTHER WORKS

Source	*Process*	*Power (μW)*	*Area (μm²⁾*	*Error (°C)*	*T Range*
Shor, International Solid-State Circuits Conference (ISSCC)2012[7]	32nm	3780	10800	±1.5	[40°C,80°C]
Sasaki, IEEE Transactions on Semiconductor Manufacturing, 2008[8]	90nm	25	460	1 *	[50°C,125°C]
Souri K., International Solid-State Circuits Conference (ISSCC)2012[9]	0.16μm	6.8	80000	±0.15	[-55°C,125°C]
This Work	0.18μm	1.026 1% duty cycle	328.6	0.21	[-20°C,100°C]

*. Using ideal current source to bias circuit

IV. CONCLUSION

An all-CMOS accurate temperature sensor targeting on-chip thermal control is designed. With a 1% duty cycle, the sensor consumes only 1.026μW and requires an extremely small area of 328.56μm^2. Five chips fabricated in a ONC18 1P6M process with a single-temperature calibration and batch slope/curvature correction showed a maximum absolute error of 0.21° over the temperature range [-20°C, 100°C]. This accuracy is high and accurate to achieve on-chip temperature sensing.

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