A Selection Method of Ring Oscillators for An On-chip Digital Temperature And Voltage Sensor

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***Abstract*— An on-chip digital sensor using three types of ring oscillators (ROs: Ring Oscillators) has been proposed to measure temperature and voltage of a VLSI. Each RO has inherent frequency characteristics with respect to temperature and voltage, which differ from those of the other two ROs. Measurement accuracy of the sensor depends on the combination of the ROs. This paper proposes a RO-selection method for the sensor with high accuracy. The proposed method takes particular note of temperature or voltage sensitivity as well as linearity of the RO characteristics. Evaluation experiments with SPICE simulation in 65 nm CMOS technology show that the temperature and voltage accuracies of the sensor are 2.744 °C and 3.825 mV, respectively, and the selected combination was a nearly optimal from a menu of many different ROs.**

Keywords—Temperature sensor; Voltage sensor; Ring oscillator; Fully digital design; Field test;

I. Introduction

VLSIs have been widely used in systems which require high reliability, such as automotive, medical or social infrastructure [1, 2]. Monitoring temperature and voltage inside a chip is an effective way to ensure system reliability during their operations. Incorporating dedicated sensors inside the chip, the system can avoid malfunctions due to defective failures, deteriorations, performance degradations, or malfunctions caused by abnormal temperature rise such as thermal runaway [3] or power supply voltage droop [4]. On-chip delay measurement for in-field test [5, 6] employs a method that compensates for delay variation affected by environmental temperature or voltage fluctuations to analyze delay degradation.

Various on-chip sensors have been proposed for temperature or voltage monitoring [7-14]. An analog sensor that utilizes a thermal diode is being in general use. Although such a sensor achieves high accuracy using ADCs (analog-to-digital converters), it should satisfy severe placement constraints on area size and a delicate analog power supply. Thus, it is difficult to place the sensor at arbitrary location to get hot spots' information. A CMOS temperature sensor proposed in [8] has accuracy of ± 0.1 °C in the range of - 55 to 125 °C, but it requires a stable reference voltage supply and an ADC. A temperature sensor using TDC (time-to-digital-converter) proposed in [9] has accuracy of -0.7 to 0.9 °C in the range of 0 to 120 °C. A temperature sensor [10] has accuracy of -5.1 to 3.4 °C in the range of 0 to 60 °C. It consists of digital circuits with automatic correction processing function. A temperature sensor proposed in [11] using an FPGA has accuracy of ± 3.0 °C in the range of 20 to 80 °C. A sensor [12] is an RO (ring oscillator)-based temperature and voltage sensor which measures temperature and voltage concurrently. Since the size of ROs is rather small, the sensor is allocatable at various locations inside the chip with little constraints. However, it needs a specially designed cell which is not included in a standard cell library.

The authors of [14, 15] proposed an on-chip digital sensor consisting of three types of ROs and counters. The sensor can measure temperature and voltage at the same time, and each RO consists of normal standard logic cells. Temperature and voltage are calculated by applying multiple regression analysis to the frequencies of the three ROs. In evaluation in 180 nm CMOS technology, the sensor has accuracies of 0.99 °C and 4.17 mV in the temperature range of 0 to 120 °C and the voltage range of 1.65 to 1.95 V. The paper [15] evaluated the effect of temporal and spatial fluctuations in measurement. In the evaluated chips, the temperature increase were 0.07 °C in 1 msec and 2.37 °C in 100 msec. As the temperature of hot spots is controlled very sensitively by the system, then, finding temperature increase of 2 °C in 1msec may be too late. Therefore, sensors should be placed close to the hot spots and should measure the temperature quickly. In the same way, voltage fluctuations were also addressed in the paper and it was shown that the sensor is superior to analog sensors in these points of view.

As a circuit structure of the ROs affects frequency characteristics with respect to temperature and voltage, three types of ROs are adopted for the sensor [14]. One of the important factors for high accuracy is selection of optimum RO types. For instance, as the characteristics changes remarkably in the range of high temperature or low voltage, the measurement accuracy worsens under such conditions if only one type of RO is used. Furthermore, it is known that the characteristics of the state-of-the-art CMOS is quite different from the conventional ones. For instance, the tendency of frequency on temperature reverses under some conditions. Then, in order to improve accuracy of the sensor, the precisive selection of three RO types which correspond to these conditions is required.

This paper proposes a RO selection method for the RO-based digital temperature and voltage sensor. The RO selection aims at finding a combination of three ROs from various RO menus (e.g. ROs that consist of INV, NAND, or ORNAND). The previous work [14] focuses only on a linearity of RO characteristics as a selection scale. The proposed method in this paper takes particular note of temperature or voltage sensitivity of ROs as selection scales as well as the linearity of RO characteristics, Experimental evaluation using SPICE simulation in 65 nm CMOS technology shows that the method can select the optimal combination of RO types from a menu of various compositions. The temperature and voltage accuracies of the sensor using the selected RO types are 2.744 °C and 3.825 mV, respectively. Furthermore, the paper claims the method improves accuracy when only focusing on either temperature or voltage.

This paper is organized as follows. Section 2 introduces the conventional RO-based temperature and voltage sensor and the RO selection method [14]. Section 3 addresses the novel RO selection method focused on the sensitivities to temperature and voltage. Section 4 shows evaluation experiments using SPICE simulation in 65 nm CMOS technology. Section 5 concludes the paper.

II. On-Chip Digital Temperature and Voltage Sensor

A. RO-Based Temperature and Voltage sensor[14]

A digital temperature and voltage sensor (TVS) using ring oscillators (ROs) is firstly proposed for in-field test. The sensor has the following features;

- The sensor consists of three types of ROs, which have different frequency characteristics each other with respect to temperature and voltage.
- The sensor calculates a temperature and a voltage from the measured RO frequencies by digital processing.
- As the sensor does not need any analog circuit such as an ADC, its size is small, and it can be allocated at various places on the chip.
- The measurement accuracy under process variations is guaranteed by a calibration technique.

As there are strong relations between RO frequency and temperature or voltage, ROs have inherent temperature and voltage characteristics for frequency. The sensor firstly measures the frequencies of three types of the ROs which have different characteristics. Then it calculates temperature and voltage by applying multiple regression analysis for RO frequency *F*, temperature *T*, and voltage *V*. Before measuring in field, the initial measurement of RO frequency is performed under well-controlled environment such as manufacturing test (i.e., frequency F_0 of each RO is counted under known temperature and voltage (T_0, V_0)). The chip temperature and voltage are calculated from the following equations.

$$\Delta T = a_{\Delta T} * \Delta F_1 + b_{\Delta T} * \Delta F_2 + c_{\Delta T} * \Delta F_3 + d_{\Delta T} \quad (1)$$

$$\Delta V = a_{\Delta V} * \Delta F_1 + b_{\Delta V} * \Delta F_2 + c_{\Delta V} * \Delta F_3 + d_{\Delta V} \quad (2)$$

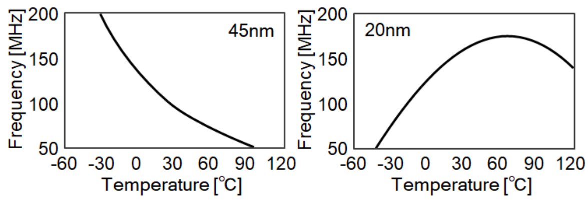
where $\Delta F_i (i = 1,2,3), \Delta T, \Delta V$ are difference from F_0, T_0 and V_0. The coefficients $a_{\Delta T}, a_{\Delta V}, b_{\Delta T}, b_{\Delta V}, c_{\Delta T}, c_{\Delta V}, d_{\Delta T}$, and $d_{\Delta V}$ are generated by multiple regression analysis using SPICE simulation results. Here, the relationships between frequency F_i, temperature *T*, and voltage *V* are got with SPICE simulation at the design phase. As the sensor has little constraints of placement and its size is small, it is possible to measure the on-chip temperature and voltage at various spots by distributing more than one sensors in the chip. Note that, although the sensor can measure power supply voltage droops as an average voltage during the oscillation period, it is difficult to measure instantaneous dynamic voltage drops.

B. Temperature and Voltage Characteristics in RO

Since the parameter values of gate delay are different depending on the circuit structure, the ROs have respective frequency characteristics for temperature and voltage [16]. Even if the same types of ROs are used, their characteristics are different depending on CMOS process technology. Figure 1 shows an example. In CMOS technology such as 45nm or more, the circuit delay increases when a temperature increases. However, the circuit delay may decrease when a temperature increases in the ultra-fine CMOS technology such as 20nm or less.

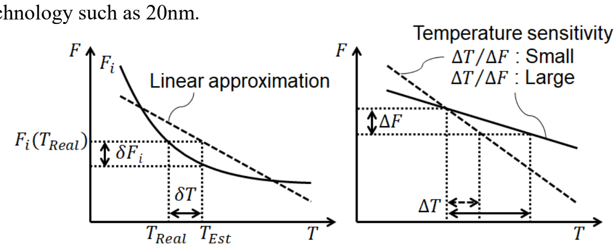
Figure 2 (a) shows the relationship between temperature and frequency, and its linear approximation. Here, we define the approximation error as a difference between an estimated value and a real value. The linearity of 'temperature for frequency' is defined as $\delta F = F(T_{Real}) - F(T_{Est})$. Where T_{Real} is the real temperature and T_{Est} is the temperature calculated by equation (1). When linearity δF is small, it means that the relationship between temperature and frequency is close to a straight line.

Figure 2(b) shows linear approximation of the relationship between temperature and frequency. The temperature sensitivity for frequency is defined as $\Delta T/\Delta F$. When $\Delta T/\Delta F$ is small, the frequency varies more sensitively for temperature variation. Furthermore, the sensitivity can have different values even though the linearity values are the same. Conversely, when the sensitivity is the same, the linearity may differ. In the same way, the voltage linearity and the voltage sensitivity are discussed.



(a) (b)

Fig. 1. Relation between CMOS technologies and RO characteristics. (a) Commonly Used CMOS Technology such as 45nm. (b) Ultra-fine CMOS technology such as 20nm.



(a) (b)

Fig. 2. (a) Relation between RO characteristics and the linear approximation. (b) Relation between the linear approximation and temperature sensitivity.

C. Simple RO Selection Focusing on Linearity of ROs[14]

A simple RO selection method that selects three ROs from various RO types is introduced in the paper [14]. The method defines an approximation error as a linearity of temperature or voltage characteristic. The linearity of temperature and voltage are calculated by SPICE simulation. Then, three types of ROs whose linearity is the smallest can be candidates. The first RO has the RO with the smallest linearity of temperature. The second RO has the smallest linearity of voltage. The third RO has small linearity of both temperature and voltage. This method is simple and easy to implement. However, since the temperature sensitivity or voltage sensitivity of RO can be different even if the linearity of ROs are the same, the combination with highest accuracy may be lost in the selection. Furthermore, the method does not consider the specific range as an evaluation scale for selecting ROs where RO frequency remarkably varies such as high temperature and low voltage. Thus, it cannot deal with a problem that measurement accuracy decrease in the specific temperature or voltage range.

III. The Proposed RO Selection Method

A. Concept of the Proposed Method

In this section, a novel RO selection method for a temperature and voltage sensor is proposed. It uses temperature sensitivity and voltage sensitivity as selection scales as well as linearity of RO characteristics. Figure 3 shows the concept of the proposed selection method. RO_i $(i = 1,2,3,\dots,N)$ are available RO types. In this section, the outline is shown, and the detail of each steps are described in following sections.

Step.1) Evaluation for temperature and voltage characteristics of each RO: In order to make evaluation scales for selecting ROs, a linearity of temperature and voltage, and a temperature and voltage sensitivity in each RO are evaluated. The evaluation is performed for each divided range because it is necessary to correspond to sudden changes of the characteristic in a specific range.

Step.2) Evaluation for combination of two ROs: The number of combinations of two ROs is ${}_NC_2$. The linearities of temperature and voltage of the two ROs are evaluated using the evaluation values of each RO calculated in Step 1. By using the worst value of the evaluation scale of each divided range, it can deal with an issue that measurement accuracy decrease in a specific temperature or voltage range.

Step.3) Evaluation for combination of three ROs: The number of combinations of two ROs is ${}_NC_3$. Combinations of three ROs are evaluated using the evaluation values of the two ROs calculated in Step 2. The combinations of the two ROs are listed in ascending order of the evaluation value. Then, to select two ROs pair from the list as a combination of three ROs. The selected three ROs (RO_X, RO_Y, RO_Z) are implemented as a temperature and voltage sensor.

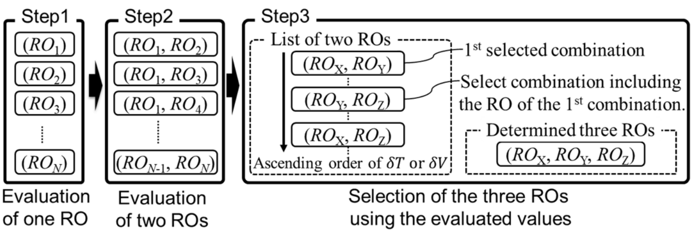


Fig. 3. Concept of the proposed RO selection method.

B. Evaluation for Temperature and Voltage Characteristics

In order to make evaluation scales for selecting ROs, linearities of temperature and voltage, a temperature sensitivity, and a voltage sensitivity of each RO are calculated. The values are evaluated for each divided temperature and voltage ranges. Figure 4(a) shows a relation between a temperature characteristic of an RO and divided temperature ranges. By using the divided range, it can correspond to sudden changes of the characteristic in a specific temperature range. A voltage range is also divided as well as temperature, both temperature and voltage range are divided as shown in Figure 4(b).

Figure 5 shows the concept of evaluation for temperature characteristics of an RO. $F_i(T)$ $(i = 1,2,3,\dots,N)$ is an RO frequency at a temperature T. N is the number of available ROs. T_1 and T_2 are temperature values at both ends of the temperature range, and $\Delta F_i(T)$ is a frequency difference between the ranges (T_1,T_2). T_j and T_{j+1} are temperature values available within the range (T_1,T_2) that depend on measurement points in SPICE simulation. Each linearity of temperature for frequency $\delta F_i(\delta T_j)$ in each measurement points of the divided range (T_1,T_2) are calculated from $\delta F_i(\delta T_j)=\delta F_i(\delta T_{j+1}) - \delta F_i(\delta T_j)$. The maximum value $Max(|\delta F_i(\delta T_j)|)$ is used the evaluation scale in the range (T_1,T_2). As well as temperature, $\Delta F_i(V)$ is a frequency difference at voltage range (V_1,V_2), and V_k and V_{k+1} are voltage values available within the range (V_1,V_2). Each linearity of voltage for frequency $\delta F_i(\delta V_j)$ in each measurement points of the range (V_1,V_2) are calculated from $\delta F_i(\delta V_j)=\delta F_i(\delta V_{j+1}) - \delta F_i(\delta V_j)$. The maximum value $Max(|\delta F_i(\delta V_j)|)$ is used the evaluation scale in the range (V_1,V_2). Thus, the linearity for both temperature and voltage $\delta F_i(T,V)$, δT and δV are expressed by the following relationship, respectively.

$$\delta F_i(T,V)=F_i(T_{j+1},V_{k+1}) - F_i(T_j,V_k) \quad (3)$$

$$\delta T=T_{j+1} - T_j \text{ for a fixed } V_k,\ \delta V=V_{k+1} - V_k \text{ for a fixed } T_j \quad (4)$$

A temperature sensitivity and a voltage sensitivity are calculated as shown in the equation (5) and (6), respectively.

$$\frac{\partial F_i}{\partial T} = \frac{F_i(T_{j+1},V_k)-F_i(T_j,V_k)}{T_{j+1}-T_j} \quad (5)$$

$$\frac{\partial F_i}{\partial V} = \frac{F_i(T_j,V_{k+1})-F_i(T_j,V_k)}{V_{k+1}-V_k} \quad (6)$$

When using the RO frequency F_i for estimation, assuming that the estimated temperature is ΔT_{Est}, the actual temperature is ΔT_{Real} , and the approximation error as the linearity of temperature is δT. The relation is $|\Delta T_{Real} - \Delta T_{Est}| \le \delta T$. As well as, assuming that the estimated voltage is ΔV_{Est}, the actual voltage is ΔV_{Real}, and the approximation error as the linearity of voltage is δV , the relation is $|\Delta V_{Real} - \Delta V_{Est}| \le \delta V$. The relation satisfying the actual temperature T and voltage V is as follows.

$$\Delta F_i(T,V) + \delta F_i = \frac{\partial F_i}{\partial T}\Delta T + \frac{\partial F_i}{\partial V}\Delta V \quad (10)$$

When the voltage is constant, the linearity of temperature is expressed as equation (7). Also, when the temperature is constant, the linearity of voltage is expressed as equation (8).

$$\delta F_i(\delta T) = \left(\frac{\partial F_i}{\partial T} \times (T_{j+1} - T_j)\right) + F_i(T_j,V_k) - F_i(T_{j+1},V_k) \quad (7)$$

$$\delta F_i(\delta V) = \left(\frac{\partial F_i}{\partial V} \times (V_{k+1} - V_k)\right) + F_i(T_j,V_k) - F_i(T_j,V_{k+1}) \quad (8)$$

The linearity for both the temperature and the voltage can be derived from the equations (7) and (8).

$$\delta F_i(\delta T)=\delta F_i(\delta V)=\left(\frac{\partial F_i}{\partial T}\times\left(T_{j+1}-T_j\right)+\frac{\partial F_i}{\partial V}\times\left(V_{k+1}-V_k\right)\right)+F_i\left(T_j,V_k\right)-F_i\left(T_{j+1},V_{k+1}\right) \qquad (9)$$

The maximum linearity in each ranges can be evaluated by calculating for all temperature and voltage measurement points in the range. The calculated maximum linearity is used as the evaluation scale of RO selection as frequency error $\delta F_i T_j V_k$ at each RO.

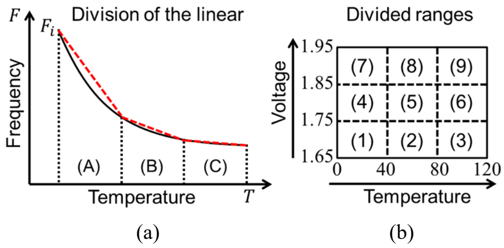


Fig. 4. (a) Temperature characteristic of RO and division of temperature range. (b) Division of both temperature and voltage ranges.

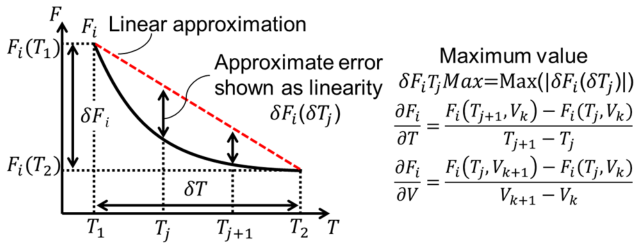


Fig. 5. Concept of characteristics evaluation for RO alone

C. Evaluation for Combinations of Two ROs

The linearity of temperature $\delta F_i(\delta T)$ and the linearity of voltage $\delta F_i(\delta V)$ as a combination of two ROs are evaluated. The relation between the two ROs frequencies F_1 and F_2 , and the temperature estimation are derived as shown in equation (11) from the equation (10) and the relation of $|\Delta T_{Real}-\Delta T_{Est}|\leq \delta T$.

$$\Delta T_{Real}=\frac{\begin{vmatrix}\Delta F_1+\delta F_1 & \frac{\partial F_1}{\partial V}\\ \Delta F_2+\delta F_2 & \frac{\partial F_2}{\partial V}\end{vmatrix}}{\begin{vmatrix}\frac{\partial f_1}{\partial T} & \frac{\partial f_1}{\partial V}\\ \frac{\partial f_2}{\partial T} & \frac{\partial f_2}{\partial V}\end{vmatrix}}=\frac{\frac{\partial F_2}{\partial V}\times(\Delta F_1+\delta F_1)-\frac{\partial F_1}{\partial V}\times(\Delta F_2+\delta F_2)}{\frac{\partial F_1}{\partial T}\times\frac{\partial F_2}{\partial V}-\frac{\partial F_1}{\partial V}\times\frac{\partial F_2}{\partial T}}$$

$$=\Delta T_{Est}+\frac{\delta F_1}{\frac{\partial F_1}{\partial T}-\frac{\partial F_1}{\partial V}\times\left(\frac{\frac{\partial F_2}{\partial T}}{\frac{\partial F_2}{\partial V}}\right)}+\frac{\delta F_2}{-\left(\frac{\frac{\partial F_1}{\partial T}}{\frac{\partial F_1}{\partial V}}\right)\times\frac{\partial F_2}{\partial V}+\frac{\partial F_2}{\partial T}} \qquad (11)$$

Thus, the linearity of temperature for two ROs $\delta T(F_1,F_2)$ corresponds to the following expression in expression (11).

$$\delta T(F_1,F_2)=\frac{\delta F_1}{\frac{\partial F_1}{\partial T}-\frac{\partial F_1}{\partial V}\times\left(\frac{\frac{\partial F_2}{\partial T}}{\frac{\partial F_2}{\partial V}}\right)}+\frac{\delta F_2}{-\left(\frac{\frac{\partial F_1}{\partial T}}{\frac{\partial F_1}{\partial V}}\right)\times\frac{\partial F_2}{\partial V}+\frac{\partial F_2}{\partial T}} \qquad (12)$$

As well as temperature, the linearity of voltage for two ROs $\delta V(F_1,F_2)$ are derived as shown equations (13) and (14).

$$\Delta V_{Real}=\frac{\begin{vmatrix}\frac{\partial F_1}{\partial T} & \Delta F_1+\delta F_1\\ \frac{\partial F_2}{\partial T} & \Delta F_2+\delta F_2\end{vmatrix}}{\begin{vmatrix}\frac{\partial F_1}{\partial T} & \frac{\partial F_1}{\partial V}\\ \frac{\partial F_2}{\partial T} & \frac{\partial F_2}{\partial V}\end{vmatrix}}=\frac{\frac{\partial F_1}{\partial T}\times(\Delta F_2+\delta F_2)-\frac{\partial F_2}{\partial T}\times(\Delta F_1+\delta F_1)}{\frac{\partial F_1}{\partial T}\times\frac{\partial F_2}{\partial V}-\frac{\partial F_1}{\partial V}\times\frac{\partial F_2}{\partial T}}$$

$$=\Delta V_{Est}+\frac{\delta F_2}{\frac{\partial F_2}{\partial V}-\frac{\partial F_2}{\partial T}\times\left(\frac{\frac{\partial F_1}{\partial V}}{\frac{\partial F_1}{\partial T}}\right)}+\frac{\delta F_1}{-\left(\frac{\frac{\partial F_2}{\partial V}}{\frac{\partial F_2}{\partial T}}\right)\times\frac{\partial F_1}{\partial T}+\frac{\partial F_1}{\partial V}} \qquad (13)$$

$$\delta V(F_1,F_2)=\frac{\delta F_2}{\frac{\partial F_2}{\partial V}-\frac{\partial F_2}{\partial T}\times\left(\frac{\frac{\partial F_1}{\partial V}}{\frac{\partial F_1}{\partial T}}\right)}+\frac{\delta F_1}{-\left(\frac{\frac{\partial F_2}{\partial V}}{\frac{\partial F_2}{\partial T}}\right)\times\frac{\partial F_1}{\partial T}+\frac{\partial F_1}{\partial V}} \qquad (14)$$

The linearities δT and δV for temperature and voltage are evaluated in each divided ranges as shown in figure 4 (b). Then, the worst value of the linearity of temperature and voltage for two ROs in each range is taken as the evaluation scale for RO selection. By using the worst value, it is possible to deal with the problem that the selected RO decreases a measurement accuracy in a specific range.

D. Evaluation for Combinations of Three ROs

To select a combination of three ROs using the combination evaluation result of the two ROs calculated in Section 3.C. The selection procedure is shown below.

Step 3.1) To select a combination of two ROs with the smallest linearity of temperature δT.

Step 3.2) To select a combination of two ROs with the smallest linearity of voltage δV. The selected ROs in this step include one of the ROs selected in Step 3.1.

Step 3. 3) To determine the selected two combinations in Step 3.1 and 3.2 as three ROs used for the sensor.

When the combination of two ROs selected in Step 3.1 is (RO_X, RO_Y), the selected combination in Step 3.2 included one of RO_X or RO_Y, and to select a combination of the smallest linearity of voltage. That is, when the selected combination in Step 3.1 is (RO_X, RO_Y), the selected combinations in Step 3.2 is (RO_X, RO?) or (RO_Y, RO?). Then, when the selected combination in Step 3.2 is (RO_X, RO_Z), a combination of three ROs used for the sensor is (RO_X, RO_Y, RO_Z).

When selecting two combinations of two ROs, it is possible to prioritize temperature estimation accuracy or voltage estimation accuracy according to the purpose of measurement. Table I shows a relation between the priority of temperature or voltage when selecting ROs, and estimation accuracy. There are the following three cases as measurement targets of the sensor.

Case 1: Target is temperature only; that is, high temperature estimation accuracy is required for the sensor. In this case, to prioritize temperature estimation at both the first combination in Step 3.1 and the second combination in Step 3.2. By only using the linearity of temperature δT in the RO selection, a combination with high temperature estimation accuracy can be selected. Although it is possible to realize high accuracy of temperature estimation, voltage estimation accuracy is low because voltage is not considered.

Case 2: Target is voltage only; that is, high voltage estimation accuracy is required. As well as temperature, to prioritize voltage estimation for both the first and second combinations. By only using the linearity of voltage δV in the RO selection, a combination with high voltage estimation accuracy can be selected. Although it is possible to realize high accuracy of voltage estimation, temperature estimation accuracy is low.

Case 3: Target is both temperature and voltage; that is, high temperature and voltage estimation accuracy are required. In this case, to prioritize temperature estimation at the first combination and to prioritize voltage estimation at the second combination. Conversely, to prioritize voltage and temperature at the first and second combinations, respectively. In both cases, it is possible to select a combination that improves accuracy of temperature and voltage estimation.

TABLE I. RELATION BETWEEN TEMPERATURE AND VOLTAGE ERRORS WHEN SELECTING TWO PAIR FROM A COMBINATIONS OF TWO ROS

Target (priority)	Selected combination of two ROs (Step.2)		Selected combination of three ROs (Step.3)	
	Comb. (A,B)	Comb. (B,C)	Temperature error	Voltage error
Temperature only	Temperature	Temperature	◎	×
Temperature & Voltage	Temperature	Voltage	○	○
Temperature & Voltage	Voltage	Temperature	○	○
Voltage only	Voltage	Voltage	×	◎

IV. EVALUATION USING SPICE SIMULATION

A. Experimental Setup

In order to evaluate the effectiveness of the proposed RO selection method, SPICE simulation in 65 nm CMOS technology is performed. Table II shows available menus of RO types. Each RO has 51 stages, the fan-out number of each stage is 1, and cell types with the minimum drive strength are used. When the number of RO types is 10, the number of combinations for three ROs are 120 (${}_{10}C_3$). A temperature range for simulation is 0 °C to 120 °C with 10 °C increment, and a voltage range is 1.06 V to 1.34 V with 0.02 V increment. The ranges of temperature and voltage are divided into three ranges, respectively. Therefore, the divided ranges used for the evaluation are nine. The relation among temperature, voltage, and RO frequency as $F(T, V)$ are obtained from the simulation. Note that, the RO stage number is set to 51 in order to let the RO frequency be at about 150 to 300 MHz. Also, in order to increase the number of ROs types for the evaluation, the ROs are not limited to an NBTI-tolerant structure as shown in previous work [14].

TABLE II. AVAILABLE RO MENUS FOR EVALUATION

Technology	65 nm CMOS technology
Cell type	INV, 2-NAND, 3-NAND 3-ORNAND, 4-ORNAND, 6-ORNAND 2-NOR, 3-NOR, 2-XNOR, 2-XOR
Combination of three ROs	${}_{10}C_3 = 120$

B. Effectiveness evaluation for the proposed procedure

First, temperature and voltage characteristics of each RO are evaluated as shown in Section 3.B. Linearities of temperature and voltage characteristics $\delta F_i(\delta T)$ and $\delta F_i(\delta V)$ are calculated using equation (7) and (8), respectively.

Next, combinations of each RO pair of two ROs are evaluated using the $\delta F_i(\delta T)$ and $\delta F_i(\delta V)$ of each RO. Table III and Table IV show the evaluated linearity of temperature and voltage in each pair of two ROs, respectively. The $\delta T(F_1, F_2)$ and $\delta V(F_1, F_2)$ are calculated using equation (12) and (14). Range (1) to (9) in Table III and Table IV are the divided temperature and voltage ranges as shown in Figure 4(b). The worst value of the $\delta T(F_1, F_2)$ and $\delta V(F_1, F_2)$ in all ranges are used as an evaluation value of the RO pair. For example, in a combination of (RO1, RO2), an evaluated value in range (7) is the worst value in each range. Range (7) is a low temperature and high voltage range. The value suggests that measurement accuracy becomes worse in the range if the RO pair is selected. By using the worst value in each range, it is possible to reveal a combination of ROs that locally decreases a measurement accuracy in a specific range.

TABLE III. LINEARITY OF TEMPERATURE FOR TWO ROS IN DIVIDED RANGE

Combination of two ROs	Temperature error [°C]									
	Range (1)	Range (2)	Range (3)	Range (4)	Range (5)	Range (6)	Range (7)	Range (8)	Range (9)	Worst
(RO1, RO2)	0.670	0.332	0.225	0.504	0.280	0.628	0.812	0.295	0.544	0.812
(RO1, RO3)	0.087	0.384	0.373	0.075	0.671	0.294	0.763	0.006	0.282	0.763
~	~	~	~	~	~	~	~	~	~	~
(RO8, RO9)	2.263	0.542	0.191	0.201	1.902	0.642	0.312	1.019	1.960	2.263
(RO9, RO10)	1.854	3.861	0.145	3.236	1.671	5.526	1.848	5.868	0.840	5.868

TABLE IV. LINEARITY OF VOLTAGE FOR TWO OF ROS IN DIVIDED RANGE

Combination of two ROs	Voltage error [mV]									
	Range (1)	Range (2)	Range (3)	Range (4)	Range (5)	Range (6)	Range (7)	Range (8)	Range (9)	Worst
(RO1, RO2)	0.116	0.266	0.463	0.246	0.379	0.477	0.220	0.188	0.574	0.574
(RO1, RO3)	0.256	0.296	0.444	0.083	0.242	0.481	0.234	0.264	0.266	0.481
~	~	~	~	~	~	~	~	~	~	~
(RO8, RO9)	0.087	0.340	0.152	0.306	0.382	0.198	0.066	0.728	1.463	1.463
(RO9, RO10)	6.541	8.654	16.055	13.551	12.909	30.033	12.090	22.551	28.194	30.033

C. Evaluation for combination of three ROs

In order to select three ROs with high measurement accuracy, combinations of three ROs are evaluated using the evaluation scales of the two ROs. Table V shows the selected three ROs by the previous method [14] and the proposed method, and temperature and voltage error as a sensor. Table V also shows a relation between the priority of temperature and voltage when selecting the ROs. The proposed method selected three ROs with a small temperature error by using temperature priority. On the other hand, three ROs with small voltage error was selected by using voltage priority. When selecting a combination with good balance between temperature and voltage, the temperature error of the selected ROs was 2.744 °C, and the voltage error was 3.825 mV. It was confirmed that it is possible to select the combination that prioritized temperature, the combination that prioritized voltage, and the combination with good balance, by the proposed method.

The temperature and voltage errors of the selected ROs using the previous method are 5.316 °C and 5.426 mV, respectively. Comparison with the previous method shows that the temperature accuracy was improved from 5.316 °C to 2.744 °C, and the voltage accuracy was also improved from 5.426 mV to 3.825 mV by the proposed method.

Table VI shows the temperature errors for each divided ranges in the combination that prioritized temperature and the combination with the good temperature and voltage balance. In the all range (i.e. range of 0 to 120 °C and 1.06 to 1.34 V), the temperature error of temperature priority and that of the good balance both temperature and voltage are 2.781 °C and 2.744 °C, respectively. The temperature error of the combination of good balance was smaller than that of the temperature priority. However, in the divided sub-range, the maximum temperature error of the combination that prioritized temperature priority is 0.690 °C, and that of good balance is 0.694 °C. The error of priority is smaller than that of good balance in the sub-range. This is because the difference in the RO characteristics for each sub-range is reflected by the proposed method. The results suggest that the ROs with high temperature accuracy can be selected by the proposed method in the case of temperature priority.

Therefore, it is confirmed that the proposed method can select a combination of three ROs that prioritizes temperature or voltage, or a combination with good balance both temperature and voltage. Then, it is confirmed that the proposed method can deal with a problem that measurement accuracy decrease in the specific temperature or voltage range.

TABLE V. TEMPERATURE AND VOLTAGE ERRORS OF THE SELECTED THREE ROS

Selection method		Selected ROs	Temperature error [°C]	Voltage error [mV]
Previous method [14]		INV, 3-NAND, 6-ORNAND	5.316 (RANK: 106)	5.426 (RANK: 88)
Proposed	Temperature priority	3-NAND, 3-ORNAND 4-ORNAND	2.781 (RANK: 27)	4.826 (RANK: 63)
	Voltage priority	INV, 3-NAND, 3-ORNAND	5.391 (RANK: 109)	3.048 (RANK: 32)
	Both	INV, 3-NAND, 4-ORNAND	2.744 (RANK: 24)	3.825 (RANK: 42)
#RANK:1 (Temperature and voltage, respectively)			2.164	1.143
Average of all combinations			4.419	3.979

TABLE VI. TEMPERATURE ERROR IN THE DIVIDED RANGES.

65nm		Temperature error [°C]							
Selection Priority		Temperature priority				Both			
		Full-range	Sub-range			Full-range	Sub-range		
		0~120°C	0~40°C	40~80°C	80~120°C	0~120°C	0~40°C	40~80°C	80~120°C
Full-range	1.06~1.34v	2.781	-	-	-	2.744	-	-	-
Sub-range	1.25~1.34v	-	0.389	0.374	0.329	-	0.397	0.331	0.338
	1.15~1.25v	-	0.509	0.392	0.317	-	0.602	0.460	0.309
	1.06~1.15v	-	0.690	0.601	0.492	-	0.694	0.441	0.527

V. CONCLUSIONS

This paper proposed a RO selection method for improving measurement accuracy in a digital temperature and voltage sensor using three types of ROs. The proposed method focuses on frequency characteristic of ROs taking particular note of temperature sensitivity and voltage sensitivity as well as linearity. The method treats temperature and voltage in three ranges respectively, where RO characteristics are quite different. With simulation evaluation using 65 nm CMOS technology, it is confirmed that the selected three ROs improve measurement accuracy. Temperature and voltage measurement accuracies were improved from 5.316 °C to 2.744 °C and 5.426 mV to 3.825 mV compared with the previous method, respectively. Future works include an extension of the method to improve accuracy at the specific temperature or voltage range.

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