On the effects of real time and contiguous measurement with a digital temperature and voltage sensor

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***Abstract*— The proposed digital sensor measures both temperature and voltage simultaneously in field. The sensor is ring oscillator (RO)-based and its design is fully digital. Its measurement time is shorter than the conventional analog sensors' and it can be placed at any place such as the boundary of a CPU core, GPU core, or Memory. This paper investigates the accuracy of the sensor derived from reduction of temporal and spatial variations. The variations are evaluated by the measurement of a fabricated test chip. When the measurement time is long like the analog sensors, the variations during measurement has a great influence on sensor' accuracy. The comprehensive evaluations show that the total measurement error is smaller than the analog sensors' and it implies the importance of real time and contiguous measurement.**

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

I. Introduction

Increasing system complexity and structural shrinking in semiconductor fabrication process make it harder and harder to achieve high reliability of VLSI systems. It is an important issue to guarantee high reliability during system operation [1, 2], especially for safety-related systems such as automobiles or social infrastructure systems. Because an abnormal temperature increase such as thermal runaway or excessive supply voltage drop often causes system failures or performance degradation, monitoring the on-chip temperature or voltage is effective to prevent them [3, 4]. Some systems require a long-life time in various environments where the temperature and supply voltage are not well controlled. Avoidance of delay-related failures caused by aging is an important issue of state-of-the-art VLSI systems. A method of an on-chip delay measurement cancelling a delay variation due to the temperature and voltage variation was proposed in [5]. Aging-induced delay degradation in field was discussed in [6].

There are a lot of researches regarding on-chip sensors to measure temperature and/or voltage [7-13]. The most popular sensor for LSIs is a temperature sensor using a bipolar transistor or a thermal diode. Although the sensor has an advantage of high accuracy, it imposes various restrictions on their design and measurement. For example, while a CMOS temperature sensor using the substrate bipolar transistor [8] has an error of ±1 °C in the range of −40 °C to 120 °C, it needs a constant reference voltage and an analog-to-digital converter (ADC). A time-to-digital-converter (TDC) based temperature sensor [9] has an error of -0.7 °C to +0.9 °C in the range of 0 °C to 120°C. However, at most one sensor with an analog circuit can be embedded on the chip, because the sensor size is large and they have strict physical constraints in terms of sensor location. As an alternative to the analog sensors, a ring-oscillator (RO)-based digital sensor has been proposed, which can measure not only the temperature but also the voltage concurrently [10]. Note that, in this paper, a sensor using an analog circuit such as ADC is called "an analog sensor", and a sensor which consists of only digital circuits is called "a digital sensor". In general, the accuracy of the analog sensors are high, but its size is large and it has strict physical constraints. On the other hand, although the digital sensor has lower accuracy than the analog sensors, it is smaller and its power consumption is lower. In addition, as the restriction on sensor location is small, more sensors can be embedded in the chip. However, since the sensor in [10] requires special cells which are not generally included in standard cell libraries, they must be designed additionally.

The authors of [12, 13] have proposed a ring oscillator (RO)-based aging-tolerant temperature and voltage sensor, which is suitable for field test, on-line test, hot spot monitoring and many other applications. According to circuit simulation in 180 nm CMOS technology, the sensor achieves an error of 0.99 °C and 4.17 mV in the range of 0 °C to 120 °C, and 1.65 V to 1.95 V. Since design of the sensor is fully digital, it is easy to implement, i.e., the sensor circuit consists of logic gates in a standard cell library without any special cell. Therefore, the digital sensor can be placed at various locations including hot spots of the chip.

Temperature and voltage sensors are sometimes utilized to optimize circuit performance [4]. For instance, embedding the sensor in a multi-core LSI makes it possible to apply dynamic performance optimization by the power management and DVFS (Dynamic Voltage Frequency Scaling) for the cores. In this application, when measurement time is long, a temporal variation during measurement may invalidate the measured value. Because the chip temperature can change so quickly, the measured temperature and the temperature when reflecting the measured result will be quite different. Especially, if a thermal runaway occurs in a system, the temperature rises rapidly in a short time. Then, it may cause a system failure before system control is performed to reduce power by lowering the operating frequency. In addition, a spatial variation may cause a temperature difference due to the gap between required measuring target position and the actual sensor position. If the temperature and voltage are not monitored in the vicinity of the hot spot or the target position, the measured values are not reliable. Therefore, when using the sensor, it is necessary to take into account its resolution of measurement time and granularity of measurement location as well as its accuracy.

Then, the analog sensors and the digital sensors have different characteristics, and their measurement errors should be evaluated from this point.

This paper investigates accuracy of the digital sensor [12, 13] which is derived by reducing temporal and spatial on-chip variations in temperature and voltage measurement. In order to make sure the effectiveness of real time and contiguous measurement with the digital sensor, the temperature and voltage variations are evaluated using a digital temperature and voltage sensor on a fabricated test chip with 180 nm CMOS technology. Experimental results on temporal variation show 2.73 °C increase and 7.16 mV decrease in a short time of 100 ms on a single chip. It also showed large deviations of 0.03[℃/μm] and 0.17[mV/μm]. By such a comprehensive evaluation, it is confirmed that the total measurement error of the digital sensor is smaller than that of the analog sensors.

This paper is organized as follows: Section 2 describes temporal and spatial variations in on-chip temperature and voltage. Section 3 describes the procedure for evaluation with a test chip. Section 4 shows results of the test chip evaluation. Section 5 concludes this paper.

II. Temporal and Spatial Variation in On-Chip Temperature and Voltage

A. On-Chip Temperature And Voltage Variations

In order to discuss temporal and spatial variations of temperature and voltage, this section discusses errors including temporal and spatial variations. Figure 1(a) and Figure 1(b) show a temporal variation due to a measurement time and a spatial variation due to sensor location, respectively. Suppose that *sensor_A* is an analog sensor which needs a long measurement time and cannot be placed near the hot spot and that *sensor_B* is a digital sensor which has a short measurement time and can be placed near the hot spot. $T(t)$ is a temperature at time t. Let t_A and t_B be measurement time of *sensor_A* and *sensor_B*, respectively. ε_{time} denotes an error caused by temporal variation. Since the temperature changes during measurement, the temperature just before starting the measurement is different from the temperature just after finishing the measurement. Similarly, $\varepsilon_{location}$ denotes an error by a spatial variation based on the distance between the target location and the sensor location. When an error of a sensor itself which corresponds to accuracy of the sensor is denoted as ε_{sensor}, total error ε_{total} is calculated by the following equation:

$$\varepsilon_{total} = \varepsilon_{sensor} + \varepsilon_{time} + \varepsilon_{location} \qquad (1)$$

Let T_A and T_B be temperatures at intermediate time of the measurement time $t_A/2$ and $t_B/2$, respectively. $t_{feedback}$ is a required time to reflect the measured values to the system control. $\varepsilon_{time}(A)$ and $\varepsilon_{time}(B)$ are errors due to the temporal variations at each sensor, the $\varepsilon_{time}(A)$ is a difference between a temperature $T(t_A + t_{feedback})$ at the time to reflect the measured result $(t_A + t_{feedback})$ and a temperature $T(t_A/2)$ at a time of the measurement by the sensor. Thus, $\varepsilon_{time}(A)$ is derived by the following equation.

$$\varepsilon_{time}(\mathrm{A}) = T(t_A + t_{feedback}) - T(t_A/2) \qquad (2)$$

$\varepsilon_{location}(A)$ and $\varepsilon_{location}(B)$ are errors due to the spatial variations at each sensor. When the measurement time is long, error $\varepsilon_{time}(A)$ is increased due to a temporal variation, because a chip temperature and voltage might be changed rapidly. Furthermore, when the sensor cannot be placed near the target location, error $\varepsilon_{location}(A)$ is increased due to a spatial variation, because a distance between the sensor and the target location is large. Therefore, $\varepsilon_{total}(A)$ is determined by not only $\varepsilon_{sensor}(A)$ but also $\varepsilon_{time}(A)$ and $\varepsilon_{location}(A)$, as shown in equation (1). Temporal and spatial variations with respect to voltage are derived as well as the temperature. Note that; since heat of hot-spot is transmitted most quickly to the nearest sensor, a temporal variation of its location is responded more sensitively than that of other sensor. Thus, the temporal and spatial errors are not independent, and there are correlations among ε_{sensor}, ε_{time}, and $\varepsilon_{location}$. However, influence of the correlations would be negligibly small. Therefore, this paper assumes that ε_{sensor}, ε_{time}, and $\varepsilon_{location}$ are independent for simplicity of discussion.

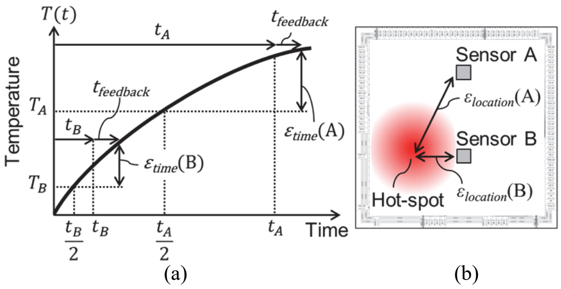


Fig. 1. Temporal and spatial variations in on-chip temperature. (a) Temporal temperature variation (b) Spatial temperature variation.

B. Analog And Digital Sensor

Table I shows comparisons of the digital sensor [12, 13] with general analog sensors with respect to the errors. ε_{sensor} of analog sensors is smaller than that of the digital sensor. On the other hand, $\varepsilon_{location}$ of analog sensors is larger than that of the digital sensor because the analog sensors may not be placed near the target location. Since a measurement time of the analog sensor is longer than that of the digital sensor (e.g., a measurement time of an analog sensor [8] is 100 ms), ε_{time} of analog sensors is larger than that of the digital sensor. Thus, when evaluating the accuracy of sensors, it is needed to take the influence of the measurement time and location of the sensors into consideration. This paper experimentally evaluates total error ε_{total} by comparing the digital sensor in a fabricated chip with a virtual analog sensor.

TABLE I. Relation Between Accuracy And Sensor Type

Type	Error of sensor itself (ε_{sensor})	Impact on temporal variation (ε_{time})	Impact on spatial variation ($\varepsilon_{location}$)	Total error at the time of sensor use (ε_{total})
Analog	Small	Large	Large	?
Digital	Large	Small	Small	?

C. Measurement of Temporal And Spatial Variation

An error ε_{sensor} and a measurement time t_{sensor} are determined from sensors. $\varepsilon_{location}$ can be computed by creating a temperature map and a power map after layout design. $t_{feedback}$ is determined from a requirement of target applications such as a power management or DVFS. Though it is difficult to compute ε_{time} including t_{sensor} and $t_{feedback}$ by simulation at the design phase, ε_{time} can be observed by a sensor with high resolution with regard to measurement time. Thus, by using the error information, a total measurement error ε_{total} can be measured.

III. Evaluation with a Test Chip

A. Overview of Evaluation

In order to evaluate the influence of a measurement time and location upon errors of sensors, a measurement for a temporal and spatial variation of an on-chip temperature and voltage is performed using a fabricated test chip with 180 nm CMOS technology, in which a digital temperature and voltage sensor is embedded. The temporal variation of the temperature and voltage is observed by repeating the measurement. The spatial variation of the temperature and voltage is observed by using sensors that are disposed at a plurality of positions in the chip.

B. Temperature and Voltage Sensor Using Ring-Oscillators[13]

The authors of [13] have proposed a RO-based temperature and voltage sensor which is a digital sensor, and the sensor is used for evaluation. The sensor has the following features.

- The sensor consists of three types of RO, which have different frequency characteristics each other with respect to a temperature and a voltage.
- The sensor calculates temperature and voltage from RO frequencies with fully digital processing.
- Because the sensor does not require an analog circuit such as an ADC and sensor size is small, the sensor can be placed at various locations in a chip.
- The sensor can be guaranteed its measurement accuracy by using calibration technique even if a process variation is included.
- Because of its aging-tolerant structure, it can be tolerable in a long-term field use.

In general, there are relations between the RO frequency and the temperature, and between the RO frequency and the voltage, the RO has an individual temperature and voltage characteristics for the RO frequency. The sensor can calculate on-chip temperature and voltage from the frequencies of three types of the ROs with different temperature and voltage characteristics each other, by applying multiple regression analysis for RO frequency F, temperature T, and voltage V.

Before measuring temperature and voltage of the chip, initial measurement of RO frequency is done under well-controlled environment in manufacturing test, i.e., the frequency F_0 of each RO is counted under the known temperature and voltage (T_0, V_0) at the initial measurement. Using difference between F_0 and a frequency F measured at unknown temperature and voltage, the chip temperature and voltage can be calculated from the amount of the frequency variations ΔF by the temperature and voltage variation during system works. Furthermore, since a frequency of a RO is influenced of process variation in a field, an error occurs in a calculation result. In order to deal with the influence of process variation, the initial measurement is useful as calibration that corrects a difference between the measured frequencies and typical frequencies by comparing these frequencies at the initial measurement. By correcting the influence of the process variation, it is possible to measure the on-chip temperature and voltage from RO frequencies even if the process variation is included. By correcting the influence of the process variation, the on-chip temperature and voltage can be measured from the RO frequencies and an accuracy of its measurement can be guaranteed even if the process variation is included.

C. Test Chip for Experiment

Figure 2 shows architecture of the digital temperature and voltage sensor (TVS) [13]. The TVS consists of three pairs of ROs and counter. Each RO counter counts its frequency during the oscillation mode and oscillation stops after a lapse of a specified time. Then, temperature and voltage are calculated from the RO frequencies according to a prepared calculation equation, respectively.

Figure 3 shows a test chip with 180 nm CMOS technology. The test chip is composed of the following parts.

- *TVS*: three pairs of RO and counter.
- *TVS_controller*: a controller of the TVS.
- *Heating_Circuit*: four heating circuits that consist of 1000 ROs with 9 stage of inverter. The percentage of oscillating ROs is controllable and hence various chip temperatures can be realized by self-heating effects of the oscillating ROs.
- *Heating_Citcuit_Controller*: a controller of the heating circuits.

RO1 of the TVS has 51 stages of 2NAND with one fan-out. RO2 has 19 stages of 4ORNAND with four fan-outs. RO3 has 21 stages of 2NAND with seven fan-outs. Different characteristics for temperature and voltage can be derived by changing the numbers of fan-outs and gate types. The area of the TVS is 0.027 mm^2 with 180 nm CMOS technology. Further details of the TVS are given in [13].

Six TVSs are embedded in the test chip. Four TVSs are placed at the chip boundary, and the remaining two TVSs are placed near the center of the chip. Four heating circuits are placed between two TVSs. the chip temperature is controlled by the ratio of oscillating ROs in heating circuits, e.g., 10 % means that 100 out of 1000 ROs in a heating circuit are running and the remaining 900 ROs of the heating circuit stop oscillation. In evaluation to investigate the influence on the distance from the sensor to target location, the four heating circuits are assumed as one DUT. The embedded TVSs measures the temperature and voltage variation caused by self-heating effects or voltage-drop by the heating circuits. The test chip is packed in QFP which has only two pair of power supply (VDD/VSS) pins at the top and the bottom of the chip as shown in Figure 3.

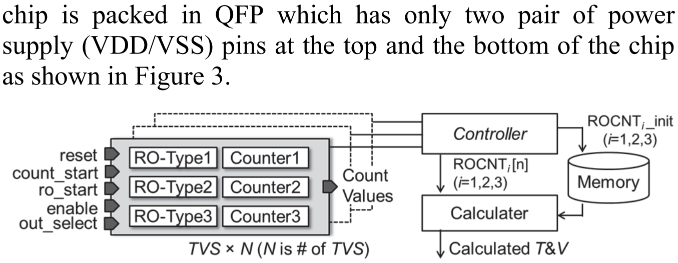
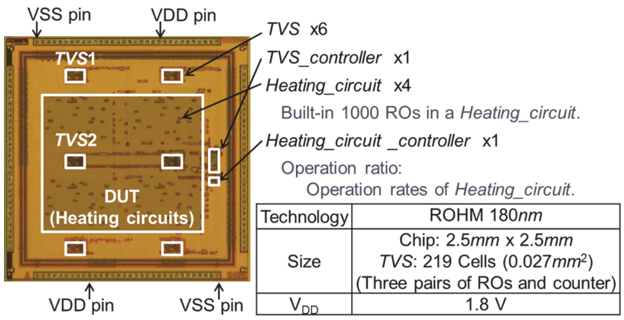


Fig. 2. TVS Architecture



Technology	ROHM 180*nm*
Size	Chip: 2.5*mm* x 2.5*mm* *TVS*: 219 Cells (0.027mm^2) (Three pairs of ROs and counter)
V_{DD}	1.8 V

Fig. 3. Test Chip Architecture

D. Experiment Setup

Figure 4 shows an experiment setup. In order to know the actual temperature and voltage of the chip, a thermostatic bath (SU-241, Espec, Corp.) and a tester (CX1000D, Cloud Testing Service, Inc.) were used. This experiment assumed that the internal and external temperatures of the chip are the same by putting the chip in the thermostatic bath for a sufficient period to stabilize the temperature of the chip. That is, the initial temperature of the chip is the same as a temperature set to the thermostatic bath. From preliminary experiments, it has been confirmed that the chip temperature stabilizes in 10 minutes after the temperature in the thermostatic bath has reached the set temperature. The tester controls supply voltage and chip operation including pattern generation and application. Calculation of temperature and voltage from the measured RO frequencies is performed on a PC connected to the tester.

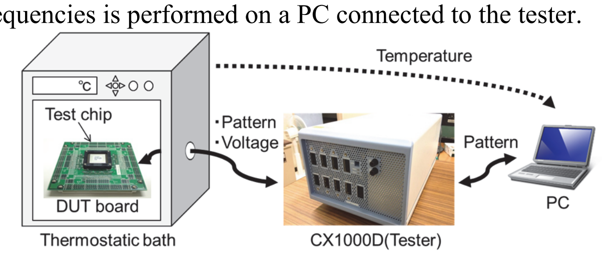


Fig. 4. Experiment Setup

E. Experiment Procedure

In order to observe temporal and spatial variations in the chip, temperature and voltage measurement using the TVSs is performed repeatedly. Figure 5 shows a rough timing chart for measurement. The DUT and the TVS start at the same time. While the DUT keeps running, the chip continues to heat up by self-heating effects. As a result, the chip temperature goes up and the chip voltage goes down. The change of temperature and voltage can be observed by the TVSs. In this experiment, the RO oscillation time for the measurement is set to 328 µs. Then, in order to measure a temporal variation, the measurement by the sensor is performed for 100 ms at 1 ms intervals. Note that a self-heating effect due to the oscillation of the TVS itself is negligible, because a non-oscillation time of the TVS is longer than the oscillation time and the number of stages of ROs in TVSs is more than 18. The experiment assumes that an operating ratio of the DUT is 10 % in normal operation, and that the circuit falls into a state of thermal runaway when the operation ratio of the DUT is 100 %.

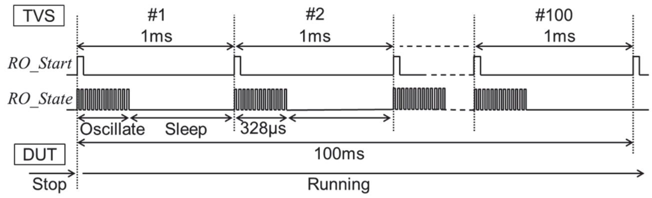


Fig. 5. Rough Timing Chart

IV. Evaluation Results

A. Temperature and Voltage at Initial Measurement

As described in Section 3B, initial measurement of RO frequency is first done under well-controlled environment, and the difference between the initial frequency and a frequency under unknown temperature and voltage is used for calculation of temperature and voltage. The initial measurement plays a role as calibration to relax an influence of process variation. A frequency of each RO in TVSs is counted under a condition that the temperature of the thermostat bath is 60 °C, the supply voltage is 1.8V, and the operating ratio of the DUT is 0 %. Then, temperature and voltage are calculated by the TVSs, while examining several ratios of oscillating ROs in the heating circuits.

B. Observation of Voltage Drop

Figure 6 and Figure 7 show the measured temperature and voltage in case of the operating ratios of the DUT are 10 % and 100 %. TVS1 is one of the sensors which are placed at the chip boundary, and TVS2 is one of the sensors which are placed near the center of the chip. It was observed that an instantaneous voltage drop immediately occurred in the first 2 ms just after starting the operation of the DUT. The instantaneous voltage drop is caused by sudden increase of current in DUT. During counting RO frequencies in 328µs of the first and the second oscillation modes, voltage is changing (falling down). Because the calculation equation could not take such a sudden voltage drop during oscillation into consideration, the accuracy of the temperature computed together with the voltage is not high for the first 2 ms.

C. Temporal Temperature and Voltage Variation

Figure 8 and Figure 9 show the differences of temperature and voltage from the measured values at the first 2 ms, respectively. Regardless of the operating ratio of the DUT or the sensor locations, the TVSs observed that it continues to heat up by self-heating effects of the DUT and a gradual voltage drop occurs which is not the instantaneous voltage drop. Table II shows temporal variations in temperature and voltage. For TVS1 in 100% operating ratio, the temperature was increased 0.07 °C from 2 ms to 3 ms, the temperature was increased 2.73 °C in 100 ms. Then, the voltage was reduced 0.7 mV in 1 ms, and reduced 7.16 mV in 100 ms. ε_{time} of temperature and voltage can be computed from the relations between the measured values and times using the equation (2). For example, when a measurement time of the sensor t_{sensor} is 98 ms and $t_{feedback}$ is 1 ms, ε_{time} of temperature and voltage are 0.59 °C and 0.45 mV, respectively. Note that the value of t_{sensor} corresponds to t_A in equation (2). When a measurement time of the sensor t_{sensor} is 1 ms and $t_{feedback}$ is 1 ms, ε_{time}

of temperature and voltage are 0.14 °C and 0.34 mV, respectively. Therefore, in order to reduce the error ε_{time} of difference between an actual value and a measured value that occur with the passage of time, it is important to measure in a short time.

D. Spatial Temperature and Voltage Variation

From Table II it is confirmed that there is a large difference of measured temperature due to the sensor location. For example, a difference of measured temperature between TVS1 and TVS2 is 15.33 °C at 100 ms in 100 % operating ratio. In this case, since TVS2 is placed at a shorter distance to DUT (the center of DUT) than TVS1, the measured temperature by TVS2 can estimate the temperature of the center of DUT more accurately than that by TVS1. This result implies that a sensor should be located as close as possible to the target location.

It is also confirmed that a measured voltage difference between TVS1 and TVS2 is 88.62 mV. Since the chip has only two pairs of VDD and VSS pins at the chip boundary, the voltage near the center of the chip is not stabilized quickly compared with the voltage at the chip boundary. Thus, a voltage drop of TVS2 is larger than TVS1. Furthermore, Table III shows a relation between the sensor location and the measured voltage at 100 ms in 100 % operation ration. A relation between the temperature and the distance from the center of DUT to the sensor is 0.03 [°C/μm], and a relation between the voltage and the distance is 0.17 [mV/μm]. Thus, in order to measure accurately an actual temperature and voltage of the target location, it is important to place a sensor near a target location and to reduce the error $\varepsilon_{location}$ of difference between those locations.

E. Effectiveness of the Digital Sensor

A measurement time of an analog sensor reported in [8] is 100 ms. In general, when a target location is a digital circuit like a CPU core, an analog sensor cannot be placed close to hot-spots of the CPU core and is placed outside the circuit. In order to evaluate measurement errors between a virtual analog sensor and the digital sensor [12, 13], the following assumptions are made:

- The target location is the center of DUT.
- Measurement results of TVS1, which is placed at the boundary of the chip, at 100 ms are obtained from an analog sensor.
- Measurement results of TVS2, which is placed near the target location, at 1 ms are obtained from the digital sensor.
- The size of error $\varepsilon_{location}$ is proportional to the distance from the sensor to the target location. Note that this assumption is valid if a heat source of the chip exists at only the target location. Therefore, although it is meaningful to look into the difference of measured values depending on the sensor location, the values of $\varepsilon_{location}$ themselves are the actual errors.

Table IV summarizes measurement errors defined in Section 2. As a temperature error and a voltage error of the analog sensor itself (ε_{sensor}), accuracy of the analog thermal sensor [8] and the voltage sensor [14] are referred, respectively. $\varepsilon_{location}$ is computed from the relations among the measured temperature, the measured voltage, and the distance between the target location and each sensor. ε_{time} is computed from measurement results of TVS1 and TSV2 that are assumed to be the analog sensor and the digital sensor. $\varepsilon_{location}$ is computed from spatial gradients of temperature and voltage such as 0.03 [°C/μm] or 0.17 [mV/μm]. The gradients are derived from the distance from the center of DUT to those sensors and the measured values. ε_{total} of the analog sensor for temperature and voltage are 31.23 °C and 173.51 mV, respectively. Similarly, ε_{total} of the digital sensors are 15.98 °C and 88.66 mV, respectively. In comprehensive evaluation including the influence of the measurement time and the sensor location, it was confirmed that the errors of the digital sensor could become smaller than that of the analog sensor. Furthermore, regardless of the types of the sensor, it was confirmed that the error caused by the sensor location is larger than the error caused by the measurement time. Therefore, high resolution of measurement time and fine granularity of measurement locations are required for accurate sensors. When using the sensor to applications such as the system control or dynamic performance optimization, it would be effective to use the digital sensor which has short time measurement and flexibility of the sensor location.

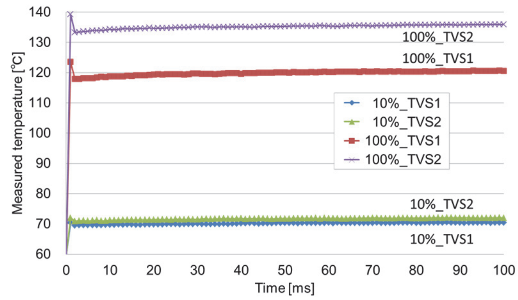


Fig. 6. Measurement of temperature by TVS

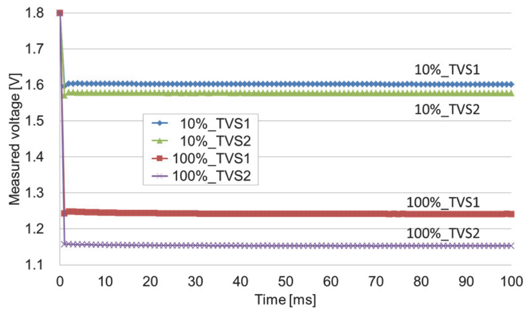


Fig. 7. Measurement of voltage by TVS

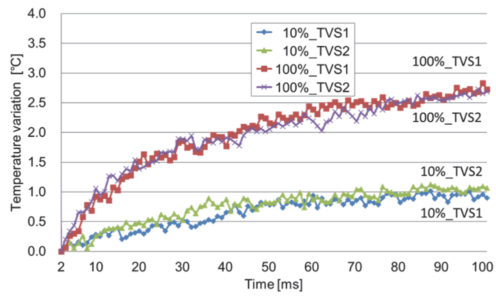


Fig. 8. Differences of temperature from the measured values at 2 ms

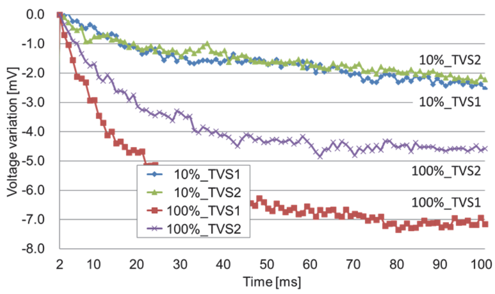


Fig. 9. Differences of voltage from the measured values at 2 ms

TABLE II. TEMPORAL TEMPERATURE AND VOLTAGE VARIATION

	Measured temperature [°C]				Measured voltage [mV]			
Operating ratio	10%		100%		10%		100%	
Time [ms]	TVS1	TVS2	TVS1	TVS2	TVS1	TVS2	TVS1	TVS2
2	69.46	70.93	117.85	133.22	1603.68	1578.92	1248.51	1157.30
3	69.52	71.01	117.92	133.42	1603.63	1578.83	1247.81	1156.96
10	69.74	71.19	118.78	134.28	1603.24	1578.17	1245.58	1155.61
20	69.80	71.42	119.37	134.61	1602.50	1577.80	1243.80	1154.16
30	69.99	71.46	119.71	135.11	1602.23	1577.49	1242.92	1153.94
40	70.12	71.81	119.62	135.13	1602.10	1577.69	1241.78	1153.20
50	70.24	71.75	120.01	135.28	1601.96	1577.25	1241.88	1152.95
60	70.40	71.80	120.24	135.41	1602.05	1577.19	1241.82	1152.83
70	70.32	71.97	120.37	135.41	1601.66	1577.16	1241.71	1152.49
80	70.28	71.89	120.27	135.72	1601.36	1576.96	1241.16	1152.77
90	70.40	71.97	120.41	135.77	1601.36	1576.87	1241.24	1152.70
100	70.36	72.00	120.58	135.91	1601.15	1576.70	1241.35	1152.73

TABLE III. SPATIAL TEMPERATURE AND VOLTAGE VARIATION

	Distance from the chip center [μm]	Measured temperature [°C]	Measured voltage [mV]
TVS1	1018	120.58	1241.35
TVS2	495	135.91	1152.73
Difference	523	15.33 (0.03[°C/μm])	88.62 (0.17[mV/μm])

TABLE IV. RELATION BETWEEN ERROR AND SENSOR TYPE

Type	Temperature error [°C]				Voltage error [mV]			
	ε_{sensor}	ε_{time}	$\varepsilon_{location}$	ε_{total}	ε_{sensor}	ε_{time}	$\varepsilon_{location}$	ε_{total}
Analog	0.10	0.59	30.54	31.23	0.50	0.45	173.06	173.51
Digital	0.99	0.14	14.85	15.98	4.17	0.34	84.15	88.66

F. Use of Sensor suitable for Target Application

Since there are a lot of researches regarding digital sensors, it is also necessary to compare the proposed sensor with other digital sensors. An auto-calibrated digital temperature sensor of [15] has a small area and short measurement time, and it is suitable for temperature monitoring. A sensor of [16] has long measurement time, but it can be realized in FPGAs. In this paper, the digital temperature and voltage sensor of [13] was used. Although its accuracy is lower than other sensors, it is suitable when a target application wants to monitor not only temperature but also voltage simultaneously. Thus, since each sensor has each advantages and features, it is important to select a sensor that is suitable for the target application.

V. CONCLUSIONS

This paper investigated accuracy of a digital sensor which is derived from the reduction of temporal and spatial variations during the measurement. The experiments using the proposed digital sensor on the test chip showed 2.73 °C increase and 7.16 mV decrease in 100 ms on a single chip. It also showed large deviations of 0.03 [°C/μm] and 0.17 [mV/μm]. Thus, when the measurement time is long like the analog sensors and it cannot be placed near the hot spot, it was confirmed that the temporal and spatial on-chip variations has a great influence on the measured values. The comprehensive evaluation shows the importance of real time and contiguous measurement. It also shows the importance of sensor location. Thus, high resolution of measurement time and fine granularity of measurement locations are required for accurate sensors. The proposed digital sensor could satisfy these requirements. In this meaning, the sensor has less total error than the conventional analog sensors' and it can be suitable for various applications such as system-power control required in safety-related systems and field test. Further extended research is being planned with finer process chips using 65 nm CMOS technology.

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