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A Temperature Monitor Circuit with Small Voltage Sensitivity using a Topology Reconfigurable Ring Oscillator

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***Abstract*—This paper propose a temperature monitor circuit that exhibits a small supply-voltage sensitivity adopting a circuit topology of a reconfigurable ring oscillator. The circuit topology of the monitor is crafted such that the oscillation frequency is determined by the amount of leakage current which has an exponential dependency to temperature. Another important characteristic of the monitor is its low supply-voltage sensitivity. The measured oscillation frequency of a test chip fabricated in a 65 nm CMOS process varies only 2.6% under a wide range of supply-voltage from 0.4 V to 1.0 V at room temperature. Temperature estimation error ranges from $-0.6\ ^\circ\mathrm{C}$ to $1.2\ ^\circ\mathrm{C}$ over a temperature range of $10\ ^\circ\mathrm{C}$ to $100\ ^\circ\mathrm{C}$ in simulation.**

I. Introduction

An impact of parameter variations on the performance of LSIs becomes significant in scaled technologies. There are three major sources of variation: process (P), voltage (V) and temperature (T). They are commonly referred as PVT variations which have become a major performance limiting factor in a scaled LSI process [1].

In order to monitor process, Ref. [2] proposes a method to estimate the amount of process variation from the frequency of a reconfigurable ring oscillator (RO). The circuit takes advantage of the reconfiguration such that a single circuit can be configured to various topologies from which process variation can be characterized effectively. Ref. [3] introduces a new circuit configuration of the same circuit for temperature sensing that exploits an exponential sensitivity of leakage current to temperature.

In this work, we propose an updated circuit topology of a reconfigurable ring oscillator that inherits a strong sensitivity of Process (P) and Temperature (T) while showing a small sensitivity of Voltage (V). Measured oscillation frequency varies only 2.6% when the supply voltage varies from 0.4 V to 1.0 V.

II. Reconfigurable RO

A Ring Oscillator (RO) is easy to implement and its oscillation frequency is easy to measure. It is therefore one of commonly used circuits for evaluating parameter variations in P, V, and T. For example, Ref. [4] proposes a set of delay cells used in a RO for the estimation of process parameter variations. In Ref. [2], a reconfigurable delay cell is developed that can be configured as the proposed set of delay cells, as shown in Fig. 1.

Ref. [3] extends the usage of the reconfigurable RO in Ref. [2] for temperature sensing by introducing a new circuit configuration in

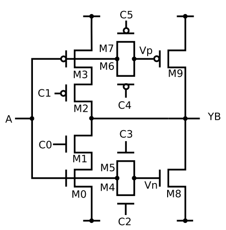


Fig. 1: Reconfigurable RO proposed in Ref. [2].

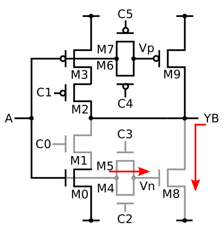
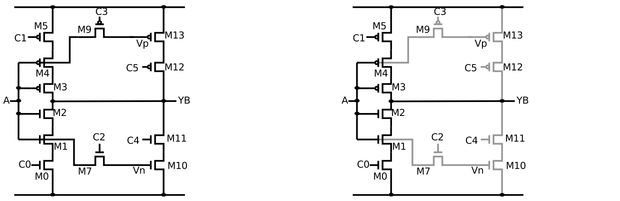
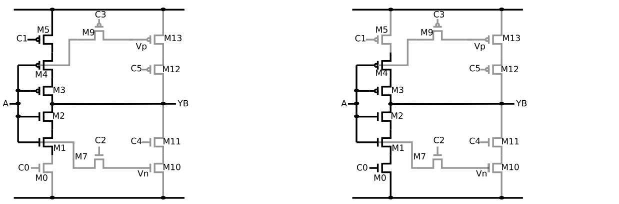


Fig. 2: Temperature monitoring configuration using reconfigurable RO proposed in Ref. [3].



(a) Proposed circuit (b) "Standard" configuration

Fig. 3: Proposed topology–reconfigurable RO and configuration example.



(a) "N_leak" configuration (b) "P_leak" configuration

Fig. 4: Proposed temperature sensing configurations.

which pull-up or pull-down is performed by a leakage current. The circuit configuration is shown in Fig. 2. By turning off transistors M1, M4, and M5, transistor M8 pulls down the output YB by a leakage current produced with a small amount of gate voltage Vn as illustrated in Fig. 2. The leakage current has an exponential dependency to temperature so that the oscillation frequency of the new configuration exhibit a large sensitivity to temperature. This property enables a good temperature monitoring capability, which has been verified by a test chip measurement in Ref. [3]. Although the circuit in Fig. 2 shows a good potential for temperature sensing, the amount of leakage current is primary determined by the floating node voltage of Vn. Since the gate node of M8 is kept in a high impedance state during the pull-down, the node volatile may be disturbed by surrounding circuit activities through parasitic coupling, which may introduce uncertainties in temperature monitoring.

In this paper, we propose a new circuit topology for a reconfigurable delay cell as shown in Fig. 3(a). Fig. 3(b) show the configuration example "Standard" which behaves like a stacked inverter. In the proposed circuit topology, the second stage has cut-off transistors M11 and M12 so that a leakage current can be well-controlled by the stacked transistors. The first stage also incorporates a stacked structure that provides a larger ratio of on current to leakage current. Temperature sensing configurations in the proposed circuit topology are shown in Fig. 4. With those modifications, oscillation characteristics of Fig. 4 by leakage current can become more predictable than those of Fig. 2 .

III. Simulation and Measurement Result

In this section, we show temperature characteristics of the proposed circuit configuration by simulation, together with measured voltage characteristics.

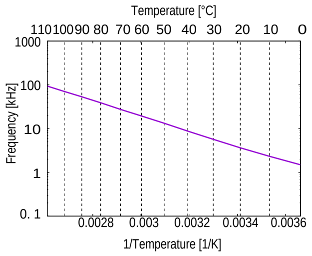


Fig. 5: Simulated result of temperature dependence in "N_leak" configuration.

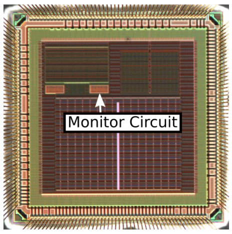


Fig. 6: Test chip structure fabricated in 65 nm CMOS process.

Fig. 5 show the oscillation frequency of the "N_leak" configuration in Fig. 4 (a) as a function of temperature. In a logarithmic scale, the oscillation frequency exhibits close-to-linear dependency to the inverse of the temperature, which property is the same as that of the original circuit proposed in Ref. [2]. Therefore we can expect the similar level of temperature monitoring capability. The proposed reconfigurable RO has been fabricated in a 65nm CMOS technology. A micro-graph of the test chip is shown in Fig 6. Voltage sensitivity of the proposed "N_leak" configuration has been measured by the test chip. For comparison, voltage sensitivity of the "Standard" has also been measured. Fig. 7 shows the oscillation frequency of each configuration as a function of supply voltage. The oscillation frequency of "N_leak" configuration keeps almost constant over a wide range of supply voltage from 0.4 V to 1.0 V. The frequency at 1.0 V supply is only 2.6% larger than the frequency at 0.4 V supply. On the other hand, the frequency of "Standard" exhibits a large voltage sensitivity. The frequency at 1.0 V supply is 1,573% larger than that at 0.4 V supply.

IV. Temperature Estimation on Simulation

We can exploit the exponential sensitivity shown in Fig. 5 for temperature monitoring. We approximate the logarithm of the frequency a linear function of the inverse of the temperature as,

$$\ln(F) = a_{\mathrm{T}} \cdot \frac{1}{T} + b_{\mathrm{T}}, \tag{1}$$

where F is frequency, T is absolute temperature, a_{T} and b_{T} are temperature coefficients. If we apply a two-point calibration, we can derive parameter values of a_{T} and b_{T}. Fig. 8 shows the amount of estimation error by the proposed monitor circuit after 2-point

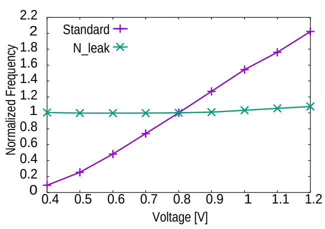


Fig. 7: Measurement result of the test chip in "N_leak" configuration and "Standard" configuration at room temperature.

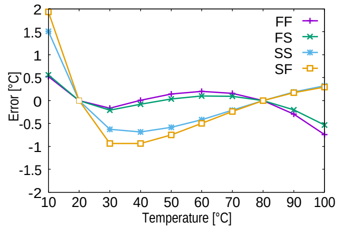


Fig. 8: Sensing error versus temperature after two-point calibration at the supply voltage of 1.0 V.

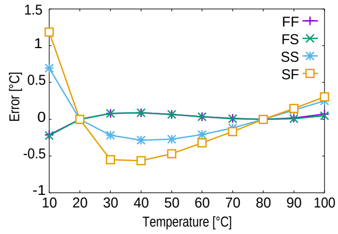


Fig. 9: Sensing error versus temperature after correction at the supply voltage of 1.0 V.

calibration at the supply voltage of 1.0 V. In the simulation, we assume process variations at the four worst corners of SS, FF, FS and SF. Calibration is assumed to be performed at 20 °C and 80 °C. The amount of estimation error ranges from -1.0 °C to 2.0 °C over a temperature range of 10 °C to 100 °C.

As seen from Fig. 8, the logarithm of the oscillation frequency deviates from a linear function, especially in a low temperature region where the threshold voltage becomes high and a subthreshold leakage current becomes small. This deviation is attributed to the existence of gate leakage current appeared in this process technology. A possible method to work around this issue is, instead of assuming a liner function of Eq.(1), to adopt a simulated non-linearity in the 2-point calibration. For example, if we use the actual temperature dependency at the T-T condition, we can improve the accuracy of temperature estimation as shown in Fig. 9. The estimated error is now reduced to -0.6 °C to 1.2 °C.

V. Conclusions

We have proposed a method for measuring temperature using a reconfigurable RO that has very small voltage sensitivity. A test chip has been fabricated in a 65nm CMOS process. The circuit can operate under a wide range of supply voltage from 0.4 V to 1.0 V. Measured oscillation frequency varies only 2.6 % when the supply voltage changes from 0.4 V to 1.0 V at room temperature. The estimation error in temperature sensing ranges from 0.6 °C to 1.2 °C over a temperature range of 10 °C to 100 °C by simulation. Measurement of temperature characteristics is under preparation.

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