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# Pulse-Output Readout Circuit with Temperature Compensation for a Temperature-Dependent Input Voltage

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## Abstract

**A CMOS pulse-output readout circuit with temperature compensation for a temperature-dependent input voltage is presented. The circuit consists of a voltage-to-current (V-I) converter, a current-controlled oscillator (CCO), and a temperature sensor with proportional-to-absolute-temperature (PTAT) output current. An input voltage, $V_{sen}$, is converted into a current by the V-I converter and then the current is used to generate a pulse output through the CCO. The PTAT current can be mirrored into the CCO in order that the temperature-induced current drift of the V-I converter can be compensated if the $V_{sen}$ will decrease with increasing temperature. The output pulse frequency of the CCO is linearly proportional to the $V_{sen}$ with a linearity of at least 99.998%. The suitability of the readout circuit for ion-sensitive field effect transistors (ISFETs), which effective gate voltage related to pH value decreases with increasing temperature, was estimated and measurement results show that output frequency variation with temperature is decreased by a factor of at least 10 under the compensation of the PTAT current.**

## 1. Introduction

The output transfer characteristic of silicon-based sensors is usually temperature-dependent owing to temperature dependence of material parameters of devices themselves or analyte [1-2]. Ion-sensitive field effect transistors (ISFETs) are being developed for many applications in the fields of environmental and biomedical analysis [3]. The ISFET is a floating-gate MOSFET. Its gate oxide or an extra coated gate insulator such as $Si_3N_4$, $Al_2O_3$ is used as a sensing membrane for $H^+$ ions. The ISFET, traditionally referred to as a pH sensor, has been used to measure $H^+$-ion concentrations in a solution, causing an interface potential on the gate insulator. Under the bias voltage from an added reference electrode, the variation in the ion concentration is measured as a change in the threshold voltage or a change in the effective gate voltage [4].

In ref. [1], threshold voltage variations resulting from temperature dependence of electrochemical component for ISFETs in different wafers at pH=4 and pH=10 were shown. The $dV_{TH}/dT$ was 0.44 and 0.7 mV/°C, respectively for ISFETs in waters at pH=4 and pH=7. Because the drain current of a MOSFET is a function of ($V_{GS}$-$V_{TH}$), the positive $dV_{TH}/dT$ under a fixed bias voltage of the reference electrode, which is considered as the gate of the ISFET, can be equivalent to negative effective gate voltage variations on the floating gate of the ISFET. In this paper, a CMOS pulse-output readout circuit with temperature compensation for a temperature-dependent input voltage is presented. The readout circuit has successfully been implemented by the TSMC 0.35μm process. The supply voltage is 3V.

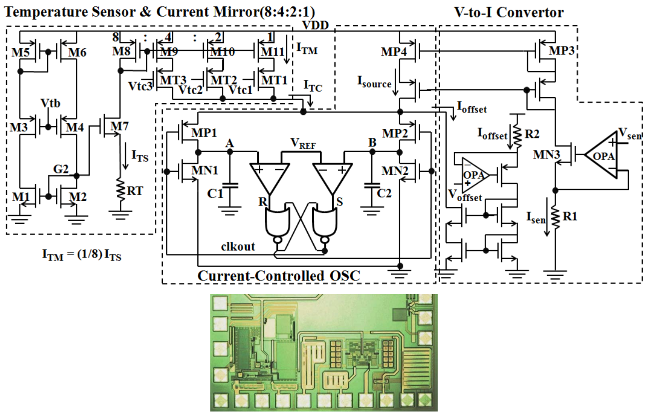



Fig. 1 The circuit schematic and chip photograph of the readout circuit

## 2. Circuit Design and Measurement Results

Fig.1 shows the circuit schematic and chip photograph of the readout circuit. The circuit consists of a voltage-to-current (V-I) converter, a current-controlled oscillator (CCO), and a temperature sensor with proportional-to-absolute-temperature (PTAT) output current $I_{TS}$ [4, 5]. An input voltage $V_{sen}$ is converted into a current $I_{sen}$ (=$V_{sen}$/R1=$I_{source}$) by the V-I converter and then the current is used to generate a pulse output through the CCO. The output current of the V-I converter can has a negative temperature coefficient owing to positive temperature coefficients of R1 and R2 or negative temperature coefficient of its input voltage $V_{sen}$. The PTAT current, which can be adjusted by its bias voltage $V_{tb}$ [5], is mirrored into the CCO by three switches and hence the adjustable PTAT current $I_{TC}$ can be used to compensate the temperature-induced current drift of the V-I converter. The three mirrored currents are $0.5I_{TS}$, $0.25I_{TS}$, and $0.125I_{TS}$ ($=I_{TM}$) and are switched by $V_{tc3}$, $V_{tc2}$, and $V_{tc1}$, respectively. Fig. 2 shows simulated temperature characteristics of these mirrored currents under $V_{tb}$=0.9V. The sensitivities are 7.6, 3.8, 1.9nA/°C with linearity of at least 99.99%. The charging current of the CCO equals $I_{TC}+I_{source}-I_{offset}$. The $I_{offset}$ equals $(V_{DD}-V_{offset})/R2$ and is used to adjust the charging current of the CCO in order that transfer characteristics of pulse frequency versus input voltage can be shifted down [4].

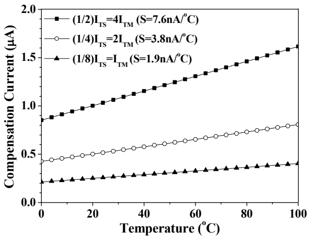



Fig. 2 Simulated temperature characteristics of three mirrored currents under $V_{tb}$=0.9V.

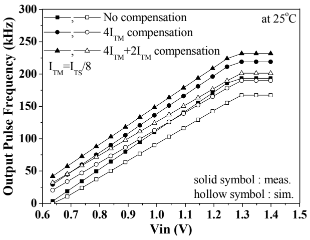
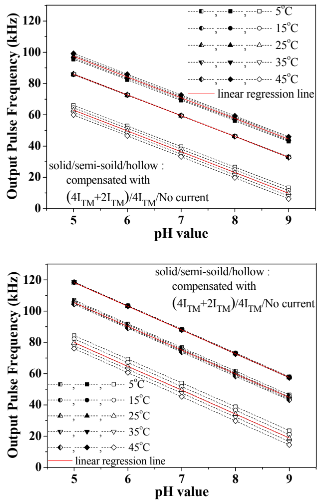



Fig. 3 Simulated and measured transfer characteristics of pulse frequency versus input voltage under the $V_{offset}$ values of 2.35V.

Fig. 3 shows the simulated and measured transfer characteristics of pulse frequency versus input voltage ranging from 0.65 to 1.4V under $V_{offset}$=2.35V and $V_{REF}$=1.5V at 25 °C with compensation currents of 0, $4I_{TM}$, and $6I_{TM}$, respectively. Within the input voltage range from 0.65 to 1.25V, the simulated and measured transfer characteristics exhibit linearity of at least 99.999% and 99.998%, respectively. The simulated and measured sensitivities are about 258 and 298 kHz/V, respectively. This means that process variation makes the R1 value smaller than the value used in simulation. The input transistor of the operational amplifier for the input voltage $V_{sen}$ can be operated as an extended-gate ISFET [4]. In this work, we directly give input voltage to the gate of the input transistor and assume that it acts as an ISFET. The effective gate voltage is a function of temperature and pH value [1]. By using the $dV_{TH}/dT$ values presented in ref. [1] and assuming that the effective gate voltage equals 0.8V and the sensitivity is -50 mV/pH at pH=7 and 25 °C, the effective gate voltages at some temperatures and pH values can be calculated. Fig.4 shows the simulated and measured transfer characteristics of pulse frequency versus pH value at 5, 15, 25, 35, and 45 °C, respectively. Without temperature compensation, the transfer characteristics at the five temperatures separate from each other. The simulated transfer characteristics almost overlap together under the compensation current of $4I_{TM}$. The measured transfer characteristics almost overlap together under the compensation current of $6I_{TM}$. To obtain good temperature compensation, the compensation current used in measurement is larger than that used in simulation owing to process variation induced reduction of resistance value. If the linear regression lines without and with temperature compensation at 25°C are used as the ideal linear transfer characteristics, the extracted temperature-induced pH-value drift from output pulse frequency is about -0.015 pH/°C and less than -0.0015 pH/°C respectively for the circuit operated under no and nearly optimal temperature compensation.




(a)

(b)

Fig. 4 (a) Simulated and (b) measured transfer characteristics of pulse frequency versus pH value at 5, 15, 25, 35, and 45 °C.

## 3. Conclusions

A CMOS pulse-output readout circuit with temperature compensation has successfully been designed and fabricated. The circuit occupies a chip area of 1200×570 $\mu m^2$ and the current consumption is about 0.7 mA under $V_{sen}$=0.8V at 25 °C. The multi-channel scaled and adjustable compensation current makes the readout circuit flexible for different compensation requirements which come from different sensitivity of input voltage versus temperature or the performance drift induced by process variation and native temperature dependence of device parameters.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