

A CMOS ISFET Interface Circuit With Dynamic Current Temperature Compensation Technique

P. K. Chan and D. Y. Chen

Abstract—This paper presents a new ion-sensitive field-effect transistor (ISFET) readout circuit including a novel nonlinear temperature compensation method that is based on the theoretical work for formulating a body-effect-based ISFET drain current expression, the derivation of a unified temperature-dependent ISFET threshold voltage expression, and the use of iterative method for solving design parameters in nonlinear equations. Regarding the basic readout circuit, it comprises only one source follower and one current source to establish a self-biased configuration for a single ISFET device. Due to elimination of body effect, it displays linear transfer characteristic in the experimental result. Incorporating temperature compensation further improves the thermal stability of the ISFET device in pH sensing function. This has been validated by the experimental results on pH values ranging from 4 to 9 in a temperature range of 22 °C to 50 °C from the measurement setup. The pH7 parameter is used as a reference in the method. The proposed works are attractive in terms of circuit simplicity, temperature-compensated performance, cost and compatibility for smart sensor operation.

Index Terms—CMOS circuit, ion-sensitive field-effect transistor (ISFET) interface circuit, ISFET sensor, temperature compensation, zero temperature coefficient.

I. INTRODUCTION

ION-SENSITIVE field-effect transistors (ISFETs) are emerging as important sensing devices in the areas of environmental monitoring applications, analytical chemistry, and biomedical applications since the pioneer work on ISFET pH sensor introduced by Bergveld [1]. It has appreciable advantages over traditional glass-electrode pH sensors on the basis of its small size, robustness (unbreakable), simplicity in fabrication and low cost. Many research works [2]–[8] have exploited different circuit architectures of readout circuits, which usually play the role in translating the pH values to voltage domain presentation, with the goal to obtain good sensitivity as well as linearity. However, it is common to observe that circuits with nonzero body bias would not only affect linearity through bulk modulation, but also introducing undesirable temperature-dependent effect. Since the temperature characteristic of ISFET sensor is also a complex function related to the reference electrode, electrolyte-insulator potential and ISFET-based MOS transistor, the composite temperature effect greatly limits the

performance of ISFET sensors, leading to unacceptable results in critical measurements. Simultaneously, other research efforts [9]–[14] have contributed to various temperature compensation techniques such as the proper choice of biasing current for athermal operating point to minimize ISFET temperature coefficient [12], the use of a p-n junction diode [12] for temperature compensation on a single ISFET device, the employment of an ISFET operational amplifier [9]–[11] that improves temperature stability or the combination of ISFET operational amplifier and p-n junction diode [13] for enhanced thermal stability. Of the methods, it can be seen the temperature characteristic is stabilized at particular pH or in a narrow pH range. For broader range of pH values, the temperature compensation becomes more difficult because the temperature coefficient (*T.C.*) of electrochemical component is a function of pH value. More importantly, the ISFET temperature characteristic tends to exhibit nonlinear behavior. The straight-line-based temperature compensation limits its scope when dealing with actual nonlinear temperature characteristic of ISFET device at different pH values. In addition, the temperature coefficient of measuring circuit also introduces another temperature contribution. As a result, ease of incorporating temperature compensation scheme, effectiveness of compensation technique, circuit simplicity as well as circuit sensitivity with respect to body effect become the key design considerations in an interface circuit design. Therefore, it is particularly challenging for ISFET sensors to operate in an environment in context of measuring different pH range against different temperature. Based on this study, it is necessary to understand the thermal behavior of an ISFET from a foundation work together with the research of a robust ISFET interface circuit coupled with improved temperature compensation. In view of the above problems, a new ISFET interface circuit having very simple structure is proposed. This is in conjunction with the investigation of novel dynamic biasing current temperature compensation technique, which is concerned with the combination of mutual compensation in ISFET's MOS transconductance characteristics and numerical iteration technique for finding optimum biasing current dynamically in order to solve nonlinear temperature compensation, thus resulting in almost zero temperature coefficient (*Z.T.C.*) for nonlinear biasing points at any pH value. This enables a single ISFET sensor and its interface circuit on the measurement of different pH values at different temperature simultaneously.

The paper is organized as follows. Section II presents the ISFET model and temperature characteristic of an ISFET sensor. In Section III, the representative published ISFET interface circuits are reviewed together with the introduction of a new readout circuit. In Section IV, the published ISFET temperature compensation techniques are firstly reviewed, which

Manuscript received January 30, 2006; revised August 31, 2006. This paper was recommended by Guest Editor D. Wilson.

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Digital Object Identifier 10.1109/TCSI.2006.887979

is then followed by the novel ISFET temperature compensation method, analysis and measurement procedures. In Section V, the measurement results are presented to validate the proposed works. Finally, the concluding remarks are drawn in Section VI.

II. ISFET SENSOR

The ISFET sensor begins with the saturation drain current expression which is derived from the electrochemical theory and semiconductor theory of MOS transistor, with indication of key process model parameters and their definitions. This is then described with an ISFET model that permits better understanding on the basic components. Besides, the thermal behavior of respective component in ISFET gives the insight on how the temperature variation impacts on the ISFET sensing device. This serves as useful information for temperature compensation design

A. Drain Current Expression of ISFET in Saturation

The operation principle of ISFET has been studied in [15]–[19]. Like the standard MOSFET, the I_D – V_{GS} transfer characteristic for a long-channel ISFET operating in saturation region is given by

$$I_{ds} = \frac{\mu C_{OX} W}{2L} (V_{gs} - V_{th(ISFET)})^2 \quad (1)$$

where the μC_{OX} is the process transconductance parameter, W/L is the aspect ratio and the ISFET threshold voltage [19] combined with the MOS transistor counterpart which includes body effect in a four-terminal device [20] can be unified as

$$V_{th(ISFET)} = V_{th-chem} + V_{th-mos} \quad (2)$$

or

$$V_{th(ISFET)} = E_{Ref} + \Delta\varphi^{lj} - \Psi_{eo} + \chi^{sol} + \left[\frac{-\Phi_{Si}}{q} - \frac{Q_{OX} + Q_{SS} + Q_B}{C_{OX}} + 2\varphi_f + \gamma \left(\sqrt{2\varphi_f + V_{SB}} - \sqrt{2\varphi_f} \right) \right] \quad (3)$$

$$\text{with } V_{th-chem} = E_{Ref} + \Delta\varphi^{lj} - \Psi_{eo} + \chi^{sol} \quad (4)$$

and

$$V_{th-mos} = \frac{-\Phi_{Si}}{q} - \frac{Q_{OX} + Q_{SS} + Q_B}{C_{OX}} + 2\varphi_f + \gamma \left(\sqrt{2\varphi_f + V_{SB}} - \sqrt{2\varphi_f} \right) \quad (5)$$

where $V_{th-chem}$ denotes the chemical threshold voltage of ISFET. E_{Ref} is the potential of the Ag/AgCl reference electrode. $\Delta\varphi^{lj}$ is the potential drop between the reference electrode and the solution, which has typical value of 3 mV [22] and can be neglected. ψ_{eo} is a chemical input parameter being a function of the solution pH, whereas χ^{sol} , having typical value of 50 mV [22], is the surface dipole potential of the solvent being independent of pH. The combined $-\Psi_{eo} + \chi^{sol}$ item is

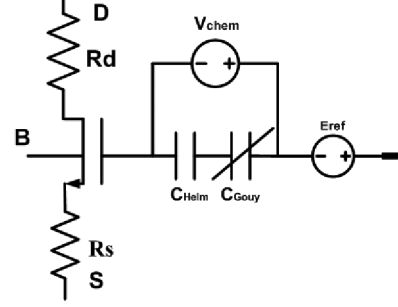


Fig. 1. ISFET modeling components.

now defined as V_{chem} to represent the potential between the electrolyte and insulator. Regarding the ISFET-based MOS threshold voltage V_{th-mos} , the terms in (5) are similar to that of the standard MOSFET threshold voltage, except absence of the gate metal work function. In (5), the first three terms represent the threshold voltage at zero body-to-source bias whereas the fourth term denotes the presence of body effect if $V_{SB} \neq 0$. It should also be mentioned that the n-type ISFET is mostly used for its low-drift and high-mobility properties [13]. Hence, in the application of an integrated microsystem where the ISFET sensor and interface circuit are fabricated in the same die, the source-to-bulk potential of ISFET plays a crucial role in circuit performance when referencing to the apparent body effect item in (3).

B. ISFET Model

The ISFET can be represented by a model as depicted in Fig. 1.

It consists of a chemical part and an MOS transistor part. In chemical part, two series capacitances C_{Helm} and C_{Gouy} represent the equivalent Gouy–Chapman and Helmholtz capacitance [21], which has already been developed by site-binding theory and the electrical double-layer theory [15]. Two voltage sources E_{ref} and V_{chem} are connected in series to denote the voltage components of chemical threshold voltage of ISFET in (4). V_{chem} consists of two potentials $-\Psi_{eo} + \chi^{sol}$, in which χ^{sol} is a constant with respect to the pH value, and ψ_{eo} is the only chemical parameter that is responsible for ISFET pH sensitivity.

The pH sensitivity of ψ_{eo} , which is defined as the change of ψ_{eo} with respect to a change of the pH value of the solution $\partial\psi_{eo}/\partial\text{pH}$, has already been explained by the Hal and Eijkel's theory [18]. This is elaborated using the general accepted site-binding model and the Gouy–Chapman–Stern model [15] to yield

$$\frac{\partial\psi_{eo}}{\partial\text{pH}} = -2.303 \frac{kT}{q} \alpha \quad (6)$$

where α is a dimensionless sensitivity parameter, with the value ranging between 0 and 1. The other physical constants have their usual meanings. By integrating (6), the pH sensitive parameter ψ_{eo} can be obtained as

$$\psi_{eo} = -2.303 \frac{kT}{q} \alpha \cdot \text{pH} + C \quad (7)$$

where C is a constant. Therefore, the voltage source V_{chem} becomes

$$V_{\text{chem}} = 2.303 \frac{kT}{q} \alpha \cdot \text{pH} + (\chi^{\text{sol}} - C) \quad (8)$$

where the first term is pH-dependent and the constant terms in the parentheses are pH-independent. Finally, the drain-and-source diffusion resistors R_d and R_S are added to take into account for a typical ISFET having longer source and drain diffusion area than MOSFET counterparts [3].

C. ISFET Temperature Characteristic

Several investigations [22]–[25] have demonstrated that the ISFET exhibits thermal instability. The temperature characteristic of the ISFET is a complex function pertaining to the reference electrode, electrolyte-insulator potential, and MOS transistor. It can be expressed as

$$T.C_{\text{total}} = T.C.R. + T.C.F. + T.C.I. \quad (9)$$

where $T.C_{\text{total}}$ is the total temperature coefficient of ISFET. $T.C.R.$ is the temperature coefficient of E_{Ref} , which has been investigated by [22] with a typical value of $0.14 \text{ mV}/^\circ\text{C}$. $T.C.F.$ is the temperature coefficient of MOS structure of ISFET. Based on the device physics [20], [28], two parameters are mainly responsible for the temperature characteristics of MOS transistor: one is the mobility whilst the other is the threshold voltage. For a given temperature, T_1 , they are modeled as

$$\mu(T)|_{T=T_1} = \mu(T_0) \left(\frac{T_1}{T_0} \right)^m \quad (10)$$

$$V_T(T)|_{T=T_1} = V_T(T_0) + K_{VT}(T_1 - T_0) \quad (11)$$

where T_0 is reference absolute temperature (note that the room absolute temperature is taken as reference). m is a constant, with typical values between -1.9 to -2.2 [26], depending on the doping concentrations of silicon. K_{VT} is the temperature coefficient of the threshold voltage, usually between $-0.5 \text{ mV}/^\circ\text{C}$ and $-3.0 \text{ mV}/^\circ\text{C}$ [20]. The third item in (9), $T.C.I.$, is the temperature coefficient of the electrolyte-insulator interface potential. It has been studied that $T.C.I.$ is also a function of pH value [22]–[25]. It may vary from $0.54 \text{ mV}/^\circ\text{C}$ to $1.1 \text{ mV}/^\circ\text{C}$ as the pH increases from 4 to 10 [23].

III. ISFET INTERFACE CIRCUITS

For measuring pH physical variable, the ISFET sensor has to be associated with an analog interface circuit for sensor signal processing. The section gives the overview of different interface circuits as well as presents the new transducer.

A. Review of ISFET Interface Circuits

Tremendous research works [2]–[8] are dedicated to the design of different types of ISFET interface circuits. The first category refers to the pH-sensing electrical signal derived from the source of ISFET. The nonsaturation-based ISFET

source follower structures [2]–[6] are common structures used to test ISFET sensors. One of the representative circuits [2] is operated with both the constant drain-to-source voltage and drain-to-source current, but the usual Ag/AgCl reference electrode of ISFET is applied with a reference voltage. Therefore, according to (7), any change in the solution pH will be translated to the variation of electrolyte-insulator potential ψ_{eo} . As a consequence, it causes the variation on ISFET threshold voltage, which is reflected from changing its gate-to-source voltage. The output signal is finally read from the buffered ISFET source terminal. In this case, it can be observed that the ISFET threshold voltage in (3) is not only a function of ψ_{eo} , but also displaying body effect. In second category, for any variation of ISFET threshold voltage caused by the pH variation, the sensor can also be read from the reference electrode [4], [7], [8]. In [4], the drain-to-source voltage and source voltage of nonsaturation ISFET are biased with constant voltages. The threshold voltage changes according to the pH value. In order to maintain the constant drain current, the feedback mechanism of the circuit will tend to regulate the reference electrode voltage. Thus, the output signal is now obtained directly from the reference electrode. Although this configuration reduces the effect of ac-based source-to-bulk modulation on ISFET threshold voltage, they still have body effect biased constant dc voltage which is also a function of temperature. In [7], direct or indirect feedback on the saturation-based ISFET interface circuits provides interesting means of pH sensing. The operation principle is to equalize the ISFET current and current of constant current source via direct feedback to the reference electrode or indirect feedback to current source. The schemes eliminate the body effect and offer simple structures (using only one op-amp in the core interface) but they are subject to stability issue due to the existence of two high impedance nodes in the feedback structures. In recent work [8], the voltage-current (VI) converter-based ISFET interface circuit moves towards similar direction but having only one high impedance node in the circuit, and hence it is easy to ensure stability under feedback condition.

B. New ISFET Interface Circuit

On the basis of the nonsaturation-based ISFET readout circuit design [8], a new ISFET readout circuit can be devised for classification as the second category. The simplified schematic is depicted in Fig. 2, which comprises an ISFET device operating in saturation region via the constant current source I_B and a source follower formed by the transistor M_1 and current source I_o .

The ISFET readout circuit aims at detecting the change of the ISFET threshold voltage that reflects the variation of the pH value in the solution. The V_{GS} of ISFET will become self-biased through a source follower in a feedback loop. The operation is explained as follows. When passing a constant current through the ISFET, the V_{GS} must be established to fulfill the biasing condition. As the gate of ISFET is tied to the source of transistor M_1 , a floating dc will be developed in the gate of M_1 due to the V_{GS1} being established by I_o . Any change on the ISFET's V_{GS}

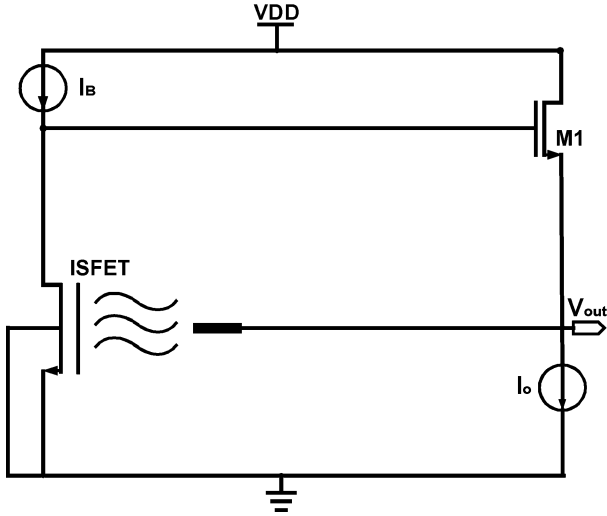


Fig. 2. Simplified schematic of the proposed saturation-based ISFET readout circuit.

will shift the V_{GS1} dynamically in the source follower. Therefore, the output of the readout circuit or the reference electrode voltage of the ISFET is forced to settle to a value determined by the pH value of the solution where the ISFET is immersed. Besides, the source follower also performs as an economical voltage buffer for driving next stage electronic circuit. This is advantageous because of the elimination of an op-amp-based buffer. According to (1) and (3), when an ISFET is operated in saturation region, the output of the proposed interface circuit can be derived as

$$V_{out} = V_{gs} = V_{th(ISFET)} + \sqrt{\frac{2I_B}{\mu_n C_{OX} \left(\frac{W}{L}\right)}} + I_B R_S \quad (12)$$

where the second term is defined as a quiescent dc biasing voltage arising from the gate-overdrive bias, and the third term is a dc component caused by the voltage drop across the source diffusion resistor. Nevertheless, it can be negligible as far as the product $I_B R_S$ is made small in the design. Therefore, the output V_{out} becomes the only function of threshold voltage of ISFET V_{th_ISFET} , which is linearly proportional to pH value of the solution. With grounding ISFET's source and bulk terminals, the body effect dc does not alter the sensitivity but the temperature-dependent body effect contributes few percentages to the total $T.C.$ of temperature-uncompensated output, which is insignificant. This new self-adjusted V_{GS} ISFET sensing circuit fulfills the first step for basic sensing function whilst meeting simplicity and almost eliminating temperature-dependent body effect item. The second step for temperature compensation will be discussed in next section.

IV. ISFET TEMPERATURE COMPENSATION

Referencing to the ISFET temperature characteristics in Section II, the strong temperature dependence of the ISFET sensor would limit its accuracy on the ISFET-based measurement systems. Therefore, another essential feature of the sensor

signal processing circuits is to support temperature compensation schemes. Herewith, the ISFET temperature compensation techniques are firstly reviewed prior to the introduction of a new temperature compensation methodology together with its detailed second-order analysis and measurement procedures.

A. Review of ISFET Temperature Compensation Techniques

Research efforts have been spent on various ISFET temperature compensation techniques [3], [4], [9]–[14] in along with interface circuit design. In earlier work [12], the thermal stability of an ISFET is improved when biasing in an experimental determined athermal operating point. However, the athermal operating point of ISFET varies in different pH buffer solutions due to the pH-dependent $T.C.I.$ in (9). This standalone constant ISFET biasing method would not be sufficient for temperature compensation in a wide range of pH. Other major research works [4], [9]–[11], [13] have focused on the hybrid differential-pair amplifier configuration, commonly known as ISFET operational amplifier, which appear in various circuit element or method combinations: 1) differential pair of ISFET/MOSFET [4], [9]; 2) differential pair of ISFET/MOSFET incorporating a p-n junction diode method [13]; 3) differential pair of ISFET/REFET [11]; and 4) differential pair of ISFET/ISFET with different materials for different pH sensitivities [3], [10]. The first operational transducer [9], comprising an ISFET/MOSFET source-coupled differential pair, fabricated with the same technology, can provide certain immunity on the temperature sensitivity of MOS structure of ISFET, or $T.C.F.$ in (9). It may not be sufficient for compensation of temperature sensitivity arising from electrochemical component such as $T.C.I.$ term. This problem has been relaxed by using an ISFET/MOSFET source-coupled differential pair configuration in combination with a p-n junction diode method [13] for successful temperature compensation around the pH6 buffer solution. This can be explained by the fact that the negative $T.C.$ of p-n junction diode counteracts the positive $T.C.$ of reference electrode potential and electrolyte-insulator interface potential [23] of the ISFET. However, the pH-independent $T.C.$ of a p-n junction diode is also not adequate for maintaining effective temperature compensation for pH-dependence $T.C.I.$ in a wide pH range.

In circuit design perspective, arising from the mismatch in the differential hybrid transistors, the input offset voltage of ISFET operational amplifier consists of several nonideal process-dependent and design-related terms that display different temperature coefficients. For an example, the mismatch of total gate capacitance, semiconductor bulk charges, insulator interface charges, and biasing current [4] can lead to a mismatch in ISFET/MOSFET differential pair. Besides, for ISFET/REFET differential pair operation scenario, the reference field-effect transistor, REFET, has an additional ion blocking surface layer, hence the ISFET and REFET may not be electrically identical, resulting in a residual differential signal [19].

B. ISFET Athermal Biasing Points in Reference pH7

This proposed temperature compensation technique stems from the physical theory of mutual compensation of mobility

and threshold voltage temperature variation to achieve the *Z.T.C.* biasing point in MOSFET. However, the main difficulty rises from the fact that the *T.C.* of ISFET threshold voltage is a function of pH value. To deal with this problem, the electrochemical theory of ISFET is combined with the physical theory of MOS transistor to establish the theoretical basis for the research of dynamic biasing current temperature compensation technique. Mutual compensation of mobility and threshold voltage temperature effects in field-effect transistors are exploited in the literature [20], [28]. Detailed investigation for *Z.T.C.* point in MOS transconductance characteristics has been reported by [26]. Despite the difference between the MOSFET and ISFET comes from their threshold voltages, the mutual compensation analytical approach on MOSFET aspect can be extended to ISFET counterpart. Due to the variation of *T.C.* of ISFET threshold voltage in different pH buffer solutions, it is natural to choose the pH7 buffer solution as the reference parameter with respect to other buffer solutions. The measured and analytical results of the reference parameters form the initial guess values for solving the nonlinear equations in the temperature compensation process in next phase. Therefore, the analysis of mutual compensation on ISFET in pH7 buffer solution is carried out firstly. Similar to the analysis on MOSFET in [26], it is possible to incorporate temperature effect on mobility (10) and threshold voltage (11) and neglecting the dc voltage drop of source diffusion resistor in an ISFET. When a constant current source $I_B = I_{DS}$ is applied to a drain level-shifted diode-connected ISFET in Fig. 2, the gate-to-source voltage of ISFET (12) in pH7 buffer solution, for a given temperature T_1 can be approximated as

$$V_{GS(\text{pH7})}(T)|_{T=T_1} \approx V_{\text{th}(\text{pH7})}(T_0) + K_{VT(\text{pH7})} \times (T_1 - T_0) + \sqrt{\frac{2I_{DS}}{1 + \theta \left[\frac{\beta_0}{V_{GS(\text{pH7})}(T_1) - V_{\text{th}(\text{pH7})}(T_1)} \right]}} \left(\frac{T_1}{T_0} \right)^m. \quad (13)$$

Here, $V_{\text{th}(\text{pH7})}(T_0)$ is the threshold voltage of ISFET in pH7 buffer solution at room temperature and $K_{VT(\text{pH7})} = \partial V_{\text{th}(\text{pH7})} / \partial T$ is *T.C.* of ISFET threshold voltage in pH7 buffer solution. θ is the mobility degradation parameter and $\beta_0 = \mu_0(T_0)C_{OX}(W/L)$. In a saturation-based ISFET, the variation of the temperature-dependent mobility term $\theta (V_{GS(\text{pH7})}(T_1) - V_{\text{th}(\text{pH7})}(T_1))$, from temperature T_1 to another operation temperature T_2 can be significantly small due to minute value of θ , $(V_{GS(\text{pH7})}(T_1) - V_{\text{th}(\text{pH7})}(T_1))$ and the square root effect in the gate overdrive term. For this reason, the room temperature-based constant $\theta (V_{GS(\text{pH7})}(T_0) - V_{\text{th}(\text{pH7})}(T_0))$ as a replacement of $\theta (V_{GS(\text{pH7})}(T_1) - V_{\text{th}(\text{pH7})}(T_1))$ will be useful to simplify the calculation without losing accuracy. Therefore, (13) can be further approximated as

$$V_{GS(\text{pH7})}(T)|_{T=T_1} \approx V_{\text{th}(\text{pH7})}(T_0) + K_{VT(\text{pH7})} \times (T_1 - T_0) + \sqrt{\frac{2I_{DS}}{1 + \theta \left[\frac{\beta_0}{V_{GS(\text{pH7})}(T_0) - V_{\text{th}(\text{pH7})}(T_0)} \right]}} \left(\frac{T_1}{T_0} \right)^m. \quad (14)$$

Then, the *T.C.* of $V_{GS(\text{pH7})}(T)$ can be obtained as

$$\left. \frac{\partial V_{GS(\text{pH7})}(T)}{\partial T} \right|_{T=T_1} = K_{VT(\text{pH7})} + \sqrt{\frac{2I_{DS}}{1 + \theta \left[\frac{\beta_0}{V_{GS(\text{pH7})}(T_0) - V_{\text{th}(\text{pH7})}(T_0)} \right]}} \left(\frac{T_1}{T_0} \right)^{(-m/2)-1} \left(\frac{-m}{2} \right) \frac{1}{T_0}. \quad (15)$$

Like the compensation analysis of MOSFET [26], for any given temperature T_1 , one can find a biasing current that is able to satisfy $\partial V_{GS(\text{pH7})} / \partial T|_{T=T_1} = 0$. This is regarded as *Z.T.C.* point or athermal operating point. This optimum biasing current can be obtained by solving the equation

$$\left. \frac{\partial V_{GS(\text{pH7})}(T)}{\partial T} \right|_{T=T_1} = 0. \quad (16)$$

Thus, the corresponding optimum biasing current for ISFET to sense in pH7 buffer solution can be derived as

$$I_{DS(\text{pH7})} = \frac{2K_{VT(\text{pH7})}^2 T_0^2}{m^2} \times \frac{\beta_0}{1 + \theta \left[\frac{\beta_0}{V_{GS(\text{pH7})}(T_0) - V_{\text{th}(\text{pH7})}(T_0)} \right]} \left(\frac{T_1}{T_0} \right)^{m+2}. \quad (17)$$

Therefore, the (13)–(17) form the basis for the nonlinear temperature compensation in next section.

C. Dynamic Biasing Current Temperature Compensation

Instead of constant biasing current, the ISFET can be biased dynamically via a systematic calculation of specific parameters in a smart sensor operation environment. There is a possibility to achieve *Z.T.C.* at different pH values in a defined temperature range. In order to accomplish the task, it begins with the derivation of ISFET temperature-dependent threshold voltage in a unified form and the optimum biasing current for athermal point at any pH in a temperature range. Steps are summarized at the end.

With reference to (7), the value of ψ_{eo} at pH7 and other pH solution can be expressed as follows:

$$\begin{aligned} \psi_{eo(\text{pH7})} &= -2.303 \frac{kT}{q} \alpha \cdot \text{pH7} + C \\ \psi_{eo(\text{pH})} &= -2.303 \frac{kT}{q} \alpha \cdot \text{pH} + C \\ &= -2.303 \frac{kT}{q} \alpha \cdot (\text{pH} - \text{pH7}) + \varphi_{eo(\text{pH7})}. \end{aligned} \quad (18)$$

When incorporating the pH7 as a reference value and the respective temperature-dependent term for threshold voltage related chemical part (19) and MOS part (11), the unified temperature-dependent threshold voltage of ISFET in any pH value can be written as

$$V_{\text{th}(\text{ISFET})}(T)|_{T=T_1} = V_{\text{th}(\text{pH7})}(T_0) + K_{VT(\text{pH7})}(T_1 - T_0) + 2.303 \frac{kT_1}{q} \alpha \cdot (\text{pH} - \text{pH7}) \quad (20)$$

at a temperature T_1 . Furthermore, in (20)

$$\Delta\text{pH} = \text{pH} - \text{pH7}. \quad (21)$$

Similar to (14), the temperature-dependent gate-to-source voltage of ISFET in any pH value can be approximated as

$$V_{GS(\text{pH})}(T)|_{T=T_1} \approx V_{\text{th}(\text{ISFET})}(T_1) + \sqrt{\frac{2I_{\text{DS}}}{\frac{\beta_0}{1+\theta[V_{GS(\text{pH})}(T_0) - V_{\text{th}(\text{ISFET})}(T_0)]} \left(\frac{T_1}{T_0}\right)^m}} \quad (22)$$

at a temperature T_1 .

Using the same method of analysis on the pH7 buffer solution and assuming a biasing current of I_{DS} , the *T.C.* of gate-to-source voltage of ISFET in any given pH buffer solution can be derived as follows:

$$\begin{aligned} \left. \frac{\partial V_{GS(\text{pH})}(T)}{\partial T} \right|_{T=T_1} &= K_{VT(\text{pH7})} + 2.303 \frac{k}{q} \alpha \cdot \Delta\text{pH} \\ &+ \sqrt{\frac{2I_{\text{DS}}}{\frac{\beta_0}{1+\theta[V_{GS(\text{pH})}(T_0) - V_{\text{th}(\text{ISFET})}(T_0)]} \left(\frac{T_1}{T_0}\right)^{(-m/2)-1} \left(\frac{-m}{2}\right) \frac{1}{T_0}}}. \end{aligned} \quad (23)$$

Similarly, for any given pH buffer solution, the optimum biasing current that forces ISFET to operate at the athermal point can be obtained from

$$\left. \frac{\partial V_{GS(\text{pH})}(T)}{\partial T} \right|_{T=T_1} = 0. \quad (24)$$

By solving (24), we have

$$I_{\text{DS}(\text{pH})} = \left(K_{VT(\text{pH7})} + 2.303 \frac{k}{q} \alpha \cdot \Delta\text{pH} \right)^2 T_0^2 \frac{2}{m^2} \left(\frac{T_1}{T_0} \right)^{m+2} \times \frac{\beta_0}{1 + \theta [V_{GS(\text{pH})}(T_0) - V_{\text{th}(\text{ISFET})}(T_0)]}. \quad (25)$$

Therefore, the optimum biasing current required for the ISFET to work around the athermal point in different pH buffer solutions is a function of ΔpH and pH through (21). However, the difficulty of implementing this methodology in practical pH measurement is that the value of ΔpH cannot be obtained directly. It is because the pH value of the measured solution can be unknown. To overcome the obstacle, a numerical iteration technique is proposed. This stems from the fact that $V_{\text{out}} = V_{GS}$ is linearly proportional to pH value in absence of body effect at fixed temperature while the temperature-dependent sensitivity of ISFET device displays nonlinear relationship with the drain current I_{DS} . As pH is a function of V_{out} and I_{DS} is a function of temperature-dependent sensitivity, the initial guess values at room temperature can be approximated to obtain $I_{\text{DS}(\text{pH7})}$ (17) from extracted process parameters and measured reference parameters, and to obtain pH from the ISFET reference sensitivity. It is then solved nonlinearly for finding the optimum biasing current to achieve *Z.T.C.* of ISFET at different pH values using an

iterative method in numerical analysis. The procedures to implement the iteration algorithm are summarized as follows.

Step 1) Measure the ISFET V_{out} —pH transfer characteristic at different biasing currents for targeted test solutions pH_{min} , pH7 and pH_{max} at room temperature as reference data. Since pH7 lies between pH_{min} and pH_{max} , for a natural choice, the $I_{\text{DS}(\text{pH7})}$ (17) is treated as an initial biasing current for ISFET operating around the athermal point in pH7 buffer solution. Using the slope concept, the pH_C can be estimated through the reference sensitivity data using the following equations:

$$\text{pH}_C = \text{pH4} + \frac{V_{\text{out}} - V_{\text{out}(\text{pH4})}}{\frac{V_{\text{out}(\text{pH7})} - V_{\text{out}(\text{pH4})}}{(\text{pH7} - \text{pH4})}} \quad (26)$$

or

$$\text{pH}_C = \text{pH7} + \frac{V_{\text{out}} - V_{\text{out}(\text{pH7})}}{\frac{V_{\text{out}(\text{pH9})} - V_{\text{out}(\text{pH7})}}{(\text{pH9} - \text{pH7})}}. \quad (27)$$

Note that pH_C is the pH value being converted from the measured output voltage of the transducer. If V_{out} is smaller than $V_{\text{out}(\text{pH7})}$, (26) will be used, otherwise, (27) will be selected.

Step 2) Then, the pH_C is substituted into (21). Since $\Delta\text{pH} = \text{pH} - \text{pH7} = \text{pH}_C - \text{pH7}$, the calculated ΔpH is substituted into (25) again to iterate another new biasing current.

Step 3) The ISFET is then applied with the new biasing current to obtain another new voltage output of interface, which is used to find another new pH_C .

The proposed iteration-based temperature compensation method will be demonstrated in electrochemical measurement in next section.

V. MEASUREMENT RESULTS AND DISCUSSIONS

This involves numerous preparation tasks such as sensor device characterization, parameter extraction, equipment setup and test circuit prototype prior to test the functionality of new readout circuit and to confirm the effectiveness of novel temperature compensation method for the sensor as well as its transducer to measure different pH values against a range of temperature.

A. Measurement Setup and ISFET Parameters Extraction

The Si_3N_4 -gate pH-sensitive ISFET sensor is commercially available by D+T Microelectrónica, A.I.E (CNM), Spain. The interface circuit was built on a prototype board using discrete electronic components. The MOS transistor M1 was realized by a CD4007 transistor array IC chip having four nMOS transistors as well as four pMOS transistors. The constant biasing currents I_B and I_O were established through two LM134 ICs, with a 3-terminal adjustable current source programmable from $1 \mu\text{A}$ to 10 mA in each IC. The whole circuit worked at a single

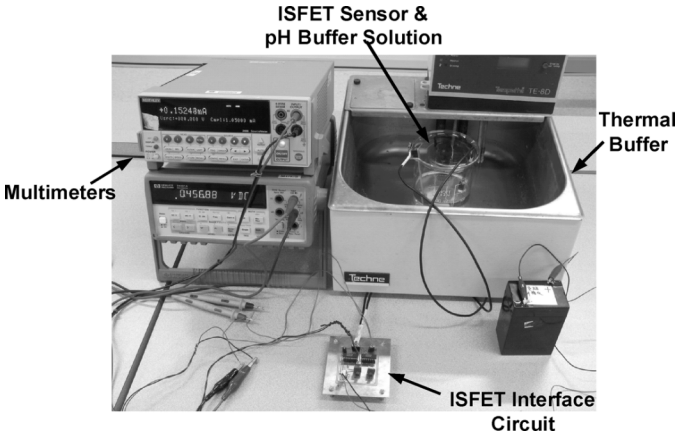


Fig. 3. Experimental setup for the ISFET interface circuit.

3.3-V supply, having adequate headroom for the ISFET device to operate in saturation region under discrete implementation. The output of the circuit V_{out} and the biasing current I_B , were monitored by HP 3486 multi-meters. The buffer solution where the ISFET was inserted was kept in a thermal buffer so as to control temperature of buffer solution during the measurement process. Although the thermal buffer supported the measurement at room temperature or above, the temperature compensation method was still verified. Fig. 3 shows the experimental setup for the interface circuit.

The I_D - V_{GS} characterization of the ISFET device under test (biasing in deep triode region in another circuit board) was performed using HP4156 Semiconductor Parameter Analyzer in targeted buffer solutions, leading to the extracted ISFET threshold voltages $V_{th(pH_{min})} = V_{th(pH4)} = -244.413$ mV, $V_{th(pH7)} = -87.6536$ mV, and $V_{th(pH_{max})} = V_{th(pH9)} = -21.8782$ mV at room temperature. Besides, the threshold temperature coefficient in pH7 was extracted as $K_{VT(pH7)} = -2.034$ mV/ $^{\circ}C$. Regarding the ISFET temperature compensation methodology described in Section IV, some of the important parameters of ISFET were extracted on the basis of measured transfer characteristics at room temperature. This was done using MATLAB. The extracted parameters for computation are summarized as follows: $\beta_0 = 0.001357$ A/ V^2 , $\theta = 0.0821$ V $^{-1}$ and $m = -2.2$. In another remark, the pH sensitive parameter $\alpha \approx 0.9187$ at room temperature was calculated from the measurement result of interface circuit. It is interesting to point out that the variation of ISFET biasing current has almost no effect on its pH sensitivity [25] but the temperature has direct impact on ψ_{eo} as revealed in (6).

B. Measured Results of ISFET Interface Circuit in Room Temperature

The electro-chemical measurements of the proposed readout circuit were conducted in three kinds of standard buffer solutions having pH value of 4, 7, and 9. The ISFET and source follower was biased at respective constant biasing current, with $I_B = 100$ μ A and $I_o = 30$ μ A under stable room temperature (22 $^{\circ}C$). The output signal was measured when inserting the ISFET sensor into different standard buffer solutions. The

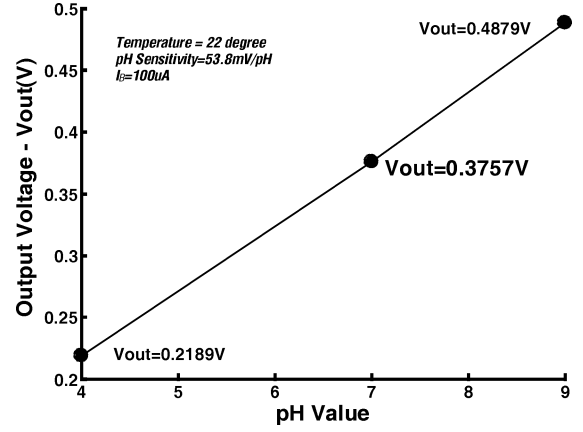


Fig. 4. Measured output signal (V_{out}) of readout circuit against different pH values at 22 $^{\circ}C$.

ISFET sensor had been cleaned by Deionized (DI) water every time before it was inserted into a new buffer solution. The measurement result is plotted in Fig. 4. The slope denotes the pH sensitivity of the readout circuit, showing about 53.8 mV/pH. Hence, the experimental result has validated that the proposed interface circuit is able to detect the variation of the ISFET threshold voltage.

Unlike part of previous works, there is no critical matching requirement in the design. Even though the body effect induced to the source follower appears in a form of minute change of drain potential in the ISFET, the drain current remains stable because the drain current is almost independent against finite variation of drain-to-source voltage in a long channel ISFET device. Due to absence of body effect in the ISFET sensor, a linear response has been obtained by the measurement result in Fig. 4. It is important to highlight that only a few reported works [7], [8] can claim such an advantage. Table I compares the readout circuit with the prior-art works. It can be seen that the proposed readout circuit displays very simple structure (three transistors plus 1 ISFET to form a core interface). Not only does it reduce the number of current sources and operational amplifier(s), it is expected to exhibit low dc offset sensitivity and to benefit the temperature compensation in an ease manner. Furthermore, the source follower formed by the transistor M1 and current source I_o in Fig. 2 offers low sensitivities with respect to design and process parameters as well as good bandwidth efficiency, so the circuit stability can be guaranteed easily when only one high impedance node exists in the feedback structure.

C. Measured Results of Dynamic Biasing Current Temperature Compensation

For demonstrating the temperature compensation method, different buffer solutions (pH4, pH7, and pH9) are used in the experiment. Consider the case of testing a pH4 buffer solution at 40 $^{\circ}C$ as the first example; the steps for the iteration method are given as follows.

Step 1) The ISFET V_{out} —pH transfer characteristics for specific test solutions pH_{min} , pH7 and pH_{max} at different biasing currents are measured in room temperature, and the measured output voltage at specific pH point ($pH_{min} = 4$, pH7 or $pH_{min} = 9$)

TABLE I
COMPARISON OF PROPOSED CIRCUIT WITH REPORTED REDOUT CIRCUITS

Design parameters	Sensitivity to body effect	No of major Op-amps	DC offset sensitivity to non-ideal components
Ravezzi Ref[2] 1998	Yes	3	Offsets in 3 op-amps + 2 current sources
Yuan-Lung Ref[13] 2001	Yes	1	Offset in 1 op-amp + ISFET/MOSFET differential pair
Tukkieami Ref[4] 2002	Yes	2	Offsets in 2 op-amps + 2 current source
Morgenshtein Ref[7] 2004	No	1	Offset in 1 op-amp + 1 current source
D.Y.Chen Ref[8] 2005	No	1	Offset in 1 op-amp + 1 current source
This Work 2006	No	0	1 current source

in Table II is converted back to corresponding pH value, which will be treated as the initial reference data. As can be seen from the look-up Table II, the linear response of output of the proposed ISFET readout circuit with respect to the pH value of the solution can represent the ISFET device characteristics.

The term $(T_1/T_0)^{m+2} = (T_1/T_0)^{-0.2}$ in (17) can be simplified via Taylor series to get the approximation

$$f(T_1) = \left(\frac{T_1}{T_0}\right)^{-0.2} \cong f(T_0) + f'(T_0)(T_1 - T_0) \\ = 1.2 - 0.2 \left(\frac{T_1}{T_0}\right). \quad (28)$$

Since the temperature range in this experiment is from 22 °C to 50 °C, the average value of 36 °C is used as initial guess value. Through (28), one can calculate the reference $I_{DS(\text{pH}7)} \cong 192 \mu\text{A}$ using (17) with the extracted parameters in Section V-A and the measured output voltage of $V_{\text{out}} \approx V_{GS(\text{pH}7)} = 0.4175 \text{ V}$. Since the output voltage is smaller than the $V_{\text{out}(\text{pH}7)}$ at a biasing current of $I_{DS(\text{pH}7)} \cong 192 \mu\text{A}$ in Table II, (26) is selected and the result of calculation gives the initial guess of $\text{pH}_C = \text{pH}_{C1} = 3.789$.

Step 2) When $\text{pH}_C = 3.789$ is obtained from step 1. It is then substituted into (21) to get $\Delta\text{pH} = \text{pH} - \text{pH}7 = \text{pH}_C - \text{pH}7 = -3.211$. Then, the calculated ΔpH is substituted into (25) to calculate the new biasing current, which is $I_{B(1)} \approx 316 \mu\text{A}$.

Step 3) The ISFET is biased with this new current $I_{B(1)}$ and a new output voltage of the interface circuit can be measured as $V_{\text{out}} = 0.6480 \text{ V}$. Since it is smaller than the $V_{\text{out}(\text{pH}7)}$ at a biasing current of $I_{DS(\text{pH}7)} \cong 316 \mu\text{A}$ in Table II, (26) is selected

TABLE II
MEASURED RESULTS OF ISFET READOUT CIRCUIT AT ROOM TEMPERATURE (22 °C) FOR REFERENCE DATA

Biasing current I_B (μA)	Output Voltage of Readout Circuit – (V)		
	$V_{\text{out}(\text{pH}4)}$ (at pH4)	$V_{\text{out}(\text{pH}7)}$ (at pH7)	$V_{\text{out}(\text{pH}9)}$ (at pH9)
$I_B=100$	0.2189	0.3757	0.4879
$I_B=102$	0.2244	0.3814	0.4937
:	:	:	:
$I_B=192$	0.4286	0.5863	0.6989
:	:	:	:
$I_B=306$	0.6319	0.7901	0.9031
$I_B=308$	0.6351	0.7933	0.9062
:	:	:	:
$I_B=316$	0.6477	0.8058	0.9186
:	:	:	:
$I_B=360$	0.7214	0.8798	0.9935

again and the result of calculation gives $\text{pH}_{C2} = 4.006$ for the second iteration.

Step 4) As $\text{pH}_{C2} \neq \text{pH}_{C1}$ (initial guess value), the step 2 and step 3 would be repeated. $\text{pH}_{C2} = 4.006$ from step 3 is substituted into (21) again to obtain the $\Delta\text{pH} = \text{pH}_{C2} - \text{pH}7 = -2.994$, which is then substituted into (25) to calculate the new biasing current of $I_{B(2)} \approx 308 \mu\text{A}$. Hence, a new output voltage of the readout circuit becomes $V_{\text{out}} = 0.6348 \text{ V}$. A new pH_C can be converted from Table II to get $\text{pH}_{C3} = 3.994$.

Step 5) Since $\text{pH}_{C3} \neq \text{pH}_{C2}$, which means the iteration result is not converged, the step 2 and step 3 would be repeated in the same way as described in step 4. As a result, a new biasing current $I_{B(3)} \approx 308 \mu\text{A}$ and the corresponding output voltage $V_{\text{out}} = 0.6348 \text{ V}$ are obtained. From Table II and (26), the converted pH value is $\text{pH}_{C4} = 3.994$. When $\text{pH}_{C4} = \text{pH}_{C3}$, the pH_C converges from successive iterations. Finally, the ISFET device will be biased at $I_{B(3)}$, which forces the ISFET device operating around the *Z.T.C.* point and so $\text{pH} = \text{pH}_{C4} = 3.994$ becomes the final result.

Following the same procedures as described in above steps, the iteration results of ISFET temperature compensation as well as the final biasing current for providing the temperature compensation in pH4 buffer solution at 30 °C and 50 °C are shown in Table III. This will be repeated for pH7 and pH9 at identical temperature. The measured results for pH4, pH7, and pH9, with and without temperature compensation, are depicted in Figs. 5–7, respectively. The final biasing currents that achieve ISFET temperature compensation in pH7 at 30 °C, 40 °C, and 50 °C are 192, 190, and 190 μA , while the final biasing currents for pH9 at 30 °C, 40 °C, and 50 °C are 130, 130, and 134 μA .

Fig. 5 shows the negative *T.C.* (without compensation) in pH4 is compensated. However, the minute compensation in pH7 can be explained by the fact that it is used as the reference in the compensation process and the calculated initial current (17) already forces the ISFET to work in athermal point in

TABLE III
MEASURED RESULTS OF ISFET DYNAMIC TEMPERATURE COMPENSATION IN pH4 BUFFER SOLUTION

Temperature (°C)	30	40	50
Actual pH value	4.01	4.01	4.00
Before compensation	3.924	3.789	3.509
First iteration	3.998	4.006	3.926
Second iteration	3.998	3.994	3.874
Third iteration		3.994	3.899
Fourth iteration			3.899
Deviation	0.012	0.016	0.101
Final Biasing Current	306 μA	308 μA	312 μA

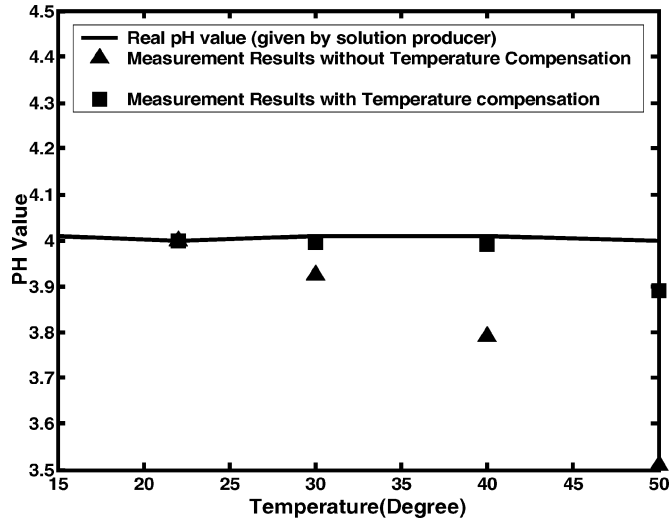


Fig. 5. Measured results of temperature compensation in pH4.

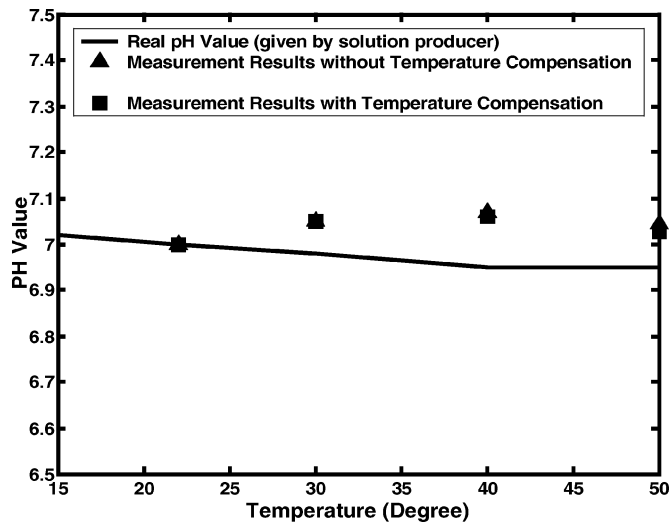


Fig. 6. Measured results of temperature compensation in pH7.

pH7. The compensation method also works for compensating positive $T.C.$ (without compensation) in pH9. Hence, the experimental evidence has confirmed that the proposed ISFET

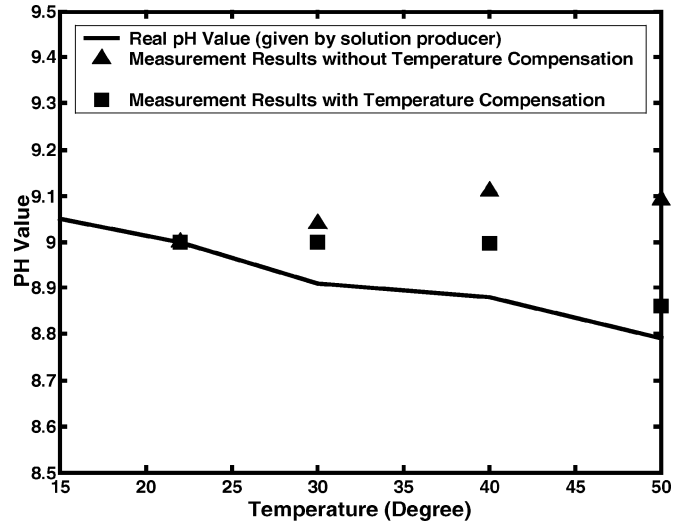


Fig. 7. Measured results of temperature compensation in pH9.

TABLE IV
TEMPERATURE COEFFICIENTS OF BUFFER SOLUTION PROVIDED BY MANUFACTURER AND MEASURED pH VALUES

	pH4	pH7	pH9
	a_1 (pH/°C)	a_1 (pH/°C)	a_1 (pH/°C)
	a_2 [pH/(°C) ²]	a_2 [pH/(°C) ²]	a_2 [pH/(°C) ²]
Buffer solution	0.0002143 -2.77E-6	-0.003079 4.474E-5	-0.007263 1.579E-5
Without temp. compensation	-0.01406 -2.79E-5	0.007171 -1.903E-4	0.007237 -1.342E-4
With temp. compensation	-0.002543 -1.23E-5	0.007158 -2.095E-4	-0.007263 9.579E-5

iteration temperature compensation technique is able to perform compensation in the pH measurement range of 4 to 9. It is noted that the full solid line within each figure represents the temperature effect of pH buffer solution, which is provided by the manufacturer and is served as a reference.

A quadratic polynomial is employed to approximate a pH temperature-dependent function as follows:

$$f(T_1) = a_0 + a_1(T_1 - T_0) + a_2(T_1 - T_0)^2 \quad (29)$$

where T_0 is the reference temperature (room temperature). $f(T_1)$ is defined as the pH value at a given temperature T_1 in the range of T_0 to 50 °C. a_0 is defined as the pH value at T_0 . The respective value obtained for a_0 in pH4, pH7, and pH9 buffer solution is 4, 7, and 9. a_1 and a_2 is the corresponding first-order and second-order temperature coefficient. The extracted values for a_1 and a_2 by MATLAB are given in Table IV.

As observed, the small values in first-order and second-order temperature coefficients reflect the effectiveness of the temperature compensation scheme. As pH7 is treated as reference, the temperature coefficients remain very close with or without temperature compensation. The reason has already been mentioned. Unlike prior-art work of ISFET temperature compensation techniques, this proposed technique is nonlinear temperature compensation. This is very suitable for compensation of nonlinear

$T.C.$ of ISFET threshold voltage in different pH buffer solutions such that the deviation of measured pH value from actual pH value will not be enlarged significantly with temperature, thus demonstrating its advantage for supporting wider temperature range. Since the ISFET temperature compensation technique can compensate the temperature effect on a single ISFET, it supports ease of fabrication, thus leading to a low cost solution for smart sensors. Besides, the fabrication process for separated functional devices can be optimized to improve the performance of ISFET sensor [19]. Finally, there is no temperature sensor, such as p-n junction diode [13], to be fabricated and calibrated. Despite of current discrete implementation, in integrated IC application perspective, the biasing current of mutual compensation can be further minimized by reducing the W/L aspect ratios of ISFET device for lowering the total power consumption [13] or optimized in the ISFET process technology. In the future work, a micro-controller-based measurement system will be employed to carry out the ISFET temperature compensation automatically.

VI. CONCLUSION

A new CMOS ISFET readout circuit is presented. Validated by electro-chemical measured results, the circuit has shown insensitivity to the body effect. Therefore, the pH sensitivity of the readout circuit well reflects the pH sensitivity of the ISFET sensor. Besides, the intrinsic simple structure not only reduces the circuit components and its circuit sensitivity, it also supports a novel ISFET temperature compensation technique, at expense of increased computation complexity, to give a low cost solution. The derivation of a unified expression for temperature-dependent ISFET threshold voltage in association with mutual compensation analysis on mobility and threshold voltage establish the theoretical basis equations for temperature compensation purpose. Through iteration method for solving nonlinear equations, there exists an optimum biasing current for athermal point of the ISFET at different pH values in a temperature range. This is contrasting to conventional techniques that use circuit means to provide linear or nonlinear $T.C.$ compensation, which is valid for narrow pH range. The proposed compensation method has been verified by the experimental results. As a result, the new ISFET readout circuit in along with the dynamic biasing current temperature compensation technique will be very useful for smart sensors.

REFERENCES

- [1] P. Bergveld, "Development of an ion-sensitive solid-state device for neurophysiologic measurements," *IEEE Trans. Biomed. Eng.*, vol. 17, no. 1, pp. 70–71, Jan. 1970.
- [2] L. Ravezzi and P. Conci, "ISFET sensor coupled with CMOS read-out circuit micro-system," *Electron. Lett.*, vol. 34, no. 23, pp. 2234–2235, Nov. 1998.
- [3] B. Palán, F. V. Santos, J. M. Karam, B. Courtois, and M. Husák, "New ISFET sensor interface circuit for biomedical applications," *Sens. Actuat. B*, vol. 57, pp. 63–68, 1999.
- [4] K. Tukineami, "Study of CHMFET interface electronics," in *Proc. MIXDES Conf.*, 2002, pp. 20–22.
- [5] S. Casans, A. E. Navarro, D. Rmirez, E. Castro, A. Baldi, and N. Abramova, "Novel voltage-controlled conditioning circuit applied to the ISFETs temporary drift and thermal dependency," *Sens. Actuat. B*, vol. 91, pp. 11–16, 2003.
- [6] C. H. Yang, W. Y. Chung, K. K. Lin, D. G. Pijanowska, and W. Torbicz, "A low-power telemetric system design for ISFET-based sensor array applications," in *Proc. Eur. Conf. Circuit Theory Design (ECCTD)*, Sep. 2003, vol. I, pp. 260–263.
- [7] A. Morgenshtein, L. Sudakov-Boreysya, and U. Dinnar, "CMOS readout circuitry for ISFET micro-systems," *Sens. Actuat. B*, vol. 97, pp. 122–131, 2004.
- [8] D. Y. Chen, P. K. Chan, and M. S. Tse, "A CMOS ISFET interface circuit for water quality monitoring," in *Proc. IEEE Conf. Sensors*, Irvine, CA, Nov. 2005, pp. 1217–1220.
- [9] A. Sibbald, "A chemical-sensitive integrated-circuit: The operational transducer," *Sens. Actuat.*, vol. 7, pp. 23–38, 1985.
- [10] H. S. Wong and M. H. White, "A CMOS-integrated 'ISFET-Operational amplifier chemical sensor employing differential sensing'," *IEEE Trans. Electron Devices*, vol. 36, no. 3, pp. 479–487, Mar. 1989.
- [11] L. Ravezzi, D. Stoppa, M. Corrá, G. Soncini, G.-F. Dalla Betta, and L. Lorenzelli, "A CMOS ASIC for differential read-out of ISFET sensors," in *Proc. Int. Conf. Electronics, Circuits Syst.*, Sep. 2001, vol. 3, pp. 1513–1516.
- [12] C. Y. Aw and P. W. Cheung, "A pH-ISFET sensor with on-chip temperature sensing," in *Proc. IEEE Int. Conf. Eng. Medicine Biol.*, 1998, pp. 772–773.
- [13] Y. Lung, J. C. Chou, T. P. Sun, W. Y. Chung, and S. K. Hsiung, "A novel pH sensitive ISFET with on chip temperature sensing using CMOS standard process," *Sens. Actuat. B*, vol. 76, pp. 582–593, 2001.
- [14] A. Morgenshtein, L. Sudakov-Boreysya, U. Dinnar, C. G. Jakobson, and Y. Nemirovsky, "Wheatstone-Bridge readout interface for ISFET/REFET applications," *Sens. Actuat. B*, vol. 98, pp. 18–27, 2004.
- [15] C. D. Fung, P. W. Cheung, and W. H. Ko, "A generalized theory of an electrolyte-insulator-semiconductor field-effect transistor," *IEEE Trans. Electron Devices*, vol. ED-33, no. 1, pp. 8–18, Jan. 1986.
- [16] D. L. Harme and L. Bousse, "Ion-sensing device with silicon nitride and borosilicate glass insulators," *IEEE Trans. Electron Devices*, vol. ED-34, no. 8, pp. 1700–1707, Aug. 1987.
- [17] M. Grattarola, G. Massobrio, and S. Martinoia, "Modeling H^+ -sensitive FET's with SPICE," *IEEE Trans. Electron Devices*, vol. 39, no. 4, Apr. 1992.
- [18] R. E. G. Van Hal, J. C. T. Eijkel, and P. Bergveld, "A novel description of ISFET sensitivity with the buffer capacity and double-layer capacitance as key parameters," *Sens. Actuat. B*, vol. 24–25, pp. 201–205, 1995.
- [19] P. Bergveld, "Thirty years of ISFETOLOGY what happened in the past 30 years and what may happen in the next 30 years," *Sens. Actuat. B*, vol. 88, pp. 1–20, 2000.
- [20] Y. P. Tsividis, *Operation and Modeling of the MOS Transistor*. New York: McGraw-Hill, 1999.
- [21] S. Martinoia and G. Massobrio, "A behavior macro-model of the ISFET in SPICE," *Sens. Actuat. B*, vol. 62, pp. 182–189, 2000.
- [22] P. R. Barabash, R. S. C. Cobbold, and W. B. Wlodarski, "Analysis of the threshold voltage and its temperature dependence in electrolyte-insulator-semiconductor field-effect transistor (EISFET's)," *IEEE Trans. Electron Devices*, vol. 34, pp. 1271–1282, 1987.
- [23] S. Martinoia, L. Lorenzelli, G. Massobrio, P. Conci, and A. Lui, "Temperature effects on the ISFET behaviour: Simulations and measurements," *Sens. Actuat. B*, vol. 50, pp. 60–68, 1998.
- [24] J. C. Chou, Y. F. Wang, and J. S. Lin, "Temperature effect of a-Si:H pH-ISFET," *Sensor and Actuators B*, vol. 62, pp. 92–96, 2000.
- [25] J. C. Chou, C. Y. Weng, and H. M. Tsai, "Study on the temperature effect of Al_2O_3 gate pH-ISFET," *Sens. Actuat. B*, vol. 81, pp. 152–157, 2002.
- [26] I. M. Filanovsky and A. Allam, "Mutual compensation of mobility and threshold voltage temperature effects with applications in CMOS circuits," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 48, no. 7, pp. 876–884, Jul. 2001.
- [27] F. M. Klaassen and W. Hes, "On the temperature coefficient of the MOSFET threshold voltages," *Solid-State Electron.*, vol. 29, no. 8, pp. 787–789, 1986.
- [28] S. M. Sze, *Physics of Semiconductor Device*, 2nd ed. New York: Wiley, 1981.



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