A Time-domain Method for Correction of Instability in Sensors Based on Field Effect Transistors (FETs)

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Abstract— A time-domain method for correction of threshold voltage instability, commonly known as drift, in FET-based sensors is presented. The instability of the dc operating point in this class of sensors is characterized by a relatively slow, monotonic temporal drift in the threshold voltage of the FET in the absence of variations in the measurand of interest. The proposed method is equivalent to correction of drift by constructing a corrected sensor response via integrating the differential of the measuring signal arising solely from changes in the measurand. This method allows accurate continuous monitoring of the measurand in presence of drift if the drift rate is sufficiently smaller than the product of sensor sensitivity and the rate of change of the measurand. The validity of the proposed method is experimentally confirmed under *in vitro* conditions approximating rapid changes in physiological pH such as those encountered clinically in acute metabolic acidosis or cardiopulmonary bypass operation. Finally, the relevance of the distinction between drift and flicker (*1/f*) noise to the proposed method is discussed.

Keywords— Continuous monitoring, Drift, FET-based Sensor, Instability, ISFET, Pd-gate MOSFET.

I. Introduction

THE pH-sensitive ion-selective field effect transistor (ISFET) and the hydrogen-sensitive, catalytic metal-insulator-semiconductor field effect transistor (MISFET) gas sensor represent two prevalent sensors belonging to the general class of FET-based sensors. In 1970 ISFET was introduced [1] as a solid state device linking the chemical sensitivity exhibited by a membrane with the field-sensing capability of a FET. A hydrogen-sensitive gas sensor compatible with integrated circuit (IC) technology was introduced in 1975 using a catalytic metal, namely palladium, as the gate metal of an MOS transistor [2]. FET-based sensors offer such advantages as small size, robustness, and low cost over sensors relying on conventional chemical electrode technology such as the glass pH-meter. While commercially available electrodes are small enough for *in vivo* applications, their fragility and relatively high manufacturing cost represent significant disadvantages. In contrast, FET-based sensors can be manufactured using the CMOS IC technology, which not only provides the level of miniaturization necessary for installation of FET-based biosensors in catheter tips, but also offers the tremendous cost advantage resulting from batch fabrication.

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However, threshold voltage instability commonly known as drift, has presented a serious impediment to commercialization of FET-based sensors. Drift is characterized by a relatively slow, unidirectional temporal variation in the threshold voltage and, hence, in the drain current of FET in the absence of changes in the measurand of interest (e.g. concentration of the ion or partial pressure of gas). Instability in FET-based sensors typically exhibits complex nonlinear dynamics characterized by a random-looking evolution in time following an initial, relatively fast transient [3],[4]. To date a physical model for drift in FET-based gas sensors, which is capable of accounting for experimental drift data quantitatively, has not been advanced. However, a deterministic physical model providing an accurate, quantitative description of the dynamics of the nonlinear drift behavior exhibited by Si_3N_4-gate and Al_2O_3-gate pH ISFETs [5],[6] has been proposed. While nonlinear processes can be evaluated in presence of unknown noise statistics and unmodeled dynamics [7], rigorous application of established methods employed in the Nonlinear Dynamics discipline such as stability analysis [8],[9] can shed a new light on the sensor drift behavior.

The high accuracy commonly required in continuous monitoring applications imposes stringent requirements on the tolerable drift rate in FET-based sensors. For example, continuous monitoring of plasma pH during surgery requires an accuracy of 0.02pH unit over a 10-hour period without recalibrations. Assume an H^+-sensitive FET is to be used for this application. The ideal sensitivity, $\partial M/\partial pH$ of a FET employing inorganic insulators as the pH-sensitive gate material is given by [10]

$$\frac{\partial M}{\partial pH} = -\ln(10)\cdot\frac{kT}{q} = -2.30\frac{kT}{q} \qquad (1)$$

where M is the measuring signal (sensor output), and k, T, and q represent the Boltzman constant, the absolute temperature, and the charge of an electron respectively. Therefore, for a pH-sensitive ISFET with ideal sensitivity, the accuracy requirement of 0.02pH unit over a 10-hour period dictates a maximum equivalent drift rate of 0.002pH/hour or a maximum tolerable drift rate of (61.8mV/*p*H)(0.002*p*H/hour) or 0.12mV/hour in the sensor output signal at the normal core body temperature of 37C. Typically, at pH=7, the drift rate in pH-sensitive ISFETs employing CMOS-compatible inorganic gate insulators such as silicon nitride is on the order of millivolts per hour following the exposure of the insulator surface to an electrolyte, whereas the long-term drift rate is on the order of several tenths of a millivolt per hour following an exposure period of 12-16 hours [11]. Therefore, a typical pH-sensitive ISFET does not satisfy the stability requirements for *in vivo* continuous monitoring.

The approaches suggested as potential solutions to the ISFET instability problem can be categorized into three groups. The first category consists of drift correction or compensation techniques involving post-processing of the measuring signal [3], [4] [12], [13], [14], [15]; the second methodology comprises circuit approaches counteracting drift [16], [17], [18], [19], while the third category consists of approaches employing sensing materials, which inherently exhibit a higher resistance to long-term chemical modification [20], [21], [22]. The remedies corresponding to the second and third categories of solutions to ISFET instability are generally more costly; circuit approaches lead to higher component count and increased power consumption, while use of novel sensing materials is associated with an increase in process complexity and manufacturing costs.

Physically-informed signal processing has been shown to serve as an effective approach to correction of ISFET drift [3], [4], [12], [13], [14]. Application of this approach has been justified based on the physical model for ISFET drift [5],[6]. In this work a time-domain method for correction of drift in FET-based sensors is presented. The validity of this method is experimentally confirmed using Si_3N_4-gate pH-sensitive ISFETs through continuous monitoring of pH under *in vitro* conditions approximating acute metabolic acidosis or cardiopulmonary bypass operation, which involve abrupt changes in pH.

II. Time-domain Correction Method

The general formulation of the proposed time-domain method for extraction of the measuring signal from the sensor output signal containing the superimposed temporal variations associated with drift is developed in this section. In general for a FET-based sensor suffering from threshold voltage drift the measuring signal, M (sensor output) consists of a signal arising from the measurand to be sensed, S and a superimposed drift component with explicit time dependence. The total differential of the sensor output signal, therefore, can be written as

$$dM = \frac{\partial M}{\partial S}\cdot dS + \frac{\partial M}{\partial t}\cdot dt \tag{2}$$

where $\partial M/\partial S$ is the sensitivity of the of the sensor to the measurand of interest. As far as the interaction between the sensor and the measurand is concerned, the measurand can be considered to be a function of time only. Therefore, equation (2) yields

$$dM = (\frac{\partial M}{\partial S}\cdot\frac{dS}{dt} + \frac{\partial M}{\partial t})\cdot dt \tag{3}$$

Examination of the measured drift data [2],[5],[6], however, reveals that the long-term instantaneous drift rate, $\partial M/\partial t$ in FET-based sensors is relatively small. Therefore, over sufficiently small intervals of time, $\Delta t \rightarrow dt$, equation (3) can be rewritten as

$$\Delta M = \frac{\partial M}{\partial S}\Delta S \tag{4}$$

provided that

$$\frac{\partial M}{\partial S}\cdot\frac{dS}{dt} >> \frac{\partial M}{\partial t} \tag{5}$$

For a sensor with a high sensitivity, $\partial M/\partial S$, the requirement given by equation (5) is readily satisfied, if the rate of change of measurand is relatively high. From equation (4) over sufficiently small sampling times, Δt, the sensor responds only to variations in the measurand, thereby allowing construction of a corrected response by integrating the differential change in the measuring signal.

It is important to note that the validity of the proposed method requires that throughout monitoring, the variations in the measuring signal over individual sampling times, Δt arise only from changes in the measurand. Hence, ΔM values must be clearly discerned from variations arising from drift and/or noise. This can be accomplished by choosing sufficiently small sampling times, Δt (e.g., several seconds) as compared to the overall monitoring period (e.g., several hours) and assessing the validity of equation (5). The magnitude of variations in the sensor output signal originating from the measurand over successive sampling times, Δt, are consistently of a given polarity (either positive or negative), whereas variations arising from drift and/or noise frequently alternate in polarity. These distinguishing features can be easily implemented in software. Assuming the sensitivity of the sensor does not change with time, dividing ΔM by the sensitivity, $\partial M/\partial S$ yields the variation of the measurand as a function of time.

III. Experimental Verification

The proposed method has been applied to correct the operating point instability exhibited by Si_3N_4-gate pH-sensitive ISFETs [12],[13],[14].

A. Characterization of ISFET Drift

The ISFET is commonly operated in two measurement modes. In the feedback mode, the drain current, I_D is fixed by applying a compensating feedback voltage to the solution side of the gate (e.g., using a double junction type calomel reference electrode) as shown in Fig. 1. Ideally, the changes in this feedback voltage characterize the ISFET response to variations in the ion concentration. Alternatively, a constant gate voltage, V_{GS} can be applied to the reference electrode using a reference voltage or simply a dc power supply as

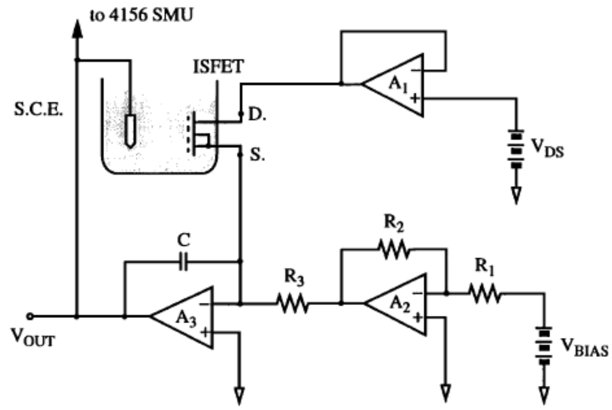

Fig. 1. Circuit used for characterization of ISFET Drift in the feedback mode, A_1, A_2, A_3 are opamps.

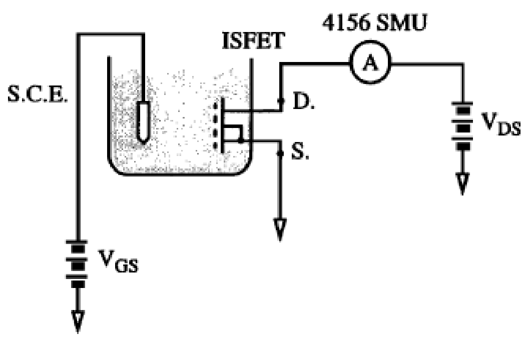

Fig. 2. Circuit used for characterization of ISFET drift with a constant voltage applied to the reference electrode.

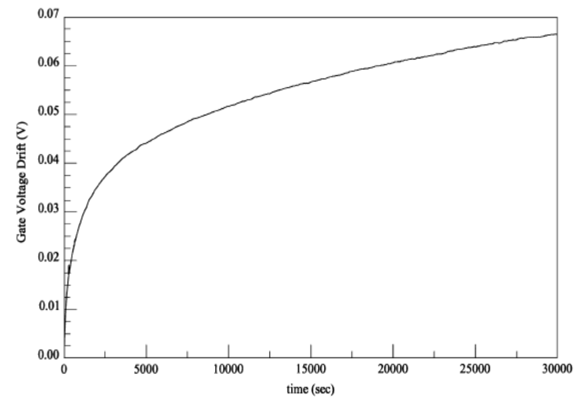

Fig. 3. Si_3N_4-gate ISFET drift characteristics in the feedback mode I_D=100μA , pH = 7.

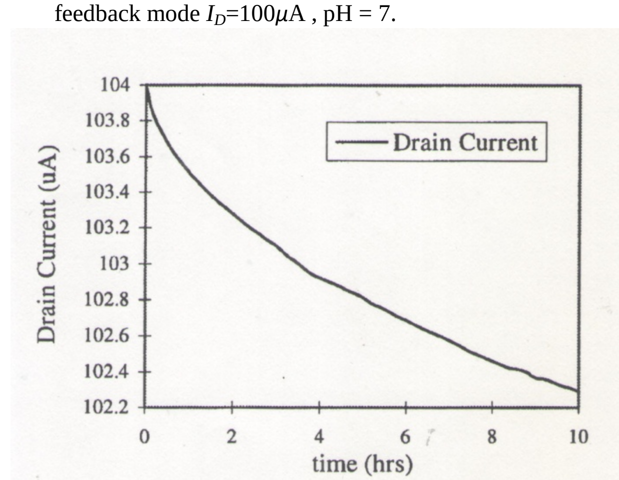

Fig. 4. Si_3N_4-gate pH-ISFET Drift Characteristics, pH=7

shown in Fig. 2, in which case the ISFET response corresponds to changes in the drain current. This measurement mode may, therefore be referred to as the current mode. Characterization of drift behavior involves measuring the temporal change in the ISFET's dc operating point, either I_D or the compensating feedback voltage, V_{GS} at a constant ion concentration (e.g., pH). The two modes of operation, however, are in principle equivalent to one another as far as the accuracy associated with detection of concentration changes in presence of drift is concerned [23]. In particular, for a given operating point, in both modes of operation the signal-to-drift ratio, *S/D* which denotes the ratio of device response arising from pH variations to that arising from drift, is given by [23]

$$S/D = (-2.30\frac{kT}{q}) \cdot \left(\frac{1}{\frac{\partial V_{TH}(t)}{\partial t}} \right) \cdot \left(\frac{dpH}{dt} \right) \quad (8)$$

where V_{TH} denotes the threshold voltage of the ISFET.

The typical drift characteristics of a Si_3N_4-gate pH-sensitive ISFET in the feedback mode and with a constant voltage applied to the gate (reference electrode) are shown in Figs. 3 and 4, respectively.

Examination of the measured drift data reveals that over time durations on the order of seconds, the gate voltage in the feedback mode of operation exhibits only random fluctuations which may be attributed to fundamental sources of noise and/or reference voltage variations. Furthermore, according to the proposed model for drift [5],[6], the time constant characterizing drift is on the order of several hours, which implies that over a time interval of several seconds, drift is negligible. The relatively slow, temporal variation characterizing long-term drift in pH-sensitive ISFETs, and palladium-gate MOSFETs forms the basis of the proposed analytical method for correction of instability in FET-based sensors.

B. Current-mode Correction of ISFET Drift

The validity of the proposed method has been examined using a Si_3N_4-gate pH-sensitive ISFET operating in the current mode to monitor pH variations in the 3.5-10.0 range [12],[14]. In all measurements the ISFET's were biased in the triode region with V_{GS}=2.1V, and V_{DS}=0.2V. Solutions with pH values of 3.5, 5.4, 7.0, 9.0, and 10.0 were obtained by adding 1M HCl or 1M KOH to a solution with 0.05M phosphate monobasic and 0.142M KCl concentrations. pH values were measured using the a Corning semi-microcombination pH probe and the Orion Research™ 601A pH meter with an accuracy of ± 0.01pH unit. The ISFET was calibrated using the five pH values indicated above, and the calibration curve was constructed using the average of five measured drain current values at each pH. The device sensitivity (change in the triode drain current per unit change in pH) was determined based on linear regression to be -4.234μ*A*/*p*H at room temperature. Five beakers were prepared each of which contained one of the solutions with the given pH value. Following device calibration, the ISFET was arbitrarily exposed to each of the solutions for various time intervals. The resulting pH response was monitored by measuring the drain current at 30-second intervals. To estimate the change in the pH value the difference between the drain current immediately prior to transfer of the ISFET from the given solution and the drain current measured after transfer to the new solution was determined. The magnitude of the drain current difference divided by the measured device sensitivity represented the change in pH value. During the transfer the ISFET and the reference electrode were manually placed in the new solution with a maximum time delay of 30 seconds. The pH response of the ISFET is shown in Fig. 5.

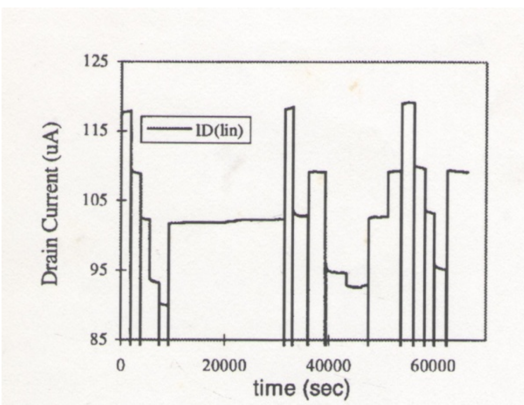

Fig. 5. pH Response of the Si_3N_4-gate pH- ISFET

The pH transitions corresponded to abrupt changes in the drain current, and the spikes were due to erroneous initial readings obtained immediately following the introduction of the ISFET and reference electrode into the new solution. The pH transitions along with the measured changes in the pH determined using the ISFET are given in chronological order in Table1. As indicated in Table 1, with the exception of large step changes in pH (i.e. $|\Delta pH|>3$) and the 9.0→10.0 pH transition, the accuracy of the estimated change in pH is within ± 0.1pH unit of the values of change predicted by the pH meter.

C. Correction of Drift in the Feedback-mode

The application of the proposed method has also been demonstrated by continuous monitoring of pH under in vitro conditions approximating acute metabolic acidosis using a Si_3N_4 gate pH-sensitive ISFET biased in the feedback mode at I_D=100μA [13,24]. In order to ensure high accuracy, the ISFET had been previously immersed in a Potassium phosphate buffer at pH=7 for a period of one hour to avoid the relatively high initial drift rate. The sensitivity of the ISFET had been determined to be 44.647 mV/pH prior to the exposure of the device to the buffer solution, using standard buffer solutions of pH=4 and pH=7. The decrease in pH simulating a worsening metabolic acidosis condition was induced by adding 50μL of 2N hydrochloric acid to a 0.05M potassium phosphate monobasic/0.142M KCl buffer solution (initially at pH=7) at 5-minute intervals, and the compensating feedback voltage applied to the Calomel reference electrode was monitored over sampling times of 3-second duration. During this experiment, the pH was also monitored using a Piccolo Plus pH meter with an accuracy of ± 0.01pH pH unit. The measured pH response is shown in Fig. 6.

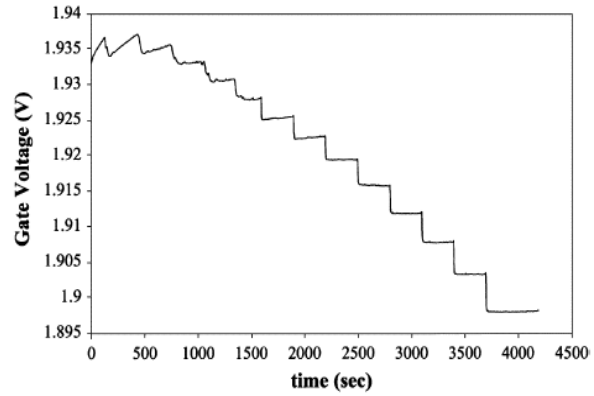

Fig. 6. pH response of a Si_3N_4-gate ISFET with 50μL of acid added at 5-min intervals.

The sharp decrease in the gate voltage at the end of each 5-min interval corresponds to the resulting drop in pH following addition of the acid. The large initial drift rate is evident from the relative magnitude of the increase in the gate voltage during the first and second time intervals. Based on the correction method described above, the variations in the pH were extracted from the gate voltage-versus-time data of Fig. 6. As shown in Fig. 7, the variations in pH estimated based on the corrective scheme are in good agreement with that measured using the pH meter over the entire monitoring period. The observed differences are within the accuracy of the meter ($\pm$ 0.01 pH unit).

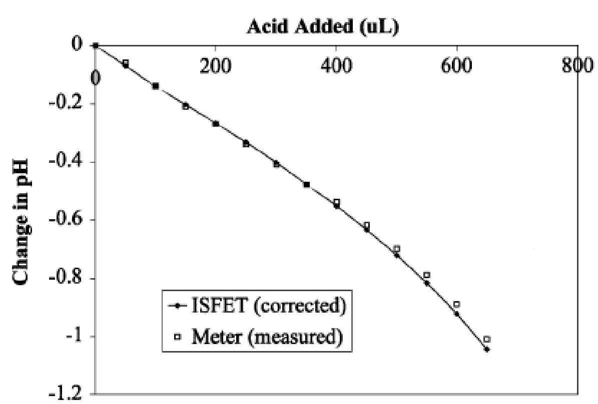

Fig. 7. Corrected pH variation measured using the pH-sensitive ISFET versus that measured by the pH meter at 5-min intervals.

IV. Distinction of Drift From Low-Frequency Noise

The drift behavior of pH-sensitive ISFETs, and palladium-gate MOSFETs [2],[5],[6] indicates that following an initial, relatively fast transient, the drift is characterized by a significantly slower and irregular temporal evolution, which does not quite reach equilibrium as $t \to \infty$. Therefore, following the initial, fast transient resulting from drift, correction of drift is possible by cutting the measuring signal (i.e. the sensor output) into segments of sufficiently short duration over which a relatively fast deterministic response associated with sensor transfer function is detectable.

The choice of the appropriate signal segment duration (i.e. sampling time), should be justified by distinguishing between drift and low frequency noise. Such a distinction can be made using the deterministic physical model for drift [5],[6]. In particular, given the accuracy of the analytical formulation of this model (coefficients of correlation better than 0.999), the output noise spectrum can be readily extracted from the measured output characteristics of the ISFET at a fixed pH. For an ISFET operating in the feedback mode, the output noise can be written as [24]

$$s_n(t) = s_0(t) - s_{drift}(t) \qquad (9)$$

where $s_n(t)$, $s_0(t)$, and $s_{drift}(t)$ are the signals associated with the noise, the device output at fixed pH, and the modeled drift characteristics respectively. The ISFET input-referred noise spectrum, $S(f)$, is the Fourier transform of $s_n^2(t)$. The noise power spectral density of a Si_3N_4-gate pH-sensitive ISFET operating in the feedback mode with I_D=100μA was extracted based on equation (9) using the fast Fourier transform algorithm. The resulting noise spectrum, which is depicted in Fig. 8., has been accurately modeled (coefficient of correlation of 0.993) over the 10-100 Hertz frequency range by an expression of the form A/f^n. with A=7.31×10^{-13} and n=1.13. This expression is commonly used to model gate-referred low frequency flicker (*1/f*)noise in MOSFET's.

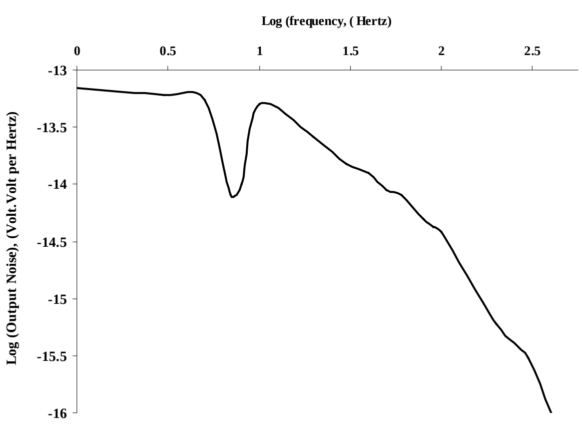

Fig. 8 Extracted ISFET Noise Spectrum

Fig. 8 indicates that below a frequency of 10 Hz, the noise spectrum of the ISFET does not correspond to a first order model described by a single decaying exponential. Furthermore, roughly below 3 Hertz the output noise spectrum exhibits a diminishing dependence on frequency. Given the fact that the modeled drift data was subtracted from the measured output characteristics of the device, this implies that below a frequency of 3 Hertz, the output fluctuations were solely associated with the drift mechanism. Therefore, the appropriate signal segment duration over which the proposed method for correction of drift may be applied is on the order of a few seconds.

V. Disscussion

The drift behavior of hydrogen-sensitive palladium-gate MOSFETs is similar to that of pH-sensitive ISFETs exhibiting a relatively fast transient after the exposure of the sensor surface to gaseous medium followed by a significantly slower long-term drift in the sensor output characterized by a random-looking evolution in time. In fact, the time dependence of drift in palladium-gate MOSFETs [2] is accurately described by the deterministic drift model accounting for instability in pH-sensitive ISFETs [5],[6]. The underlying mechanism of drift in catalytic metal-gate FETs can, therefore, be postulated to be associated with hopping and/or trap-limited dispersive diffusion within the amorphous material forming the gate insulator. Therefore, the proposed method for correction of drift, which has been experimentally verified using pH-sensitive ISFETs, is also applicable to FET-based gas sensors provided that the requirement given by equation (5) is satisfied.

pH Transition	Estimated pH Change
(1) 3.5 → 5.4	1.98
(2) 5.4 → 7.0	1.42
(3) 7.0 → 9.0	1.99
(4) 9.0 → 10.0	0.59
(5) 10.0 → 7.0	-2.71
(6) 7.0 → 3.5	-3.70
(7) 3.5 → 7.0	3.48
(8) 7.0 → 5.4	-1.48
(9) 5.4 → 9.0	3.12
(10) 9.0 → 10.0	0.44
(11) 10.0 → 7.0	-2.27
(12) 7.0 → 5.4	-1.52
(13) 5.4 → 3.5	-2.09
(14) 3.5 → 5.4	2.07
(15) 5.4 → 7.0	1.43
(16) 7.0 → 9.0	1.83
(17) 9.0 → 5.4	-3.30

Table 1. Estimated pH Changes based on the Proposed Correction Method in the current model

The inaccuracy associated with the proposed method in estimation of large step changes in pH (i.e. |pH|>3) and the 9.0→10.0 pH transition indicated in Table 1 is due to errors resulting from the pH dependence of drift. pH-sensitive ISFETs are known to exhibit higher drift rates at larger pH values [5],[6]. Dependence of drift rate $\partial D/\partial t$ on initial conditions, namely pH, is an aspect of the drift behavior in pH-sensitive ISFETs which may indicate that the complex nonlinear dynamics characterizing this phenomenon may involve weak chaos [3], [4]. The sensitivity $\partial M/\partial S$ of pH-sensitive ISFETs also exhibits pH dependence and saturation. Furthermore, both drift rate and sensitivity exhibit temperature dependence. These limitations notwithstanding, the proposed method for correction of drift has been demonstrated to be effective in applications where the range of measurand variations are small and temperature is relatively constant such as continuous monitoring of physiological pH.

Although the ISFET drift behavior following the initial relatively fast transient has been modeled deterministically [5], [6], given the random-looking evolution in time associated with long-term instability in ISFETs, drift has been interpreted as low frequency noise. In fact, some authors [25] describe drift as ultra low frequency noise in sensors whose outputs exhibit non-monotonic, slow temporal variations. Conversely, the appearance of *1/f* noise at the output of a sensor is very often described as drift [26]. The long-term deterministic drift dynamics, however, can be distinguished from the low frequency (*1/f*) noise by extracting the noise power spectral density from the measured drift characteristics using the ISFET drift model [5], [6]. Analysis of the resulting spectrum indicates that the lower limit on the frequency of pH variations to which the ISFET can faithfully respond is imposed by drift.

VI. Conclusion

A method for correction of threshold voltage drift in FET-based sensors was presented. This method was shown to be effective for correction of drift in pH-sensitive ISFETs when large step changes in pH exceeding three units are not involved and/or the pH dependence of drift is unimportant. The proposed method, therefore, is promising for applications such as continuous monitoring of blood pH, where changes in pH are within physiological limits. The distinction between the deterministic drift behavior and the low frequency (*1/f*) noise characteristics was elucidated to justify the choice of sampling time in application of the proposed method. Furthermore, the general applicability of the proposed method for correction of drift in FET-based sensors such as the hydrogen-sensitive palladium-gate MOSFET was discussed. The proposed method for correction of instability may be generally applicable to other sensor types whose output contains a superimposed drift component. However, the requirement for the validity of this method is that the product of sensor sensitivity and the rate of change of the measurand be considerably larger than the rate of drift in the measuring signal. The proposed method may also be implemented in real-time using CMOS circuit techniques by frequently sampling the measuring signal, evaluating the difference between consecutive values of the sampled signal, and adding the resulting differences over time.

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