Counteracting Threshold-Voltage Drift in Ion-Selective Field Effect Transistors (ISFETs) Using Threshold-Setting Ion Implantation

ALI EL YASI, MAJID FOULADIAN, AND SHAHRRIAR JAMASB

1 Department of Electronics, College of Engineering, Islamic Azad University (Saveh Branch), Saveh 39197-15179, Iran
2 Department of Biomedical Engineering, Hamedan University of Technology, Hamedan 65169-13733, Iran

CORRESPONDING AUTHOR: S. JAMASB (e-mail: jamasb@hut.ac.ir)

This work was supported by the Hamedan University of Technology under Grant 18/96/1/590.

ABSTRACT

Ion-selective field effect transistors (ISFETs) exhibit instability, commonly known as drift, in the form of a slow, monotonic, temporal increase in the threshold voltage of the device. A method for counteracting instability inspired by a physical model for threshold voltage drift in pH-sensitive ISFETs is presented. This method involves adjusting the charge density at the insulator-semiconductor interface using threshold-setting ion implantation such that the net charge induced in the semiconductor at the operating point of the device is minimized. The proposed method is analytically validated based on characterization and modeling of drift in an Al2O3-gate pH-sensitive ISFET. Counteraction of ISFET drift by ion implantation is also demonstrated using TCAD simulations. The optimum donor-type implant dose of 3.25 × 10^{11} \text{cm}^{-2} determined based on ATLAS simulations is in good agreement with the corresponding dose of 6.58 × 10^{11} \text{cm}^{-2} obtained analytically.

INDEX TERMS

pH-sensitive ISFET, instability, drift counteraction, continuous monitoring.

I. INTRODUCTION

In 1970 Bergveld introduced the ion-selective field effect transistor (ISFET) [1], which may be regarded as a solid state device incorporating the chemical sensitivity exhibited by a membrane and the field-sensing capability of a FET. ISFETs not only offer the advantages of miniature form factor, robustness, and very low manufacturing cost, but also provide the capability of implementing sophisticated smart sensor systems based on the CMOS integrated circuit technology. However, threshold voltage instability, also known as drift, has prevented ISFET-based biosensors from gaining a dominant position in the marketplace. Drift is characterized by a relatively slow, unidirectional temporal variation in the threshold voltage and, hence, in the drain current of ISFET in the absence of changes in the concentration of the given ion.

The high accuracy required for in vivo continuous monitoring of plasma pH imposes rigorous requirements on the tolerable drift rate in pH-sensitive ISFETs. For example, continuous monitoring of blood pH during surgery requires an accuracy of 0.02pH unit over a 10-hour period without recalibration. For an ISFET with ideal sensitivity operating in the feedback mode, such an accuracy amounts to a maximum equivalent drift rate of 0.002pH/hour or a maximum tolerable drift rate of (61.8mV/pH)/(0.002pH/hour)=0.12mV/hour in the measuring signal at the normal body temperature of 310K. In pH-sensitive ISFETs employing CMOS-compatible inorganic gate insulators, such as silicon nitride, the typical long-term drift rate at neutral pH is on the order of several tenths of a millivolt per hour following an exposure time interval between 12 to 16 hours. A drift rate of such magnitude, therefore, does not satisfy the stringent stability requirements for in vivo continuous monitoring without a correction or compensation scheme.

The first device-level method proposed for drift counteraction involved differential measurement using an ISFET and a Reference FET (REFET) [2] intended to eliminate drift as a common signal between the pH-sensitive ISFET and the ion-insensitive REFET. However, establishing a chemically inert interface between the REFET and the electrolyte has proven to be a challenging task. The recent 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]–[5]; the second methodology comprises circuit approaches to drift counteraction [6]–[9], while the third category consists of approaches employing sensing materials, which inherently exhibit a higher resistance to long-term chemical modification [10]–[12]. 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.

A physical model for the drift behavior of Si$_3$N$_4$-gate [13] and Al$_2$O$_3$-gate pH-sensitive ISFETs [14], [15] forms the basis of the method for drift counteraction presented in this work. Notably, this model shows that drift can be counteracted by establishing charge neutrality in the semiconductor at a given device operating point. The merit of adjusting the interface charge density using threshold-setting ion implantation in order to achieve the flatband condition will be demonstrated using the quantitative model developed for ISFET drift in an Al$_2$O$_3$-gate pH-sensitive ISFET. Furthermore, using the TCAD simulation model developed for the electrolyte-insulator interface by Chung et al. [16], the proposed device design approach to drift counteraction will be confirmed based on ATLAS simulations.

II. THEORETICAL

In this section ISFET drift will be examined in light of the monotonic, temporal decrease in the inversion layer charge density in order to justify the proposed approach to drift counteraction. Specifically, based on the closed-form expression for the gate voltage drift we will establish that adjustment of the charge density at the semiconductor-insulator interface can serve as a practical device design approach to drift counteraction.

A. PHYSICAL INTERPRETATION OF DRIFT

In Si$_3$N$_4$-gate pH-sensitive ISFETs drift is believed to be associated with diffusion of hydrating species within the insulator leading to transformation of the insulator surface to an oxynitride [13]. Chemical modification of the insulator surface is also believed to be responsible for the drift observed in Al$_2$O$_3$-gate pH-sensitive ISFETs, although the extent of chemical modification of aluminum oxide surface as determined by the thickness of the modified surface layer can be considerably smaller than that of silicon nitride surface [14], [15]. Chemical modification of the insulator surface implies that the dielectric constant of the modified surface layer will differ from that of the bulk insulator. Therefore, the overall insulator capacitance, which is determined by the series combination of the capacitance of the modified surface layer and that of the underlying insulator, will exhibit a relatively slow, temporal decrease as surface modification proceeds. This, in turn, will give rise to a monotonic temporal increase in the threshold voltage and a corresponding decrease in the drain current of the ISFET. The rate of surface modification of Al$_2$O$_3$ can be modeled by a hopping diffusion mechanism known as dispersive diffusion. In an amorphous solid hopping motion through localized states leads to a characteristic power-law decay of diffusivity given by [17]

$$D(t) = D_{00}(\omega_0 t)^{\beta - 1}$$

where $D_{00}$ is a temperature-dependent diffusion coefficient obeying an Arrhenius relationship, $\omega_0$ is the hopping attempt frequency, and $\beta$ is the dispersion parameter satisfying the relation $0 < \beta < 1$. The time dependence of diffusivity is due to dispersion in the separation distances between nearest-neighbor localized sites and/or dispersion in their energies [17].

Although it has been reported that Al$_2$O$_3$ does not hydrate [18], the time dependence of drift in Al$_2$O$_3$-gate pH-sensitive ISFETs can also be explained in terms of a dispersive diffusion mechanism. Specifically, species originating in the solution may diffuse into the insulator in presence of buried surface sites, giving rise to a chemically-modified surface layer of thickness $x_{SL}(t)$. The kinetics of the growth of this layer has been shown to be limited by a dispersive diffusion mechanism, with $x_{SL}(t)$ exhibiting a stretched exponential time dependence of the form $[1 - \exp(-t/\tau)^\beta]$, where $\tau$ is the time constant associated with structure relaxation [13]. The time dependence of drift is, in fact, determined by the temporal variation in the overall insulator capacitance resulting from the growth of this layer.

B. QUANTITATIVE MODEL FOR DRIFT

In an ISFET operating in the feedback mode, a constant drain current is established by applying a feedback voltage to the solution side of the gate via a reference electrode. The experimentally observed temporal decrease in the overall insulator capacitance resulting from exposure to the electrolyte [13] leads to a slow increase in the absolute value of the compensating feedback voltage. The change in the gate voltage can be written as

$$\Delta V_G(t) = V_G(t) - V_G(0)$$

Equation (2) can be rewritten in terms of the insulator capacitance, $C_I$ as

$$\Delta V_G(t) = -Q_S \left( \frac{1}{C_I(t)} - \frac{1}{C_I(0)} \right)$$

where $Q_S$ represents the semiconductor charge density given by $Q_S = Q_D + Q_l + Q_n$ with $Q_D$ and $Q_n$ representing the charge densities of the semiconductor depletion layer and the inversion layer respectively, and $Q_l$ designating the effective charge per unit area induced in the semiconductor by the various types of charges that may be present in the insulator. Equation (3) can be simplified to yield [13]

$$\Delta V_G(t) = - \left( Q_D + Q_l + Q_n \right) \left( \frac{\varepsilon_{AO} - \varepsilon_{SL}}{\varepsilon_{AO} \varepsilon_{SL}} \right) x_{SL}(t)$$

$$\Delta V_G(t)$$

is the change in gate voltage, $V_G(t)$ and $V_G(0)$ are the gate voltages at time $t$ and 0, respectively, $Q_S$ is the semiconductor charge density, $Q_D$, $Q_l$, and $Q_n$ are the charge densities of the semiconductor depletion layer, the inversion layer, and the surface layer, respectively, $\varepsilon_{AO}$ and $\varepsilon_{SL}$ are the dielectric constants of the bulk and surface layers, respectively, and $x_{SL}(t)$ is the thickness of the surface layer.
where \( \varepsilon_{SL} \) represents the dielectric constant of the chemically-modified surface layer, and \( \varepsilon_{AO} \) is the dielectric constant of \( \text{Al}_2\text{O}_3 \). According to (4), the time dependence of drift is identical to that associated with the modified surface layer thickness. Based on Fick’s first law of diffusion, an expression for \( x_{SL}(t) \) can be derived by considering the power-law time dependence of the diffusivity associated with dispersive diffusion and the decay in the density of the sites occupied by the species undergoing diffusion yielding [13]

\[
x_{SL}(t) = x_{SL}(\infty) \left\{1 - \exp\left[\frac{-(t/\tau)^\beta}{\tau}\right]\right\}
\]

in which \( x_{SL}(\infty) \) is the final thickness of the modified surface layer.

C. EFFECT OF DRIFT ON CHARGE DISTRIBUTION

The effect of drift on charge distribution in the electrolyte-insulator-semiconductor (EIS) system has to be addressed in order to justify the proposed method for drift counteraction, which essentially involves adjustments to the charge balance in the semiconductor.

Charge neutrality throughout the EIS system requires that

\[
\sigma_D + \sigma_o + Q_s = 0
\]

where \( \sigma_D \) represents the diffuse layer charge density, and \( \sigma_o \) designates the surface charge density at the electrolyte-insulator interface. Adopting the site binding model to account for the pH sensitivity of the EIS system [19], the charge and potential distribution in an EIS system for the case \( \text{pH}<\text{pH}_{\text{zc}} \), i.e., with the surface acquiring positive charge is shown in Fig. 1b.

The instability arising from drift may be interpreted as a temporal decrease in the inversion charge density \( \Delta Q_n(t) \), as indicated in Fig. 1b, which originates from the reduction of the overall insulator capacitance with time in absence of pH variations. As required by charge neutrality \( \Delta Q_n(t) \) induces an equal but opposite charge on the electrolyte side of the insulator. The change in the amount of charge stored by the insulator capacitance due to drift, in turn, causes a change in the interfacial potential, \( \Delta \Psi_{\text{oH}}(t) \). In presence of pH variations, \( \Delta \Psi_{\text{oH}}(t) \), which represents a change in the threshold voltage of the ISFET, cannot be distinguished from the change in the pH-dependent interfacial potential, thereby rendering interpretation of the measurement ambiguous.

In order to estimate \( \Delta \Psi_{\text{oH}}(t) \) we note that in the sketch of Fig. 1, OHP represents the well-known outer Helmholtz plane, and \( C_H \) denotes the effective Helmholtz capacitance. With the semiconductor surface biased into strong inversion the surface potential \( \Psi_s \) remains relatively constant. Furthermore, assuming a large diffuse layer capacitance, \( C_D \) as is the case for electrolytes with high ionic strength, the potential drop over the diffuse layer becomes negligible and the potential at the outer Helmholtz plane may be approximated by that of the reference electrode \( V_G \). Therefore, the series combination of \( C_H \) and \( C_D \) can be approximated by \( C_H \). The small signal model of the EIS system of Fig. 1 can be represented by the schematic of Fig. 2. Using the small signal model the change in the surface potential at the electrolyte-insulator interface resulting from the positive charge induced by drift can be computed. Specifically, \( \Delta \Psi_{\text{oH}}(t) \) can be considered as the sum of two
components, namely the potential drop across the insulator capacitance, $\Delta \Psi_{\text{drop}}(t)$ and the potential drop across the Helmholtz capacitance, $\Delta \Psi_{\text{2shift}}(t)$. It should be noted that for $\Delta Q_d(t) > 0$, these potential drops are of opposite polarity with $\Delta \Psi_{\text{drop}}(t) < 0$ and $\Delta \Psi_{\text{2shift}}(t) > 0$ since the semiconductor surface potential and the potential at the outer Helmholtz planes are assumed to be at the constant levels of $\Psi_s$ and $V_G$ respectively. Therefore, $\Delta \Psi_{\text{drop}}(t)$ can be expressed as:

$$\Delta \Psi_{\text{drop}}(t) = \Delta \Psi_{\text{drop}}(t) + \Delta \Psi_{\text{2shift}}(t) = \Delta Q_d \left( -\frac{1}{C_I(t)} + \frac{1}{C_H} \right)$$

(7)

For an ISFET operating in the feedback mode the gate voltage drift, $\Delta V_G(t)$ given by (3) is the additive inverse of $\Delta \Psi_{\text{drop}}(t)$, i.e., $\Delta V_G(t) = -\Delta \Psi_{\text{drop}}(t)$ so that a constant drain current or equivalently a result, (3) and (7) yield

$$\Delta Q_d \left( -\frac{1}{C_I(t)} + \frac{1}{C_H} \right) = Q_S \left( -\frac{1}{C_I(t)} + \frac{1}{C_I(0)} \right)$$

(8)

The relative change in the semiconductor charge due to drift, therefore, is given by

$$\frac{\Delta Q_d}{Q_S} = -\left( \frac{1}{C_I(t)} - \frac{1}{C_I(0)} \right)$$

(9)

For an $n$-channel ISFET $Q_S < 0$, therefore with $\Delta Q_d(t) > 0$, we will have $\frac{\Delta Q_d}{Q_S} < 0$. Inasmuch as the insulator capacitance decreases with time the numerator of the fraction on the right-hand side of (9) is positive. In addition, with the charge separation associated with the effective Helmholtz capacitance being on the order of several angstroms and given typical insulator thicknesses on the order of several hundreds of angstroms, the insulator capacitance is typically much smaller than $C_H$. Therefore, the denominator of the right-hand side of (9) would also be positive, making the right-hand side of (9) negative as expected. Furthermore, considering the slow, temporal decrease in the insulator capacitance, which has been experimentally confirmed [13], the right-hand side of (9) is much smaller than one, implying that $\frac{\Delta Q_d}{Q_S} \ll 1$. Consequently, we may conclude that the drift phenomenon does not disturb the charge balance in the semiconductor region significantly.

**D. DRIFT COUNTERACTION BY ADJUSTING $Q_I$**

The physical model for ISFET drift readily suggests that drift can be counteracted by constraining the net semiconductor charge to approach zero. Ideally, in order to eliminate gate voltage drift the net semiconductor charge density, $Q_S$ has to be set equal to zero. This can be accomplished simply by adjusting the interface charge density using threshold-setting ion implantation. With $Q_S = 0$ the flatband condition corresponding to charge neutrality in the semiconductor prevails. Therefore, if the values of $Q_I$ and $Q_n$ are given, the optimum depletion-charge density with the adjustment implant, $Q_D$ can be calculated based on the following expression for charge neutrality in the semiconductor:

$$Q_D + Q_I + Q_n = 0$$

(10)

The optimum implant dose can, in turn, be estimated using the resulting value for the charge density of the depletion layer. In order to determine the effect of the implant on the space charge density, the implanted dopant distribution following the annealing step may be approximated by the box distribution in which the dopant density is assumed to have a constant value $N_{di}$ from the surface to a depth $x_i$ [20]. The implant dose $N'$ in cm$^{-2}$ is, then, given by $N' = N_{di}x_i$. Balancing the negative charge associated with the space charge region and the inversion layer in an $n$-channel ISFET requires implantation of donor-type impurities so as to obtain a net semiconductor charge of zero. If the implanted region is entirely contained within the space charge region near the surface, the assumption of an approximate box distribution for the implanted ions permits invoking the depletion approximation yielding the following expression for the depletion-charge density in absence of back bias [20]:

$$Q_D = qN_{di}x_i - qN_{ax_{\text{max}}}$$

$$= qN' - \sqrt{2qN_a} \in_s\left( |\phi_{ns}| + |\phi_p| \right) + q^2 x_i N_a N'$$

(11)

where $q$ is the charge of an electron, $x_{\text{max}}$ represents the maximum width of the depletion layer, $N_a$ denotes the $p$-well doping concentration in an $n$-channel ISFET, $\phi_{ns}$ designates the surface Fermi potential corresponding to the donor-type dopant density given by $\phi_{ns} = \left( \frac{qN_a}{n_i} \right) \ln \left( \frac{n_i}{N_{di}} \right)$, and $\phi_p$ is the bulk Fermi potential expressed as $\phi_p = \left( \frac{qN_{di}}{n_i} \right) \ln \left( \frac{N_{di}}{N_{di}} \right)$ with $k$, $T$, and $n_i$ representing the Boltzman constant, the absolute temperature, and the intrinsic carrier concentration respectively. Applying a low implant energy ensures that the depth characterizing the box distribution of the implanted ions is smaller than the maximum depletion width, i.e., $x_i < x_{\text{max}}$. A value equal to twice the projected range, $R_p$ associated with the given implant energy may be adopted as a reasonable value for $x_i$. With the appropriate value of $x_i$ selected, the optimum implant dose, $N'$ can be determined by substituting the expression for $Q_D$ given by (11) into (10).

**III. EXPERIMENTAL**

In this section certain experimental details of the ISFET fabrication process employed are presented, which are of relevance to modeling and correction of drift based on analytical techniques as well as modeling of the ISFET characteristics using TCAD. In addition, the experimental set-up used for characterization of drift in the feedback mode of operation is specified.

**A. DEVICE FABRICATION**

The $n$-channel ISFETs used for the study of drift behavior were fabricated based on modification of a standard metal-gate, $p$-well CMOS process. An n-type, (100) silicon wafer whose resistivity lied in the 4-6 $\Omega$cm range was
The ISFET was defined as an intrinsic semiconductor having a relative dielectric constant equal to that of water ($\varepsilon_r = 80$). The source and drain regions were constructed by diffusion of phosphorous producing typical junction depths and doping concentrations, of $1.15 \mu m$ and $10^{19} \text{cm}^{-3}$ respectively. The ISFETs had channel lengths, and gate widths of $15 \mu m$ and $450 \mu m$ respectively. The extent of source and drain diffusions along the transistor channel was $500 \mu m$. The double-layer insulator consisted of a 50nm film of thermally-grown SiO2 on top of which a 65-nm layer of $\gamma$-Al2O3 was deposited by standard chemical vapor deposition using the reaction between aluminum bromide and water vapor. No threshold-setting ion implantation was carried out.

**B. DRIFT CHARACTERIZATION**

The drift characteristics of n-channel, Al2O3-gate pH-sensitive ISFETs fabricated according to the process introduced above were measured. Room temperature ISFET drift data was collected in the feedback mode using the circuit of Fig. 3, which allows maintenance of a constant drain current by applying a feedback voltage to the electrolyte. The drain current was set to $I_D = 100 \mu A$ using a constant drain-to-source voltage in the absence of back bias. The ISFET gate voltage was applied using a commercial Calomel reference electrode immersed in a Potassium phosphate buffer at pH=7.

**IV. SIMULATION OF ISFET DRIFT USING TCAD**

The ISFET drift behavior was simulated using TCAD to evaluate the device-level method for drift compensation proposed in this work. In particular, using Silvaco’s ATLAS the ISFET was defined as an n-channel MOSFET without the metal gate but having, otherwise, an identical device cross section and dimensions as that of the fabricated ISFET employed for drift characterization and modeling. The electrolyte-insulator interface was modeled using the approach proposed by Chung et al. [16]. Significantly, since ATLAS does not support direct modeling of the electrolyte, the ionic solution in contact with the pH-sensing insulator was defined as an intrinsic semiconductor having a relative dielectric constant equal to that of water ($\varepsilon_r = 80$). For a 1:1 electrolyte such as potassium chloride (KCl) the charge distribution in the electric double layer given by the Poisson-Boltzman (PB) equation can be approximated using the Poisson equation describing the charge distribution in an intrinsic semiconductor [16]. The two equations will have the same form under conditions permitting the Fermi-Dirac distribution for electrons and holes to be estimated using the Maxwell-Boltzman (MB) distribution. Specifying a bandgap energy of 1.5eV for the intrinsic semiconductor representing the electrolyte ensures predominance of MB statistics. In order to specify the ionic concentrations, the density of allowed states for the intrinsic semiconductor are determined by setting the density of holes and electrons equal to the molal concentration of the positive and negative ions in the solution respectively. To complete the modeling of the electrolyte, following the approach introduced by Chung et al. [16], the electron affinity ($\chi_e$) of the intrinsic semiconductor representing the electrolyte was determined as a fitting parameter so as to achieve a good agreement between the simulated and the measured current-voltage characteristics of the ISFET. The cross-section of the modeled ISFET is illustrated in Fig. 4 showing the doping profile in color-coded format. As indicated, platinum was used as a quasi-reference electrode. In order to simulate the ISFET drift behavior, the temporal shift in the drain current versus the gate voltage ($I_D - V_G$) characteristics was determined using Silvaco’s ATLAS. To this end, the model parameters $\tau$ and $\beta$ were extracted from the measured drift characteristics in order to compute the thickness of the modified surface layer as a function of time. To determine the variation of the threshold voltage due to drift using device simulations the insulator structure has to be redefined to reflect the temporal surface modifications. This can be accomplished in ATLAS by specifying the calculated value of $x_{SL}(t)$ at a given time and the value of the relative dielectric constant of the modified surface layer extracted from the measured drift data. The $I_D - V_G$ characteristics obtained based on ATLAS simulations can then be used to determine the temporal shift in the threshold.
voltage. By using the model parameters extracted from measured drift data the temporal variations in the structure of the pH-sensing insulator are accurately reflected in device-level simulations. Therefore, a good fit between the simulated and the measured drift data can be expected.

V. RESULTS AND DISCUSSION

A. ANALYTICAL VALIDATION

The proposed approach to drift counteraction is demonstrated using the drift model developed for a typical Al₂O₃-gate pH-sensitive ISFET. The modeled-versus-measured drift characteristics for the given ISFET are shown in Fig. 5. The modeled data were computed based on (4) and (5) using both known and extracted physical parameters. The known parameters were the relative permittivity of Al₂O₃, \( \varepsilon_{AO,r} = 8.5 \), \( Q_D = -4.8 \times 10^{-8} \text{ C/cm}^2 \) and the inversion charge density corresponding to a drain current of 100 \( \mu \text{A} \), \( Q_n = -5.6 \times 10^{-8} \text{ C/cm}^2 \). The fit depicted in Fig. 5 is characterized by a coefficient of correlation of 0.999. The model parameters extracted from the measured drift data, were the fixed positive interface charge density at the oxide-silicon interface, \( Q_I = 7.47 \times 10^{-9} \text{ C/cm}^2 \), the relative dielectric constant of the modified layer, \( \varepsilon_{SL,r} = 1.7 \), the dispersion parameter, \( \beta = 0.458 \), and the final thickness of the modified surface layer, \( x_{SL}(\infty) = 13.39 \times 10^{-8} \text{ cm} \). The extracted values of these parameters, which were determined using the Levenburg-Marquardt nonlinear extraction algorithm, provide a very good fit to the measured drift data and fall within the physically meaningful ranges for these parameters. A more rigorous validation of the drift model, however, requires independent experimental determination of some of these parameters. The final thickness of the modified surface layer, for example, can be measured using modern surface characterization techniques following exposure of the pH-sensitive insulator to an electrolyte for a relatively long period of time, e.g., several days. An extracted value for \( x_{SL}(\infty) \) of roughly 13 angstroms implies that chemical modification of the Al₂O₃ surface has occurred over a distance equivalent to several atomic layers. In contrast, the typical extracted value for \( x_{SL}(\infty) \) in Si₃N₄-gate pH-sensitive ISFETs has been reported to be in the 100 angstroms range [13], which is about an order of magnitude higher than that in ISFETs employing Al₂O₃ as the pH-sensitive gate insulator. This suggests that the extent of surface modification in Al₂O₃ is not as significant as that occurring in Si₃N₄ due to hydration. However, presence of a modified surface layer containing OH sites buried beneath the surface as suggested by Bousse et al. [21] supports the model advanced for drift in Al₂O₃-gate pH-sensitive ISFETs [14, 15].

Given the known value of \( Q_n \) and the extracted value of \( Q_I \) given above for the Al₂O₃-gate pH-sensitive ISFET, whose drift characteristics appear in Fig. 5, the optimum implant dose \( N' \) can be determined such that the net semiconductor charge vanishes. Using phosphorous as the donor type impurity for ion implantation with implant energy of 16.25 keV, the mean penetration depth of the implanted ions would be \( R_p = 20 \text{nm} \) [22]. Choosing \( x_I = 2R_p = 40 \text{ nm} \), \( N' \) can be determined by trial and error from (10) and (11). Specifically, at room temperature (\( T = 300 \text{ K} \)) with \( n_i = 1.45 \times 10^{10} \text{ cm}^{-3} \), the bulk Fermi potential \( \phi_p = 0.35 \text{V} \) for \( N_d = 10^{16} \text{ cm}^{-3} \); therefore given the value of \( 11.7 \times 8.85 \times 10^{-14} \text{ F/cm} \) for the dielectric constant of silicon (10) and (11) yield \( N'=6.58 \times 10^{11} \text{ cm}^{-2} \). In practice, the optimum implant dose has to be determined experimentally through evaluation of the measured drift characteristics obtained for various applied doses. In order to assess the effect of threshold-setting ion implantation on the ISFET drift behavior, modeled drift data were computed based on (4) using the expression for \( Q_D \) as a function of \( N' \) given by (11). The measured drift data for the Al₂O₃-gate pH-sensitive ISFET given in Fig. 5 are compared against the modeled drift data computed as a function of the implant dose in Fig. 6. The uppermost curve in Fig. 6 represents the...
measured drift data of Fig. 5, while the other curves depict the modeled drift data as a function of the implant dose. The values of donor-type implant doses used to construct Fig. 6 were chosen so as to demonstrate the trend indicating that as the value of the dose \( N' \) in (11) is increased within practical limits relative to the case where no implantation was performed (i.e., the measured data), the magnitude of drift is reduced. As is evident, threshold-setting ion implantation permits drift counteraction with the gate voltage drift tending towards zero as the value of the dose approaches the optimum value of \( 6.58 \times 10^{11} \text{cm}^{-2} \).

The optimum implant dose producing the flatband condition in the semiconductor is determined for a specific value of the inversion charge density, \( Q_n \). However, during the actual device operation variations in pH cause changes in the interfacial potential \( \Psi_0 \), which, in turn, lead to corresponding changes in \( Q_n \). In order for the proposed method to be valid the changes in \( Q_n \) resulting from pH variations should not disturb the flatband condition. For the devices characterized in this work, given the insulator thicknesses specified in Section III-A, the initial value of insulator capacitance can be readily computed to be \( C_I(0) = 4.32 \times 10^{-9} \text{F/cm}^2 \). Considering the slow variation of \( C_I(t) \), the initial value may be used to compute the worst-case change in the inversion layer charge density as \( \Delta Q_n(t) \equiv C_I(0) \Delta \Psi_0 \).

Assuming an ideal Nernstian response, a one unit change in pH gives \( \Delta \Psi_0 = 1(59) = 59 \text{mV} \) at room temperature, yielding \( \Delta Q_n(t) \equiv 2.55 \times 10^{-9} \text{C/cm}^2 \). Accordingly, given the known value of \( -5.6 \times 10^{-5} \text{C/cm}^2 \) for \( Q_n \), the worst-case relative change in the inversion charge density would be \( \Delta Q_n \equiv 0.045 \). This implies that the charge neutrality associated with the flatband condition, \( Q_S = 0 \), prescribed by the proposed method will not be significantly disturbed for a unit change in pH, which falls outside the normal range of physiological pH variations. That is, the semiconductor region remains quasineutral in spite of significant changes in pH, thereby satisfying the requirement for drift counteraction.

**B. VALIDATION BY DEVICE-LEVEL SIMULATION**

The proposed method for counteraction of ISFET drift was also validated based on device-level simulations using the ATLAS software. Expressly, using the approach described in Section III, the change in threshold voltage drift in response to various implant doses was determined in order to verify the efficacy of threshold-adjust implantation in countering ISFET drift. Fig. 7 shows the simulated \( I_D - V_G \) characteristics of the ISFET following the initial exposure of the device to the electrolyte and after exposure over an interval of 10 hours along with the characteristics of an ISFET receiving a threshold-adjust ion implantation using donor impurities with a dose of \( 3.25 \times 10^{11} \text{cm}^{-2} \). The simulations were carried out for a device of unit width. Evidently, the simulated temporal shift in the characteristics of Fig. 7 is in good agreement with the measured drift characteristics of Fig. 5, indicating a threshold voltage drift of roughly 50mV over a 10-hour interval and also exhibiting the correct direction of drift. Furthermore, Fig. 7 indicates that a threshold-adjust ion implantation using the optimum dose of \( 3.25 \times 10^{11} \text{cm}^{-2} \), which was determined based on ATLAS simulations, all but eliminates drift. Since the analytically-determined optimum dose \( N' \) is obtained based on the approximation of a box distribution for the implanted ions, the simulated value of \( 3.25 \times 10^{11} \text{cm}^{-2} \) determined using more accurate distributions, such as the Guassian distribution, may serve as a better estimate for \( N' \). The device-level simulation results, therefore, not only agree with the drift behavior predicted by the quantitative physical model for drift, but also validate the proposed method for drift counteraction based on interface charge density adjustment using ion implantation. It is important to note that the additional mask required for the threshold-adjust ion implantation step does not introduce a significant increase in costs given the relatively low number of masks required to build a basic ISFET.

**VI. CONCLUSION**

A method for counteracting instability, commonly known as drift, in pH-sensitive ISFETs was presented. This method was inspired by a physical model which quantitatively accounts for drift in terms of a temporal decrease in the effective insulator capacitance resulting from chemical modification of the pH-sensitive insulator surface. The proposed method essentially requires balancing the static and dynamic charge to impose charge neutrality in the semiconductor at a given quiescent point. The validity of this method was analytically demonstrated, and its efficacy was confirmed based on TCAD simulations. Furthermore, the device design approach to implementation of this method, which involves optimizing the well doping profile using threshold-setting ion implantation, was expounded. Rigorous experimental verification of this method, however, requires comparing the drift characteristics of ISFETs fabricated with different threshold-setting implant doses. A comprehensive approach to drift counteraction involves simultaneous optimization of
the static and dynamic components of the semiconductor charge, by varying the bulk doping profile and the device operating point, in order to achieve the flatband condition.

ACKNOWLEDGMENT

Shahriar Jamasb would like to express his sincere appreciation to Dr. Rosemary L. Smith, Professor of Electrical Engineering, and Dr. Scott D. Collins, Professor of Chemistry at the University of Maine, Orono not only for their contribution to development of the physical model for ISFET drift, but also for their implacable belief that a fundamental understanding of this phenomenon was attainable. The authors would also like to thank Professors Smith and Collins for providing the ISFET devices used in the measurements.

REFERENCES


ALI EL-YASİ received the B.Sc. degree in electronic engineering from Islamic Azad University (Saveh Branch), Saveh, Iran, in 2007 and the M.Sc. degree in electronic engineering from Central Tehran Branch, Islamic Azad University, Tehran, Iran, in 2011. He is currently pursuing the Ph.D. degree in electronic engineering with Islamic Azad University (Saveh Branch). His doctoral dissertation is on correction of ISFET instability. His main interests and expertise are in the areas of semiconductor and biomedical devices, image processing, and robotics.

MAJID FOULADIAN received the M.S. degree from the Isfahan University of Technology, Isfahan, Iran, in 2008 and the Ph.D. degree from the Department of Electrical and Computer Engineering, Islamic Azad University Science and Research Branch, Tehran, Iran, in 2016. He is currently a Faculty Member with the Department of Electrical Engineering, College of Technical and Industrial Engineering, Islamic Azad University (Saveh Branch), Saveh, Iran. His current research interests include mobile networks, next generation wireless communication systems, with a focus on routing protocols, resource management, and analysis of network architectures and protocols.

SHAHRIAR JAMASB received the B.S. and M.S. degrees in electrical engineering and the Ph.D. degree in biomedical engineering from the University of California at Davis. His graduate study in electrical engineering concerned analog and digital integrated circuit design for implementation of a decision feedback equalizer, and his Ph.D. dissertation research focused on modeling and correction of drift in pH-sensitive ISFETs. He has over 13 years of experience as a Device Engineer with Samsung Semiconductor Inc., San Jose, CA, USA, a Manager of the device modeling group with Cirrus Logic Inc., Fremont, CA, USA, a Technical Manager with Commquest, an IBM company, Enginicus, CA, USA, and an Electronic Design Principal Engineer with Conexant Systems Inc., Newport Beach, CA, USA. He also served as a Lecturer with the University of California at Irvine and the University of California at San Diego. In 2010, he joined the faculty of the Hamedan University of Technology, Hamedan, Iran, where he is currently an Assistant Professor in biomedical engineering. His principal research interests include integrated sensors for biomedical applications, solid-state device physics, and instability phenomena.