Determination of Low-frequency Noise Spectrum in Ion-sensitive Field Effect Transistors (ISFET's) based on a Physical Model for Drift

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ABSTRACT

A physical model for drift in pH-sensitive ISFET's is employed to extract the inherent low-frequency noise power spectral density associated with these devices. The noise spectrum extracted from measured drift data demonstrates ideal *1/f* noise behavior down to 10Hz. At lower frequencies, however, the resolution and accuracy of the ISFET is dominated by the drift behavior of the device. The distinction between drift and low-frequency noise is discussed based on the physical bases underlying each phenomenon.

Keywords: Flicker (*1/f*) Noise, Drift, ISFET

1 INTRODUCTION

Instability in sensor response, commonly known as drift, as well as fundamental sources of noise such as thermal noise, and low-frequency (*1/f*) noise in semiconductors impose limitations on sensor accuracy. While white noise can be easily distinguished from frequency-dependent disturbances, the appearance of *1/f* noise at the output of a sensor is very often described as drift [1]. In fact, some authors [2] describe drift as ultra-low frequency noise, since for some sensors drift may be bi-directional. The physical mechanisms responsible for noise and drift, however, may be entirely different.

As a solid state device, which combines the pH-sensing properties of an insulator such as Si_3N_4 with the field-sensing characteristics of a FET, the pH-sensitive ion-selective field effect transistor (ISFET) is subject to inaccuracies originating from both drift and *1/f* noise. While the *1/f* noise in MOSFET's has been extensively studied and is rather well understood [3,4,5,6], relatively little effort has been made to develop a model for drift. Recently, a physical model has been presented which provides an accurate, quantitative description of the drift behavior of Al_2O_3-gate and Si_3N_4-gate pH ISFET's [7,8,9]. In this work, the ISFET drift model is employed to distinguish between the inherent *1/f* noise and the instability and the lack of repeatibility imposed by drift.

2 ISFET DRIFT MODEL

The origin of drift is postulated to be associated with the relatively slow chemical modification of the gate insulator surface as a result of exposure to the electrolyte. The chemical modification of the surface is assumed to result from a transport-limited reaction whose rate is modeled by a hopping and/or trap-limited transport mechanism known as dispersive transport. The change in the chemical composition of the insulator surface leads to a decrease in the overall insulator capacitance with time, which gives rise to a monotonic temporal increase in the threshold voltage. Based on the expression for the threshold voltage of an ISFET, Fick's first law of diffusion, and the dispersive transport theory, the expression for drift is given by [9]

$$v_{drift}(t) = v_{drift}(\infty)\left(1 - \exp\left(-(t/\tau)^{\beta}\right)\right) \tag{1a}$$

$$v_{drift}(\infty) = -(Q_D + Q_I + Q_{inv})x_{SL}(\infty)\left(\frac{\varepsilon_{ins} - \varepsilon_{SL}}{\varepsilon_{ins}\varepsilon_{SL}}\right) \tag{1b}$$

where Q_I is the effective charge per unit area induced in the semiconductor by the various types of charges that may be present in the insulator, Q_D and Q_{inv} represent the charge stored in the semiconductor depletion layer and the inversion charge respectively, ε_{ins} and ε_{SL} are the dielectric constants of the chemically-modified surface layer, and the pH-sensitive respectively, $x_{SL}(\infty)$ is the final thickness of the modified surface layer, τ is the time constant associated with structural relaxation, and β is the dispersion parameter characterizing dispersive transport satisfying $0<\beta<1$. As is evident from Fig. 1, the drift expression fits the measured drift data for an *n*-channel Si_3N_4-gate pH-sensitive ISFET with a high degree of accuracy (coefficient of correlation of 0.9999) based on optimization of $x_{SL}(\infty)$, τ and β within each parameter's physically meaningful range.

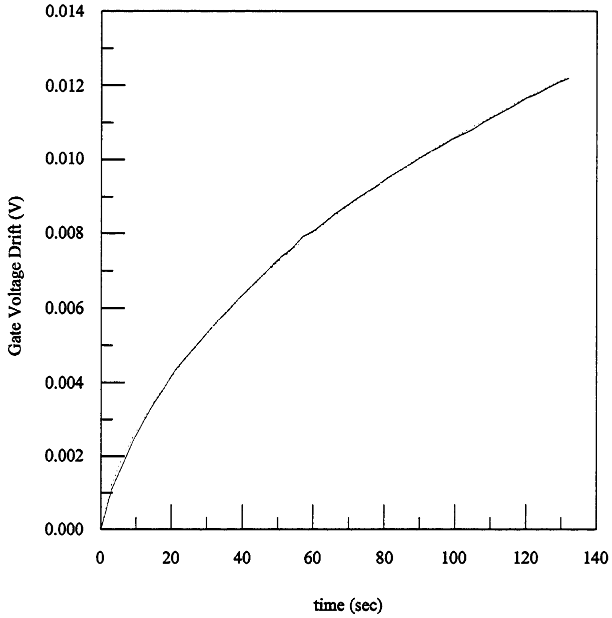

Fig. 1 Modeled (dotted) versus Measured (solid) ISFET Drift, pH=7

The ISFET whose drift behavior is shown in Fig. 1, was fabricated in a standard metal gate, *p*-well CMOS process [10]. The substrate material was an *n*-type silicon wafer of $\langle 100 \rangle$ orientation with a resistivity in the 4-6 Ωcm range, and the typical *p*-well doping concentration was 10^{16}cm^{-3}. The ISFET had a channel length of 15 μm, W/L=30, and a dual dielectric, composed of a lower layer of SiO_2 and an upper layer of 1100 ± 100A° LPCVD Si_3N_4. No threshold setting implants were performed. The gate voltage change was recorded over time at room temperature using a feedback circuit [11], which maintained a 100 μA drain current with a constant drain-to-source voltage and with no back bias. The ISFET gate voltage was applied using a commercial Calomel reference electrode immersed in a phosphate buffer solution with pH=7. The drift characteristics of the ISFET was measured by monitoring the gate voltage using a HP^{TM} 4156A semiconductor parameter analyzer in the high integration mode, in order to reduces measurement errors caused by line frequency noise or any other environmental noise sources. The high resolution of HP^{TM} 4156A for voltage measurement (2 μV for voltages in the 0-2.2Vrange) simplifies the measurement set-up, since a high-resolution A/D converter will no longer be required. The measured-versus-modeled fit of Fig.1 is characterized by a coefficient of correlation of 0.9999 with $v_{drift}(\infty) = 26.9mV$, $\tau = 274.6$ sec, and $\beta = 0.680$.

3 Extraction of *1/f* Noise Spectrum

Given the accuracy of the proposed drift model (typical correlation coefficient of 0.999), the *1/f* noise spectrum can be readily extracted from the measured drift characteristics of the ISFET (i.e. output characteristics at a fixed pH) in the absence of a major source of transmitted low-frequency noise. In particular, for an ISFET exposed to an electrolyte of known pH and operating in the feedback mode (i.e. at a constant drain current) the output noise can be written as

$$v_n(t) = \Delta V_G(t) - v_{drift}(t) \qquad (2)$$

where the measured output signal in the feedback mode at a given pH value is given by $\Delta V_G(t) = V_G(t) - V_G(0)$, and the modeled output drift, $v_{drift}(t)$, is given by the drift expression given by (1).

The ISFET input(gate)-referred noise spectrum $S_n(f)$ is the Fourier transform of $v_n^2(t)$:

$$S(f) = \Im[v_n^2(t)] \qquad (3)$$

The noise spectral density for the ISFET of Fig. 1 was extracted based on equation (3), using the fast Fourier transform algorithm (solid line in Fig. 2). The noise

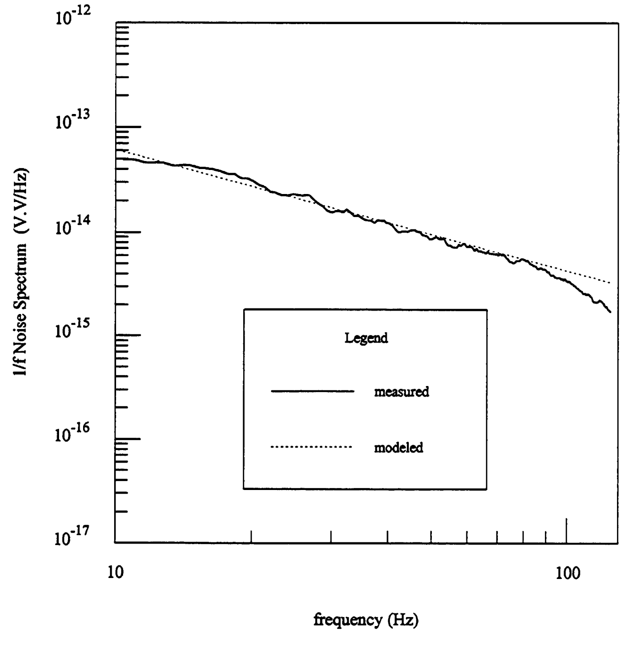

Fig. 2 Modeled versus Measured ISFET Noise Spectrum

spectrum of Fig.2 is accurately described (a 0.990 correlation coefficient) by an equation of the form A / f^n, commonly used to model gate-referred low-frequency noise in MOSFET's, with $A = 8.665 \times 10^{-13}$ and $n = 1.154$ for frequencies down to 10Hz.

4 DISCUSSION

The empirical expression commonly used in describing MOSFET Flicker noise behavior [12] is given by

$$S_{V_G} = q^2 N_{tot} / C_i^2 WLf^n \qquad (4)$$

where S_{V_G} is the gate-referred *1/f* noise spectrum, N_{tot} is the effective oxide trap density per unit area, C_i is the insulator capacitance per unit area, and W, and L are the device width and length respectively. For the measured ISFET, based on the device parameters given above, $C_i = 3.18x10^{-8}$F/cm-2, W=450 μm, and L=15 μm, the extracted value of $A = 8.665 \times 10^{-13}$ yields an effective oxide trap density of N_{tot} =2.31X10^6 cm^{-2}, which is a reasonable value for advanced CMOS technologies. This value is also in good agreement with the 8X10^{6}cm^{-2} reported in the most recent study on the *1/f* noise in ISFET's [13]. The extracted value of $n = 1.154$ is also within the $0.7 < n < 1.2$ commonly associated with the career-density fluctuation model, which attributes the *1/f* noise to the fluctuation of the channel free careers due to random capture and emission by the interface traps.

Agreement of ISFET *1/f* noise behavior with (4) suggests that the origin of low-frequency noise in these devices is trapping–detrapping of careers at the Si/SiO$_2$ interface. This is also supported by the fact that the gate-referred *1/f* noise in ISFET's is independent of gate bias [13]. Furthermore, the gate-referred *1/f* noise in ISFET's is independent of pH [13], which may suggest that the interface between the solution and the gate insulator does not contribute to *1/f* noise. However, as shown in Fig. 3, our results indicate that at frequencies below 10Hz, ISFET noise behavior deviates from (4). In particular, Fig. 3 exhibits a diminishing dependence on frequency below 10Hz, since the drift data is subtracted from the measured output characteristics of the device. However, over larger time scales (corresponding to frequencies on the order of 1Hz and below) the inaccuracy arising from drift actually dominates over *1/f* noise. Therefore, the lower limit on the frequency associated with pH variations monitored using the ISFET is imposed by drift. Based on our drift model, dispersive transport at the electrolyte-insulator interface leads to chemical modification of the insulator surface. Furthermore, dispersive transport results from non-uniform spatial distribution and/or the distribution of energy levels associated with the traps. This model is in sharp contrast to the uniform spatial distribution of oxide traps near the Si/SiO$_2$ interface which gives rise to a distribution of time constants which add up to yield the MOSFET *1/f* noise spectrum [6].

In the present work, the ISFET drift model has been employed to distinguish between the inherent *1/f* noise associated with the FET structure and the instability imposed by drift. Although *1/f* noise is believed to manifest itself as an apparent drift [1], our results clearly demonstrate that the physical bases for these two phenomena are entirely different.

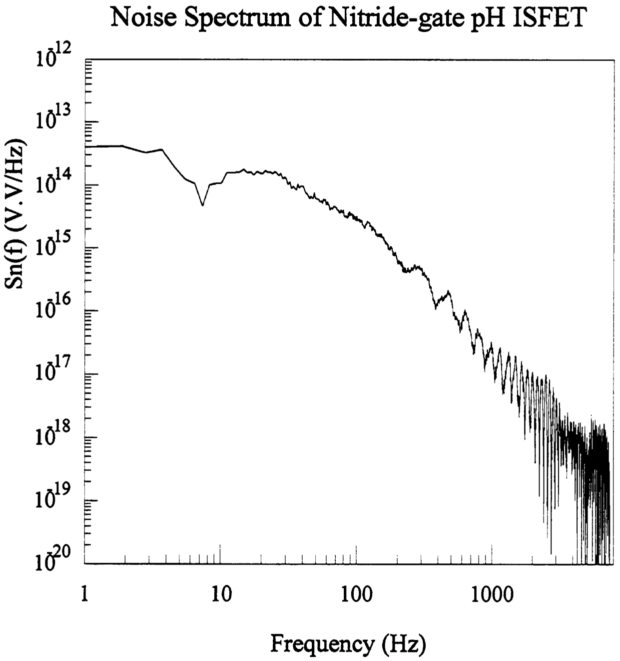

Fig. 3 Extracted ISFET Noise Spectrum

REFERENCES

[1] J. K. Atkinson, R. P. Sion, and E. Sizeland, " The Characterization and compensation through sensor array signal processing techniques of drift and low frequency noise in thick-film semiconductor sensors", Sensors and Actuators A, 41-42, pp. 607-611, 1994.

[2] J. Fraden, in *Handbook of Modern Sensors*, 2^{nd} Edition, Springer-Verlag, New York, 1996.

[3] A. L. McWhorter, "*1/f* noise and germanium surface properties", in *Semiconductor Surface Physics*. Philadelphia: University of Pennsylvania Press, 1957.

[4] F. N. Hooge, "*1/f* noise", *Physica*, vol. 83B, p. 14, 1976.

[5] A. van der Ziel, *Noise in Solid State Devices and Circuits*. New York: Wiley, 1986.

[6] K. K. Hung, P. K. Ko, C. Hu, "A unified Model for the Flicker Noise in Metal-Oxide-Semiconductor Field-Effect Transistors", IEEE Trans. on Electron Devices, vol. 37, No. 3, March 1990.

[7] S. Jamasb, S. D. Collins, and R. L. Smith, "A Physical Model for Drift in Al_2O_3-gate pH ISFET's", Proc. 9th Int. Conf. Solid-State Sensors and Actuators (Transducers '97), Chicago, USA, June 15-19, 1997.

[8] S. Jamasb, S. D. Collins, and R. L. Smith, "A Physical Model for Threshold Voltage Instability in H+-sensitive FET's (pH ISFET's)", IEEE Trans. on Electron Devices, vol. 45, No. 6, June 1998.

[9] S. Jamasb, S. D. Collins, and R. L. Smith, "A Physical Model for Drift in pH ISFETs", Sensors and Actuators B: Chemical (49) (1-2) (1998) pp. 146-155.

[10] R. L. Smith, and D. C. Scott, "An Integrated Sensor for Electrochemical Measurements", IEEE Trans. Biomed. Eng., vol. BME-33, No. 2, pp. 83-90, 1986.

[11] J. Janata, and R. J. Huber, in *Solid State Chemical Sensors*, Academic Press, Orlando, Florida, 1985.

[12] Y. P. Tsividis, in *"Operation and Modeling of the MOS Transistor"*, McGraw Hill, 1998.

[13] C. G. Jakobson, and Y. Nemirovsky, "*1/f* Noise in Ion Sensitive Field Effect Transistors from Subthreshold to Saturation", IEEE Trans. on Electron Devices, vol. 46, No. 1, January 1999.