1/f Noise in Ion Selective Field Effect Transistors compared to MOSFETs

C.G.Jakobson

Dept. of Biomedical Engineering
Technion - Israel Institute of Technology
32000 - Technion City - Haifa - Israel

Y.Nemirovsky

Dept. of Electrical Engineering
Technion - Israel Institute of Technology
32000 - Technion City - Haifa - Israel

Abstract

pH ISFETs are very interesting sensors for biomedical microsystems including in vivo measurements of pH. The noise phenomena and related resolution of these sensors are still not understood. In this paper measurements of low frequency noise in pH ISFETs are presented and compared to similar measurements performed in MOSFETs. Various bias conditions are used, corresponding to the gate voltage changing from subthreshold to saturation, in the frequency range between 1 Hz to 100kHz. ISFET noise measurements were performed in solutions with pH in the range of pH4 to pH10, at room temperature. The measured ISFETs exhibit clearly 1/f noise. The dependence of the drain current noise power spectral density upon average drain current follows the same behavior of 1/f noise that the observed in MOSFETs. The measured noise characteristics shown here indicate that the Si/SiO$_2$ *interface dominates the noise behavior of the ISFET. No pH dependent effects are observed and the interface between the solution and the gate insulator does not contribute measurable noise.*

1. Introduction

Ion Selective Field Effect Transistors (ISFETs) have been under extensive study in the last decade [1-10]. In spite of the several inherent difficulties in terms of stability and reliability, ISFETs are currently produced commercially and promise to become important sensors for biomedical microsystems operating *in vivo*.

The study of noise in ISFETs is important for two main reasons. First, any source of noise present in the sensor will impose a fundamental limit on the resolution and accuracy of the measurements and hence the sensitivity of ISFETs is limited by sensor noise. Second, a study of noise can provide a microscopic probe and additional insight into the basic physical mechanisms in the sensor.

While the importance of noise studies is widely established and noise has been extensively studied in MOSFETs and additional electronic devices, so far the noise research of ISFETs has been very limited [11-15].

In this paper, the noise present in ISFETs is compared to the observed in MOSFETs. It is well known that MOSFETs presents a behavior that is inversely proportional to frequency, namely 1/f, even at large frequencies of the order of 10-100KHz. This characteristic is stronger in n-channel MOSFETs than in p-channel MOSFETs. In last years, there is an extended consensus about 1/f noise being originated in the Si-SiO$_2$ interface of the MOSFET. An ISFET showing the same behavior than a MOSFET is supposed to be dominated by the Si-SiO$_2$ interface.

This paper presents the first measurements of low frequency noise in ISFETs under various bias conditions corresponding to the gate voltage changing from subthreshold to saturation, in the frequency range between 1 Hz to 100kHz. The ISFETs under study are commercial pH ISFETs with a relatively matured fabrication and packaging technology [16]. The noise measurements were performed in solutions with pH in the range of pH=4 to pH=10, at room temperature. In contrast to the preliminary results previously reported [11-13], the measured ISFETs exhibit clearly 1/f noise

2. Modeling

It has been established that capture and emission at single, individual traps in the SiO$_2$ gate oxide of sub-micron MOSFETs causes discrete modulations of the source-drain coductance in the form of random telegraph signals (RTSs) [17-19]. While the superposition of even few RTSs already gives rise to 1/f noise, in ordinary MOSFETs, the superposition includes a large number of traps, resulting in 1/f noise.

Thus, it is now recognized that the physical origin of low frequency noise in MOSFETs is basically the carrier number fluctuation theory known also as the trapping-detrapping model, originally proposed by McWhorter. The low frequency noise is caused primarily by fluctuation of the number of inversion layer carriers as they are trapped and detrapped to and from traps in the oxide. These fluctuations can also induce fluctuations in the channel mobility of the remaining carriers in the

0-7803-3879-0 / 98 / $10.00

channel since the traps act as scattering sites when they capture a carrier. However, in large scale MOSFETs, in particular in strong inversion, the scattering effects are effectively screened by the gate and the channel and these induced mobility fluctuations are normally negligible [20].

Empirically, 1/f noise in MOSFETs is described by the expression

$$S_I = \frac{Mg_m^2}{C_{ox}^2 WL}\frac{1}{f} \qquad (1)$$

where S_I is the drain 1/f noise current spectral density, W,L are respectively the width and channel length, and C_{ox} is the oxide capacitance per unit area. The relationship between Eq. 1 and the physical model is presented in [21]. When the transistor behaves following a pure trapping-detrapping process, M is a real constant depending only on the trap density on the oxide. Scattering effects already mentioned result in gate voltage dependence of M.

3. Experimental setup

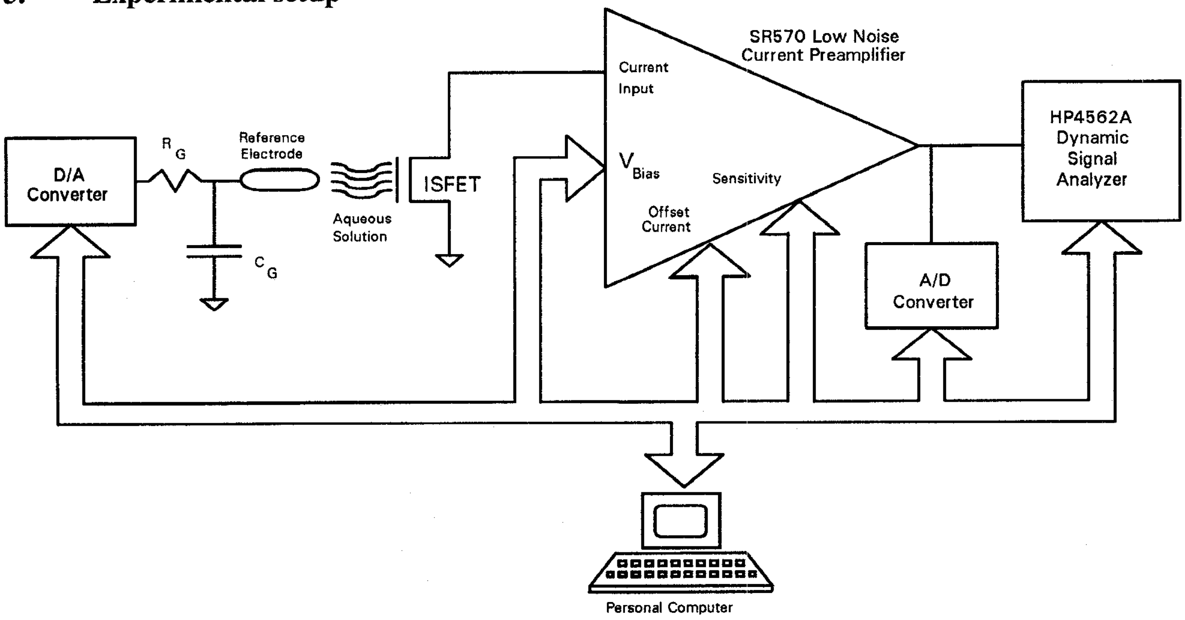

Fig.1: Experimental setup for the measurement of ISFET drain current noise.

The experimental setup for measuring the low frequency drain current noise spectrum of the ISFET is shown in Fig.1. The ISFET is connected in a common source configuration and is DC coupled to the Stanford Research SR570 Low Noise Current Amplifier. The output of this amplifier is connected to an HP3562 Dynamic Signal Analyzer which samples this signal and calculates its Fourier transform. This transform provides the power spectral density of the incoming voltage in the frequencies of interest. The experimental set-up for measuring MOSFET noise is similar to the corresponding to ISFET, only differing in the lack of reference electrode and electrolyte.

To study the dependence of 1/f noise upon DC operation point, it is necessary to achieve a good precision in the variations of the DC parameters of the ISFET. To this end, an experimental setup fully controlled by a PC has been built, which can work stand alone for hours as required for these measurements.

4. Experimental Results.

Fig. 2 shows the ISFET gate transconductance characteristics in the saturation region. The slope of the characteristics is given by $\mu_{eff} C_i W / L$ where the channel width W is 600μm, the channel length L is 20μm, and μ_{eff} is the effective mobility which is approximately equal to 600 cm^2/Vsec. From these values the insulator capacitance per gate unit area is C_i=2.974·10^{-8} F/cm^2 .

The threshold voltage is calculated by extrapolating to the gate voltage axis the straight gate transconductance characteristics in the saturation region, as shown by the dashed line in Fig. 2. The threshold voltages obtained are 220mV, 380mV, 520mV for pH=4,7,10 respectively. The average shift of the threshold voltage which expresses the pH sensitivity is 50 mV per unit pH and is roughly linear.

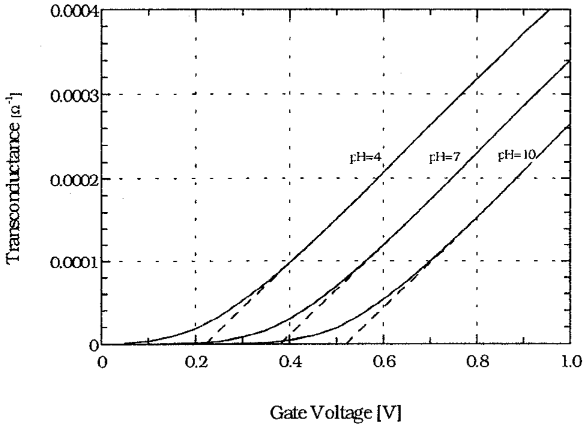

Fig.2. Gate transconductance characteristics in saturation and calculation of threshold voltage of the pH ISFET with V_{BS}=0, V_{DS}=2V, pH=4,7,10.

Fig. 3 shows the drain current noise spectra measured for pH=7 and current ranging from 10 nA to 10 μA. The maximum frequency shown for each curve corresponds to the bandwidth limit of the low noise current amplifier. The lower bandwidth is obtained for the smaller currents where a high gain is required.

For comparison, the upper line in the graph shows a 1/f slope. It is seen that the noise is clearly 1/f down to 1 Hz. The dependence of this noise upon bias condition is presented. The white noise seen in the lower graph corresponding to I_D=10nA is introduced by the current amplifier.

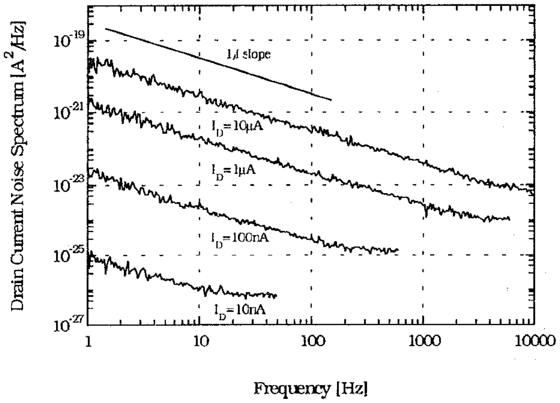

Fig.3. Drain current noise spectra measured for drain current ranging from 10nA to 10μA. In all the measurements V_{DS}=1V, V_{BS}=0V and pH=7.

Using the gate transconductance characteristics already presented, the gate referred voltage noise spectrum is calculated as

$$S_{VG} = \frac{S_{ID}}{g_m^2} \qquad (2)$$

and results are presented in Fig. 4, for several pHs. It is clearly seen that at low frequency the gate referred noise power spectral density is constant for any pH and gate voltage applied. The average measured gate voltage noise power spectral density $S_{VG}=2\cdot 10^{-12}$ V²/Hz. Comparing with Eq. 1, the average value of M obtained is $2.12\cdot 10^{-31}$ C²/cm². This value of M corresponds to typical values observed in MOSFETs used for analog applications [20,22].

In addition, in MOSFETs modeled by a trapping-detrapping noise mechanism, the value for M is related to the effective oxide trap density by

$$M = q^2 N_{ot} \qquad (3)$$

that yields $N_{ot}=8\times 10^{6}\,\mathrm{cm}^{-2}$, a very reasonable value for state-of-the-art MOSFETs.

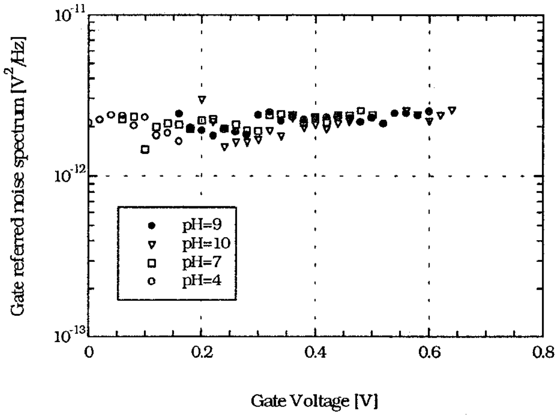

Fig.6. Gate referred noise power spectral density as a function of the average gate voltage for pH=4,7,9,10. The noise is evaluated at f=1Hz. In all the measurements V_{DS}=1V and V_{BS}=0V.

The results of Fig. 4 are compared to those obtained in several MOSFETs of n-channel type presented in Fig. 5. The measured values of M according to Eq. 1 are presented. The values of M obtained range between 1-5x10⁻³¹ C²/cm², very close to the values obtained for the pH ISFETs.

The measured noise characteristics shown here indicate that the same mechanism of trapping-detrapping that control the behavior of the MOSFET is presented by ISFETs, namely, the Si/SiO$_2$ interface dominates the noise behavior of the ISFET

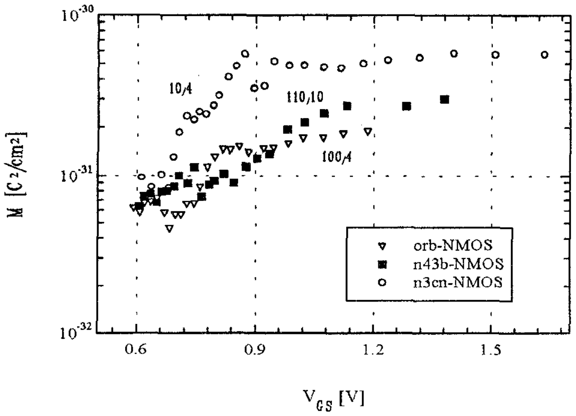

Fig.5. Empirical constant M for various n-channel MOSFETs of different dimensions

5. Summary

The ISFET is a modified MOSFET where the gate insulator is in contact with ionic electrolytes and a reference electrode immersed in the solution provides the gate bias voltage. The ISFET integrates selective ion sensing capabilities contributed by the specific gate insulator in contact with the solution and intrinsic amplification added by the FET structure. Like every sensor, the performance of ISFETs is limited by the signal-to-noise ratio.

The present paper studies the noise behavior of a state-of-the-art ISFET for pH measurements. The results clearly indicate that the ISFET noise is dominated by the FET transistor noise. The dominant low frequency noise is 1/f noise. The dependence of the drain current noise power spectral density upon average drain current follows the predicted behavior of a MOSFET. The gate voltage noise power spectral density is independent of the average gate voltage as predicted by trapping-detrapping 1/f noise modeling of MOSFET. The measured noise characteristics shown here indicate that the Si/SiO_2 interface dominates the noise behavior of the ISFET. No pH dependent effects are observed and the interface between the solution and the gate insulator does not contribute measurable noise.

The ultimate performance of the ISFET as a sensing device will be obtained when the noise will be dominated by the measurand, namely the pH. This requires a significant reduction in the noise contributed by the FET. It is possible to attain this goal by designing ISFETs based on p-MOSFET instead of the commonly used n-channel since it is well established that the noise of p-MOSFET is lower by nearly two orders of magnitude. Moreover, the MOSFET noise level is scaled by $1/C_{ox}^2$ and hence by decreasing the gate insulator thickness (increasing C_i) the noise will be reduced. A low noise design based on p-channel and a thin gate insulator is expected to yield ISFETs exhibiting solution related noise mechanisms that may provide new insight on ISFET fundamentals.

Acknowledgments

This research was supported by the Kidron Foundation and was performed in the laboratories donated by Etia and Miguel Meilichson. The research was also supported by Technion V.P.R. Fund-Promotion of Sponsored Research.

References

[1] C. D. Fung, P.W. Cheung, W.H. Ko, "A Generalized Theory of an Electrolyte-Insulator-Semiconductor Field-Effect-Transistor," *IEEE Trans. On Electron Devices*, Vol. ED-33, No. 1, pp. 8-18 (1986).

[2] P.R. Barabash, R.S.C. Cobbold, W.B. Wlodarski, "Analysis of the Threshold Dependence in Electrolyte-Insulator-Semiconductor Field-Effect Transistors (EISFETs)," *IEEE Trans. On Electron Devices*, Vol. ED-34, No. 6, pp. 1271-1282 (1987).

[3] D. Ewald, A. Van Der Berg, A. Grisel, "Technology for Backside Contacted pH-Sensitive ISFETs Embedded in a p-Well Structure," *Sensors & Actuators*, B1, pp. 335-340 (1990).

[4] W. Olthuis, J. Luo, B.H. Van Der Schoot, J.G. Bomer and P. Bergveld, "Dynamic Behavior of ISFET-Based Sensor-Actuators Systems," *Sensors & Actuators*, B1, pp. 416-420 (1990).

[5] C. Cui, P.W.Cheung, S. Yee and R. Muller, "An Experimental Study of Instability in Inorganic Gate ISFETs," *Sensors & Actuators*, B1, pp. 421-424 (1990).

[6] Y. Dun, W. Ya-Dong, W. Gui-hua, "Time-Dependent Response Characteristics of pH-Sensitive ISFET," *Sensors & Actuators*, B 3, pp. 279-285 (1991).

[7] P. Bergveld, "Future Applications of ISFETs," *Sensors & Actuators*, B 4, pp. 125-133 (1991).

[8] Ke-Ming Chen, Guo-Hua, Lang-Xing Chen and Yan Zhu, "Improvement of Structural Instability of the Ion-Sensitive Field-Effect-Transistor (ISFET)," *Sensors & Actuators*, B 13-14, pp. 209-211 (1993).

[9] W. Oelbner, J. Zosel, F. Berthold and H. Kaden, "Investigation of the Dynamic Response Behavior of ISFET pH Sensors by Means of Laser Doppler Velocimetry (LDV)," *Sensors & Actuators*, B 26-27, pp. 345-348 (1995).

[10] C. Cane, I. Garcia and A. Merlos, "Microtechnologies for pH ISFET Chemical Sensors," *Microelectronics Journal*, V. 28, pp. 389-405 (1997).

[11] A. Haemerli, J.Janata and J.J.Brophy, "Ion Noise in ISFETs," *Proc. of the Sixth International Conference on Noise in Physical Systems,* pp. 332-4 (1981).

[12] A. Haemerli, J.Janata and J.J.Brophy, "Equilibrium Noise in Ion Selective Field Effect Transistors," *J. Electrochem. Soc.*, pp. 2306-2312 (1982).

[13] J.Janata, "Electrochemistry of Chemically Sensitive Field Effect Transistors," *Sensors & Actuators*, 4, pp. 255-265 (1983).

[14] P.R.Barabash and R.S.C. Cobbold, "Basic Limitations of ISFET and Silicon Pressure Transducers: Noise Theory, Models and Device Scaling," *Sensors & Actuators*, 4, pp. 427-438 (1983).

[15] P.R.Barabash and R.S.C. Cobbold, "Electrochemical Noise in ISFETs: An Analytical Approach," *TRANSDUCERS '85, Proc. of the 1985 International Conference on Solid-State Sensors and Actuators,* pp. 445-450 (1985).

[16] Sentron® Integrated Sensor Technology, Sentron 1000 pH electrode, The Netherlands.

[17] K.S.Ralls et al., "Discrete Resistance Switching in Submicrometer Silicon Inversion Layers: Individual Interface Traps and Low-Frequency (1/f?) Noise," *Phys. Rev. Lett.* Vol. 52, pp. 228-31 (1984).

[18] H.H. Mueller and M. Schultz, "Conductance Modulation of Submission MOSFETs by Single-Electron Trapping," *J. of Appl. Physics*, 79, pp. 4178-4186 (1996).

[19] H.H. Mueller and M. Schultz, " Statistics of Random Telegraph Noise in Sub-micron MOSFETs", *Proc. of Noise in Physical Systems and 1/f Fluctuations 97*, p.195 (1997).

[20] C.G. Jakobson, I. Bloom, Y. Nemirovsky, "1/f Noise in CMOS Transistors for Analog Applications from Subthreshold to Saturation," Submitted to *Journal of Solid State Electronics* (1997).

[21] M.J. Kirton and M.J. Uren, "Noise in Solid-State Microstructures: A New Perspective on Individual Defects, Interface States, and Low-Frequency (1/f) Noise," *Adv. in Phys.*, V.38, pp. 367-468 (1989).

[22] C.G. Jakobson, "CMOS Low Noise Switched Charge Sensitive Preamplifier for X-ray Detection," M.Sc. Thesis, Technion - Israel Institute of Technology, s