$1/f$ Noise in Ion Sensitive Field Effect Transistors from Subthreshold to Saturation

C. G. Jakobson and Y. Nemirovsky

***Abstract*—The present paper presents extensive measurements of low frequency noise in pH ion sensitive field effect transistors (ISFET's) under various bias conditions corresponding to the gate voltage changing from subthreshold to saturation, in the frequency range between 1 Hz and 100 kHz. The noise measurements were performed in solutions with pH in the range of pH4 to pH10, at room temperature. In contrast to previously reported results, the measured ISFET's exhibit clearly $1/f$ noise down to 1 Hz.**

I. Introduction

Ion sensitive field effect transistors (ISFET's), originally introduced by Bergveld [1], have been under extensive study in the last decade [2], [3], and references therein. In spite of several inherent difficulties in terms of stability and reliability, ISFET's are currently produced commercially and promise to become important and generic biosensors for many applications including *in vivo* sensors.

The study of noise in ISFET's 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 ISFET's 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 MOSFET's and additional electronic devices, so far the noise research of ISFET's has been very limited [4]–[8].

The present paper presents the first extensive measurements of low frequency noise in ISFET's under various bias conditions corresponding to the gate voltage changing from subthreshold to saturation, in the frequency range between 1 Hz and 100 kHz. The ISFET's under study are commercial pH ISFET's with a relatively matured fabrication and packaging technology [9]. The pH ISFET's measured show a drift of 0.06 pH units during the first 4.5 hours and a maximum drift of 0.15 pH units in 24 h. The reference electrode used is Ag/AgCl and is not integrated with the ISFET. 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 [4]–[6], the measured ISFET's exhibit clearly $1/f$ noise down to 1 Hz.

II. Experimental Setup

A data acquisition system has been built that can measure drain current noise spectrum of the sensor in a wide range of drain currents [10]. The ISFET is connected in a common source configuration and is dc coupled to a Stanford Research SR570 Low Noise Current Amplifier. The output of this amplifier is connected to an HP3562 Dynamic Signal Analyzer that samples this signal and calculates its Fourier transform. This transform provides the power spectral density of the incoming voltage in the frequencies of interest.

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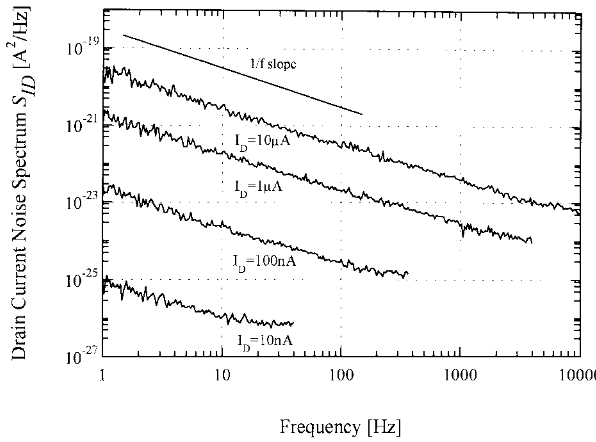

Fig. 1. Drain current noise spectra measured for drain current ranging from 10 nA to 10 μA. In all the measurements $V_{\rm DS} = 1$ V, $V_{\rm BS} = 0$ V and pH $= 7$.

The relative importance of the different noise components in this setup has been presented in [10]. The noise floor of the SR570 is 70 fA/sqrt(Hz) at 10 Hz and 7 fA/sqrt(Hz) above 1 KHz. The bandwidth of the preamplifier depends upon its gain. In the measurements presented the gain of the preamplifier varies from 10^5 to 10^8 Ω, from higher to lower drain currents, and the corresponding bandwidth varies from 50 KHz to 50 Hz.

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, the data acquisition system controls the dc voltages of the reference electrode and the drain. This experimental setup can work stand-alone for hours as required for the noise measurements.

III. Results and Discussion

The pH ISFET measured has a channel width W of 600 μm, a channel length L of 20 μm, and insulator capacitance per gate unit area C_i of 2.97 $\times$ 10^{-8} F/cm^2. The sensor is biased from the subthreshold to the saturation region at a constant drain-source voltage $V_{\rm DS} = 1$ V. The measured pH sensitivity in the 4–10 pH range is 50 mV per unit pH and is roughly linear.

Fig. 1 shows the drain current noise spectra S_{ID} measured for pH $= 7$ and mean drain current I_D 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. Assuming a $1/f^\alpha$ dependence, the exponential slope α measured is 0.86 ± 0.04. This value fits the $0.8 < \alpha < 1.2$ range usually observed for $1/f$ noise in MOSFET's. The dependence of this noise upon bias condition is presented in detail in the following figures. The white noise above 10 Hz corresponding to $I_D = 10$ nA is introduced by the SR570. The thermal noise of the ISFET is modeled by $(8/3)kTg_m$ in the saturation region and $2qI_D$ in the subthreshold region, where k is the Boltzmann constant, T is the absolute temperature, q is the electron

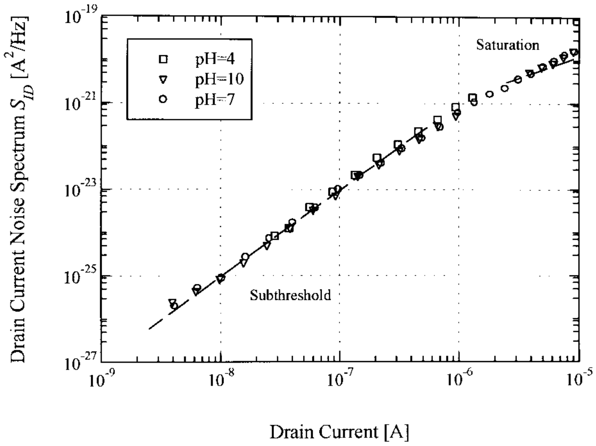

Fig. 2. Drain current noise power spectral density as a function of the average drain current for pH $= 4, 7, 10$. The noise is evaluated at $f = 1$ Hz. In all the measurements $V_{\rm DS} = 1$ V and $V_{\rm BS} = 0$ V. The dashed lines correspond to (1) and (2) calculated with $C_{\rm ox} = 3 \times 10^{-8}$ F/cm^2, $W = 600$ μm, $L = 20$ μm, $N_{\rm ot} = 8 \times 10^6$ cm^{-2}, $\mu = 600$ cm^2/V $\cdot$ sec.

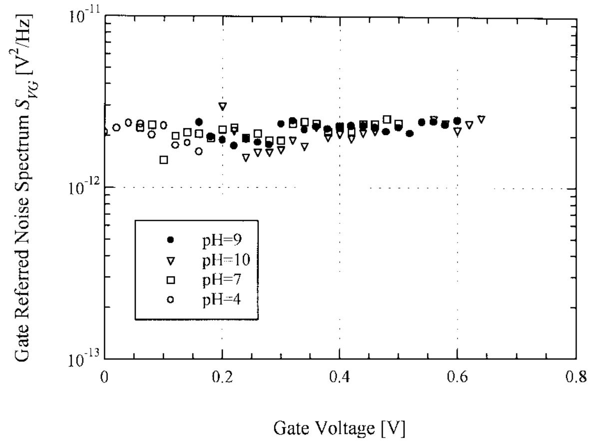

Fig. 3. Gate referred noise power spectral density as a function of the average gate voltage for pH $= 4, 7, 9, 10$. The noise is evaluated at $f = 1$ Hz. In all the measurements $V_{\rm DS} = 1$ V and $V_{\rm BS} = 0$ V.

charge and g_m the gate transconductance. This noise is well below the $1/f$ noise within the frequency range studied.

Fig. 2 presents the dependence of the measured drain current noise spectra at 1 Hz upon mean drain current. S_{ID} increases with increasing I_D. Moreover, S_{ID} is proportional to I_D^2 in subthreshold and to I_D in saturation, as indicated by the lines added to Fig. 2. The measured mean drain current dependence is in good agreement with the following expressions corresponding to a MOSFET modeled by trapping-detrapping $1/f$ noise [10]–[13]

1) At subthreshold:

$$S_{ID} = \frac{C_{\rm inv}^2}{(C_{\rm ox} + C_D)^4} \frac{q^4 N_{\rm ot}}{(kT)^2 WL} I_D^2 \frac{1}{f}. \tag{1}$$

2) At saturation:

$$S_{ID} = \frac{q^2 \mu N_{\rm ot}}{C_{\rm ox} L^2} I_D \frac{1}{f} \tag{2}$$

where $C_{\rm inv}$, $C_{\rm ox}$, and C_D are the inversion, oxide, and depletion capacitance per unit area, and $N_{\rm ot}$ is the effective oxide traps density per unit area.

The gate transconductance g_m is measured from the I_D-$V_{\rm GS}$ characteristics with $V_{\rm DS} = 1$ V and calculated as $g_m = \partial I_D / \partial V_{\rm GS}$. Using the measured g_m values, the gate referred voltage noise spectrum is calculated as

$$S_{\rm VG} = \frac{S_{ID}}{g_m^2}. \tag{3}$$

The results are presented in Fig. 3 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 is $S_{\rm VG} = 2 \times 10^{-12}$ V^2/Hz. Following the empirical expression usually used to simulate the MOSFET noise behavior [14]

$$S_{\rm VG} = \frac{M}{C_{\rm ox}^2 WLf} \tag{4}$$

the average value of M obtained is 2.12 $\times$ 10^{-31} C^2/cm^2. This value of M corresponds to typical values observed in MOSFET's used for analog applications [10], [13].

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

$$M = q^2 N_{\rm ot} \tag{5}$$

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

IV. Summary

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 is 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 ISFET's 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 $1/C_{\rm ox}^2$ 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 ISFET's exhibiting solution related noise mechanisms that may provide new insight on ISFET fundamentals.

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