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Modeling and Analysis of Low Frequency Noise in Ion-Field-Effect Transistors Sensors

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Abstract

Ions Sensitive Field Effect Transistors (ISFETs) are becoming the platform sensors for important chemical and biomedical applications. However, the accuracy of ISFET output measurement is greatly affected by the presences of low-frequency noise, drift and slow response of the device. This requires more safety in measured results and the tools of analysis. In this paper, we present fundamental limits on the sensitivity of ISFETs micro-sensors, arising from intrinsic and extrinsic noise sources. We developed an algorithm in MATLAB in order to model the frequency analysis of the $1/f$ noise in ISFET sensor using Hooge theory. We have shown that the $1/f$ noise of the ISFETs sensors is due to both the electrochemical system (pH solution) and the MOS component (canal size, insulator thickness). The temperature effect on the ISFET noise and the signal conditioning are also performed.

Keywords

Top-Spice Modeling, Ion Sensitive Field Effect Transistor, Low-Frequency Noise

1. Introduction

In the last decade, Ion Sensitive Field Effect Transistors (ISFETs), originally introduced by Bergveld [1], have been under extensive study because of rapid response, small size, as well as applicability of semiconductor and clear operation principle based on site binding theory [2] [3]. For many years, numerous studies on different sources of ISFET noise were reported [4] [5] and thereafter an important development has already been made

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regarding the ISFET noise reduction and drift compensation technique in different circuits and experimental levels [6]-[9]. The study of noise in ISFETs is important for the reason that any source of noise present in the sensor imposes a fundamental limit to the accuracy of measurements and, therefore, the sensitivity of ISFETs is limited by the noise sensor. While noise studies were largely established in MOSFETs, the research of ISFETs noise was very limited. An ISFET sensor has several intrinsic and extrinsic sources noises. The intrinsic noise is generated by the electronic device itself. Since ISFET is essentially a MOS structure, the noise sources of the MOS transistor are present in the noise ISFET. Electrochemical noise is produced by ion-membrane interactions, in the liquid and the reference electrode.

In several works [5] [10] [11], it is believed that the presences of 1/*f* low-frequency noise in ISFET sensors are mostly contributed by the FET structure of the device, which is dominated by the Insulator-Semiconductor interface [12]. More the pH-dependent 1/*f* electrochemical noise in ISFET is considered to be negligible in some device [4] [10]. In this work, we used a MATLAB program to prove that many parameters can affect the 1/*f* noise in ISFET devices as well as the pH solution. The goal of the modeling consists to predict the operating ISFET system as function as technical parameters defining the detection system.

Contrary to previous work [12], we found that for frequency range <1 Hz [13], the pH solution has a significant effect on the 1/*f* noise. More the 1/*f* noise of ISFET can be influenced par other parameters like the insulator thickness and the channel size. Additional, the modeling of temperature contribution in the spectacle density of 1/*f* noise in ISFET and afterward are investigated in our present work.

2. Modeling Setup

The 1/*f* noise in MOSFETs has been under investigation for many years. Two different theories have been proposed to explain the physical origins of 1/*f* noise: number fluctuation [14] [15] and mobility fluctuation [16] [17]. These two theories are based on the fluctuation of the conductivity of MOS transistors that is:

$$\sigma = \mu n q \tag{1}$$

where μ and n are respectively the mobility and the concentration of the carriers. Hence, from Equation (1) it is clear that a fluctuation of the conductivity is induced either by a fluctuation of the number of carriers (Worther model) [14] [15] or a fluctuation in the channel mobility (Hooge model) [15] [16]. In our work we used the Hooge model which defines the normalized drain current spectral density in ohmic operation by the equation below [18] [19]:

$$\frac{S_{I_d}}{I_d^2} = \frac{q\alpha_H}{fL^2}\mu_{eff}\frac{V_d}{I_d} \tag{2}$$

where f is the frequency and α_H is the Hooge parameter ($a_H \approx 10^{-5}$).

Another way to express the noise is to calculate the power spectral density of the gate voltage witch given by [20]:

$$S_{V_g} = \frac{S_{I_d}}{I_d^2}\frac{I_d^2}{g_m^2} \tag{3}$$

The ISFET parameters used in our modeling process are these same of ISFET device manufactured at the Laboratoire d'Analyse et d'Architecture des Systémes (LAAS) in Toulouse, France [21]. These devices are n-type enhancement mode transistors with the channel size 800 × 40 µm, the thickness SiO_2/Si_3N_4 insulator Tox = 100 nm and the doping substrate Nsub = 3.27×10^{15}. The silanol and amine sites are respectively 3×10^{14} - 2×10^{14} cm^{-2}.

3. Results and Discussion

3.1. Dependence of 1/*f* Noise on pH Solution

The modeled ISFET has a channel width of 800 µm, a length of 40 µm and an insulator thickness of 100 nm. The micro-sensor is biased in the strong inversion region at a voltage Vds = 1 V. **Figure 1** shows the noise spectrum of the drain current Sid for different pH solution (from pH = 1 to pH = 14) and at temperature of 25˚C.

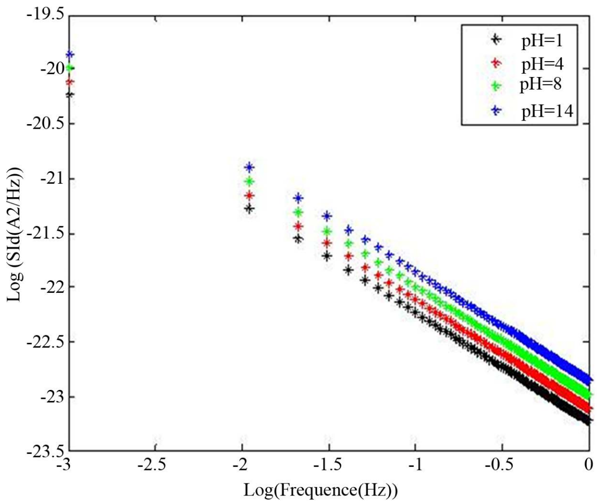


Figure 1. The noise spectral density of an ISFET at different pH (pH = 1, 4, 8 and 12).

As it can be shown the level of 1/*f* noise increases by increasing the pH solution. This modeling result is in good agreement with experimental results found in [22]. The 1/*f* noise dependence on the pH buffer is correlated to the ionic conductivity of the electrolyte [22]. The source of this noise is probably defined as the Brownian noise which is believed to be originated from the electrode-electrolyte structure of the ISFET. The origin of noise in electrode-electrolyte systems can be divided into two categories, namely, the thermal equilibrium noise and non equilibrium noise [11] [22]. The thermal equilibrium fluctuations are the only source of noise in the equilibrium condition where as recombination and generation of charged particle is the main cause of the non-equilibrium fluctuation [11]. Modeling results shows that the 1/*f* noise is more significant at low frequencies $f < 40$ MHz, beyond the white noise that is dominant. The figure below illustrates the evolution of the 1/*f* noise towards the pH solution for three different frequencies $f = 10$ MHz, 100 MHz and 1 Hz.

In **Figure 2** we note at $f = 10$ MHz the noise increase with pH solution linearly. Increasing the frequency the linear line slop decreases. From 1 Hz the effect of pH on the noise is practically negligible. The modeling result in **Figure 3** confirms that the measured ISFET 1/*f* noise is generated by both the electrochemical system and the FET devices.

3.2. Influence of Channel Size

In order to investigate the dependence of 1/*f* noise towards the channel size of MOS structure [23] [24], we modeled the noise at different channel lengths (L = 20 µm, 30 µm, 40 µm and W = 800 µm) and for different channel width (W = 600 µm, 700 µm, 800 µm and L = 30 µm).

As it can be noticed in **Figure 4**, a decrease in channel length results a significant rise in 1/*f* noise.

Modeling results proves that the 1/*f* noise is more significant for small lengths [23] [24]. This phenomenon is due to variation of channel resistance as well as variation in access resistances of gate (R_g) and source (R_s) [25]. In fact, a decrease in size gate causes more variation of canal resistance, hence, an increase in 1/*f* noise. This is justified by the fact that the influence of the access resistances appears especially in strong inversion when the channel resistance decreases [25]-[27].

3.3. Impact of the Insulator Thickness

Reducing the insulator thickness remains a key lever to improve the performance of the ISFET based microsensors. **Figure 5** shows the significant impact of the insulator thickness on the 1/*f* noise.

As it can be noticed from **Figure 5(a)** and **Figure 5(b)**, the flicker noise increases by reducing the insulator thickness. This increase can be attributed to the increase in noise leakage by direct tunneling. Indeed, the reduction of the insulator thickness causes an increase in the gate depletion, gate dopant penetration into the channel region, and the leakage current for direct tunneling increases, which leads to an increase of 1/*f* noise [28].

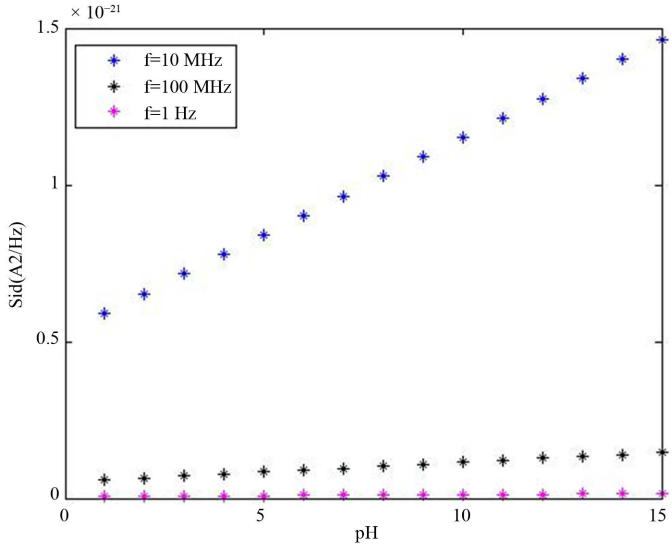


Figure 2. Variation of the spectral noise density of ISFET based pH at different frequencies f = 100 MHz, 10 MHz and 1 Hz.

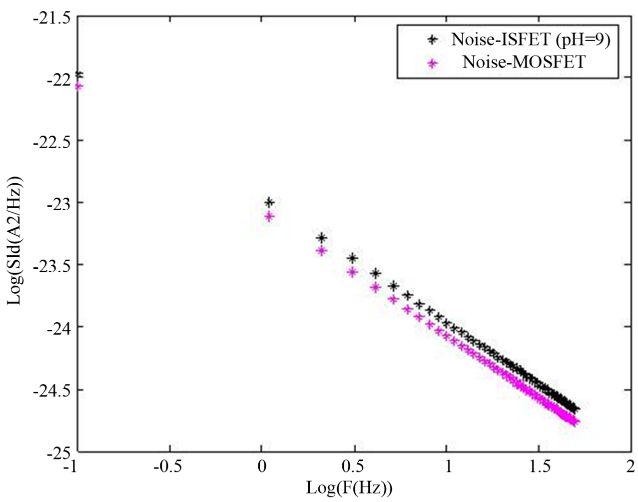
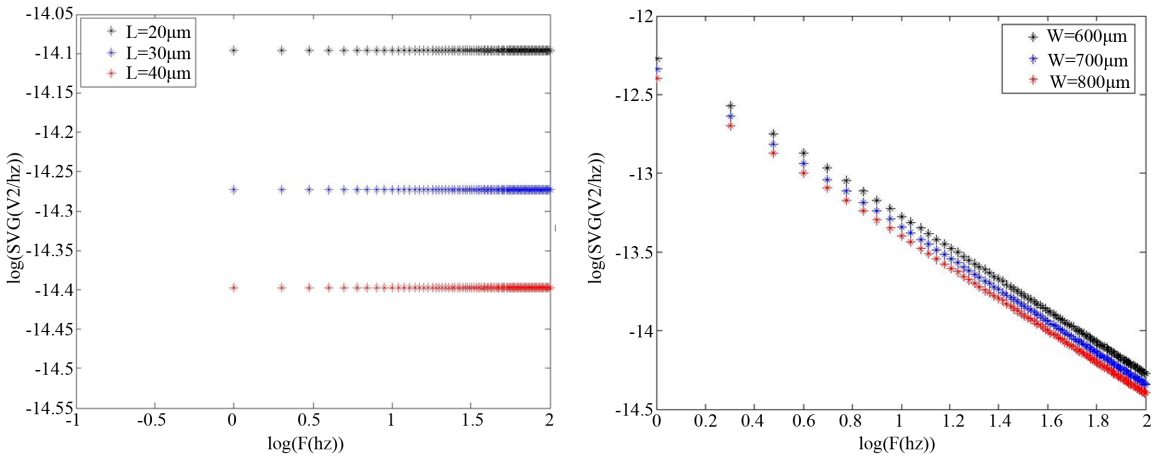


Figure 3. The flicker noise associated to the ISFET sensors towards the one of the MOSFET device.

3.4. Influence of Temperature

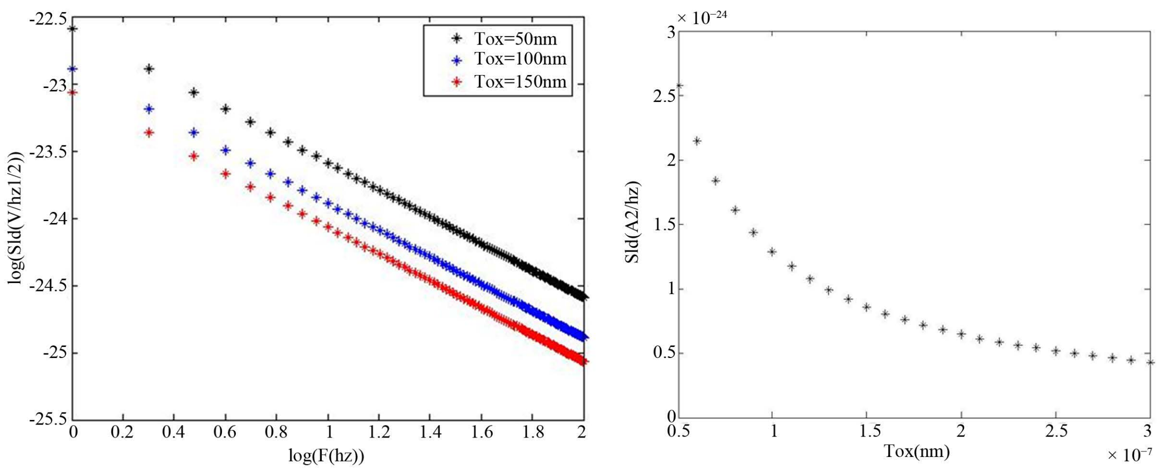
The temperature effect on the ISFET behavior is classified into two classes: influence resulting from the electronic component (MOSFET) and another due to the electrochemical component. This latter is function of the reference electrode, the electrolyte and the potentials of interface. To study the effect of temperature on the electrochemical component we modeled the potential behavior of the electrolyte/insulator (ψ_0) interface for a wide range of temperature (from 295 K to 335 K). The surface potential ψ_0 depends on the type of the sensitive membrane, the electrolyte pH and the operating temperature [29].

Figure 6 shows that the potential electrolyte/insulator interface increases with increasing the temperature. Indeed the sensitivity of the micro-ISFET sensor increases as a function the temperature as result of the increasing in the mass transfer and the activation of electrochemical reactions. **Figure 7** shows that for pH = 5 the spectral noise density of ISFET decreases with increasing the temperature. On the contrary, when pH = 7 the flicker noise increase with temperature. This behavior may be due, in addition to the instability of the FET structure as



(a) (b)

Figure 4. (a) S_{V_g} noise density as a function of frequency for different channel length and fixed width; (b) S_{V_g} noise density for different width and a fixed length.



(a) (b)

Figure 5. (a) Shift of the spectral noise density of the ISFET according to the frequency for various insulator thicknesses (Tox = 100 nm, 200 nm and 300 nm); (b) Evolution of noise as a function of Tox.

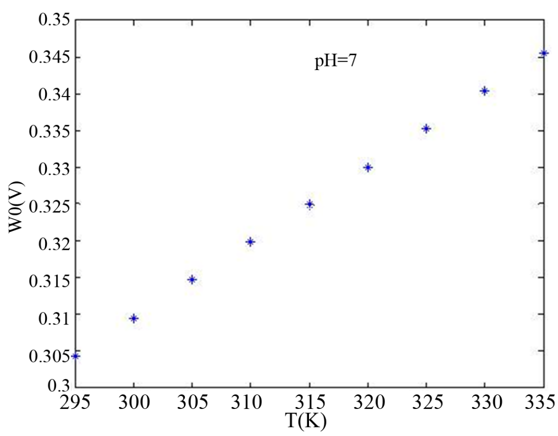


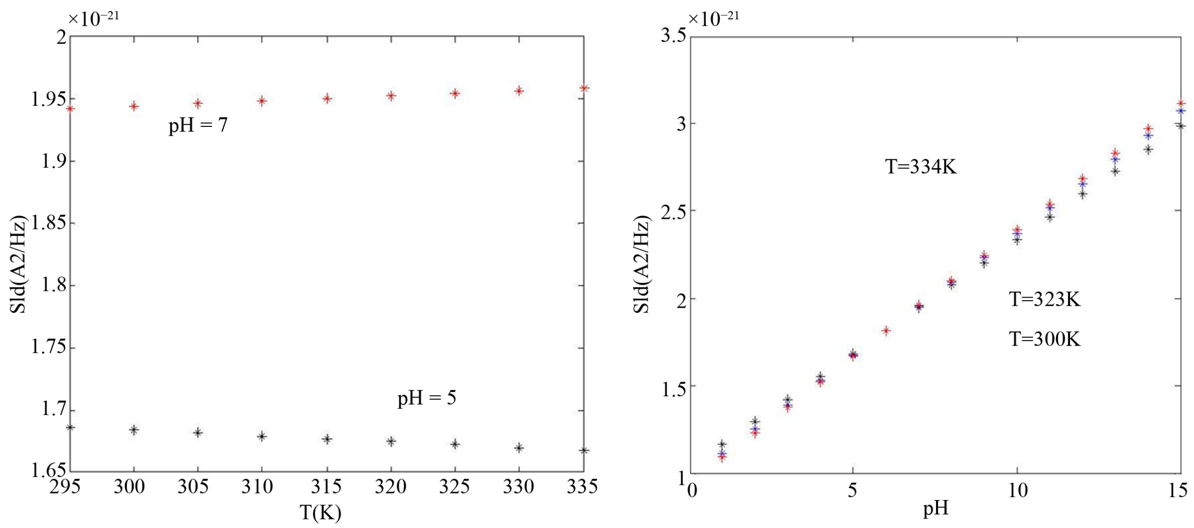
Figure 6. The potential interface shift as function of the temperature in pH = 7.

function of temperature, to the variation of the noise in the electrode-electrolyte interface. Thus, more the electrolyte is less acid more the ion transfer is favored.

4. Signal Conditioning

Various studies have turned to the use and the development of differential circuits in order to improve the ISFET sensitivity and reduce the undesirable effects specially the temperature. Differential measurement is a method using an ISFET sensor sensitive to the detected species and a reference Field Effect Transistor. The Reference FET (ReFET) should in ideal case show insensitivity to all species present in the sample solution [30].

In order to investigate the noise generated by different conditioning circuit, we implemented an ISFET macro-model in TopSpice and we simulated the total noise of the system. **Figure 8** summarizes the principle of ISFET macro-model. The macro-model is defined by the association of a V_{pH} function to the MOSFET device. The V_{pH} function is defined in terms of the potential reference (E_{ref}) and the surface potential (ψ_0). We previously used this macro-model to simulate the outputs sensor with different conditioning circuits [31]-[33] and it was shown that the Wheatstone bridge one can ensure the better temperature compensation [34] (in press). In this present work, we modeled the total noise of the same circuit (**Figure 9(a)**) discussed in [34] (in press). The normalized modeling results are illustrated in **Figure 9(b)**. As it can be seen, the 1/*f* noise system increases with



(a) (b)

Figure 7. (a) Behavior of the spectral density of the 1/*f* noise S_{id} as a function of temperature for pH = 5 and pH = 7; (b) Shift of S_{id} according to pH for different temperatures (T = 27˚C, 50˚C and 60˚C).

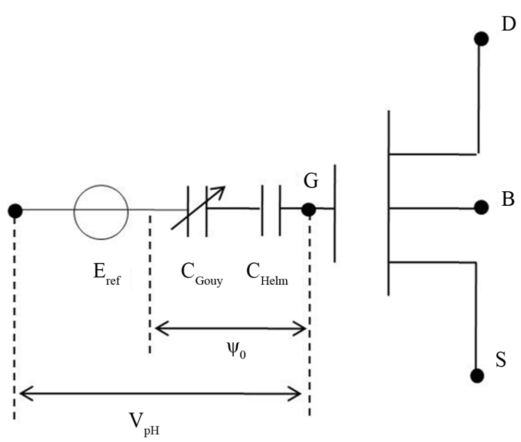
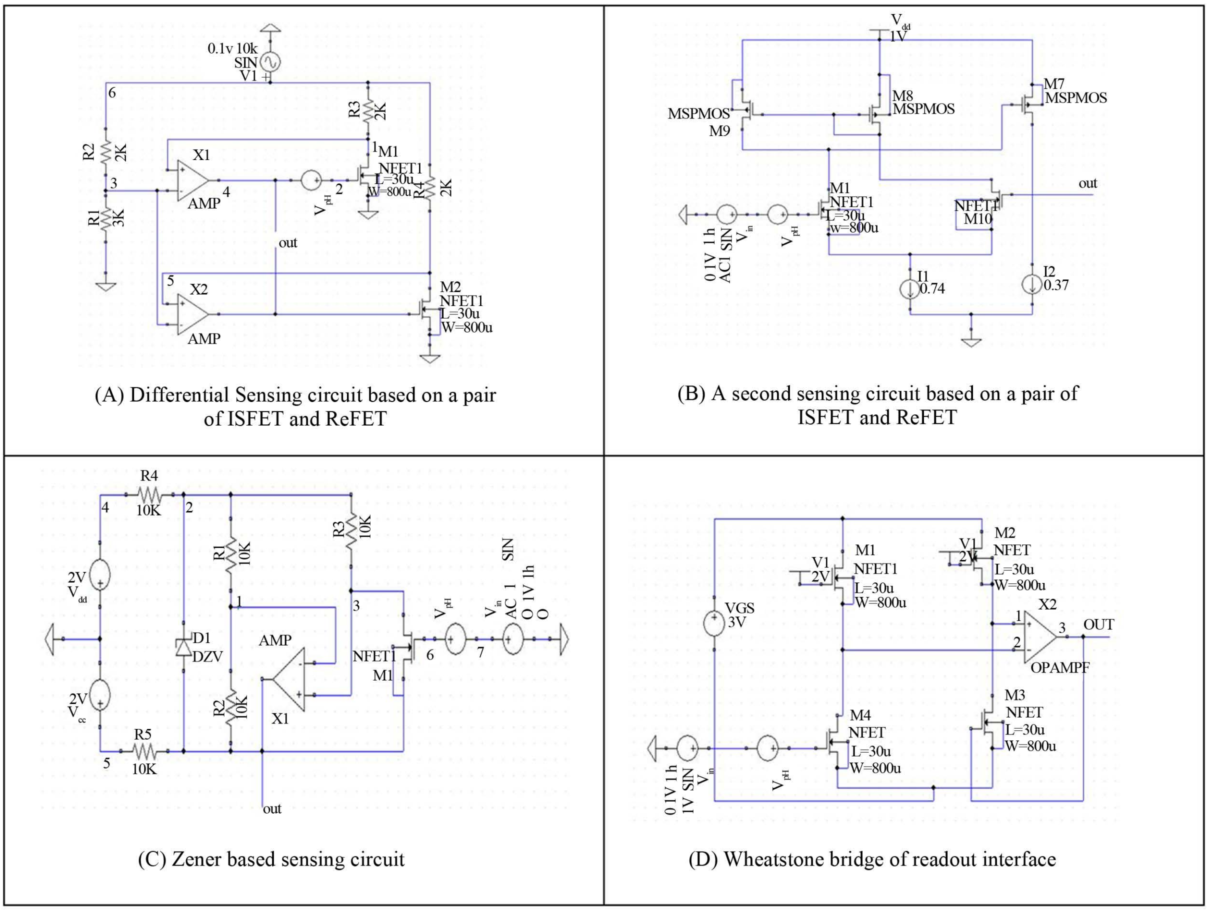
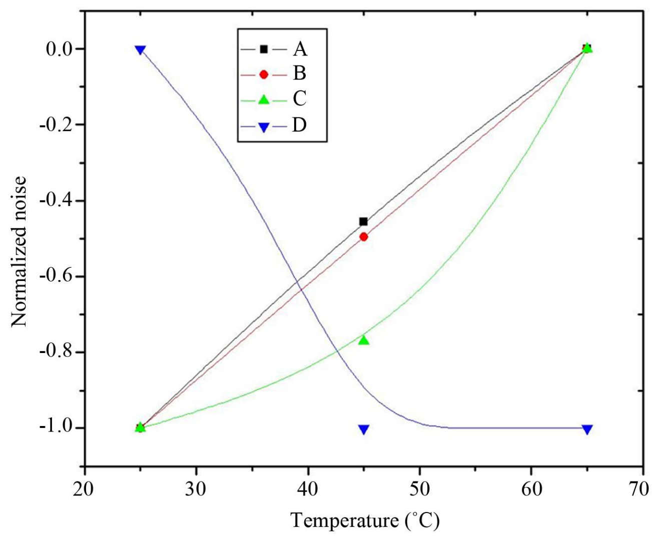


Figure 8. ISFET macro-model.



(a)



(b)

Figure 9. (a) The different modeled conditioning circuits; (b) The normalized noise of each conditioning circuits.

temperature for the first three circuits. However, for the Wheatstone bridge circuit, the 1/*f* noise decreases strongly with the temperature. Therefore, this latter circuit is the most appropriate in the strategy of 1/*f* noise reduction. This result is in good agreement with the results found in [34]. We conclude that the Wheatstone bridge circuit allows both the better reduction of 1/*f* noise and the better thermal compensation.

5. Conclusion

In this piece of work, we modeled the 1/*f* noise source in the ISFET microsensors. We proved the dependency of 1/*f* low-frequency noise on pH buffer. We found that the contribution of the pH solution appeared especially at low frequencies. By increasing the frequency, the effect of pH on the 1/*f* noise decreases. We also confirmed the contribution of the MOS structure at low-frequency noise. Indeed, the channel dimensions and the insulator thickness are the most important 1/*f* noise sources for MOS component. The study of different measurement circuits developed to the temperature compensation proves that the Wheatstone bridge circuit is also the most appropriate to reduce the 1/*f* noise.

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