A New Preprocessing Circuit for ISFET•

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Abstract. A *new circuit for processing signals from ISFET (Ion Sensing Field Effect Transistor) is proposed to allow for measuring hydrogen ion concentration in electrolyte. In comparison to ordinary approaches, a sensing and an reference ISFET are incorporated into a switched flip-flop circuit that has two stable states, namely a "one" and a "zero" state. The principle of measurement consists in the fact that the concentration of hydrogen ions changes the threshold voltage of sensing ISFET and thus breaks the symmetry of the switched flip-flop. This asymmetry is compensated by the voltage introduced to a flip-flop in such a way that the probability of the "one" is equal to probability of the "zero". This voltage consists of two parts. The first one corresponds to the concentration of hydrogen ions and the second one to mismatches in the elements of the flip-flop. First, the voltage without influence of hydrogen ions is obtained. Then it is subtracted from the voltage obtained by the measurement carried out with presence of hydrogen ions of electrolyte to compensate for these mismatches. In addition, as the voltage is set by using a feedback circuit that processes "ones" and "zeros" from the flip-flop output, the result is obtained directly in the digital form.*

Keywords: ISFET, pH sensitivity, switched flip-flop.

1. Introduction

Essentially, the ISFET is a Metal Oxide Semiconductor FET (MOSFET) in which the standard metal-polysilicon gate is replaced by a more complex structure sensing to hydrogen ion concentration. The gate structure, presented in Fig. 1, consists of a reference electrode and an insulating material between which a measured electrolyte flows.

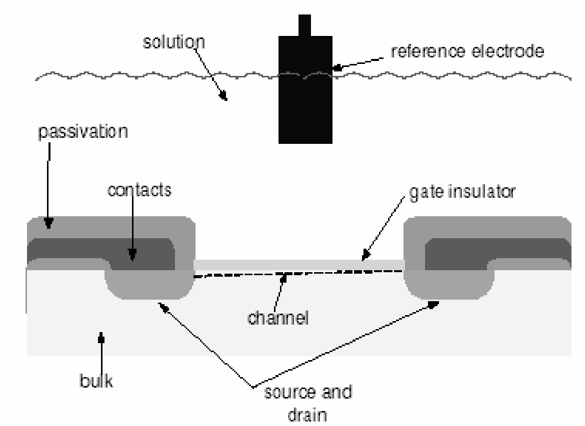

Fig. 1. Cross-section of an ISFET structure

• En extended version of the paper has been published in [2].

The electrolyte closes the electric gate-source circuit and the ion concentration influences the gate potential, which in turn modifies the transistor threshold voltage. In such a way the hydrogen ion concentration can exercise electrostatic control on the drain-source current [1].
The sensitivity of an ISFET is usually expressed as the gate voltage change per decade of the hydrogen ion concentration pH, where the pH denotes -log $[H^+]$. For example, if the value of the pH is equal to 2, the concentration of the hydrogen ions amounts to 10^{-2} mole per liter.
As to measurement methods, the ISFETs are usually operated in the constant drain current mode, which means that the change of the drain current due to the change of the ion concentration in the electrolyte is compensated for by the modification of the reference electrode potential (the gate voltage). The gate voltage is usually measured by using an analog-to-digital converter ADC [1].
This ordinary approach has several disadvantages. At first, to keep the drain current constant, other electronics, of which uncertainty can influence the resultant precision, is needed. Secondly, the hydrogen ion concentration does not correspond directly to gate voltage but only to a change of the gate voltage. In the third place, to represent the result in a digital form, other ADC as a separate electronics component, is needed.
In this paper a new approach in processing signals from ISFET is presented. The originality consists in the use of a switched flip-flop circuit with ISFETs, which is described in the following section.

2. Switched flip-flop with ISFETs

Fig. 2a shows a flip-flop with ISFETs. The circuit is controlled by an impulse generator and has two stable states, namely a “one” and a “zero” state. Activating the flip-flop with a voltage impulse, the circuit switches to one of two stable states [2]. It depends on the value asymmetry of the flip-flop which stable state it will be.

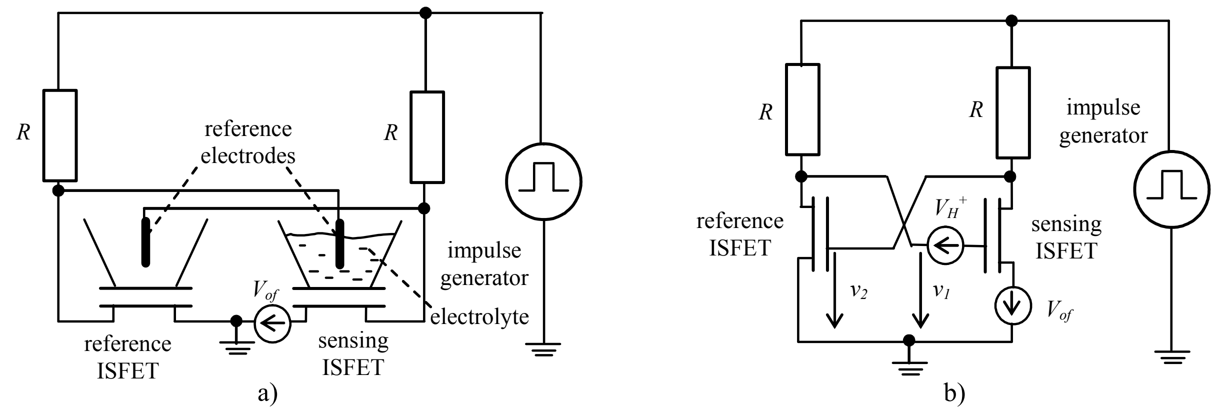

Fig. 2a Flip-flop circuit with ISFETs, b Equivalent circuit diagram

Let us consider the asymmetry caused by mismatches in the reference as well as in the sensing ISFET. Since, however, only threshold voltage of the sensing ISFET is influenced by H^+ ion concentration of the electrolyte, an equivalent circuit diagram according to Fig. 2b[1] can be drawn.
Here, the voltage source V_H^+ represents the change of the sensing ISFET threshold voltage by value $(R_gT/F).\log(H^+)$ [1], where R_g is the gas constant, T is the absolute temperature (K), F is Faraday constant, and H^+ is the hydrogen ion concentration. The principle of measurement is based on compensating this asymmetry by a voltage V_{of}. Compensating the flip-flop

[1] [1] The reference ISFET can be replaced by a standard MOSFET of which characteristics are identical to the sensing ISFET when influence of H^+ ion concentration is absent.

asymmetry we can achieve $v_1=v_2$ [2]. Therefore, in a balanced state $V_{of}=-(R_gT/F).\log(H^+)$. Then, the thermal and shot noise mean values [3] being zero, the probability of a "one" and a "zero" will be 0.5. This is known as the 50 % state of switched flip-flop [2].

The symmetry of a real flip-flop can be broken by other disturbances, such as the influence of flicker noise, mismatches in resistors, output characteristics of ISFETs etc. As shown in [2], the measured voltage V_{of} is given by formula

$$V_{of} = -\frac{R_g T}{F}\log\left(H^+\right) + V_{offset} \tag{1}$$

where V_{offset} is the voltage needed to compensate for the above disturbances. Thus, to eliminate the disturbances, two measurements must be performed, the measurement of V_{offset} when the influence of H^+ ions is absent and the measurement of V_{of} when the influence of H^+ ions is active. Then the given chemical parameter can be calculated from Eq.1. If, for example, pH sensitivity is to be measured by using Eq.1 we get

$$pH = \frac{V_{of} - V_{offset}}{R_g T} F \tag{2}$$

where $pH=-\log(H^+)$[2].

3. Measurement setup

As explained in the previous section, the voltage V_{of} reflects the hydrogen ion concentration. To set the voltage automatically, let us consider the measurement setup depicted in Fig. 3.

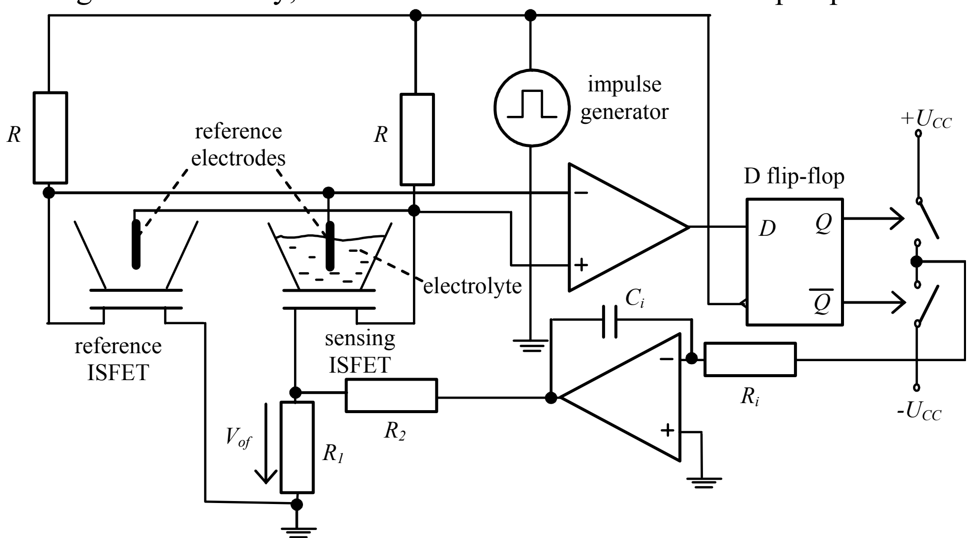

Fig. 3. Measurement set up

As can be seen, the feedback circuit contains a buffer amplifier, D flip-flop, integrator and resistive divider. The two outputs of the flip-flop are connected to a buffer amplifier and the buffer output is connected to D flip-flop. The actual logical state is sampled by the D flip-flop and depending on this state, one of two switches is turned on. Thus the resistive divider voltage is being decreased or increased to balance the switched flip-flop. By processing the series of impulses from the output Q of the D flip-flop, the chemical parameter to be measured is represented in digital form.

Detailed information about the uncertainty of the measurement the reader can find in [2].

[2] Differential pH sensitivity is calculated from Eq.2 in case that also the threshold voltage of reference ISFET is changed by influence of other electrolyte.

4. Results of simulation

The measurement system pictured in Fig. 3 was simulated in TSPICE. The approach when the threshold voltage is modified in dependence on hydrogen ion in existing SPICE MOSFET model was used for modeling ISFET [1]. Thus, H^+ ion concentration induces the change of the threshold voltage of the sensing ISFET by the value (R_gT/F).log(H^+). Other parameters of the used model are shown in Table 1.

Table 1. Parameters of ISFET SPICE model

Parameter	Value	Unit
Low field carrier mobility μ_0	0.097	[m^2/Vs]
Maximal carrier velocity v_{max}	1.10^5	[m/s]
Mobility modulation coefficient Θ	0.176	[V^{-1}]

The remaining parameters were set as follows: U_{CC}= 5 V, T_S= 3.34 10^{-5} s, R_i= 200 kΩ, C_i=100nF, R_1= 200 Ω, R_2= 10 Ω, R=6.8 k Ω, and T= 294 °K. The pH was changed from 4.7 to 11. The pH was calculated using Eq. 2. The corresponding relative error characteristic is shown in Fig. 4. As it can be seen, the maximal relative error is only 0.2 %.

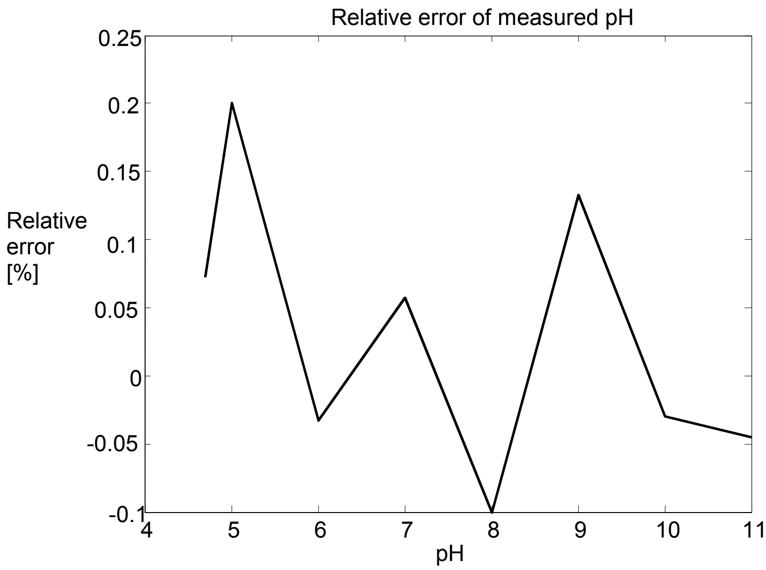

Fig. 4. A relative error of the measured pH

5. Conclusions

A new preprocessing circuit for signals from ISFET has been presented. The main part is a switched flip-flop with a reference, and a sensing ISFET. The principle of the measurement is based on changing the threshold voltage of the sensing ISFET through the concentration of hydrogen ions, thus breaking the symmetry of a switched flip-flop. Simulations in TSPICE showed that a relative error of the measured pH is, in the worst case, 0.22 %.

Acknowledgement

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References

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