ISFET Operation in Pass-Transistor Mode without Readout Circuits

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Summary: An operational concept was developed and tested for ISFET chemical sensor without readout circuitry, based on a phenomenon of threshold voltage drop, which is considered as parasitic event in most of the known applications in digital electronics, but appears to be extremely useful in ISFET-based applications. The operational concept is followed by measurements of the test-chip and the commercial ISFET sensor, and by applicability discussion.

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1 Introduction

Although numerous readout techniques were developed for ISFET during the years 0, one question remains open – is it possible to derive signals from ISFET without applying any readout circuitry? The benefits of readout-less sensory are obvious: the area and power consumption are reduced, less limitations exist on bandwidth and stability of the sensor, the design complexity is minimized. Sensors without readout would be much more suitable for array-type monitoring in biotelemetry and miniaturized clinical applications.

The main reason for application of readout circuit attached to ISFET, is the fact that the fluctuations of pH influence the threshold voltage, which is the internal parameter of the FET and does not manifest itself as voltage signal at the output, but as a fluctuation of the transconductance. The transconductance is a passive parameter, and in order to derive a voltage or current signal from its fluctuations, the sensor has to be attached to conditioning and transmitting circuitry.

In this study an operational concept was developed and tested for ISFET sensor without readout circuitry. It is based on a phenomenon of threshold voltage drop, which is considered as parasitic event in most of the known applications in digital and mixed-signal electronics, but appears to be extremely useful in ISFET-based applications.

The operational concept is presented in this paper, followed by measurements of the test-chip and the commercial ISFET sensor. The applicability of the sensor is also discussed.

2 Pass-Transistor Logic

One of the fields of electronics that is “suffering” from threshold voltage drop is the Pass-Transistor Logic (PTL). This technique was initially developed in order to provide a low-power alternative to the classic CMOS logic design [2]. Although it triggered numerous research efforts in the world of digital design, it failed to capture a major role in real logic LSIs. The main reason for this is the voltage drop in the output [3], which is caused by and equal to the threshold voltage of the pass transistor.

Standard PTL is based on application of a control signal to the gate of n-type transistor. Additional input is applied to the diffusion of the MOSFET, and is transferred through the transistor according to the value of the control signal. PTL circuits are much simpler than standard CMOS implementations, but have an important drawback in means of logic signals. When the signal that is transmitted through the pass gate is high, a voltage drop occurs at the output and the value of the signal is lower than it was in the input. This drop is caused by the fact that in order to allow current conduction, the difference of the potentials between the gate and the source of the FET has to be higher than \(V_T\). As soon as the output node is charged to high value, and the voltage across the FET equalizes to \(V_T\), the current flow is stopped, and so does the output charging, leaving a \(V_T\) drop in the output. In case of the ISFET, such voltage drop becomes a valuable property, eliminating the need in conditioning and transmitting circuitry.

3 ISFET as Pass-Transistor

In order to perform the pH measurement in ISFET sensor without readout, it has to be operated in Pass-Transistor mode. The basic structure of ISFET as pass transistor is presented in Fig. 1. By applying square wave to the gate or to the drain, while keeping the second input high, we produce sampling of the pH fluctuations – each time when the pulse is high, a \(V_T\) drop occurs bringing up the changes caused by the pH. Note, that the application of a constant high voltage to gate and square pulse to drain is preferable, due to the requirement of constant potential at the reference electrode.
The verification of the Pass-Transistor concept in ISFET was performed in simulations and measurements of the test chip. The results of the simulations are presented in Fig. 2. The sinusoidal gate signal at 1 KHz was sampled by square pulses at 100KHz frequency.

Close inspection of the output waveform shows that after the immediate sampling and VT drop, there is a slow drift of the signal during the high value of the pulse. It is caused by the fact that after the transistor stops conducting, there is still a low leakage current, known as subthreshold current, which continues to charge the output node. This current is very low and its contribution to each sample value is similar, because of the similar period of the pulse. The affect of subthreshold current on the measurement is minimized by increasing the operating frequency.

The measurements of the test chip were performed using various forms and frequencies of the pH fluctuations presented in Fig. 3. and Fig. 4. Note, that Fig. 4. shows the response to sinus signal that was measured simultaneously by n-type and p-type FETs. The operational concept of p-type Pass-Transistor is similar to n-type, but the drop occurs at low voltage ($V_T$ appears instead of expected 0V).

If needed, the original $V_T$ fluctuations in it analog form can be easily derived from the set of samples by applying a Low Pass Filter (LPF) to the output of the ISFET. Fig. 5. a presents the results of measurement of pass-transistor response to sinusoidal input, while Fig. 5. b shows the resulting output signal after filtering by LPF.

In order to assure proper operation in real ISFET devices, measurements were performed using commercial ISFET sensors. During the experiment the ISFET sensor was placed in pH7, pH4 and pH9 solutions. Fig. 6. shows the results of one of the experiments in which ISFET was operated as pass-
transistor, sampling a sinusoidal (a) and triangle (b) signal at higher frequency.

![Image of sinusoidal and triangle signals]

**Fig. 6.** Commercial ISFET operating in Pass-Transistor mode.

### 4 Applicability of ISFET Pass-Transistor

A simple and yet efficient operational concept of ISFET Pass-Transistor makes it an attractive platform for various applications. Some examples of the applications are presented in this Section.

**Embedding in ADC**

The pulse amplitude modulation that is performed during ISFET pass transistor operation is identical to sampling operation in the input of Analog-to-Digital Converter. Thus, the ISFET pass transistor can be combined with the ADC, as part of the Sample & Hold structure. In this way, an additional efficiency is achieved, by eliminating the need in sample circuits in ADC.

**1/f Noise Immunity**

The normal fluctuations frequency of pH is in order of 10 Hz. As was shown in [4], the ISFET is strongly influenced by 1/f noise, which occurs at low frequencies. Thus, if the readout feedback is following the pH fluctuations in same frequency, the 1/f noise is influencing the sensor causing measurement errors. The typical spectral power density of the ISFET noise, derived from simulations, is shown in Fig. 7. In case of Pass Transistor ISFET, the sampling is carried out at relatively high frequencies, which are above the practical frequency of pH fluctuations in clinical applications.

![Image of ISFET noise spectral power density]

**Fig. 7.** Spectral power density of ISFET noise

Higher frequency contributes to more accurate result. In most systems, the sampling is performed according to the Nyquist sampling theorem, which requires that the simulation sampling rate be greater than two times the highest frequency of the modulated signal, in order for the demodulator to recover the signal correctly.

In case of ISFET, the additional advantage of sampling is that the 1/f noise is reduced, because of high-frequency operation of the FET. This allows adjusting the sampling rate in a way that will provide a minimal noise appearance. If the 1/f noise is assumed as dominant, the sampling frequency can be increased beyond the rate that is needed for signal recovery. This maximal over-sampling rate is defined by the bandwidth limit of the overall system, and the number of switched sensors in the system.

**Drift Elimination by Surface Discharging**

In most of the ISFETs reported in the literature, a drift of the drain current is observed while operating under constant bias conditions of the reference electrode and the drain-source voltage.

The main hypothesis explaining this process [5] is the fact that the basic sites on the gate insulator surface are positively charged and the application of negative reference voltage attracts the positive charges from the sites, increasing the negative charge at the surface. This, in turn, biases the ISFET further into conduction, increasing the drain current. If the reference voltage removed, the surface sites return into equilibrium with the solution. Application of the positive voltage drives the protons to return to the surface, but alters the equilibrium.

In correlation with this hypothesis, it was experimentally shown that the drift can be compensated for by using a symmetric biasing scheme, in based on a sequence of positive and negative sweeps applied to the reference electrode. This raises an additional advantage of ISFET operation as Pass Transistor – the by-product of the square wave application to the gate is the drift compensation in drain current.

**Digital Data Transportation through ISFET**

In the presented experiments, the pH signal was modulated by a square wave, which is a sequence of high and low voltages. In means of digital data it can be considered as a series of alternately switching
"ones" and 'zeros'. If the modulating wave is related as a digital data sequence, it means that the modulation can be performed by any sequence of digits.

Thus, one can perform the modulation of ISFET using the digital data from the biotelemetry system that is anyway has to be transmitted to the output, for example: synchronization series, location data, pixel counting, etc. In this way, the need in a separate data line is eliminated.

The only limiting condition is that the maximal time between the modulating "ones" is not longer than it is defined by Nyquist frequency. In case of combined n-type and p-type ISFET modulation, where p-type sensor is modulated by "zeros", this condition is not necessary.

**REFET Operation and Body Effect Elimination**

When the on-chip integration of the ISFET is considered, the issues of REFET operation and body effect have to be covered. Because of the body effect limitations, the ISFET in its basic pass-transistor configuration in standard CMOS has to be p-type FET. The reason is the fact that in n-type devices the bulk is constantly connected to the ground, thus a potential difference is developed between the bulk and the modulated source signal. However, this problem can be solved by using a circuit in Fig. 8.

![Fig 8. Differential interface for REFET operation and body effect elimination](image)

This differential structure can be used for both body effect elimination and REFET operation. In case of body effect, the ISFET has to be connected with a common MOSFET. The modulating signal is inputted to both devices, and during the differentiation performed by the subtractor the body effect influence is rejected as a common mode signal. Thus, the only signal that appears in the output is the pH-caused fluctuations.

In case of REFET operation, the subtraction is performed on the responses of the ISFET and the REFET, rejecting the influence of the pseudo-reference electrode instability and the body effect, as common mode signals.

This configuration also allows temperature compensation by two FETs with similar dimensions.

**Array-type Sensors**

The Pass Transistor ISFET has a potential for implementation in array-type sensors, where the small size of the sensor is of a great importance. The configuration of pass transistor without attached readout circuitry allows fabrication of sensor structures with reduced complexity and simple control.

One example for such system could be an array of p-type ISFET sensors with common reference electrode constantly connected to the ground. A high-low-high pulse is sequentially introduced to the drain of each of the sensors, resulting in output signal modulated according to the threshold voltage drop of each sensor. The control can be easily performed using analog switches, as is done in any array-type monitoring system.

**5 Conclusions**

A simple but efficient operational concept of ISFET as Pass Transistor was presented based on the threshold voltage drop, which is known as problematic in logic design, but appears to be useful in pH sensing. The method was tested in test-chip measurements and experiments with commercial ISFET sensors, showing a response fully correlated with theoretical expectations.

The removal of readout interface at the sensor level proves to be an important benefit, which can contribute to simplified and efficient design and operation of pH sensors in biotelemetry and miniaturized clinical equipment. The simplified structure of ISFET sensor as pass transistor increases the potential of integration of ISFET in a combined multiple-mode sensors.

**References**


