**Wheatstone-Bridge Readout Interface for ISFET-Based Applications**

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**SUMMARY**

The paper presents a novel readout configuration for ISFET sensors based on Wheatstone-Bridge connection. This design technique allows on-chip integration, temperature compensation and measurements from ISFET/REEFET pairs in future implementations. A direct and indirect feedback configurations are presented with operational analysis, simulations and application options.

**Keywords:** ISFET, readout, Wheatstone-Bridge.

**Subject category:** 10. Applications.

**INTRODUCTION**

The ISFET sensor’s integration in clinical applications for pH and pCO₂ measurements [1,2] demands developing of high-performance analog interfaces. One of the most important required features is the temperature compensation.

Wheatstone-Bridge technique is widely used in numerous measurement applications [3], as resistance measurements, strain gauges, etc. due to its exclusive structure that allows reduced temperature sensitivity.

The novel ISFET readout interface based on Wheatstone-Bridge configuration is presented in this paper. Feedback implementation and a combination of ISFET and MOSFET devices in on-chip integrated structure, allows high system accuracy, low temperature sensitivity and compatibility for CMOS-based applications. Operational analysis, simulation results and a 4X4mm² test chip fabricated for future applications are presented.

**WHEATSTONE-BRIDGE READOUT INTERFACE**

The ISFET sensor’s operation [4,5] is based on conversion of the pH changes into a corresponding channel resistance. Thus, a detection of fluctuations of channel conductivity can lead directly to pH level detection. The changes of channel resistance are caused by the threshold voltage V_T, which is correlated with pH with a certain sensitivity factor (about 58 mV/pH in high-performance sensors). Wheatstone-Bridge configuration is the best candidate for implementation in this type of system, where temperature-compensated resistance detection is requested.

Fig. 1 shows the structure of Wheatstone-Bridge readout interface. An ISFET sensor and 3 MOSFET devices are applied in place of standard resistors. In order to maintain a balanced bridge, the diagonal is connected to the operational amplifier with feedback to the reference electrode of ISFET (direct feedback) or the gate of a corresponding MOSFET.

In a standard bridge (Fig. 2) with gage connected in diagonal, the following expression describes the relationship between the changes of four resistances and the diagonal voltage V_G:

\[
\Delta V_G = \frac{r}{(1 + r)} \left( \frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} - \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) V_S
\]

where \( r \) is the ratio between the corresponding resistors.

Two important properties can be derived from (1): (a) the changes in resistance due to temperature fluctuations result in zero total contribution to \( V_G \), assuming similar influence of temperature on devices, (b) changes in channel resistance of ISFET will contribute to \( V_G \) change. The operational amplifier detects this change and feedback is applied to the reference electrode or the gate of MOSFET, to maintain the balance of the bridge. The value of the
feedback voltage to the gate area is equal to the change in $V_T$ value of ISFET, because of the equivalent influence on the channel current according to Shockley model [6]:

$$I_s = \frac{\beta}{2} (V_p - V_T^s) \cdot (1 + \lambda \cdot V_{gs})$$

This allows a simple and direct expression for $V_{out}$:

$$\Delta V_{out} = \Delta V_T = \Delta V_T(pH)$$

Note, that by replacing the M3 device in the presented structure with a low-sensitive ISFET, a REFET measurement can be obtained, when such devices will be available. In this case the result will be proportional to the pH response ratio of ISFET and REFET.

ELIMINATION OF BODY EFFECT IN WHEATSTONE-BRIDGE CIRCUIT

The threshold voltage of Field-Effect Transistor in CMOS technology is expressed as:

$$V_T = V_{FB} - \frac{Q_b}{C_{ox}} + 2\phi_F$$

where $V_{FB}$ is the flat-band voltage, $Q_b$ is the depletion charge in the silicon and $\phi_F$ the Fermi potential [4]. The regular assumption for ISFET is that $V_{FB}$ contains also terms, which reflect the interfaces between the liquid and the gate oxide, and the liquid and the reference electrode; which makes $V_{FB}$ sensitive to the changes of pH. Terms $Q_b$, $\phi_F$ and $C_{ox}$ are assumed to be constant and uninfluenced by pH or operation point changes.

However, even if not influenced by pH, the threshold voltage $V_T$ is not constant with respect to the voltage difference $V_{BS}$ between the substrate and the source of the MOS transistor.

When an on-chip implementation of ISFET together with related readout interfaces is considered, it is important to remember, that all devices comprising an MOS device are made on a common substrate. In a standard CMOS technology, it is a p-type substrate with an equal voltage of 0V.

In most of the existing readout techniques, the source of ISFET is not constantly biased, and is used as an internal node of the circuit, or a point of feedback application. When $V_{BS}$ is not 0, the expression for the threshold voltage is modified to incorporate $V_{BS}$ as follows:

$$V_T = V_{gs} + \sqrt{2\varepsilon_{ox} \cdot q \cdot N_s \cdot (2\phi_F + V_{BS})}$$

This expression is critical, because of the influence of $V_{BS}$ on the value of $V_T$ in integrated implementations of ISFET. The term of $V_{BS}$, if getting a non-zero value (which will happen in most of the on-chip realizations of known readout interfaces) causes a parasitic change in $V_T$ that is not due to the change of pH level. The error that occurs in case of body effect is significant, and depending on technology and operation point, the threshold shift can reach more than a half of the initial $V_T$.

Wheatstone-Bridge technique in configurations that were presented in Fig. 1 has an advantage that allows elimination of body-effect influence on measurement results. The body effect occurs in M1 (ISFET) and M2 when the bulks are connected to ground (as all the substrate of the chip) and not to sources, as shown in Fig. 1. However, this does not change the final result of readout, due to an equal influence of body effect on M1 and M2, causing equal changes in transistors conductivity (if the transistors are of the type and sizes). So, according to (1) same relations will be obtained between the changes of four resistances and the diagonal voltage $V_{gs}$, resulting in a same output voltage as was without the body effect.

However, if needed, one can prevent the appearance of body effect in ISFET in Wheatstone-Bridge technique by using p-type MOSFETs as components of the bridge, as shown in Fig. 3. These transistors have to be properly sized to match the resistance demands that were applied to n-type MOSFETs in a regular configuration. This ratio is between 2.3 to 4 and is depending on technology parameters. An appropriate gate voltage has to be applied to the gates of the devices in order to maintain the desired operation point in the saturation region. This allows placing the n-type ISFET, so that its source and the substrate will be constantly and equally biased.

$$V_T = V_{gs} + \sqrt{2\varepsilon_{ox} \cdot q \cdot N_s \cdot (2\phi_F + V_{BS})}$$

Fig. 3. A body-effect-free Wheatstone-Bridge circuit. Resized p-FETs are used instead of n-FETs
TEST RESULTS AND IMPLEMENTATIONS

Test circuit was implemented in Cadence, using transistor models from MOSIS fabrication process. Test simulations were performed by Spectre simulator, using 1.6µm technology models. An n-channel 300/30µm n-type ISFET sensor was used in simulation with 400mV amplitude sinusoidal voltage source applied to its gate, to represent various pH levels. The simulations were performed at 1-500Hz frequencies, to assure operation in different conditions of pH fluctuations. Three 300/30µm n-MOSFETs and 5V P-P amplifier were connected to obtain the required configuration. A constant 2.3V bias was applied to the reference electrode (in indirect configuration), or to the correspondent MOSFET gate (in direct feedback) to maintain operation in saturation region. A 1V voltage was given to the opposite MOSFET pair; while an additional 128.5 µV were applied to the gate of M4 to compensate the built-in offset voltage of the designed operational amplifier. In case of discrete applications, adjusting of the commercial amplifier can perform same compensation.

The results of the simulation can be seen in Fig. 4. An accuracy of less then 9µV was observed for the maximal pH levels. Temperature compensation was obtained, due to the identical FET parameters.

![Fig. 4. Test results of Wheatstone-Bridge interface](image)

The layout implementations of Wheatstone-Bridge readout circuit in 1.6µm CMOS technology are presented in Fig. 5. The layout area of 1800/860µm makes the circuit suitable for implementation in a common catheter with 1mm diameter for clinical applications. In this circuit an operational amplifier was implemented on-chip together with FET devices.

In order to perform a characterization and operational tests in realistic conditions, discrete interfaces have to be associated with ISFET sensors and MOSFETs in a standard CMOS technology. Fig. 6 shows the microphotograph of a 4X4 mm² test chip that was fabricated, containing 28 various ISFET sensors and 8 MOSFETs, which can be used as a basis for bridge structures in future tests and applications.

![Fig. 5. Layout of Wheatstone-Bridge circuit](image)

![Fig. 6. Microphotograph of ISFET sensors chip](image)

CONCLUSIONS

A novel readout technique for ISFET-based applications based on Wheatstone-Bridge circuit was presented, allowing temperature-compensated pH measurement without body effect, by determination of the channel resistance changes in ISFET sensor. Test results showing 9µV accuracy were presented. A 4X4mm² test chip for future applications was fabricated in 1.6µm CMOS technology. Further research is expected in order to obtain REFET measurements.

REFERENCES