ABSTRACT—A novel ultra-low-power readout circuit for a pH-sensitive ion-sensitive field-effect transistor (ISFET) is proposed. It uses an ISFET/reference FET (REFET) differential pair operating in weak-inversion and a simple current-mode metal-oxide semiconductor FET (MOSFET) translinear circuit. Simulation results verify that the circuit operates with excellent common-mode rejection ability and good linearity for a single pH range from 4 to 10, while only 4 nA is drawn from a single 1 V supply voltage.

Keywords—ISFET, CMOS, low power, weak inversion.

I. Introduction

The recent success of ion-sensitive field-effect transistor (ISFET) fabrication in a standard CMOS process [1] has triggered a vast research effort toward the integration of ISFET-based chemical and biochemical sensors and CMOS signal processing circuitry in a single chip [2]. More recently, the subthreshold region has been demonstrated to exist in CMOS-compatible ISFET, and it has been exploited together with the translinear principle of weak-inversion metal-oxide semiconductor FETs (MOSFETs) to realize an ultra-low-power current-mode readout circuit [3]. Such a single-chip “smart sensor” with extremely low power consumption holds great potential for real-time biochemical sensing for implantable biomedical systems. In this letter, a novel ultra-low-power differential readout circuit for pH-sensitive ISFET is proposed.

II. Proposed ISFET/REFET Readout Circuit

Figure 1 shows the schematic diagram of the proposed ultra-low-power differential readout circuit. An ion-insensitive FET, also known as a reference FET (REFET), is used together with an ISFET to realize a source-coupled differential pair with a shared quasi-reference metal electrode as their gate connected to a stable DC reference voltage ($V_{\text{REF}}$). This suppresses the output current variation due to common-mode disturbances in the electrode potential and permits the use of a solid-state quasi-reference electrode. All MOSFETs, the ISFET, and the REFET operate in the saturated weak-inversion region (that is, $V_{GS}<V_{TH}$ and $V_{DS}>4U_{T}$) with identical DC bias current ($I_0$). The

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Fig. 1. Proposed differential ISFET/REFET readout circuit.
drain currents of the subthreshold ISFET [2] and REFET differential pair can be derived in (1) and (2), respectively, where \( I_0 \) is the quiescent drain current of the ISFET and REFET at the reference pH of 7, \( \alpha \) is a dimensionless sensitivity parameter of the ISFET [2], \( U_T = kT/q \) is the thermal voltage, \( n \) is the subthreshold slope parameter, and \( \Delta pH \) is the differential pH variation. Therefore, \( i_{D,\text{ISFET}} \) equals \( 2I_0 \) and \( i_{D,\text{REFET}} \) is zero for a large negative \( \Delta pH \), and vice versa for a large positive \( \Delta pH \). This is similar to the operation of a conventional MOSFET differential pair.

\[
i_{D,\text{ISFET}} = 2I_0 \cdot e^{\left(-\frac{2.3 \Delta pH}{nU_T}\right)} \tag{1}
\]

\[
i_{D,\text{REFET}} = 2I_0 - i_{D,\text{ISFET}} = 2I_0 \cdot \frac{1}{1 + e^{\left(-\frac{2.3 \Delta pH}{nU_T}\right)}} \tag{2}
\]

Applying the translinear principle to \( M_1 \) to \( M_4 \), the output current \( i_{\text{OUT}} \) can also be rewritten as (4) and (5) since \( \Delta pH = -\log_{10}[H^+] \), where \( [H^+] \) is the differential change in hydrogen ion concentration. Since \( 0 < \alpha < 1 \) and \( n > 1 \), the index \( \alpha/n \) is always between 0 and 1. Therefore, if a linear relationship between \( i_{\text{OUT}} \) and \([H^+]\) is desired, \( i_{\text{OUT}} \) can be applied to an appropriate translinear circuit as in [2].

\[
i_{\text{OUT}} = i_{D1} \cdot \frac{i_{D2}}{i_{D3}} = i_{D,\text{ISFET}} \cdot \frac{i_{D0}}{i_{D,\text{REFET}}} = I_0 \cdot e^{\left(-\frac{2.3 \Delta pH}{nU_T}\right)} \tag{3}
\]

\[
i_{\text{OUT}} = I_0 \cdot \Delta[H^+]^{\alpha/n} \tag{4}
\]

\[
\log_{10} i_{\text{OUT}} = \log_{10} I_0 - \frac{\alpha}{n} \Delta pH \tag{5}
\]

Assuming that all devices are in close proximity and thermally matched, the ratio metric relationship of the translinear principle reduces the temperature dependence of the circuit, together with the ISFET/REFET differential topology, the body effects of MOSFETs, ISFET, and REFET can easily be shown to cancel out, at least in theory [3]. A temperature-independent current source \( I_0 \) can be provided by a bandgap voltage reference generator, and assuming that \( \alpha \) and \( n \) are temperature-independent parameters to a first-order approximation, \( i_{\text{OUT}} \) is inherently temperature insensitive.

III. Simulation Results

The proposed ISFET readout circuit was designed to operate with a single 1 V power supply voltage. The ISFET and REFET were modeled with the behavioral macromodel described in [4], and the circuit was simulated with Cadence and component parameters from a 0.35 \( \mu \)m CMOS technology. All MOSFETs have the aspect ratio of 5 \( \mu \)m/2 \( \mu \)m, while the ISFET and REFET have a large aspect ratio of 100 \( \mu \)m/10 \( \mu \)m for good matching. Both DC current sources were realized with simple current mirrors with large channel length for good accuracy and large output resistance. The index \( \alpha/n \) is around 0.7, \( I_0 \) is 1 nA, and \( V_{\text{REF}} \) is 200 mV. All bias currents and voltages were chosen to center the circuit operation on the reference pH of 7. The circuit dissipates 4 nW.

Figure 2 plots the simulated \( i_{\text{OUT}} \) against the pH value at various \( V_{\text{REF}} \) values. At the nominal \( V_{\text{REF}} \) of 200 mV, a good linearity is obtained for the pH range of 4 to 10. This is limited by the weak-inversion operating range of the ISFET [2], which spans about 3 to 5 decades of drain current. Figure 2 shows that a large voltage variation of over 200 mV (100% fluctuation) in \( V_{\text{REF}} \) has virtually no effect in \( i_{\text{OUT}} \) in the pH range of 5 to 9. However, at lower and higher pH values, evident fluctuations in \( i_{\text{OUT}} \) were observed because the ISFET/REFET differential pair saturated with either \( i_{D,\text{ISFET}} \) or \( i_{D,\text{REFET}} \) was practically zero.

To test the common-mode signal rejection ability of the circuit, a 20 mV and 50 Hz disturbance voltage was added to the common reference electrode \( V_{\text{REF}} \), while the input pH value was ramped up and down between 4 and 10 within 1 second. Figure 3 plots a transient response of \( i_{\text{OUT}} \). No significant changes in \( i_{\text{OUT}} \) were observed because the ISFET/REFET differential pair saturated with either \( i_{D,\text{ISFET}} \) or \( i_{D,\text{REFET}} \) was practically zero.
than 5 or more than 9. The noticeable disturbance in the low and high pH values is due to the saturation of the ISFET/REFET differential. Figure 4 plots the transient response of $i_{\text{OUT}}$ of the circuit with and without the tail current source at pH = 7 when a common-mode disturbance of 20 mV at 50 Hz was applied to the reference electrode. With the tail current source, $i_{\text{OUT}}$ was virtually constant, while a variation of around 10 pA (i.e. 1% of $I_o$) was shown when the tail current source was omitted. Figures 3 and 4 clearly demonstrate the superior common-mode rejection ability of the proposed circuit.

IV. Conclusion

A simple ultra-low-power readout circuit for pH-sensitive ISFET was presented. The circuit employs an ISFET/REFET differential pair operating in weak-inversion and a simple current-mode translinear circuit to achieve good linearity, excellent suppression of common-mode disturbance in the reference electrode, and compensation of the body effects. The proposed circuit was demonstrated to be an attractive candidate for signal processing front-end of a real-time implanted biochemical sensing system.

References