Ultra-Low-Power Differential ISFET/REFET Readout Circuit

Apinunt Thanachayanont and Silar Sirimasakul

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.

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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_{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_O). The

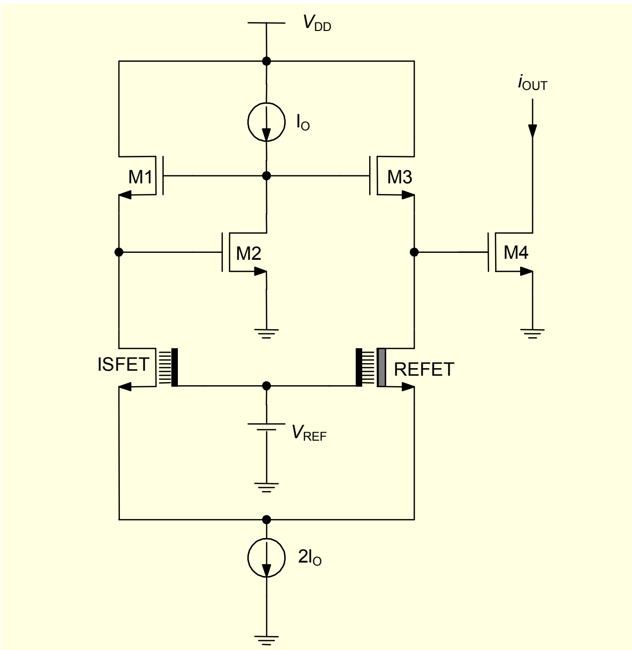

Fig. 1. Proposed differential ISFET/REFET readout circuit.

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

$$i_{D,ISFET} = 2I_O \cdot \frac{e^{(-2.3\alpha U_T \Delta pH/nU_T)}}{1+e^{(-2.3\alpha U_T \Delta pH/nU_T)}}, \tag{1}$$

$$i_{D,REFET} = 2I_O - i_{D,ISFET} = 2I_O \cdot \frac{1}{1+e^{(-2.3\alpha U_T \Delta pH/nU_T)}}. \tag{2}$$

Applying the translinear principle to M_1 to M_4, the output current i_{OUT} can be calculated as in (3). The current i_{OUT} can also be rewritten as (4) and (5) since $\Delta pH = -\log_{10}\Delta[H+]$, where $\Delta[H+]$ is the differential change in hydrogen ion concentration. Since $0<\alpha<1$ and $n>1$, the index (α/n) is always between 0 and 1. Therefore, if a linear relationship between i_{OUT} and $\Delta[H+]$ is desired, i_{OUT} can be applied to an appropriate translinear circuit as in [2].

$$i_{OUT} = \frac{i_{D1} \times i_{D2}}{i_{D3}} = \frac{i_{D,ISFET} \times I_O}{i_{D,REFET}} = I_O \cdot e^{(-2.3\alpha U_T \Delta pH/nU_T)}, \tag{3}$$

$$i_{OUT} = I_O \cdot \Delta\left[H^+\right]^{\alpha/n}, \tag{4}$$

$$\log_{10} i_{OUT} = \log_{10} I_O - \frac{\alpha}{n}\Delta pH. \tag{5}$$

Assuming that all devices are in close proximity and thermally matched, the ratiometric relationship of the translinear principle reduces the temperature dependence of the circuit, and 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_O can be provided by a bandgap voltage reference generator, and assuming that α and n are temperature-independent parameters to a first-order approximation, i_{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 μm CMOS technology. All MOSFETs have the aspect ratio of 5 μm/2 μm, while the ISFET and REFET have a large aspect ratio of 100 μm/10 μm 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 α/n is around 0.7, I_O is 1 nA, and V_{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.

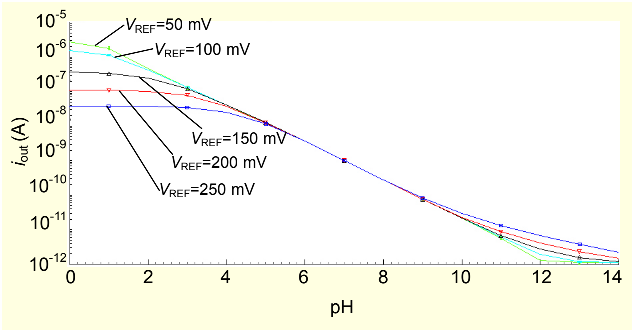

Fig. 2. Simulated i_{OUT} vs. pH at different values of V_{REF}.

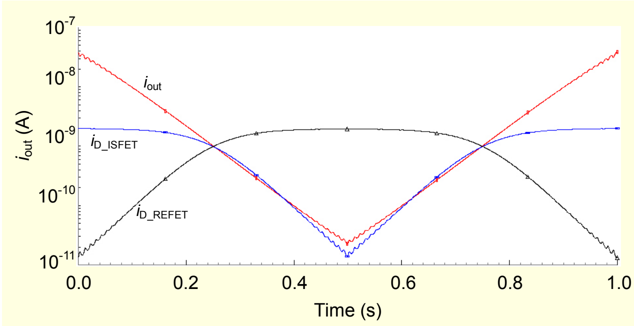

Fig. 3. Simulated transient response due to changes in pH.

Figure 2 plots the simulated i_{OUT} against the pH value at various V_{REF} values. At the nominal V_{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_{REF} has virtually no effect in i_{OUT} in the pH range of 5 to 9. However, at lower and higher pH values, evident fluctuations in i_{OUT} were observed because the ISFET/REFET differential pair saturated with either $i_{D,\,ISFET}$ or $i_{D,\,REFET}$ 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_{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 $i_{D,\,ISFET}$, $i_{D,\,REFET}$, and i_{OUT}. All signal currents are virtually free of common-mode disturbance except for the regions where the pH is either less

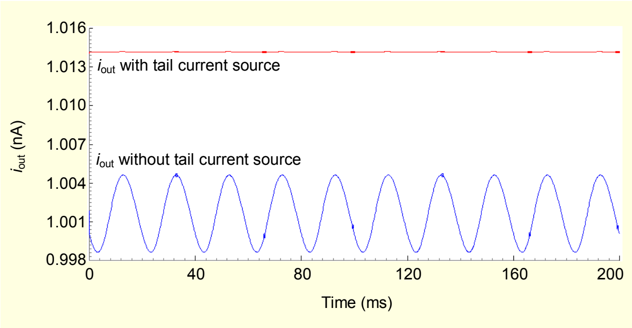

Fig. 4. Simulated i_{OUT} with and without the tail current source.

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_{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_{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

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