

# 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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Apinunt Thanachayanont (phone: + 66 818394328, email: ktapinun@kmitl.ac.th) and Silar Sirimasakul (email: silarsi@gmail.com) are with the Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand.

## 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 ( $I_0$ ). The

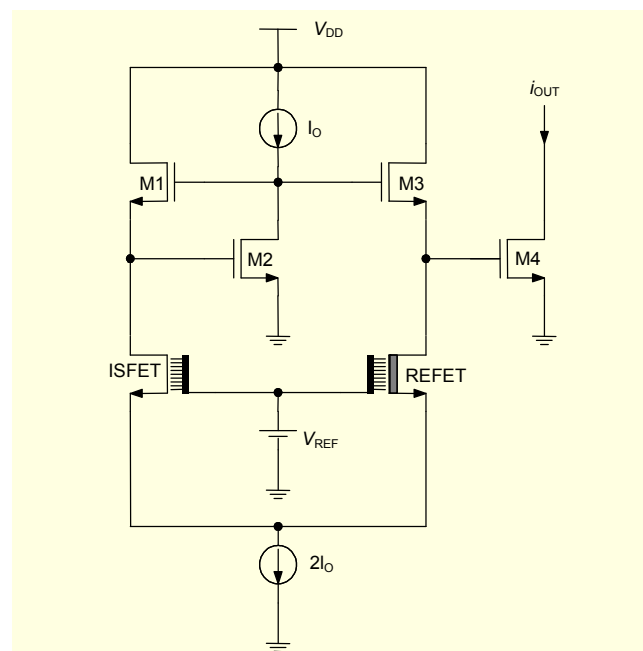


Fig. 1. Proposed differential ISFET/REFET readout circuit.

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,  $\alpha$  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,  $i_{D, ISFET}$  equals  $2I_O$  and  $i_{D, REFET}$  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.

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

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

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 ( $\alpha/n$ ) 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].

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

$$i_{OUT} = I_O \cdot \Delta[H^+]^{\alpha/n}, \quad (4)$$

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

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  $\alpha$  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

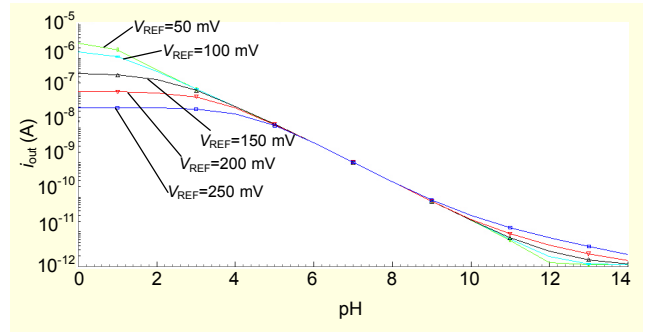


Fig. 2. Simulated  $i_{OUT}$  vs. pH at different values of  $V_{REF}$ .

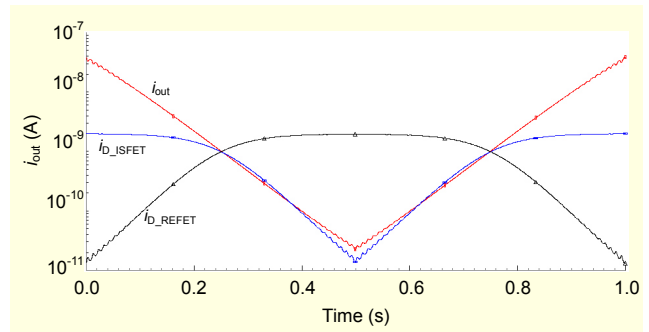


Fig. 3. Simulated transient response due to changes in pH.

and component parameters from a 0.35  $\mu\text{m}$  CMOS technology. All MOSFETs have the aspect ratio of 5  $\mu\text{m}/2 \mu\text{m}$ , while the ISFET and REFET have a large aspect ratio of 100  $\mu\text{m}/10 \mu\text{m}$  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,  $I_O$  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.

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

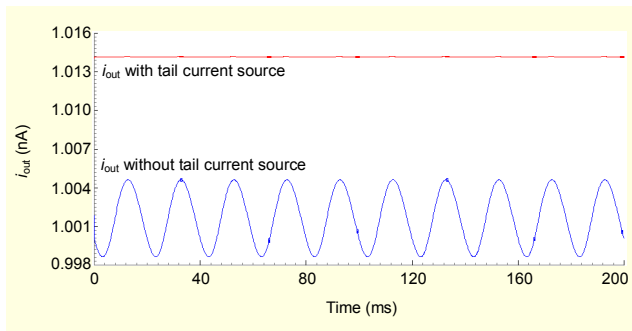


Fig. 4. Simulated  $i_{OUT}$  with and without the tail current source.

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  $\text{pH} = 7$  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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