A 0.72 nW, 1 Sample/s Fully Integrated pH Sensor with 65.8 LSB/pH Sensitivity

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Abstract

This paper presents a 0.85 mm^2 fully integrated pH sensor IC utilizing an ion sensitive field effect transistor (ISFET) and reference field effect transistor (REFET) pair in which the native foundry passivation layer is used as an ion sensitive layer. The pH sensor has 10 bit resolution with 65.8 LSB/pH sensitivity, while consuming only 0.72 nW at 1 sample/s, improving an overall figure of merit (FoM) that accounts for power, sampling frequency, and sensitivity by > 4000×.

Introduction

As a measure of acidity, pH is an important factor for many biological processes. For many biomedical applications, an implantable pH sensor needs to have a small displacement volume, a low power consumption, and a high sensitivity to deliver long term, accurate readout of pH changes *in vivo*. Conventional pH sensors Fig. 1(a) adopt an ion-exchange-membrane-covered electrode, whose voltage output varies linearly against the same electrode in a pH-buffered medium, leading to cm-scale bulky instrumentation [1]. The introduction of ISFET [2] devices created the opportunity to fully integrate pH sensors directly with data processing electronics and wireless transmission circuitry on one chip in commercial IC foundries to minimize their size and cost. Pairing an ISFET with a REFET [2] further increases the pH specificity of such sensors with the REFET tracking the potential changes in the solution while showing a negligible sensitivity to pH. In this paper, we propose a pseudo-differential-source-follower-like ISFET frontend topology utilizing I-V characteristics of the deep-subthreshold region of a FET, allowing for ultra-low power without loss of pH sensitivity. The fully integrated circuit delivers digitized pH data at 1 sample/s at sub-nW power consumption within an area of 0.85 mm^2, making it ideal for minimally invasive *in vivo* pH sensing.

System Design

In this work, we use a foundry-compatible ISFET/REFET design as shown in Fig. 1(b), where the top passivation layer is directly used as an ion-sensitive layer. This layer will associate and dissociate with protons (H^+) from an aqueous solution, creating a surface charge as a function of the pH. This charge modulates the gate voltage V_G of the FET underneath with respect to the quasi reference electrode (QRE) in contact with the solution. Conventional ISFET-based sensing frontend circuits utilize a constant-voltage-constant-current (CVCC) circuit for pH readout, as shown in Fig. 2(a); by fixing the V_{DS} and I_D, the source voltage V_S tracks the change in V_G. Since the V_G of the REFET changes negligibly with pH, the difference between the V_S of the ISFET and REFET is only a function of pH ($\Delta V_S = \Delta V_G = \Psi(\text{pH})$). However, such an implementation requires complicated circuitry, which increases power and area overhead.

In this work, we instead propose a simple pseudo-differential-source-follower-like topology (Fig. 2(b)) to directly translate the changes in the gate voltage into the source node. Because of the extremely low dependence of drain current I_D on V_{DS} in deep-subthreshold when $V_{DS} > 4kT/q$ ($\approx$ 100 mV at room temperature), the penalty for not keeping V_{DS} fixed becomes negligible. Simulation shows that under an 800 mV supply voltage, a swing of 600 mV in $\Delta V_G = \Psi(\text{pH})$ creates < 0.03% nonlinear distortion in the difference between ΔV_S and ΔV_G (Fig. 2(c)). Thus, this circuit scheme enables significant power and area reduction without loss of accuracy. The ISFET/REFET pair were implemented using thick-oxide devices to minimize long term potential drift from the discharge of the floating gate, improving their sensing stability.

A fully differential switched-capacitor amplifier with a gain of two further amplifies the ΔV_S in the frontend and shifts the pH-dependent common mode voltage (V_{CM}) to a fixed $V_{DD}/2$ (Fig. 3). This common mode voltage adjustment is necessary to optimize the performance of the 10-bit differential SAR ADC. The digital output of the ADC is serialized and wrapped with a header and parity check bits to reduce I/O count and enhance transmission reliability. All digital circuits are synthesized using a custom designed standard cell library optimized for area and leakage reduction. Current biases are mirrored from a digitally controlled current source, whose output increases linearly with the input current code (CC).

System Verification

The IC is fabricated in a TSMC 0.18 μm MSRFG technology with core mixed signal circuits using only thick oxide devices. Post-processing is performed to shield the REFET's sensing area with a 700-nm-thick parylene-C layer. A 25-Hz clock (1 sample/s), 0.8-V supply voltage, and one half of the maximum current bias (CC = 0x80, or 7 pA at the current source output from simulation) are used for all measurements unless otherwise stated. Fig. 4 shows the measured current consumption as a function of time along with the output data stream measured in the time domain; the time-averaged power consumption is 0.72 nW when fully functioning. Five buffered solutions with pH equally spaced between 6 and 10 are used to characterize the performance of the pH sensor circuit; the time-domain readout from the chip is plotted in Fig. 5. A measured 65.8 LSB/pH (25.7 mV/pH) sensitivity is demonstrated through repeated experiments ($n \geq 3$ for each pH value), and is shown in Fig. 6. Fig. 7 shows a maximum of 7 LSB (5.5 mV) difference observed across a five-hour-long measurement in a buffered pH=7 environment. Further power reduction can be achieved at a lower current bias with a reduced sampling rate, as shown in Fig. 8. A die micrograph is available as Fig. 9. A FoM is defined to capture the power consumption required to achieve the same sampling frequency and sensitivity (Table 1). Compared with previously published works, the proposed pH sensor achieves > 4000× improvement in this FoM, delivering precise and digitized pH readings with the lowest reported power to date, while occupying 41% less area over the current state-of-the-art.

Acknowledgement

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References

[1] SNOA529A, Application Report from Texas Instrument, 2013
[2] P. Bergveld, Sens. Act. B: Chem., 2003 [3] T. Kang, et al., VLSI 2019 [4] P. A. Hammond, et al., IEEE TBME., 2015 [5] M. Kalofonou, et al., IEEE TBioCAS., 2014

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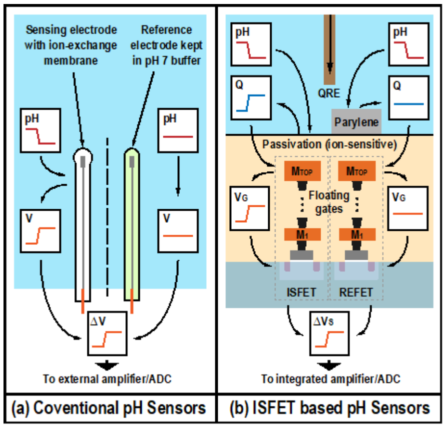

Fig 1. Working principle of (a) a conventional pH sensor and (b) the ISFET/REFET pH sensor

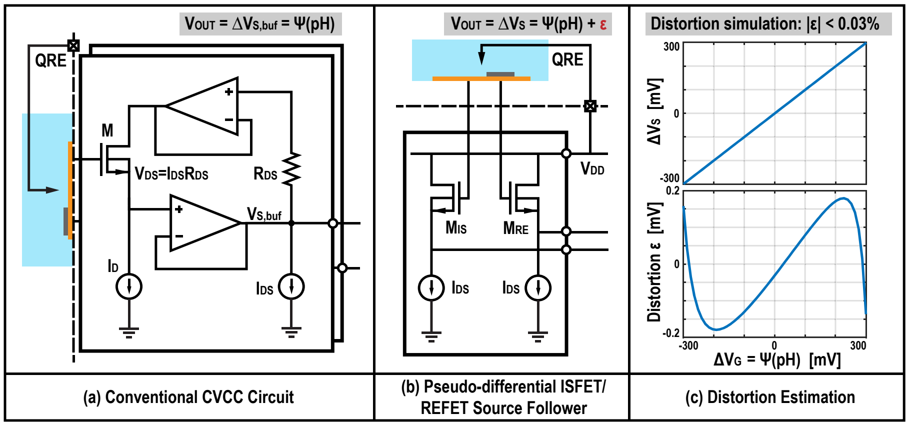

Fig 2. (a) Schematic of a conventional CVCC circuit used as an ISFET front-end, (b) the proposed pseudo differential ISFET/REFET source follower, and (c) simulated maximum error

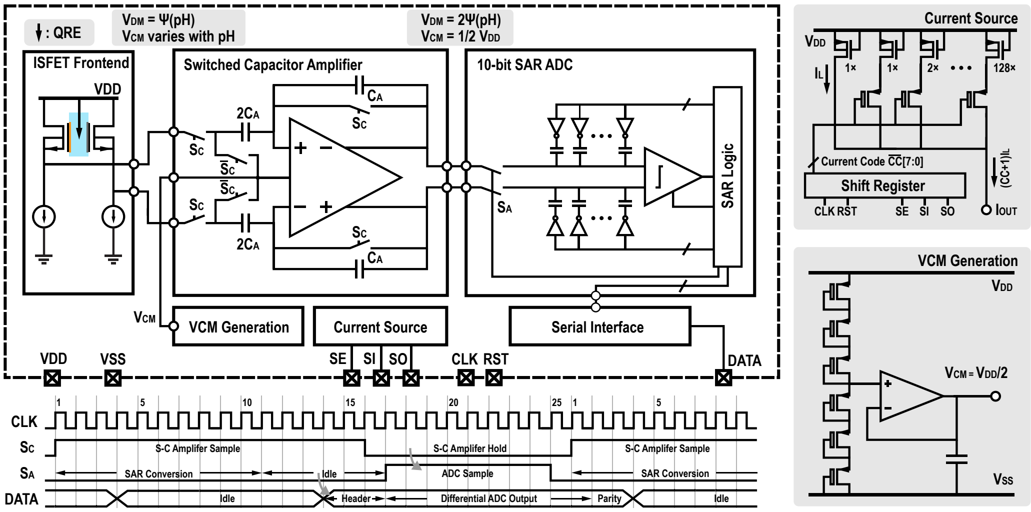

Fig 3. System architecture and timing waveforms. The schematic of current source and V_{CM} generation circuit are shown on the right. The IC delivers one 10 bit pH sample every 25 clock cycles.

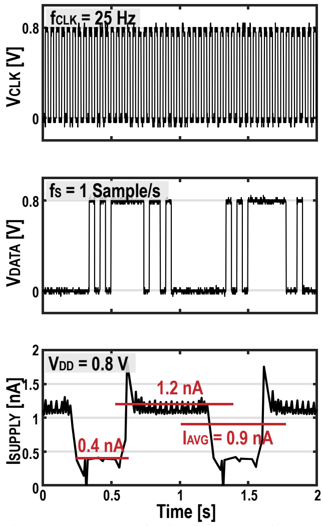

Fig. 4. Measured clock (top), data output (middle) and supply current consumption (bottom)

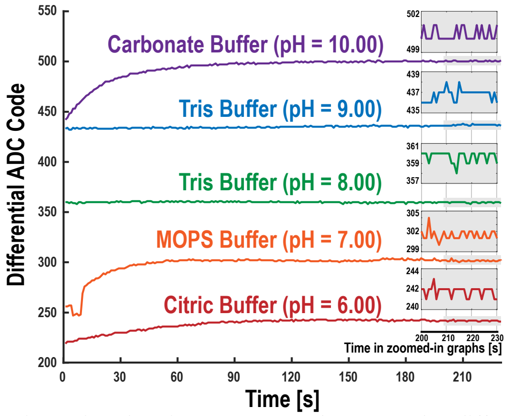

Fig 5. Time domain ADC output when exposed to different pH buffers. The data of the last 30 seconds is available as insets.

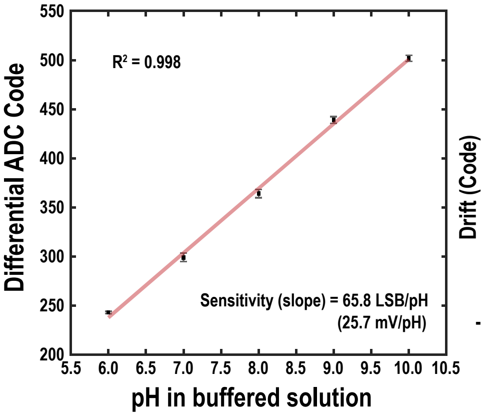

Fig 6. Measured sensitivity with more than 3 samples for each pH value.

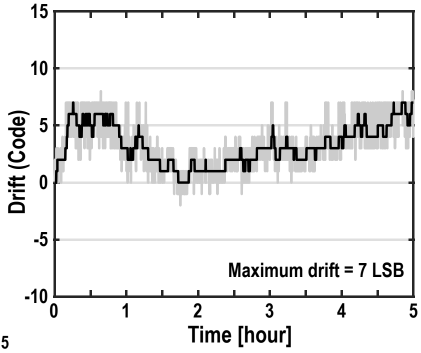

Fig 7. Output drift over the course of five hours in a pH 7 buffer. A 4 mHz 2nd order low-pass filter is used to isolate long term drift (black) from noise (gray)

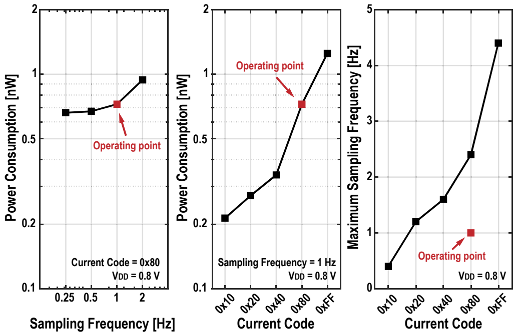

Fig 8. Measured power as a function of f_S and current code

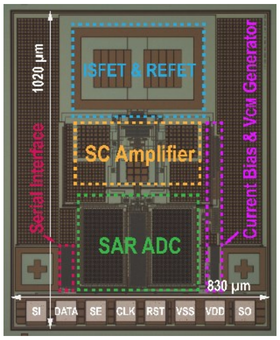

Figure 9. Die photo.

TABLE I
COMPARISON TABLE

	This Work	[3]	[4]	[5]
Technology	0.18 µm (I/O)	0.18 µm	0.6 µm	0.35 µm
ISFET Frontend Topology	Pseudo-differential Source Follower	Differential CVCC with CDAC	Differential CVCC	Chemical Gilbert Cell
Digital Output	Yes	Yes	Yes	No
Sensitivity	65.8 LSB/pH	7.86 LSB/pH	37 LSB/pH	5.5 nA/pH*
	25.7 mV/pH	9.7 mV/pH	48 mV/pH	45 mV/pH
Area	0.85 mm^2	1.45 mm^2	21.4 mm^2	8.01 mm^2
Power Consumption	0.72 nW	176 nW	29.7 mW	165 nW
Sampling Frequency F_S	1 sample/s	0.5 sample/s	1 sample/s	N/A
FoM: $\frac{\text{Power}}{F_S \times \text{Sensitivity}}\left[\frac{\text{nW·s·pH}}{\text{LSB}}\right]$	0.011	44.8	802.7k	N/A

*: Calculated from Table III using I_{gain} = 10nA, which is used to report power consumption in the work.