A Capacitance-to-Digital Converter with Differential Bondwire Accelerometer, On-chip Air Pressure and Humidity Sensor in 0.18 μm CMOS

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Abstract - This paper presents a sensor front-end for air pressure sensor, relative humidity (RH) sensor, and accelerometer in a standard CMOS process. For air pressure and RH, interdigitated top metals in air and polyimide are exploited respectively, which exhibit the change in dielectric constant. For acceleration, separation among three bondwires is exploited. These sensing transducers induce capacitance change that is quantized by a CDC based on a dual quantization architecture that employs a single-bit 1st-order ΔΣ modulator and a 7-bit SAR ADC.

I. INTRODUCTION

As CMOS scaling may not provide many advantages especially in cost [1], there has been a growing interest in exploring new functions and applications of CMOS technology. If we exploit CMOS technology for implementing sensing transducers [2], then sensor front-end can gain great advantage in integration level as well as cost. In this paper, we present a sensor front-end that demonstrates the capability of CMOS technology as sensing elements. Equipped with a wide input range high resolution capacitance-to-digital converter (CDC), the proposed sensor front-end implemented in a standard CMOS process can sense air pressure, relative humidity (RH), and acceleration, without using MEMS or any post-processing.

II. TRANSDUCERS USING CMOS AND BONDWIRES

The block diagram of the proposed sensor front-end which consists of sensing transducers, CDC and control logic is shown in Fig. 1. The transducers are composed of three kinds of capacitors (C_{Pres}, C_{Hum}, C_{AP}&C_{AN}). The CDC is composed of a dual quantization-based modulator, a reference capacitor array (C_{Ref}) and an auto-calibration logic. When a sensor mode is selected, the desired sensing capacitor is connected to the CDC via an analog multiplexer, and the value of C_{REF} is coarsely set to transducer's capacitance by the auto-calibration logic. The dual quantization-based modulator quantizes the only difference between the sensing capacitance (C_{Sense}) and C_{REF}.

A conceptual illustration of the proposed sensing transducers are shown in Fig. 1. Air pressure transducer is formed using a comb-structured interdigitated top metal capacitor exposed to air. It exploits change in dielectric constant due to air pressure, which is about 34ppm/psi [3]. RH transducer uses the same metal-comb structure but one that is covered by polyimide whose permittivity changes due to moisture-induced swelling [4]. The proposed acceleration transducer is implemented using three bondwires of which

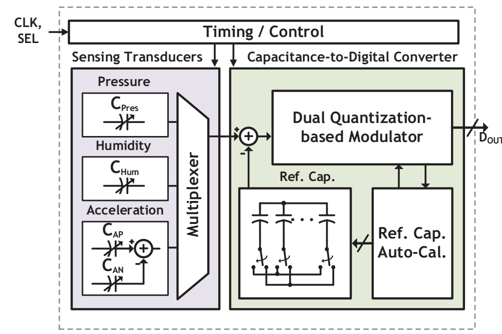

Fig. 1. Block diagram of the proposed sensor front-end.

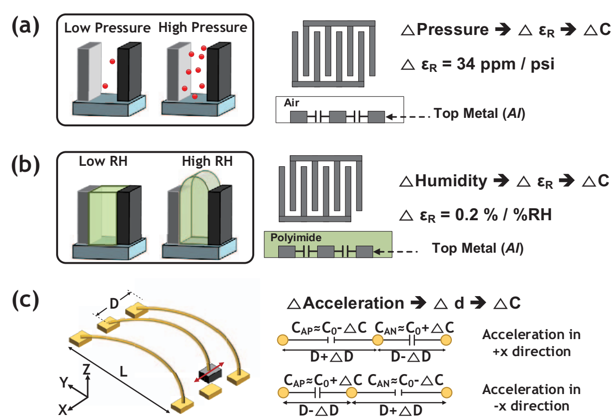

Fig. 2. Concept and implementation details of the proposed sensing transducers for (a) air pressure, (b) RH, and (c) acceleration.

the center wire has a proof-mass attached to its hanging end. Together with the neighboring bondwires, they form two capacitors that are inherently differential. Compared with previous accelerometers using resonant bondwires [5], the proposed accelerometer consumes much less power as it senses capacitance rather than inductance.

III. DUAL QUANTIZATION-BASED CDC

The proposed transducers have different capacitance range and require different resolution. Instead of having three dedicated CDCs for each sensor, we propose a wide input range high resolution CDC that can reduce the die area and design cost. The proposed CDC consists of a dual quantization-based ΔΣ modulator for high resolution and a SAR-calibrated C_{Ref} for wide input range.

The overall circuit schematic and timing diagram of the CDC is shown in Fig. 3, which determines C_{Sense} in two steps. In an auto-calibration step, a synchronous 9-bit SAR logic is used to match the base capacitance of C_{Sense} to C_{Ref}. Thus,

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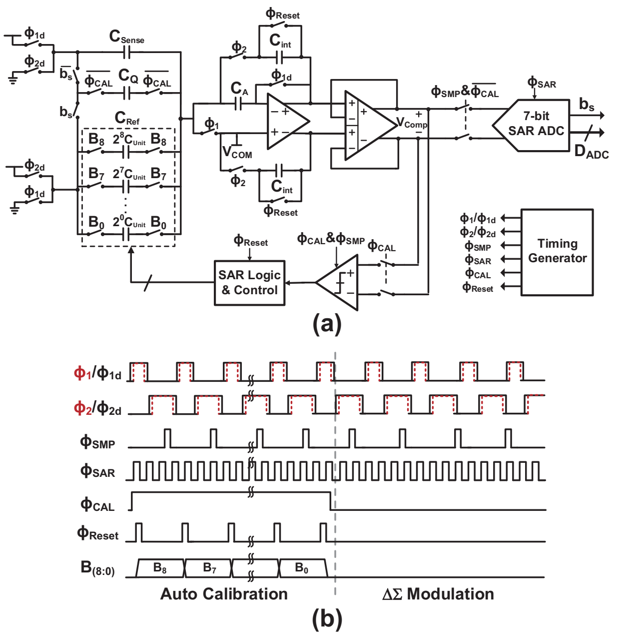

Fig. 3. Overall (a) circuit and (b) timing diagram of the CDC.

only the difference between C_{Ref} and C_{Sense} is applied to the next ΔΣ step. Auto-calibration is activated when a sensor mode is selected or when C_{Sense}-C_{Ref} is out of dynamic range of the ΔΣ modulator. In a ΔΣ modulation step, unlike existing ΔΣ CDCs, we propose a dual quantization-based architecture that employs a single-bit 1st-order ΔΣ modulator and multi-bit quantizer (similar to 1-0 MASH). Its advantage is that the linearity of the ΔΣ modulator is ensured by the single-bit quantizer while the quantization noise is reduced by the 7-bit SAR ADC. The use of 1st-order ΔΣ modulator also allows larger input range, and thus relaxes the minimum resolution necessary in C_{Ref}. The output of the CDC can be expressed as $D_{OUT}=z^{-1}\cdot(C_{Sense}-C_{Ref})/C_Q+(1-z^{-1})\cdot Q_2$, where Q_2 is the quantization error from the SAR ADC.

IV. MEASUREMENT RESULTS

A prototype chip has been implemented in a 0.18-μm standard CMOS process that has six layers of metal, of which the top metal is aluminum. The chip photo is shown in Fig. 5. The measured noise spectrum of CDC is shown in Fig. 4, where it can be seen that the proposed dual quantization CDC achieves lower q-noise than a 1st-order ΔΣ modulator. The minimum achievable resolution is about 116-aF when the input capacitance is 40fF at 9.38kS/s and 0.85ms conversion time. The CDC consumes 3μW from 1.1V supply. Performance summary and comparison with other high resolution and low power state-of-the-art CDCs are shown in Table.1. Measurement results of sensors together with the CDC are shown in Fig. 6. The air pressure sensor has a linear range of 20psi to 80psi with a resolution of 0.14psi/√Hz and accuracy of ±0.7psi after two-point calibration. RH sensor was measured from 30~90%RH with a resolution of 0.001%RH/√Hz and its accuracy is within ±1.64%RH after two-point calibration. The accelerometer was placed on a rotating table to apply centrifugal force. The measurement range was within ±4.6g. The noise floor and bias instability

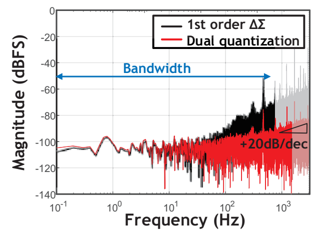

Fig. 4. Measured 2^{16}-point noise spectrum of the CDC.

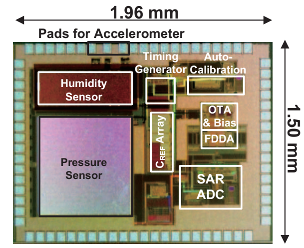

Fig. 5. Die photo graph.

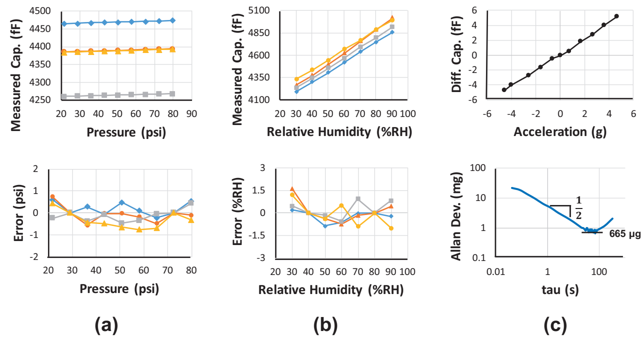

Fig. 6. Measurement results of (a) air pressure sensor, (b) RH sensor, and (c) accelerometer.

Table 1. Performance summary and comparison.

	Z. Tan, JSSC 13	Y. He, ISSCC 15	B. Li, TCAS-I 18	S. Oh, VLSI 14	**This Work**
Process [μm]	0.16	0.16	0.18	0.18	**0.18**
Conversion Method	3rd ΔΣ	PM	2nd ΔΣ	Zoom SAR + 2nd ΔΣ	**Zoom SAR + (1st ΔΣ + SAR)**
Supply [V]	1.2	1	1.5	1.4	**1.1**
Cap. Range	0.54 - 1.06 pF	0 - 8 pF	1 pF - 10 nF	0 - 24 pF	**0 - 18.12 pF**
Meas. Time [ms]	0.8	0.21	0.13	0.23	**0.85**
Power [μW]	10.32	14	15	33.7	**2.92 - 3.09**
Abs. Resolution (Measured C_{Sense})	70 aF (N.A.)	1443 aF (8 pF)	207 aF (2 pF)	160 aF (N.A.)	**116 aF (40 fF) - 1.24 fF (17.1 pF)**
FoM_S [μJ·ppm²] (Measured C_{Sense})	431(N.A.)	1145 (8 pF)	250 (2 pF)	4.1 (N.A.)	**165 (17.1 pF)**

FoM_S = Power × Meas. Time × (Resolution [ppm])^2

was measured to be 4.6mg/√Hz and 665μg and respectively. The proposed work is very competitive despite its implementation in a fully CMOS process.

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