IEEE Asian Solid-State Circuits Conference
November 12-14, 2007 / Jeju, Korea

A 0.026mm^2 Capacitance-to-Digital Converter for Biotelemetry Applications Using a Charge Redistribution Technique

Kota Tanaka, Yasuhide Kuramochi, Takashi Kurashina, Kenichi Okada, and Akira Matsuzawa
Department of Physical Electronics, Tokyo Institute of Technology
2-12-1-S3-27 Ookayama, Meguro-ku, Tokyo 152-8552 Japan
Tel/Fax: +81-3-5734-3764, E-mail: astrokt@ssc.pe.titech.ac.jp

Abstract - **This paper proposes a direct capacitance-to-digital converter (CDC) for biotelemetry applications. The proposed circuit is based on a charge redistribution technique using a capacitive sensor and a ranging capacitor array. The circuit does not require accurate reference voltages, so it is robust for fluctuation of supply voltage. Output-code range can be dynamically zoomed in arbitrary capacitance range of sensor output by using the ranging capacitor array.**

An 8-bit converter with an active area of 0.026mm^2, consuming 0.9nJ per sample, is demonstrated. The proposed circuit maintains its performance even in the condition of 28% fluctuations in supply voltage. Measurement results of the readout circuit are also demonstrated, which shows that the proposed circuit can work well in the presence of large parasitic capacitances.

I. INTRODUCTION

Recently, wireless health monitoring systems have been developed to achieve convenient medical measurement and reduce pain and suffering of patients [1,2]. For example, swallowable capsules for stomach and intestine monitoring [3,4], blood pressure monitoring systems [5,6], and bladder pressure measurement systems [7] have been reported. For more comfortable measurements, a smaller device is required. Therefore, a smaller battery as well as low-power circuit operation is of interest. In such systems, a capacitive pressure sensor is often used because it does not consume static current.

In capacitive pressure sensors, the capacitance of the sensors varies with the pressure. Various circuits have been proposed for measuring the capacitance. In [8,9], the sensor capacitance is utilized to generate the carrier frequency for wireless transmissions. However, re-transmission is impossible for such circuits, even though the re-transmission is indispensable for robust sensing. In other implementations, a capacitance-to-voltage converter (CVC) and an analog-to-digital converter (ADC) are utilized for readout of a capacitive sensor [10,11]. The capacitance of the sensor is converted by the CVC, and the output voltage is converted to a digital code. However, such a redundant architecture results in large power consumption and a large chip area. Direct readout circuits are reported in [12,13], which employ a delta-sigma ADC. However, the circuits require large power dissipation due to the operational amplifiers (opamp) in the ADC.

This paper proposes a low power and small area capacitance-to-digital converter suited for biotelemetry systems. The proposed circuit is realized by incorporating a pressure sensor and a ranging capacitor array into successive approximation register (SAR) technique. The pressure sensor sometimes has large parasitic capacitance, and it degrades the dynamic range of the conventional readout circuits using the SAR technique [14,15]. The proposed circuit can cancel the parasitic capacitance by using the ranging capacitor array, which also enables to shift output-code range into intended range of sensor capacitance. The ranging capacitor can subtract offset capacitance. Moreover, the total dynamic range of the readout circuit is scalable, which is controlled by the reference voltage. These two mechanisms realize dynamic zooming of sensing range.

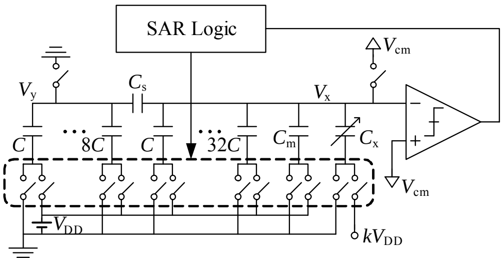
The proposed circuit does not require accurate reference voltages. Only relative accuracy to supply voltage is required because comparisons for SAR are performed in the capacitance domain. In this paper, measurement results using a micro-electro-mechanical systems (MEMS) sensor are demonstrated. The proposed circuit is highly compatible with biotelemetry applications.

II. CIRCUIT ARCHITECTURE

A. *Overview of the Proposed Circuit*

Fig. 1 shows the block diagram of the proposed circuit. It consists of a capacitive sensor C_x, a ranging capacitor array C_m, a main capacitor array, a serial capacitor C_s, a comparator, a SAR and switches. The proposed circuit has two advantages; the dynamic zooming of sensing range with the ranging capacitor array, and voltage scalability caused by a direct-capacitance-comparison technique. The dynamic range can be adjusted by the reference voltage, and offset capacitance can be canceled by the ranging capacitor array. Thus, output code can be mapped into an arbitrary capacitance range of sensors. Using the direct-capacitance-comparison technique, the capacitance of sensor is directly compared and converted to a digital code. The voltages of every nodes in the capacitor array are scalable to the supply voltage V_{DD}, so the output codes are consistent to the supply voltage V_{DD}, which is a very important feature for implantable devices. Moreover,

1-4244-1360-5/07/$25.00 ©2007 IEEE



C_x : Capacitive sensor

Fig. 1. Block diagram of the proposed circuit.

the circuit does not use opamps, so it can operate with low power consumption.

B. Operation and reference voltage scaling

The direct-capacitance-comparison technique enables the circuit to compare the sensor capacitance with the selected capacitances in the array. The selection and comparison is successively performed from the largest capacitor to the smallest capacitor. The comparison is along with each step, and the output code is obtained one by one. The operation of the circuit and comparison are described as follows.

The circuit operates in two steps. The first step is the "sampling" step. The switches connected to nodes V_x and V_y are turned on, the C_x port is connected to the reference voltage kV_{DD}, and the other ports are connected to ground. k is a scale factor to scale dynamic range of the sensor. Then, charge is stored on the nodes V_x and V_y, which is derived from

$$Q_{vx} = C_x(V_{cm} - kV_{DD}) + (C_{all\_vx} + C_s)V_{cm}, \quad (1)$$

$$Q_{vy} = -C_s V_{cm}, \quad (2)$$

where C_{all_vx} is the total capacitance between the node V_x and ground.

The second step is the "conversion" step. The switches connected to nodes V_x and V_y are turned off, and the most significant bit (MSB) capacitor port is connected to V_{DD}. When the law of charge conservation is applied to nodes V_x and V_y,

$$V_x = V_{cm} + \frac{C_{MSB} - kC_x}{C_x + C_{all\_vx} + \dfrac{C_s C_{all\_vy}}{C_{all\_vy} + C_s}} V_{DD} \quad (3)$$

is obtained, where C_{MSB} is the MSB capacitance. C_{all_vy} is the total capacitance between the node V_y and ground.

The voltage is compared with V_{cm} and the MSB is determined as "1" (when $V_x < V_{cm}$) or "0" (when $V_x > V_{cm}$). Here, the factor m is defined as

$$m = \frac{1}{C_x + C_{all\_vx} + \dfrac{C_s C_{all\_vy}}{C_{all\_vy} + C_s}}. \quad (4)$$

Then, (3) can be re-described as

$$V_x - V_{cm} = (C_{MSB} - kC_x)mV_{DD}. \quad (5)$$

Comparing V_x with V_{cm} means the comparison of C_{MSB} and kC_x because m and V_{DD} are positive. This is the direct-capacitance-comparison technique. If C_{MSB} is larger than kC_x, the MSB is "0"and else, the MSB is "1". Moreover the important point is that V_{DD} does not affect the output code. The robustness to fluctuation in supply voltage is achieved by this feature.

The MSB is determined as above. If the code is "1", the MSB capacitor is connected to V_{DD} for the remaining conversion steps. If the code is "0", it is connected to ground for the remaining conversion steps. After then, the next lower bit capacitor is connected to V_{DD}. Then, the voltage V_x is compared with V_{cm} and the second significant bit is determined. The conversion steps continue until the least significant bit (LSB) is determined.

Due to the charge conservation at the nodes V_x and V_y, the voltage at the comparing node V_x is calculated as (6) for each step.

$$V_x - V_{cm} = (C_{on\_vx} + \frac{C_s C_{on\_vy}}{C_{all\_vy} + C_s} - kC_x)mV_{DD}, \quad (6)$$

where C_{on_vx} is the total capacitance between nodes V_x and V_{DD}. It is the total capacitance whose code is "1" at node V_x. Similarly, C_{on_vy} is the total capacitance between nodes V_y and V_{DD}. From MSB to LSB, each capacitor in the array is evaluated and appended to C_{on_vx} and C_{on_vy}, so that V_x approaches V_{cm}. When all bits have been determined, the output code indicates the approximated value of the kC_x. kC_x is the sensor capacitance scaled by k.

The scale factor k is used to map the sensing range into the internal capacitance range. The maximum value of C_{on_vx} and C_{on_vy} is fixed; it is the value when all the output code is "1". However, MEMS sensor often shows far larger capacitance than the readout circuit. The scalability enables the circuit to convert large capacitance and decreases the requirement for large capacitance in the readout circuit. Thus, small layout area can be easily achieved by this architecture.

C. Offset Cancellation and Ranging

Capacitive sensors have an initial capacitance. Initial capacitance is an invariant capacitance of a sensor in the environment where it is used. Conventional capacitance readout circuits convert the total capacitance of the sensor, including variable and initial value. However, many codes are associated with the values lower than the initial capacitance, and the codes are left unused. The initial capacitance degrades the actual resolution in the conventional readout circuits, which is a ranging problem. Another problem is the offset caused by charge injection. The charge emitted by the switches vary the charges which are stored at nodes V_x and V_y .The range and the offset problems are compensated by the ranging-capacitor array C_m shown in Fig. 2. C_m has a similar structure as the main capacitor array. The operation is as follows. First, initial condition is set to the sensor. Then, the same "sampling" step described in Sec. II.B is executed. Including the effect of charge injection, (1) and (2) can be re-

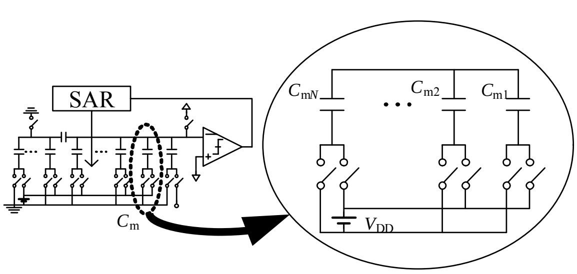


Fig. 2. Ranging capacitor array.

written as

$$Q_{vx} = C_{x\_init}(V_{cm} - kV_{DD}) + (C_{all\_vx} + C_s)V_{cm} + Q_{chvx}, \quad (7)$$

$$Q_{vy} = -C_s V_{cm} + Q_{chvy}, \quad (8)$$

where C_{x_init} is the initial capacitance of the sensor. Q_{vx} and Q_{vy} are the charge emitted by the switch connected to the node V_x and V_y, respectively. Then, the "conversion" steps described in Sec. II.B are executed, using the ranging capacitor array instead of the main capacitor array. (6) is then re-described as

$$V_x - V_{cm} = m((C_{on\_cm} - kC_{x\_init})V_{DD} + Q_{chvx} + \frac{C_s Q_{chvy}}{C_{all\_vy} + C_s}), \quad (9)$$

where C_{on_cm} is the total capacitance between the node V_x and V_{DD}. After N bit conversion, N bit offset codes are obtained. SAR logic operates causing V_x to approach V_{cm}. Thus, the term in the right side of (9) approaches zero, and the output codes become the cancellation of the initial capacitance and the offset of charge injection.

Here, it is assumed that the sensor capacitance actually varies with the pressure. C_x can be divided into an initial value C_{x_init} and a changeable value C_{x_val}. When the offset codes are attached to C_m at the first conversion step, (6) can be rewritten as

$$V_x - V_{cm} = (C_{on\_vx} + \frac{C_s C_{on\_vy}}{C_{all\_vy} + C_s} - kC_{x\_val})mV_{DD} + m((C_{on\_cm} - kC_{x\_init})V_{DD} + Q_{chvx} + \frac{C_s Q_{chvy}}{C_{all\_vy} + C_s}). \quad (10)$$

The last term in the right side of (10) can be canceled. Thus, (10) shows that only variable range of C_x is adjusted to the dynamic range of the capacitor array. Any dynamic range can be achieved by the features of the scale factor k and the ranging capacitor array C_m.

III. Experimental Results

The circuit is fabricated in a 0.18-μm CMOS process with six metal layers and metal-insulator-metal capacitors (MIM-CAP). Fig. 3 shows the die photo. The active area is 0.026mm^2, which is dominated by the capacitor array with the total capacitance of 6pF. The sensor capacitor can be connected through the pads.

Fig. 4 shows the measurement result of the capacitance to digital conversion. A MEMS capacitive sensor is used. Because of the measurement environment, more than 50pF parasitic capacitance exists, even though the variation of the sensor is only 3pF. However, the ranging capacitor array C_m works well and conversion can be observed. The result shows a similar characteristic to the reference one provided by Omron [16]. A MEMS capacitive sensor readout is demonstrated.

Some biotelemetry systems utilize wireless-power supplying, which often has large voltage fluctuation. Table I shows that the proposed circuit is robust for fluctuations in V_{DD}. Almost the same SNR and ENOB results are obtained when V_{DD} changes by 28%. The result is obtained when a fixed 3pF capacitor is used as the sensor capacitance, and a 3kHz sinusoidal source is applied to the reference voltage kV_{DD}.

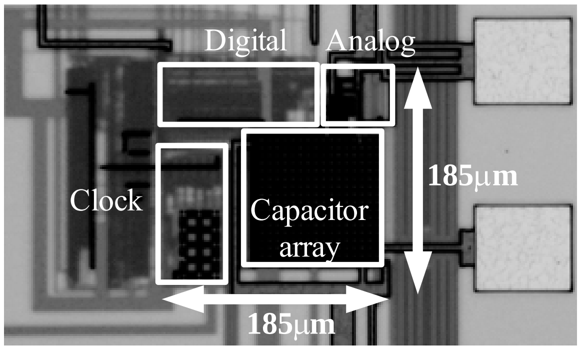


Fig. 3 Die photo.

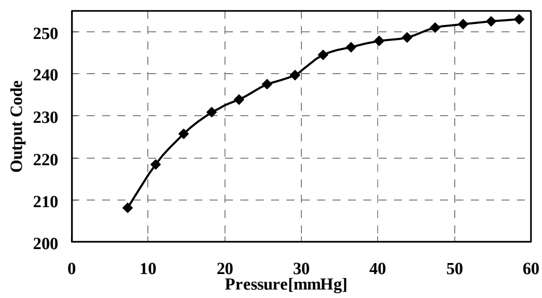


Fig. 4. Conversion results of the capacitive pressure sensor.

TABLE I
Performance for Supply Voltage Change

Supply Voltage	1.0 V	1.4 V	1.8 V
SNR	43.41dB	43.22 dB	43.22 dB
ENOB	6.88 Bit	6.83 Bit	6.84 Bit

TABLE II

MEASUREMENT RESULTS

Resolution	8 Bit
Supply Voltage	1.4 V
Sampling Rate	262 kHz
SNR	43.22 dB
ENOB	6.83 Bit
Current Consumption	169 μA 360 μA (when using internal clock)
Minimum DNL	-0.97 LSB
Maximum DNL	0.79 LSB
Minimum INL	-1.27 LSB
Maximum INL	0.99 LSB
Area	0.026 mm^2 0.034 mm^2 (when including clock)

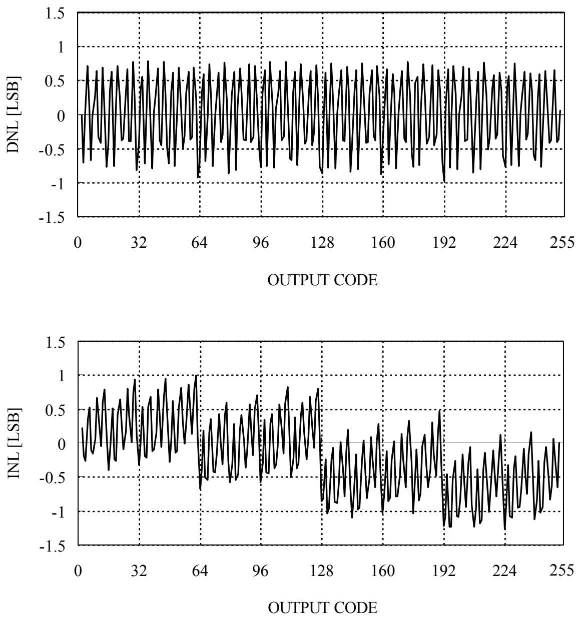


Fig. 5. Static DNL and INL error plots measured with a 1.4V supply voltage.

Table II shows the measured performance. To evaluate the whole code of converter, a 52Hz sine wave is applied as the input voltage instead of sensor variation. The reference voltage kV_{DD} is supplied and a 3pF fixed capacitor is attached as C_x. Most of the current is consumed in the parts of the circuit creating the bias voltages and the common-mode bias voltage V_{cm}. Fig. 5 shows typical plots for the low-frequency differential nonlinearity (DNL) and integral nonlinearity (INL) error. The measurement environment is the same as the environment where Table II is obtained.

IV. CONCLUSION

An opamp-less and small area capacitance-to-digital converter has been presented. The architecture is realized by incorporating capacitive pressure sensor and ranging capacitor array into a SAR technique. The special feature of the proposed circuit is the dynamic zooming. The variable capacitance of the sensor is dynamically scaled by the reference voltage, and the static capacitance of the sensor is cancelled by the ranging capacitor array. By the two mechanisms, the proposed circuit achieves the dynamic zooming and full-scale measurement of the sensor capacitance.

In the experimental results, an 8-bit converter with an active area of 0.026mm^2, consuming 0.9nJ per sample, is obtained. The capacitance-to-digital conversion is demonstrated, which works well even for a MEMS sensor that has a large parasitic capacitance. Furthermore, it is shown that the system performs well even under 28% fluctuation in supply voltage, because the proposed circuit does not need accurate reference voltages. The capacitive sensor readout circuit is highly suited for robust biotelemetry applications.

AKNOWLEDGEMENT

This work is supported by the VLSI Design and Education Center (VDEC), the University of Tokyo in collaboration with Cadence Design Systems, Inc. Omron Corp. kindly provided the pressure sensor used in this research project.

REFERENCES

[1] K. Arshak, E. Jafer, G. Lyons, D. Morris, and O. Korostynska, "A review of low-power wireless sensor microsystems for biomedical capsule diagnosis," *Microelectronics International*, Vol. 21, No. 3, pp. 8-19, 2004.

[2] K. Hung, and Y.T. Zhang, "Implementation of a WAP-based telemedicine system for patient monitoring," *IEEE Transactions on Technology in Biomedicine*, Vol. 7, No. 2, pp. 101-107, June 2003.

[3] Z. Fireman, E. Mahajna, E. Broide, M. Shapiro, L. Fich, A. Sternberg, Y. Kopelman, and E. Scapa, "Diagnosing small bowel Crohn's disease with wireless capsule endoscopy," *Gut Online*, pp. 390-392, 2003.

[4] [Online]. Available:http://www.rfnorika.com/

[5] S. Chatzandroulis, D Tsoukalas, and P. A. Neukomm, "A miniature pressure system with a capacitive sensor and a passive telemetry link for use in implantable applications," *Journal of Microelectromechanical Systems*, Vol. 9, No. 1, pp. 18-23, March 2000.

[6] K. Hung, Y.T. Zhang, and B. Tai, "Wearable medical devices for tele-home healthcare," *International Conference of the Engineering in Medicine and Biology Society*, Vol. 7, pp. 5384-5387 September 2004.

[7] J. Coosemans, and R. Puers, "An autonomous bladder pressure monitoring system," *Sensors and actuators A : Physical*, Vol. 123-4, pp. 155-161, 2005.

[8] A. DeHennis, and D. W. Kensall, "A double-sided single-chip wireless pressure sensor," *IEEE International Conference on Micro Electro Mechanical Systems*, pp. 252-255, 2002.

[9] O. Akar, T. Akin, and K. Najafi, "A wireless batch sealed absolute capacitive pressure sensor," *Sensors and Actuators A : Physical*, Vol. 95, No. 1, pp. 29-38, December 2001,

[10] J. C. Lotters, W. Olthuis, P. H. Veltink, and P. Bergveld, "A sensitive differential capacitance to voltage converter for sensor applications," *IEEE Transactions on Instrumentation and Measurement*, Vol. 48, No.1, pp. 89-96, February 1999.

[11] K. Mochizuki, T. Masuda, and K. Watanabe, "An interface circuit for high-accuracy signal processing of differential-capacitance transducers," *IEEE Transactions on Instrumentation and Measurement*, Vol.47, No. 4, pp. 823-827, August 1998.

[12] M. Yamada, and K. Watanabe, "A capacitive pressure sensor interface using oversampling Δ-Σ demodulation techniques," *IEEE Transactions on Instrumentation and Measurement*, Vol.46, No.1, pp. 3-7, February 1997.

[13] J. O'Dowd, A. Callanan, G. Banarie, and E. Company-Bosch, "Capacitive sensor interfacing using sigma-delta techniques," *Sensors, 2005 IEEE*, 4 p, October - November 2005.

[14] C.P.L. van Vroonhoven, D. Rocha, M.J. Vellekoop, and C. Nohammer "A readout circuit for capacitive biosensors with integrated SAR A/D conversion," *IEEE International Symposium on Circuits and Systems*, 4 p, May 2006.

[15] B. Bechen, D. Weiler, T. v. d. Boom, B.J. Hosticka, "A 10 bit very low-power CMOS SAR-ADC for capacitive micro-mechanical pressure measurement in implants," *Advances in Radio Science*, Vol. 4, pp. 243-246, 2006.

[16] I. Kimura, and T. Itakura, "Development of Pressure Sensor for Blood Pressure Monitors," (written in Japanese), *Omron Tech*, Vol. 41 No. 2, pp.138-143, 2001.