Dual-Slope Capacitance to Digital Converter
Integrated in an Implantable Pressure Sensing System

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Abstract — This work presents a dual-slope capacitance to
digital converter for pressure sensing. The design uses base
capacitance subtraction with a configurable capacitor bank and
dual precision comparators to improve energy efficiency,
consuming 110nW with 9.7b ENOB and 0.85pJ/conv-step FoM.
The converter is integrated with a pressure transducer, battery,
processor, and radio to form a complete 1.4mm×2.8mm×1.6mm
sensor system aimed at implantable devices. The system operates
from a 3.6V battery.

I. INTRODUCTION

Implantable systems are increasingly in demand for
emerging biomedical applications and face stringent power
budgets due to their small system volume. Pressure sensing is a
key modality in implantable devices with applicability to
glaucoma treatment [1], blood pressure monitoring [2], and
tumor diagnosis, among others. For these systems, a MEMS
capacitive sensor is typically used and a moderate (9-10b)
resolution, low-power capacitance to digital converter (CDC)
is required. Dual-slope converters are well known for their
simplicity, good accuracy, and low power consumption.
However, pressure sensing suffers from a large nominal base
capacitance while the capacitance value change due to external
pressure is very small. This makes it difficult to achieve
sufficient resolution with high energy efficiency due to the
need to charge and discharge the large base capacitance in
dual-slope CDCs (DS-CDC).

To address this challenge, we propose iterative charge
subtraction/accumulation using a source follower and
configurable capacitor banks to zoom-in and amplify the
variable input region, thereby reducing conversion time and
energy. The design also uses dual precision comparators to
achieve the high resolution of a fine comparator with the low
power consumption of a coarse comparator. It does so by only
enabling the fine comparator in the final stages of conversion.
The CDC has a low power consumption of 110nW which
makes it compatible with ultra-small batteries which often
suffer from low peak current capacity. We demonstrate CDC
operation when integrated with a complete pressure sensing
system using a MEMS pressure sensor, processor, memory,
battery, and radio for pressure readout.

II. PROPOSED TECHNIQUE

The proposed DS-CDC consists of a current mirror, charge
subtraction/accumulation devices, two comparators, a ripple
carry counter, and digital control logic. The DS-CDC core is
shown in Fig. 1 with associated waveforms given in Fig. 2.

Figure 1. (a) Dual slope CDC implementation, (b) C_base bank
circuit.

Figure 2. CDC waveform.

During the sampling state, OTA_1 and OTA_2 are enabled
and non-overlapping clocks φ_1 and φ_2 repeatedly
charge/discharge C_sensor and C_base. The OTAs drive the source
followers to track V_{ref_a} with little error. A current mirror above
the source followers flips the direction of current from $C_{sens}$. Since both $C_{sens}$ and $C_{base}$ are simultaneously clocked, saturation of $V_{integ}$ is avoided while repeated sampling amplifies the charge difference, increasing resolution. $C_{sens}$ is an off-chip sensor capacitor and $C_{base}$ is a programmable MIM capacitor bank (0 ~ 22pF) composed of capacitors and NMOS switches, allowing for adjustment of the capacitance measurement range.

While $\phi_1=1$, charge is removed from $C_{sens}$ and $C_{base}$ by shorting both nodes of the capacitors to ground. With $\phi_2=1$, the top plate node of these capacitors are set to $V_{ref_o}$ due to the feedback of the OTA and the device gated by $\phi_2$. Since $\phi_1=0$ in this phase, all current conducted by the source followers is accumulated on $C_{sens}$ or $C_{base}$. As a result, the amount of transferred charge $Q_{add}$ added to $C_{integ}$ (4pF) for each $\phi_2$ cycle is:

$$Q_{add} = (C_{sens} - C_{base}) \times V_{ref_o}$$

The full sampling operation consists of 4$\phi_2$ cycles, during which 4$Q_{add}$ is transferred, thus providing $4 \times$ charge amplification. In the following discharge state, OTA3 and one of the two comparators is turned ON. Similarly, the amount of charge that is subtracted from $C_{integ}$ for each $\phi_2$ cycle (denoted $Q_{sub}$), and the value of $V_{integ}$ at the $N_{count}$ cycle of the discharge stage are given by:

$$Q_{sub} = C_{ref} \times V_{ref_o}$$

$$V_{integ} = V_{ref_o} + (4Q_{add} - N_{count}Q_{sub}) / C_{integ}$$

$C_{ref}$ is a 36fF MIM capacitor. The discharge state ends when $V_{integ}$ becomes smaller than $V_{ref_o}$, the total number of required cycles is recorded by a ripple carry counter as a digital code.

$$Code = \lfloor \frac{Q_{add}}{Q_{sub}} \rfloor = \lfloor \frac{C_{sens} - C_{base}}{C_{ref}} \rfloor$$

The charge subtraction/accumulation circuit is redrawn in Fig. 3. The settling time constant for the OTA feedback loop is $\tau = C_{out}/(\beta I_{ref,OTA})$. In a conventional approach (Fig. 3a) this time constant becomes $C_{out}/I_{ref,OTA}$ [3], whereas in the proposed method it is almost equal to $C_{out}/I_{ref,OTA}$ since the $V_{integ}$ node is isolated. $C_{out}$ is much smaller than $C_s$, allowing for significantly lower OTA tail current for a fixed sampling rate. OTAs in the proposed design use a single stage design with 32nW tail-currents. Although this feedback approach trades off dynamic range, the relatively high 3.6V supply voltage (from battery) mitigates this concern. The current mirror (Fig. 1) uses the battery voltage, guaranteeing sufficient $V_{ds}$ across $M_f$.

The proposed CDC uses two clocked comparators (Fig. 4); a coarse comparator with minimum size transistors (720μV rms input referred noise, simulated) and a fine comparator with 10$\times$ larger transistors (100μV rms noise, simulated). Triggering of the coarse comparator turns on the fine comparator, which then makes the final determination that $V_{integ} < V_{ref_c}$ (Fig. 4(b)). To accomplish this, either different reference voltages could be used to compensate for input offset mismatch between the two comparators or the comparators can be designed with intentional offset, allowing them to trigger off one reference

![Figure 3. Charge subtraction/accumulation (a) conventional method, (b) proposed method.](image)

![Figure 4. Dual comparators (a) diagram, (b) operation concept. Detailed circuit implementation of (c) coarse comparator, (d) fine comparator.](image)

![Figure 5. 60pW reference voltage generator for (a) comparators and (b) OTAs.](image)
The proposed CDC was integrated in a complete pressure sensing system constructed from stacked IC layers to demonstrate CDC operation in an ultra-low power sensor platform (Fig. 6).

The system is powered by a custom 2uAh thin-film battery with 3.6V output voltage, which is down-converted to 1.2V and 0.6V by a switched-capacitor power management unit (PMU). The DS-CDC uses all three power domains: 0.6V for digital control logic, 1.2V for most analog blocks, and 3.6V for the current mirror. The system also includes an ARM Cortex-M0 processor and 3kB low power retentive memory, which controls the radio and CDC operation. The radio and CDC are located on the top IC layer (Fig. 11(a)) and communicate to the processor via an inter-layer bus. The entire electronics stack is placed on a custom MEMS pressure sensor (Fig. 11(b)) with the sensing diaphragm at the bottom of the stack to allow exposure to the ambient; two electrodes at the top of the sensor connect the CDC to the sensor. This configuration allows encapsulation of the electronics stack with a glass cap that is sealed with epoxy to the sensor (not shown), enabling implantation.

IV. TESTING RESULT

The CDC was implemented in 180nm CMOS. By changing $C_{\text{base}}$, the CDC can measure capacitances ranging from 5pF to 31pF. To test the CDC across continuous $C_{\text{sensor}}$ values, the voltage of the bottom plate is swept (Fig. 7). Each $C_{\text{base}}$ has 4pF linear range and capacitance ranges overlap to avoid missing codes. A linearity error plot (Fig. 8) combines results from 9 different ranges – maximum error is 16.5fF. Power and resolution are measured at the worst-case, maximum input capacitance condition. Total CDC power is 110nW, consuming 90nW from 1.2V and the other 20nW from 0.6V, which makes it suitable for miniature sensor node systems which often have batteries with low peak current capacity. The measured resolution is 8.7fF, resulting in 9.7b ENOB and 0.85pJ/conv·step FoM. Table I summarizes CDC performance and compares with previously reported CDCs. The proposed design has improved power and FoM, and comparable

![Figure 6. System integration block diagram.](image1)

![Figure 7. Code versus $C_{\text{sensor}}$ for various $C_{\text{base}}$ values.](image2)

![Figure 8. CDC linearity error.](image3)

![Figure 9. Pressure measurement result with 32 OSR, taken using complete pressure sensing system in a pressure chamber.](image4)
accuracy.

Fig. 10 shows measurements from system operation. The sensor system periodically wakes up from a low power sleep mode (<8nW) and enters active mode (~50 μW). It first initializes the radio and CDC and then initiates pressure measurement. Upon completion, the digital pressure value is stored and can be accessed for later transmission. For clarity, Fig. 10 shows immediate data transmission after which the system returns to sleep mode. Each pressure measurement cycle consumes 6.5μJ, resulting in 17.7 days of operation without charging the 2µAh battery (assuming pressure is recorded every 10 minutes). Testing the entire system in a pressure chamber, the CDC shows 0.77mmHg resolution with 32 OSR (Fig. 9) to reduce 1.2V supply noise.

![Figure 10. Measured system waveforms and timing diagram.](image)

![Figure 11. (a) Complete pressure sensing system, (b) MEMS pressure sensor, (c) CDC die photo.](image)

V. CONCLUSIONS

This paper proposed an energy efficient dual-slope capacitance to digital converter suitable for an implantable pressure sensing system. It achieves 9.7b ENOB and 0.85pJ/conv-step FoM employing input region zoom-in by configurable capacitor bank and dual precision comparators. Also, we demonstrated a complete 1.4mm×2.8mm×1.6mm pressure sensor system with a MEMS pressure sensor, processor, memory, battery, and radio. It requires only a 3.6V battery for operation with no external references.

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REFERENCES


