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DOI
10.1109/ESSCIRC.2018.8494283

Publication date
2018

Document Version
Final published version

Published in
ESSCIRC 2018 - IEEE 44th European Solid State Circuits Conference

Citation (APA)
Hussaini, S., Jiang, H., Walsh, P., MacSweeney, D., & Makinwa, K. A. A. (2018). A 15nW per Button Noise-Immune Readout IC for Capacitive Touch Sensor. In *ESSCIRC 2018 - IEEE 44th European Solid State Circuits Conference* (pp. 78-81). Article 8494283 IEEE. https://doi.org/10.1109/ESSCIRC.2018.8494283

A 15nW per Button Noise-Immune Readout IC for Capacitive Touch Sensor

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***Abstract*— This paper presents a readout IC that uses an asynchronous charge-redistribution-based capacitance-to-digital-converter (CDC) to digitize the capacitance of a touch sensor. Thanks to the power efficient tracking algorithm, the CDC consumes negligible power consumption in the absence of touch events. To facilitate stand-alone or wake-on-touch applications, the CDC can be periodically triggered by a co-integrated ultra-low power relaxation oscillator. At a 38 Hz scan-rate, the readout IC consumes 15 nW per touch sensor, which is the lowest reported to date.**

Keywords—Stand-alone touch sensor; Asynchronous tracking logic; CDC; Ultra-low power oscillator.

I. INTRODUCTION

Due to their low-cost and low power consumption [1], capacitive touch sensors are widely used in mobile applications to robustly realize functions such as buttons, sliders and wheels. In such applications, the power consumption of their readout circuitry is often a crucial determinant of battery life. This is because, unlike other system blocks that can be switched off to save power, at least one touch sensor must be "always on" to facilitate system wake-up [2-4]. This requires a readout IC with ultra-low power consumption, which, to avoid energy-wasting decision errors, must also be robust to human finger noise and common mode interference [1].

In conventional readout ICs [2-4], a processing unit is periodically awakened to look for touch events. However, this duty-cycled approach can only reduce power consumption to a limited extent, since there will always be some power overhead associated with turning the processing unit on and off. Thus, there is a need for ultra-low power readout systems that can operate without CPU intervention.

This paper presents a stand-alone readout IC for self-capacitance touch sensors. It consists of an energy-efficient tracking capacitance-to-digital converter (CDC), whose power consumption is not static, but increases with touch activity, and a nano-power oscillator that periodically triggers the CDC at certain rate. The CDC employs a differential architecture, enabling it to detect touch events while simultaneously attenuating common mode and human finger noise. At a 38 Hz scan-rate, the readout IC consumes only 15 nW per sensor pad, which is about 46× better than the state of the art [2].

In the following, Section II describes the operating principle of the proposed readout IC. Section III and Section IV discuss its circuit implementation, detailed design, measurement results, and comparison with the state of the art. Finally, conclusions are drawn.

II. OPERATING PRINCIPLE

A. Touch Sensing System

A block diagram of a touch sensing system comprising the readout IC and a PCB-based touch sensor is shown in Fig. 1. The touch sensor consists of a conductive pad that is shielded electrically by a ground plane and mechanically by an overlay material (typically glass, or plastic). The sensor pad has a relatively large parasitic capacitance to ground, which will increase slightly when touched. This configuration is usually referred to as a self-capacitance touch sensor.

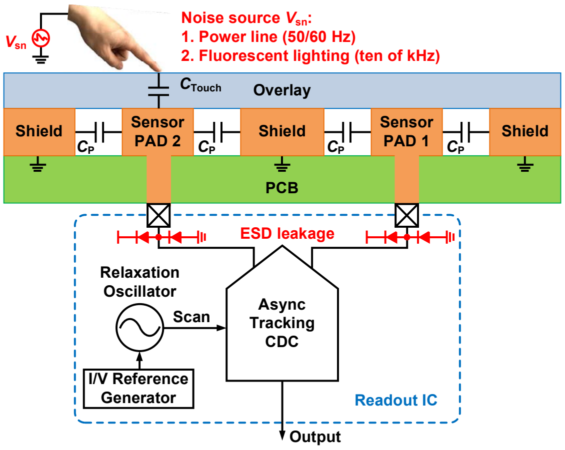

Fig. 1. Ultra-low power stand-alone self-capacitance touch readout IC with two channel PCB sensor PADs.

The readout IC consists of a CDC and an ultra-low-power relaxation oscillator that periodically triggers the CDC. Since the touch sensor is exposed to the environment, external interference from the mains and from fluorescent lighting will couple to the sensor and contaminate the touch signal. Thus, to minimize detection errors, the readout IC should be robust to such interference.

However, conventional CDCs are ill suited for ultra-low power applications, since most of their dynamic range, and hence their power dissipation, will be used to digitize the sensor's relatively large baseline capacitance with enough precision to detect the relatively small capacitance changes caused by touch events. To address this problem, a tracking CDC is proposed in this work, whose activity, and hence power dissipation, is dependent on the change in sensor capacitance between successive readout cycles.

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B. *Tracking Algorithm*

For medium resolution data converters, a well-known and low power method of digitizing an analog quantity is to use the Successive Approximation Register (SAR) algorithm. As depicted in Fig. 2 (top), where the capacitance value is applied to the analog input of a conventional SAR CDC, the SAR algorithm will be executed during every conversion cycle; even when the capacitance value has not changed e.g. during cycles #2 and #4. The corresponding SAR cycles are thus unnecessary and waste energy. Using an LSB-first SAR algorithm would save energy, at the expense of increased design complexity [5].

A more efficient algorithm is shown in Fig. 2 (bottom), in which the CDC uses the stored digital output of the previous conversion cycle as a starting point and only updates its digital output if the capacitance changes, in effect tracking changes in sensor capacitance. Like the LSB-first algorithm, the result is higher energy efficiency but with simpler control logic.

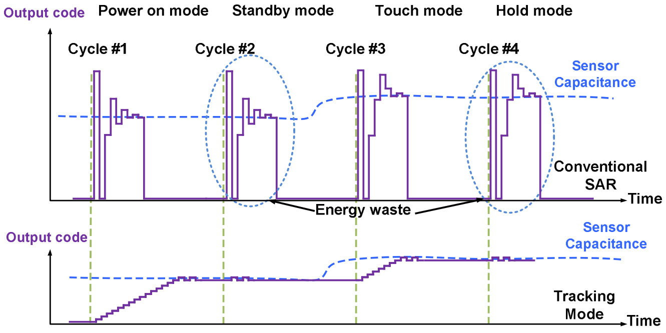
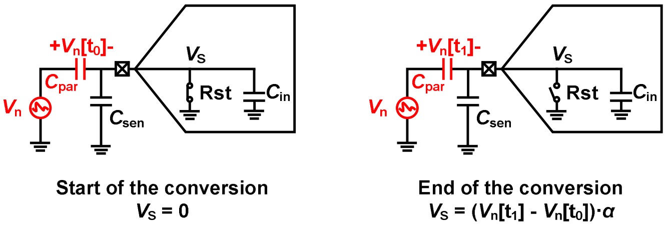


Fig. 2. SAR algorithm (top) and tracking algorithm (bottom).

C. *Interference immunity*

The proposed tracking CDC is designed to operate in a differential manner, by digitizing the difference in capacitance between two neighboring touch sensing pads. Environmental interference that couples to both inputs of the CDC will then appear as a common mode voltage, and be rejected. Due to the mismatch between the two sense-pad capacitances, a small fraction of this interference will still appear as a differential voltage, but in practice this residual interference is quite negligible.

Another source of error is human finger noise, due to mains (50/60 Hz) and fluorescent lighting (tens of kHz) pick-up [1], which couples into the CDC via the human body, denoted by V_n in Fig. 3. Fortunately, the CDC is only sensitive to changes in V_n, since it is effectively sampled on the parasitic capacitance C_{par} at the start of each conversion. The corresponding correlated-double sampling (CDS) transfer function suppresses interference at low-frequencies (< $1/T_{conv}$). Thanks to the short conversion time of the CDC (~ 200 ns), human finger noise will be heavily attenuated. The residual interference will be further attenuated by the capacitive divider formed by C_{par} and the combined capacitance of the sensor C_{sen} and the CDC's input capacitance C_{in}.



Start of the conversion
$V_S = 0$

End of the conversion
$V_S = (V_n[t_1] - V_n[t_0])\cdot\alpha$

Fig. 3. Input CDS function of the CDC. α is the ratio of C_{par} to the total input capacitance of the system.

III. CIRCUIT IMPLEMENTATION

Fig. 4 shows the schematic/timing diagram of the proposed CDC. It reads out the difference in capacitance ΔC between two external capacitors C_{s1} and C_{s2}. At the start of each conversion, their voltages, V_{s1} and V_{s2}, respectively, are first reset to zero and then pulled up towards V_{dd} by fixed base-line-compensating capacitors C_z (= 9.2 pF). These ensure that $V_{s1,2}$ remains within the comparator's common-mode range even with large sensor capacitances (up to 50pF). An asynchronous logic unit and a binary counter then forces $V_{s1} = V_{s2}$ by ramping two capacitive DACs (CDACs) up and down, respectively, starting from their mid-code. The final counter code Data is then proportional to ΔC. To minimize false decisions, the conversion is stopped only after the comparator's output changes sign three times. During the next conversion, the counter is loaded with the previous code and is either incremented or decremented to force $V_{s1} = V_{s2}$ again. The CDC's activity is thus proportional to the change in ΔC between read-out cycles. To further minimize activity, the CDAC and the comparator were sized such that the CDC is quantization-noise limited.

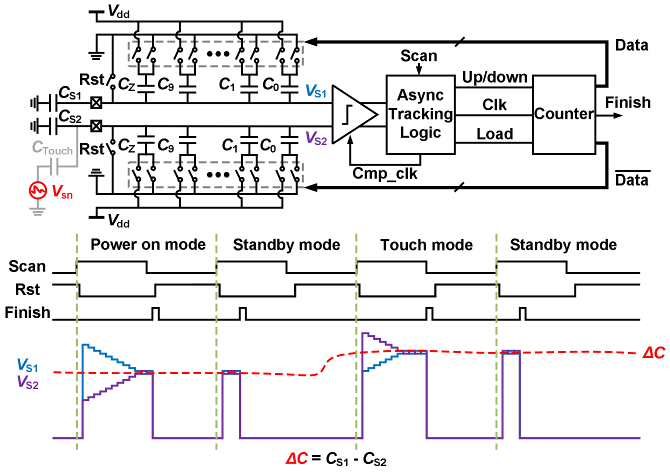
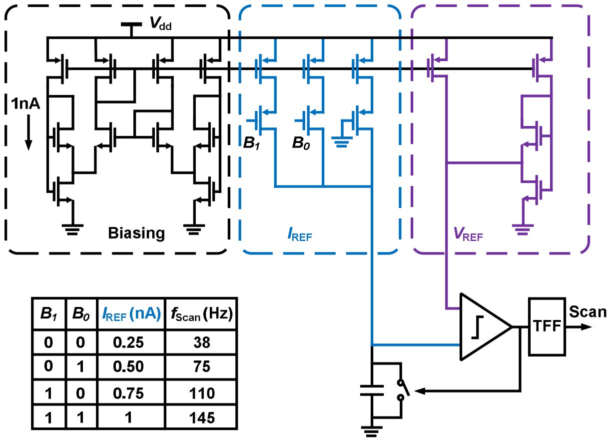


Fig. 4. Asynchronous Tracking CDC and simplified timing diagram.

To reduce the energy, which would still be wasted at the counter's mid-code transition, when all the CDAC capacitors toggle, the single CDAC of Fig. 4 is replaced by the combination of a 4-bit coarse CDAC and a 6-bit fine CDAC whose range is equivalent to two coarse LSBs. The fine CDAC is then reset to its mid-code each time the coarse CDAC toggles, thus ensuring that the latter only toggles when ΔC changes by more than one coarse LSB (~320 fF). For such fine-only conversions, this technique reduces the maximum CDAC switching losses by ~16×.

The CDC employs asynchronous logic based on a self-oscillating loop formed by the delay (~30 ns) between the comparator's clock signal and its ready signal. The resulting conversion time T_{conv} (~90 ns to ~1 μs for fine-only conversions) is then fast enough to ensure that (ESD) leakage currents do not cause decision errors by discharging the CDAC capacitors. As explained in section II.C, this fast conversion results in a CDS action that effectively suppresses environmental interference. Moreover, interference common to the two CDC inputs will be rejected by its differential architecture [1].

For stand-alone operations, the CDC can be periodically triggered by a co-integrated ultra-low power relaxation oscillator. As shown in Fig. 5, both its charging current and threshold voltage are derived from the same constant-inversion-current source, making its measured output frequency (~38 Hz) quite stable over temperature (0.07%/°C). To compensate for process spread, it can also be trimmed by adjusting the charging current via a 2-bit current DAC controlled by B_1 and B_0.



B_1	B_0	I_{REF} (nA)	f_{Scan} (Hz)
0	0	0.25	38
0	1	0.50	75
1	0	0.75	110
1	1	1	145

Fig. 5. Low-power Oscillator.

IV. MEASUREMENT RESULTS AND COMPARISON

The readout IC is implemented in a standard TSMC 0.18 μm CMOS process, and occupies an active area of 0.1 mm^2 (Fig. 6). For good matching, the unit capacitors of the 6-bit fine CDAC are realized with fringe capacitors (~11fF/LSB), while the 4-bit coarse CDAC is realized with MOM capacitors (~320 fF/LSB), to save area. Fig. 7 (top) shows the readout IC's response to an actual touch when sampled at a 38 Hz frame rate. For this measurement, the two buttons have baseline capacitances of ~9 pF and ~11 pF, respectively. Together, the CDC and the relaxation oscillator then draw 30 nW (CDC: 13.8 nW; Oscillator: 16.2 nW) from a 1.35 V supply.

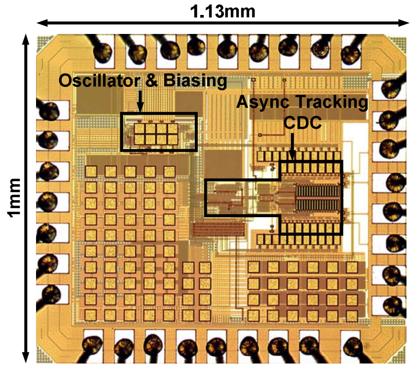


Fig. 6. Die micrograph of the readout IC.

The CDC has a ±10.8 pF input range when connected to 9.2 pF baseline capacitors. Triggered at 10 kHz, the CDC then draws 333 nA from a 1 V supply. It achieves a quantization-noise limited resolution of 11.4 6 fF$_{\text{rms}}$ (39.7 fF LSB), and a FoM$_{\text{Walden}}$ of 61 fJ/c-s. Fig. 7 (bottom) shows the CDC's measured power consumption at different frame rates when the sensor's capacitance changes by ΔC per cycle. This is emulated by using an external voltage source to drive its ground node, thus preloading it with a well-defined differential charge. As shown in Fig. 7 (bottom), the CDC's power consumption is roughly proportional to the *ΔC* per cycle. Fig. 8, shows the linearity of the prototype CDC, measured by sweeping voltage across the input capacitors, which is bounded to 0.1%.

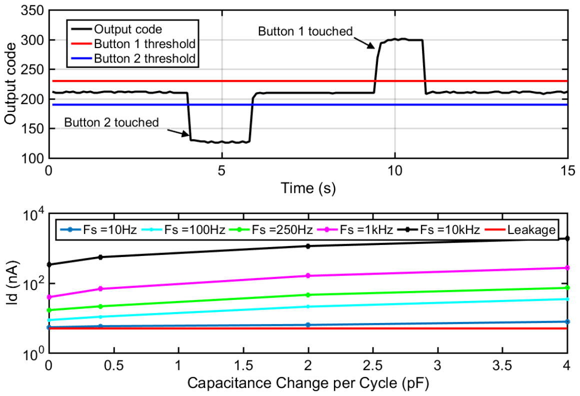


Fig. 7. Measured current consumption, Id, of the CDC (buttom) and measured outputs of CDC and 9pF(button 1) and 11pF(button 2) touch sensors (top).

The CDC's immunity to interference was characterized by coupling a voltage source to one of its inputs via a 1 pF capacitor and measuring the resulting rms error (2^{15} samples). Fig. 9 shows that low frequency interference, e.g. 50/60 Hz, is indeed strongly attenuated. At higher frequencies, this attenuation becomes amplitude-dependent, since large signals increase T_{conv}, and thus reduce the cut-off frequency of the CDC's CDS function.

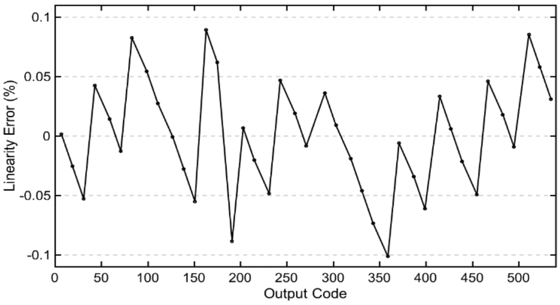


Fig. 8. CDC measured linearity error.

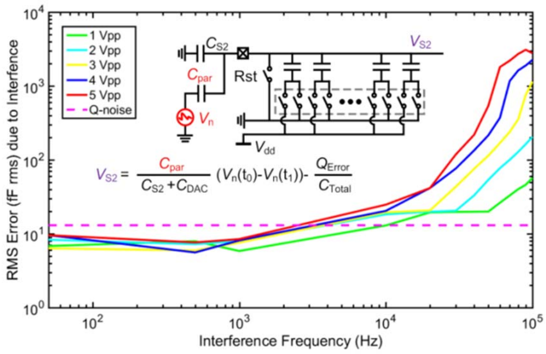


Fig. 9. CDS transfer function for interference and the measured rms error. (Cpar = 1pF).

In Table I and II, the performance of the tracking CDC is summarized and compared with the state-of-the-art and to commercial products. Compared to prior CDCs [5-8], it achieves competitive energy-efficiency, while offering self-capacitance sensing capability with excellent interference immunity. Compared to state-of-the-art stand-alone readout systems for touch sensors, it consumes 15 nW per button, which is 46× better than the state of the art [2]. These characteristics make the presented readout IC a promising candidate for self-capacitance touch sensors with a limited power budget.

Table I. Comparison with state-of-the-art CDCs

	This work				[6]	[7]	[8]	[9]
Technique	**Asynchronous Tracking**				ID	PM	DS+SAR	SAR
Support Self-capacitance	**Yes**				Yes	No	No	No
Differential	**Yes**				No	No	No	Yes
Technology (μm)	**0.18**				0.04	0.16	0.18	0.18
$T_{Measurement}$ (μs)	**100**				19	210	4000	16
Cap-range (pF)	**±10.8**[1]				11.3	8	2.5-75.3	12.66
Resolution (fFrms)	**11.46**[1]				12.3	1.4	6	1.1
Cap-change (LSB/Cycle)	**0**	**10**	**50**	**100**	--	--	--	--
Power (μW)	**0.33**	**0.55**	**1.14**	**1.86**	1.84	14	0.16	7.25[2]
FoM[3](fJ/c-s)	**61**	**100**	**208**	**342**	141	1870	181	35[2]

1. Measured with baseline capacitors of 9.2pF.
2. Excluding high frequency clock generator for power gating amplifier, and SAR logic.
3. FoM = Power·($T_{Measurement}$)/(2^{ENOB}), ENOB = (20log((Cap-range/2√2)/(LSB/√12) - 1.76) / 6.02.

Table II. Comparison with state-of-the-art stand-alone touch sensors

Product	Year	Scan rate	Power/Button (μW)
EFM32 [3]	2016	10 Hz	1.561
MSP430FR2633 [2]	2015	8 Hz	0.6901
PSOC4 [4]	2016	8 HZ	3.961
This Work	2017	38 Hz	0.015

V. CONCLUSION

This paper has presented an ultra-low power stand-alone readout IC for self-capacitance touch sensors. Low-power operation is achieved by utilizing the charge redistribution technique. An asynchronous tracking algorithm is proposed to realize data-dependent power consumption. This is especially efficient in wake-on-touch applications where the touch sensor spends most of the its time in idle mode. Employing a differential architecture together with an intrinsic correlated-double sampling function heavily attenuates the effect of environmental interference and human finger noise. Including the on-chip relaxation oscillator, the readout IC achieves competitive energy-efficiency, while offering self-capacitance sensing capability with excellent interference immunity. The readout IC consumes only 15 nW per button from a 1.35 V supply (coin cell), which is the lowest power dissipation ever reported (46× better than the state of the art). These characteristics make the presented readout IC a promising candidate for self-capacitance touch sensors with a limited power budget.

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