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Published in:
FLEPS 2024 - IEEE International Conference on Flexible and Printable Sensors and Systems, Proceedings

DOI:
10.1109/FLEPS61194.2024.10603811

Published: 01/01/2024

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Tanweer, M., Monga, D. C., & Halonen, K. (2024). Ultra-Low-Power Front-end Design on Flexible IC Technology for Capacitive Sensors. In *FLEPS 2024 - IEEE International Conference on Flexible and Printable Sensors and Systems, Proceedings* (IEEE international conference on flexible and printable sensors and systems). IEEE. https://doi.org/10.1109/FLEPS61194.2024.10603811

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Ultra-Low-Power Front-end Design on Flexible IC Technology for Capacitive Sensors

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***Abstract*—This paper presents an application-specific integrated circuit (ASIC) front-end, to interface the printed capacitive sensors, using an amorphous Indium-Gallium-Zinc-Oxide (a-IGZO) thin film transistors (TFT) on flexible integrated circuit (FlexIC) technology. A ring oscillator (RO) based front-end sensor interface is designed with 0.024 mm^2 area using 600 nm channel length of n-type TFTs consuming 183 nW at a supply voltage of 1 V. It generates output frequency sensitive to the change in the input capacitance of the printed coplanar sensor introduced by the moisture variations. Measurement results show that the front-end ASIC can detect the change in capacitance from 10 pF up to 500 pF of the printed coplanar sensor making it suitable not only for moisture detection but also for the evaluation of voided liquid volumes inside diapers to realize economical, disposable and battery-less Internet of Things (IoT) sensor nodes using green energy harvested from urine.**

***Index Terms*—Flexible electronics, Printed electronics, Printed Sensors, Disposable electronics, Ultra-low-power, IoT sensor node, Energy harvesting.**

I. INTRODUCTION

The surge in IoT devices, particularly in healthcare, with 16.7 billion sensor nodes set to double in the next couple of years and potentially reach hundreds of billions [1], underscores the need for sustainable electronics. The traditional silicon-based electronics, the main driver of IoT-ecosystem, face criticism for their environmental impact, highlighting the urgency for a green shift emphasized by the Greenpeace report [2]–[4]. Pragmatic FlexIC technology employs sustainable processes by utilizing flexible substrates and thin-film materials to offer a viable, eco-friendly alternative hence making it feasible for cost-effective, and sustainable IoT solutions to promise single-use applications aligning with calls for greener production practices [5], [6].

Powering a large number of IoT devices, especially in single-use applications is another challenge and the use of batteries is not feasible economically. The environmental and health hazards also posed by the disposal of lithium batteries in IoT devices present significant challenges, highlighting the urgent need for sustainable power solutions [7]. There is a need to develop economical power-efficient sensor electronics for energy-harvesting applications to eliminate toxic batteries. Recent developments in the low-cost, flexible, and printed electrodes to harvest the green energy from urine [8] and the development of printed flexible capacitive sensors have made it possible to not only detect moisture but also quantify the liquids [9]–[12]. These advancements have paved the way for the development of economical disposable battery-less IoT sensor nodes powered by harvested energy.

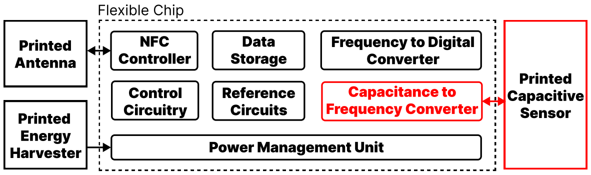

Fig. 1. Block diagram of flexible IoT sensor node with printed capacitive sensors for moisture detection.

Voltage mode measurements can be used to measure the changes in the capacitance as described in [13], [14]. However, this method is compromised by inaccuracies from the voltage buffer and the inherent noise of kT/C particularly in the case of smaller capacitance range [15]. By utilizing the oscillation frequency, which varies with the input sensor capacitance, a relative change in capacitance can be directly correlated to a change in frequency. Given the higher resolution achievable in frequency measurements compared to voltage, this technique promises enhanced precision of the sensor. Several capacitance variation measurement techniques have employed an RO to offer a more precise method for capacitance sensor assessment in terms of frequency. A frequency-based measurement system was developed by [15] to evaluate mismatches between small capacitances. A low-power gesture sensor was developed by [16] to detect capacitance changes up to 2 pF and a front-end circuit was developed by [17] to detect capacitance variations up to 200 pF. All the discussed systems employ expensive complementary metal oxide (CMOS) Integrated circuit fabrication processes that have sustainability challenges.

In this study, an ultra-low-power capacitance-to-frequency (C2F) converter is designed using Pragmatic FlexIC technology to interface the capacitive sensors as developed in [12] and [17]. Figure 1 depicts the scope of this study as a red-highlighted front-end sensor interface in the block diagram of a low-cost battery-less IoT sensor node powered with harvested green energy in disposable applications such as smart diapers.

II. FLEXIBLE CIRCUIT DESIGN

The front-end C2F converter is designed on a 600nm Pragmatic FlexIC technology using a-IGZO TFTs. The proposed

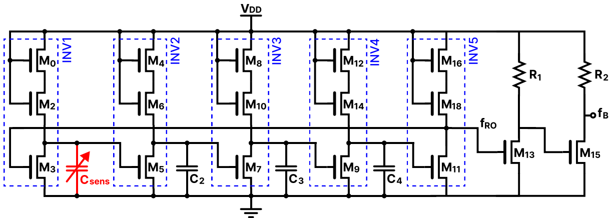

Fig. 2. Schematic of the proposed C2F converter in TFT-based technology.

C2F converter employs circuit topology adopted by [16] using bulk CMOS technology. Figure 2 shows the schematic of the RO designed using five inverter stages highlighted in blue where each deployed with a series connected pair of n-type TFTs in diode configuration. The transistors M_3, M_5, M_7, M_9 and M_{11} are sized equally. The M_0, M_2, M_4, M_6, M_8, M_{10}, M_{12}, M_{14}, M_{16} and M_{18} are diode connected TFTs and sized equally. The output frequency of the RO f_{RO} is fed to the on-chip buffer designed with transistors M_{13} and M_{15} having resistive loads of R_1 and R_2 respectively.

The output of the first inverter INV1 is designed to interface with the sensor and the outputs of each inverter from INV2 to INV4 are connected with 10 pF load using on-chip capacitors to reduce the phase noise at high sensor capacitance. The voltage supply is set to 1 V to interface with digitization circuits designed on other technologies operating at the same voltage level. In the schematic-level simulations, the W/L ratio of TFTs in the C2F converter is varied from 1.W/L to 4.W/L to analyze the operation and switching speed. The diode-connected TFTs are designed with a fixed W/L ratio of 0.4 using a long length (L) to optimize the power consumption of each inverter. The sensitivity $\alpha = \{\Delta f/f\}/\{\Delta C/C\}$ as defined in [15], resolution and average power consumption of the C2F converter are measured over various W/L ratios of TFTs. The schematic-level circuit simulations are tabulated in Table I, for an input sensor capacitance range of 150 - 200 pF to compare with [17] and for the implemented sensing range extension of 450 - 500 pF.

The schematic-level simulation results in Table I show that the sensitivity and resolution remain almost the same for various W/L ratios over the sensor capacitance range of 150 - 200 pF and small W/L ratio can be adapted to optimize the power consumption of the C2F converter. However, the sensitivity and resolution drop drastically for smaller W/L ratios over the capacitance range of 450 - 500 pF which is required for better quantification of liquids. The frequency response of the C2F converter using various W/L ratios of TFTs is shown in Figure 3 over the implemented sensing range from 10 pF to 500 pF. The larger the W/L ratio of TFTs, the better the frequency response of the front-end circuit, especially at higher capacitance values of the input sensor

TABLE I
SCHEMATIC-LEVEL SIMULATIONS AT VARIOUS W/L RATIOS OF TFTS.

TFT ratio (W/L)	Sensor capacitance range				Average Power (µW)
	(150 - 200 pF)		(450 - 500 pF)		
	Sensitivity (α)	Resolution (pF)	Sensitivity (α)	Resolution (pF)	
1.W/L	0.68	7	0.21	50	0.158
2.W/L	0.70	5	0.61	29	0.172
3.W/L	0.71	5	0.69	14	0.179
4.W/L	0.70	5	0.72	11	0.183

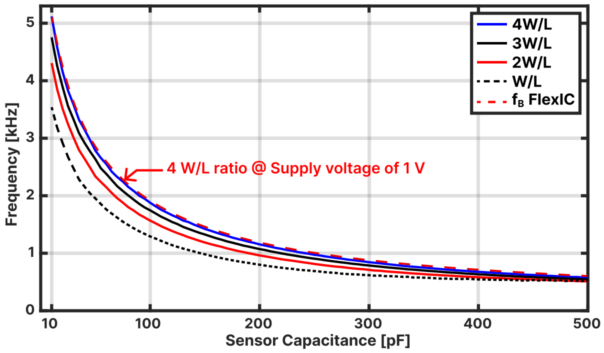

Fig. 3. The frequency response of C2F converter designed with various W/L ratios of TFT and the post layout buffer output with 4W/L.

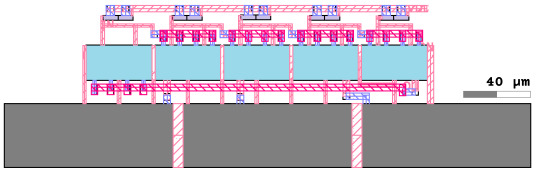

Fig. 4. Layout of the proposed C2F converter in TFT-based technology.

III. POST LAYOUT SIMULATION RESULTS AND DISCUSSION

The circuit layout is drawn using 4.W/L to achieve better resolution and sensitivity. The functionality of the proposed fabrication-ready C2F converter is verified with post-layout simulations. Figure 4 depicts the layout of the front-end design with five inverter stages occupying an area of 0.024 mm^2 on Pragmatic FlexIC. The post-layout frequency response f_o at the buffer output with the supply voltage of 1V over the sensor capacitance range of 10 - 500 pF is depicted in Figure 3. The sensor capacitance of 10 pF results in an output frequency of 5.1 kHz. The output frequency drops by 122 Hz when the sensor capacitance changes from 10 pF to 11 pF. The output frequency of 577 Hz is obtained when the sensor capacitance is increased to 500 pF. The peak-to-peak output voltage swing for the proposed C2F converter is 0.5 V over the entire capacitance range of the capacitive sensor. The output waveform f_{RO} of the RO and the output waveform f_B of the on-chip buffer circuit are shown in Figure 5 for input capacitance C_{sens} values of 10 pF, 100 pF, and 500 pF

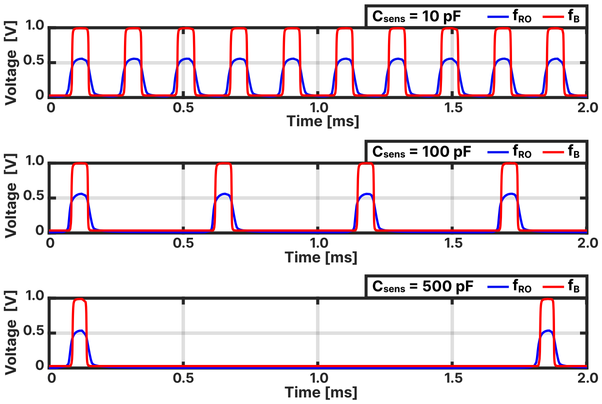

Fig. 5. The output voltage waveform of the C2F converter and on-chip buffer.

TABLE II
POST-LAYOUT SIMULATION RESULTS AT VARIOUS SUPPLY VOLTAGES.

Supply Voltage (V)	Sensor capacitance range				Average Power (µW)
	(150 - 200 pF)		(450 - 500 pF)		
	Sensitivity (α)	Resolution (pF)	Sensitivity (α)	Resolution (pF)	
1.0	0.70	5	0.70	17	0.183
1.5	0.70	4	0.85	6	1.049
2.0	0.70	3	0.84	5	3.328
2.5	0.70	2	0.83	4	8.017
3.0	0.70	1	0.82	3	16.325

The post-layout simulations are performed by varying the supply voltages from 1 to 3 V with a step increment of 0.5 V. The resolution, sensitivity, and average power consumption are evaluated over the input sensor capacitance range of 150 - 200 pF to make a comparison with state-of-the-art CMOS circuits [16], [17] and over 450 - 500 pF to evaluate the proposed extended range of the capacitive sensor. The results of the post-layout simulations are tabulated in Table II. A stable sensitivity α of 0.70 is obtained for sensor capacitance C_{sens} range of 150 - 200 pF. The resolution can be improved from 5 pF to 1 pF by increasing the supply voltage from 1 V to 3 V, albeit with a trade-off in power consumption. The sensitivity of the C2F converter is measured as 0.70 with supply voltages of 1 V for the input sensor capacitance C_{sens} range of 450 - 500 pF which is comparable to the sensitivity at the input sensor capacitance range of 150 - 200 pF.

The designed front-end achieves a resolution of 17 pF, enabling it to interface with a flexible capacitive sensor as developed by [12] to quantify a fluid change of 100ml and distinguish between salt and sugar concentrations of 5g in half a liter of liquid. The designed TFTs operate in sub-threshold operating regions to ultra-low power of 183 nW at a supply voltage of 1 V to achieve the desired results for energy harvesting-based bio-medical applications. The sensitivity improves by 21.4% and resolution improves three times by increasing supply voltages from 1 to 1.5 V. It is observed that the output frequency and the average power consumption have a similar response towards the change in the supply voltages as depicted in Figure 6 where the output frequency at C_{sens} of 10 pF is plotted together with an average power consumption over the supply voltage from 1 to 3 V for entire C_{sens} range of 10 - 500 pF.

TABLE III
SUMMARY OF PERFORMANCE AND COMPARISON

Reference	**This Work**	[17]	[16]
Channel length (nm)	600	65	180
Device structure	Unipolar a-IGZO	CMOS	CMOS
Inverter stages	5	5	3
Frequency (kHz)	5.1	6.1	110
Supply Voltage (V)	1	1.2	0.8
Power Consumption (nW)	183	2500	462[a]
Sensitivity (α) at Csens {150 - 200 pF}	0.7	0.64	-
Sensitivity (α) at Csens {450 - 500 pF}	0.7	0.3[b]	-
Capacitance range (pF)	500	200	2
Area (mm^2)	0.024	0.375[c]	0.032[d]

[a] Includes the digital block of the cascaded integrator comb filter.
[b] redesigned on bulk CMOS to evaluate the sensitivity.
[c] Includes the energy harvester circuits.
[d] Calculated from micrograph figure.

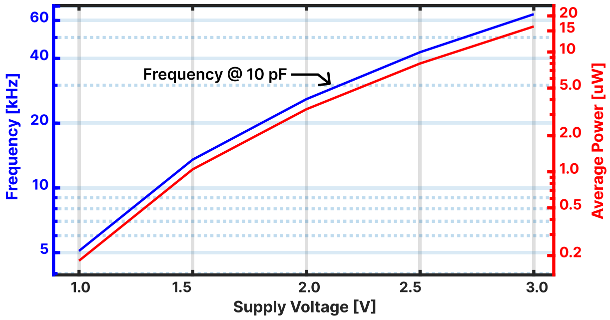

Fig. 6. Frequency response and average power consumption of C2F converter.

Table III presents a comparison of this work with two capacitance-to-frequency conversion systems developed on CMOS technology. The post-layout simulation results of the proposed front-end design show that a ring-oscillator topology similar to [16] can be adopted to develop the C2F converter circuit on FlexIC to achieve comparable performance using the same number of inverter stages as in [17]. It is capable of interfacing with the printed capacitive sensor having a capacitance range of 10 - 500 pF [12] for moisture detection and liquid quantification to realize self-powered economical IoT sensor nodes for disposable applications such as smart diapers.

IV. CONCLUSION

In this study, an ultra-low-power front-end interface is designed using 600 nm a-IGZO Pragmatic IC technology on a flexible substrate for a printed capacitive sensor to detect moisture and quantify liquids. A five-stage RO-based capacitance-to-frequency converter is designed to operate in the sub-threshold region for ultra-low power consumption of 183 nW at a supply voltage of 1 V with output frequency sensitive to the changes in sensor capacitance due to variations in the moisture levels. The post-layout simulations are executed to validate the functionality of the designed capacitance-to-frequency converter. The designed front-end provides a sensitivity of 0.70 for the input sensor capacitance range of 10 - 500 pF making it suitable to integrate the sensor front-end with low-voltage digitization circuits and high-frequency radios designed on other ASIC technologies.

In the future, a low-power frequency-to-digital converter can be designed using similar FlexIC technology to further digitize the output of capacitance-to-frequency converter for low-cost self-powered moisture detection and liquid amount quantification IoT sensor nodes to realize the disposable smart products such as smart diapers.

ACKNOWLEDGMENT

The study is conducted under EHIR project (grant 13334487) funded by the Academy of Finland.

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