A Fully Dynamic Capacitive Touch Sensor With Tri-Level Energy Recycling and Compressive Sensing Technique

Xiangdong Feng, *Member, IEEE*, Zhiyu Wang, *Member, IEEE*, Haoyang Li, Jiaqing Li, *Graduate Student Member, IEEE*, Wei-Chin Lin, *Graduate Student Member, IEEE*, Xin Hu, Zhong Tang, *Member, IEEE*, Yuyan Liu, *Graduate Student Member, IEEE*, Qinwen Fan, *Senior Member, IEEE*, Yuxuan Luo, *Senior Member, IEEE*, and Bo Zhao, *Senior Member, IEEE*

***Abstract*—Capacitive touch screens have become the dominant user interface over the past decade. Achieving high framerates with low power consumption remains a critical design goal for touch systems. The conventional charge-recycling technique reduces driving power by 64%, but it relies on off-chip capacitors. To address this issue, we propose a tri-level energy recycling scheme, in which energy released during the 2-to-1 transition is recycled to power the 0-to-1 transition on the complementary channel. This approach achieves a 25% power reduction using on-chip transmission gates. Additionally, a compressive sensing method is introduced to selectively process touched RX channels while bypassing the others, reducing the number of fine ADCs by a factor of four compared to conventional two-step sensing. The proposed techniques are implemented in a 65-nm CMOS process and integrated into a 32 × 20 channel prototype occupying 2.4 mm^2. Measurement results show that the chip consumes only 2.6 mW at a framerate of 1513 Hz. The signal-to-noise ratio (SNR) reaches 49.7 dB for finger touch and 28.7 dB for a 1-mm Φ stylus, resulting in an energy efficiency of 10.66 pJ/step.**

***Index Terms*—Capacitive touch sensor, compressive sensing, energy efficiency, energy recycling, fully dynamic.**

I. Introduction

Capacitive touch sensing systems are widely used in portable devices such as tablets [1], [2], [3]. In these battery-powered systems, low chip power consumption is essential for extending battery life. In addition, high framerates are required to accurately track dynamic touch points—for example, the iPad Pro employs a touch framerate of 240 Hz. However, higher framerates demand increased driving power in the transmitter (TX) circuits. For instance, the 64 direct digital synthesizer (DDS)-based sine-wave excitation channels in [4] consume 125 mW at a framerate of 3.9 kHz. On the receiver (RX) side, supporting high framerates also requires additional readout channels and faster scanning speeds, resulting in increased die area and power consumption. The 104-channel RX circuit in [4] consumes 70.29 mW and occupies approximately 13.57 mm^2.

To tackle this problem at the TX end, the charge-recycling technique [5] [Fig. 1(a)] was proposed, achieving a 64% reduction in driver power consumption. It reduces excitation energy through staircase charging and lowers cost by merging two energy-storing capacitors into a single one. Nevertheless, it still requires an off-chip capacitor. A two-step sensing approach [Fig. 1(c)] was introduced in [6] to address the issue at the RX end. The system first estimates the touch location using self-capacitance sensing, and then activates only the relevant mutual-capacitance readout circuits. Despite this, 40 mutual-capacitance channels are still implemented. Area limitations necessitate slope-based readout circuits, resulting in limited SNR.

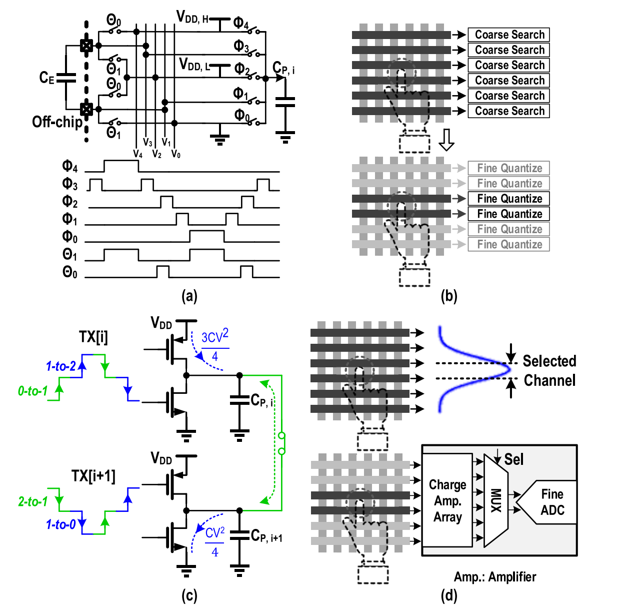

Fig. 1. (a) Conventional charge recycling. (b) Conventional two-step sensing. (c) Proposed tri-level energy recycling. (d) Proposed compressive sensing.

This work presents a capacitive touch sensor with a framerate of 1513 Hz and energy efficiency of 10.66 pJ/step. Two main techniques enable this performance (first introduced in [1]): 1) a fully differential tri-level energy recycling technique is proposed [Fig. 1(b)], recycling the energy released during the 2-to-1 transition to support the 0-to-1 transition of the complementary channel. This reduces the driving energy by 25%, and 2) a compressive sensing technique is introduced [Fig. 1(d)], which selectively processes the touched RX channels while bypassing the rest. Compared to the two-step approach [6], this technique reduces the number of fine ADCs by 4 × at the same framerate, resulting in a smaller die size. Moreover, the framerate and power consumption are fully scalable to accommodate various user scenarios, saving power dynamically.

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Xiangdong Feng, Zhiyu Wang, Haoyang Li, Jiaqing Li, Wei-Chin Lin, Xin Hu, Yuxuan Luo, and Bo Zhao are with the College of Integrated Circuits, Zhejiang University, Hangzhou 311200, China (e-mail: zhaobo@zju.edu.cn).

Zhong Tang is with the Zhejiang Key Laboratory of Analog Integrated Circuits, Hangzhou Institute of Technology, Xidian University, Hangzhou 311231, China, and also with the School of Integrated Circuits, Xidian University, Xi'an 710071, China.

Yuyan Liu and Qinwen Fan are with the Department of Microelectronics, Delft University of Technology, 2628 CD Delft, The Netherlands.

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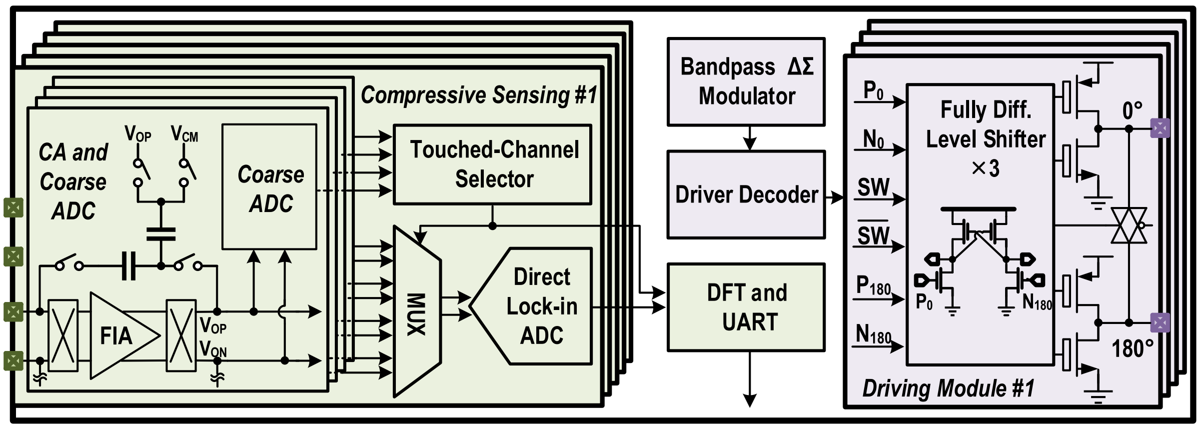

Fig. 2. System architecture of proposed fully dynamic capacitive touch sensor.

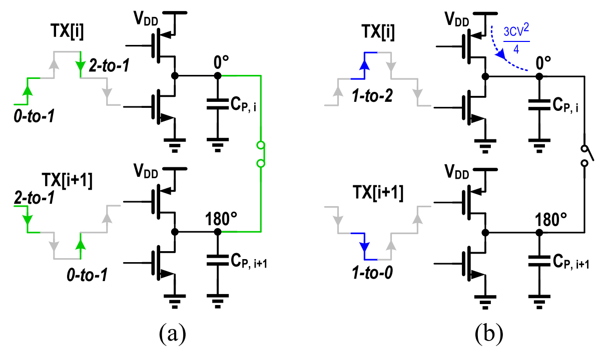

Fig. 3. Energy recycling techniques: (a) 0-to-1 and 2-to-1 transitions. (b) 1-to-2 and 1-to-0 transitions.

II. System Architecture and Proposed Techniques

Fig. 2 presents the system structure. The TX circuit includes 16 1.5-bit bandpass $\Delta\Sigma$ modulators, 16 driver decoders, and 16 sets of tri-level energy-recycling driver circuits, operating at the system frequency f_S. They generate 16 sets of differential signals using four frequencies (f_0, $2f_0$, $3f_0$, and $4f_0$, where $f_0 = f_S/10$). Each frequency is associated with four phase shifts (0°, 45°, 90°, and 135°), along with their differential counterparts. These are used to drive 32 channels on a 10.1-inch 32 × 20 touch screen panel (TSP). The RX sensing circuit contains five compressive sensing readout modules that operate simultaneously, supporting five touches at full framerate. Each module includes four fully dynamic, fully differential charge amplifiers, four coarse ADCs, a touched channel selector, a multiplexer, and a direct lock-in ADC [3]. Additionally, a discrete Fourier transform (DFT) processor calculates the amplitude and phase of the signal to locate touch coordinates. Each frame consists of 30 coarse ADC cycles, 1000 direct lock-in ADC conversion cycles, and one reset cycle. Accordingly, the 1513-Hz framerate corresponds to a system frequency f_S of 1.56 MHz (1031 × 1513 Hz).

The principle of tri-level energy-recycling driving is detailed in Fig. 3. The driver signal switches among GND (0), VCM (1), and VDD (2). A 0-to-1 transition refers to the change from GND to VCM, with the other transitions defined similarly. During the 0-to-1 and 2-to-1 transitions [Fig. 3(a)], the 0° and 180° channels are connected while the inverter drivers are turned off. In this configuration, the energy released in the 2-to-1 transition is recycled to power the complementary channel's 0-to-1 transition, whereas conventional driving circuits dissipate this energy as loss. Consequently, these transitions draw no energy from the supply. For the 1-to-2 and 1-to-0 transitions [Fig. 3(b)], the transmission gate remains open, and although energy is drawn from the supply, it is limited to $3CV^2/4$.

Fig. 4(a) illustrate the operational principle of the proposed compressive sensing technique. In practice, only a few channels on the entire TSP are touched, making compressive sensing feasible. Fig. 4 shows half of the signal chain with only R_{X1} touched. Here, (R_{X1} & R_{X2}) and (R_{X3} & R_{X4}) are connected to charge amplifiers and coarse ADCs, respectively. The coarse ADC includes a notch filter and a window comparator. The charge amplifier for (R_{X1} & R_{X2}) outputs a combined signal of chopped offset and amplified input signal. The amplified input signal is digitized by the window comparator after the chopped offset is removed using the notch filter. In contrast, the charge amplifier for (R_{X3} & R_{X4}) only outputs a chopped offset, which is reduced to 0 V by the notch filter, resulting in a zero output from the subsequent window comparator. Fig. 4(b) illustrates the principle of touched-channel selector with two examples. It accumulates the outputs of the four coarse ADCs within one compressive sensing readout module and sums adjacent totals to determine the weight of each channel. The RX channel with the maximum weight is then selected and connected to the direct lock-in ADC for further processing, which remains valid even when the touch point is not precisely aligned with the RX electrode. Consequently, when R_{X1} to R_{X4} in a compressive sensing readout module are touched, charge amplifiers #1 to #4 will be connected to the direct lock-in ADC, accordingly. When multiple touch points fall into different readout modules, our prototype captures them simultaneously. Compressed sensing becomes ineffective only when multiple touches occur within the same four-channel module, but the practical impact is minimal, as tablet applications are dominated by single-point stylus input.

III. Circuit Designs

As shown in the right part of Fig. 2, the tri-level energy-recycling driving circuit consists of three fully differential level shifters, two thick-oxide-gate inverters, and an analog transmission gate. Details of the bandpass $\Delta\Sigma$ modulators are provided in Fig. 5. The modulators employ a 1.5-bit quantizer to generate tri-level outputs with third-order noise shaping. In this process, a 14-bit sinusoid is truncated into a 1.5-bit representation, exploiting the narrow bandwidth and low-noise characteristics of sinusoidal signals. The driver decoders convert the output of the bandpass $\Delta\Sigma$ modulator into gate control signals for the tri-level energy-recycling driving circuit. For instance, the decoded signal MID is set to 1 to turn on the transmission gate when the $\Delta\Sigma$ modulator outputs a value of 1. Each decoded signal along with its delayed version passes through a NAND gate to ensure

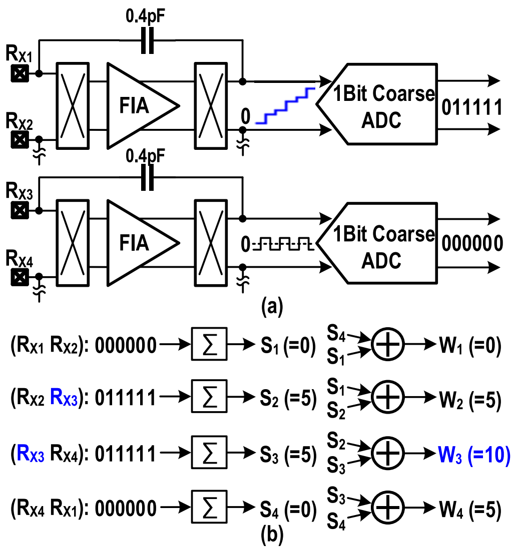

Fig. 4. Half of the compressive sensing signal chain with only R_{X1} touched.

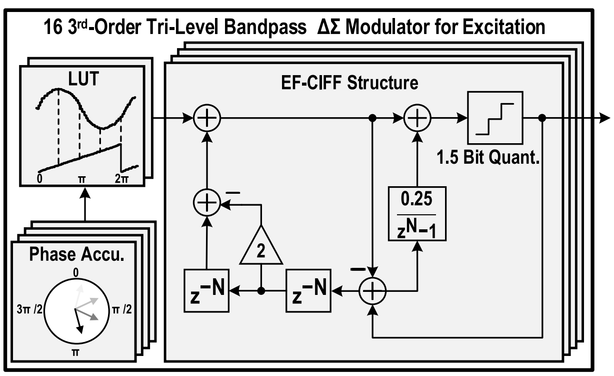

Fig. 5. Schematic of bandpass ΔΣ modulators for excitation.

that these signals do not overlap, which prevents large short-circuit current.

The RX sensing circuit mainly consists of fully differential charge amplifiers, coarse ADCs, and direct lock-in ADCs. In the direct lock-in ADC, the excitation frequencies are precisely aligned with the zeros of its NTF, thereby minimizing noise energy at the signal frequencies. Floating inverter amplifiers (FIAs) are used in the fully dynamic charge amplifiers for their low thermal noise and dynamic operation. Due to the low-noise performance of FIA, the circuit maintains an SNR of 47 dB, even with a small touch-induced capacitance change of 100 fF and a large load of 300 pF. To address gain loss caused by the parasitic capacitance of the TSP, correlated level shifting (CLS) is applied in the charge amplifier. With the CLS technique, the FIA achieves a gain exceeding 100 dB while maintaining an output swing from −0.9 to 0.9 V, making the gain degradation from the 10.1-inch panel's parasitic capacitance negligible. Chopping is used in the charge amplifier to suppress offset. With the chopping frequency set to half the system frequency, the offset is modulated to $f_S/2$. The coarse ADC's notch filter (Fig. 6) has a transfer function of $(1 + z^{-1})/2$, which effectively cancels the modulated offset. The window comparator (Fig. 6) includes two intentionally mismatched dynamic comparators with an offset of V_{OS}, followed by an XOR gate. It outputs zero when the notch filter's output voltage difference is less than V_{OS}. In this work, a direct lock-in ADC is employed due to its low noise bandwidth, high SNR, and support for simultaneous multichannel readout. It processes all four RX channels in a single compressive sensing module, helping reduce die area.

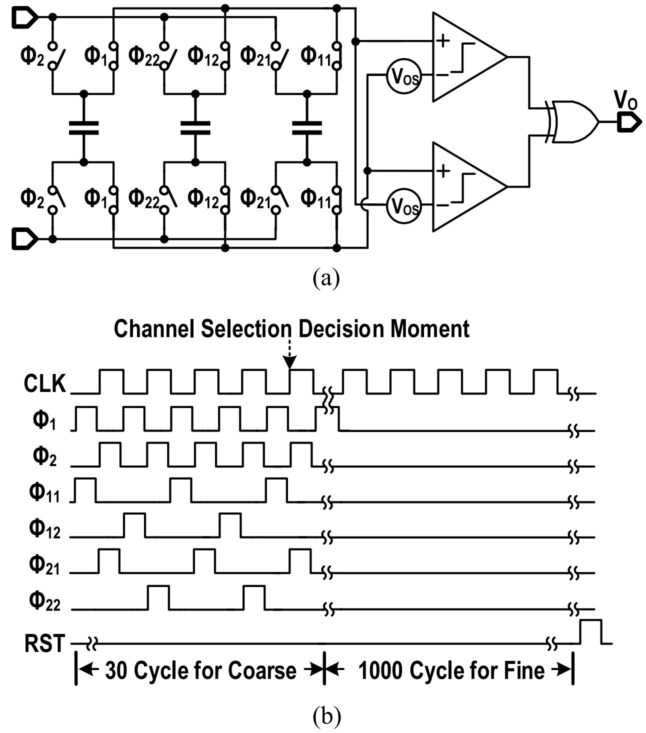

Fig. 6. (a) Schematic of notch filter and window comparator in coarse ADC. (b) Timing diagram of the overall system.

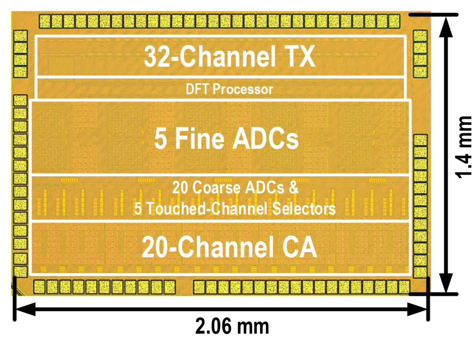

Fig. 7. Die photo.

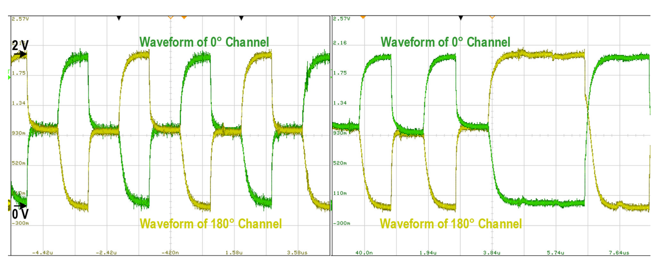

Fig. 8. Measurement results of tri-level energy recycling driving.

IV. Experimental Results

The chip is implemented using 65-nm CMOS technology, occupying an active area of 2.4 mm^2 (Fig. 7). As shown in Fig. 8, the driving signal features a symmetrical tri-level waveform, with its pulse width affected by ΔΣ modulation. Compressive sensing was evaluated using four different touch locations at different times

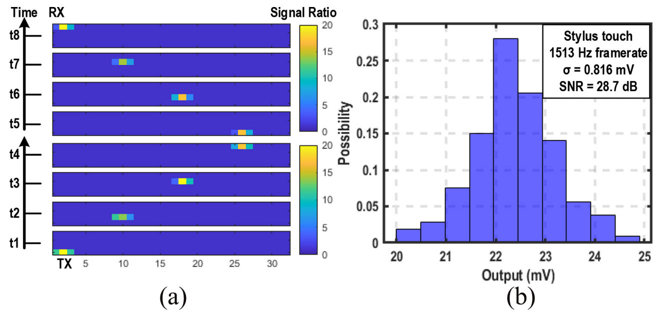

Fig. 9. Measurement results of (a) compressive sensing and (b) output voltage histogram of stylus under 1513-Hz framerate.

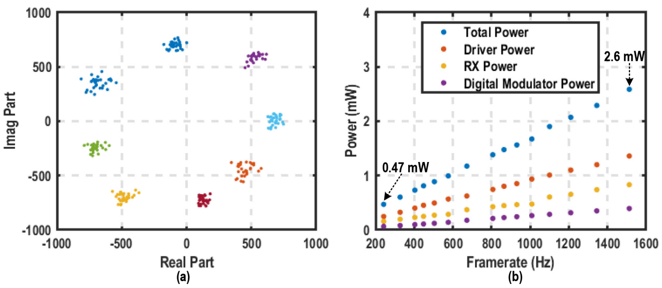

Fig. 10. Measurement result of (a) eight-phase excitation signal and (b) power versus framerate.

within each module. Fig. 9(a) shows the signal ratio diagram before and after a 1-mm Φ stylus touch, where the highlighted channel aligns with the actual touch position. Fig. 9(b) displays the output voltage histogram when the chip operates at a framerate of 1513 Hz with the 1-mm Φ stylus touch. The measured SNR in this case is 28.7 dB. When a finger is used for touch input at the same framerate, the SNR increases to 49.7 dB. The eight phases of the excitation signal are measured using a 1-mm Φ stylus as shown in Fig. 10(a), with standard deviations of 4.09 °, 2.20 °, 3.06 °, 3.74 °, 2.09 °, 2.40 °, 2.02 °, and 5.57 ° at the RX end. To ensure correct demodulation of the 8 excitation phases, the phase shift caused by parasitic components must be within 22.5 °. Modeling based on the measured parasitics indicates that a 22.5 ° phase shift occurs at 670 kHz for the longest signal path. At a framerate of 1513 Hz, the maximum signal frequency is 623 kHz, meeting the requirement. The power consumption of the presented chip scales linearly with the framerate as shown in Fig. 10(b), confirming its fully dynamic operation. At a framerate of 1513 Hz, the power consumption is 2.6 mW.

TABLE I
PERFORMANCE COMPARISON

	This work	[2]	[3]	[5]	[6]
Supply (V)	1.2/2.0	1.5/3.3/8	1.2/1.0/2.0	1.8/3.3	3.3
Process (nm)	65	130/350	65	180	350
Core area (mm^2)	2.4	2.81	1.31	7.1	1.37
TSP size (inch)	10.1	5	7	5.8	4.5
# of electrodes	32×20	18×21	16×28	16×33	80×80
Framerate (Hz)	1513	316	120	120	322
SNR (Finger, dB)	49.7	47.3	58.9	57.0	41
SNR (Stylus, dB)	28.7	N. R.	41.3	N. R.	32
Power (mW)	2.6	22.4	0.977	17.8	21.8
Fully dynamic	Yes	No	No	No	No
Energy effi.$^{(a)}$	10.66	990.5	25.2	350	115.4

(a) Energy effi.=Power/($2^{(SNR-1.76)/6.02}$ · # of node · framerate).

V. CONCLUSION

Table I summarizes the chip's performance and compares it with state-of-the-art designs. By employing the proposed tri-level energy recycling and compressive sensing techniques, the design achieves 1513-Hz framerate with 10.66-pJ/step energy efficiency. Furthermore, this is the first reported fully dynamic TSP sensing IC.

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