6.7 A 2.3mW 11cm-Range Bootstrapped and Correlated-Double-Sampling (BCDS) 3D Touch Sensor for Mobile Devices

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Contactless (3D) touch sensors, when integrated with displays, offer many advantages over that of conventional touch-panel screens by offering a more hygienic and a more immersive & interactive human/machine interface for 3D user experiences [1]. While significant progress has been made in developing 3D contactless touch sensors for larger television and monitor type displays [2-3], the technology has yet to be infused into space- and battery-constrained mobile devices (i.e., tablets and smartphones). For successful insertions into these systems, a paradigm shift in touch-sensor system design is essential to enable seamless sensing operations with smaller-size, more tightly spaced, strongly coupled, and highly resistive display electrodes. In addition, any successful 3D sensing solution for mobile devices must consume low power and small silicon area to be compatible with limited battery and space resources.

To address these mobile-specific challenges and facilitate 3D touch sensing in mobile devices, we present an oscillator-based Bootstrapped and Correlated Double Sampling (BCDS) sensing scheme with its circuit block diagram shown in Fig. 6.7.1. The BCDS sensor contains an inverter-based active resonator whose frequency is monitored via a digital counter with a specific integration window time to estimate the oscillator's loading capacitance. To achieve high sampling accuracy, the unloaded capacitance of each sensing channel is first calibrated to a reference value using a 6b cap array based on a SAR algorithm (runs on startup) as detailed in Fig. 6.7.2. During each measurement cycle, the oscillator is first connected to the desired input channel for a given integration time (programmable from 0.1 to 100ms) and then connected to a reference channel with identical capacitance (calibrated by the cap array during initialization) for the same integration window. During each integration window, a digital counter records the number of periods that the oscillator exhibits for both input channel and reference channel (a correlated double sampling process), allowing the flicker noise and other environmental drift effects on the oscillator to be removed by subtracting between the two values. The subtracted value reflects the input channel's capacitance difference compared to the reference channel, which is due to the additional capacitance induced by a finger. During the operation, each channel of the input array is scanned sequentially. Beyond the double sampling, the BCDS sensor also uses a bootstrapping technique to reduce the inter-channel coupling (typically inter-channel coupling capacitance is on the order of 10 to 30pF and channel intrinsic capacitance is 0.3 to 0.5pF for a 4" mobile device screen) by a factor of at least 100×, which is essential for increasing Z-axis range to beyond 10cm and boosting X-Y axis resolution at large Z-offsets. Details of the bootstrap circuitry including measurements are shown in Fig. 6.7.3. As the electrode array is scanned, a unity-gain amplifier is used to sense the time-domain voltage of the active channel and replicate it on the remaining idle channels to nullify the coupling capacitance by enforcing equal potential across the inter-channel coupling capacitors.

Special considerations are given to the design of the oscillator, with schematic and phase noise measurements shown in Fig. 6.7.4. The nature of high-resolution self-capacitance sensing prefers a single-ended capacitance-modulation action with low phase noise as opposed to a differential implementation. The limited bandwidth of the bootstrapping amplifier requires a sinusoidal waveform to avoid performance deterioration of waveform replication at higher harmonics. To avoid a large on-chip or off-chip passive element used in prior arts (such as an off-chip inductor used in [2]), the BCDS sensor employs an active resonator with gain stage supplied by simple inverters similar to that reported in [4]. A total of 5 inverters are used with one creating a negative resistance and 4 constituting the equivalent inductor. To further ease the amplifier design for power reduction, diode clamps are paired with each inverter to reduce the swing of oscillation. Finally, the oscillator includes a digitally controlled capacitor array to alter the active inductor value so that the free-running frequency can be varied from 2 to 10MHz, making it compatible with a wide range of scan rates and screen formats (varying integration time and channel counts).

To demonstrate mobile touch-screen operation, a BCDS SoC with 7 channels is fabricated to connect with an HTC 3.4" mobile touch-screen array (Number of channels: X=16 Y=10) and the user's finger is hovered in height and position as the counter readout is monitored. First, to evaluate the double sampling operation, we measure the counts of both the reference and active channel independently, plot their values and compute their standard deviation. Second, we perform the subtraction operation to produce the correlated double sampling (CDS) output. Figure 6.7.5 shows that CDS has reduced the output standard deviation by 10.5dB. Figure 6.7.5 also plots the finger Z distance versus BCDS output as the height of the finger is varied above the touch screen. Based on output codes difference among various finger heights, a final Z-direction resolution of 10mm is computed and the finger can be detected up to a maximum range of 11cm. Finally, to evaluate the bootstrap circuitry performance, the active channel is fixed to one vertical channel (Y channel) located in the center of the HTC screen, while a finger is positioned from left to right on the touch screen (across this channel electrode). The large code difference between positioning the finger over an active channel and over an idle channel demonstrates the strong isolation between these two channels.

The BCDS SoC is implemented in standard 65nm CMOS and consumes 2.3mW of power and 2 mm^2 of die area, making it highly compatible with mobile devices. Figure 6.7.6 compares the performance of the BCDS touch sensor with several other state-of-the-art touch sensors [2-3][5]. The BCDS extends the traditional 2D touch-sensing approach [5] to enable emerging 3D applications, while allowing the cost of power and area to be reasonable for mobile devices by using an active resonator to reduce size and by limiting the oscillator output swing to confine DC power. BCDS also provides comparable Z range and resolution to other 3D contactless touch sensors reported previously for large displays where there is far less inter-channel capacitance due to the large electrode spacing and substantially large electrode area for attracting more finger capacitance. To show that the BCDS sensor is more suitable for small mobile screens, we have normalized the sensing height based on the overall touch panel size as indicated in Row 6 of Fig. 6.7.6. The realized BCDS sensor provides a factor of 3-to-17× improvement in normalized sensing height over that of prior arts. Finally, Fig. 6.7.7 shows a die photo of the BCDS SoC chip with major blocks identified.

Acknowledgements:
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References:

[1] K. Yoshino and H. Shinoda, "Contactless Touch Interface Supporting Blind Touch Interaction by Aerial Tactile Stimulation", *IEEE Haptics Symposium*, pp 347-350, Feb 2014.
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[4] H. Barthelemy, S. Bourdel, J. Gaubert, and M. Battista, "CMOS Inverters Based High Frequency Voltage Controlled Sinusoidal Oscillator", *IEEE Int. Conf. Electronics, Circuits and Systems*, pp. 490-493, Dec. 2007.
[5] K.-D. Kim, *et al.*, "A Capacitive Touch Controller Robust to Display Noise for Ultrathin Touch Screen Displays", *ISSCC Dig. Tech. Papers*, pp.116-117, Feb. 2012.

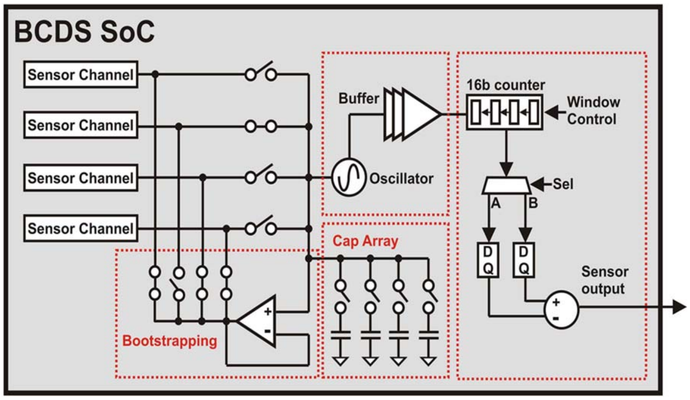

Figure 6.7.1: Bootstrapped and correlated double sampling (BCDS) SoC block diagram with major circuit blocks identified.

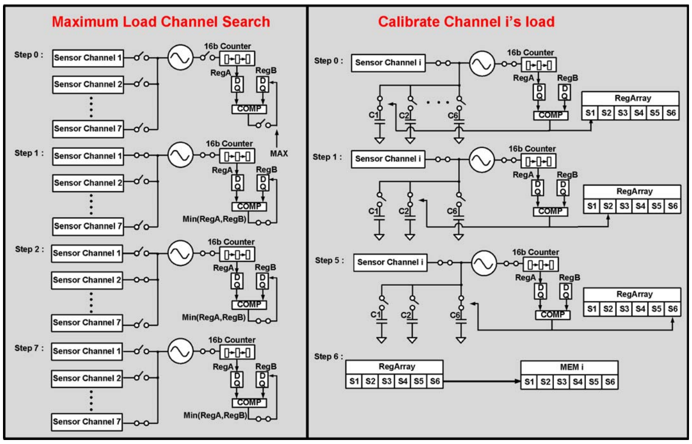

Figure 6.7.2: Calibration algorithm to trim channel load. First, the channel with the largest capacitance is identified, then switched capacitors match other channels to this value based on SAR algorithm.

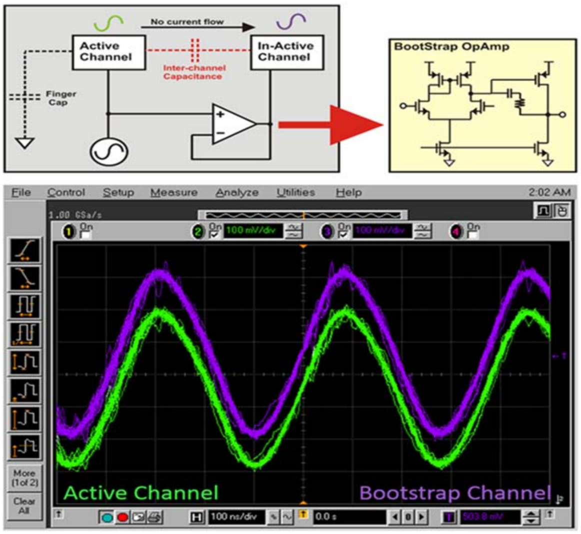

Figure 6.7.3: Measurement of the oscillator signal in the active channel of the BCDS sensor and the boostrapped signal on an inactive channel.

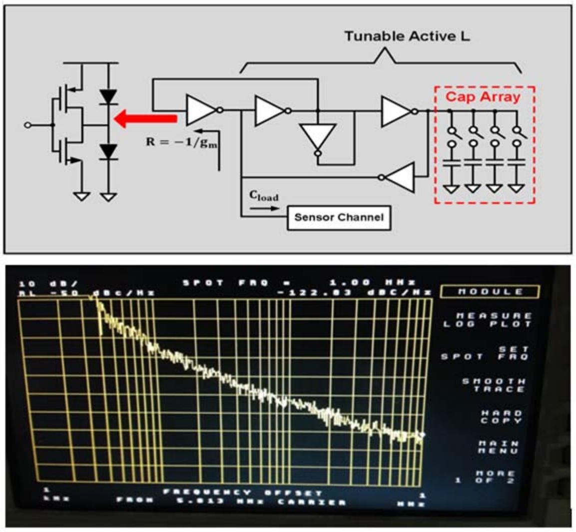

Figure 6.7.4: Oscillator circuitry with its capacitor array and active resonator. Phase noise measurement indicating -122.8dBc/Hz at 1MHz offset.

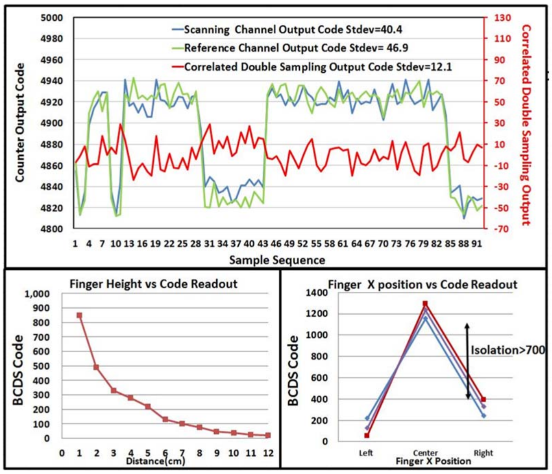

Figure 6.7.5: Measurement of the counter output for the reference and active channel (Top); Output Code vs. Finger Height (Left); Output code vs lateral (X) finger position on the screen showing the ability of bootstrapping to reduce inter-channel coupling effect (Right).

	K-D,Kim ISSCC12 [5]	Y.Z,Hu ISSCC14 [2]	Microchip MGC3130 [3]	This Work
Sensing Type and Format	2D Mobile	3D Large Screen	3D Large Screen	3D Mobile
Cancel Environmental Drift Effect	No	No	No	Yes
External Component Required	No	Yes(33uH inductor)	No	No
Electrode Size	X	10mm×400mm	79mm×118mm	4.8mm×72mm (Standard HTC3.4" Screen)
Electrode Spacing$^+$	X	100mm	48mm	4.8mm
Normalized Sensing Height (Height/Panel Area)	0	0.018cm^{-1} (30cm/(40cm×40cm))	0.1cm^{-1} (15cm/(14.8cm×9.9cm))	0.32cm^{-1} (11cm/(7.2cm×4.8cm))
Height Resolution	X	10mm (Screen Size: 40cm×40cm)	X	10mm (Screen size:7.2cm×4.8cm)
SNR	35dB@0cm	50dB@5cm 30dB@16cm	X	36dB@1cm 25dB@5cm
Power Consumption	10.6mW	19mW	150mW	2.3mW
Die Area	6.87mm^2	4.2mm^2	X	2mm^2
Channel	30	8	5	7
Scan Frequency	120Hz	240Hz	200Hz	up to 250Hz@10MHz sensing
Technology	1.5/5.5/30V 90nmLDI	1.2/2.5V 130nm CMOS	X	1V 65nm CMOS

+Electrode Spacing is distance between two nearby RX Electrodes measured from center to center.

Figure 6.7.6: Performance summary and comparison with other state-of-the-art touch sensors.

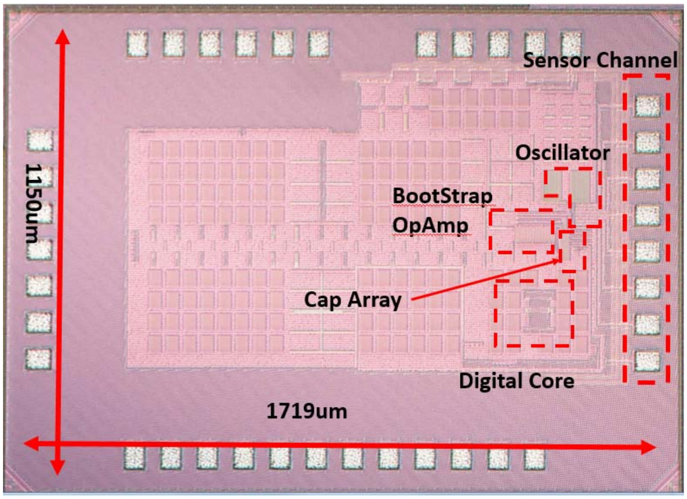

Figure 6.7.7: Chip photograph of the BCDS sensor SoC with major blocks and chip dimensions identified.