A 143 × 81 Mutual-Capacitance Touch-Sensing Analog Front-End With Parallel Drive and Differential Sensing Architecture

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***Abstract*—This paper presents an analog front-end (AFE) IC for mutual capacitance touch sensing with 224 sensor channels in 0.18 μm CMOS with 3.3 V drive voltage. A 32-in touch sensing system and a 70-in one having 37 dB SNR for 1 mm diameter stylus at 240 Hz reporting rate are realized with the AFE. The AFE adopts a parallel drive method to achieve the large format and the high SNR simultaneously. With the parallel drive method, the measured SNRs of the AFE stay almost constant at a higher level regardless of the number of sensor channels, which was impossible by conventional sequential drive methods. A novel differential sensing scheme which enhances the immunity against the noise from a display device is also realized in the AFE. While the coupled LCD is on and off, the differences between the measured SNRs are less than 2 dB.**

***Index Terms*—Analog front-end (AFE), CMOS, differential sensing, parallel drive, touch screen.**

I. Introduction

Capacitive touch-sensing is widely used as a de-facto standard touch user interface for smart phones and tablets. However, realization of a mutual-capacitance touch-sensing system spanning over 30 in is not a straightforward task, because the SNRs of conventional sequential drive controllers degrade as the number of sensor channels increases. This SNR issue is resolved by driving the sensor channels in parallel [1], [2]. Although the parallel drive mixes up the signals from the multiple channels driven at the same time, the original signals can be reconstructed from the sequence of mixed signals if the drive sequences are linearly independent from each other. By appropriately designing the parallel drive sequences, the SNR is enhanced by $\sqrt{\mathrm{M}}$ times compared with that of the sequential drive, where M is the number of drive channels [3].

When a touch sensor is mounted on or built in a display, the switching operation of the display device injects electrical noise into the touch sensor through the capacitive coupling between the sensor and the display. The noise from the display device has to be reduced so as not to degrade the high SNR attained with the use of the parallel drive method. Although the noise from the display device is very strong, it is commonly injected to adjacent sensor channels in most cases. A novel differential sensing scheme is applied to cancel the strong common mode noise. Original capacitance signals with the common-mode noise rejected are recovered by summing up the differential signals.

An analog front-end (AFE) IC capable of driving and sensing a 143 × 81 mutual-capacitance sensor is developed in 0.18 μm 1P5M CMOS. A 32-in system and a 70-in touch system are realized with the use of the AFE and an SNR over 37 dB for 1 mm diameter stylus is attained in either system.

This paper is organized as follows. Section II describes the comparison between the parallel drive method and the conventional sequential drive. Real LCD noise and the effect of differential sensing are studied in Section III. The details of the differential sensing scheme and the AFE IC design are introduced in Section IV, and the implementations of the 32-in system and the 70-in system are described in Section V. The performance evaluation of the IC and the systems and the comparison with the state of the art are presented in Section VI. Finally Section VII summarizes the work as a conclusion.

II. Sequential Drive Versus Parallel Drive

A. Sequential Drive Method

The sequential drive method commonly adopted in conventional touch systems is modeled as shown in Fig. 1(a). Since the signal from each drive channel is only read once per scan of all of the drive channels, the SNR degrades as the total number of drive channels increases provided that the cycle time of drive and sense operation is constant, where SNR is defined as the ratio between the signal strength of a touch and the noise in the touch signal. One common way to overcome this drawback is to increase the driving voltage, which however results in the increase of the system complexity and cost because it requires high-voltage circuits and devices.

B. Parallel Drive Method

This SNR issue is resolved by driving the sensor channels in parallel as shown in Fig. 1(b). Although the parallel drive mixes up the signals from the multiple channels driven at the same time, the original signals can be reconstructed from the sequence of mixed signal if the drive sequences are linearly independent each other. For example, if the parallel drive sequences are made up of $+1$ and -1, and orthogonal to each other, then the SNR is enhanced by $\sqrt{\mathrm{M}}$ times compared with that of the sequential drive as described in Appendix A, where M is the number of

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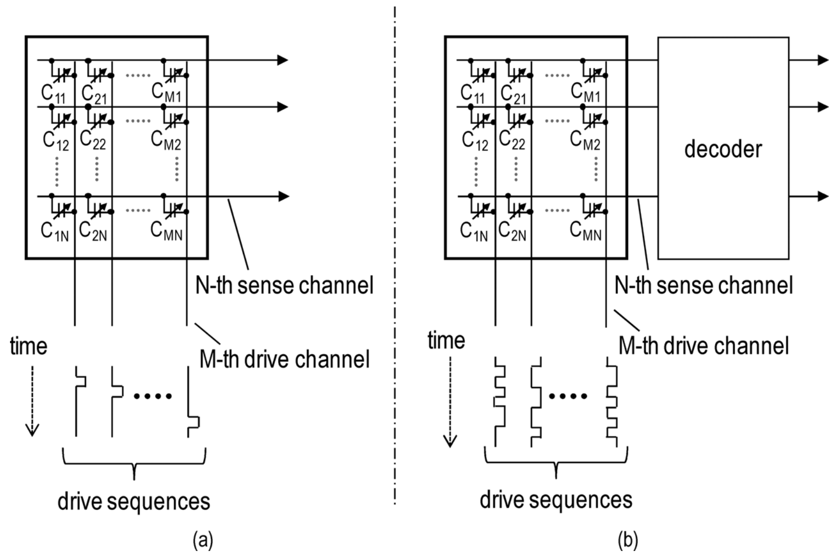


Fig. 1. Comparison of the drive methods. (a) Sequential drive. (b) Parallel drive (modified from [1]).

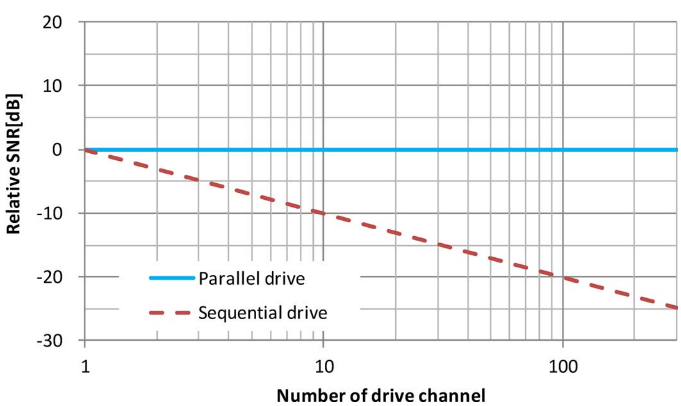


Fig. 2. Relationships between the SNR and the number of drive channels.

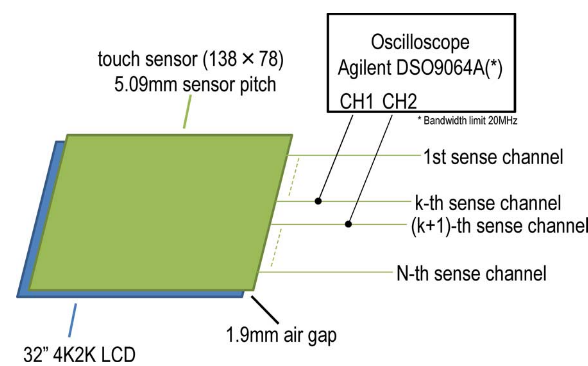


Fig. 3. Noise measurement method of adjacent sense channels.

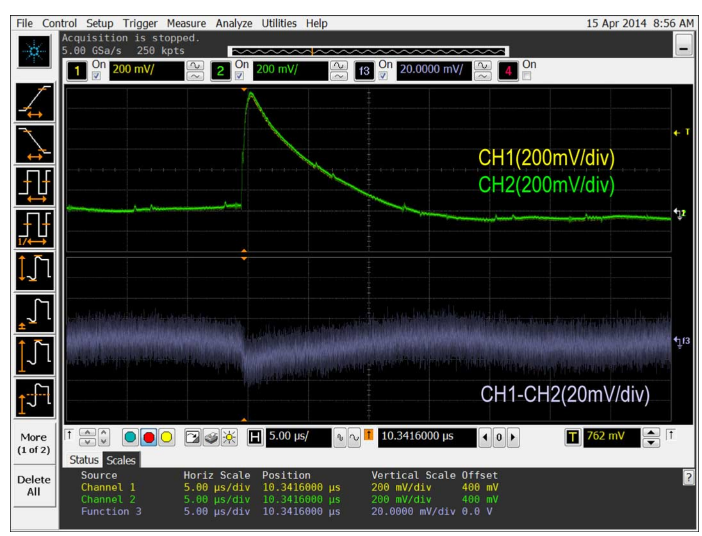


Fig. 4. Measured noise waveforms of adjacent sense channels.

drive channels. Simulated relationships between the SNR and the number of drive channels for both the sequential drive and the parallel drive are compared in Fig. 2.

III. LCD Noise and Fully Differential Sensing Scheme

A. LCD Noise

The switching operation of a flat panel display device injects noise into the touch sensor paired with the display. An experiment to measure the noise coupling is carried out with a 32-in touch sensor mounted on a 32-in LCD, as shown in Fig. 3. Outputs from two adjacent channels of the sensor are probed and connected to two channels of an oscilloscope. As the waveforms of CH1 and CH2 in Fig. 4 show, the noise coupling is so strong that the resulted voltage swing is over 1 V. However, the two waveforms are almost identical and the difference of them is around ± 20 mV, as shown in Fig. 4, because the LCD noise is commonly injected to the adjacent channels. This common mode noise rejection can be realized in mutual capacitance touch sensing systems effectively by employing a fully differential sensing scheme described in the following.

B. Single-Ended Versus Differential

The differential sensing has further advantages compared to single-ended sensing. The configurations of the single-ended sensing and the differential sensing are shown in Fig. 5, where

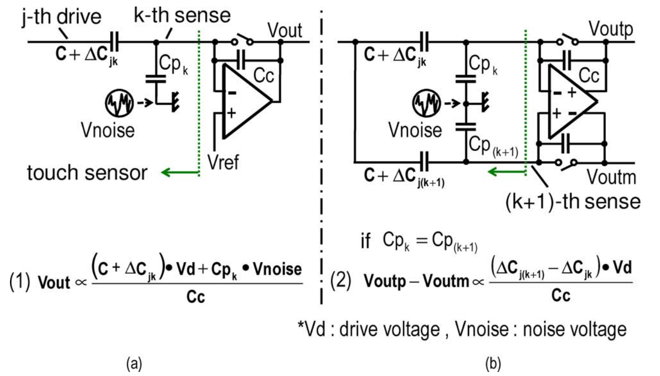


Fig. 5. Comparison of the sensing methods. (a) Single-ended. (b) Differential.

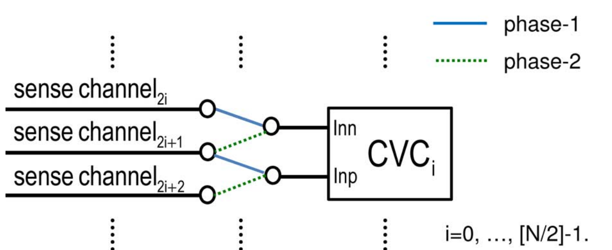


Fig. 6. Fully differential sensing scheme with a time-interleaving operation.

C is the mutual capacitance between a sense channel and a drive channel, $\Delta\mathrm{C}$ is the capacitance change signal induced by a touch operation, Cp is the parasitic capacitance of the sensor channel to the ground, Cc is the feedback capacitance of the charge integrator, Vd is the drive voltage, and Vnoise is the external noise voltage, respectively. The output voltage level of the single-ended sensing is given by

$$\mathrm{Vout} \propto \frac{(\mathrm{C} + \Delta\mathrm{C_{jk}})\,\mathrm{Vd} + \mathrm{Cp_k Vnoise}}{\mathrm{C_c}}. \tag{1}$$

In the differential sensing, the LCD noise commonly injected to adjacent channels can be drastically reduced since the parasitic capacitances $\mathrm{Cp_k}$ and $\mathrm{Cp_{(k+1)}}$ of two adjacent channels are almost the same. Furthermore the output voltage level is far lower than that of the single-ended sensing, because C and Vnoise appearing in (1) are cancelled such that

$$(\mathrm{Voutp} - \mathrm{Voutm}) \propto \frac{\left(\Delta\mathrm{C_{j(k+1)}} - \Delta\mathrm{C_{jk}}\right)\mathrm{Vd}}{\mathrm{C_c}}. \tag{2}$$

This enables the touch sensing systems to boost the signal gain effectively. As a result, the weak capacitance change signal can be detected and the higher SNR is obtained with the differential sensing. This gain boost is not easy to realize with a dual single-ended sensing followed by a differential circuits proposed in [4].

C. Fully Differential Sensing Scheme

A fully differential sensing scheme with a time interleaving operation is invented to obtain the difference in signals for all pairs of adjacent channels consistently. The scheme consists of $[\mathrm{N}/2]$ units of charge-to-voltage converter (CVC) for N sense channels and has two phase operations as described in Fig. 6, where $[\mathrm{x}]$ represents the integer part of x. In phase-1, the $(2\mathrm{i}+1)$th and the $2\mathrm{i}$th sense channel are connected to the Inp node and Inn node of the ith CVC respectively, while in phase-2 the $(2\mathrm{i}+2)$th and the $(2\mathrm{i}+1)$th sense channel are connected to the Inp node and Inn node of the ith CVC, respectively, where $\mathrm{i} = 0, \ldots, [\mathrm{N}/2] - 1$.

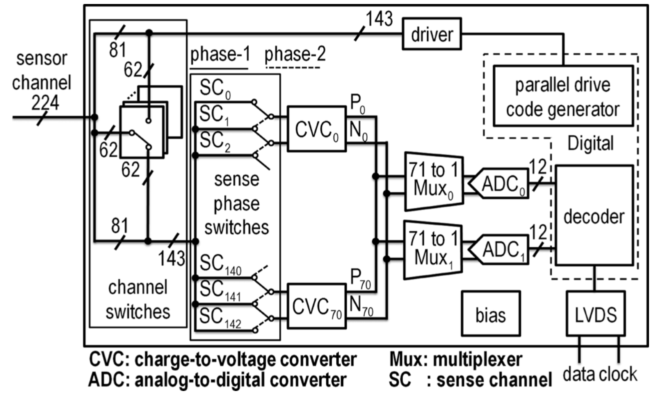


Fig. 7. Block diagram of the AFE IC (modified from [1]).

IV. AFE IC Design

The AFE has 224 sensor channel connections, 143 channel drivers with 3.3 V drive voltage, and 71 CVCs. Using the channel switches shown in Fig. 7, the first 81 channels are connected to the drivers, each of the next 62 channels is connected to either a driver or a CVC via a switch, and the last 81 channels are connected to CVCs. Each phase of the CVCs is designed to settle in 2 μs, if the *RC* time constant of an accompanied touch sensor is sufficiently small. The output voltage signals are transferred from the CVCs to the dual 12 b 20 MHz pipeline ADCs through two multiplexers, where ADCs take 1.8 μs (= 36 × 1/20 MHz) to convert all of the signals from 71 CVCs. A capacitance distribution of a touch sensor (= a capacitance frame) is reconstructed in the decoder with a linear algebra algorithm described in Appendix A and then transferred to the following digital back-end (DBE) circuitry through a 200 MHz low-voltage differential signaling (LVDS) interface. The reconstruction calculation of 143 × 81 mutual capacitances takes $\mathrm{L}\times 4\ \mu$s, where L is the length of the parallel drive sequences. The DBE is an image signal processor that filters out unwanted noise, finds peaks in the capacitance distribution, calculates properties of touches such as position and strength by locally integrating the capacitance frame around the peaks, and manages the consistency of the touch identifications. LVDS is selected to ensure reliable data transmission between AFE and DBE through long wiring up to 3 m for large format applications. The supply voltages of the analog circuit block and digital circuit block are 3.3 and 1.8 V, respectively.

Fig. 8 shows the schematic of a CVC block and its operation. The first stage is a charge integrator with switchable feedback capacitances. The next stage is a correlated double sampler (CDS) to cancel the dc offset and low-frequency noise. The charge integrator is reset by closing the switches (SW_CI) which are connected between the inputs and the outputs of the amplifier while a charge integrator reset signal (RESET_CI) is high level. The CDS is also reset in the same way while a CDS reset signal (RESET_CDS) is high level. After resetting

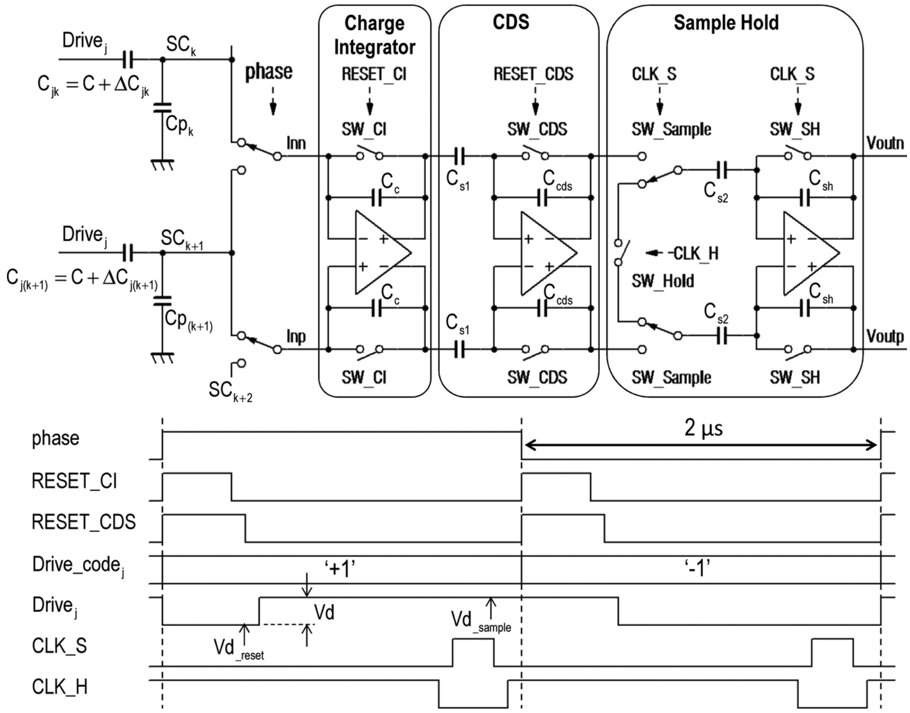


Fig. 8. Schematic of the CVC (modified from [1]).

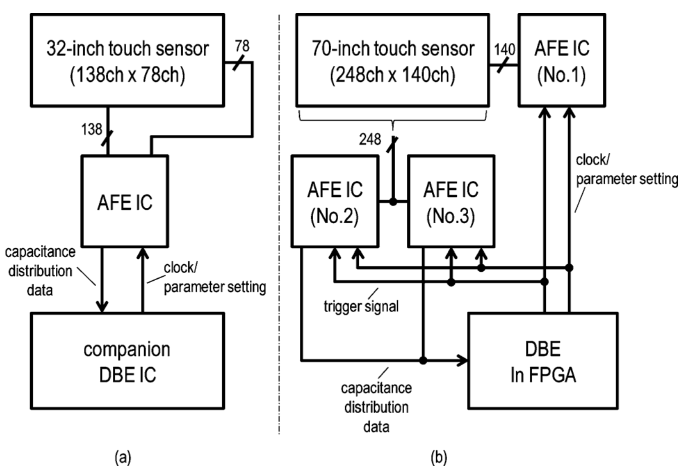


Fig. 9. Application block diagrams: (a) 32-in application system and (b) 70-in application system [1].

TABLE I
SYSTEM CONFIGURATION

Size [inch]	32	70
Number of channels	138ch × 78ch	248ch × 140ch
Analog front-end	1 AFE IC	3 AFE ICs
Digital back-end	1 DBE IC	1 DBE (in FPGA)
Sensor channel pitch [mm]	5.09	6.25
Cover glass thickness [mm]	1.80	1.90
air gap [mm]	1.90	3.24
LCD type	4K2K	Full HD

the charge integrator and the CDS, the drive channel is driven from low level to high level when the drive code is $+1$. If the drive code is -1, the drive channel is driven from high level to low level. The third stage is a sample-and-hold circuit to feed the differential signal to the ADCs. The sample-and-hold circuit samples the output of CDS while a sample signal (CLK_S) is high level. In addition, it holds the signal level when the hold signal (CLK_H) is at a high level. The cycle time of the drive and sense operation in one phase is 2 μs in this example.

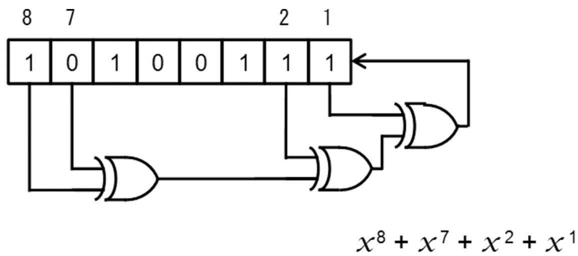
The output voltage level of CVC is given by (3)–(5), shown at the bottom of the page, where $\mathrm{Vd}_{\mathrm{\_sample}}$ is the voltage of drive channel at sampling and $\mathrm{Vd}_{\mathrm{\_reset}}$ is the voltage of drive channel at resetting as shown in Fig. 8.

Since the parasitic capacitances $\mathrm{Cp_k}$ and $\mathrm{Cp_{(k+1)}}$ are much larger than the mutual capacitances $\mathrm{C_{jk}}$ and $\mathrm{C_{j(k+1)}}$ in typical large-format touch systems, $\mathrm{Voffset}$ becomes small, and the terms of parasitic capacitances in (3) can be ignored. Even if this

$$\mathrm{Vout} = \frac{\left(\Delta \mathrm{C_{j(k+1)}} - \Delta \mathrm{C_{jk}}\right)(\mathrm{Vd} - \mathrm{Voffset}) - \left(\mathrm{Cp_{(k+1)}} - \mathrm{Cp_k}\right)\mathrm{Voffset}}{\mathrm{C_c}} \cdot \frac{\mathrm{C_{cds}}}{\mathrm{C_{s1}}} \cdot \frac{\mathrm{C_{sh}}}{\mathrm{C_{s2}}} \tag{3}$$

$$\mathrm{Voffset} = \frac{\mathrm{C_{jk}} + \mathrm{C_{j(k+1)}}}{\mathrm{C_{jk}} + \mathrm{C_{j(k+1)}} + \mathrm{Cp_k} + \mathrm{Cp_{(k+1)}} + 2\mathrm{C_c}} \mathrm{Vd} \tag{4}$$

$$\mathrm{Vd} = \mathrm{Vd_{\_sample}} - \mathrm{Vd_{\_reset}} \tag{5}$$



(a)

```
Bit#(size_r) mtap = 'hc3;
mseq <= truncate({mseq ,^(mseq & zeroExtend(mtap))});
```

(b)

MSB (bit 255)

```
1 1 1 0 0 0 0 0 0 0 1 1 0 1 1 0 1 0 1 0 0 0 1 0 0 1 0 1 1 1 1 0
0 1 0 1 1 0 0 0 1 0 0 0 1 1 0 0 1 1 0 0 0 1 1 1 0 0 0 0 1 1 0 0
0 0 0 1 1 1 0 1 1 0 0 0 0 1 0 1 0 1 1 0 0 1 0 0 1 1 1 0 0 1 1 1
0 1 0 1 0 1 1 1 1 1 1 1 1 0 1 1 0 1 1 0 0 1 1 1 1 0 0 0 1 1 0 1
0 1 1 1 0 0 1 0 0 0 0 1 1 1 1 0 1 1 1 0 1 1 1 1 0 1 0 0 0 0 0 1
0 0 0 0 0 0 1 0 1 1 0 1 1 1 1 1 0 0 1 1 0 1 1 1 0 0 0 1 0 1 1 1
0 1 0 0 1 1 0 0 1 0 1 0 1 0 1 0 0 1 0 0 1 0 0 0 1 0 1 0 0 0 0 1
0 0 1 1 0 1 0 0 0 1 1 1 1 1 0 1 0 1 1 0 1 0 0 1 0 1 0 0 1 1 1
```

LSB (bit 1)

(c)

Fig. 10. MLS example with a code length of 255 using an LFSR. (a) An 8-bit Fibonacci LFSR and the feedback polynomial. (b) Example code of the MLS generator using Bluespec SystemVerilog. (c) MLS generated by the code.

is not the case, the effect of parasitic capacitances result in constant shifts on sense channels in a capacitance frame and can be compensated in the DBE.

V. Implementation of 32-in and 70-in Systems

Two large application systems shown in Fig. 9 are built with the use of the AFE and a 7 μm thickness copper mesh sensor technology. Copper mesh technology is suited for the realization of capacitive touch sensors having large formats and small time constants at the same time. The sheet resistance of the 7 μm thickness copper is less than 0.003 Ω/square, which is smaller than that of ordinary ITO by four orders. The 32-inch system is built up from one AFE, a companion DBE IC, 5.09 mm channel pitch 138 × 78 metal mesh sensor laminated to a 1.8 mm thickness cover glass, and mounted on a 4K2K LCD with 1.9 mm air gap. The 70-in system is built up from three AFEs, a DBE implemented in an FPGA, 6.25 mm channel pitch 248 × 140 metal mesh sensor laminated to a 1.9 mm thickness cover glass, and mounted on a full HD LCD with 3.24 mm air gap. The drive and sense operations of the three AFE are synchronized with a trigger signal generated in the DBE as described in Fig. 9(b). The specifications of the 32-in and the 70-in systems are summarized in Table I. The air gap is designed so that the cover glass does not touch the LCD surface when deformed by self-weight and human touches. The width of the copper mesh is designed to be 7 $\mu\mathrm{m}$, which is narrow enough to reduce the unwanted visual effects caused by stacking the mesh sensors on the LCDs. The width of the lines and spaces in the edge region for addressing the sensor channels are 20 and 60 μm, respectively, where the address wirings are placed in one edge of each drive and sense channels. The resistance of the longest channel of the 70-in touch sensor is less than 300 Ω, which is sufficiently low for the AFE to operate at its highest frequency.

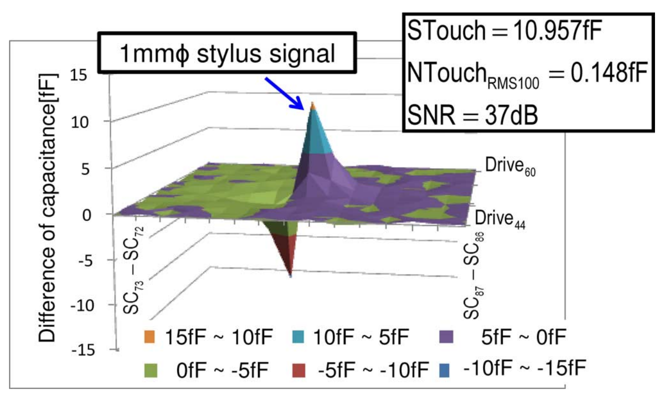


Fig. 11. Touch signal of a 1 mm diameter stylus (modified from [1]).

In both systems, a maximum length sequence (MLS) [5] with a code length of 255 is used for the parallel drive sequences. Therefore, the cycle time to construct one capacitance frame is 1.02 ms (= 255 × 2 μs × 2 phase). MLS is selected because it not only makes the drive sequences pseudo orthogonal but also has randomness preferred for spread spectrum. The meaning of "pseudo orthogonal" is described at the end of Appendix A. MLSs can be generated by using a linear feedback shift register

TABLE II
SPECIFICATION AND PERFORMANCE SUMMARY (MODIFIED FROM [1])

		[4]	[2]	This work			
Size[inch]		10.1	5	**32**		**70**	
Number of channels		27ch (Tx) × 43ch(Rx)	30ch(Tx) × 24ch(Rx)	**78ch(Tx) × 138ch(Rx)**		**140ch(Tx) × 248ch(Rx)**	
Mode		undescribed	High SNR (CDMS DS-SC)	Slow	Normal	Slow	Normal
Reporting rate[Hz]		120	240	120	240	120	240
SNR[dB]	Finger	39	55	**50.8**	**56.6**	**47.5**	56.2
	Pen (1mmΦ)	undescribed	35	**31.6**	**37.4**	**31.5**	**37.7**
Process		0.35μm CMOS	2P6M 0.18μm CMOS EEPROM	1P5M 0.18μm CMOS			
Power consumption	Total [mW]	18.7	52.8	214.7	559.9	562.8	1247.0
	Per node [uW/node]	16.1	73.3	19.9	**52.0**	**16.2**	**35.9**
Supply voltage		3.3V	3.3V	3.3V, 1.8V			
Die size		4mm × 4mm	4.06mm × 3.66mm	7.55mm × 9.43mm			

(LFSR). For example, an MLS with a code length of 255 is derived from polynomial $(x^8 + x^7 + x^2 + x^1)$, as shown in Fig. 10. According to the MLS, the parallel drive sequence is obtained such that $+1$ and -1 of the sequence correspond to 1 and 0 of the MLS, respectively.

VI. MEASUREMENT RESULTS

Fig. 11 shows the capacitance change induced by a touch of 1 mm diameter stylus on the 32-in system, where the peak signal is around 10 fF with 37.4 dB SNR. The SNR [6] is defined as follows (see Appendix B):

$$\mathrm{SNR\,(dB)} = 20\log\frac{\mathrm{STouch}}{\mathrm{NTouch}_{\mathrm{RMS100}}}. \tag{6}$$

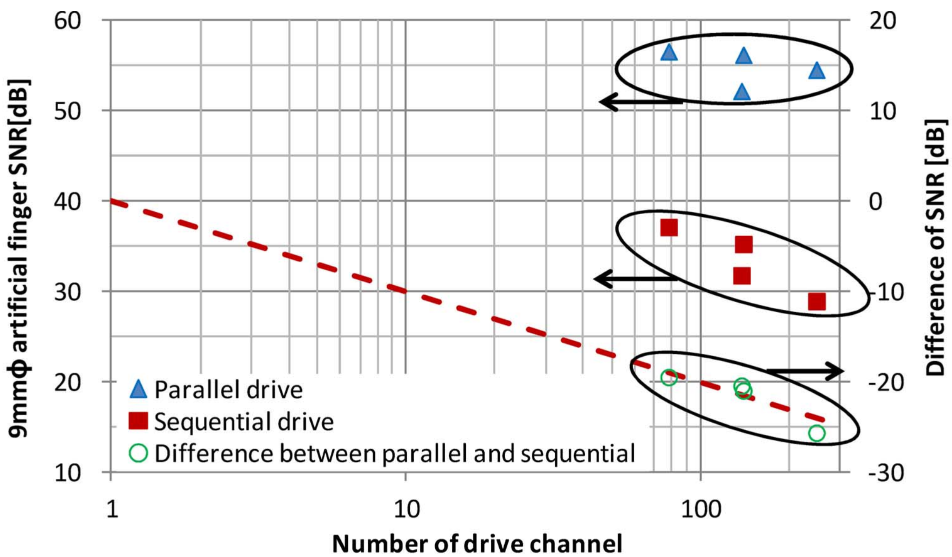
Specifications and measurement results are compared with the state of the art [2], [4] in Table II, where all of the SNRs of this work are measured while the LCD is displaying white image and the touch objects are electrically connected to the system ground. A series of SNR measurements were carried out for raw data coming out from the decoder without any digital filtering. In the normal mode four capacitance frames are summed to obtain enough SNR and the reporting rate is 240 Hz; however, one capacitance frame without summation is reported at 120 Hz in the slow mode aiming to reduce the power consumption. The SNR in the normal mode is higher than the one in the slow mode by around 6 dB as expected. The number of channels of this work is the largest reported and the SNRs for 1 mm diameter stylus and 9 mm diameter artificial finger are the highest. The power consumption per node (= total power consumption divided by the total number of mutual capacitances) is near the lowest. The independence of the SNRs from the number of the channels is the result of adopting the parallel drive method. Thanks to the differential sensing, the dependence of SNRs on the LCD on/off status is less than 2 dB.

Fig. 12 shows the measured SNRs for 9 mm diameter artificial finger for 78, 138, 140, and 248 drive channels. The data for 78 and 138 channels are obtained with the 32-in 138 × 78 sensor by swapping the connections of drive channels and sense channels, and the data for 140 and 248 channels are obtained with the 70-in 248 × 140 sensor in the same way. The data for the sequential drive are obtained by changing the drive sequences to the ones shown in Fig. 1(a). The SNRs for the parallel drive stay almost constant regardless of the total number of drive channels, and the SNR differences between the parallel drive and the sequential drive are on a line as expected in Fig. 2.

Fig. 13 shows the micrograph of the AFE. The die size is 7.55×9.43 mm^2 including 0.2 mm scribe line. It is assembled in an 18×18 mm^2 ball grid array (BGA) package with 364 balls.

VII. CONCLUSION

A parallel drive method is introduced to realize large-format mutual capacitance touch-sensing systems with high sensitivity. The SNR of the parallel drive system stays at a higher level independent of the number of the drive channels compared to the conventional sequential drive system whose SNR degrades as the number of the drive channels increases. A fully differential sensing scheme is also introduced to realize a strong immunity against the noise from coupled LCDs, which cancels out the noise commonly injected to the adjacent sense channels. A



Drive method	Size[inch]	Number of channels		Code length	Number of frames	Scan time[ms]
		Sense	Drive			
Parallel	32	138	78	255	4	4.080
		78	138	255	4	4.080
	70	248	140	255	4	4.080
		140	248	255	4	4.080
Sequential	32	138	78	78	16	4.992
		78	138	138	8	4.416
	70	248	140	140	8	4.480
		140	248	248	4	3.968

Fig. 12. SNR comparison between the parallel drive and the sequential drive.

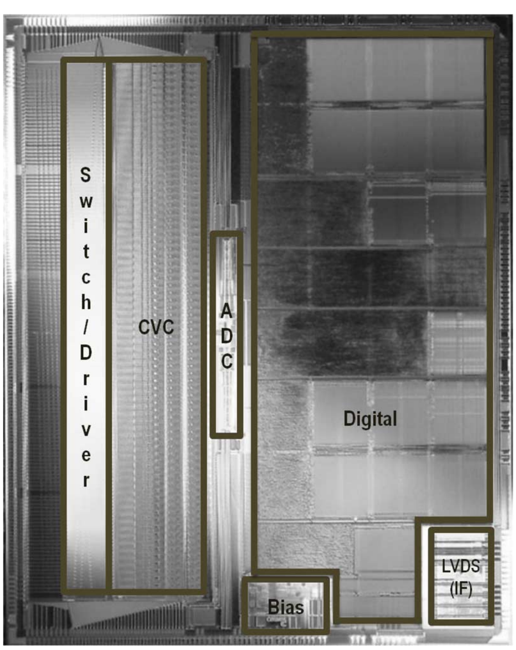


Fig. 13. Die micrograph of the AFE [1].

224-channel AFE IC incorporating these two techniques with 3.3 V drive voltage is developed in 0.18 μm CMOS. A 32-in touch sensing system and a 70-in one are realized with the use of the AFE and a 7 μm thickness copper mesh sensor technology. The 32-inch system is built up from one AFE, a companion DBE IC, 5.09 mm channel pitch 138 × 78 metal mesh sensor laminated to a 1.8 mm thickness cover glass, and mounted on a 4K2K LCD with 1.9 mm air gap. The 70-in system is built up from three AFEs, a DBE implemented in an FPGA, 6.25 mm channel pitch 248 × 140 metal mesh sensor laminated to a 1.9 mm thickness cover glass, and mounted on a full HD LCD with 3.24 mm air gap. Although the numbers of the drive channels of the systems are different: 78 and 140, respectively, the measurement results under the noise injection from the coupled LCDs shows that they both have the same 37 dB SNR as expected for 1 mm diameter stylus at 240 Hz reporting rate.

APPENDIX A

Let $\mathbf{V_i} = (\mathrm{V_{i1}}, \ldots, \mathrm{V_{iL}})$ be the drive sequence of the ith drive channel, where L is the length of the drive cycle, $\mathrm{i} = 1, \ldots, \mathrm{M}$, and M is the number of drive channels.

The parallel drive sequences are assumed to be orthogonal and to have inner products:

$$(\mathbf{V_i}, \mathbf{V_l}) = \sum_{k=1}^{L} \mathrm{V_{ik}} \mathrm{V_{lk}} = \mathrm{L}\delta_{\mathrm{il}}$$

where

$$\delta_{\mathrm{il}} = 1, \qquad \text{if } \mathrm{i} = \mathrm{l}$$
$$= 0. \qquad \text{otherwise.}$$

The output signal sequence $\mathbf{S_j} = (\mathrm{S_{j1}}, \ldots, \mathrm{S_{jL}})$ from jth sense channel is assumed to be a linear combination of $\mathbf{V_i}$ and expressed as

$$\mathbf{S_j} = \sum_{i=1}^{M} \mathrm{C_{ij}} \mathbf{V_i},$$

where $\mathrm{C_{ij}}$ is the mutual capacitance between ith drive channel and jth sense channel, $\mathrm{j} = 1, \ldots, \mathrm{N}$, and N is the number of sense channels.

By calculating the inner product of $\mathbf{S_j}$ and $\mathbf{V_l}$, the original capacitance signal $\mathrm{C_{lj}}$ is reconstructed with its amplitude multiplied L times as follows:

$$\begin{aligned}(\mathbf{S_j}, \mathbf{V_l}) &= \left(\sum_{i=1}^{M} \mathrm{C_{ij}} \mathbf{V_i}, \mathbf{V_l}\right)\\ &= \sum_{i=1}^{M} \mathrm{C_{ij}} (\mathbf{V_i}, \mathbf{V_l})\\ &= \sum_{i=1}^{M} \mathrm{C_{ij}} \mathrm{L} \delta_{il}\\ &= \mathrm{C_{lj}} \mathrm{L}.\end{aligned}$$

This signal of the parallel drive is M times greater than the signal of the sequential drive obtained in L drive length which is expressed as $\mathrm{C_{lj}L/M}$, because the signal $\mathrm{C_{lj}}$ is read out once per a scan cycle M. The SNR is enhanced $\sqrt{\mathrm{M}}$ times since the noise is also enhanced $\sqrt{\mathrm{M}}$ times.

When the drive sequences are made up from an MLS code by a cyclic shift, they become pseudo orthogonal each other and have inner products:

$$(\mathbf{V_i}, \mathbf{V_l}) = \sum_{k=1}^{L} \mathrm{V_{ik}} \mathrm{V_{lk}} = \mathrm{L} \delta_{il}$$

where

$$\begin{aligned}\delta_{il} &= 1, \qquad \text{if } i = l\\ &= -\frac{1}{L}, \qquad \text{otherwise.}\end{aligned}$$

APPENDIX B

The SNR is defined as follows [6]:

$$\mathrm{SNR\,(dB)} = 20\log \frac{\mathrm{STouch}}{\mathrm{NTouch_{RMS100}}},$$

$$\mathrm{STouch} = \mathrm{Signal_{Touch,AVG100}} - \mathrm{Signal_{Untouch,AVG100}},$$

$$\mathrm{Signal_{Touch,AVG100}} = \frac{\sum_{n=0}^{99} \mathrm{Signal_{Touch}}[n]}{100},$$

$$\mathrm{Signal_{Untouch,AVG100}} = \frac{\sum_{n=0}^{99} \mathrm{Signal_{Untouch}}[n]}{100},$$

$$\mathrm{NTouch_{RMS100}} = \sqrt{\frac{\sum_{n=0}^{99} \left(\mathrm{Signal_{Touch}}[n] - \mathrm{Signal_{Touch,AVG100}}\right)^2}{100}},$$

where $\mathrm{Signal_{Touch}}[n]$ is the touch signal level and $\mathrm{Signal_{Untouch}}[n]$ is the untouched signal level.

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REFERENCES

[1] M. Hamaguchi, A. Nagao, and M. Miyamoto, "A 240 Hz-reporting-rate 143 × 81 mutual-capacitance touch-sensing analog front-end IC with 37 dB SNR for 1 mm-diameter stylus," in *IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers*, Feb. 2014, pp. 214–214.

[2] H. Shin, S. Ko, H. Jang, I. Yun, and K. Lee, "A 55 dB SNR with 240 Hz frame scan rate mutual capacitor 30 × 24 touch-screen panel read-out IC using code-division multiple sensing technique," in *IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers*, Feb. 2013, pp. 388–389.

[3] M. Miyamoto, "Linear Device Value Estimating Method, Capacitance Detection Method, Integrated Circuit, Touch Sensor System, and Electronic Device," Japan Patent 4927216, Feb. 17, 2012.

[4] J.-H. Yang, S.-H. Park, J.-M. Choi, H.-S. Kim, C.-B. Park, S.-T. Ryu, and G.-H. Cho, "A highly noise-immune touch controller using filtered-delta-integration and a charge-interpolation technique for 10.1-inch capacitive touch-screen panels," in *IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers*, Feb. 2013, pp. 390–391.

[5] G. D. Forney, "Coding and its application in space communications," *IEEE Spectrum*, vol. 7, pp. 47–58, Jun. 1970.

[6] S. Ko, H. Shin, J. Lee, H. Jang, B.-C. So, I. Yun, and K. Lee, "Low noise capacitive sensor for multi-touch mobile handset's applications," in *Proc. IEEE Asian Solid-State Circuits Conf.*, Nov. 2010, pp. 1–4.

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