Touch sensor readout circuit with comparator threshold self-adjustment

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Abstract: This work describes a capacitive type touch sensor readout circuit using a current based capacitance-to-time converter with comparator threshold level self-adjustment. The proposed circuit generates an output pulse with duty-cycle corresponding to the panel capacitance variation using a simple switch control block, a current generator, and a comparator. This does not require additional amplifiers and passive capacitors/resistors. As a result, the proposed scheme can lead to small size and low power on-chip solution with fast detection time compared to conventional touch sensor readout circuits. Furthermore, due to the comparator threshold level self-adjustment, the readout circuit is less sensitive to component mismatch and process variations. The readout circuit is implemented using CMOS 0.35 µm technology with core area of 100 µm × 27 µm and power consumption of 52 µW, which can detect the touch panel capacitance ranging from 5 pF to 50 pF.

Keywords: capacitance-to-time converter, capacitive type touch sensor, comparator threshold level self-adjustment, smart user interface

Classification: Integrated circuits

References

[1] H.-K. Kim, \textit{et al.}: “Capacitive tactile sensor array for touch screen application,” Sens. Actuators A Phys. 165 (2011) 2 (DOI: 10.1016/j.sna.2009.12.031).
[2] J. H. Yang, \textit{et al.}: “A novel readout IC with high noise immunity for charge-based touch screen panels,” IEEE Custom Integrated Circuits Conference (2010) 1 (DOI: 10.1109/CICC.2010.5617378).
[3] H.-R. Kim, \textit{et al.}: “A mobile-display-driver IC embedding a capacitive-touch-screen controller system,” IEEE International Solid-State Circuits Conference Digest of Technical Papers (2010) 114 (DOI: 10.1109/ISSCC.2010.5434080).
[4] S. Ko, \textit{et al.}: “Low noise capacitive sensor for multi-touch mobile handset’s applications,” Solid State Circuits Conference (2010) 1 (DOI: 10.1109/ASSCC.2010.5716570).
[5] H. Park, \textit{et al.}: “Low power multi-channel capacitive touch sensing unit using capacitor to time conversion method,” IEEE International Symposium on
1 Introduction

Due to the user friendly interface, touch screens and touch panels will continuously serve as the key component for future smart user interface. Until now, the low cost resistive type touch panels have been widely used, however the capacitive type touch panels are becoming the main stream [1]. In order to incorporate the multi-touch feature even with large-sized display panels, touch sensors with small area, low power, improved accuracy, and fast detection time are highly demanding. The capacitive type touch panels require sensor readout circuits that can effectively detect the touch panel capacitance variation. Conventional capacitive type touch sensor readout circuits are based on capacitive charge transfer [2, 3, 4] or capacitance-to-time (C-to-T) conversion [5]. Charge transfer schemes require huge off-chip capacitors that limit the on-chip implementation and require longer detection time. In contrast, current based touch sensor readout circuits similar to [6] can enable small area, low power, and fast detection time. However, current based circuits are sensitive to component mismatch and process variation which requires a compensation scheme.

In this paper, a current based touch sensor readout circuit with comparator threshold self-adjustment is proposed. This scheme can lead to a small area, low power, fast detection time with extended capacitance detection range compared to the conventional capacitive-type touch sensor readout circuits. The paper is organized as follows: The capacitive touch panel is explained in Section II. The proposed touch sensor readout circuit is shown in Section III. Circuit implementation and experimental results are addressed in Section IV and V. The conclusions are given in Section IV.

2 Capacitive type touch panels

A capacitive type touch panel consists of an insulator (glass plate) that is coated by a conductive material such as ITO (indium tin oxide). When a human finger approaches the panel surface, the distortion of the screen’s electrostatic field

References

[6] T. Singh, et al.: “Current-mode capacitive sensor interface circuit with single-ended to differential output capability,” IEEE Trans. Instrum. Meas. 58 (2009) 3914 (DOI: 10.1109/TIM.2009.2021241).
[7] J. M. Steininger: “Understanding wide-band MOS transistors,” IEEE Circuits Devices Mag. 6 (1990) 26 (DOI: 10.1109/101.55332).
[8] P. Gray and R. Meyer: Analysis and Design of Analog Integrated Circuits (John Wiley & Sons, New York, 1993) 3rd ed.
[9] Data Sheet, Quantum Research Group, QProx™ QT113, charge-transfer touch sensor.
[10] K. Ueno, et al.: “A 300 nW, 15 ppm/°C, 20 ppm/V CMOS voltage reference circuit consisting of subthreshold MOSFETs,” IEEE J. Solid-State Circuits 44 (2009) 2047 (DOI: 10.1109/JSSC.2009.2021922).
[11] B. Liu, et al.: “On-chip touch sensor readout circuit using passive sigma-delta modulator capacitance-to-digital converter,” IEEE Sensors J. 15 (2015) 3893 (DOI: 10.1109/JSEN.2015.2403132).
changes the capacitance between the sensing electrodes as shown in Fig. 1(a). The most common capacitive type touch panels nowadays is the projected capacitance type. The projected capacitance touch (PCT) technology detects the touch by measuring the capacitance at each addressable electrode. Once the finger approaches an electrode, it disturbs the electromagnetic field and alters the capacitance. This capacitance variation can be measured by the readout circuits, and then converted into the corresponding X-Y coordinates so that the system can detect the touch. The value of the capacitance at each coordinate can vary from 10 pF to 50 pF. PCT panels can be divide into self-capacitance and mutual capacitance type touch panels where the electrode arrangements and the equivalent circuits are shown in Fig. 1(b).

3 Proposed touch sensor readout circuit

3.1 Sensor readout block

Fig. 2 shows the block diagram of the proposed touch sensor. The proposed scheme is based on the capacitance-to-time conversion where the readout circuit includes a reference current, voltage generator, switch control block, and comparator. In
addition, \( C_p \) represents the panel capacitance where the value changes between the touched and the un-touched panel condition. Two switches \( S_1 \) and \( S_2 \) control the detection and the reset operation. In the detection phase when \( CLK \) is low, \( S_1 \) is on and \( S_2 \) off, hence \( I_{REF} \) is injected into \( C_p \). During the reset phase when \( CLK \) is high, \( S_2 \) prepares the readout circuit for the next detection phase by discharging \( C_p \). However, in the proposed scheme instead of sampling a voltage in \( C_p \), a DC current \( I_{REF} \) is directly injected to \( C_p \) and detects its variation by checking the capacitor voltage \( V_{CAP} \). The level of \( V_{CAP} \) will be different for the touched and the un-touched scenario. As the comparator compares \( V_{CAP} \) with a threshold level \( V_{TH} \), it generates an output pulse \( V_{comp} \) that remains high until \( C_p \) discharges in the next reset phase. During the detection phase, the comparator output becomes high for both the touched and the un-touched cases, but with different pulse width denoted as \( \Delta T \) (shown in Fig. 2). Since the comparator output level changes when the capacitor voltage \( V_{CAP} \) reaches the comparator threshold level \( V_{TH} \), the interval for \( V_{comp} = \text{low} \) can be described as:

\[
T_C = \frac{C_p V_{TH}}{I_{REF}}. \tag{1}
\]

Assuming the discharging time of \( C_p \) is negligible compared to the charging time, the \( V_{comp} \) pulse width for the touched and the un-touched case is expressed as:

\[
\Delta T = \frac{T}{2} - T_C \tag{2}
\]

where \( T \) is the period of \( CLK \) which has a 50% duty cycle.
Using a bandgap voltage reference to generate $V_{TH}$ does not guarantee insensitivity to process variations. For instance, under a certain process corner where $V_{TH}$ increases and $I_{REF}$ decreases, the comparator output might not change even when the panel is touched or un-touched. As shown in Eq. (2), $\Delta T$ depends on the ratio of $V_{TH}$ to $I_{REF}$. Therefore, the proposed approach generates $V_{TH}$ and $I_{REF}$ so that they vary in the same direction (either increase or decrease) under different process corners so that $\Delta T$ becomes less sensitive to process variations.

### 3.2 Sensor readout circuit

Fig. 3 shows the proposed touch sensor readout circuit which consists of the switch control block ($M_{12}$ and $M_{13}$), current mirror ($M_{14}$ and $M_{15}$), reference current $I_{REF}$ generator ($M_1 \sim M_3$, $M_8 \sim M_{11}$), and comparator threshold voltage generator ($M_4 \sim M_7$). A CMOS version of the self-biasing Widlar current source is used for the current generator [7]. Conventional current reference circuits use a passive resistor as the bias resistor, whereas the proposed circuit utilizes an NMOS device $M_3$ as a resistor. By biasing $M_3$ with the supply voltage $V_{DD}$, it operates in the triode region. Compared to the passive resistor, an NMOS transistor occupies a very small chip area. Moreover, integrated resistors realized with conventional CMOS technology can have the worst case variation up to $\pm20\%$ which can cause $I_{REF}$ and $V_{TH}$ variation as well. Under process variations, resistor value change can lead to false detection of the touched and un-touched condition. In the proposed circuit the $V_{TH}$ generation block tracks the variations of $I_{REF}$, thus $V_{TH}$ and $I_{REF}$ always change in the same direction under different process corners. In addition, generating the gate bias of $M_3$ does not require any additional biasing branch, since it is biased with $V_{DD}$.

The robustness of the proposed readout circuit to process variation is verified through the following procedure. The reference current $I_{REF}$ can be expressed as:

$$I_{REF} = \frac{V_{GS1} - V_{GS2}}{R_{on,3}}$$  \(3\)

where $R_{on,3}$ is the on-resistance of $M_3$ which operates in the triode region. Assuming $M_3$ operates in the triode region, the on-resistance of $M_3$ is given by [8]:

![Proposed touch sensor readout circuit](image-url)
where $\mu_n C_{ox}$ is the process trans-conductance parameter and $V_{tn3}$ is the threshold voltage of $M_3$. Assuming $(W/L)_2/(W/L)_1 = K$ and neglecting the body effect of $M_2$ and the channel length modulation of the transistors, the reference current can be re-written as:

$$I_{REF} = \frac{2}{R_{on,3}^2 \mu_n C_{ox}} \left( 1 - \frac{1}{\sqrt{K}} \right)^2.$$  \hfill (5)

As a result, the current mainly depends on the value of the bias resistor $R_{on,3}$. By setting $K = 16$ in this design and replacing $R_{on,3}$ with Eq. (4), the reference current is given as:

$$I_{REF} = \frac{9 \mu_n C_{ox} (W/L)_3^2 (V_{DD} - V_{tn3})^2}{8 (W/L)_1}.$$  \hfill (6)

The comparator threshold voltage $V_{TH}$ is generated by $M_4$ $M_5$, $M_6$, and $M_7$, where $M_4$ copies the reference current $I_{REF}$ and $M_5 \sim M_7$ generate the $V_{TH}$ voltage. The basic concept of the $V_{TH}$ generator is to adjust the $V_{TH}$ level depending on the $I_{REF}$ change caused by process variations. Assuming the diode connected transistors $M_5 \sim M_7$ have the same aspect ratio ($W/L$), the comparator threshold voltage can be written as:

$$V_{TH} = V_{DD} - 3 \left[ \frac{2I_{REF}}{\mu_n C_{ox} (W/L)_{5,6,7}} + V_{tn5} \right],$$  \hfill (7)

where $V_{tn5}$ is the threshold voltage of $M_5$ that is equal to the threshold voltage of $M_6$ and $M_7$ (the PMOS bodies are tied to the source). Replacing $I_{REF}$ with Eq. (6), Eq. (7) can be re-written as:

$$V_{TH} = V_{DD} - \frac{9}{2} \left[ \left( \frac{W}{L} \right)_3 (V_{DD} - V_{tn3})^2 + \frac{2}{3} V_{tn5} \right].$$  \hfill (8)

In this case, $V_{TH}$ is only affected by $V_{tn}$ variation of $M_1$ and $M_3$, and are not affected by the transistor parameters $\mu_n C_{ox}$ and $\mu_p C_{ox}$ which is the one reason for insensitivity. Furthermore, noticing $V_{tn3}$ and $V_{tn5}$ will change in the same direction under different process corners, the $V_{tn5}$ term will compensate the $V_{tn3}$ variation, thus adjusting the $V_{TH}$ level depending on the $I_{REF}$ variation. As a result, the insensitivity of $V_{TH}$ to $V_{tn3}$ and $V_{tn5}$ can be obtained by:
where the aspect ratio of $M_5$ should be set such that Eq. (9) is satisfied. For the fast corner (F), $\mu$ increases and $V_{tn}$ decreases which makes $I_{REF}$ increase compared to the typical corner. The voltage reference $V_{TH}$ expressed in Eq. (8) is mainly determined by $V_{in}$, which increases in order to compensation the $I_{REF}$ variation. This will work similar for the slow corner (S), but $I_{REF}$ and $V_{TH}$ will both decrease, compared to the typical corner.

### 3.3 Comparator

Fig. 4 shows the comparator circuit where a two-stage open loop OTA without a compensation network is used. The bias current of the first stage and the second stage is set to $I_{REF}/4$ and $I_{REF}/2$, respectively. The second stage current was doubled, since it requires a larger current to drive the load connected to the comparator output branch. In addition, PMOS is used for the differential input pairs since the range of $V_{TH}$ is below $V_{DD}/2$.

![Fig. 4. Two-stage comparator.](image)

### 4 Circuit implementation

Capacitive type touch panels have a different range of panel capacitance $C_P$ that typically varies between 1 pF to 50 pF [9]. In order to be compatible with various touch panels, the readout circuit design has been focused on extending the detection range. Considering a 10.4” projective touch panel including arrays of $29 \times 21$ touch patterns and a scanning rate of 50 Hz, we set the main clock CLK frequency to 40 kHz. This corresponds to an operation period $T$ of 25 $\mu$s. Considering the minimum and maximum $C_P$ range of 5 to 50 pF, $I_{REF}$ and $V_{TH}$ are set to 3.4 mA and 470 mV, respectively. However, there is a trade-off between the scanning rate and current consumption based on Eq. (1), a higher $I_{REF}$ leads to a faster scanning rate ($a1/T$). However, the 50 Hz scanning rate was chosen because it is fairly higher than the maximum human finger movement frequency which is around 10 Hz.
The proposed circuit is implemented using CMOS 0.35 µm technology (4-metal, 2-poly process) with supply voltage of 3.3 V. Table I lists the size of each transistor used in the readout circuit. In order to improve the matching, transistors’ length $L$ is much larger than the minimum length except $M_{12}$ and $M_{13}$ which are used as switches.

Table I. Readout circuit transistor sizes.

| Transistor | $(W/L)$ [µm/µm] |
|------------|------------------|
| $M_1, M_4$ | (2/4)            |
| $M_2, M_3$ | (32/4)           |
| $M_5, M_6, M_7$ | (0.5/10) |
| $M_8, M_9, M_{10}, M_{11}, M_{14}, M_{15}$ | (4/4) |
| $M_{12}, M_{13}$ | (2/0.35) |

Fig. 5(a) and (b) shows the circuit simulation results for $V_{\text{comp}}$ pulse width $\Delta T$ versus the panel capacitance $C_p$ for five different process corners, where Fig. 5(a) is for the bandgap reference circuit [10] that generate $V_{\text{TH}}$ and $I_{\text{REF}}$, and Fig. 5(b) is for the proposed circuit. For the same panel capacitance value, the bandgap reference circuit shows more variation in $\Delta T$ compared to the proposed circuit. This means the proposed circuit is less sensitive to the process variations, where the pulse width varies linearly with the panel capacitance change. In addition, there is no false detection since the worst case scenario happens with $C_p = 50$ pF at the FS corner, which its corresponding pulse width is 3 µs. This result shows the robustness of the proposed readout circuit with different process corners.

Table II depicts the $I_{\text{REF}}$ and $V_{\text{TH}}$ values for different corners. Based on Eq. (6) and (8), we expect corners (SS, SF) and (FF, FS) to show similar behaviors. It is obvious that in each case, both current and voltage change in the same direction, and consequently the corresponding pulse width for touched and un-touched conditions is less sensitive to process variations.
Table II. $I_{\text{REF}}$ and $V_{\text{TH}}$ values for different corners.

| Process corners | $I_{\text{REF}}$ [µA] | $V_{\text{TH}}$ [mV] |
|-----------------|-----------------------|-----------------------|
| Typical (TT)    | 3.4                   | 470                   |
| Slow-Slow (SS)  | 2.66                  | 289                   |
| Fast-Fast (FF)  | 4.27                  | 661                   |
| Fast-Slow (FS)  | 3.66                  | 686                   |
| Slow-Fast (SF)  | 3.15                  | 282                   |

Table III shows $I_{\text{REF}}$ and $V_{\text{TH}}$ with temperature and $V_{\text{DD}}$ variations obtained from circuit simulations. With a fixed temperature, $I_{\text{REF}}$ and $V_{\text{TH}}$ are consistent with $V_{\text{DD}}$ variations. However, although $I_{\text{REF}}$ and $V_{\text{TH}}$ change in the opposite direction with temperature variations, the amount of change is not significant in the temperature range between −20 to 70°C which is the standard range for consumer electronic devices. Therefore, this result shows the robustness of proposed circuit to $V_{\text{DD}}$ and temperature variation.

Table III. $I_{\text{REF}}$ and $V_{\text{TH}}$ with temperature and $V_{\text{DD}}$ variations.

| Temp. (°C) | $V_{\text{DD}} = 2.97$ V | $V_{\text{DD}} = 3.3$ V | $V_{\text{DD}} = 3.63$ V |
|------------|-------------------------|-------------------------|-------------------------|
|            | $I_{\text{REF}}$ [µA]  | $V_{\text{TH}}$ [mV]   | $I_{\text{REF}}$ [µA]  | $V_{\text{TH}}$ [mV]   | $I_{\text{REF}}$ [µA]  | $V_{\text{TH}}$ [mV]   |
| −20        | 3.21                    | 291                     | 3.61                    | 451                     | 4.03                    | 624                     |
| 27         | 2.98                    | 308                     | 3.4                     | 470                     | 3.81                    | 641                     |
| 70         | 2.64                    | 338                     | 3.11                    | 501                     | 3.53                    | 683                     |

Fig. 6 shows the proposed touch sensor readout circuit die photograph and the layout where the core area is 2700 µm². In order to reduce the mismatch and improve the device symmetry, general layout techniques including common centroid and inter digitized structures are used.

Fig. 6. Die photograph and layout.

5 Experimental results

Fig. 7 illustrates the test set up for the touch sensor readout IC (touch panel and printed circuit board). In order to verify the operation of the proposed readout circuit, a 10.4” projected capacitance type touch panel which includes 29 × 21 rows
and columns has been used. For measurement purposes, the middle of touch panel was targeted. The corresponding terminals for the 15th row and the 10th column were directly connected to the printed circuit board containing the readout IC.

![Touch panel](image1)

Fig. 7. Touch sensor readout IC test set-up.

Fig. 8 shows the measured output waveforms for the touched and un-touched scenarios. For the touched case, $V_{comp}$ pulse width $\Delta T$ was measured as 10.2 $\mu$s with corresponding frequency $f = 1/\Delta T = 98.04$ kHz.

![Waveform](image2)

Fig. 8. Readout circuit output waveforms. (a) Touched case (b) Un-touched case.
This is distinguishable for $\Delta T$ and $1/\Delta T$ of the un-touched case that showed 8.80 $\mu$s and 113.4 kHz, respectively. The pulse width $\Delta T$ can be simply measured by a counter that counts the number of CLKs within the pulse width. The $V_{TH}$ was measured as 462 mV which is near the typical corner. Based on the simulation and measurement results, the panel capacitance values for the touched and the un-touched cases can be estimated around 15 pF to 25 pF that match the values with the previous study [11].

Table IV shows the touched and the un-touched case pulse width $\Delta T$ measured from five different readout ICs. The results definitively show a sufficient margin between the touched and the un-touched case. Since the detection frequency of the proposed readout circuit is relatively low, it simplifies the signal processing unit. Overall, the results obtained for different ICs show the robustness of the proposed scheme under different process corners.

| Chip # | $\Delta T$ [µs] | $1/\Delta T$ [kHz] |
|--------|----------------|-------------------|
| Touched |                |                   |
| 1      | 10.20          | 98.04             |
| 2      | 10.36          | 96.52             |
| 3      | 10.25          | 97.56             |
| 4      | 10.12          | 98.81             |
| 5      | 10.05          | 99.50             |
| Un-touched |            |                   |
| 1      | 8.80           | 113.63            |
| 2      | 8.95           | 111.73            |
| 3      | 8.85           | 112.99            |
| 4      | 8.70           | 114.94            |
| 5      | 8.66           | 115.47            |

Table V shows the performance comparison with other touch sensor readout circuits. The detection time is defined as the time it takes the readout circuit to detect the panel condition, touched or un-touched. As shown, the proposed touch sensor readout circuit has a very small area and low power compared to other readout circuits. Although the detection time of [2] is faster than the proposed circuit, it has higher power for identical detection time since the power is inversely proportional to the detection time. The proposed current based capacitive touch sensor circuit does not require extra amplifiers and resistors/capacitors which leads to small area and low power consumption. Fast detection time is achieved for current based capacitance-to-time converters since it does not need multiple operation cycles to convert the detected charge into a pulse, unlike the charge transfer based touch sensor readout circuits [9]. Current based capacitive type touch sensor readout circuits are sensitive to process variations which require self-adjustment and calibration schemes, such as the proposed comparator threshold voltage generator with self-adjustment. Overall, the advantage of the proposed touch sensor readout circuit is a simple and compact on-chip solution that is insensitive to process variation. This approach can replace the external comparator threshold voltage adjustment schemes for touch sensors using micro-controllers.
6 Conclusions

In this paper, a capacitive type touch sensor readout circuit with comparator threshold self-adjustment is proposed. The proposed circuit only requires several control switches, a current generator, and a comparator. This enables a fast detection time, very small area, and lower power consumption compared to the conventional touch sensor readout circuits. The operation of the proposed circuit was verified through circuit level simulations and IC measurements. Due to the compact size and low power, the proposed scheme is suitable for capacitive type touch panel readout circuits.

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Table V. Performance comparison with other touch sensor readout circuits.

|                  | [2]       | [3]       | [4]       | [5]       | This Work |
|------------------|-----------|-----------|-----------|-----------|-----------|
| Technology       | CMOS 0.35 µm | CMOS 90 nm | CMOS 0.18 µm | CMOS 0.18 µm | CMOS 0.35 µm |
| Core area        | 0.35 mm²   | 0.04 mm²  | 4 mm²     | 0.28 mm²  | 0.0027 mm² |
| Power            | 1.15 mW    | 0.81 mW   | 19 mW     | 0.3 mW    | 52 µW     |
| Detection time   | 0.62 µs    | 34.7 µs   | 48.1 µs   | -         | 25 µs     |