A Parasitic-Insensitive Charge Transfer Circuit for Capacitive Sensing using Active Output Voltage Feedback Technique

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Abstract
This paper introduces a new parasitic-insensitive charge transfer circuit using active output voltage feedback. The proposed parasitic-insensitive charge transfer circuit uses a passive charge transfer circuit for maximum output voltage dynamic range. A feedback loop between the transfer and output nodes is formed using a unity-gain opamp to make the two nodes’ potentials same, which prevents the charges stored at parasitic capacitors from transferring to the output. With those two characteristics, the proposed parasitic-insensitive charge transfer circuit offers full supply output voltage dynamic range for capacitive sensing without degradation of the linearity from the effects of parasitic components. The proposed parasitic-insensitive charge transfer circuit’s performances were simulated with standard 0.35 μm CMOS technology and compared with those of a passive charge transfer circuit. It can be concluded from the results that the proposed parasitic-insensitive charge transfer circuit can be effectively used as a capacitive sensor with improved touch sensitivity for wider range of touch devices which include larger parasitic components.

Keywords: Touch Screen Panel, Parasitic-Insensitive, Charge Transfer Circuit, Parasitic Capacitance, Capacitive Sensing.

1. Introduction
Capacitive sensor devices, such as a touch screen panel (TSP), are becoming more popular and spreading rapidly because of their many advantages over other input devices, such as a keyboard or a mouse, especially in mobile systems. A capacitive sensor as touch input device provides effective and interactive input functions, such as multi-touch, proximity sensing, and a pattern input. Moreover, capacitive sensors are widely used for various applications such as moisture sensing, bio-sensing and special purpose sensing [1-3].

Recently, the display units in many mobile applications are becoming much wider in their size, therefore it needs more touch points for higher resolution. Since the electrodes which are generally formed by Indium-Tin Oxide (ITO) in TSP include parasitic components such as capacitance and resistance, these parasitic components may cause severe performance degradation in both touch sensitivity and accuracy.

To decrease the parasitic effect, a parasitic-insensitive discrete-time integrator can be used as a capacitive sensor [4]. However, since a capacitance of TSP only decreases in touch conditions, this circuit uses only half of the supply voltage which reduces touch sensitivity.

This paper introduces a new parasitic-insensitive charge transfer circuit using an active output voltage feedback, which offers maximum output dynamic range. A passive type charge transfer circuit as an integrator is used to provide maximum output voltage range and eliminate the charges of the parasitic capacitance by getting back an active output voltage to the sense capacitor. To verify the theoretical performance of the proposed circuit, simulations have been performed using standard 0.35 μm CMOS technology.

2. Charge Transfer Capacitive Touch Sensor Circuit
2.1. Capacitive Touch Sensor using Charge Transfer Scheme
A charge transfer scheme can be used for capacitive sensing [5-7]. Figure 1 shows the typical capacitive sensing based on a charge transfer scheme developed by Quantum [5]. Note that Cs accumulates charges originally from the X drive by switching on the Y receive line. To obtain a
sufficient voltage for touch decision, an amplifier is used at Cs before the signal is fed into an ADC. When a touch is made on a TSP, the Cx between the X and the Y electrodes changes, which causes a variation of charges from the X drive. As a result, voltages at Cs between touch and non-touch conditions are different.

**Figure 1.** A capacitive sensing scheme using charge transfer by Quantum [5].

### 2.2. Charge Transfer Capacitive Touch Sensor Circuit

As touch input devices such as TSP are getting bigger and wider, parasitic components, such as capacitance and resistance, are also increased. Therefore, it is very important to reduce the effect of parasitic components to maintain touch sensitivity. This section introduces a parasitic-insensitive charge transfer circuit using active output voltage feedback and analyzes its charge transfer behavior which is modified with a parasitic-insensitive switched capacitor integrator [8-9].

Wider capacitive sensing devices may suffer from more parasitic components in their touch sensitivity and performance. To remove this parasitic effect, a parasitic-insensitive switched capacitor integrator can be used [8].

Figure 2(a) shows a parasitic-insensitive switched capacitor integrator as a capacitive touch sensing circuit. The clock signals, $\phi_1$, $\phi_2$, control MOS switches and the resulting output voltage of the integrators are shown in Figure 2(a) [8]. When $\phi_1$ is high, the node of the parasitic capacitor, $C_{p2}$, is charged to reference ground. Obviously, the node of negative input of an opamp is virtually shorted to the positive input whose potential is reference ground in the circuit. Therefore, there are no charges transferred from $C_{p2}$ to $C_s$ because the two nodes of $C_{p2}$ are of the same potential with that of the output node whose charges are transferred from $C_t$ to $C_s$. Therefore, the overall transfer function of the proposed circuit does not include parasitic capacitance as represented in (1), where $z$ is a parameter from z-transform.

$$H(z) = \left(\frac{C_t}{C_s}\right) \frac{z}{z - 1} \quad (1)$$

Figure 2(b) shows a modified parasitic-insensitive integrator circuit as a capacitive sensing circuit introduced in [4]. A variable capacitor, $C_t$, represents the capacitor formed between the X and Y drive lines of TSP. $R_p$ and $C_p$ represent parasitic resistance and capacitance of the drive lines, respectively. $V_{in}$ is set to 0V and charges are transferred to $C_s$. This capacitive sensing circuit can remove the effect of parasitic components because it has the same operational architecture as a parasitic-insensitive switched capacitor integrator [8]. A drive signal is fed into one node of $C_t$ and the charge stored in $C_t$ is transferred to $C_s$ by switching operation. Touch action will change the capacitance of $C_t$ because a conductive touch material absorbs part of the electric fields formed between the X and Y drives lines.
Therefore, the capacitance of $C_t$ is decreased when touch on the touch device. The simulation results of [4] show the parasitic insensitive characteristics which increase touch sensitivity of the circuit.

Figure 2. (a) A switched capacitor integrator including parasitic capacitances, (b) A parasitic-insensitive charge transfer circuit for capacitive sensing and modeling of parasitic components (c) non-overlapping switch control signals and output voltage.

2.3. Charge Transfer Capacitive Touch Sensor Circuit

Due to the fact that the variation of the capacitance of $C_t$ is one-directional for some array-type capacitive sensing devices, such as TSP and fingerprint sensors, $C_t$ is only decreased (or increased) in touch conditions [2, 10]. Therefore, one major drawback of this parasitic-insensitive switched capacitor integrator as a capacitive circuit for touch devices is that it can only use a limited output voltage dynamic voltage range which is half of the supply voltage (Vdd/2). It may be a critical issue for a low-voltage system. A passive type integrator as shown in Figure 3 can increase dynamic output voltage range by fully using the supply voltage range.

Figure 3 shows a passive charge transfer circuit by removing an opamp from a parasitic-insensitive integrator circuit. $C_s$ is normally several times larger than $C_t$. $C_s$ is reset with VDD because of negative transfer characteristic. Therefore, the output voltage will decrease from VDD during charge transfer operations. The Cs might be reset after proper evaluation. The amount of charges to be transferred from $C_t$ to $C_s$ at certain period is determined by the voltage difference between $C_t$ and $C_s$. Unlike a parasitic-insensitive integrator, a passive charge transfer circuit cannot remove the effect of the parasitic components because the voltage of node, $v_g$, changes instead of maintaining virtual reference ground. Thus, the charges accumulated in $C_p2$ are also transferred to $C_s$ which contributes to the output voltage. Therefore, this passive style charge transfer circuit has severe degradation of its linearity in charge transfer characteristic compared to that of a parasitic-insensitive switched capacitor integrator. The output voltage can be derived as (2).
\[
H(z) = \frac{\frac{C_s + C_p}{C_t}}{z - 1} \tag{2}
\]

Figure. 3 A switched capacitor integrator including parasitic capacitances, (b) A parasitic-insensitive charge transfer circuit

To resolve this problem, this paper proposes an active output voltage feedback charge transfer circuit as shown in Figure 4. In general, charges flow from higher voltage node to lower voltage until the voltages are equal. Therefore, it is required to charge \(C_p2\) to the same voltage of the output node when charges are being transferred to eliminate the parasitic effect of \(C_p2\). The proposed charge transfer integrator uses \(C_s\) with ground connected node, which is similar to the passive style charge transfer circuit. To remove the charges transferred from the parasitic capacitance, \(C_p2\), the output voltage is fed into a voltage follower and feedback to the node of switch MN2. When \(\phi_1\) is high state, that means MP1, MN2 are turned on, the voltage of node \(v_p\) is charged to the same voltage of node \(v_g\), by feedback output voltage generated from voltage follower of \(v_g\). As a result, the charge stored in \(C_p2\) does not affect the output voltage. Of course, all the switches can be replaced with CMOS transmission gates for rail-to-rail operation.

Figure. 4 The proposed charge transfer circuit using active output voltage feedback.

The transfer function of the proposed active output voltage feedback charge transfer circuit can be represented as (3). Different from the transfer function of the parasitic-insensitive switched capacitor integrator, the transfer function of the proposed circuit has negative relationship between input and output rather than positive. One drawback of the circuit is that the voltage of the node, \(v_g\), changes during the charges when transferred from \(C_t\) to \(C_s\), which may degrade the linearity of transferring charge. Thus, the resulting transfer function roughly equal to that of the proposed parasitic-insensitive charge transfer circuit. And the amount of charge to be transferred to \(C_s\) is determined as expressed in (4).
$$H(z) \approx \left( \frac{C_i}{C_s} \right) \frac{z}{z-1}$$  \hspace{1cm} (3)

$$\Delta V_{\text{proposed}} \approx \frac{C_i}{C_i + C_s} V_{dd}$$  \hspace{1cm} (4)

3. Simulations

To examine the characteristics of the proposed parasitic-insensitive charge transfer circuit, output voltage were simulated with touch and non-touch conditions and then compared to those of a passive style one. As shown in Figure 4, \( V_{in} \) is fixed with \( V_{dd} \) in order to transfer the maximum charges from \( C_t \) to \( C_s \). For the simulation purposes, only the values of parasitic capacitance are changed to focus on the effect of parasitic capacitance because the parasitic resistances only affect the charge transfer timing. Thus it is assumed that a parasitic resistance of 10kΩ for the x, y drive line, and 30pF of \( C_s \) are assigned. It is also assumed that the capacitance of 1.3pF has formed at a touch point (cross point between x and y line) and the value of capacitance of the touch point varies about 25% when a touch is made on the TSP. Two phase non-overlapping clock signals of 1MHz control the four switches for charge transfer operation. Figure 5 shows both the output voltages of the passive and proposed charge transfer circuit. The voltage difference per single charge transition of the proposed is about 90mV which agrees to the theoretical \( \Delta V \) represented in (4). As shown in Figure 5, linear output voltage is obtained over the full voltage range.

![Figure 5](attachment:image.png)

Figure 5. Time domain voltage output characteristics during charge transitions of the conventional passive charge circuit and the proposed parasitic-insensitive charge circuit

Figure 6 shows the output voltages of the passive and proposed parasitic-insensitive charge transfer circuits for touch and non-touch conditions. Touch and non-touch conditions are assumed by varying 25% of \( C_t \) value. No parasitic capacitance is assumed for this simulation. The maximum voltage difference between touch and non-touch conditions of the passive charge transfer circuit is about 350mV after six charge transitions while more than 700mV for the proposed charge transfer circuit. From the results, the parasitic capacitance can be effectively removed in the proposed charge transfer circuit as it has examined in theory.
To analyze touch sensitivity, the voltage differences between touch and non-touch states with various parasitic capacitances were simulated. Figure 7 shows the simulated voltage difference between the touch and non-touch state with various parasitic capacitances for the passive and proposed parasitic-insensitive charge transfer circuits.

As shown in Figure 7, the voltage difference between touch and non-touch state degradation with various parasitic capacitance of the proposed parasitic-insensitive charge transfer circuit is about two times higher than that of the passive charge transfer circuit with no parasitic capacitance. With parasitic capacitance of 10pF, the voltage difference of the parasitic-insensitive charge transfer circuit is about 520mV which is more than 5 times larger than that of the passive charge transfer circuit. Obviously, this voltage difference is directly related to the touch sensitivity.

Figure 6. Time domain voltage output characteristics during charge transitions of the conventional passive charge circuit and the proposed parasitic-insensitive charge circuit for touch and non-touch conditions.

Figure 7. Voltage difference between touch and non-touch state with various parasitic capacitance (Ct=1.3pF).
A relative voltage differences between touch and non-touch states is defined as (5) to analyze the relative touch sensitivity in more detail. The voltage difference with no parasitic capacitance is used as a reference.

\[
V_{\text{diff-ratio}}(\%) = \frac{\Delta V_{\text{parasitic}}}{\Delta V_{\text{no-parasitic}}} \times 100
\]  

Figure 8 shows the relative ratio of voltage differences with various parasitic capacitances. As shown in Figure 8, the ratio of voltage differences of the passive charge transfer circuit decreases rapidly. Thus only 20% of the initial voltage difference is obtained with a parasitic capacitance of 10pF. On the other hand, the ratio of the voltage difference of the maximum voltage difference 75% of the initial value, which means the proposed parasitic-insensitive charge transfer circuit for capacitive sensing is much less susceptible to parasitic capacitances.

![Figure 8](image.png)

**Figure 8.** Relative voltage differences between touch and non-touch states of conventional passive charge transfer circuit and proposed parasitic-insensitive charge transfer circuit.

### 4. Conclusion

This paper proposed a parasitic-insensitive charge transfer circuit using active output voltage feedback. The simulation results verified the theoretical performance of the parasitic-insensitive charge transfer circuit using standard 0.35μm CMOS technology. With 10pF parasitic capacitance, which is about 10 times of the sense capacitance in the simulation, the proposed parasitic-insensitive charge transfer circuit’s touch difference voltage is degraded only 25% of the initial value while a passive charge transfer circuit is degraded as much as about 80%.

From the simulation results, the proposed circuit has characteristics of transferring charges linearly over full supply voltage range with little degradation of linearity compared to that of a parasitic-insensitive discrete-time integrator. Therefore, it can be concluded that the proposed parasitic-insensitive charge transfer circuit can be effectively used as a capacitive sensor for touch devices such as with maximum touch sensitivity.

In conclusion, the proposed active output voltage feedback parasitic-insensitive charge transfer circuit combined with decision logic circuits can be effectively used as a high sensitive and large dynamic range of capacitive sensor for touch devices such as TSP.
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6. References