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A New Fingerprint Sensor based on Signal Integration Scheme using Charge Transfer Circuit

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Abstract

This paper proposes a fingerprint sensor cell and driver architecture based on a charge integration scheme. The fingerprint sensor cell uses an active output voltage feedback (AOVF) integrator as a capacitance-to-voltage converter. A multiple integration scheme is suggested to improve signal-to-noise ratio (SNR) and amplify the sensing signal, which enables a simple and robust fingerprint sensor driver architecture. A prototype fingerprint sensor array of 1x64 is implemented with an AOVF integrator. The performances of the proposed fingerprint sensor were simulated with standard 0.35μm CMOS technology. By simulations, the proposed fingerprint sensor senses even sub-femto farad differences and has large sensing voltage range.

Keywords: *Fingerprint sensor, Capacitive sensor, Capacitance-to-voltage converter, Discrete-time integrator, Charge transfer circuit, Signal integration*

1. Introduction

Biometric recognition systems, such as a fingerprint system, are for personal verification. So far, a fingerprint system or other biometric systems have not been popular in the consumer market due to its inconvenience for use and relatively high cost. However, the need for identifying a person is becoming more popular these days. Especially, mobile systems start to put a fingerprint sensor in service as a personal authentication method nowadays [1-2]. The integrated biometric devices with small volume and low cost help to accelerate the consumer market of mobile systems such as a smart phone and a tablet PC. Therefore, a low-power, a low-cost and a reliable fingerprint system is more required in the system. Usually, a fingerprint system consists of three parts of a sensing unit, an encoding unit, and a processing unit. Since a fingerprint identification processing has to be spent, capturing a high quality image is crucial in the fingerprint systems [3-4].

This paper introduces a new fingerprint sensor which uses a direct sensing method using an active output voltage feedback (AOVF) integrator. The proposed fingerprint sensor amplify the sensing signal by increasing integration times rather than using an amplifier or a programmable-gain-amplifier (PGA), which will improve signal-to-noise ratio (SNR) greatly and allow a simple fingerprint driver architecture also. To verify the theoretical performances of the sensors, the proposed 1x64 fingerprint sensor array and driver were designed and simulated and compared with the theoretical performances using standard 0.35μm CMOS technology.

2. Fingerprint Sensor Cell Circuit

Many fingerprint sensors based on capacitive sensing has been introduced already [5-12]. A capacitive sensor based on charge transfer circuit has also been introduced [13-

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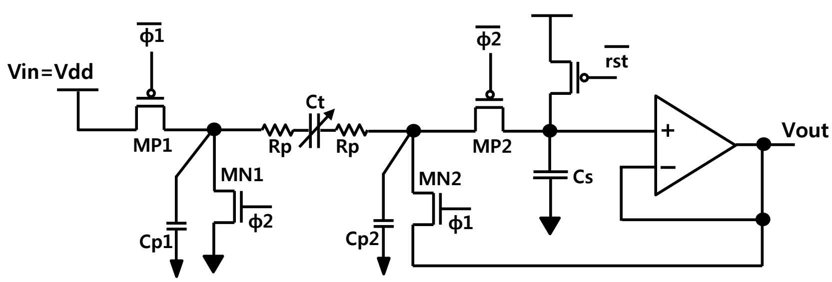
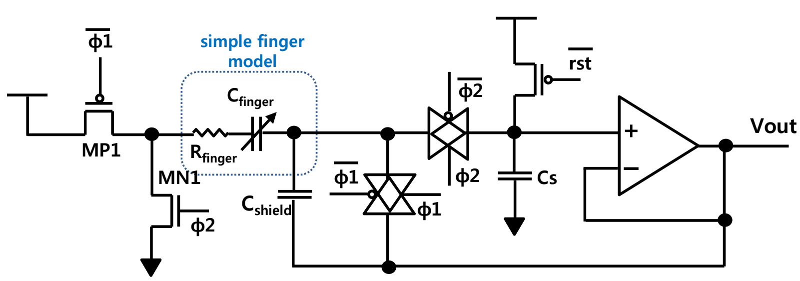
14]. An integrator based on an AOVF charge transfer circuit for capacitive sensing to get large output sensing range of capacitive sensing has been introduced as shown in Figure 1(a) [15-16]. Since this circuit combines a passive integrator and a parasitic-insensitive discrete-time integrator, the circuit can use the capacitive sensing range of full supply voltage, which is suitable for low voltage and low power applications. To apply this circuit to a fingerprint sensor, the AOVF integrator is modified as shown in Figure 1(b). MN2 and MP2 are replaced by a transmission gate in order to get maximum output swing range and the sensor output is connected to the one node of C_{shield}. The sensor plate is shielded by a metal to prevent the noise from the circuit under the sensor plate, which forms a parasitic capacitance between the sensor plate and the metal shield shown in Figure 2. Since C_{shield} is relatively large compared to C_{finger}, it should be removed. To effectively remove this parasitic capacitance, C_{shield}, the output is applied to the bottom node of C_{shield} to maintain the same potential of the both nodes of C_{shield} as shown in Figure 1(b), which maximizes the sensitivity of the fingerprint sensor. The fingerprint sensor using direct method uses a bezel as a contact to apply signal directly to a finger through it. A signal driven to a finger returns back through the sensor plate.

Since the AOVF integrator is less sensitive to offset voltage of an opamp, an simple opamp shown in Figure 1(c) can be used in the sensor without much degradation of the proposed fingerprint sensor's performance. However, the input range of the opamp may affect the behavior of the sensing evaluation of the fingerprint sensor because the capacitive sensor uses full supply voltage range. And Figure 1(d) shows the two-phase non-overlapping clocks used to control the MOS switches. This paper uses an NMOS input simple opmap because the input range of the opamp is must be high enough to guarantee the initial operation while the sensor evaluation starts from Vdd. If the evaluation starts from 0V, an opamp with a PMOS input is required.

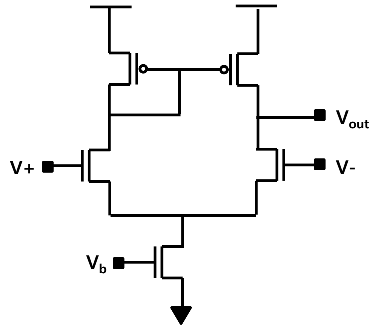
Some fingerprint sensors based on direct sensing method, which use a bezel as a signal contact to finger directly, have been introduced [1-2, 17-18]. The fingerprint sensor using direct sensing method uses bezel as a contact to apply signal directly to a finger through it. A signal driven to a finger returns back through the sensor plate.



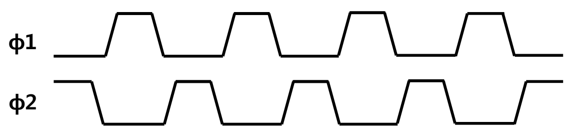
(a)



(b)



(c)



(d)

Figure 1. Charge transfer circuits for capacitive sensing based on AOVF integrator, (a) conventional capacitive sensor circuit, (b) proposed fingerprint sensor cell circuit with parasitic capacitance cancellation, (c) a simple opamp used in the fingerprint sensor circuit, (d) Two-phase non-overlapping clocks applied to sensor circuits

Figure 2 shows the fingerprint sensor cell structure applied in MOS technology. A fingerprint is modeled with a series-connected resistor and a capacitor. The capacitor formed between the sensor electrode and finger is also modeled as shown in Figure 2. The sensor electrode is separated by the passivation layer. Therefore, the sensor capacitor, C_{finger}, is composed of two series-connected capacitors which are a capacitor between the electrode and chip surface and a capacitor between a chip surface and the finger skin. The parasitic capacitance of C_{shield} ranges 60~100fF which is depend on sensor cell size. The signals generated from the driver are directly fed into the finger through bezel contact. The finger is simply modeled with a series resistor and a capacitor formed between the finger and a chip surface, C_{finger}. A parasitic capacitor between the sensor plate and metal shield is represented as C_{shield}. To effectively remove the parasitic capacitor, C_{shield}, the metal shield is connected to the sensor output to maintain the same potential of both nodes of C_{shield} as mentioned.

The accumulated charges in the C_{finger} are transferred to the output capacitor, C_S. C_{finger} changes according to ridge and valley of a finger, which is represented as C_{ridge} or C_{valley}, respectively. C_{ridge} matches a capacitor between the electrode and chip surface while C_{valley} matches series-connected capacitors of C_{air} and C_{pass}. So, the capacitances of the fingerprint for C_{ridge}, C_{valley} can be represented as (1) (2), respectively.

$$C_{ridge} \approx C_{pass} \tag{1}$$

$$C_{valley} \approx \frac{C_{air} \cdot C_{pass}}{C_{air} + C_{pass}} \tag{2}$$

C_{finger} is either C_{ridge} or C_{valley}, so the variation of the C_{finger} can be represented as the difference between C_{ridge} and C_{valley} represented as (3).

$$\Delta C_{finger} \approx C_{ridge} - C_{valley} \tag{3}$$

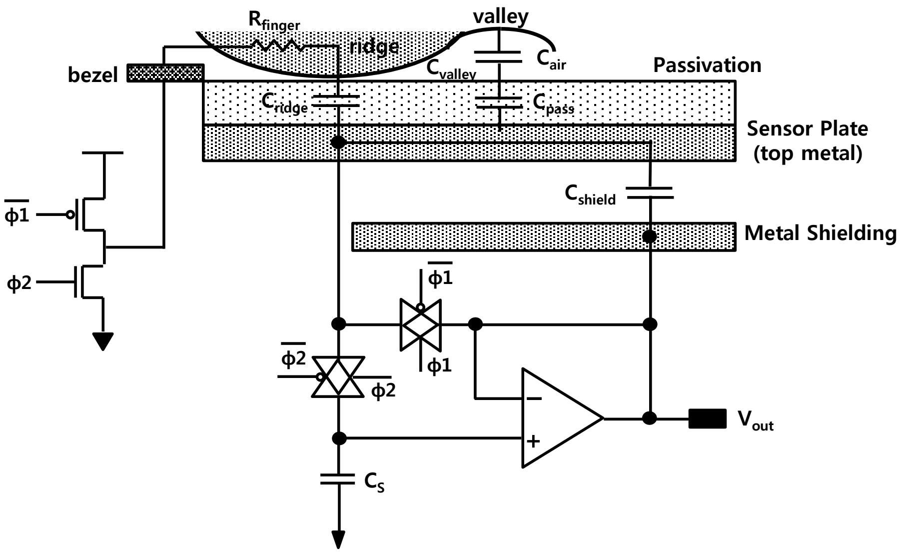


Figure 2. The Proposed Fingerprint Cell Structure based on an AOVF Integrator Applied in MOS Technology

As analyzed in [13], the variation of the output voltage for single charge transition of the sensor can be derived as (4). Since C_{shield} does not contribute to the output voltage change by charge transition because C_{shield} is effectively removed by maintaining the same potential of the both nodes of C_{shield}, the output voltage of the proposed fingerprint sensor per single transition is given by

$$\Delta V_{out}(t) \cong -\frac{C_{finger}}{C_{finger}+C_S}V_{dd} \tag{4}$$

where C_{finger} is either C_{ridge} or C_{valley}. And we can rewrite the transfer function with parameter Z as (5).

$$H(Z) = -\frac{C_{finger}}{C_{finger}+C_S}\frac{1}{Z-1} \tag{5}$$

From (4), the output voltages for C_{ridge} and C_{valley} can be derived and the voltage difference between the output voltages for C_{ridge} and C_{valley}, is defined as (6).

$$V_{diff} = \left(\frac{C_{ridge}}{C_{ridge}+C_S} - \frac{C_{valley}}{C_{valley}+C_S}\right)V_{dd} \tag{6}$$

Since the fingerprint sensor circuit is based on AOVF integrator, the final fingerprint voltage difference after n-time integrations is represented as n times V_{diff}. Finally, the output sensing voltage, V_{sense}, between C_{ridge} and C_{valley} after n-time integrations is derived as (7).

$$V_{sense} = n \cdot V_{diff} \tag{7}$$

If it is assumed that C_{valley} is small enough compared to C_{ridge}, then V_{diff} is simplified as (8).

$$V_{diff} \cong \left(\frac{C_{ridge}}{C_{ridge} + C_S} \right) V_{dd} \tag{8}$$

Therefore, V_{sense} after n-time integration is also simplified as (9).

$$V_{sense} \cong n \cdot \left(\frac{C_{ridge}}{C_{ridge} + C_S} \right) V_{dd} \tag{9}$$

3. Noise Characteristics

From (4), the output signal of the proposed sensor is defined as (10). Since the proposed fingerprint sensor cell is based on a discrete-time integrator, the magnitude of signal output after n-time integrations can be described as (10), if it is assumed the initial signal starts from 0V.

$$V_{out} = n \cdot \Delta V_{out} \tag{10}$$

To define a signal-to-noise ratio (SNR) of the fingerprint sensor circuit, it is assumed that the noise signals are fed into the input port of the each sensor with additive white Gaussian noise (AWGN). SNR of the fingerprint sensor of single charge integration can be defined as (11), where V_{out} is integrated signal and σ2 is variance of the AWGN noise.

$$SNR_{single} = \frac{Signal\ Power}{Noise\ Power} = 10 \cdot \log\left(\frac{V_{out}^2}{\sigma^2} \right) = 10 \cdot \log\left(\frac{\Delta V_{out}^2}{\sigma^2} \right) dB \tag{11}$$

Therefore, the SNR with n-time integrations can be derived as (12) because the mean and the variance of the noise signal remain zero and σ, respectively.

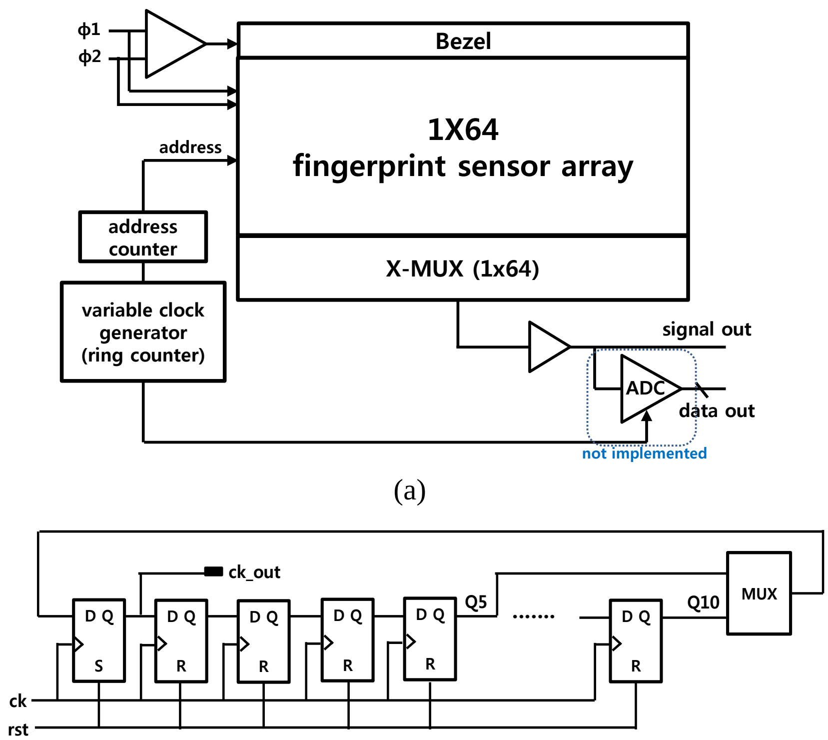
$$SNR_{n-\text{int}} = 10 \cdot \log\left(\frac{V_S^2}{\sigma^2} \right) = 10 \log\left(\frac{(n \cdot \Delta V_{out})^2}{\sigma^2} \right) = SNR_{single} + 20 \log(n) dB \tag{12}$$

As expressed in (12), SNR of the sensor is increased by 20log (n) dB. For example, SNR of 20dB improved after 10-time integrations. This noise characteristic is similar to that of a moving average filter with AWGN, which has low-pass filtering characteristic [19].

4. Simulations

This paper simulates fingerprint sensor cell array of 1x64 with an AOVF integrator in order to examine the performances of the proposed fingerprint sensor. Figure 3 shows the simplified 1x64 fingerprint sensor driver structure for the simulation. Some biometric sensor uses ADCs and PGAs to get better image quality [2, 8]. Generally, a PGA the detected signal from the sensor is amplified to get reasonable signal level for ADC, which might increase system complexity.

This paper proposes that a fingerprint sensor amplify the detected signal by integration times using variable clock generator shown in Figure 3(b) rather than an amplifier. The output sensing voltage, V_{sense}, for two different fingerprint capacitances of 0.5fF, 1fF were simulated to examine the proposed capacitive fingerprint sensor cell. The capacitances of 0.5fF, 1fF are roughly comparable to C_{ridge} and C_{valley} with 50μmX50μm sensor plate with a passivation of 100μm thickness, respectively. And the resistance of finger skin, R_{finger}, of 1MΩ is reasonably assumed to model the resistance of dry skin for the simulation purposes. C_{shield} of 80fF is also assumed which is roughly calculated with the same cell size. Figure 4(a) shows the simulated output voltage of the proposed fingerprint sensor with C_{finger} of 0.5fF, 1fF which represent C_{ridge} and C_{valley}, respectively. In this paper, a 10MHz clock is assumed for the signal which is applied to a finger skin through the bezel. And the finger skin is modeled as a series-connected resistor and a capacitor as shown in Figure 2.



(b)

Figure 3. (a) A Simplified Proposed 1x64 Fingerprint Sensor Driver Structure (b) A Variable Clock Generator Implemented by Ring Counter

According to the simulation results, the final output voltages after 10-time signal integrations were about 2.39V, and 2.02V for 0.5fF and 1fF, respectively. Therefore, V_{sense}, defined as (4), is about 190mV without additional signal amplification. V_{sense} of about 60mV is obtained with 5-time signal integrations. However, V_{out} is not properly evaluated for the first two or three clocks because the output voltage range of the opamp is saturated, which can easily be improved by adjusting the starting voltage of sensing evaluation. V_{diff} is about 45mV between 9th and 10th clock which is well matched with calculated value of about 50mV from (6). Hence, it can be confirmed that the proposed fingerprint sensor can effectively remove the parasitic capacitance, C_{shield}, formed between the sensor plate and the metal shield. As mentioned earlier, the output voltage can be amplified by increasing integration times of signal instead of using an amplifier or programmable-gain-amplifier (PGA), which enables a simple and robust fingerprint sensor driver architecture.

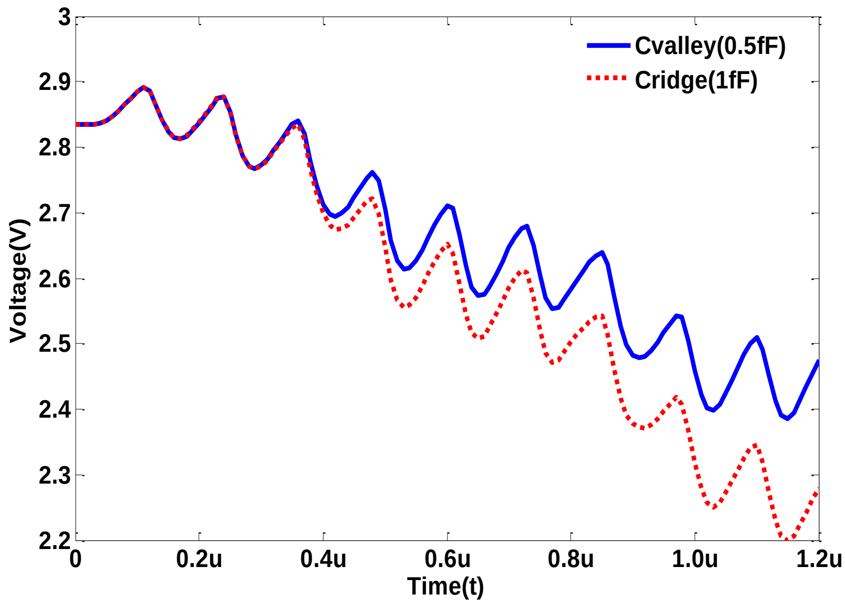


Figure 4. Simulated Sensing Output Voltages of the Proposed Fingerprint Sensor for C_{valley}(0.5fF), C_{ridge}(1fF)

The relative voltage differences between C_{ridge} and C_{valley} can be defined as V_{sense} as seen in (7). Table I summarizes V_{out} and V_{sense} after 10-time signal integration with various finger capacitances. V_{sense} was measured with the reference V_{out} for C_{finger} of 0.2fF. From the simulation results, V_{sense} were obtained 70mV, 260mV and 470mV for 0.5fF, 1fF and 1.5fF, respectively. Figure 5 shows the V_{sense} characteristics as described in Table I. As shown in Figure 5, the V_{sense} is increased linearly in accordance with the C_{finger} increase. As a result, V_{sense} is proportional to the signal integration times, which will improve the sensitivity of the fingerprint sensor

Table 1. v_{out} and v_{sense} of the Fingerprint Sensor for c_{finger}

C_{finger}	0.2fF	0.5fF	1fF	1.5fF
V_{out} [1]	2.46V	2.39V	2.2V	1.99V
V_{sense} [2]	-	70mV	260mV	470mV

1. V_{out} is measured after 10-time signal integrations
2. V_{sense} is measured as the voltage difference between the reference C_{finger} of 0.2fF

5. Conclusion

This paper analyzed a fingerprint sensor based on an AOVF charge transfer capacitive sensor with parasitic-capacitance cancellation. To verify the theoretical performances of the fingerprint sensor, 1x64 fingerprint sensor array were designed and simulated using standard 0.35μm CMOS technology.

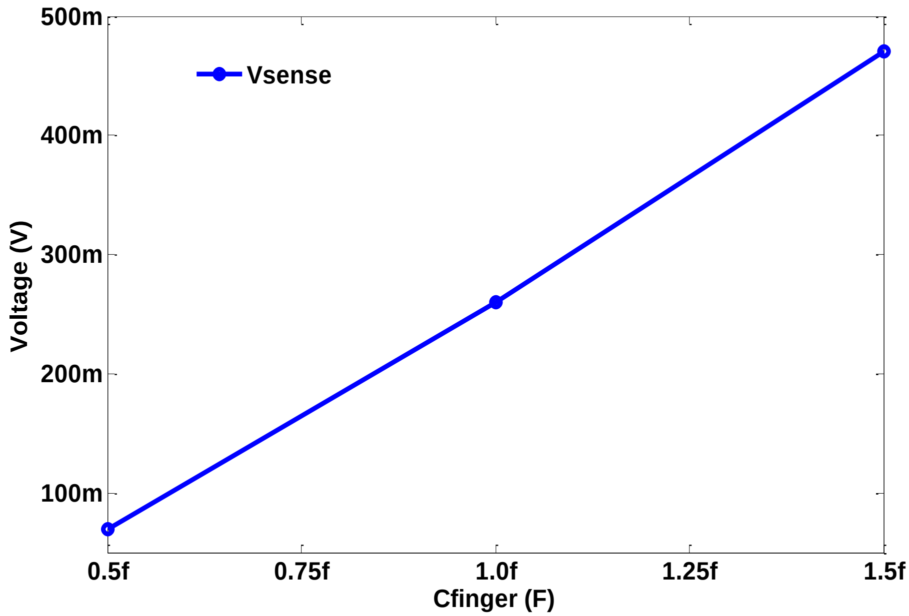


Figure 5. Relative Voltage Differences between Cridge and Cvalley, Vsense, of the Proposed Fingerprint Sensor for 0.5fF, 1fF, 1.5fF with Reference of 0.2fF

And the noise performance with AWGN of the proposed fingerprint sensor cell was analyzed. The proposed fingerprint sensor improves SNR of 20dB with 10-time integration by analysis. The sensitivity of the proposed fingerprint is linearly propositional to the number of signal integration which was fairly well matched with that of the theoretical analysis. Therefore, the proposed fingerprint sensor can effectively be used in a fingerprint sensor with large sensing voltage and improved SNR, which was evaluated that enhanced capacitive sensitivity senses even sub-femto farad difference by simulations. The signal amplification by multiple integrations of the signal enables a simple and robust fingerprint sensor architecture by eliminating PGA. In addition, since the proposed fingerprint sensor uses full voltage range, it can be a good solution for low-voltage and low-power systems, such as mobile applications.

In conclusion, the proposed fingerprint sensor is expected to be used as a fingerprint sensor very efficiently for low-voltage and low-power systems with much improved SNR.

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