High-Speed Differential Sensing Fingerprint Sensor Chip Design

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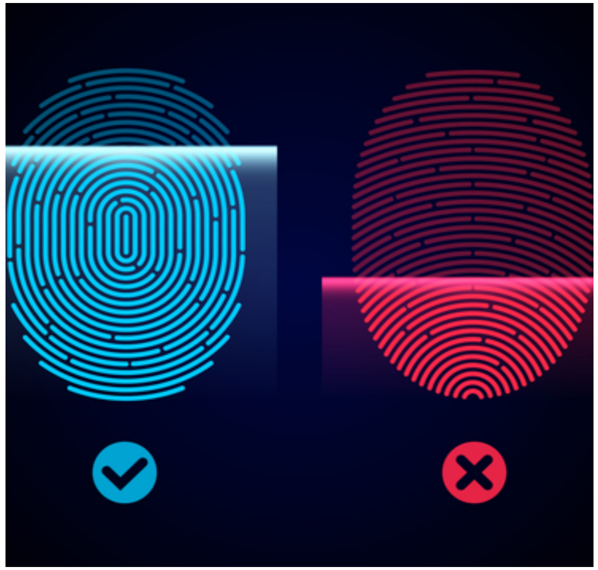
Fingerprint Recognition

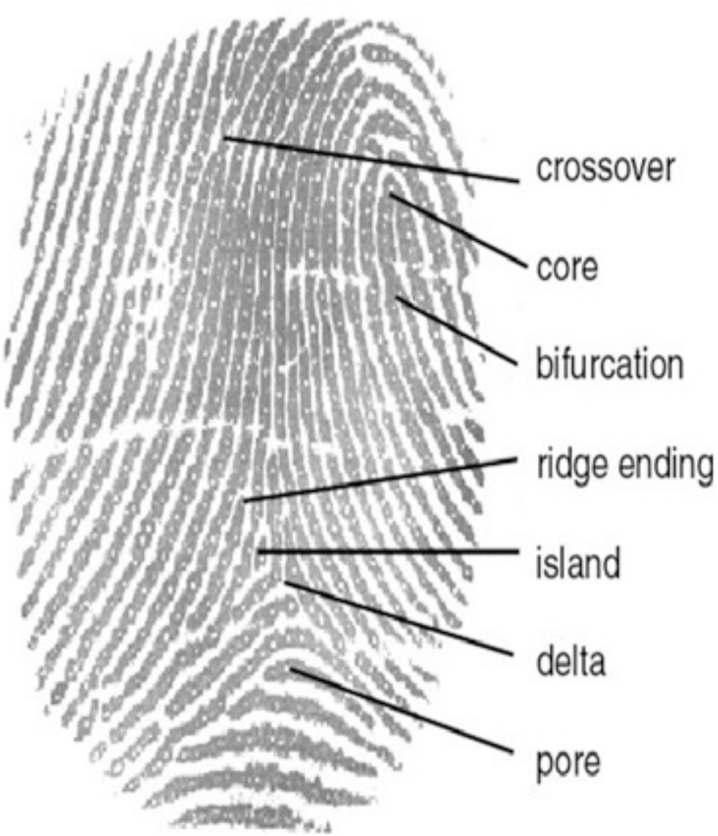
Fingerprint Recognition



- Fingerprint recognition enables an easy to use, reliable and cost efficient way to **authenticate and identify an individual**.
- The advantages of the technology have already led to the wide spread use of fingerprint sensors in mobile devices such as smartphones and tablets.
- But the future holds many more **attractive applications** of biometrics and fingerprint recognition, for example in ***payments, access, automotive, wearables and home appliances.***

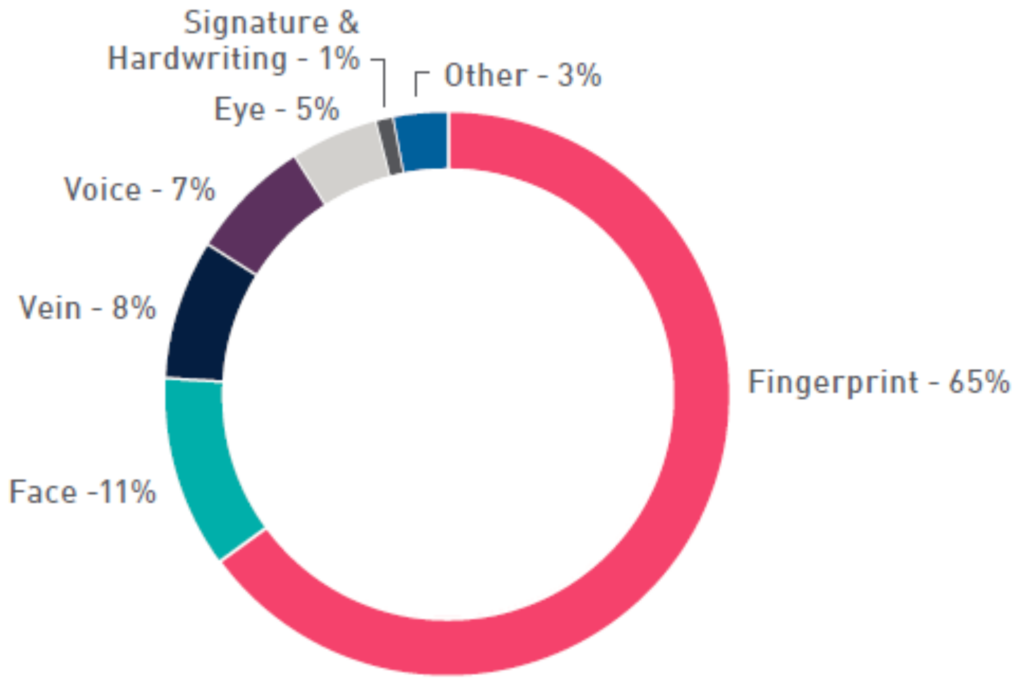
Fingerprint Recognition Principles and Features

- The ridges on the skin of our fingertips form unique patterns shown in our fingerprints.
- The patterns that are formed by the ridges are called ***minutiae***.
  - Examples of minutiae are ridge endings, crossovers, cores and bifurcations



The unique characteristics of a fingerprint can for example be read by ***optical, capacitive, ultrasonic, thermal or piezo-electrical sensors types***, each type having its own benefits and drawbacks.

Market Shares by Biometric Type, 2016



Biometrics market share by system type, based on revenue.
Source: ABI Research 2016

Fingerprint Recognition is the major biometric identifier in use.

Fingerprint Recognition Principles and Features*

Comparison of some biometric modalities. Source: Redeye, April 2016

	Fingerprint	Iris	Retina	Eyeprint	Face	Voice	Vein
Uniqueness	●	●	●	●	◗	◔	●
Permanence	●	●	●	●	◗	◔	●
Measurability	●	◗	◔	◗	◗	◗	◗
Collectability	●	◗	◔	◗	◗	◗	◗
Standards	●	◗	◔	○	◗	◗	○

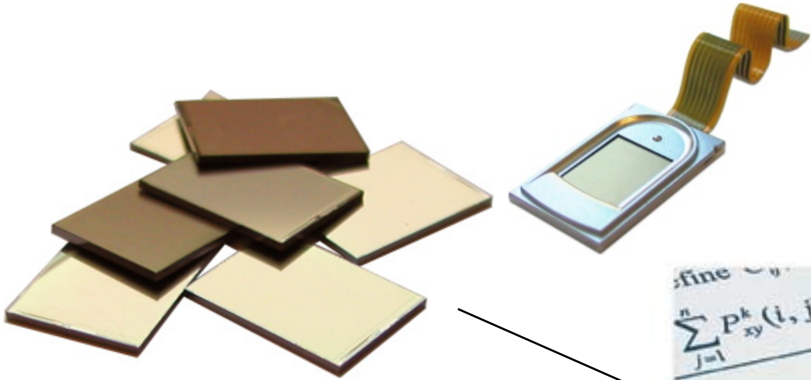
● Very high ◕ High ◗ Medium ◔ Low ○ Very low

The main reasons why fingerprint recognition is the dominant biometric modality used in commercial applications today can be summarized as:

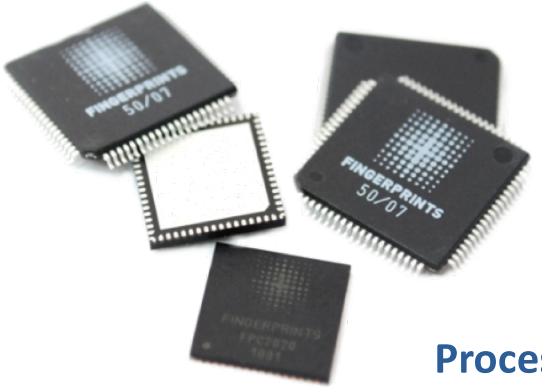
- Each fingerprint has a **very high level of uniqueness**, i.e. authentication is *definite*.
- The fingerprint normally **stays *permanent* during the whole lifespan of a person**.
- Existing technologies allows for a **cost efficient sensing and measurement** of the fingerprint.
- The **sensed parameters** of the fingerprint **can easily be quantified and allows for creation of efficient algorithms** identifying the owner.
- A number of ***standards*** relating to fingerprint recognition are already in place and have created the basis for an economy of scale, i.e. have **lowered the cost of fingerprint hardware and software**.

Fingerprint Sensors and Modules

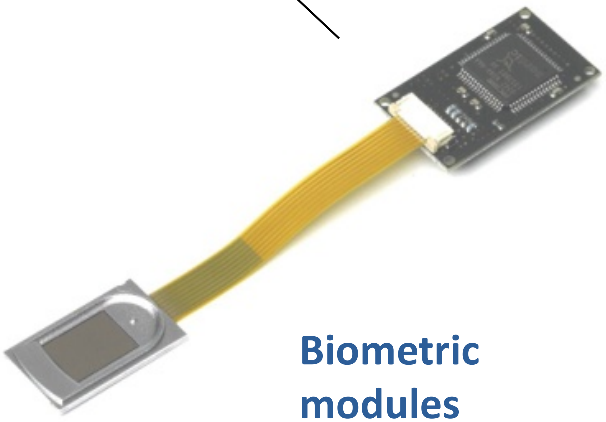
Fingerprint Sensors



Algorithms



Processor for Fingerprint image handling



Biometric modules

Classification of Fingerprint Identification Technology

- Fingerprint identification technology has developed rapidly in recent years, widely used in attendance, access control, intelligent devices, especially in smart phones.
- Classification of Fingerprint Identification Technology:
  - **Optical Fingerprint Technology:**
    - It is an early fingerprint identification technique.
    - Light emitted from an optical emitter is reflected on the finger and then reflected back to the machine to obtain data and compare it with the database.
    - Optical recognition can only reach the epidermis (Surface Layer) of the skin and can't reach the dermis (Inner Layer).
    - Requirements for fingers and lenses are relatively high. The size of optical fingerprint sensor is often large and difficult to use in embedded devices.
  - **Capacitive Fingerprint Technology:**
    - Capacitive identification is based on making two capacitor plates at a distance (Ridge or Valley).
    - Capacitive fingerprint sensor is the most widely used technology at present.
  - **Ultrasonic Fingerprint Technology:**
    - It is based on different acoustic reflection on the ultrasonic impedance of skin
    - Ultrasonic can penetrate the skin surface to obtain dermal lines to get the information.
    - The cost is high.

Performance comparison of fingerprint sensors

	Optical	Capacitive	Ultrasonic
Imaging Ability	Dry, sweaty and dirty fingers gives poor im age.	Dry, sweaty and dir ty fingers can be d etected, however, dirt on skin can lea d to a poor image.	Very Good.
Imaging Area	Large	Small(Can be embe dded)	Medium
Resolution	<500 DPI	~600 DPI	~1000 DPI
Durability	Very Long	Small	Medium
Power Consumpti on	Large	Small	Large
Cost	High	Low	Very High

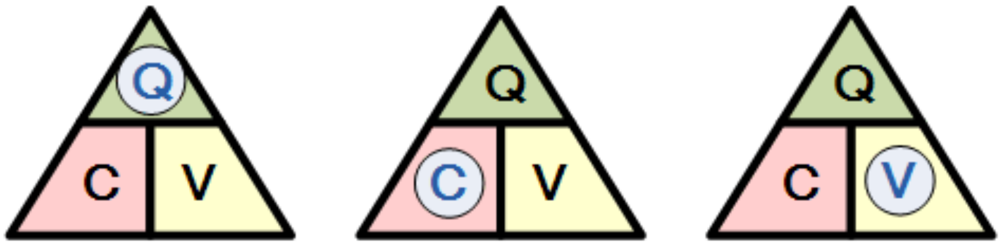
Advantages and Disadvantages of Capacitive Fingerprint Technology

- Difficult to cheat: capacitive fingerprinting uses the parameters of living fingers to form images of the fingers.
- Eliminate daily changes of fingerprints: fingerprint images are not affected by daily changes of fingerprints (e.g., wounds, dirt, etc.).
- Small size: easy to integrate into embedded devices.
- Low power consumption
- High resolution: typical capacitive fingerprint sensor with a resolution of 500dpi.

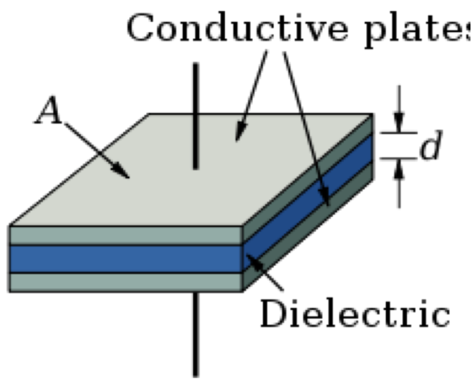
Capacitive Sensing Readout Circuits

Capacitive Sensing Schemes

- Sensing Schemes include:
  - Sample and Holding Scheme
  - Feedback Capacitive Sensing Scheme
  - Charge Transfer Scheme
  - **Charge Sharing Scheme**

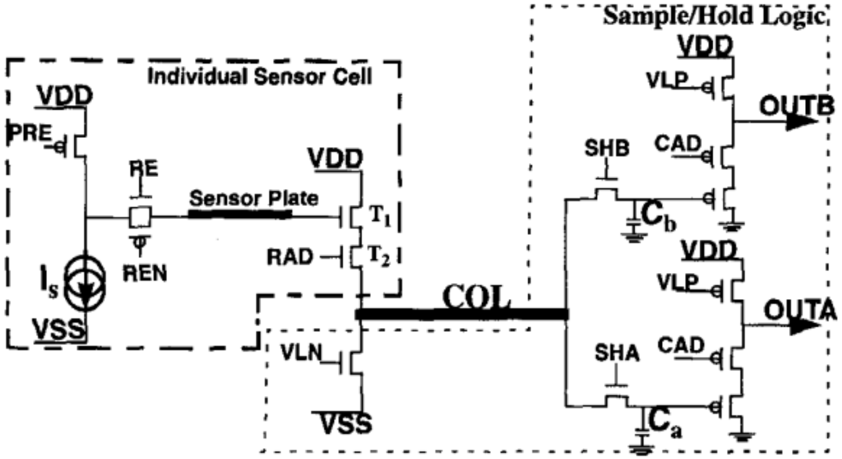


$Q = C \times V$ $\quad C = \frac{Q}{V}$ $\quad V = \frac{Q}{C}$



$$C = \frac{\varepsilon A}{d}$$

Sample and Holding Scheme*



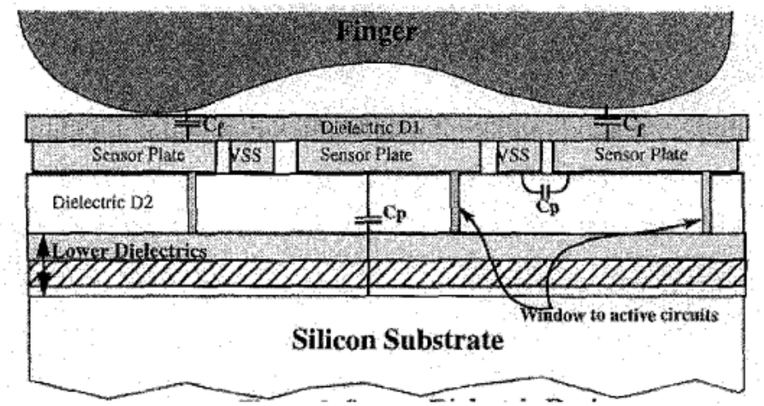
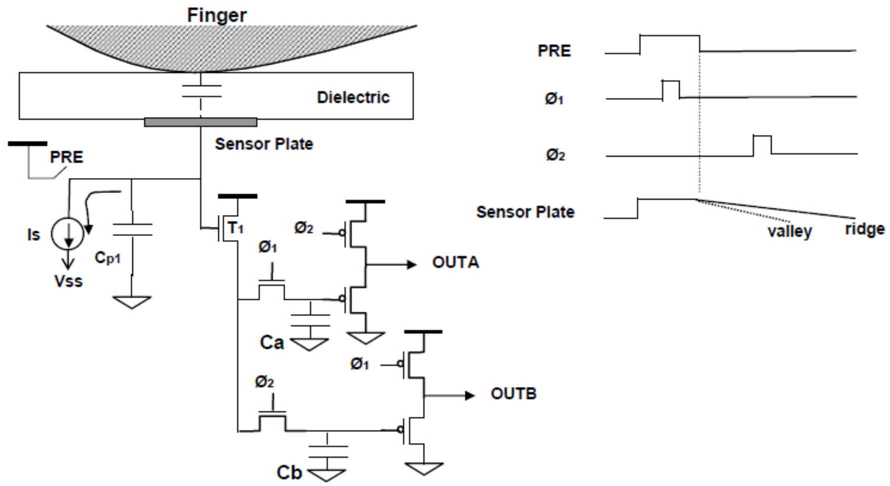


Figure 3: Sensor dielectric design.



500dpi Direct Contact Fingerprint Sensor

Die Size - 16.5mm X 15.5mm

Technology - 0.5µm, 3.3V, 3LM Digital CMOS

Sensor pitch - 50µm X 50µm

Array size - 300 X 300 sensors

Device count - 582K transistors

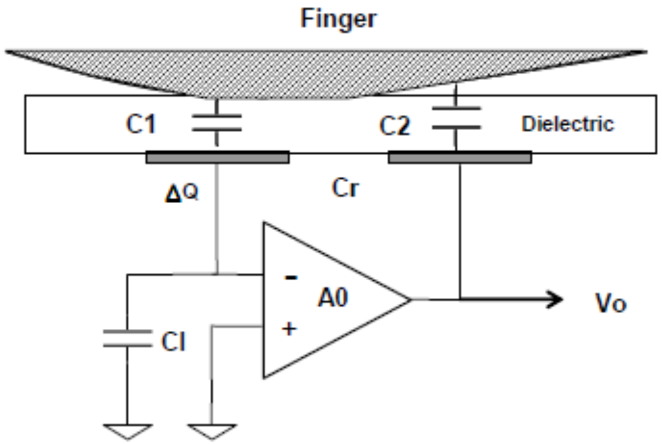
Resolution - 500dpi

Power - 250µW @ 1.8V and 60frm/s.

RAD: Row Select Address.
CAD: Column Select Address.

*Inglis C., Manchanda L., Comizzoll R., Dickinson A., Martin E., Mandis S., Silveman P., Weber G., Ackland B., O'Gorman L., "A robust 1.8 V 250 uW direct- contact 500 dpi fingerprint sensor," *45th ISSCC 1998 IEEE International Solid-State Circuits Conference 1998. Digest of Technical Papers*. pp. 284 – 285 5-7 Feb. 1998.

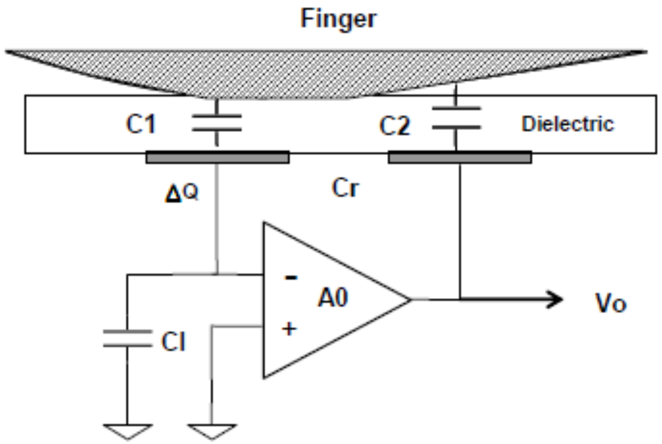
Feedback Capacitive Sensing Scheme*



- This approach is **based on two coplanar plates per cell** that interact with the overlying portion of the finger surface.
- The capacitance variation is sensed by a **charge amplifier** located in the cell area.
- Even if the capacitance per unit area is reduced, by **using this approach the small charge variation is sensed within the cell area**, thus increasing the noise immunity and the robustness of the readout structure.
- Furthermore, unlike other approaches, assumption of the finger surface at ground potential is not necessary.

*M. Tartagni and R. Guerrieri, "A Fingerprint Sensor Based on the Feedback Capacitive Sensing Scheme," *IEEE J. of Solid-state circuits*, vol.33, pp133-142, Jan. 1998.

Feedback Capacitive Sensing Scheme*



$$V = \frac{Q}{C}$$

- The feedback capacitance **Cr consists of three plates**; two of three plates are coplanar and face the third one. The third one is modeled as finger skin.
- If a ΔQ of charge is taken from the input, the following general expression of the output voltage can be derived:

$$\Delta V_o = \frac{\Delta Q}{\frac{Cl}{A0} + \left(1 + \frac{1}{A0}\right) Cr}$$

where Cl is the input capacitance and Cr is the feedback capacitance. If the gain of the amplifier A0 >> 1 and the parasitic capacitance Cp << Cr , then:

$$\Delta V_o \approx \frac{\Delta Q}{Cr} = \frac{\Delta Q}{C1 + C2}$$

A linear relationship of the output voltage versus distance between the plate and finger skin.

*M. Tartagni and R. Guerrieri, "A Fingerprint Sensor Based on the Feedback Capacitive Sensing Scheme," *IEEE J. of Solid-state circuits*, vol.33, pp133-142, Jan. 1998.

Charge Transfer Scheme*

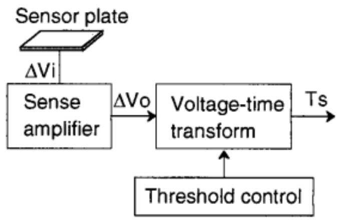


Fig. 1 Sensor cell architecture

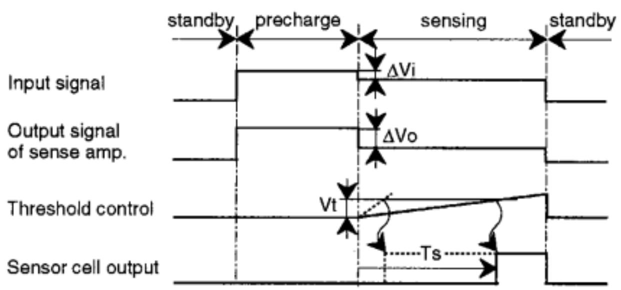


Fig. 2 Sensing operation

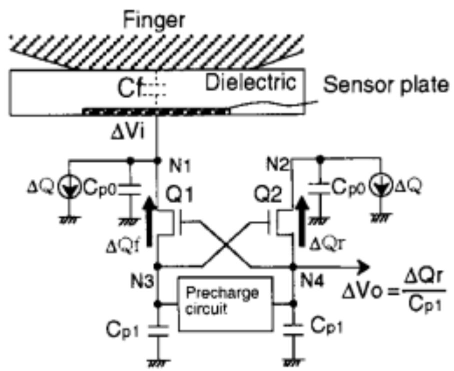


Fig. 3 Sensing circuit with charge-transfer amplifier

The sensing operation is as follows:

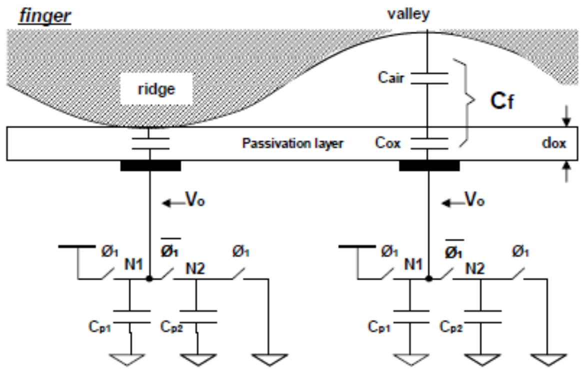
- First, **N1 and N2 are pre-charged** through Q1 and Q2.
- When Q is discharged from N1 and N2, the charge on N3 and N4 is transferred to N1 and N2 through Q1 and Q2.
- The voltage changes of N3 and N4 are Qf/Cp2 and Qr/Cp2, respectively, where Qf and Qr are the amount of transferred charge, and Cp2 is the capacitance of N1 and N2. Hence, *these voltage change are not dependent on Cp1 (i.e. Parasitics)*.
- For this circuit, ***Qf and Qr are not the same because the transconductance of Q1 and Q2 are different due to the difference of input voltages caused by Cf***.
- This causes the voltage difference between N3 and N4, and the output signal Vo is amplified by positive feedback.
- The differential scheme also reduces the variation of Vo due to the noise on the supply voltage and the subthreshold leakage current of Q1 and Q2.

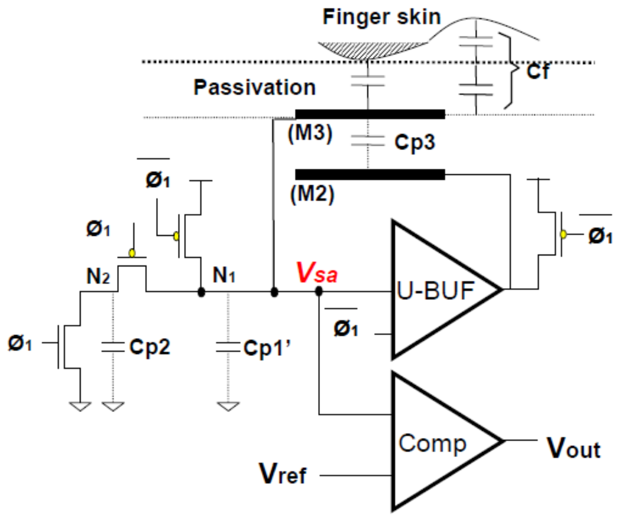
*H. Morimura, S. Shigematsu and K. Machida, ,"A High-Resolution Capacitive Fingerprint Sensing Scheme with Charge-Transfer Technique and Automatic Contrast Emphasis," 1999 Symposiμmon VLSI Circuits Digest of Technical Papers, Feb. 1999. pp157-160.

Charge Sharing Scheme*

- It is assumed that the potential of the finger surface is at some fixed potential. The only requirement is that the skin is an equipotential surface.
- The Cp1 and Cp2 represent the internal parasitic capacitance related to the nodes 1 and 2.
- The sensing operation is as follows:
    - In the **precharge phase**, the switches Ø1 is on. Then, the nodes N1 and N2 are precharged to VDD and GND, respectively.
    - At the beginning of the evaluation phase, the switches Ø1 is turned off, and Øbar1 is turned on.
    - Then, **the charges stored at the nodes N1 and N2 in the precharge phase are now redistributed between the nodes**.
    - The final voltage can be expressed as follows:

$$V_o = \frac{C_{p1} + C_f}{C_{p1} + C_{p2} + C_f} V_{dd}$$





- The output voltage Vo decreases sharply as the distance from the chip surface to the finger skin increases.
- This characteristic discriminates the ridges and valleys.

*Jeong-Woo Lee, Dong-Jin Min, Jiyoun Kim, Wonchan Kim, "A 600-dpi capacitive fingerprint sensor chip and image-synthesis technique," *IEEE Journal of Solid-State Circuits* Vol. 34 No. 4 pp. 469 – 475 April 1999.

Comparison of the Capacitive Sensing Schemes

Sensor detection type	Advantage	Disadvantage	Notes
Charge sharing	- Simple circuit - High image quality	- Influenced by a parasitic capacitance	Shielding can solve this issue
Charge transfer	- Simple circuit -Small leakage current	- Sensitive on process variation - Weakness on noise	Mismatches can reduce the accuracy
Feedback capacitive	- High image quality	- Charge injection - Low image resolution	Using coplanar increases the area of sensing plates→ reduces DPI
Sample and hold	- Simple circuit	- Use two dielectric materials by special sensor process - Long image capture time	Use of two circuits for comparison. (CDS concept)

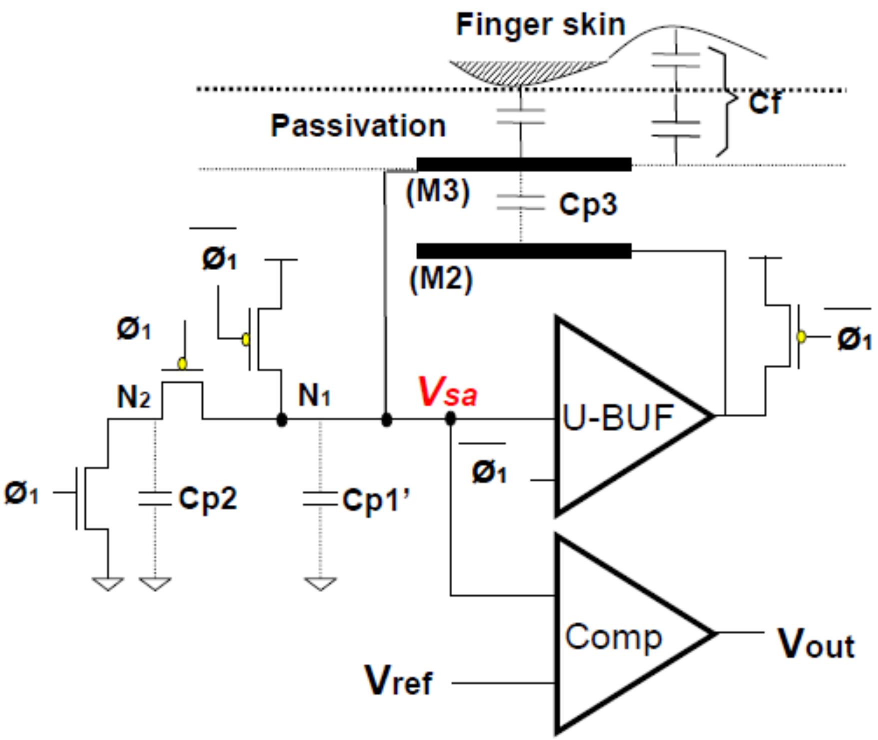
Design of Sensor Detection Circuit Based on Charge Sharing Scheme

Goal:

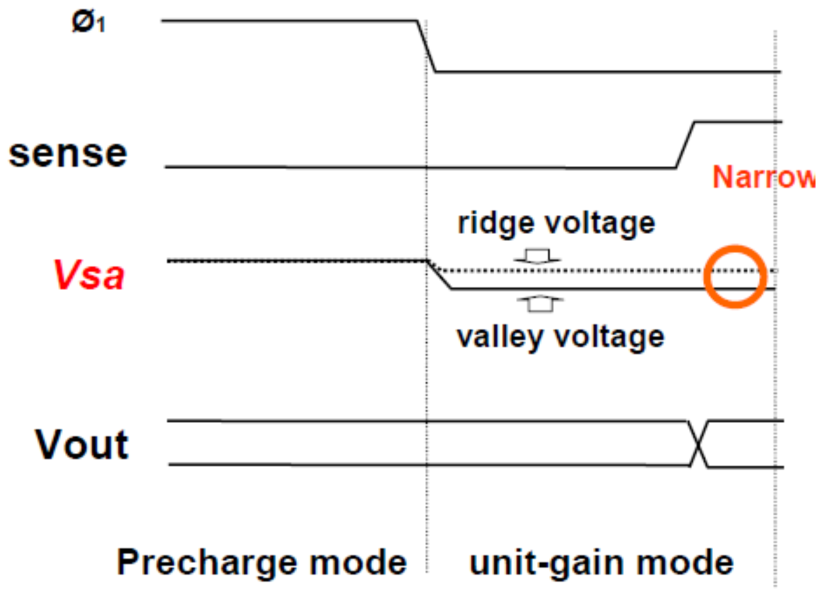
Minimize the influences of parasitics and ambient noise

Maximize the voltage difference between a ridge and valley

Typical Charge Sharing Circuit (Design 1)

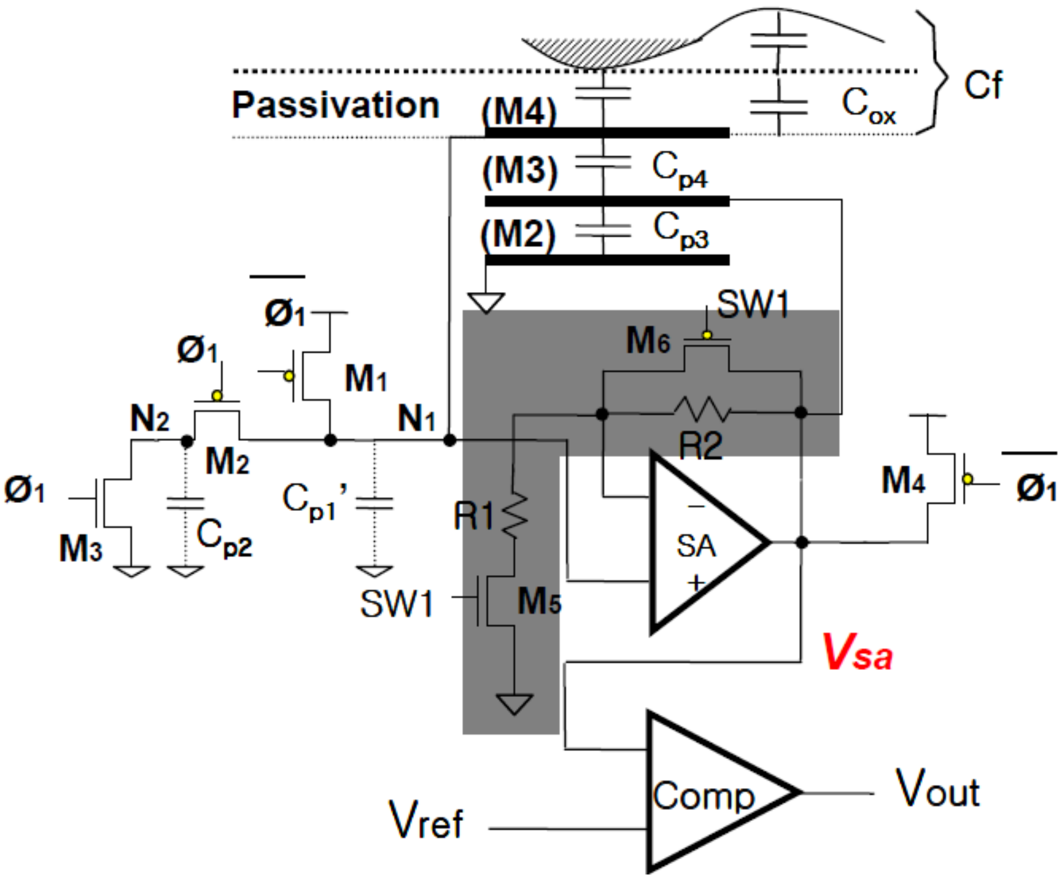


Typical Charge Sharing Circuit with unit-gain buffer (Design 1)

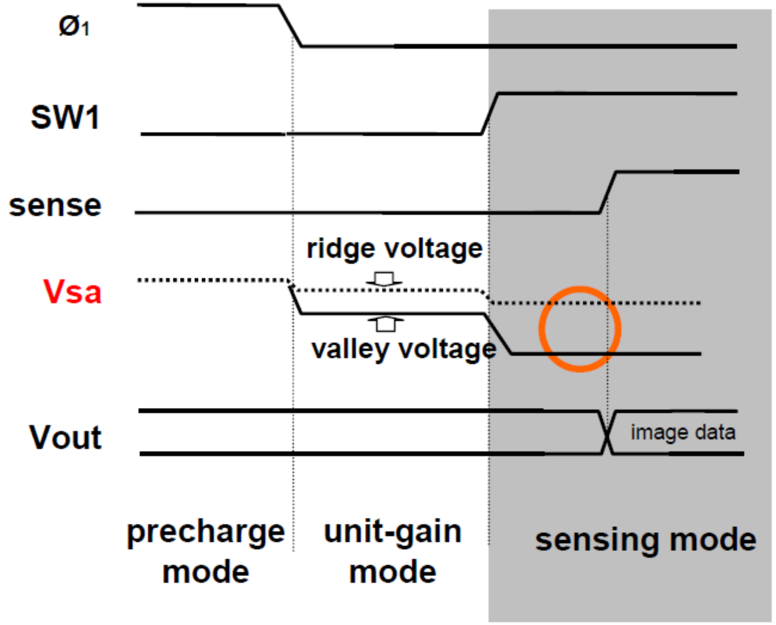


Timing diagram

Typical Charge Sharing Circuit (Design 2)

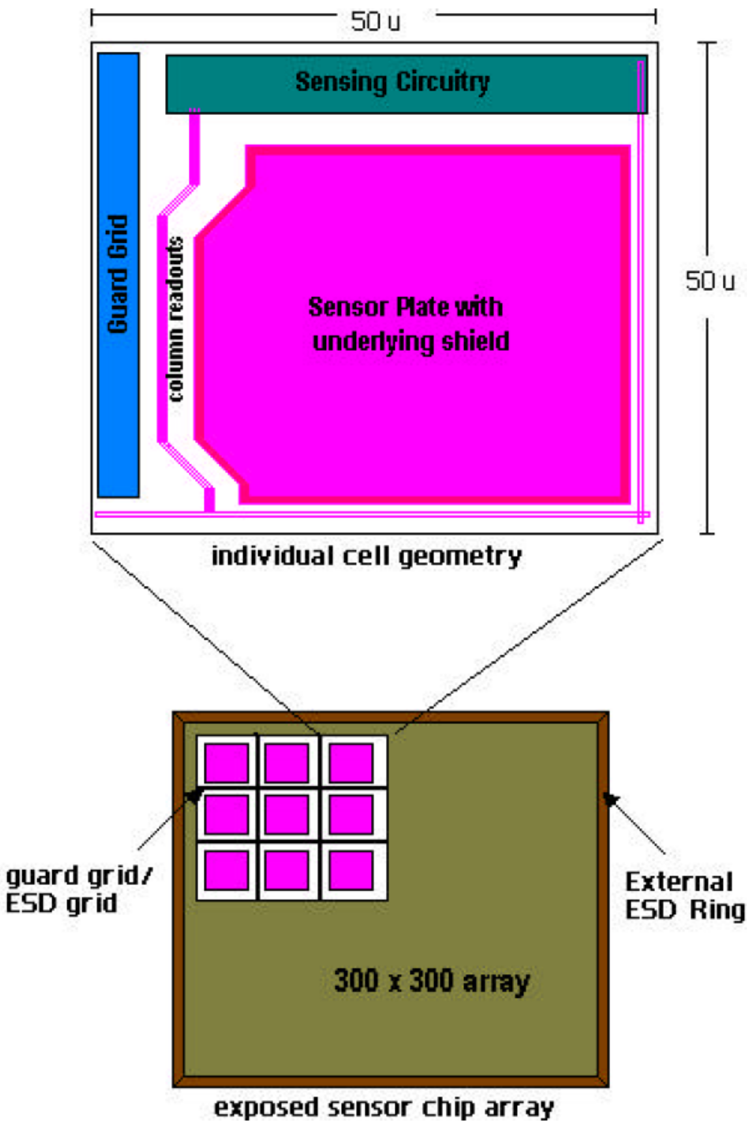


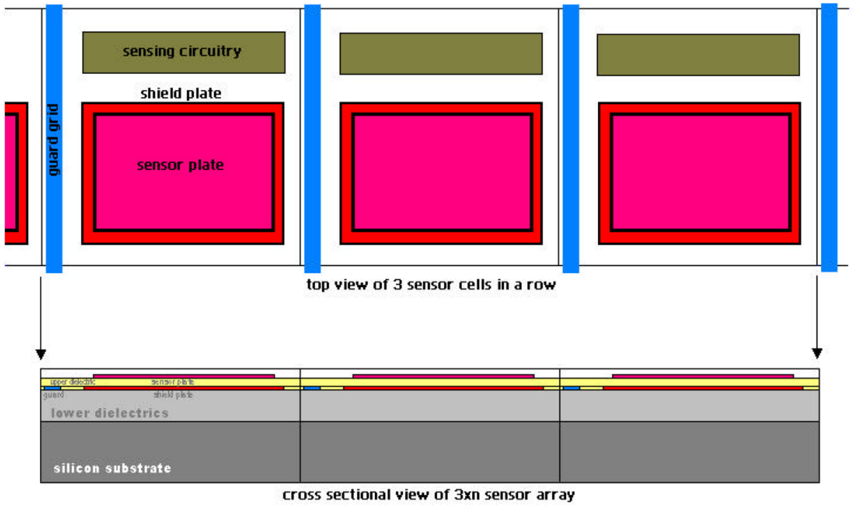
Typical Charge Sharing Circuit with Sensing amplifier (Design 2)



Timing diagram

Sensor Array and Sensor Cell*



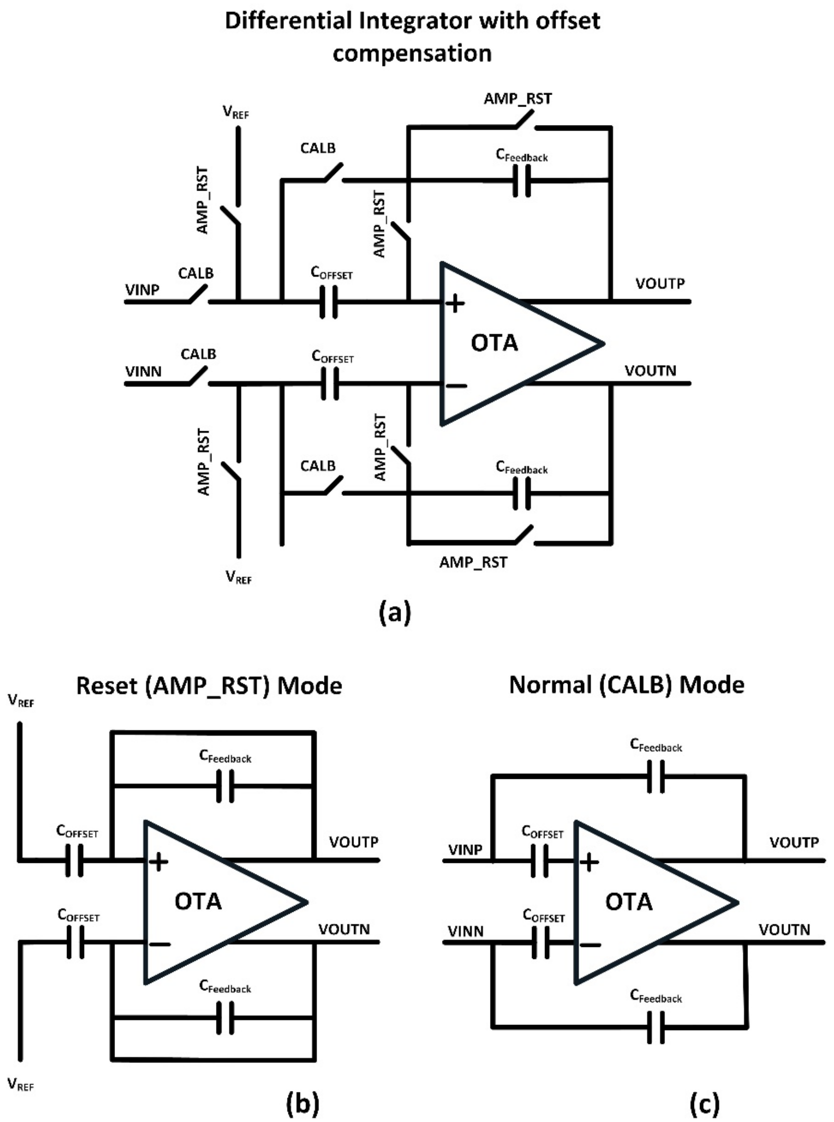


Each cell of size 50 x 50 micrometers has primarily a sensor plate, a shield plate, sensing circuitry and a guard grid, with over 60 % of the sensor cell area is devoted to the sensor plate.

Proposed Fingerprint Chip Design

Parallel Readout Circuit Using Differential Integrators

- It is composed of a fully-differential operational transconductance amplifier (OTA), feedback capacitors $C_{Feedback}$, offset cancellation capacitors C_{OFFSET}, and control switches AMP_RST and CALB.
- In each integration step, the controller repeatedly drives and reads the corresponding sensor cell.
- During the sensing mode, the controller turns on switch CALB, so the integrator charges $C_{Feedback}$. During the drive mode, it turns off CALB, so the integrator can hold its output voltages.

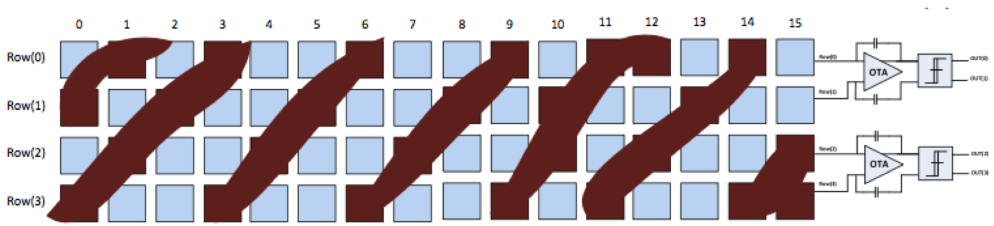


Fingerprint Detection Result

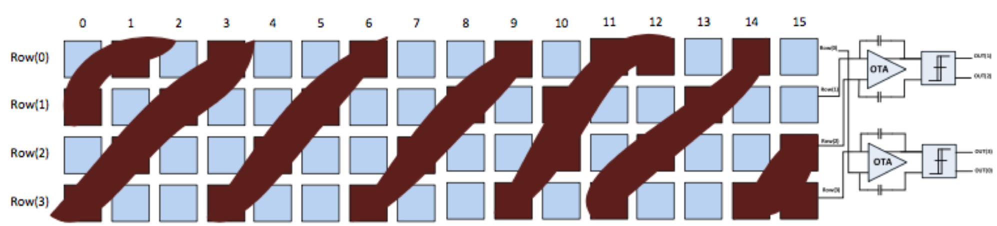
A sample of finger features.

Row \ Column	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	0	1	0	1	0	0	1	0	0	1	0	1	1	0	1	0
1	1	0	1	0	0	1	0	0	1	0	1	0	0	1	0	0
2	0	1	0	0	1	0	0	1	0	0	1	0	1	0	0	1
3	1	0	0	1	0	0	1	0	0	1	0	1	0	0	1	1

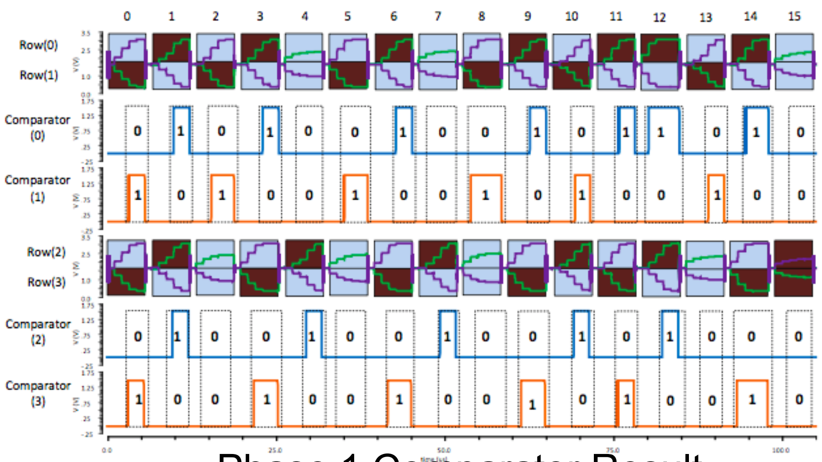
Reading Phase 1 (Even rows)



Reading Phase 2 (Odd rows)

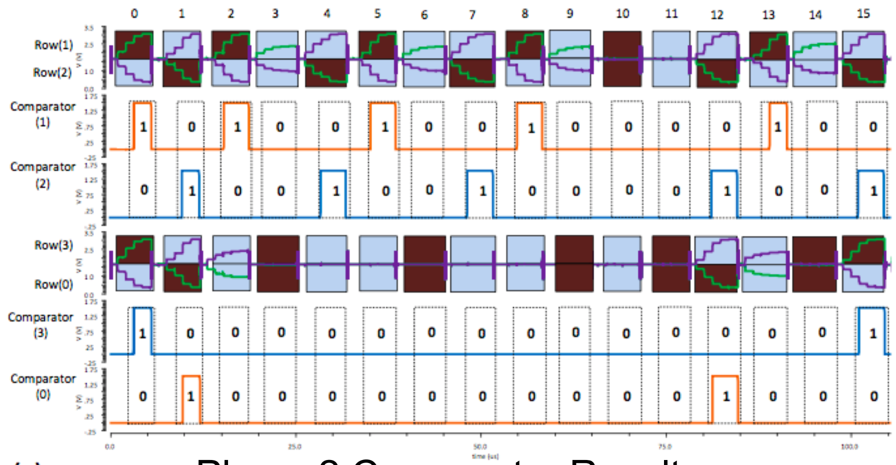


(b)



Phase 1 Comparator Result

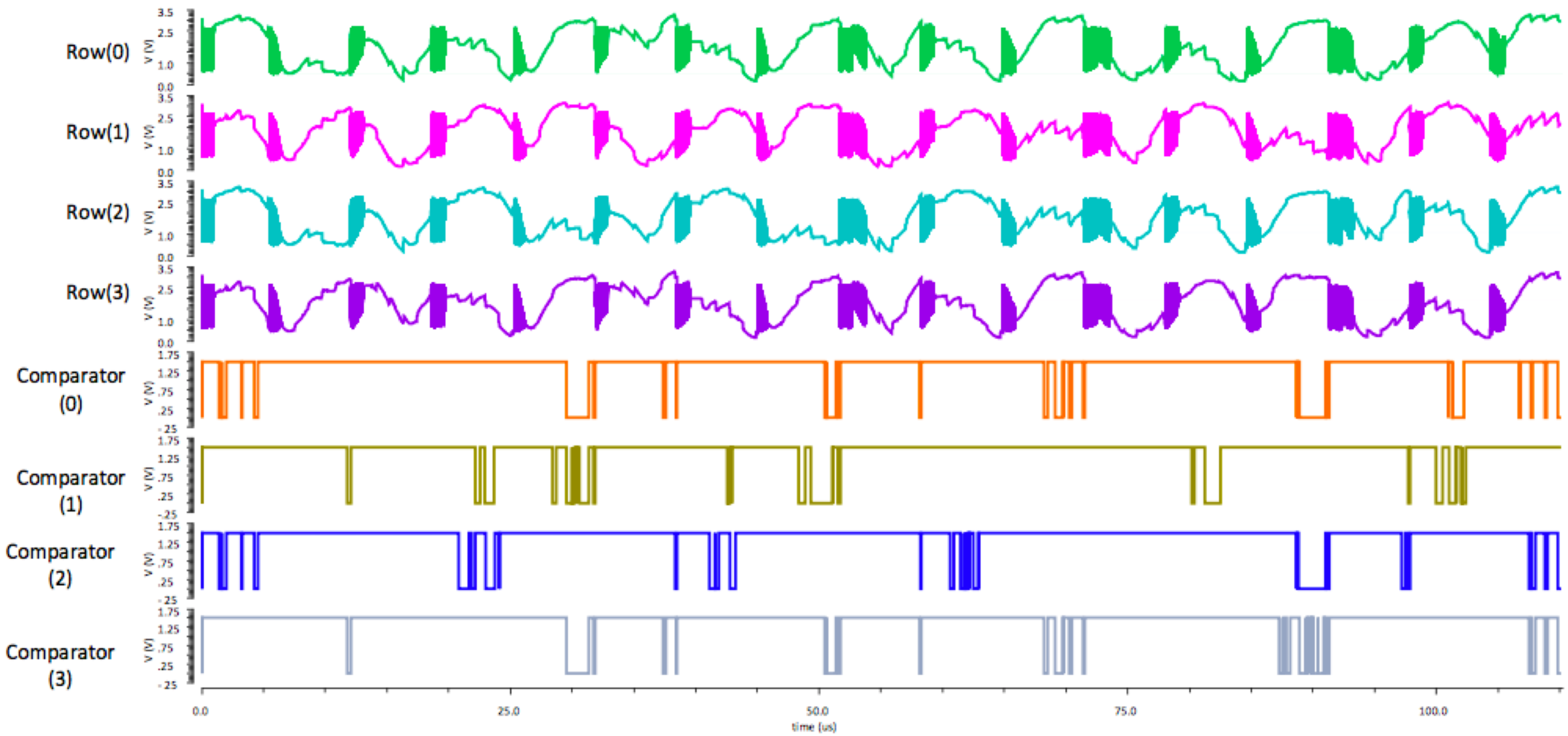
(c)



Phase 2 Comparator Result

Comparison with Single-ended Fingerprint Sensing

- Single-ended integrator output cannot provide the exact decision under the noisy environment



Sensitivity Performance Comparison

- SNR Calculation Method for Capacitor Sensors
  - Comparison of the sensitivity SNR between the differential sensing and single-ended sensing techniques.

$$Signal_{(R\ or\ V)} = AVG_{(R\ or\ V)}$$

$$Noise = \sqrt{\frac{\sum_{i=0}^{n}(Signal(i)_{(R\ or\ V)} - AVG_{(R\ or\ V)})^2}{n}}$$

$$SNR(dB) = 20\log\left(\frac{Signal_{(R\ or\ V)}}{Noise}\right)$$

Noise Signal applied for Simulation

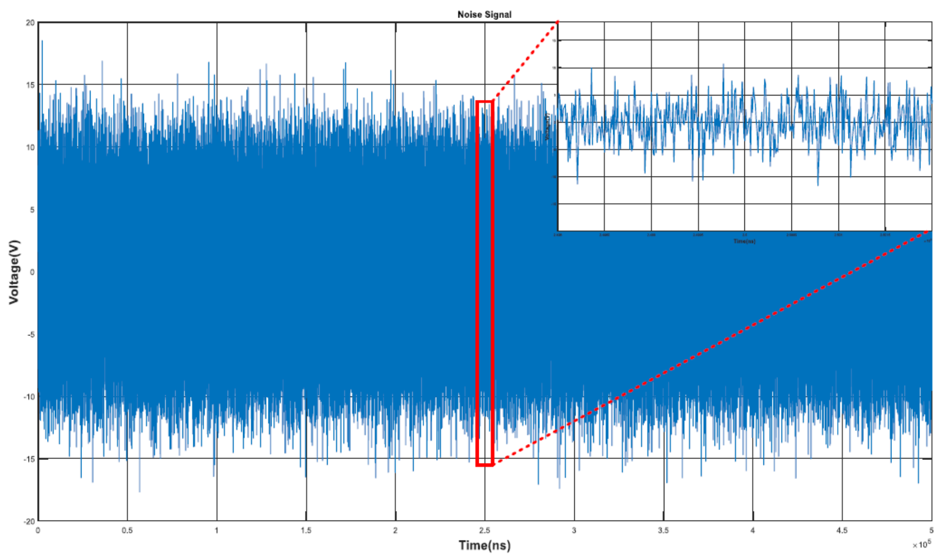


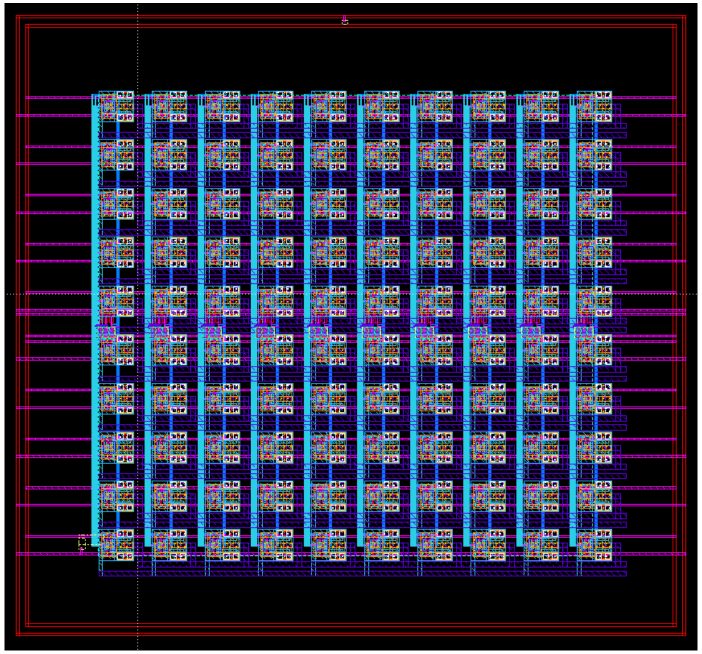
Table 3. SNR for Different Cases of Finger Features.

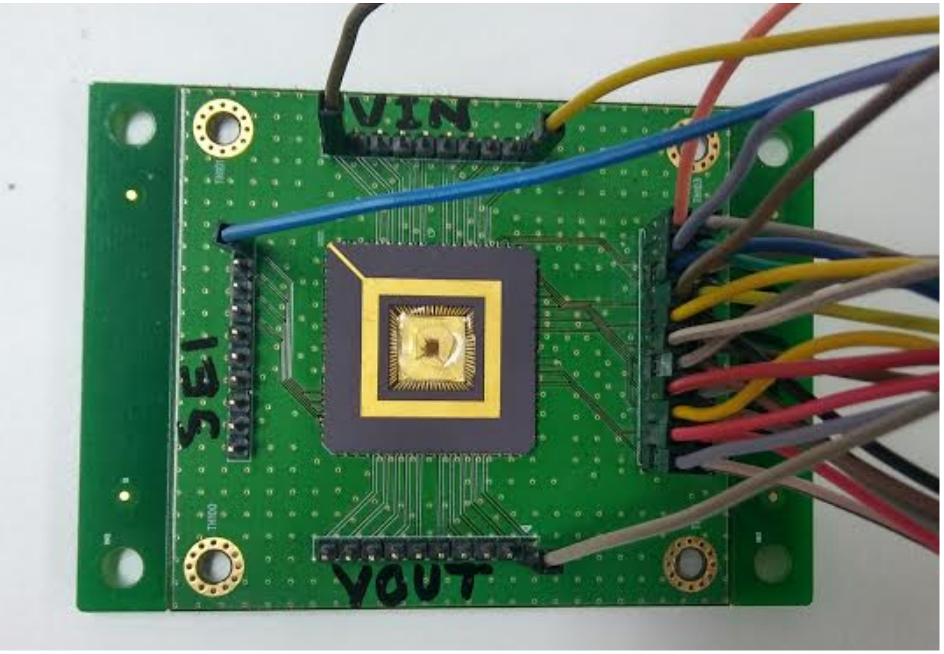
	Readout Circuit Input	Single-Ended Integrator Output	Differential Integrator Output	
Fingerprint Pattern	-	Valley-Ridge	Valley-Ridge	Ridge-Valley
SNR(dB)	0.62	13.62	53.99	54.01
SNR gain (dB)	-	13	53.37	53.39

Implemented Fingerprint Chips

Implementation of 1st Fingerprint Sensor Chip (Samsung 65nm Process)

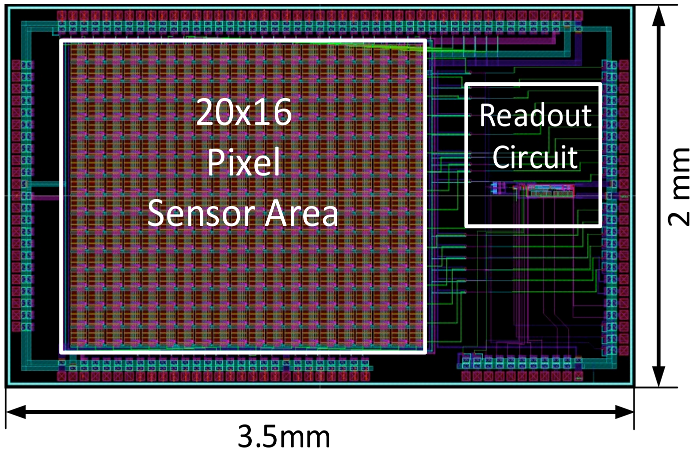
- 10x10 Fingerprint sensor array.
- Only Sensor Cells are Integrated
- Readout circuit and MCU are external



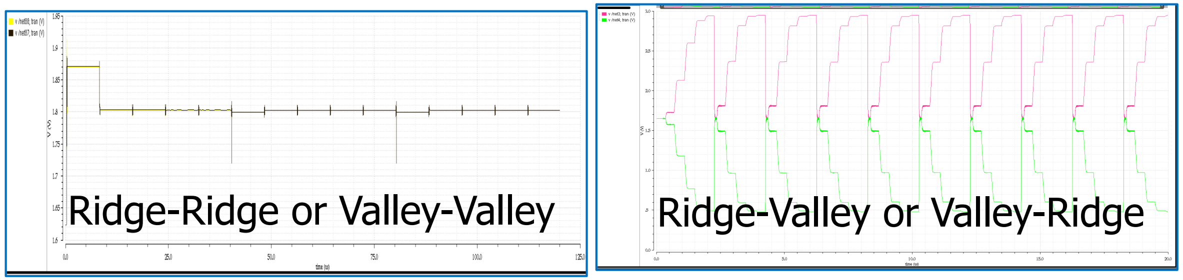


Implementation of 2nd Fingerprint Sensor Chip (MagnaChip 130nm Process)

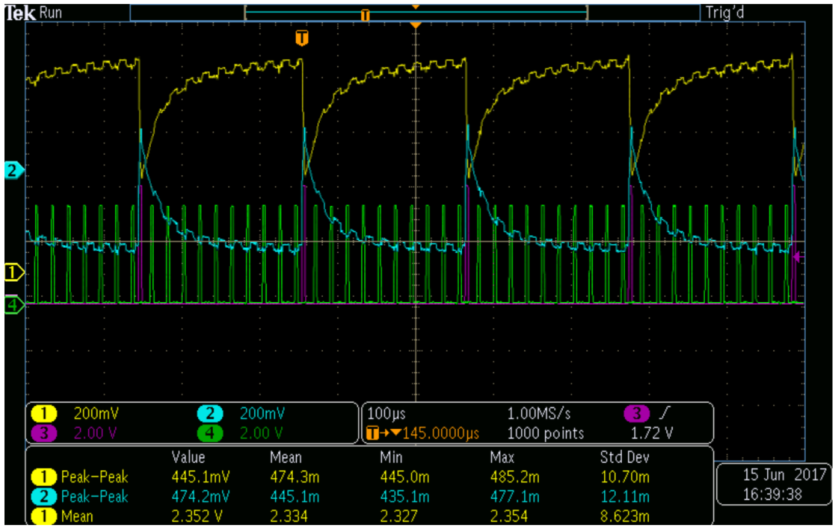
- ❑ Used Differential Sensing Circuit
- ❑ Sequential Sensing Architecture
- ❑ Sensing circuit is on-chip

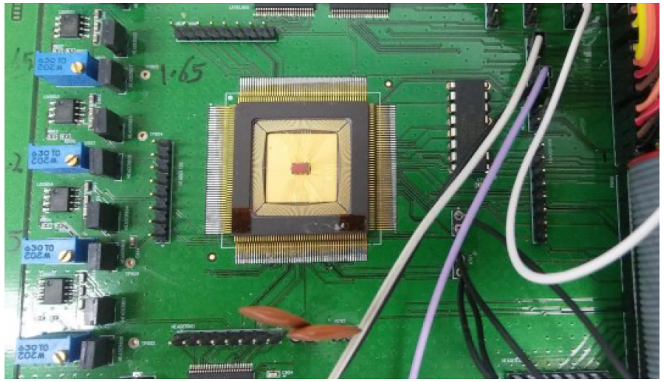


Output of the Integrator



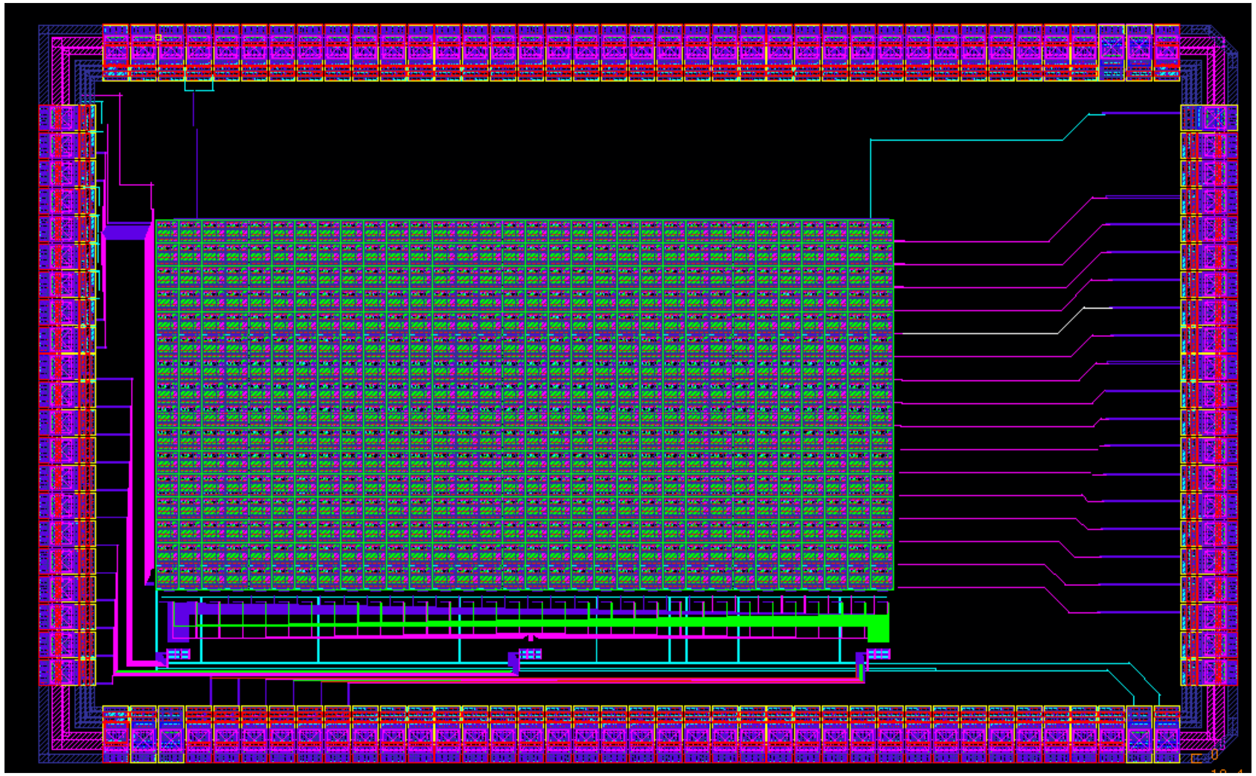
Measurement of the Integrator Output





Implementation of 3rd Fingerprint Sensor Chip (MagnaChip 130nm Process)

- Configurable Amplifier and Dynamic Comparator
- Parallel Differential Sensing Circuit
- Optional comparator circuits in each sensor cell



Future Work