An ultra-low power mixed signal SoC for detrusor pressure sensing capsules and a brief introduction of the researches on IC technology for biomedical applications in Japan

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Contents

• An ultra-low power mixed signal SoC for detrusor pressure sensing capsules
  – An ultra-low power capacitance to digital converter
  – An ultra-low power resonated inductive coupling communication in the distance of 15 cm

• A brief introduction of the researches on IC technology for biomedical applications in Japan
  – Retinal prosthetic devices
  – Brain Implantable devices
  – ISFET or relevant devices
An ultra-low power mixed signal SoC for detrusor pressure sensing capsules
A measurement of detrusor function by monitoring the bladder pressure over three days is required to the patient. A tube is inserted to the bladder through the urethral tube.
Capsule to measure the bladder pressure

It can measure the bladder pressure and send the data in short range (15 cm) for 3 or 4 days.

Due to short battery life
4 days with total current of 100uA

All analog and RF circuits are allowed to consumes only 30uA
Developed SoC

We have developed a low power mixed signal SoC suitable for detrusor sensing capsules.

V\text{DD}: 1.55V
Logic gates: 28.5k
ROM: 6KB
RAM: 8KB
CLK: 161kHz
P\text{d}: 94uW

2.5mm x 2.5mm
0.18um CMOS
Analog and RF circuits in the SoC

V_{DD}: 1.55V
Standby current: 4uA
Com. Length: 15cm
Data rate: 5kbps
Data transfer efficiency: 230pJ/bit
RF frequency: 15cm
Capacitive sensor interface

Capacitive pressure sensor is used because of no static power. An ultra low power capacitance to digital converter is required.

Conventional circuits

- C/Freq converter & FM <4mW
  - Coding and Re-transmission is difficult
- C/Volt converter & ADC
  - Enlarged area and power consumption
- C/Digit converter (ΔΣ type) <4.25mW
  - OpAmp: Large power consumption

A. Matsuzawa Titech, NTU MEW 2012.11.29
We have developed an ultra-low power capacitance to digital converter (CDC) using SAR ADC method.

- Ultra-low power (No OpAmp)
- It can compensate the offset capacitance
- Small area
- Insensitive to the supply voltage

Kota Tanaka, Yasuhide Kuramochi, Takashi Kurashina, Kenichi Okada, and Akira Matsuzawa

“A 0.026mm² Capacitance-to-Digital Converter for Biotelemetry Applications Using a Charge Redistribution Technique”
A-SSCC 2007
An offset capacitance should be cancelled and the CDC dynamic range should be matched with that of the capacitive sensor range.
Solution & novelty

1. Offset canceling
2. Reference voltage scaling

Full range conversion
1. Store the charge at each node.
2. Charge conservation
3. MSB conversion

\[ V_x - V_{cm} = \frac{V_{DD}}{C_{total}} (C_R + C_{MSB} - kC_x) \]
3. MSB conversion

\[ V_x - V_{cm} = \frac{V_{DD}}{C_{total}} (C_R + C_{MSB} - kC_x) \]
4. Capacitance comparison

\[ V_x > V_{cm} \iff \frac{V_{DD}}{C_{total}} \left( C_R + C_{MSB} \right) - kC_x > 0 ? \]
Conversion feature

\[ \frac{V_{DD}}{C_{total}} \left( \frac{C_R}{C_{MSB}} + \frac{C_{MSB}}{C_x} - kC_x \right) > 0 ? \]

1. \( V_{DD} \) does not affect the conversion result

\( V_{DD} \) : Supply voltage

2. Offset is canceled

\( C_R \) : Offset canceling capacitor

3. Sensor capacitance is scaled

\( k \) : scaling factor
Chip photo and performance

1st CDC chip demonstrated the basic idea of the CDC. However, power consumption was still not sufficiently low.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Resolution</td>
<td>8 Bit</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>1.4 V</td>
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<tr>
<td>Sampling Rate</td>
<td>262 kHz</td>
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<tr>
<td>SNR</td>
<td>43.22 dB</td>
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<tr>
<td>ENOB</td>
<td>6.83 Bit</td>
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<tr>
<td>Current Consumption</td>
<td>169 (\mu)A</td>
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<tr>
<td></td>
<td>360 (\mu)A (when using internal clock)</td>
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<tr>
<td>Minimum DNL</td>
<td>-0.97 LSB</td>
</tr>
<tr>
<td>Maximum DNL</td>
<td>0.79 LSB</td>
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<tr>
<td>Minimum INL</td>
<td>-1.27 LSB</td>
</tr>
<tr>
<td>Maximum INL</td>
<td>0.99 LSB</td>
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<tr>
<td>Area</td>
<td>0.026 mm(^2)</td>
</tr>
<tr>
<td></td>
<td>0.034 mm(^2) (when including clock)</td>
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</tbody>
</table>

Ex) \(\Delta\Sigma\) CDC 4.2mW

2012.11.29
A. Matsuzawa Titech, NTU MEW
Second version CDC has been developed and attained an ultra-low power consumption.

1. 10b SAR like architecture
2. Single to differential
3. Self-clocking

3nA @ 30 times/sec

Tuan Minh Vo, Yasuhide Kuramochi, Masaya Miyahara, Takashi Kurashina, and Akira Matsuzawa
“A 10-bit, 290 fJ/conv. Steps, 0.13mm2, Zero-Static Power, Self-Timed Capacitance to Digital Converter.”
SSDM 2009, OCT.
A differential scheme can be realized by inserting the sensor between the differential input terminals. It increases an accuracy and realizes the stable operation.

\[
V_X - V_Y = \frac{1}{16} C(B_{10} + B_9 + \ldots + B_n) - kC_{X_{\text{sam}}} \quad 2C_{X_{\text{con}}} + \left[ C_m + 2^5 C + \ldots + C + \frac{C_S(2^3 C + \ldots + C)}{C_S + 2^3 C + \ldots + C} \right] \cdot \frac{V_{\text{ref}}}{V_{\text{ref}}}
\]
A dynamic comparator is very high speed, yet consumes no static power.

It can realize an ultra-low power A/D conversion.


2012.11.29  A. Matsuzawa Titech, NTU MEW
Self clocking technique

Self-clocking technique is very useful for ..

1) Reducing power consumption (Clock circuits, routing clock, )
2) Just an enable command signal is required. No need of clock.
   Suitable for micro controller.

Comparison is ended if the output voltages are not same.

Output voltage of the dynamic comparator

Self-clocking scheme

2012.11.29
A. Matsuzawa Titech, NTU MEW
Accuracy of the CDC

High accuracy as an impedance meter.

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Accuracy of the CDC

High accuracy as an impedance meter.
Performance comparison

<table>
<thead>
<tr>
<th></th>
<th>Version 1</th>
<th>Version 2</th>
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</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>1.4 V</td>
<td>1.4 V</td>
</tr>
<tr>
<td>Resolution</td>
<td>8 bit</td>
<td>10 bit</td>
</tr>
<tr>
<td>Current consumption of CDC</td>
<td>169 uA</td>
<td>8.45 uA</td>
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<tr>
<td>Conversion Frequency</td>
<td>262 kSps</td>
<td>262 kSps</td>
</tr>
<tr>
<td>Area</td>
<td>0.026 mm² (C_m = 3.6pF)</td>
<td>0.11 mm² (estimated) (C_m = 10pF x 2)</td>
</tr>
</tbody>
</table>

Ultra-low power
High resolution
Stable for change of capacitance

2012.11.29
A. Matsuzawa Titech, NTU MEW
Wireless communication

Resonated inductor coupling can communicate in 15 cm distance.

Store the energy in the capacitor

Release the energy

13.5 MHz

Communication distance (cm)

BER

V_n=10mV

V_n=2mV

V_n=1mV

2012.11.29 A. Matsuzawa Titech, NTU MEW
Wireless data transmission

Very simple circuits to recover the data

Input data | Received | Amplified | Envelope | Output data
---|---|---|---|---

[Graph showing signal levels and circuit components]

2012.11.29

A. Matsuzawa Titech, NTU MEW
We had a plan to develop the body surface chip to communicate with the in vivo chip.
A brief introduction of the researches on IC technology for biomedical applications in Japan

Courtesy of Prof. Ohta, NAIST
Biomedical Device Researches in Japan

• Retinal prosthetic devices
  – NAIST/Osaka U/Nidek

• Brain implantable device
  – NAIST
  – Toyohashi Tech
  – Osaka U/NICT

• ISFET or relevant devices
  – Toyohashi Tech
  – U of Tokyo
  – Nagoya U
Retinal prosthetic devices


Retinal prosthetic devices

Total system of retinal prosthesis has been developed

NAIST/Osaka U/Nidek

Courtesy of Nidek Co., Ltd.
Components of retinal prosthesis

- Primary coil and camera
- Signal processing system
- Secondary coil
- Rx circuits
- Return electrode
- Stimulus electrode array

Courtesy of Nidek Co., Ltd.

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Implantation of retinal prosthetic device


Wireless circuits & Current generator

Semi-chronical trials
Implanted in one month


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A. Matsuzawa Titech, NTU MEW
Retinal stimulator: Multi-microchip architecture

[Backside] [Stimulus side] [Microchip]

Distributed place of microchips
- Reduction of the wire number
- Mechanical flexibility

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Fabricated distributed retinal prosthesis device

(For rabbit: 1x4 microchips)

Stimulation experiment of rabbit’s retina

No need of opening the eye ball, the device is mounted on a sclera pocket. A wide view can be obtained, since large area can be used on the sclera.

A stimulus device is mounted on a sclera pocket

According to the guideline of the experimental animals’ protocols of Osaka Univ.

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Retina stimulation experiment

EEP signals from multiple microchips

Pulse width: 500 µs, Current amp.: 500µA, Anodic single pulse

Clear EEP signals were obtained corresponding to the different microchip

EEP (Electrical Evoked Potential) Response in rabbit’s visual cortex

A. Matsuzawa Titech, NTU MEW

2012.11.29
Brain Implantable Devices


Implantable micro imager

By using fluorescent labels and the implantable micro imagers, an intra-brain activity can be visualized, even at free action.
CMOS micro imager

Implanted into the brain of a freely-moving mouse

CMOS sensor with only 4 IOs (VDD, GND, CLK, OUT)

Captured image

Implantation in mouse brain

A. Matsuzawa Titech, NTU MEW

2012.11.29
Toyohashi Tech has developed the micro-Si probe electrode arrays for probing the cells. They glowed with the vapor phased epitaxy on the silicon substrate.

Tohoku University has developed Si Double-sided Micro-electrode. An optical waveguide and a micro-fluidic channel can be formed.

Osaka university has developed the wireless sensor device to monitor the brain activity.


A. Brain surface microelectrodes conformable to the outer surface of the individual brain.
B. Brain surface microelectrodes conformable to the brain groove.
C. A titanium head casing / artificial skull bone.
D. A fluorine polymer body casing.
E. A wireless rechargeable unit, F. A wireless data transfer unit.

A: Target frequency bands and gains to cover ECoG signals and local field potentials (LFP). B: A circuit schematic of low-noise amplifier. C: A 128-channel integrated analog amplifier board.
ISFET or relevant devices


Toyohashi Tech has developed the pH image sensor of which sensitivity can be increased by the charge accumulation method.

The 2D pH imager can visualize the synaptic activity.
Extended gate MOSFET

The university of Tokyo has developed the “Genetic FET” that can detect the specific DNA by measuring the charge.


A. Matsuzawa Titech, NTU MEW
Extended gate MOSFET array

Nagoya University has developed an IC for the biosensor array.

Extended-gate MOSFET Biosensor Array LSIs

Kazuo Nakazato, Mitsuo Ohura, Kiyomasa Sugimoto, Junichi Tsukada, and Shigeyasu Uno
Department of Electrical and Computer Science, Graduate School of Engineering, Nagoya University

- label free, electrical detection
- system-on-a-chip + lab-on-a-chip

Detection of biomolecules
- sensor device structure
- device fabrication process
- control circuit of sensor device
- sensing signal processing
- sensing methods

Control of biomolecules
- physical movement of molecules
- enhancement and suppression of molecular interactions
- supply of biomolecules

Fabrication of Device and Measurement Method

1. Fabrication of chip using standard CMOS process
   - LOCOS (800nm 0.35μm, Motola 1.2μm)
2. Formation of Extended Gate
   - Au/Ti evaporation
   - optical photolithography
   - plasma O2
   - Au wet etching
   - Ti wet etching
   - Ti/C oxide
   - Removal of resist
3. Hybridization of target DNA
4. Measurement

1M(10^6) cell array

- technology: 0.35μm CMOS
- array size: 20mm x 24.6mm
- power consumption: 64mW

Target: Genomic Analysis of 10 bases (410) simultaneously


2012.11.29
A. Matsuzawa Titech, NTU MEW
Summary

• An ultra-low power mixed signal SoC for detrusor pressure sensing capsules

An ultra-low power sensor and sensing circuit (3nA@30S/s: CDC) are possible by using the capacitive sensor, SAR architecture, the dynamic comparator, and the self clocking techniques.

• A brief introduction of the researches on IC technology for biomedical applications in Japan

IC technology for biomedical applications is not so much active in Japan. However, the retinal prosthetic devices becomes very practical and the micro-Si probe electrode arrays and 2D imaging sensor devices, (e.g. pH sensor array) look interesting.