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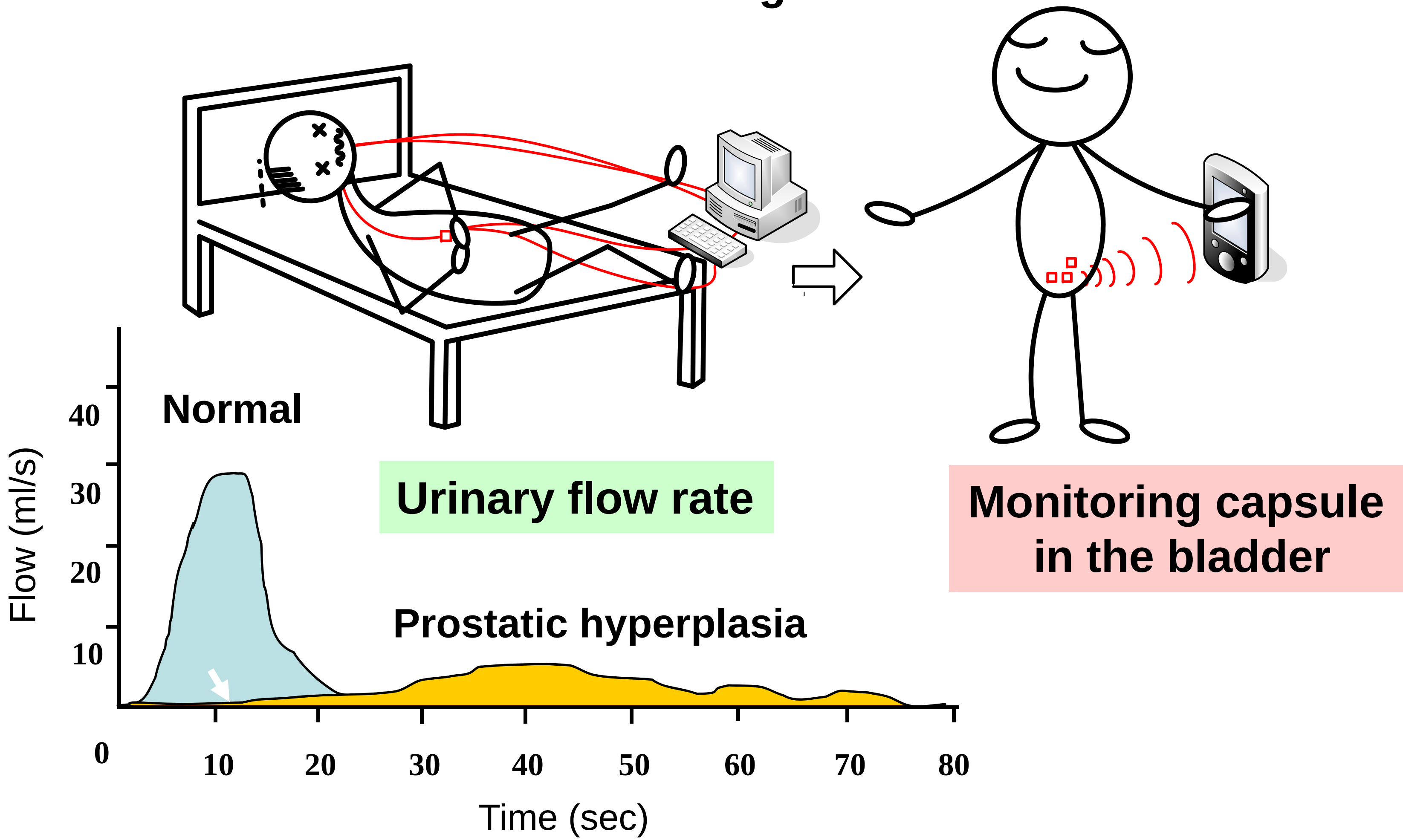
An ultra-low power mixed signal SoC for detrusor pressure sensing capsules

TOKYO TECH
Pursuing Excellence

Matsuzawa & Okada Lab.

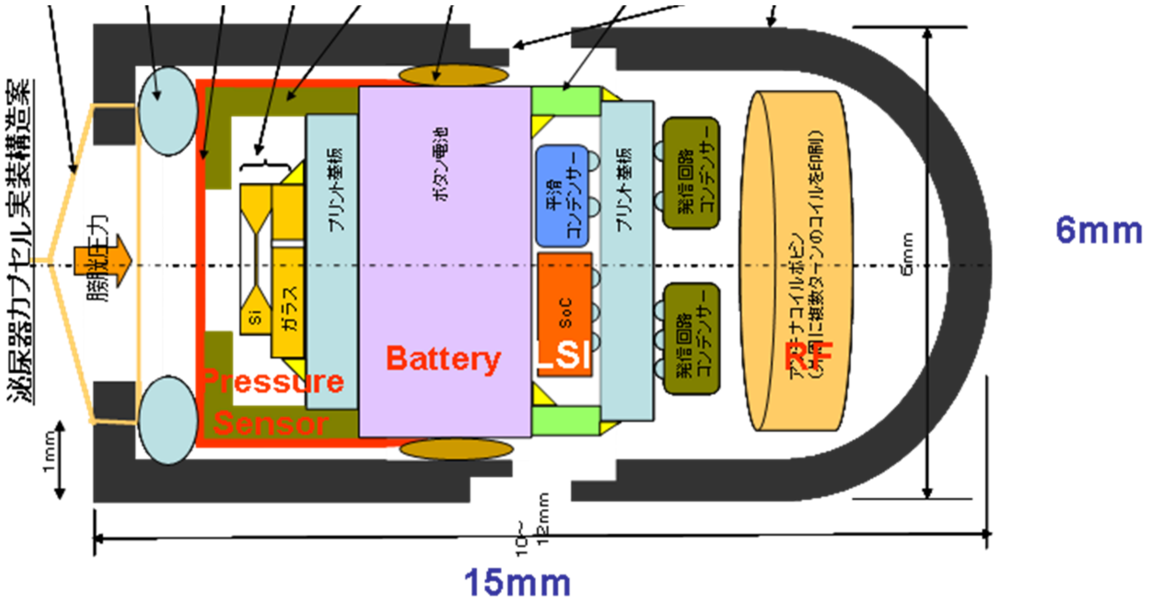
Current measurement of detrusor function

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

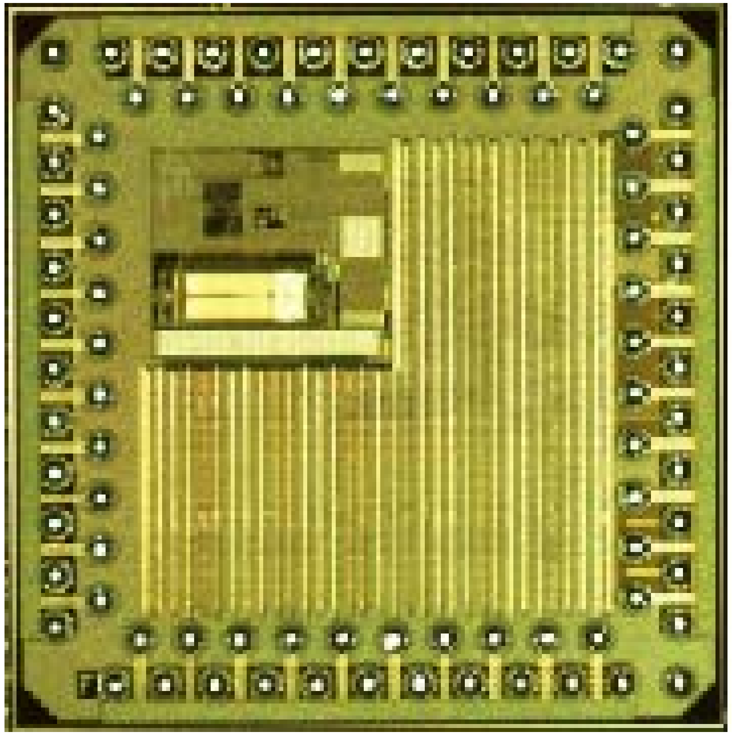
Image: Capsule in bladder

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

Developed SoC

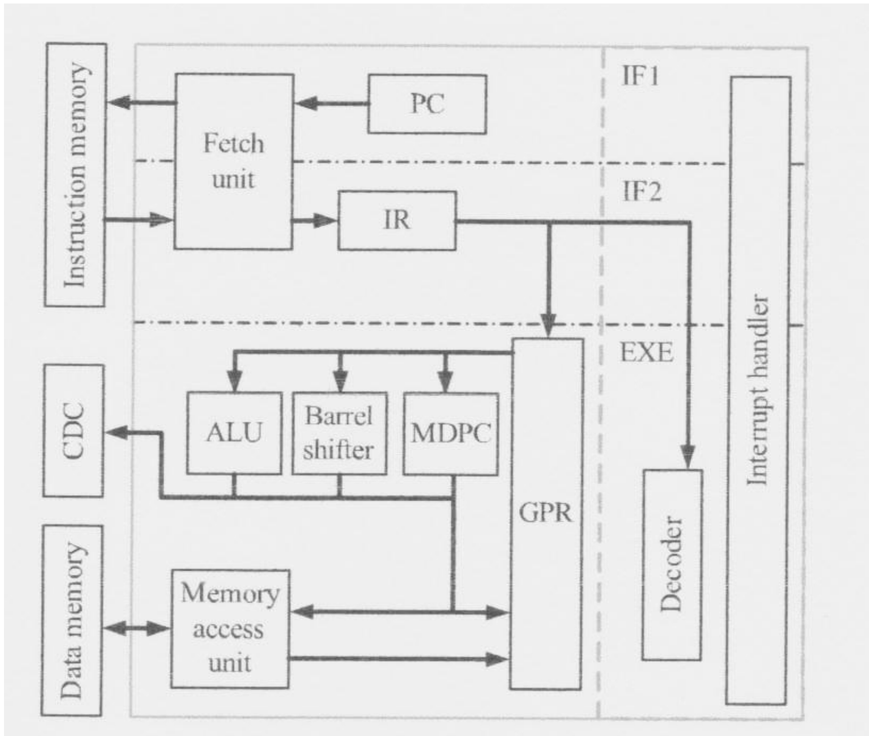
We have developed a low power mixed signal SoC suitable for detrusor sensing capsules.

V_{DD}: 1.55V
Logic gates:28.5k
ROM: 6KB
RAM: 8KB
CLK: 161kHz
P_d: 94uW

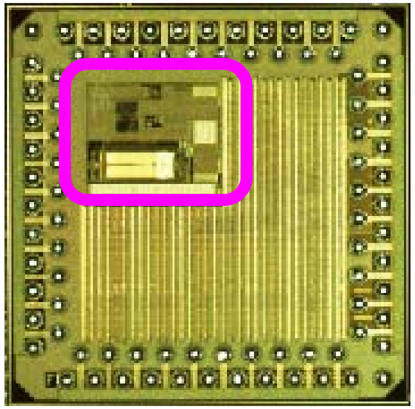


2.5mm x 2.5mm
0.18um CMOS

Block diagram

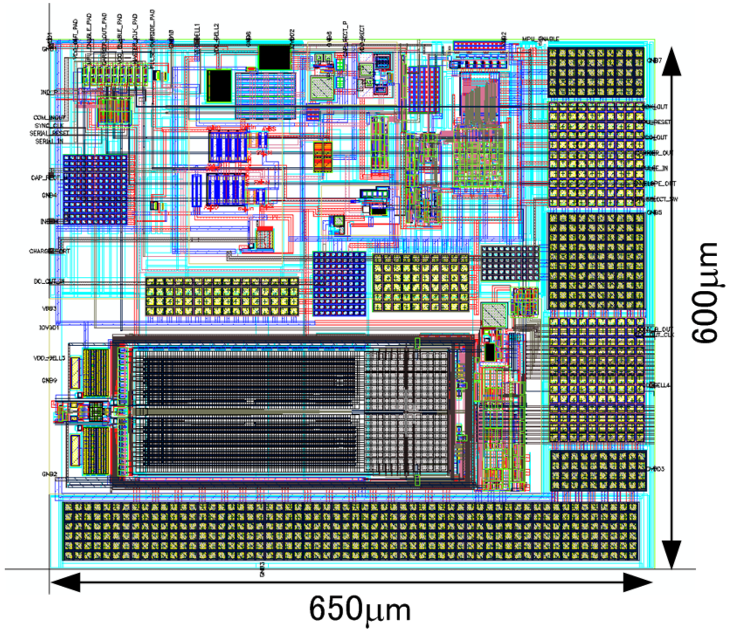


Analog and RF circuits in the SoC

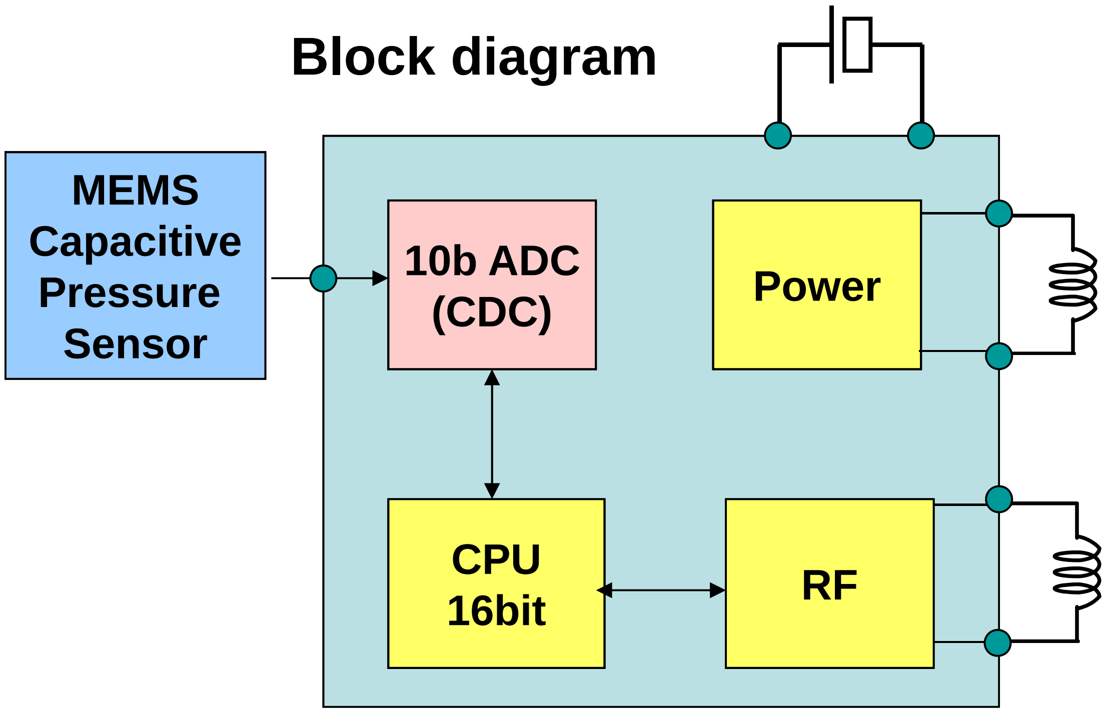


V_{DD}: 1.55V
Standby current: 4uA
Com. Length: 15cm
Data rate: 5kbps
Data transfer efficiency: 230pJ/bit
RF frequency: 15cm

Analog and RF circuits

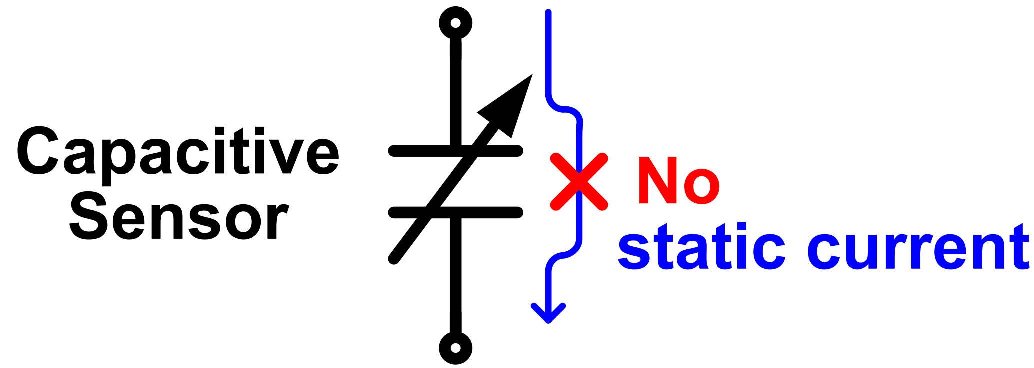


Block diagram



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

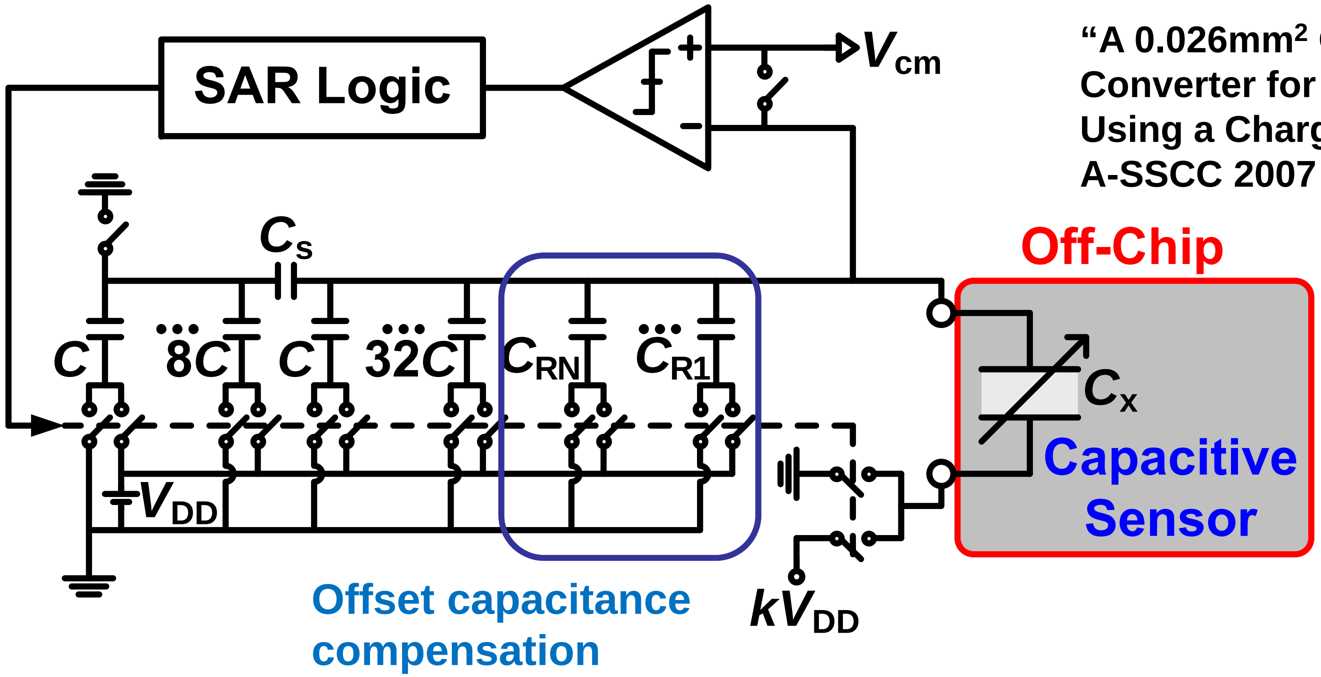
- **C/Freq converter & FM <4mW**
  - ☹Coding and Re-transmission is difficult
- **C/Volt converter & ADC**
  - Enlarged area and power consumption
- **C/Digit converter (ΔΣ type) <4.25mW**
  - ☹OpAmp: Large power consumption

SAR Capacitance to Digital Converter

We have developed an ultra-low power capacitance to digital converter (CDC) using SAR ADC method.

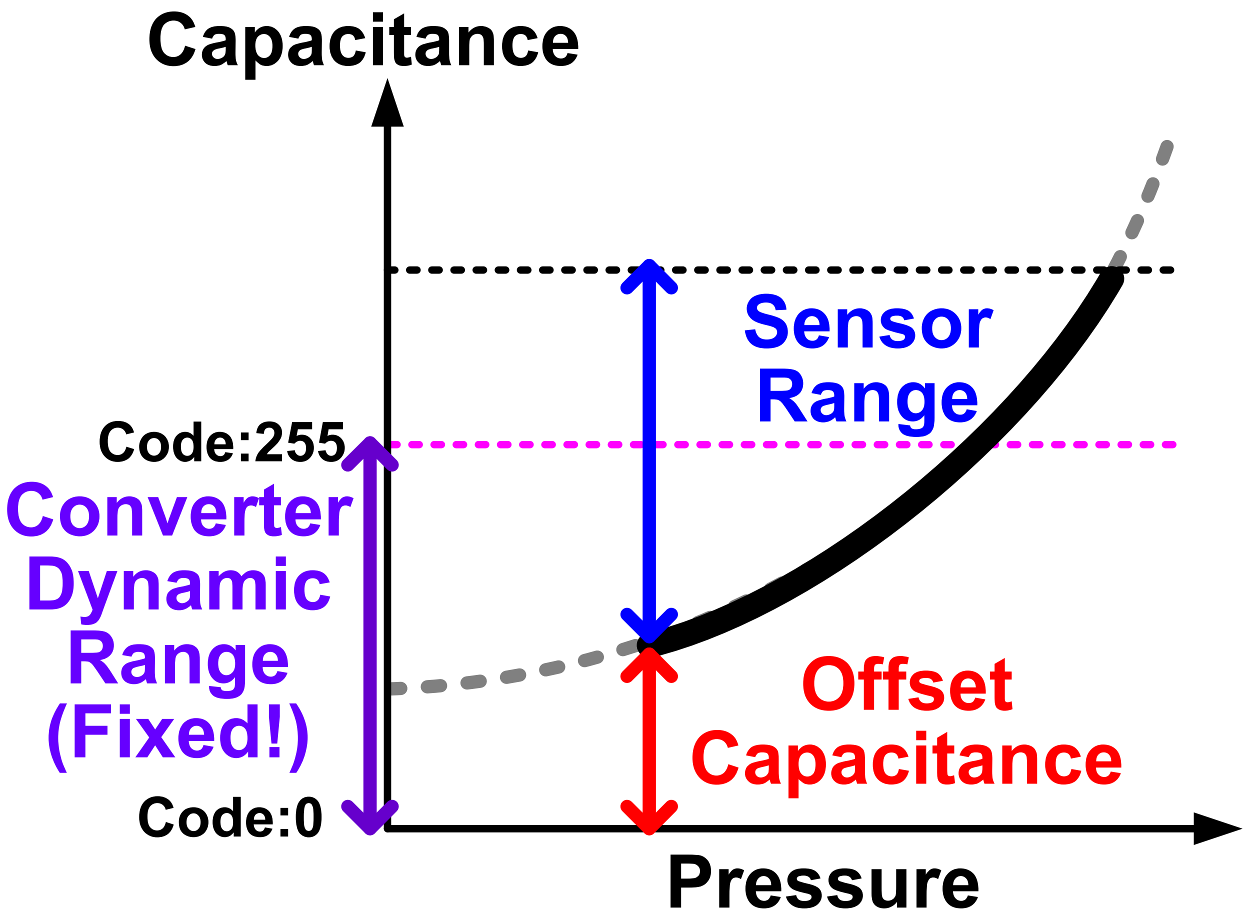
- Ultra-low power (No OpAmp)
- It can compensate the offset capacitance
- Small area
- Insensitive to the supply voltage

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

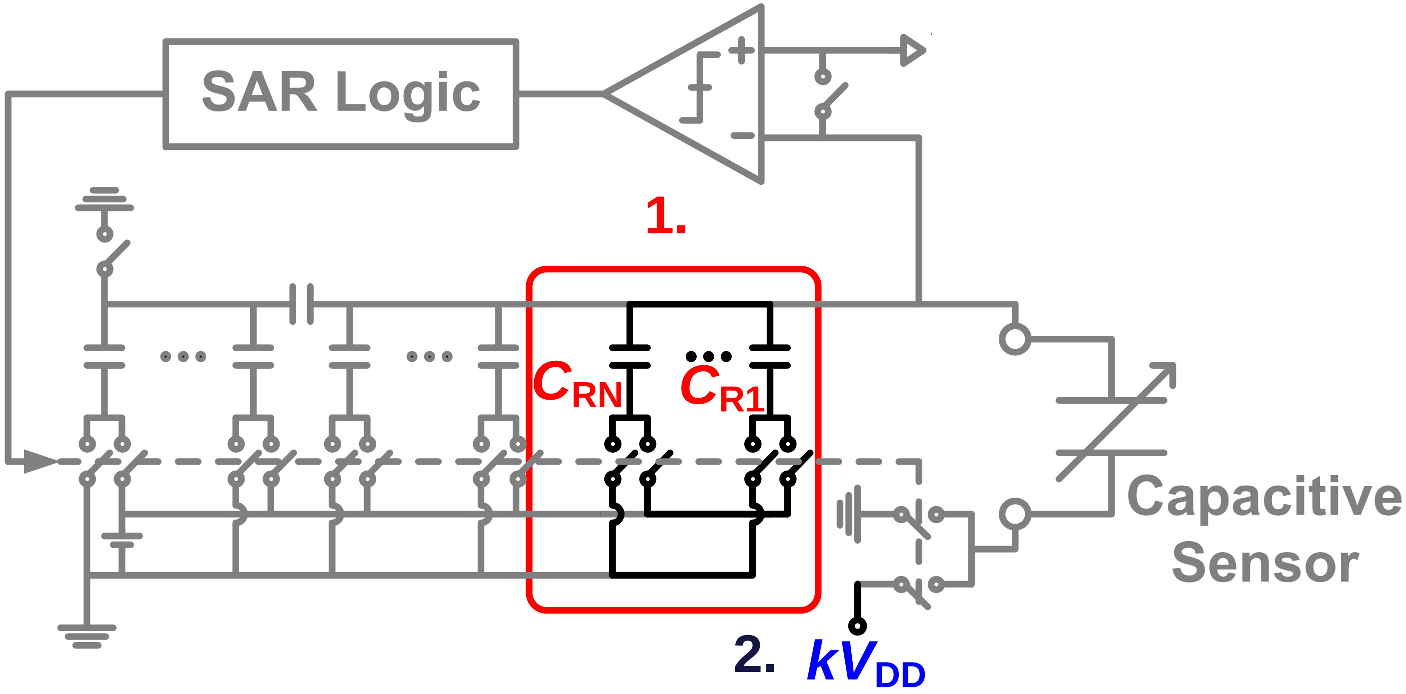


Issue of capacitive sensors

An offset capacitance should be cancelled and the CDC dynamic range should be matched with that of the capacitive sensor range.



Solution & novelty

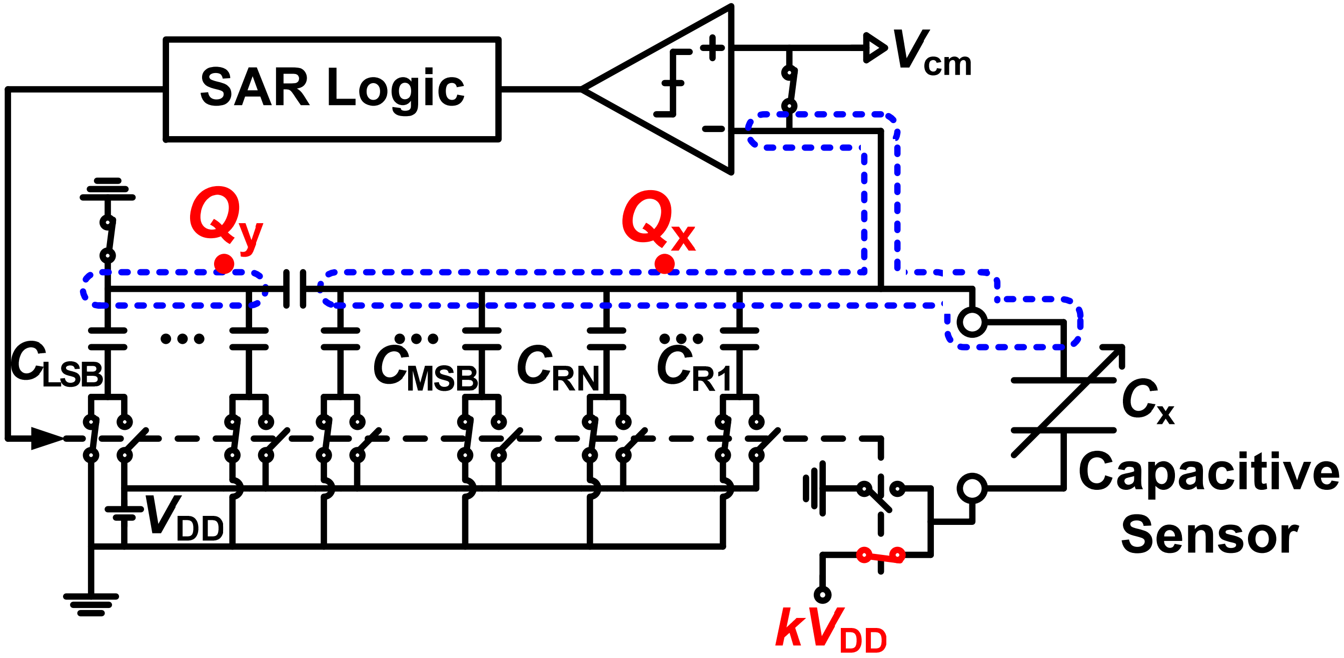


1.Offset canceling

2.Reference voltage scaling

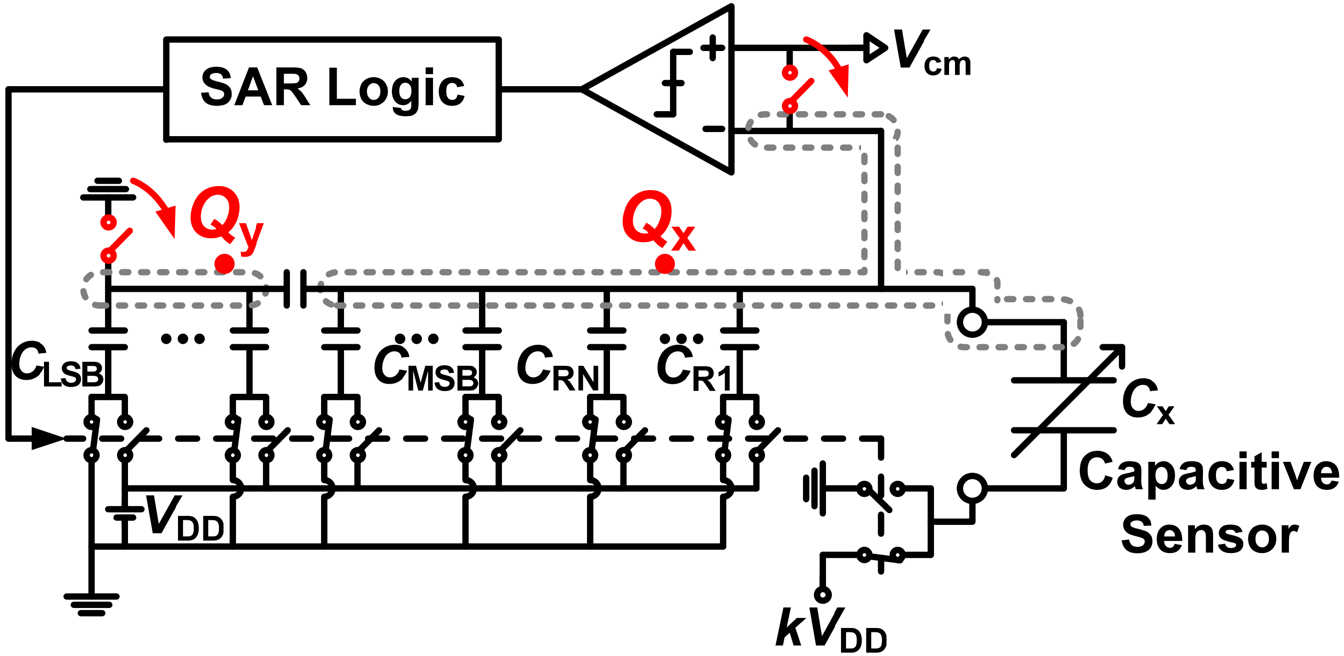
➡ Full range conversion

Operation (1 of 4)



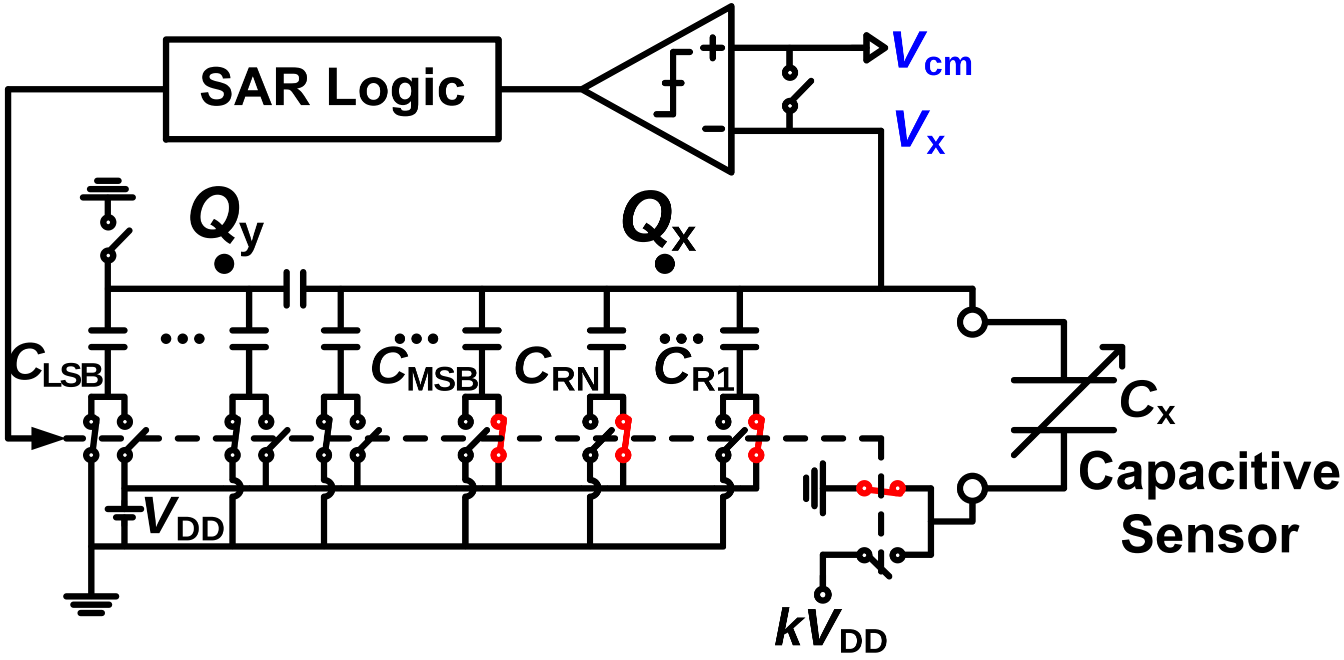
1. Store the charge at each node.

Operation (2 of 4)



2. Charge conservation

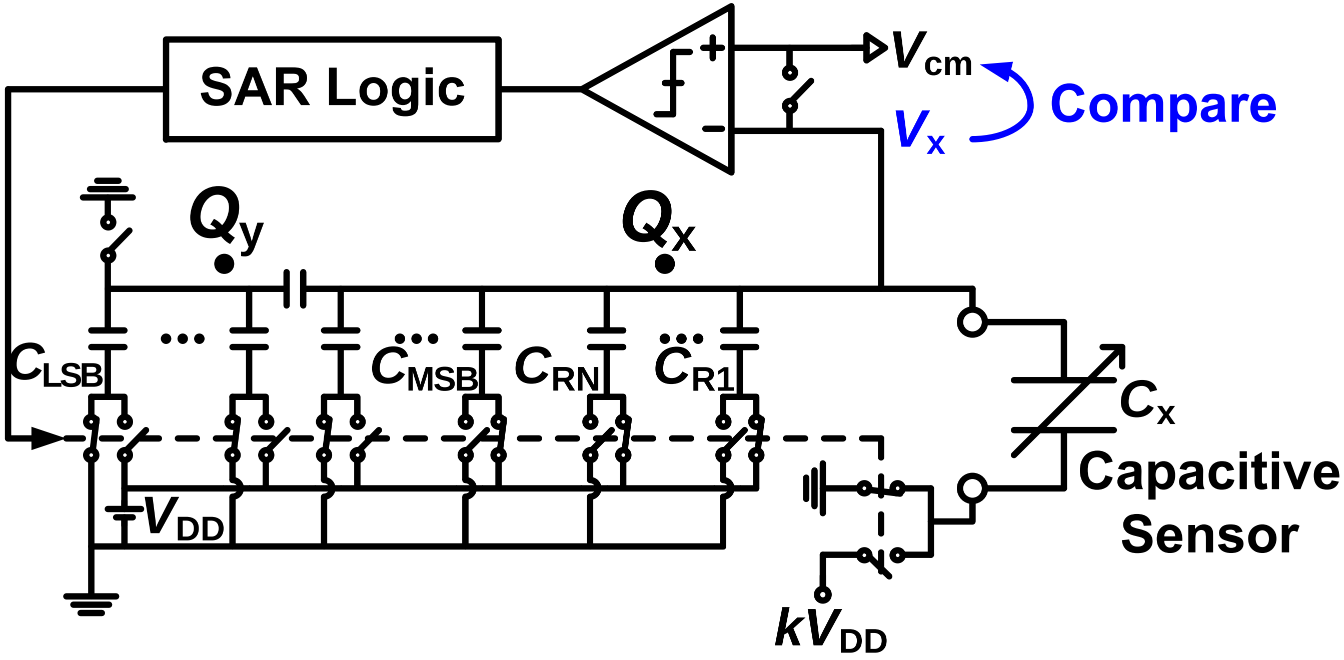
Operation (3 of 4)



3. MSB conversion

$$V_x - V_{cm} = \frac{V_{DD}}{C_{total}}(C_R + C_{MSB} - kC_x)$$

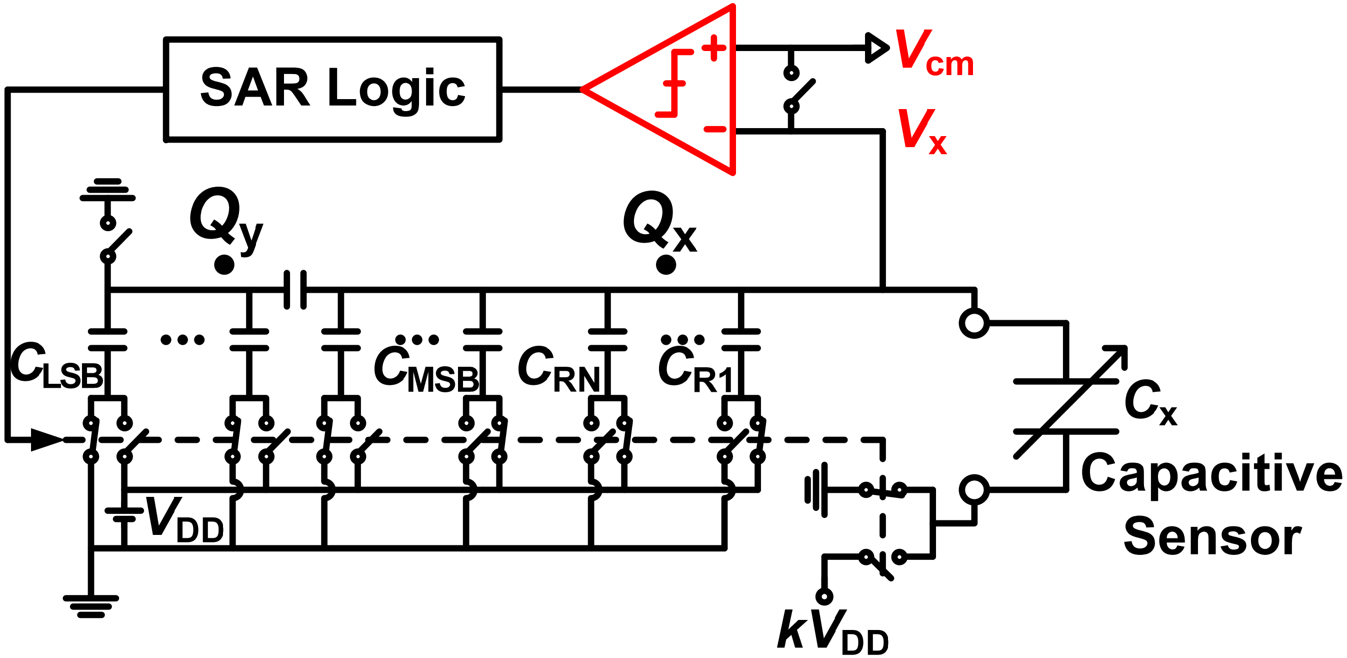
Operation (3 of 4)



3. MSB conversion

$$V_x - V_{cm} = \frac{V_{DD}}{C_{total}}(C_R + C_{MSB} - kC_x)$$

Operation (4 of 4)



4. Capacitance comparison

$$V_x > V_{cm}\ ? \Leftrightarrow \frac{V_{DD}}{C_{total}}\left(C_R + C_{MSB} - kC_x\right) > 0\ ?$$

on-chip off-chip sensor

Conversion feature

$$\frac{V_{DD}}{C_{total}}(C_R + C_{MSB} - kC_x) > 0 \,?$$

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

2. Offset is canceled

V_{DD} : Supply voltage

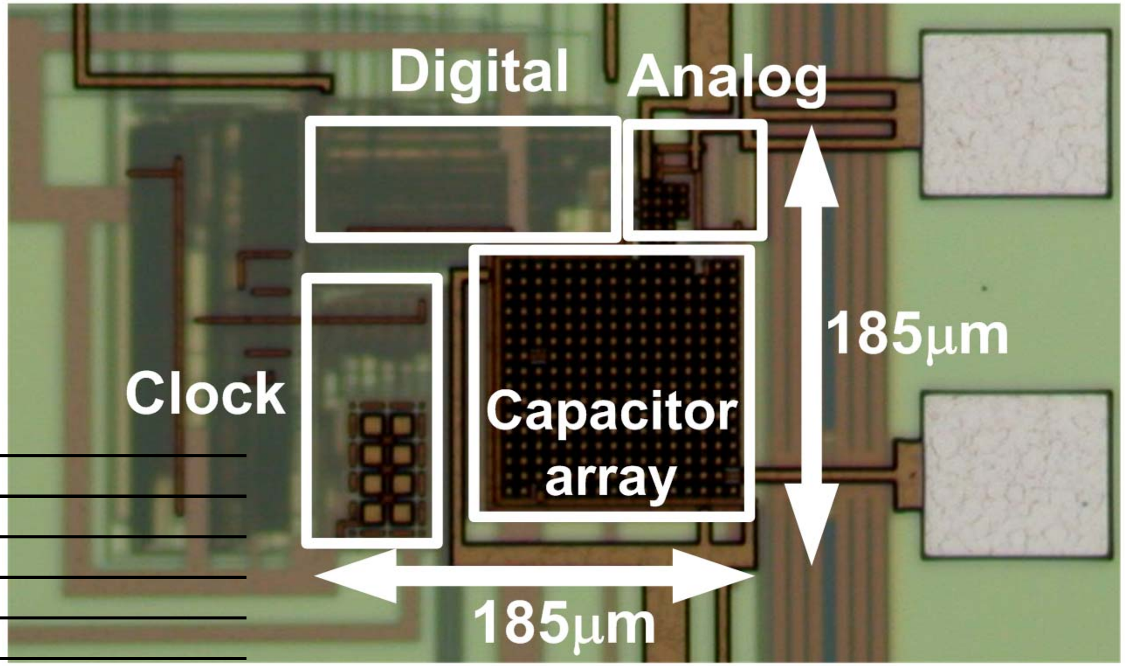
C_R : Offset canceling capacitor

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.



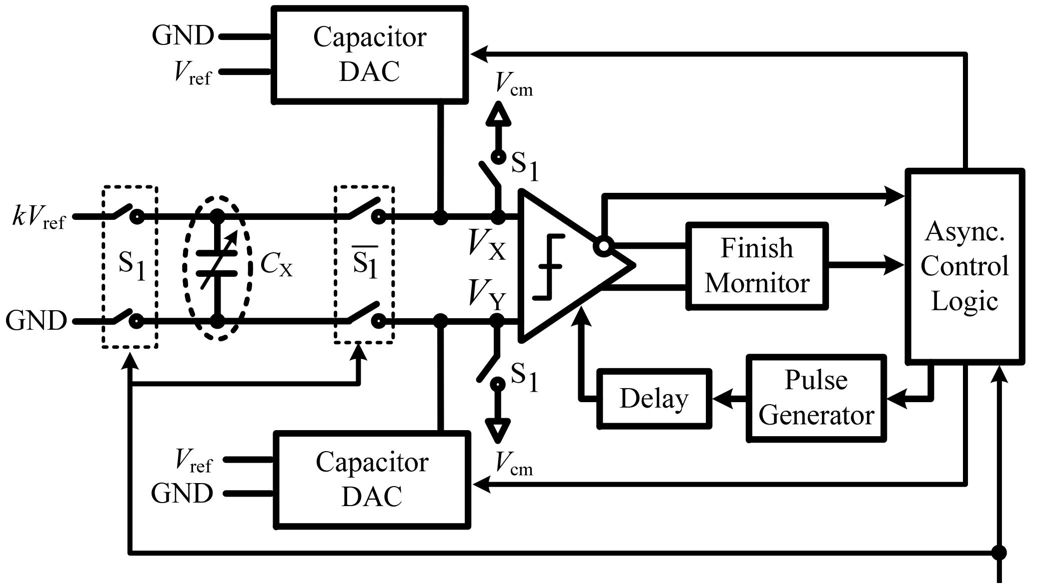
Resolution	8 Bit
Supply Voltage	1.4 V
Sampling Rate	262 kHz
SNR	43.22 dB
ENOB	6.83 Bit
Current Consumption	169 µA 360 µA (when using internal clock)
Minimum DNL	-0.97 LSB
Maximum DNL	0.79 LSB
Minimum INL	-1.27 LSB
Maximum INL	0.99 LSB
Area	0.026 mm^2 0.034 mm^2 (when including clock)

Ex) ΔΣ CDC 4.2mW

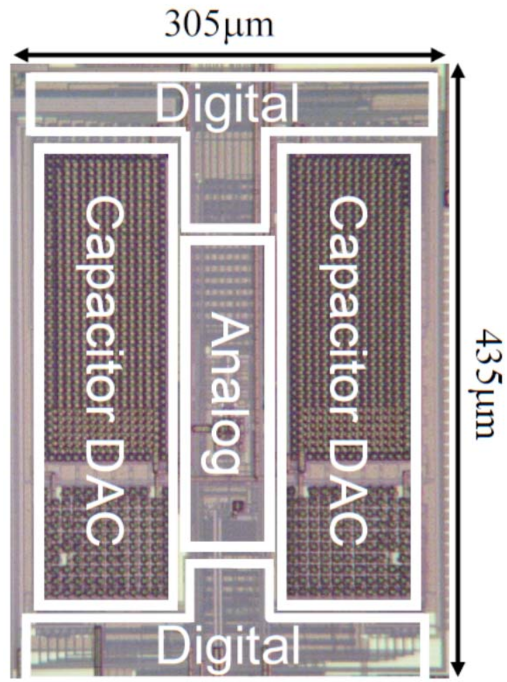
Second version CDC

Second version CDC has been developed and attained an ultra-low power consumption. **3nA @ 30 times/sec**

1. 10b SAR like architecture
2. Single to differential
3. Self-clocking
4. Fully dynamic analog circuits.



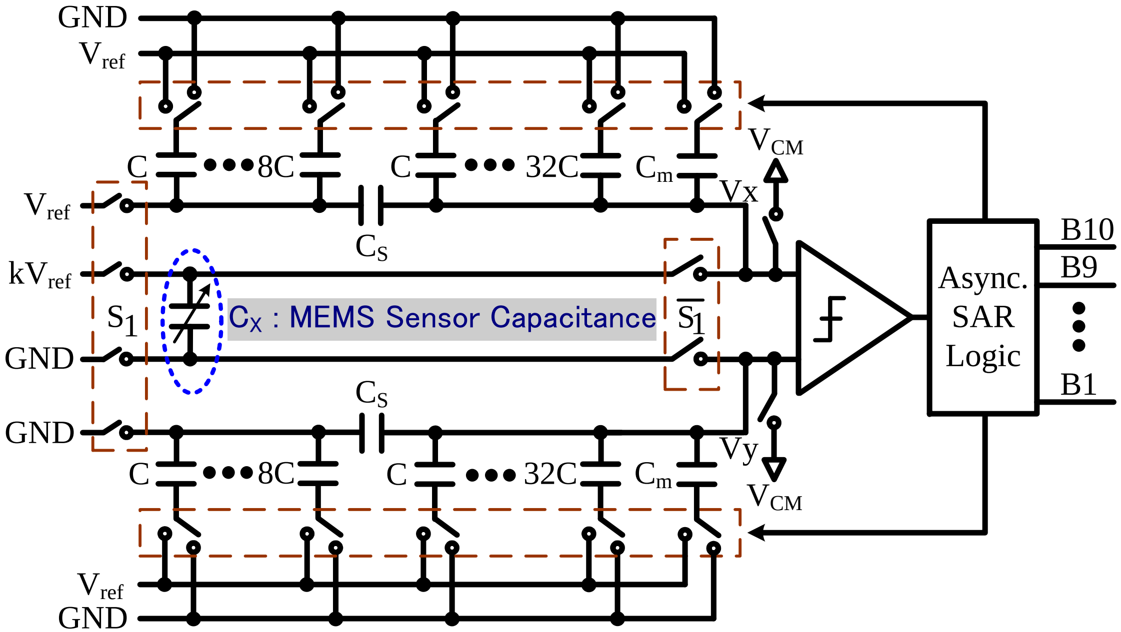
C_X : Capacitive Pressure Sensor



Tuan Minh Vo,Yasuhide Kuramochi, Masaya Miyahara,Takashi Kurashina, and Akira Matsuzawa
"A 10-bit, 290 fJ/conv. Steps, 0.13mm22, Zero-Static Power, Self-Timed Capacitance to Digital Converter."
SSDM 2009, OCT.

Differential scheme

A differential scheme can be realized by inserting the sensor between the differential input terminals. It increases an accuracy and realizes the stable operation.

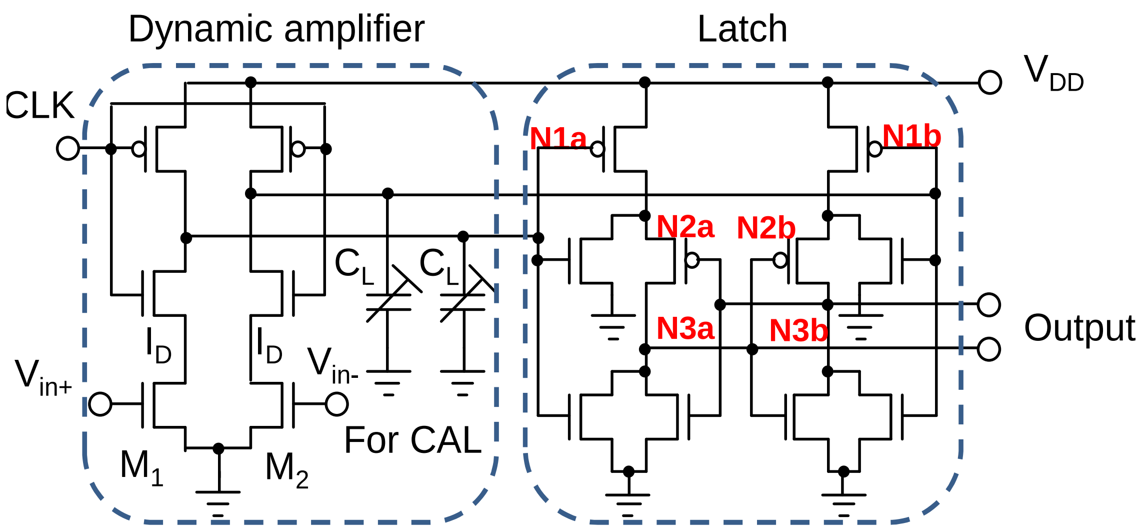


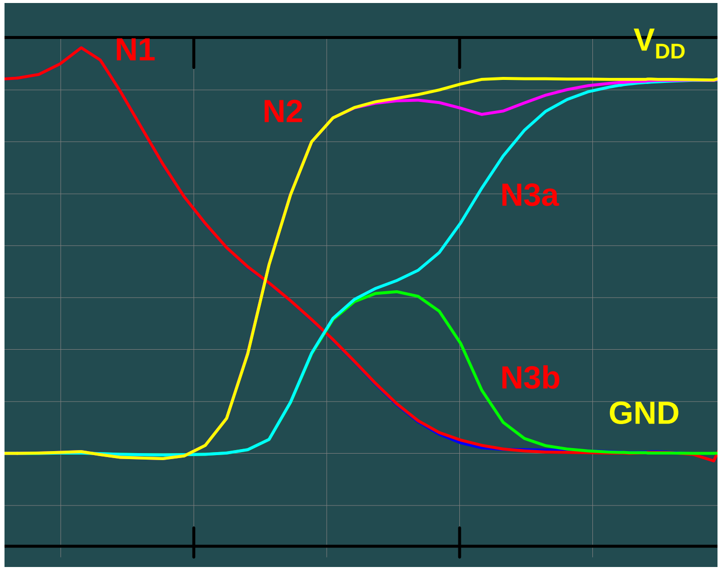
$$V_X - V_Y = \frac{\frac{1}{16}C(B_{10} + B_9 + \ldots + B_n) - kC_{X\_sam}}{2C_{X\_con} + \left[C_m + 2^5 C + \ldots + C + \frac{C_S(2^3 C + \ldots + C)}{C_S + 2^3 C + \ldots + C}\right]} V_{ref}$$

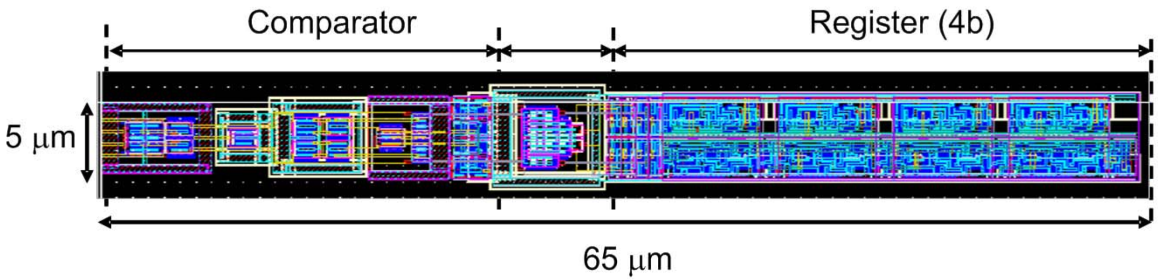
Dynamic comparator

A dynamic comparator is very high speed, yet consumes no static power.

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







M. Miyahara, Y. Asada, D. Paik, and A. Matsuzawa, "A Low-Noise Self-Calibrating Dynamic Comparator for High-Speed ADCs," A-SSCC, Nov. 2008.

A. Matsuzawa," IEEE 8th International Conference on ASIC(ASICON), pp. 218-221, Oct. 2009.

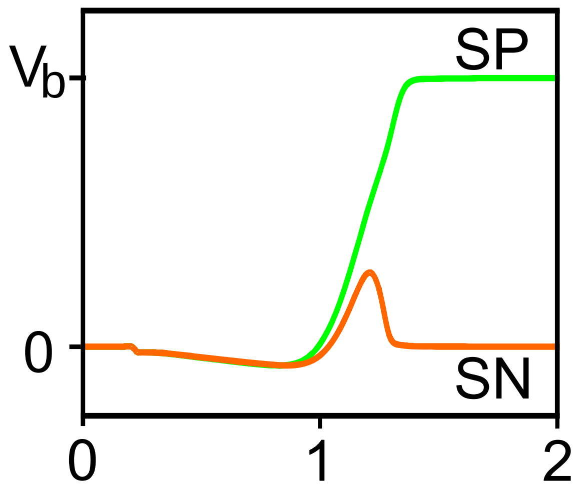
Self clocking technique

Self-clocking technique is very useful for ..

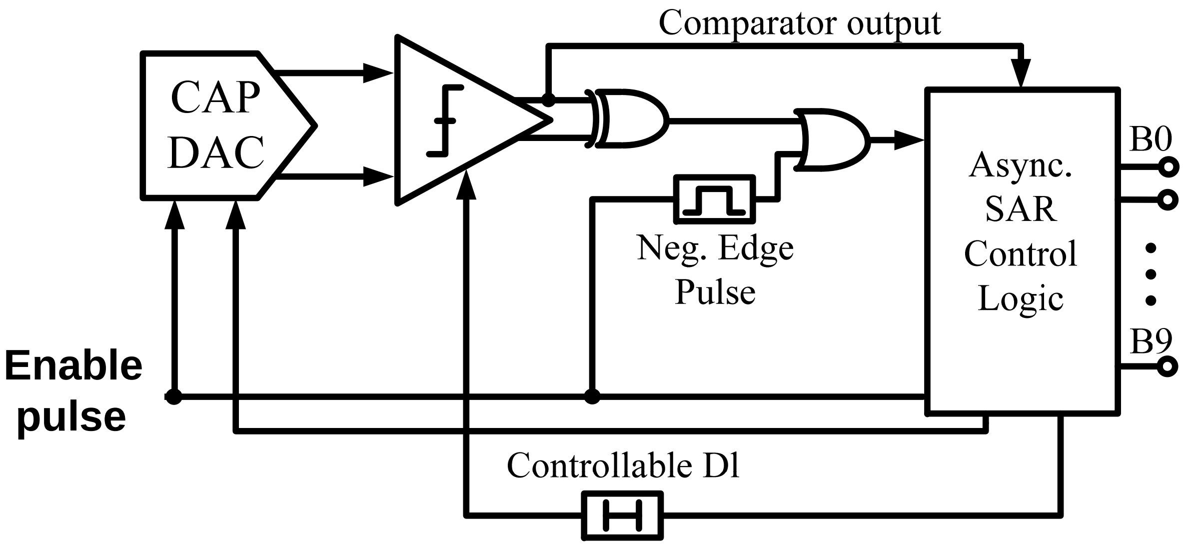
1) Reducing power consumption (Clock circuits, routing clock,)
2) Just an enable command signal is required. No need of clock.
   Suitable for micro controller.

Comparison is ended if the output voltages are not same.

Output voltage of the dynamic comparator

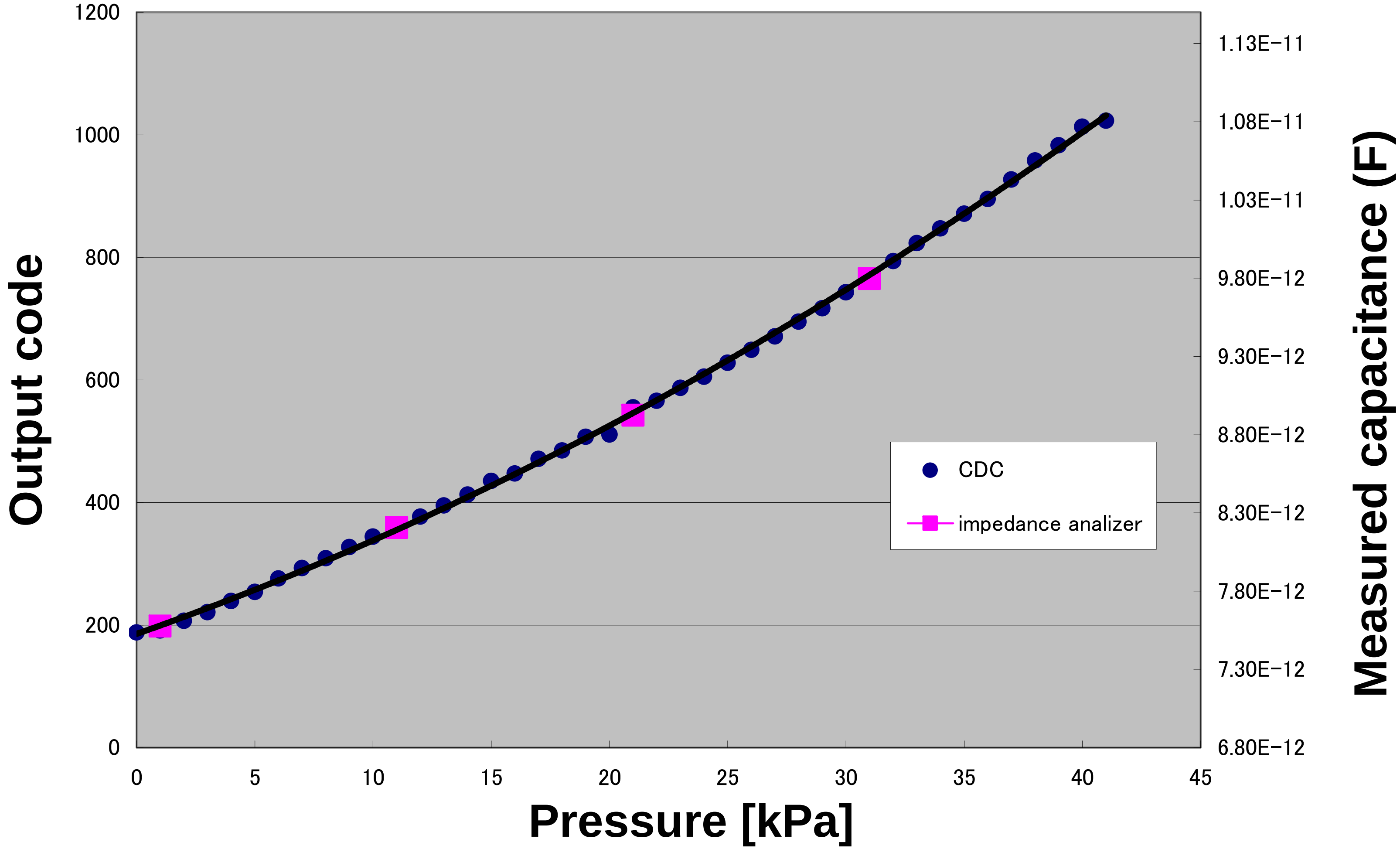


Self-clocking scheme

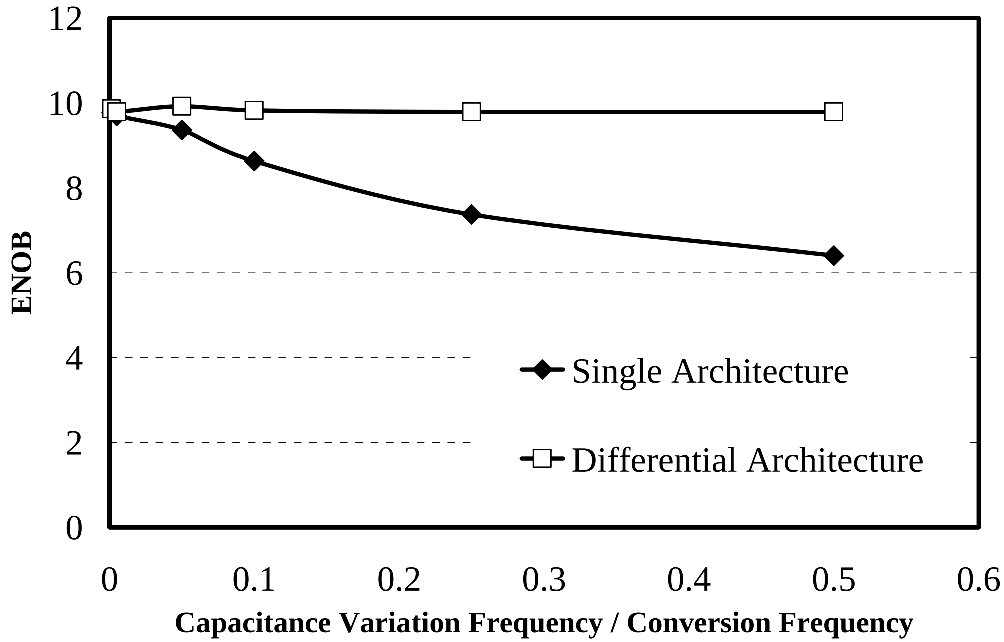


Accuracy of the CDC

High accuracy as an impedance meter.



Performance comparison



Ultra-low power

High resolution

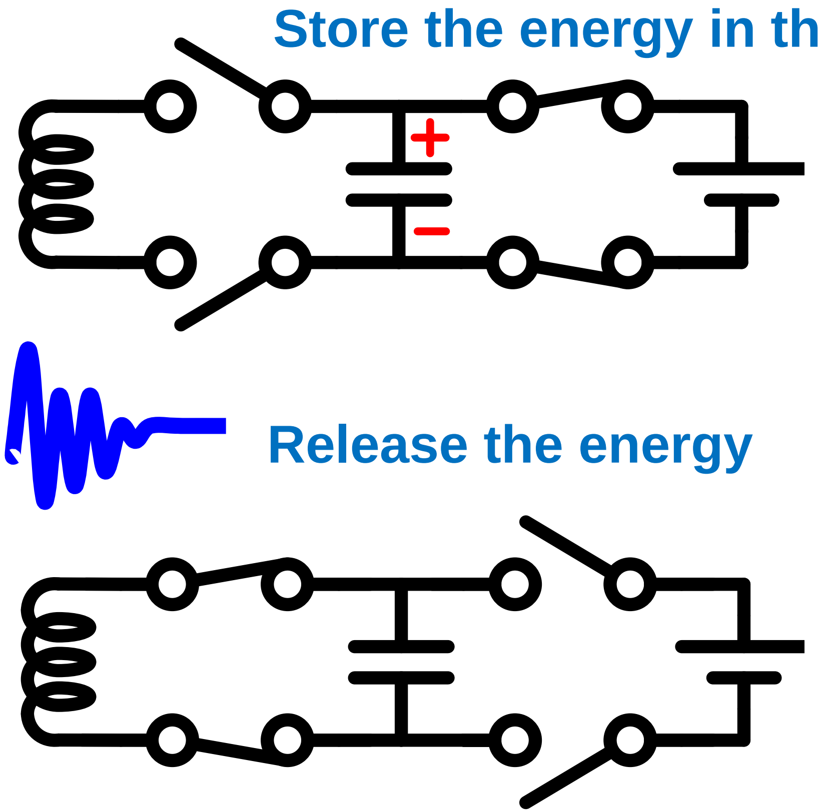
Stable for change of capacitance

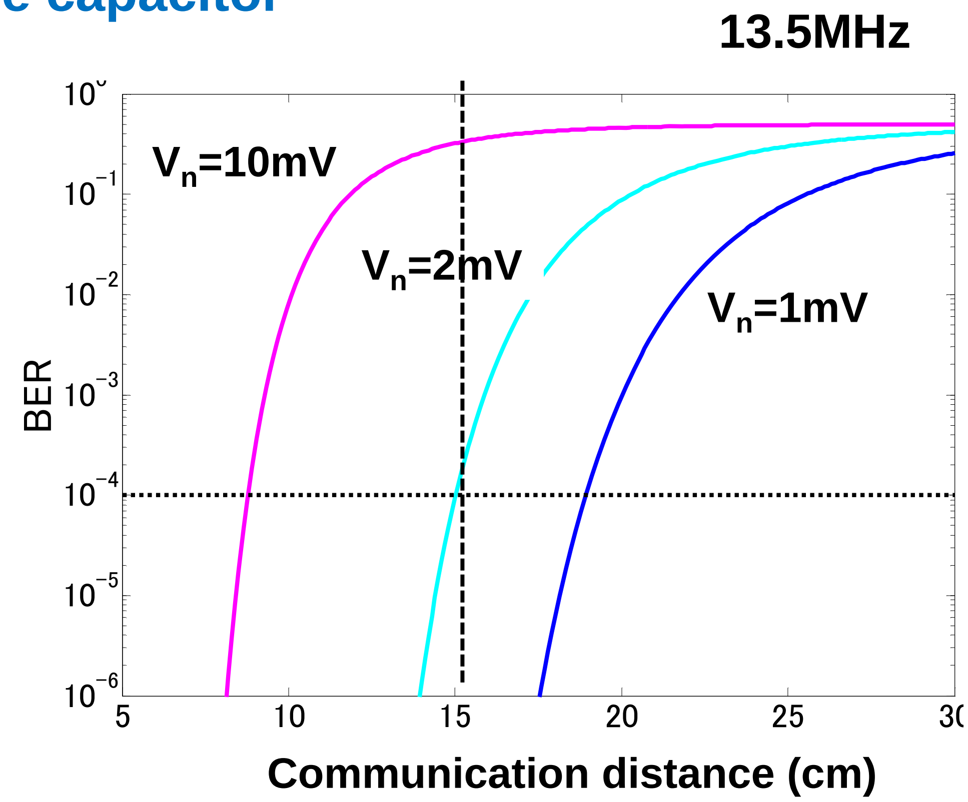
	Version 1	Version 2
Supply Voltage	1.4 V	1.4 V
Resolution	8 bit	10 bit
Current consumption of CDC	169 uA	8.45 uA
Conversion Frequency	262 kSps	262 kSps
Area	0.026 mm^2 (C_m = 3.6pF)	0.11 mm^2 (estimated) (C_m = 10pF x 2)

1/20

Wireless communication

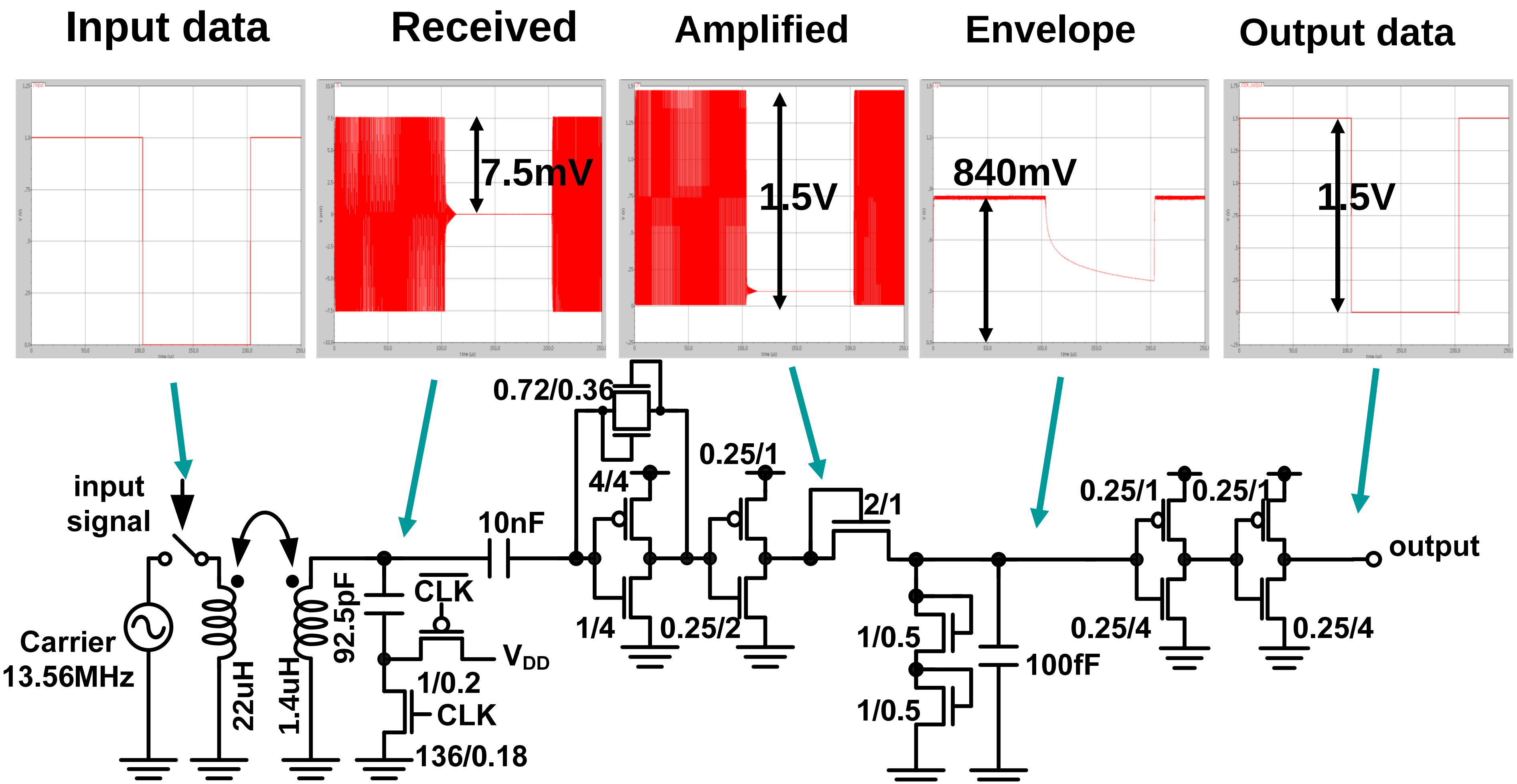
Resonated inductor coupling can communicate in 15cm distance.





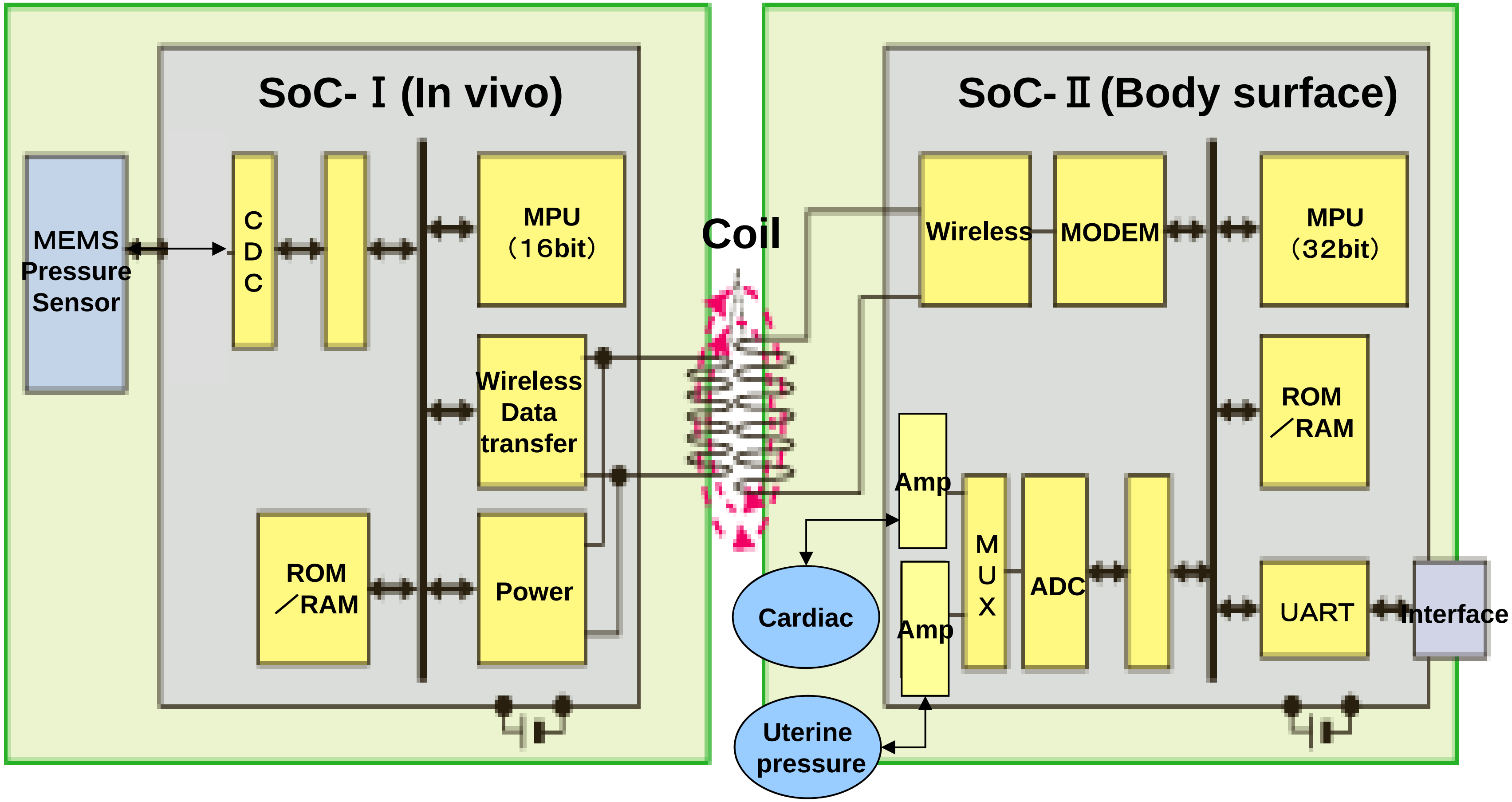
Wireless data transmission

Very simple circuits to recover the data



In-vivo and body surface chips

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

T. Fujikado et al., Testing of Semi-chronically Implanted Retinal Prosthesis by Suprachoroidal-Transretinal Stimulation in Patients with Retinitis Pigmentosa. Invest Ophthalmol Vis Sci. 52:4726-33,2011.

T. Tokuda et al., Development and in vivo Demonstration of CMOS-Based Multichip Retinal Stimulator With Simultaneous Multisite Stimulation Capability, IEEE Transactions on Biomedical Circuits and Systems . 2: 445 – 453,2011.

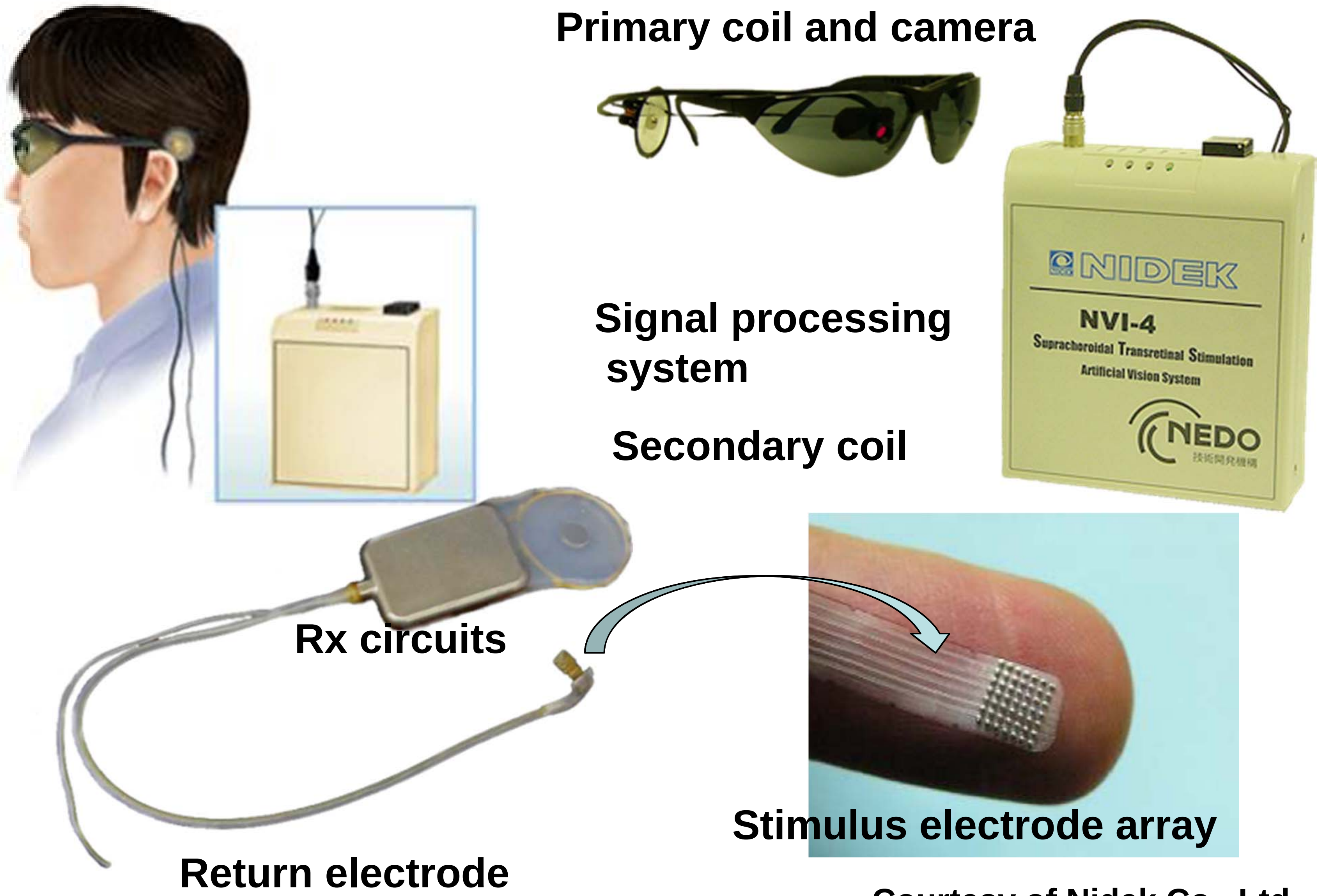
Retinal prosthetic devices

Total system of retinal prosthesis has been developed

NAIST/Osaka U/Nidek

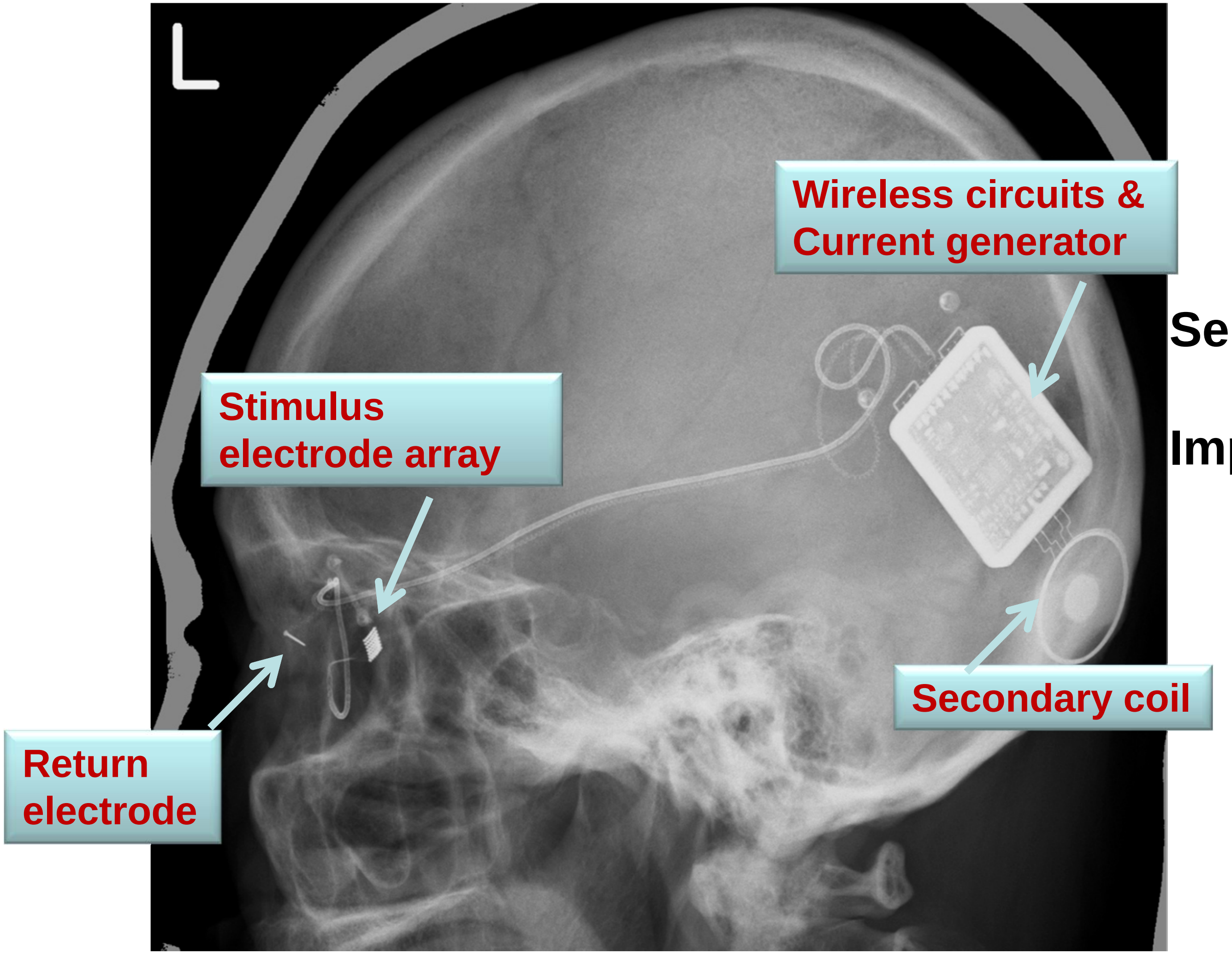
Courtesy of Nidek Co., Ltd.

Components of retinal prosthesis



Courtesy of Nidek Co., Ltd.

Implantation of retinal prosthetic device



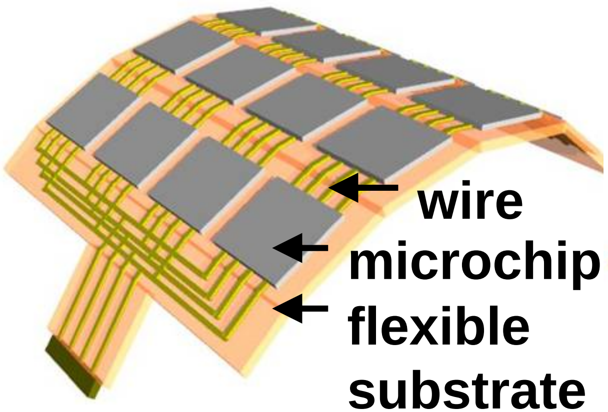
Semi-chronical trials

Implanted in one montl

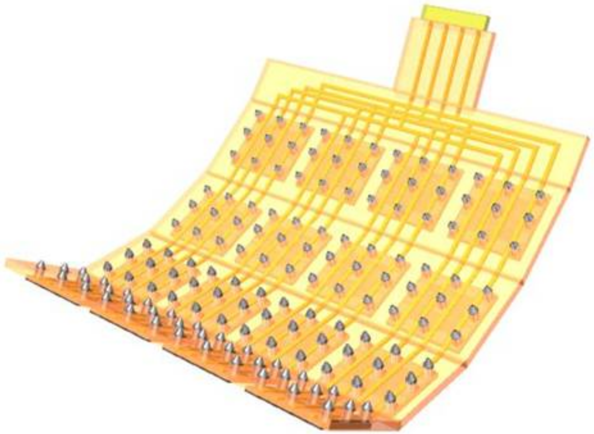
T. Fujikado *et* al., Invest Ophthalmol Vis Sci. 2011.

Retinal stimulator: Multi-microchip architecture

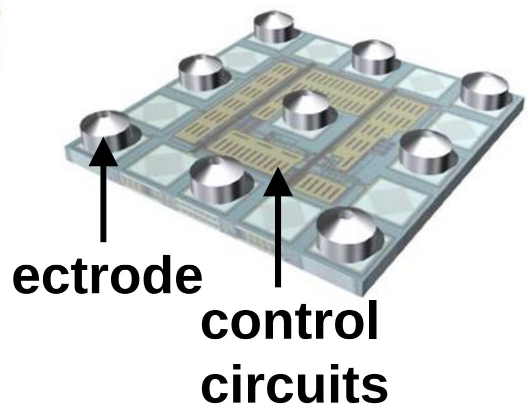
[Backside]



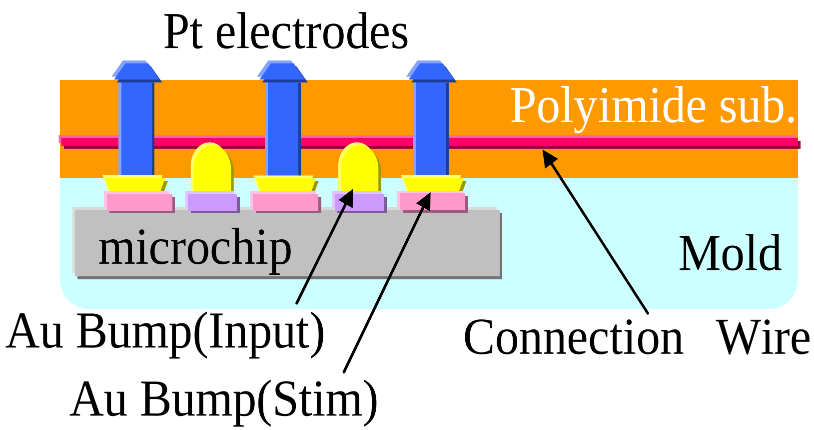
[Stimulus side]



[Microchip]



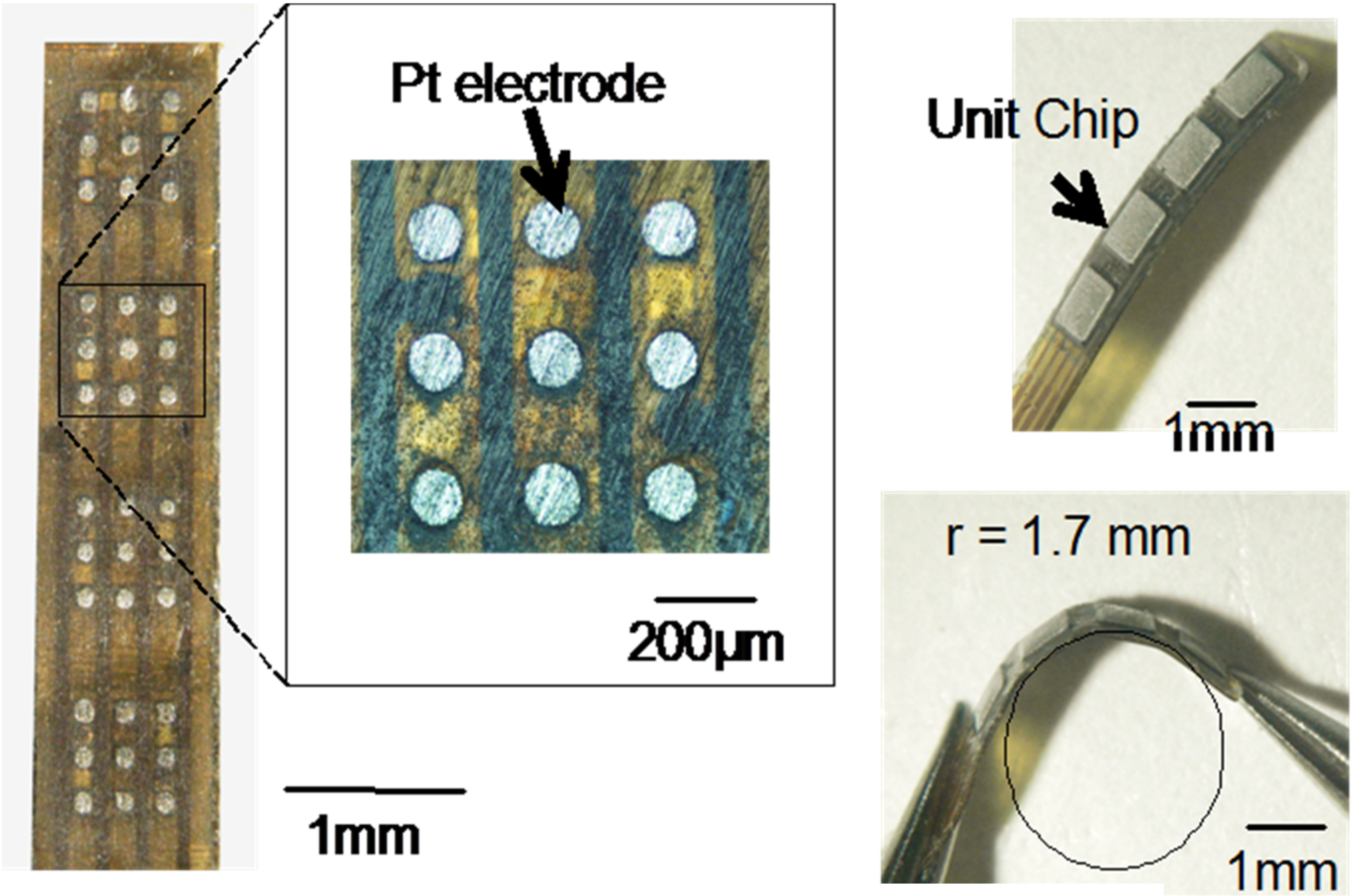
[Device cross-section]



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

Fabricated distributed retinal prosthesis device

(For rabbit: 1x4 microchips)

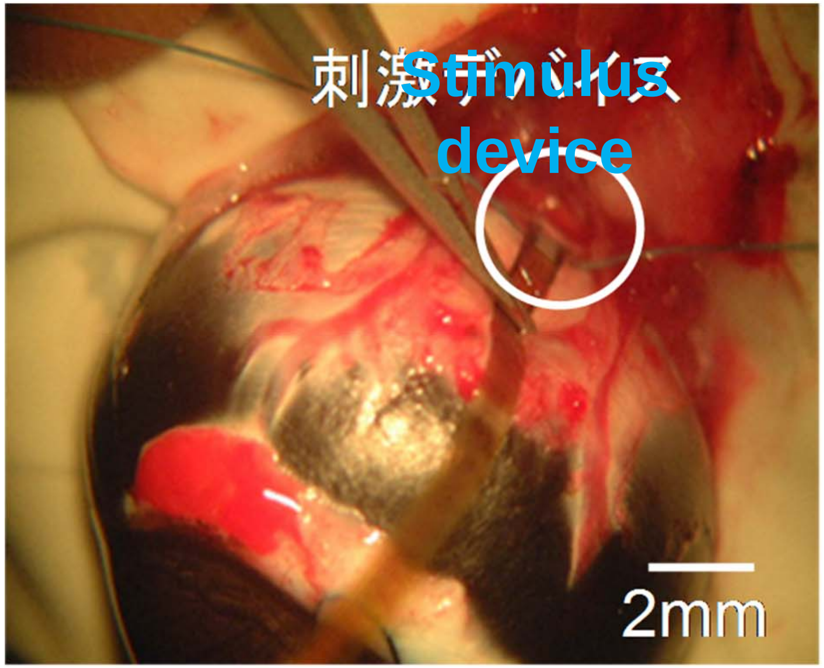


T. Tokuda *et al.*, Sensors & Actuators A, 2005.

Stimulation experiment of rabbit's retina

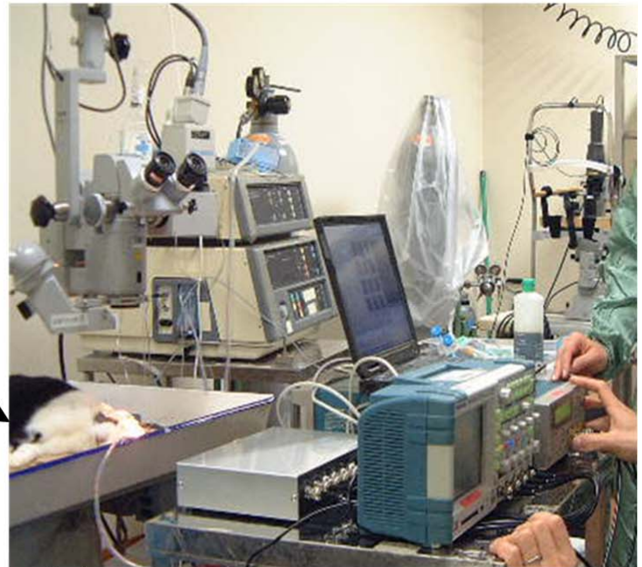
No need of opening the eye ball, the device is mounted on a sclera pocket.

A wide view can be obtained, since large area can be used on the sclera.



A stimulus device is mounted on a sclera pocket

Rabbit



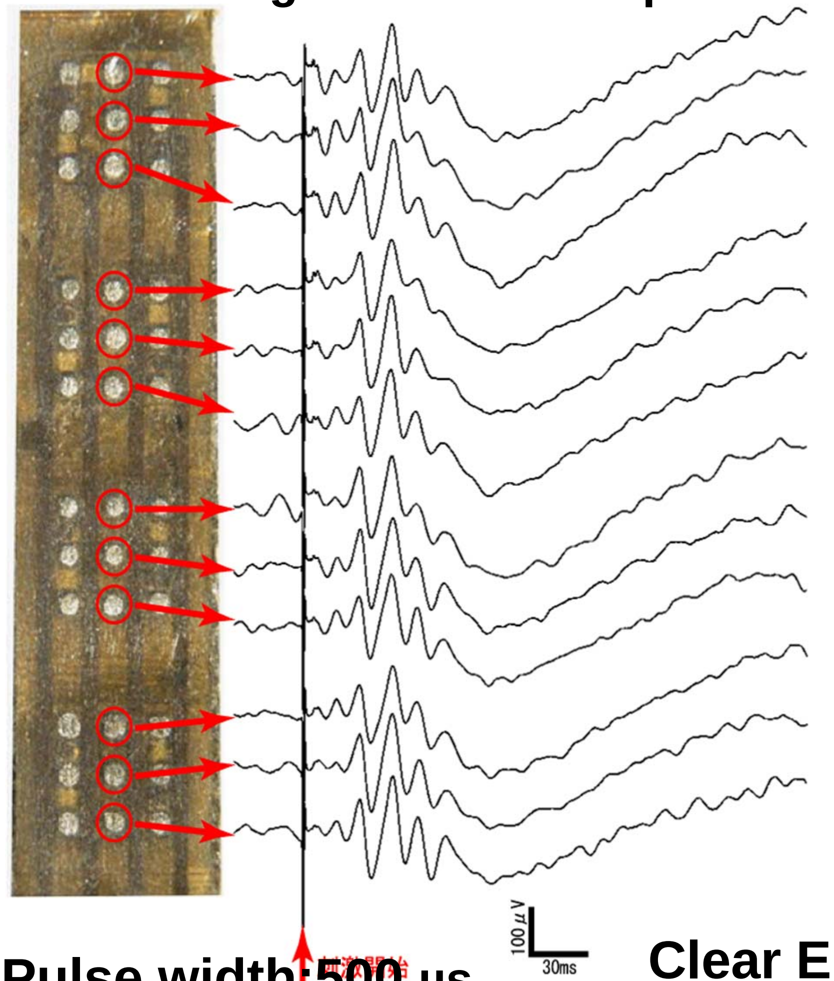
Control system

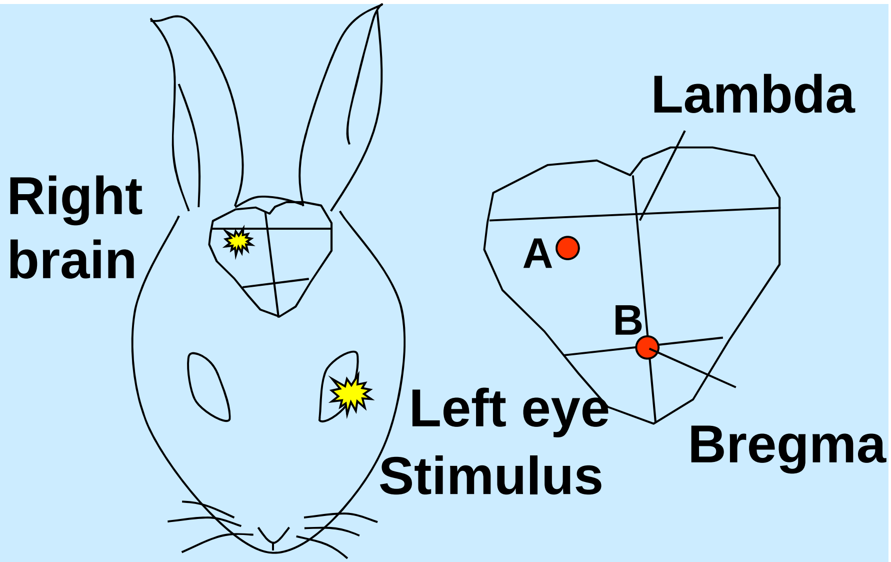
Wire cables

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

Retina stimulation experiment

EEP signals from multiple microchips





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

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

Clear EEP signals were obtained corresponding to the different microchip

T. Tokuda *et al.,* Sensors & Actuators A,, 2005.

Brain Implantable Devices

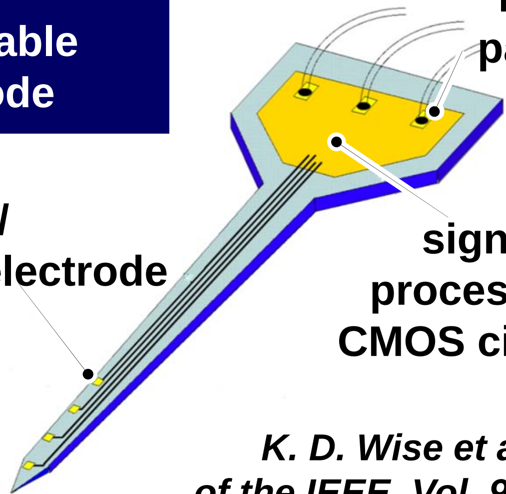
T. Kobayashi et al., “Novel implantable imaging system for enabling simultaneous multiplanar and multipoint analysis for fluorescence potentiometry in the visual cortex ,” Biosensors & Bioelectronics, 38 (1), 321–330, 2012.

H. Tamura et al., "One-chip sensing device (biomedical photonic LSI) enabled to assess hippocampal steep and gradual up-regulated proteolytic activities J. Neuroscience Methods," 173 (1), 114-120, 2008.

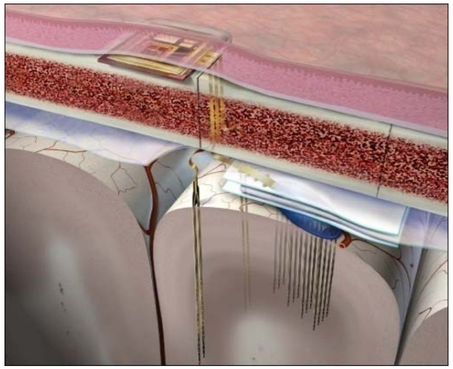
Implantable micro imager

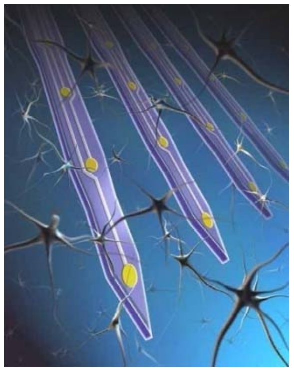
By using fluorescent labels and the implantable micro imagers,
An intra-brain activity can be visualized, even at free action.

Implantable electrode



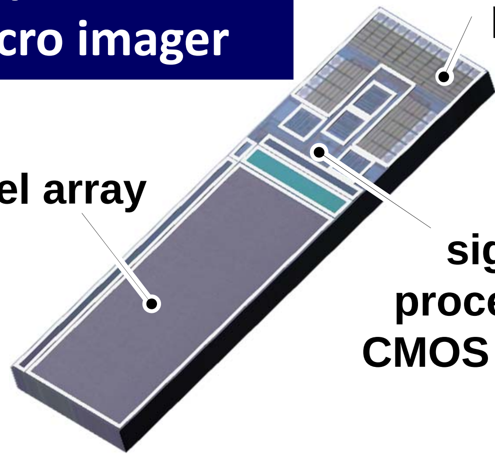
K. D. Wise et al., Proc. of the IEEE, Vol. 96, No. 7, 2008

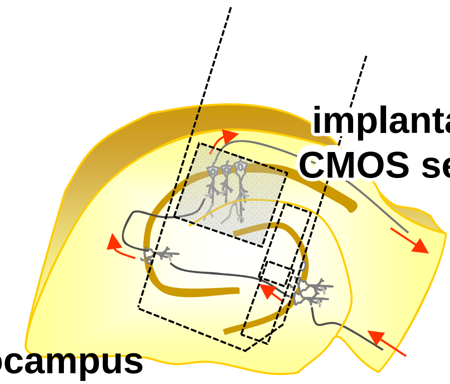




Neural stimulation/recording

Implantable micro imager

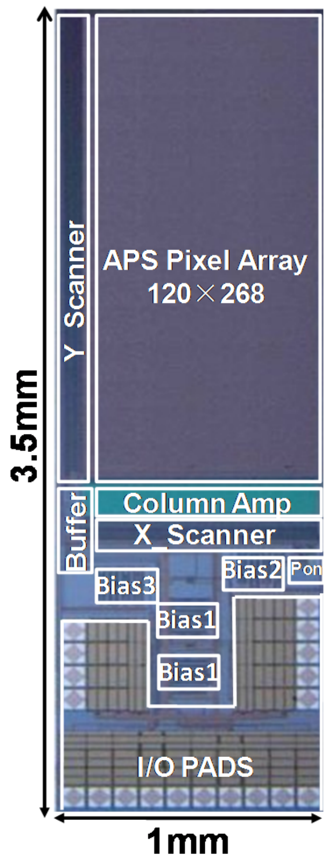




Fluorescent imaging

CMOS micro imager

Implanted into the brain of a freely-moving mouse



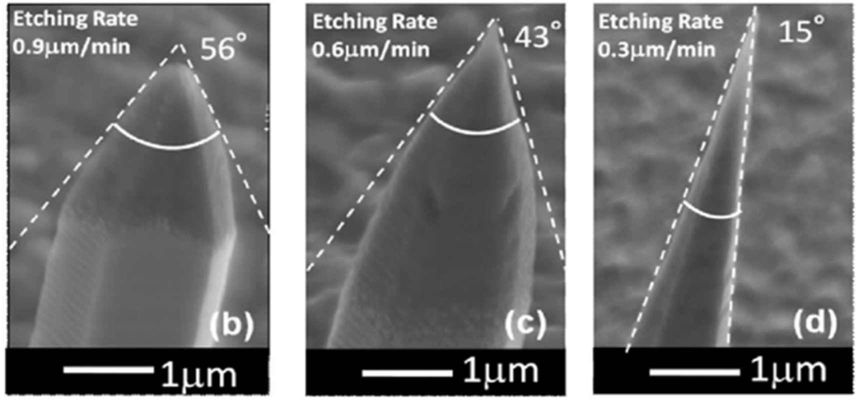
CMOS sensor with only 4 IOs (VDD, GND, CLK, OUT)

Captured image

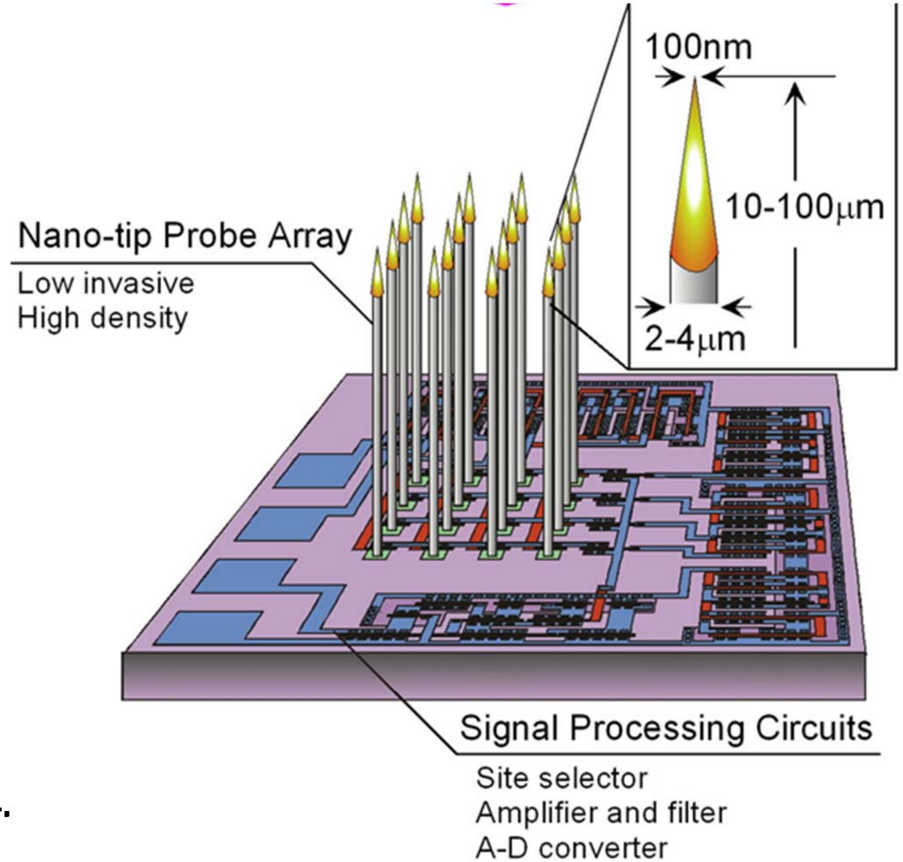
Implantation in mouse brain

Micro-Si probe electrode arrays

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.



Controllable probe-tip angles by silicon etching



Integration of nano-scale tip probes for cell/neuron

T. Kawano et al., "Selective Vapor-Liquid-Solid Epitaxial Growth of Micro-Si Probe Electrode Arrays with On-chip MOSFETs on Si (111) Substrates." IEEE Transactions on Electron Devices, Vol. 51, No. 3, pp. 415-420, March 2004.

Double-Sided Microelectrode

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

R. Kobayashi et al., “Development of Si Double-Sided Microelectrode for Platform of Brain Signal Processing System,” Japanese Journal of Applied Physics, 48(4), C194-1-C194-5, 2009.

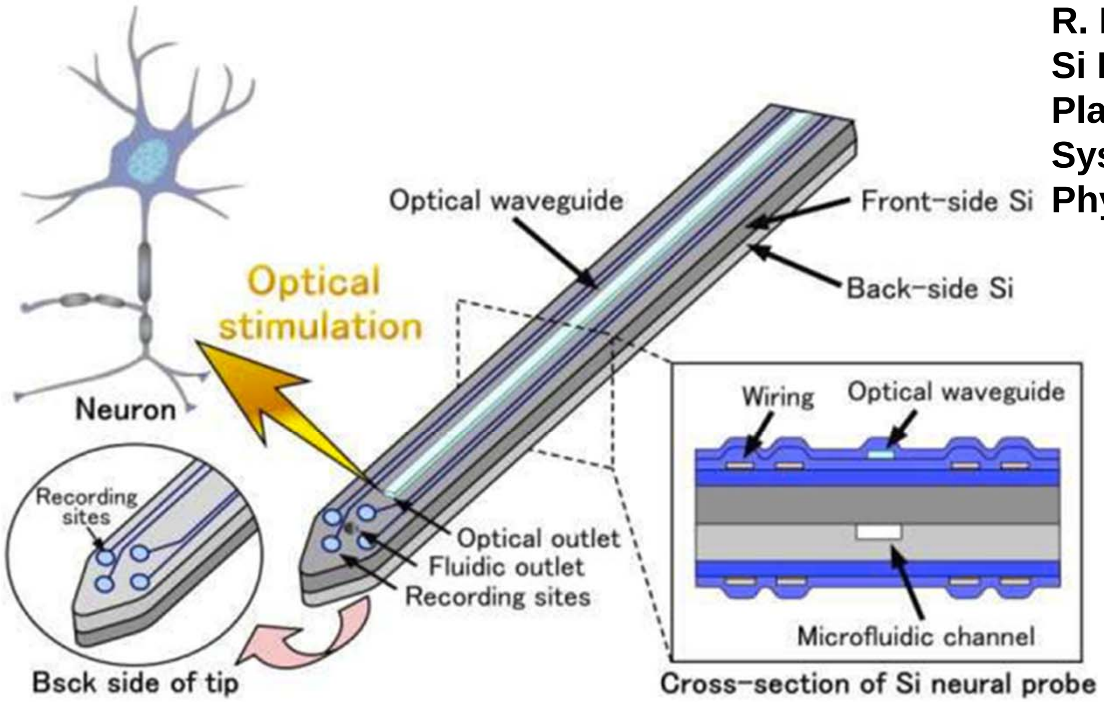
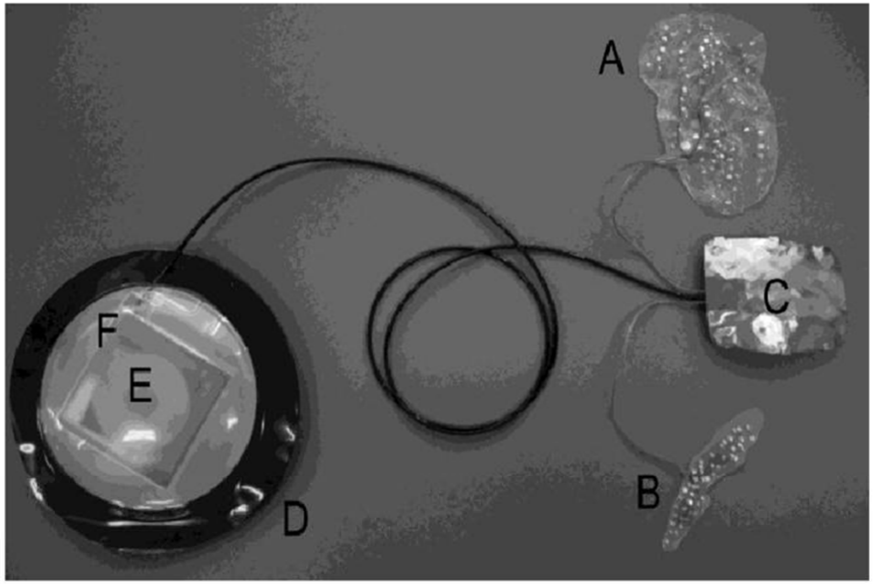


Fig. 1. Multifunctional Si neural probe with optical waveguide, microfluidic channel, and double-sided recording sites.

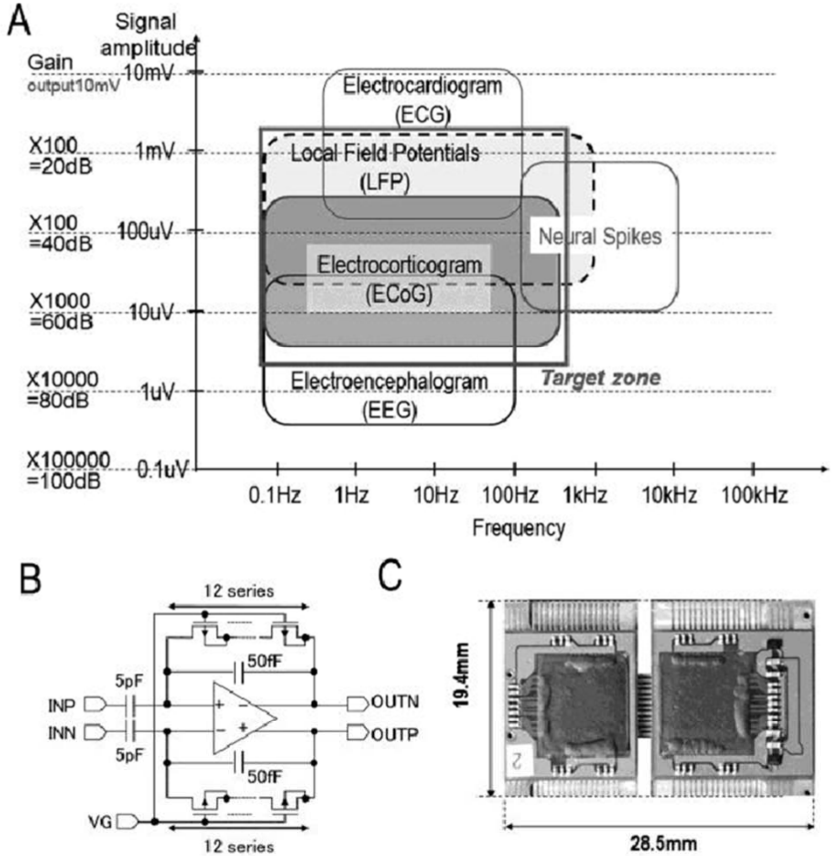
Wireless sensor device for the brain activity

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

M. Hirata et al., "A Fully-Implantable Wireless System for Human Brain-Machine Interfaces Using Brain Surface Electrodes: W-HERBS," IEICE Trans. Commun., E94-B (9), 2448, 2011.



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

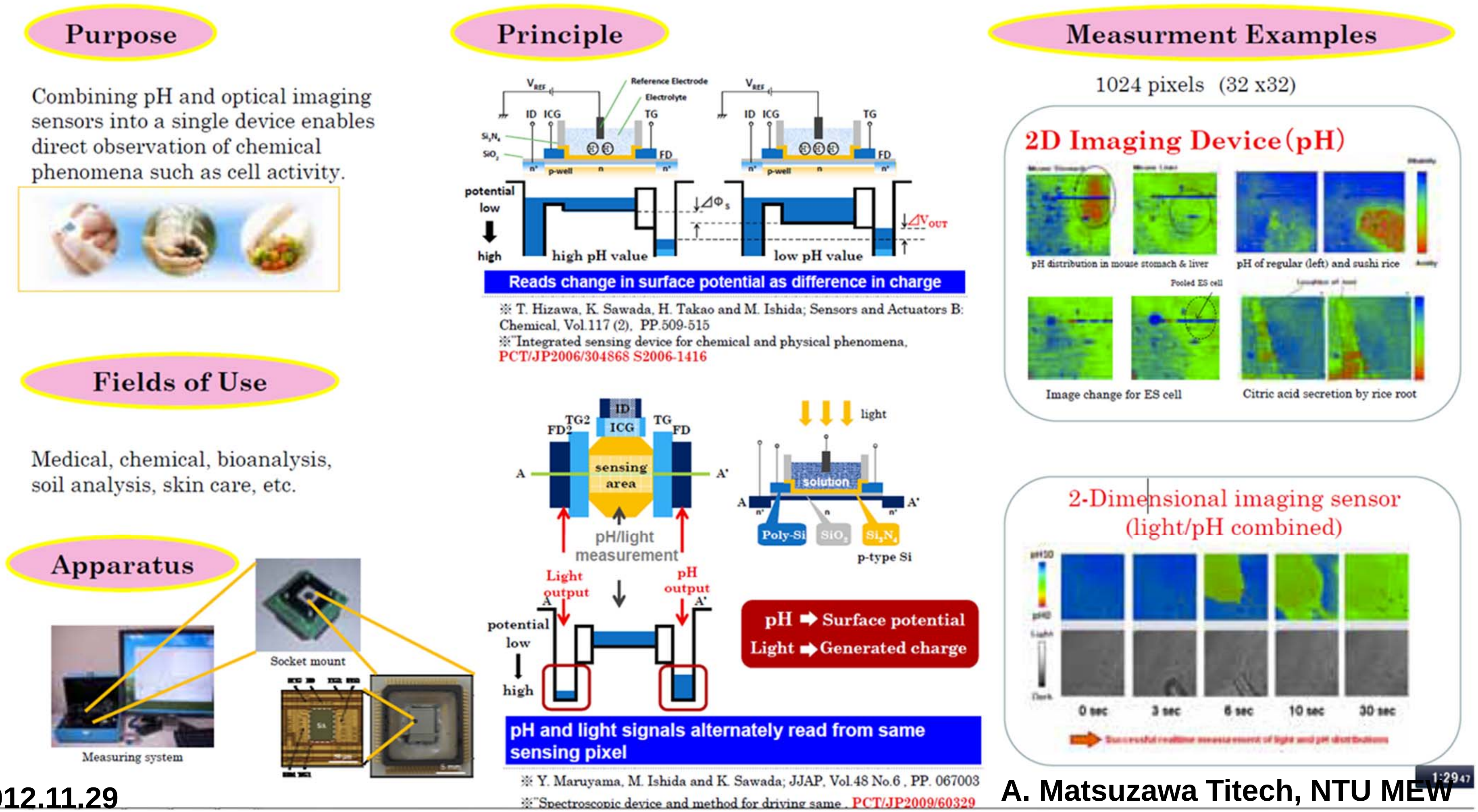
H. Nakazawa et al., "A Fused pH and Fluorescence Sensor Using the Same Sensing Area," Applied Physics Express, Vol. 3, No. 4, Article No. 047001, 2010.

Toshiya Sakata and Yuji Miyahara,
"Direct transduction of allele-specific primer extension into electrical signal using genetic field effect transistor",
***Biosens. Bioelectron.*, 2007, *22*, 1311-1316.**

pH image sensor

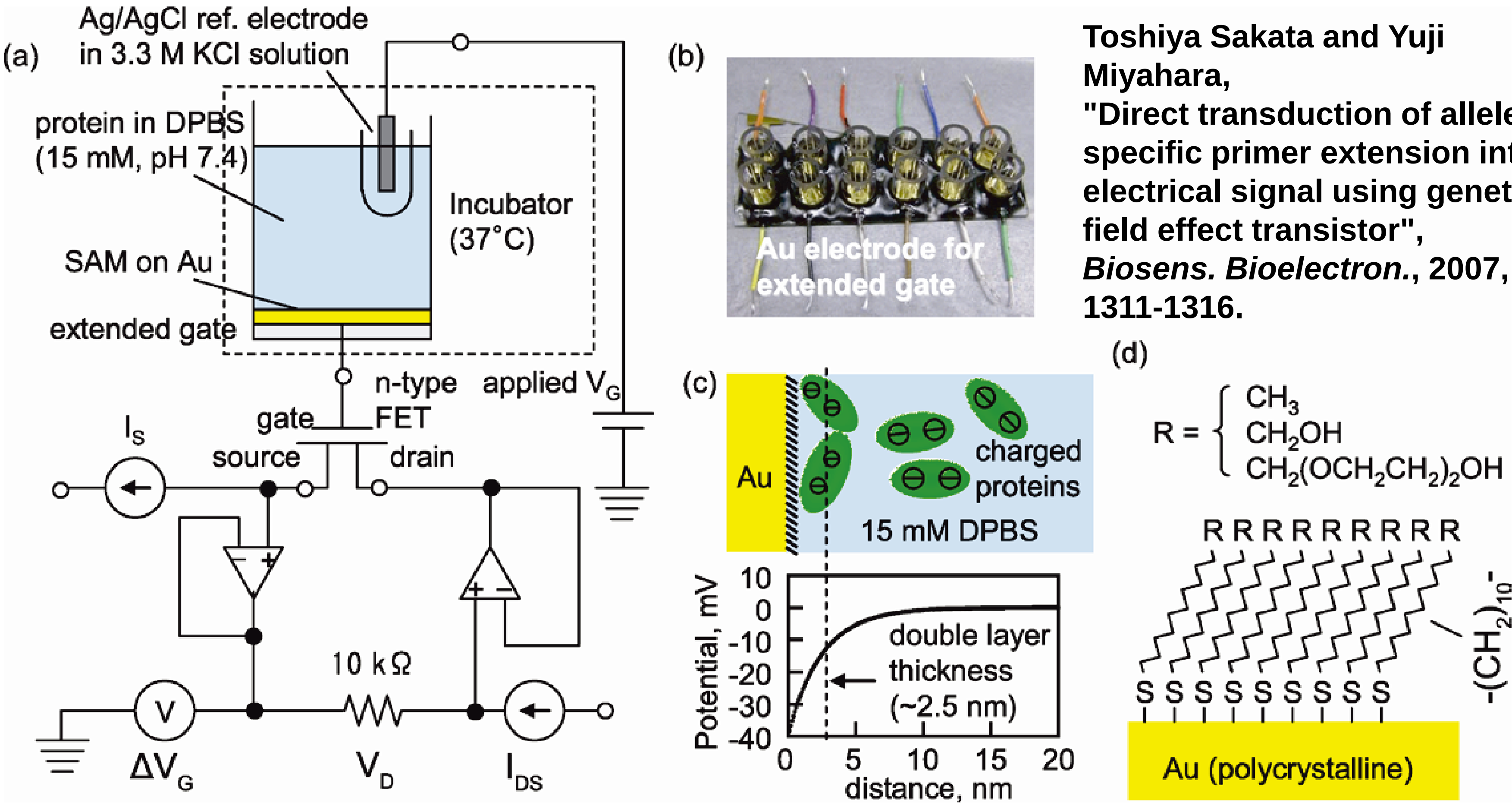
Toyohashi Tech has developed the pH image sensor of which sensitivity can be increased by the charge accumulation method.

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.



Toshiya Sakata and Yuji Miyahara, "Direct transduction of allele-specific primer extension into electrical signal using genetic field effect transistor", *Biosens. Bioelectron.*, 2007, *22*, 1311-1316.

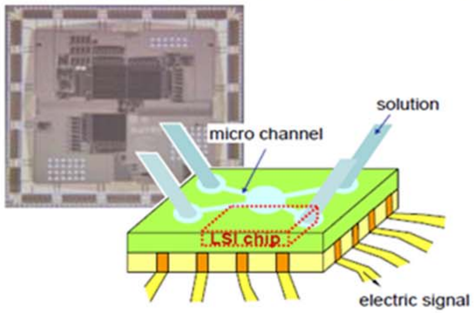
Extended gate MOSFET array

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

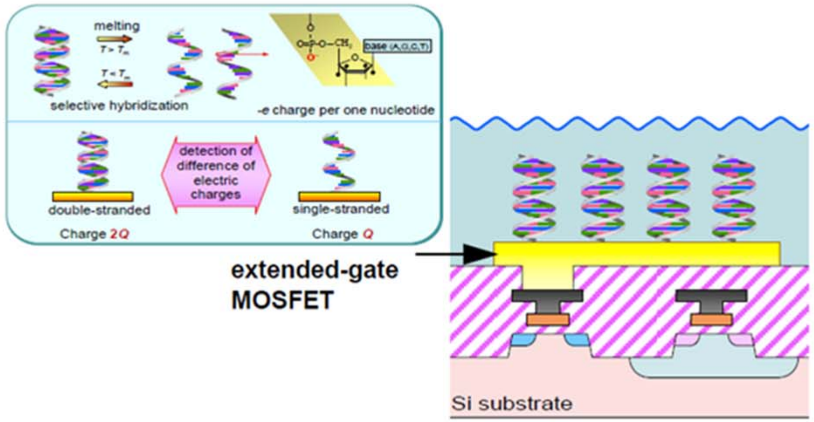
- label free, electrical detection
- system-on-a-chip + lab-on-a-chip



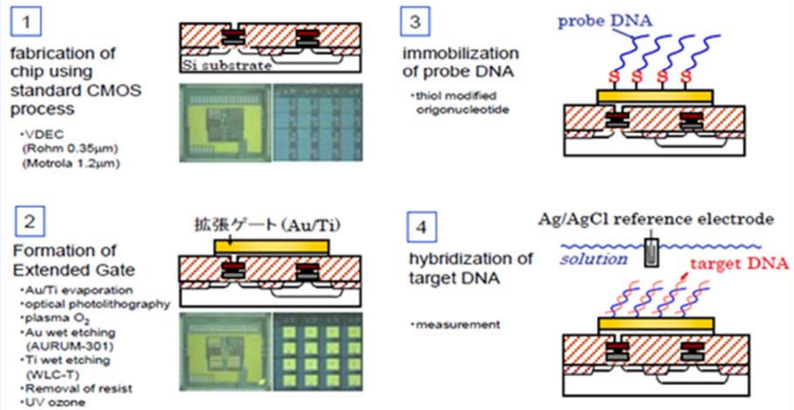
Detection of biomolecules
- ○ sensor device structure
- ○ device fabrication process
- ○ control circuit of sensor device
- ○ sensing signal processing
- ○ sensing methods

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

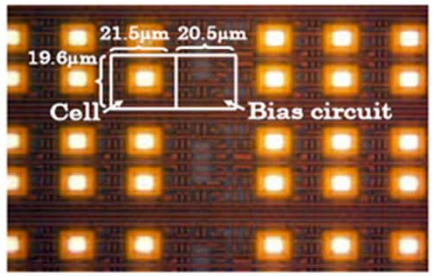
Supply of biomolecules



Fabrication of Device and Measurement Method



1M(10^6) cell array



technology	0.35μm CMOS
array size	20mm×24.6mm
power consumption	64mW

target: Genomic Analysis of 10 bases (4^{10}) simultaneously

M Ohura, S Uno, and K Nakazato, "An Analog BioCMOS Circuit for the Electrical Detection of Biomolecular Charges with Extended Gate MOSFET Cells," 2006 IEEJ International Analog VLSI Workshop, November 16-18, 2006, Hangzhou, China

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.