17th INTERNATIONAL FORUM ON MPSoC

A Wearable Biomedical Sensing System with Normally-off Computing Architecture

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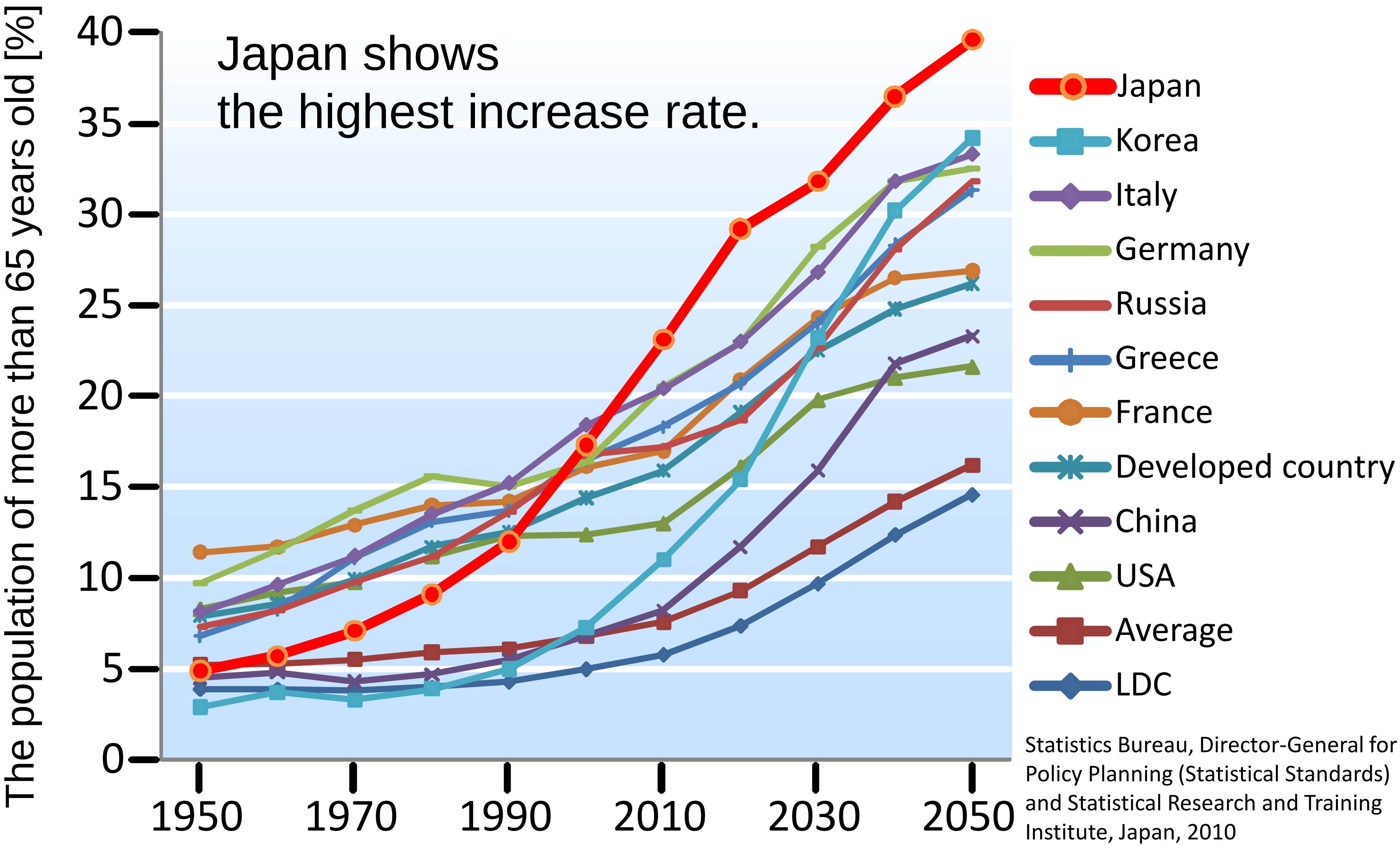
Outline

- Background
- Design Issues and Design Features
- Low Power VLSI Design for ECG and Tri-axial Acceleration Monitoring
- Fabrication & Field Testing Results
- Summary

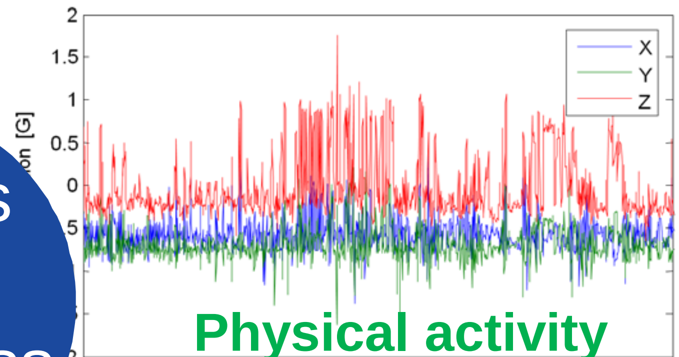
Population of more than 65 years old



Suppresion of lifestyle desease

Measure-
ment

Analysis
&
Awareness



Physical activity estimation:
type,
intensity,
duration.

Lyfe style
- Change

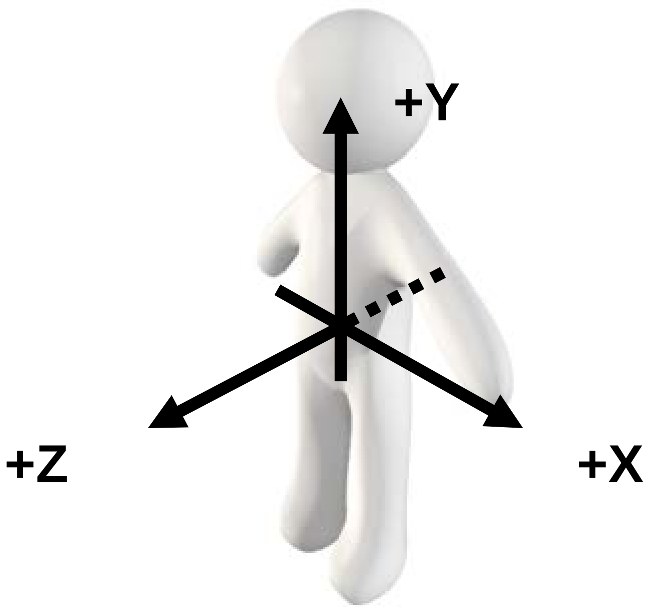
- **Exercise**
- **Intake**
- **Sleep**

Ex.）Diabetes(糖尿病) ⇔ Scedentary

Physical activity estimation for scedentary break

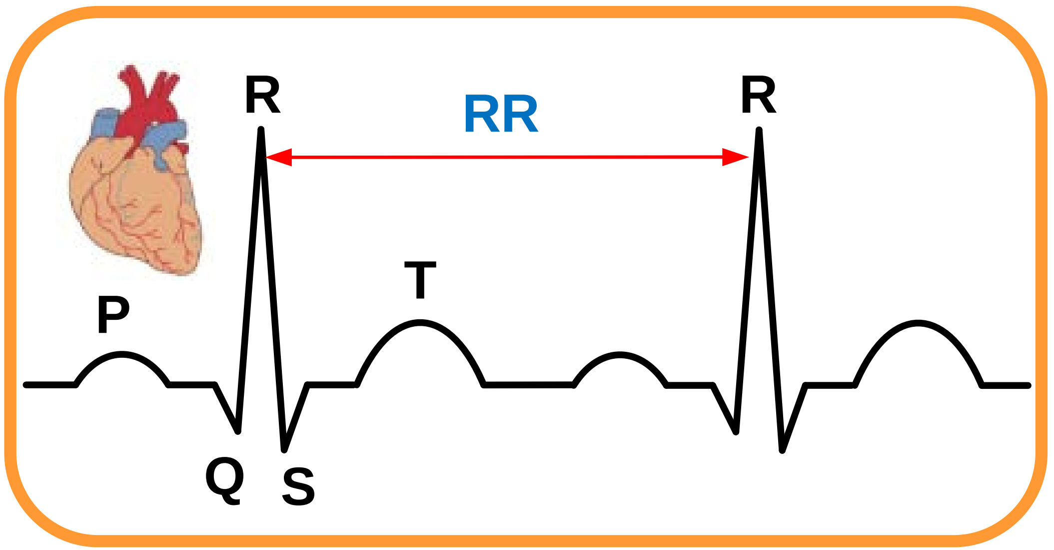
Biomedical data for physical activity estimation

- Triaxial Acceleration



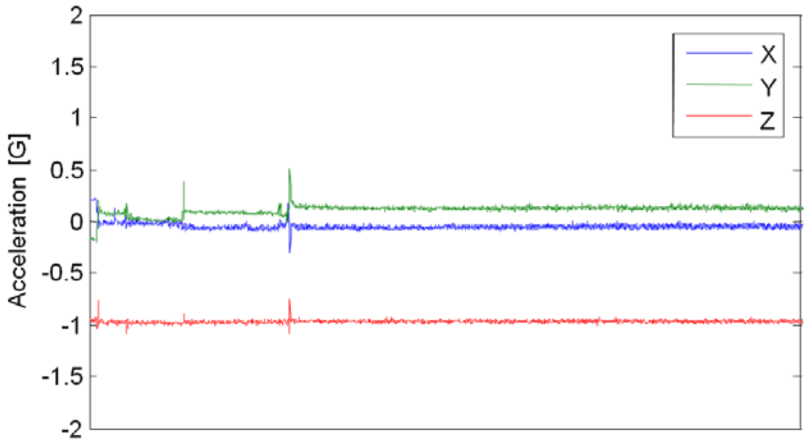
- Instantaneous Heart Rate (IHR)

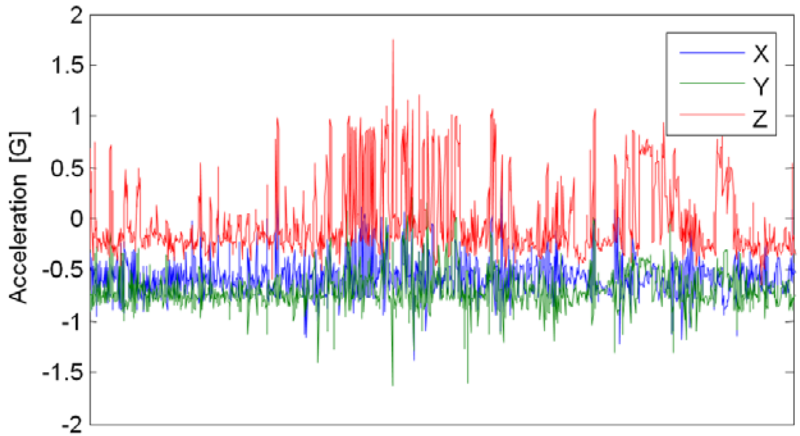
= 60 / (latest RR[s]) [bpm]



Energy expenditure is estimated by the above two kind of biosensing data.

Ex) Triaxial acceleration measurement





3-axis Acceleration

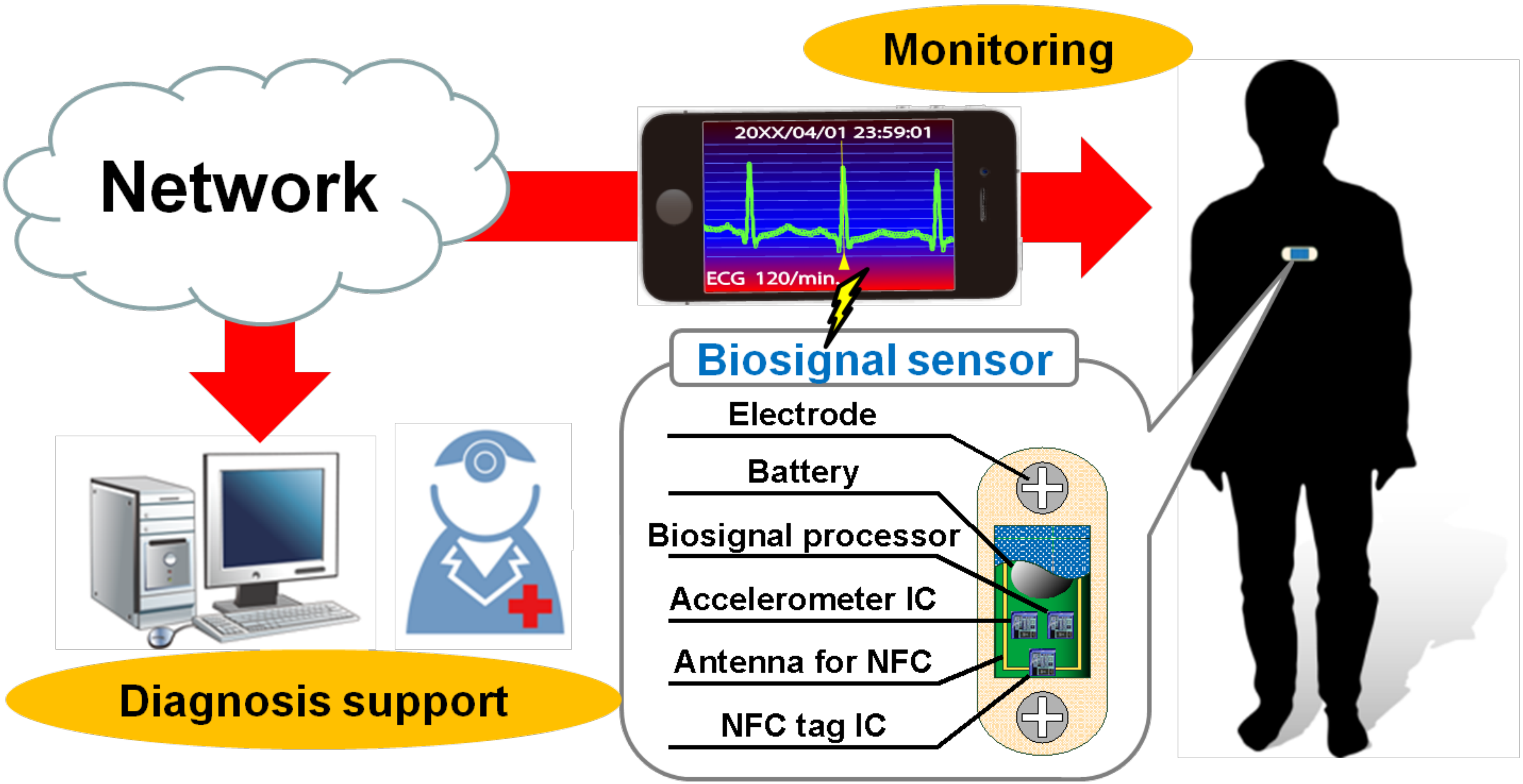
↓

Activity Estimation

↓

Energy Expenditure

Development of wearable bio-medical sensor



- **Requirements**

  → **Low power, Small size and Light weight**

Design issues

- Ultra low power consumption for longer life operation with tiny battery.

- Noise tolerant IHR(Instantaneous Heart Rate) Monitoring at short distance electrode condition to realize wearable small size sensor.

Design Features

- Non-volatile memory and Non-volatile MCU(Micro-Control Unit)
  for normally-off computing

- Algorithm of noise-tolerant IHR(Instantaneous Heart Rate) extraction

Normally-off computing

	Frequency component
ECG	0.1 - 150Hz
EEG	0.5 - 60Hz
VEP	0.5 - 60Hz
EMG	few kHz

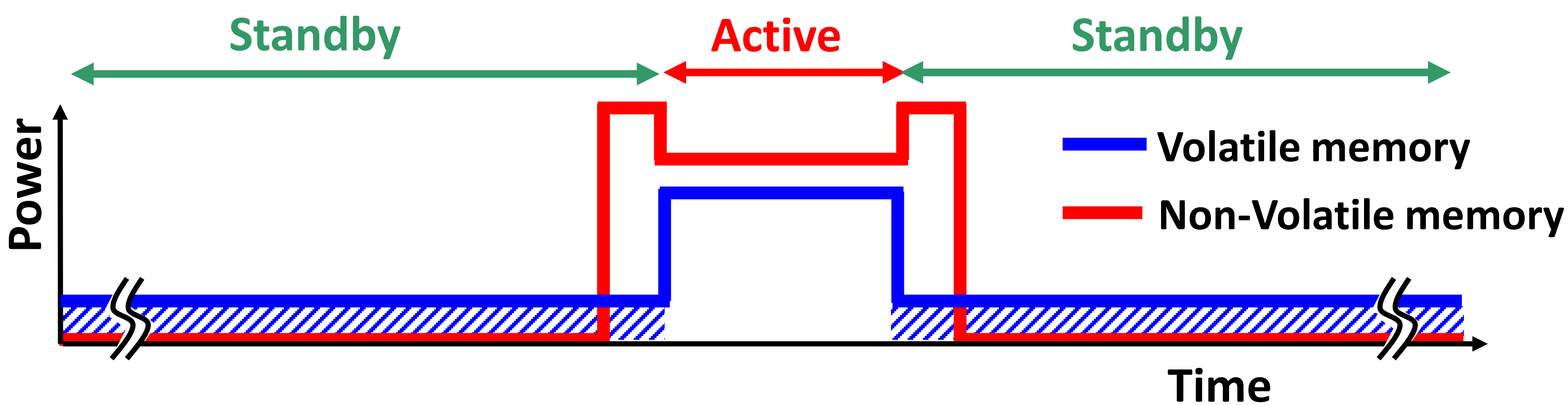
<

Operational clock

- ✓CPU
- ✓MPU

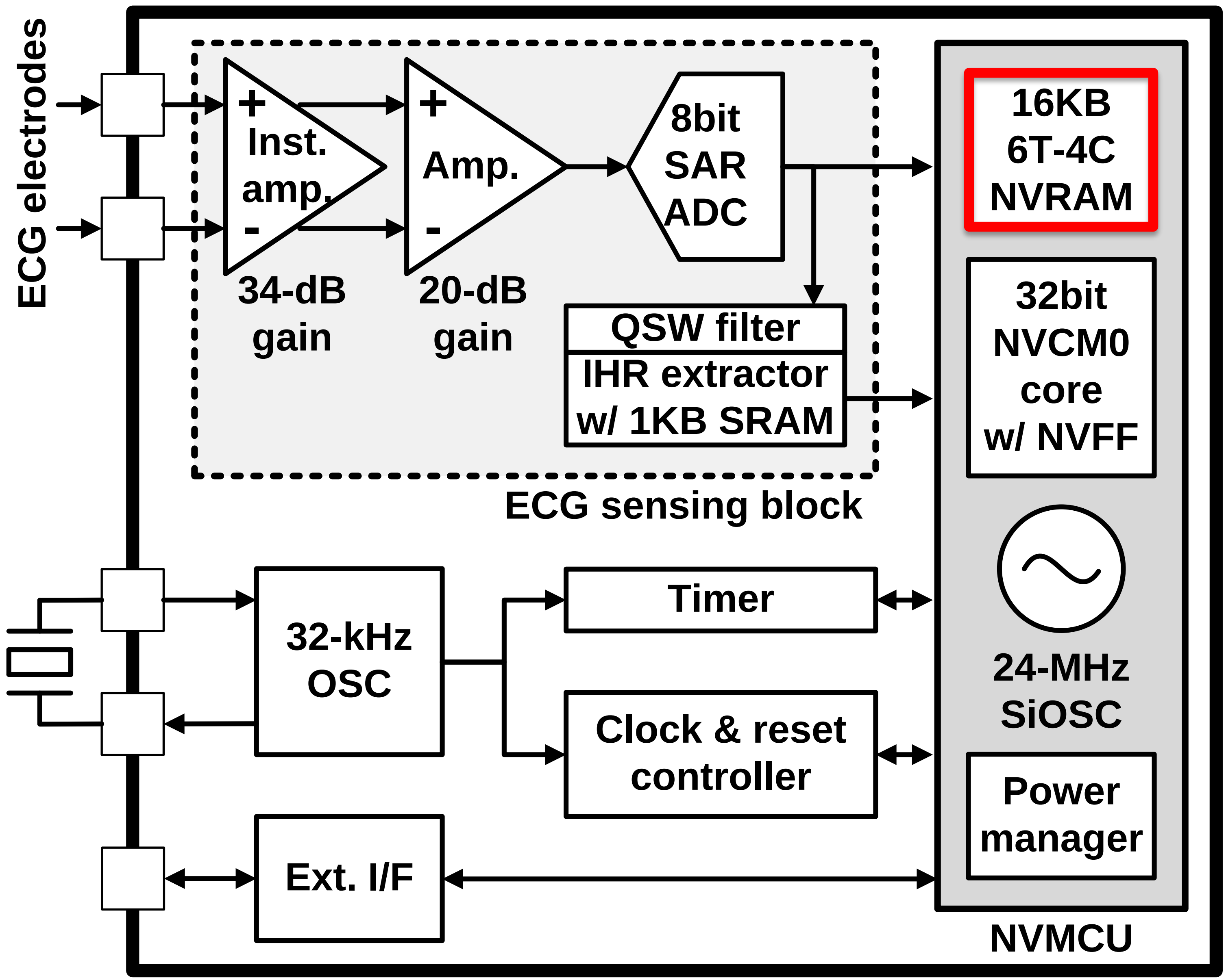
etc…

- **Extremely Low frequency range of Bital signal**
- **→ Standby power reduction is effective**



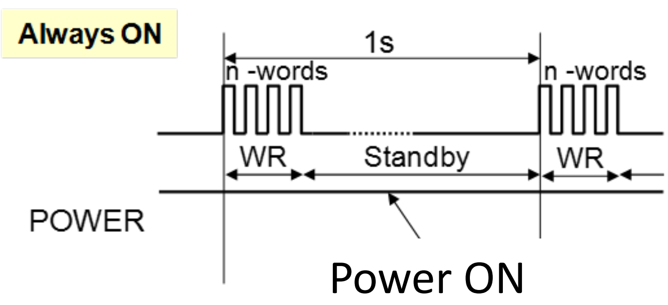
Non-volatile FeRAM was employed to suppress standby leak.

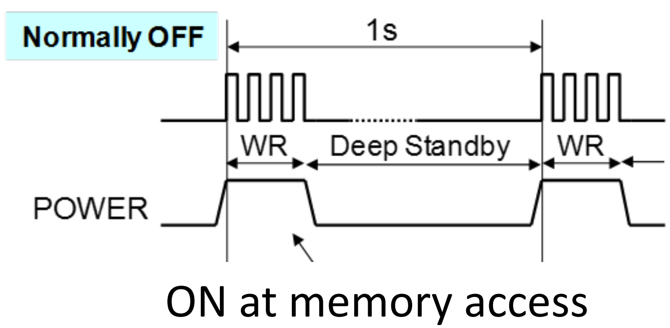
VLSI block diagram of bio-medical sensor

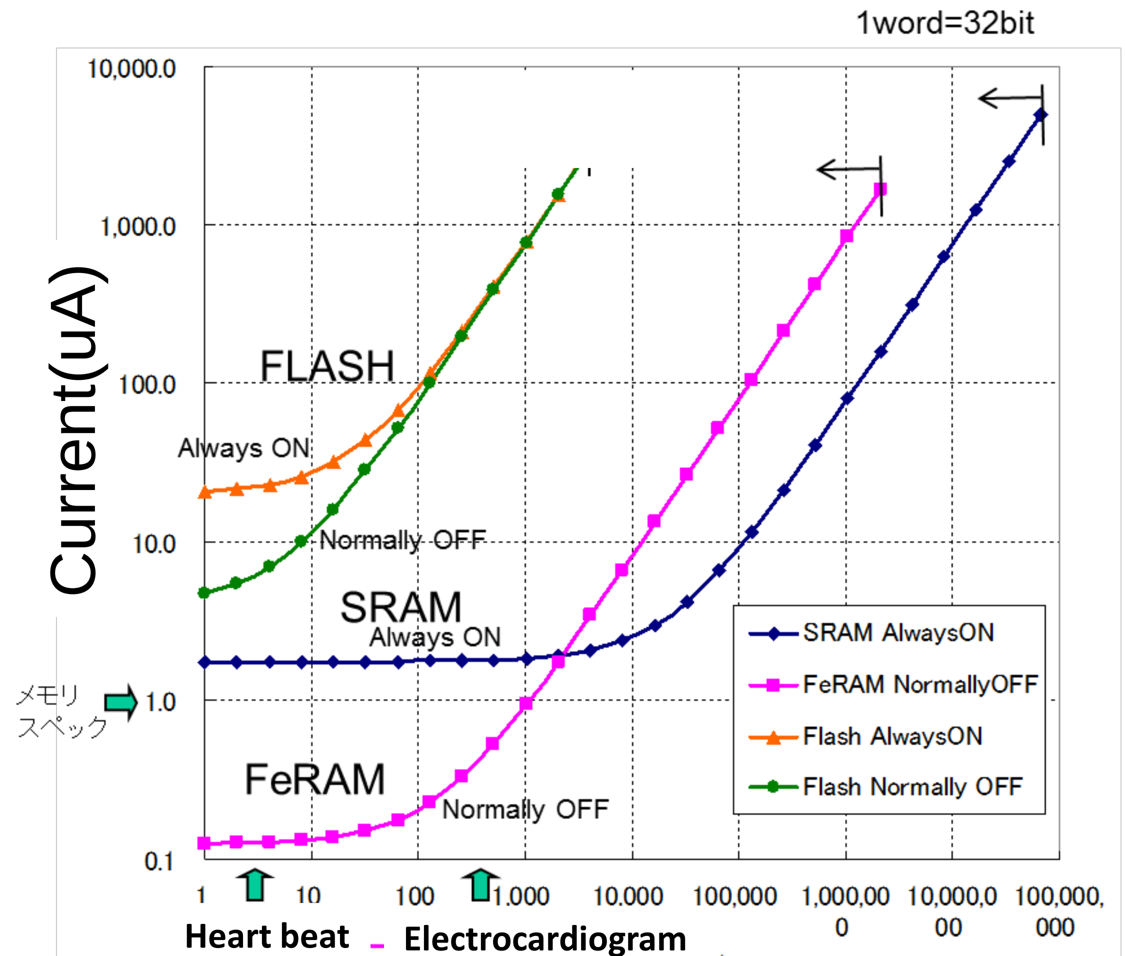


Normally-off computing with Non-volatile memory

Operating condition







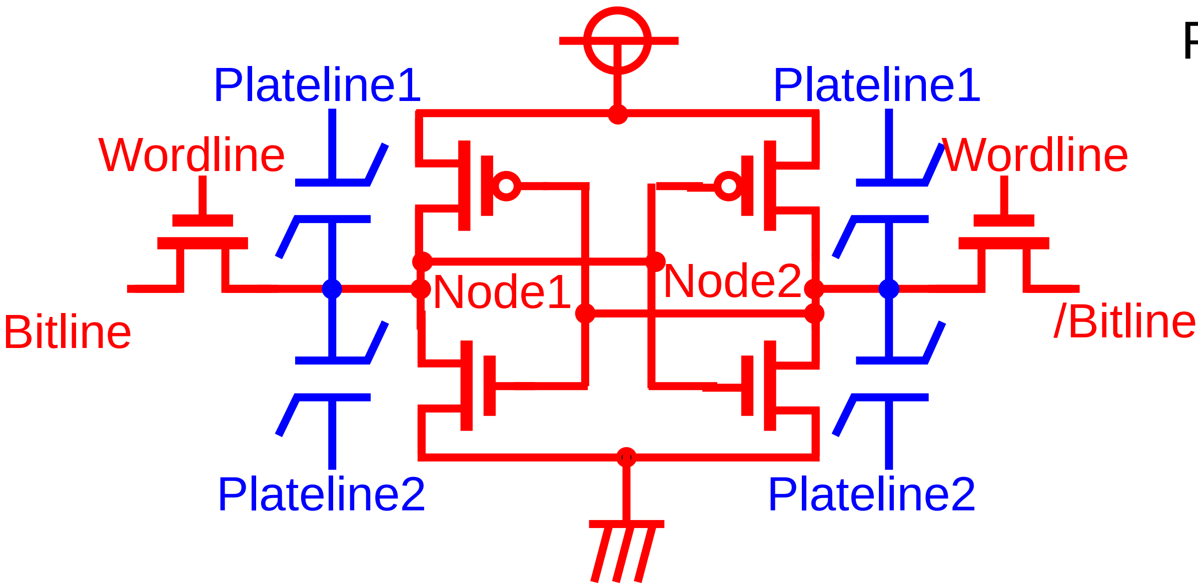
N-words access per second

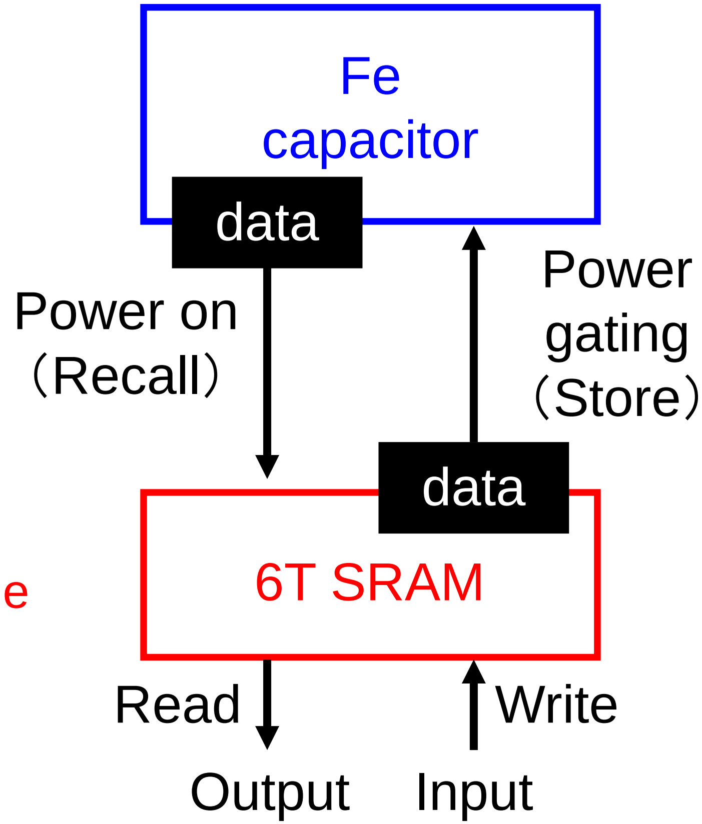
FeRAM has the lowest leak-power feature for bio-medical sensing.

6T-4C non-volatile memory

6T-4C shadow memory

6T SRAM + Fe capacitor
= 6T-4C shadow memory



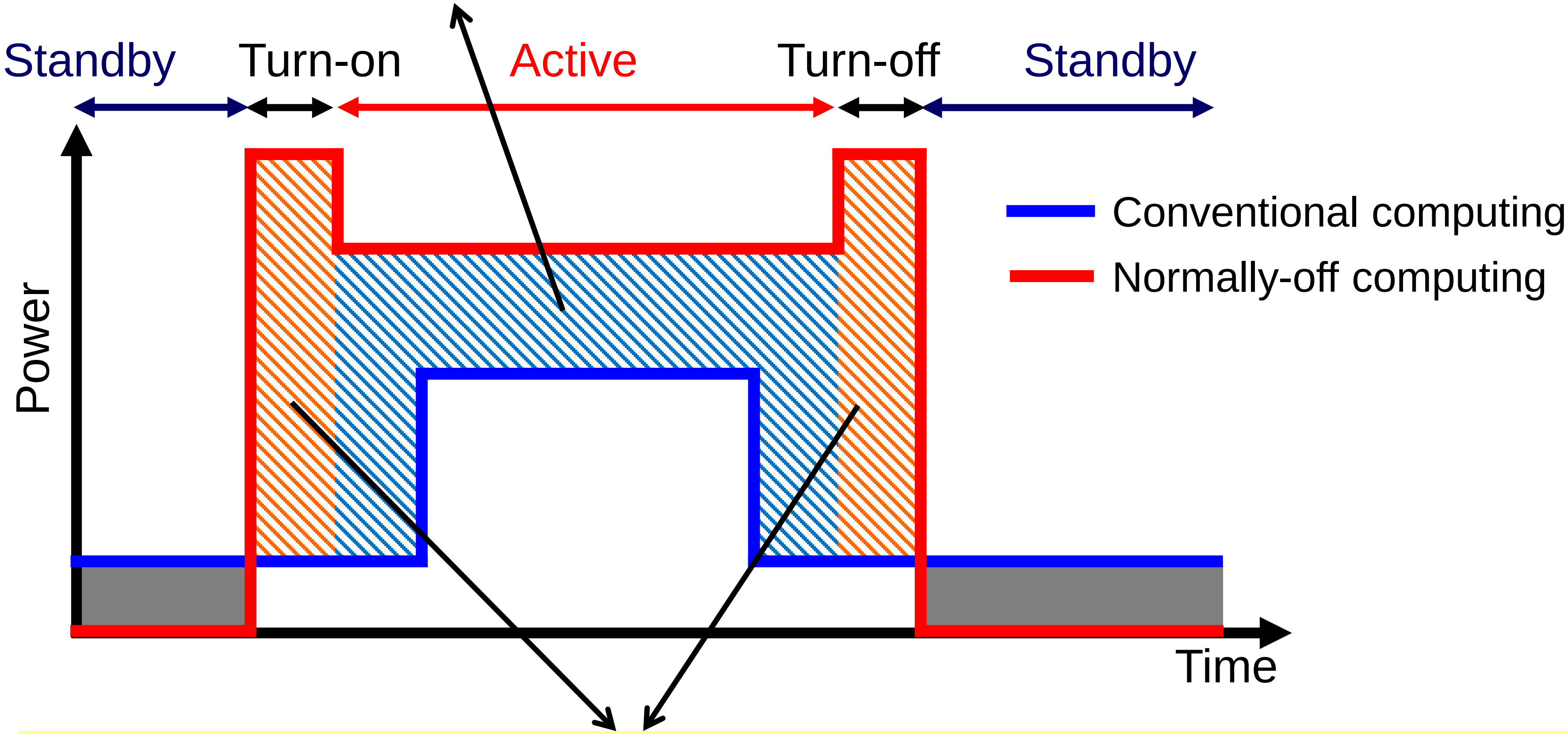


Active: 6T SRAM
Sleep: Nonvolatile memory

Design issue of 6T-4C non-volatile memory

Problem

1.Increase of the active energy consumption

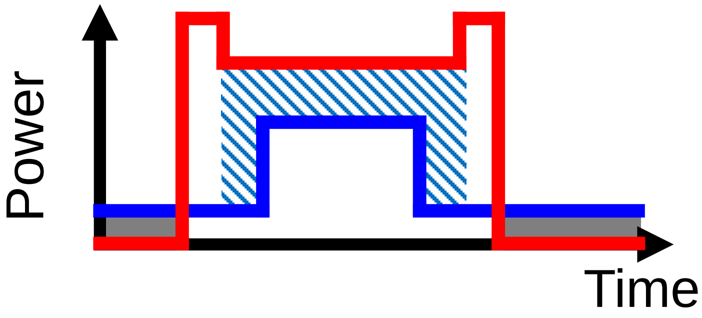


2.Increase of the energy consumption during transition period

Circuit technolgy for power reduction

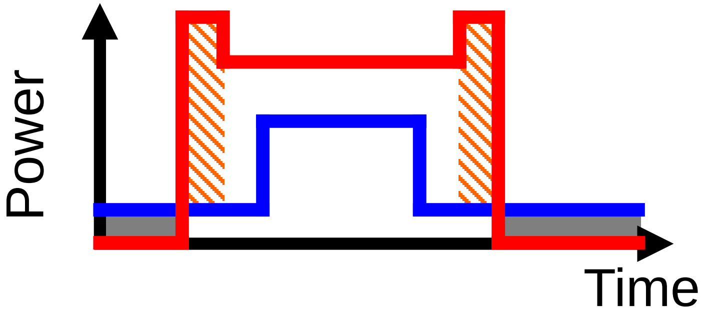
1.Bit-line Non-precharge

→Reducing the active energy consumption



2.Plate-line Charge sharing

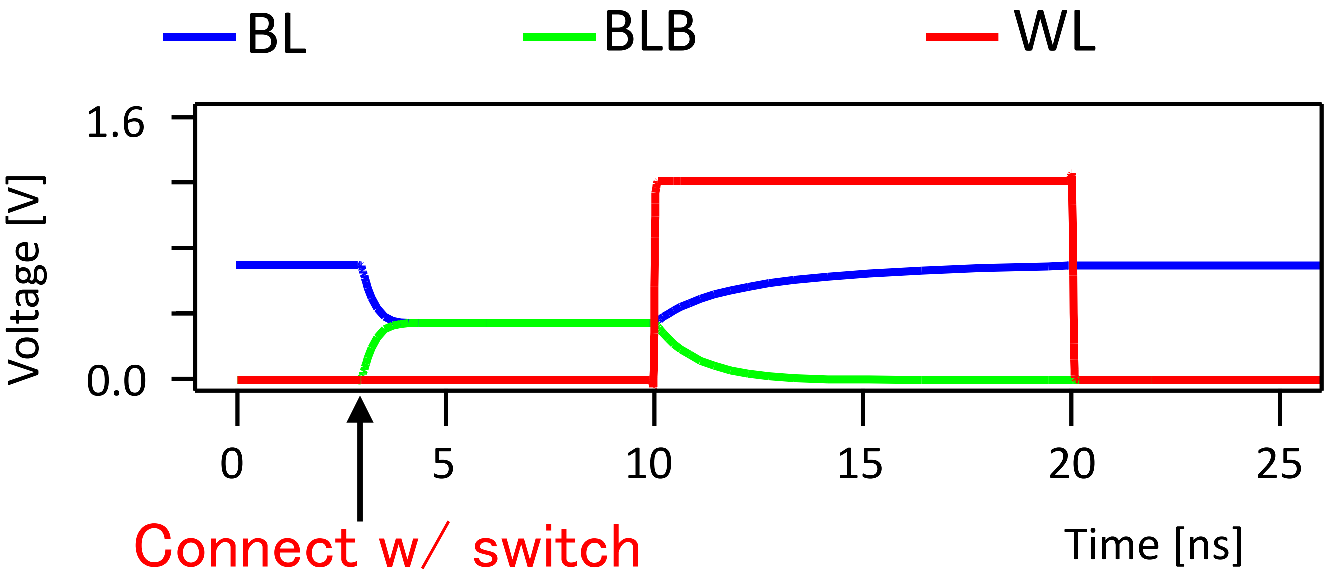
→Reducing the turning-on/off energy consumption



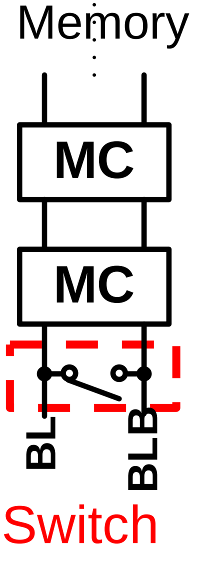
Bit-line Non-precharge

Proposed method

Connecting a bit-line pair w/ switch



BL: Bit-line
WL: Word-line
MC: Memory cell

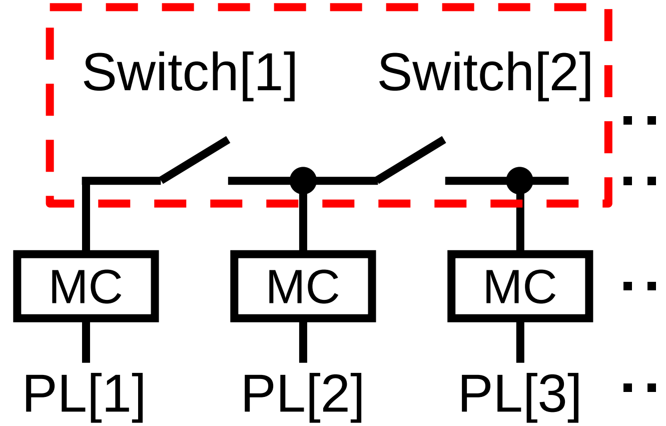


The energy consumption for charging is reduced

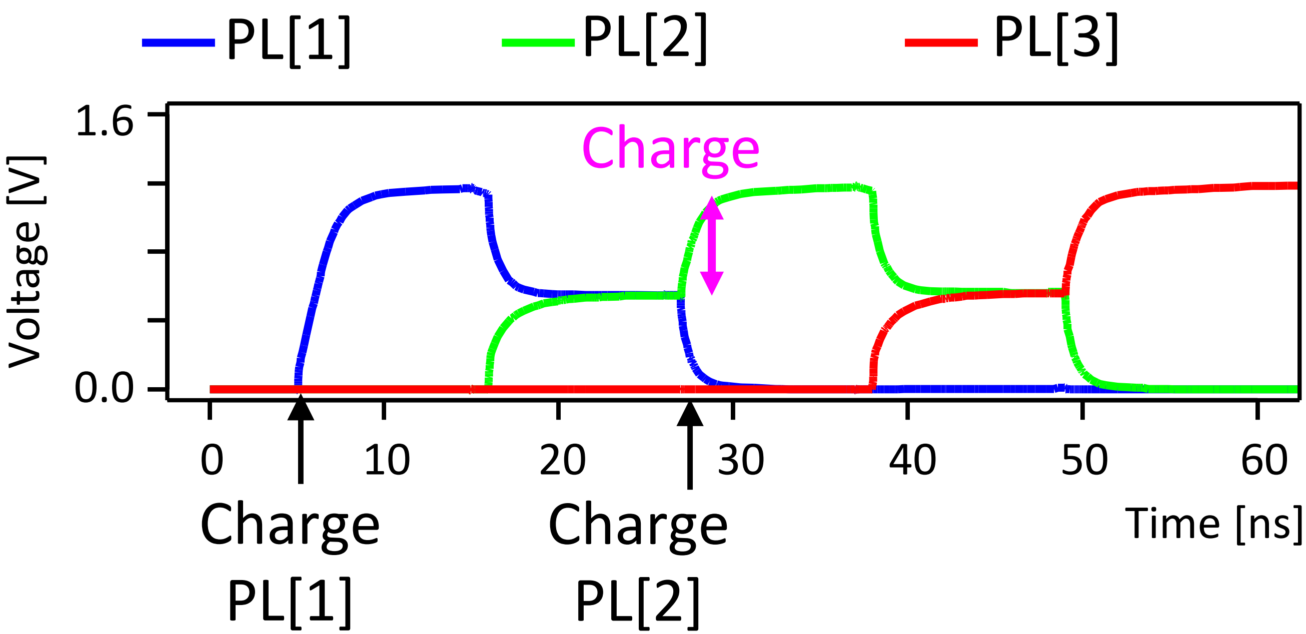
Plate-line Charge share

Proposed method

When charging PL, reusing an electric charge of previous one



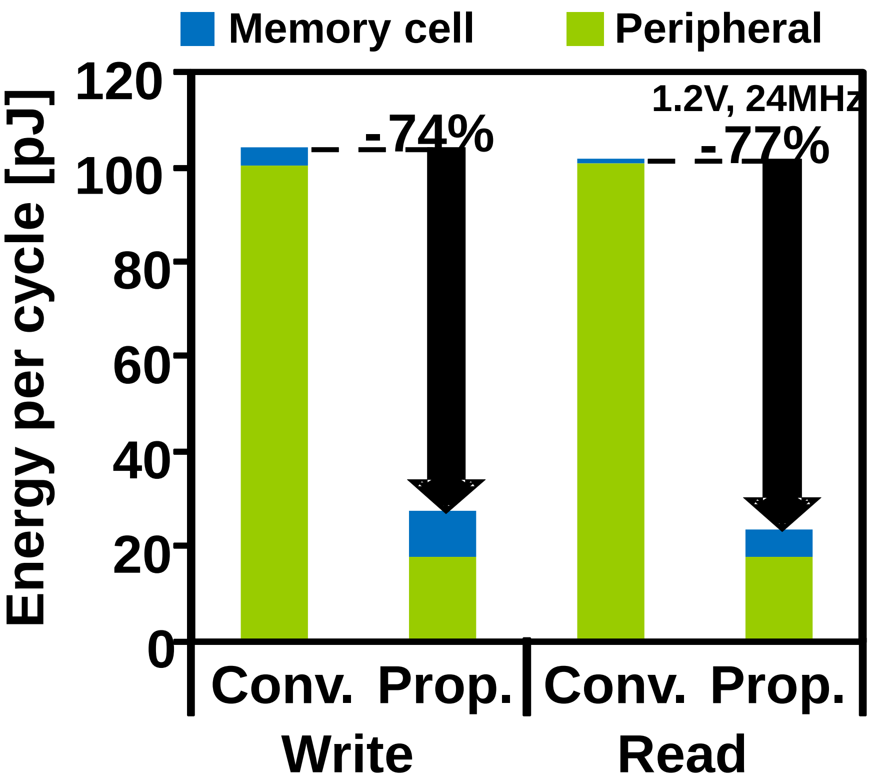
PL: Plate-line



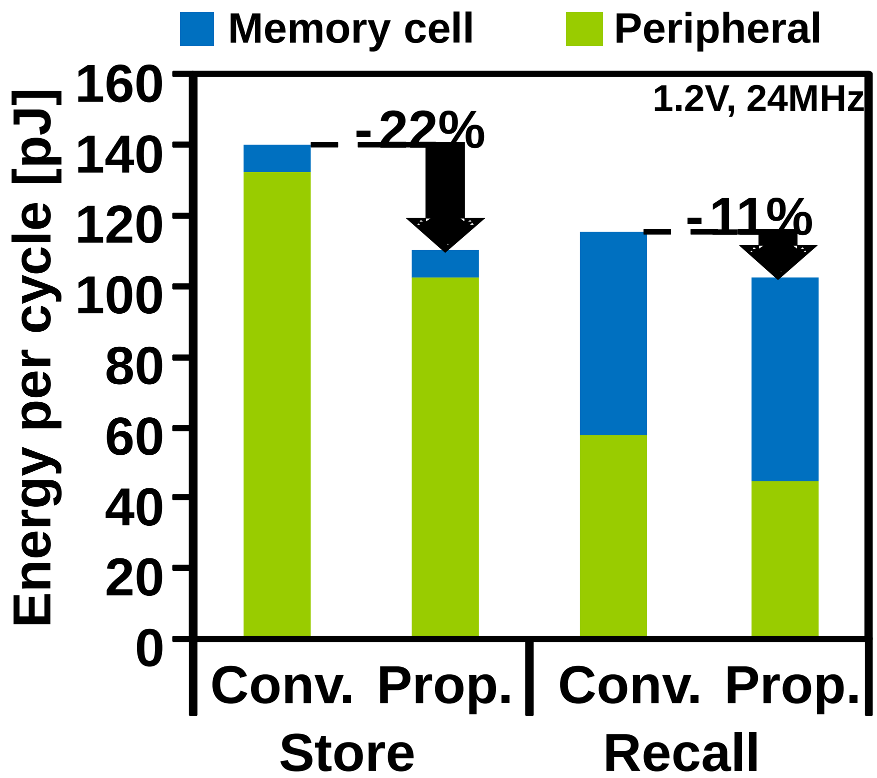
Charging rate is reduced

Power reduction of 6T4C memory

1.Bit-line Non-precharge

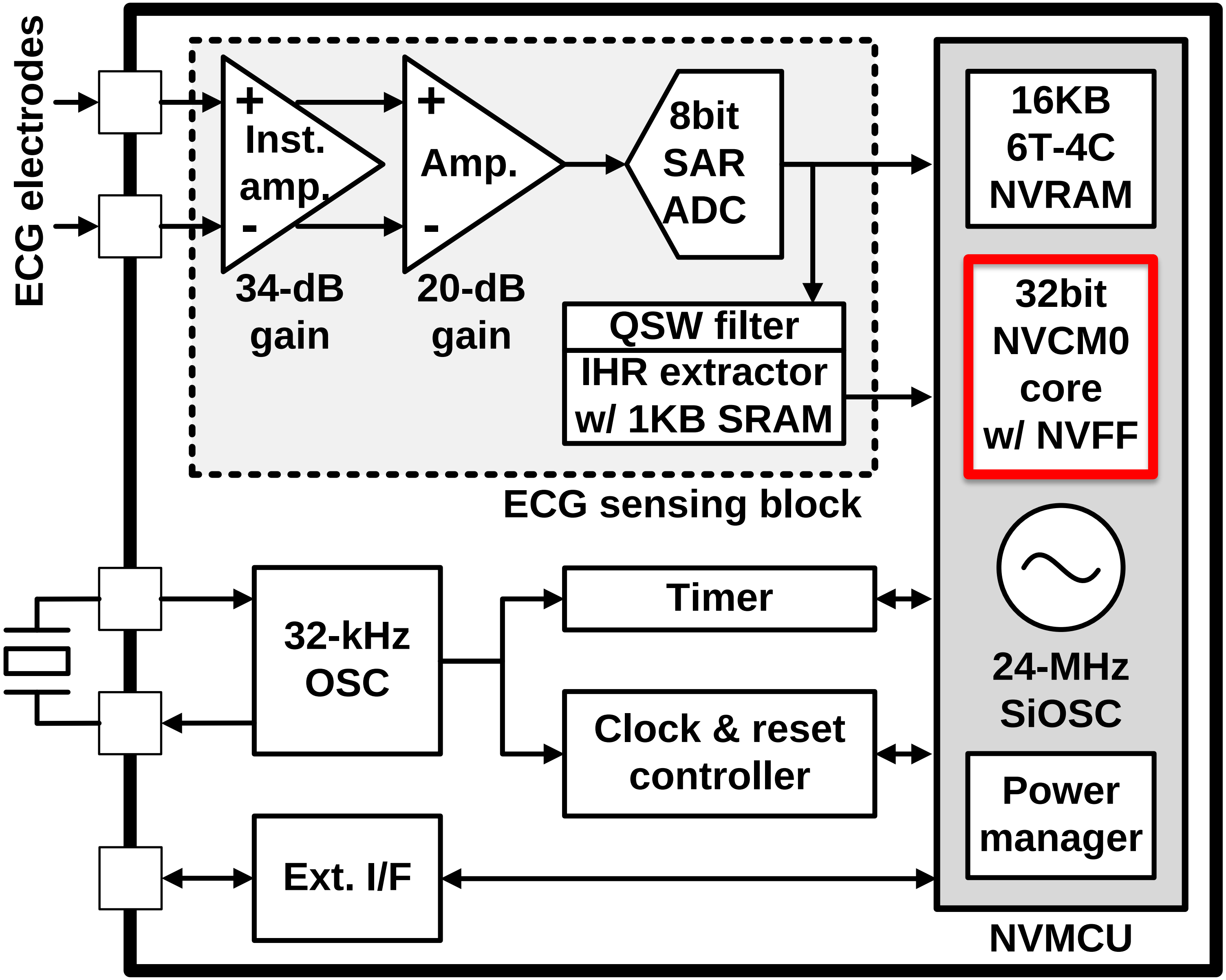


2.Plate-line Charge sharing



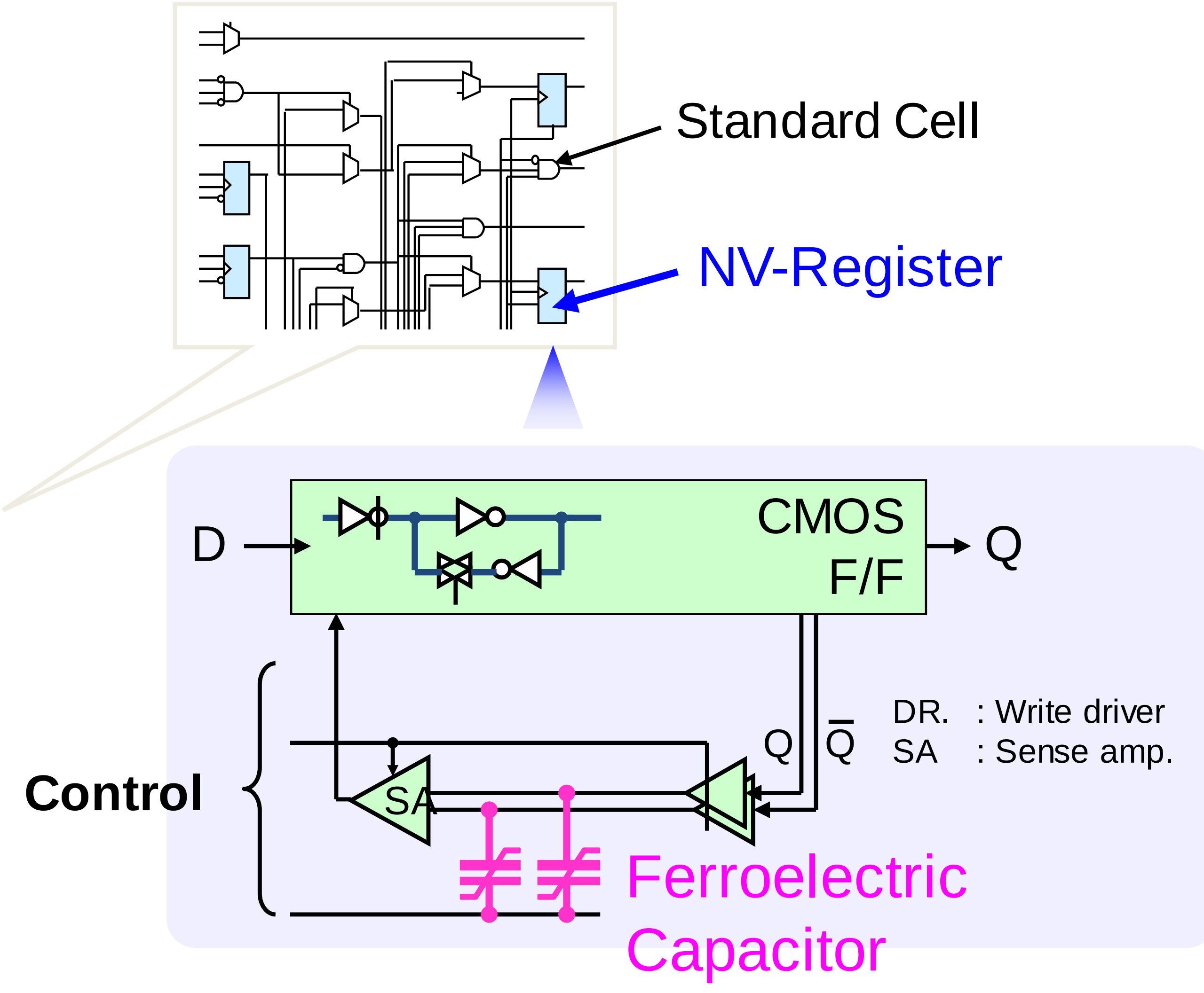
→ **Improvement of Break-even time**

VLSI block diagram of bio-medical sensor



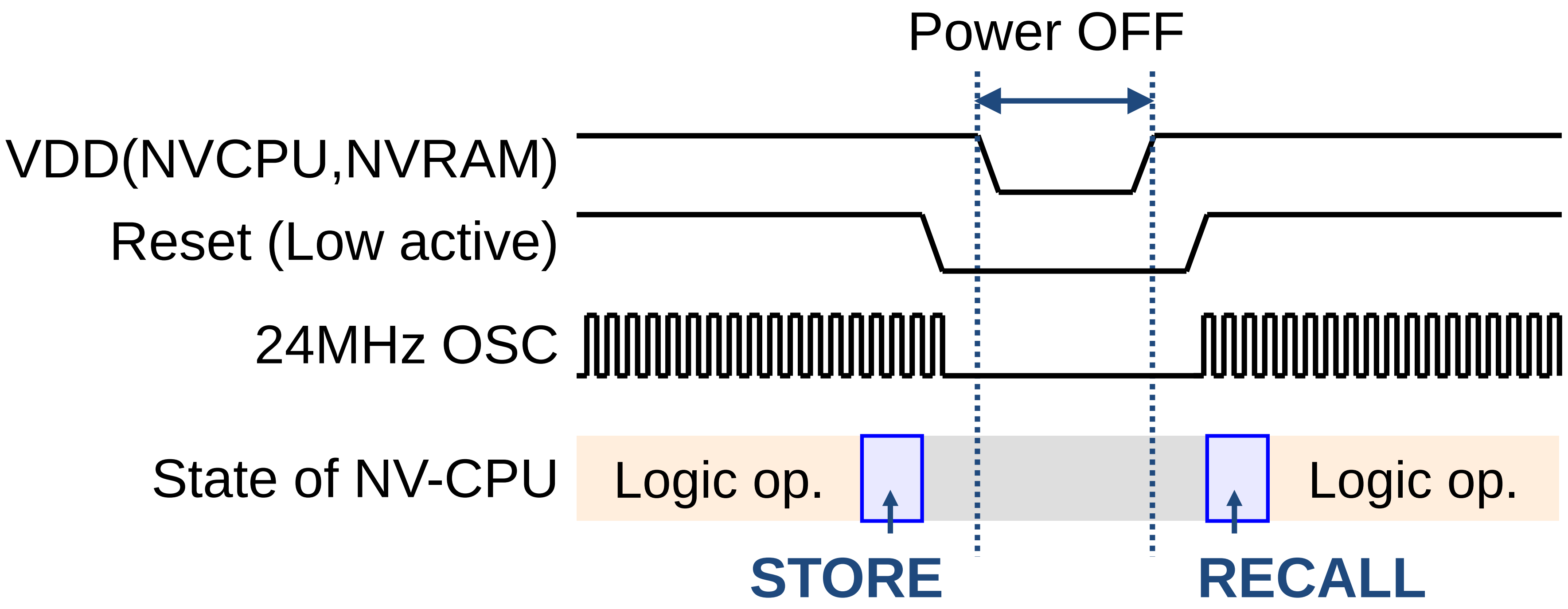
Non-volatile logic

NVFF has capability to retain a logic state w/o power supply.



Ferroelectric capacitor retains data during power off state.

Basic operation

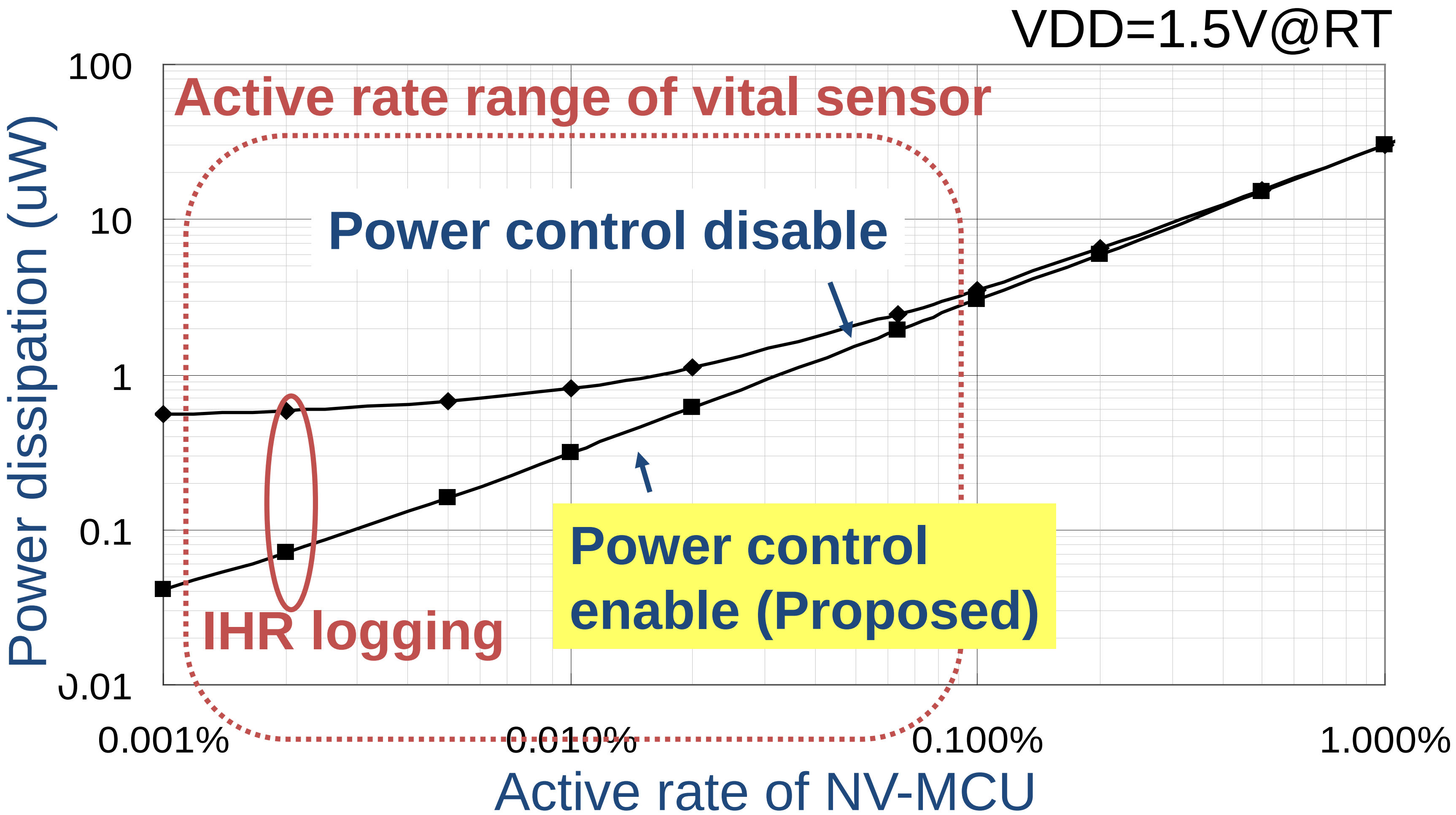


Logic op: NVCPU executes instruction in NVRAM at 24MHz.

STORE: Logic state in NVFF is written into FE capacitors.

RECALL: Logic state is recovered from FE capacitors.

Power dissipation of non-volatile MCU



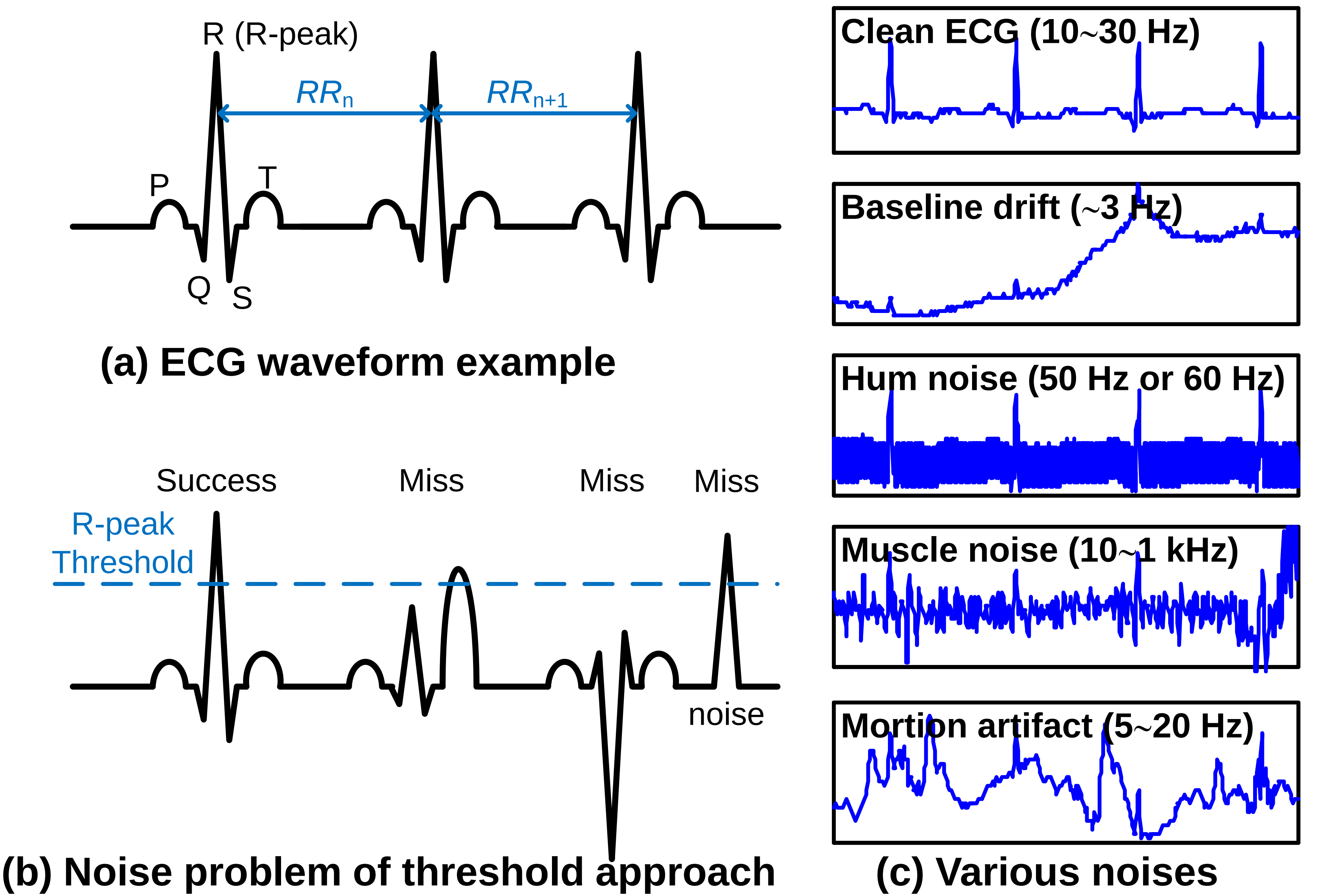
Non-volatile Flip-Flop circuit (NVFF) is useful to reduce power dissipated in the MCU for vital sensor application.

Design features

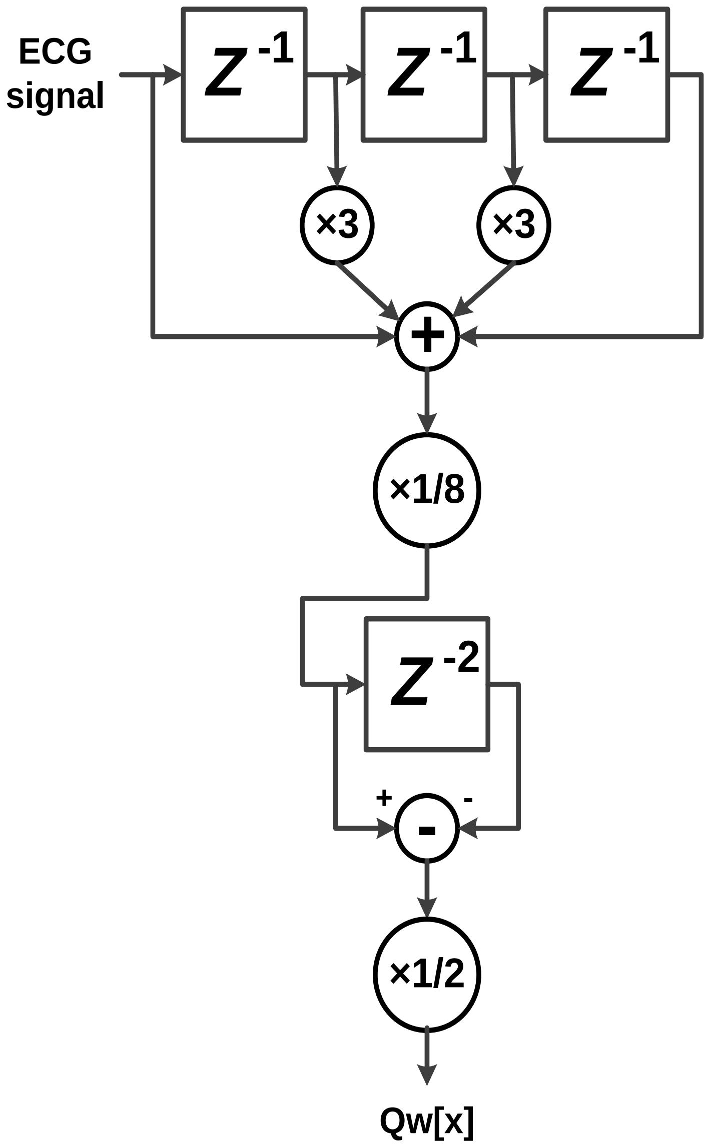
- Non-volatile memory and Non-volatile MCU(Micro-Control Unit) for normally-off computing

- Algorithm of noise-tolerant IHR(Instantaneous Heart Rate) extraction

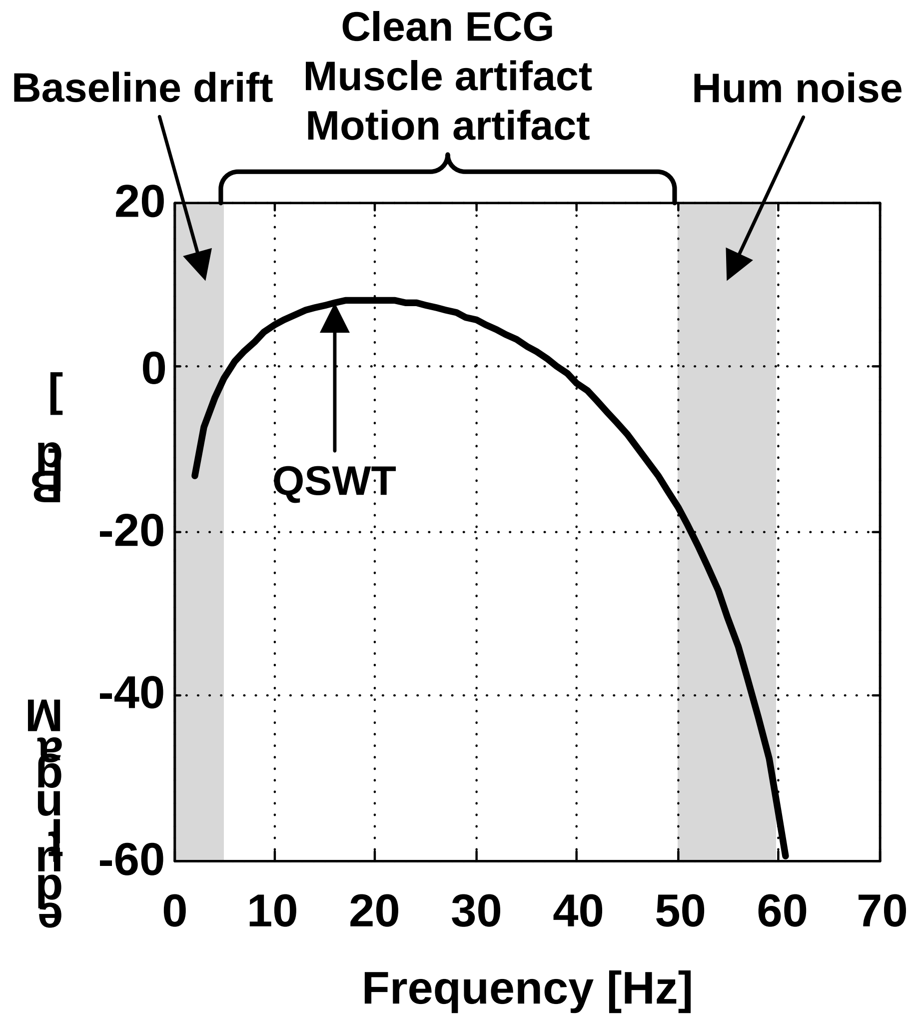
Various noises in ECG wave



QSWT filter for noise suppression

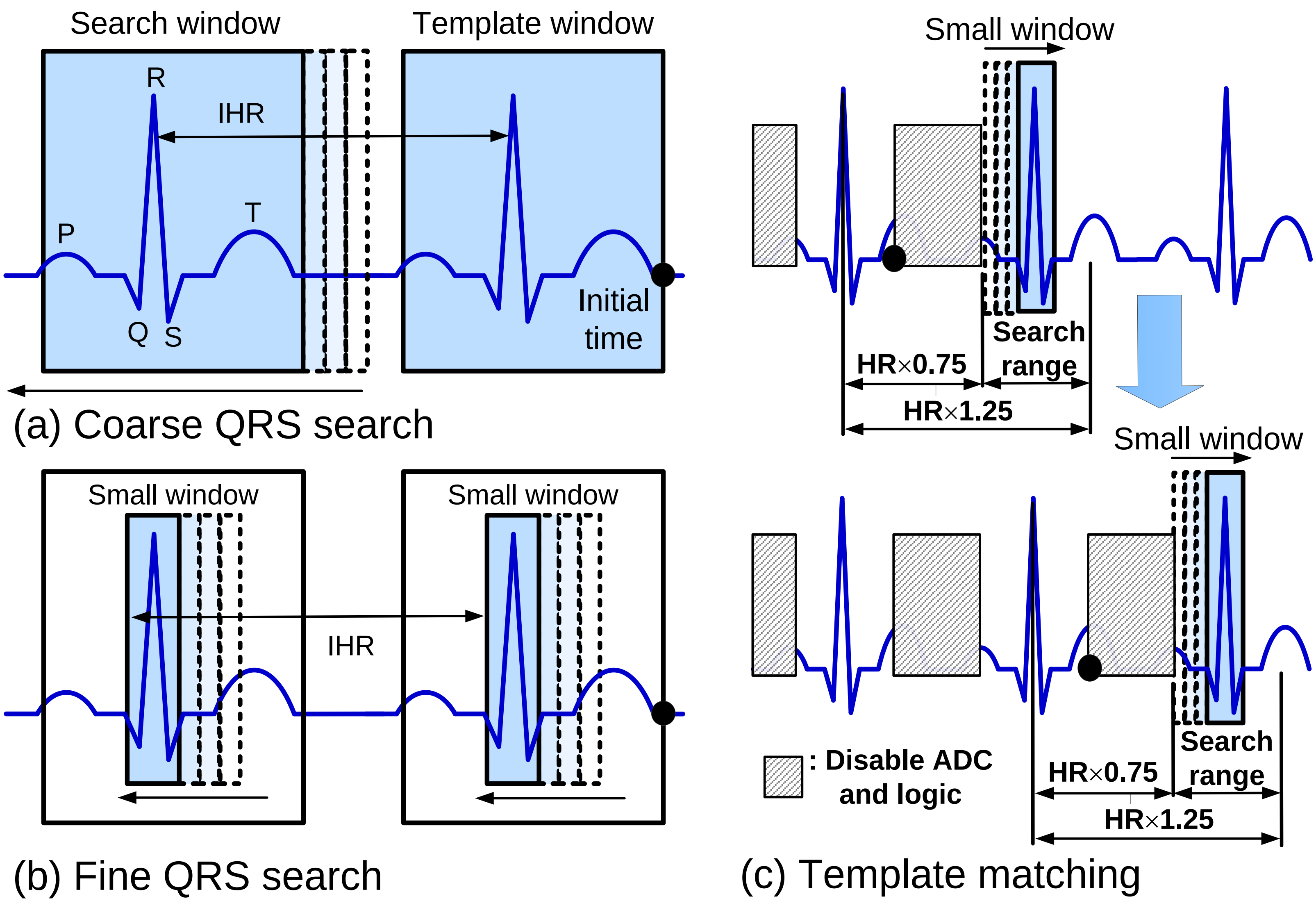


(a) Block diagram



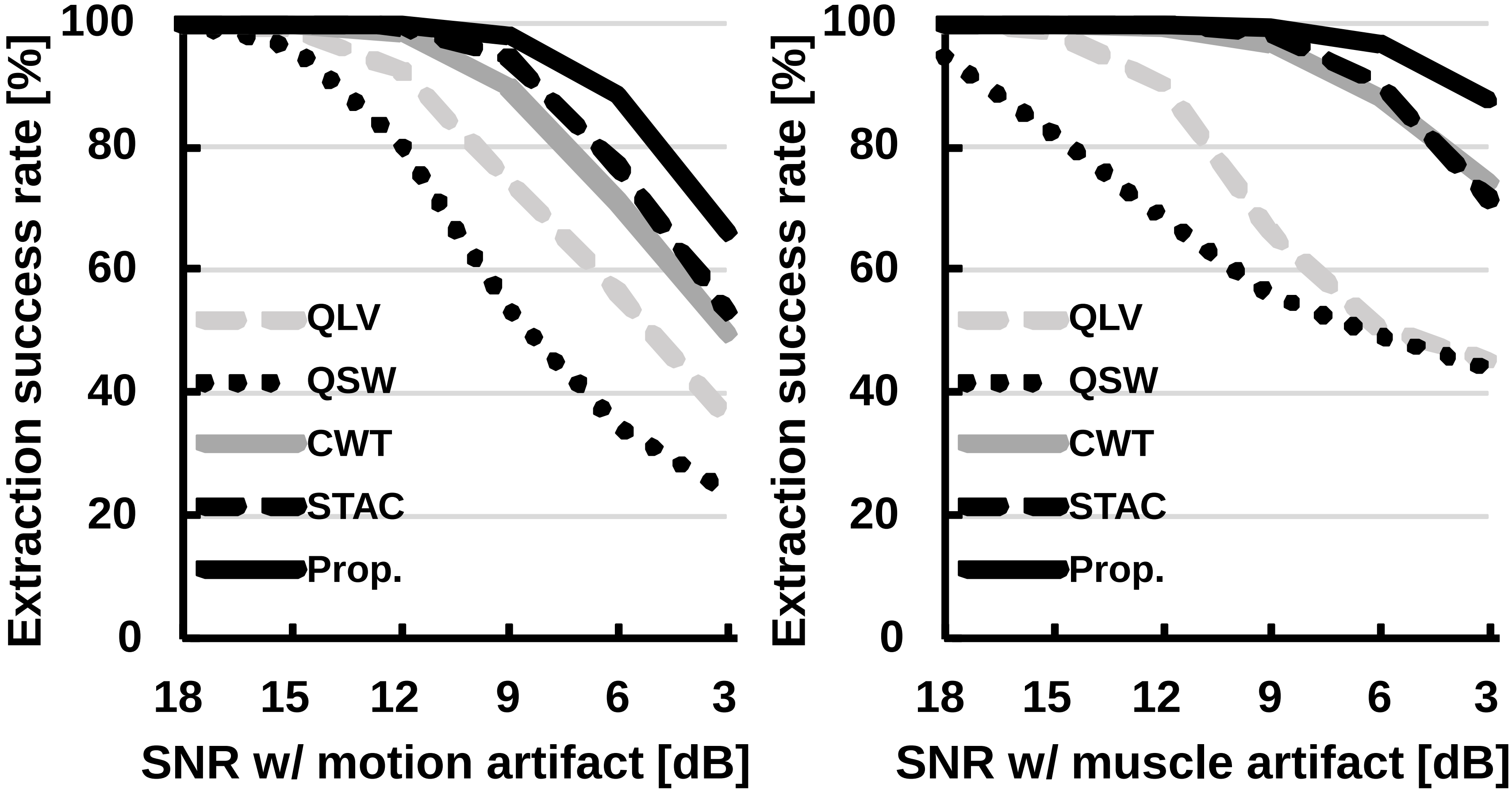
(b) Frequency characteristics

Algorithm of noise torelant IHR extraction



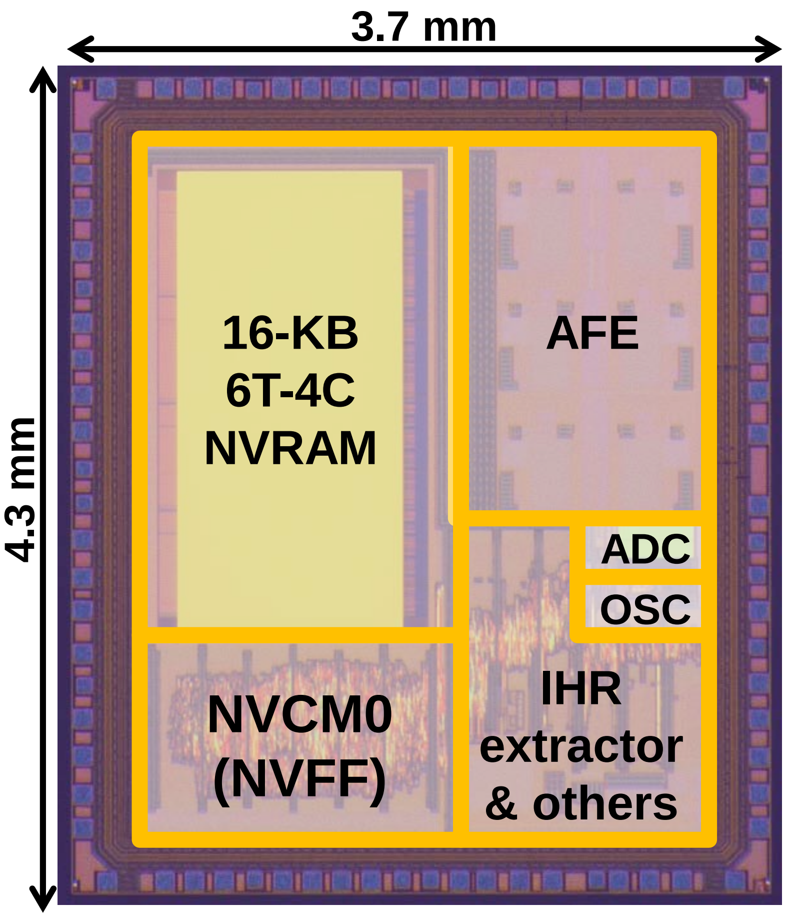
Coarse-fine QRS template generation and template matching with QRS prediction.

Success rate evaluation of IHR extractor



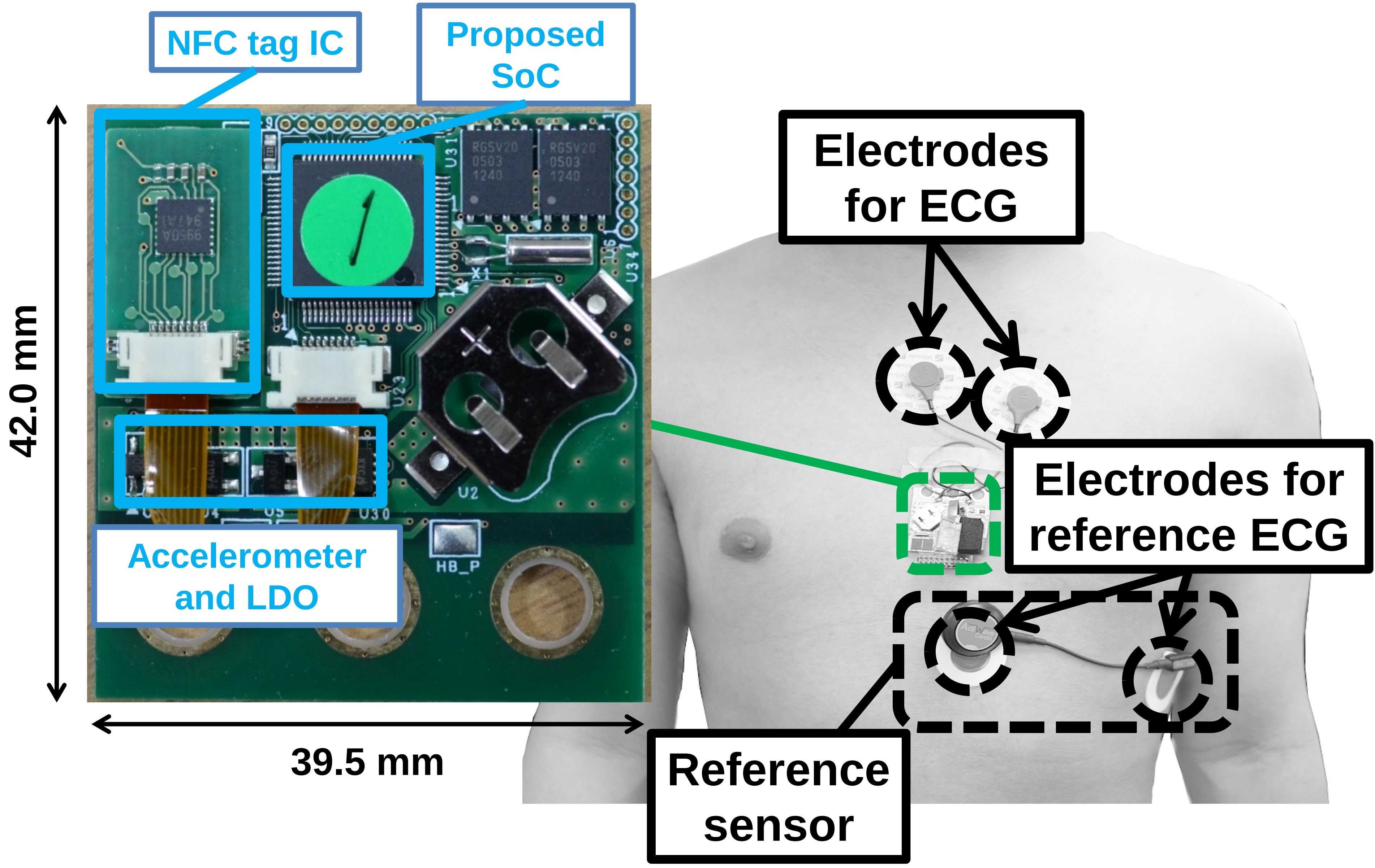
The IHR extractor can also suppress motion artifact and muscle artifacts.

Photo of VLSI wearable bio-medical sensor

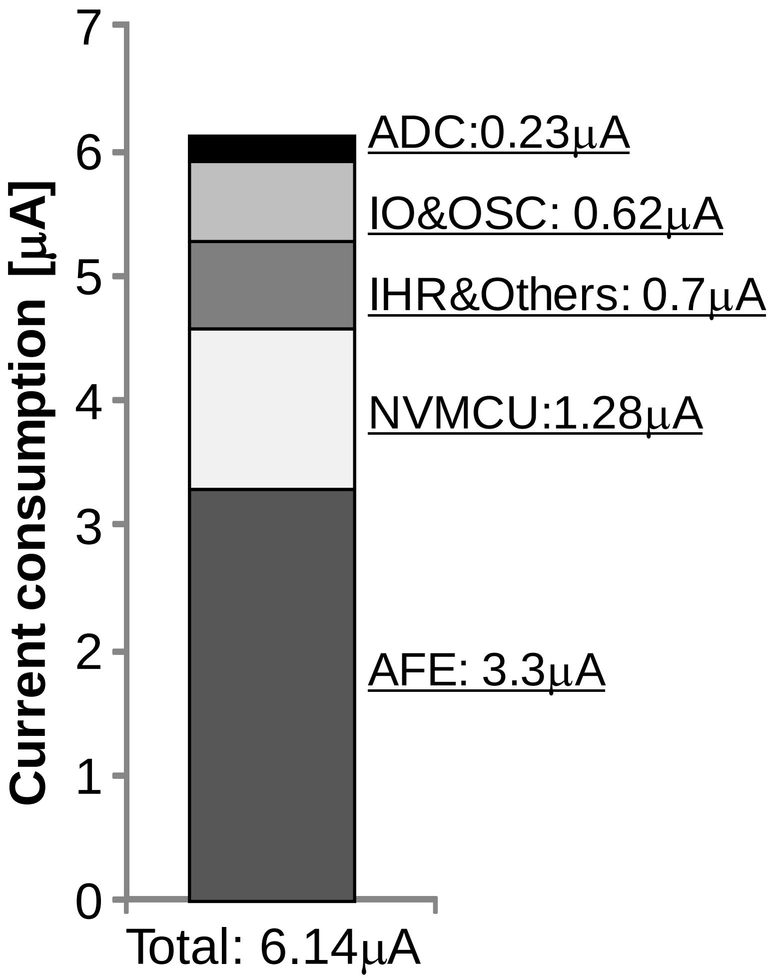


Technology		0.13 μm CMOS
Supply voltage		1.2 V (AFE, ADC, Logic, Memory)
		3.0 V (32.768-kHz OSC and I/O)
Chip area		3.7×4.3 mm^2
Frequency		24 MHz (for processor)
		32 kHz (for other blocks)
Processor		32-bit Cortex M0 (with NVFF)
On chip memory		16-KByte 6T-4C NVRAM
AFE	Gain	54 dB
	Bandwidth	700 Hz
	CMRR	73 dB
ADC	Resolution	8 bit
	Current	0.23 μA@128 S/s, 1.0 μA@1 kS/s

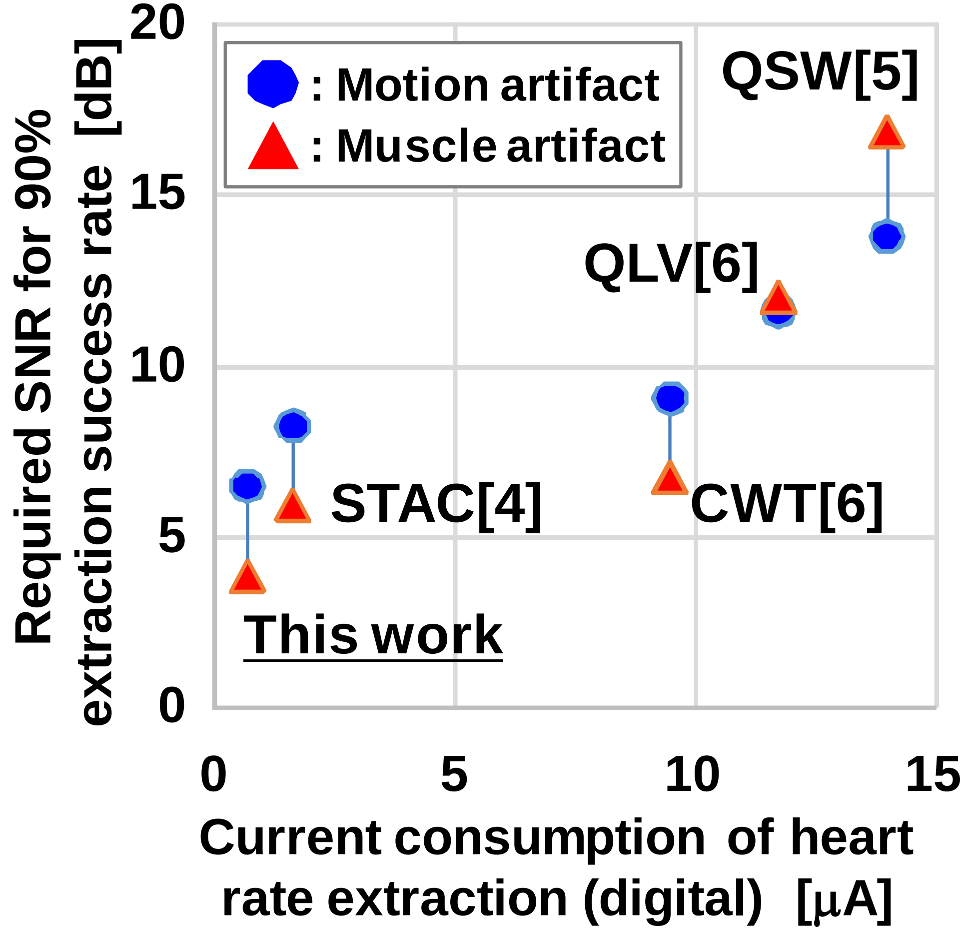
Experimental wearable bio-medical sensor



Measurement results

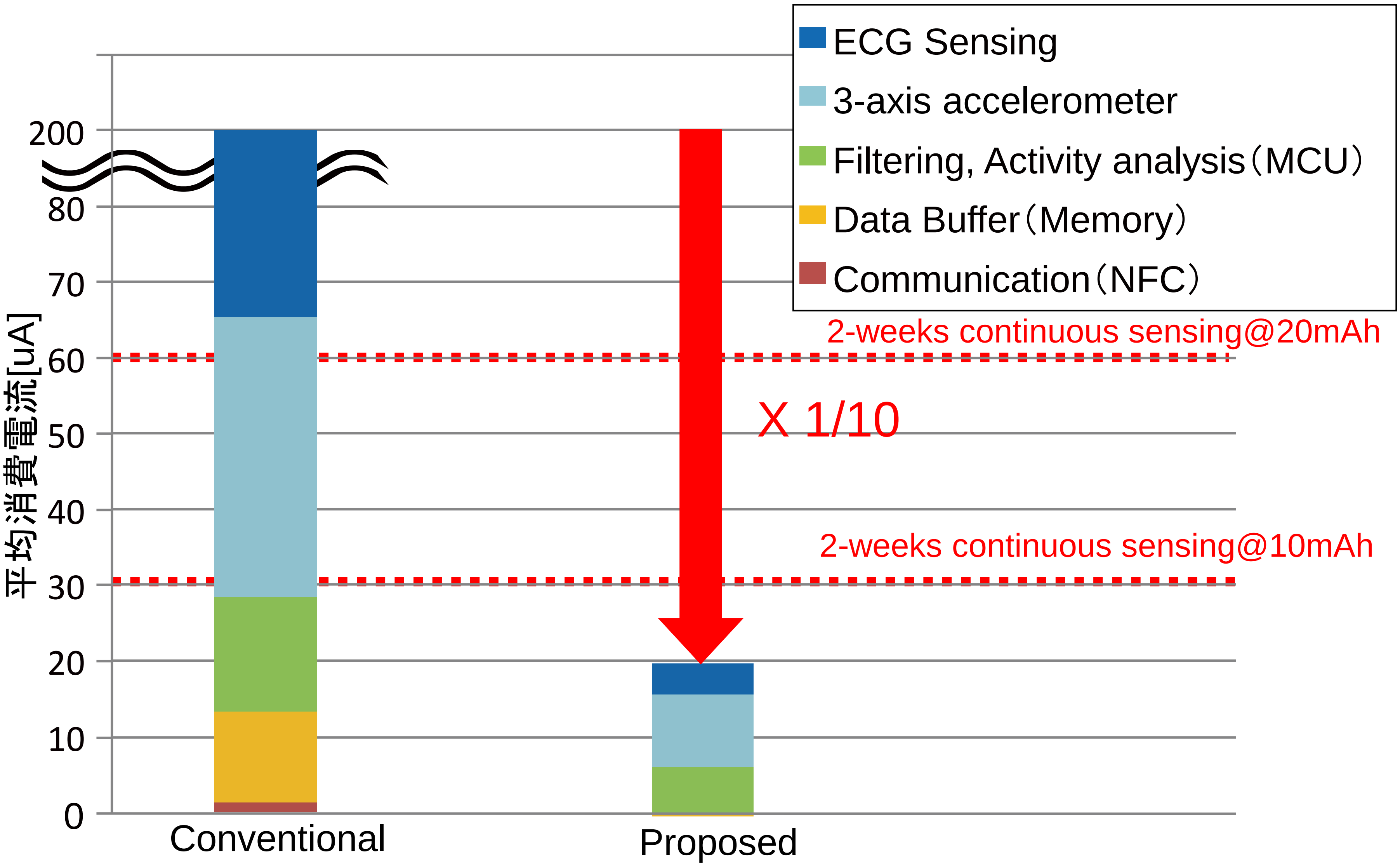


(a) Total power

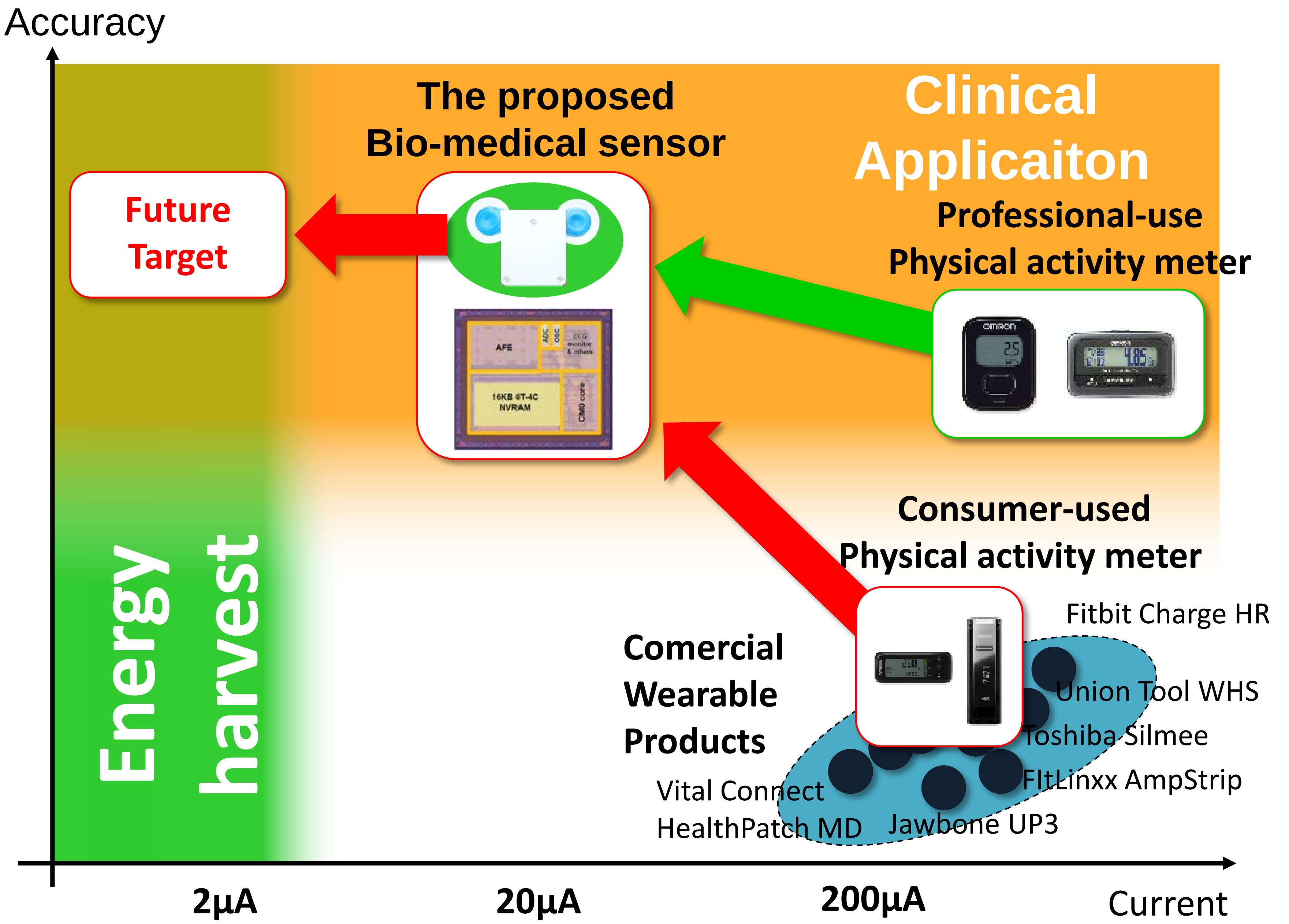


(b) IHR extractor comparison

Power reduction in sensor module



Technical position of the bio-medical sensor



Summary

- The wearable bio-medical sensor has been developed, which features heart rate monitoring and tri-axial acceleration using newly developed low power SoC.
- Non-volatile MCU for normally-off computing and noise-tolerant IHR detection algorithm have been employed for ECG-SoC design.
- The fully integrated ECG-SoC consumes 6.14μA for ECG monitoring and the sensor system dissipates 20uA, allowing 2-weeks continuous sensing only using a 10-mAh thin-type lithium-ion battery.
- The activity classification using data from field testing attains ~90% accuracy.

Acknowledgement

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