연구 분야 소개

한양대학교 ERICA 전자공학부

김종석

이력 및 대표연구

김종석
jskim383@hanyang.ac.kr
www.SIDLAB.net

총 40회 이상 반도체 IC Chip 개발

다양한 전자회로 시스템 개발

이력사항

- 2023 - 현재 : 조교수, **한양대 ERICA 전자공학부**
- 2022 – 2023 : 조교수, **가천대 전자공학부**
- 2018 – 2022 : 책임연구원, **SK Hynix Flash 설계팀**
- 2012 – 2019 : 박사과정, **한양대 전자컴퓨터통신공학과**
  (학위논문: High-Reliability Gate Driver and Small-Area High-Resolution Data Driver for Flexible Active-Matrix Displays)

대표 연구실적

- **[Display Circuit] IEEE ISSCC 2025 (반도체 올림픽), IEEE JSSC 2025** (under review)
  *세계 최초 6285 PPI급 OLED-on-silicon display용 source driver IC 개발
- **[Display Circuit] VLSI Symp 2026 (세계 최고 권위 회로 학회)**
  *세계 최소면적, 최고속도, 최고 균일도 source driver IC 개발
- **[Memory circuit] IEEE ISSCC 2022 (반도체 올림픽)**
  *세계 최고 효율 최저 면적 flash memory 전원관리회로 개발
- **[Biomedical Circuit] IEEE ESSERC 2025, IEEE TBioCAS 2025** (under review)
  *세계 최초 비침습적 시간적 간섭 자극술 (Temporal Interference Stimulation) 회로 개발
- **[Biomedical Circuit] Nat. Electron. 2021 (IF=33.25)**
  *세계 최초, 인간의 촉각인식 과정을 최대한 모사한 인공촉각 시스템 개발
  (촉각 센서, 센서 readout 회로, 신경자극 회로)
- **[Sensor Circuit] SID 2025**
  *세계 최초, Bottom-Emission OLED 디스플레이용 Touch Sensor 개발
- **[Sensor Circuit] IEEE Sensors Journal 2023 (IF=4.3)**
  *세계 최초, active-matrix sensor 의 TFT on-resistance 영향을 제거한 회로 개발
- **[PMIC] IEEE Trans. On Power Electronics 2022 (IF=5.97)**
  *세계 최초, 저잡음 고효율 특성을 동시에 갖는 PFM buck converter 개발

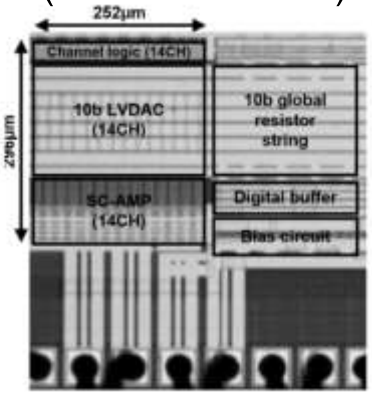
Research Area

World Best Next-Generation System IC Design
세계 최고 차세대 시스템 반도체 회로 설계

Display Circuit	Memory Circuit	AI Circuit	Sensor Circuit	Power Circuit	Biomedical Circuit
AR/VR OLEDoS driving & pixel circuit Micro-LED display Pixel & driving circuit Compensation circuits for OLED & Micro LED displays	Driving & readout circuit for NAND flash memory Built-in-self-test (BIST) circuit for memory system High-efficiency charge pump & regulator for NAND flash memory	Compute-in-memory circuit using TFT Calibration circuits for AI system Analog & Digital TFT circuits for TFT CIM	Sensor circuit for Physical AI Touch & Stylus sensor readout circuit Sensor uniformity enhancement circuit Readout circuits for R/L/C sensors	IoT PMIC GaN Driver Automotive PMIC Flash Memory PMIC Ultra-low-voltage LDO	Neural tactile sensing system Non-invasive brain stimulation circuit Neural stimulator Tumor treatment circuit
IEEE ISSCC 2025 **VLSI Symp. 2026** **IEEE TCAS-I 2026** **IEEE JSSC 2021**	**IEEE ISSCC 2022**	**IEEE TED 2018, 2017** JJAP 2013, 2012	**SID 2025** **Nature Elec. 2021** **IEEE Sensors 2025**	**IEEE TPE 2022** AICSP 2016	**IEEE ASSCC 2025** **Nature Elec. 2021**
SAMSUNG SAMSUNG DISPLAY LX세미콘	SK hynix	ETRI 한국전자통신연구원	SONY LG Japan Lab Inc. University of Pittsburgh	DB HiTek SAMSUNG SAMSUNG DISPLAY	서울대학교 KERI 한국전기연구원

Research Area - System IC Design -

Display Circuit
(Column driver IC)

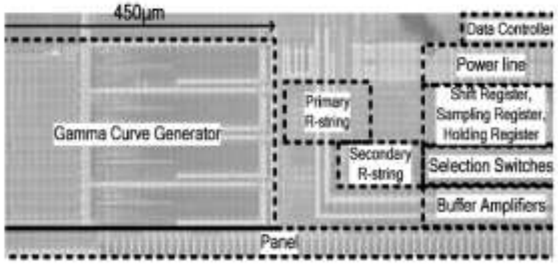


IEEE JSSC

Memory Circuit (Flash memory)

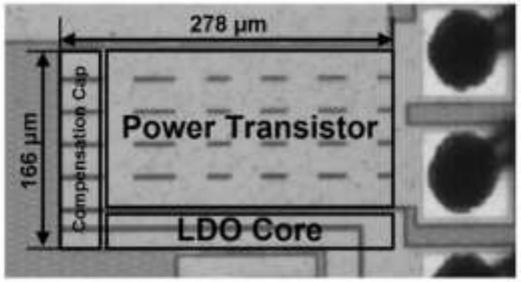
IEEE ISSCC

Power Management IC (SMPS)

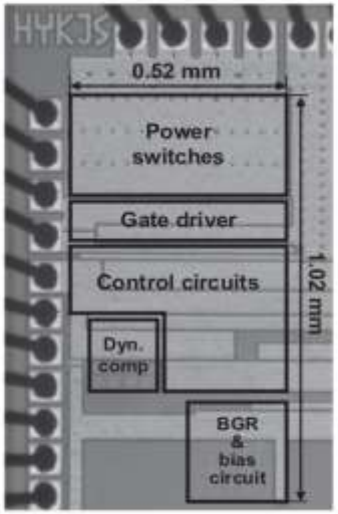


IEEE TCE

Power Management IC (LDO)

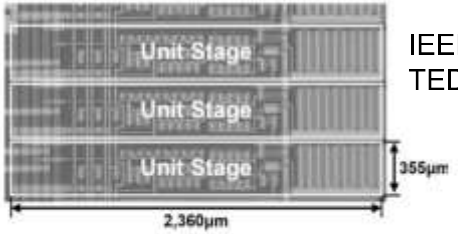


Power Management IC
(SMPS)



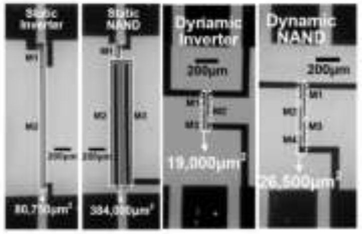
IEEE TPE

Display circuit (gate driver)



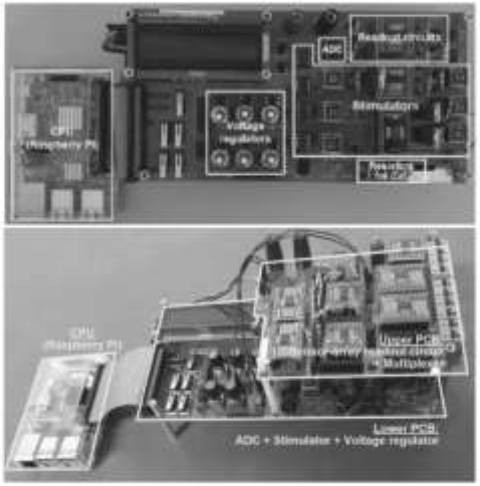
IEEE TED

TFT circuit (logic gates)



IEEE TED

Biomedical circuit (artificial skin)



Nature Electronics

연구분야

디스플레이 회로
AR/VR OLED-on-Silicon (OLEDoS) LED-on-silicon (LEDoS) 회로

협력기관

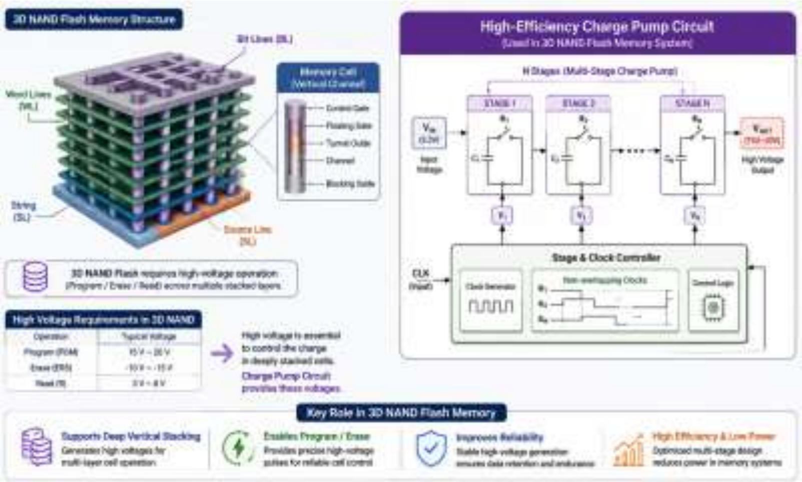
SAMSUNG DISPLAY

LX세미콘

SK hynix

SAMSUNG 삼성전자

메모리 회로
DRAM / Flash memory 용 Analog 회로설계



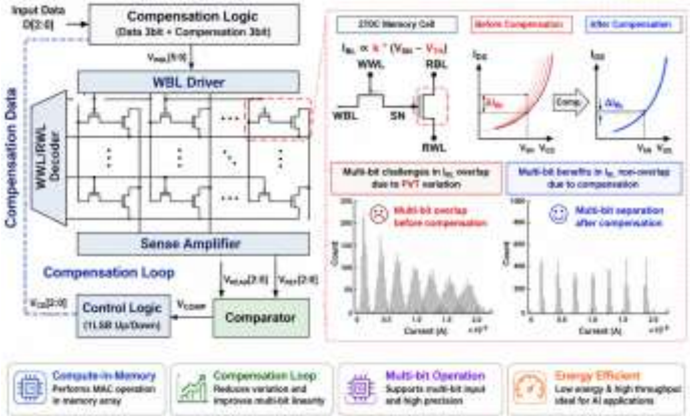
협력기관

SK hynix

연구분야

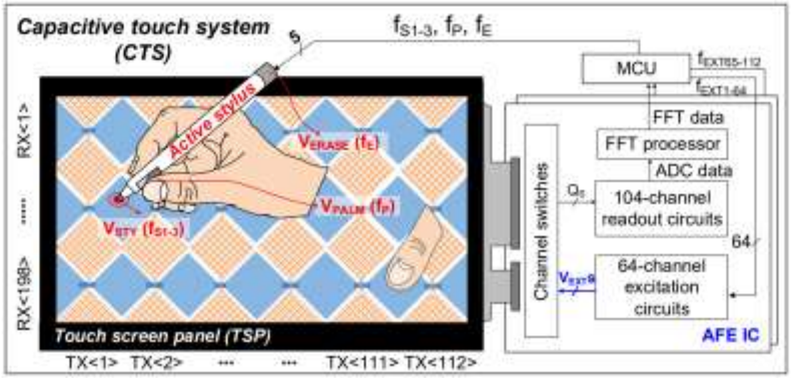
AI 회로

Compute-in-Memory (CIM) 회로



센서회로

OLED in-cell touch & stylus sensor ROIC



협력기관

ETRI
한국전자통신연구원
Electronics and Telecommunications Research Institute

협력기관

SONY

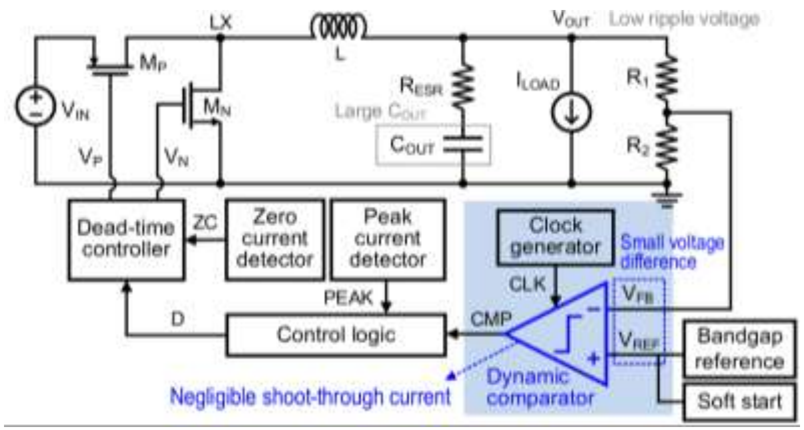
LG
Japan Lab Inc.

SAMSUNG
삼성전자

University of Pittsburgh

연구분야

Power 회로
차량용 PMIC, Mobile용 PMIC, LDO, Charge pump



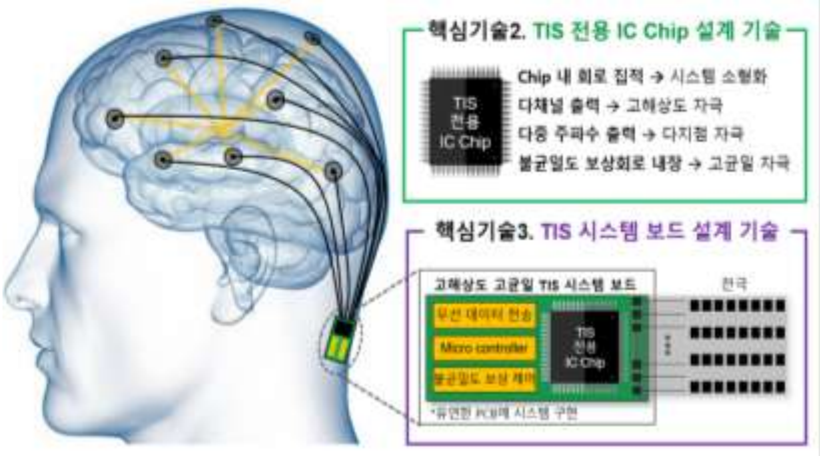
협력기관

DB HiTek

SAMSUNG DISPLAY

KATECH 한국자동차연구원

바이오메디컬 회로
비침습적 뇌자극 회로 개발



협력기관

서울대학교

KERI 한국전기연구원

System IC Design Lab (SIDLAB) -연구원 & 연구시설-

연구원 현황

대학원생	2026년 5월
박사과정 & 석박통합과정	4
석사과정	7
학부연구생	5

설계/실험 장비 구축 현황

	수량	사양 / 비고
Oscilloscope	5 EA	2.5GHz, 4CH
Power supply	12 EA	3CH, 0.1mV/0.1mA Res.
Function generator	5 EA	100 MHz
Digital I/O	2 EA	32 Ch, 200 MHz
Digital multimeter	2 EA	6.5 digit
Workstation	6 EA	-
EDA tool	완비	Synopsys, Cadence, Siemens 등

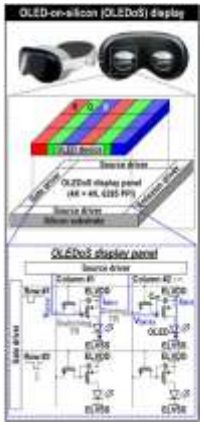
실험실 및 실험장비 구축 완료

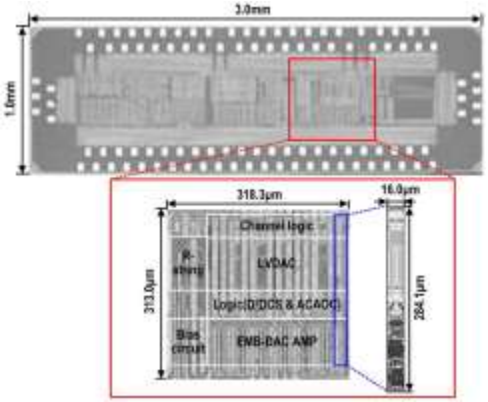
실험 환경

최근 연구 성과

IEEE ISSCC 2025 발표
(세계 최고권위 회로 학회)

고해상도, 저면적, 고균일
OLED-on-Silicon (OLEDoS) 구동 IC chip 개발

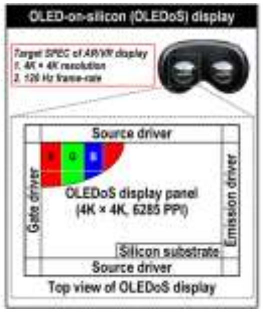


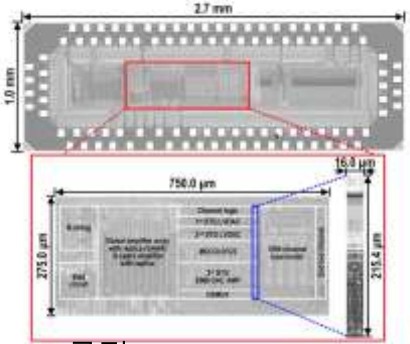


공정: TSMC 65nm

IEEE VLSI. Symp 2026 발표
(세계 최고권위 회로 학회)

고해상도, 저면적, 고균일
OLED-on-Silicon (OLEDoS) 구동 IC chip 개발





공정: TSMC 65nm

중앙일보

한양대 김종석 교수팀, AR·VR용 마이크로디스플레이 구동 기술 개발

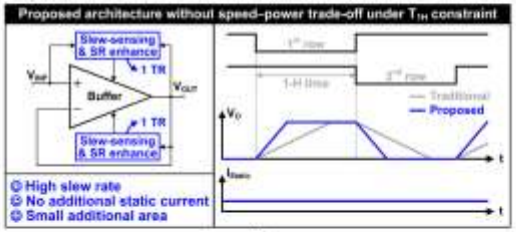
문화일보

한양대 연구팀, VR·AR 초고해상도 디스플레이 핵심 기술 개발 성공

최근 연구 성과

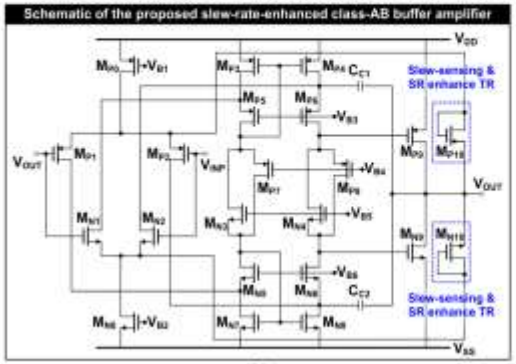
IEEE TCAS-I 2026
(Major 회로 저널)

전류 재사용 방식의
저전력 고속 Amplifier 회로 개발

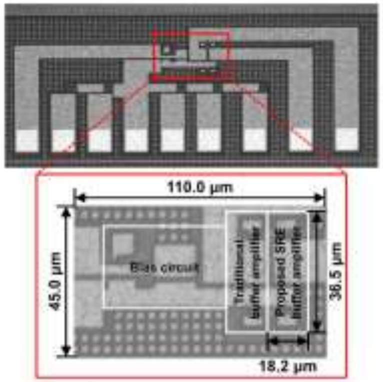


☺ High slew rate
☺ No additional static current
☺ Small additional area

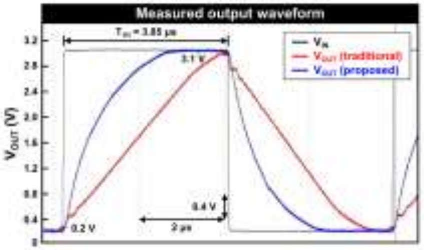
(a)



(b)

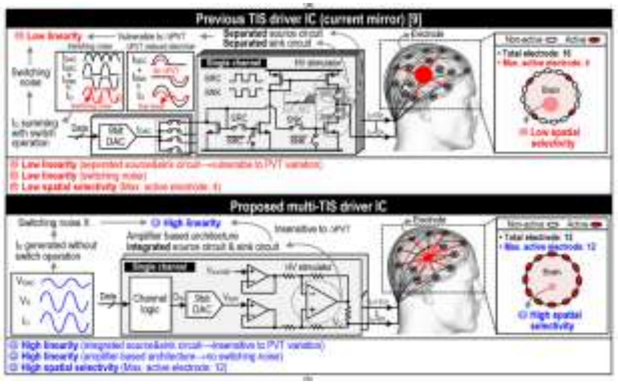


공정: TSMC 180nm BCD (40V)



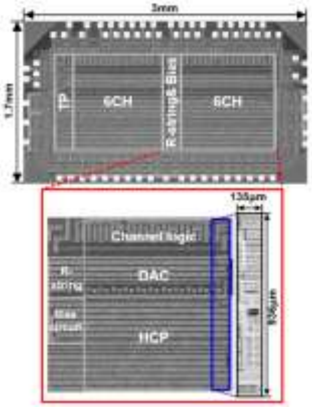
IEEE ASSCC 2025 발표
(Major 회로 학회)

세계 최초 비침습적 뇌자극
multi-TIS driver IC chip 개발



☹ Low linearity (separated source&sink circuit→vulnerable to PVT variation)
☹ Low linearity (switching noise)
☹ Low spatial selectivity (Max. active electrode: 4)

☺ High linearity (integrated source&sink circuit→insensitive to PVT variation)
☺ High linearity (amplifier based architecture→no switching noise)
☺ High spatial selectivity (Max. active electrode: 12)

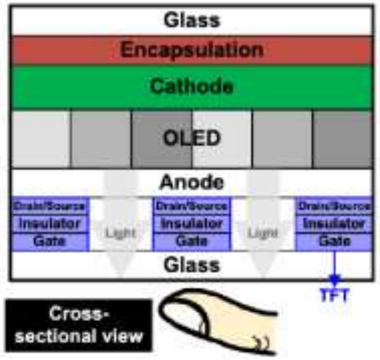


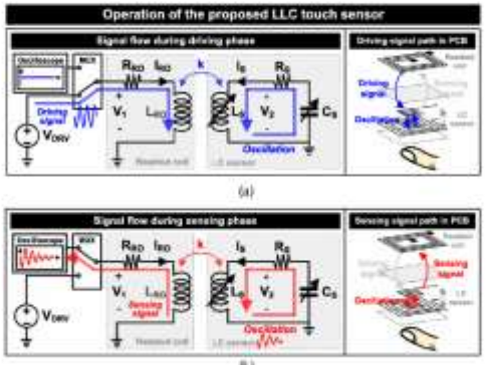
공정: TSMC 180nm BCD (40V)

최근 연구 성과

IEEE SID 2025 발표
(세계 최고권위 디스플레이 학회)

세계 최초 Bottom-Emission Display용
Inductor 기반 터치센서 및 전용회로 개발





최근 연구 성과

김종석 교수, 세계 최고 권위 반도체 학술대회 ISSCC TPC 위원으로 선정돼

한양대학교 ERICA 전자공학부 김종석 교수가 반도체 집적회로 분야에서 세계 최고 권위를 자랑하는 IEEE International Solid-State Circuits Conference(ISSCC)의 기술 프로그램 위원회(Technical Program Committee, TPC) 위원으로 선정되었다.

ISSCC는 1954년 시작된 이후 반도체 회로 분야의 최신 기술과 혁신이 가장 먼저 공개되는 글로벌 최고 권위 학술대회로, '반도체 회로 분야의 올림픽'으로 불린다. 인텔, 삼성전자, TSMC 등 글로벌 선도 기업과 세계 유수 대학 연구진이 참여하며, 학계와 산업계를 아우르는 기술 발전의 중심 축 역할을 수행하고 있다.

김종석 교수는 이번 TPC 위원 선정을 통해 제출 논문의 엄정한 심사, 우수 논문 선정, 기술 세션 및 플래너리 프로그램 기획 등 학회의 핵심 의사결정 과정에 참여하게 된다. ISSCC TPC 위원은 해당 분야에서 탁월한 연구 성과와 국제적 영향력을 인정받은 연구자에게만 초청되는 자리로, 매우 제한된 인원만이 참여할 수 있는 최고 수준의 학술적 위상으로 평가된다.

김종석 교수는 SK hynix에서 NAND 플래시 메모리용 아날로그 회로 설계 등을 수행하며 산업계에서의 실무 경험을 쌓았으며, 이후 Nature Electronics, IEEE Journal of Solid-State Circuits, IEEE Transactions on Power Electronics 등 세계적 권위의 학술지에 연구 성과를 발표하여 국제적 연구 경쟁력을 입증해 왔다. 특히 한양대학교 ERICA 부임 이후에는 시스템반도체 회로설계 분야에서 세계 최고 수준의 연구 성과를 단기간 내 연속적으로 창출하며, ISSCC 2025, VLSI Symposium 2026, ASSCC 2025 등 최고 권위 국제 학술대회에서의 연속적인 성과를 바탕으로 이번 TPC 위원에 선정되었다. 이는 산업계 경험과 학문적 성과가 결합된 경쟁력을 바탕으로 이룬 결과로, 김종석 교수 개인의 연구 역량뿐만 아니라 우리 대학 전자공학 분야의 연구 경쟁력이 세계적 수준에 도달했음을 보여주는 중요한 성과로 평가된다.

향후 김종석 교수는 ISSCC TPC 위원으로서 글로벌 반도체 기술 트렌드를 선도하고, 차세대 집적회로 기술의 방향성을 설정하는 데 핵심적인 역할을 수행할 것으로 기대된다.

최신뉴스

- 한양대, '2026 미래 예술창작 아카데미' 성료 참여…
- 한양대, '2026 응용 언어인지과학 국제심포지엄(…
- 광고인 꿈 꾸는 한국 대학생들, 한스 학생 어워즈…
- 논리와 추론에 관심 있다면?… 철학과 해외 학…
- "자취생 기숙사생 주목" 한양대 학생복지위원회, '…

포토뉴스

[포토뉴스] 한양YK인터칼리지 융합전공 …

인기 TOP10

1 한양대, '박화영음악관' 기공식 개최… 글로벌 아

2 한양대, '2026 라치오스 : 찬란' 라인업 공개해 화

[연구분야: 디스플레이 회로]

AR/VR 기기용 Micro Display 회로

Publication: ISSCC 2025

Publication:
ISSCC 2025(반도체 올림픽), San Francisco, California, USA, Feb. 2025

Title:
A 10b Source-Driver IC with All-Channel Automatic Offset Calibration and Slew-Rate-Enhanced Amplifier Achieving 2273µm^2/Channel and 1.9mV DVO for 6285-PPI OLED-on-Silicon Displays

A 10b Source-Driver IC with All-Channel Automatic Offset Calibration and Slew-Rate-Enhanced Amplifier Achieving 2273µm^2/Channel and 1.9mV DVO for 6285-PPI OLED-on-Silicon Displays

Junghwan Oh, Wiman Yoo, Dong-Kun Lee, and Jong-Seok Kim

Hanyang University, Ansan, Korea

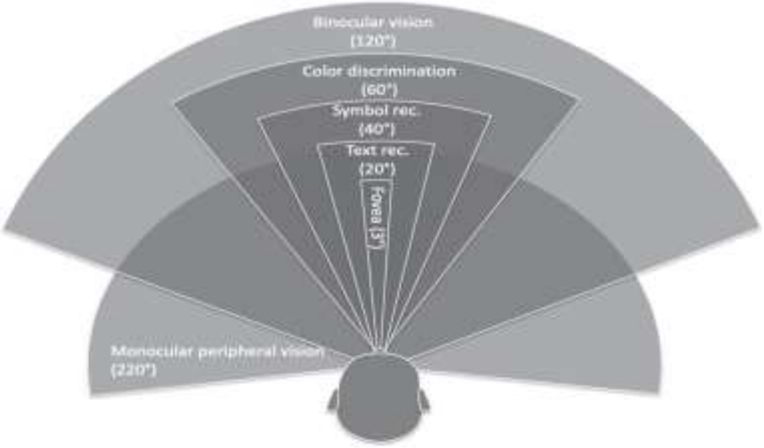
Background

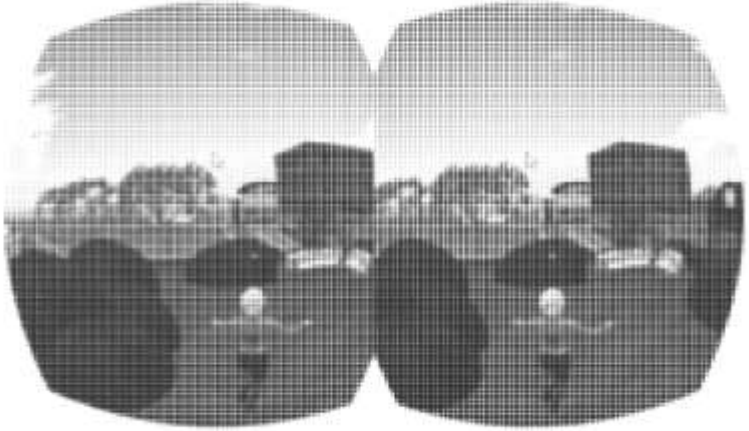
Image: Apple, Vision Pro

Background -Resolution-

Field of view (FoV)

Pixel per degree (PPD)

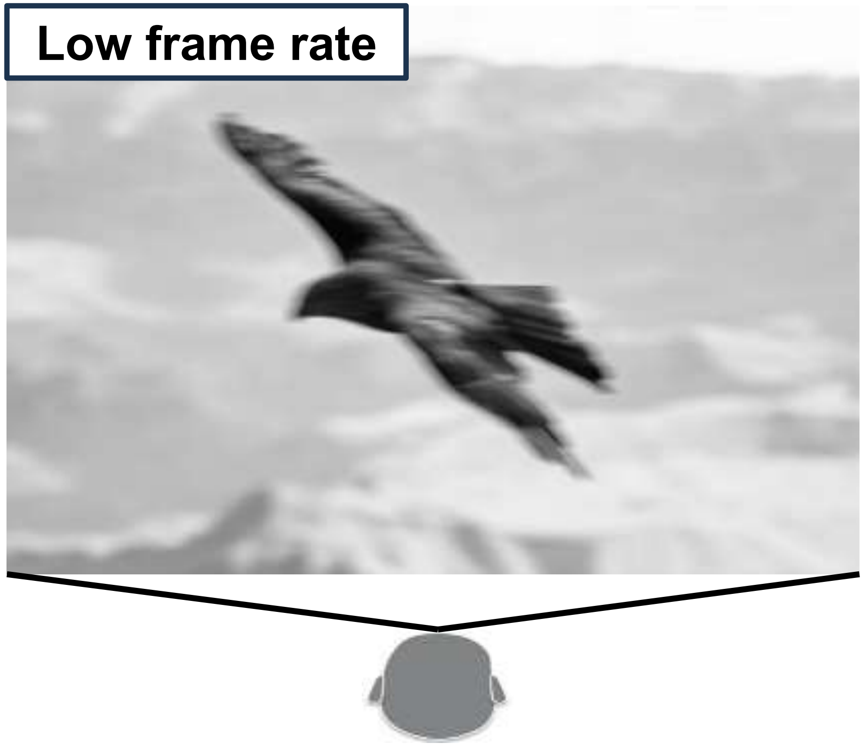




Required specification	
Field of view (FoV)	Horizontal: 120º*, Vertical: 120º*
Pixel per degree (PPD)	60PPD*
Resolution	**7.2K × 7.2K** (120×60) × (120×60)

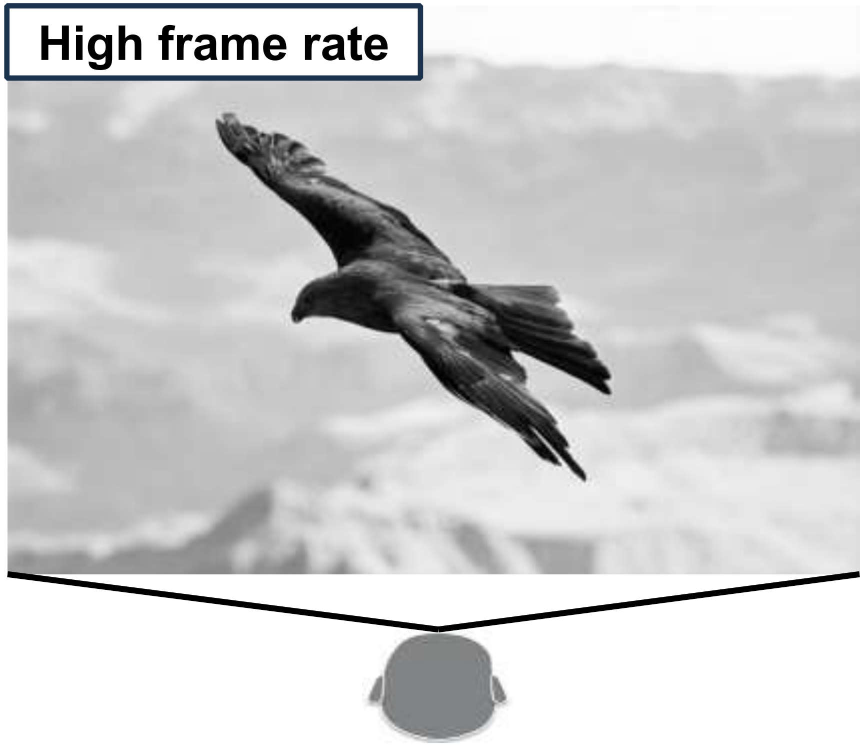
*120º FoV and 60PPD are required for realistic vision.

Background -Frame Rate-



Low frame rate

Dizziness, blurred vision

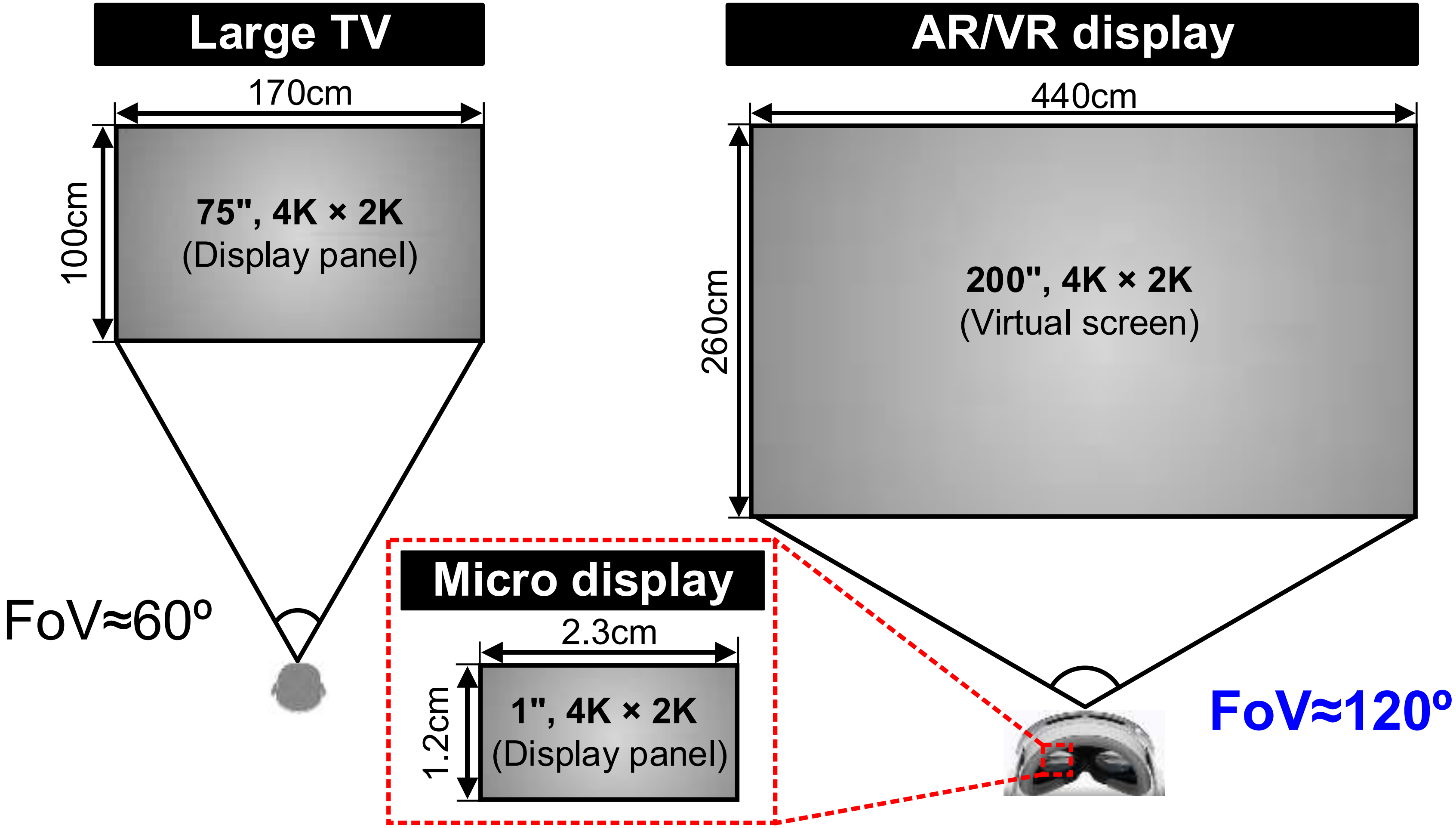


High frame rate

No dizziness, clear vision

- Frame rate of at least 120Hz is required.

Background -Micro Display for AR/VR Device-



Large TV

170cm

100cm

75", 4K × 2K
(Display panel)

FoV≈60º

AR/VR display

440cm

260cm

200", 4K × 2K
(Virtual screen)

FoV≈120º

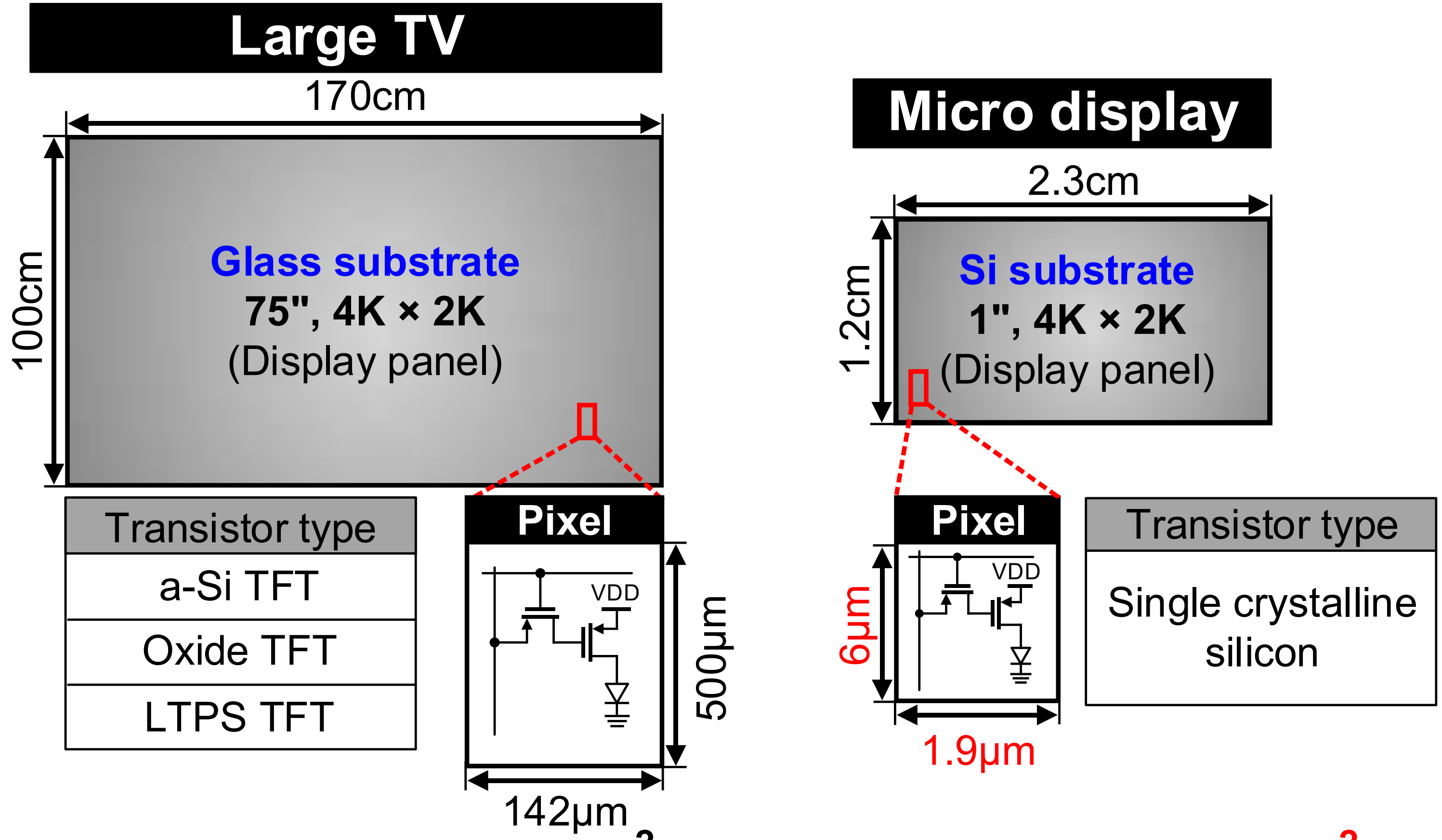
Micro display

2.3cm

1.2cm

1", 4K × 2K
(Display panel)

Background -Pixel Size-



Large TV

170cm

100cm

Glass substrate

75", 4K × 2K

(Display panel)

Transistor type
a-Si TFT
Oxide TFT
LTPS TFT

Pixel area: 71000μm^2

Micro display

2.3cm

1.2cm

Si substrate

1", 4K × 2K

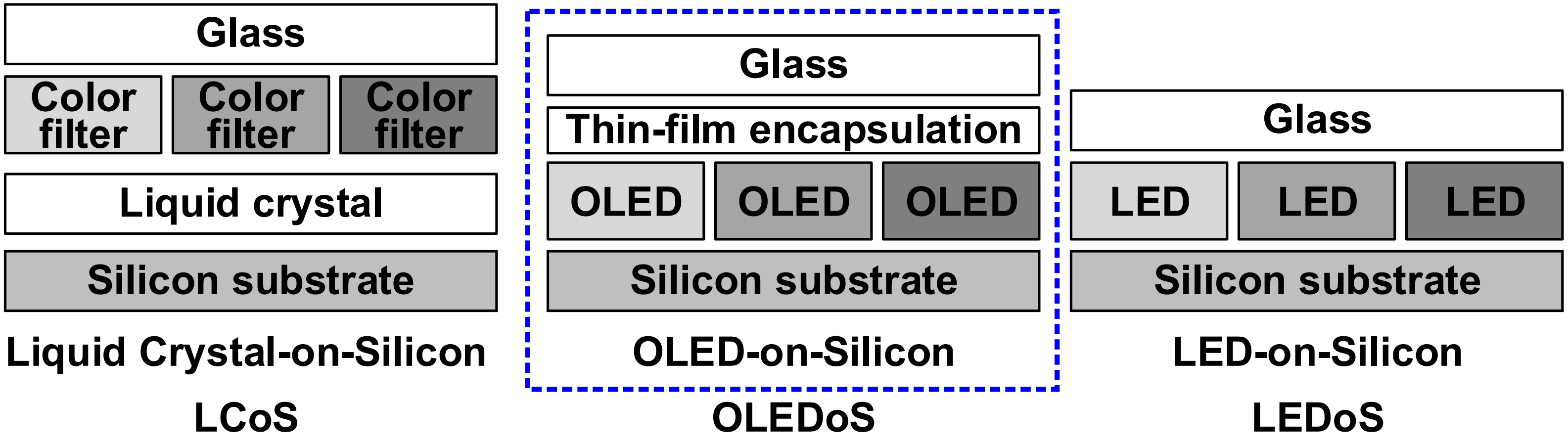
(Display panel)

Transistor type
Single crystalline silicon

Pixel area: 11μm^2

- Small pixel area is required → silicon substrate & CMOS process

Background -AR/VR Device Application-



Glass

Color filter | Color filter | Color filter

Liquid crystal

Silicon substrate

Liquid Crystal-on-Silicon

LCoS

Glass

Thin-film encapsulation

OLED | OLED | OLED

Silicon substrate

OLED-on-Silicon

OLEDoS

Glass

LED | LED | LED

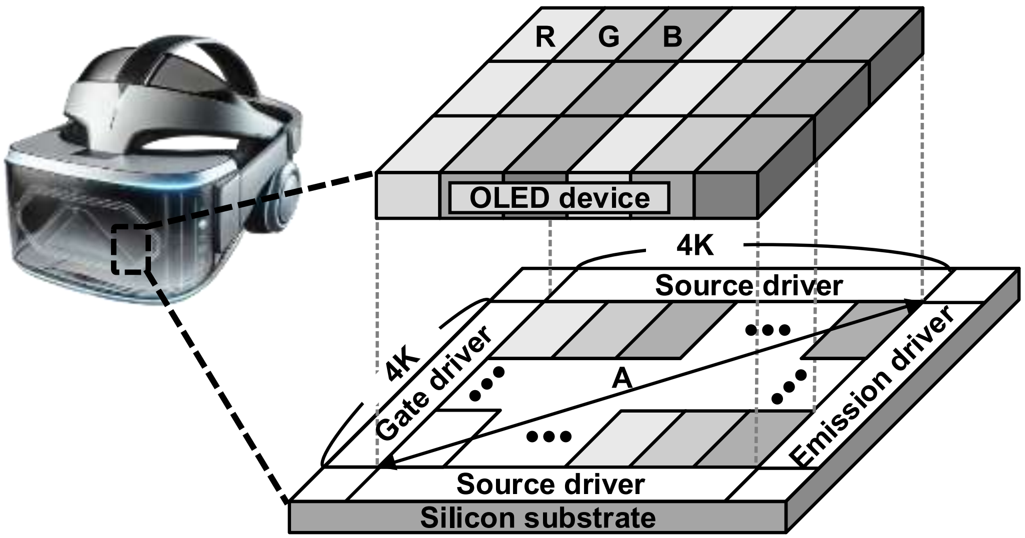
Silicon substrate

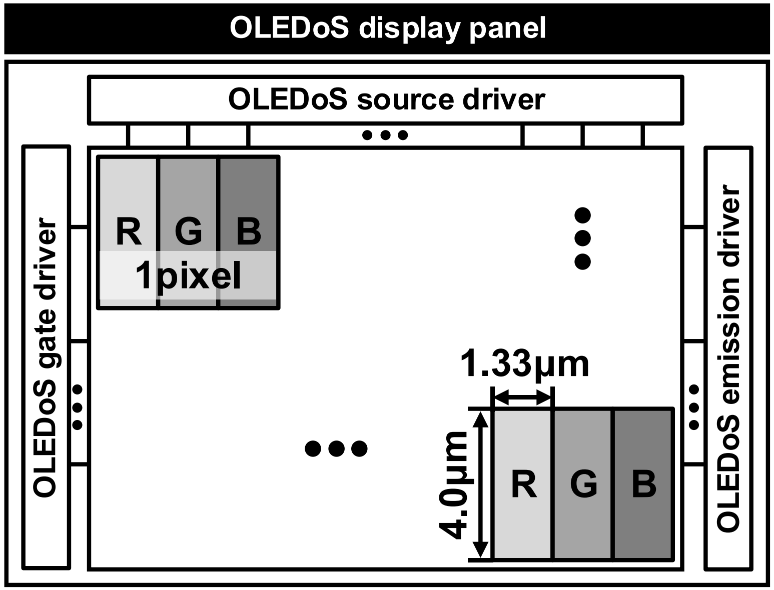
LED-on-Silicon

LEDoS

Application	**AR glass**		**VR headset**			**This work**
Manufacturer	**Rokid**	**Xreal**	**Apple**	**Meta**	**Pico**	**-**
Product name	Joy 2	One Pro	Vision Pro	Quest 3	Pico 4 ultra	-
Release year	2024	2025	2024	2023	2024	2025
Technology	OLEDoS	OLEDoS	OLEDoS	LCOS	LCOS	OLEDoS
Resolution(per eye)	1920×1080	1920×1080	3660×3200	2064×2208	2160×2160	4000×4000
Diagonal size(inch)	-	0.55	1.41	2.48	2.56	0.9
Pixel per inch(PPI)	-	-	3386	1218	1200	6285
Frame rate(Hz)	120	120	100	120	90	120
Image						-

Background -Architecture of OLEDoS Display-



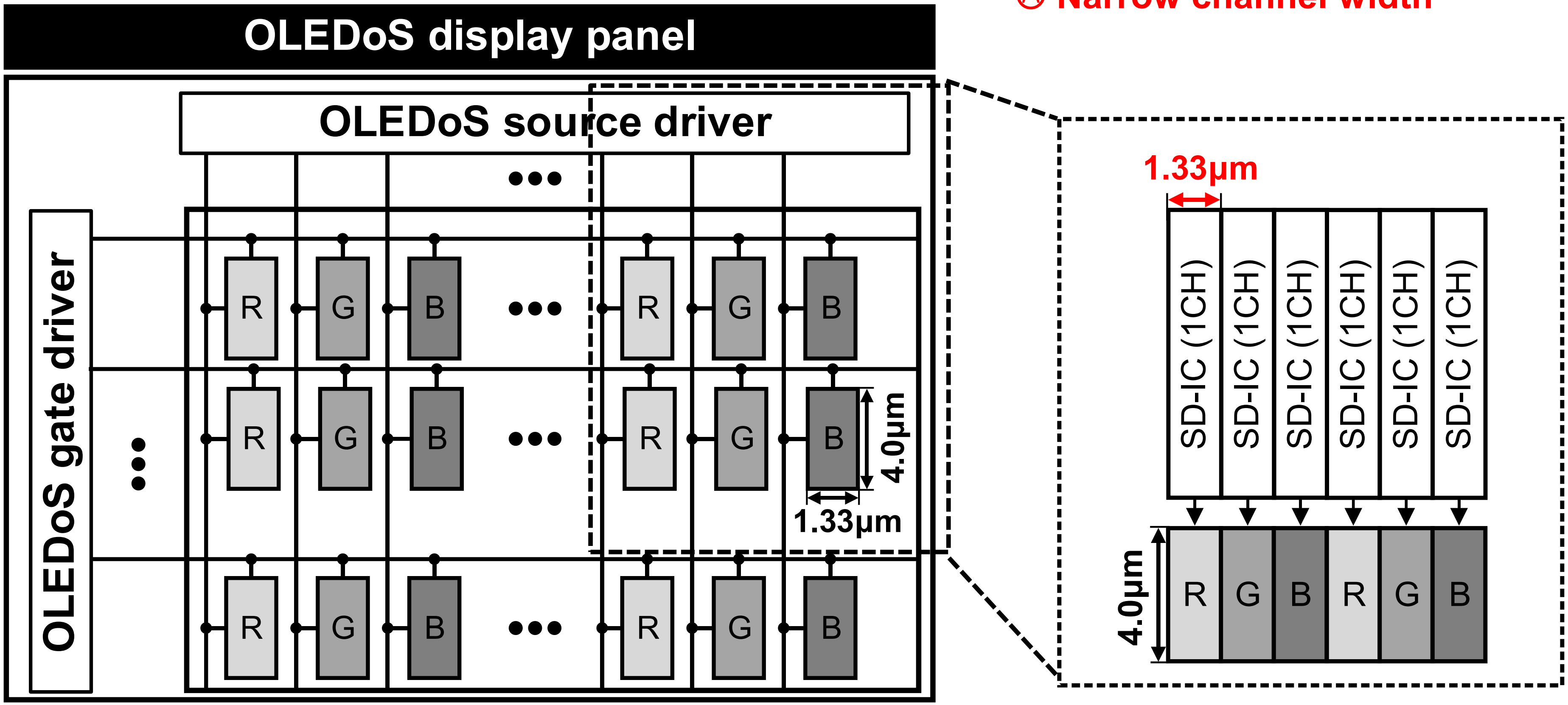


*1 pixel = 3 sub pixels (R,G,B)

Design specifications for OLEDoS display panel			
Diagonal size (A)	0.9”	PPI=(C×$\sqrt{2}$)/A	6285PPI
Resolution (C)	4K × 4K	Pixel pitch=1inch/PPI	4.0μm

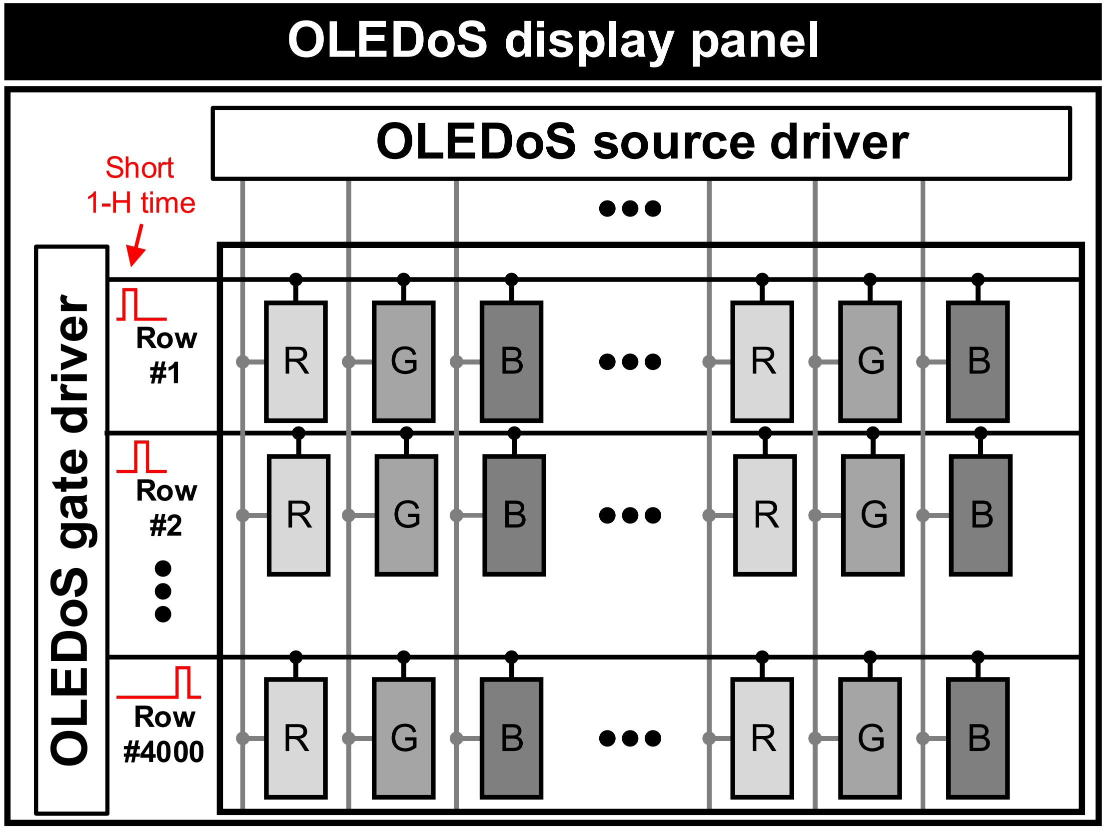
Background -OLEDoS Challenge 1: Narrow Channel Width-

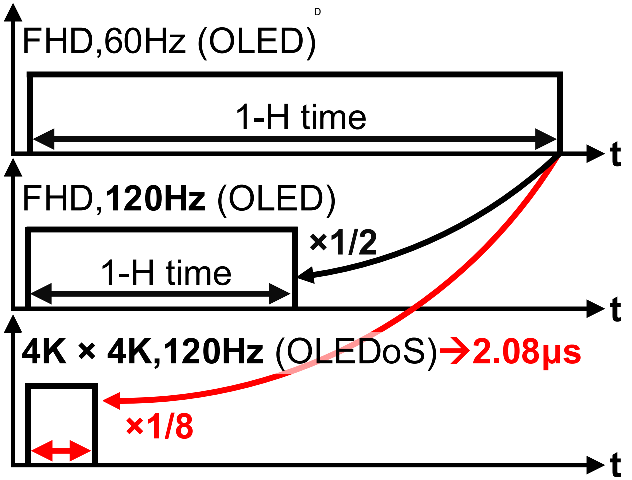
☹ **Narrow channel width**



- Requirement: **Small-area source driver IC (SD-IC)**

Background -OLEDoS Challenge 2: Short 1-H Time-



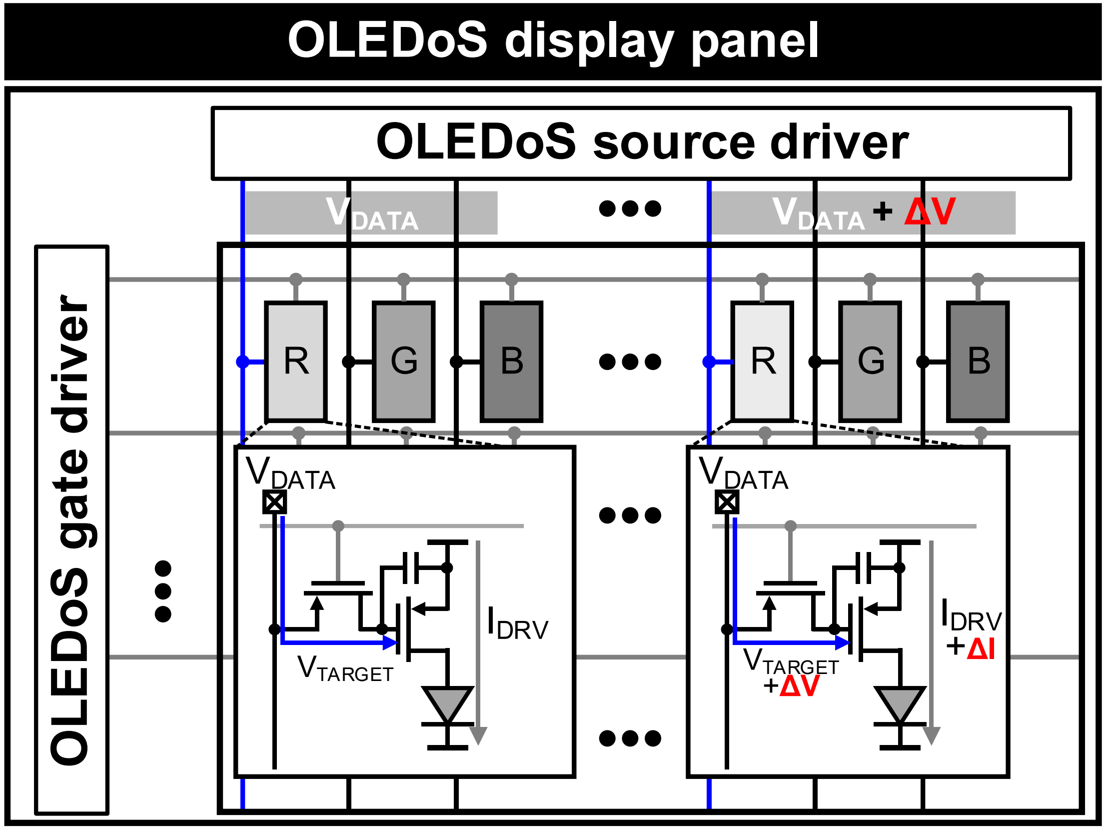


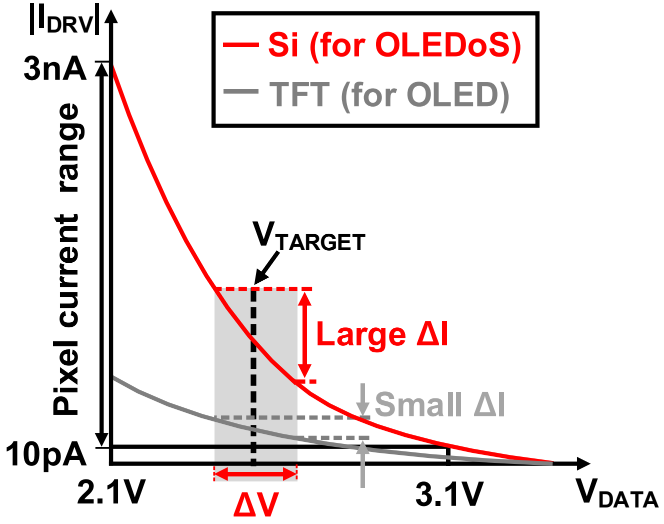
☹ Short 1-H time

$$\text{1-H} = \frac{1}{\text{Number of row line} \times \text{frame rate}}$$

- Requirement: **Fast SD-IC**

Background -OLEDoS Challenge 3: Voltage Deviation-

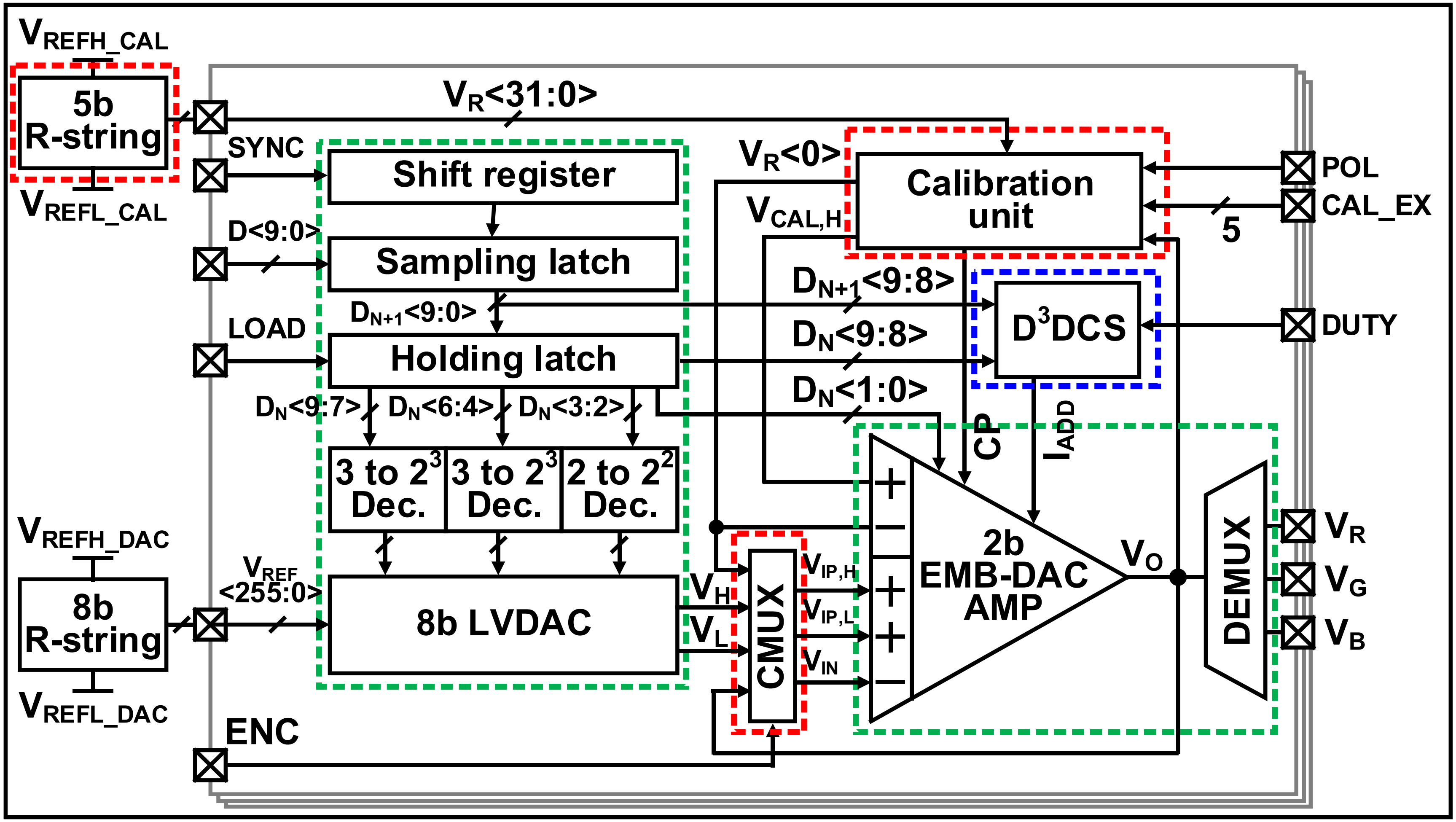




☹ Voltage variation of SD-IC
→ pixel current variation

- Requirement: **Small deviation of voltage output (DVO) SD-IC**

Proposed OLEDoS SD-IC -Architecture of SD-IC-

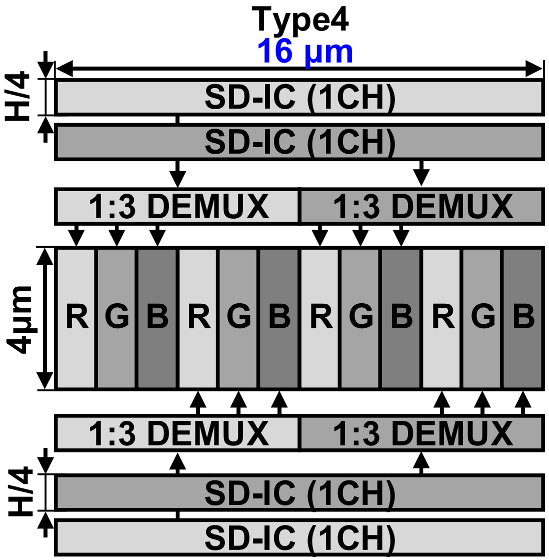


🟩 Small Area

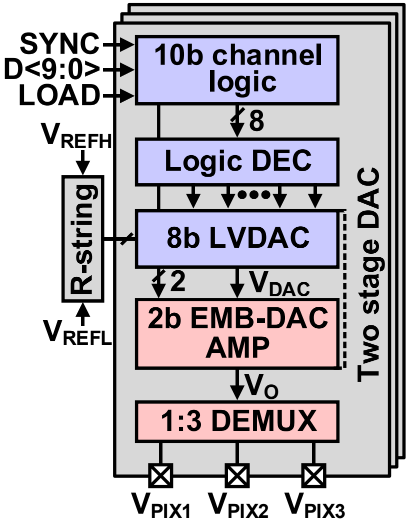
🟦 Fast Settling

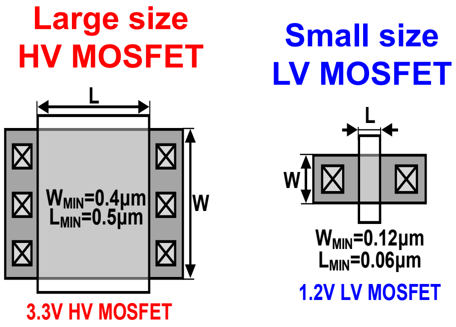
🟥 Small DVO

Small-Area SD-IC -Methods to Achieve Small Area-



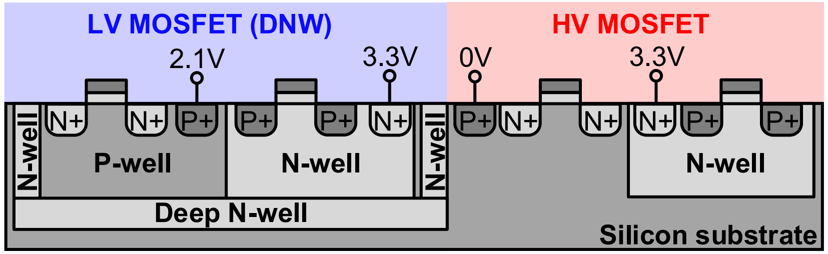
Proposed 10b SD-IC





LVMOSFET HVMOSFET

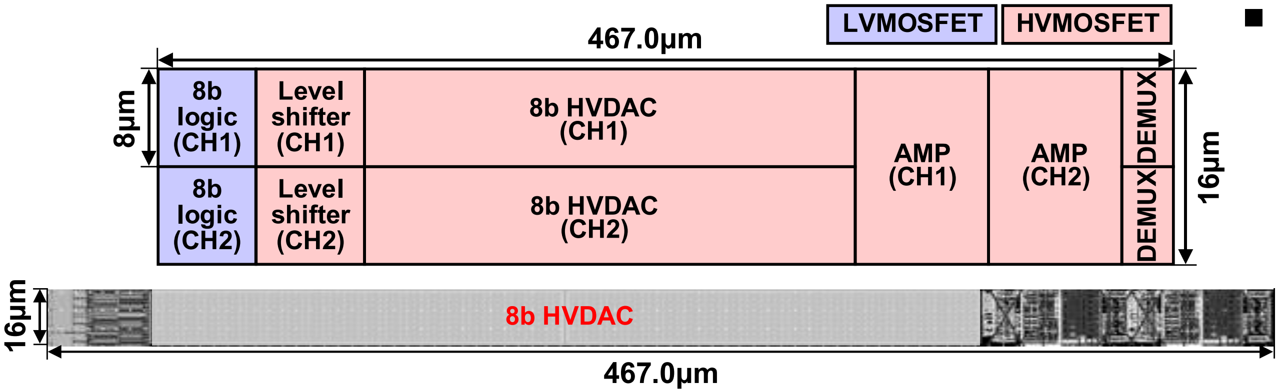
LV MOSFET (DNW) and HV MOSFET structure



- 1:3 DEMUX → **small area**
- LV MOSFET → **small area**
- Deep N-well→ **small area**
- 2b EMB-DAC AMP & logic decoder → # of DAC switches ↓→ **small area**

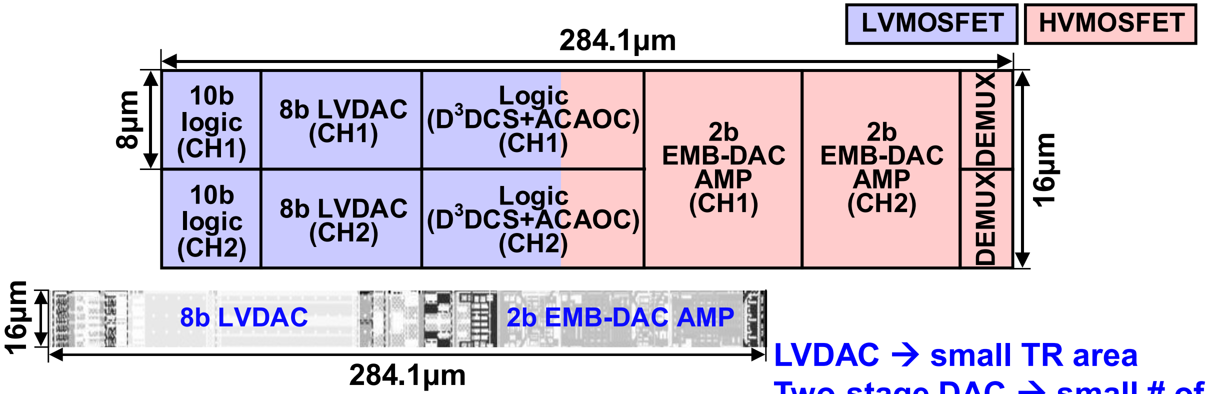
Small-Area SD-IC -Area Comparison-

Conventional 8-bit source driver (2 channels)



- **Large area**
  →conventional 8b HVDAC

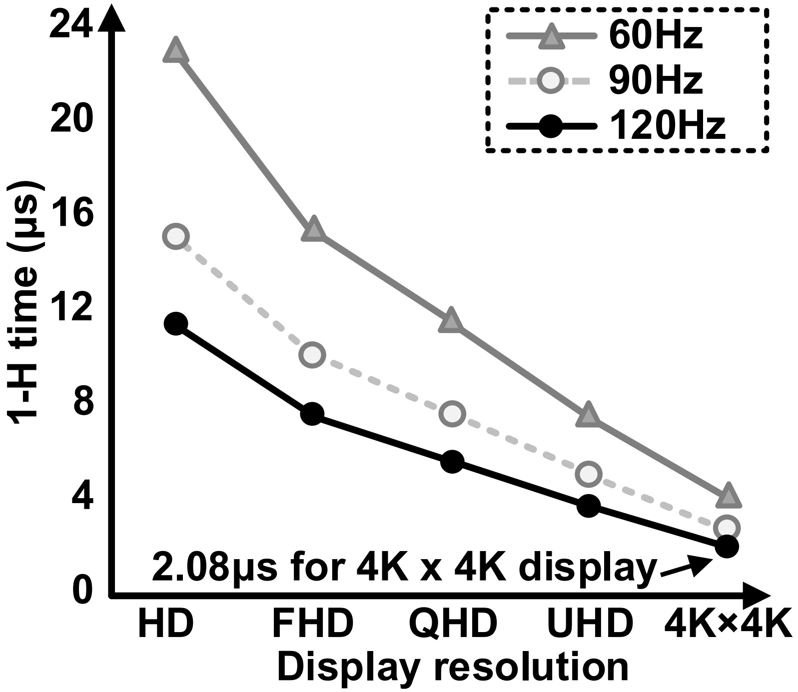
Proposed 10-bit source driver (2 channels)

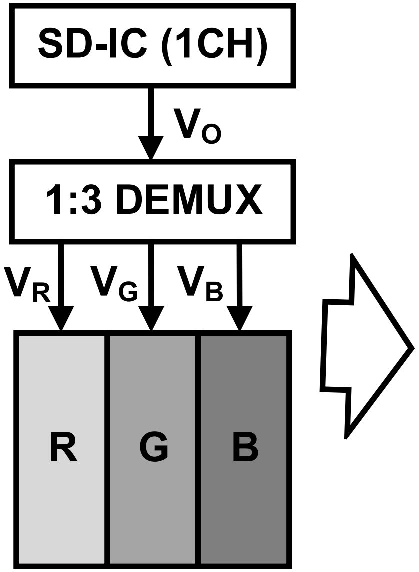


LVDAC → small TR area
Two-stage DAC → small # of TR

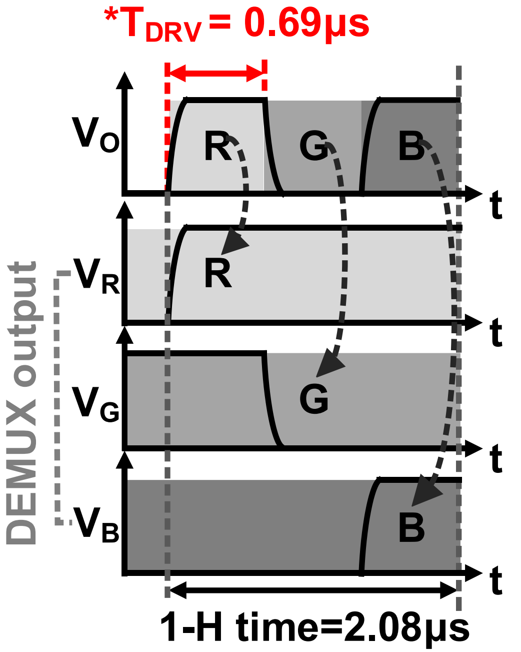
- **Small area** proposed 10b DAC
  →8b LVDAC + 2b EMB-DAC AMP

Fast SD-IC -Short Settling Time-





Operation of 1:3 DEMUX

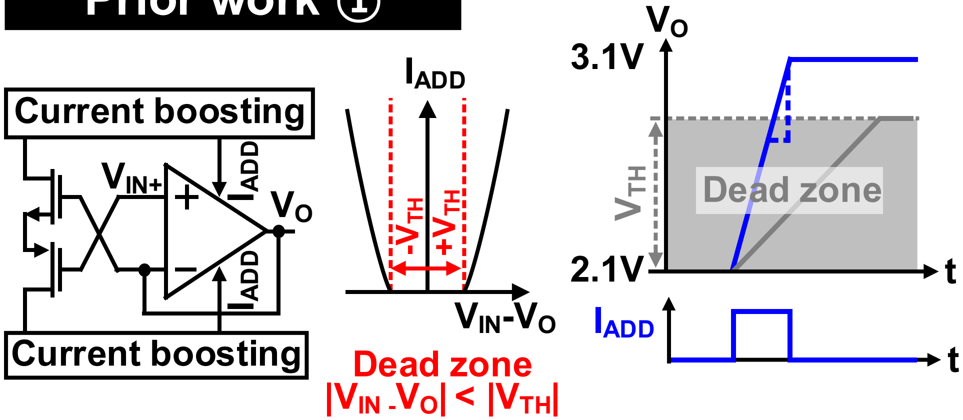


$$\text{*Driving time}(T_{DRV}) = \frac{1}{4K \times 120\ \text{Hz} \times 3} = 0.69\mu s$$

- For 4K x 4K resolution, 120 Hz frame rate, and 1:3 DEMUX
  → setting time ≤ **0.69μs**

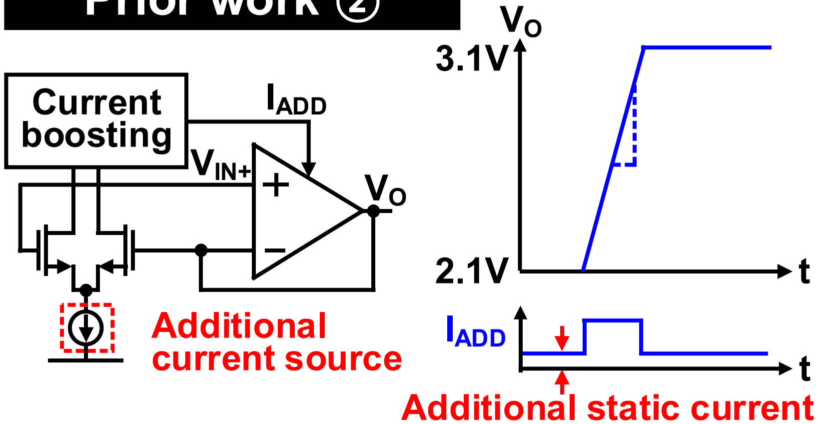
Fast SD-IC -Limitations of Prior Works-

Prior work ①



G.-G. Kang SOVC 2021

Prior work ②



Y.Park ISSCC 2024

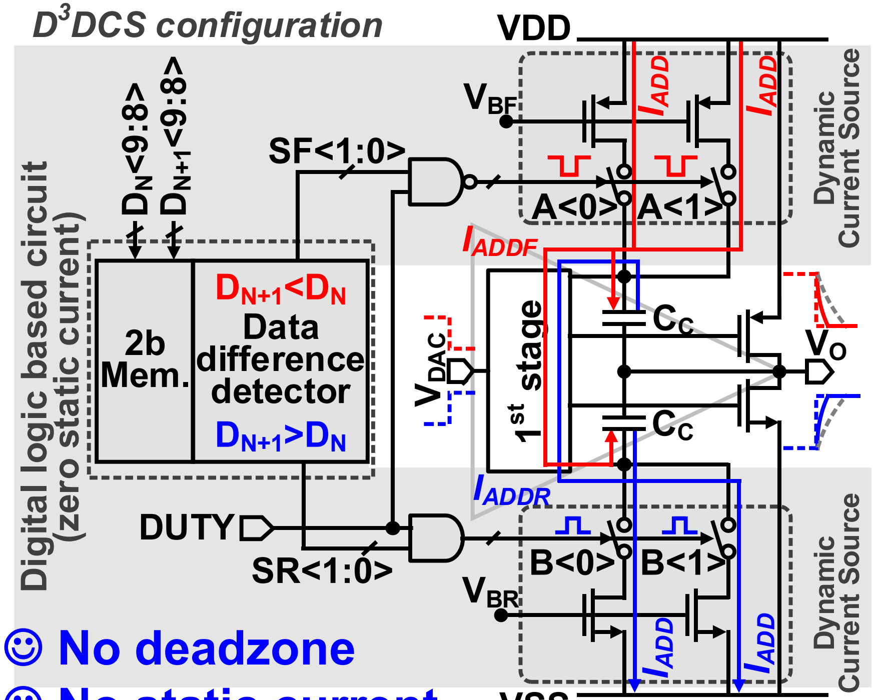
☹ Deadzone

☹ Additional static current

- To turn on boosting circuit, the IN/OUT difference should be larger than V_{TH}.
  - Small difference
    → Current boosting is **not activated.**

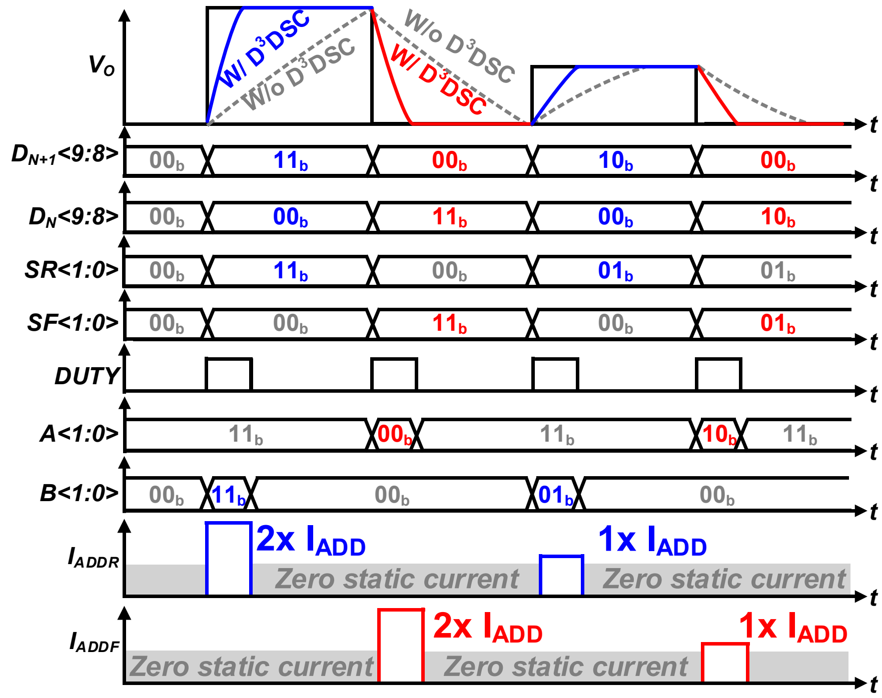
- To compare the IN/OUT difference, a comparator is used.
  - Additional static current
    → **Increased static power**

Fast SD-IC -Architecture of Proposed D³DCS-



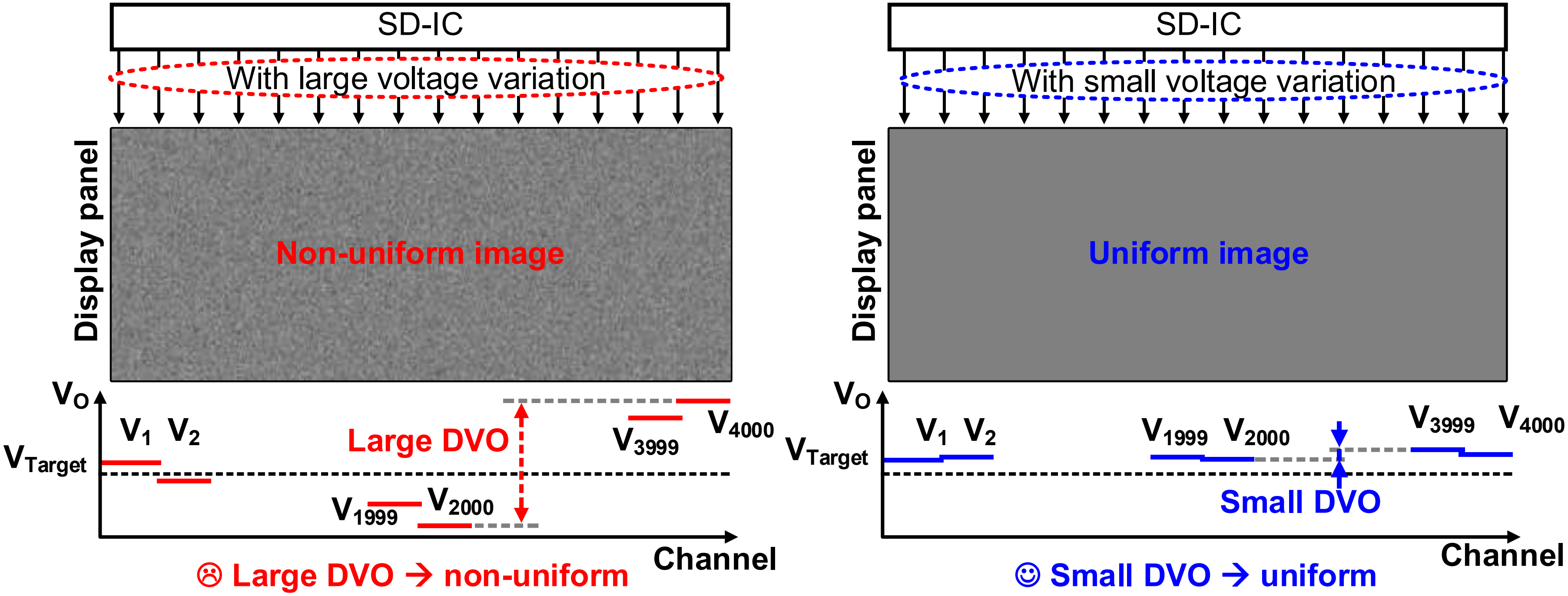
☺ **No deadzone**

☺ **No static current**



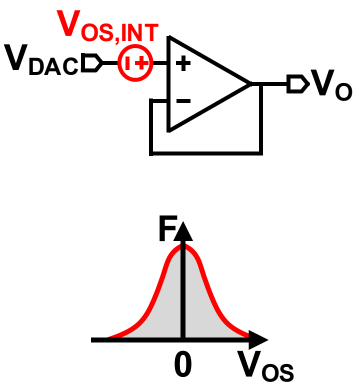
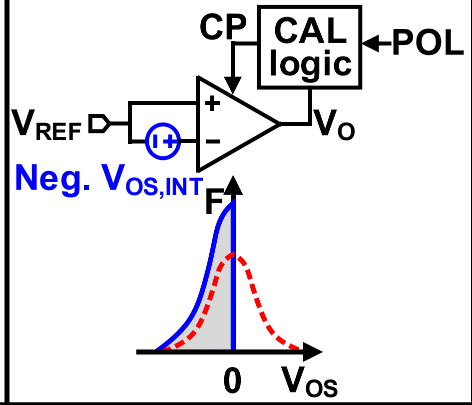
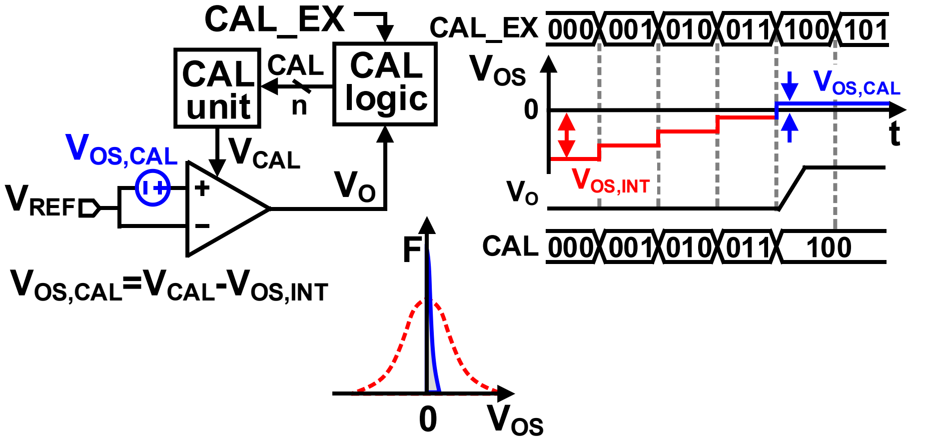
- Data-difference-dependent dynamic current source (D³DCS)
  - System operates when MSB 2b's difference is 2 or 3 code ($\Delta V_O \geq 0.5V$).
  - **No additional static current,** as digital logic is implemented.

Small-DVO SD-IC -Voltage Variation-



- Output voltage variation of SD-IC degrades the image quality of the display panel.
- Large deviation of voltage output (DVO) → non-uniform image

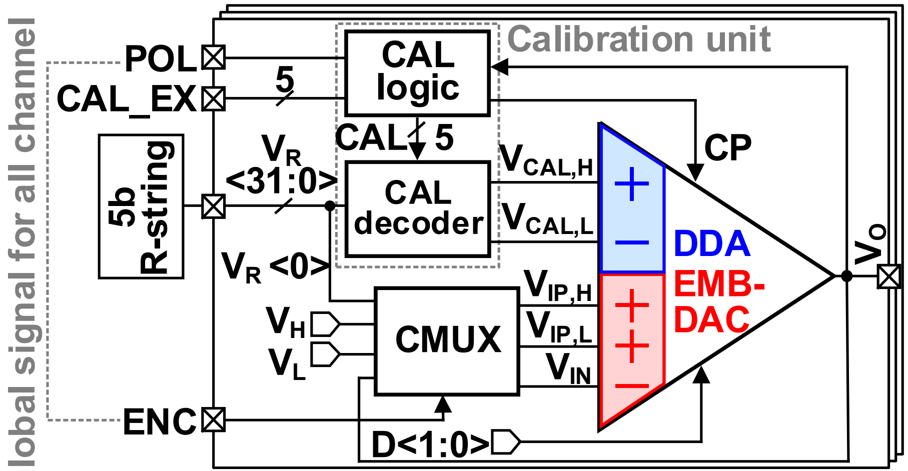
Small-DVO SD-IC -Proposed Offset Calibration-

Before Calibration	Calibration Operation #1. V_{OS} Polarity Unification	Calibration Operation #2. V_{OS} Magnitude Minimization
		
☹ Dual polarity ☹ Large V_{OS}	☺ Single polarity ☹ Large V_{OS}	☺ Single polarity ☺ Small V_{OS}

- The proposed calibration technique can reduce the random offset voltage.

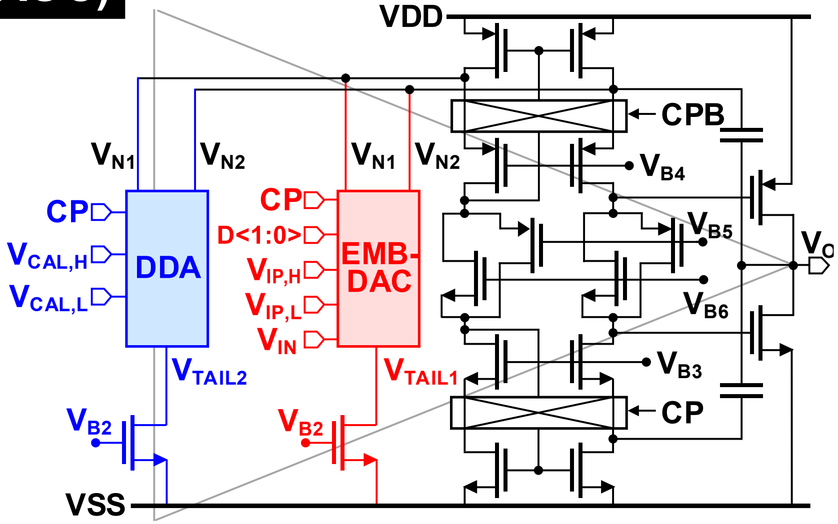
Small-DVO SD-IC -Implementation of ACAOC-

All-channel automatic offset calibration (ACAOC)



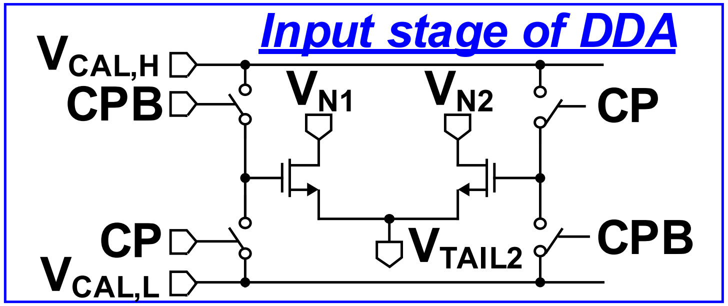
All channel's V_{OS} are calibrated at the same time

Proposed core amplifier

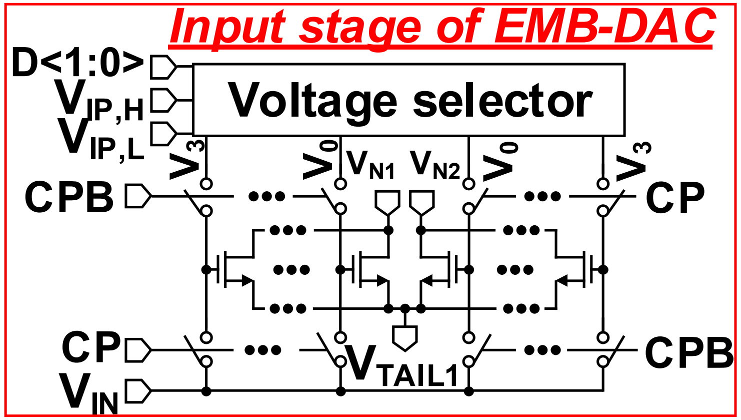


- All-channel automatic offset calibration (ACAOC)
  - ☺ **Single V_{OS} polarity**
  - ☺ **Small V_{OS} magnitude**

Input stage of DDA

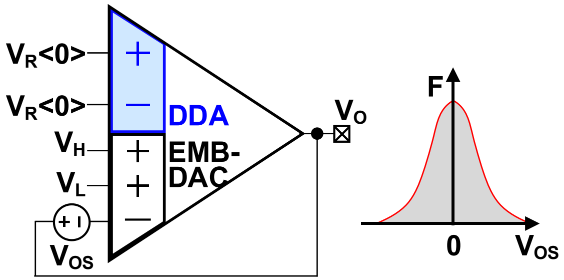


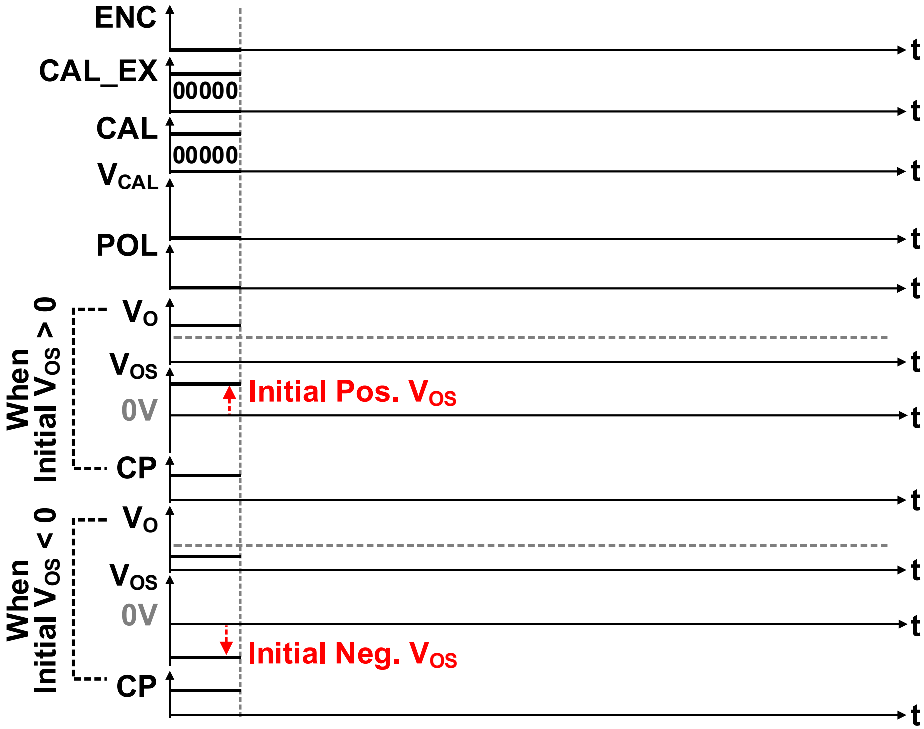
Input stage of EMB-DAC



Small-DVO SD-IC -ACAOC Operation(1/6)-

Phase#1: before calibration



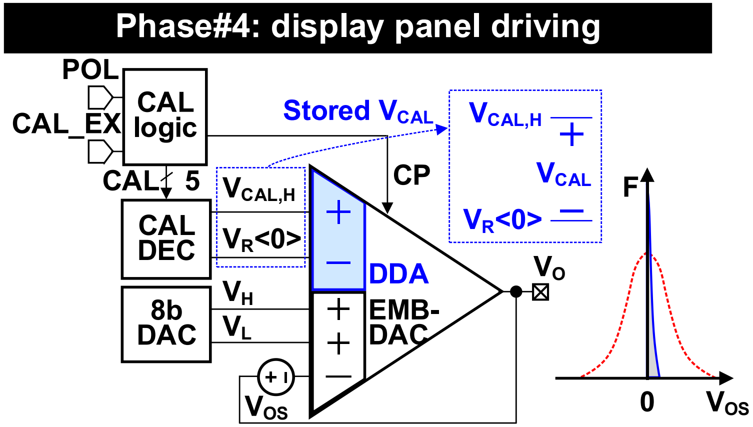


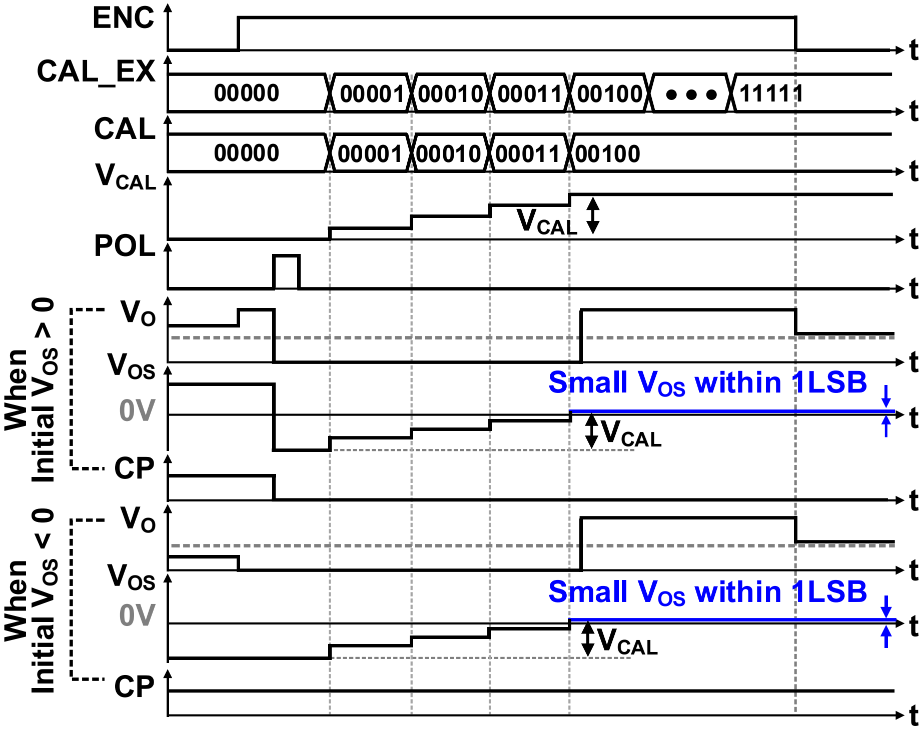
☹ **Dual polarity**

☹ **Large V_{OS}**

Small-DVO SD-IC -ACAOC Operation(6/6)-

Phase#4: display panel driving

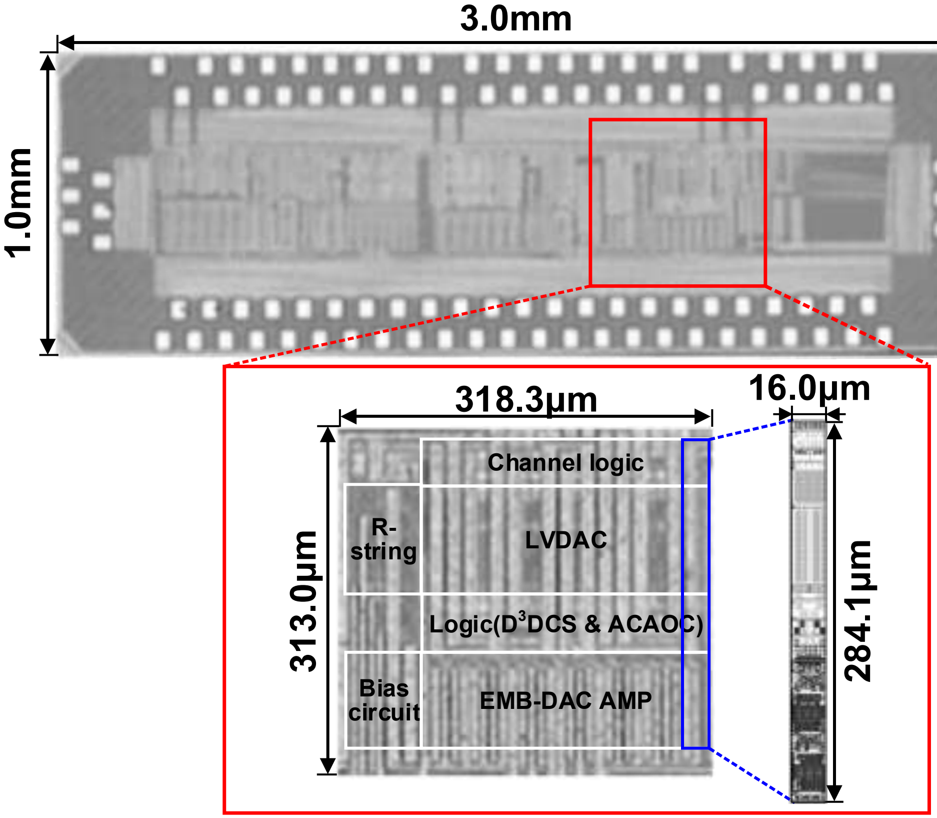




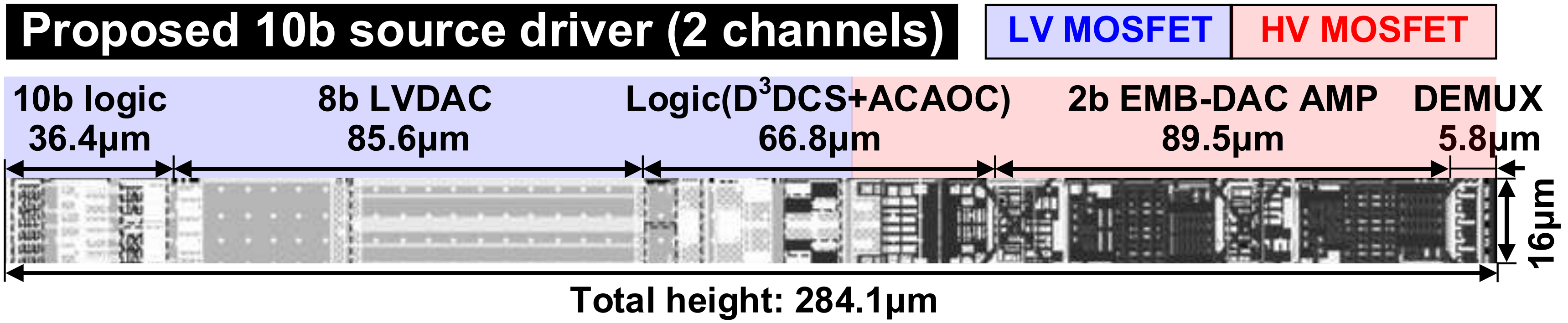
- ☺ **Single polarity**
- ☺ **Small V_{OS}**

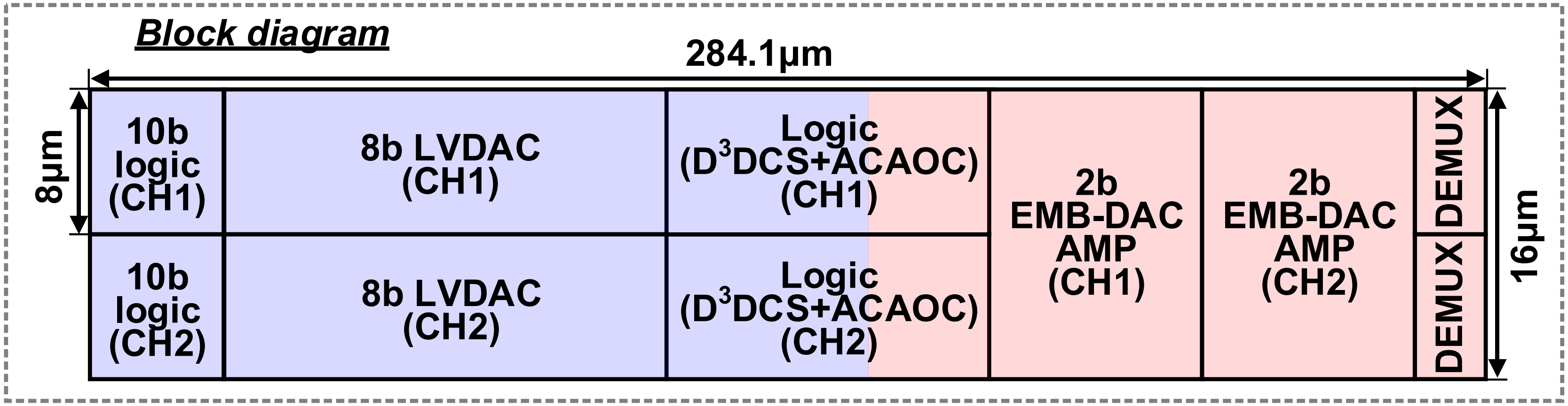
Die Micrograph

- **TSMC 65nm CMOS process**



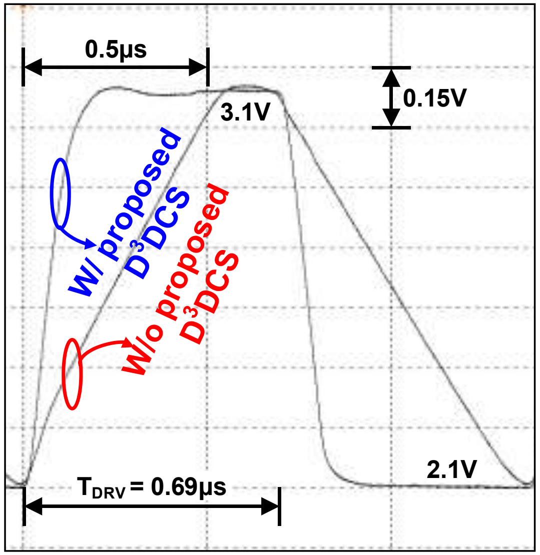
Layout of Proposed SD-IC


Proposed 10b source driver (2 channels)

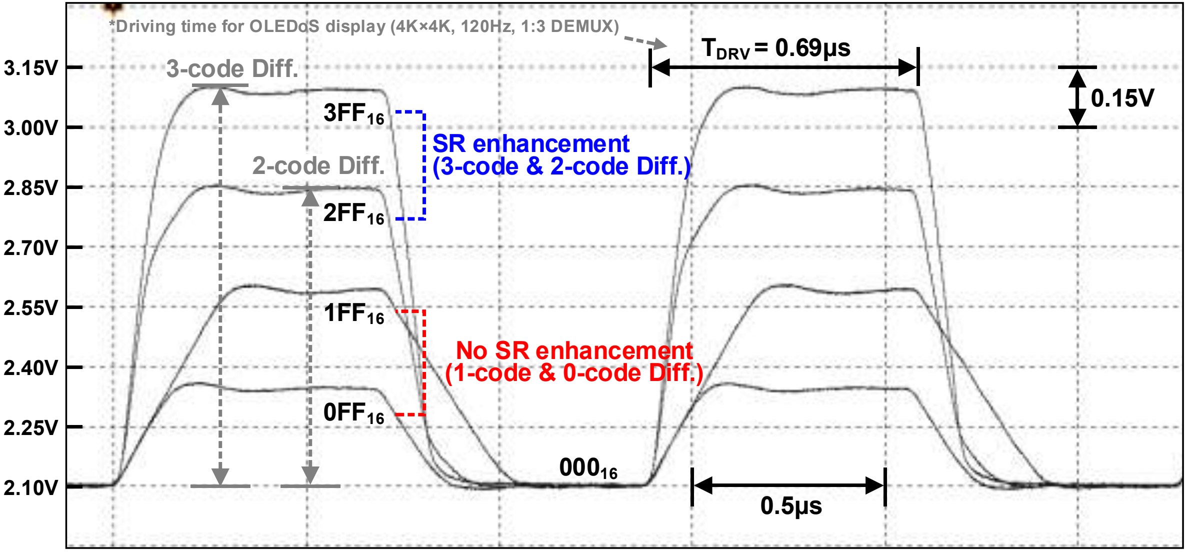


- Achieved 2,273μm²/channel → small area SD-IC

Measured Waveforms



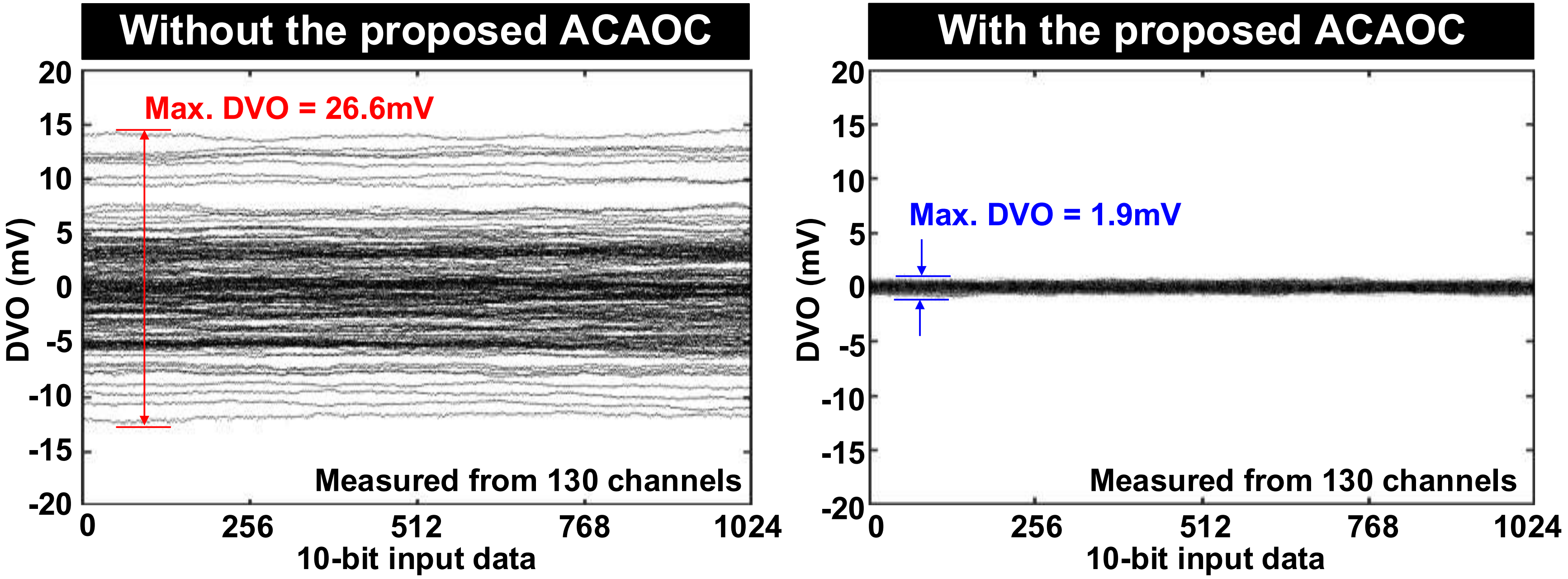
Measured waveform with D^{3}DCS



Measured output waveform

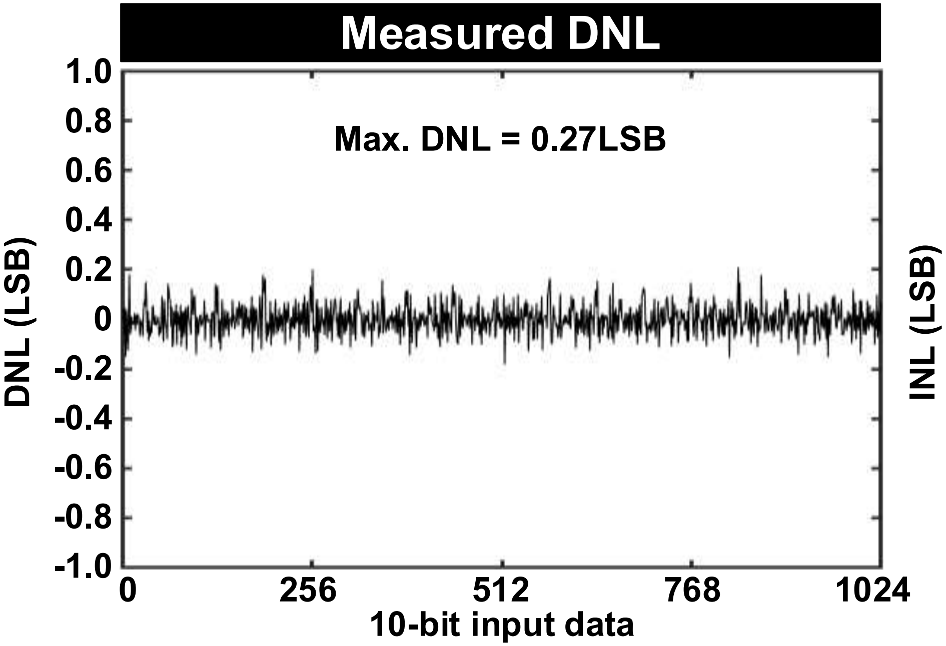
- Achieved a settling time of 0.69μs → fast SD-IC

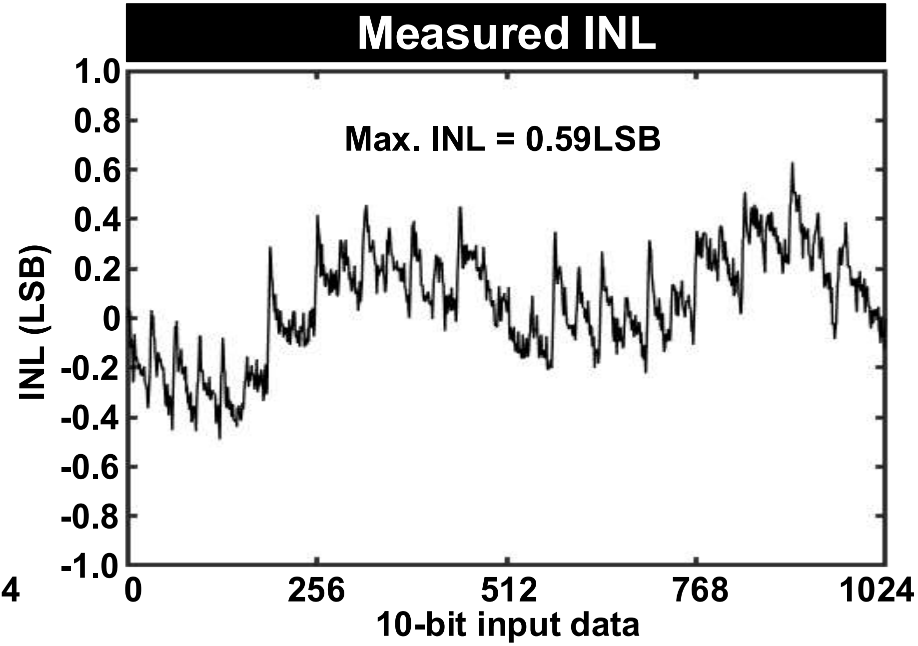
Measured DVO



- Achieved a DVO of 1.9mV → small DVO SD-IC

Measured Linearity





- Achieved DNL/INL of 0.27/0.59 LSB, respectively.

Performance Comparison

	J.-S.Kim JSSC 2021	G.-W.Lim JSSC 2023	S.Shin JSSC 2024	Y.Park ISSCC 2024	J.Ahn ISSCC 2024	This Work
Technology	90nm CMOS	130nm CMOS	180nm CMOS	180nm CMOS	65nm CMOS	65nm CMOS
Application	OLED	OLED	OLED	OLED	OLED	OLEDoS (6285PPI)
Output range	0.2V to 4.8V	0.3V to 4.5V	0.1V to 4.9V	0.25V to 4.5V	0.3V to 4.7V	2.1V to 3.1V*
Gray scale	10-bit	10-bit	10-bit	10-bit	10-bit	10-bit
Gamma curve	Fully nonlinear	Linear	Piecewise linear	Piecewise linear	Fully nonlinear	Piecewise linear
Frame rate	-	60Hz	60Hz	240Hz	60Hz	120Hz
Panel resolution	-	2560 X 1600	2520 × 1080	3840 x 2160	3840 x 2160	4000 x 4000
DEMUX	-	-	-	-	-	1:3 DEMUX
DNL / INL	0.20/0.42LSB	0.39/0.90LSB	-0.39/1.17LSB	0.21/1.21LSB	0.49/0.85LSB	0.27/0.59LSB
Max. DVO	7.9mV (4.2x)	4.8mV (2.5x)	15.5mV (8.2x)	11.5mV (6.1x)	10.0mV (5.3x)	1.9mV (1.0x smallest)
Settling time	2.2μs (3.2x)	5.3μs (7.9x)	1.5μs (2.2x)	1.5μs (2.2x)	5.0μs (7.2x)	0.69μs (1.0x fastest)
R_{LOAD}/C_{LOAD}	30kΩ/30pF	30kΩ/30pF	3kΩ/100pF	3kΩ/100pF	30kΩ/30pF	10kΩ/10pF
Static current per channel	2.8μA	1.8μA	1.7μA	2.4μA	1.5μA	5.4μA
Channel area (1CH)	5328μm^2 (296.0 × 18.0μm^2) (2.3x)	2688μm^2 (168.0 × 16.0μm^2) (1.2x)	4065μm^2 (243.4 × 16.7μm^2) (1.8x)	4815μm^2 (321.0 × 15.0μm^2) (2.1x)	2411μm^2 (150.7 × 16.0μm^2) (1.1x)	2273μm^2 (142.1 × 16.0μm^2) (1.0x smallest)
Channel area (2CH)	10656μm^2 (592.0 × 18.0μm^2) (2.3x)	5376μm^2 (336.0 × 16.0μm^2) (1.2x)	8130μm^2 (486.8 × 16.7μm^2) (1.8x)	9630μm^2 (642.0 × 15.0μm^2) (2.1x)	4822 μm^2 (301.4 × 16.0μm^2) (1.1x)	4546μm^2 (284.1 × 16.0μm^2) (1.0x smallest)

*Output range for OLEDoS pixel circuit with PMOS driving TR

Summary

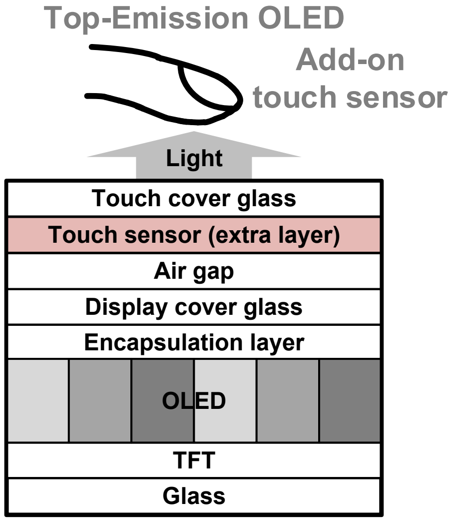
- Small area, fast, and small DVO SD-IC is required for OLEDoS display.
- **Small area SD-IC** is achieved using LVDAC, DEMUX, and two-stage DAC architecture, resulting in a channel area of **2273μm²**.
- **Fast SD-IC** is implemented by D^3DCS, achieving a settling time of less than **0.69μs**.
- **Small DVO SD-IC** is realized by ACAOC, reducing DVO to less than **1.9mV**.
- The proposed SD-IC is well-suited for OLEDoS displays.

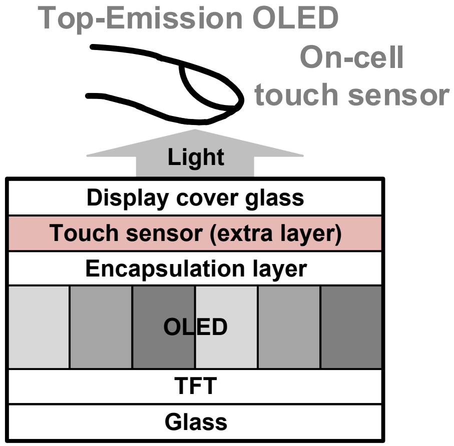
[연구분야: 센서 회로]

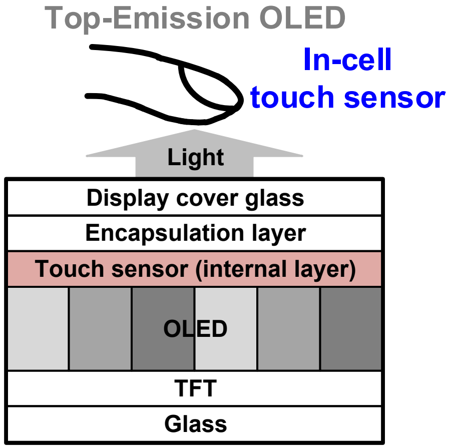
Touch Sensor

Background

Background -Top-Emission OLED Touch Sensor Type-





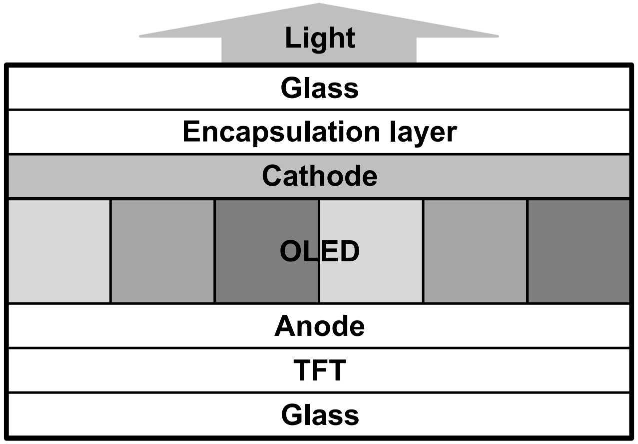


Add-on touch sensor	On-cell touch sensor	In-cell touch sensor
☺ SNR ↑ (near finger)	☹ SNR ↓ (far from finger & near DDI)	☹ SNR ↓ (far from finger & near DDI)
☹ Luminance ↓ (air gap → visual issue)	☺ Luminance ↑ (no air gap)	☺ Luminance ↑ (no external sensor layer)
☹ Manufacturing cost ↑ (additional sensor layer)	☹ Manufacturing cost ↑ (no air gap)	☺ Manufacturing cost ↓ (no external sensor layer)

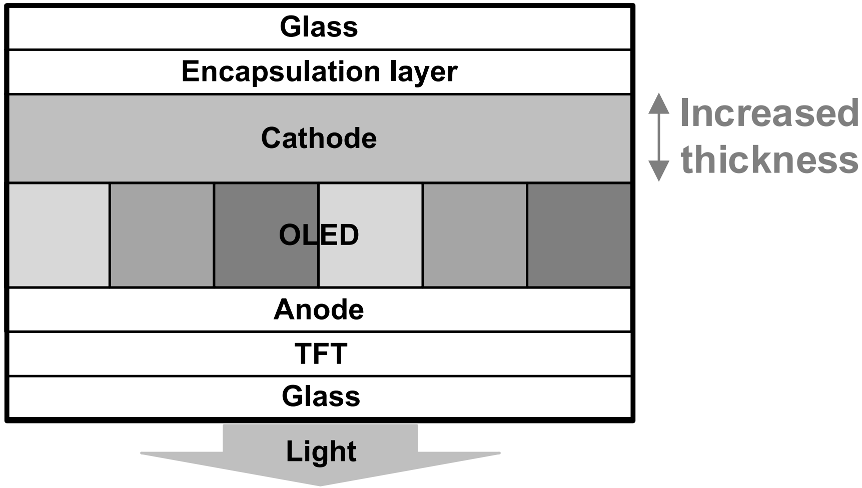
Advantages of in-cell touch sensor

Background -Top-Emission OLED vs Bottom-Emission OLED-

Top-Emission OLED



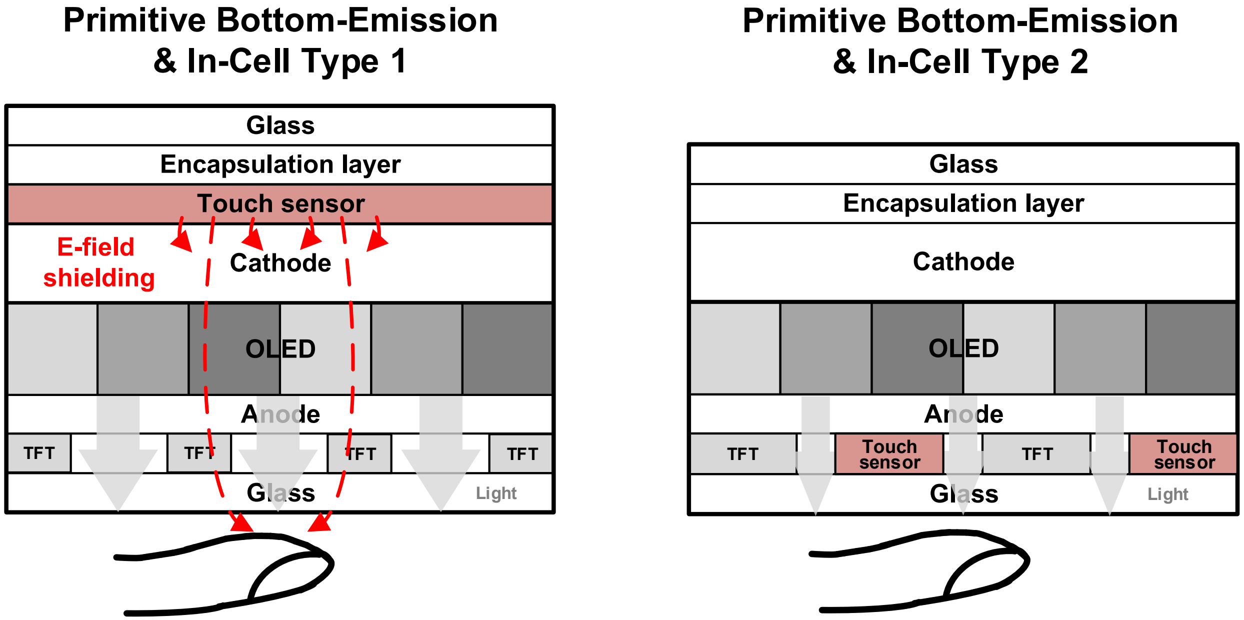
Bottom-Emission OLED



Top-emission OLED	Bottom-emission OLED
☹ **Manufacturing cost ↑** (transparent cathode → costly material)	☺ **Manufacturing cost ↓** (opaque cathode → cheaper material)
☹ **Luminance ↓** (thin cathode → high sheet R →current injection ↓)	☺ **Luminance ↑** (thick cathode → low sheet R → current injection ↑)

Advantages of bottom-emission OLED

Background -Challenges of In-Cell Touch Sensor for Bottom-Emission OLED-



Type 1	Type 2
☹ **SNR↓** (E-field is shielded by cathode layer)	☹ **Luminance↓** (aperture ratio↓)

A new in-cell touch sensor suitable for bottom-emission OLED is needed.

Background

-Summary of OLED Displays and Touch Sensor Type-

Top-emission OLED		
☹ MFG. cost ↑ ☹ Luminance ↓		
Add-on touch sensor	On-cell touch sensor	In-cell touch sensor
☹ MFG. cost ↑	☹ MFG.cost ↑	☺ MFG. cost ↓
☹ Luminance ↓	☺ Luminance ↑	☺ Luminance ↑

Bottom-emission OLED		
☺ MFG. cost ↓ ☺ Luminance ↑		
In-cell touch sensor (E-field)		In-cell touch sensor (H-field)
Type1	Type2	This work
☹ SNR ↓	☹Luminance↓	☺ MFG. cost ↓ ☺ Luminance ↑ ☺ SNR ↑

This work combines

bottom-emission OLED & in-cell touch sensor

☺ Manufacturing cost ↓

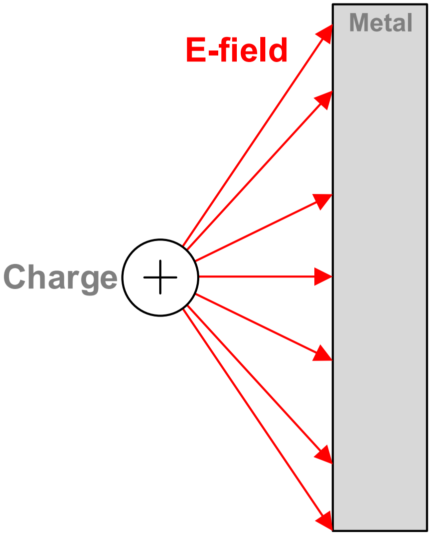
☺ Luminance ↑

☺ Manufacturing cost ↓

☺ Luminance ↑

Background - E-field vs H-field -

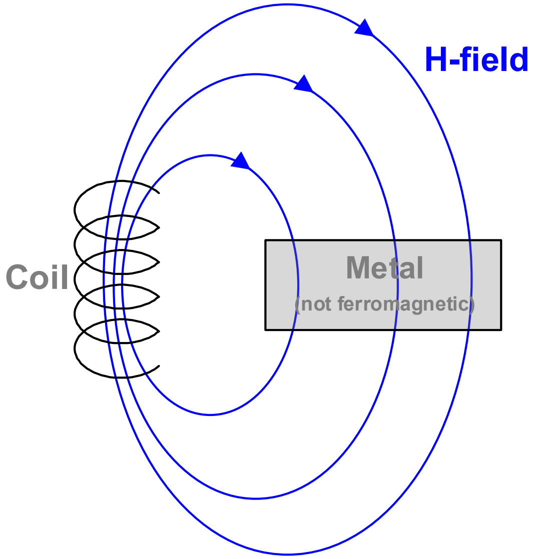
E-Field



E-field is shielded by metal

H-Field

Principle of H-field Penetration Through Metal



<u>H-field is not shielded by metal</u>

Application #1: Wireless Charging System

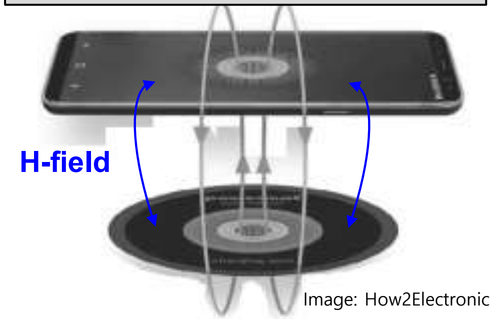


Image: How2Electronics

Application #2: EMR Stylus Pen

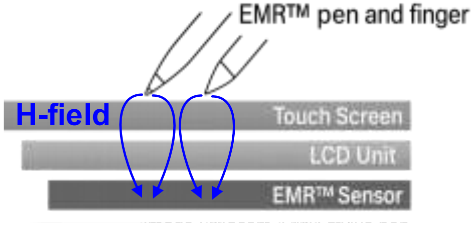
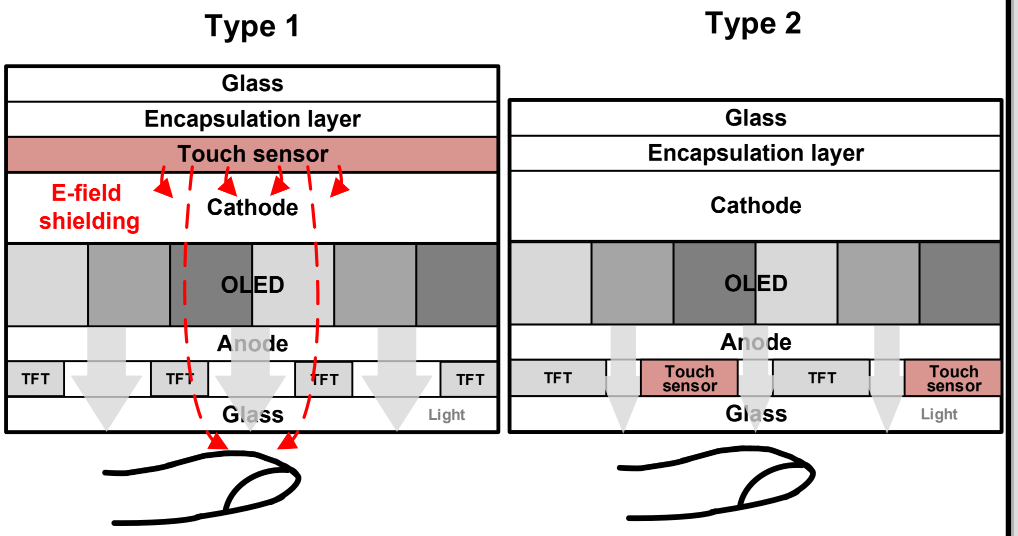


Image : Wacom, EMR stylus pen

Architecture of Proposed LLC Touch Sensor

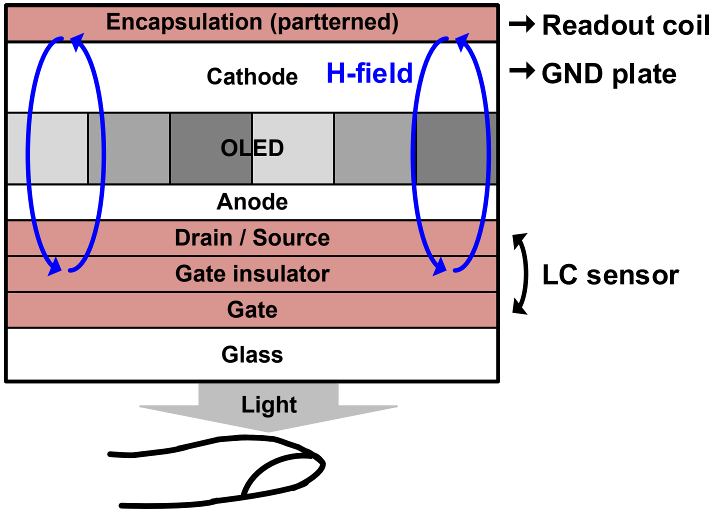
Bottom-Emission OLED with In-Cell Touch Sensor (E-Field)



☹ SNR↓

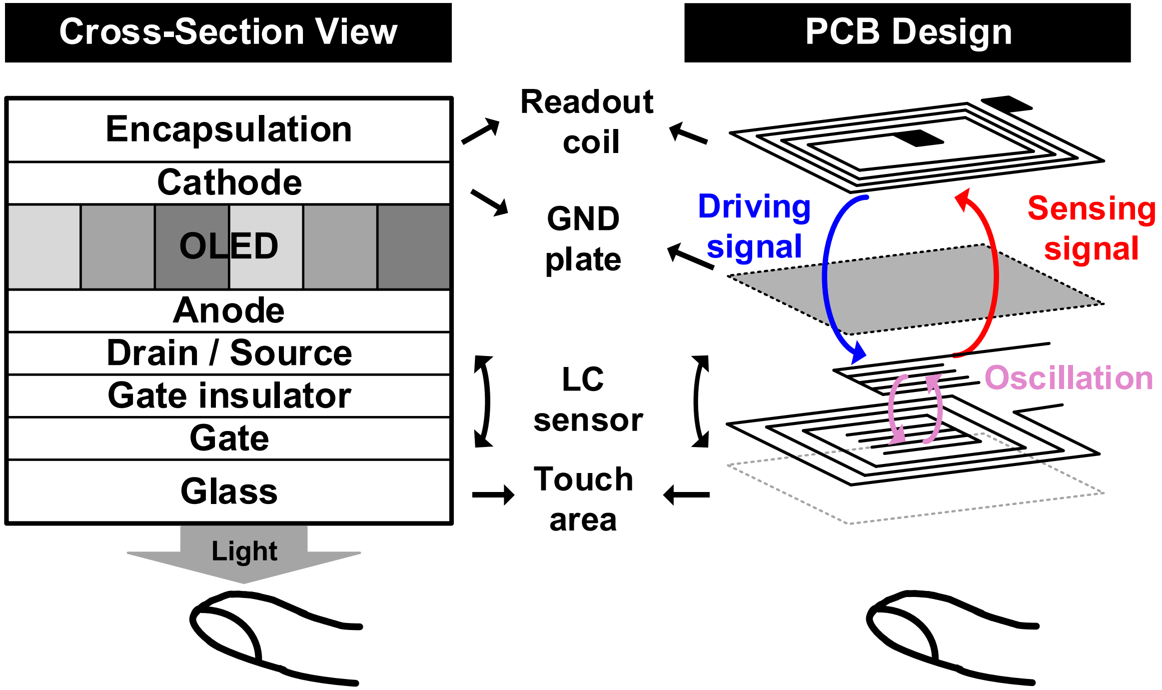
☹ Luminance↓

Bottom-Emission OLED with In-Cell Touch Sensor (H-Field)



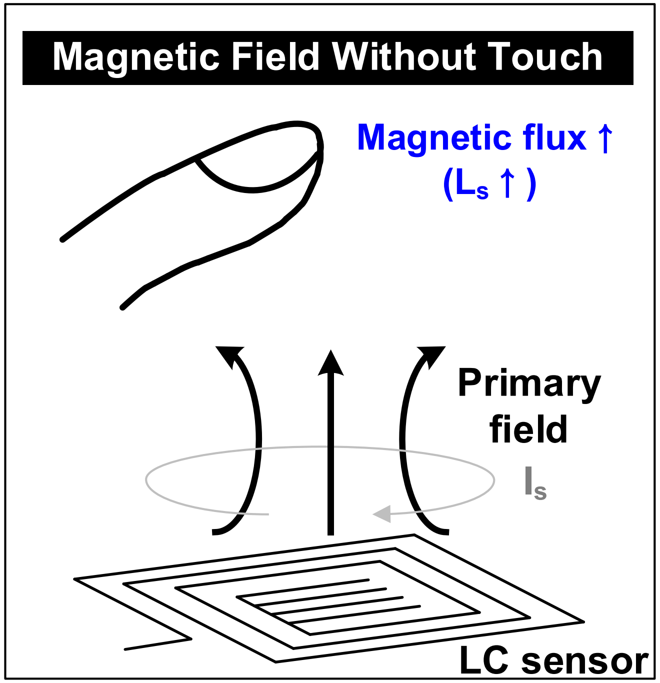
- ☺ Manufacturing cost↓
- ☺ Luminance↑
- ☺ SNR↑

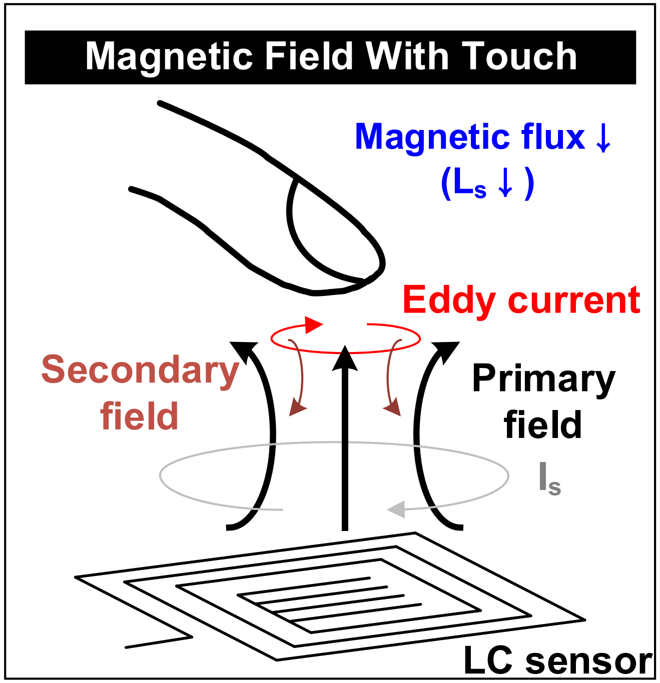
Principle of Operation



- **Driving / sensing signal** via **inductive coupling** (**LC sensor ⇄ readout coil**)
- **Resonance** by **L** and **C** in the **LC sensor**

Analysis of Characteristics -Inductance-

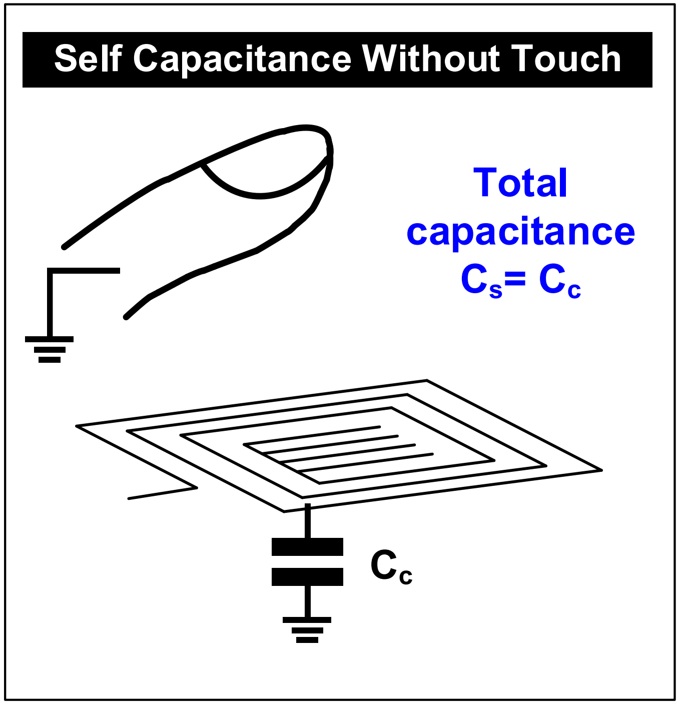




Inductance formed by primary magnetic field

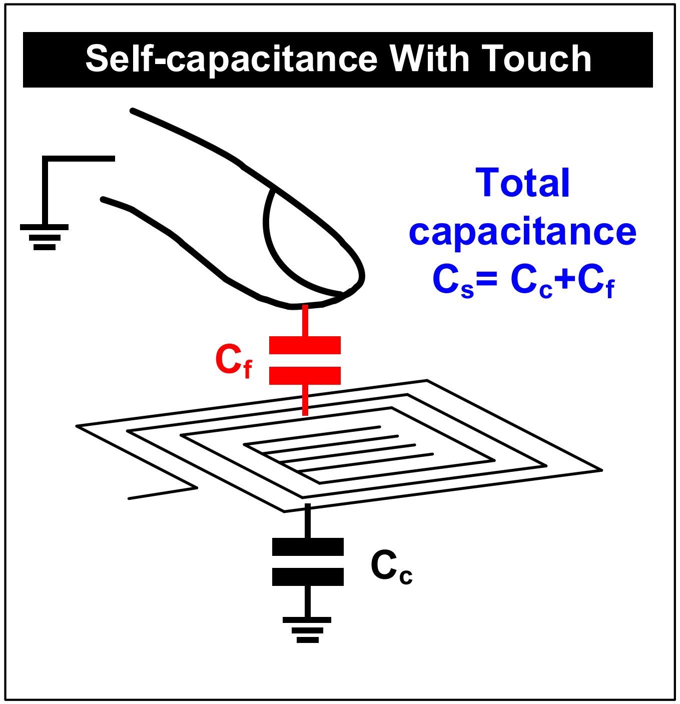
Eddy current reduces **inductance** **(L_s ↓)**

Analysis of Characteristics -Capacitance-



Self Capacitance Without Touch

Total capacitance $C_s = C_c$



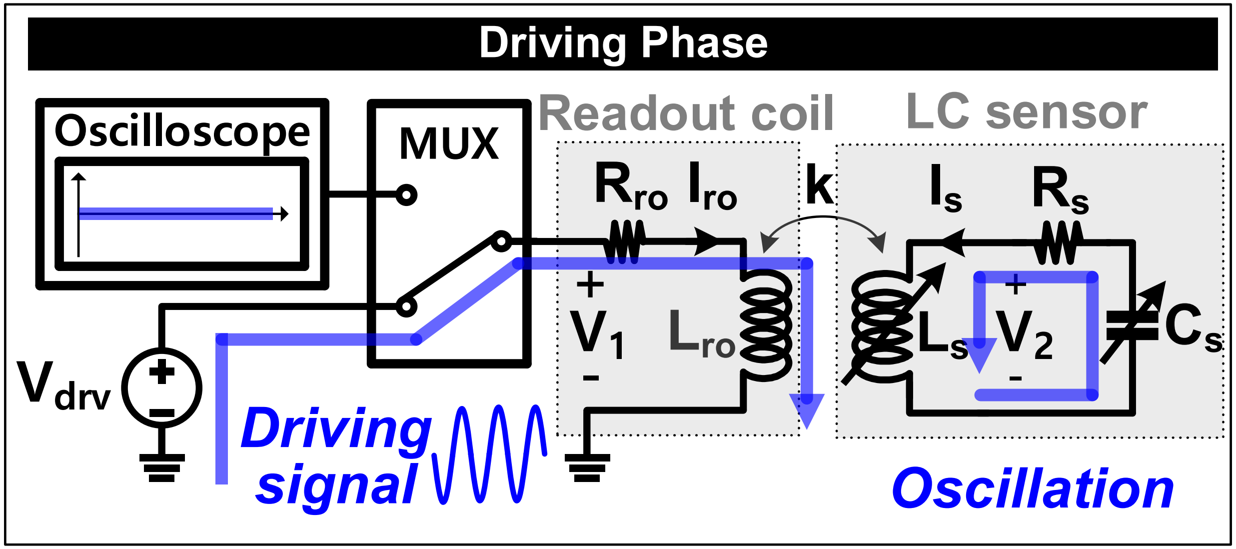
Self-capacitance With Touch

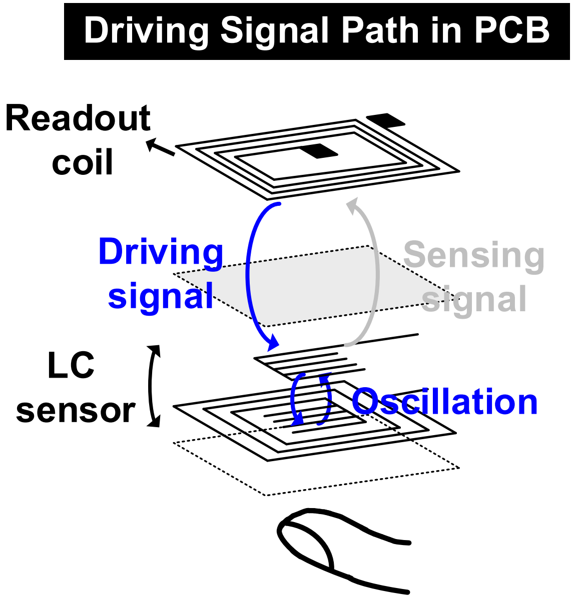
Total capacitance $C_s = C_c + C_f$

Baseline self-capacitance

Finger-induced C_f is added → C_s ↑

Driving & Sensing Method -Driving Phase-





- V_{DRV} → L_{ro} via **MUX**
- **Inductive coupling** : L_{ro} → L_s

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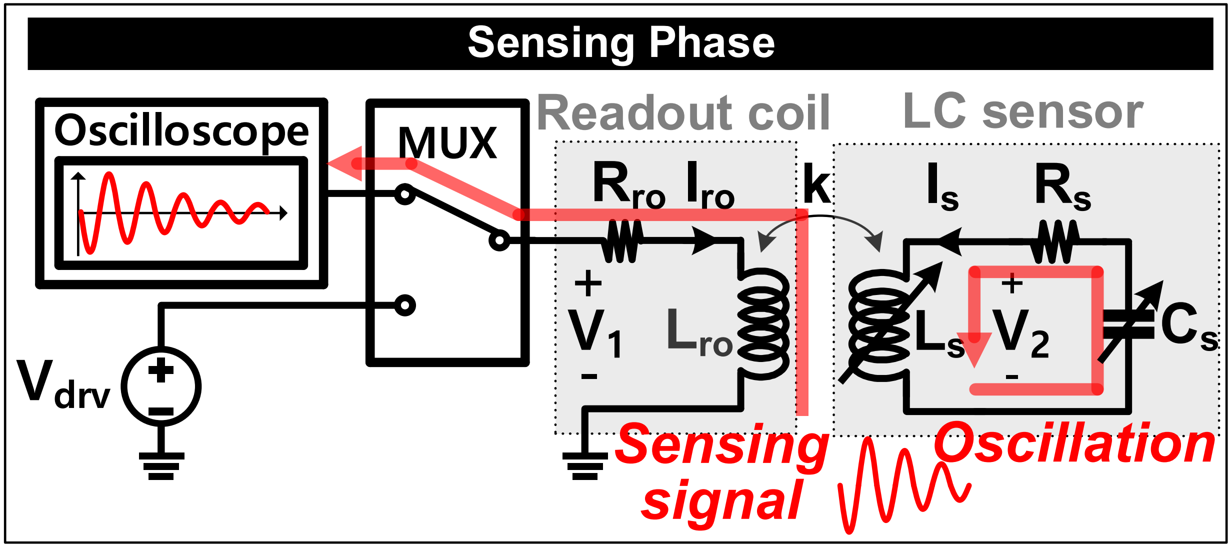
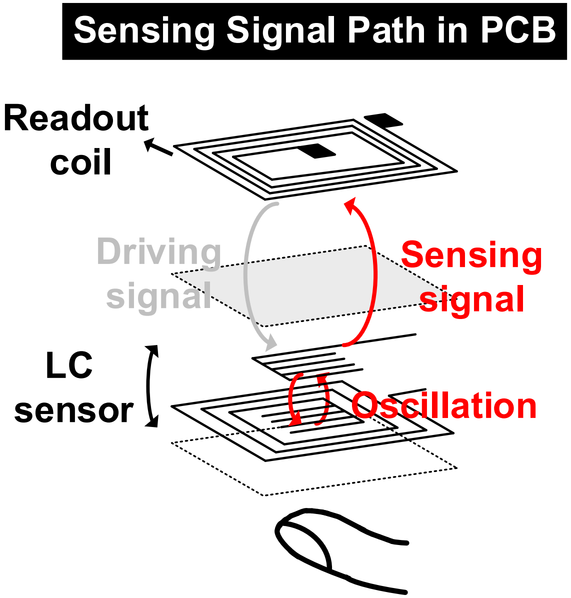
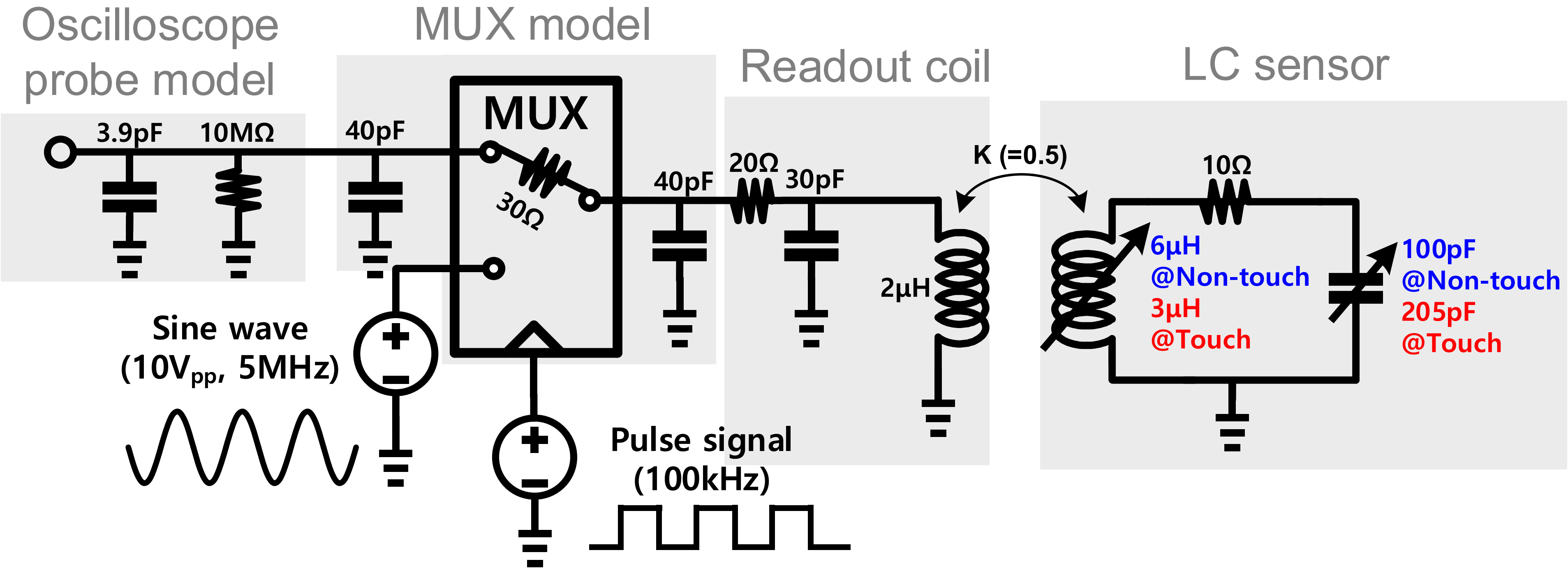
Driving & Sensing Method -Sensing Phase-



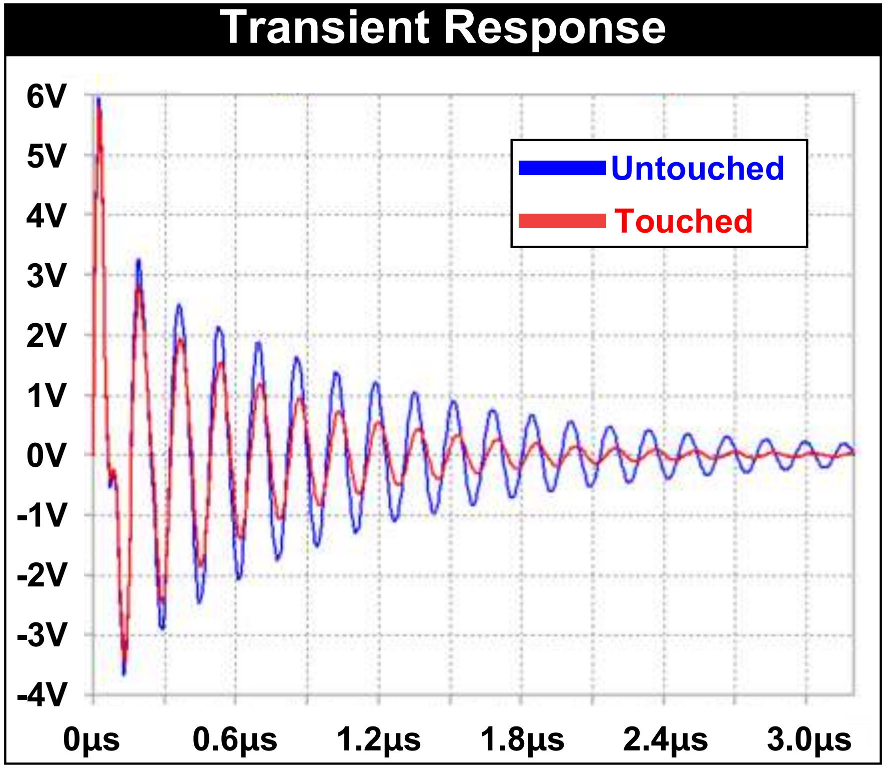


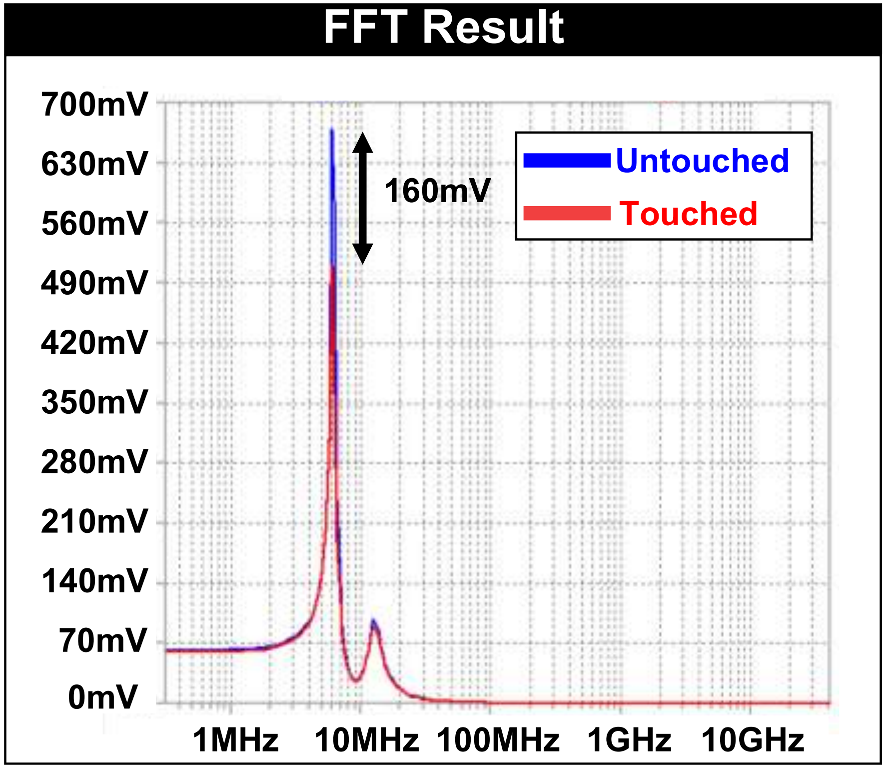
- MUX links sensing signal to oscilloscope
- Touch: L_s decrease, C_s increase → sensing signal change

Proposed LLC Touch Sensor -Simulation Condition-



Proposed LLC Touch Sensor -Simulation Result-

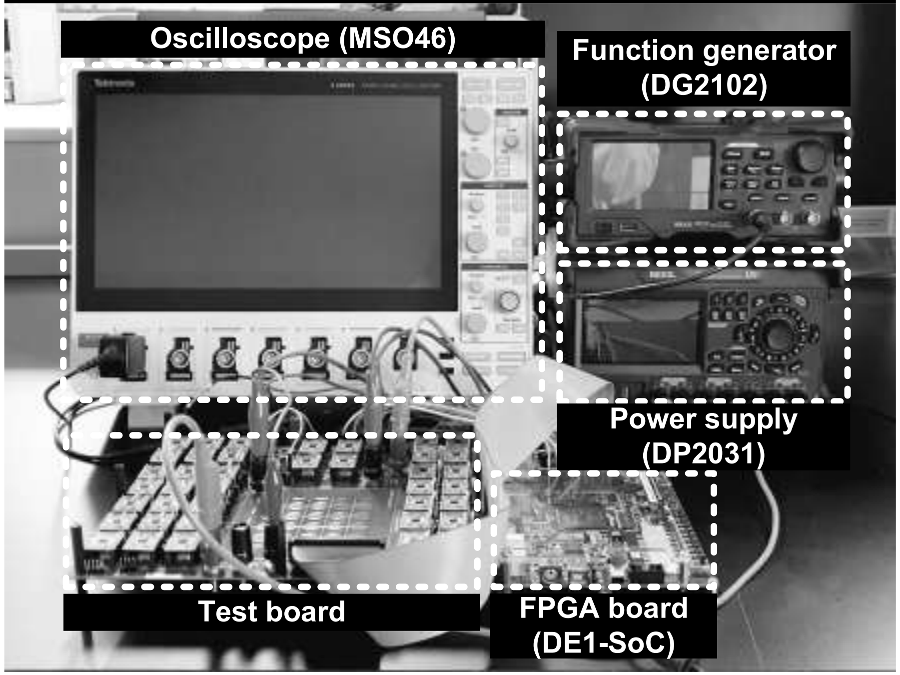




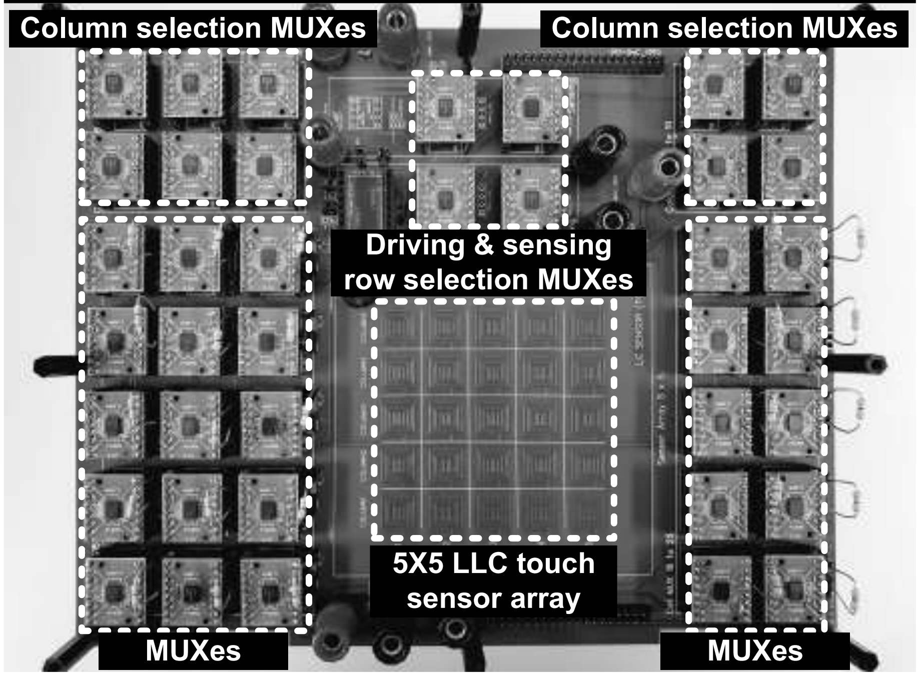
Measurement Result

-Measurement Setup-

Measurement Setup

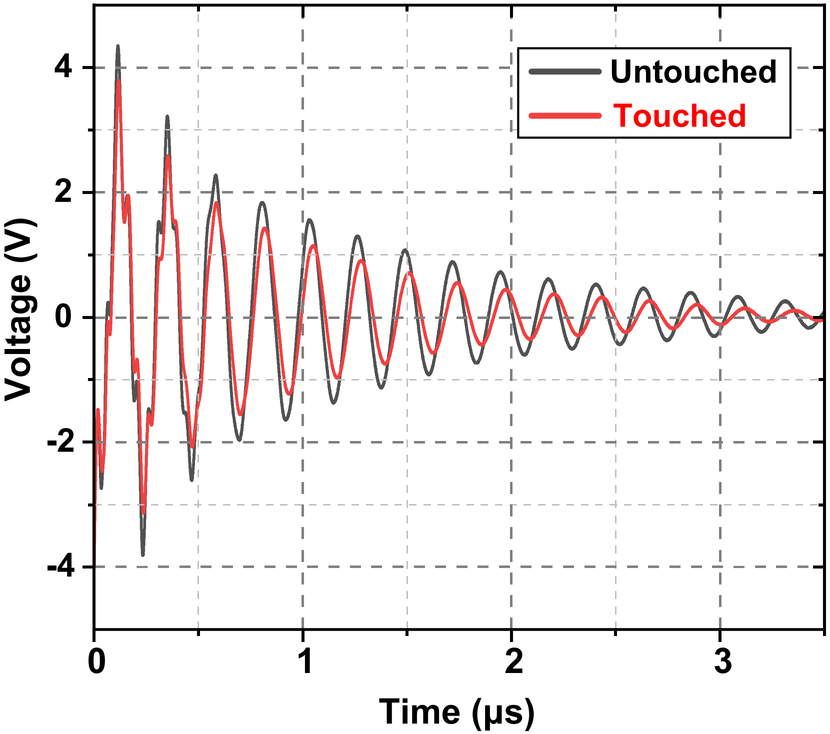


Test Board for Proposed LLC Touch Sensor

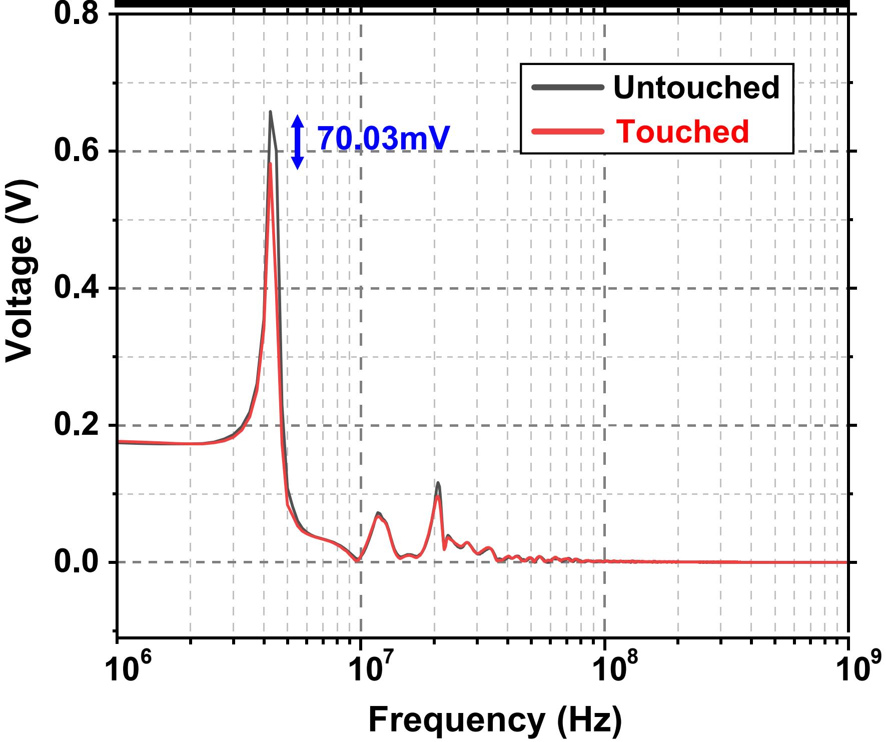


Measurement Result -Single-Sensor-

Measured Transient Response

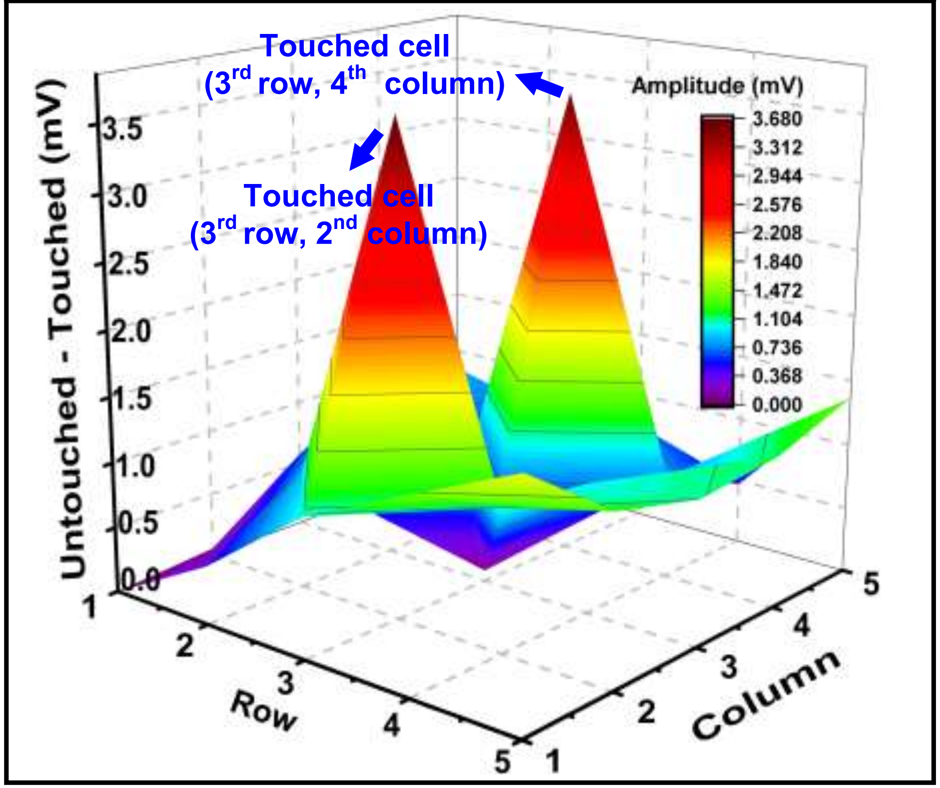


Measured FFT Result



Measurement Result - Measured Profile Image-

Measured Multi-Touch Result



This measurement result was obtained using the revised PCB.

[연구분야: 전원관리 회로]

Touch Sensor

Power Circuit Researches

[Switched-Inductor Power Supply Circuit]

1. **Automotive 용 PMIC**
   - 40V Buck-boost converter 및 전용 gate driver IC Chip 개발 (BCD Process)
   - 40V Buck converter 및 전용 gate driver IC Chip 개발 (BCD Process)

2. **저전력 IoT 용 PFM buck converter**
   - 저리플, 고효율 특성을 동시에 갖는 PFM buck converter 개발
   - Ripple < 2mV, Efficiency >82%, Maximum Efficiency > 93%, IOUT=100mA)

3. **Mobile용 고효율 buck-boost converter** (AICSP 2016)
   - 입력 전압 변화에 따른 Mode-selection 기능 → battery 사용시간 증가

4. **(ongoing) 저리플, 높은 효율을 동시에 갖는 OLED ELVSS용 PFM buck-boost converter**
   - Output voltage ripple : 1 mV, Max. efficiency 95%, PFM control

[Switched-Capacitor Power Supply Circuit]

5. **4D 320단 NAND Flash Memory 양산제품용 고효율/고속 charge pump** (@SK Hynix)
   - 세계 최고 효율 variable-stage charge pump 개발 (30V charge pump, 8V charge pump)

6. **4D 128단 NAND Flash Memory 양산 제품용 고효율 negative charge pump** (@SK Hynix)
   - Charge pump stage 개선 및 charge pump controller 개선

[Linear regulator]

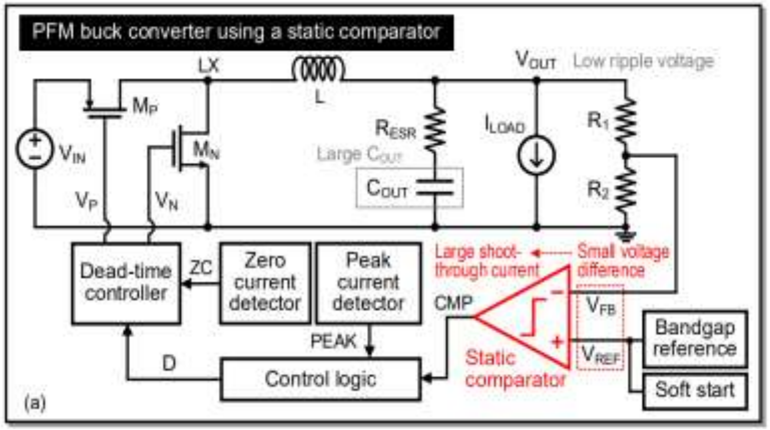
7. **Volage Droop 개선한 Capacitorless LDO**

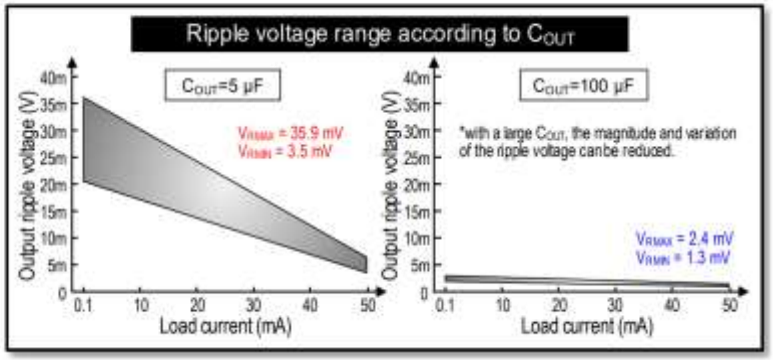
1. 저전력 IoT 용 PFM buck converter

- **A High-Light-Load-Efficiency, Low-Ripple-Voltage PFM Buck Converter for IoT Applications**
- IEEE Transactions on Power Electronics (IF: 5.967) 2022

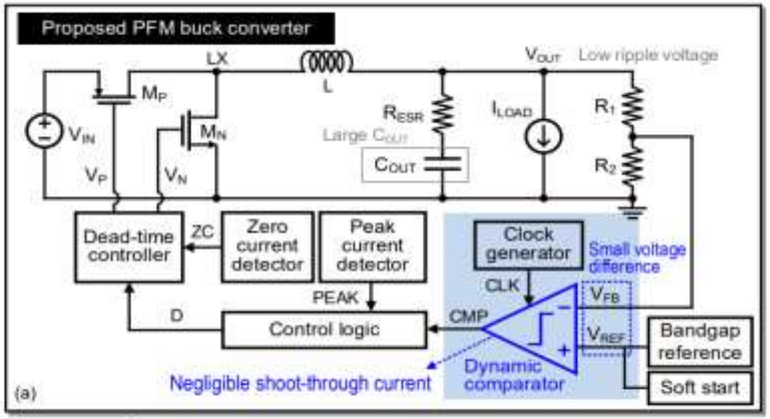
고효율 및 저리플 특성을 동시에 갖는 PFM buck converter 개발

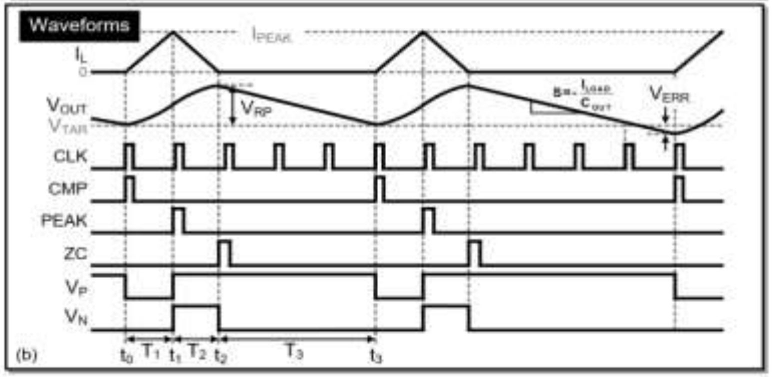
Conventional PFM buck converter
Tradeoff between Efficiency and Ripple


PFM buck converter using a static comparator


Ripple voltage range according to C_{OUT}

Proposed PFM buck converter
breaks the tradeoff (Efficiency and Ripple)


Proposed PFM buck converter

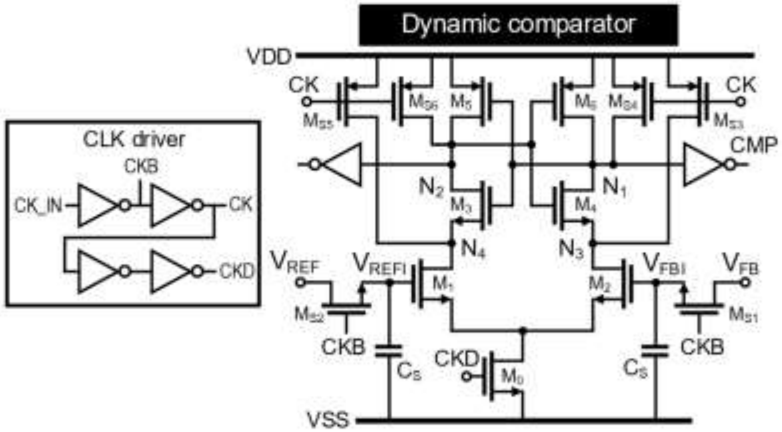

Waveforms

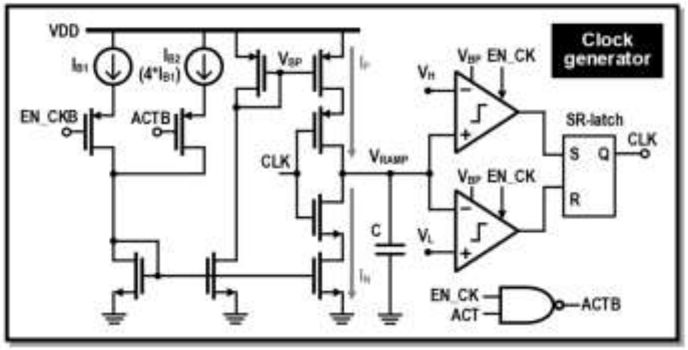
1. 저전력 IoT 용 PFM buck converter

- **A High-Light-Load-Efficiency, Low-Ripple-Voltage PFM Buck Converter for IoT Applications**
- IEEE Transactions on Power Electronics (IF: 5.967) 2022

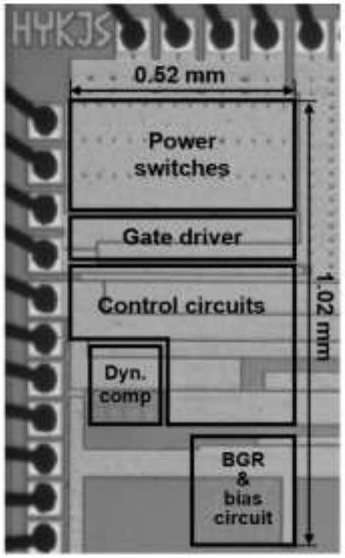
고효율 및 저리플 특성을 동시에 갖는 PFM buck converter 개발

Dynamic comparator → No shoot-through current

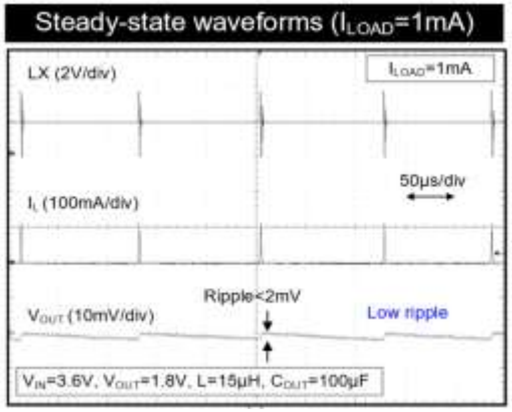

Dynamic comparator

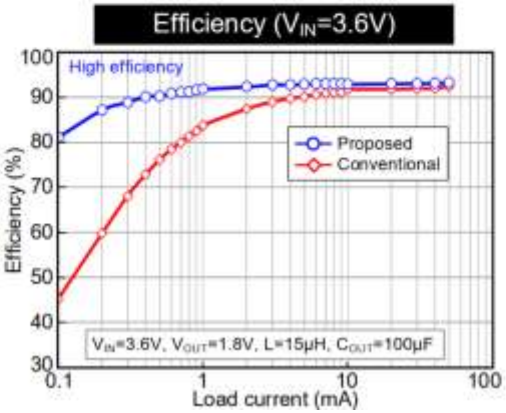


*Process: 350nm CMOS



High efficiency & low ripple


Steady-state waveforms (I_{LOAD}=1mA)


Efficiency (V_{IN}=3.6V)

1. 저전력 IoT 용 PFM buck converter

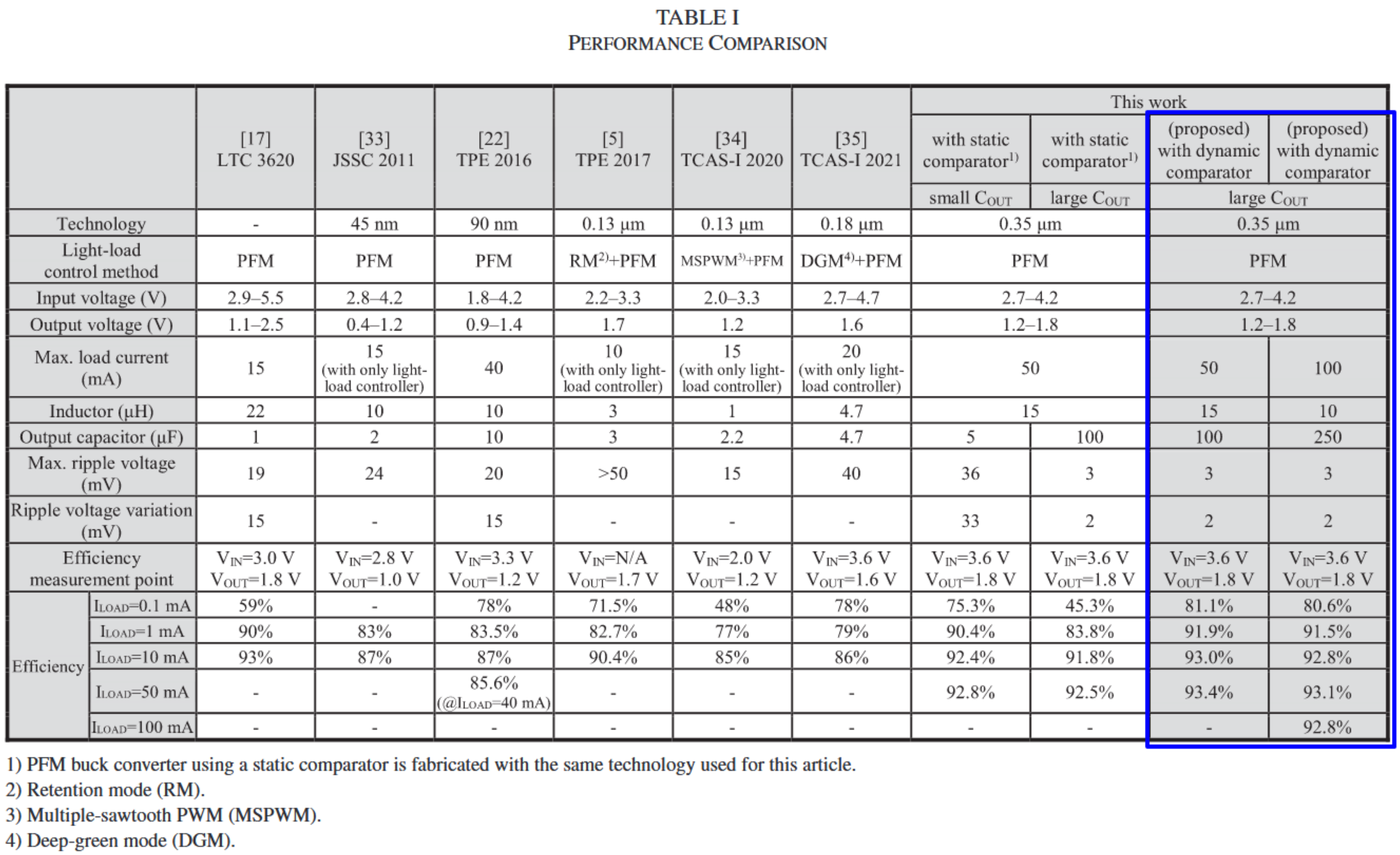


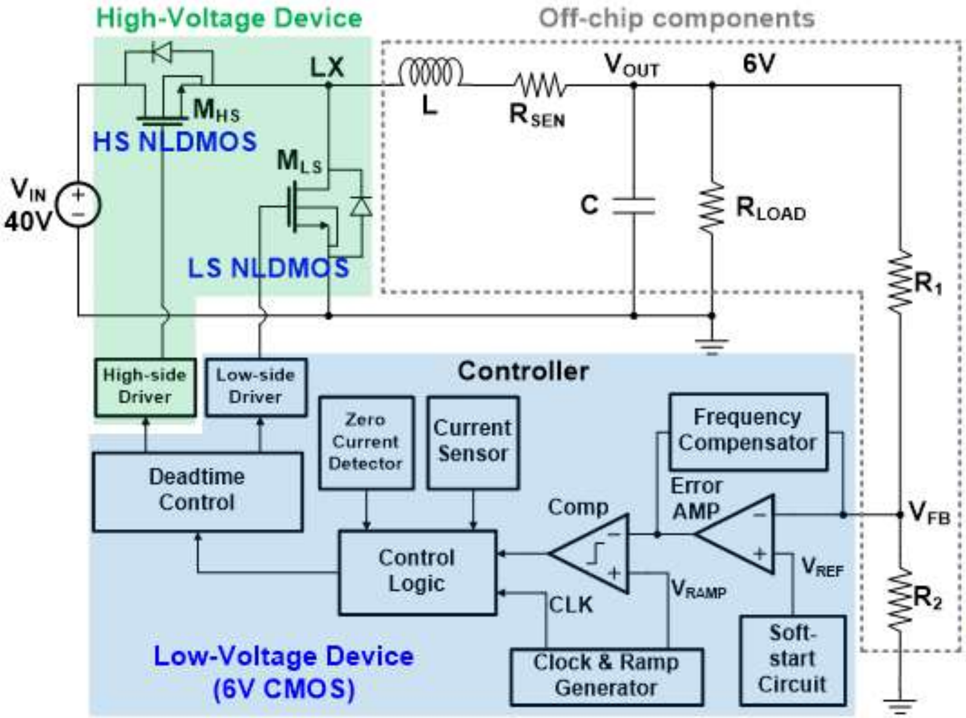
TABLE I
PERFORMANCE COMPARISON

		[17] LTC 3620	[33] JSSC 2011	[22] TPE 2016	[5] TPE 2017	[34] TCAS-I 2020	[35] TCAS-I 2021	This work			
								with static comparator[1]	with static comparator[1]	(proposed) with dynamic comparator	(proposed) with dynamic comparator
								small C_{OUT}	large C_{OUT}	large C_{OUT}	
Technology		-	45 nm	90 nm	0.13 µm	0.13 µm	0.18 µm	0.35 µm		0.35 µm	
Light-load control method		PFM	PFM	PFM	RM[2]+PFM	MSPWM[3]+PFM	DGM[4]+PFM	PFM		PFM	
Input voltage (V)		2.9–5.5	2.8–4.2	1.8–4.2	2.2–3.3	2.0–3.3	2.7–4.7	2.7–4.2		2.7–4.2	
Output voltage (V)		1.1–2.5	0.4–1.2	0.9–1.4	1.7	1.2	1.6	1.2–1.8		1.2–1.8	
Max. load current (mA)		15	15 (with only light-load controller)	40	10 (with only light-load controller)	15 (with only light-load controller)	20 (with only light-load controller)	50		50	100
Inductor (µH)		22	10	10	3	1	4.7	15		15	10
Output capacitor (µF)		1	2	10	3	2.2	4.7	5	100	100	250
Max. ripple voltage (mV)		19	24	20	>50	15	40	36	3	3	3
Ripple voltage variation (mV)		15	-	15	-	-	-	33	2	2	2
Efficiency measurement point		V_{IN}=3.0 V V_{OUT}=1.8 V	V_{IN}=2.8 V V_{OUT}=1.0 V	V_{IN}=3.3 V V_{OUT}=1.2 V	V_{IN}=N/A V_{OUT}=1.7 V	V_{IN}=2.0 V V_{OUT}=1.2 V	V_{IN}=3.6 V V_{OUT}=1.6 V	V_{IN}=3.6 V V_{OUT}=1.8 V	V_{IN}=3.6 V V_{OUT}=1.8 V	V_{IN}=3.6 V V_{OUT}=1.8 V	V_{IN}=3.6 V V_{OUT}=1.8 V
Efficiency	I_{LOAD}=0.1 mA	59%	-	78%	71.5%	48%	78%	75.3%	45.3%	81.1%	80.6%
	I_{LOAD}=1 mA	90%	83%	83.5%	82.7%	77%	79%	90.4%	83.8%	91.9%	91.5%
	I_{LOAD}=10 mA	93%	87%	87%	90.4%	85%	86%	92.4%	91.8%	93.0%	92.8%
	I_{LOAD}=50 mA	-	-	85.6% (@I_{LOAD}=40 mA)	-	-	-	92.8%	92.5%	93.4%	93.1%
	I_{LOAD}=100 mA	-	-	-	-	-	-	-	-	-	92.8%

1) PFM buck converter using a static comparator is fabricated with the same technology used for this article.
2) Retention mode (RM).
3) Multiple-sawtooth PWM (MSPWM).
4) Deep-green mode (DGM).

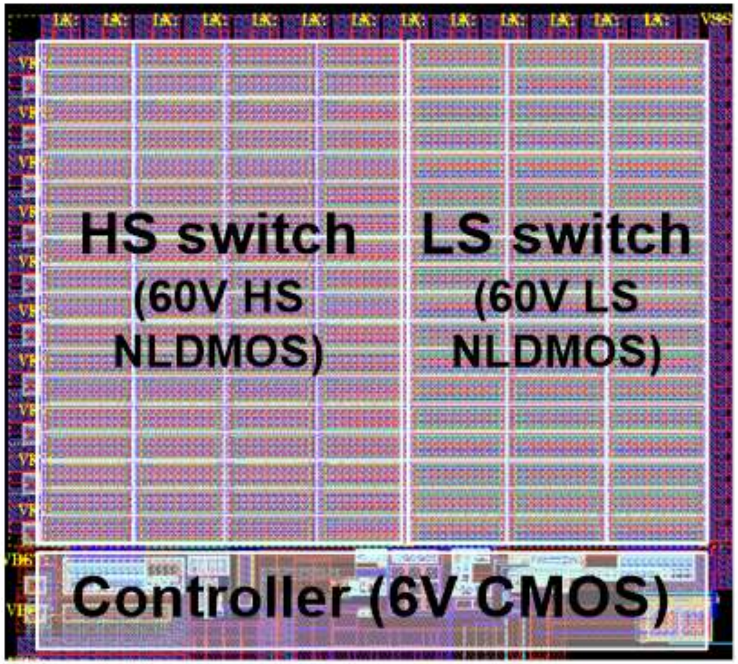
2. Automotive 용 Buck-Boost Converter

- **Purpose of the circuit**
  - To find the effect of parasitic devices between HV & LV devices



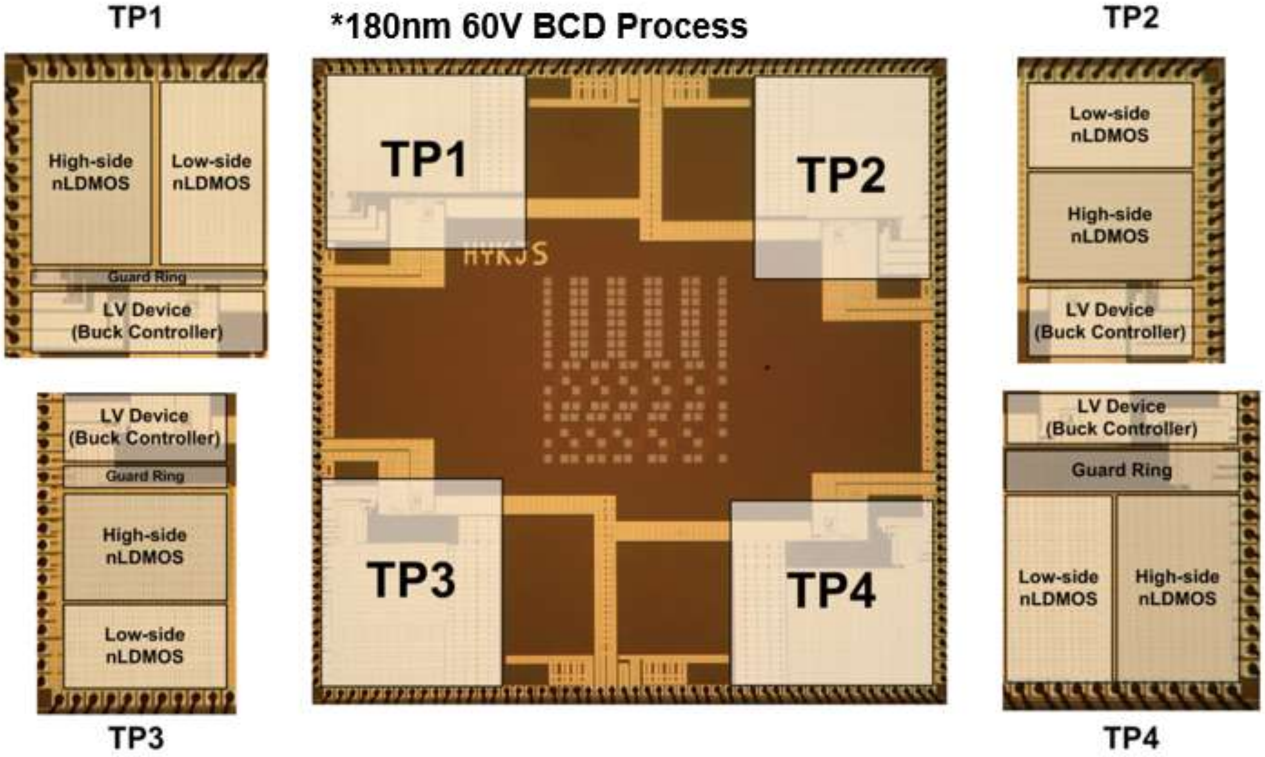
Block diagram

*180nm 60V BCD Process



Layout

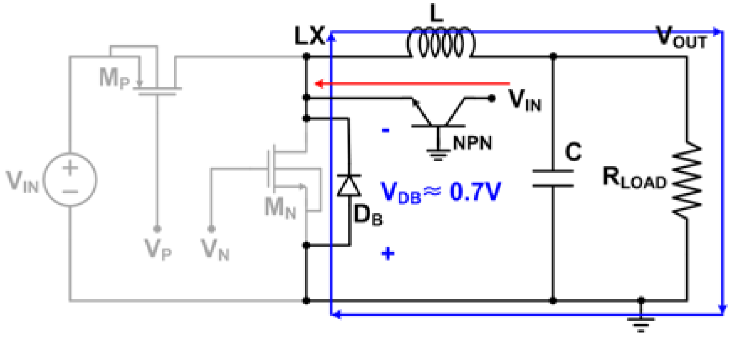
2. Automotive 용 Buck-Boost Converter


*180nm 60V BCD Process

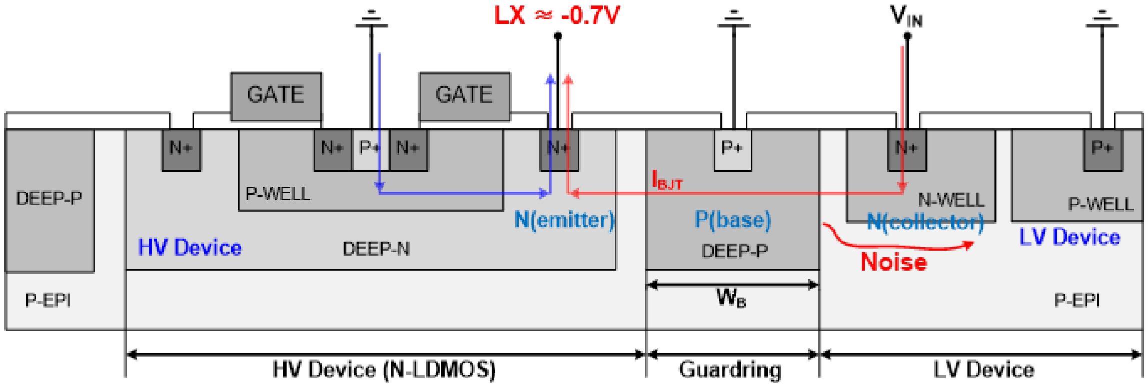
TP	Guard-Ring (Width)	Placement of Switches
1	O (15 μm)	Lateral
2	X	Vertical
3	O (200 μm)	Vertical
4	O (200 μm)	Lateral

2. Automotive 용 Buck-Boost Converter

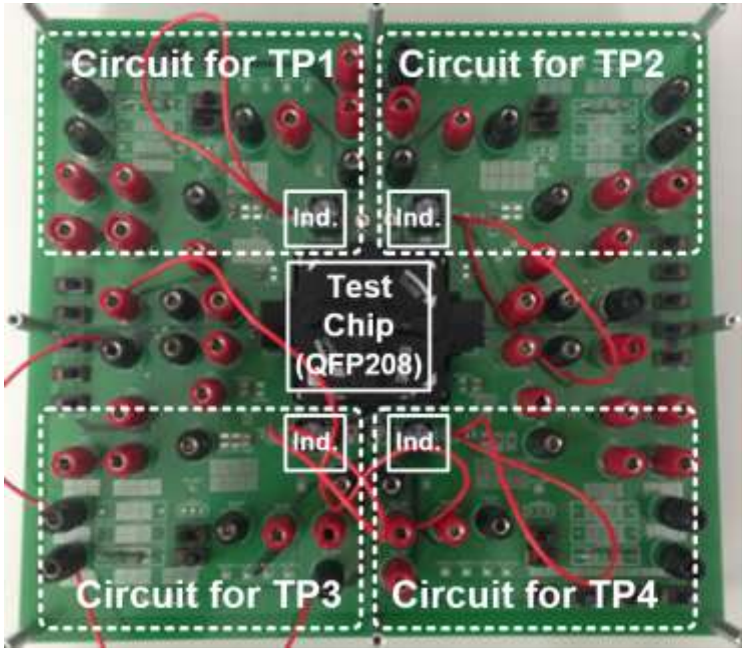
- **Operation**
  - Dead-time → body diode ON → V_{LX} < -0.7V → parasitic NPN on → substrate noise in LV device region → mal-function of DCDC

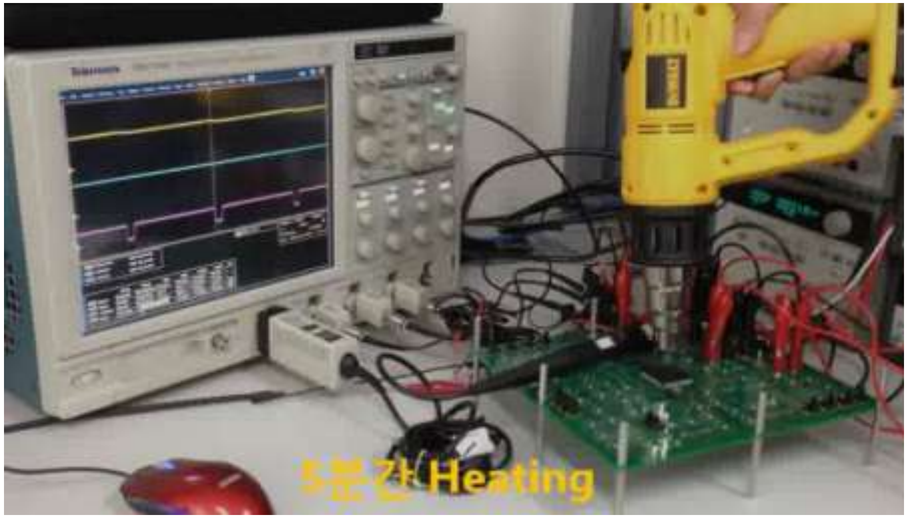


- **To reduce the effect of parasitic device**
  - β of NPN should be reduced
    - Large distance between HV and LV



2. Automotive 용 Buck-Boost Converter





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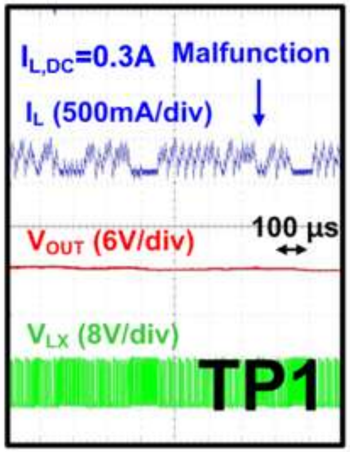
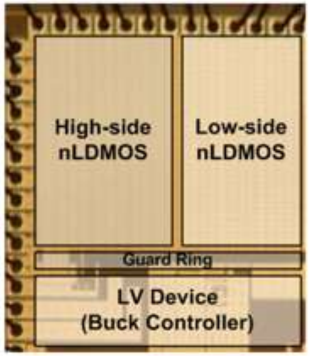
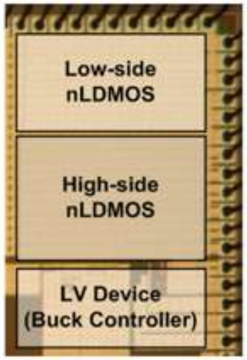
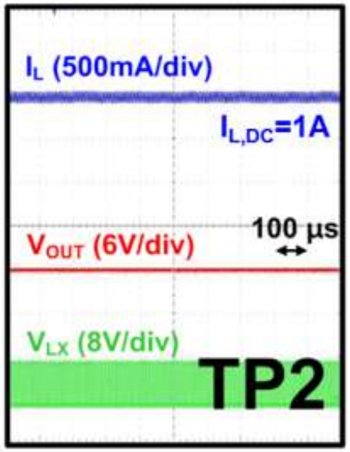
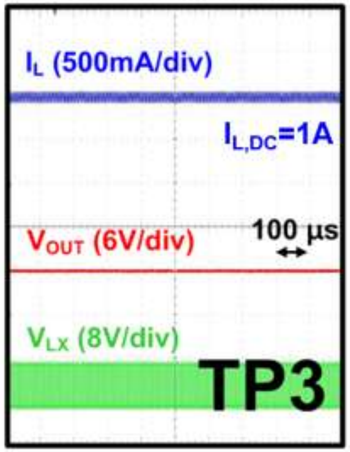
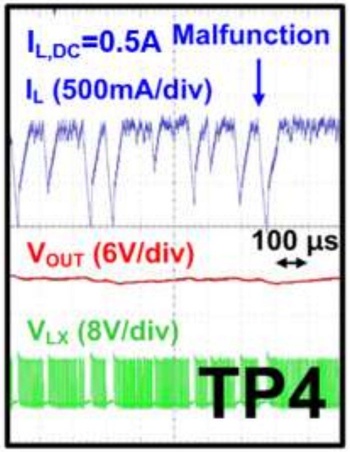




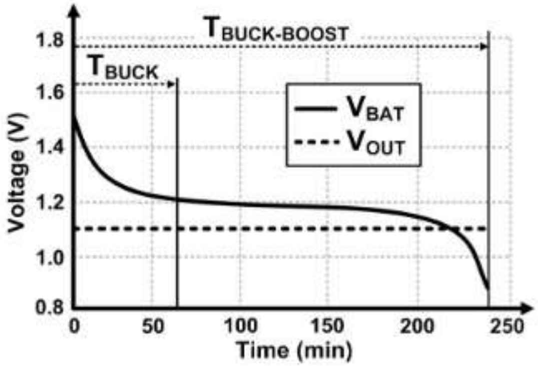


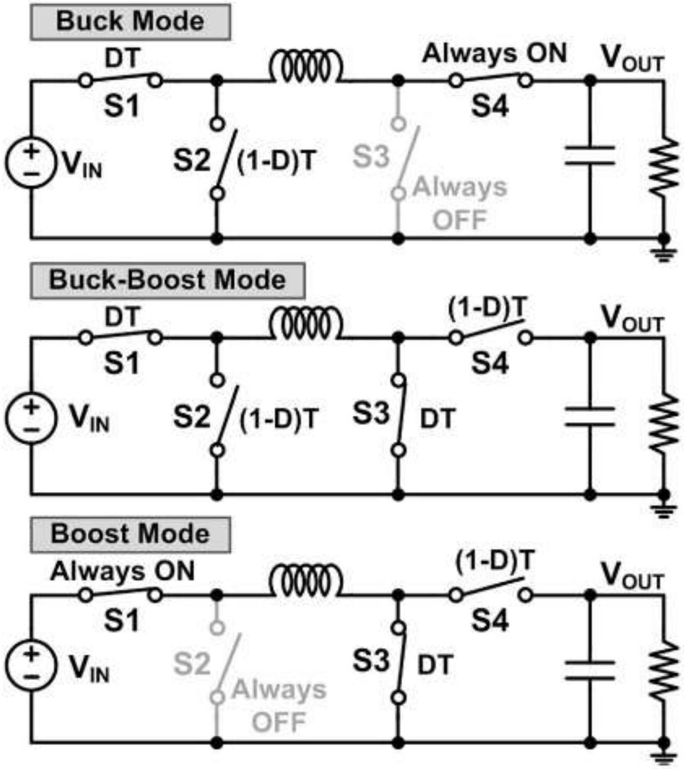


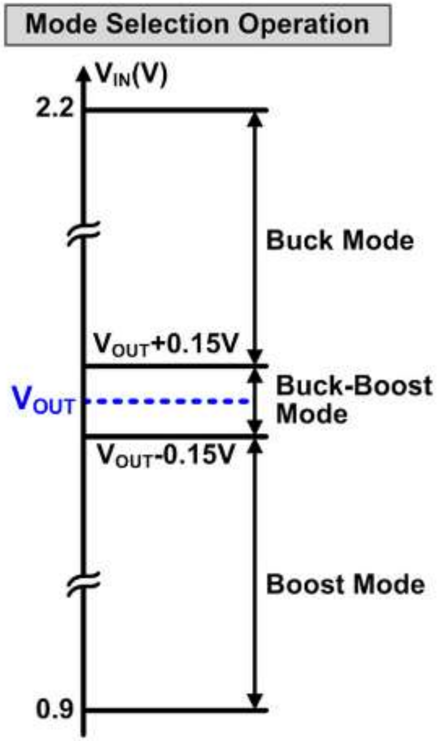




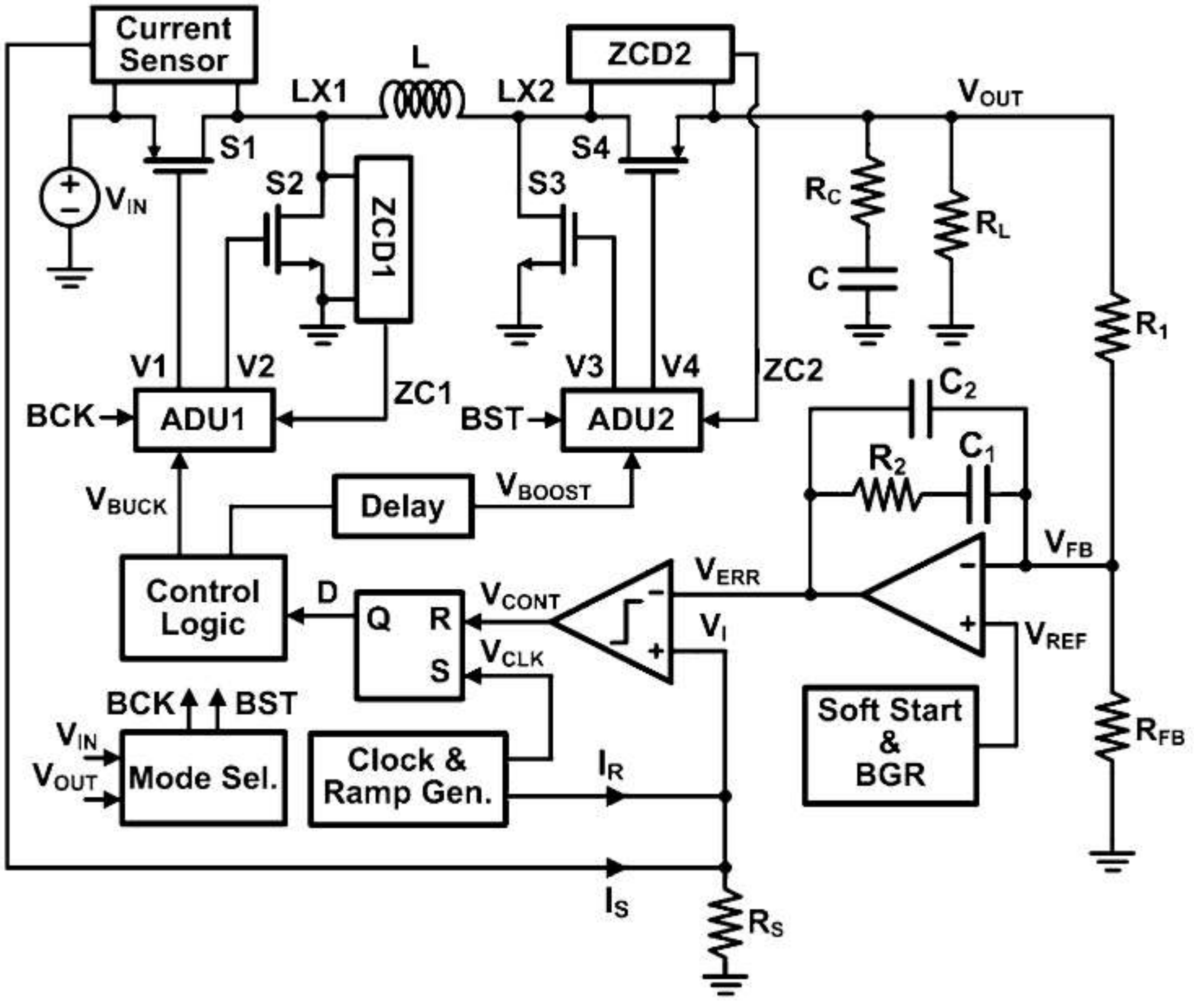
3. Mobile용 고효율 buck-boost converter



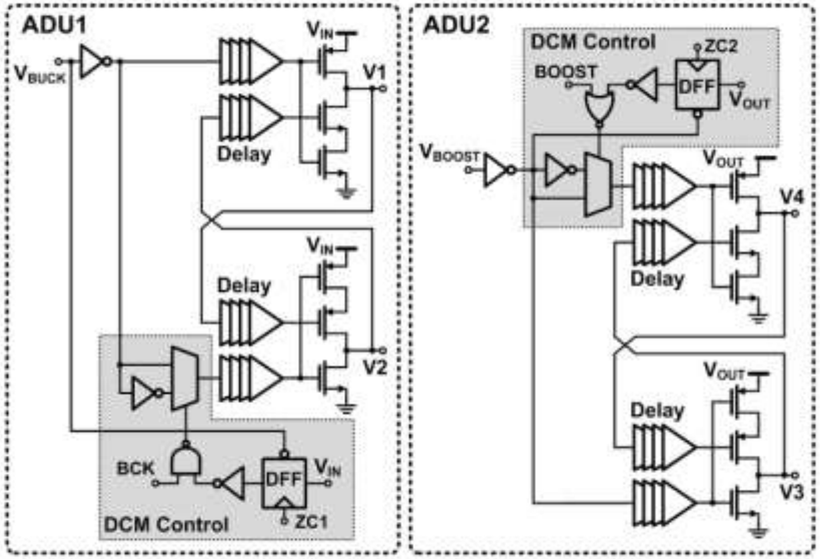


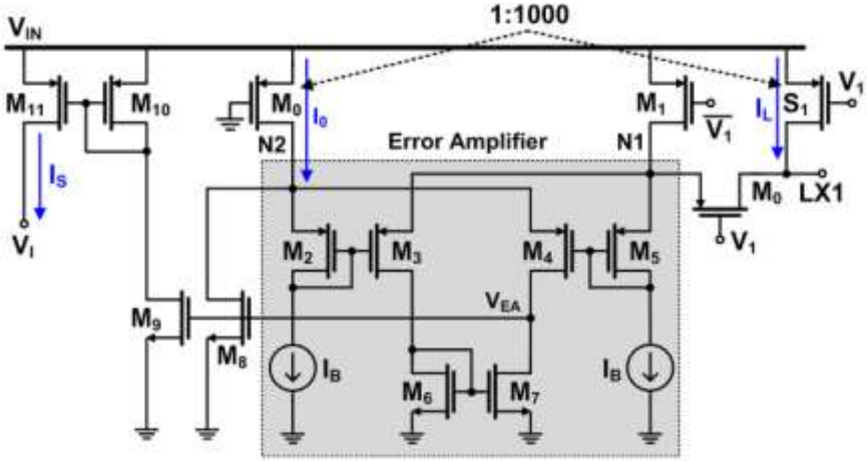


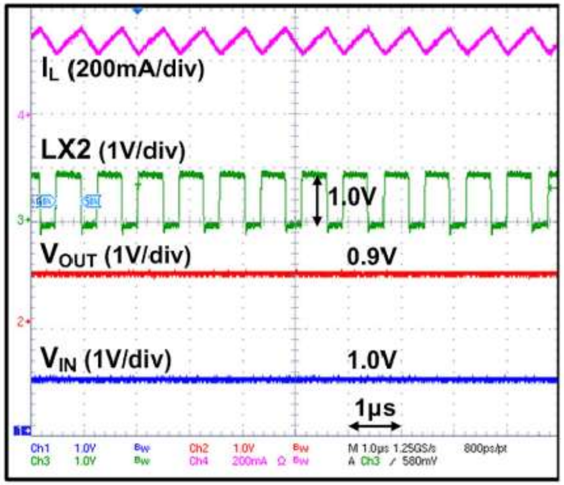
3. Mobile용 고효율 buck-boost converter

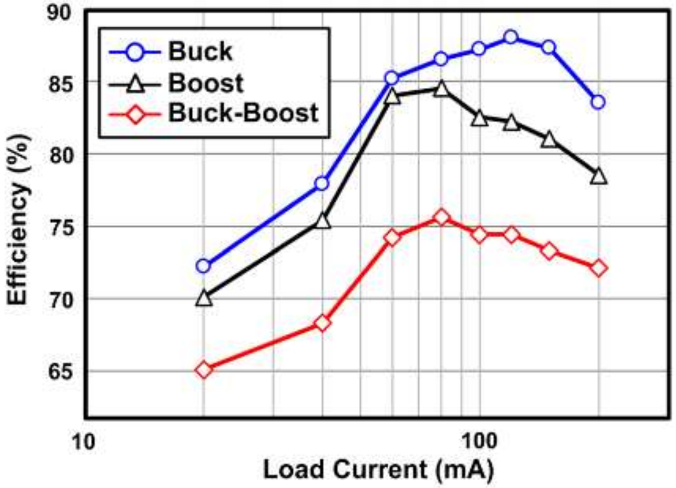


3. Mobile용 고효율 buck-boost converter

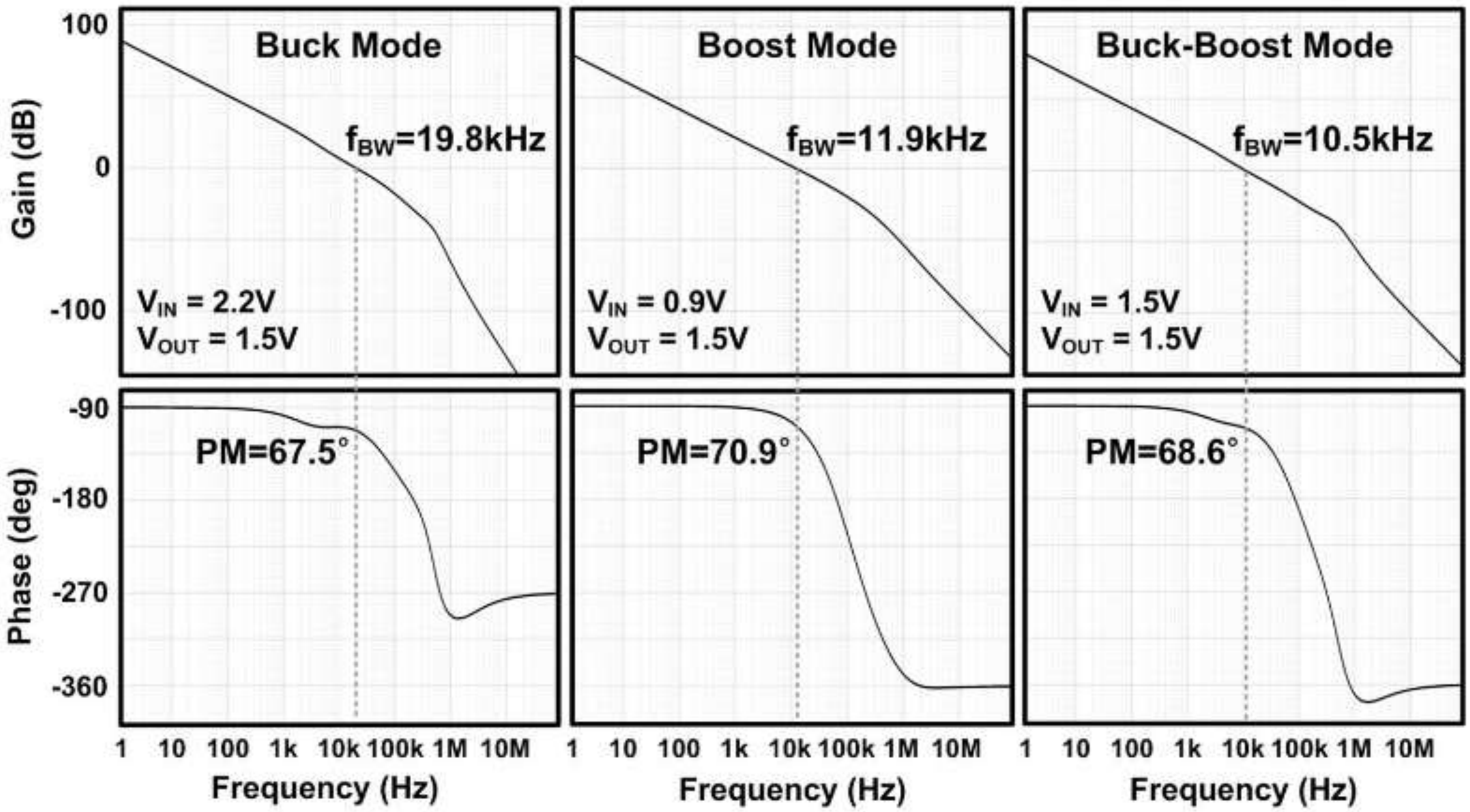




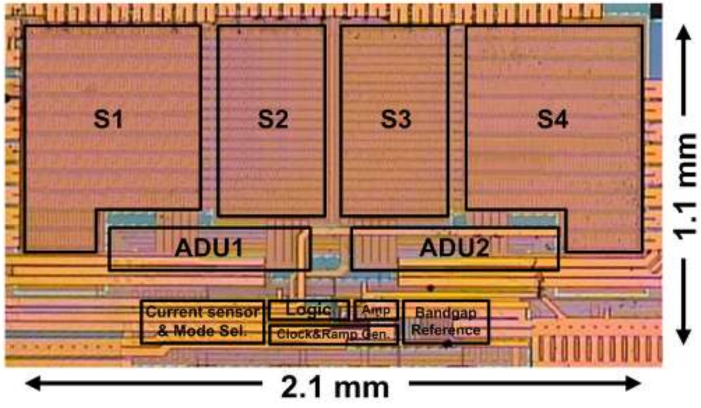




3. Mobile용 고효율 buck-boost converter

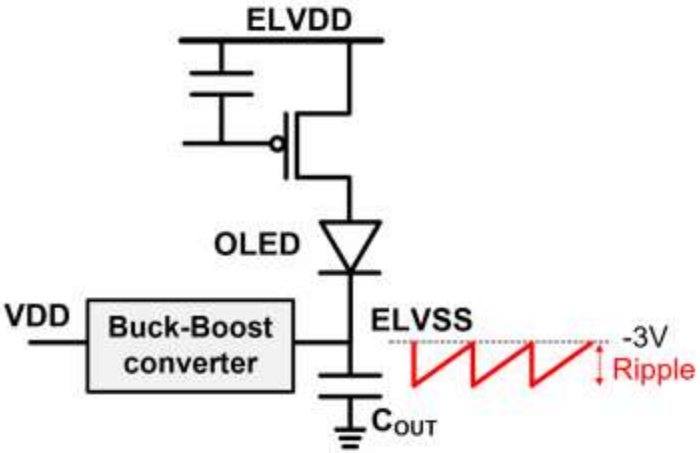


3. Mobile용 고효율 buck-boost converter



	[2]	[18]	This work
Process	0.35 μm	0.35 μm	0.18 μm
Supply voltage	2.5–5.0 V	2.3–5.0 V	0.9–2.2 V
Inductor	18 μH	4.7 μH	4.7 μH
Capacitor	47 μF	22 μF	10 μF
Switching frequency	0.5 MHz	0.5 MHz	1 MHz
I_{OUT} (Max)	330 mA	200 mA	200 mA
Output voltage	3.3 V (fixed)	3.3 V (fixed)	0.9–2.2 V (variable)
Max. efficiency (buck mode)	91.6 %	92.0 %	88.0 %
Max. efficiency (boost mode)	<80 %	N/A	84.5 %
Max. efficiency (buck–boost mode)	<65 %	N/A	75.6 %
Line regulation	N/A	0.05 V/V	0.05 V/V

4. Buck-Boost Converter for ELVSS

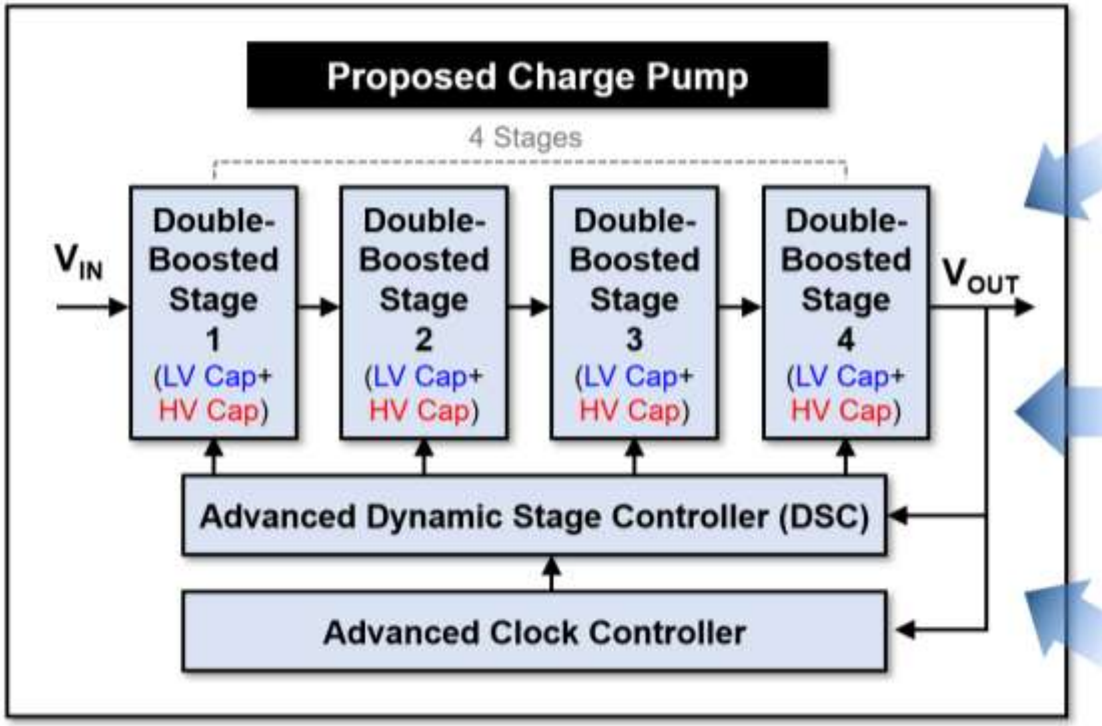


*연구 진행 중

	Conventional	Typical PFM	Proposed
Control method	PWM (FCCM)	PFM	Advanced PFM
C_{OUT}	Large	Large	Large
Ripple	Small (5 mV)	Small (5 mV)	Very small (< 2 mV)
Efficiency at light load (<10mA) *at low gray level	Very bad (reverce current)	Very bad (shoot-through current)	Good

Low ripple, high efficiency 동시 달성 → OLED 화질 향상 & Power 감소 동시 달성

5. 4D NAND Flash Memory 용 (320단) 고효율/저면적/고속 Charge Pump (@SK Hynix)



Proposed Charge Pump

4 Stages

V_{IN}

Double-Boosted Stage 1 (LV Cap+ HV Cap)

Double-Boosted Stage 2 (LV Cap+ HV Cap)

Double-Boosted Stage 3 (LV Cap+ HV Cap)

Double-Boosted Stage 4 (LV Cap+ HV Cap)

V_{OUT}

Advanced Dynamic Stage Controller (DSC)

Advanced Clock Controller

① LV-HV Hybrid Double-Boosted Stage (DBS)

- 모든 stage에 LV Cap + HV cap 적용
  → unit stage 면적 감소
- 각 stage에서 두 번 voltage boosting
  → stage 개수 절반으로 감소

② Advanced Dynamic Stage Controller (ADSC)

- V_{OUT} 감소시 (@WL rising), stage 개수 조절 개선
  → 효율 증가 & 구동력 증가

③ Advanced Clock Controller

- 4-Phase clock control
  → Non-overlap time 제거 가능
  → Max. frequency 증가 → 면적 감소

Advantages

① LV-HV Hybrid Double-Boosted Stage → Stage 면적 감소 & Stage 개수 감소

② Advanced Dynamic Stage Control (ADSC) → 효율 증가 & 구동력 증가

③ Advanced Clock Control → 면적 감소 & 효율 증가

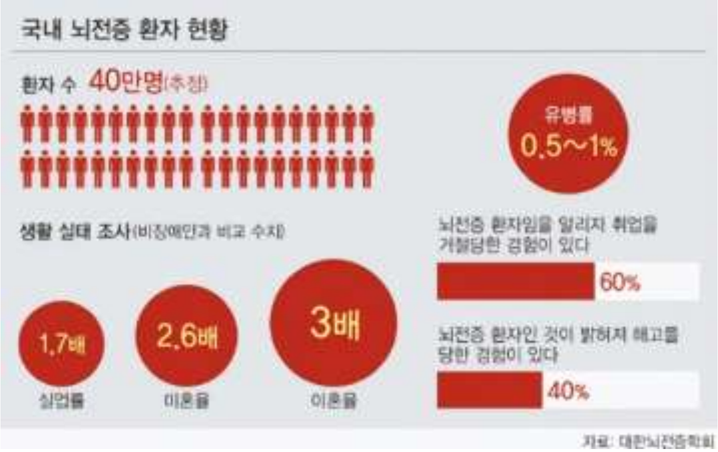
[연구분야: Biomedical Circuit]

비침습적 뇌자극 회로 및 시스템

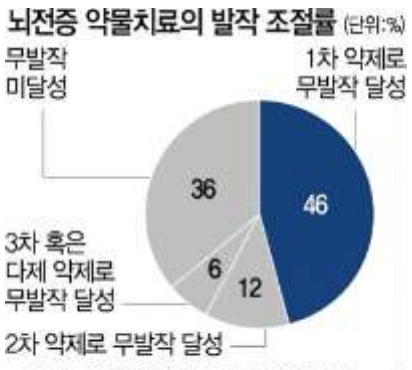
뇌전증 치료용 전자약의 필요성

- **뇌전증 현황 및 사회경제적 비용**
  - 뇌전증: 신경의 과도한 흥분으로 비정상 발작이 반복적으로 발생하는 질환
  - 인구의 고령화 - 고령층에서 특히 많이 발생하는 뇌전증 케이스의 증가 (국내 뇌전증 환자 약 40만명 추정)
  - 급속도로 증가하고 있는 의료적, 복지적, 사회적 비용에 대한 해결책이 필요한 상황

- **뇌전증 환자를 위한 현재의 치료법**
  - 약물치료: 주 치료 방법. 단 약 30%는 약물에 의한 효과가 없는 난치성 뇌전증 환자로 분류
  - 수술적 치료: 병변 부위를 대상으로 한 절제 수술. 수술로 인한 뇌기능의 손상 우려



자료: 대한뇌전증학회



자료 : 미국의학회지(JAMA) 신경학회저널(Neurol.)

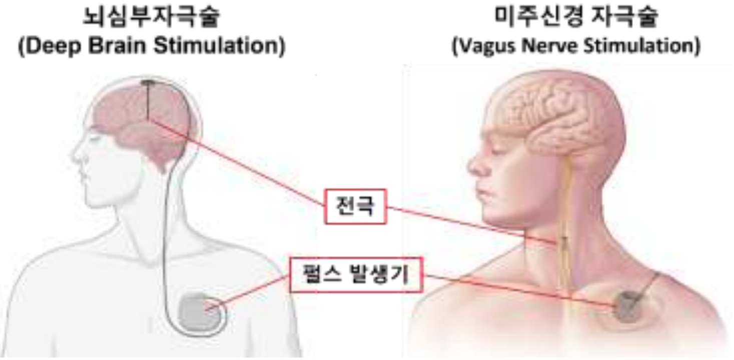
병변 부위 대상 절제술

기존 전자약 기술의 한계

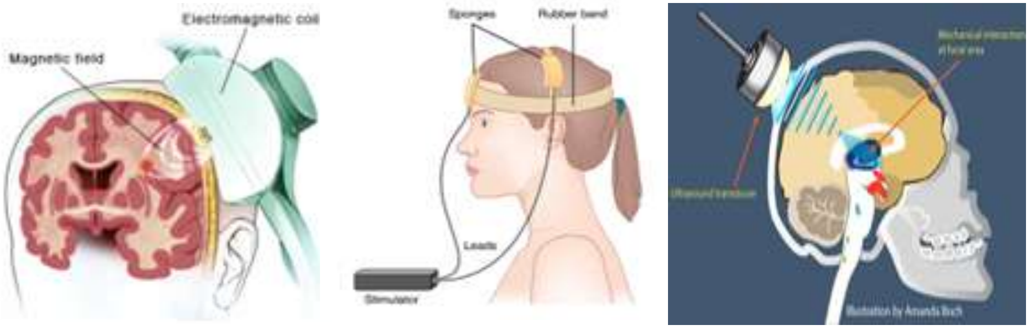
- **기존 침습적 전자약 기술의 한계**
  - **뇌심부자극술(DBS)**: 뇌에 직접 전극을 임플란트 하여 자극
  - **미주신경자극술(VNS)**: 유연한 형태의 전극을 신경에 감아 자극
    - 매우 높은 난이도의 수술이 요구됨
    - 기기/조직간 물성 차이로 인한 염증 반응: 장기적 사용 제한
    - 타 장기에 의도치 않은 부작용을 초래

- **기존 비침습적 전자약 기술의 한계**
  - 경두개 직류전기자극법 (tDCS), 경두개 자기 자극법 (TMS), 초음파 신경자극법 (Ultrasonic Modulation)
  - **낮은 공간적 해상도**: 원하지 않는 부위 자극에 의한 부작용, 깊은 곳에 위치한 신경 자극의 어려움

기존 침습적 전자약 기술

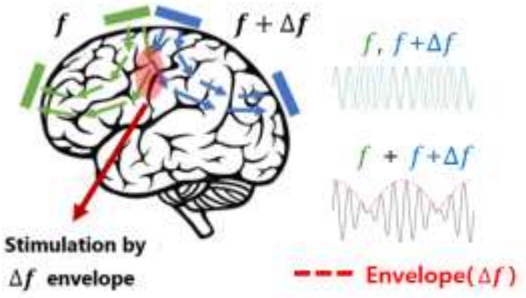


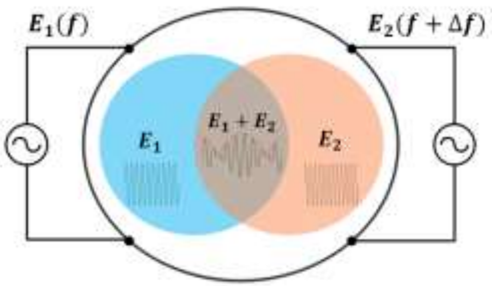
기존 비침습적 전자약 기술

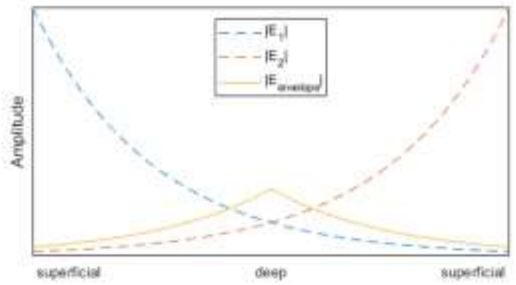


시간적 간섭 자극술 (Temporal Interference Stimulation, TIS)

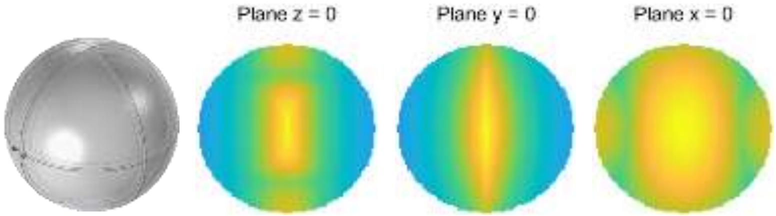
- **TIS 원리**
  - 전기장 간의 **간섭으로 인한 맥놀이 현상**을 이용하여 신경을 자극하는 기술
  - 신경세포가 고주파에서는 반응하지 않고, 저주파에서는 반응한다는 점을 이용
  - 두 고주파 전기장 간섭이 발생한 부분에서만 저주파의 포락선이 형성되어 자극이 이루어짐
  - 비침습적 방법임에도 불구하고 **뇌심부를 선택적으로 자극할 수 있다는 장점**



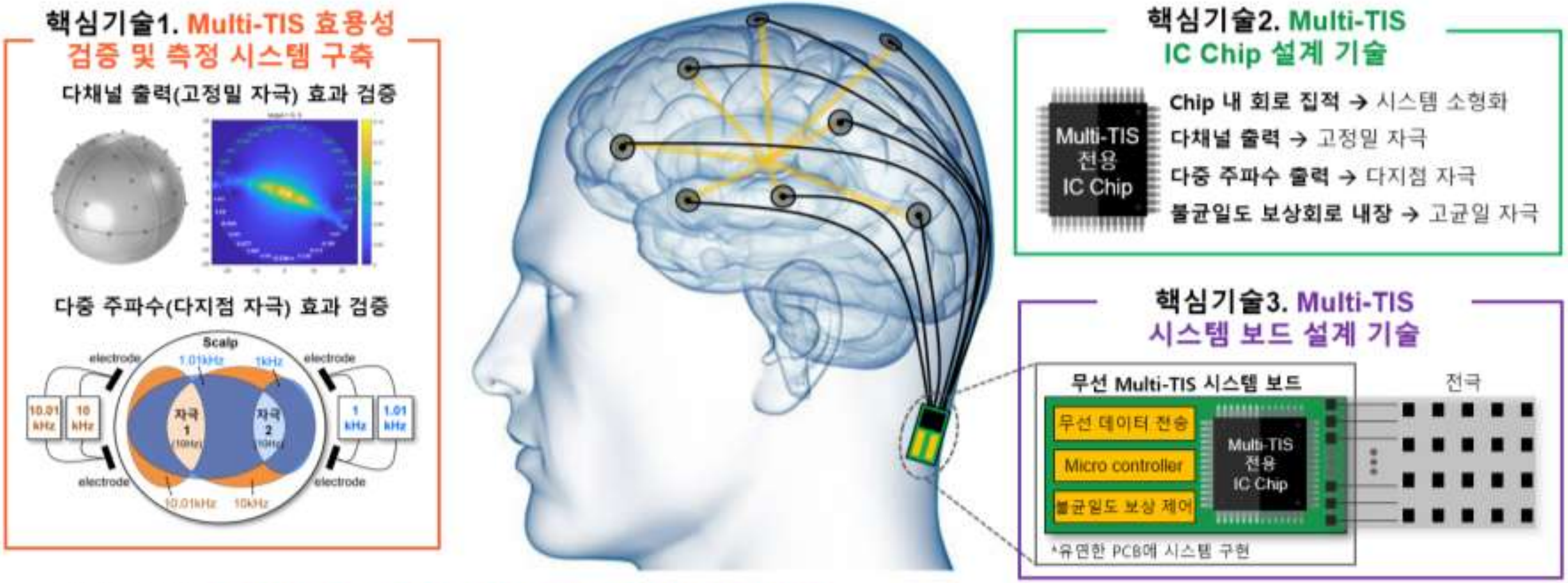




- **TIS 기술의 현재 한계점**
  - 침습적 방법에 비해서는 여전히 공간적 해상도 부족
  - 목표영역 자극을 위한 전극위치 및 자극강도 선택의 어려움
  - 동시에 다지점 자극 불가



Multi-TIS 회로 및 시스템 개발



핵심기술1. Multi-TIS 효용성 검증 및 측정 시스템 구축

다채널 출력(고정밀 자극) 효과 검증

다중 주파수(다지점 자극) 효과 검증

핵심기술2. Multi-TIS IC Chip 설계 기술

Chip 내 회로 집적 → 시스템 소형화
다채널 출력 → 고정밀 자극
다중 주파수 출력 → 다지점 자극
불균일도 보상회로 내장 → 고균일 자극

핵심기술3. Multi-TIS 시스템 보드 설계 기술

*유연한 PCB에 시스템 구현

핵심기술1. Multi-TIS 효용성 검증 및 측정 시스템 구축

다채널 출력 (고정밀 자극), 다중 주파수 (다지점 자극) 효과 검증 및 측정 시스템 구축

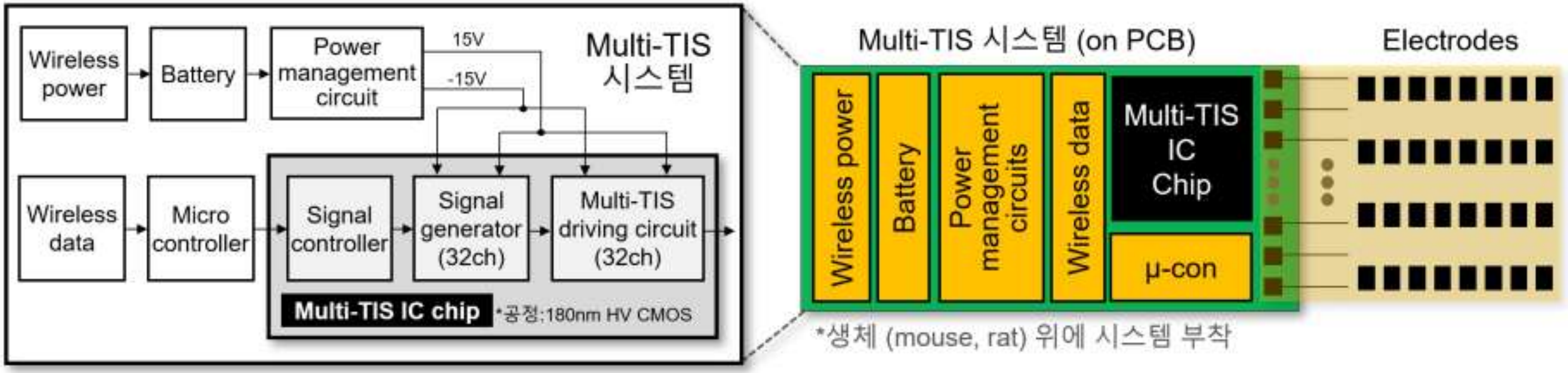
핵심기술2. Multi-TIS IC Chip 설계 기술

다채널 (고정밀), 다중 주파수 (다지점), 불균일도 보상 (고균일) 기능을 갖는 회로를 전용 IC chip으로 구현

핵심기술3. Multi-TIS 시스템 보드 설계 기술

무선 데이터 전송 및 채널 불균일도 보상 제어 가능한 시스템 보드 개발

Multi-TIS 회로 및 시스템 개발

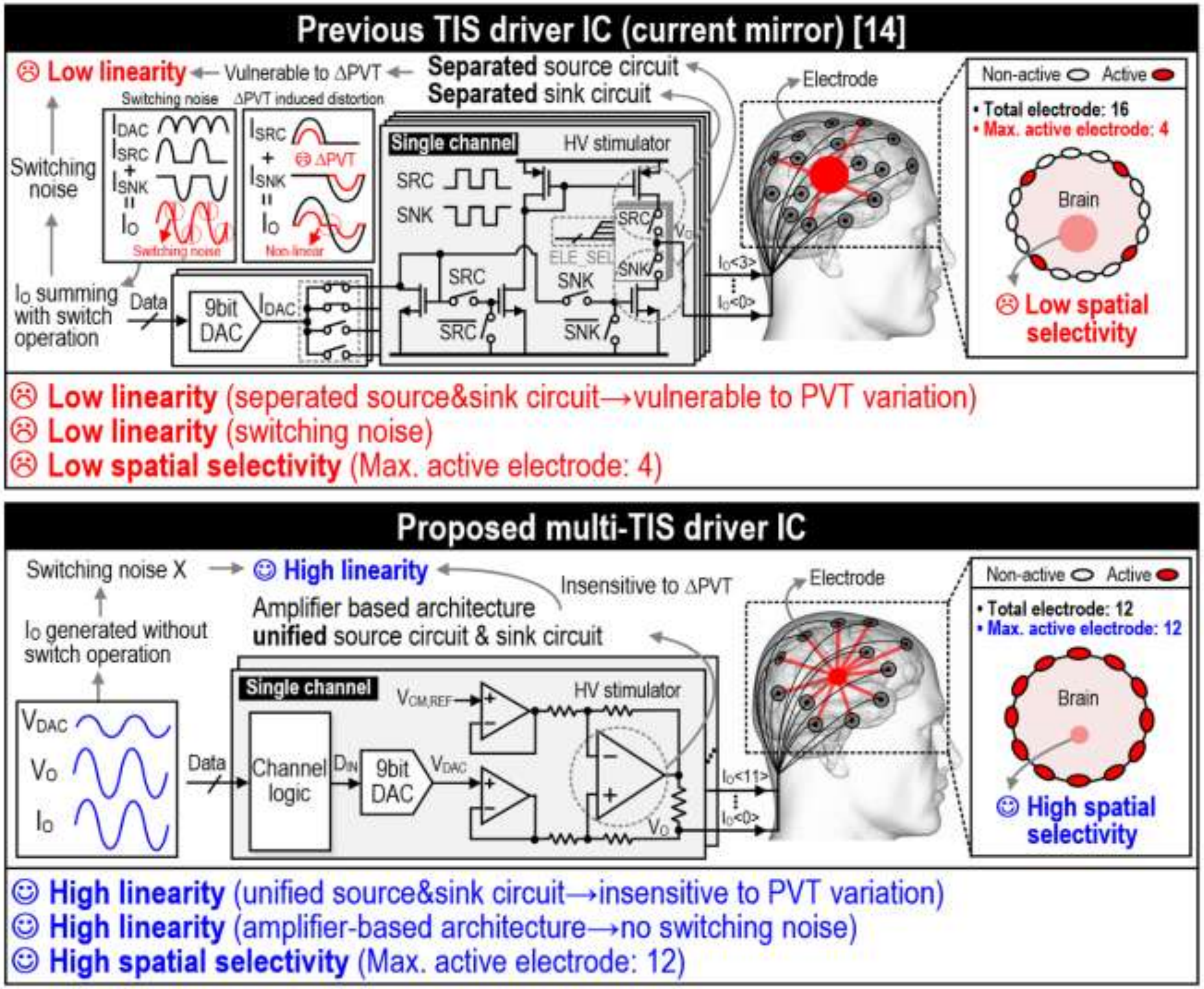


*생체 (mouse, rat) 위에 시스템 부착

핵심 개발 기술
- 고정밀 주파수 생성 회로 (0.1% 단위 주파수 조절 가능)
- 고전압 (±15V) 고균일 (mismatch < 0.1%) 구동회로
- 다채널 IC chip (최대 32 ch)
- 무선 데이터 / 전력 전송 회로

연구 진행 상황 및 계획
- 2023: 전용 IC chip 구성회로 설계 완료
- 2023: 1차 시제품 (IC chip) 제작 중: TSMC 180nm BCD 공정
- 2024: 2차 시제품 (IC chip) 제작
- 2025: 2차 시제품 (IC chip) 이용한 시스템 구성 및 생체 (rat, mouse) 대상 실험

TIS IC Chip 개발 내용



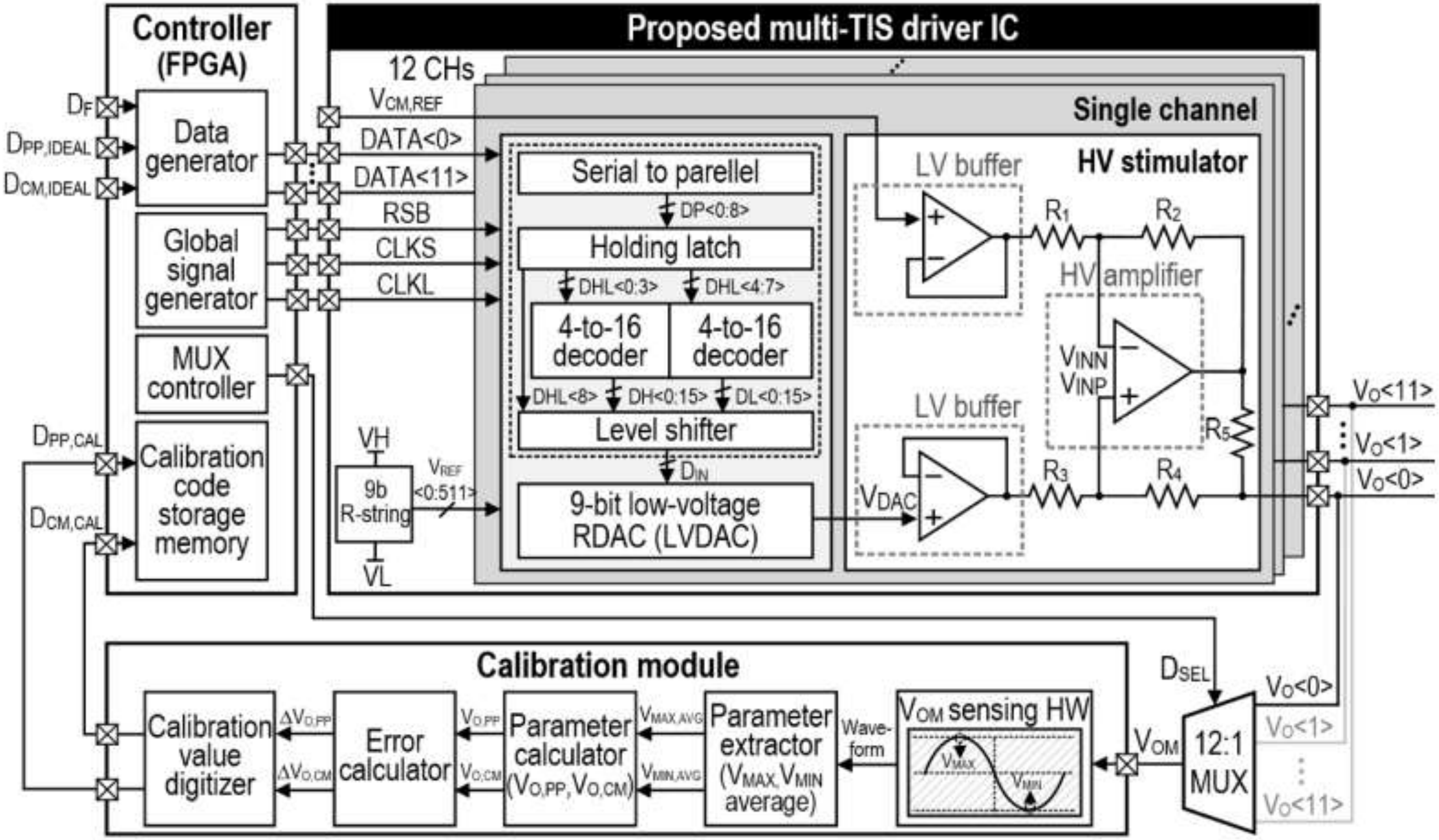
Previous TIS driver IC (current mirror) [14]

☹ **Low linearity** (seperated source&sink circuit→vulnerable to PVT variation)
☹ **Low linearity** (switching noise)
☹ **Low spatial selectivity** (Max. active electrode: 4)

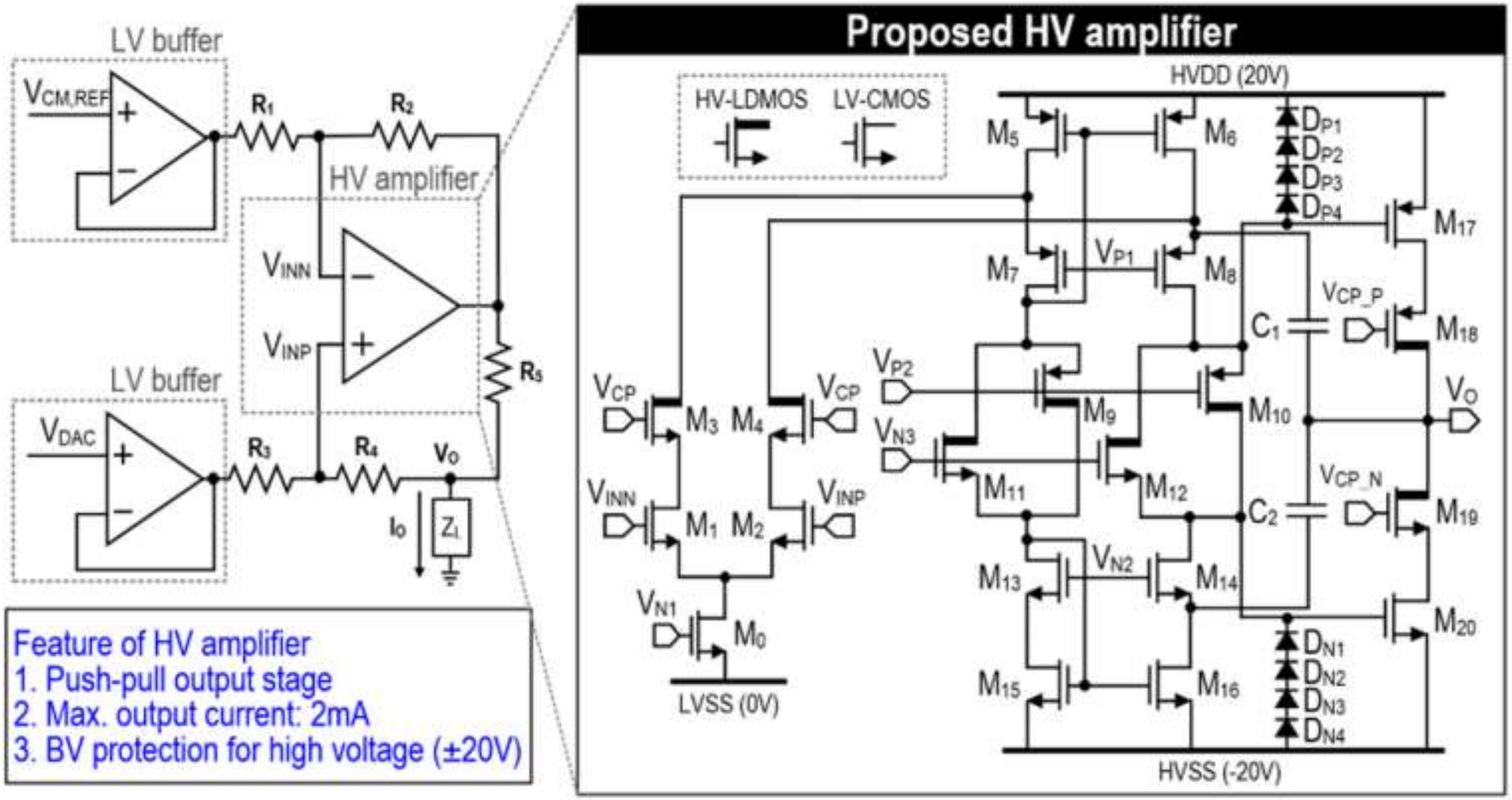
Proposed multi-TIS driver IC

☺ **High linearity** (unified source&sink circuit→insensitive to PVT variation)
☺ **High linearity** (amplifier-based architecture→no switching noise)
☺ **High spatial selectivity** (Max. active electrode: 12)

TIS IC Chip 개발 내용



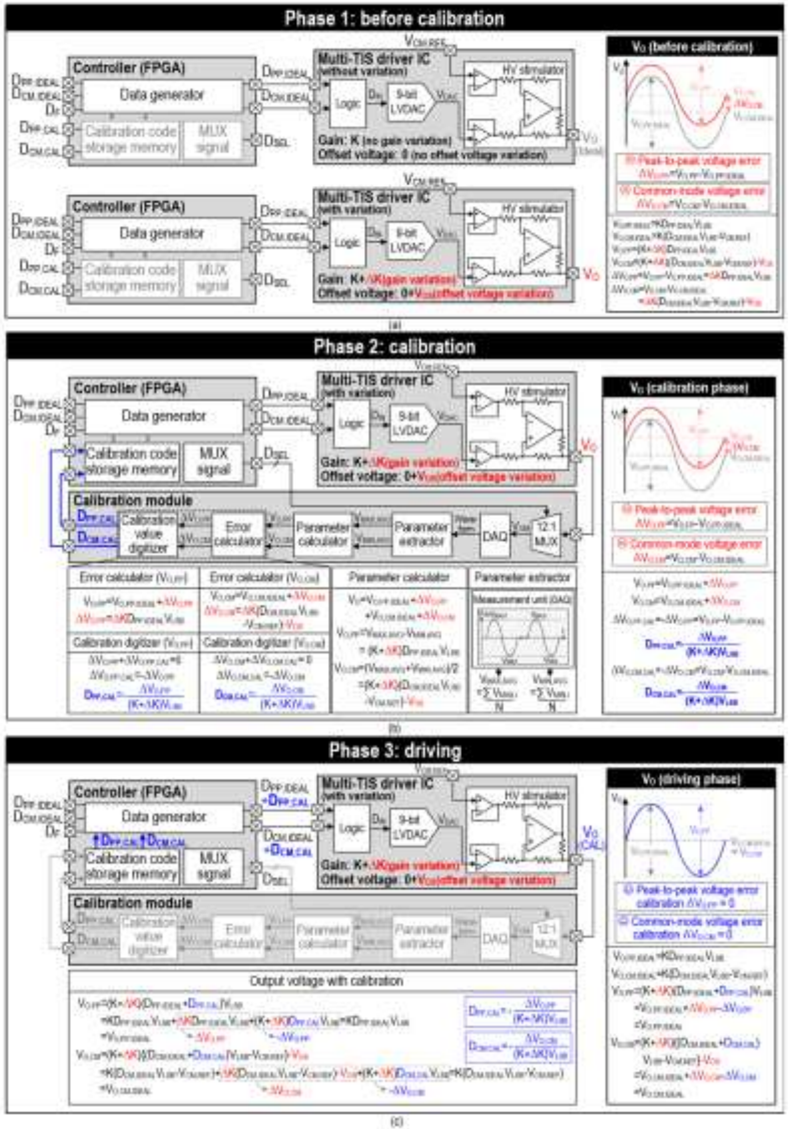
TIS IC Chip 개발 내용



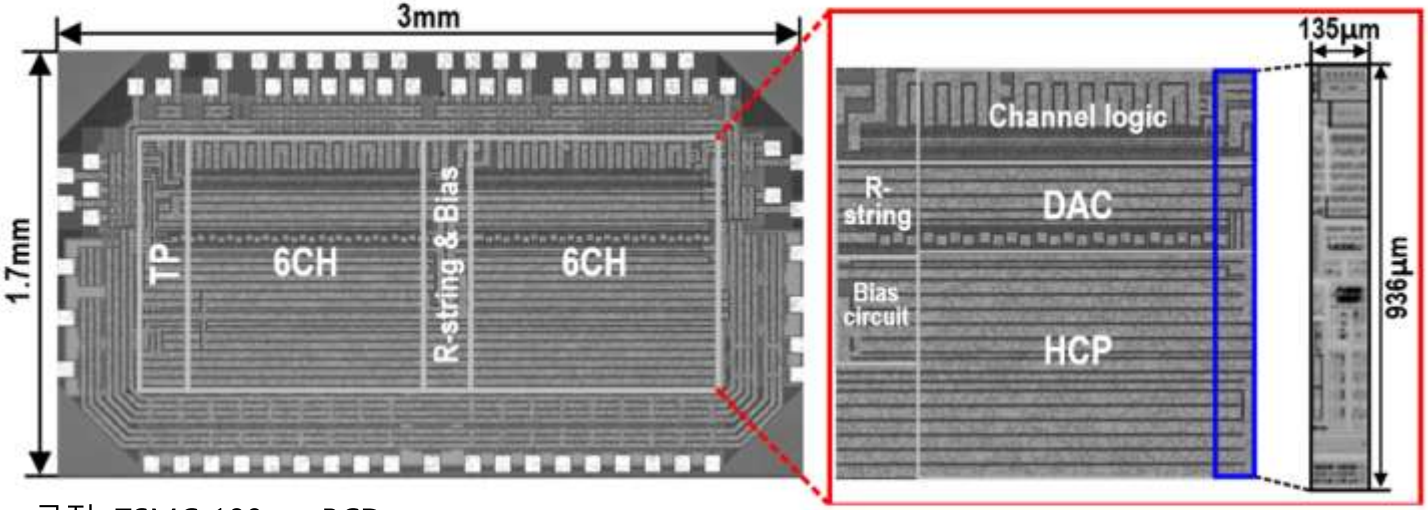
Feature of HV amplifier

1. Push-pull output stage
2. Max. output current: 2mA
3. BV protection for high voltage (±20V)

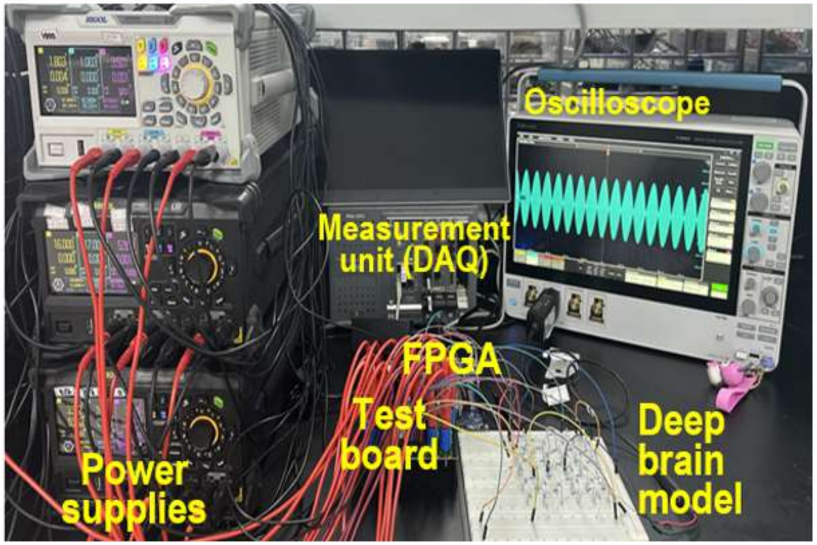
TIS IC Chip 개발 내용



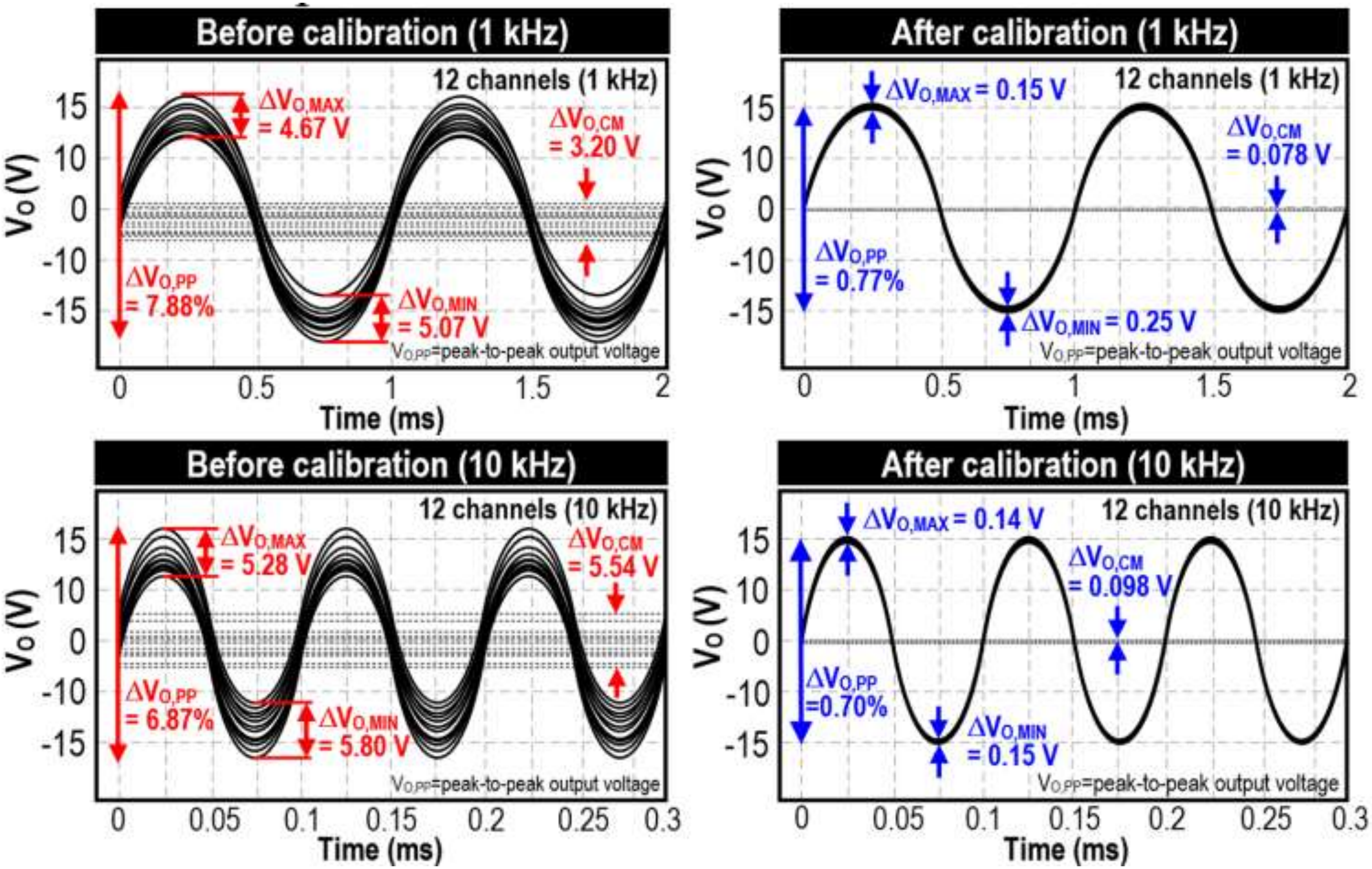
TIS IC Chip 개발 내용



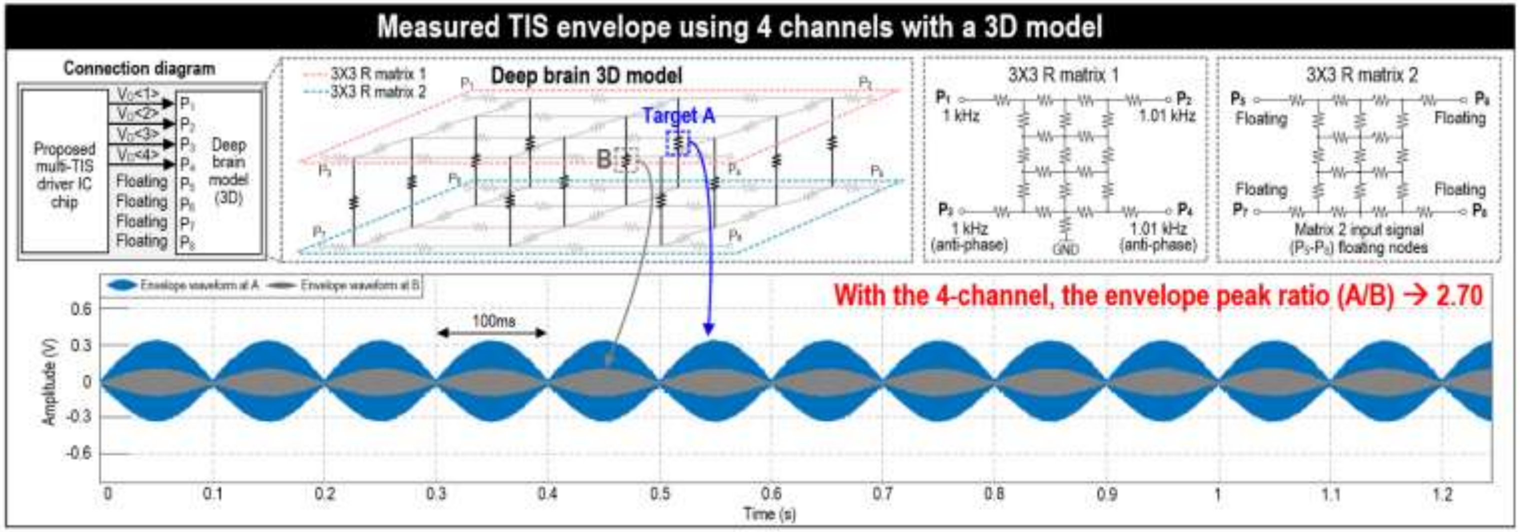
공정: TSMC 180nm BCD



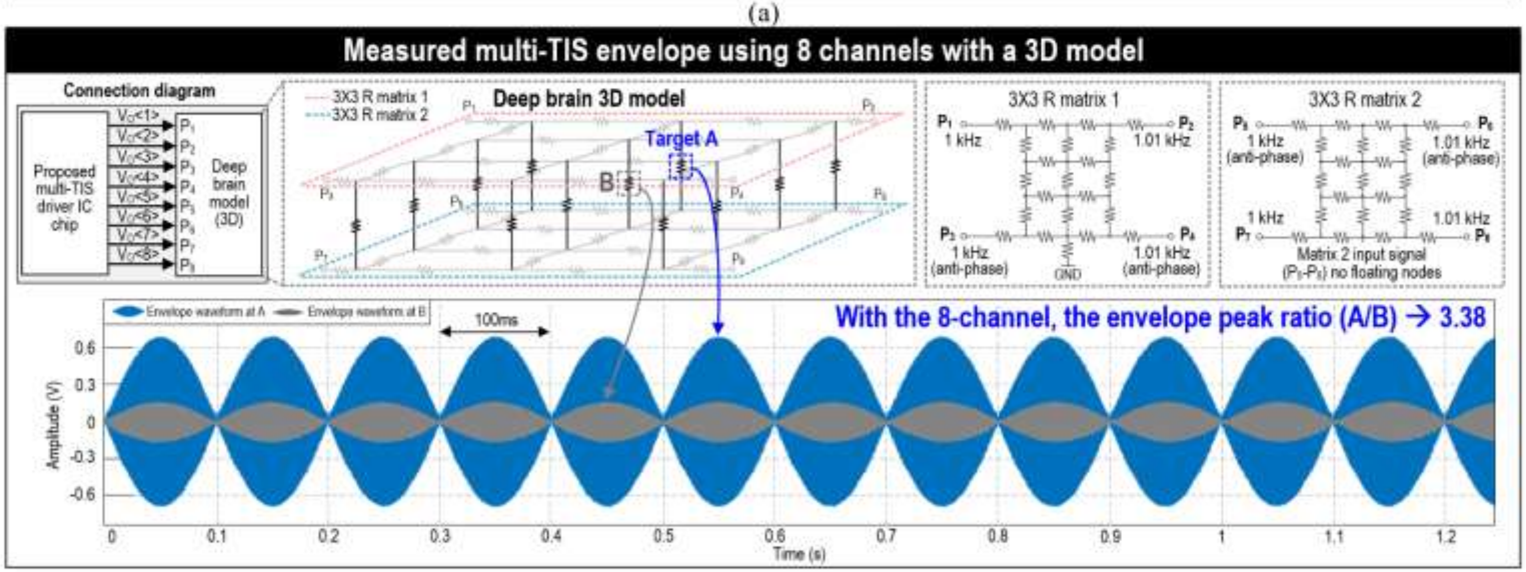
TIS IC Chip 개발 내용



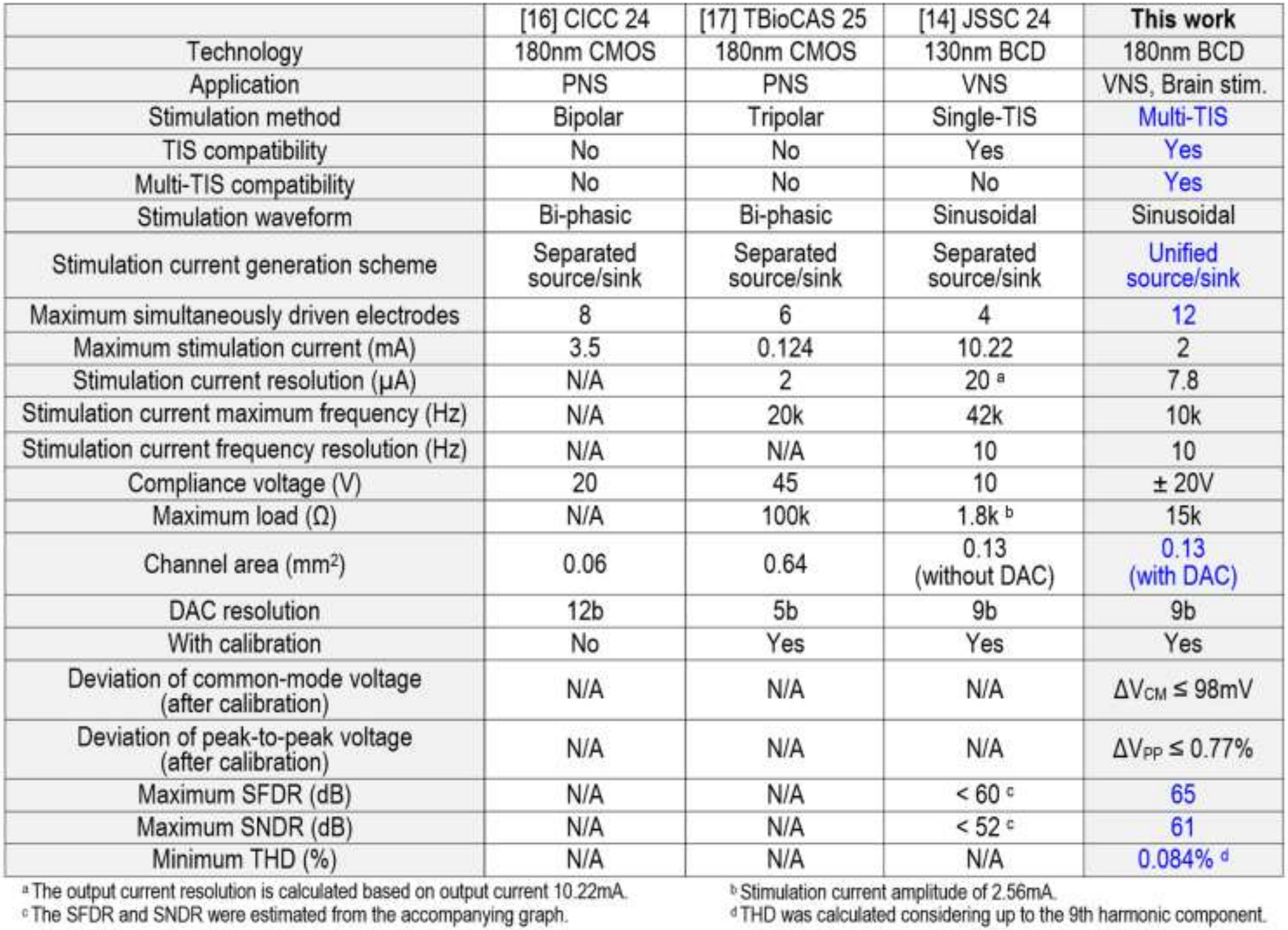
TIS IC Chip 개발 내용



(a)



TIS IC Chip 개발 내용



	[16] CICC 24	[17] TBioCAS 25	[14] JSSC 24	**This work**
Technology	180nm CMOS	180nm CMOS	130nm BCD	180nm BCD
Application	PNS	PNS	VNS	VNS, Brain stim.
Stimulation method	Bipolar	Tripolar	Single-TIS	Multi-TIS
TIS compatibility	No	No	Yes	Yes
Multi-TIS compatibility	No	No	No	Yes
Stimulation waveform	Bi-phasic	Bi-phasic	Sinusoidal	Sinusoidal
Stimulation current generation scheme	Separated source/sink	Separated source/sink	Separated source/sink	Unified source/sink
Maximum simultaneously driven electrodes	8	6	4	12
Maximum stimulation current (mA)	3.5	0.124	10.22	2
Stimulation current resolution (μA)	N/A	2	20 [a]	7.8
Stimulation current maximum frequency (Hz)	N/A	20k	42k	10k
Stimulation current frequency resolution (Hz)	N/A	N/A	10	10
Compliance voltage (V)	20	45	10	± 20V
Maximum load (Ω)	N/A	100k	1.8k [b]	15k
Channel area (mm^2)	0.06	0.64	0.13 (without DAC)	0.13 (with DAC)
DAC resolution	12b	5b	9b	9b
With calibration	No	Yes	Yes	Yes
Deviation of common-mode voltage (after calibration)	N/A	N/A	N/A	$\Delta V_{CM} \leq 98$mV
Deviation of peak-to-peak voltage (after calibration)	N/A	N/A	N/A	$\Delta V_{PP} \leq 0.77\%$
Maximum SFDR (dB)	N/A	N/A	< 60 [c]	65
Maximum SNDR (dB)	N/A	N/A	< 52 [c]	61
Minimum THD (%)	N/A	N/A	N/A	0.084% [d]

[a] The output current resolution is calculated based on output current 10.22mA.

[c] The SFDR and SNDR were estimated from the accompanying graph.

[b] Stimulation current amplitude of 2.56mA.

[d] THD was calculated considering up to the 9th harmonic component.

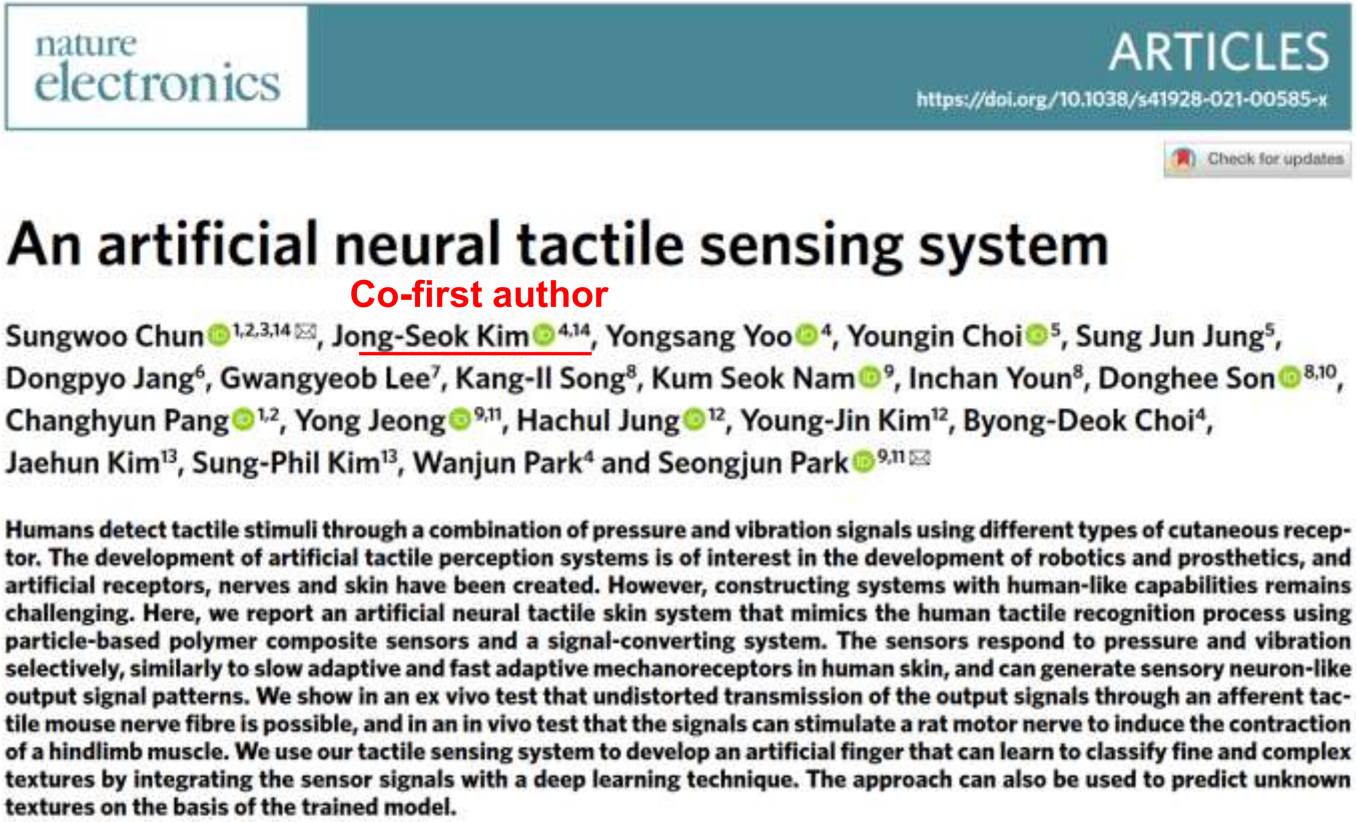
[Biomedical Circuit]

인공피부 시스템 개발

Reference

This presentation is based on the following paper.

“An artificial neural tactile sensing system,” *Nature Electronics*, Vol. 4, No.6, June, 2021



nature electronics

ARTICLES

https://doi.org/10.1038/s41928-021-00585-x

Check for updates

An artificial neural tactile sensing system

Co-first author

Sungwoo Chun[1,2,3,14] ✉, **Jong-Seok Kim**[4,14], Yongsang Yoo[4], Youngin Choi[5], Sung Jun Jung[5], Dongpyo Jang[6], Gwangyeob Lee[7], Kang-Il Song[8], Kum Seok Nam[9], Inchan Youn[8], Donghee Son[8,10], Changhyun Pang[1,2], Yong Jeong[9,11], Hachul Jung[12], Young-Jin Kim[12], Byong-Deok Choi[4], Jaehun Kim[13], Sung-Phil Kim[13], Wanjun Park[4] and Seongjun Park[9,11] ✉

Humans detect tactile stimuli through a combination of pressure and vibration signals using different types of cutaneous receptor. The development of artificial tactile perception systems is of interest in the development of robotics and prosthetics, and artificial receptors, nerves and skin have been created. However, constructing systems with human-like capabilities remains challenging. Here, we report an artificial neural tactile skin system that mimics the human tactile recognition process using particle-based polymer composite sensors and a signal-converting system. The sensors respond to pressure and vibration selectively, similarly to slow adaptive and fast adaptive mechanoreceptors in human skin, and can generate sensory neuron-like output signal patterns. We show in an ex vivo test that undistorted transmission of the output signals through an afferent tactile mouse nerve fibre is possible, and in an in vivo test that the signals can stimulate a rat motor nerve to induce the contraction of a hindlimb muscle. We use our tactile sensing system to develop an artificial finger that can learn to classify fine and complex textures by integrating the sensor signals with a deep learning technique. The approach can also be used to predict unknown textures on the basis of the trained model.

***공동연구(주저자):**
고려대 천성우 교수(sensor), 한양대 김종석 교수(circuit & system), 서울대 박성준 교수(biology)

Future Applications of Artificial Skin

Prosthetics

Remote Robot

Artificial Surgery

Entertainment

Image courtesy: KIST

Artificial Skin

Compared to other senses,
tactile requires more research and development.

Sense of Vision

Commercial Product

"Artificial Retina"

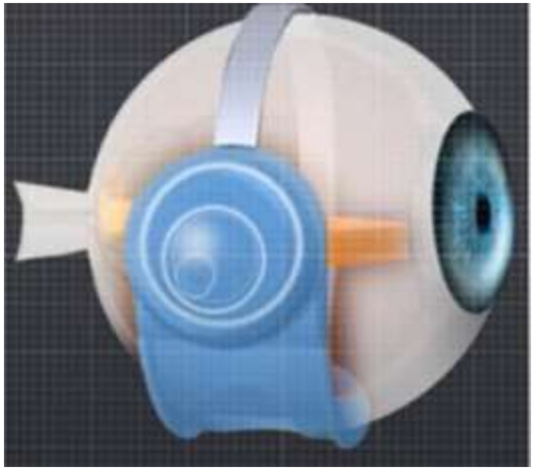


Image courtesy: Second Sight

Sense of Hearing

Commercial Product

"Artificial Cochlear"

Image courtesy: Medical Device Network

Sense of Tactile

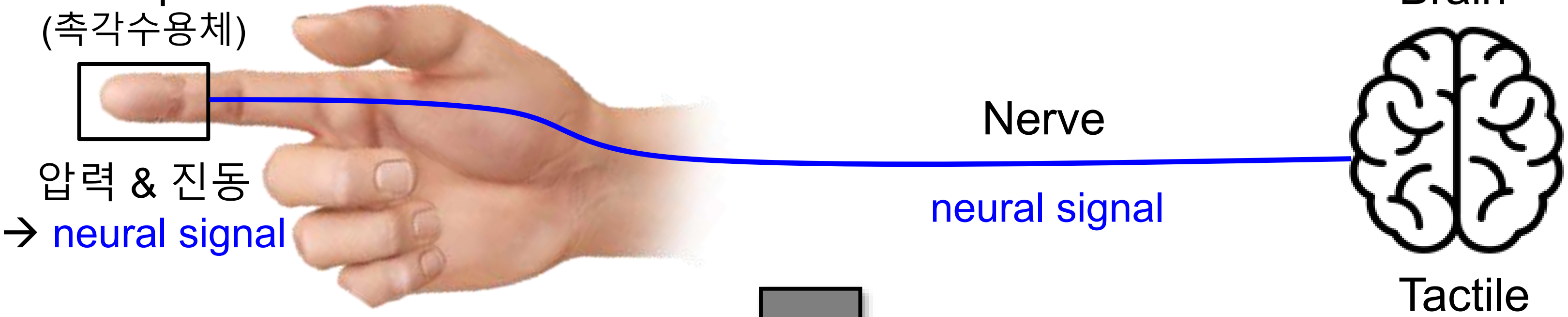
Commercial Product

"**Artificial Skin**"

No
commercial product

Human Skin VS. Artificial Skin

Human skin



Receptor
(촉각수용체)

압력 & 진동
→ neural signal

Nerve

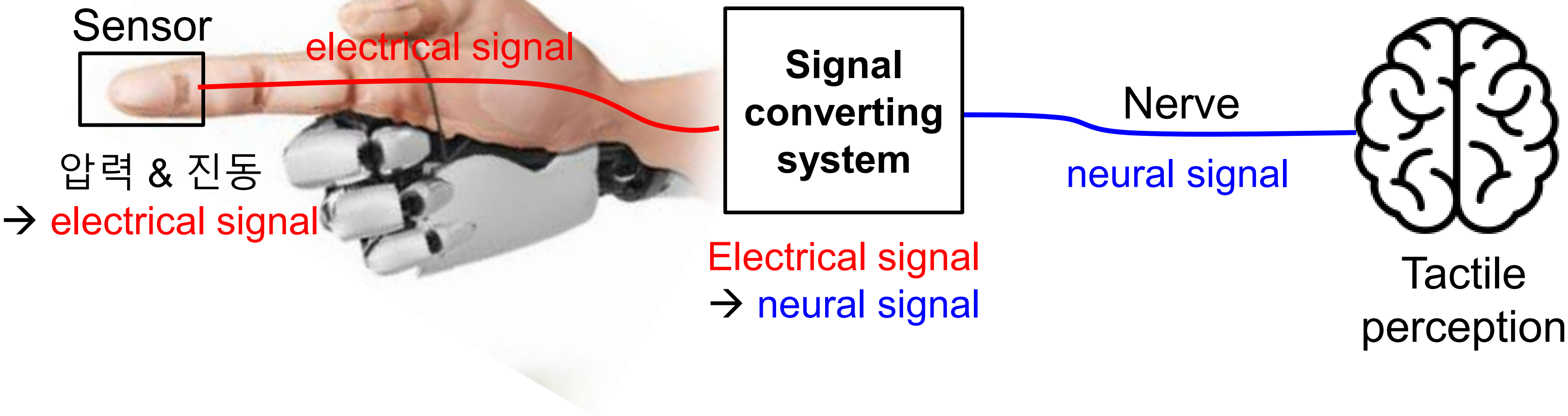
neural signal

Brain

Tactile perception

모방

Artificial skin



Sensor

electrical signal

압력 & 진동
→ electrical signal

Signal converting system

Electrical signal
→ neural signal

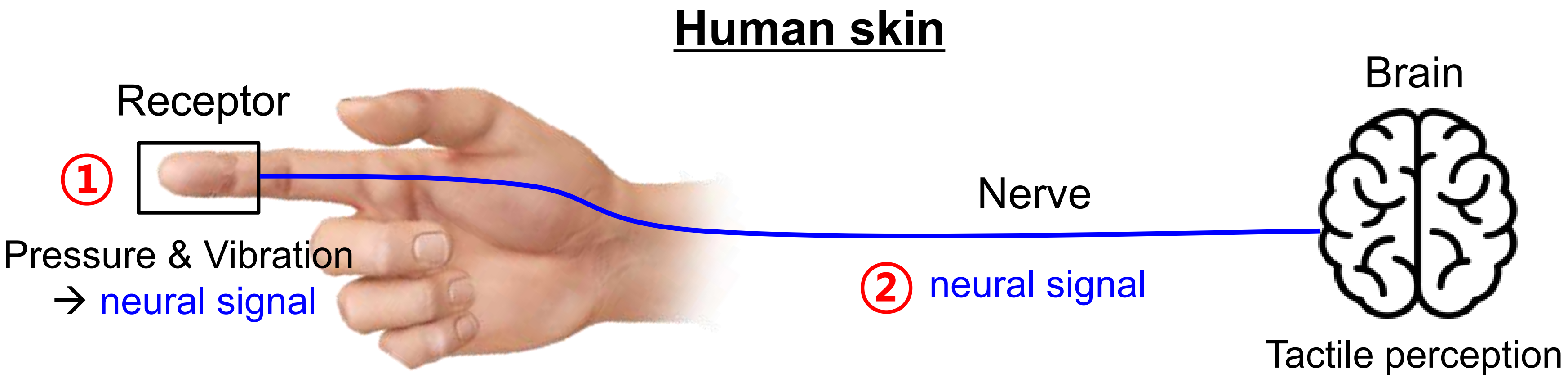
Nerve

neural signal

Brain

Tactile perception

Research Items



Human skin

Receptor

①

Pressure & Vibration
→ neural signal

Nerve

② neural signal

Brain

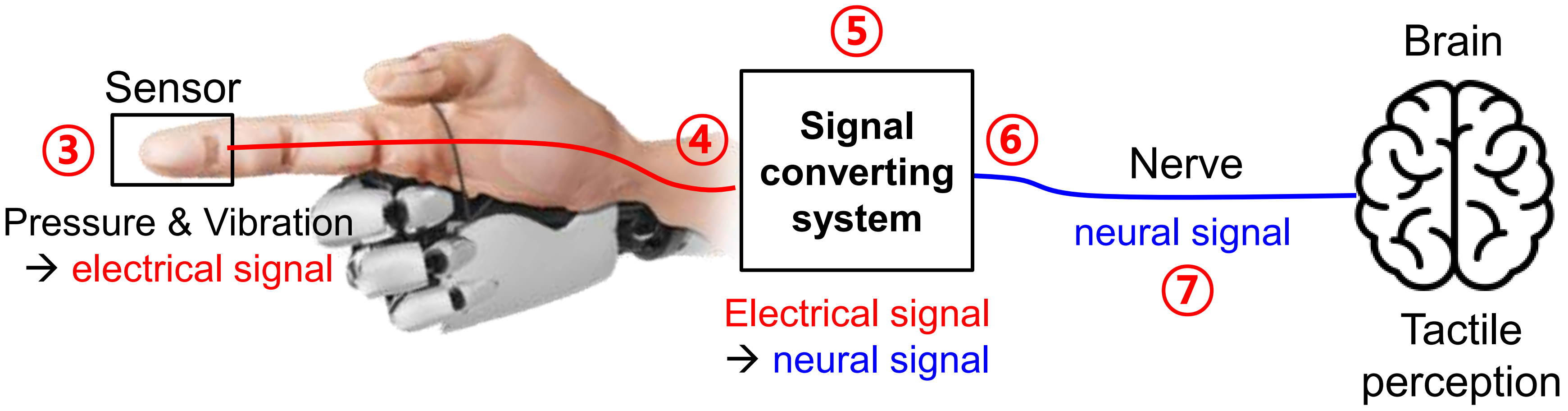
Tactile perception

① 촉각수용체(receptor)의 종류?

② 촉각수용체(receptor)에서 생성되는 neural signal 의 형태?

Research Items

Artificial skin



③ **센서**: 인간 촉각수용체(receptor) 를 어떻게 모방할 수 있나?

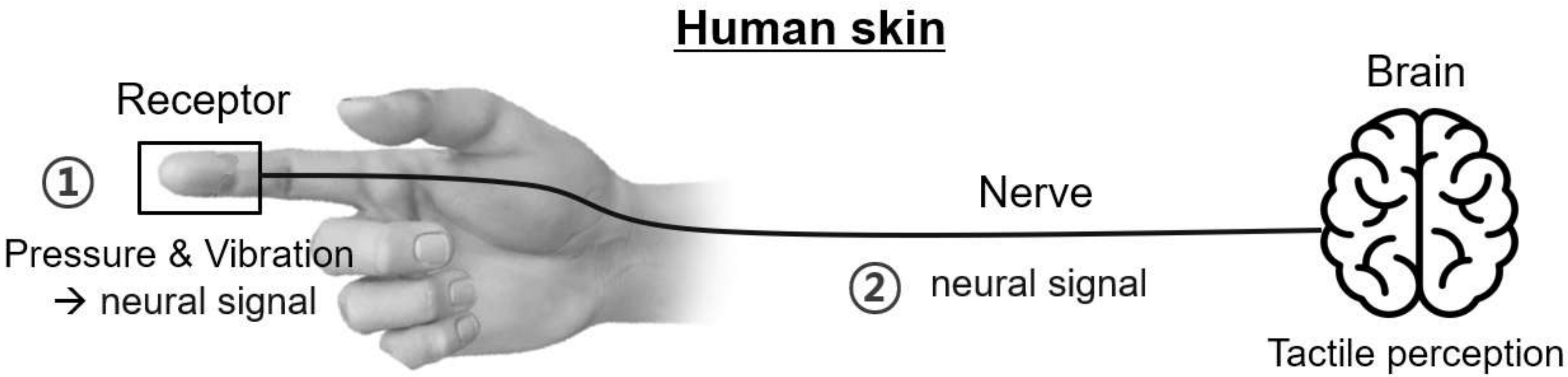
④ **센서 readout**: 센서 전기 신호를 왜곡 없이 읽는 방법?

⑤ **Signal converting**: 센서에 인가된 물리적 정보를 판단하고, neural signal을 생성

⑥ **Neural stimulator**: 신경이 인식할 수 있는 형태로 신호 변경 및 신경 구동

⑦ **생체실험**: 신경에서 신호가 잘 전달됨을 확인하는 방법?

Research Items



① 촉각수용체(receptor)의 종류?

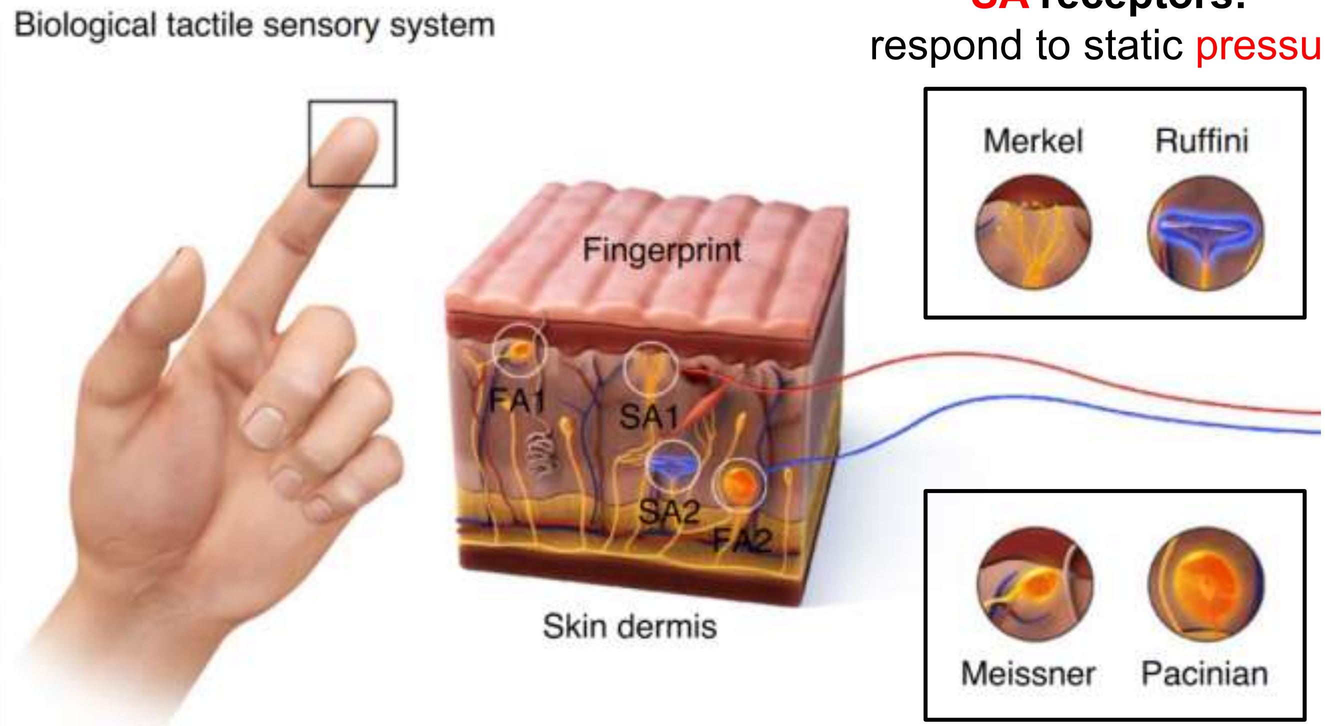
② 촉각수용체(receptor)에서 생성되는 neural signal 의 형태?

Biological Tactile Sensory System

● Human Tactile Perception

- Human perceives tactile stimuli through the mechanoreceptors.
- Slow adaptive (SA) receptors respond to the static pressure
- Fast adaptive (FA) receptors respond to the vibration (high-frequency dynamic pressure)

SA receptors:
respond to static pressure

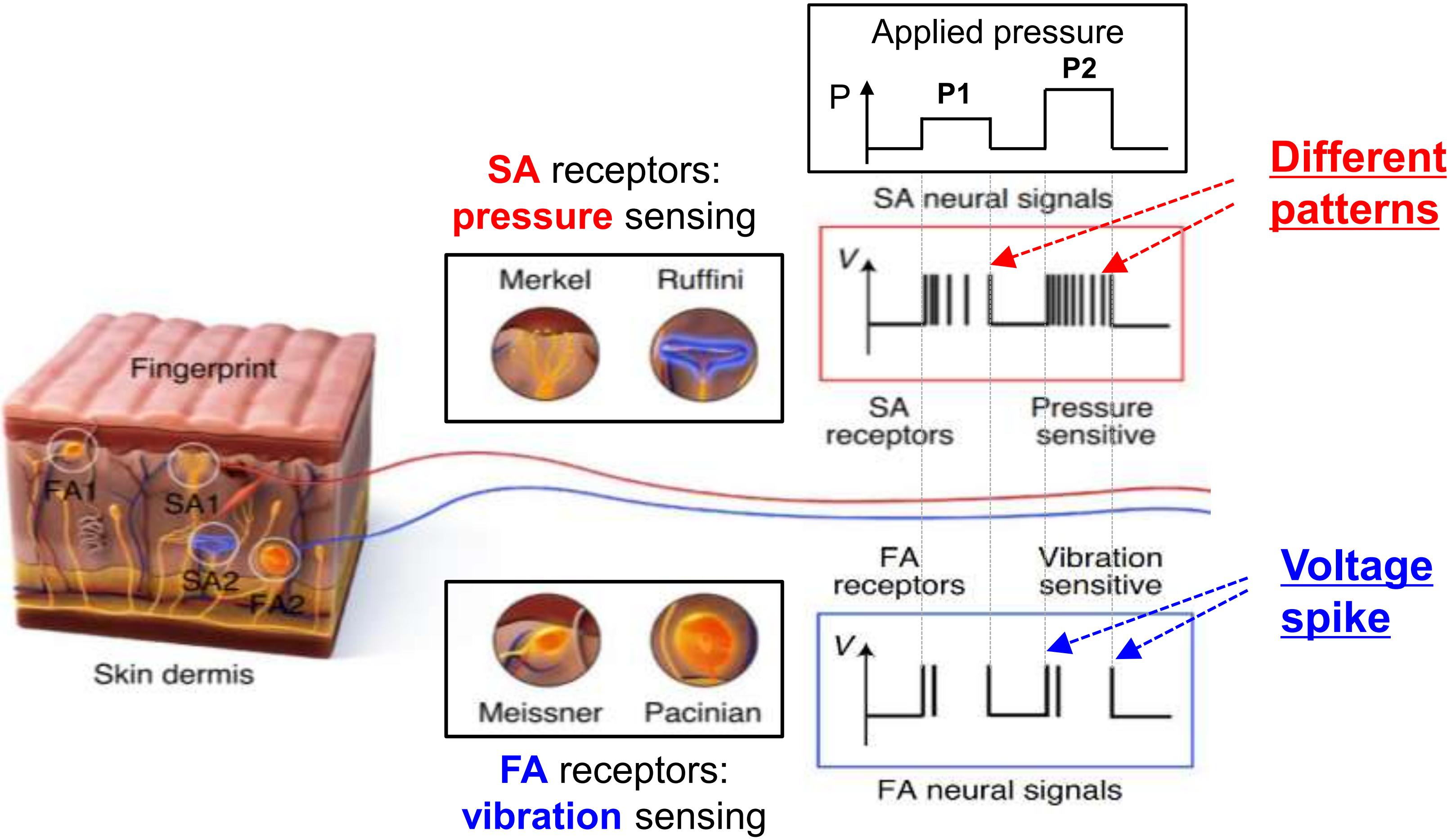


FA receptors:
respond to vibration

*vibration: high-frequency dynamic pressure

Biological Tactile Sensory System

- **Neural Signals**
  - SA receptors generate different patterns depending on the static **pressure**
  - FA receptors generate spike at initial contact and final release of the stimuli (**vibration**)



SA receptors: **pressure** sensing

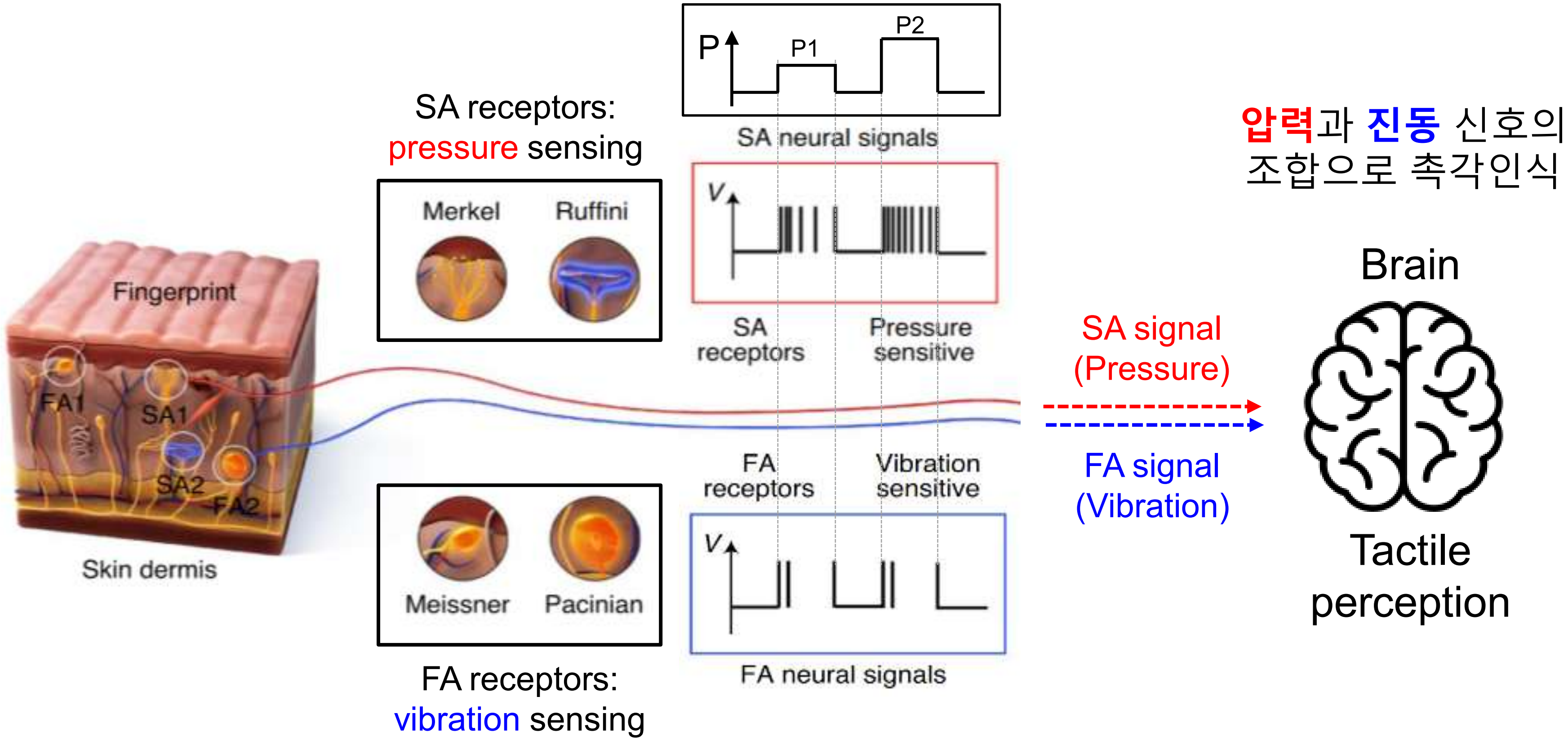
Different patterns

FA receptors: **vibration** sensing

Voltage spike

Biological Tactile Sensory System

- **Tactile Perception of Brain**
  - SA & FA signals are delivered separately, and then integrated in the human brain.
  - The brain perceived tactile with a combination of the pressure and vibration signals.



SA receptors:
pressure sensing

SA neural signals

FA neural signals

FA receptors:
vibration sensing

SA signal
(Pressure)

FA signal
(Vibration)

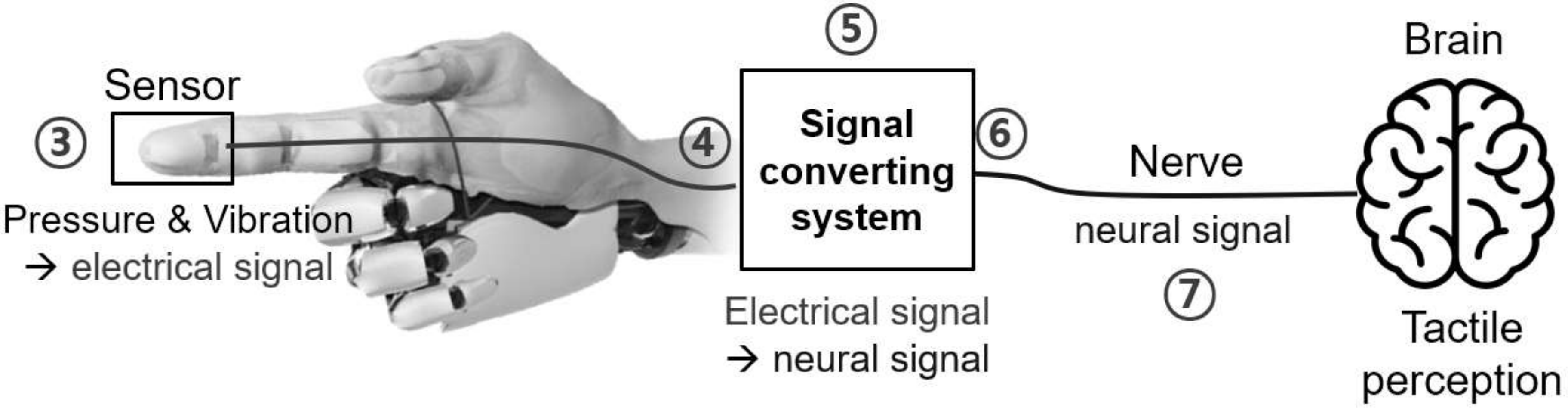
압력과 진동 신호의
조합으로 촉각인식

Brain

Tactile
perception

Research Items

Artificial skin



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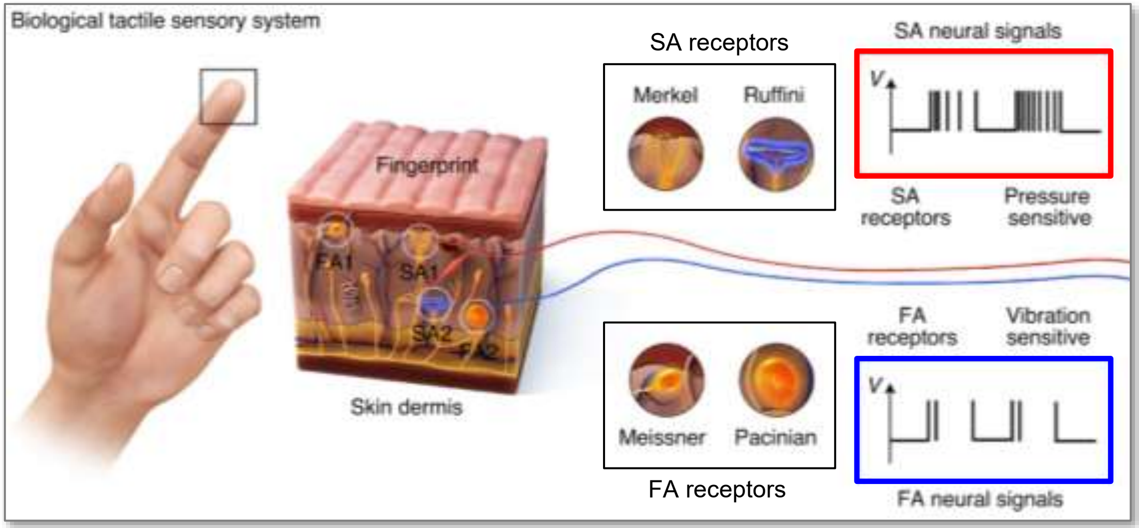
⑦ **생체실험**: 신경에서 신호가 잘 전달됨을 확인하는 방법?

Artificial Tactile Sensory System



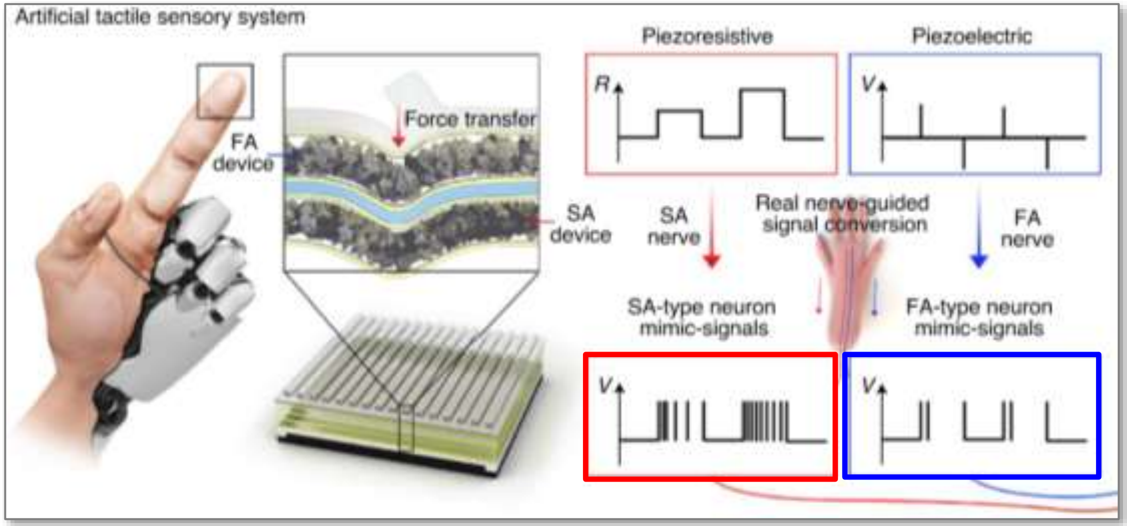
Human

SA, FA receptors

SA, FA neural signals

Mimicking

Mimicking



This work

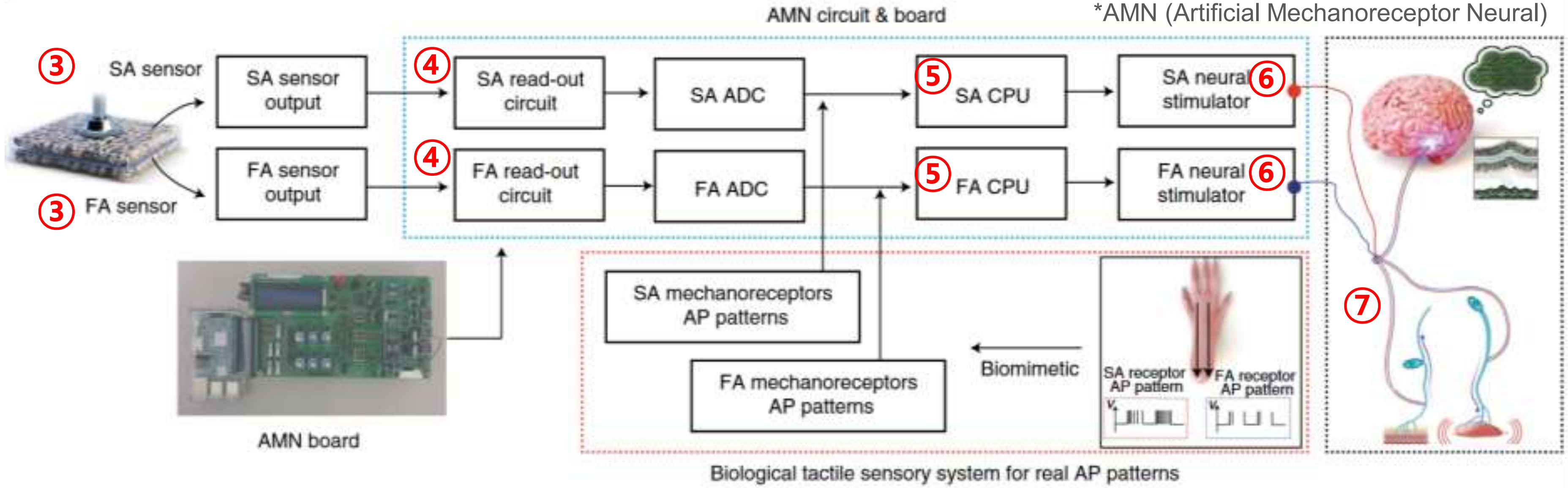
SA, FA sensors

SA, FA neuron mimic signals

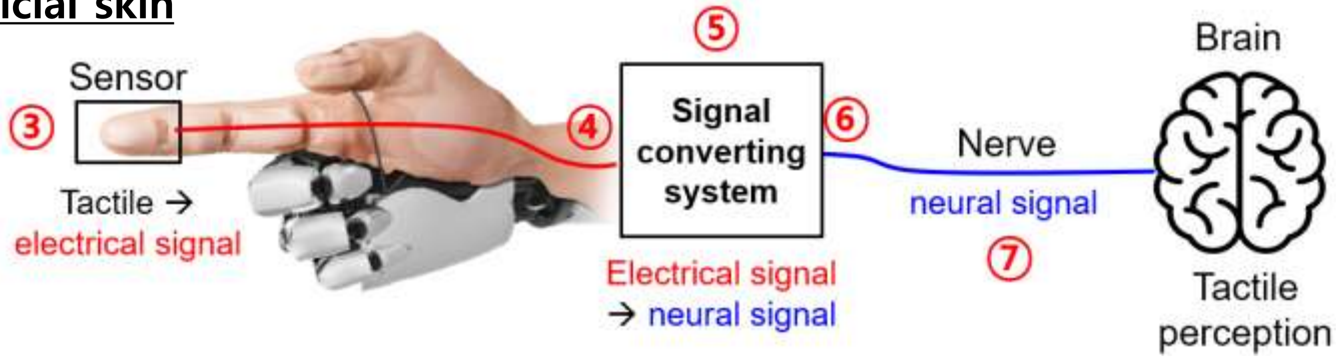
Proposed Artificial Tactile Sensory System

Block Diagram of the Proposed Tactile Sensory System

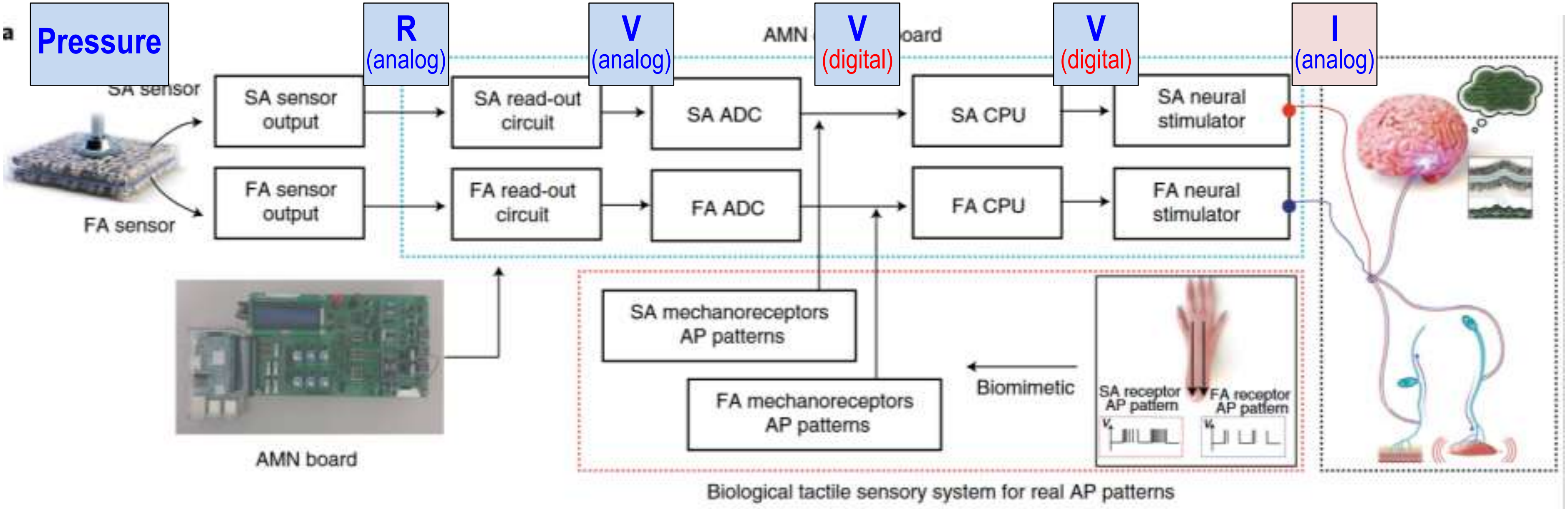
*AMN (Artificial Mechanoreceptor Neural)



Artificial skin



Proposed Artificial Tactile Sensory System



Pressure

R (analog)

V (analog)

V (digital)

V (digital)

I (analog)

Novelties of The Proposed System

① **SA & FA Sensors**
  - New tactile sensors with particle-based polymer composites

② **SA & FA Mechanoreceptor's Action Potential (AP) Pattern**
  - SA & FA mechanoreceptor's AP patterns are obtained from real nerve of mouse

③ **Artificial Mechanoreceptor Neural (AMN) Circuit & Board**
  - SA & FA sensor outputs are translated to the SA & FA mimicked neural signals

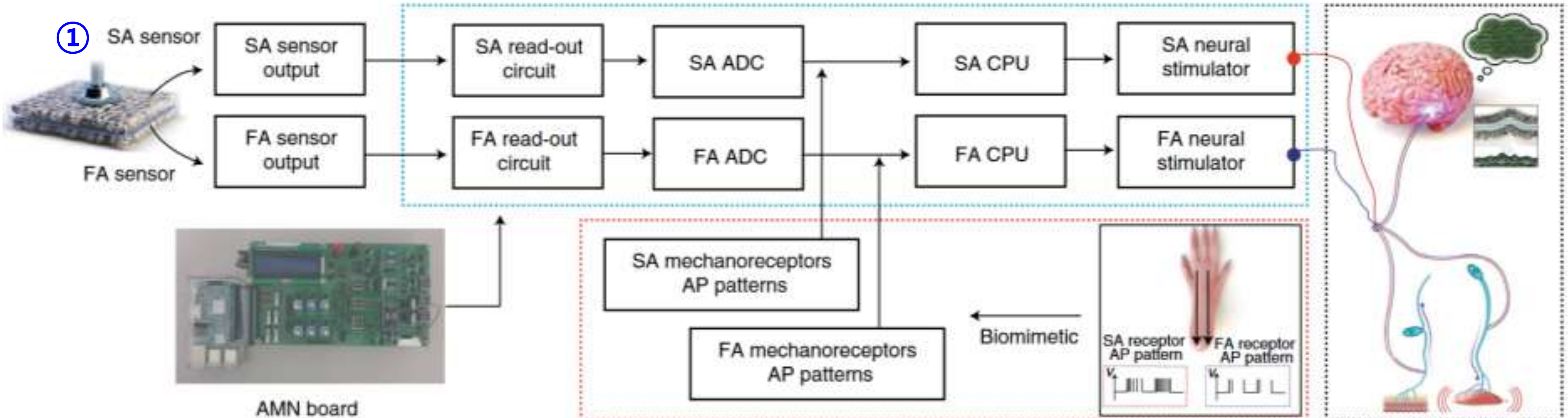
④ **Surface Texture Recognition**
  - Texture recognition accuracy is verified using deep learning.

⑤ **In vivo & Ex vivo Animal Experiments**
  - Neural signals generated by the proposed system are verified with in vivo & ex vivo experiments

Block Diagram of the Proposed Tactile Sensory System

⑤ Animal Experiments
(using SA & FA output signal)

③ AMN circuit & board



① SA sensor

FA sensor

SA sensor output

FA sensor output

SA read-out circuit

FA read-out circuit

SA ADC

FA ADC

SA CPU

FA CPU

SA neural stimulator

FA neural stimulator

AMN board

SA mechanoreceptors AP patterns

FA mechanoreceptors AP patterns

Biomimetic

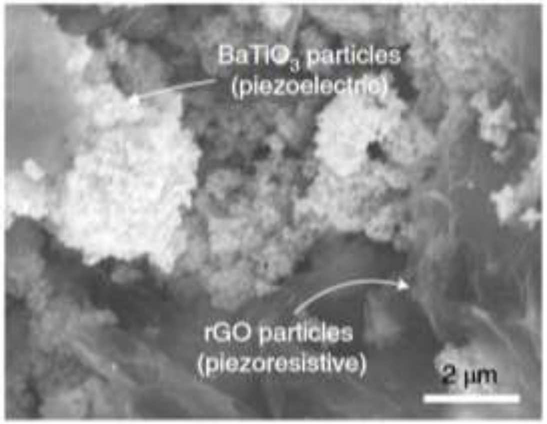
② Biological tactile sensory system for real AP patterns

④ Surface Texture Recognition

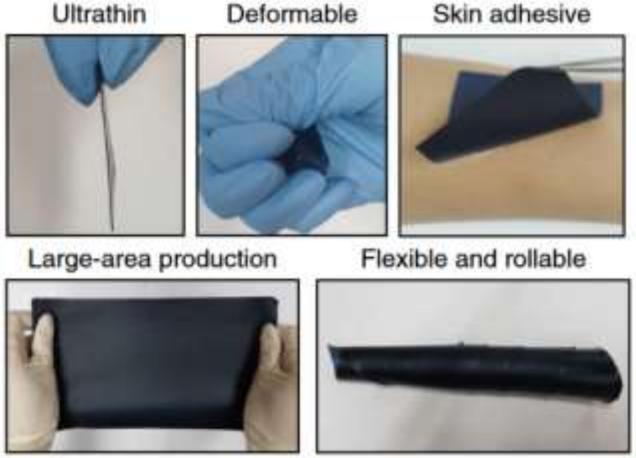
① T-Skin Sensor

- **T-Skin Film**
  - Combination of rGO (reduced graphene oxide) & $BaTiO_3$ (Barium Titanate)
  - rGO: changes conductivity according to the magnitude of pressure
→ SA receptor mimicking
  - $BaTiO_3$: generates piezoelectric potential according to the changes of pressure
→ FA receptor mimicking
- **T-Skin Sensor**
  - rGO enriched film → SA sensor
  - $BaTiO_3$ enriched film → FA sensor
  - Vertically stacked → SA and FA signals are generated simultaneously

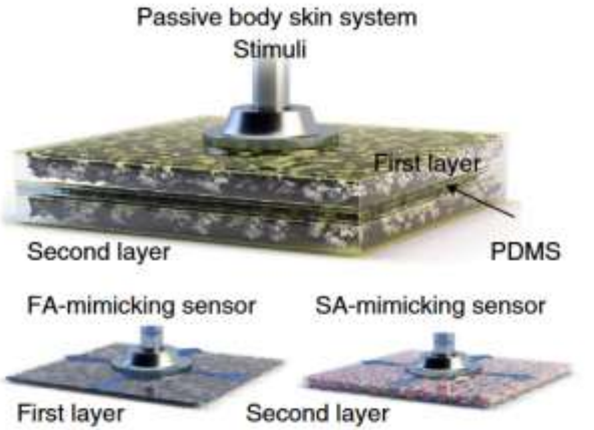
Cross-section of T-Skin Film



Characteristics of T-Skin Film



Configuration of T-Skin Sensor



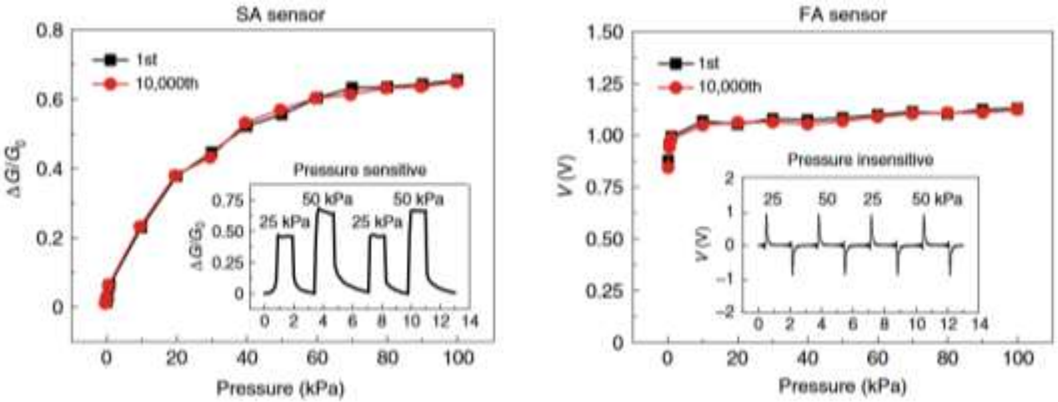
$BaTiO_3$-enriched rGO-enriched

① T-Skin Sensor

- **SA sensor** (similar to SA mechanoreceptor)
  - Pressure sensitive
- **FA sensor** (similar to FA mechanoreceptor)
  - Pressure insensitive
  - Detects high-frequency vibration (1,000Hz) *Human vibration detection: Max. 500 Hz

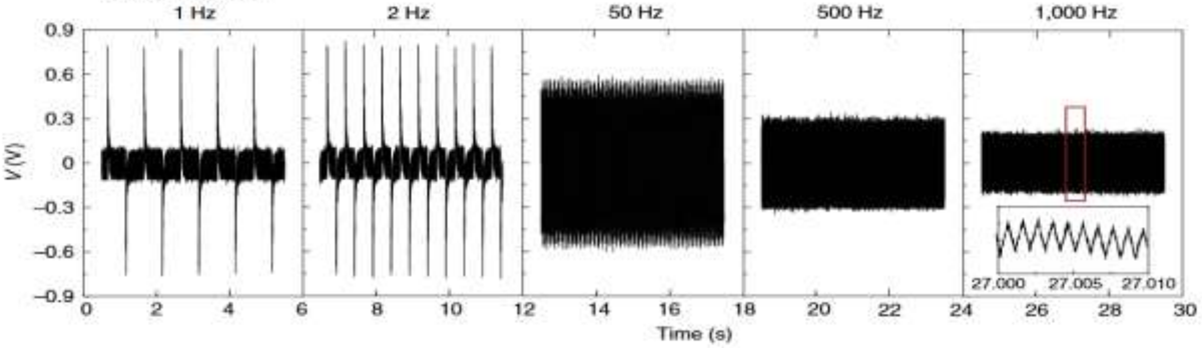
Responses under static pressure (10,000 repeated measurement)

SA sensor
(pressure sensitive)



FA sensor
(pressure insensitive)

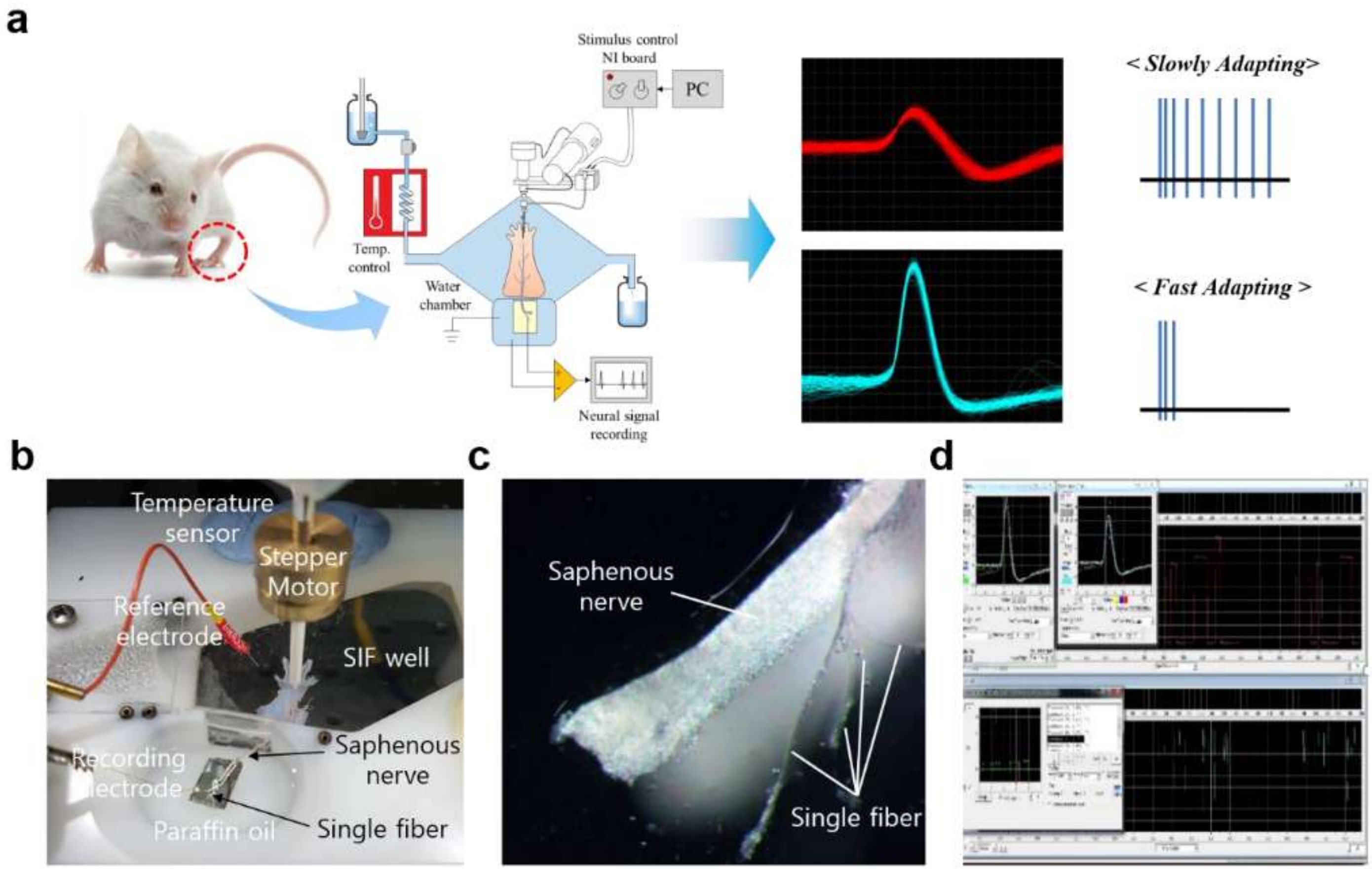
Vibration-sensing capability of the FA sensor in 1 Hz to 1,000 Hz



② Mechanoreceptor Action Potential (AP) Pattern

● Obtaining AP Pattern from Real Nerve

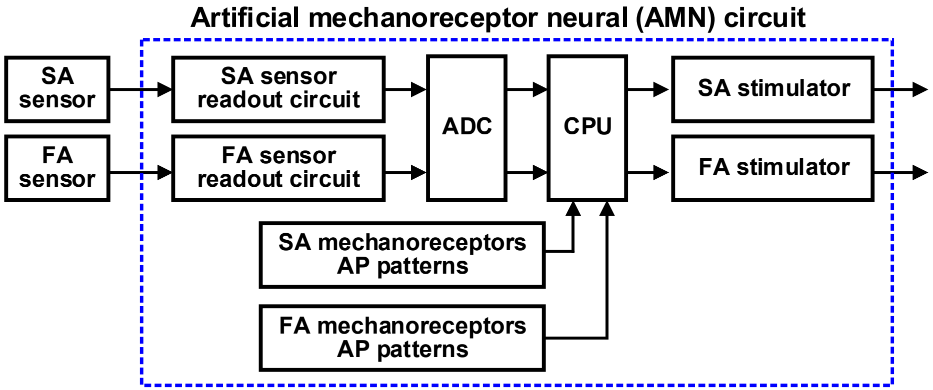
- AP patterns against mechanical stimuli were obtained from real nerve of mouse.
- AP patterns were collected for SA and FA mechanoreceptors independently.



③ Artificial Mechanoreceptor Neural (AMN) Circuit

- **Configuration of AMN Circuit**
  - **Sensor readout circuit + ADC + CPU + neural stimulator**
  - Mechanoreceptor AP patterns are stored in nonvolatile memory.

Block Diagram of AMN Circuit



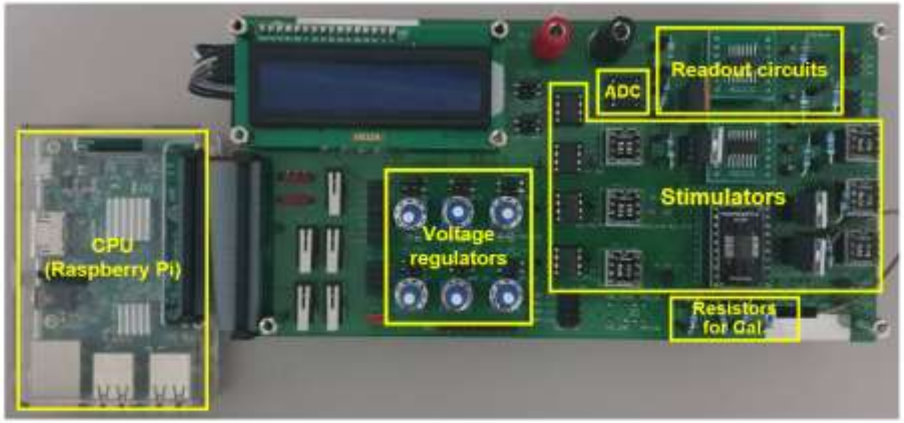
① **Sensor Readout circuit**
Converts the sensor response to voltage domain

② **ADC**
Converts voltage to digital domain

③ **CPU (in Raspberry Pi)**
Digital processing & selects AP pattern

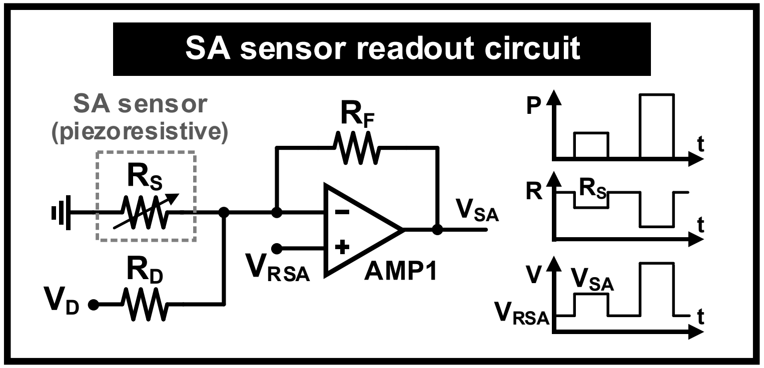
④ **Neural stimulator**
Converts AP pattern to current domain

Fabricated AMN Circuit Board



③ Artificial Mechanoreceptor Neural (AMN) Circuit

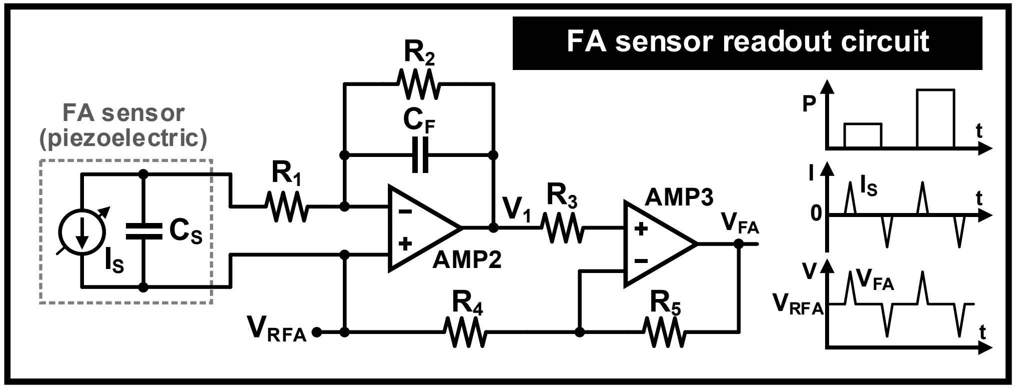
- **Electrical Model of Sensor**
  - SA sensor: pressure dependent resistor
  - FA sensor: vibration dependent current source (AC current)
- **Sensor Readout Circuit**
  - SA readout circuit: resistance is converted to voltage level
  - FA readout circuit: AC current is converted to voltage spike



Pressure on SA sensor

→ resistance (conductivity) variation

→ output voltage level change



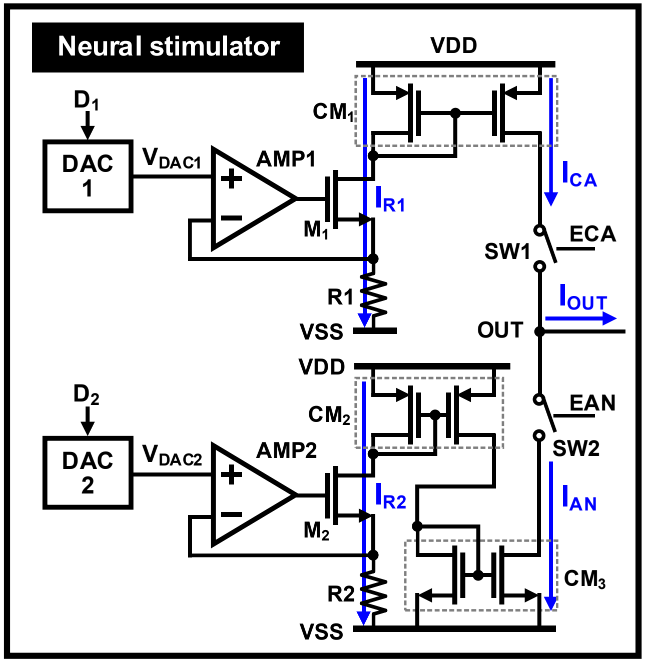
Vibration on FA sensor

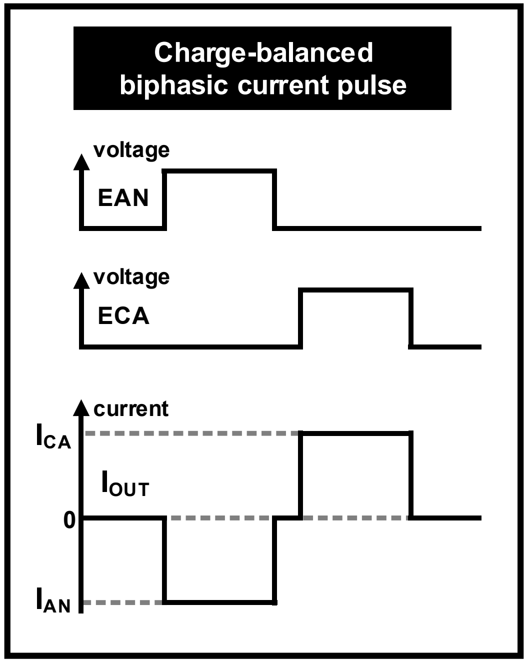
→ AC current generation

→ output voltage spike

③ Artificial Mechanoreceptor Neural (AMN) Circuit

- **Neural Stimulating**
  - "Charge balanced biphasic current pulse" method
    → maintaining charge balance in the biological environment to prevent tissue damage
- **Proposed Neural Stimulator**
  - Current mirror based current stimulator → biphasic current pulse
  - Charge balance between I_{CA} & I_{AN} → prevents tissue damage during stimulation

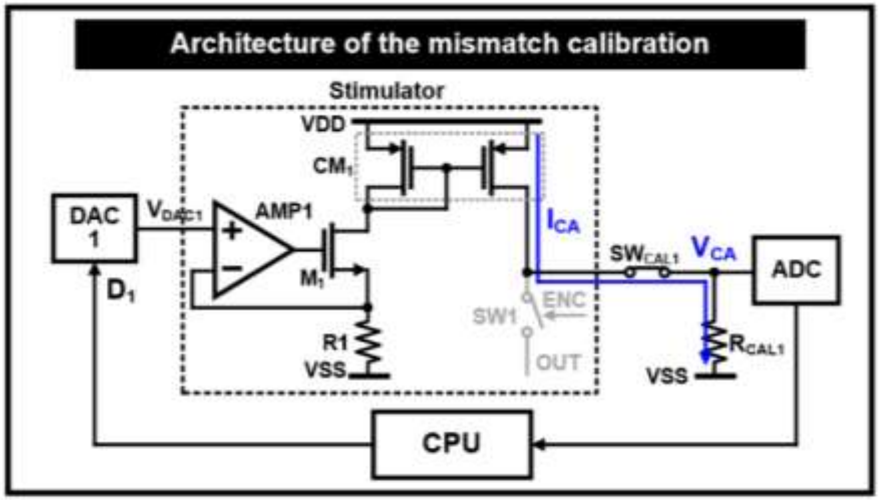




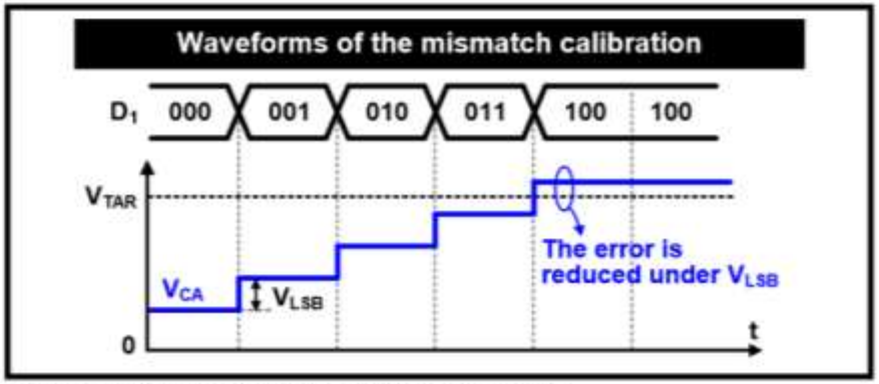
③ Artificial Mechanoreceptor Neural (AMN) Circuit

● Neural Stimulator (Calibration Method)

- Current mismatch by process variation → unbalanced charge → tissue damage
- Current mismatch calibration (by adjusting the DAC voltage) → balanced charge



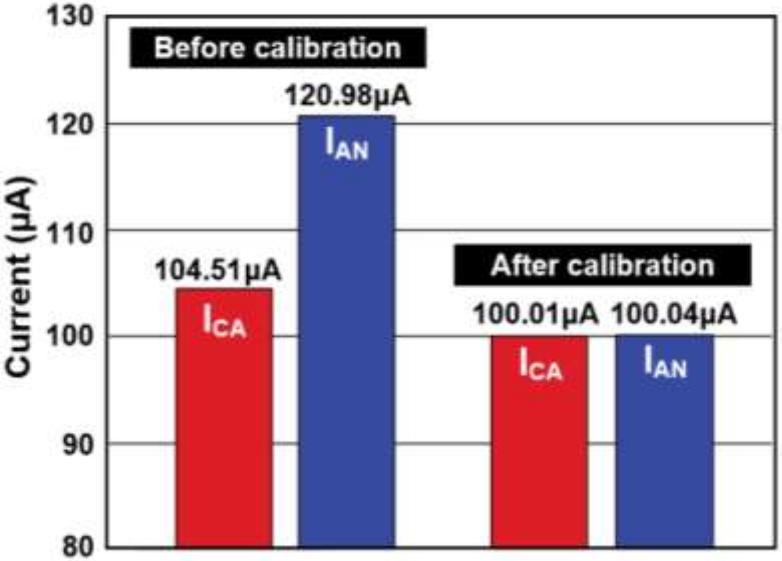
Architecture of the mismatch calibration



Waveforms of the mismatch calibration

*This example uses a 3-bit DAC resolution for a simplicity.

Measurement Result

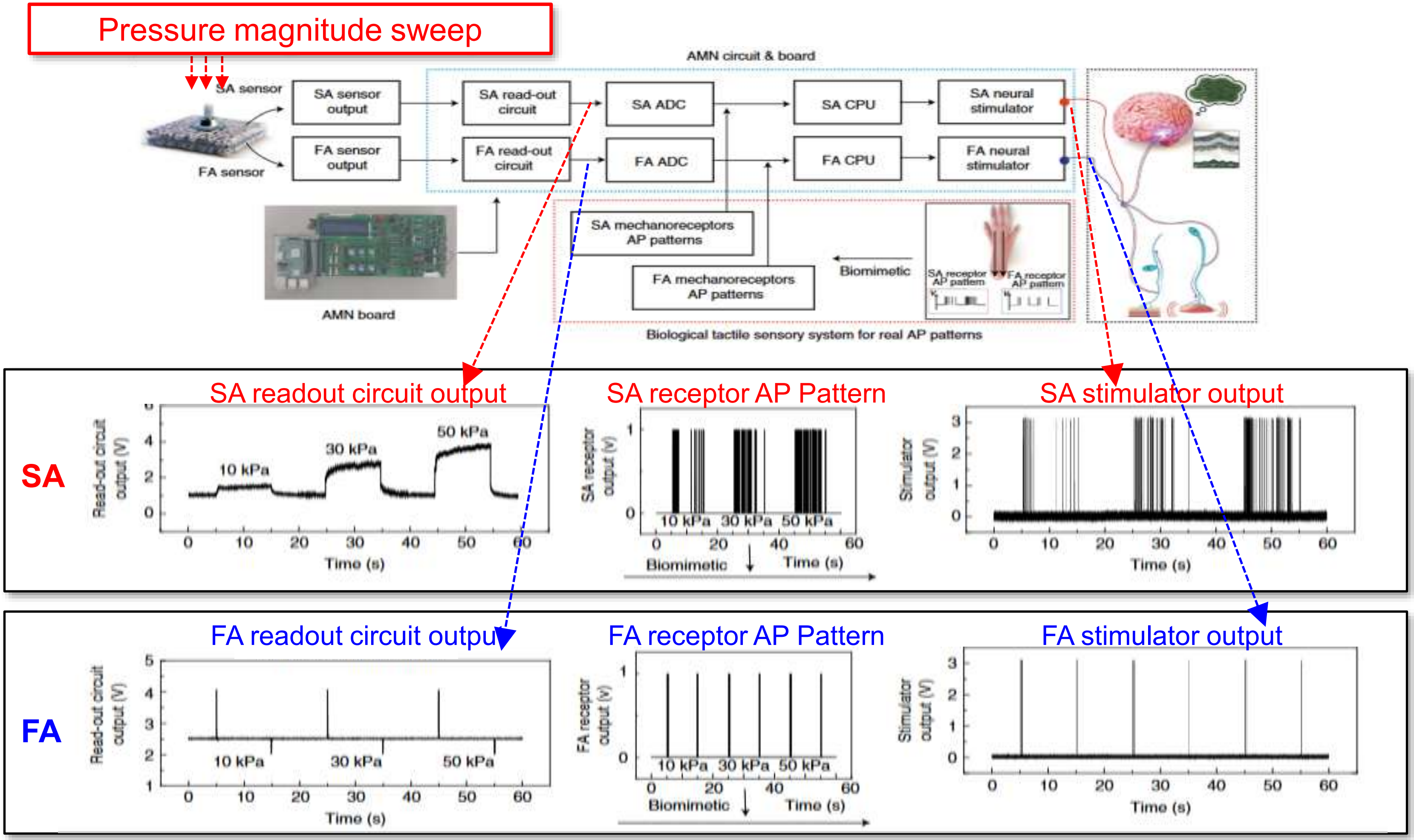


Mismatch 16% → Mismatch 0%

③ AMN Circuit - Experiments -

● Pressure Magnitude Sweep

- SA stimulator output: different pattern according to the pressure magnitude
- FA stimulator output: voltage spike at initial contact and final release (vibration)



Pressure magnitude sweep

SA

SA readout circuit output

SA receptor AP Pattern

SA stimulator output

FA

FA readout circuit output

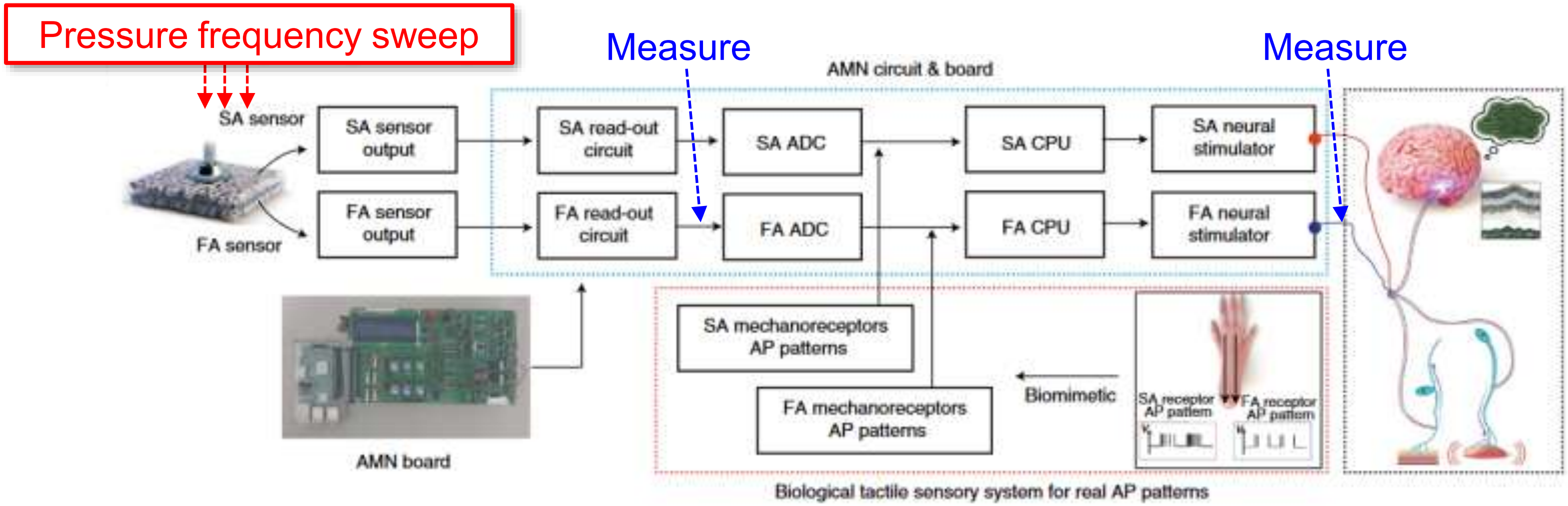
FA receptor AP Pattern

FA stimulator output

③ AMN Circuit - Experiments -

Pressure Frequency Sweep

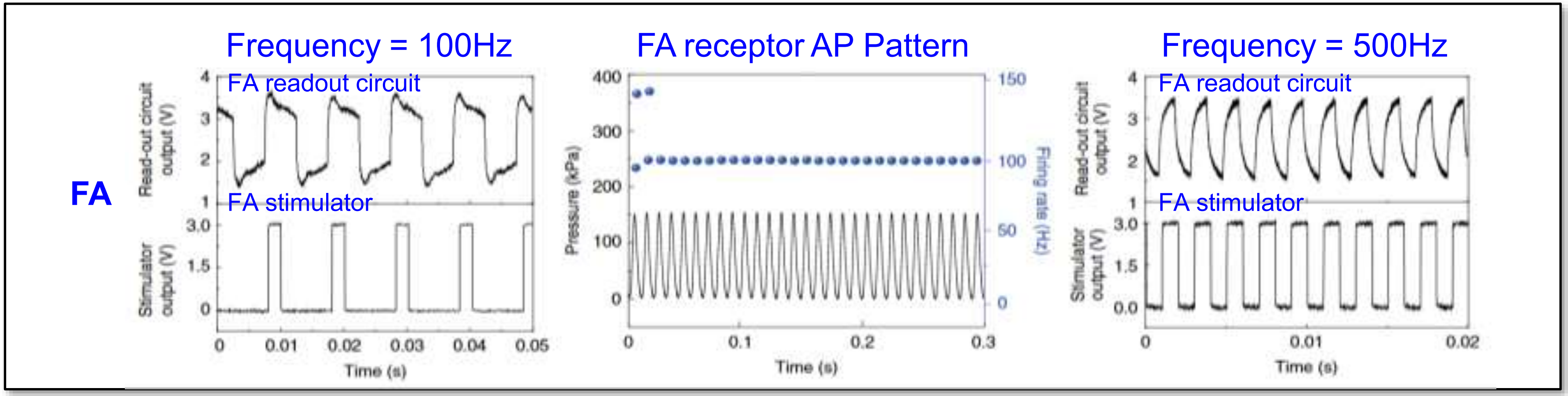
- FA circuits can cover 100Hz and 500Hz (Max 1kHz) of vibrations



Pressure frequency sweep

Measure

Measure



FA

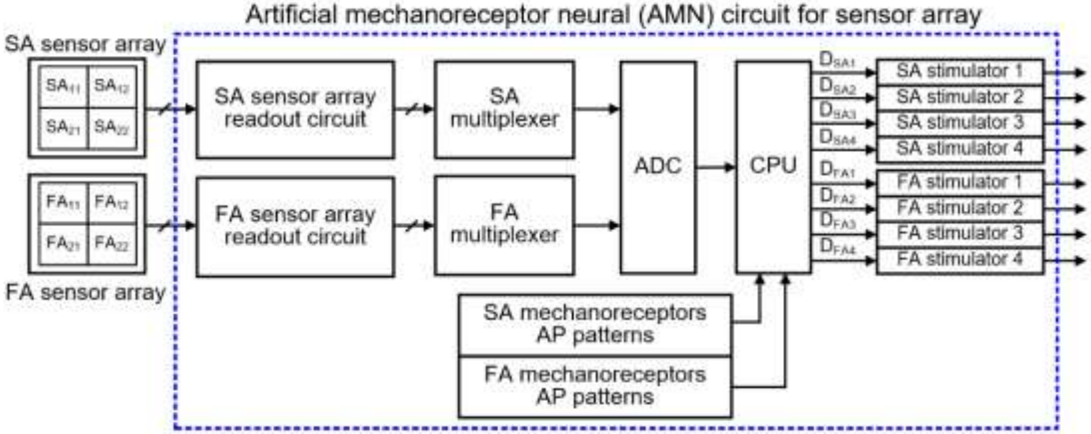
Frequency = 100Hz

FA receptor AP Pattern

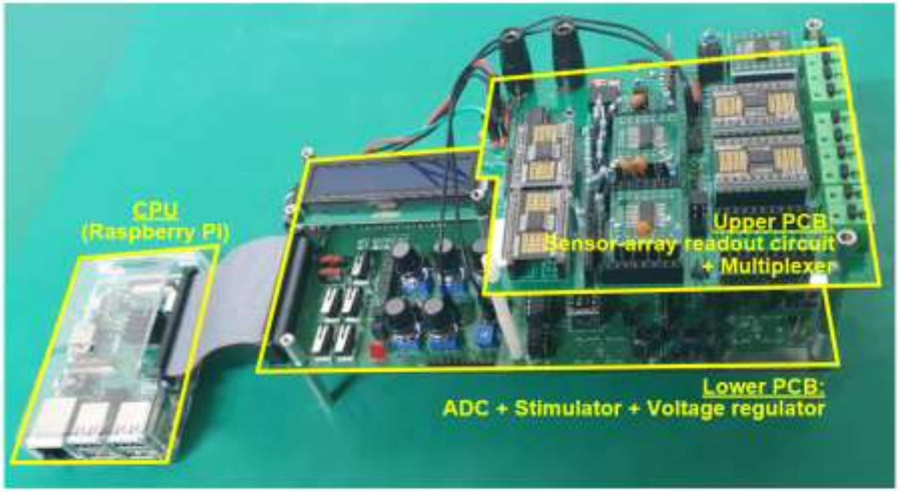
Frequency = 500Hz

③ AMN Circuit - for Sensor Array -

AMN Circuit for 2X2 Sensor Array



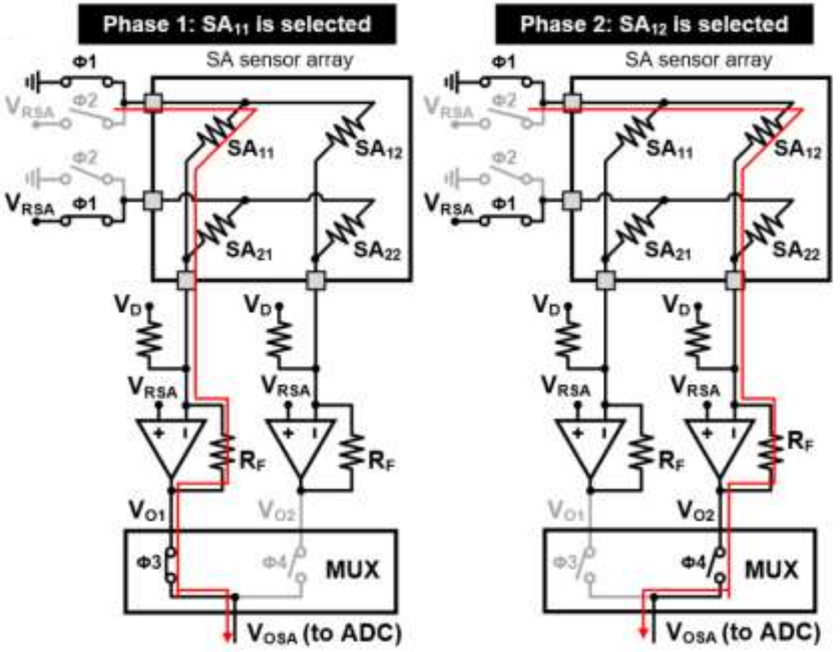
AMN Circuit Board for 2X2 Sensor Array



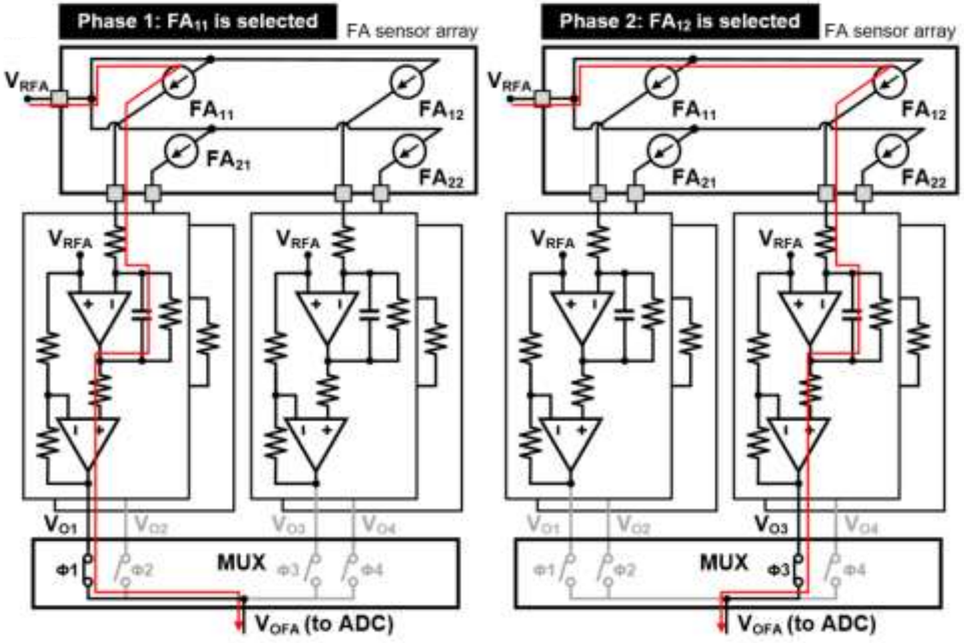
③ AMN Circuit - for Sensor Array -

- **Readout Circuits** (for 2X2 Sensor Array)

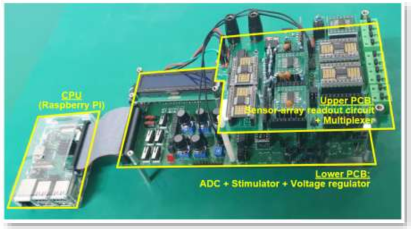
SA sensor array readout circuit

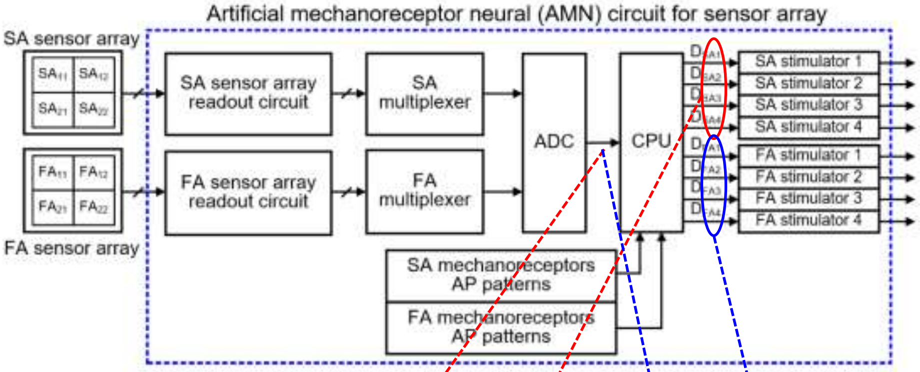


FA sensor array readout circuit



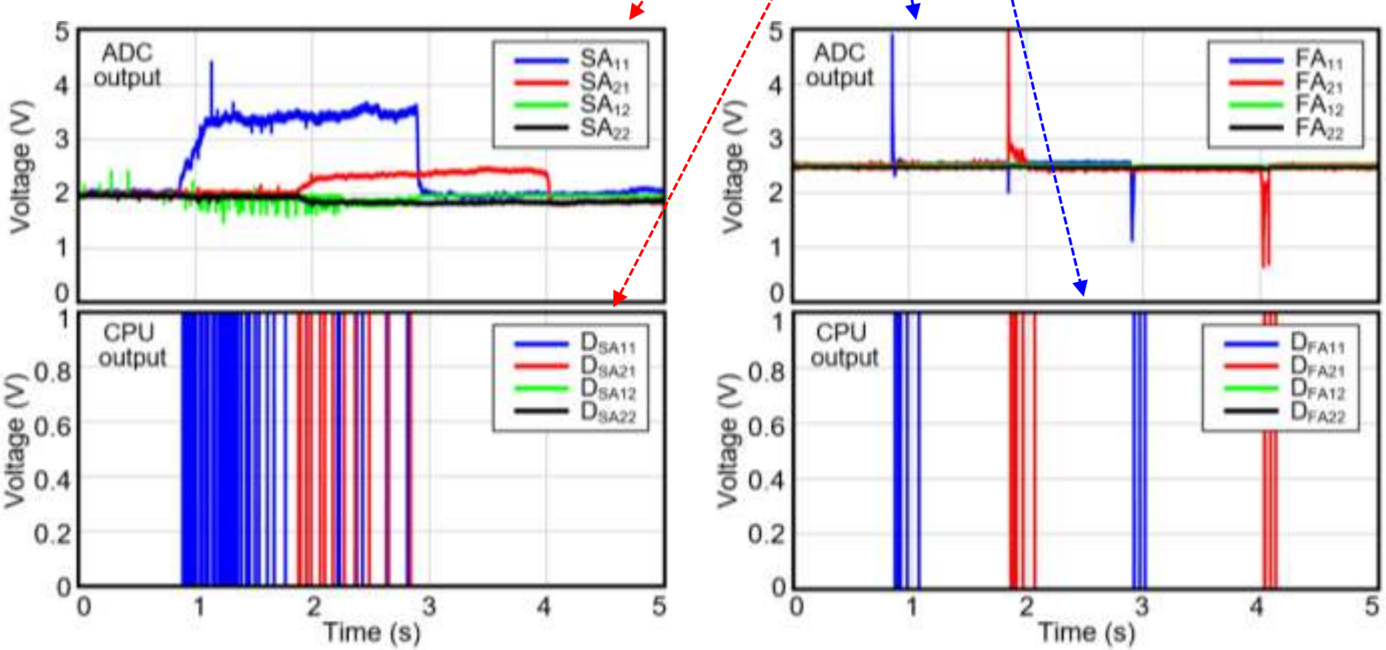
③ AMN Circuit - for Sensor Array -





SA
ADC

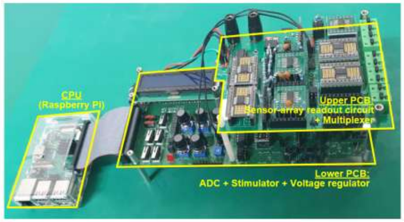
SA
CPU

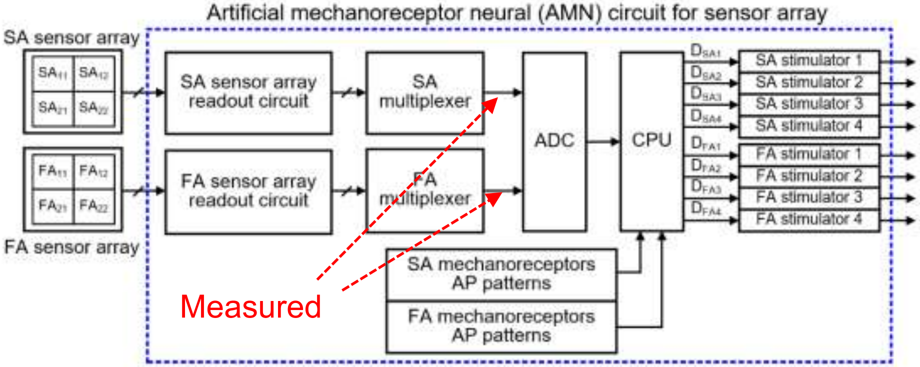


FA
ADC

FA
CPU

③ AMN Circuit - for Sensor Array -




Artificial mechanoreceptor neural (AMN) circuit for sensor array

SA sensor array
SA_{11} SA_{12}
SA_{21} SA_{22}

FA sensor array
FA_{11} FA_{12}
FA_{21} FA_{22}

SA sensor array readout circuit

FA sensor array readout circuit

SA multiplexer

FA multiplexer

ADC

CPU

D_{SA1} D_{SA2} D_{SA3} D_{SA4}
D_{FA1} D_{FA2} D_{FA3} D_{FA4}

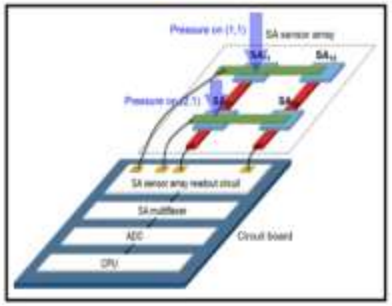
SA stimulator 1
SA stimulator 2
SA stimulator 3
SA stimulator 4
FA stimulator 1
FA stimulator 2
FA stimulator 3
FA stimulator 4

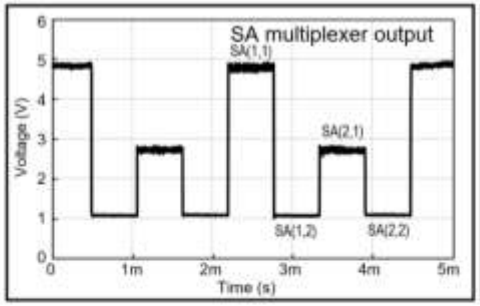
SA mechanoreceptors AP patterns

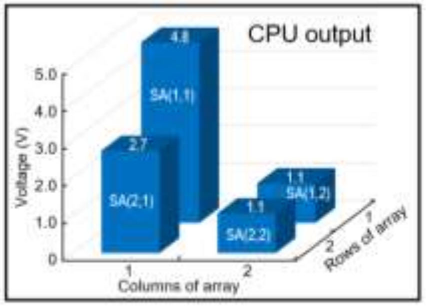
FA mechanoreceptors AP patterns

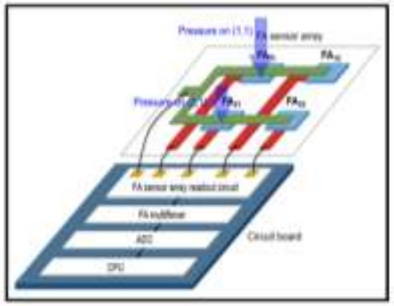
Measured

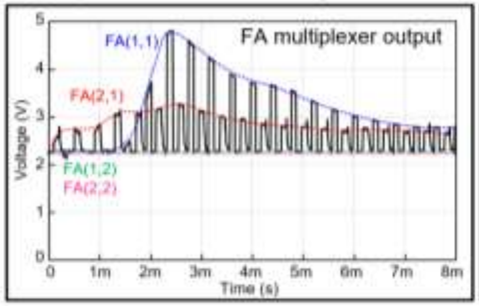
Pressure is selectively applied to the array

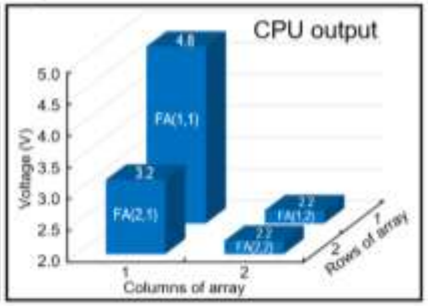








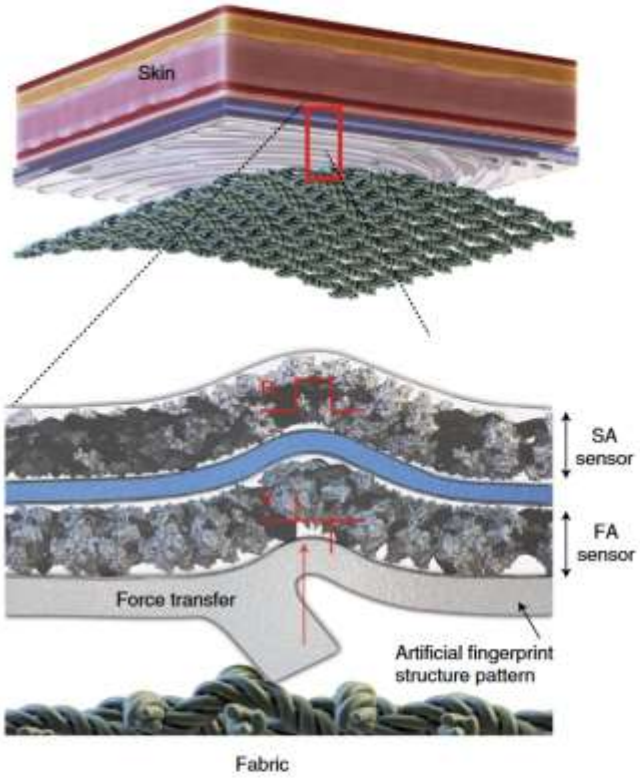




④ Surface Texture Recognition

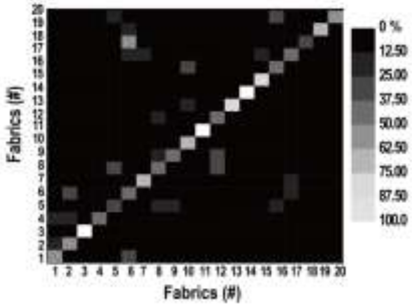
- **Proposed T-skin System**
  - Higher texture classification accuracy (99.1%) after combining SA and FA signals using deep learning

Active Finger Skin System



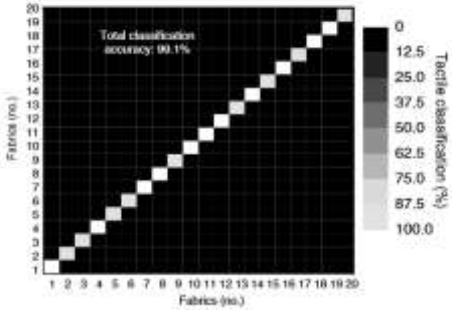
Texture Classification (Human)

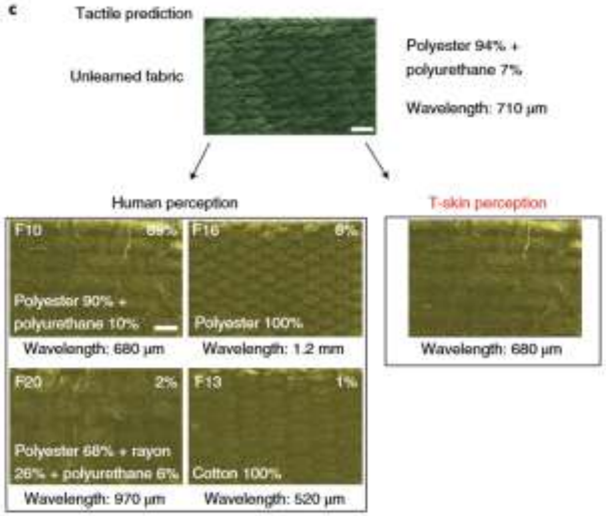
Classification accuracy: 59.1%



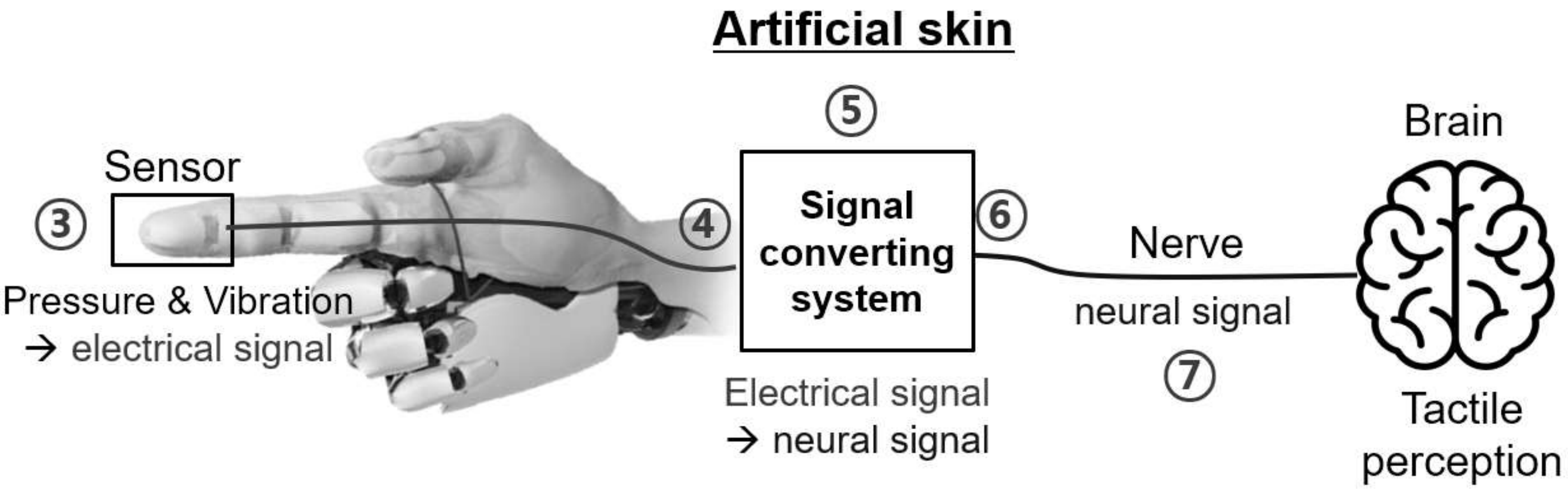
Texture Classification (T-Skin)

Classification accuracy: 99.1%





Research Items



③ **센서**: 인간 촉각수용체(receptor) 를 어떻게 모방할 수 있나?

④ **센서 readout**: 센서 전기 신호를 왜곡 없이 읽는 방법?

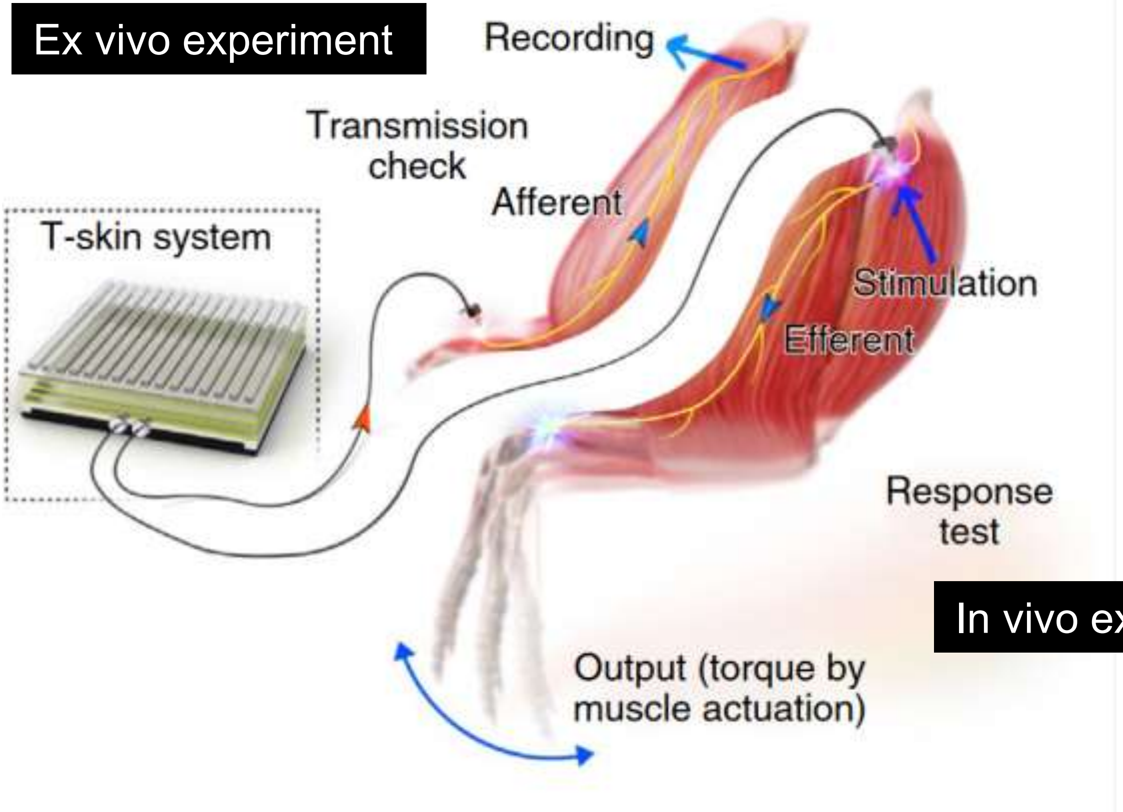
⑤ **Signal converting**: 센서에 인가된 물리적 정보를 판단하고, neural signal을 생성

⑥ **Neural stimulator**: 신경이 인식할 수 있는 형태로 신호 변경 및 신경 구동

⑦ **생체실험**: 신경에서 신호가 잘 전달됨을 확인하는 방법?

⑤ Animal Experiment

- **#1. Ex vivo Experiment** (목적: 생성한 신호가 신경을 통해 전달됨을 확인)
  - To check the transmission of the generated signals in the explanted afferent nerve.
- **#2. In vivo Experiment** (목적: 생성한 신호로 근육 자극이 가능함을 확임.)
  - To confirm that efferent nerve stimulation would generate the response of the hindlimb muscle.



Ex vivo experiment

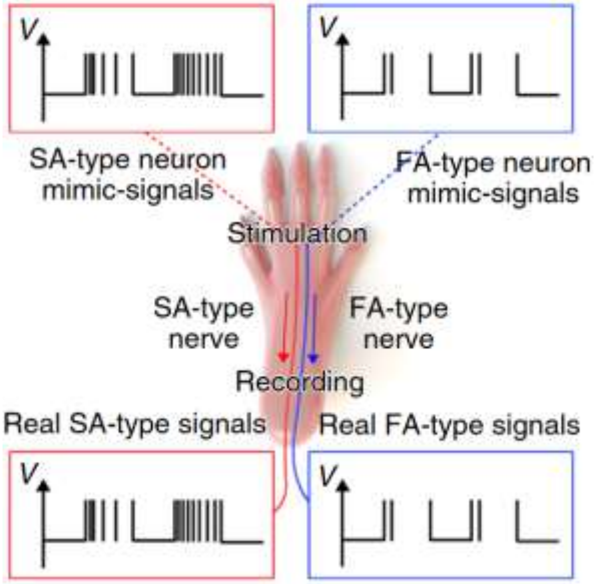
In vivo experiment

⑤ Animal Experiment

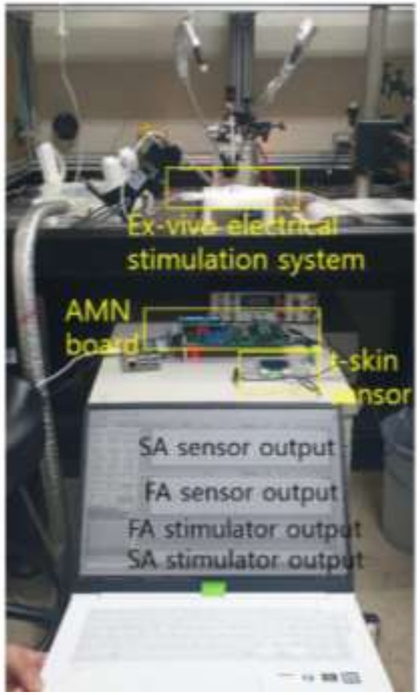
● #1. Ex vivo Experiment

- To check the transmission of the SA & FA signals in the explanted afferent nerve.
- SA & FA signals are applied to a single fiber in skin from hindlimb of mouse

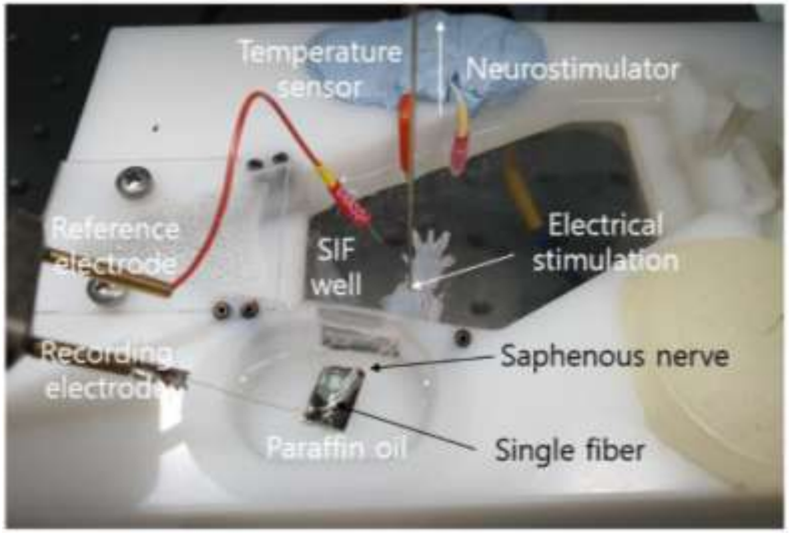
Concept



Experiment Setup



Experiment Setup

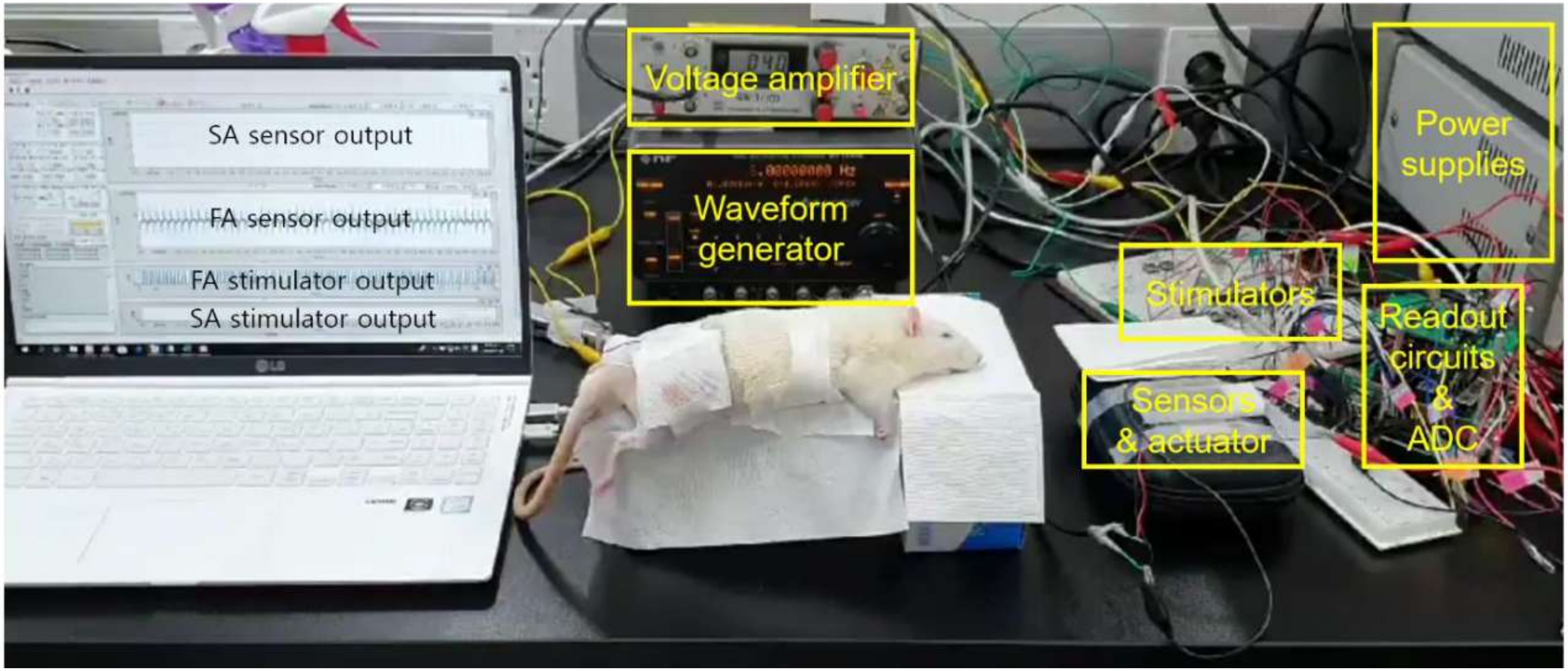


⑤ Animal Experiment

#2. In vivo Experiment

- To confirm that efferent nerve stimulation would generate the response of the hindlimb muscle.

Experiment Setup



Human Skin Vs. Proposed T-Skin

Main skin functions		Real human skin	Proposed tactile skin
Slow adaptive	Pressure sensitivity	Sensitive to pressure	0.01/kPa (0.1-50 kPa) 0.002/kPa (50-100 kPa)
	Pressure detection range	0.1 ~ 100 kPa	0.1 ~ 100 kPa
	Stretchability	< 40-50%	< 100%
Fast adaptive	Response time	> 2 ms for Pacinian Corpuscle	> 1 ms for FA sensors
	Frequency ragne	< Max. 500 Hz for Pacinian Corpuscle	< 1,000 Hz for FA sensors
Skin	Durability	Infinite without pain	< 10,000 cycles
Main property	Stimuli selectivity	SA and FA receptors are selectively sensitive to pressure and vibration	SA and FA sensors are selectively sensitive to pressure and vibrations

Research Team

- **Researchers**
  - Prof. Jong-Seok Kim (Hanyang Univ.): Co-first author
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  - Youngin Choi (Hanyang Univ.)
  - Prof. Sung Jun Jung (Hanyang Univ.)
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  - Kum Seok Nam (KAIST)
  - Inchan Youn (KIST)
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  - Prof. Chaghyun Pang (Sungkyunkwan Univ)
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  - Hachel Jung (Osong Medical Innovation Foundation)
  - Young-Jin Kim (Osong Medical Innovation Foundation)
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  - Jaehun Kim (UNIST)
  - Prof. Sung-Phil Kim (UNIST)
  - Prof. Wanjun Park (Hanyang Univ.)

Research Team

언론 보도: MBC, KBS, 연합뉴스, 헤럴드경제 등


피부 감각을 느낀다…박성준 교수팀, 메타버스 기반 '인공 감각 시스템'


인간의 촉각 인식 원리 본뜬 '인공 감각 시스템' 개발

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