ASP-DAC 2022 Session 1A
University Design Contest-1

A 0.5 mm^2 Ambient Light-Driven Solar Cell-Powered Biofuel Cell-Input Biosensing System with LED Driving for Stand-Alone RF-Less Continuous Glucose Monitoring Contact Lens (1A-1)

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Outline

- Background, motivation, and objective
- Proposed stand-alone RF-less CGM system architecture
- Measurement results
- Performance comparison and summary

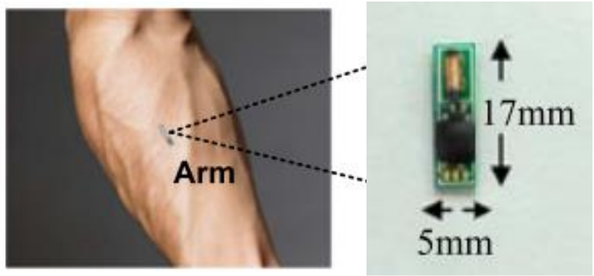
Background

- Continuous glucose monitoring (CGM) for real-time diabetes monitoring

[1]

Under the Skin

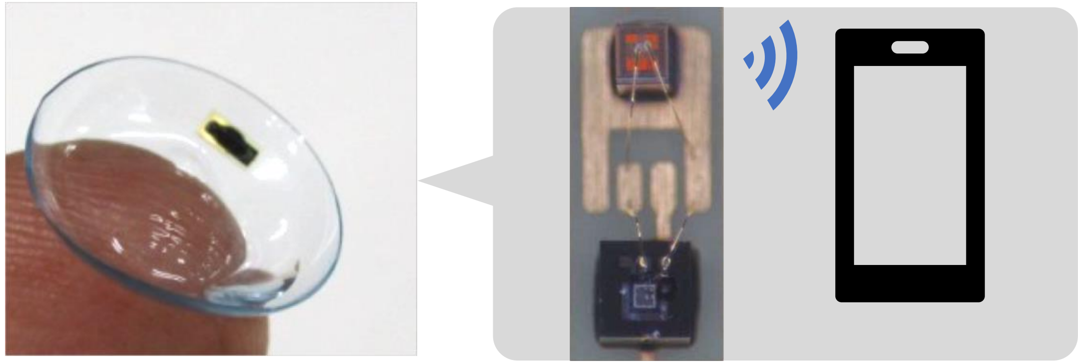
❌ Invasive, life span, battery…



[2]

Fully-Passive Sensor Tag

❌ Invasive, bulky…



[3]

Tear Glucose

○ Non-invasive, high time resolution…

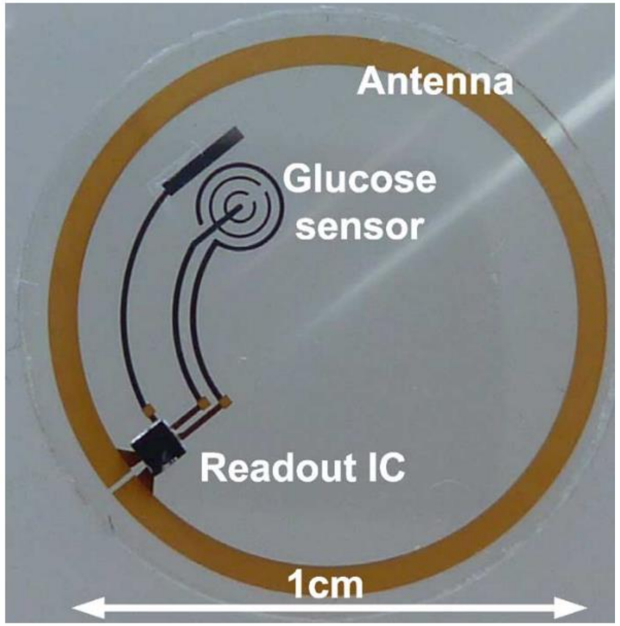
↓

Hyperglycemia (high glucose) and hypoglycemia (low glucose condition) tracking

[1] Eversense. [2] Z. Xiao et al., IEEE JBHI, May. 2015, pp. 910.
[3] K. Hayashi et al., BioCAS, Oct. 2018, pp. 379

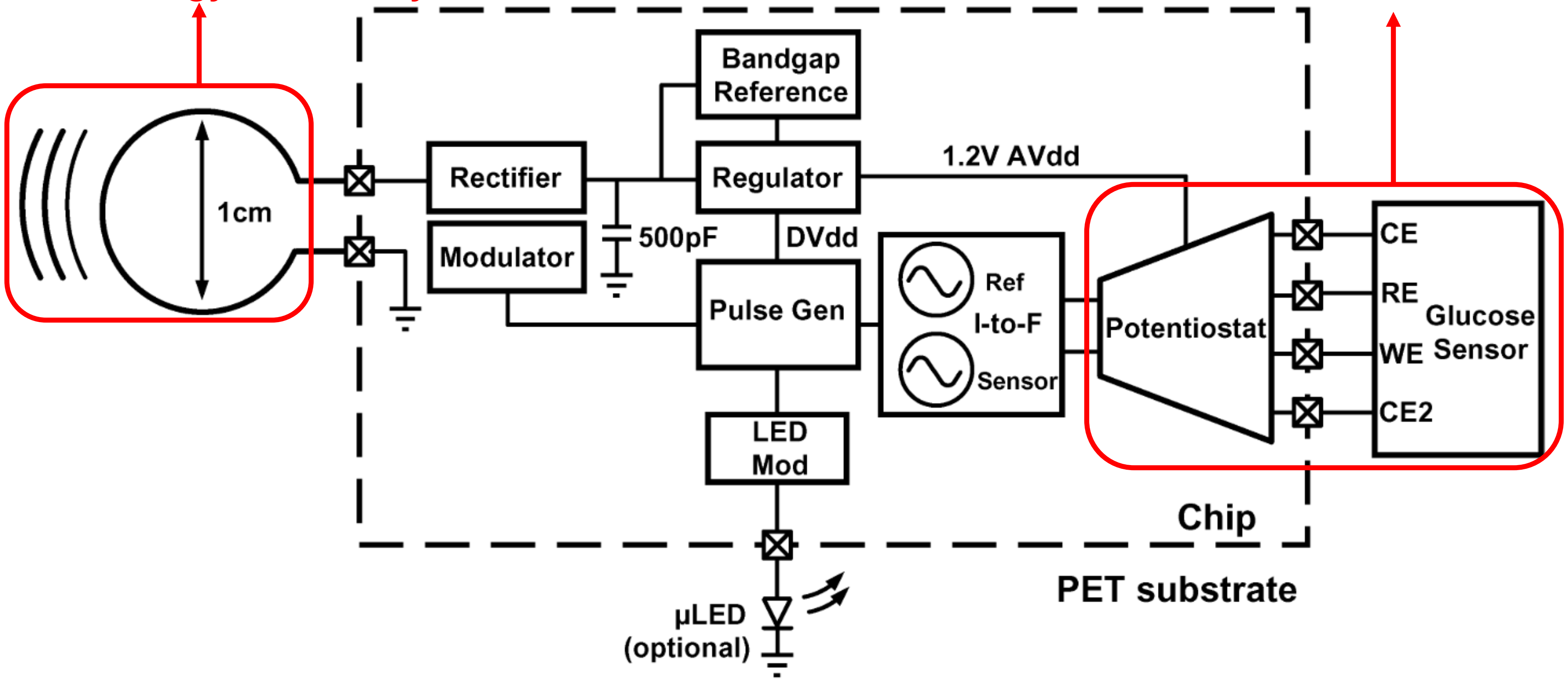
Conventional CGM Contact lens 1

- Conventional type [4–6]:RF powered + Potentiostat



Wireless Power Transfer
Low Energy Efficiency

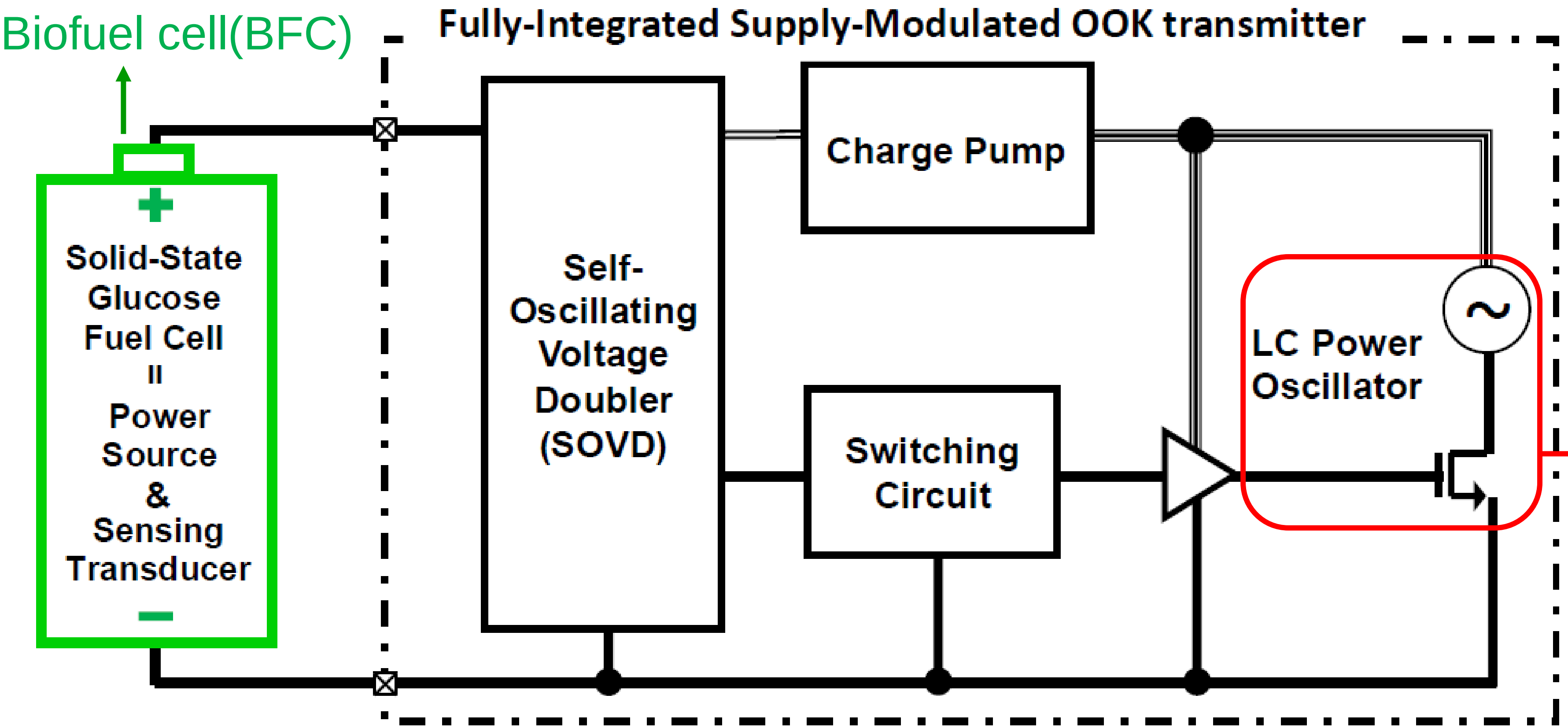
Potentiostat
Power-hungry (400–500nW)

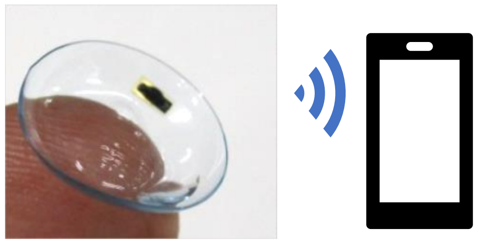


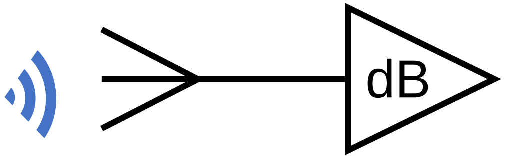
[4] Y. T. Liao et al., JSSC, Jan. 2012, pp. 335. [5] Y. T. Liao et al., ISSCC, Feb. 2011, pp. 38 [6] C. Jeon et al., VLSI Circuits, Jun. 2019, pp. C294

Conventional CGM Contact lens 2

- Our previous work [3]: BFC powered + BFC interface





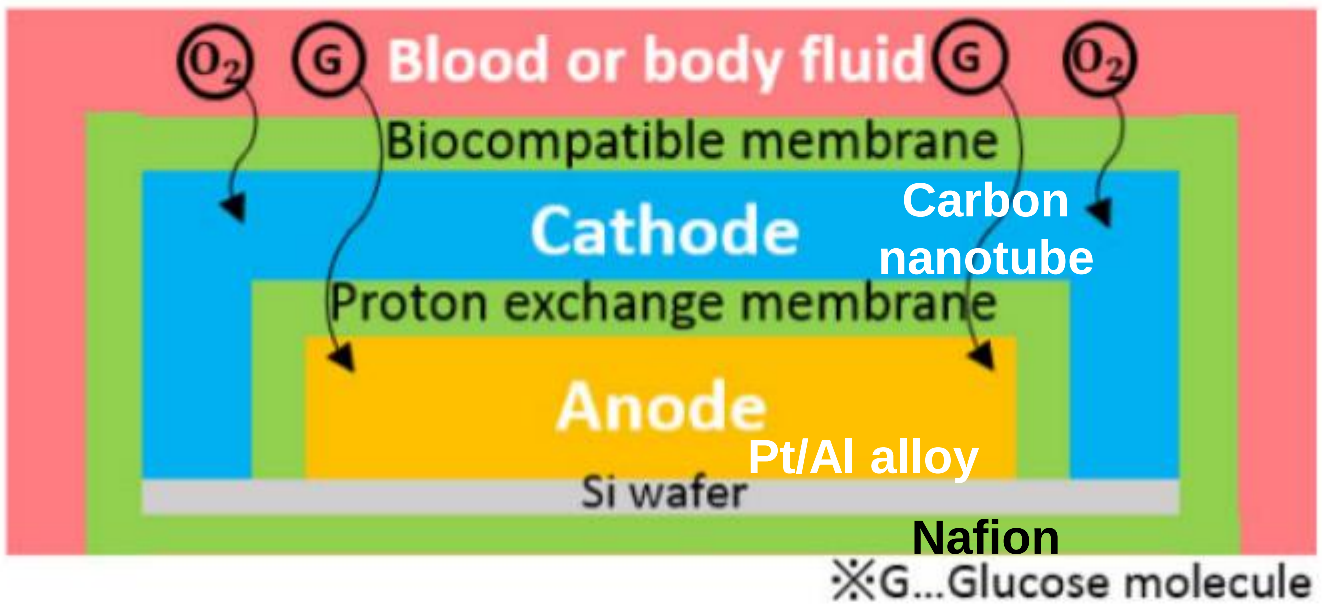


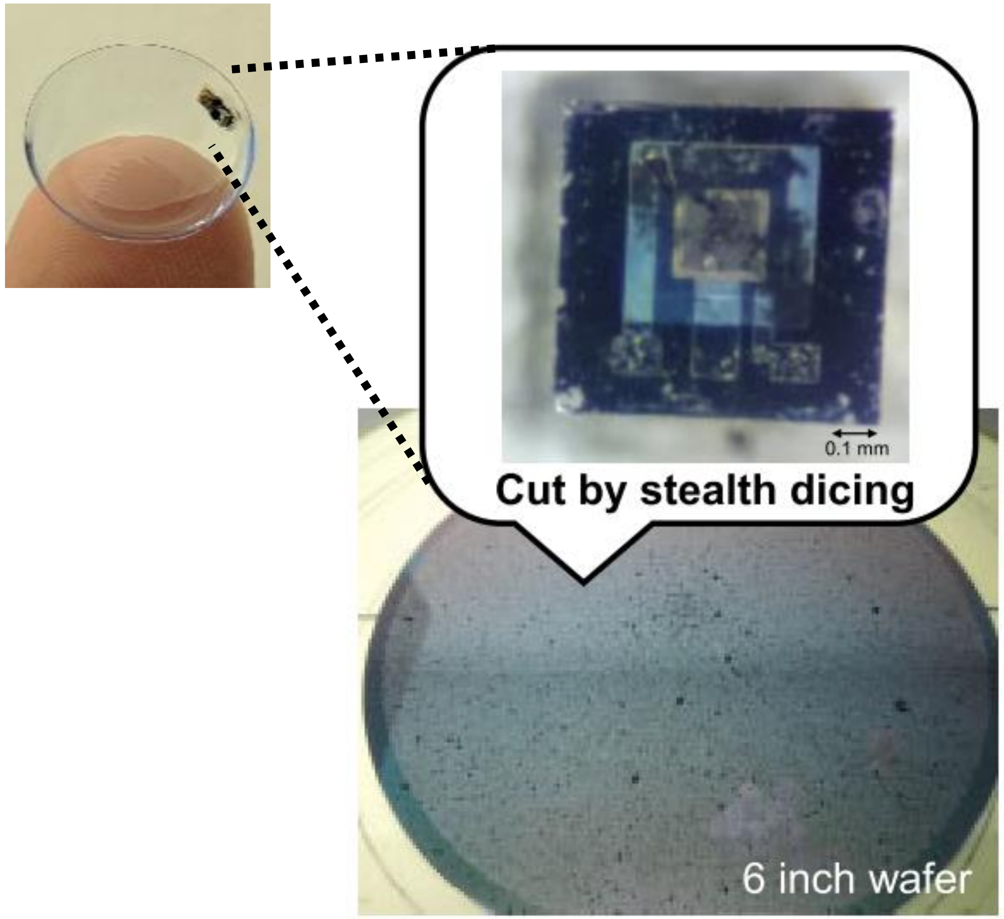
Wireless Transmitter (Tx)
External Receiver (Rx)

[3] K. Hayashi et al., BioCAS’18, pp. 379.

Micro Glucose BFC Element

Cross section conceptual graph of the BFC [8]



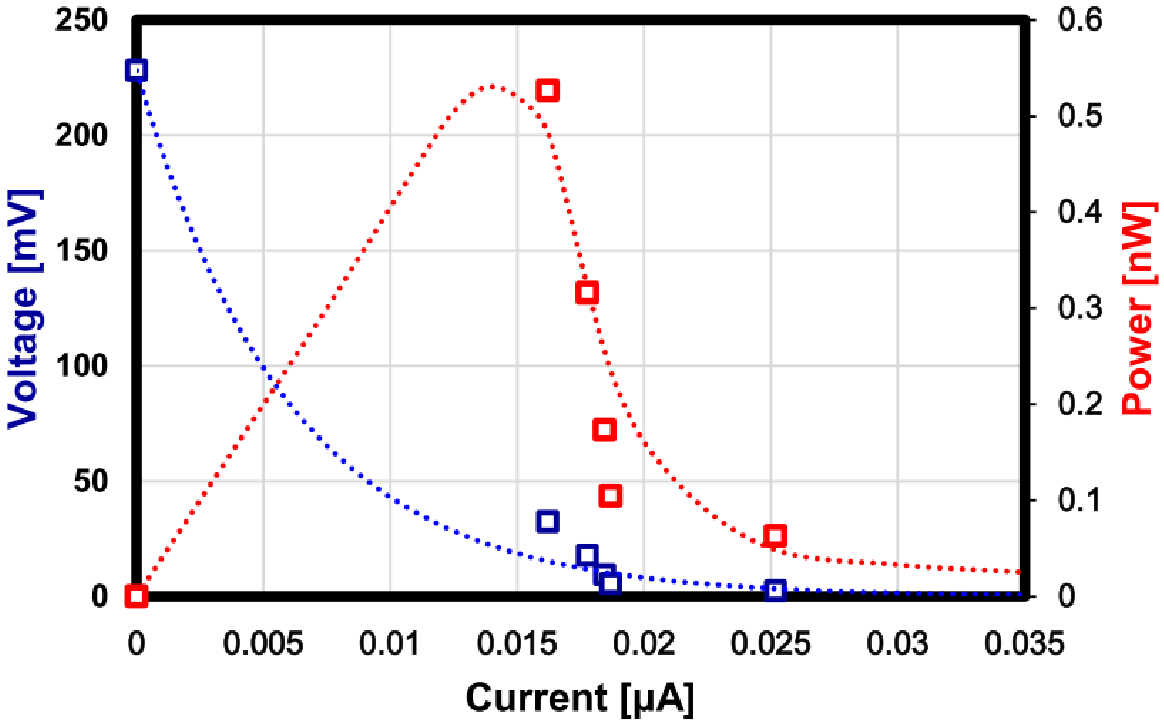


- ☐ Manufacturing 0.36 mm^2 power generation element by wafer process [9]

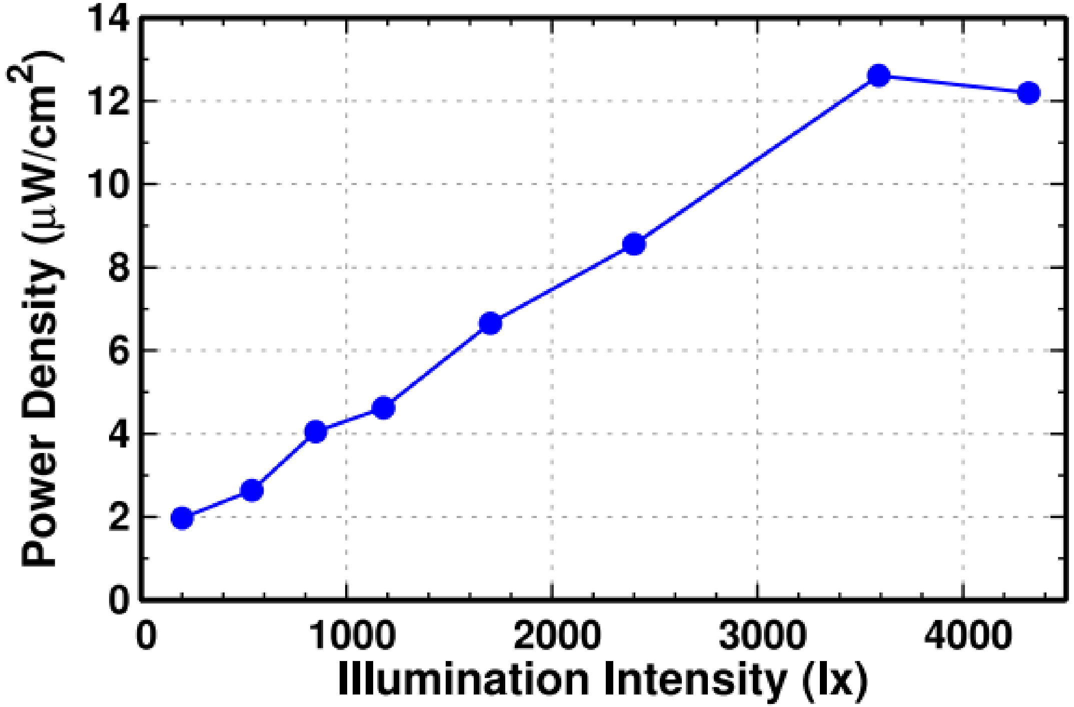
[8] K. Niitsu et al., Jpn. J. Appl. Phys. 56, 2017, pp. 01AH04
[9] S. Arata et al., Jpn. J. Appl. Phys., Mar. 2018, pp. 04FM04

Micro Glucose BFC Performance

BFC with a power density of 0.14 μW/cm² [9]



Measured power density of the SC in [10]

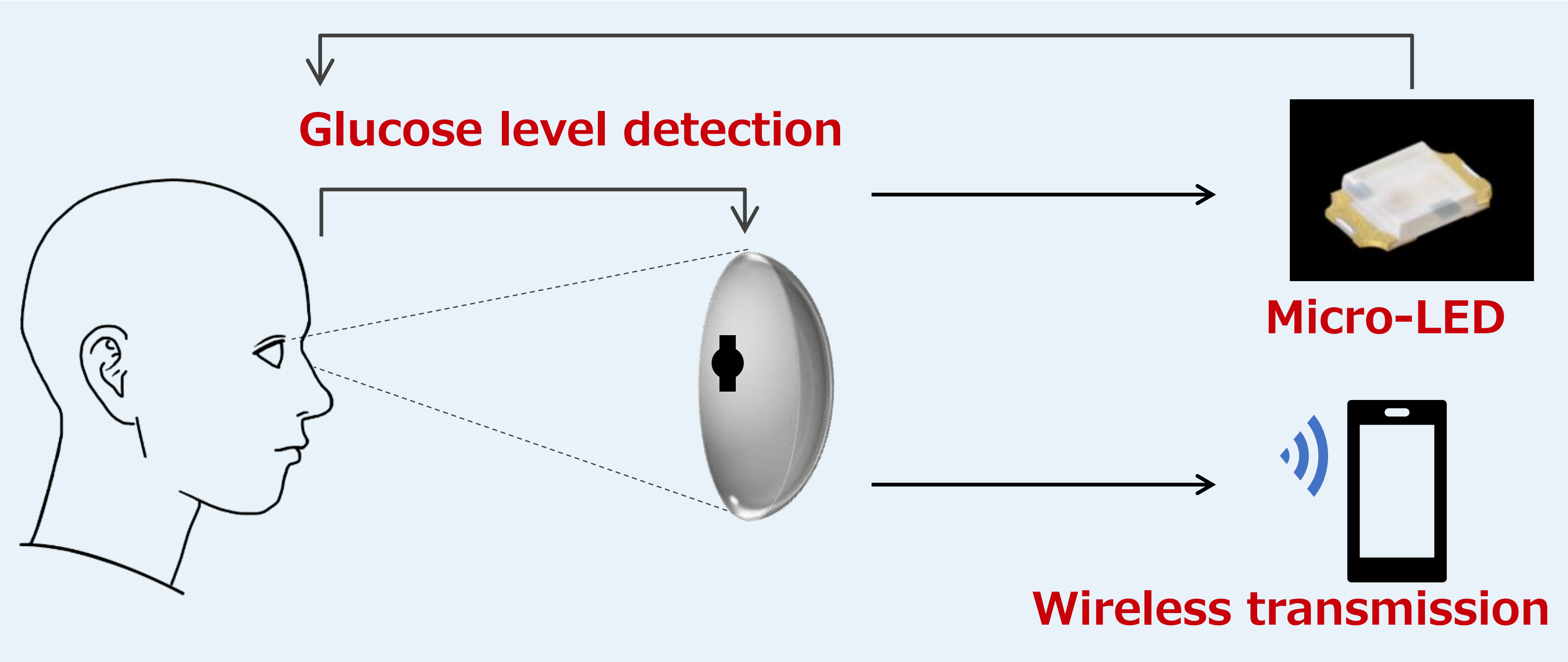


- The low power density of BFC limits Tx's link budget, requiring high-gain receiver
- Solar cell (SC) is a substitute providing 10–100× larger power density [10]

[10] A. Kobayashi et al., IEEE ICECS, Nov. 2019, pp. 61

Reading Out Method

- Micro-LED is a good option to achieve a fully stand-alone operation [7]

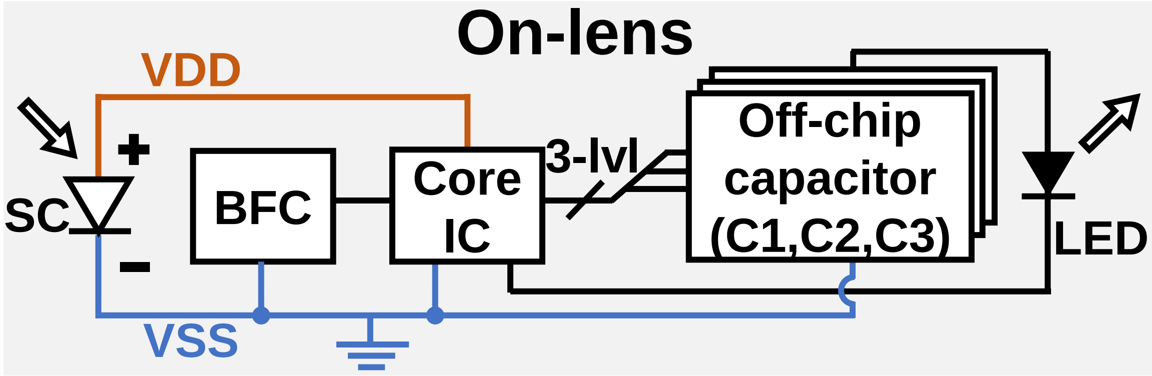


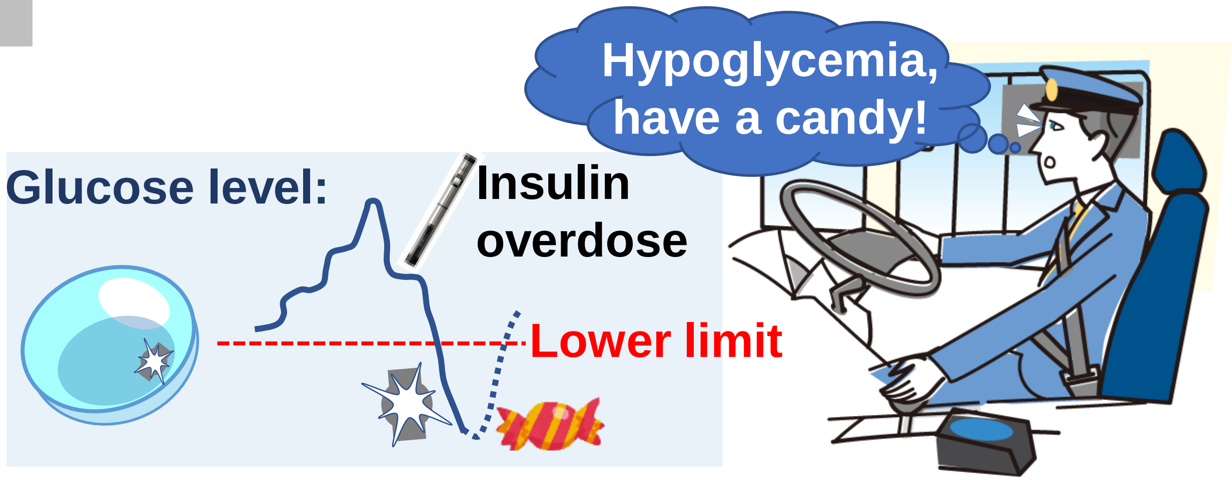
Customized LED [7]

[7] J. Pandey et al., TBioCAS, Dec. 2010, pp. 454

Motivation

Our proposal:
SC powered + BFC input / LED

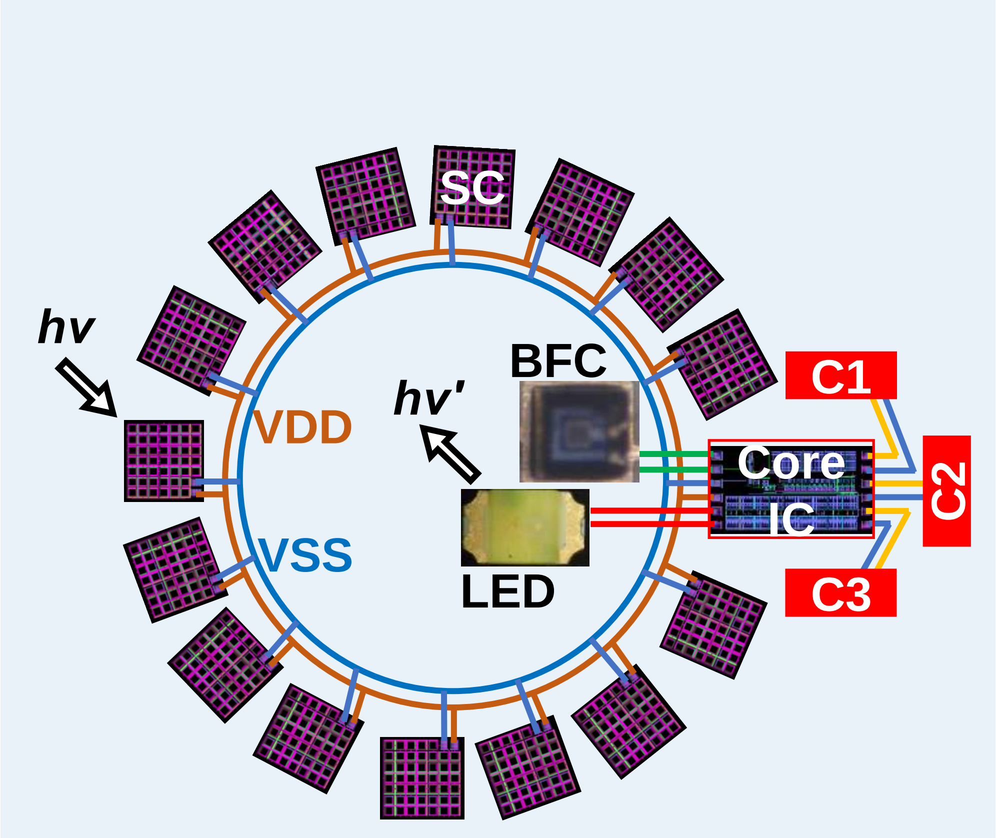




- ☐ Localized energy generation by SC
- ☐ Localized information display by LED

Objective

- ☐ To realize a fully stand-alone RF-less biosensing system for CGM contact lens



- ☐ Target specifications of Core IC:
  - High input impedance for BFC [GΩ]
  - High sensitivity for glucose range [0–25 mg/dL]
  - High V_{LED} for LED driving [>3 V]
  - Low standby power consumption [<150nW]
  - Low area cost [<1 mm^2]

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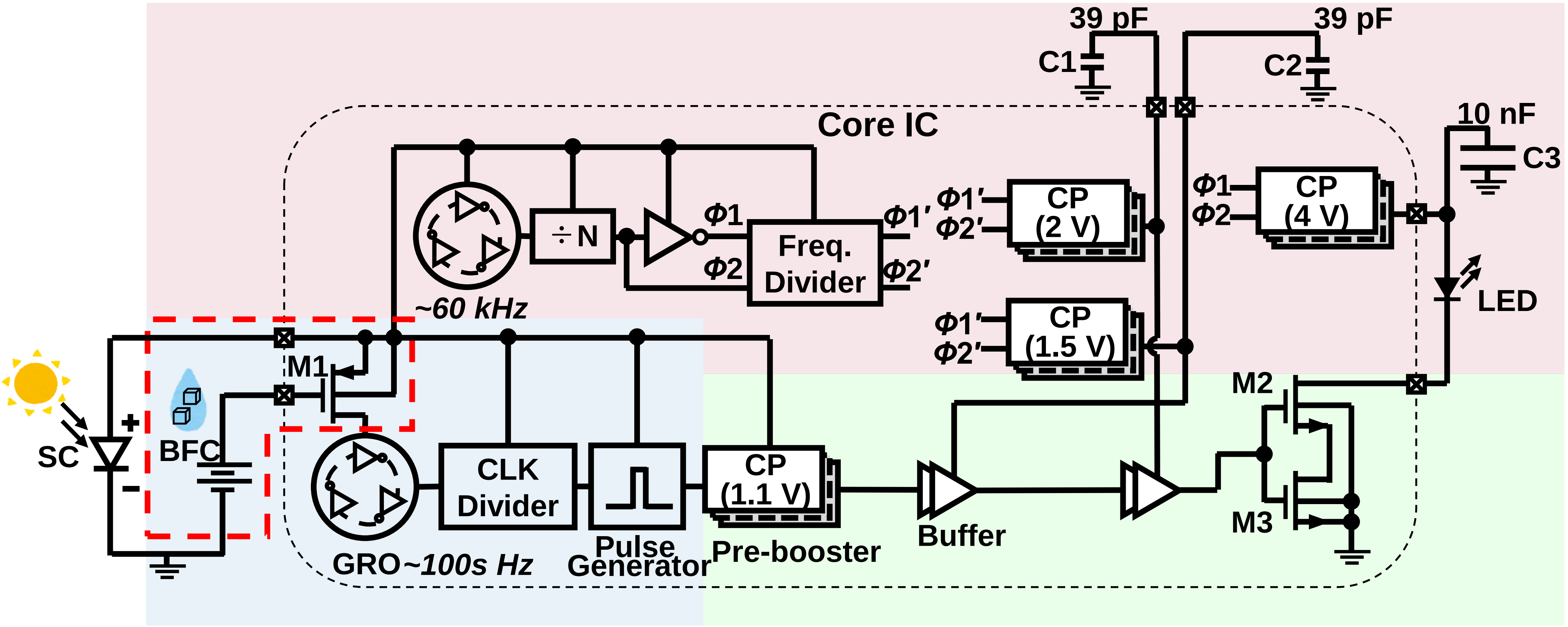
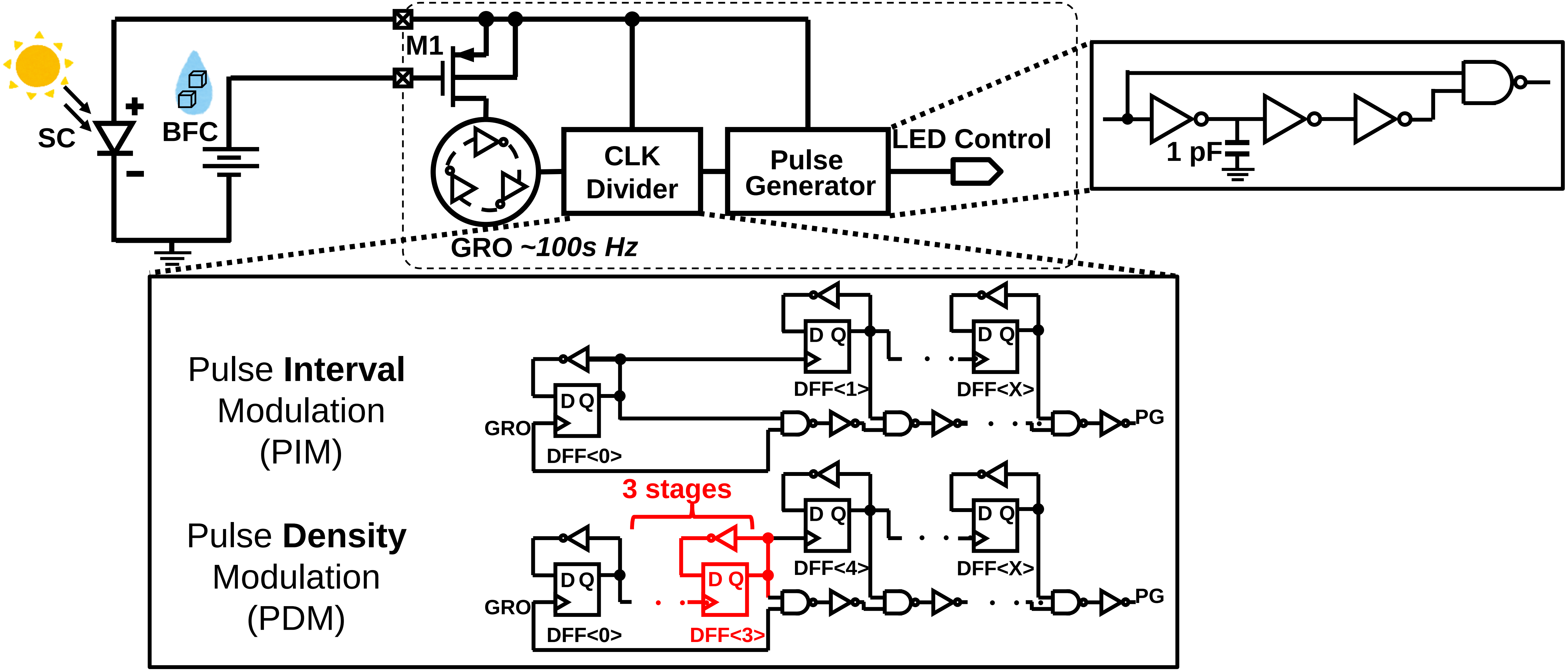
CGM System Architecture

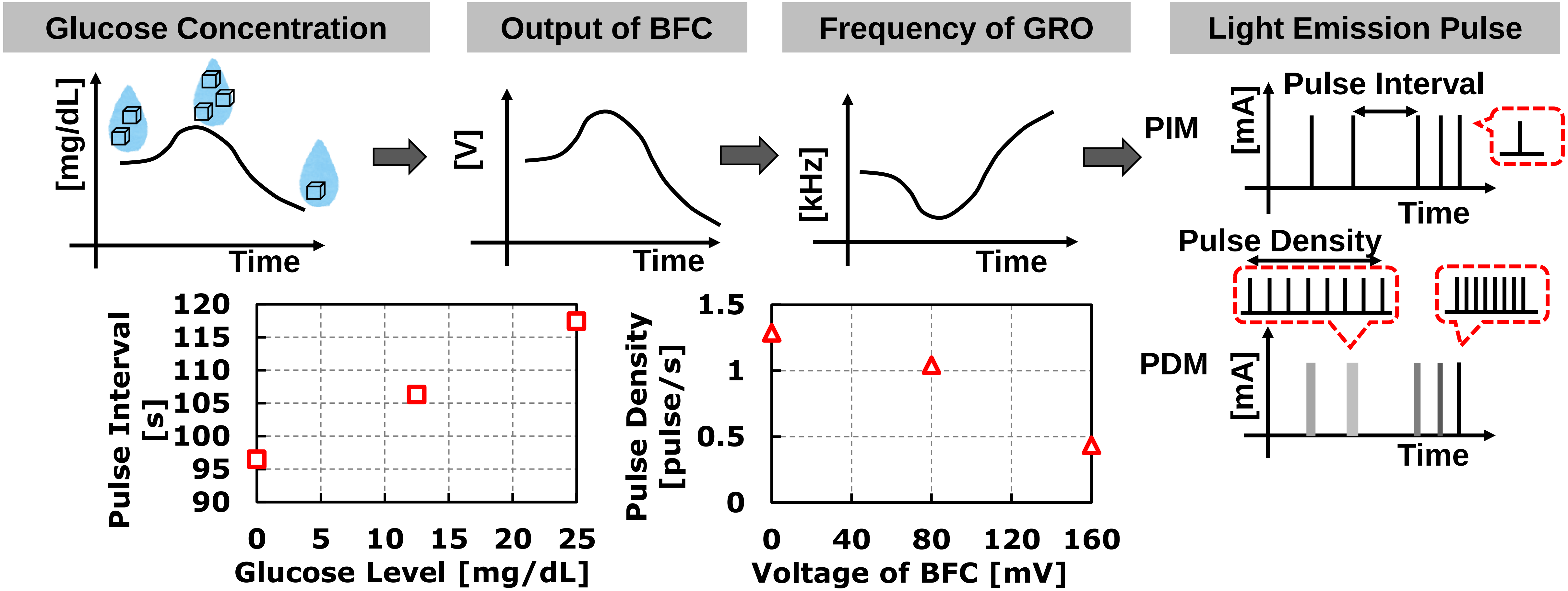


- Function division: signal modulation, LED driving, LED switching
- Sensing part: M1 provides high input impedance for BFC-input port

LED Lighting Timing Modulation



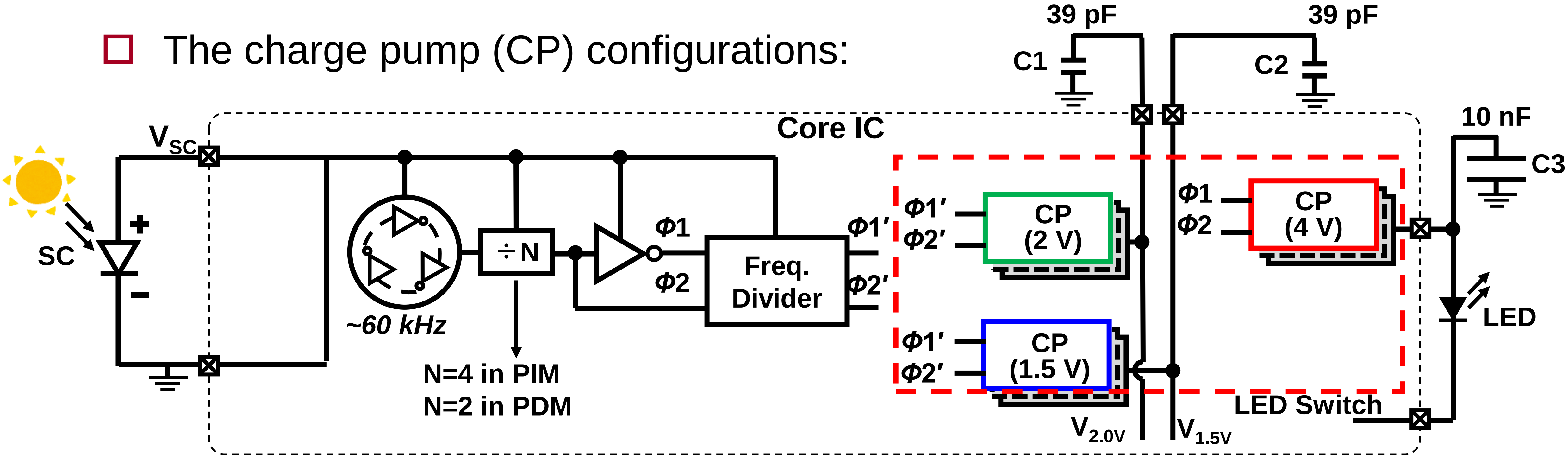
LED Lighting Pattern of PIM and PDM

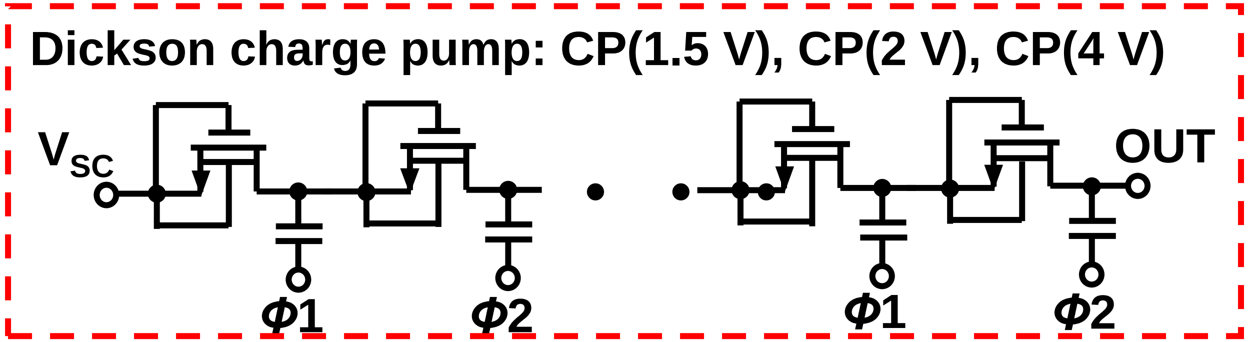


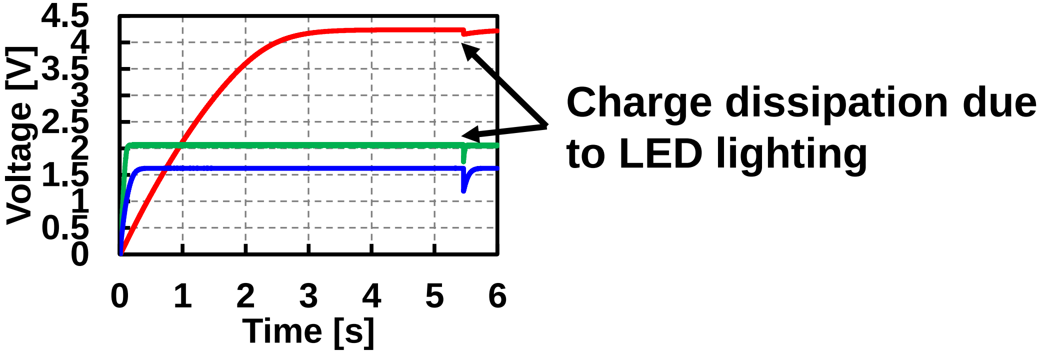
- The pulse interval and pulse density indicate the glucose information

LED Driving Capability

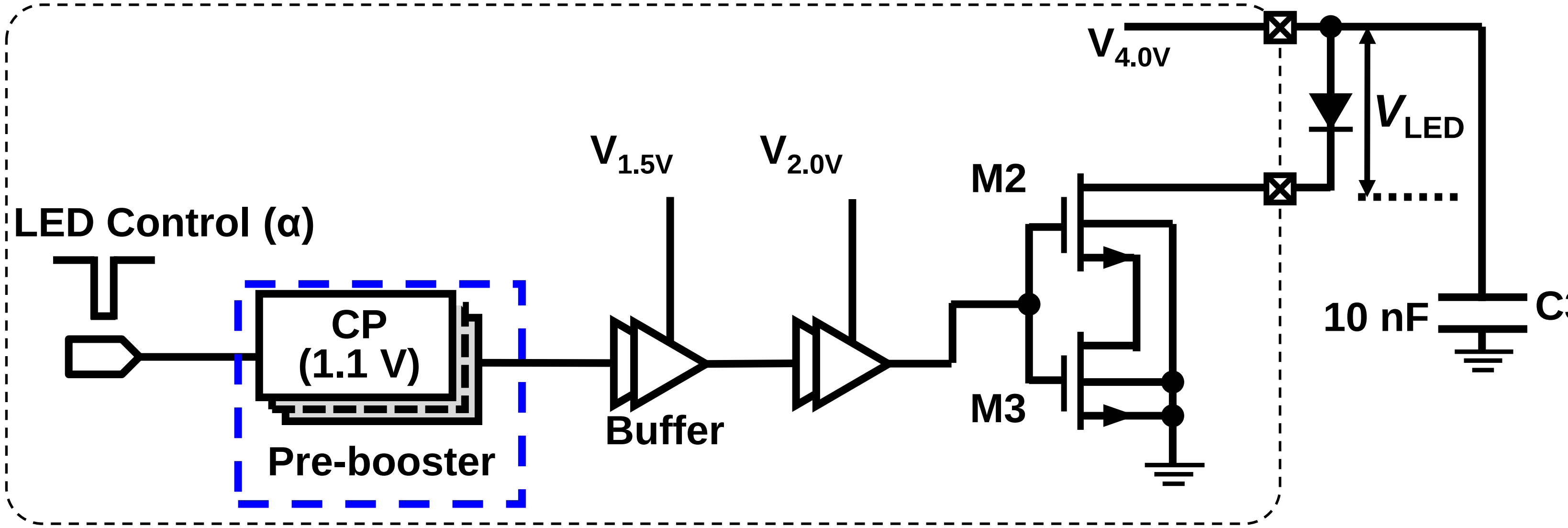
- The charge pump (CP) configurations:

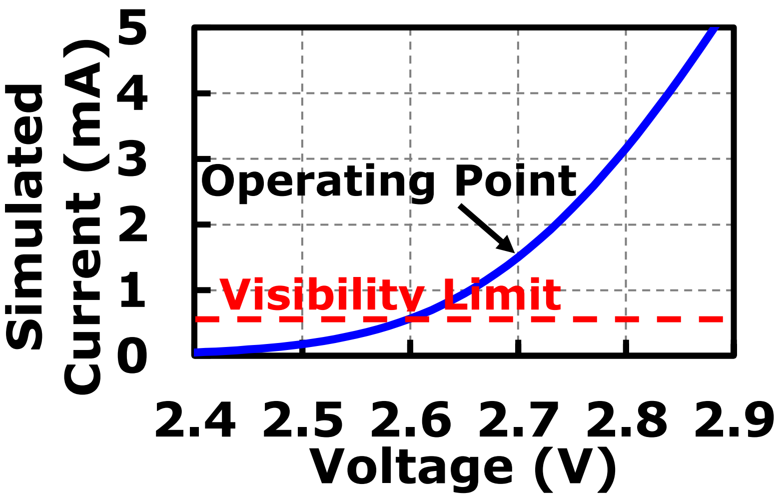


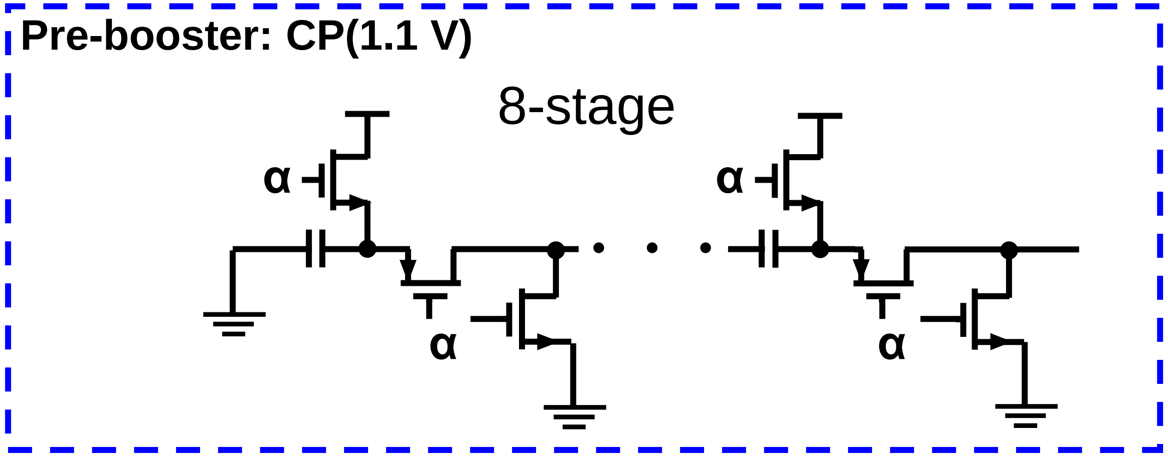




Switch Gate Driver







- ☐ Simulated I-V Curve (right top) of the LED with the LED SPICE model
- ☐ The buffers switch on the LED at

$$V_{\text{LED}} = 2.7\ \text{V}$$

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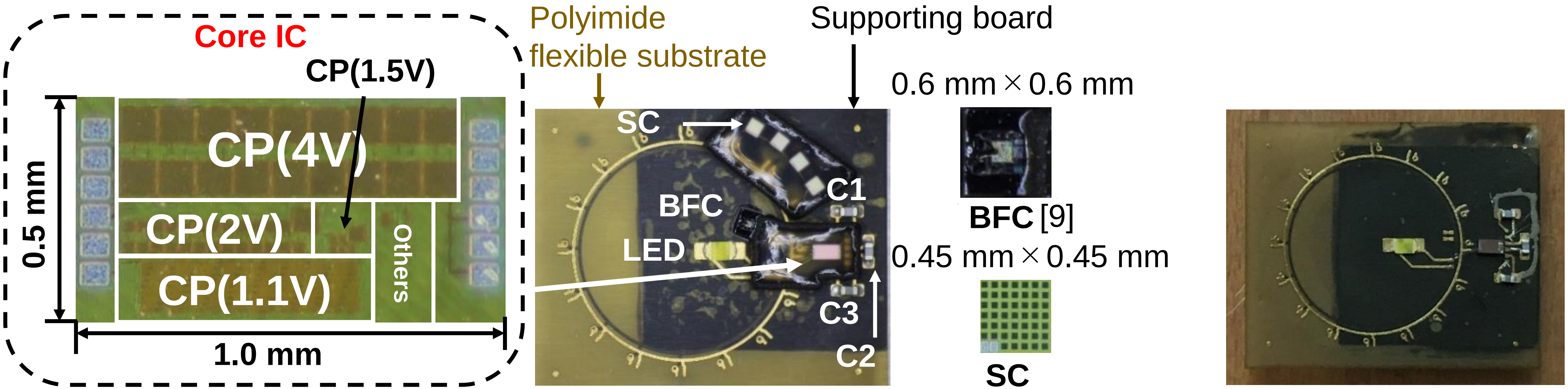
Implemented Prototype



PIM Sample

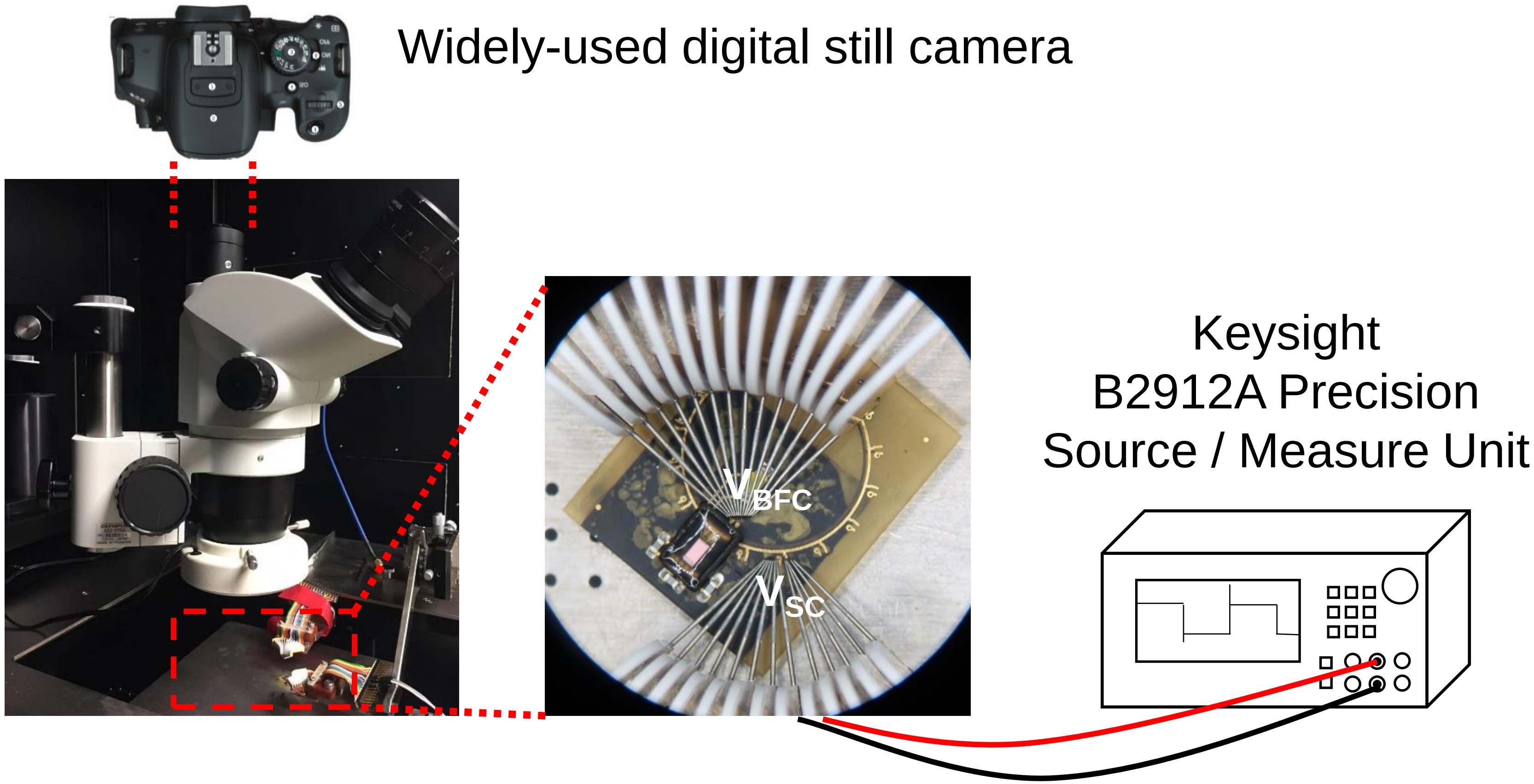
PDM Sample

- ☐ The Core IC and on-lens SCs were implemented in 65-nm CMOS process
- ☐ The Core ICs with PIM and PDM were prototyped separately
- ☐ Commercial LED [11] was utilized to maintain a low cost

[9] S. Arata et al., Jpn. J. Appl. Phys., Mar. 2018, pp. 04FM04

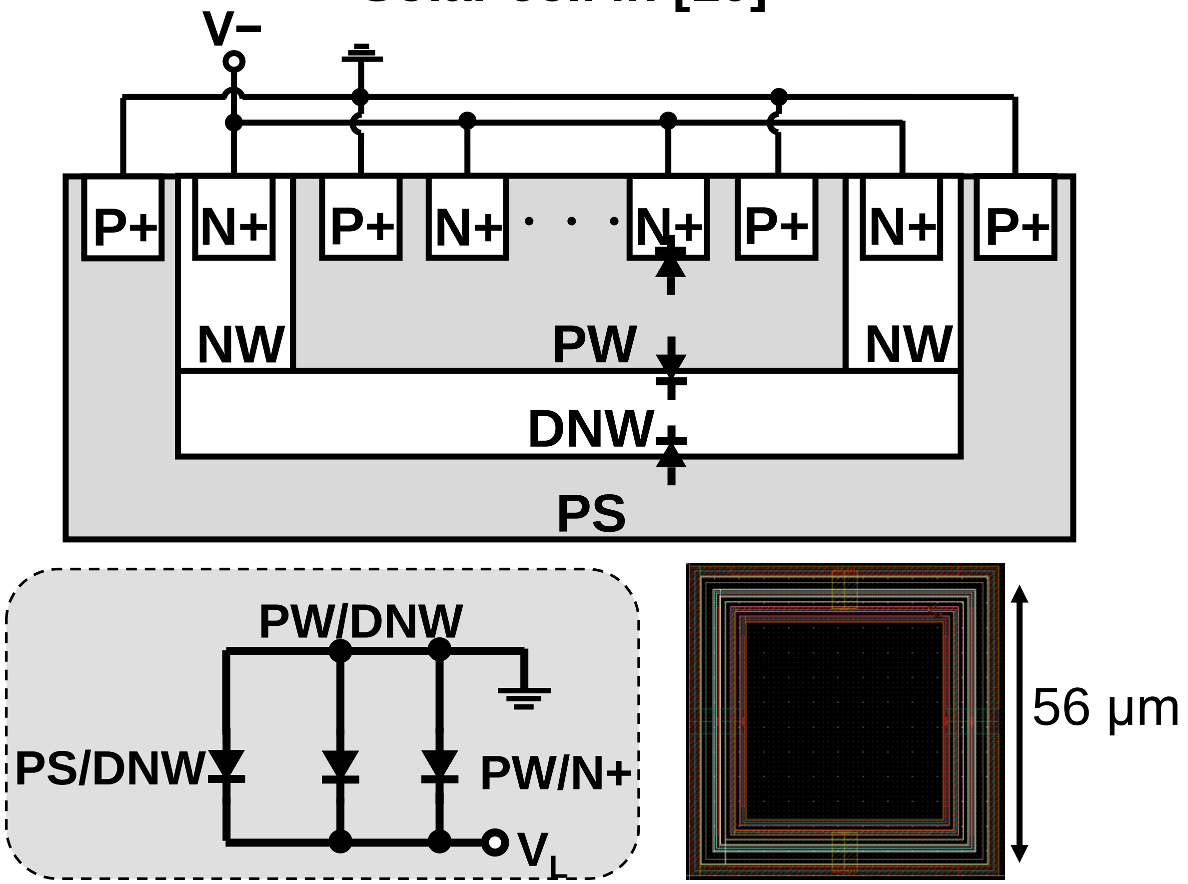
[11] SML-P12x/P13x Series PICOLED, Rohm Semiconductor, 2020

Measurement Setup

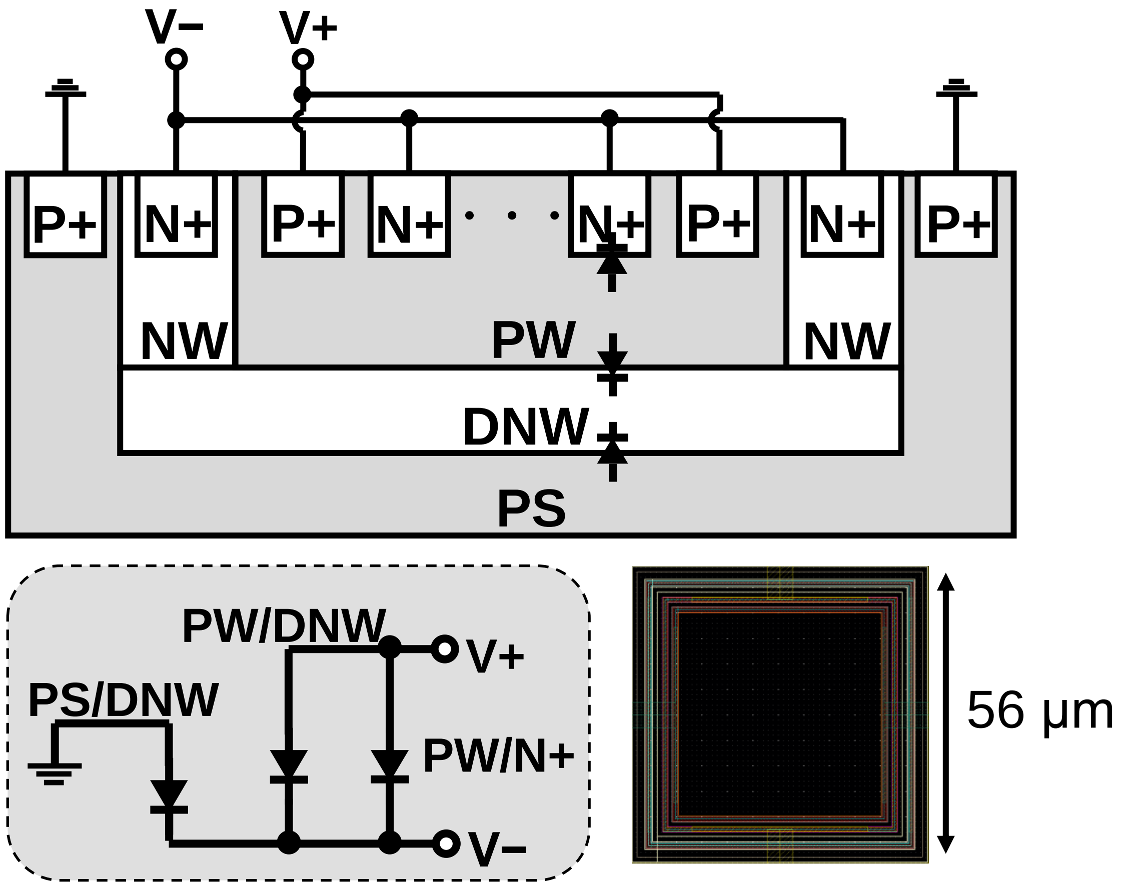


Solar Cell Implementation

Solar cell in [10]



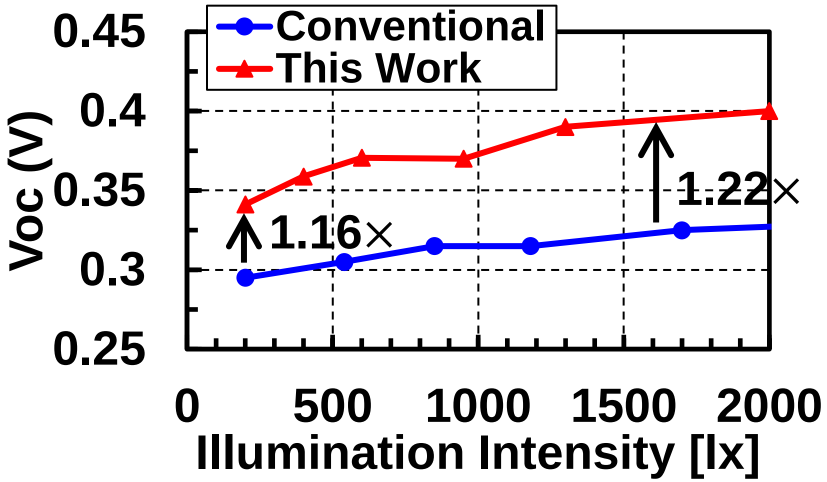
This Work

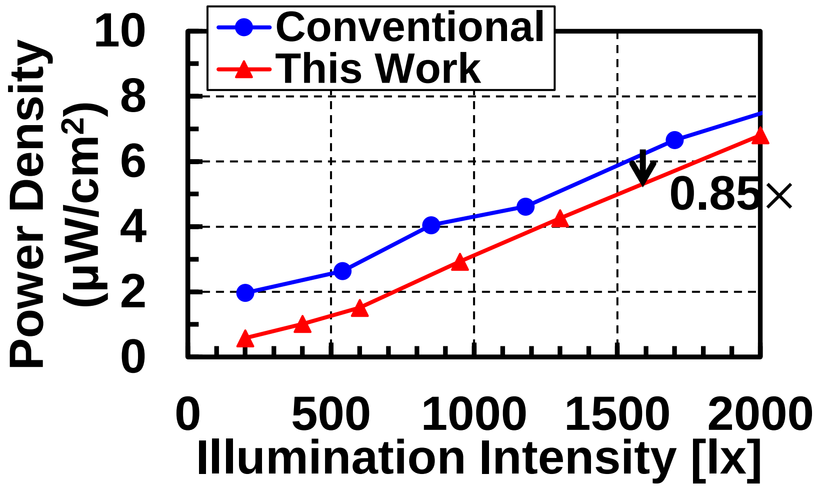


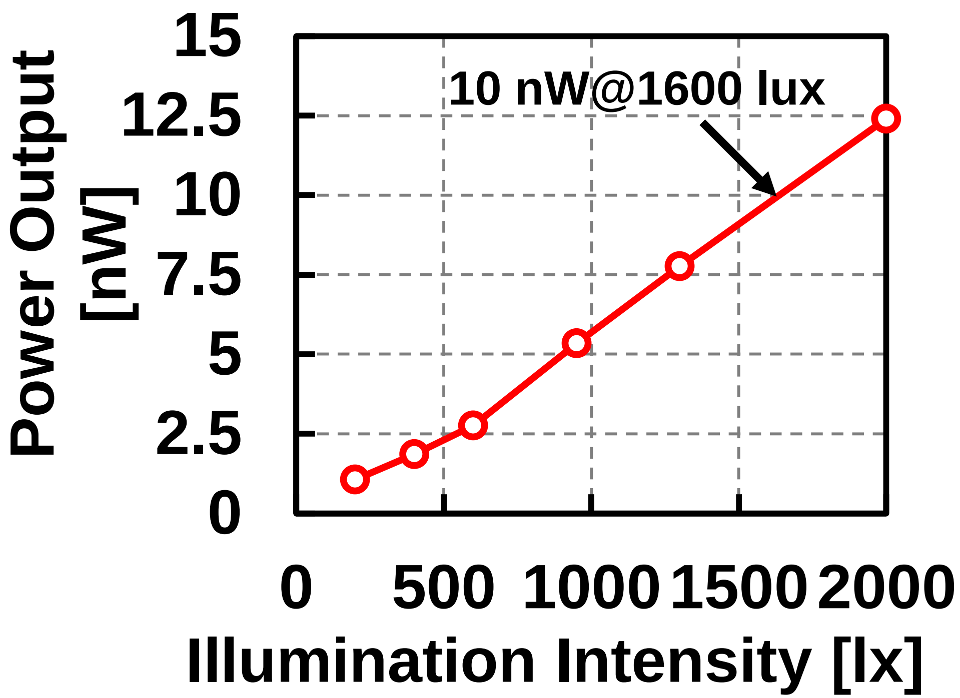
- The connection of PS/DNW is separated to maintain a high open-circuit voltage

[10] A. Kobayashi et al., IEEE ICECS, Nov. 2019, pp. 61

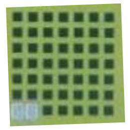
Solar Cell Performance





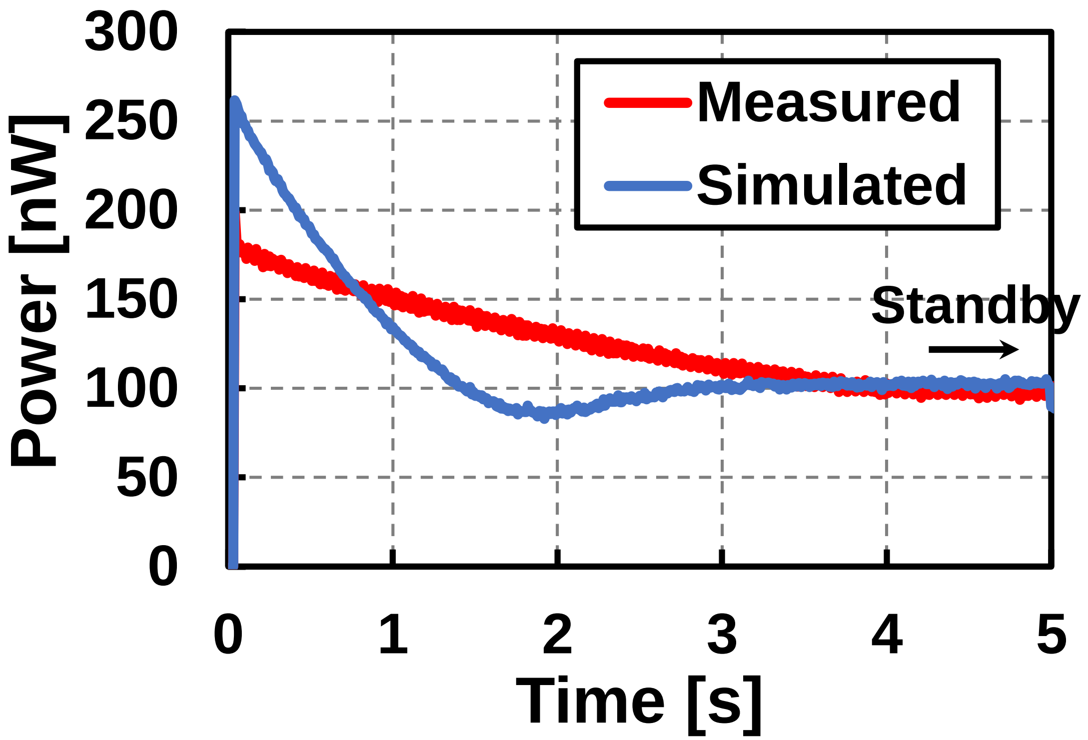


- Single solar cell chip: 0.45 mm × 0.45 mm

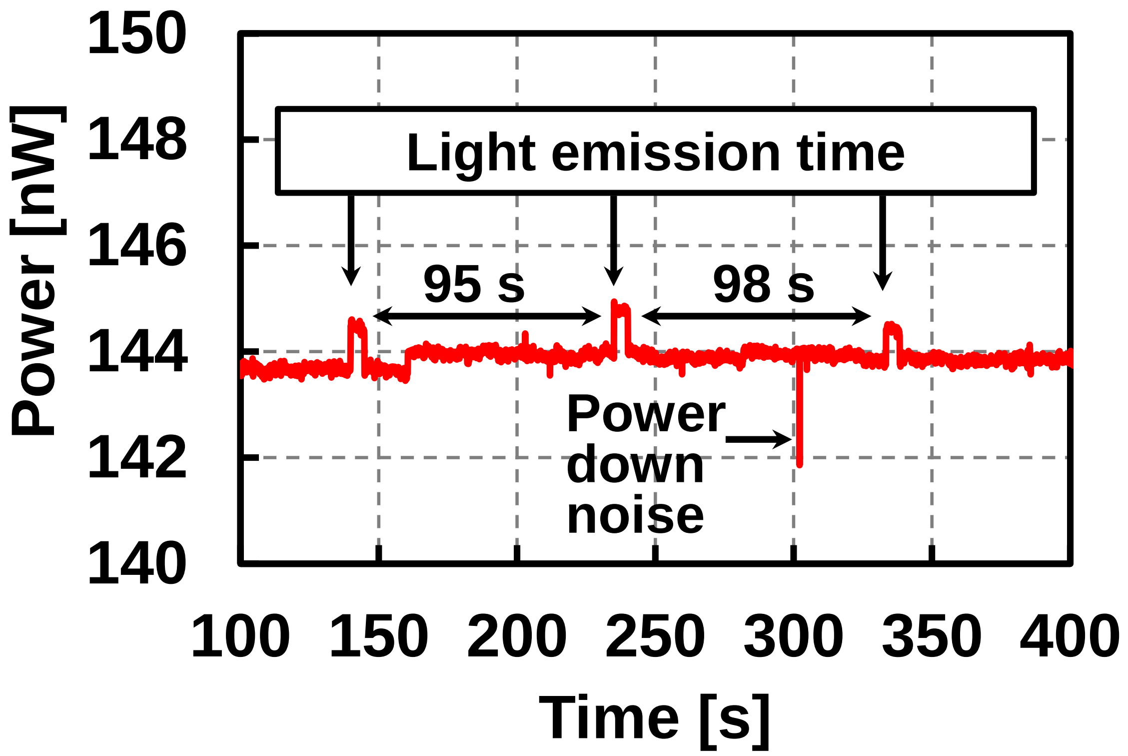


Power Consumption

Cold Start-up (PIM)



Lighting and Standby (PDM)

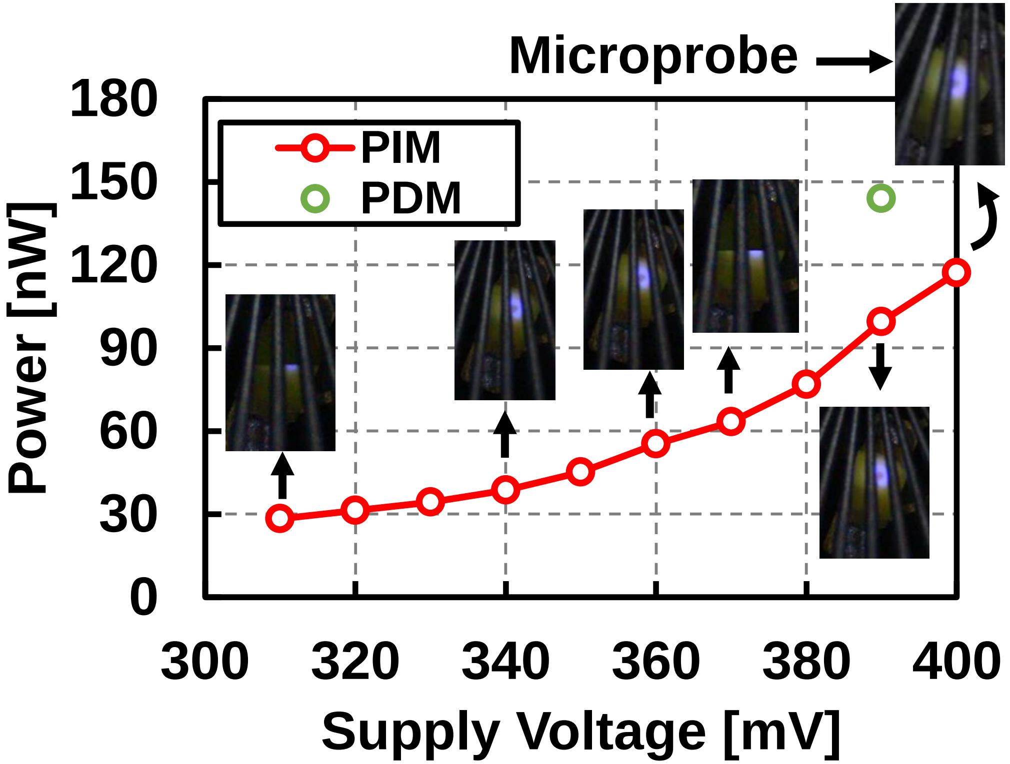


- The standby power of 144 nW at 0.39 V in PDM can be managed by the SC group

LED Lighting and Average Power

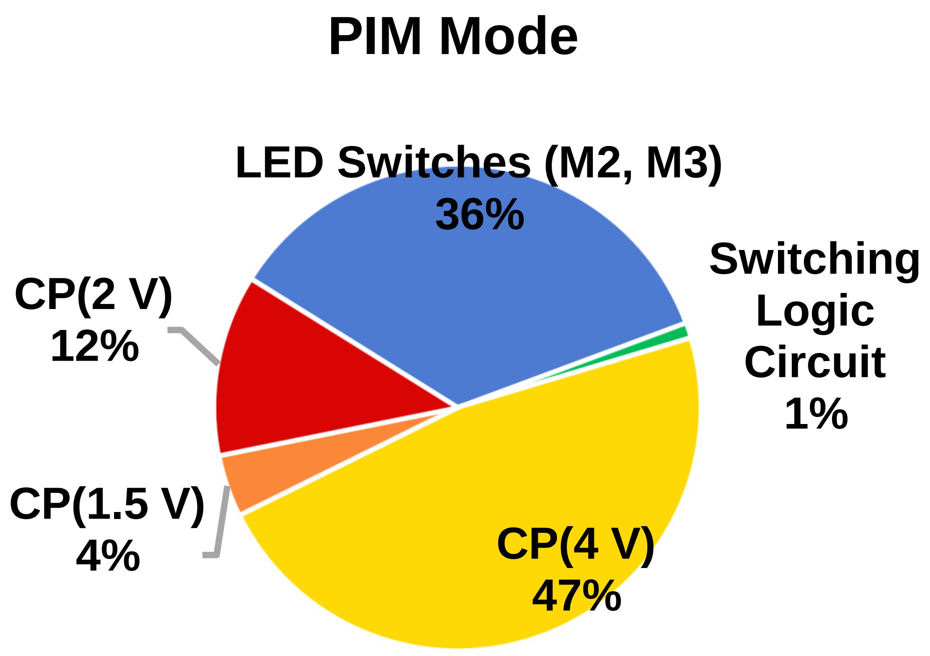
Camera-Captured Image

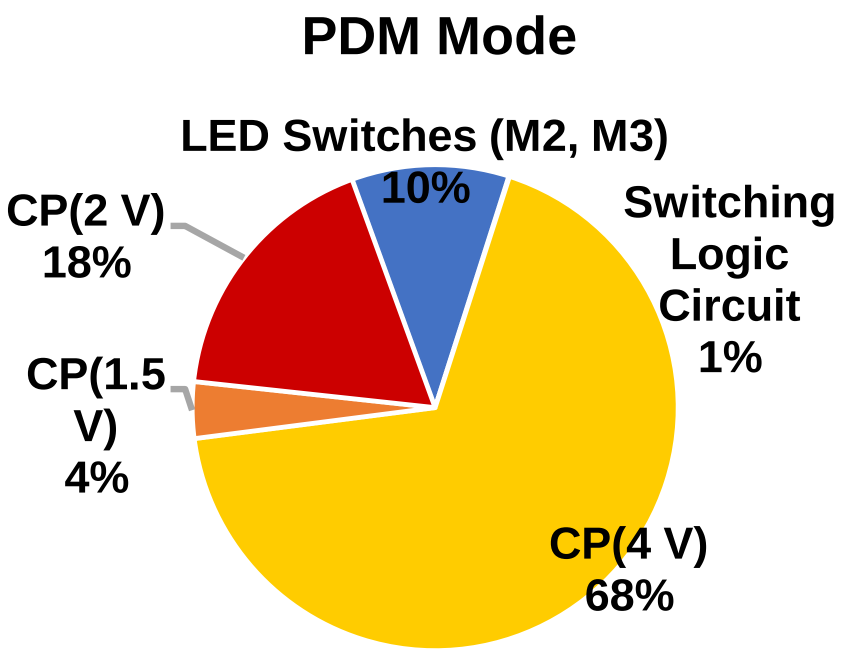
Average Power Consumption



- The light emission has been confirmed in PIM mode from 0.31 V to 0.4 V

Power Breakdown





- The switching logic circuits are sub-nW
- The charge pumps can be power-gated during standby period in future work

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Performance Comparison

	This work	[5] ISSCC'11	[3] BioCAS'18	[6] VLSI'19
Target application	CGM + LED display	CGM + RFID	CGM + Wireless TX	CGM + RFID
Supply voltage [V]	0.31–0.4 (PIM) 0.39 (PDM)	1.2 (regulated)	0.165–0.39	2.0 (regulated)
Energy and sensing source	Solar cell-powered + BFC-input/LED	RF-powered + Potentiostat/RF Tx	BFC-powered + BFC-input/RF Tx	RF-powered + Potentiostat/RF Tx
Modulation scheme	Hybrid PIM/PDM	FM-LSK	Supply-modulated OOK	LSK + OOK
Power	28–117 nW (PIM) 144 nW (PDM)	3 μW (only tag)	0.27–11.8 nW (only TX)	143 nW (only tag)
Off-chip capacitor	1×10 nF 2×39 pF	None	None	1 (RF mode)
External device	Fully stand-alone	RFID Reader/ Writer	Data Receiver	RFID Reader/ Writer
Readout distance	Display on lens	15 cm	> 10 cm	1 cm
Process	65 nm	0.13 μm	65 nm	0.18 μm
Chip area [mm^2]	0.5	0.5	0.1482	2.25
Glucose level [mg/dL]	0–25	0–36	180–540	3–25

Summary

- This work demonstrates the feasibility of a SC-powered BFC-input stand-alone RF-less CGM system for the first time

- This biosensing system shows the feasibility of helping the users to prevent low-glucose conditions with the on-lens LED

- The prototype shows the possibility of operation by on-lens solar cells under office-room ambient light

Reference

- [1] Eversense, https://www.ascensiadiabetes.com/eversense/eversense-cgm-system/
- [2] Z. Xiao et al., “An Implantable RFID Sensor Tag toward Continuous Glucose Monitoring,” in IEEE Journal of Biomedical and Health Informatics, vol.19, no. 3, pp. 910–919, May 2015.
- [3] K. Hayashi et al., “A 385μm × 385μm 0.165 V 0.27 nW fully-integrated supply-modulated OOK CMOS TX in 65nm CMOS for glasses-free, self-powered, and fuel-cell-embedded continuous glucose monitoring contact lens,” in Proc. IEEE Biomed. Circuits Syst. Conf., Oct. 2018, pp. 379–382.
- [4] Y. Liao, H. Yao, A. Lingley, B. Parviz and B. P. Otis, “A 3μW CMOS Glucose Sensor for Wireless Contact-Lens Tear Glucose Monitoring,” in IEEE Journal of Solid-State Circuits, vol. 47, no. 1, pp. 335–344, Jan. 2012.
- [5] Y. Liao, H. Yao, B. Parviz, and B. Otis, “A 3μW wirelessly powered CMOS glucose sensor for an active contact lens,” in Proc. IEEE Int. Solid-State Circuits Conf., Feb. 2011, pp. 38–40.
- [6] C. Jeon et al., “A 143nW glucose-monitoring smart contact lens IC with a dual-mode transmitter for wireless-powered backscattering and RF-radiated transmission using a single loop antenna,” in Proc. IEEE Symp. VLSI Circuits, Jun. 2019, pp. C294–C295.
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- [8] K. Niitsu et al., “Enhancement in open-circuit voltage of implantable CMOS-compatible glucose fuel cell by improving the anodic catalyst”, Jpn. J. Appl. Phys., vol. 56, p. 01AH04, 2017.

Reference

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Acknowledgement

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Thank you for listening!