Wearable and Battery-Free Health-Monitoring Devices With Optical Power Transfer

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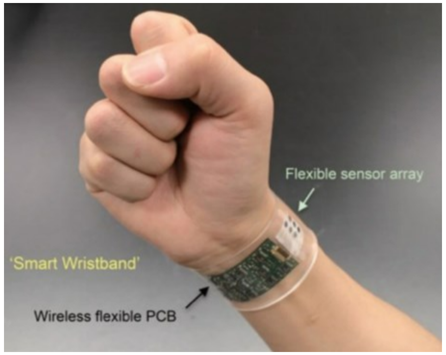
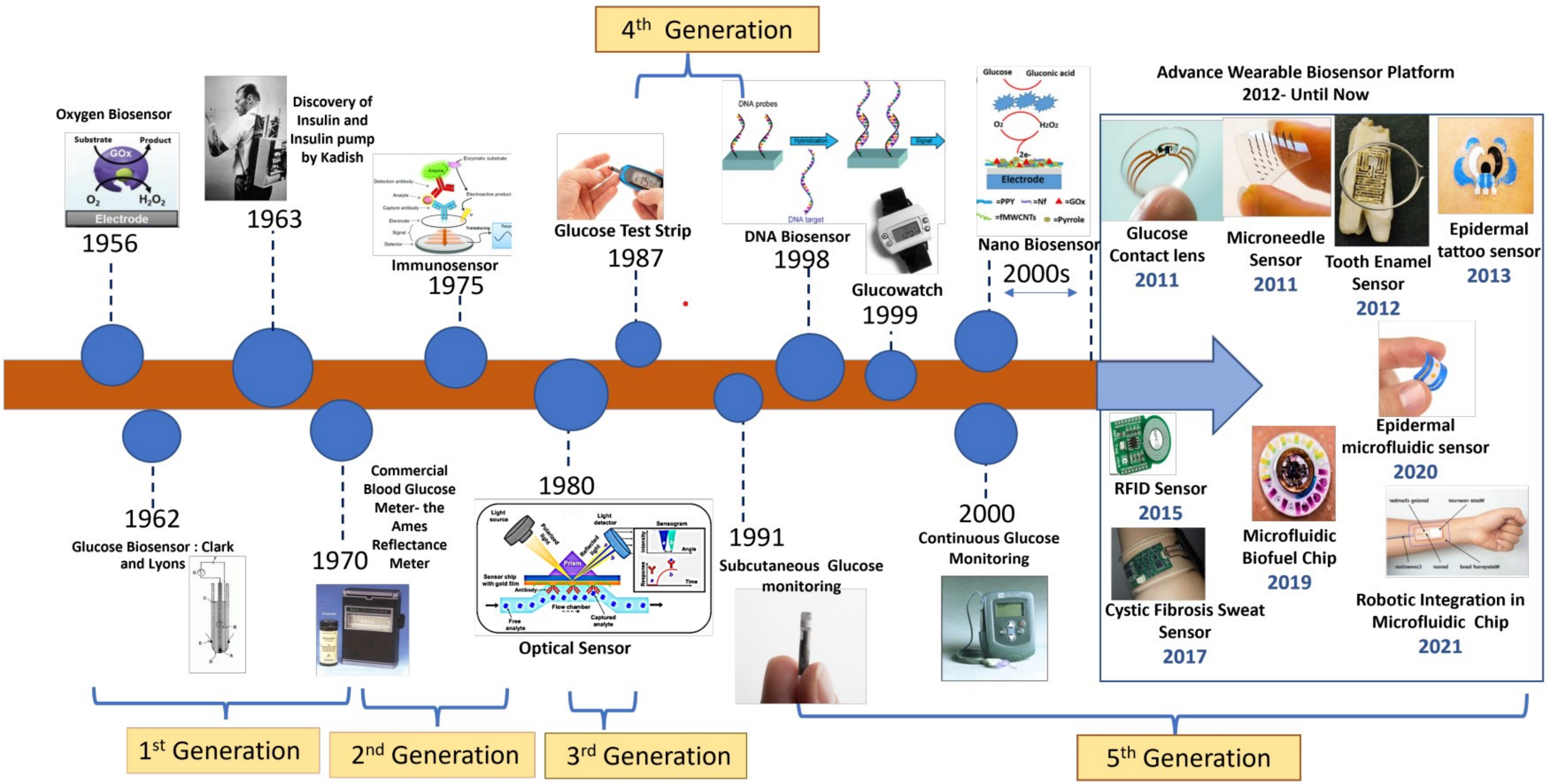
Introduction

- Wireless epidermal attachable devices are smart electronic devices used for
  - Monitor Physiological signal
  - real time heath monitoring
  - transmit data wirelessly etc
- Personalized healthcare helps both patients and healthcare professionals to
  - Prevent detection, diagnosis, follow-up and decision making by improving the capability
  - Predict health risks
  - Determine and quantify the dynamics of disease development
  - Target therapeutic approaches to the needs of the individual.



History of Biosensor development



❖ *Zafar, H., Channa, A., Jeoti, V., & Stojanović, G. M. (2022). Comprehensive review on wearable sweat-glucose sensors for continuous glucose monitoring. Sensors, 22(2), 638.*

Introduction

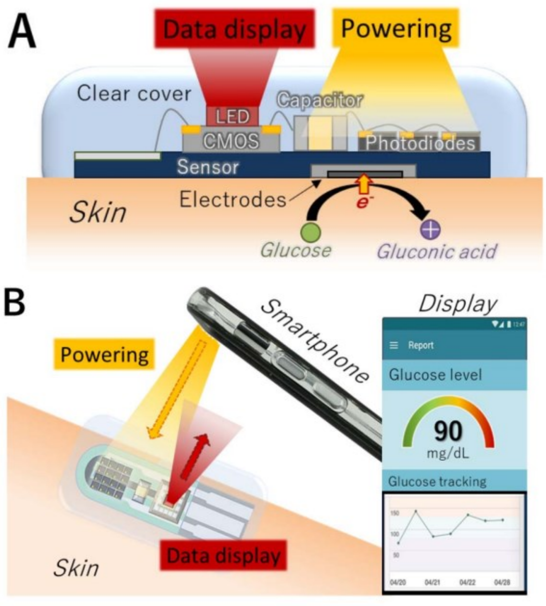
- One of the bottlenecks of wireless device technology is a battery
  - It limits system lifetime.
  - Increases system volume
  - Unhandy maintenance
- To solve the limitation of battery, a wireless energy harvesting system from the ambient energy source is introduced.
- It mainly accumulate power from an ambient energy source like.
  - Solar/Light
  - Thermal
  - Wind
  - Vibration

Introduction

- Light, including solar energy can be directly converted into electric energy by the photovoltaic effect.
- The typical voltage generated by a silicon solar cell is approximately 0.4 V.
- So sufficient voltage can obtain using series-connected photovoltaic cells.
- Amperometric measurement:-

Objective

- Design a device to easily attach to human skin like a band.
- The device operates
  - By using a smartphone flashlight
  - The power from the power-transfer system operates a measurement system
- Detects a glucose concentration from sweat.
- Data display system receives the measured glucose concentration and generates a data signal.
- This data signal can be collected and displayed by a camera on the smartphone.



A = Side view Structure
B = Conceptual operation of battery-free attachable device

Background Study

- Electrochemical sensors has been developed for noninvasive measuring electrolytes in biofluids such as **sweat, tear, or saliva.**
- They measures the concentration of a target metabolite by oxidizing or reducing.
- From the oxidation/reduction reaction, electrons are produced/reduced.
- The electron exchange creates a current at Bio/CMOS interface which has the opposite direction in oxidation and reduction.
- The current from this reaction is called “Faraday current” as an example of glucose oxidation

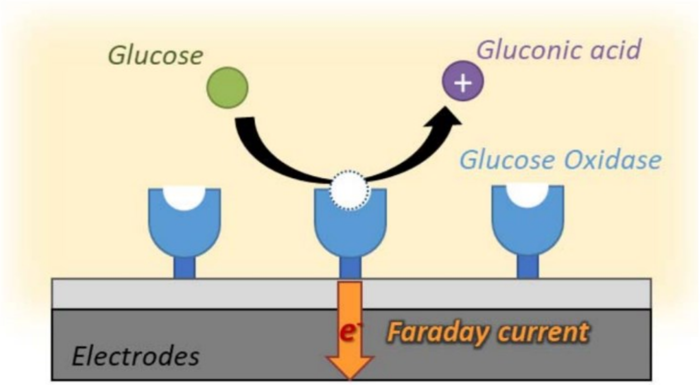
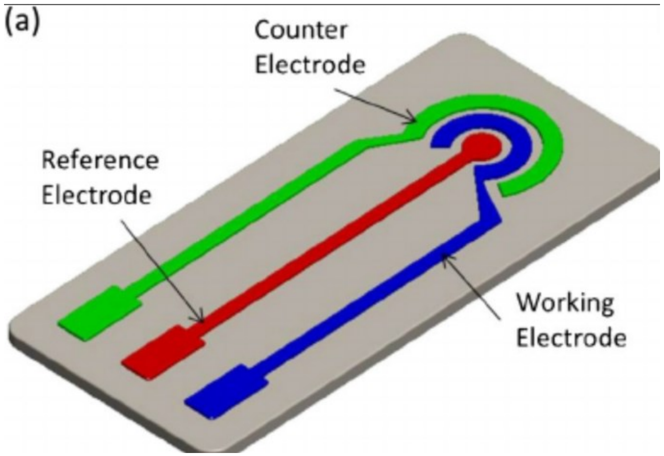


Fig. 1. Chemical reaction and illustrator of glucose oxidation reaction on working electrode of electro chemical sensor.x.

Background Study

- Three electrode electrochemical sensor contains –
  - Working electrode : contains all the bio- or nano materials contained by the biosensor
  - Reference Electrode: Supplies a right potential to get the right reaction
  - Counter electrode: To measure the faraday current



Background Study

- 24 hours Glucose monitoring is very important for diabetes patient
- Hence chose Glucose as the target metabolites.
- If pancreas does not release enough insulin →
  - Blood glucose level can be too high
  - Can damage nerves, blood vessels
  - Lead to hearth disease and health problems
- Commonly used glucose monitoring is the finger prick method.
- Limitation of blood-based type:
  - Pain and accompanying intense stress of repetitive blood collection

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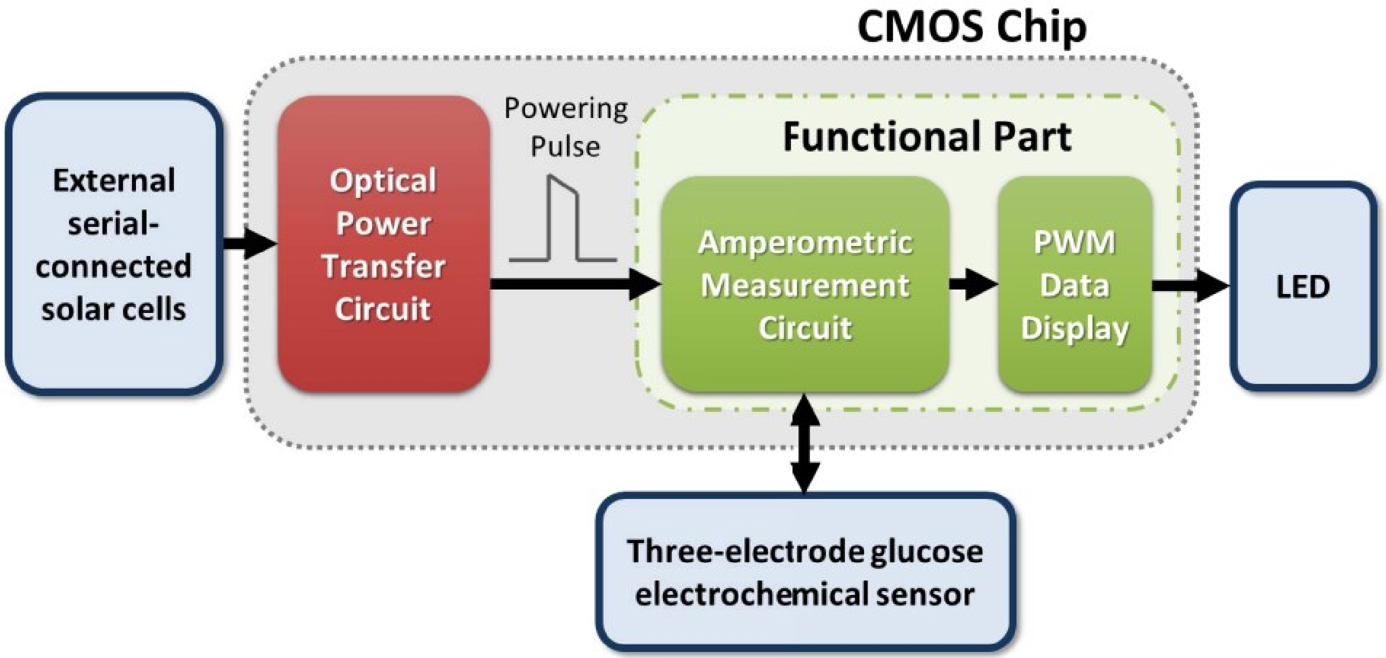
Method



Block Diagram of battery free attachable health monitoring device

Optical Power Transfer Part

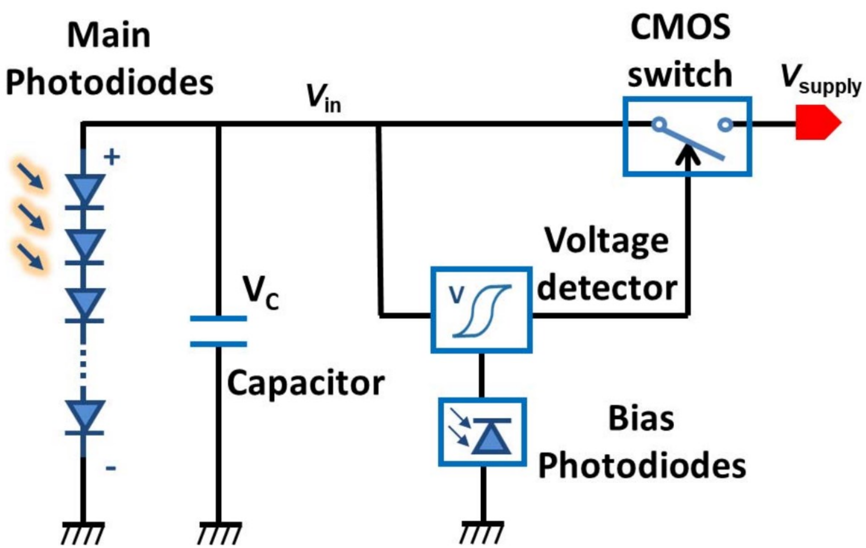


Figure: Block diagram of optical power transfer part.

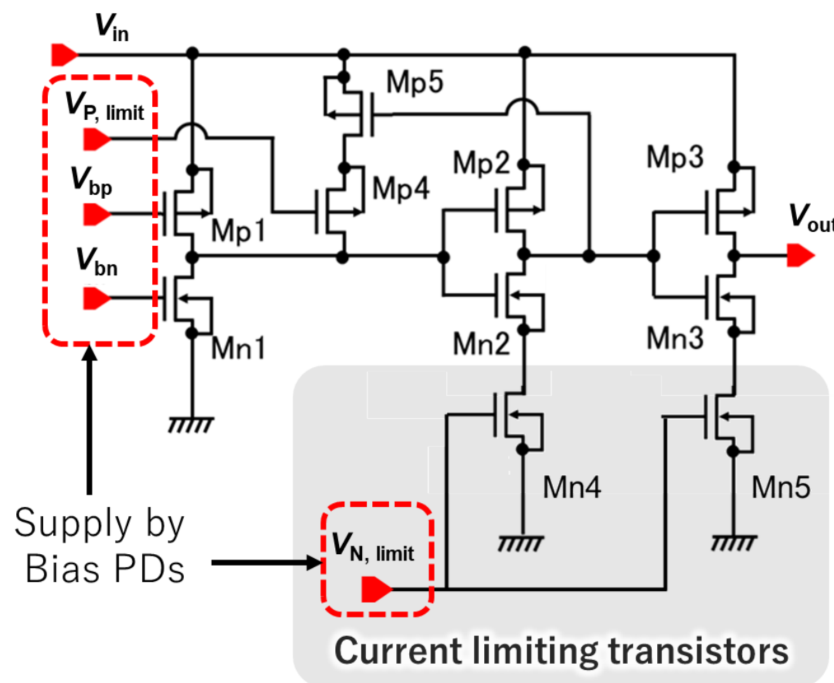


Figure. MOS-level schematic of voltage-detector

Optical Power Transfer Part

- The photodiodes convert light to electrical power
- Charge the external capacitor with the current generated by the photovoltaic effect.
- When Vc = Von, Supplies power to functional part
- So, the capacitor is started discharging.
- Then Vc = Voff, state, Stop supplying power and start charging
- Therefore, the supply power signal is intermittent pulses with voltage decay.

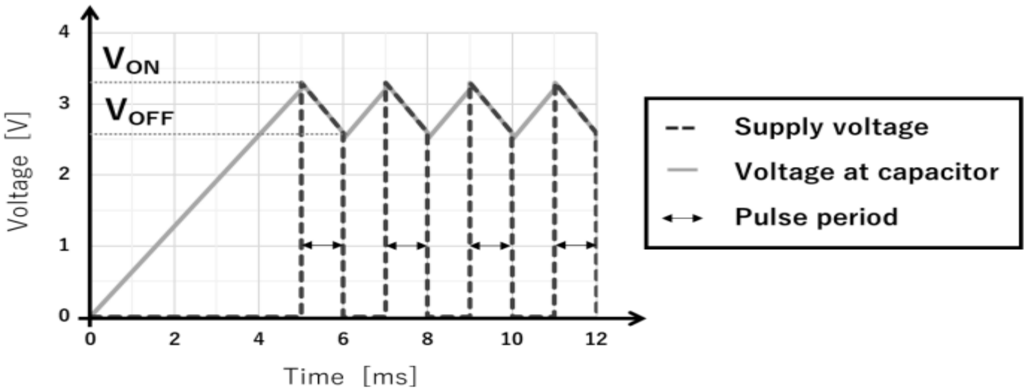
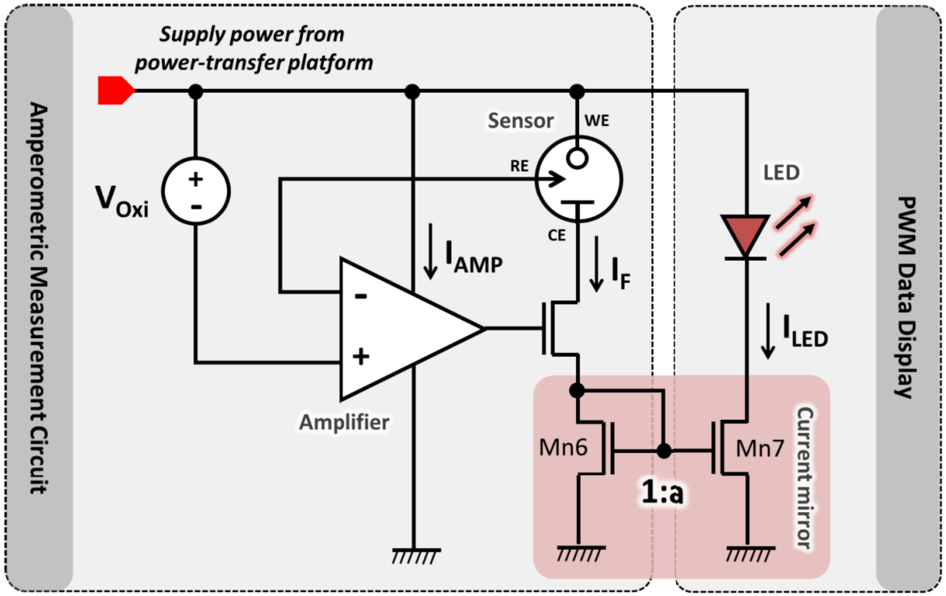
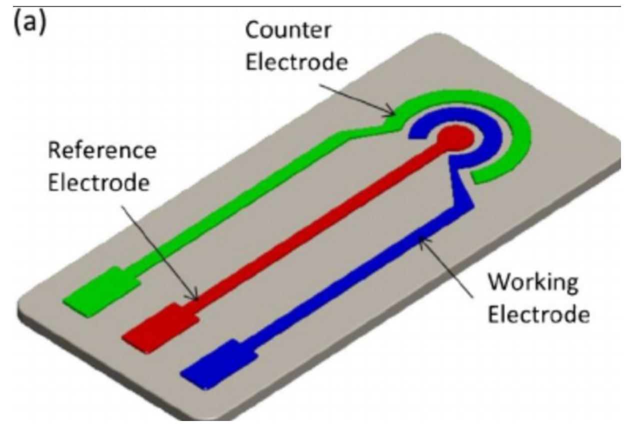


Figure: Simulated signal of optical power transfer part.

Functional Part



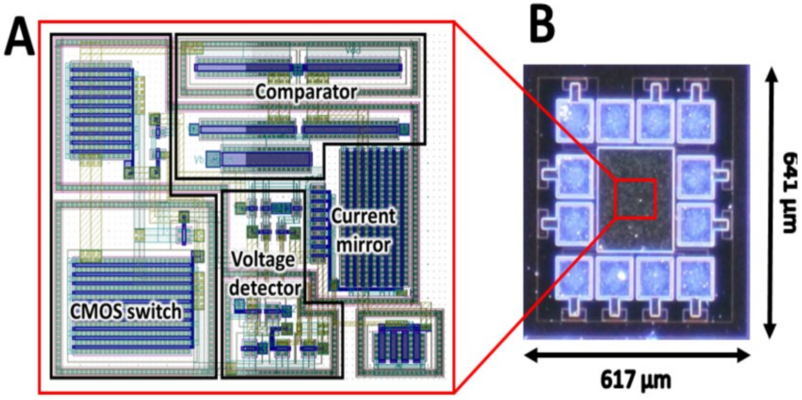


- A three-electrode electrochemical Sensor is used, $V_{WE\text{-}RE} \sim 0.45v$
- A current mirror to copy Faraday current from CE and build up a new LED current to transmit measured value.
- Total Current consumption, $I_{Total} = I_{AMP} + I_F + I_{LED} = I_{AMP} + (1+a)\, I_F$
- Total charges for single pulse, $Q_{Pulse} = C \times (V_{ON} - V_{OFF})$
- Duration for single pulse, $T_{Pulse} = Q_{Pulse} / I_{Total}$

Manufactured Chip

SPECIFICATIONS OF CMOS HEALTH MONITORING CHIP

Specification	Details
fabrication process	0.35 µm two-poly four-metal standard CMOS
circuit layout size	67.15 x 50.35 um^2
chip size (with pads & ESD)	641 x 617 μm^2
list of included circuits	- optical power transfer circuit - amperometric measurement circuit - pulse-width-modulated (PWM) data display circuit
required external components	- two set of series connected photodiodes for powering and biasing - capacitor - three-electrode electrochemical sensor - light-emitting diode (LED)



Results

1. Intermittent operation of Optical power transfer
2. Completely Optical Power operation
3. Relation between Concentration and PWM Light pulse
4. Device Performance in artificial sweat detection

Intermittent operation of Optical Power transfer

- A function generator is used instead of photodiodes
- Constant 0-4v supply
- Functional part stop when supply voltage is <2.6v

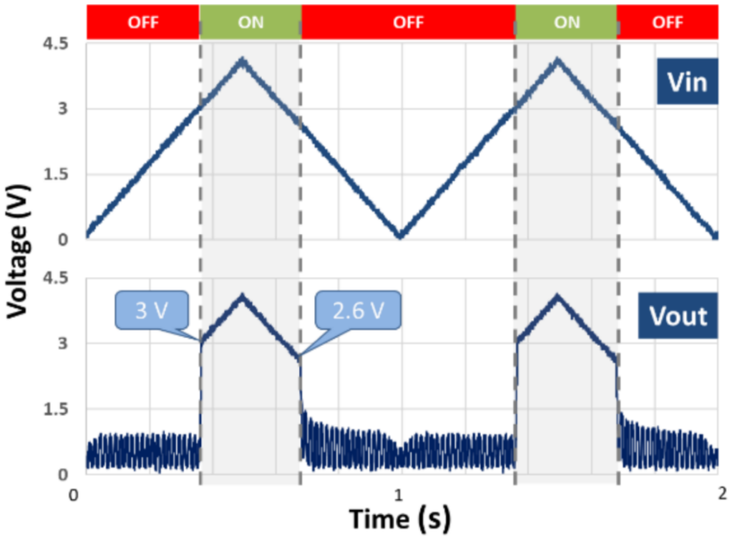
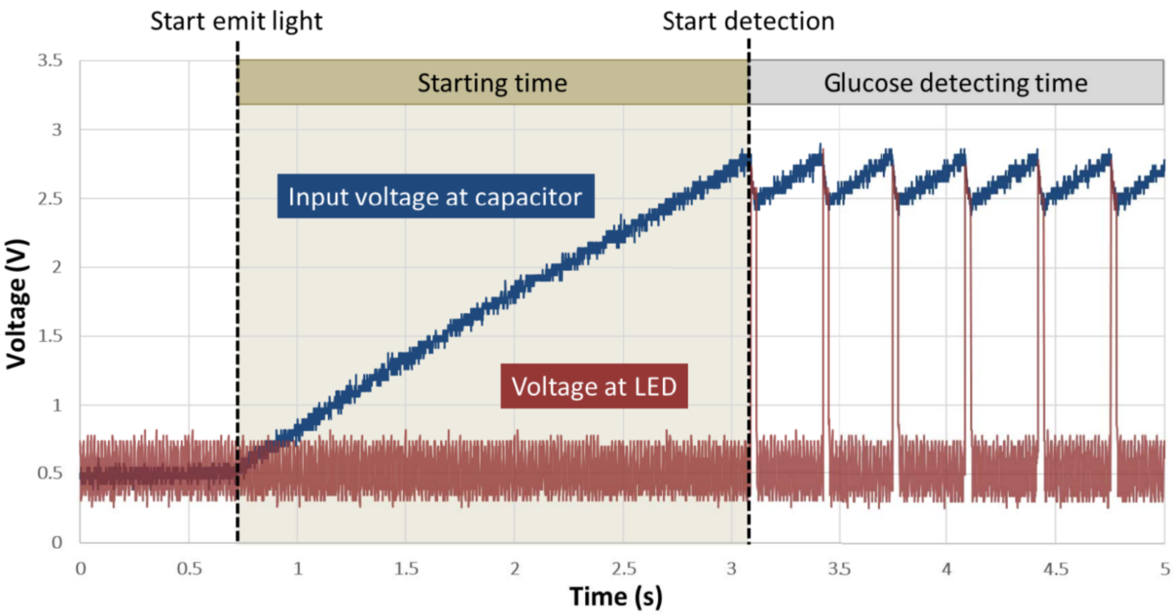


Figure: Switching Characteristics of optical power transfer circuit

Completely Optical Power operation



Input voltage = 4v (10PD)
Oxidation voltage = 0.4v
Bias voltage in amplifier = 0.4v
Electrochemical sensor = GluTest by Kenkyusho co. ltd
Data display = Blue LED

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Relation between Concentration and PWM Light pulse

- Faradey Current,
  - $I = \frac{nFAC\sqrt{D}}{\sqrt{\pi t}}$
  - n= Number of electrons
  - F = Faraday constant
  - C = Target Concentration
- The higher glucose concentration the higher faraday current.
- The period of LED emitting pulse is shorter
- Also, shorter the capacitor discharging time

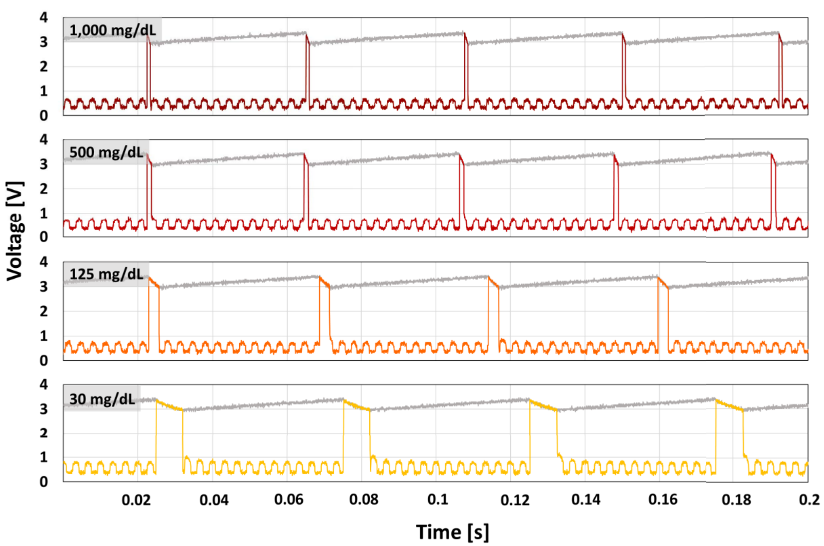

Figure: Tracking signal of LED in fully optical operation

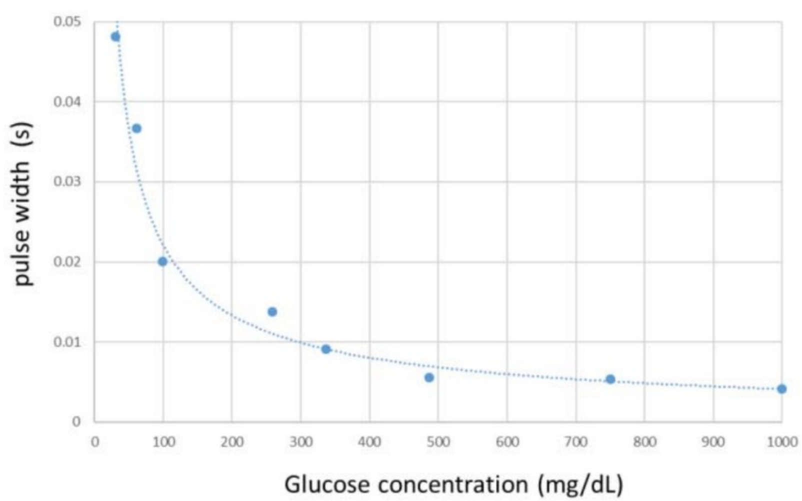

Figure: Relation between pulse width and glucose concentration

Device Performance in artificial sweat detection

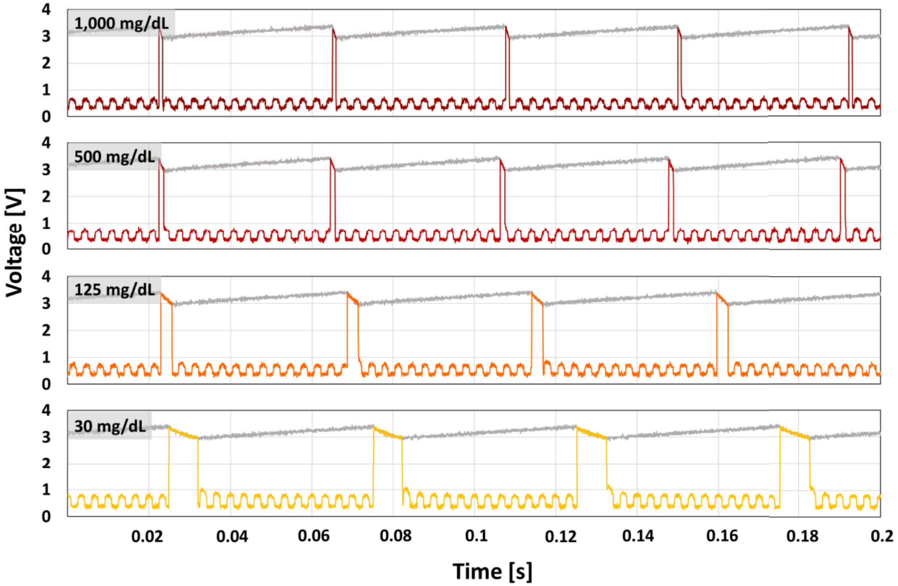

Figure: Tracking signal of LED in fully optical operation

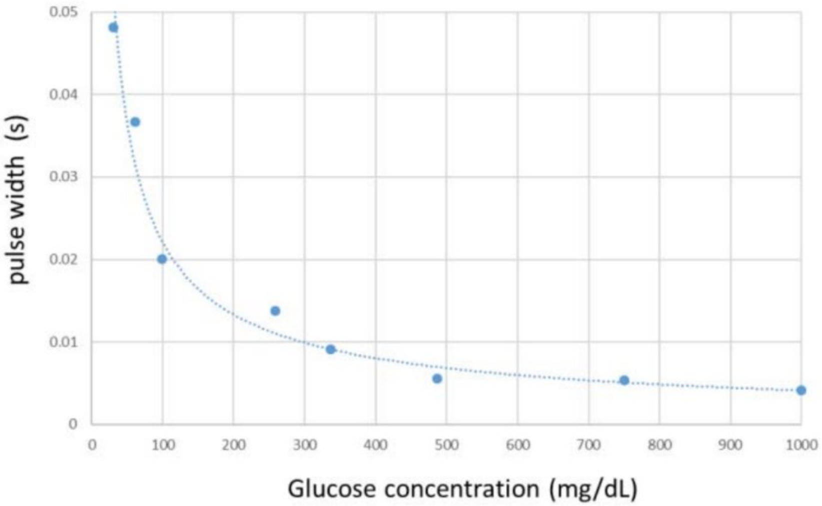

Figure: Relation between pulse width and glucose concentration of artificial sweat

Discussion

- The pulse width of pure glucose solution is shorter than the artificial sweat.
- Current mirror circuit increase the PWM of the data display part
- Optical Power transfer part is flexible.
- Distance between device and light source around 15cm
- Optical power transfer part operating current is 2.4 uA

TABLE V
VALUES OF CURRENTS AND PULSE WIDTH IN THE EXPERIMENT

Glucose concentration (mg/dL)	Faraday current (μA)	Total current consumption (μA)	Pulse width of LED emitting pulse (ms)
1,000	45.73	503.03	4.11
750	35.40	389.37	5.31
500	33.57	369.29	5.60
250	20.58	226.42	9.13
125	13.62	149.86	13.81
60	9.38	103.17	20.04
30	5.13	56.43	36.65
15	3.91	42.96	48.14

Comparison

TABLE IV
COMPARISON OF DIFFERENT WEARABLE ENERGY HARVESTING DEVICES

Reference	Pillatsch *et al.* [37]	Leonov *et al.* [38]	Liao *et al.* [39]	Chai *et al.* [40]	Jia *et al.* [41]	Renaud *et al.* [42]	Talla *et al.* [43]	**This work**
Energy harvesting technology	Piezoelectric	Thermoelectric	Electromagnetic	Solar power	Biofuel	Kinetic power	RF	**Optical power**
Main materials	Bimorph piezoelectric beam	BiTe thermopiles	Nd/Fe/B magnet	TiN nanowire	CNT/TTF/ LOx/Chit	PZT & AlN	-	**Si**
Architecture	discrete device baesd	discrete device baesd	LSI-based	discrete device baesd	discrete device baesd	LSI-based	discrete device baesd	**LSI-based**
Size	5 cm^3	6 cm^2	10 x 10 x 2 mm^3	-	-	7.5 mm^3	25.7 x 7.5 mm^2 (antenna only)	**~1 cm^2**
Weight	10.5 g	-	-	-	-	-	-	**130 mg (without glucose sensor)**
Supply power	43 μW	50-100 μW	7.23 mW	0.9 mW/cm^2	5-70 mW/cm^2	40 μW	2.5 μW	**0.8 μW**
Output voltage	-	1.2-1.3 V	4.5 V	1.2 V	0.14 V	-	2.05 V	**3-4 V**
Wearable Structure	Mounted on the upper arm	Watch	-	Cloth	Tattoo	-	-	**Band-Aid**

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Weakness

- Electrochemical sensors are only for one time uses.
- Charging capacity depends on the intensity of light
- Higher sensitivity glucose sensor needed for Sweat detection

Conclusion

- This tool is made to non-invasively detect target metabolites and display them on smartphones
- Ultrasonic skin treatment allows blood glucose readings from the skin surface
- The device takes 2.5 seconds to initialize detection
- By changing the type of sensor used, the tool can be used to detect substances other than glucose

Reference

- Zafar, H., Channa, A., Jeoti, V., & Stojanović, G. M. (2022). Comprehensive review on wearable sweat-glucose sensors for continuous glucose monitoring. Sensors, 22(2), 638.
- Wuthibenjaphonchai, N., Haruta, M., Sasagawa, K., Tokuda, T., Carrara, S., & Ohta, J. (2021). Wearable and battery-free health-monitoring devices with optical power transfer. *IEEE Sensors Journal*, *21*(7), 9402-9412.

Thank You!

For Your Attention