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A Solar-Cell-Assisted, 99% Biofuel Cell Area Reduced, Biofuel-Cell-Powered Wireless Biosensing System in 65nm CMOS for Continuous Glucose Monitoring Contact Lenses

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SUMMARY This brief proposes a solar-cell-assisted wireless biosensing system that operates using a biofuel cell (BFC). To facilitate BFC area reduction for the use of this system in area-constrained continuous glucose monitoring contact lenses, an energy harvester combined with an on-chip solar cell is introduced as a dedicated power source for the transmitter. A dual-oscillator-based supply voltage monitor is employed to convert the BFC output into digital codes. From measurements of the test chip fabricated in 65-nm CMOS technology, the proposed system can achieve 99% BFC area reduction.

key words: biofuel cell, biosensing system, CMOS, continuous glucose monitoring, solar cell.

1. Introduction

Biofuel cell (BFC)-powered biosensing systems have been demonstrated as an efficient means of monitoring physiological signals (e.g., glucose, or lactate concentration) for wearable healthcare Internet of Things (IoT) applications [1–4]. These systems are directly powered by the BFCs, which harvests energy from the electrochemical reactions in or near-human body. The output power is in accordance with the biofuel concentration. Therefore, the biological information can be noticed according to the output power, which can be read out by RF, [1–4], or light signal [5]. These features are promising in continuous glucose monitoring (CGM) contact lens applications [3], [6], [7], since glucose BFC can harvest energy from tear glucose in human eyes that correlates with human blood glucose [8].

An Analog-to-digital converter (ADC) can be exploited to convert the BFC output into the digital code for data readout. However, these kinds of the analog frontend are usually power-hungry, consuming hundreds of nW [2]. To achieve battery-less BFC-powered operation at low biomolecule concentration, some researchers utilize the variant output power to drive the timer with a different frequency to process and modulate the transmission signal [1], [3], [9]. The energy-efficient timer, which only consumes power at pW, reduces the power consumption significantly, without sacrificing accuracy too much.

Although with the ultra-low-power frontend techniques, a transmitter circuit (TX) for wireless communication is typically the most power-consuming component of these systems. In previous works, the power of entire systems was on the order of tens of μW [1], which is difficult to achieve even with the state-of-the-art BFC energy harvester [10], [11]. Moreover, most of the BFCs are with a bulky size of mm² level, which is infeasible to be accommodated in contact lenses. Although previous work has proposed a circuit architecture of a CGM contact lens that utilizes a lens-compatible 0.6 mm×0.6 mm BFC as shown in Fig. 1 [3], [12], it only focuses on TX operation using BFC power at the expense of transmission distance and low accuracy. Thus, TX is the obstacle to reducing the required BFC area.

To integrate the smallest BFC into the area-constrained CGM contact lenses, this brief proposes a solar-cell-assisted BFC-powered wireless biosensing system as an innovative solution. To exclude the TX from circuits that are directly connected to the BFC and facilitate BFC area reduction, an on-chip solar cell is introduced to the system as a dedicated power source for the TX. Furthermore, a self-controlled dual-oscillator-based supply voltage monitor [9], powered by the BFC, is used to monitor the BFC output correlated biological signals. This proposed architecture enables 99% BFC area reduction, [7], compared with the state-of-the-art BFC-based biosensing systems [1–3].

The proposed biosensing system is presented in Section 2, while Section 3 describes the measurement results. Finally, Section 4 concludes this brief. In addition, this brief is an extended version of the previous conference paper [7].

Fig. 1 State-of-the-art BFCs power extraction capabilities.

Fig. 2 Block diagram of the proposed solar-cell-assisted biofuel-cell-powered wireless biosensing system for CGM contact lens.
2. System Architecture

2.1 Overall Architecture of the Biosensing System

A block diagram of the proposed solar-cell-assisted BFC-powered wireless biosensing systems and the conceptual image for area-constrained CGM contact lenses are shown in Fig. 2. The on-chip solar cell is used to deliver power to the TX via a self-oscillating voltage doubler (SOVD)-based energy harvester, which boosts the output voltage of the on-chip solar cell. The supply voltage monitor is directly powered by the BFC and converts $V_{\text{BFC}}$ to an 8-bit supply voltage code for biosensing. The supply voltage monitor also controls the energy harvester and TX to ensure operation order. Directly connecting the circuits to the BFCs to acquire power and perform biosensing by reading the BFC outputs appears to be profitable [2], despite the fact that the power density of the BFC is limited to the pW/mm$^2$ region in tear glucose level [6].

On the other hand, solar cells can be integrated into CMOS technologies and are characterized by larger power density at tens of nW/mm$^2$ since PN junctions used as photodiodes inherently reside in CMOS process [13]. This implies that solar cells are a suitable power source for the TX instead of using BFC output power. After separating the system power into two parts, i.e., wireless communication and signal conversion with timing management, the required BFC area can be determined by only considering the power of the supply voltage monitor, whose power consumption can potentially reduce to become the pW region. Therefore, the tens-of-mm$^2$ BFC is no longer necessary, and the sub-mm$^2$ BFC [14] with the sub-mm$^2$ IC with on-chip solar cells can be integrated on CGM contact lenses.

Fig. 3 shows the operation principle of the proposed system. The operation can be divided into three phases, i.e., energy harvesting, code generation, and data transmission. Signals from the supply voltage monitor control all three phases. First, during the energy harvesting phase, the harvester control signal enables the energy harvester to begin extracting energy from the solar cell to store power for the TX (Harvester Control = High). Consequently, the supply voltage monitor generates an 8-bit supply voltage code according to the $V_{\text{BFC}}$ during the code generation phase (Rst and Count). After the supply voltage monitor ceases to generate the 8-bit supply voltage code (Hold), the 8-bit supply voltage code modulates the resonant frequency of the TX. Then, the TX transmits the data by enabling a TX control signal (TX Control = Low to High). It’s worth mentioning that the three phases for one-time transmission take less than 1 s, and the entire operation can be duty-cycled below 1% to save power since the physiological signals vary slowly.

2.2 Direct-RF TX Circuits

Fig. 4 shows the direct-RF power oscillator architecture of the TX. The direct-RF power oscillator architecture is selected for short active time operation in reference to [2], [14] with the on-chip center-tapped loop antenna. The 4-turn top-metal-based antenna, with a size of 385 μm×385 μm, features an inductance of 4 nH at each half side confirmed by simulation, which is the same as the antenna in [3]. The antenna operates both as a resonant and radiative element, eliminating the necessity of a power amplifier and bulky matching networks.

An 8-bit binary-weighted capacitive digital-to-analog converter (DAC), totaling approximately 4.83 pF, is implemented for resonant frequency tunability. Each capacitive DAC consists of a metal-insulator-metal (MIM) capacitor and pull-down switch that uses a high $V_{\text{TH}}$ transistor. A stacked power gating switch is used to reduce leakage to 29 pA during TX sleep time with a $V_{\text{TX}}$ of 1 V, exhibiting 79% lower leakage in simulation compared with an approach that uses a single transistor switch. To activate the TX using the $V_{\text{BFC}}$, the TX control signal is transmitted to the TX via the booster to double $V_{\text{BFC}}$ to drive the gate of the stacked power gating switch.

2.3 Solar Cells-Powered SOVD-Based Energy Harvester

Fig. 5 shows the details of the solar cell implementation. Three types of PN junctions, i.e., N+/P-well (PW), PW/deep-N-well (DNW), and DNW/ P substrate (PS), can be used as photodiodes in triple-well CMOS technology. There are two kinds of wire connection of photodiodes which are the solar cells uses PS/DNW in this work (a) and its counterpart without using PS/DNW (b). The difference is lying on the wire connection of PS. As all of the P-type semiconductor are interconnected in this work, once light is imposed, all diodes can supply the current. However, another kind of connection (b) which separates the P-type semiconductor inside the PW from PS, excludes the
PS/DNW diodes from the supply source. The PS/DNW diodes only bias the voltage. Only PW/DNW and PW/N+ supply the current, resulting in poor current density. As the priority of this work is harvesting energy in area-constrained environment, this design implements the solar cell with PS/DNW to improve the maximum output current.

Cascaded SOVDs [15] serves as the voltage converter in the proposed energy harvester, as shown in Fig. 6. The up-conversion ratio is set to 7. To perform energy harvesting from a small solar cell output voltage, inverters consisting of low $V_{TH}$ transistors are used in the 1$^\text{st}$ stage doubler. The controllability of the energy harvester is implemented by adding a switch to one of the inverters in the 1$^\text{st}$ stage doubler so that the energy harvester can be shut down during the holding time to save the energy. The thick oxide devices with higher $V_{TH}$ are used in 2$^\text{nd}$ stage and 3$^\text{rd}$ stage doubler to reduce the leakage and maintain a higher output voltage. The output MIM capacitor of 25 pF is adopted for TX operation which is the same as [3].

2.4 Supply Voltage Monitor

The supply voltage monitor is implemented using the self-controlled dual-oscillator architecture with different-supply-sensitivity oscillators [9]. Fig. 7 (a) shows the details of the supply voltage monitor architecture. Unlike typical biosensing systems that employ an analog frontend using an ADC, the supply voltage monitor converts the BFC output into an 8-bit supply voltage code via frequency subtraction using a supply sensitivity difference between the oscillators, i.e., $\text{OSC}_H$ and $\text{OSC}_L$. As shown in Fig. 7 (b) and (c), the measured frequency of the two oscillators over four samples shows different supply sensitivities. The supply-insensitive oscillator, $\text{OSC}_L$, and supply-sensitive oscillator, $\text{OSC}_H$, can successfully generate an 8-bit supply voltage code as in [9].

The control signals from the divider are for the energy harvester and TX control. It’s worth mentioning that the

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**Fig. 5**  The cross-section conceptual diagram and schematic of two types of solar cells using CMOS process with DNW.

**Fig. 6**  Schematic of the SOVD-based energy harvester [7].

**Fig. 7**  (a) Block diagram of the supply voltage monitor [9], (b) measured frequency of $\text{OSC}_H$ and $\text{OSC}_L$ vs. supply voltage over four samples, (c) measured frequency of $\text{OSC}_L$ vs. supply voltage over four samples.

**Fig. 8**  Chip micrograph of the biosensing IC.
leakage power consumption of the supply voltage monitor is only 103 pW at 0.3-V $V_{\text{BFC}}$ during the holding time confirmed by post-layout simulation, which makes the BFC-powered scheme feasible.

3. Measurement Results

The chip micrograph fabricated in 65-nm CMOS technology is shown in Fig. 8. The total active circuit area of the proposed system is only 0.3187 mm$^2$, which is feasible to be implemented on contact lenses. The measurement setup for the TX verification is shown in Fig. 9, which adopts the same setup as reference [3], because the same on-chip antenna and transmitter circuits are used in this work. Due to the high gain of receiver side, the extremely low power of TX can be achieved. This kind of energy-budget-unbalanced configuration is beneficial for the biofuel-cell-operated sensor.

Fig. 10 (a), (b), and (c) plots the measured results of the on-chip solar cell implemented in 65-nm CMOS technology. As a comparison, two types of solar cells, i.e., with and without using the PN junction, PS/DNW, are implemented with the same area efficiency, which means the area size of NW and PW are the same. The measured I-V characteristic of the on-chip solar cell shows that the solar cell with PS/DNW used in this work improves $3 \times$ current density from the solar cell without using PS/DNW at 200-lx illumination intensity. Because the area size of PS/DNW is the largest among the three kinds of diodes, thus providing the largest current in dim environment. The measured output power density of the solar cell with PS/DNW at 200 lx is 1.97 $\mu$W/cm$^2$, which is $2.4 \times$ larger than that of the solar cell without PS/DNW. However, as the PS/DNW diodes lie beneath the other two, the light reaching the PS/DNW is constrained, limiting the output voltage and current. Even though the illumination intensity increases upon 1000 lx, the power density benefit from using PS/DNW is almost kept the same, as shown in Fig. 10 (b).

As shown in Fig. 10 (c), although the open-circuit voltage of the solar cell used in this work is smaller due to the low output voltage of PW, it shows less sensitivity to the illumination intensity because the parallel connection of photodiodes can relieve output imbalance. The supply voltage for the TX is stabler so that the operating frequency of the TX has less deviation from the desired one.

Fig. 10 (d) plots the measured performance of the energy harvester. The energy harvester receives a minimum input of 200 mV and achieves an output larger than 1 V in a load current region below 10 pA while consuming 380 pW. Considering the simulated leakage current of the stacked power gating switch is 29 pA during TX sleep time with a $V_{\text{TX}}$ of 1 V, the measured performance of the energy harvester can well satisfy the TX circuits when solar cells provide a 0.3-V supply voltage. However, the output voltage of the solar cell is always smaller than the open-circuit voltage due to the leakage current. In order to achieve a better performance of the TX, it’s better to operate the biosensing system under an illuminated environment to obtain a high solar cell output voltage.

The simulated power breakdown is shown in Fig. 11 (a). The SOVD-based energy harvester is the dominant part of power consumption because of the voltage up-conversion for TX. The power consumption of TX is only 8% due to the duty-on time in 10s of ns level, which is much shorter than one cycle time of 300 ms. Fig. 11 (b) shows the measured power consumption of supply voltage monitor vs. supply voltage from BFC. The power consumption during standby and counting-up are different. The average power consumption during one cycle time is below 1 nW.

Table I shows the comparison to the previous works of BFC-powered systems which integrates TX for wireless communications. The BFC in this work only supplies the power of the supply voltage monitor and the booster, which is 30 pW in total at 0.3 V. When the same power density of BFC is applied to these systems, the proposed biosensing system only requires a BFC of 0.45 mm$^2$. The proposed fully on-chip system can achieve 99% BFC area reduction compared to the state-of-the-arts. To the best of the authors’ knowledge, the world-smallest glucose-based BFC [12] is sufficient for the operation of the supply voltage monitor.

4. Conclusions

A design of solar-cell-assisted, BFC-powered wireless
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