A 6.1-nA Fully Integrated CMOS Supply Modulated OOK Transmitter in 55-nm DDC CMOS for Glasses-Free, Self-Powered, and Fuel-Cell-Embedded Continuous Glucose Monitoring Contact Lens

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***Abstract*—This brief presents the lowest-current fully integrated sub-mm^3 OOK transmitter, the transmission of which is modulated by its supply voltage. By combining the transmitter with a glucose fuel cell that functions as both the power source and sensing transducer, a self-powered continuous glucose monitoring system (CGMS) contact lens can be emerged. The prototype in 55-nm deeply depleted channel CMOS with on-chip inductor and antenna requires an average current of 6.1 nA under 0.32-V supply without any external signal, which demonstrates the potential for self-powered operation.**

***Index Terms*—Glucose monitoring, CMOS, healthcare, point-of-care testing, wearable computing.**

I. Introduction

At PRESENT, diabetes has become one of the most serious life-style diseases, making it necessary for the development of a low-invasive continuous glucose monitoring system (CGMS). In order to address this issue, an RFID-based smart contact lens, which uses the smart glasses as the reader and utilizes RF wireless power transfer and backscatter communication, has been developed [1]. However, this requires a dedicated glasses, which degrades the patients' comfort and privacy.

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In this brief, we proposed a new CGMS smart contact lens system. It uses the fuel cells as both the power source and sensing transducer from tear's glucose concentration. This architecture associated with low-power CMOS OOK transmitter enables self-powered operation and eliminates requirement of reader glasses.

This brief is organized as follows: the proposed supply-sensing biosensor platform and its design principle are introduced in Section II. The design of the prototype CMOS sensor and measurement setup are summarized in Section III. Section IV presents the measurement results and demonstration of the self-powered operation, respectively. Section V concludes this brief.

II. Supply-Modulated OOK TX for Self-Powered Glasses-Free CGMS Contact Lens

A. Concept

In this brief, we firstly demonstrate the potential of using a combination of low-power CMOS OOK transmitter and glucose fuel cell for the development of glasses-free CGMS contact lens. The recent progress in the field of biofuel cells has enabled the fabrication of glucose fuel cells on silicon wafer [2]. It is capable of achieving an output of 2.3 μW/cm^2 and an open-circuit voltage of 0.55 V, which is maintained for at least 48 hours. In the fuel cell, glucose oxidation and oxygen reduction occur in the anode and cathode, respectively. Under an oxygen-rich environment with oxygen-permeable contact lens, the output power depends on glucose concentration. Therefore, a self-powered independent CGMS, which does not require any external signal nor power can be developed by combining it with a supply-modulated OOK transmitter. By using the fuel cells as both the power source and sensing transducer from tear's glucose concentration, the costly off-chip antenna for wireless power delivery and sensing electrodes can be avoided, which dramatically reduces production cost. Besides, since human blood glucose concentration is guaranteed to be higher than a certain level, the power supply from glucose is expected to be more

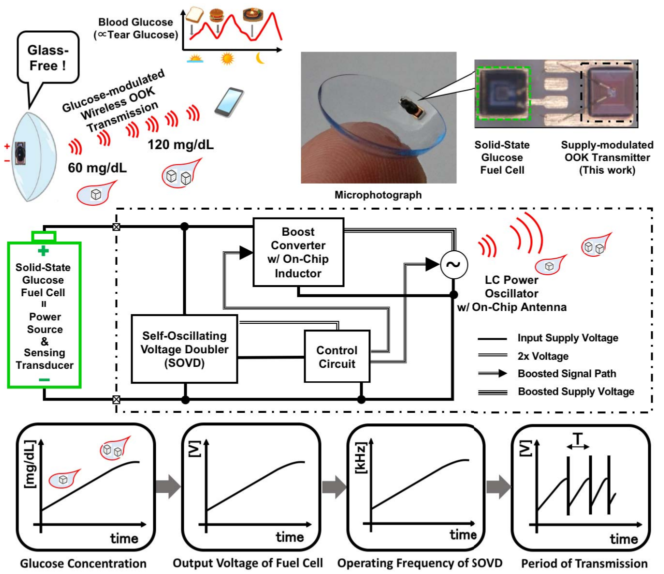

Fig. 1. Conceptual image of the proposed OOK transmitter for glasses-free CGMS (Continuous Glucose Monitoring System).

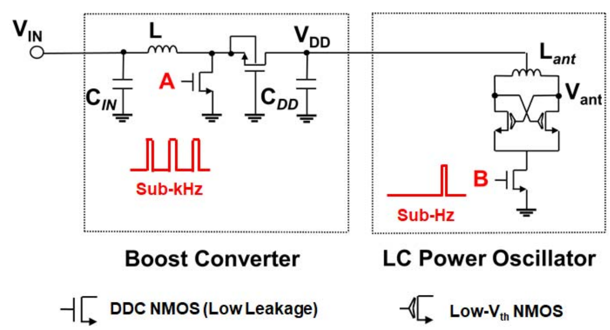

Fig. 2. Circuit diagram of the boost converter and LC power oscillator.

stable than wireless power delivery or other energy harvesting sources.

A test chip was fabricated in 55-nm DDC CMOS technology featuring low-leakage and low-voltage operation. Except for the cross-couple NMOSs in the LC power oscillator and the switches in the switched-capacitor voltage multiplier, all the transistors are DDC transistors. For the purpose of reducing the fabrication cost, an on-chip antenna was implemented. The footprint of the CMOS prototype is 0.36 mm^2 (0.6 mm $\times$ 0.6 mm), which is the same as that of the CMOS read-out chip in [1].

Fig. 1 shows the conceptual image of the proposed CGMS. The entire system can be divided into two parts: Glucose fuel cell and CMOS chip. The size of the fuel cell is same as that of the CMOS chip. The miniaturization was achieved by introducing RIE [3]. Since the output power depends only on the glucose concentration under an oxygen-rich environment, the fuel cell can be used as both the sensing transducer as well as the power source [4]. As shown in bottom of Fig. 1, higher glucose concentration results in higher output power of the fuel cell [3]. Since the power of supply-sensitive self-oscillating voltage doubler is supplied by the fuel cell, its operating frequency results in higher frequency.

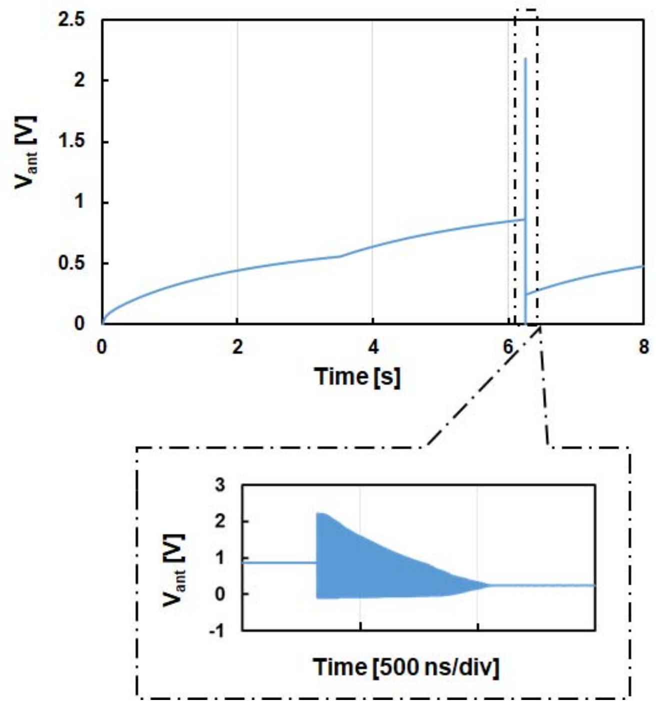

Fig. 3. Simulated waveforms of the boost converter and LC power oscillator.

Transmission rate is determined by the divided output of self-oscillating voltage doubler, and thus higher transmission rate can be obtained. This relationship is effective in lower glucose concentration. This architecture eliminates the requirement of a sensor part, which requires a large area as in the prior art [1]. The CMOS chip is capable of supply-modulated OOK wireless transmission. The chip consists of on-chip-inductor-based boost-converter, self-oscillating-voltage-doubler-based control circuit, and LC power oscillator. Two chips are integrated in the PCB board, and the total size is less than 1 mm^3.

B. Circuit Implementation

Figs. 2 and 3 show the schematics of the proposed circuit of a boost converter and an RF LC-based power oscillator including its simulated result. To improve compatibility with volume-limited contact lens application, an off-chip-inductor-based boost converter [5] cannot be adopted. However, the conventional switched-capacitor-based converter [6] cannot satisfy our requirement from the viewpoint of leakage current. For reducing leakage current with a small volume, we implemented on-chip-inductor-based boost converter. In order to compensate low-efficiency of the boost converter due to low-performance of an on-chip inductor, the LC power oscillator is activated with much lower frequency than the boost converter as shown in the simulated waveform. Time resolution of several seconds is sufficient for CGMS application. Low-V_{th} NMOSs are implemented in the cross-couple part of LC power oscillator. The control signals are fed into by the control circuitry described as followings.

Figs. 4, 5, and 6 show the schematic and simulated waveform of the self-oscillating voltage doubler and the control circuit. The control circuit consists of FF-based clock divider,

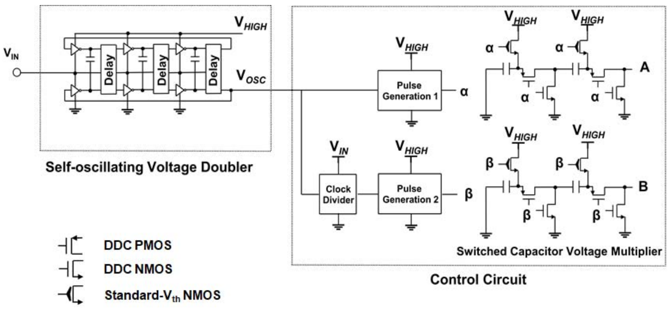

Fig. 4. Circuit diagram of the self-oscillating voltage doubler and control circuit.

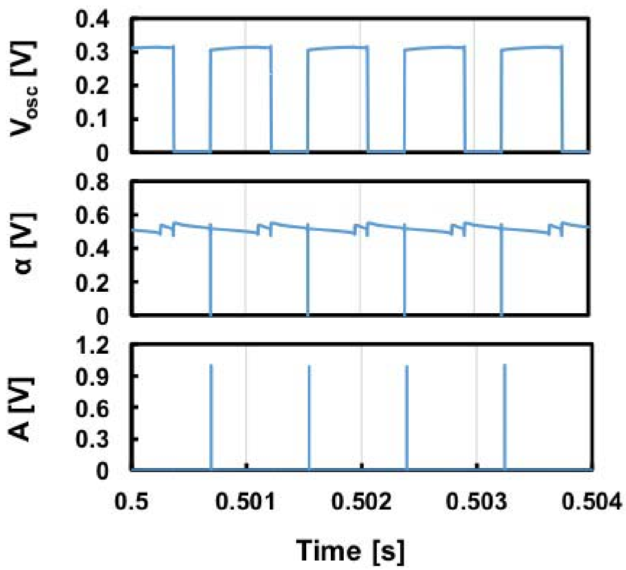

Fig. 5. Simulated waveforms of the self-oscillating voltage doubler and control circuit for boost converter.

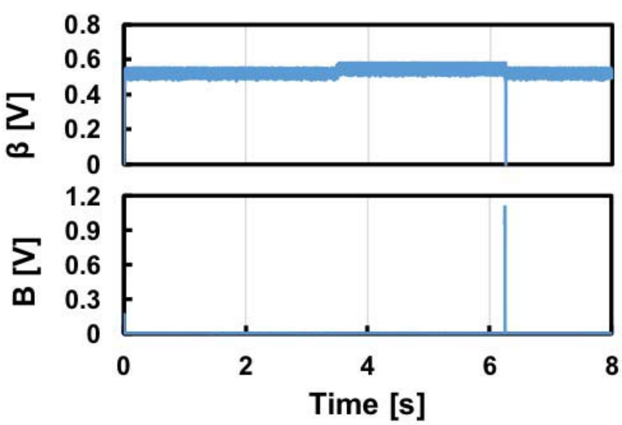

Fig. 6. Simulated waveforms of the control circuit for LC power oscillator.

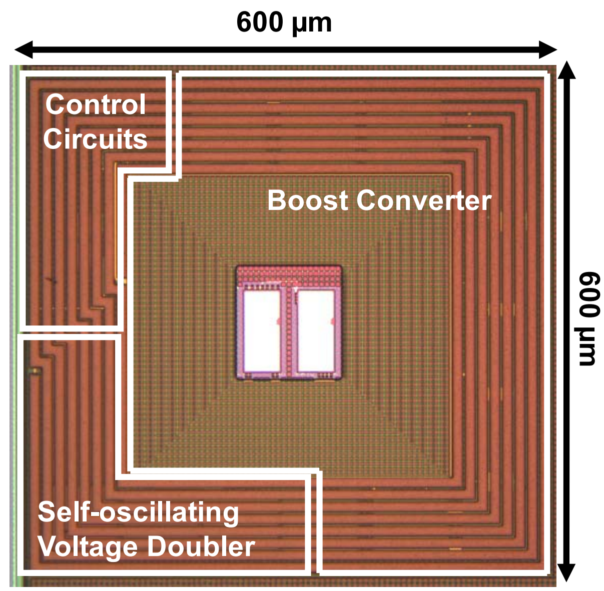

Fig. 7. Testchip microphotograph.

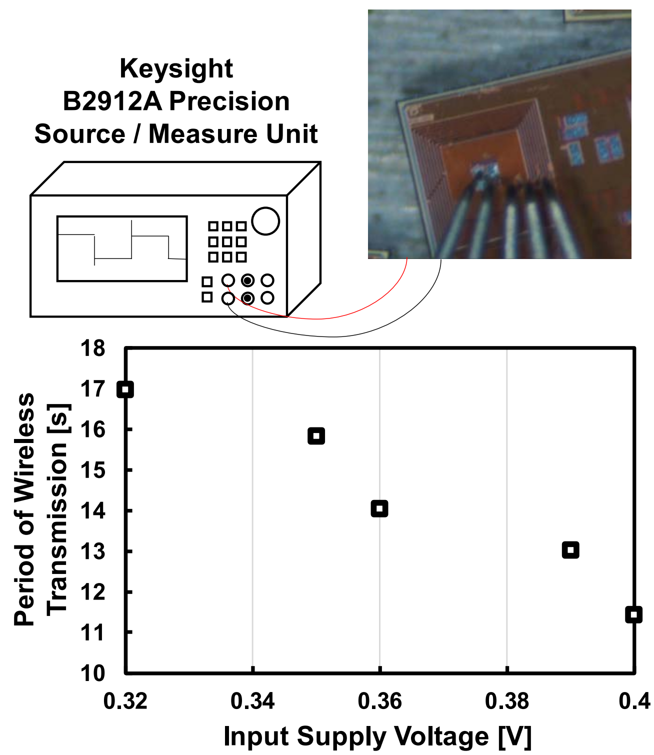

Fig. 8. Measurement setup and measured result of the supply current and period of wireless transmission dependence on supply voltage.

pulse generators, switched-capacitor-based voltage multipliers. A self-oscillating voltage doubler [7] provides the boost conversion and clock signal. Since insufficient slew rate in activation signal (A) increases dynamic loss in the boost converter, high slew rate operation must be achieved. Therefore, the supply voltage of the control circuit was provided by the voltage doubler. This is also helpful for reducing the required number of stages of large-leakage switched-capacitor-based voltage multiplier. The clock divider generates sub-Hz activation signal (B), of which division ratio is determined to guarantee the oscillation of LC power oscillator.

III. Test-Chip Design and Measurement Setup

Fig. 7 illustrates testchip microphotograph. Figs. 8 and 9 show the measurement setup, and measured waveform

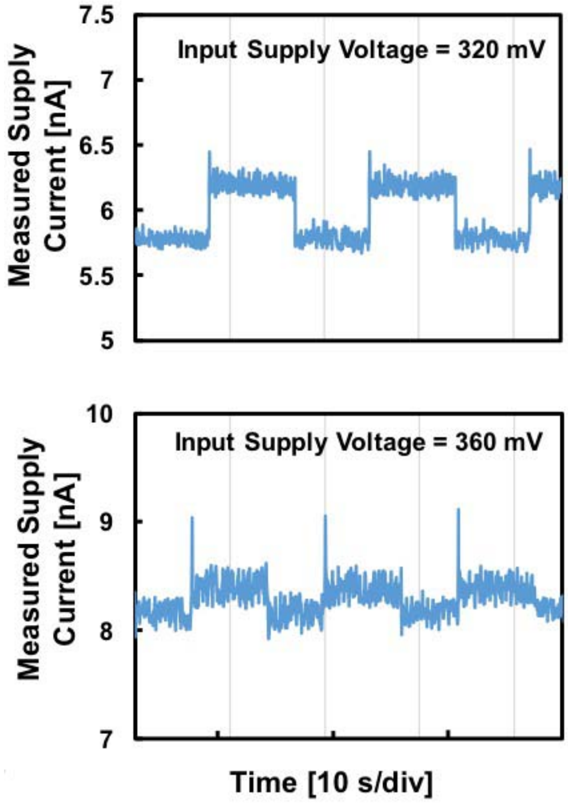

Fig. 9. Measured supply current dependence on supply voltage.

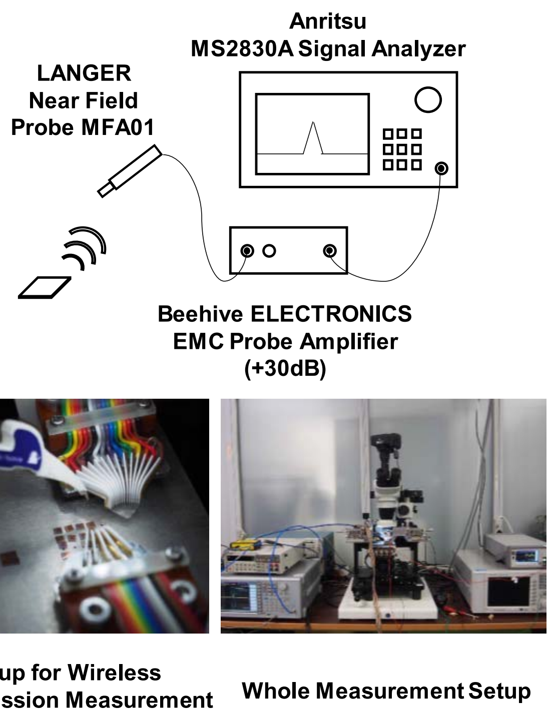

Fig. 10. Measurement setup for functional test.

of the supply current, and measured period of wireless transmission dependence on input supply voltage of the developed CMOS prototype. For simulating real-life environment with glucose fuel cell, only two signals are fed into the chip using a manual prober (Apollowave, a100) and SMU (Keysight, B2912A). The period of spike due to oscillation of LC power oscillator was increased by increment of input supply voltage from 320 to 400 mV. Periodical boost conversion whose period monotonically depends on the supply voltage was verified. This result implies the capability for supply-modulated OOK transmission.

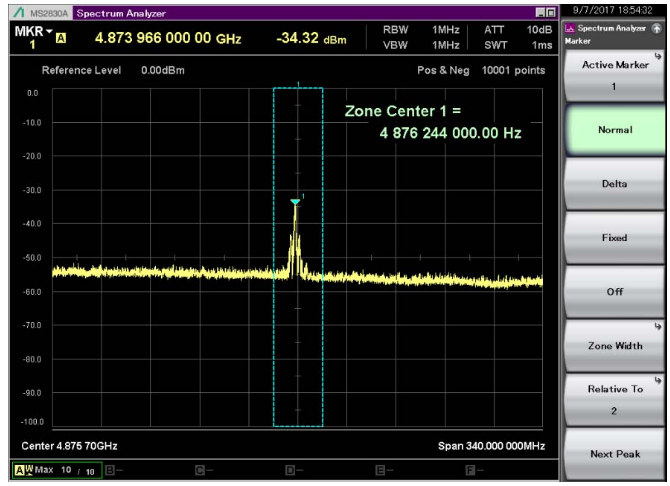

Fig. 11. Measured spectrum obtained from the prototype chip.

TABLE I
PERFORMANCE SUMMARY

	JSSC 2012 [1]	JSSC 2014 [4]	TCAS-I 2015 [5]	This Work
Process	130 nm	180 nm	32 nm SOI	55 nm DDC
Minimum input power	3 μW	1.1 nW	3 nW	1.9 nW
Minimum input current	750 nA	11 nA	23 nA	6.1 nA
On / off chip	Off chip antenna, electrode, sensor	Off chip inductor, capacitor, antenna	Fully onchip	Fully onchip
Process characteristic	-	-	Deep-trench capacitors (250 fF/μm²)	Low leakage
Kick start	Needed	Needed	No needed	No needed
Wireless	2.4 GHz	-	33 GHz	4.87 GHz
Architecture of boost converter	Rectifier	Inductor based	Switched capacitor based	Inductor based
Size	0.6 mm × 0.6 mm	9 mm × 11 mm *	0.3 mm × 0.3 mm	0.6 mm × 0.6 mm

* Implantable sensor board size which designed to fit into human mastoid cavity

IV. MEASUREMENT RESULTS

A. Results of the Functional Test

Figs. 10 and 11 depicts the measured spectrum obtained by the developed CMOS prototype and its measurement setup. A wireless transmission with 4.87 GHz center frequency was confirmed by the magnetic probe (LANGER, MFA01), the amplifier (Beehive, 150A), and the spectrum analyzer (Anritsu, MS2830A). The actual measured communication distance from the center of on-chip antenna to the tip of the near field probe is longer than 5cm. A wireless transmission of -34 dBm power under 10-dB attenuation was verified. The communication distance can be extended by introducing an external antenna.

B. Performance Evaluation

Table I shows the performance comparison among the state-of-the-art low-power CMOS glucose sensor [1], a boost converter [5], and a pulsed transmitter with two input terminals [6]. Our proposed sensor outperforms the others in terms of current consumption while maintaining a competitive size. An average current consumption of 6.1 nA at 0.32 V can be obtained using the 0.6-mm square glucose fuel cell [2], [3]. Thus, this brief demonstrates the feasibility of glasses-free CGMS contact lens. Furthermore, this can be applied to other bio-fuel-cell-powered biosensing systems [7]–[9].

V. Conclusion

A 6.1nA fully-integrated CMOS supply-modulated OOK transmitter enabling glasses-free, self-powered, and fuel-cell-embedded continuous glucose monitoring contact lens was presented. The transmitter consists of self-oscillating voltage doubler, inductor-based boost converter, controller, and LC power oscillator, which enables low power operation. Measurement results with prototype fabricated in 55nm DDC CMOS successfully demonstrates supply modulated OOK transmission capability. This result shows feasibility of the concept.

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