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Self-powered Wireless Disposable Sensor for Welfare Application

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***Abstract*—A self-powered urinary incontinence sensor consisting of a flexible urine-activated battery and a wireless transmitter has been developed as an application for wireless biosensor networks. The flexible urine-activated battery is embedded in a disposal diaper and makes possible both the sensing of urine leakage and self-powered operation. An intermittent power-supply circuit that uses an electric double-layer capacitor (EDLC) with a small internal resistance suppresses the supply voltage drop due to the large internal resistance of the battery. This circuit supplies the power to a wireless transmitter. A 315-MHz-band wireless transmitter performs low-power operation. To verify the effectiveness of the circuit scheme, we fabricated a prototype sensor system. When 80 cc of urine is poured onto the diaper, the battery outputs a voltage of 1 V; and the sensor can transmit an ID signal over a distance of 5 m.**

I. Introduction

Healthcare services are experiencing increasing demand for personal health monitoring systems using biosensors. One type of biosensor monitors the composition of a bodily fluid, such as blood or urine. Two key requirements that make a biosensor easy to use are a wireless capability, which enables a person to move about freely, and self-powered operation, which eliminates the need for a battery that usually takes up almost the whole volume and weight of the sensor. Battery-less system has a small footprint and also eliminates the need for periodic battery replacement. We have already developed a self-powered wireless system [1] that consists of a 0.5-V digital LSI, a 1-V analog/RF LSI, and a DC-DC converter and has a power source consisting of solar cells and a thermoelectric generator. Our research showed that self-powered operation requires the development of two key elements. One is an ultralow-power module with power dissipation at the 1-mW level. The other is a micro-power generator that produces a power of over 1 mW from an ambient energy source, such as the light, movement, and thermal energy around us.

As the ambient energy source is applied to the self-powered system, it is required to understand that the energy source has some disadvantages. The output of the energy source is unstable and the energy source has large internal resistance. When the energy source is directly connected to a wireless transmitter whose equivalent impedance is equal to the internal resistance, the supply voltage of the transmitter drops to half. That is, the large internal resistance of the energy source causes a large power dissipation, which makes the transmitter stop functioning.

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In this paper, we described a urinary incontinence sensor system [2, 3] that combines a urine-activated battery and an intermittent power-supply circuit with an electric double-layer capacitor (EDLC). The power-supply circuit has a small internal resistance, which allows it to drive the transmitter at 2 V. The system can transmit an ID signal over a distance of 5 m when the volume of urine is 80 cc.

II. Urine-Activated Battery

A. Principle of Urine-Activated Battery

A basic urine-activated battery [2] (Fig. 1) consists of a Zn anode, a paper suspension, a separator, and a sheet of MnO_2 and carbon for the cathode. The whole assembly is sandwiched between the two parts of a metal case. The lower part of the case has holes that allow urine to enter. When a drop of urine touches the battery, it is absorbed by the paper between the MnO_2 and the Zn. Then, the chemicals dissolve and react to produce electricity. The nominal voltage for this kind of zinc-carbon battery is 1.5 V. The battery has a diameter of 2.25 cm, a thickness of 1.8 mm, and a weight of 2.3 g. The holes are 3.6 mm in diameter.

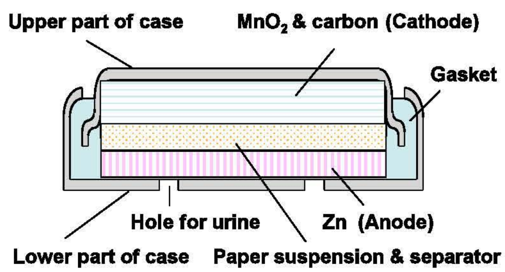

Figure 1. Cross section of urine-activated coin battery.

Equations (1) and (2) show the chemical reactions at the anode and cathode, respectively:

$$Zn + 2OH^- \rightarrow Zn(OH)_2 + 2e^-, \quad (1)$$

$$2MnO_2 + 2H_2O + 2e^- \rightarrow 2MnOOH + 2OH^-, \quad (2)$$

and the overall reaction is

$$Zn + 2MnO_2 + 2H_2O \rightarrow 2MnOOH + Zn(OH)_2. \quad (3)$$

Figure 2 shows how the output voltage of the battery changes over time when the volume of urine is 0.2 ml. The curves are for four people and were measured without an output load. The battery starts outputting a voltage of over 1.3 V at around 90 seconds.

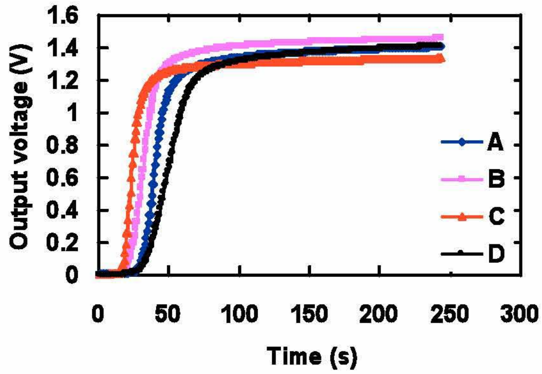

Figure 2. Power generation characteristics of urine-activated battery without load for four people(A,B,C,D).

To determine which component of urine is mainly responsible for the generation of power in the battery, we prepared artificial urine [4] from the ingredients in Table 1. For this experiment, we used a simple parallel-plate battery in a beaker and connected it to a 10-mF capacitor to enable precise measurement of the output voltage. The electrodes were Zn and MnO_2 sheets with a length of 35 mm, a width of 5 mm, and a spacing of 6 mm. A 20-mm-long section of the electrodes was immersed in the artificial urine. The output voltage characteristics (Fig. 4) were measured for artificial urine (pH = 6).

TABLE I. COMPOSITION OF ARTIFICIAL URINE

Ingredient	Amount (mg)
Na^+	333
K^+	147
Ca^{2+}	13
Cl^-	600
Uric acid	53
Urea	2000

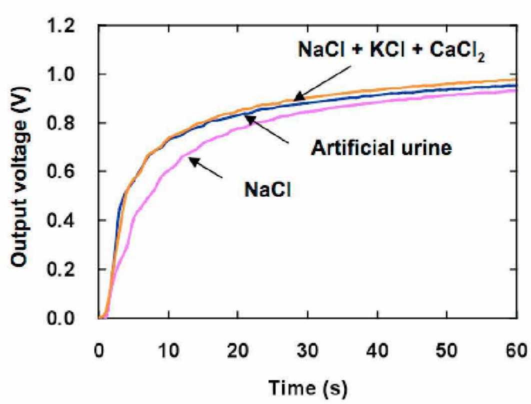

Figure 3. Power generation characteristics for various solutions.

We also measured for a 0.3% NaCl solution and a multiple electrolyte solution (NaCl + KCl + $CaCl_2$) but without urea or uric acid, both of which had the same pH as the artificial urine. The output voltage for the multiple electrolyte solution is larger than that for the NaCl solution because the K^+ and Ca^{2+} cations suppress the IR drop [5] in the solution. Moreover, the curve is close to that for the artificial urine. These results show that cations (K^+, Ca^{2+}, etc.) added to a NaCl solution are the important components responsible for power generation in a urine-activated battery.

B. Flexible Wire-type Urine-Activated Battery

A flexible wire-type urine-activated battery for disposable diapers [3] (Fig. 4) consists of two long electrodes, each of which is composed of a layer of electrode material (Al for the anode, MnO_2 for the cathode) printed on a flexible plastic sheet. The battery is 287 mm × 9 mm in size, the plastic sheet is 0.2 mm thick, and an electrode layer is 282 mm × 4 mm × 0.075 mm (LWH) in size. Figure 5 shows a photograph and a cross section of a diaper containing the battery, which is oriented downward with the electrodes touching the absorbent material.

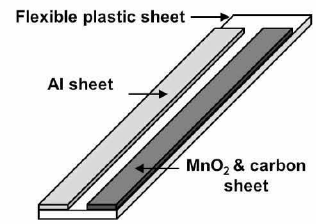

Figure 4. Structure of flexible wire-type urine-activated battery embedded in diapers.

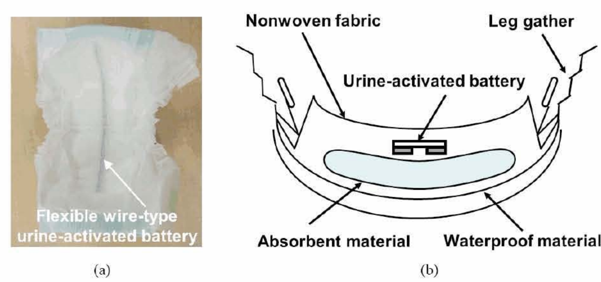

Figure 5. Flexible wire-type urine-activated battery embedded in diapers: (a) photograph and (b) cross-section.

Figure 6 shows the characteristics of the output voltage for an output load of 1kΩ and for no output load comparison.

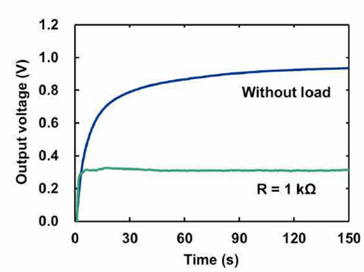

Figure 6. Power generation characteristics of flexible wire-type urine-activated battery.

When the output load is 1kΩ, the output voltage drops to about 0.3 V due to the internal resistance of the battery. Since the voltage drop at the internal resistance is 0.6 V, the value of that resistance is 2 kΩ. So, a large amount of power is dissipated there. And when the battery is directly connected to a wireless transmitter with an equivalent impedance of 1 kΩ, the output voltage of the battery drops too much for the transmitter to function.

III. Intermittent Power Supply Scheme

The large internal resistance causes the output voltage of the battery to drop when the battery is connected to the transmitter. We devised an intermittent-power-supply scheme (Fig. 7) that employs an electric double-layer capacitor (EDLC) with a small internal resistance and two switches (SW_1, SW_2). First, the battery supplies power to the EDLC through SW_1. When the EDLC is fully charged, it starts discharging at a voltage of 0.85 V. This supplies power to the output load through SW_2. Since the internal resistance of the EDLC is much smaller than that of the battery, there is only a slight drop in output voltage.

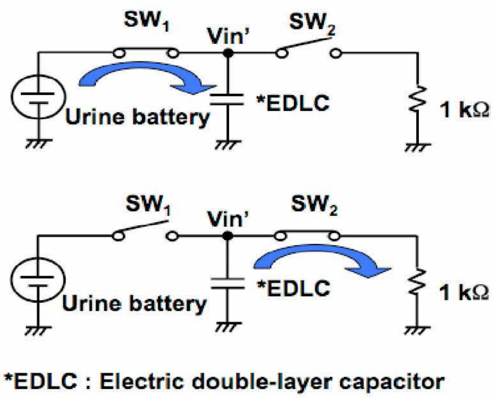

Figure 7. Concept of power supply scheme with EDLC: (a) Power supply to EDLC and (b) power supply from EDLC.

An intermittent power supply circuit [3] (Fig. 8) consists of an EDLC and a DC-DC converter that boosts the output voltage of the battery from 0.8 to 2 V. A boosting operation starts when the voltage of the external reset terminal is 0.8 V. The EDLC, which has a small internal resistance, stores the power from the battery; and when it is charged, it supplies power to the DC-DC converter. If the EDLC were connected directly to both the reset terminal and the supply voltage terminal, the reset circuit and the boosting circuit of the DC-DC converter would start operating at the same time when the output voltage of the EDLC reached 0.8 V. That would cause the supply voltage to drop for an instant below 0.8 V (the voltage of the reset terminal), with the result that the DC-DC converter would not start operating when it should. So, to prevent the supply voltage from dropping, we put a resistor, R, and a level shift diode, D_1, with a voltage shift of less than 50 mV at a current of 1 μA between the EDLC and the reset terminal. The DC-DC converter starts a boosting operation when the output of the EDLC is 0.85 V. Since the boosting circuit in the DC-DC converter starts operating after the reset circuit starts operating, there is no error. Diode D_2, which is in the feedback loop between the input and output terminals of the DC-DC converter, performs hysteresis control for the intermittent power supply. The resistor, R, also blocks the reverse current from the output to the supply voltage of the DC-DC converter.

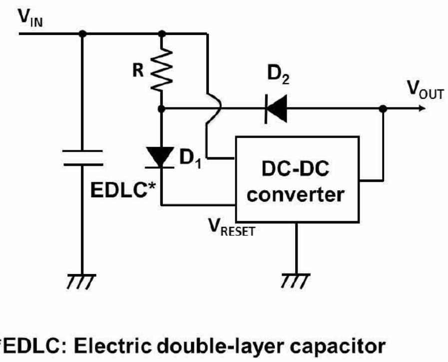

Figure 8. Intermittent power supply circuit scheme.

IV. Wireless Self-Powered Urinary Incontinence Sensor System

The wireless self-powered urinary incontinence sensor system (Fig. 9) consists of a wireless self-powered urinary incontinence sensor and a receiver. The sensor consists of a flexible urine-activated battery, an intermittent power supply circuit, and a wireless transmitter that operates at 2 V. In the prototype wireless urinary incontinence sensor (Fig. 11), the diameter of the transmitter with the intermittent power supply circuit is 25 mm. The transmitter operates at a frequency of a 315 MHz. The electrode of the battery acts as a wide ground plane for the antenna of the transmitter, thereby providing a large radiated power.

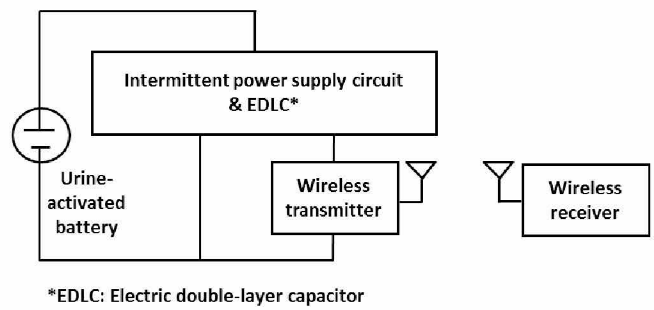

Figure 9. Block diagram of self-powered wireless urinary incontinence sensor system.

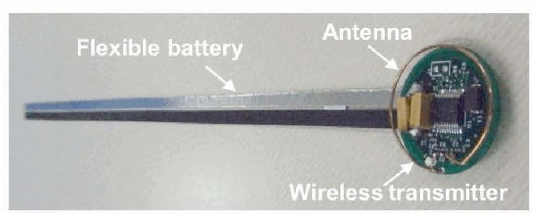

Figure 10. Photograph of wireless urine-activated sensor.

The measured radiation pattern (Fig. 11) of the transmitter in the prototype wireless sensor with and without a battery shows that a battery makes the radiation pattern omnidirectional and improves the antenna gain. The average antenna gain is -5.65 dBi.

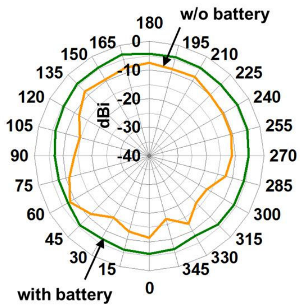

Figure 11. Measured radiation pattern of wireless sensor.

A prototype wireless urinary incontinence sensor and a receiver were fabricated to test the transmission of ID data. The transmitter in the sensor has 12 ID codes and operates at a frequency of a 315 MHz. Figure 12 shows the input and output waveforms. A 1-V power source with an internal resistance of 10 kΩ was used for evaluation as an equivalent substitute for the flexible urine-activated battery. A voltage of 2 V was supplied to the wireless transmitter for 180 ms of every minute, during which time and the transmitter sent the ID data three times.

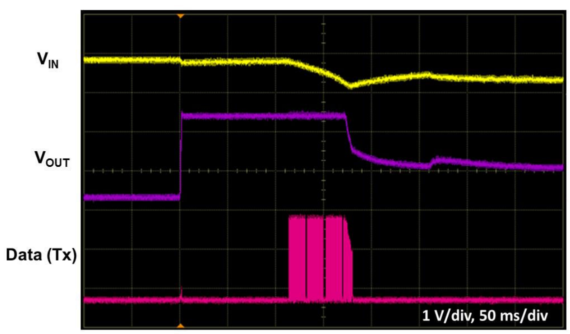

Figure 12. Waveforms of input and output voltages of wireless urinary incontinence sensor.

Figure 13 shows waveforms of ID data for the transmitter and the receiver, which was 5 m away. The ID data is composed of a serial number, a parity bit, the actual ID, and a flag. The figure shows that the parity bit (1) and the ID (1110) were successfully transmitted.

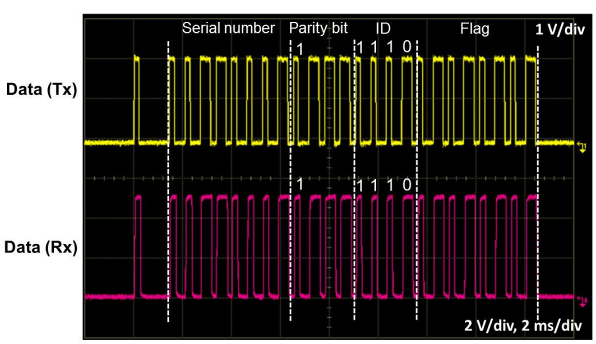

Figure 13. Waveforms of ID data for wireless sensor and receiver.

Figure 14 shows a photograph of the prototype sensor system. The receiver has a turnstile antenna with good sensitivity over a wide range of angles because the wearer might be standing, sitting, or reclining. The sensor system can transmit an ID signal over a distance of 5 m when 80 cc of urine are poured onto the diaper. The power dissipation of the sensor is 9 mW.

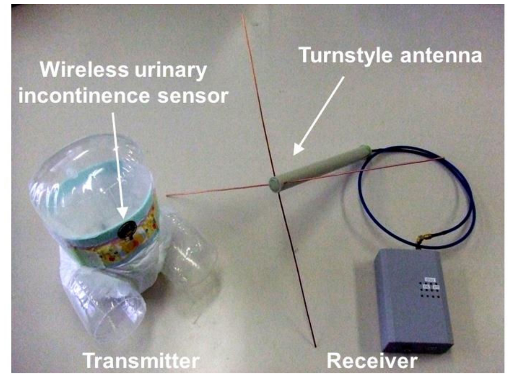

Figure 14. Photograph of self-powered wireless urinary incontinence sensor system.

V. CONCLUSION

A self-powered wireless urinary incontinence sensor for use in a disposal diaper was described. The flexible wire-type urine-activated battery embedded in a diaper conforms to the shape of the diaper when the diaper is worn. The electrode of the battery acts as a wide ground plane for the antenna of the transmitter, thereby providing a large radiated power. The intermittent power-supply circuit with an electric double-layer capacitor (EDLC) allows it to drive the transmitter. A urine incontinence sensor system embedded in a diaper will be useful for the care of infants and bed-ridden elderly people in hospitals.

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REFERENCES

[1] T. Douseki, M. Yonemaru, E. Ikuta, A. Matsuzawa, K. Kameyama, S. Baba, T. Mogami, and H. Kyuragi, "Ultralow-voltage MTCMOS/SOI Circuits for Batteryless Mobile System," *IEICE Trans.*, Vol. E87-C, pp. 437-447, 2004.
[2] A. Tanaka, Y. Nakagawa, K. Kitamura, F. Utsunomiya, N. Hama, and T. Douseki "A Wireless Self-powered Urinary Incontinence Sensor System," *IEEE SENSORS 2009 Conference*, pp. 1674-1677, 2009.
[3] A. Tanaka, T. Yamanaka, H. Yoshioka, K. Kobayashi, and T. Douseki "Self-powered Wireless Urinary Incontinence Sensor for Disposable Diapers," *IEEE SENSORS 2011 Conference*, pp. 1491-1494, 2011.
[4] http://www.nupals.ac.jp/society/img/02.pdf
[5] R. A. Day. Jr. and A. L. Underwood, "Quantitative Analysis, 3rd edition," *Printice-Hall, Inc.*, p. 266, 1974.