LETTER

Implementation of Smart Dressing Systems Based on Flexible pH Sensors Using PET Films

Seok-Oh YUN[†,††a)], Jung Hoon LEE[†††b)], *Nonmembers*, Jin LEE[††††c)], *Member*, *and* Choul-Young KIM[†d)], *Nonmember*

SUMMARY In this paper, a smart dressing system was implemented based on flexible pH sensors that can monitor the infection of a wounded area by tracking the pH value of the area. Motivated by the fabrication process widely used for semiconductors, the flexible pH sensor fabrication process was devised with a polyester (PET) film and a Si wafer, which deposits Au and Ag on a PET film. Because the electrodes are comprised of a working electrode and a reference electrode, the reference electrode was fabricated by synthesizing the Polyaniline (PANI) on Ag/AgCl, while the pH sensor has four channels to evenly measure the pH value in a wide area. The smart dressing system was constructed with four pH sensors, a single temperature sensor, a level shifter, a regulator, an analog-to-digital converter (ADC), and a monitoring PC. The measurement results show that our smart dressing system has a size of $5 \times 5\,\mathrm{cm}^2$ and can monitor the pH value range found in [3, 9] with a sensitivity slope of 50 mV/pH.
key words: *pH sensor, pH meter, smart dressing, wound infection*

1. Introduction

In recent years, pH sensors have been widely used for various purposes in laboratories, clinics, and industries [1]–[4] because they provide a logarithmic measure of hydrogen ion concentration. As many biological and chemical reactions are dependent on pH level, pH sensors play important roles in human health care, water quality, food quality, etc.

Nowadays, flexible/wearable sensors have attracted great attention, especially for human health monitoring [5]–[10]. For example, the authors of [10] devised bandage-based pH sensors for real-time wound pH monitoring. Also, the authors of [11] developed textile-based pH sensors to measure the pH of sweat and found that sweating rate and pH values are correlated.

One of the most popular treatments for wounds is the wet environment treatment, which maintains skin exudates and so rapidly heals the wounded area without scarring. In some cases, however, the wet environment may cause some trouble by allowing growth of bacteria, which can even lead to patient death by infection. Therefore, medical doctors replace dressings frequently to avoid infection. Although infection of a wounded area can be fatal to the patient, smart dressings that monitor wounded areas have not been fully studied yet.

In this paper, a smart dressing system that monitors the infection of a wounded area was implemented. Our main contribution is to implement the smart dressing system that prevents the infection of a wounded area by monitoring the pH value of the area. In a normal stage, human skin is slightly acidic, with a pH value of 5.5. However, the pH value increases to 9 when the wounded area is infected. Thus, our smart dressing system monitors infection by observing pH value of wounded area. For ease of attachment to the skin, our smart dressing system adopts flexible pH sensors.

First, motivated by the fabrication process widely used for semiconductors, the flexible pH sensor fabrication process is proposed with a PET film and Si wafer. Then, the smart dressing system is constructed with four pH sensors, a single temperature sensor, a level shifter, a regulator, an analog-to-digital converter (ADC), and a monitoring PC.

This paper is organized as follows. In Sect. 2, we explain the implementation of our smart dressing system including the overall architecture, the flexible sensor design, and the system integration on PCB. In Sect. 3, we evaluate our smart dressing system. Then, Sect. 4 concludes our paper.

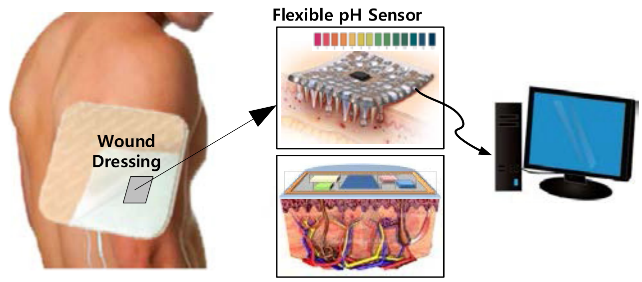

Fig. 1 Concept of the smart dressing for monitoring infected wounds.

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[†]The authors are with the Department of Electronics, Chungnam National University, Daejeon, 34134, South Korea.
[††]The author is with National Nanofab Center, Daejeon 34141, South Korea.
[†††]The author is with the Department of Electronics Engineering and Applied Communications Research Center, Hankuk University of Foreign Studies, Yongin 17035, South Korea.
[††††]The author is with the Department of Information and Communication, Pyeongtaek University, Pyeongtaek, 17869, South Korea.
a) E-mail: soyun@nnfc.re.kr
b) E-mail: tantheta@hufs.ac.kr
c) E-mail: mygenie79@ptu.ac.kr
d) E-mail: cykim@cnu.ac.kr (Corresponding author)
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2. Implementation of a Smart Dressing System Based on Flexible pH Sensors

2.1 Overall Architecture

The overall architecture of our smart dressing system based on flexible pH sensors is illustrated in Fig. 2. Our smart dressing system consists of four pH sensors, a single temperature sensor, a level shifter, a regulator, an analog-to-digital converter (ADC), and a monitoring PC. In our smart dressing system, to more precisely monitor the pH values of a wide wounded area, four identical pH sensors were used.

The operation of our smart dressing system is as follows.

The pH sensor first measures the pH value and produces a corresponding small voltage signal. Then, the amplifier and the level shifter boost the signal to the operating range, and the ADC digitizes the voltage value. Finally, the PC reads the digitized pH value via the USB interface.

Similarly, the PC obtains the temperature using the temperature sensor, the amplifier, and the ADC. In this case, negative temperature coefficients (NTC) were adopted: the ADC in the micro-controller unit (MCU) reads the voltage of the reference resistor. Note that both of the sensing values (i.e., the pH and the temperature values) can be calibrated from the sensors' statistic features.

2.2 The Proposed pH Sensor Design for Flexibility

Our smart dressing system adopts flexible pH sensors for ease of attachment to the body. To make the pH sensor flexible, fabrication processes were devised that use both a Si wafer and a PET film, as illustrated in Fig. 3.

The fabrication processes of our flexible pH sensor are as follows.

(a) A glue layer, which is a thermal release tape, is coated on the Si substrate using a spin coater.

(b) A PET film is attached onto spin coating on the Si wafer, with an ultraviolet (UV) curing process.

(c)–(d) Patterned stencil mask is drawn on the PET file and filled with Ti/Au to thicknesses of 200Å/2,000Å, respectively.

(e) Once the deposition of Ti/Au is complete, the stencil mask is removed.

(f) A Ti/Ag layer is deposited to thickness of 200Å/2,000Å, and sensor structure is obtained.

(g) The PET film is removed from the Si wafer, and the flexible sensor part is obtained.

After obtaining the flexible sensor structure, AgCl was coated on both the working electrode and the reference electrode.

Our pH meter was evaluated with a simulation block whose schematic diagram is depicted in Fig. 4. The simulation block is comprised of an operational amplifier (OpAmp) with a level shifter. In this case, the sensitivity is 50 mV/pH. Also, the input signal is amplified 30 times at OpAmp and then transferred to the level shifter. In Table 1, the sensing voltages and the final output voltages are sum-

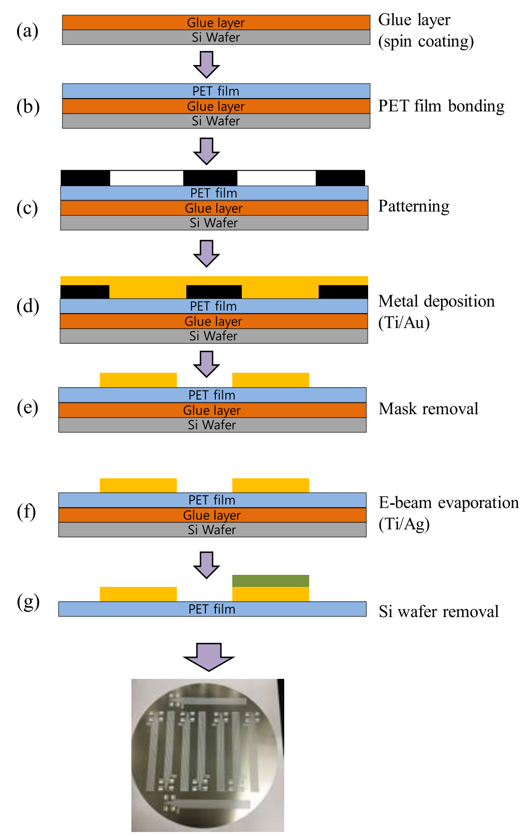


Fig. 3 Fabrication processes for pH sensor with a Si wafer and a PET film.

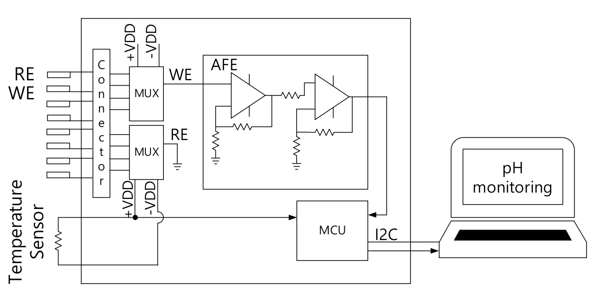


Fig. 2 The block diagram of our smart dressing system.

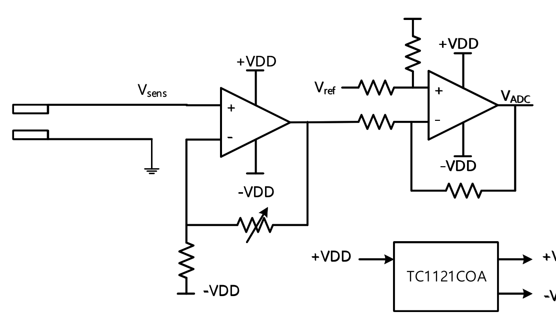


Fig. 4 The schematic diagram for the pH meter evaluation.

Table 1 The sensing voltages and the final output voltages according to the various pH values

pH	Vsens (mV)	Vout (V)	pH	Vsens (mV)	Vout (V)
0	414.14	0.172	8	-59.16	1.591
1	354.96	0.349	9	-118.3	1.769
2	295.80	0.527	10	-177.5	1.946
3	236.64	0.704	11	-236.6	2.123
4	177.48	0.881	12	-295.8	2.301
5	118.32	1.059	13	-354.9	2.478
6	59.16	1.236	14	-414.1	2.656
7	0	1.414	-	-	-

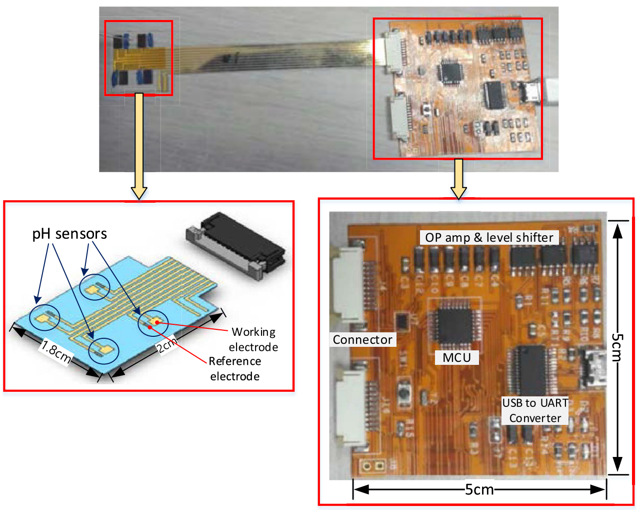


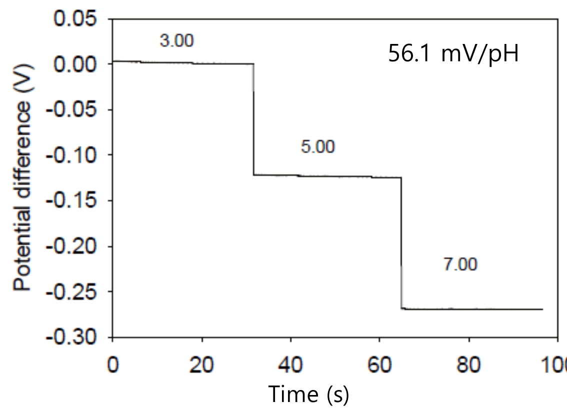
Fig. 5 The system integration on PCB for our smart dressing system.

marized with respect to the pH values. For adjustment of the pH values for the temperature, the Nernst equation was used, which represents the relationship between pH value temperature.

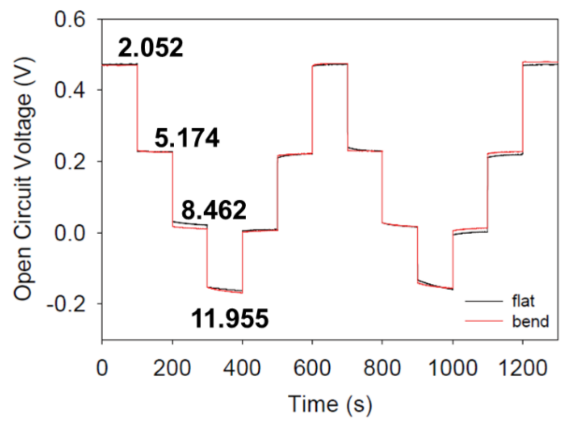
2.3 System Integration on PCB

This section explains the system integration on PCB for our smart dressing system. Figure 6 shows the final product of our smart dressing system. As we showed in Fig. 5, there are four pH sensors, each of which has working and reference electrodes. Then, the sensors are connected to the pH meter with a wire bonding process. In this case, the pH meter is comprised of two layers for PCB design. The first layer contains the OpAmp, the level shifter, and the temperature sensor, while the second layer contains MCU and USB, with a universal asynchronous receiver-transmitter (UART) converter.

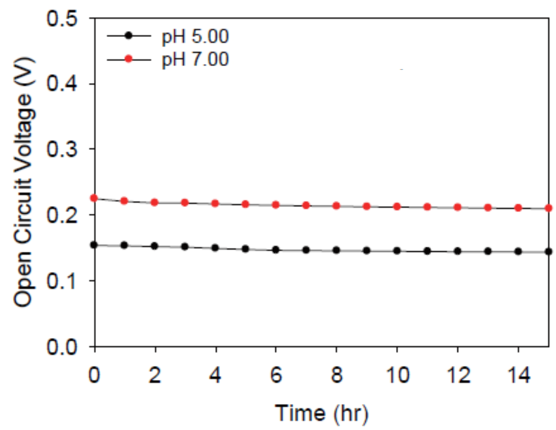
To evaluate the sensitivity of our flexible pH sensors, the open circuit voltage between the polyaniline working electrode and the Ag/AgCl reference electrode was measured. The voltage value measured at the pH sensor becomes the input of the OpAmp and the level shifter. In this case, the OpAmp amplifies the output signal of each pH sensor to the operating voltage, and the level shifter centers the amplified signal at 3.3 V. Then, the analog signal passes the ADC, and so is converted to a digital signal.



(a) The potential difference according to pH changes over time



(b) The open circuit voltages for a pH value pattern



(c) The stabilities of open circuit voltages at pH 5 and pH 7 over time

Fig. 6 Various measurements for our smart dressing system.

Figure 6 shows the electrical characteristics of our pH flexible sensors. In Fig. 6 (a), the changes of the potential difference were measured by varying the pH values from 3 to 5 to 7. In Fig. 6 (a), we can check that our pH sensor detects potential differences well when dipped in various solutions of different pH value. In Fig. 6 (b), to check the reproducibility, the open circuit-voltages are shown as derived from the repeated pH value patterns over time. For the reproducibility test, the pH values were varied with the patterns of [2.052, 5.174, 8.462, 11.955] and the open circuit voltages were measured when the flexible pH sensors were flat and bent, respectively. As can be seen in Fig. 6 (b), differences among measured pH values corresponding to the same input pH value are far less than pH 0.1, which ensures that our smart dressing system produces a reproducible open-circuit voltage for every pH level. Figure 6 (c) shows the open circuit voltages measured over 15 hours at pH values of 5 and 7. As can be seen in Fig. 6 (c), our smart dressing system shows almost the same open circuit voltage for each pH value over a long period. In this case, the voltage changes are less than 0.64 mV and 0.49 mV per hour for pH values of 5 and 7, respectively.

3. Conclusion

In this paper, a smart dressing system was implemented based on flexible pH sensors with a PET film and a Si wafer that can monitor the infection of a wounded area in real time by tracking the pH value of that wounded area. Flexible pH sensor fabrication process was devised to deposit Au and Ag on a PET film. Then, we constructed the smart dressing system consisting of four pH sensors, a single temperature sensor, a level shifter, a regulator, an ADC, and a monitoring PC. The measurement results show that our smart dressing system performed well. Our pH sensing system can be improved by adopting wireless communication techniques such as Bluetooth and RFID and by adopting flexible batteries or connecting it to a smartphone for portability and ease of use. These are our on-going research topics.

Acknowledgments

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