IEICE TRANS. ELECTRON., VOL.E101–C, NO.11 NOVEMBER 2018

INVITED PAPER *Special Section on Electronic Displays*

Wireless Sensor Chip Platform Using On-Chip Electrochromic Micro Display

Takashiro TSUKAMOTO[†a)], **Yanjun ZHU**[†], ***and*** **Shuji TANAKA**[†], ***Nonmembers***

SUMMARY In this paper, a proof-of-concept sensor platform for an all-in-one wireless bio sensor chip was developed and evaluated. An on-chip battery, an on-chip electrochromic display (ECD), a micro processor, a voltage converter and analog switches were implemented on a printed circuit board. Instead of bio-sensor, a temperature sensor was used to evaluate the functionality of the platform. The platform successfully worked in an electrolyte and the encoded measurement result was displayed on the ECD. The displayed data was captured by a CMOS digital camera and the measured data could be successfully decoded by a computer program.

key words: *disposable bio-sensing chip, on-chip battery, on-chip electrochromic display*

1. Introduction

Recently, the medical expense has been increasing maily due to the aging society. To reduce the medical cost, early detection and treatment of the disease is effective. However, the frequent disease diagnosis becomes a burden especially for the elderly person. A point-of-care disease inspection system using an easy-to-use disposable bio-sensor chip is one of the solution to realize a daily health care. For this purpose, an all-in-one wireless bio sensing chip has been proposed, in which an immunoassay-based bio-sensing part [1], a CMOS signal processor, a power source and a data transmitter are integrated.

Figure 1 shows the schematic of the proposed system. To detect the specific disease marker with high selectivity and sensitivity, immuno assay based method is used. Antibodies, which specifically binds to the target disease marker, are fixed on the sensor. If the disease marker, which act as the antigen, is contained in the inspection specimen, the markers is fixed on the sensor by antigen-antibody reaction. The trapped target molecule is then labelled by super paramagnetic micro beads, which can be detected by the Hall sensor array implemented in the CMOS chip [1], [2]. Finally, the inspection result is transmitted.

To make the system easy to use, the sensor chip must be wireless. In the proposed system, the inspection result is encoded and displayed on an on-chip electrochromic display (ECD). The displayed data is captured by a CMOS camera and the measurement result is decoded by an image recognition algorithm. All the electric components including a Hall sensor array, a signal processor and the ECD are powered by an on-chip Mg/AgCl battery [3].

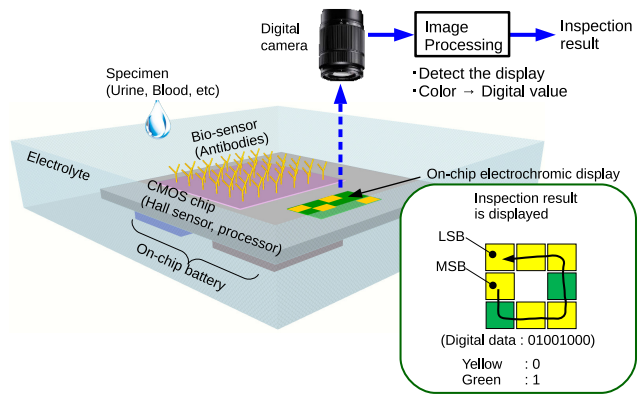

Fig. 1 Schematic of bio-sensing system using all-in-one wireless sensing chip.

In this paper, a sensor platform, consisting of the on-chip battery, the on-chip ECD, a voltage converter and a signal processor, was developed. A CMOS temperature sensor instead of the bio-sensor was used for the demonstration of stand-alone operation. In addition, a pattern recognition system, which automatically detects the displayed data and convert it to the digital data, was developed to receive the data from the chip.

2. Sensor Platform

2.1 On-Chip Electrochromic Display

As mentioned in Sect. 1, the sensing data should be wirelessly transmitted. A lot of methods have been proposed such as using magnetic field coupling [4], light emission [3] and capacitive coupling [5]. However, from the view points of size and power consumption, a data transfer method using an on-chip electrochromic display (ECD) is advantageous, in which the inspection result is shown on the chip surface as a color pattern [6]. The color of some materials such as poly-aniline (PANi) [7]–[10], PEDOT:PSS [11], [12] and Tungsten oxide [13], [14] can be controlled due to its redox states, which is known as electrochromism. A PANi thin film was used for the on-chip display because the micro patterning is easily done by the electro-deposition [15] with pre-patterned electrodes [6].

Figure 2 shows the structure of the ECD. To make the structure simple, the inspection solution is utilized as the electrolyte for the electrochemical reaction. The electric po-

Manuscript received March 3, 2018.
Manuscript revised May 24, 2018.
[†]The authors are with Tohoku University, Sendai-shi, 980–8579 Japan.
a) E-mail: t_tsuka@mems.mech.tohoku.ac.jp
DOI: 10.1587/transele.E101.C.870

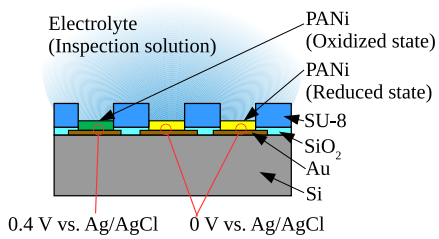

Fig. 2 Schematic of on-chip electrochromic display.

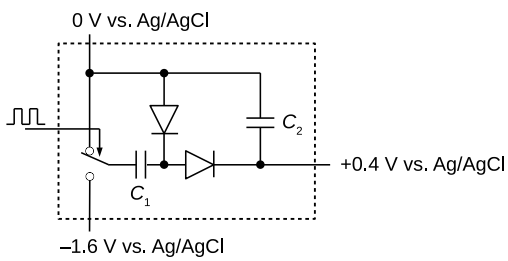

Fig. 3 Circuit diagram of the voltage converter.

tential of each micropatterened PANi film can be controlled by the electrode underneath the PANi film [6]. It only requires micro-patterned PANi films on the chip and the working voltage range is less than 0.4 V, which are advantageous in terms of the simplicity and power consumption. An 8-bit on-chip ECD, of which each pixel had 160×160 μm active area, was fabricated on the silicon substrate.

2.2 On-Chip Battery

In addition to the data transmission, the electric components in the chip must be operated without external wire connection. Some power transmission methods such as using magnetic field coupling [16]–[18], photovoltaic cell [19] and ultrasonic transducer [20] have been proposed for the small wireless chip. However, in terms of power density, an on-chip galvanic cell is advantageous. In the proposed system, Mg and AgCl were used as the cathode and anode materials, respectively, and the inspection solution was utilized as the electrolyte to simplify the battery structure [3]. The open circuit voltage as high as 1.6 V can be obtained by a single cell [3], which is sufficient for the CMOS circuit.

2.3 Voltage Converter

The PANi film is yellow or green at the applied voltage of 0 or 0.4 V vs. Ag/AgCl, respectively [6], [9], which is out of the voltage range generated by the Mg/AgCl battery (between −1.6 and 0 V vs. Ag/AgCl). To let the battery and the ECD operating in the same electrolyte (inspection solution), the generated voltage should be converted to which the ECD works. A simple voltage conversion circuit [21], which can be implemented in the CMOS chip, was used to convert the voltage range. Figure 3 shows the circuit diagram of the voltage converter to generate 0.4 V vs. Ag/AgCl

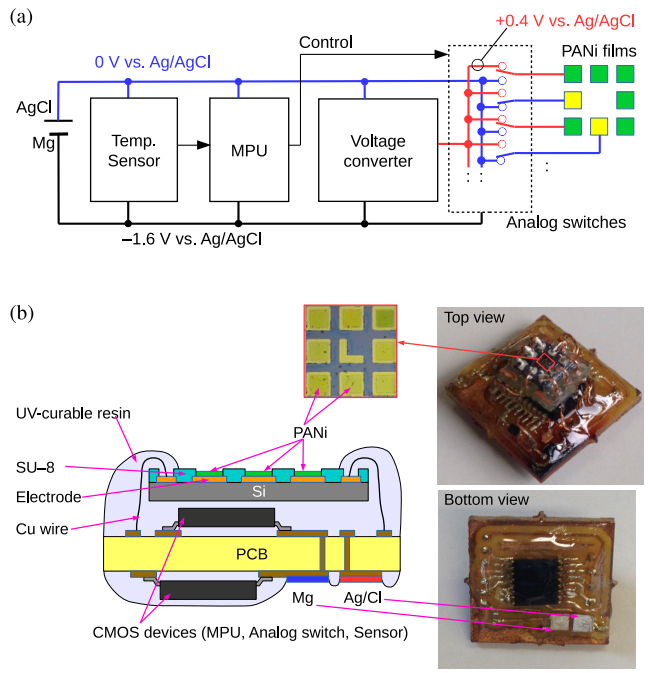

Fig. 4 (a) System diagram and (b) structure of sensor platform. CMOS temperature sensor instead of bio-sensor was used to demonstrate the stand-alone operation.

from the voltage range between −1.6 and 0 V vs. Ag/AgCl. The switching frequency was 1 MHz and the values of capacitors were $C_1 = C_2 = 100$ [pF].

2.4 Integration

Figure 4 shows the system diagram and the structure of the developed sensor platform. A temperature sensor (LMT84, Texas Instruments Inc., USA) instead of the bio sensor was used to evaluate the functionality of the system. The output signal (voltage proportional to the temperature) of the sensor was captured by an analog-to-digital converter implemented in a micro processor (PIC16LF1827, Microchip Inc., USA). The obtained digital data ("0" or "1") was displayed on the ECD as the color state (yellow or green, respectively). Analog switches controlled by the micro processor were used to control the voltage of each PANi element. CMOS chips were soldered on a printed circuit board (PCB), of which the size was 13×15 mm^2. The ECD fabricated on the Si substrate was connected to the PCB by Cu wires. The on-chip Mg/AgCl battery, of which each electrode had 1.5×1.5 mm^2 active area, was directly fabricated on the PCB. Whole external surface except the ECD and the on-chip battery were covered by a UV-curable resin for electrical insulation.

3. Data Recognition System

The displayed data was captured by a digital camera. In the practical usage, the sensing chip was not strictly fixed. Therefore, a pattern recognition software to detect the translation, rotation and scale of the device was developed, in

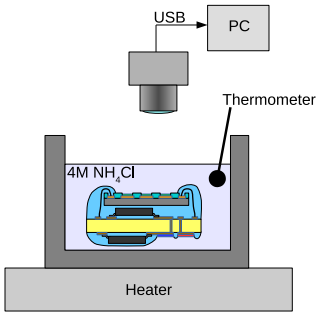

Fig. 5 Experimental setup.

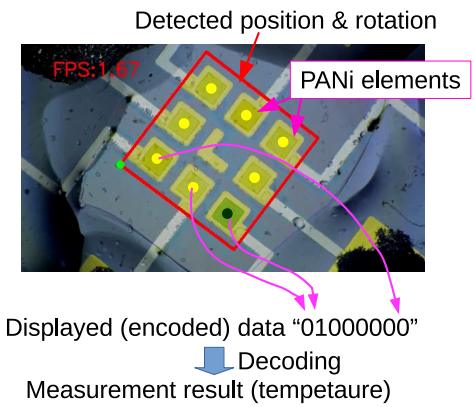

Fig. 6 Captured image of on-chip ECD during temperature measurement. Red rectangle shows the recognized area of on-chip ECD. The displayed digital data can be converted from color (Yellow or Green) to digital data ('0' or '1').

which SURF (Speeded up robust features) feature detection [22], Harr-wavelet response, FLANN (Fast approximate nearest neighbor search library) matching [23] and homography transformation [24] techniques were used. Then, the color of each PANi pixel, eventually digital data, was picked up according to the detected chip orientation. All the image processing procedures were implemented in a computer software with the help of OpenCV libraries.

4. Experimental Result

Figure 5 shows the experimental setup for the demonstration of stand-alone operation and data transfer. A 4 M NH_4Cl solution was used as the electrolyte for both the on-chip battery and the ECD. The temperature of the solution was controlled by an electric heater. A K-type thermocouple was used to directly measure the temperature.

When the demonstration device was immersed in the solution, the on-chip battery started to work and the measured temperature data was displayed on the ECD. Figure 6 shows the captured image with recognition result. A red rectangle shows the detected ECD area, and the yellow and green circles show the recognized digital data (yellow and green indicate "0" and "1", respectively). Then, the obtained digital data was decoded into the temperature value.

Figure 7 shows the decoded temperature data with the reference value measured by the thermocouple. The electic heater turned on and off at around $t = 5$ [s] and $t = 30$ [s], respectively. As can be seen, the sensor chip could detect and transmit the solution temperature correctly.

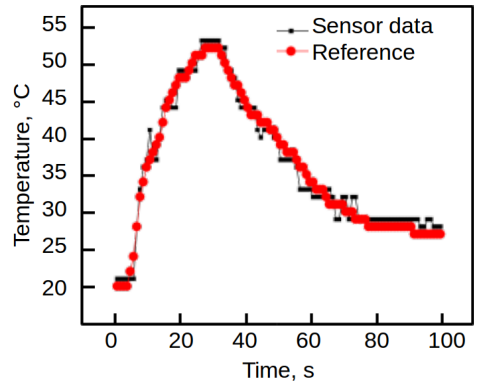

Fig. 7 Decoded temperature displayed on ECD with reference value measured by thermocouple.

5. Conclusion

In this paper, a proof-of-concept sensor platform for an all-in-one bio sensor chip was developed. The CMOS devices could be powered by an on-chip Mg/AgCl battery, and the sensing data could be displayed on an electrochromic display. The displayed digital data was captured by a digital camera and the transmitted data was automatically recovered by an image processing software. The measured data well agreed with the commercialized thermometer. In this paper, discrete components were integrated on a PCB, however, all the peripheral components, e.g. the on-chip battery, the on-chip electrochromic display and the voltage converter, could be easily integrated in or on the CMOS chip. Thus the proposed sensor platform can be applicable for the proposed bio sensor chip.

Acknowledgements

This research was partly supported by Center of Innovation Science and Technology based Radical Innovation and Entrepreneurship Program.

References

[1] T. Aytur, P.R. Beatty, B. Boser, M. Anwar, and T. Ishikawa, "An immunoassay platform based on CMOS hall sensors," Solid-State Sensor, Actuator and Microsystems Workshop, Hilton Head Island, SC, pp.126–129, June 2002.

[2] T. Tsukamoto, T. Ishikawa, and S. Tanaka, "Disposable wireless immuno-sensing chips," AUSMT, vol.7, no.1, pp.1–6, March 2017.

[3] T. Tsukamoto and S. Tanaka, "Printable on-chip micro battery for disposal bio-sensing device," Journal of Physics: Conference Series, vol.660, Dec. 2015.

[4] M.M. Ahmadi and G.A. Jullien, "A wireless-implantable microsystem for continuous blood glucose monitoring," IEEE Trans. Biomed. Circuits Syst., vol.3, no.3, pp.169–180, June 2009.

[5] H. Hafezi, T.L. Robertson, G.D. Moon, K.-Y. Au-Yeung, M.J.

Zdeblick, and G.M. Savage, "An ingestible sensor for measuring medication adherence," IEEE Trans. Biomed. Eng., vol.62, no.1, pp.99–109, Jan. 2015.
[6] Y. Zhu, T. Tsukamoto, and S. Tanaka, "On-chip electrochromic micro display for a disposable bio-sensor chip," J. Micromech. Microeng., vol.27, no.12, p.125012, Dec. 2017.
[7] T. Kobayashi, H. Yoneyama, and H. Tamura, "Polyaniline film-coated electrodes as electrochromic display devices," J. Electroanal. Chem. Interfacial Electrochem., vol.161, no.2, pp.419–423, Feb. 1984.
[8] T. Kobayashi, H. Yoneyama, and H. Tamura, "Electrochemical reactions concerned with electrochromism of polyaniline film-coated electrodes," J. Electroanal. Chem. Interfacial Electrochem., vol.177, no.1, pp.281–291, Oct. 1984.
[9] Y. Mohd, R. Ibrahim, and M. Zainal, "Electrodeposition and characterization of polyaniline films," IEEE Symposium on Humanities, Science and Engineering Research (SHUSER), pp.1301–1306, June 2012.
[10] M.F. Zainal, Y. Mohd, and R. Ibrahim, "Preparation and characterization of electrochromic polyaniline (pani) thin films," IEEE Business Engineering and Industrial Applications Colloquium (BEIAC), pp.64–68, April 2013.
[11] L. Gomes, A. Branco, T. Moreira, F. Feliciano, C. Pinheiro, and C. Costa, "Increasing the electrical conductivity of electrochromic PEDOT: PSS films - a comparative study," Sol. Energy Mater. Sol. Cells, vol.144, pp.631–640, Jan. 2016.
[12] C. Pozo-Gonzalo, D. Mecerreyes, J.A. Pomposo, M. Salsamendi, R. Marcilla, H. Grande, R. Vergaz, D. Barrios, and J.M. Sánchez-Pena, "All-plastic electrochromic devices based on PEDOT as switchable optical attenuator in the near IR," Sol. Energy Mater. Sol. Cells, vol.92, no.2, pp.101–106, Feb. 2008.
[13] A. Patra, K. Auddy, D. Ganguli, J. Livage, and P. Biswas, "Sol–gel electrochromic WO_3 coatings on glass," Mater. Lett., vol.58, no.6, pp.1059–1063, Feb. 2004.
[14] J. Arakaki, R. Reyes, M. Horn, and W. Estrada, "Electrochromism in niox and wox obtained by spray pyrolysis," Sol. Energy Mater. Sol. Cells, vol.37, no.1, pp.33 – 41, April 1995.
[15] M.C. Bernard, A. Hugot-Le Goff, S. Joiret, N.N. Dinh, and N.N. Toan, "Polyaniline layer for iron protection in sulfate medium," J. Electrochem. Soc., vol.146, no.3, pp.995–998, March 1999.
[16] K. Onizuka, H. Kawaguchi, M. Takamiya, T. Kuroda, and T. Sakurai, "Chip-to-chip inductive wireless power transmission system for sip applications," IEEE Custom Integrated Circuits Conference 2006, pp.575–578, Sept. 2006.
[17] C.-W. Chang, K.-C. Hou, L.-J. Shieh, S.-H. Hung, and J.-C. Chiou, "Wireless powering electronics and spiral coils for implant microsystem toward nanomedicine diagnosis and therapy in free-behavior animal," IEEE 4th International Nanoelectronics Conference (INEC), pp.1–2, June 2011.
[18] E.G. Kilinc, M.A. Ghanad, F. Maloberti, and C. Dehollain, "Short range remote powering of implanted electronics for freely moving animals," 11th International New Circuits and Systems Conference (NEWCAS), pp.1–4, June 2013.
[19] U. Cilingiroglu, B. Tar, and C. Ozmen, "On-chip photovoltaic energy conversion in bulk-cmos for indoor applications," IEEE Trans. Circuits Syst. I, Reg. Papers, vol.61, no.8, pp.2491–2504, Aug. 2014.
[20] T. Maleki, N. Cao, S.H. Song, C. Kao, S.-C. Ko, and B. Ziaie, "An ultrasonically powered implantable micro-oxygen generator (imog)," IEEE Transactions on Biomedical Engineering, vol.58, no.11, pp.3104–3111, Nov. 2011.
[21] J.F. Dickson, "On-chip high-voltage generation in mnos integrated circuits using an improved voltage multiplier technique," IEEE J. Solid-St. Circ., vol.11, no.3, pp.374–378, June 1976.
[22] H. Bay, T. Tuytelaars, and L. Van Gool, "SURF: Speeded Up Robust Features," omputer Vision – ECCV 2006, vol.3951, pp.404–417, Springer Berlin Heidelberg, Berlin, Heidelberg, 2006.
[23] F. Korn, N. Sidiropoulos, C. Faloutsos, E. Siegel, and Z. Protopapas, "Fast nearest neighbor search in medical image databases," VLDB '96, San Francisco, CA, USA, pp.215–226, 1996.
[24] E. Auvinet, E. Grossmann, C. Rougier, M. Dahmane, and J. Meunier, "Left-luggage detection using homographies and simple heuristics," PETS 2006, New York, USA, pp.51–58, June 2006.

Takashiro Tsukamoto received his M. Eng. degree in 2002 in thermal engineering from Tokyo Institute of Technology. He received M. Eng. degree in 2009 in microelectromechnical systems from Tohoku University. He received his Dr. Eng. degree from Tohoku University in 2012. Currently he is an assistant professor in the department of Robotics, Graduate School of Engineering at Tohoku University. He is a member of the Institute of Electrical and Electronics Engineers (IEEE), the Institute of Electrical Engineers of Japan (IEEJ) and the Japan Society of Mechanical Engineers (JSME).

Yanjun Zhu received his B.S. degree in University of Electronic Science and Technology of China. He received his M.S. degree microelectromechnical systems from Tohoku University in 2017. He is recruited by Sony Corporation now and is developing CMOS image sensor for ADAS and autonomous driving.

Shuji Tanaka received his B.S. degree in 1994 from Tokyo University, Dr. Eng. degree in 1999 from Tokyo University. He is currently a professor at department of Robotics, Graduate School of Engineering at Tohoku University. His expertise is in the area of microelectromechanical systems (MEMS). He is a member of the Institute of Electrical and Electronics Engineers (IEEE), the Japan Society of Applied Physics (JSAP), the Institute of Electrical Engineers of Japan (IEEJ), and the Japan Society of Mechanical Engineers (JSME) etc.