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Development of an Arterial Tonometer Sensor

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Abstract—**In this study, we developed arterial tonometer sensor array using piezoresistive sensor elements and PDMS coating. Computer simulation for the pressure response of the sensor was compared with measurement results. The pressure attenuation ratios for simulation and measurement by 3mm PDMS coating were 0.2145 and 0.2952, respectively. It is expected that sensitivity of the sensor array depending on PDMS coating thickness can be determined using proposed method. And by designing the sensor bonding layer and wire bonding layer separately, it can improve wire connection reliability.**

I. INTRODUCTION

THE arterial tonometer is an instrument for measuring arterial blood pressure. It measures continuous blood pressure beat by beat. However, the conventional sphygmomanometer measures only systolic and diastolic pressure. Typically, the instrument sensor is placed over a superficial artery such as radial artery[1]. The fundamental principles of arterial tonometry are similar to those for ocular tonometry[2,3]. Figure 1 shows an idealized principle of a tonometer. In Figure 1, P represents the blood pressure in a superficial artery and F is the force measured by a tonometer sensor. The integrated effect of arterial pressure acting on the segment of arterial wall is represented by a vector of magnitude P and A, contact area between transducer and skin. When the transducer is placed over the artery and hold down pressure is applied so as to flatten the artery, the tension vector, T, is perpendicular to the pressure vector. Thus, measurement of the force, F, permits one to directly infer the intra-arterial pressure[4].

Based on the principle of the tonometer, it is very important to select an appropriate superficial artery position and design of the tonometer sensor. One of the practical difficulties with the simple sensor is that the sensor should be precisely placed over the superficial artery. To avoid this problem, multi element sensor array have been developed. Another consideration of the tonometer sensor is size. In case of radial artery, spatial resolution of the sensor array meets less than 2mm.

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In this paper, we have proposed and demonstrated a tonometry sensor array for measuring arterial pulse pressure by tonometric method. A sensor array consists of 7 piezoresistive pressure sensor array. PDMS (poly-dimethylsiloxane, Sylgard 184, Dow Corning) was coated on the sensor array to protect fragile sensor while faithfully transmitting the pressure of radial artery to the sensor. Especially, to avoid of weakness on durability of wire bonding, we designed double layer PCB which makes wire connection short and straighten. In order to validate the attenuation effect due to the pressure absorbed through the PDMS layer, we compared computer simulation with measurement result.

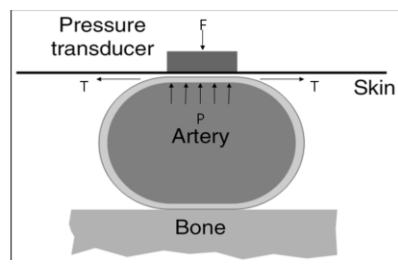

Fig. 1. Principle of an arterial tonometry

II. METHOD

A. Sensor Array Configuration

Figure 2 illustrates the conceptual diagram of the proposed tonometry sensor array. One sensor module consists of a 7 sensor elements and the sensors are arranged to form a linear array. Its spatial resolution is 2 mm, similar to that of human radial artery diameter[5]. The point is that there are die bonding layer and wire bonding layer. Because wire bonding PCB level is same with bonding pad of pressure sensor die, it is possible to route shorter than wiring on the die bonding PCB. PDMS layer protect fragile sensor and wire while faithfully transmitting the pressure of the patient's skin to the sensor.

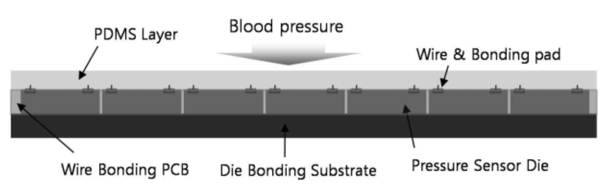

Fig. 2. Conceptual diagram of the proposed tonometry sensor array

Piezoresistive pressure sensor(ATP015, APM, Taiwan) was used as an element of sensor array (Figure 3). The ATP015 pressure sensor features a micromachined silicon solid-state sensor. It is ideal for applications requiring low hysteresis, high reliability and stability. This performance is achieved through careful resistor placement and mechanical configuration. With constant voltage 5V excitation, the ATP015 pressure sensor produces a voltage output that is linearly proportional to the input pressure within dynamic range of 15 psi. This sensor needs to add on external signal conditioning circuitry to amplify the output signal and maximize its performance.

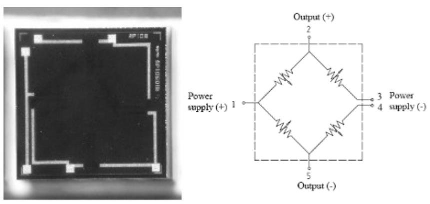

Fig. 3. ATP015 Pressure sensor (APM, Taiwan)

B. *Pressure Sensor Die Bonding*

Figure 4 shows the wire-bonded connection. ATP015 was bonded on the die bonding board using epoxy. After die bonding, wire bonding was performed to provide electrical connection between the pressure sensor die and PCB using gold wire(25um).

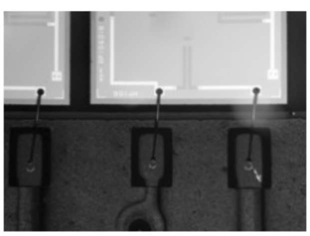

Fig. 4. Electrical connection between silicon chip and lead frame

At the beginning of the wire cycle, the bonding tool travels down to the first bond location (normally on the die). The first bond is achieved by bonding a spherical ball to the pad using thermal and ultrasonic energy. The second bond(normally on the PCB) consists of a stitch bond that bonds the opposite end of the wire and a tail bond. The tail bond is needed to form a wire tail for the next ball formation.

C. *PDMS Coating*

To protect the sensor die surface and bonded wire, 3mm thickness PDMS layer was formed. Polymeric fluid, which is PDMS was poured in the acryl frame(Figure 5) which of size is equal to sensor array PCB. Uniform fluid thickness(3mm) is formed by spin coating and achieved after spinning at 500 rpm for 1 min[5]. Then PDMS is cured at 60℃ for 2 hours. After vulcanizing PDMS, packaged sensor array was cut and peeled off.

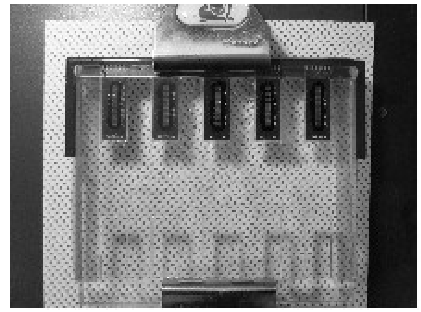

Fig. 5. Acryl frame to package the sensor with PDMS

Figure 6 shows the packaged pressure sensor array. During the measurement of pulse wave on the wrist, sensor array is mounted across the radial artery on the palmer side of wrist. The sensor array includes 7 pressure sensor dies in a linear array with length of 15mm. Therefore, this can cover the radial artery that passes between radius and tendon of wrist.

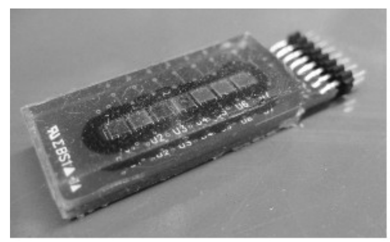

Fig. 6. Packaged pressure sensor array

D. *Simulation Test Setup*

Because PDMS is a kind of elastomer, thickness of PDMS can absorb more variation of pressure. We performed the computer simulation to estimate the effect of PDMS on pressure absorption. Simulation was conducted using computer software package(ADINA, ADINA R&D, USA) that generates solutions to practically solid mechanics problem. There are simulation condition in the Figure 7 and Table 2.

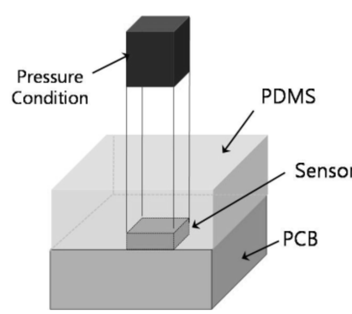

Fig. 7. Simulation condition

TABLE II
MECHANICAL PROPERTIES OF PDMS[6,7]

Parameter	Value
Poisson's Ratio	0.5
Young's Modulus	750kPa
Density	920kg/m^3
Geometry	10*10*3mm^3

E. Pressure Test Setup

Two experiments were performed to estimate the pressure sensor with or without PDMS coating. Firstly, two types of sensor array (with or without PDMS coating) were tested in air chamber. As shown in Figure 8, sensor array was placed in sealed chamber (30cmX20cmX6.5cm). Air pressure was applied by pump and inside pressure was monitored using a gauge. To measure the output of each sensor element, external circuit was used. The sensor array was excited by a constant voltage circuit for providing a 5 volt DC bias and the output was measured through a signal conditioning circuit whose gain was 2.

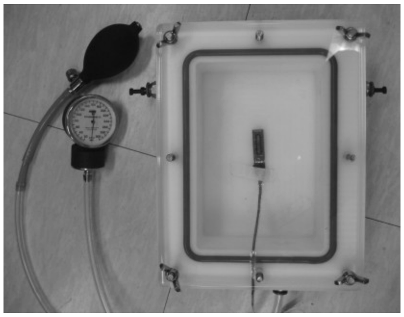

Fig. 8. Measurement setup for sensor output in air chamber

Secondly, a constant perpendicular force machine (Figure 9) was designed to do a series of experiments to verify the performance of coated sensor array. Stepping motor controlled hold down weight from 0g to 200g and the weight was monitored by precision balance(GF4000, AND, Japan). Test was conducted at room temperature.

Fig. 9. Measurement setup for sensor output vs. hold down pressure

III. RESULT & DISCUSSION

A. Simulation

Figure 10 shows the simulation results of sensor output according to hold down pressure. It was confirmed that pressure attenuation ratio by 3mm PDMS coating was estimated as 0.2145, which calculated as regression coefficient value.

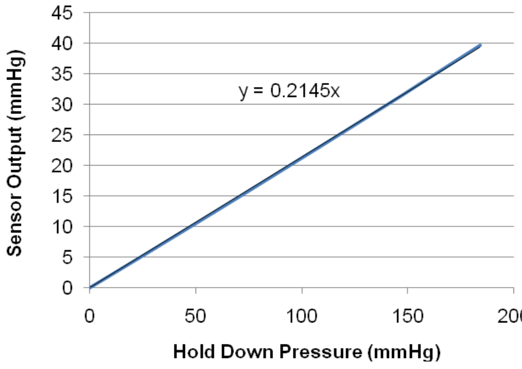

Fig. 10. Computer simulation of hold down pressure vs. sensor output pressure

B. Sensor test in air chamber

We compared sensor span voltage and output voltage of a pressure sensor in Figure 11. The full span of ATP015 is 145mV±30mV for pressure of 15 psi (775.24mmHg). This sensor characteristic was confirmed in air chamber test. Figure 11 shows the measured results of our sensor in air chamber. During increase the pressure in chamber, output voltage of sensor element was increased linearly. The measured sensitivity was 3.81mV/mmHg (gain x2). Therefore, its span voltage is expected 147.75mV for 15psi. There were no significant difference among the sensor elements and between with or without PDMS coating.

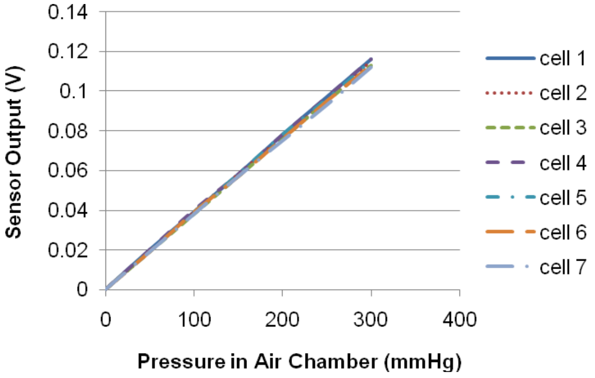

Fig. 11. Sensor array output voltage in air chamber

C. Sensor test by hold down pressure

From the measurement results by Figure 9 setup, hold down weight was converted to pressure unit dividing by sensor area and sensor voltage output was converted using previous section result. As a result, pressure response of the 3mm PDMS coated sensor array was measured (Figure 12). It was confirmed that pressure attenuation ratio by 3mm PDMS coating was 0.2952. The difference of the pressure attenuation ratio between the simulation and the measurement was considered due to mechanical property diffrence. The cured PDMS property is various depends on curing time and temperature. It is considered that Young's modulus value we adopted from reference[6,7] might be different from our real experiment.

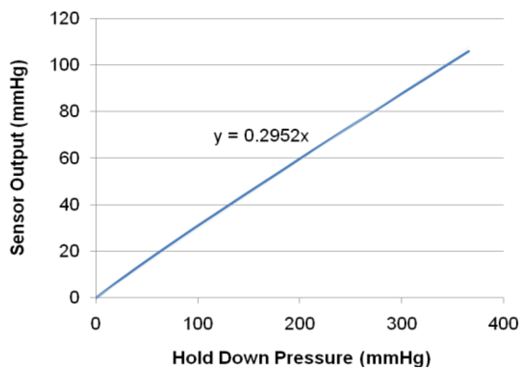

Fig. 12. Pressure response of the 3mm PDMS coated sensor array

IV. CONCLUSION

In this study, we developed arterial tonometer sensor array using piezoresistive sensor elements and PDMS coating. Even though the pressure response of the sensor array showed some difference from computer simulation, it is expected that the error will be minimized if the accurate measurement condition is applied to computer simulation. However, it is possible to estimate the sensitivity of the sensor array using proposed method. In tonometry, because the hold down pressure should be applied, the wiring is critical point in durability. In our method, it is possible to reduce the wiring curvature and it makes sensor more reliable in tonometric measurement. To realize ideal arterial tonometer sensor, spatial resolution of the sensor is must be considered by replacing with small sensor element. And consideration should be given to measurement drift caused by thermal effects and material creep.

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