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The Effect of the Deformation on the Sensitivity of a Flexible PDMS Membrane Sensor to Measure the Impact Force of a Water Droplet

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액적의 충격력 측정을 위한 유연 PDMS 멤브레인 센서의 변형에 의한 민감도의 영향

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ABSTRACT

This study investigates the effect of the deformation on the sensitivity of a flexible polydimethylsiloxane (PDMS) membrane sensor. A PDMS membrane sensor was developed to measure the impact force of a water droplet using a silver nanowire (AgNW). The initial deformation of the membrane was confirmed with the application of a tensile force (i.e., tension) and fixing force (i.e., compressive force) at the gripers, which affects the sensitivity. The experimental results show that as the tension applied to the membrane increased, the sensitivity of the sensor decreased. The initial electrical resistance increased as the fixing force increased, while the sensitivity of the sensor decreased as the initial resistance increased. The movement of the membrane due to the impact force of the water droplet was observed with a high-speed camera, and was correlated with the measured sensor signal. The analysis of the motion of the membrane and droplets after collision confirmed the periodic movement of not only the membrane but also the change in the height of the droplet.

Keywords : Membrane Sensor(멤브레인센서), Deformation(변형), Tensile Force(인장력), Drop Impact(액적충돌)

1. Introduction

Studies on the effect of water droplets on various surfaces have been conducted for a long period of time. The water droplet collision phenomenon has attracted significant attention not only in processes such as solid surface coating (spray coating) in various industries, but also the mechanical damage of the surface due to repeated exposure to impact forces and the reliability of parts[1-3]. In the field of bioscience for tissue engineering and cell printing, there has been significant interest in the droplet impact phenomenon on soft surfaces[4].

Most studies involve the rheological analysis of the

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collision phenomena on various solid surfaces. Recently, however, flexible force sensors using conductive nanoparticles, such as flexible membranes and carbon nanotubes have been developed[5-8]. Studies on impact phenomena based on performance measurements of impact forces applied to solid surfaces are also being conducted[9]. Grinspan et al. measured the impact force of low-velocity liquid droplets using a piezoelectric polyvinylidenefluoride film[10]. Pang et al. measured droplet impact forces using a flexible and highly sensitive strain sensor that includes Pt-coated polymer nanofibers[11].

In this study, a simple yet effective resistance-type sensor using a polydimethylsiloxane (PDMS) membrane to measure the impact force of water droplets is developed. In the process, the influence of changes in the mechanical deformation of the membrane at the initial state on the sensitivity of the sensor was confirmed. The motion of the membrane and droplets after the collision were analyzed using image processing techniques.

2. Preparation of PDMS membrane sensor and experimental setup

Fig. 1 shows the experimental setup to measure the impact force of water droplets using a PDMS membrane sensor. The PDMS membrane sensor was used to measure the change in resistance due to the deformation of the transfered flexible silver nanowire(AgNW) electrode. The flexible AgNW electrode was formed on the underside of the membrane. The AgNW surface is in contact with the copper foil at both grippers to establish an electrical connection.

To prepare the PDMS membrane sensor, polytetrafluoroethylene tape (ASF-110FR, Chukoh Chemical Industries, Ltd.) was attached to a Petri dish for the smooth transfer of AgNW(Flexiowire 2020, Flexio Co., Ltd.), while a masking tape(i.e., blue tape) was attached to the designed electrode pattern. To coat the AgNW solution uniformly, the Petri dish was heated to 55℃ on a hot plate. Then, the AgNW solution was sprayed for 15 s using an airbrush while maintaining a constant distance, and baked for 10 s to evaporate the solvent. This was repeated for 15 times to prepare the AgNW electrode. After the masking tape was removed, the uncured PDMS precursor (Sylgard 184 Silicone Elastomer, Dow Corning), consisting of a mixture of a resin and hardener at a 10:1 ratio, was uniformly spread on the AgNW electrode, and then cured in an oven at 70°C for 24 h. Afterward, the cured PDMS was cut into a length and width of ~ 55mm and ~ 8mm, respectively, and slowly removed to transfer the AgNW electrode. The electrical resistance of the AgNW electrode was measured in the range about 30 ~ 70Ω. The thickness of the PDMS membrane was measured as 367 ± 48µm. The resistance change of the AgNW electrode due to the droplet impact was measured at a high-speed sampling rate (~ 197kHz) using a Wheatstone bridge circuit and a data acquisition system (NI DAQ (781326-01) and LabView software). The tensile force applied to the membrane sensor was quantitatively controlled at the manual stage with a load cell (333AL, 5 kgf, KTOYO) connected to one side of the membrane. In all experiments, a syringe pump (FUSION 200, Chemyx Inc.) with a 25-gauge plastic needle was used to apply free-falling droplets from a constant height (~ 115mm) with a consistent volume (9.85 ± 0.42µL). The motions of the membrane and droplets before and after collision were recorded by a high-speed camera (FASTCAM Mini AX, Photron) with a frame rate of 30,000 frames per second. The droplet velocity and

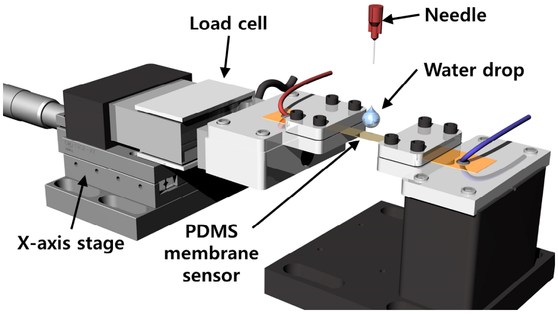

Fig. 1 Experimental setup for controlling the applied tensile force on the PDMS membrane sensor

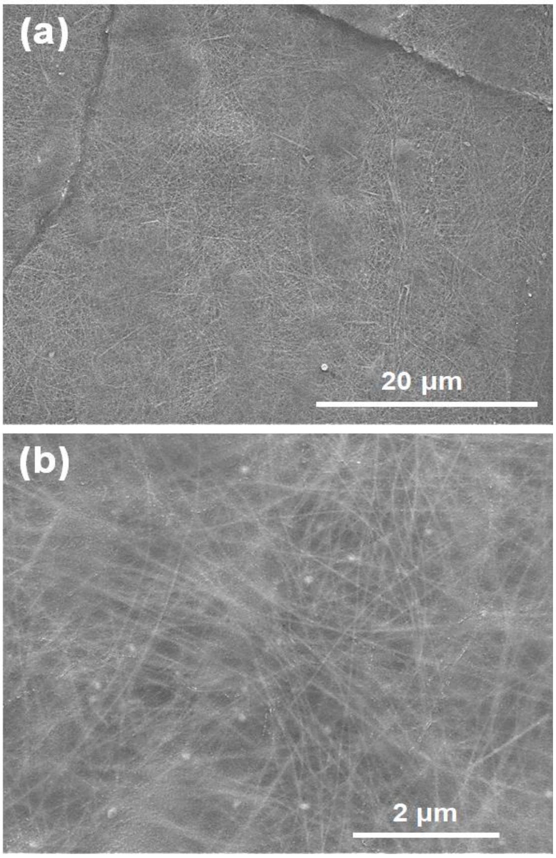

Fig. 2 (a) Low (3,000x) and (b) high (20,000x) magnification FE-SEM images of the transfered AgNW electrode on the PDMS membrane

volume were measured via image processing with MATLAB®. The average droplet velocity was approximately 1.45 ± 0.001 m/s in all experiments. The motions of the membrane and droplets after collision were analyzed.

3. Sensitivity by initial deformation of PDMS membrane

To confirm the measurement accuracy of the PDMS membrane sensor, the impact forces of water droplets were repeatedly measured by varying the applied tensile forces without adjusting the initial resistance of the sensor. The applied tensile forces were adjusted from 10 mN (P_1) to 20 mN (P_2), starting from the minimum tension (P0) available to fix the membrane. The mechanical strains at applied tensile force P_1 and P_2 were calculated to be 2.7% and 2.8%, respectively. Fig. 3(a) shows the maximum resistance change measured before and after impact compared with the initial resistance value. The results confirmed that the resistance change values before and after collision were significantly different (i.e., the coefficient of variation (CV) ranged from 73 to 110%) under the same tensile force applied to the membrane.

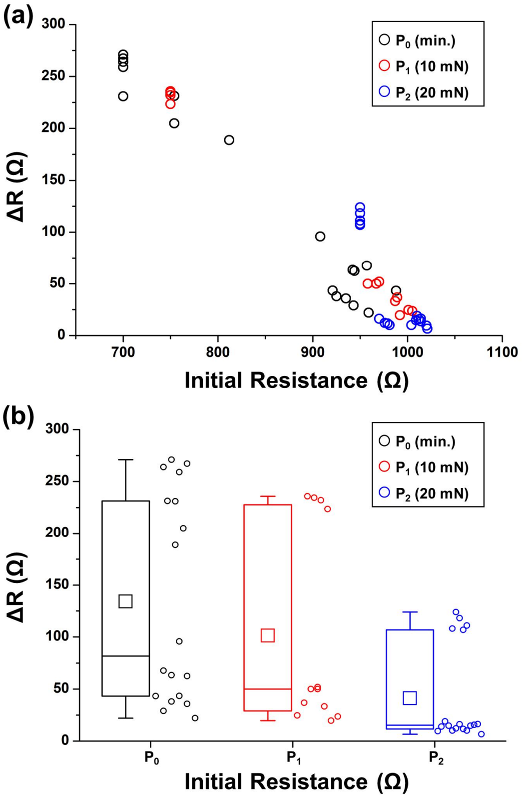

Fig. 3 Measured result of electric resistance change while varying the applied tensile force without controlling the initial resistance value: maximum difference of resistance change versus (a) the initial resistance and (b) applied tensile force on the membrane sensor

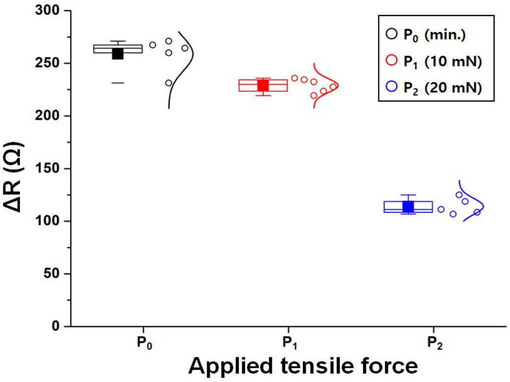

Fig. 4 Reduced variation (CV < 6%) of measured results by controlling initial resistance value

In resistance-type force sensors, the sensitivity decreases as the initial resistance increases[12]. The experimental results confirmed that the lower the initial resistance, the greater the measured resistance change due to collision (Fig. 3(b)). To fix the membrane and connect the electrodes of the sensor in the experimental setup, the AgNW surface of the sensor faced downward to make contact with the copper tape when a constant force is applied to the same area. It was confirmed that the initial resistance value of the sensor changed according to the force required to press the membrane at the connecting part. The initial resistance was constantly adjusted to the minimum value to fix the membrane and apply a constant tensile force at the connecting part. Under each tensile force condition (P_0, P_1, P_2), the initial resistance values were kept constant at 700Ω, 750Ω, and 900Ω, respectively. The measurement results in Fig. 4 show a constant resistance change value for each tensile force condition. The results were measured five or more times for each condition. In all tests, the calculated CV ranged from 2.6 to 6.0%.

4. Motion of the drop and membrane after collision

Fig. 5(a) shows the relative resistance change (i.e., divided by the initial resistance, %) of the membrane sensor over time after collision for each tensile force condition. The maximum resistance change within approximately 20 ms immediately after the impact was observed. Afterward, the increase and decrease in resistance was repeated, that is, the oscillation phenomenon was observed, and the tendency of the overall resistance to decrease was confirmed. Due to the structural characteristics of the membrane sensor, the stiffness of the membrane increases as the applied tensile force increases. As the membrane stiffness increases, the deformation of the membrane for the same droplet impact force decreases. Therefore, it was confirmed that the maximum resistance change tends to decrease as the applied tensile force increases.

The motion of the membrane and droplets after collision was analyzed using image processing techniques; the results are shown in Fig. 5(b-d). In the recorded images, the membrane and droplet after the collision were recognized as a single object (Fig. 5(b)). The maximum (y_m, green cross) and minimum (y_d, yellow cross) values of the y-axis coordinates were measured. The change in the maximum value of the y-axis coordinate indicates the change in the height of the droplet, while the change in the minimum value indicates the movement of the membrane. Based on the y-axis coordinate value (y_{m0}, y_{d0}) at the point ($t = 0$) of collision between the droplet and membrane, the relative position of the membrane ($y_m - y_{m0}$) and droplet are shown in Fig. 5(c) and (d). The relative position of the droplet ($y_d - y_{d0}$) was calculated by subtracting the membrane position (minimum y-axis value) from the measured maximum y-axis value to exclude the effect of membrane motion.

The results confirmed that not only the membrane but also the change in the height of the droplet exhibited periodic movement. Under the current experimental conditions, the sensor signal, which is indicated by the resistance change due to membrane deformation, appears to express the periodicity of the

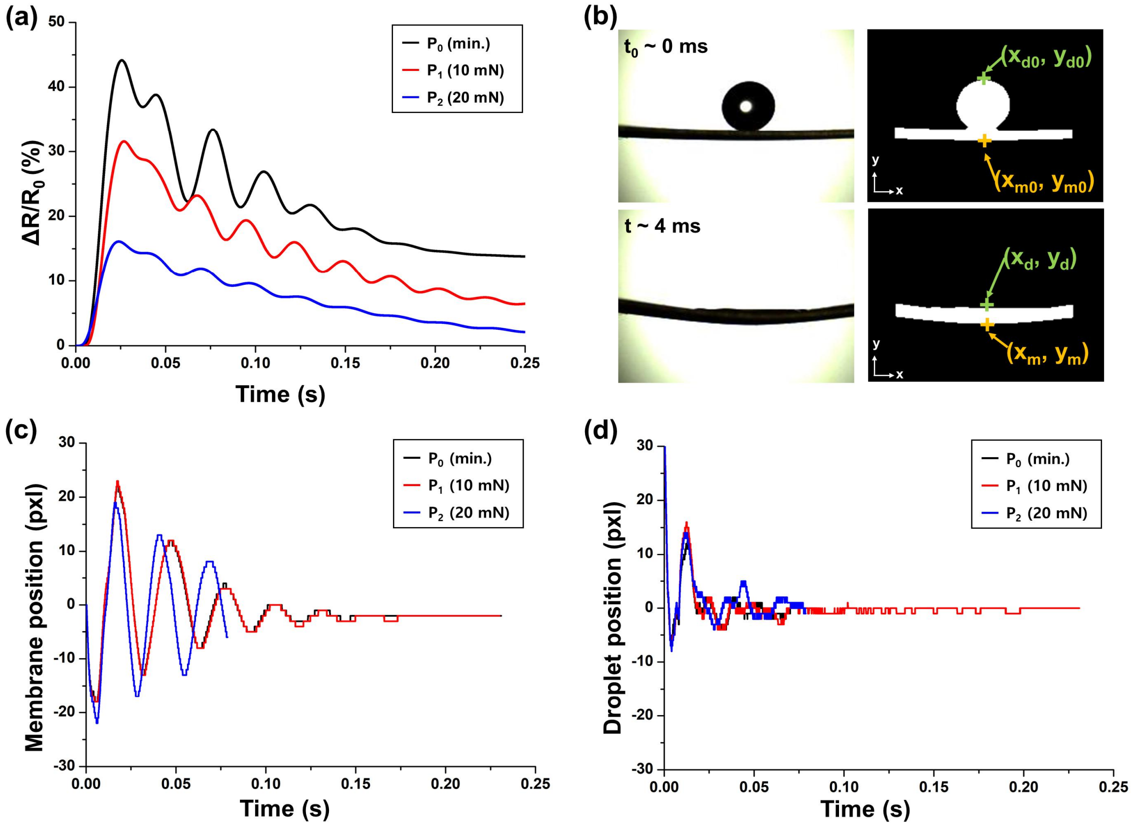

Fig. 5 Measured impact force and analyzed motion of the membrane and droplet after collision: (a) the change in relative resistance over time after collision with varying applied tensile forces; (b) recoded and processed collision images; and (c), (d) relative position of the membrane and droplet over time

membrane rather than that of the droplet. Moreover, it was confirmed that the period of the membrane slightly decreased at the applied tensile force of 20 mN. Simply, the membrane can be modeled as a mass-spring-damper system, and as the stiffness of the membrane increases, the spring constant increases. This is because the spring constant of the membrane increased owing to the increase in the applied tensile force, which increased the resonance frequency of the membrane sensor.

5. Conclusion

In this study, we confirmed the influence of the mechanical deformation of the membrane at the initial state on the sensitivity of a resistance-type membrane sensor used to measure the impact force of water droplets. Under the same tensile force condition, a constant resistance change was confirmed by maintaining a constant initial resistance value and adjusting the deflection of the membrane at the connecting part. The analysis of the motion of the membrane and droplets after collision by image processing techniques confirmed the periodic movement of not only the membrane but also the change in the height of the droplet. The changes in the measured resistance due to the movement of the PDMS membrane following water droplet collision may vary depending on the dynamic characteristics of the membrane (mass, spring, damping constant, etc.). The analysis of the dynamic motion of the membrane sensor and water droplet collision, similar to membrane motion according to the wettability of various surfaces, will be continued in future studies.

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