Micromachines **2012**, *3*, 315-324; doi:10.3390/mi3020315

OPEN ACCESS

micromachines

ISSN 2072-666X

www.mdpi.com/journal/micromachines

Article

Flexible Tactile Sensor Using Polyurethane Thin Film

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Received: 11 February 2012; in revised form: 5 March 2012 / Accepted: 13 March 2012 / Published: 10 April 2012

Abstract: A novel capacitive tactile sensor using a polyurethane thin film is proposed in this paper. In previous studies, capacitive tactile sensors generally had an air gap between two electrodes in order to enhance the sensitivity. In this study, there is only polyurethane thin film and no air gap between the electrodes. The sensitivity of this sensor is higher than the previous capacitive tactile sensors because the polyurethane is a fairly flexible elastomer and the film is very thin (about 1 μm). The polyurethane film is formed by spin-coating and etched back from 6 μm to 1 μm using 48% sulfuric acid. As a result of evaluation, the sensitivity of the developed sensor (diameter is 1 mm) is 1.3 pF/Pa (800 pF/N considering the sensing area). Young's modulus of the thin polyurethane film was estimated to be 20 kPa.

Keywords: tactile sensor; capacitive sensor; poly-urethane; elastomer; thin film

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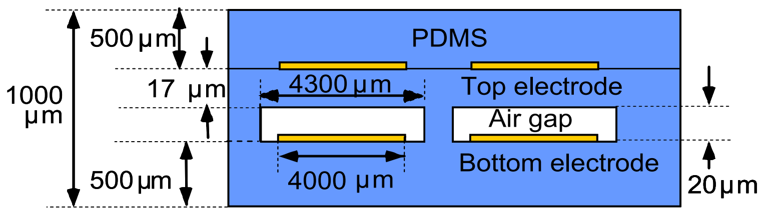
1. Introduction

Recently, there has been much interest in developing next-generation robots which can assist human daily life, such as housework, caring, medicine, security, and so on. One of the important issues when these robots perform the above-mentioned tasks is that they must be able to grasp human bodies, dishes, furniture, and other brittle items. Therefore, these robots must grasp the object with minimal force. Therefore, development of arrayed tactile sensors as sensitive as human skin is required. Additionally, a tactile sensor should be flexible in order to deform according to the contact state. Previously, many tactile sensors for robot hands have been proposed [1–6]. However, a high-sensitive and high-integrated tactile sensor comparable to the human hand has still not been reported because the human skin contains numerous highly-sensitive force-sensing receptors distributed in approximately 1 mm intervals [7].

Therefore, micromachining technology attracts much attention for fabricating the arrayed tactile sensor, since high-sensitive force sensing elements can be fabricated with fine resolution of several microns using this technology. Particularly, a micro capacitive sensor is promising for high density tactile sensors because of its simple structure. In previous work, we developed parallel-plate capacitive type tactile sensor array consisting of polydimethylsiloxane (PDMS), which is one of the flexible polymers [8,9]. The cross section of this sensor is shown in Figure 1. However, this sensor is difficult to fabricate on the curved surfaces of the robot hand, because it has an air gap between two electrodes for improvement of its sensitivity.

Figure 1. Schematic cross-section of established tactile sensor using polydimethylsiloxane (PDMS) and air gap.



In this study, we focus attention on polyurethane because it is more flexible than PDMS. The purpose of this study is to develop a tactile sensor using polyurethane film without any air gaps. We also try to thin the polyurethane film because the sensitivity of the sensor is inversely proportional to its thickness.

2. Device Design

The tactile sensor developed in this study is a simple parallel plate capacitor as shown in Figure 2. There is polyurethane thin film between two parallel electrodes. This sensor detects a change in capacitance due to compressive stress. Here, the initial distance and the decrease of distance due to compressive stress between the two electrodes are defined as d and Δd, respectively. The change in capacitance C is given by following equation:

$$\Delta C = C' - C = \varepsilon_0 \varepsilon_r S \cdot \frac{\Delta d}{d \cdot (d - \Delta d)} \tag{1}$$

where C is initial capacitance, C' is capacitance after compression, S is area of electrode, ε_0 is vacuum permittivity, ε_r is relative dielectric constant of polyurethane. When $d >> \Delta d$, Equation (1) is then written as

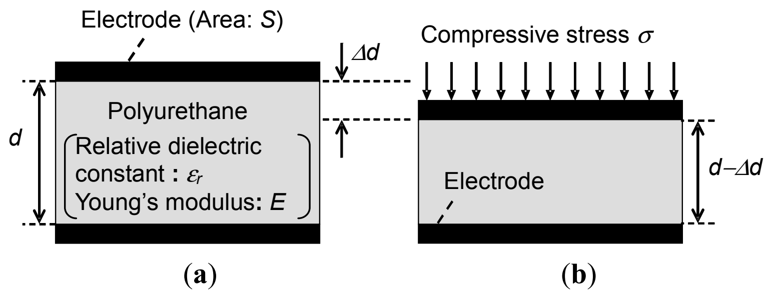
$$\Delta C \approx \varepsilon_0 \varepsilon_r S \cdot \frac{\Delta d}{d^2} = C \cdot \frac{\Delta d}{d} \tag{2}$$

Provided that the deformation by compressive stress is elastic one, Equation (2) can be rewritten using compressive stress σ and Young's modulus E as follows:

$$\Delta C \approx \frac{\varepsilon_0 \varepsilon_r S}{d} \cdot \frac{\sigma}{E} = C \cdot \frac{\sigma}{E} \tag{3}$$

This equation indicates that the sensitivity of tactile sensor is proportional to the initial capacitance *C*. Therefore, its sensitivity is increased by thinning the polyurethane film.

Figure 2. Schematic cross-section of established tactile sensor using poly-urethane without gap (**a**) at initial state; and (**b**) after compression.



3. Fabrication of Polyurethane Thin Film

Fabrication process of the polyurethane film is shown in Figure 3. In this process, the polyurethane film is formed by spin-coating method. At first, isocyanate and polyol, which are raw materials of the polyurethane, are mixed in an open vessel. Next, polyurethane reaction of the mixture progresses in a vacuumed desiccator, and defoaming treatment is carried out. Then, the mixture is spin-coated on an Au film (0.1 μm thick), which is evaporated on a silicon substrate. Finally, the spin-coated polyurethane film is baked on hotplate at 120 °C for 60 min. This heating was carried out for hastening the chemical reaction of forming urethane film from raw materials because this polyurethane is thermoset elastomer. It is not a thermoplastic urethane (TPU), using which Huang *et al*. reported a micromachined actuator [10]. Solid state parameters of the polyurethane measured by a raw material manufacturer (Exseal Corporation, Ltd.) are shown in Table 1.

Figure 3. Fabrication process of polyurethane thin film. (**a**) Mixture of raw materials; (**b**) Progress of poly-urethane reaction in vacuum; (**c**) Spin-coating of polyurethane film and bake on.

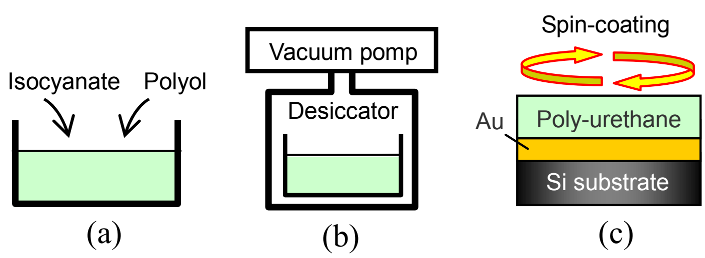
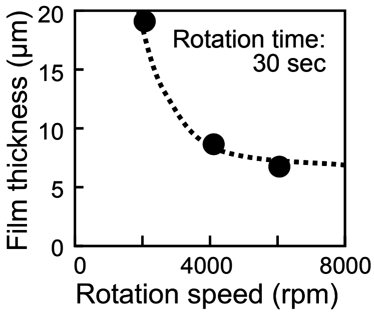


Table 1. Solid state parameters of polyurethane [11].

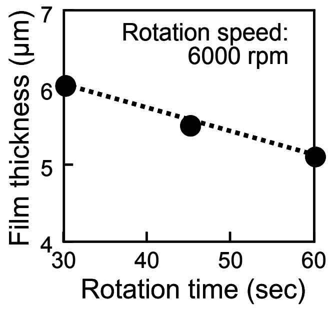
Parameter		Value
Relative density		1.04
Tensile strength [300%]	(kPa)	340
Compressive strength [30%]	(kPa)	7

Figure 4(a,b) are relationship between spin-coating condition and film thickness of polyurethane. These graphs show that the film thickness saturates at approximately 6 μm when the rotation time is set to 30 s, and it decreases as the rotation time increases.

Figure 4. (**a**) Rotation speed dependence and (**b**) rotation time dependence of film thickness of polyurethane.



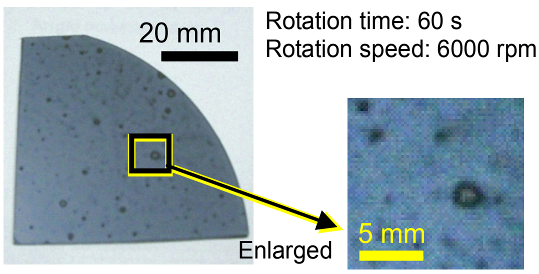
(**a**)



(**b**)

It was found that the film thickness became nonuniform when the rotation time largely exceeds 30 s, as shown in Figure 5. This result indicates that a smooth polyurethane film which is thinner than about 6 μm cannot be formed only by the spin-coating method.

Figure 5. Photograph of nonuniform surface of polyurethane film.



Therefore, we tried to etch-back the spin-coated polyurethane film. First, the polyurethane film was etched by O_2 plasma. As a result, film thickness of the polyurethane film was not decreased, but it is confirmed by a scanning electron microscopy (SEM) that its surface condition was changed, as shown in Figure 6. Next, we tried to etch the polyurethane film using 48% diluted sulfuric acid. As a result, its thickness can be reduced to 1 μm after the etching time of 30 s, as shown in Figure 7. The obtained surface was sufficiently smooth.

Figure 6. SEM image of polyurethane surface after O_2 plasma etching.

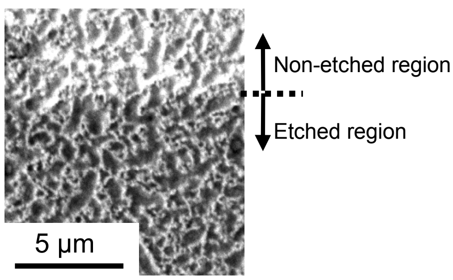
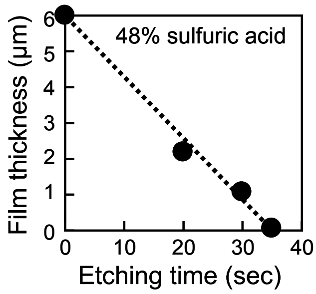


Figure 7. Decrease of film thickness by etching-back using sulfuric acid.



4. Fabrication and Characterization of Tactile Sensor Using Polyurethane Thin Film

4.1. Fabrication and Measurement of Tactile Sensor Using Polyurethane

We formed two kinds of polyurethane film for fabrication of the tactile sensors; one is 6 µm thick, and another is 1 µm thick. Figure 8 shows the fabrication process of tactile sensors. The top electrodes are directly patterned using a circular shadow mask, of which diameter is 1 mm. Figure 9 shows a photograph of fabricated tactile sensor. Figure 10 shows a schematic figure of measurement setup for characterizing of fabricated tactile sensor. In this study, compressive stress is applied using test weights. Here, one probe is contacted to the edge of top electrode of sensor, at which the test weight did not overlap to the top electrode. Since the area of each test weight S_{weight} is larger than area of the fabricated sensor, applied pressure to the sensor P is given by $P = mg/S_{weight}$, where m is mass of test weight and g is gravitational acceleration (=9.8 m/s^2). The capacitance of each sensor was measured using LCR meter (Agilent technologies, E4980A).

Figure 8. Fabrication process of tactile sensors using polyurethane thin film. (**a**) Evaporation of Au film on Si substrate; (**b**) Spin-coating and etching back of polyurethane; (**c**) Evaporation of Au film through shadow mask.

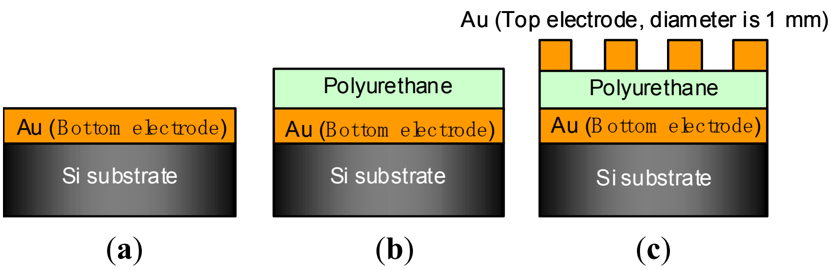


Figure 9. Photograph of fabricated tactile sensors using poly-urethane thin film and Au electrodes. Diameter of circular Au electrode (dark gold color) is 1 mm.

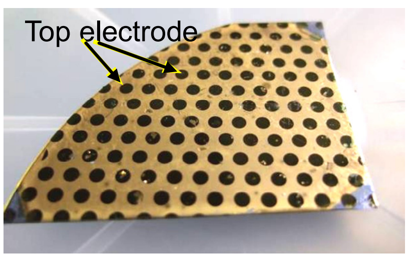
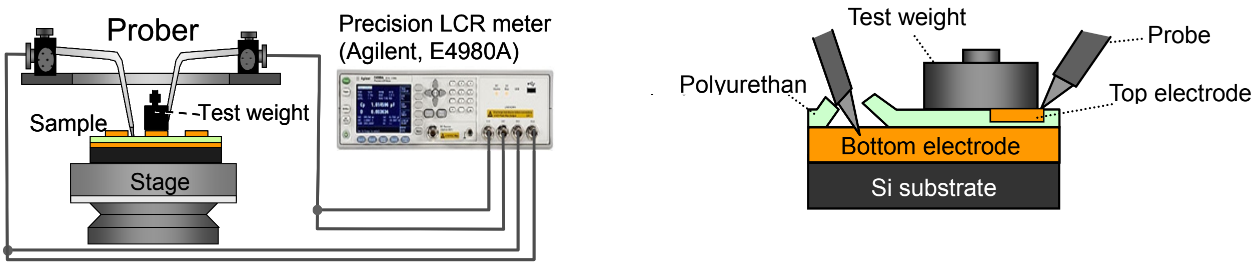


Figure 10. Measurement setup for characterizing fabricated tactile sensor.

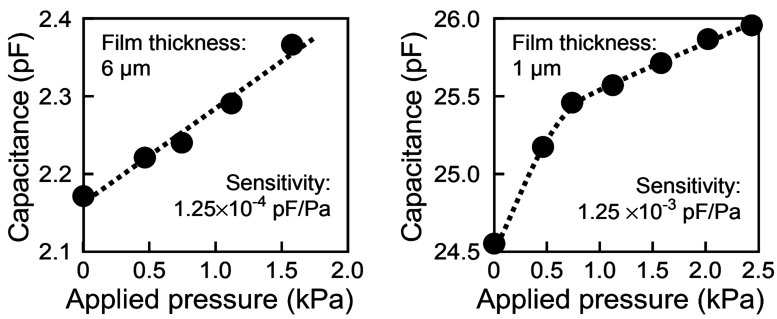


(**a**) (**b**)

4.2. Measurement Results

Figure 11(a) shows the change in capacitance of the sensor *versus* applied pressure, in case that the thickness of polyurethane film is 6 µm. As shown in this figure, the capacitance linearly increases with applied stress. It was estimated that the sensitivity is 1.25×10^{-4} pF/Pa (80 pF/N considering circular sensing area having 1 mm diameter). This value is more than ten times larger compared to a sensitivity of tactile sensor made of PDMS [12].

Figure 11. Capacitance of fabricated tactile sensor *versus* applied pressure when film thickness is (**a**) 6 µm and (**b**) 1 µm.



(**a**) (**b**)

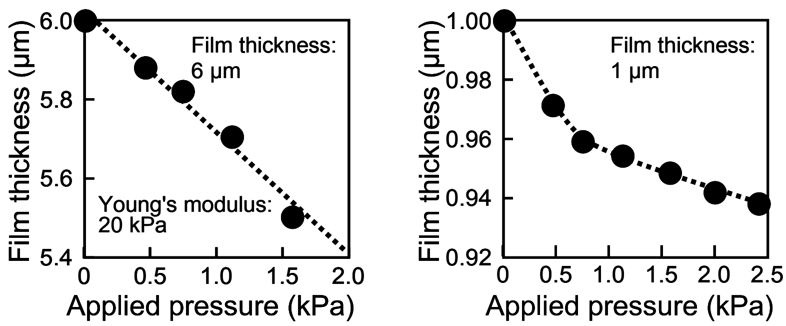
Figure 11(b) shows the change in capacitance of the sensor *versus* applied pressure, in case that the thickness of polyurethane film is 1 µm. In this case, the sensitivity of sensor is 1.25×10^{-3} pF/Pa (800 pF/N considering sensing area) when the applied pressure is smaller than approximately 0.8 kPa. This means that the sensitivity of sensor becomes ten times larger by reducing the thickness of polyurethane film from 6 µm to 1 µm. Therefore, it can be said that the sensitivity increases as the film thickness of polyurethane decreases. However, its sensitivity deteriorates to 3.12×10^{-4} pF/Pa when the applied pressure is larger than 0.8 kPa. This result indicates that the measurement range of sensor, in which the output of sensor linearly changes with applied pressure, becomes narrow by thinning the film thickness.

It is questionable that the sensitivity became ten times larger even though the polyurethane film thickness was reduced to one-sixth, *i.e.*, six times larger sensitivity makes sense intuitively. We think that the measurement data of thickness included errors, especially for the case of thin film of 1 µm thickness. The polyurethane thickness was measured using a contact line profile meter (Dectak 3, Veeco Co. Ltd.) as follows: a part of the polyurethane is etched away, followed by deposition of poly-para-xylene (Parylene) film of 5 μm in thickness to cover polyurethane and prevent it from the damage due to profiler probe scratching. The step height at interface between etched and non-etched areas was measured. Owing to these complicated measurements and undulation/uncertainty of Parylene protection film thickness, measurement error may have arisen; especially in the case that the polyurethane thickness is smaller than Parylene thickness of 5 μm. The precise measurement of polyurethane film thickness is the projected work in future.

4.3. Estimation of Young's Modulus of Polyurethane Thin Film

It is difficult to measure the change in the thickness of polyurethane film in fabricated sensor directly. Therefore, it was calculated considering both the change in capacitance by applied pressure shown in Figure 11 and the initial thickness of polyurethane used in the sensor. Figure 12(a,b) show the estimation results. Figure 12(a) indicates that the Young's modulus of the polyurethane film is approximately 20 kPa when the thickness of polyurethane is 6 μm. This value is 1/150 of the Young's modulus of PDMS. Figure 12(b) shows that Young's modulus of the 1 μm thick polyurethane film is also approximately 20 kPa when the applied pressure is smaller than 0.8 kPa. However, this Young's modulus of 1 μm thick polyurethane becomes larger when the applied pressure is more than 0.8 kPa. This result indicates that the polyurethane cannot be deformed elastically when the applied pressure is more than 0.8 kPa.

Figure 12. Thickness of polyurethane film in tactile sensor *versus* applied pressure, which is calculated considering both the initial thickness of polyurethane and the change in capacitance shown in Figure 11. (**a**) Change in thickness when initial thickness is 6 μm; (**b**) Change in thickness when initial thickness is 1 μm.

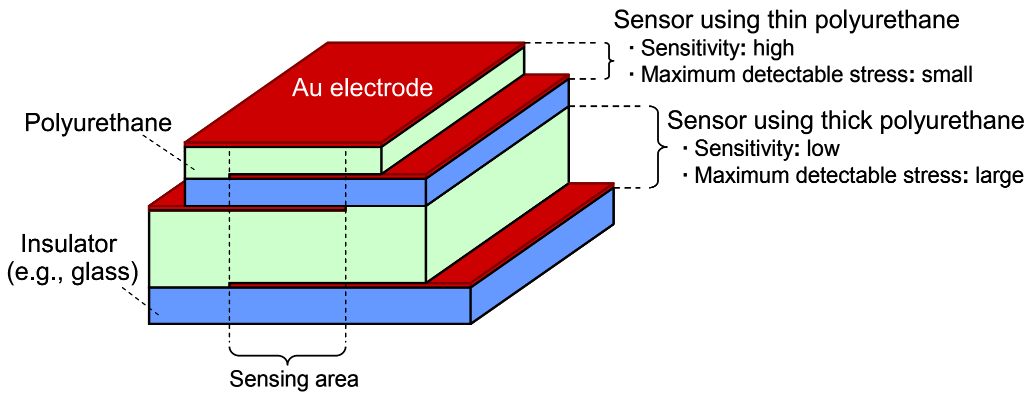


(**a**) (**b**)

The reason for this phenomenon is that Poisson ratio of the used polyurethane may decrease by applying stress over 0.8 kPa in case that its thickness is 1 μm. Namely, the resistance against applied vertical pressure increases, since the material becomes liable not to be deformed in horizontal direction due to decrease of Poisson ratio. Provided that this assumption be true, it seems difficult to improve the upper limit of applicable pressure to the sensor having 1 μm thickness.

In terms of increasing the upper limit and enlarging the measurable range of pressure, we propose a multi-layered sensor, as schematically shown in Figure 13. This device consists of stacked polyurethane films having several kinds of thickness. Small pressure can be detected by a sensor using a thin polyurethane film; on the other hand, large pressure can be detected by a sensor using a thick polyurethane film.

Figure 13. Schematic of stacked sensor for increasing measurable pressure range while keeping sensitivity.



4.4. Sensor Robustness in Terms of Electrode Breakage

It is confirmed that the electrodes were not broken in the experiments of putting test weights on the sensor, as shown in Figure 10, under the condition that the pressure is below 2.5 kPa. We also confirmed that the electrodes were not peeled from polyurethane even if they were rubbed by a probe tip. However, some electrodes were broken when the pressure far larger than 2.5 kPa was applied to it. It means that the sensor cannot endure large applied pressure owing to electrode breakage problem, degrading its robustness.

One of the reasons of electrode weakness is due to its thin film thickness of 0.1 µm. Instead of vacuum evaporation, the film was deposited by electroplating method, and thicker electrode having several microns meter thickness was obtained. The robustness evaluation of the sensor with thick film is ongoing. Alternatively, some functions to protect the electrode from breakage, such as providing a self stopper mechanism against large force, will be necessary for its practical use, which is the one remaining problem to solve in the future.

5. Summary

A capacitive tactile sensor using a polyurethane thin film is developed. This sensor is suitable for integration on a robot hand, because it is fairly flexible. The sensor has no air gap. In this study, spin-coating condition for fabricating the polyurethane film was optimized. The polyurethane film was etched back using diluted sulfuric acid, achieving very thin film of 1 µm thickness. Then, fabrication and characterization of the parallel-plate capacitors was carried out, in which the polyurethane film (1 or 6 µm in thickness) is filled between two Au electrodes. Sensitivity of this device-was higher than our pervious capacitive tactile sensors made of PDMS because the polyurethane is flexible elastomer compared to PDMS. The sensitivity was increased by decreasing the polyurethane film thickness. The best sensitivity achieved in this study is about 1.25×10^{-3} pF/Pa, in which the thickness of polyurethane film is 1 µm. Young's modulus of the polyurethane film was evaluated to be 20 kPa within its elastic range.

In this article, we focused on the change in capacitance and mechanical deformation of polyurethane film by changing applied pressure. However, characterization from other points of view remains to be conducted. For example, we have not yet evaluated the change in the mechanical properties of the sensor after exposure to moisture. A stability check against ambient humid condition is the projected work in future, since it is known polyurethane absorbs moisture [12]. As another example, surface roughness of polyurethane should be precisely evaluated using an atomic force microscope (AFM), *etc*. Also, measurement of Young's modulus of polyurethane film should be precisely measured by an indentation tester, which is generally applied to elastic thin films [13].

Acknowledgments

This work was supported in part by JSPS (Japan Society for the Promotion of Science) KAKENHI (22310083). This work was supported in part by a grant of "Strategic Research Foundation Grant-aided Project for Private Universities": Matching Fund Subsidy MEXT (Ministry of Education, Culture, Sport, Science, and Technology, Japan), 2010–2014 (S1001048). This work was carried out in part by the High Technology Research Center (HRC) in Kansai University.

References

1. Maxwell, J.C. *A Treatise on Electricity and Magnetism*, 3rd ed.; Oxford: Clarendon, 1892; pp. 68–73.
2. Kinoshita, G. Overview of the basic research needed to advance the robotic tactile sensors. *J. Robot. Soc. Jpn.* **1981**, *2*, 430–437.
3. Ishikawa, M.; Shimojjo, M. An imaging tactile sensor with video output and tactile image processing. *J. Soc. Instrum. Control Eng.* **1988**, *24*, 662–669.
4. Yamada, Y.; Cutkosky, M.R. Tactile Sensor with 3-Axis Force and Vibration Sensing Functions and its Application to Detect Rotational Slip. In *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, San Diego, CA, USA, 8–13 August 1994; pp. 3550–3557.
5. Shinoda, H. Tactile sensing for dexterous hand. *J. Robot. Soc. Jpn.* **2000**, *18*, 772–775.
6. Ohka, M.; Kobayashi, H.; Mitsuya, Y. Sensing Characteristics of an Optical Three-axis Tactile Sensor Mounted on a Multi-fingered Robotic Hand. In *Proceedings of 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Edmonton, Canada, 2–6 August 2005, 1959–1964.
7. Maeno, T.; Structure and function of finger pad and tactile receptors. *J. Robot. Soc. Jpn.* **2000**, *18*, 767–771.
8. Aoyagi, S.; Tanaka, T. Proposal of a micromachined tactile sensor having four stories and its information processing method using module networks. *Neural Information Processing - Letters and Reviews* **2007**, *11*, 147–158.
9. Aoyagi, S.; Kawanishi, M.; Yoshikawa, D. Multiaxis capacitive force sensor and its measurement principle using neural networks. *J. Robot. Mechatron*. **2006**, *18*, 442–449.
10. Huang, W.M.; Ding, Z.; Wang, C.C.; Wei, J.; Zhao, Y.; Purnawali, H. Shape memory materials. *Mater. Today* **2010**, *13*, 54–61.

11. Exseal Corporation. Available online: http://www.exseal.net/data.html (accessed on 1 March 2012).
12. Ono, D.; Fukutani, T.; Aoyagi, S. Development of an arrayed tactile sensor having four stories and recognition of contact using neural networks. *IEE J. Trans. Sens. Micromach.* **2008**, *128*, 246–251.
13. Liu, K.K.; Feng, B. A novel technique for mechanical characterization of thin elastomeric membrane. *J. Phys. D* **2001**, *34*, 3342–3349.