Implementation of a New Capacitive Touch Sensor Using the Nanoporous Anodic Aluminum Oxide (np-AAO) Structure

Chitsung Hong, Lian Chu, Weicheng Lai, Ann-Shyn Chiang, and Weileun Fang

***Abstract*—This study reports the implementation of a high-performance capacitive-type touch sensor by using the nanoporous anodic aluminum oxide (np-AAO) layer. The np-AAO layer is batch fabricated as the template to enable the direct formation of nanotexture metal film after deposition. The np-AAO is also exploited as the dielectric layer. Thus, the integration of np-AAO layer and the nanotexture metal film is employed to realize a metal-insulator-metal parallel-plate capacitance sensor. The sensitivity of the capacitive-type touch sensor is enhanced by the nanostructures. In application, the Au and Al metal layers and np-AAO are fabricated on Si substrate to form the parallel-plate capacitor. The testing demonstrates the np-AAO-based touch sensor has higher sensitivity. In addition, the detection of small object such as *Drosophila* using the fabricated np-AAO-based touch sensor is also demonstrated.**

***Index Terms*—np-AAO (nanoporous anodic aluminum oxide), capacitive sensor, nanocapacitor, touch sensor, nanotexture films.**

I. Introduction

THE nanoporus anodic aluminum oxide (np-AAO) film with uniform-distributed and high-density nanoscale pores (several microns in thickness and several nanometers in diameter) is a promising material for microelectricalmechanical systems (MEMS). Such np-AAO film finds many applications in nanostructures and devices [1]–[9]. The performances of the np-AAO-based devices can be easily improved by varying the np-AAO film characteristics, such as the nanostructure pattern, nanopore arrays distance, nanopores diameter, depth, and nanostructure materials properties [10]–[16]. The np-AAO can also integrate with metal film using planar fabrication process to realize various microsensors [17]–[20]. In these applications, the np-AAO film acting as a template to enable the formation of nanotexture metal film. The film with nanotexture shows outstanding material properties for micro sensors. Thus, the integration of nanotexture thin film and np-AAO nanostructure on Si offers an alternative for MEMS applications. Moreover, the integration of np-AAO film with other nanostructures, such as nanotubes, nanowire, nanoparticle, and nano-aggregates has also been extensively reported [21]–[27]. For instance, the existing works include atomic layer deposition (ALD), thermal CVD synthesis, and electrochemical deposition. However, complicated as well as high-temperature processes are required for these approaches. Thus, the easily fabricated np-AAO devices can find various applications such as the electrical sensing devices [28]–[31].

Recently, the capacitive type tactile or pressure sensors have been extensively reported [32]–[35]. Most of these sensors detect the tactile force by using the gap change of sensing electrodes [32]–[34]. Various approaches have also been reported to improve the sensitivity of the capacitive type tactile sensors, such as the reducing of sensing gap [32]–[34], the design of mechanical structure [33], [34], and the adopting of material with higher dielectric constant [32]. A novel capacitive sensor to detect the tactile force by using the area change of deformable sensing electrode has been presented in [35]. However, it remains challenging for the existing devices to detect the touch of objects with very small contact forces, such as the insects. Therefore, this study proposed a novel capacitive touch sensor to detect the contact of object by using the variation of sensing area using the electrodes with nanopores. This study exploits the existing nano fabrication processes to fabricate the np-AAO film as the template to form the nanotexture metal film for the capacitive type touch sensor. Thus, the sensing area of the touch sensor is significantly increased by the nanopore arrays of the np-AAO with nanotexture Au film, and the sensitivity of the touch sensor is improved. Moreover, the np-AAO film has higher dielectric constant to improve the initial capacitance of the capacitive sensing devices. In applications, the parallel-plate capacitors formed by the np-AAO layer and the Au film with nanotexture are realized and characterized. The detecting of *Drosophila* also demonstrates the capability of np-AAO-based parallel-plate capacitor as a capacitive type touch sensor for tiny objects.

Manuscript received May 11, 2011; accepted June 05, 2011. Date of publication June 23, 2011; date of current version November 02, 2011. This paper was supported in part by the Brain Research Center (99N2504E1) at the National Tsing Hua University, and in part by the National Science Council, Taiwan, under Contract NSC 98-2221-E-007-003-MY3. The associate editor coordinating the review of this paper and approving it for publication was Prof. Gerald Gerlach.

C. Hong and W. Lai are with the Institute of NanoEngineering and MicroSystems, National Tsing-Hua University, Hsinchu 300, Taiwan.

L. Chu is with the Institute of Biotechnology, National Tsing-Hua University, Hsinchu 300, Taiwan.

A.-S. Chiang is with the Institute of Biotechnology, National Tsing-Hua University, Hsinchu 300, Taiwan, and also with the Brain Research Center, National Tsing-Hua University, Hsinchu 300, Taiwan.

W. Fang is also with the Institute of NanoEngineering and MicroSystems, National Tsing-Hua University, Hsinchu 300, Taiwan, and also with the Department of Power Mechanical Engineering, National Tsing-Hua University, Hsinchu 300, Taiwan (e-mail: fang@pme.nthu.edu.tw).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSEN.2011.2160255

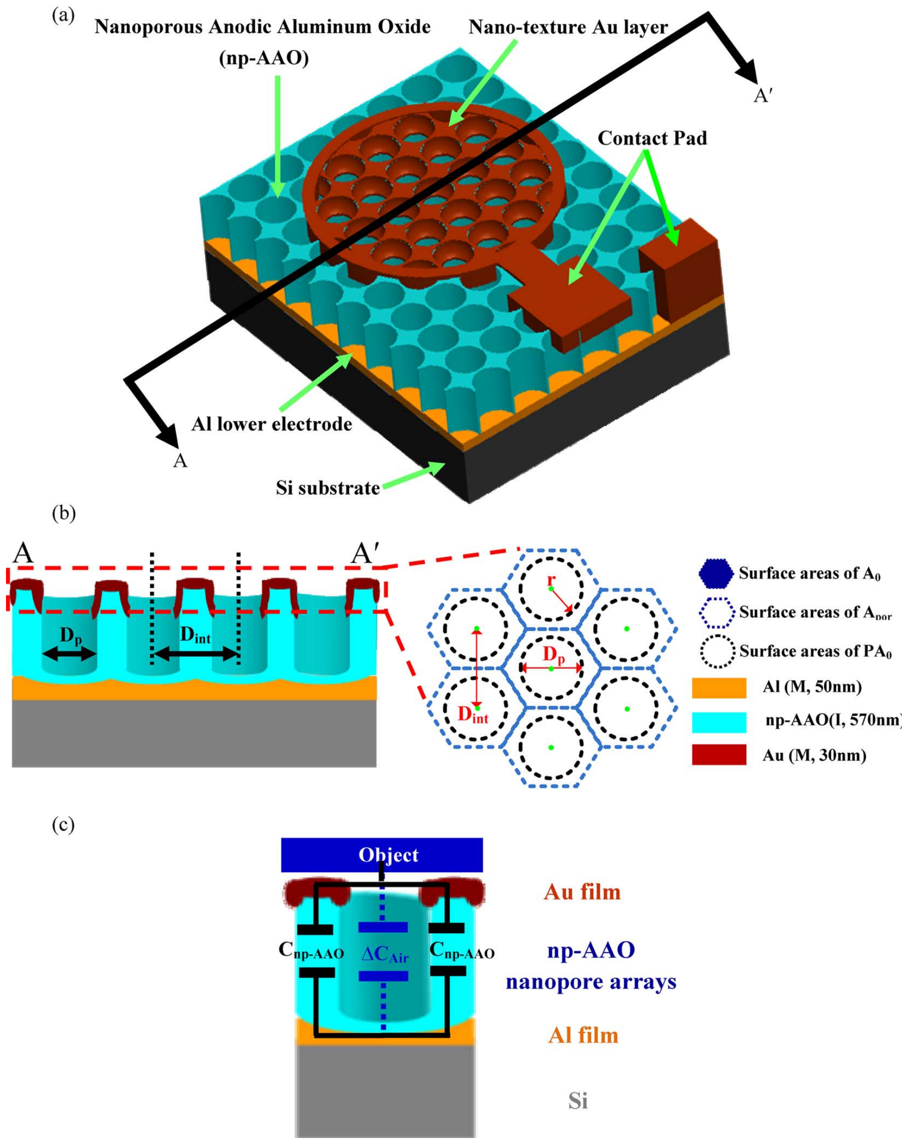


Fig. 1. (a) Scheme of the proposed capacitive-type touch sensor with np-AAO films and Au nanotexture layer. (b) Cross section to show the MIM (metal-dielectric-metal)-based touch sensor consisted of two metal films and a np-AAO dielectric layer. (c) The schematic illustration of the capacitive sensing mechanism as an object touch the MIM sensor.

II. Design and Fabrication

A. np-AAO-Based Capacitive Touch Sensor Design

This study exploits the np-AAO nanostructure to realize the parallel-plate capacitor, and further employs such capacitor for the application of touch sensor. The schematic illustration in Fig. 1(a) shows the device architecture of the present capacitive touch sensor with np-AAO nanostructure. In this design, the np-AAO is fabricated on top of the Si substrate with a lower metal electrode. Another metal film is further deposited and patterned on the np-AAO layer as the top electrode. According to the pattern transformation of np-AAO, the top metal film with nanotexture surface topography can be achieved. Since the np-AAO film acts as an insulator, the design of metal and np-AAO layers in Fig. 1(b) can be exploited to form a metal-insulator-metal (MIM) capacitor device. Due to the existing of nanopores, the object contacted with the MIM device will lead to the capacitance change, as indicated in Fig. 1(c). Thus, the MIM device with nanopores acts as a capacitive touch sensor. The initial capacitance (C_{np-AAO}) of the touch sensor is enhanced by the high dielectric constant of np-AAO film [4]. Moreover, the np-AAO film with nanopore arrays to increase sensing surface areas and significantly improves the sensitivity of the presented touch sensor. In application, the MIM capacitive type touch sensor consisted of the np-AAO dielectric layer and the gold (Au) and aluminum (Al) metal films is implemented and characterized.

B. np-AAO-Based Capacitive Touch Sensor Fabrication

Fig. 2 illustrates the fabrication process steps in this study. First, the silicon substrate was evaporated with 500 nm thick Al film, as shown in Fig. 2(a). After that, the Al film was etched by using the two-step anodization technique to prepare the np-AAO film [1], as shown in Fig. 2(b). During the anodization process, the substrate was first immersed into a 12 °C aqueous solution with 0.3 M oxalic acid at 47 V DC voltage, and the np-AAO

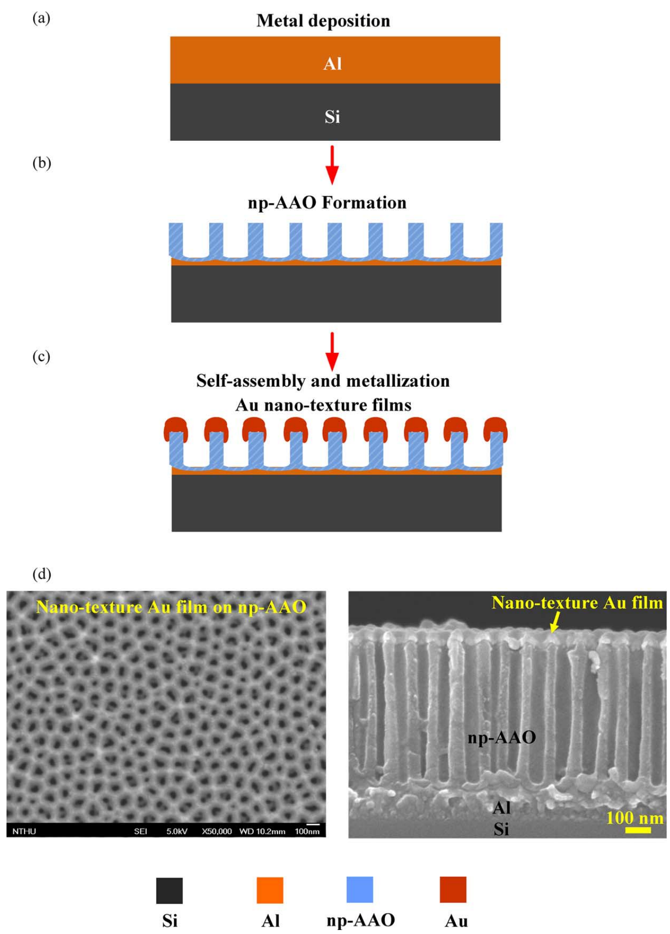


Fig. 2. (a)–(c) The fabrication process steps. (d) FESEM micrographs of typical np-AAO-based capacitive touch sensor.

layer was formed on top of the Al film. Following this, the substrate was immersed in a mixture of chromic acid (1.8 wt%) and phosphoric acid (6 wt%) at 60 °C in order to remove the np-AAO formed on top of the Al film. Next, the substrate underwent a second anodization process, with conditions the same as the first anodization step. After the anodization processes, the substrate was covered with a 30 nm thick Al film and 570 nm thick np-AAO layer, and the uniform and high density nanopore array of the np-AAO were used for capacitive touch sensor. As illustrated in Fig. 2(c), the Au film (50 nm) was evaporated by E-Gun and capped on np-AAO film. Thus, the np-AAO acted as a template to enable the formation of nanotexture Au film. The device in Fig. 2(c) forms the *Au-np-AAO-Al* parallel-plate capacitor as the capacitive touch sensor. The field emission scanning electron microscope (FESEM, JEOL 7000SF) images in Fig. 2(d) show the top view and side view of a typical fabricated *Au-AAO-Al* parallel-plate capacitor. The Au nanotexture and the nanoporous are observed from the top view FESEM image. The np-AAO film has an average nanopore diameter of 54 nm. As indicated in the side view FESEM image, the *Au-AAO-Al* layers and the Si substrate are also clearly observed. The thickness of the np-AAO film measured by the FESEM was 570 nm. According to [3], the porosity of the fabricated np-AAO film determined from the FESEM image in Fig. 2(d) is 23.57%.

III. Experimental Results and Discussion

A. *Electronic Characteristics of np-AAO-Based Capacitive Touch Sensor*

The initial capacitance of the fabricated parallel-plate capacitor has been characterized using the LCR meter (Agilent E4980A), and the input signal is consisted of a DC voltage of 1 V and a 100 KHz AC signal of 100 mV during the measurement. In comparison, the parallel-plate capacitor formed by the Au and Al metal films and the SiO_2 dielectric layer have also been fabricated and characterized. In this case, the SiO_2 film (570 nm) deposited by PECVD has no porous structure, and the top Au layer (50 nm) has no nanotexture either. The capacitance-time curve measured using the LCR meter by two probe method. The capacitance-time curve was used to evaluate the performance of two capacitive touch sensors.

As a result, the initial capacitance of the SiO_2-based capacitive touch sensor was only 1.266 nF, and the np-AAO-based capacitive touch sensor was significantly increased to 1.745 nF. According to [3], the porosity P (volume fraction of nanopores) of the np-AAO-based capacitive touch sensor can be expressed as

$$P = \frac{2\pi}{\sqrt{3}} \left(\frac{D_P}{2D_{\text{int}}} \right)^2 \tag{1}$$

where D_p is the nanopore diameter of np-AAO, and D_{int} is the inter-nanopore distance of np-AAO, as indicated in Fig. 1(b). The diameters D_p and D_{int} can be determined from Fig. 2(d) [3]. After that, the porosity P of present np-AAO-based capacitive touch sensor extracted from (1) 23.57%. Thus, according to [36], the area A_{por} of Au film capped on surface of np-AAO film (related with porosity of np-AAO film) can be expressed as

$$A_{\text{por}} = A_0(1 - P) \tag{2}$$

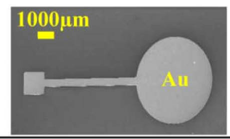
where A_0 is the area of Au film on flat surface without nanopores. The dielectric constant of np-AAO film can be expressed as

$$\varepsilon_{\text{np-AAO}} = \frac{C_{\text{np-AAO}} \cdot t}{\varepsilon_0 \cdot A_{\text{por}}} \tag{3}$$

where t is the thickness of np-AAO film, ε_0 is permittivity in the air. Thus, from the measured capacitance $C_{\text{np-AAO}}$ of np-AAO-based capacitive touch sensor, the dielectric constant of np-AAO film was determined from (1)–(3) as $\varepsilon_{\text{np-AAO}} = 7.48$. Such value is slightly higher than the dielectric constant ($\varepsilon_{\text{np-AAO}} = 7.03$) of the np-AAO grown using different approach [4], [28]. Since the dielectric constant of the proposed np-AAO is twofold higher than that of SiO_2 ($\varepsilon_{\text{SiO2}} = 3.9$), the performance of capacitive touch sensor can be improved by the np-AAO layer. Table I summarizes the characteristics of the np-AAO-based and the SiO_2-based capacitive touch sensors.

Fig. 3 shows the measurements of capacitance change during the contact tests of the fabricated touch sensors. In comparison, the np-AAO touch sensor with nanopores and the SiO_2 touch sensor without nanopores are tested. The test devices

TABLE I
THE PARAMETER OF NP-AAO-BASED AND SiO_2-BASED CAPACITIVE TOUCH SENSOR

Parameters	np-AAO-based Capacitive Touch Sensor	SiO_2-based Capacitive Touch Sensor
Dielectric layer	Nanoporous Anodic Aluminum Oxide	SiO_2
Fabrication Voltage (V)	47	Non
Dielectric layer Thickness (nm)	570	570
Dielectric constant	7.49	3.9
Porosity (%)	23.57	Nonporous
Initial Capacitance (nF)	1.7450	1.2661
Prior Design for Capacitive Touch Sensor	Radius=2500µm, d=570nm Au films as top metal layer for parallel-plate capacitor	

have a circular Au sensing electrode with a diameter of 5000 μm. Fig. 3(a) depicts the capacitance change of the np-AAO and SiO_2-based touch sensors as the top sensing electrodes fully contacted with a conductor of 5000 μm in diameter. The measurement results show that the np-AAO-based touch sensor has a capacitance change of 4.09% (in average), whereas the SiO_2-based touch sensor has a capacitance change of less than 0.3%. It demonstrates the np-AAO-based capacitive touch sensor with nanopore arrays and nanotexture Au film is much sensitive than the SiO_2 based one. Such improvement of sensitivity is mainly attributed to the existing of nanotexture on Au film. The nanotexture Au film has a porosity P of 23.57%. As the object contacting the nanotexture Au film, the nanopores will be covered and caused the capacitance change ΔC_{air}, as indicated in Fig. 1(c). For the case in Fig. 3(a), the touch sensor was fully covered by the object. According to (2), the area change was A_0P, and thus the capacitance change ΔC_{air} can be determined as

$$\Delta C_{\mathrm{air}} = \frac{\varepsilon_0 \varepsilon_{\mathrm{air}} A_0 P}{t}. \quad (4)$$

The capacitance change determined in this manner is 4.13% which is close to the measured one (4.09%). However, the Au-film on SiO_2 has no nanotexture and thus no significant area change after the contact of object. Thus, the capacitance change is much smaller than the np-AAO-based touch sensor.

This study further characterized the variation of capacitance change with the contact area for the np-AAO-based touch sensor. The measurement results in Fig. 3(b) show the measured capacitance has been increased from 0.05% to 4.09% as the contact area varies from 0.28 μm^2 to 19.63 μm^2. Linear fit of the data in Fig. 3(b) indicates the np-AAO-based touch sensor has a sensitivity of 0.21 $\Delta C(\%)/\mu m^2$. Such touch sensor with np-AAO nanopore arrays and nanotexture Au electrode is especially useful to detect object with small contact area. Table II also shows the comparison of the presented touch sensor with the existing tactile and pressure ones. Note the sensing mechanism of presented touch sensor is not the variation of sensing gap by the weight of contact object but the change of sensing area caused by the contact of object. The variation of sensing capacitance with the contact pressure

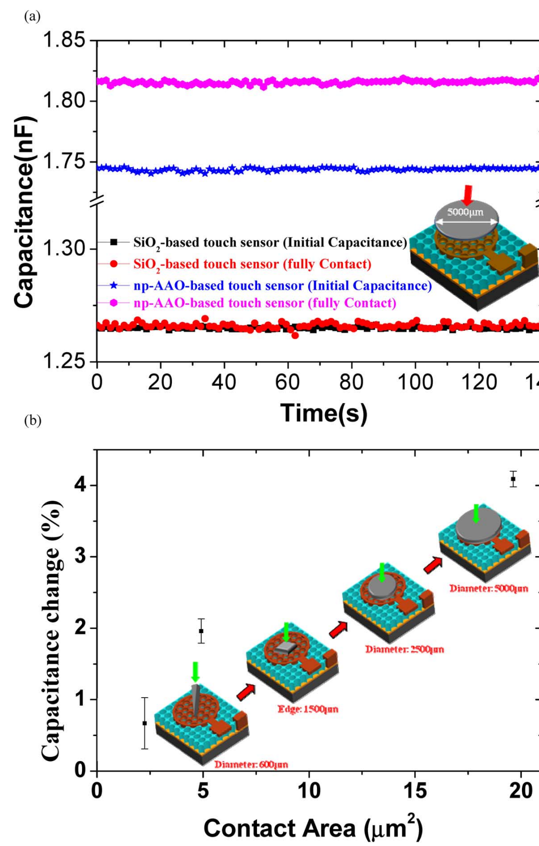


Fig. 3. (a) The measured initial capacitance and the capacitance after fully contact on the sensing pad for np-AAO-based touch sensor and SiO_2-based touch sensor. (b) Variation of the capacitance change with the contact area for the np-AAO-based capacitive touch sensor.

was also measured in this study. As shown in Fig. 4(a), the micro force gauge (HF-1, Janpan instrumentation System CO.) with z axis translation stage was used to apply load on the sensor. Measurement results in Fig. 4(a) show the sensing capacitance at different contact forces, in addition, the pressure hysteresis curve measured from loading-unloading is also presented. Note that the np-AAO-based capacitive touch sensor is depends on the area change caused by the contact object. Thus, the sensing capacitance of the presented touch sensor did

TABLE II
COMPARISON OF THE PRESENTED NP-AAO-BASED CAPACITIVE TOUCH SENSOR WITH THE EXISTING CAPACITIVE TACTILE AND PRESSURE SENSORS

	This study	S. C. B. Mannsfeld [32]	H. K. Lee [33]	H. B. Muhammad [34]	E. G. Bakhoum [35]
Unit Sizes	**19.63μm^2**	**64mm^2**	**0.48mm^2**	**0.80μm^2**	**0.196 mm^2**
Dielectric layer	**np-AAO**	**PDMS**	**Air**	**Air**	**$BaSrTiO_3$**
Dielectric constant	**7.49**	**~3**	**1**	**1**	**12000**
Porosity (P, %) [3]	**23.57**	**N/A.**	**N/A.**	**N/A.**	**N/A.**
Initial Unit Capacitance (C_0)	**1.75 nF**	**28.40pF**	**0.4608pF**	**3.54pF**	**6.76μF**
Sensing mechanism	**Area change by electrode w/ nanopores**	**Gap closing**	**Gap closing**	**Gap closing**	**Area change by deformable electrode**
Sensitivity by area	**0.21ΔC(%)/μm^2**	**N/A**	**N/A.**	**N/A.**	**N/A.**
Sensitivity by weight	**N/A.**	**15.62pF/KPa (0-2KPa)**	**28.60pF/KPa (0-250KPa)**	**0.043μF/KPa (0-120KPa)**	**2.24μF/KPa (0-3KPa)**
Temperature hysteresis (%)	**0.48%**	**N/A.**	**N/A.**	**N/A.**	**±0.05%**

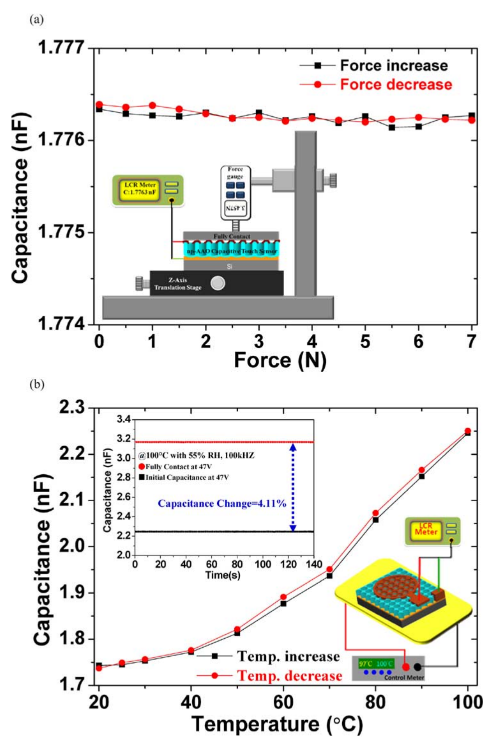


Fig. 4. (a) Variation of the capacitance change with the contact force for the np-AAO-based capacitive touch sensor. (b) The temperature hysteresis of np-AAO-based touch sensor, and the inset shows the capacitance change of fully contact np-AAO touch sensor at 100 °C ambient temperature.

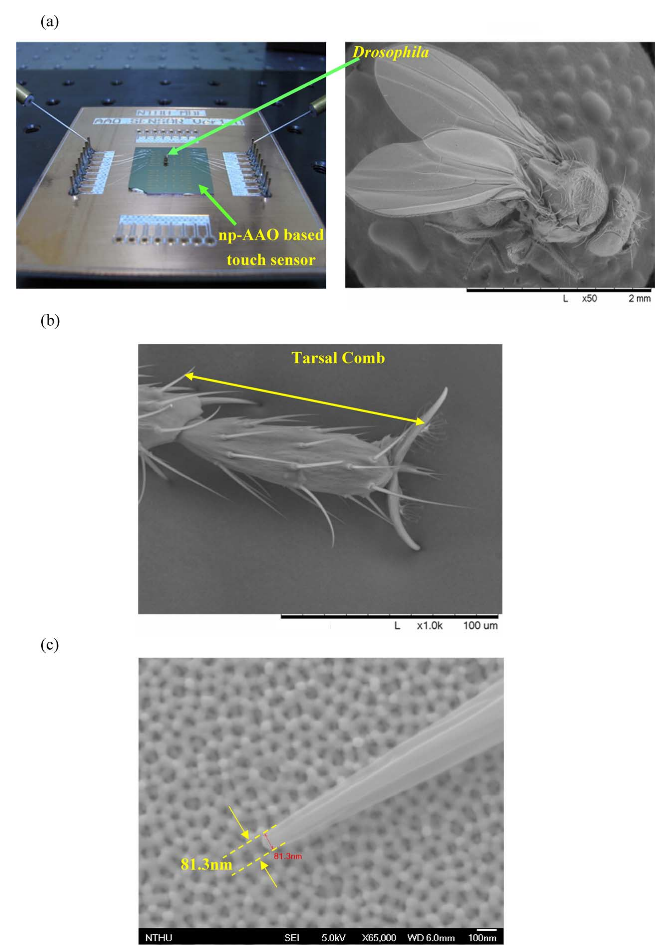


Fig. 5. The FESEM micrographs of typical np-AAO-based capacitive touch sensor. (a) Top view of the *Drosophila* contact on the np-AAO-based capacitive touch sensor. (b)Tarsal Comb of *Drosophila* leg on top of touch sensor. (c) One of the ∼81 nm wide bristle on Tarsal Comb contacting with the Au film with nanotexture.

not change with the contact pressure. Moreover, no pressure hysteresis is observed in Fig. 4(a). Measurements in Fig. 4(b) show the temperature hysteresis curve of presented capacitive touch sensor at 55% RH (relative humidity). The temperature hysteresis was 0.48% of the measured capacitance. This study also characterized the capacitance change at high ambient temperature. As shown in the inset of Fig. 4(b), the contact sensing test of np-AAO-based touch sensor was performed at 100 °C. Measurements show the sensor has a capacitance change of 4.11%, which is slightly higher than the capacitance change (4.09%) recorded in room temperature. Thus, the presented touch sensor is insensitive to the ambient temperature.

B. *np-AAO-Based Capacitive Touch Sensor for Tiny Object Sensing Application*

Fig. 5(a) shows a *Drosophila* of nearly 2 mm long on top of the presented capacitive touch sensor. The zoom-in SEM

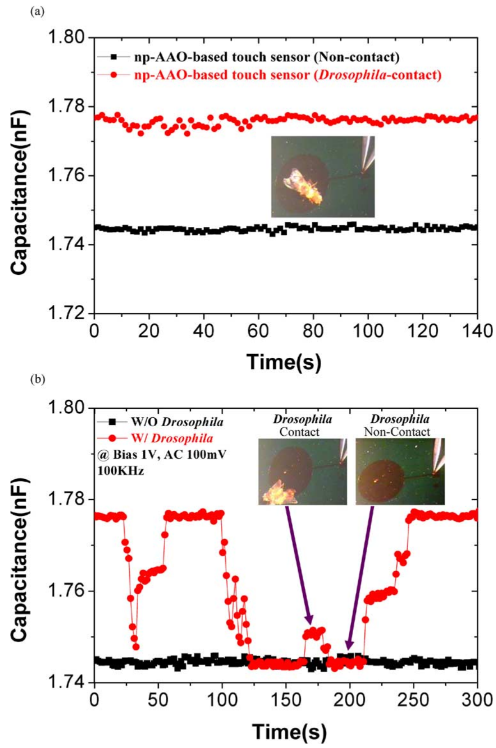


Fig. 6. The measured capacitance change of np-AAO-based touch sensor due to the contact of the *Drosophila*; and the signals respectively recorded from (a) a frozen *Drosophila* and (b) a walking *Drosophila*.

micrograph in Fig. 5(b) shows the Tarsal Comb of *Drosophila* leg (near 30 μm in wide and 100 μm in length) contacted on the surface of the touch sensor. The zoom-in micrograph in Fig. 5(c) further shows one of the ~80 nm wide bristle on Tarsal Comb contacting with the Au film with nanotexture on the surface of touch sensor.

In application, the np-AAO-based capacitive touch sensor was used to detect the contact of tiny object. The *Drosophila* was employed as the sample for the micro touch sensing tests. Since the *Drosophila* was special treated with low temperature and gene modification, it could only stand and move on the sensor surface but not fly, as the inset photo shown in Fig. 6(a). After detecting by the np-AAO-based capacitive touch sensor, Fig. 6(a) shows the typical measured capacitances before and after the contact of *Drosophila*. It indicates a 1.8% (in average) capacitance changes on touch sensor after the contact of *Drosophila*. Thus, the small *Drosophila* can be detected by the presented capacitive touch sensor with np-AAO layer and nanotexture Au electrode. Fig. 6(b) shows the capacitance recorded from the np-AAO-based capacitive touch sensor during the 5-min *Drosophila* contact and noncontact test. The *Drosophila* was walking on the surface of sensing chip during the test. Thus, the Tarsal Comb of *Drosophila* leg intermittently contacted with the surface of np-AAO-based capacitive touch sensor and leaded to the capacitance change. As depicted by the square dots in Fig. 6(b), the signal without *Drosophila* is employed as the reference. The circular dots indicate the measured capacitance change caused by the intermittent contact of *Drosophila*. Since the capacitance change varies with the total contact area between leg of *Drosophila* and sensor, the capacitor has a 0.2%–1.86% capacitance change when *Drosophila* contacting the Au sensing electrode.

IV. Conclusion

In summary, this study reports the implementation of a high performance capacitive touch sensor by means of the np-AAO layer and the nanotexture metal film. Such np-AAO-based sensing devices can be batch fabricated on Si substrate. In application, the np-AAO-based (*Au-np-AAO-Al*) parallel-plate capacitive type touch sensor has been successfully implemented and characterized. The initial capacitance of *Au-np-AAO-Al* parallel-plate capacitor has been increased for 37.82% as compare with the $Au\text{-}SiO_2\text{-}Al$ parallel-plate capacitor. Moreover, the np-AAO nanopore arrays and nanotexture Au electrode provides large sensing area for capacitive touch sensor. Thus, the np-AAO-based capacitive touch sensor has a better sensitivity. In addition, the detection of small object such as *Drosophila* using the fabricated np-AAO-based touch sensor is also demonstrated. The performance of the np-AAO-based capacitive sensor could be influenced by the characteristics of the np-AAO, such as the pore size and the porosity. It is of useful to investigate the variation of the np-AAO characteristics with the fabrication parameters. The dominant factors for the np-AAO capacitive touch sensors performance will be further analyzed in the future experiment.

Acknowledgment

The authors would also like to thank the National Tsing-Hua University, Taiwan, and the National Chiao Tung University, Taiwan, for providing fabrication facilities. They also thank Prof. T.-K. Sang and Prof. K.-C. Hwang of the National Tsing-Hua University for the preparing of *Drosophila* and the FE-SEM micrographs, respectively.

References

[1] H. Masuda and K. Fukuda, "Ordered metal nanohole arrays made by two-step replication of honeycomb structure of anodic alumina," *Science*, vol. 268, pp. 1466–1468, 1995.

[2] W. Lee, K. Schwirn, M. Steinhart, E. Pippel, R. Scholz, and U. Gösele, "Structural engineering of nanoporous anodic aluminium oxide by pulse anodization of aluminium," *Nature Nanotech.*, vol. 3, pp. 234–239, 2008.

[3] K. Nielsch, J. Choi, K. Schwirn, R. B. Wehrspohn, H. Kim, and U. Gösele, "Self-ordering regimes of porous alumina: The 10% porosity rule," *Nano. Lett.*, vol. 2, pp. 676–680, 2002.

[4] J. I. Sohn, Y. S. Kim, C. Nam, B. K. Cho, and T. Y. Seong, "Fabrication of high density arrays of individually isolated nanocapacitors using anodic aluminum oxide templates and carbon nanotubes," *Appl. Phys. Lett.*, vol. 87, p. 123115, 2005.

[5] P. S. Lee, J. Lee, N. Shin, K. H. Lee, D. Lee, S. Jeon, D. Choi, W. Hwang, and H. Park, "Microcantilevers with nanochannels," *Adv. Mater.*, vol. 20, pp. 1732–1737, 2008.

[6] J. W. Ciszek, L. Huang, S. Tsonchev, Y. Wang, K. R. Shull, M. A. Ratner, G. C. Schatz, and C. A. Mirkin, "Assembly of nanodots into designer superstrucures: The role of templating, capillary forces, adhesion and polymer hydration," *ACS Nano.*, vol. 4, pp. 259–266, 2010.

[7] M. S. Sander and L. S. Tan, "Nanoparticle array on surfaces fabricated using anodic alumina films as templates," *Adv. Funct. Mater.*, vol. 13, pp. 393–397, 2003.

[8] S. I. Cho, R. Xiao, and S. B. Lee, "Electrochemical synthesis of poly (3,4-Ethy- lenedioxythiophene) nanotubes towards fast window type electrochromic devices," *Nanotechnology*, vol. 18, p. 405705, 2007.

[9] Z. Huang, X. Zhang, M. Reiche, L. Liu, W. Lee, T. Shimizu, S. Senz, and U. Gösele, "Extended arrays of vertically aligned sub-10 nm diameter [100] Si nanowires by metal-assisted chemical etching," *Nano. Lett.*, vol. 8, pp. 3046–3051, 2008.

[10] A. Yamaguchi, K. Hotta, and N. Teramae, “Optical waveguide sensor based on porous anodic alumina/aluminum multilayer film,” *Anal. Chem.*, vol. 81, pp. 105–111, 2009.

[11] D. Ding and Z. Chen, “A pyrolytic carbon-stabilized, nanoporous Pd film for wide range H_2 sensing,” *Adv. Mater.*, vol. 19, pp. 1996–1999, 2007.

[12] D. K. Kim, K. Kerman, M. Saito, R. R. Sathuluri, T. Endo, S. Yamamura, Y. S. Kwon, and E. Tamiya, “Label-free DNA biosensor based on localized surface plasmon resinance coupled with interferometry,” *Anal. Chem.*, vol. 79, pp. 1855–1864, 2007.

[13] Y. Choi, D. Choi, and L. P. Lee, “Metal-insulator-metal optical nanoantenna with equivalent-circuit analysis,” *Adv. Mater.*, vol. 22, pp. 1–5, 2010.

[14] S. D. Alvarez, C. P. Li, C. E. Chiang, I. K. Schuller, and M. J. Sailor, “A label-free porous alumina interferometric immunosensor,” *ACS Nano.*, vol. 3, pp. 3301–3307, 2009.

[15] N. D. Hoa, N. V. Quy, Y. Cho, and D. Kim, “An ammonia gas sensor based on non-catalytically synthesized carbon nanotubes on an anodic aluminum oxide template,” *Sens. Actuators B*, vol. 127, pp. 447–454, 2007.

[16] D. Lee, N. Shin, K. H. Lee, and S. Jeon, “Microcantilevers with nanowells as moisture sensor,” *Sens. Actuators B*, vol. 137, pp. 561–565, 2009.

[17] L. M. i Codinachs, C. Birkenstock, T. Garma, R. Zierold, J. Bachmann, K. Nielsch, M. J. Schoning, and A. F. i Morral, “A micro-sized nanoporous multifunction sensing device,” *Phys. Status Solidi A*, vol. 3, pp. 435–441, 2009.

[18] M. S. Sander and L. S. Tan, “Nanoparticle arrays on surface fabrication using anodic alumina film as template,” *Adv. Funct. Mater.*, vol. 13, pp. 393–397, 2003.

[19] W. H. Kim, S. J. Park, J. Y. Son, and H. Kim, “Ru nanostructure fabrication using an anodic aluminum oxide nanotemplate and highly conformal Ru atomic layer deposition,” *Nanotechnology*, vol. 19, p. 045302, 2008.

[20] N. V. Quy, N. D. Hoa, M. An, Y. Cho, and D. Kim, “A high-performance triode-type carbon nanotube field emitter for mass production,” *Nanotechnology*, vol. 18, p. 345201, 2008.

[21] D. Choi, S. Lee, C. Lee, P. Lee, J. Lee, K. Lee, H. Park, and W. Hwang, “Dependence of the mechanical properties of nanohoneycomb structure on porosity,” *J. Micromech. Microeng.*, vol. 17, pp. 501–508, 2007.

[22] P. Banerjee, I. Perez, L. Heenn-Lecordier, S. B. Lee, and G. W. Rubloff, “Nanotubular metal-insulator-metal capacitor array for energy storage,” *Nature Nanotech.*, vol. 4, pp. 292–296, 2009.

[23] C. Langhammer, M. Schwind, B. Kasemo, and L. Zoric, “Localized surface plasmon resonances in aluminum nanodisks,” *Nano. Lett.*, vol. 8, pp. 1461–1471, 2008.

[24] W. Shi, Y. Shen, H. Jiang, C. Song, Y. Ma, J. Mu, B. Yang, and D. Ge, “Lysine-attached anodic aluminum oxide(AAO)-silica affinity membrane for bilirubin removal,” *J. Membr. Sci.*, vol. 349, pp. 333–340, 2010.

[25] S. P. Adiga, C. Jin, L. A. Curtiss, N. A. Monteiro-Riviere, and R. J. Narayan, “Nanoporous membrane for medical and biological applications,” *WIREs Nanomed. Nanobiotechnol.*, vol. 1, pp. 568–581, 2009.

[26] A. Thormann, N. Teuscher, M. Pfannmoller, U. Rothe, and A. Heilmann, “Nanoporous aluminum oxide membranes for filtration and biofunctionalization,” *Small*, vol. 3, pp. 1032–1040, 2007.

[27] A. H. D. Graham, C. R. Bowen, J. Robbins, and J. Taylor, “Formation of a porous alumina electrode as a low-cost CMOS neuronal interface,” *Sens. Actuators B*, vol. 138, pp. 296–303, 2009.

[28] B. Das and C. Garmsn, “Capacitance-voltage characterization of thin film nanoporous alumina templates,” *Microelectron. J.*, vol. 37, pp. 695–699, 2006.

[29] R. K. Nahar, “Study of the performance degradation of thin film aluminum oxide sensor at high humidity,” *Sens. Actuators B*, vol. 63, pp. 49–54, 2000.

[30] Y. Chen, F. Meng, M. Li, and J. Liu, “Novel capacitive sensor: Fabrication form carbon nanotubes arrays and sensing property characterization,” *Sens. Actuators B*, vol. 140, pp. 396–401, 2009.

[31] V. A. Antohe, A. Radu, M. Mátéfi-Tempfli, A. Attout, S. Yunus, P. Bertrand, C. A. Dutu, A. Vlad, S. Melinte, S. Mátéfi-Tempfli, and L. Piraux, “Nanowire-templated microelectrodes for high-sensitivity pH detection,” *Appl. Phys. Lett.*, vol. 94, p. 073118, 2009.

[32] S. C. B. Mannsfeld, B. C.-K. Tee, R. M. Stoltenberg, C. V. H.-H. Chen, S. Barman, B. V. O. Muir, A. N. Sokolov, and Z. Bao, “Highly sensitive flexible pressure sensor with microstructured rubber dielectric layers,” *Nat. Mater.*, vol. 9, pp. 859–864, 2010.

[33] H. K. Lee, S. I. Chang, and E. Yoon, “A flexible polymer tactile sensor: Fabrication and modular expandability for large area deployment,” *J. Microelectromech. Syst.*, vol. 15, pp. 1681–1685, 2006.

[34] H. B. Muhammad, C. M. Oddo, L. Beccai, C. Recchiuto, C. J. Anthony, M. J. Adams, M. C. Carrozza, D. W. L. Hukins, and M. C. L. Ward, “Development of a bioinspired MEMS based capacitive tactile sensor for a robotic finger,” *Sens. Actuators B*, vol. 165, pp. 221–229, 2011.

[35] E. G. Bakhoum and M. H. M. Cheng, “Novel capacitive pressure sensor,” *IEEE J. Microelet. Syst.*, vol. 19, pp. 443–450, 2010.

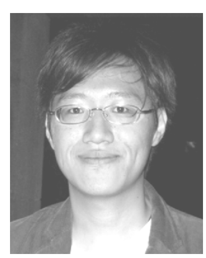
[36] Nanomaterials.it Srl Company, “Geometrical considerations about porous anodic alumina,”. San Giuliano Milanese. Milan, Italy, 2009.

Chitsung Hong was born in Taichung, Taiwan, in 1979. He received the M.S. degree from the Department of Automatic Control Engineering, Feng-Chia University, Taichung, in 2004. Currently, he is working towards the Ph.D. degree at the Institute of NanoEngineering and MicroSystems, National Tsing-Hua University, Hsinchu, Taiwan.

His major research interests include nanostructure-based micromachining process, nanostructure materials for sensor or devices application, and flexible technology integration.

Li-An Chu was born in Tainan, Taiwan, in 1985. She received the B.S. degree from the Department of Power Mechanical Engineering, National Tsing-Hua University, Hsinchu, Taiwan, in 2007. Then, she changed her major into life science and received the M.S. degree from the Institute of Biotechnology, Tsing-Hua University in 2009. Currently, she is working towards the Ph.D. degree at the Institute of Biotechnology.

Her major research interests include neuroscience including neuroimaging, animal behaviors, and developing new machines for optogenetic research.



Wei-Cheng Lai was born in Taipei, Taiwan, in 1986. He received the M.S. degree from the Institute of NanoEngineering and MicroSystems, National Tsing-Hua University, Hsinchu, Taiwan, in 2010.

His major research interests include MEMS fabrication process, and MEMS application in neuroscience research.

Ann-Shyn Chiang was born in Taipei, Taiwan. He received the Ph.D. degree in entomology from Rutgers University, Piscataway, NJ, in 1990.

He worked continuously as a Postdoctoral Fellow at Rutgers University until 1992. He joined the Department of Life Science, National Tsing-Hua University, Hsinchu, Taiwan, in 1992, where he is now a Chair Professor as well as the Director of the Brain Research Center. He is also a member of International Faculty of the Kavli Institute for Brain and Mind (KIBM), University of California San Diego, and a Joint Appointment Research Fellow in the Genomics Research Center in Academia Sinica. He has published several important papers including the first Taiwan's Cell paper in 2007. Recently, his work on mapping brain-wide neural network in *Drosophila* published in *Current Biology* has been considered by The New York Times as a work equivalent to the first genome project. He has reviewed papers for Science, Current Biology, PLoS Biology, etc. His research interests include brain research, molecular imaging, and behavioral genetics.

Prof. Chiang was a recipient of the Outstanding Research Award from the National Science Council in Taiwan in 2010.

Weileun Fang was born in Taipei, Taiwan. He received the Ph.D. degree from Carnegie Mellon University, Pittsburgh, PA, in 1995. His doctoral research focused on the determining of the mechanical properties of thin films using micromachined structures.

In 1995, he worked as a Postdoctoral Researcher at Synchrotron Radiation Research Center, Taiwan. He joined the Department of Power Mechanical Engineering, National Tsing-Hua University, Taiwan, in 1996, where he is now a Professor as well as a member of faculty of the NEMS Institute. In 1999, he was with Prof. Y.-C. Tai at the California Institute of Technology as a Visiting Associate. He is now a Board Member of the *Journal of Micromechanics and Microengineering* (JMM), and the Associate Editor of the IEEE SENSORS JOURNAL, and the *Journal of Micro/Nanolithography, MEMS, and MOEMS* (JM3). He has published more than 100 SCI journal papers, near 200 international conference papers, and 60 patents (all in the MEMS field). His research interests include MEMS with emphasis on microfabrication/packaging technologies, CMOS MEMS, CNT MEMS, micro optical systems, micro sensors and actuators, and characterization of thin-film mechanical properties.

Prof. Fang has served as the Chief Delegate of Taiwan for the World Micromachine Summit since 2008. He also served as the TPC of IEEE MEMS Conference, the EPC of Transducers Conference, and the regional Co-Chair of the IEEE Sensors Conference. He is a member of the International Steering Committee of Transducers since 2009. Moreover, he also serves as a technical consultant for many MEMS companies in Taiwan.