IJE TRANSACTIONS B: Applications Vol. 25, No. 3, (August 2012) 167-174

International Journal of Engineering

Journal Homepage: www.ije.ir

Design of Novel High Sensitive MEMS Capacitive Fingerprint Sensor

M. S. Nateri , B. A. Ganji *

Department of Electrical Engineering, Babol University of Technology, Iran

ARTICLE INFO

Article history:
Received 13 March 2012
Received in revised form 12 Aprill 2012
Accepted 19 Aprill 2012

Keywords:
MEMS Fingerprint
Slot
Stress
T-shaped Protrusion
Sensitivity

ABSTRACT

In this paper a new design of MEMS capacitive fingerprint sensors is presented**.** The capacitive sensor is made of two parallel plates with air gap. In these sensors, the capacitance changes is very important factor. It is caused by deformation of the upper electrode of sensor. In this study with making slots in upper electrode, using T-shaped protrusion on diaphragm in order to concentrate the force from finger ridges, making holes in lower electrode to reduce the air damping and using low stress material for diaphragm, we have been succeeded to design a novel MEMS fingerprint sensor with high sensitivity compared with the previous one. In the present research, simulations were carried out using FEA method.

doi: *10.5829/idosi.ije.2012.25.03b.03*

1. INTRODUCTION

In 1700, scientists discovered design in the skin of the tip of human finger which has been created ridge and valleys within them, and which is generally known as fingerprint [1]. The first application of fingerprint in knowing someone's identity goes back to the 19th century. At that time to identify a person's fingerprint, it was tried to match some designs, which was not accurate; hence, new parameters were defined (e.g. Figure 1), such as *Core* (the core can be thought of as the center of the fingerprint pattern) and *Delta* (the delta is a singular point from which three patterns deviate). To be more accurate in the identification of fingerprints, more parameters were described. Use of these new parameters increased the possibility to greatly identify fingerprints. Another problem in recognizing fingerprints is referred to human errors.

In the middle of the 19th century, it was tried to make a machine for fingerprint identification to tackle with this problem. The earliest machine was optical fingerprint sensor. After this model, various types were introduced, such as ultrasonic fingerprint sensor, active capacitive fingerprint sensor, thermal fingerprint sensor and so on. One of newest and the most efficient one is MEMS capacitive sensors made by micro electromechanical machinery (MEMS). One of the earliest pressure sensitive MEMS fingerprint sensor in history can be found out in 1997 [2]. In this presented sensor, each pixel is composed of a capacitor with a fixed metal electrode on a glass substrate and a movable electrode made of p^+ silicon suspended by two angular beams (crab legs structure). Each beam is anchored at one end and attached to the movable electrode at the other end. The silicon electrode is bossed to concentrate all the applied force on to it. A dielectric layer prevents the two capacitor plates from shorting during an over force. Another study in 2001 [3] proposed a new structure having a high strength for mechanical stress and long-term protection against contamination. It was claimed that the proposed sensor was reliable enough for conventional fingerprint identification usage. It was also claimed that a simple and cost-effective sensor fabrication process due to the use of Au electroplating and photosensitive polyamide film although more improvements were still possible. The sensor had a grounded wall for electro static discharge tolerance and a gold electrode to prevent oxidation as well as a thick, hard passivation film consisting of a layer of polyamide over a layer of SiN to keep moisture out. The group also continued to make a prototype of the whole system and the results were published in 2003. Afterward, a modified version of this sensor was proposed in 2005 by Sato et al. [4]. In this version, novel protrusions on the

*Corresponding Author Email: baganji@nit.ac.ir (B.A. Ganji)

sensor area were designed in order to detect clear fingerprint images for various finger surface conditions. The sensor area is filled with the T-shaped protrusions in order to concentrate the force from finger ridges at the center to bend the upper electrode most effectively [5].

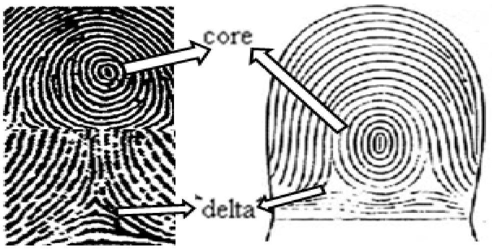

Figure 1. The defined parameters for fingerprint identification

Previous designs put an extra layer made of polyamide on diaphragm to prevent the passage of the present impurity on the skin, such as moisture and dust, between electrodes. In previous designs no path were predetermined or considered for the air to pass between electrodes. In 2008, another design whose main idea was to make a path for the air to pass between electrodes was introduced [6, 7]. In this design, first the designer removed the polyamide layer on the diaphragm and then two anchors were used to hold the diaphragm and the other two sides were left free so that there would be a path to reduce the air damping and the pressure on the diaphragm would be decreased by omitting the two anchors. This paper presents a new design to increase the sensitivity of fingerprint sensor using slots on diaphragm, reducing the diaphragm stress using doped poly silicon, making holes in lower electrode to reduce the air damping and using a T-shaped structure to concentrate the pressure on diaphragm.

2. FINGERPRINT SENSOR DESIGN

In general, the MEMS fingerprint sensor consists of a lot of cells that each of them has a capacitive sensor. The capacitive sensor is made of two parallel plates with air gap. With biasing DC voltage between two plates, they act as electrode of capacitors. The upper plate is usually moving and the lower one is fixed (Figure 2). In these sensors the diaphragm moves, so the capacitor between the plates changes. As a result, it is used for identifying a fingerprint. The sensitivity of the sensor is based on capacitive changes. Thus, the more changes, the higher sensitivity has been achieved. As mentioned earlier, diaphragm displacement must be enhanced so that the changes of capacitors can be increased. The distance between two ridges of finger surface is from 100 to 400 micrometers (Figure 3). The acceptable surface for designing each of the capacitive sensors (cells) must be maximally 50×50 μm^2 to have an appropriate output.

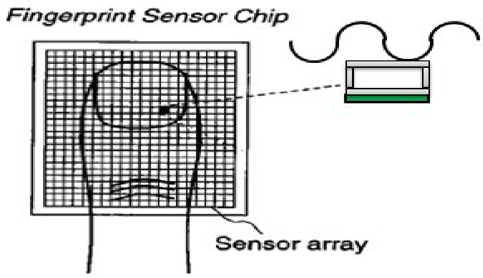

Figure 2. Fingerprint sensor with capacitive structure [4]

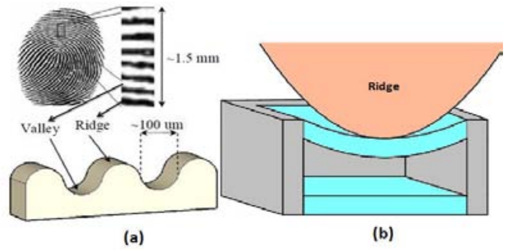

Figure 3. (a) The present ridges on the surface of skin, (b) diaphragm displacement due to contact with skin ridges

3. ANALYSIS OF THE EFFECTIVE FACTORS IN DISPLACEMENT OF DIAPHRAGM

As shown in Figure 4, in normal condition, if two electrodes are parallel at distance of d_0, the capacitor between the electrodes is obtained by Equation (1), where ε_0 is permittivity and A is the surface of the plate.

$$C_0 = \varepsilon_0 \frac{A}{d_0} \tag{1}$$

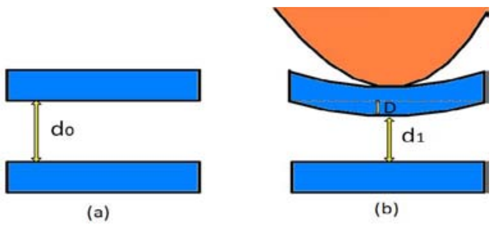

Figure 4. (a) Electrodes of fingerprint sensor before any contact with skin, (b) after contact with skin and upper electrode displacement.

From the Figure 4(b) for small deflection of diaphragm the capacitive of the structure, C1, can be obtained approximately by Equation (2).

$$C_1 = \varepsilon_0 \frac{A}{d1} = \varepsilon_0 \frac{A}{(d_0 - D)} \tag{2}$$

were, D is the diaphragm displacement. The capacitive changes can be calculated using Equation (3). It can be seen from this equation, the capacitive changes are greatly depend on D.

$$\Delta C = C1 - C0 = \varepsilon_0 A(\frac{1}{(d_0 - D)} - \frac{1}{d_0}) \quad (3)$$

The central deflection, w, of a flat and circular diaphragm with clamped edges and with initial stress, due to a homogeneous pressure, P, can be calculated from [8].

$$P = 5.33E\frac{h^4}{(1-v^2)R^4}(\frac{w}{h}) + 2.83E\frac{h^4}{(1-v^2)R^4}(\frac{w}{h})^3 + 4\frac{h^2}{R^2}(\frac{w}{h})\sigma \quad (4)$$

where, E, v, R, σ and h are Yong's modulus, poison's ratio, radius, residual stress and thickness of diaphragm, respectively. The deflection of a flat clamped square diaphragm without residual stress is given approximately by [9]:

$$P = 4.2E\frac{h^4}{(1-v^2)\hat{a}^4}(\frac{w}{h}) + 1.58E\frac{h^4}{(1-v^2)\hat{a}^4}(\frac{w}{h})^3 \quad (5)$$

where, $\hat{a}$ is the half-side length of the square diaphragm. For large value of initial tension, the deflection of a flat circular diaphragm can be represented by:

$$P = 4\frac{h^2}{R^2}(\frac{w}{h})\sigma \quad (6)$$

The theory being valid for circular membranes is converted to the square diaphragms assuming equal areas $((2\hat{a})^2 = \pi R^2)$ [10], thus the deflection of a flat square diaphragm can be approximated by replacing R^2 with $4\hat{a}^2/\pi$ in Equation (6), i.e.

$$P = \pi\frac{h^2}{\hat{a}^2}(\frac{w}{h})\sigma \quad (7)$$

This resistance to bending due to initial stress can be added to Equation (5) using the principle of superposition, i.e.

$$P = 4.2E\frac{h^4}{(1-v^2)\hat{a}^4}(\frac{w}{h}) + 1.58E\frac{h^4}{(1-v^2)\hat{a}^4}(\frac{w}{h})^3 + \pi\frac{h^2}{\hat{a}^2}(\frac{w}{h})\sigma \quad (8)$$

It can be seen from Equations (4) and (8) that if *(w/h) << 1* the relation between the center deflection and the applied pressure is approximately linear. For large values of *(w/h)* the relation is nonlinear. In Equations (4) and (8), it is assumed that the initial diaphragm stress can be neglected. The mechanical sensitivity of a diaphragm is defined as [11]:

$$S_m = \frac{dw}{dP} \quad (9)$$

For a small deflection (less than 30% of its thickness), the mechanical sensitivity of a flat square diaphragm, by neglecting the third-order term, can be expressed as:

$$S_m = \frac{w}{P} = \frac{\hat{a}^2}{\pi h[4.2Eh^2/\pi\hat{a}^2(1-v^2)+\sigma]} \quad (10)$$

Another effective factor in diaphragm displacement is the stiffness. To reduce stiffness, we can make slots on diaphragm and reduce the involvement of the edge of diaphragm with the surrounding anchors so that movement improves. The slots must be created in the four sides of diaphragm in the same size and shape to create the balance of diaphragm movements [12]. The next effective factor in movement is the utilization of the T-shape protrusion. In 2005, a new structure was presented in order to increase the efficiency of fingerprint sensor, which increases the displacement of diaphragm. This structure is made of two parts, upper surface of T-shape protrusion which concentrates the pressure and base of T which concentrated the gathered force by surface of T on the center of the diaphragm (Figure 5). This increases the displacement of the diaphragm.

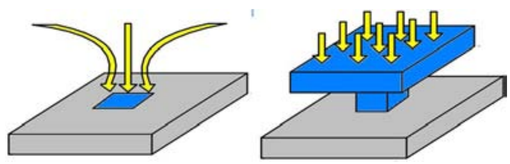

Figure 5. (right) concentrating forces of hand skin using the design, (left) concentrating the pressure of hand skin in the diaphragm center.

Another factor which can also increase the sensitivity is the diaphragm material. Young modulus and residual stress (σ) are important parameters for displacement of diaphragm. The tension of the diaphragm, T, is determined by the residual stresses of the diaphragm material (T=σ.t), which depends primarily on the deposition technique, the temperature and the crystalline structure of the deposited thin film [13]. The residual stress can also lead to degradation of electrical characteristics of a thin film. The residual stresses thin films are the sum of thermal and intrinsic stresses. Thermal stress is caused by a difference in expansion coefficient of the substrate and the thin film. Thermal stress makes the diaphragm very stiff and reduce the sensitivity of sensor. In particular, for low-pressure ranges, the nonlinearity caused by membrane stresses in a diaphragm becomes appreciable. Intrinsic stress has two components: the first originates from the volume contraction associated with crystallization and is tensile; and the second is compressive and is due to the existence of a preferred growth orientation, disorder at the crystal grain boundary, and effects related to different deposition rates or the incorporation of impurity atoms. It is known that the dominant component of stress is the intrinsic one [14]. The stress gradient along the z-axis direction of a thin film also contributes to the residual stress. There are some methods available to control the residual stress. One of them is to anneal the thin film at a high temperature between 900 °C and 1100 °C in a nitrogen atmosphere after ion implantation by boron, phosphorous or arsenic. The residual stress from 110 MPa for poly silicon thin films deposited by the plasma enhanced chemical vapor deposition (PECVD) method has been reduced to 20 MPa for high temperature annealed poly silicon thin film deposited by the low pressure chemical vapor deposition method (LPCVD) and ion implanted with phosphorous. In this study, simulations were carried out using FEA method.

4. RESULTS AND DISCUSSION

First, we examine the appropriate shape for the diaphragm of fingerprint sensor. As explained earlier, to have an appropriate output from fingerprint sensor, a square cell with dimension of 50 micrometer is needed. In this cell, capacitive sensors with various shapes can be designed (circular, square, multi-dimensional). To choose a particular shape among them, the efficiency of each of them must be investigated. Therefore, three types of diaphragms (square with dimension of 50 micrometer, circular with diameter of 50 micrometer and eight-dimension with dimension of 20.5 micrometer) have been simulated using FEA method (Figure 6). All of them have 2 micrometer thickness with similar material (Aluminium). Figure 7 shows the simulation results.

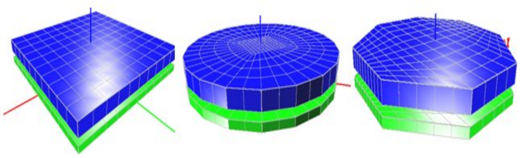

Figure 6. Capacitive sensors with various diaphragms

As can be seen in Figure 7, the best performance for fingerprint sensor diaphragm is related to the square diaphragm. Thus, it is better for fingerprint sensor to use a square diaphragm so that it can have a better sensitivity. A square diaphragm with a dimension of 50×50 μm with the thickness of 2 μm made of aluminium was examined under pressure between 0.3 and 1.5 mega pascal (The common pressure of fingerprint sensor is between 0.7 and 0.9). Figure 8 shows the square diaphragm simulated using FEA method. Figure 9 shows the central displacement of diaphragm using analytical and FEA methods. As shown in Figure 9, the central displacement of diaphragm increases when the pressure has been increased.

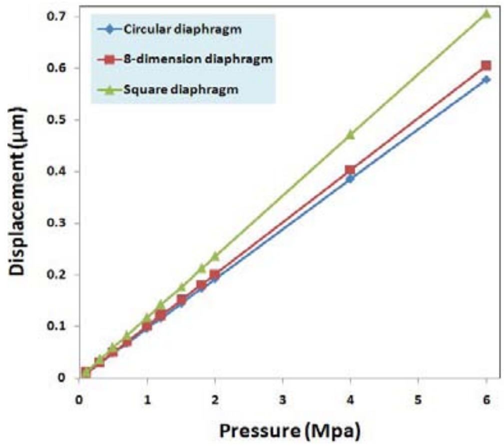

Figure7. Diaphragm displacement vs. pressure for square, circular and 8-dimensions diaphragms

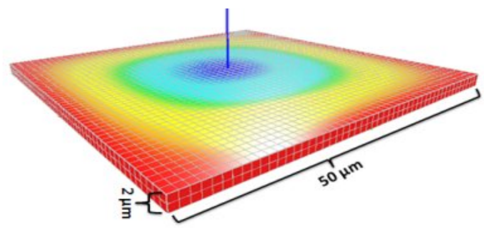

Figure 8. Simulated square diaphragm

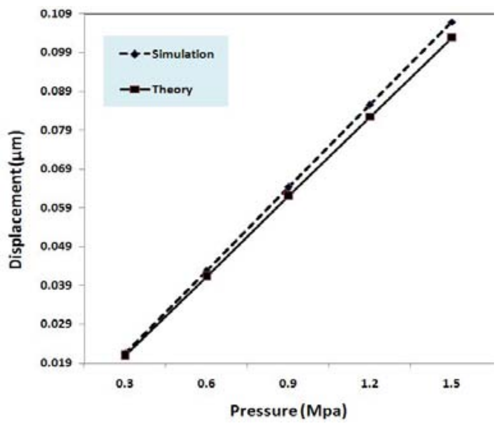

Figure 9. Diaphragm displacement under various pressures

We made slots around the square diaphragm to reduce the stiffness of diaphragm. 8 slots with dimensions of 10×2 μm^2 were created around the diaphragm (Figure 10). The simulation results for two simple and slotted diaphragms are presented in Figure 11. As shown in Figure 11, the movement of diaphragm under similar pressure has been increased in comparison with clamped diaphragm according to Equation (9). It can be seen that the mechanical sensitivity has been increased.

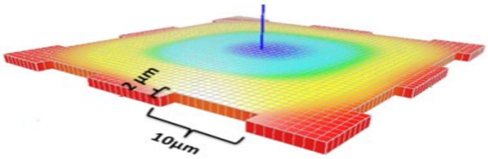

Figure 10. Simulation diaphragm with 8 slots

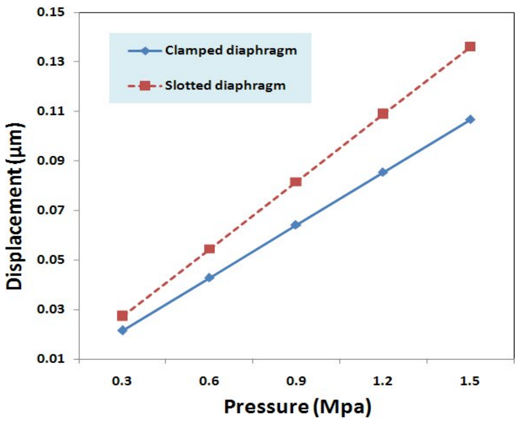

Figure11. Displacement of clamped and slotted diaphragm under various pressure

We added T-shape protrusion on clamped diaphragm with dimensions of 48×48×7 μm^3 and base of 10×10×3 μm^3 (Figure 12). Figure 13 shows the central displacement of diaphragm using FEA method. It can be seen from Figure 13 using T-shaped protrusion on diaphragm increases displacement and consequently improves sensitivity of sensor.

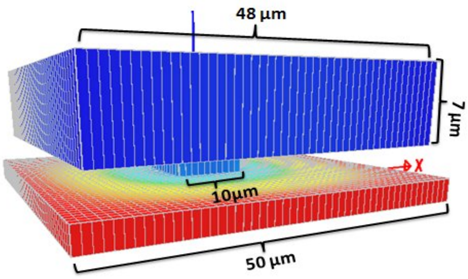

Figure 12. T-shape protrusion used on diaphragm for simulation.

Figure 14 shows the size of surface and base of T-shaped protrusion. To analyze the effect of size in T-shape protrusion, we changed the size of base from 2 to 40 μm and the size of surface from 10 to 50 μm. Figures 15 and 16 show the simulation results.

It’s mentioned earlier, stress is an important factor in modeling and analyzing diaphragm. For a diaphragm with dimensions of 50×50 μm and thickness of 1 μm under a pressure of 1 Mpa, the effect of stress on diaphragm displacement has been tested from 10 to 400 Mpa (Figure 17). The analytical and simulation results have been shown in Figure 18.

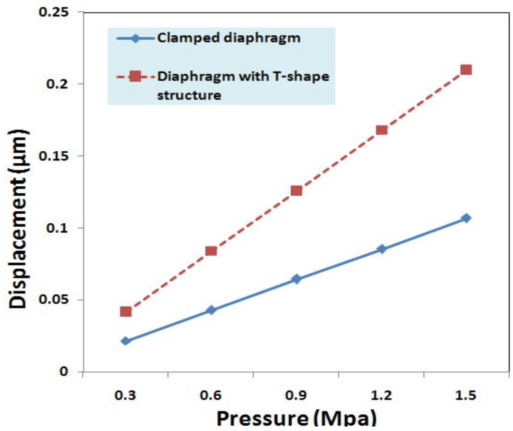

Figure 13. Displacement of clamped diaphragm with and without T-shape protrusion under various pressure

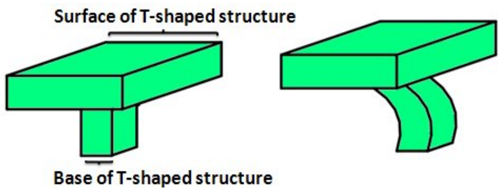

Figure 14. T-shape protrusion

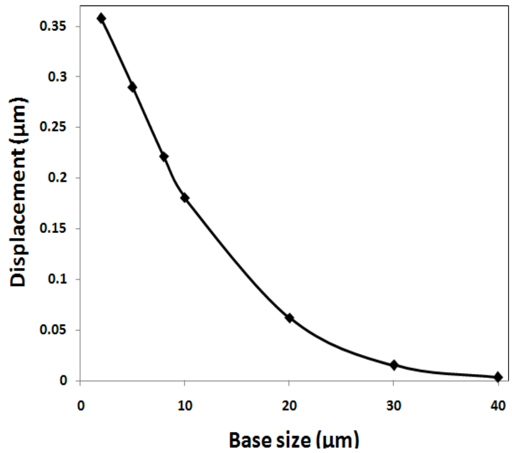

Figure 15. The effect of base size of T-shape protrusion on displacement under constant pressure

From Figure 18, when stress increases, central displacement in square diaphragm reduces. Consequently, higher mechanical sensitivity will be achived. The mechanical sensitivity with stress using Equation (10) has been shown in Figure 19. As shown in Figure 19, when stress is low, sensitivity is high. Hence, to have a high mechanical sensitivity for diaphragm a material with low stress must be selected. Poly silicon is a material that is used for making diaphragm. In general, the deposited LPCVD poly silicon thin film on silicon wafer shows large residual stress (about 100 MPa), which makes less interesting for diaphragm. High-temperature annealing of a low-pressure chemical vapor deposition (LPCVD) of poly silicon thin film that is ion implanted with phosphorous can reduce the residual stress as low as 20 MPa. Thus, low-stress poly silicon is a common choice for the diaphragm. By adding these changes in the structure of finger print sensor a new structure is defined, which is shown in Figure 20. The suggested design of fingerprint sensor has 2 slots on each side, 8 slots in general on upper electrode and also 24 holes on lower electrode for reducing the air damping between two electrodes. The diaphragm is made of poly silicon with 20 Mega pascal stress. We expect that using these factors, diaphragm stiffness, stress and air damping decrease and the performance and sensitivity of the sensor increase. Table 1 shows the comprison between new design and previous models.

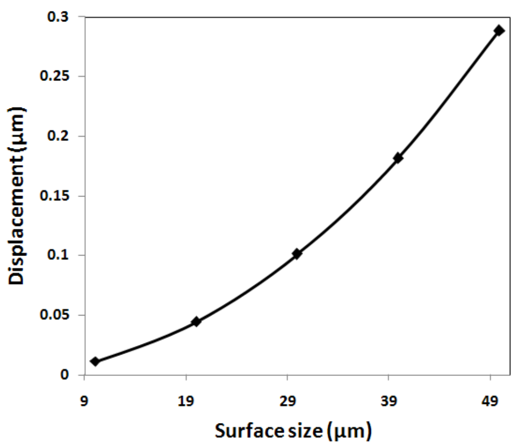

Figure 16. The effect of surface size of T-shape protrusion on displacement under constant pressure

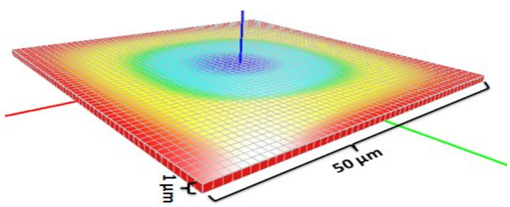

Figure 17. Diaphragm with dimension of 50×50 μm^2 and 1 μm thickness under 1 Mpa pressure

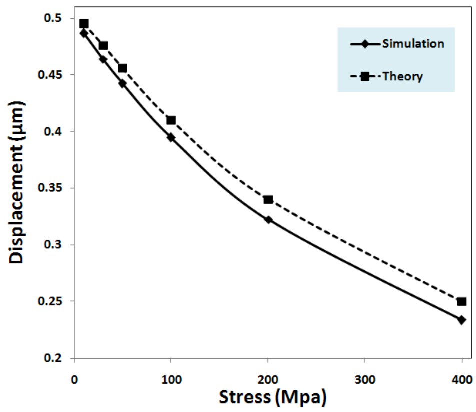

Figure 18. Diaphragm displacement vs. material stress

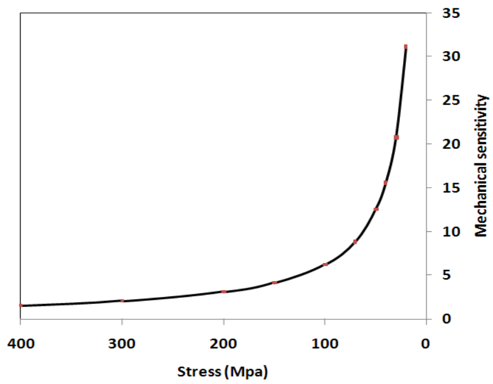

Figure 19. The effect of stress on mechanical sensitivity

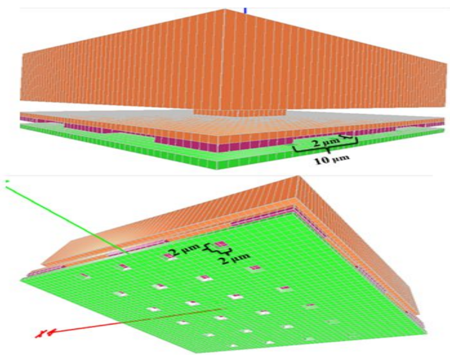

Figure 20. Picture of suggested new structure of finger print sensor

To analyze and compare the diaphragm displacement (w) based on pressure (p), we compared new design with one suggested in 2005 which has a diaphragm with four fixed sides.The simulation results are given in Figure 21 (dimensions of T-shape protrusion and electrodes are same). As shown in Figure 21, the diaphragm displacement of new design is more than pervious one. The caculated mechanical sensitivity of new design is 3.9 and pervious one is 2.27 (μm/Mpa).

TABLE 1. Charactrestics of simulated designs

	Diaphragm dimension (µm)	Diaphragm material	Number of slot	Number of anchor	Polymide layer	T-shaped protrusion (µm)
New design	2×46×46	Poly silicon	8:(2×10)	4	✓	Base:3×10×10 Surface:7×46×46
2005 design	2×46×46	Aluminium	—	4	✓	Base:3×10×10 Surface:7×46×46
2008 design	2×46×46	Aluminium	—	2	—	Base:3×10×36 Surface:7×46×46

Figure 22 shows the capacitance versus pressure of new design and two previous structures in 2008 and 2005. As can be seen from the Figure 22, the most capacitor changes is related to the new design, and if the average slope of diagram is considered as a sensitivity (Δc/Δp), the calculated sensitivity of new design is 3.22 (fF/Mpa) against 1.6 in 2008 and 1.44 in 2005. These results show a significant increase in the sensitivity for new fingerprint sensor design.

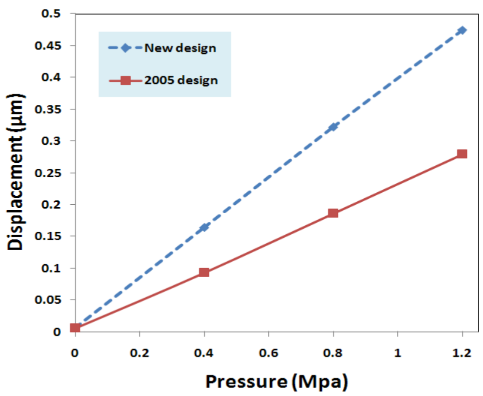

Figure 21. Displacement vs. pressure for clamped diaphragms

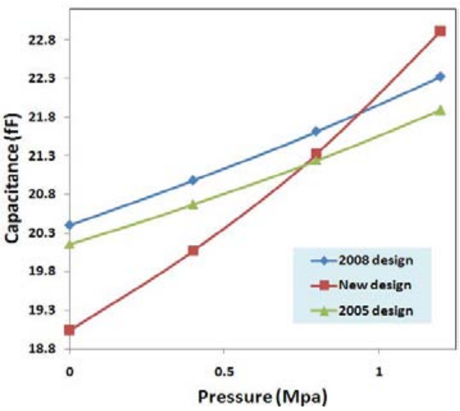

Figure 22. The capacitor vs. pressure for various fingerprint sensors

5.CONCLUSION

In this paper, certain methods have been presented to increase the sensitivity of fingerprint sensor. These methods include using a T-shape structure on diaphram and reducing diaphragm stress, making slots on diaphragm for reducing the stiffnes to increase the displacement of diaphragm. Using these techniques the new fingerprint sensor has mechanical sensitivity around 3.9 (µm/Mpa) and capacitive sensitivity around 3.22 (fF/Mpa). The sensitivity of the new structure is at least 2 times more than two previous designs.

6. REFERENCES

1. Henry, E. R., “Classification and uses of finger prints”, London: George Rutledge & Sons, Ltd, 1900.
2. De Souza, R. J. and Wise, K. D., “A very high density bulk micromachined capacitive tactile imager”, Chicago, *Proceeding of International Conference on Solid State Sensors and Actuators, Transducers*, Vol. 97, No. 2, (1997), 1473-1476.
3. Machida, K., Shigematsu, S., Morimura, H., Tanabe, Y., Sato, N., Shimoyama, N., Kumazaki, T., Kudou, K., Yano, M. and Kyuragi, H., “A Novel Semiconductor Capacitive Sensor for a Single Chip LSI FingerPrint Sensor/Identifier”, *IEEE Transaction On Electron Devices*, Vol. 48, No. 10, (2001), 2273-2278.
4. Sato, N., Shigematsu, S., Morimura, H., Yano, M., Kudou, K., Kamei, T. and Machida, K., “Novel surface structure and its fabrication process for MEMS fingerprint sensor”, *IEEE Transaction on Electron Devices*, Vol. 52, No. 5, (2005), 1026-1032.
5. Sato, N., Sato, Y., Kado, Y., Ciappa, M., Aemmer, D., Kaeslin, H. and Fichtner, W., “A Multilevel CMOS–MEMS Design Methodology Based on Response Surface Models”, *Journal of Microelectromechanical Systems*, Vol. 20, No. 3, (2011), 609-621.
6. Damghanian, M. and Majlis, B. Y., “A Modified Lift-off Technique to Prevent Pattern Following Effect in Microfabrication”, *ICSE 2008 Proceeding, Johor Bahru, Malaysia*, (2008), 634-638.
7. Damghanian, M. and Majlis, B. Y., “Design of a High Sensitivity Structure for MEMS Fingerprint Sensor”, *ICSE 2006 Proceeding, Kuala Lumpur, Malaysia*, (2006), 177-184.

8. Ganji, B. A. and Majlis, B. Y, "Analytical Analysis of Flat and Corrugated Membranes for MEMS Capacitive Sensors", *International journal of Nonlinear Dynamics in Engineering and Sciences*, Vol. 1, No. 1, (2008), 47-57.

9. Jermam, J. H., "The fabrication and use of micromachined corrugated silicon diaphragm", *Sensors and Actuatores,* Vol. A21-A23, (2001), 988-992.

10. Kressmann, R. and Mlaiber, M., "Silicon condenser microphones with corrugated silicon oxide/nitride electret membranes", *Sensors and Actuators,* Vol. A 100, (2002), 301-309.

11. Jing, C., Litian, L. and Zhijian, L., "Dynamic characteristics of novel single-chip fabricated corrugated diaphragms for micro-acoustic devices", *IEEE*, (2001), 757-760.

12. Ganji, B. A. and Nateri, M. S., "Fabrication of a novel mems capacitive microphone using lateral slotted diaphragm", *IJE Transactions B: Applications*, (2010), Vol. 23, No. 3 & 4, 191-200.

13. Chowdhury, S., Jullien, G. A., Ahmadi, M. A. and Miller, W. C., "A MEMS implementation of an acoustical sensor array", *IEEE International Symposium*, Vol. 2, (2001), 273 – 276.

14. Chowdhury, S., Ahmadi, M., and Miller, W. C., "Design of a MEMS acoustical beamforming sensor microarray", *IEEE Sensors Journal*, Vol. 2, No. 6, (2002), 617- 627.

Design of Novel High Sensitive MEMS Capacitive Fingerprint Sensor

M. Shams Nateri , B. A. Ganji

Department of Electrical Engineering, Babol University of Technology, Iran

ARTICLE INFO

Article history:
Received 13 March 2012
Received in revised form 12 Aprill 2012
Accepted 19 Aprill 2012

Keywords:
MEMS Fingerprint
Slot
Stress
T-shaped Protrusion
Sensitivity

چکیده

در این مقاله ساختار جدیدی برای حسگرهای اثرانگشت خازنی MEMS ارائه گردیده است. حسگرهای خازنی از دو صفحه موازی که در فاصله ی معینی از هم قرار دارند تشکیل شده است. در این حسگرها تغییرات خازنی عامل بسیار مهمی در تعیین عملکرد آنها می باشد، که بر اثر جابجایی الکترود بالایی ایجاد می گردد. در این مقاله با استفاده از ایجاد شکاف برروی الکترود بالایی، استفاده از برآمدگی T-شکل برروی دیافراگم بمنظور متمرکز کردن فشار ناشی از ناهمواریهای انگشت، ایجاد حفره در الکترود پایینی برای کاهش مقاومت هوای درون فاصله هوایی و استفاده از ماده با استرس پایین برای ایجاد دیافراگم، موفق به طراحی ساختار جدیدی برای حسگر اثرانگشت MEMS با حساسیت بالا نسبت به ساختارهای گذشته شده ایم. در این مقاله شبیه سازیها باروش المان محدود انجام گرفته است.

!!

doi: *10.5829/idosi.ije.2012.25.03b.03*