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Novel Structure and Characterization of Convex Touch Mode Capacitive Pressure Sensor (TMCPS) with Near Zero Touch Point Pressure (TPP)

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Abstract **Original Research Article**

In this paper, we present the structure and characteristics of a touch mode capacitive pressure sensor with a spherical substrate electrode with a touch point pressure (TPP) near zero pressure. The proposed touch mode capacitive pressure sensor consists of an elastic diaphragm-top moving electrode and a curved bottom fixed electrode that causes deformation under external pressure. The two electrodes are in touch before the external pressure is applied, and when the external pressure is applied, the upper moving diaphragm acts as a touch type, wrapping the bottom surface electrode from the beginning. In this paper, the capacitance-pressure output characteristics of the device are analyzed and compared with other touch point pressure sensors in the graphical state. With a given structural parameter, the effective operating pressure range of 0 ~ 1.75MPa was obtained, while the device capacitance was obtained in the range of 1.2×10-12 ~ 3.5×10-12F. This value is about twice as large as that of planar TMCPS. The effective operating pressure range are 0.18MPa larger compared to the TMCPS with no initial contact of the two electrodes at the same state and condition, since the TPP is near zero. The sensitivity and linearity are slightly different in the two structures.

Keywords: Touch-mode capacitive pressure sensor, Touch-point pressure, convex touch mode capacitive pressure sensor, Nonlinearity.

1. INTRODUCTION

Capacitive pressure sensors have been widely applied for their advantages such as high measurement sensitivity, wide pressure measurement range, low power consumption, robust structure, high overload characteristics, low fabrication cost and so on and especially they have been studied for the chemical process control, medical, industrial production process control. [1-28].

The research on capacitive pressure sensors mainly focuses on improving the linearity and sensitivity of the output characteristics. [15-28]

With this increasing research, touch capacitive pressure sensors (TMCPS) have been developed with much improved sensitivity and linearity than conventional planar electrodes [20-28].

The conventional capacitive pressure sensor has both a flat-plate configuration of the lower and upper electrodes. When external pressure is applied, the planar elastic top electrode diaphragm under uniform pressure is deformed and approaches the lower electrode, increasing the capacitance between the two electrodes gradually with pressure. The center of the top diaphragm then shifts linearly with pressure, but the capacitance relationship between the two electrodes with pressure appears to be nonlinear. In this configuration, the gap between the top and bottom electrodes is designed to be relatively large, and the two electrodes do not reach each other during operation. However, in the newly developed touch type pressure sensor, the gap between the top electrode diaphragm and the bottom electrode is small, and when the top electrode is subjected to relatively small external pressure, it quickly touches the bottom electrode, and the area of touch increases as the external pressure increases gradually. Thus, the capacitance between the two electrodes increases in proportion to the external pressure. At this time, the capacitance between the two electrodes increases significantly due to the thin dielectric sandwiched between the two electrodes.

A typical capacitance-pressure characteristic model of a previously developed touch mode capacitive pressure sensor (TMCPS) is shown in Fig 1.

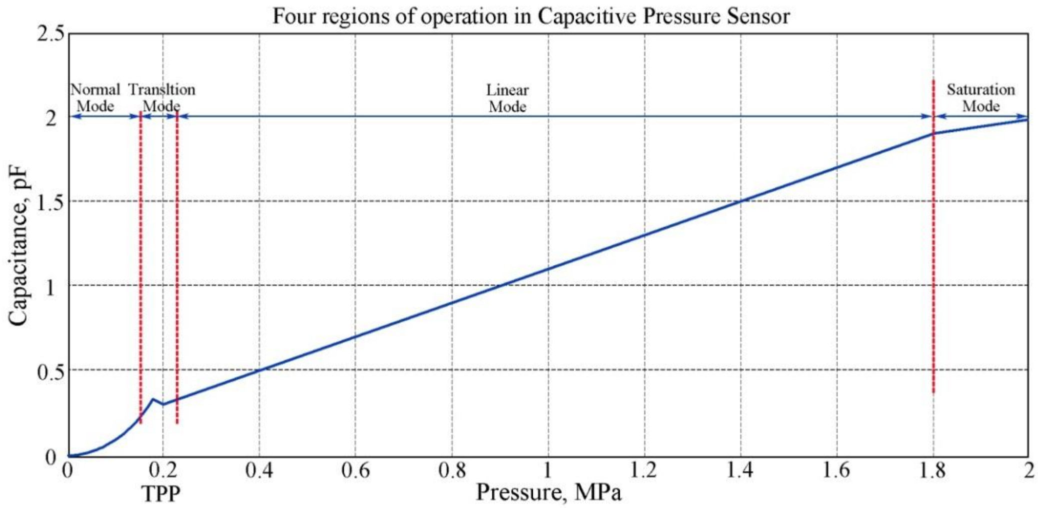

Fig. 1, Model Graph for Four Operating Modes of TMCPS. [20]

As can be seen in Fig. 1, when a uniform pressure is applied from the outside to the top electrode diaphragm of the pressure sensor, the top diaphragm deforms downward, resulting in a nonlinear capacitance increase. This part is usually the same as the operation of a flat capacitive pressure sensor and is therefore referred to as the normal operating region. As the external pressure increases gradually, the upper diaphragm finally reaches the lower electrode, and a nonlinear capacitance signal is generated due to the transient nature of the touch at the moment of touch between the upper and lower electrodes. This part is called the switching operation region. The applied external pressure is called the touch point pressure (TPP). The switching operation region is very narrow and soon a safe touch operation region is started. As the external pressure increases further, the touch area of the two electrodes increases gradually, resulting in higher capacitance and sensitivity. In this region, the feature is that with increasing sensitivity and the capacitance-pressure characteristic is linear. This linear operating region is the main application area for MTCPS devices, which is a wide pressure-operated region. As the external pressure increases further, the deformation of the top electrode diaphragm becomes saturated, and the capacitance-pressure characteristic also becomes saturated. In this region, the sensitivity is reduced and the nonlinearity is increased compared to the linear touch region in front. This region is called the saturation operating region. Thus, MTCPS has four operating zones depending on the external pressure, where the effective main operating zone is the central linear operating zone. In this linear operating region, the sensitivity and nonlinearity of the device and the allowable operating pressure region are mainly determined. Here, the allowable operating pressure region is determined between the touch point pressure (TPP) and the saturation starting pressure at which the two electrodes are touched.

Thus, in such MTCPS, a smaller TPP is beneficial to increase the allowable operating pressure region. In the literatures published previously, TPP of MTCPS has been reported differently. Table 1 shows the TPP values for different MTCPS structures.

TPP values for different MTCPS structures

No	Reference number	Touch Point Pressure	Structural parameters of TMCPS
1	Reference [10]	2 bar 4.5 bar	
2	Reference [23]	0.17×10^{6} Pa 0.23×10^{6} Pa	$a = 180\times10^{-6}$m, h = 5×10^{-6}m g = 2×10^{-6} m
3	Reference [7]	7.5MPa	$a = 180\times10^{-6}$m, h = 5×10^{-6}m g = 0.75×10^{-6} m
4	Reference [14]	0.28MPa	
5	Reference [1]	50psi	a = 400mm, h = 5mm g = 5mm
6	Reference	2 bar	

	[8]		
7	Reference [4]	8 psi	a = 255×10^{-6} m, h = 2.3×10^{-6} m g = 2×10^{-6} m
8	Reference [11]	1.7 bar	a = 75×10^{-6} m, g = 420nm
9	Reference [28]	88 Pa	a = 180×10^{-6} m, h = 2×10^{-6} m g = 2×10^{-6} m
10	Reference [19]	0.18MPa	a = 180×10^{-6} m, h = 5×10^{-6} m g = 2×10^{-6} m
11	Reference [18]	0.2MPa	a = 180×10^{-6} m, h = 5×10^{-6} m g = 2×10^{-6} m
12	Reference [12]	0.1MPa	a = 255×10^{-6} m, g = 0.5,0.75,1.2
13	Reference [20]	0.23MPa	a = 180×10^{-6} m, h = 5×10^{-6} m g = 2×10^{-6} m

As can be seen in Table 1, the TMCPSs developed previously have constant touch pressure (TPP) and their values are different. These TMCPSs perform normal mode operation between zero-pressure and touch point pressure (TPP) when external pressure is applied. The TPP of TMCPS has a direct effect on the effective operating pressure range, sensitivity and linearity of the device [1].

In literatures [5, 15, 17-19, 24, 25], a more complex structure using a double-sided sensing area is proposed to further improve the sensitivity of the developed TMCPS.

Further improvements in the design have been incorporated by etching a second notch into the substrate and using two back-to-back sensors.

In literature [16, 20, 22, 24, 25, 28], a TMCPS structure was proposed to improve the sensitivity by using a hollow spherical structure in the shape of the bottom electrode, however, these designs come with an increase in complexity in terms of both analytical modeling, fabrication and installing.

To further improve the above-mentioned properties, the authors further improved the sensitivity and linearity by choosing the shape of the bottom electrode plate of TMCPS as a curved substrate instead of being plat-substrate and accurate analysis of the structure and operating characteristics is carried out.

In literature [20], a new structure was used to reduce the touch pressure from 0.3MPa to 0.23MPa, and the saturation threshold pressure increased from 1.2MPa to 1.8MPa, compared to plat-plate MTCPS with identical structural parameters in literature [20].

The literature [28] newly presents the structure with square diaphragm to improve sensitivity of TMCPS.

In this paper, we present a structure similar to that reported by [20, 28] but touched both the electrodes from the initial state where the top electrode diaphragm and the bottom substrate are not subjected to external pressure. Therefore there is no normal operating region as shown in Fig. 1 when external pressure is applied and the touch point pressure (TPP) is close to zero.

2. STRUCTURE AND PRINCIPLE OF OPERATION

Figure 2 shows the convex TMCPS structure without touch of the top electrode diaphragm and the bottom curved electrode from the initial state without external pressure. [20]

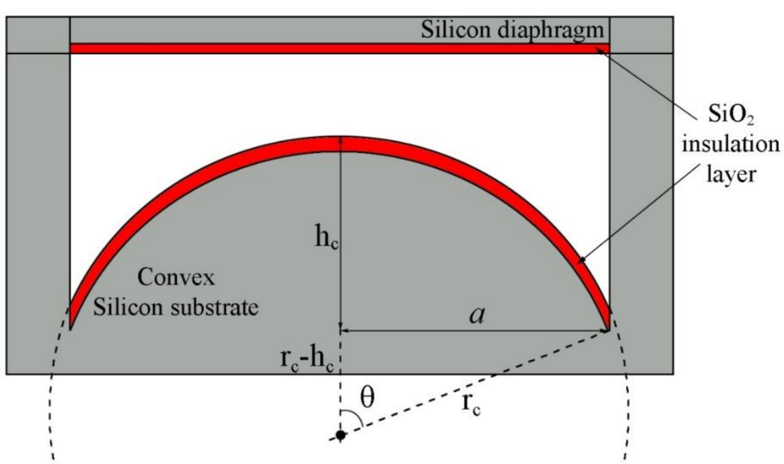

Fig. 2. Convex TMCPS structure without touch of top electrode diaphragm and bottom curved electrode [20]

As shown in the figure, the top and bottom electrodes are separated at regular intervals and when the pressure is applied outside, the top elastic diaphragm is deformed and gradually approaches the bottom and finally approaches the top of the bottom substrate electrode. The pressure is the touch point pressure (TPP) and the pressure sensor is operated in normal mode. Subsequently, with increasing external pressure, the upper diaphragm wraps the bottom substrate electrode, allowing the touch of the two electrodes and extending the area of the touched hemisphere with pressure. The two electrodes are then attached to each other, so the capacitance between the two electrodes is very large and the capacitance versus pressure is linear.

Fig. 3 newly shows the convex structure of the proposed curved electrode TMCPS.

In this paper, we consider the structure of a capacitive pressure sensor with curved substrate, in contrast to the structure of a capacitive pressure sensor with a curved substrate, in which the upper elastic electrode of a capacitive pressure sensor and a fixed bottom curved electrode are in touch from the beginning, causing the deformation to be induced downward under external pressure.

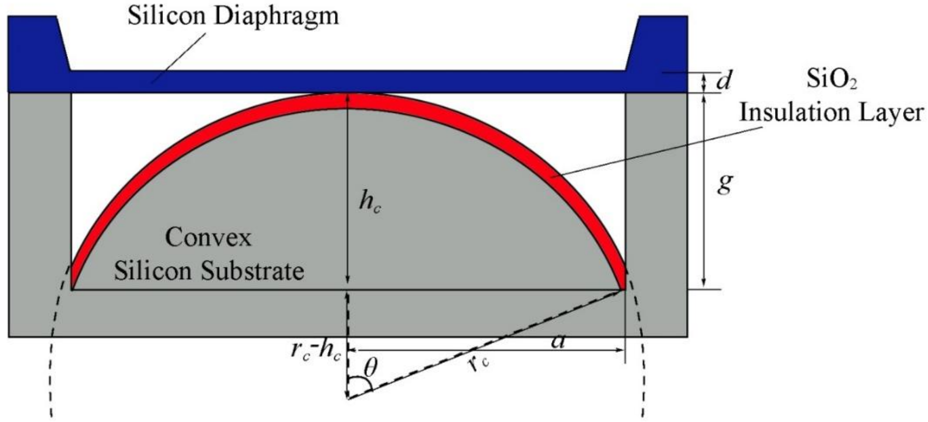

Fig. 3. Structural model of convex TMCPS proposed in this paper.

As can be seen in Fig. 3, in the structure of the device the moving-strain diaphragm located on the top of the disk-type capacitance pressure sensor is in point touch with the bottom fixed electrode tip, which is curved from the outside, without pressure. Thus, the distance g between the two electrodes of the parallel plate capacitive pressure sensor and the spherical height h of the curved electrode in this device are equal (h = g). The surface of the bottom substrate is covered with a dielectric such as SO_2, so that the top and bottom electrodes are electrically separated. When external pressure is not applied, the upper and lower electrodes are in touch with the point state to form the capacitor structure. Therefore, the initial capacitance is very small. In this situation, the total capacitance of the capacitive pressure sensor consists of the capacitance of the touch area and the capacitance of the non-touch area around the touch point, and the capacitance of the non-touch state (so-called parasitic capacitance) can,t be relatively larger than the touch state capacity.

As shown in Fig. 1, the touch mode capacitive pressure sensor is divided into four regions according to the external applied pressure. However, in the initial touch state pressure sensor presented here, there is no normal operating region in which the two electrodes of the capacitive pressure sensor are not in touch. And the operation starts from the switching operation region that exists between the normal operating region shown in Fig. 1 and the touch operating region. In this device, there is an initial unstable switching operating region depending on the initial upper moving elastic electrode and the touch state of the curved lower fixed electrode. The switching operation region is highly nonlinear and produces weak noise signals. In this sensor, the touch point pressure (TPP) is almost zero differently from the conventional touch-operated capacitive pressure sensor.

Now, when the pressure is applied to the top moving electrode deformation diaphragm from the outside, the top moving electrode diaphragm is deformed downward, wrapping the bottom surface, with the center supported on the bottom surface. Thus, the capacitive pressure sensor will be operated in touch mode from scratch immediately after the external pressure is applied.

Fig. 4 shows the operating model of a convex dome electrode capacitive pressure sensor that works in touch mode from zero pressure value.

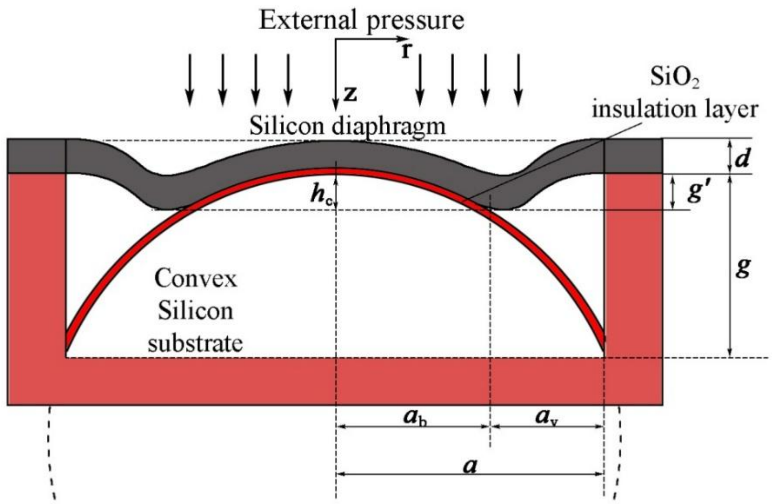

Fig. 4. A model of the behavior of a convex TMCPS operating in from the initial touch mode

As the external pressure gradually increases, the elastic diaphragm gradually wraps the lower curved electrode more tangentially, widening the touch area between the two electrodes. (Note: Figure 8 shows numeric analytical modeling result of the proposed convex TMCPS.) The capacitance between the two electrodes is then generated in the touch area with a thin dielectric film sandwiched between them, and is partially composed of the capacitance between the upper and lower surface electrodes that are not touched at the edges. The main capacitance here is the capacitance of the touch area between the top and bottom surface electrodes. The capacitance of the touched part is determined by the area of the spherical surface with the radius a_b of diaphragm cap. Then, the surface area of the cap formed by a_b is given by

$$S_{con} = 2\pi r_c \cdot g'(P) = 2\pi r_c^2 \left[1 - \sqrt{1 - \left(\frac{a_b(P)}{r_c} \right)^2} \right] \quad (1)$$

If the bottom electrode surface is flat and the upper elastic diaphragm is circular, the deformation of the upper diaphragm when the capacitor operates in a normal operating mode by the pressure exerted from the outside is expressed as [29]

$$\omega(r, p) = \frac{P \cdot a^4}{64D} \left[1 - \left(\frac{r}{a} \right)^2 \right]^2 \quad (2)$$

Where, a- the radius of the upper diaphragm.

$$D = \frac{E \cdot d^3}{12(1 - \upsilon^2)}$$

Here, E- Young's modulus of the top membrane material.

d- Thickness of diaphragm

v- Poisson ratio

However, when operating in contact mode, the deformation of the diaphragm can be approximated as follows

$$\omega(r,p)=\begin{cases} g & (0<r<a_b(p)) \\ g\left[1-\left(\dfrac{r-a_b(p)}{a_\upsilon(p)}\right)^2\right]^2 & (a_b(p)<r<a) \end{cases} \quad (3)$$

Where

$$a_\upsilon(p)=\left(\frac{64\cdot D\cdot g}{P}\right)^{1/4}$$

Whereas, in the case of a curved lower electrode surface, the deformation of the membrane can be approximated as follows:

$$\omega(r,p)=\begin{cases} g'(P) & (0<r<a_b(p)) \\ g'(P)\left[1-\left(\dfrac{r-a_b(p)}{a_\upsilon(p)}\right)^2\right]^2 & (a_b(p)<r<a) \end{cases} \quad (4)$$

Here

$$g'(P)=\frac{P\cdot a_\upsilon^4(P)}{64\cdot D}=R\left[1-\sqrt{1-\left(\frac{a_b(P)}{r_c}\right)^2}\right]$$

$$a_b(P)=a-\sqrt[4]{\frac{64\cdot D\cdot g'(P)}{P}}$$

$$g=g'(P)+C(P)$$

When the pressure is applied to the diaphragm, the total capacitance of the capacitor in the contact mode of operation is expressed as

$$C_{TO}=C_{con}+C_{nocon} \quad (5)$$

Here, the capacitance of the contact area of two electrodes, which is the main capacitance part, can be calculated as the capacitance of a planar capacitor sandwiched between a thin layers of insulation.

$$C_{con}=\varepsilon_0\varepsilon_{Si}\frac{S_{con}}{t_{Si}} \quad (6)$$

Where t_{Si}- insulation film thickness

ε_{Si}- dielectric constant of insulating film

The noncontact capacitance is derived by taking the deflection into account and subtracting the base touch radius from r and a_b.

The capacitance of the noncontact part of the electrodes can be derived by obtaining a virtual radius model and the distance between the deformed diaphragm and the lower convex substrate electrode.

Fig. 5 shows a model diagram for calculating the capacitance of the non-touching part of the two electrodes.

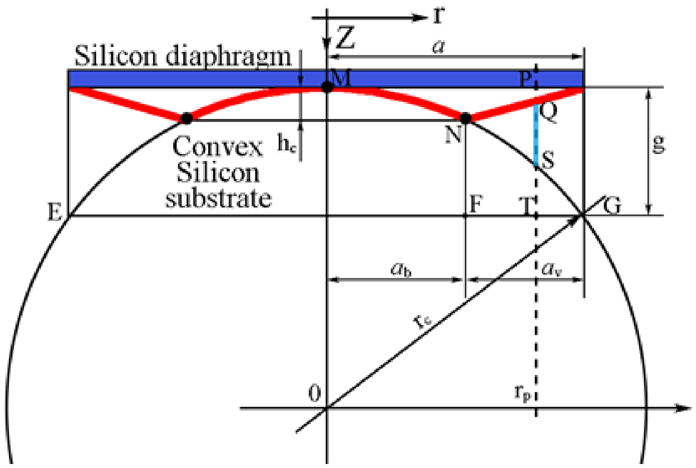

Fig5. Model for calculate the capacitance of the non-touching part of two electrodes.

The N point in the figure is the starting point at which the two electrodes fall from the touch state.

The distance between the top diaphragm and the bottom surface electrode deformed by the external pressure is the distance between the point of Q and the point of S if considered at any point r, as can be seen in the figure.

The distance between the top and bottom electrodes considering Fig.5 in noncontact part can be expressed as

$$L_{nc} = r_c - \sqrt{r_c^2 - r^2} - \omega(r,\theta) = r_c - \sqrt{r_c^2 - r^2} - \frac{Pa^4}{64D}\left[1 - \left(\frac{r - a_b}{a_\upsilon}\right)^2\right]^2 \tag{7}$$

Thus, the capacitance of the non-contact part of the two electrodes is

$$C_{nocon} = \int_0^{2\pi}\int_{a_b}^{a} \frac{\varepsilon_0 \varepsilon_{Si} \varepsilon_a \cdot r \cdot dr \cdot d\theta}{\varepsilon_{Si} t + \varepsilon_a \cdot L_{ne}} = 2\pi\varepsilon_0\varepsilon_{Si}\varepsilon_a \int_{a_b}^{a} \frac{r \cdot dr}{t + \varepsilon_a \left\{ r_c - \sqrt{r_c^2 - r^2} - \frac{Pa^4}{64D}\left[1 - \left(\frac{r - a_b}{a_\upsilon}\right)^2\right]^2 \right\}} \tag{8}$$

Thus, the total capacitance of the sensor is expressed as

$$C_{TO} = C_{con} + C_{nocon} = \frac{2\pi \cdot \varepsilon_{Si} \cdot \varepsilon_0 \cdot r_c^2}{t_{Si}}\left[1 - \sqrt{1 - \left(\frac{a_b(P)}{r_c}\right)^2}\right] +$$

$$+ 2\pi\varepsilon_0\varepsilon_{Si}\varepsilon_a \int_{a_b}^{a} \frac{r \cdot dr}{t + \varepsilon_a \left\{ r_c - \sqrt{r_c^2 - r^2} - \omega_0\left[1 - \left(\frac{r - a_b}{a_\upsilon}\right)^2\right]^2 \right\}} \tag{9}$$

Here $\omega_0 = \frac{Pa^4}{64D}$

3. RESULTS AND DISCUSSION

Figure 6 shows the pressure-capacity characteristics of the new structure. To obtain this characteristic, the mathematical model derived previously and the MATLAB computational tool were used, and compared with the published literature.

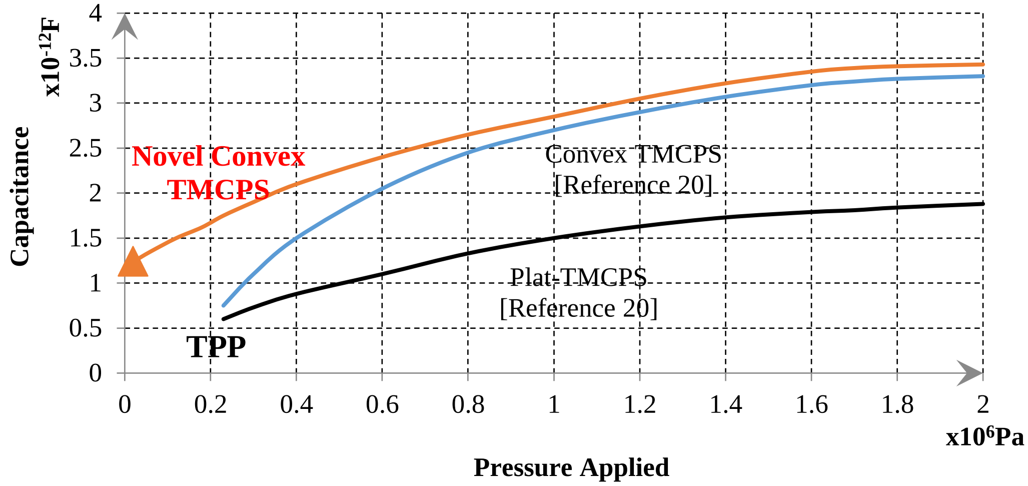

Fig.6. Capacitance variation with pressure in the new structure

As can be seen from the results obtained, the touch point pressure (TPP) of the two electrodes is near zero in the pressure-capacitance characteristic, and the starting point of the curve starts with the small capacitance due to the initial point touch area and the sum of the capacitance values of the non-fundamental capacitance value that occur in the areas where the upper and lower electrodes do not meet each other. The main part of the initial capacitance is the capacitance value between two electrodes that are not in touch with each other. When the external pressure starts to increase, the top electrode diaphragm deforms and wraps the bottom surface electrode with a thin dielectric film between them. The capacitance values obtained are much higher than those of the flat-plate pressure sensors with two electrodes floating on each other. The surface area of the wrapped sphere, determined by Eq. (1), is proportional to the pressure exerted on the outside, since the height of the dome obtained when the top electrode diaphragm wraps the lower surface. And the resulting capacitance value constitutes the basis of the capacitance value of MTCPS and is very large compared to the capacitance between two unattached electrodes in the vicinity.

In this paper, we compare the numerical results using three different surface electrodes to examine the effect of the bottom electrode surface on sensitivity and linearity. The values of the three lower electrode surfaces radii used are listed in Table 2.

Table 2 Different lower electrode surface radius

No	surface radii (r_c),m
1	13200×10^{-6}
2	16200×10^{-6}
3	19200×10^{-6}

The larger the lower electrode surface radius, the higher the capacitance value occurring in the non-touch electrode region, and thus the total capacitance value of MTCPS increases, but the nonlinearity slightly increases. The results presented in Fig.6 are to obtain with that same as the structural parameters in reference [20].

As can be seen in Fig. 7, the effective operating pressure range is from about 0 to 1.75MPa, and the saturation operating region starts at 1.75MPa. At this time, the capacitance value range is of 1.2×10^{-12}F ~ 3.35×10^{-12}F. This value is about twice one of the plat-TMCPS and the nonlinearity is about 0. 85%. The effective operating pressure range was increased to about 0.18MPa.

Since the starting point of the characteristic curve presented here is already a turning point problem in the previous study, some oscillatory phenomena should be considered. Fig.8 shows a analytical modeling result made in ANSYS 16.2.

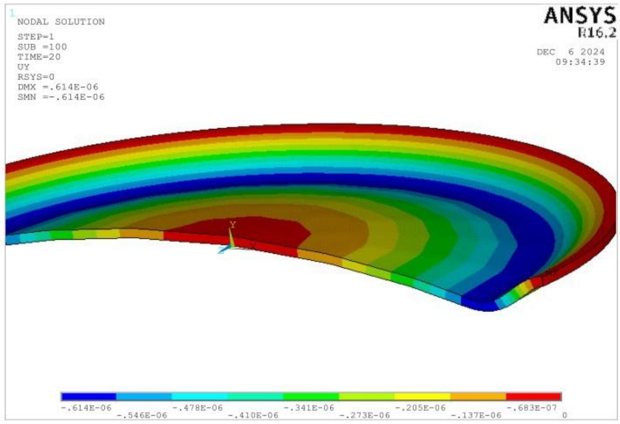

Fig.7. A numeric analytical modeling result

4. CONCLUSION

This paper presents a novel structure of convex touch mode capacitive pressure sensor (TMCPS) with circular diaphragm. The TMCPS proposed in this paper doesn't have the TPP. The proposed device has been fitted with a top and bottom electrode of a capacitive pressure sensor before external pressure is applied, and the fixed bottom electrode is spherical rather than planar. Thus, when external pressure is applied, there is usually no normal operating region appearing in TMCPS, and the touch point pressure (TPP) is located near zero or zero. When external pressure is applied, TMCPS moves from the beginning to touch mode operation, and the top electrode consisting of an elastic diaphragm gradually wraps the lower spherical electrode, increasing the touch area. We have increased the accuracy of the calculation by considering the spherical height of the curved electrode fixed below to calculate the capacitance of the non-touch area. However, this method brings about an increase in computational time and complexity. The total capacitance of the contact mode pressure sensor with a curved bottom surface is about two times larger than that of the plat-TMCPS with the same structural parameters in reference [20] and slightly larger than that of the TMCPS with the lower and upper electrodes not initially attached. At the same structural parameters, the saturated operating region was started at 1.75MPa, and the effective operating pressure region was 0.18MPa larger than the TMCPS where both electrodes were not initially attached. The sensitivity and linearity of the two different sensors are slightly different.

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