Modelling and Analysis of Dielectric Charge of CMUTs

Jucai Li, Yan Li, Peiyu Zhang*
Lab of Smart Micro/Nanoelectromechanical systems, School of Physics and Electronics, Henan University, Kaifeng, China

*Corresponding author e-mail: memszhang@yahoo.com

Abstract. Capacitive micromechanical ultrasonic transducers (CMUTs) have the remarkable advantages that the traditional piezoelectric ultrasonic transducers do not have, and they are expected to replace the traditional piezoelectric ultrasonic transducers as the mainstream product in the market. However, the dielectric charging problem has a great influence on the normal work of CMUT, and it is also one of the main obstacles to its commercialization. In this paper, the influence of dielectric charging is introduced, and then the model of non-contact charging and contact charging is established to analyse the mechanism of charging. The influencing factors of dielectric charging were found out, and the influence of each influencing factor on charging was analysed. The charging of the diaphragm and the insulating layer were compared. The results showed that silicon dioxide is less charged than the silicon nitride. Finally, based on the analysis of non-contact charging and contact charging, a method of changing the shape and coverage area of the insulating layer to reduce dielectric charging is proposed.

1. Introduction

Dielectric charging is one of the obstacles to the long-term reliability of MEMS devices, which has been studied by many research groups. At present, the research on the charge effect of CMUT is based on metal-insulator-metal capacitors and MEMS switches. G. J. Papaioannoul et al. carried out charging experiment on MEMS switch under positive and negative voltage, and observed dielectric charging caused by charge effect [1]. G. J. Papaioannoul et al. established a capacitive switch model with non-uniformly trapped charge and air gap distribution to study dielectric charging [2]. Matroni Koutsoureli et al. calculated the discharge current in the MEMS capacitor switch ing dielectric film by using the minimum capacitance offset and the thickness of the dielectric film [3].

Regarding the research on the charge effect of CMUT, in 2010, A group from University of Alberta discussed and tested the charge effect from the aspect of surface roughness of the medium, which showed that reducing the surface roughness of the medium can reduce the charge of the medium [4]. In 2011, Zheng Wei et al. established an empirical model for quantitatively characterizing surface and inside charging, and designed a double-bonded CMUT based on surface charging and inside charging. The results shown that surface charging dominated [5]. In 2013, Abhijeet Kshirsagar et al. found that the charge effect caused a large shift in voltage. By precharging the CMUT, the long-term reliability of the low-biased medical CMUT was improved [6].

Although a lot of research on the charge effect has been carried out in the past ten years, some methods have greatly improved the reliability of MEMS devices, but the mechanism of dielectric charging has not been fully studied. There is also a lot of work to be done.
Since the structure of CMUT is similar to that of parallel plate capacitor, in order to avoid the contact between the top and bottom electrodes, the dielectric layer must be added between the two electrodes to prevent the short circuit of the top and bottom electrodes in the capacitor's work. However, the dielectric layer will accumulate charge under the action of the electric field generated by the voltage of the two poles. The electric charging is a common problem in electrostatic driven MEMS devices, because large electric fields drive charges into insulating materials. With the increase of charge effect, the collapse voltage will be reduced, and even the collapse voltage will be reduced to zero, which will seriously affect the performance of CMUT and reduce the service life. Charge effect is the main hindrance to the commercialization of CMUT. Therefore, it is necessary and significant to study charge effect.

2. Modelling of charging effects

Fig. 1 shows the relationship between the CMUT capacitance and the applied voltage. The black color in the figure is the relationship between the capacitance and the voltage of the initial CMUT, and the red is the relationship between the voltage and the capacitance after a certain cycle of operation. The black arrow indicates that the applied voltage on the CMUT changes from small to large and from large to small, and the variation of the capacitance within one cycle. It can be clearly seen from the figure that the collapse voltage caused by the charge effect is shifted.

Figure 1. Schematic diagram of collapse voltage offset caused by CMUT charge effect

At present, there is little research on CMUT charging, and the charging mechanism needs to be further studied [7-9]. In this paper, based on the research of MIM capacitor and RF MEMS dielectric charging, the concepts of non-contact charging and contact charging are introduced into the study of CMUT charge effect for the first time. According to the structure, material and working mode of CMUT, the process models of non-contact charging and contact charging are established, and the possible charging forms in two cases are analyzed. Finally, the charge effect of CMUT is considered layer by layer, and then the factors that affect the charge effect of CMUT are analyzed.

Fig. 2 is a schematic view showing the model of the non-contact charging (the membrane is not in contact with the insulating layer) and the contact charging (the membrane is in contact with the insulating layer) of the established CMUT charge effect. As shown in Figure 2, the top electrode of the CMUT is connected to the positive electrode and the bottom electrode is connected to the negative electrode. At this point, a downward electric field is created between the plates. When the voltage applied by the two electrodes of the CMUT is less than the collapse voltage, the membrane does not contact the insulating layer. There is a certain amount of free charge and dipole due to internal defects in the membrane and the insulating layer. At this time, the charging is mainly due to the migration of the existing charge in the membrane and the dielectric layer and the dipole is redistributed by the initial disorder state under the action of the electric field force [10]. When the surface roughness between the bottom of the membrane and the top of the insulation layer is large, the non-contact charging can also be the injection charging, which is caused by the field emission due to the enhancement of the local electric field [11].
When the voltage on the CMUT reaches the collapse voltage, the diaphragm collapses onto the insulating layer and changes from non-contact charging to contact charging. Since the diaphragm of the CMUT is in contact with the insulating layer portion, the average gap is close to zero, and the electric field generated by the applied voltage is sharply increased due to the sharp decrease in the gap. At this time, the internal charge migration is further strengthened, and the distribution of dipoles is more regular. In addition to this, the electric field causes a large amount of charge to be injected into the diaphragm and the dielectric layer, and the charge effect sharply increases. Contact charging is one of the main factors affecting the reliability of MEMS devices [9].

Due to the influence of the charge effect, the collapse voltage will be caused to drift, and even if the voltage applied to the CMUT does not reach the initial theoretical collapse voltage, the diaphragm may collapse.

Since the vibrating membrane and the insulating layer material can be selected from various materials in the manufacturing process, the dielectric charging analysis is carried out by taking the vibrating membrane material as silicon nitride and the insulating layer material as silicon dioxide.

When the membrane of the CMUT is a silicon nitride film, it contains a large number of defects under low temperature deposition [12]. Silicon nitride films have two different transmission mechanisms, including the ohmic transmission mechanism and the Frenkel-Poole mechanism. The ohmic transmission mechanism is generally in the high temperature and low field, because the charge gets enough energy to jump from one trap to another. The Frenkel-Poole transmission mechanism is the main transmission mechanism [13]. Under the action of a direct current electric field, spatial polarization is formed in the dielectric layer. Electrons can also enter the conduction band from the impurity level of the dielectric across the barrier. This is called the Frenkel-Poole transmission mechanism.

When the insulating layer is silicon dioxide, the transmission mechanism is Schottky radiation and the Fowler-Nordheim tunneling mechanism, and the Fowler-Nordheim tunneling mechanism is the main transport mechanism [13]. For the semiconductor heterojunction or the interface barrier of MIS, when a voltage is applied, an electric field exists in the barrier, and the interface barrier of electron tunneling can be approximated as a triangular barrier, and the width and the width of the tunneling barrier are added. Voltage-dependent, this tunneling is called the Fowler-Nordheim tunneling. Although silica has good insulating properties, its crystal lattice is formed by covalent bonds or ionic bonds, which has a great influence on dielectric polarization or charge transfer. When the temperature rises, it also provides enough energy to trap the charge, release it, and cause the dipole to redistribute the barrier [14].

During the charging process of the membrane, the charge will be injected into the membrane from the top plate and redistributed under the action of electric field. In this case, the current density as a function of the effective electric field is expressed as [15]:

**Figure 2.** Schematic diagram of the non-contact and contact charging process model
\[ J_{PF} = N \mu E \exp \left[ -\frac{(\varphi - \beta_{PF} E^{1/2})}{kT} \right] \]  

(1)

Where \( J_{PF} \) is the current density, \( N \) is the density of the capture site, \( \mu \) is the effective carrier mobility, and \( E \) is the effective electric field. \( \varphi \) is the barrier to the process associated with the defect characteristics, \( k \) is the Boltzmann constant, \( \beta_{PF} \) is the Poole-Frenkel coefficient and \( T \) is the temperature of the film.

In the process of charging the insulation layer, the charge will be injected into the insulation layer from the bottom plate and redistributed under the action of electric field. In this case, the current density as a function of the effective electric field is expressed as [16]:

\[ J_{PN} = K_1 E^2 \exp(-K_2 / E) \]  

(2)

Where \( K_1 \) with \( K_2 \) are a material related parameter, and

\[ K_1 = \frac{q^3 m^3}{16\pi^2 \hbar \phi m^2}, \quad K_2 = \frac{4(2m^*)^{3/2} \phi^{3/2}}{3hq} \]  

(3)

Resonance frequency of membrane [8] \( f_r \) is as follows,

\[ f_r \approx \frac{2t_m}{\pi a} \sqrt{\frac{Y_0 + T}{1.8 \rho (1 - \sigma^2)}} \]  

(4)

Where \( q \) is the electronic charge, \( h \) is the Planck’s constant, \( m_0 \) is the electron mass, \( m^* \) is the effective electron mass, and \( \phi \) is the barrier potential.

The total current density is:

\[ J_T = J_{PF} + J_{PN} \]  

(5)

It can be seen from the formula (1) and the formula (2) that the silicon nitride film and the silicon dioxide film are directly related to the applied electric field, and

\[ E = \frac{V}{d} \]  

(6)

\[ V = \sqrt{\frac{8k(t_m / \varepsilon_m + t_g / \varepsilon_g + t_i / \varepsilon_i)^3}{27 \varepsilon_p S}} \]  

(7)

\[ d \approx \frac{t_m}{\varepsilon_m} + \frac{t_g}{\varepsilon_g} + \frac{t_i}{\varepsilon_i} \]  

(8)

Where \( V \) is the voltage applied on the CMUT element, \( d \) is the thickness between the two poles, \( t_m \) is the thickness of vibrating film, \( t_g \) is the height of the cavity, \( t_i \) is the thickness of the insulating layer, \( \varepsilon_m \) is the dielectric constant of the diaphragm, \( \varepsilon_i \) is the dielectric constant of the insulating layer. Finishing is available:

\[ J_T = \frac{t_m}{\varepsilon_m} N \mu E^2 \exp \left[ -\frac{(\varphi - \beta_{PF} E^{1/2})}{kT} \right] + \frac{t_g}{\varepsilon_g} K_1 E^2 \exp(-K_2 / E) \]  

(9)

The higher the total current density, the more charging, the more unstable the CMUT works. It can be seen from Equation 9 that the factors influencing the charge effect of the CMUT are the diaphragm and insulation material, the thickness of the diaphragm, the height of the cavity, the thickness of the insulation layer, the temperature, and the area of the CMUT.
3. Analysis and discuss

Based on the derivation of the medium charging mechanism and formula, combined with the value of each influencing factor, the parameter assignment analysis was carried out with MATLAB. The current density of different influencing factors, i.e., the charging size, was plotted as shown. In the Figures, 1 means that both the diaphragm and the insulating layer are silicon nitride; 2 means that the diaphragm is silicon nitride, and the insulating layer is silicon dioxide; 3 means that the diaphragm is silicon dioxide, and the insulating layer is silicon nitride; 4 means that both the diaphragm and the insulating layer are silicon dioxide.

![Figure 3. Thickness of the diaphragm on the current density of different materials.](image1)

![Figure 4. Cavity thickness on current density in different materials.](image2)

![Figure 5. Thickness of insulation layer on current density in different materials.](image3)

![Figure 6. Thickness of insulation layer on current density in different materials.](image4)

As can be seen from the figure 7, the current density increases as the thickness of the diaphragm, the height of the cavity, the thickness of the insulating layer, and the temperature increase. When the thickness of the diaphragm and the insulating layer is increased, the defect trap and the carrier density contained in the material are increased, so that the current density becomes large, that is, the charging is increased. When the thickness of the cavity is increased, the collapse voltage is increased, that is, the operating voltage is increased, and the electric field strength is increased, thereby causing the current density to become large. As the temperature increases, the carrier mobility of the silicon nitride material becomes larger, so that the current is increased and the charge is increased. When the area is decreased, the voltage is reduced, and the electric field strength is decreased, so that the current density is reduced and the charging is reduced.

By changing the vibration film and the insulating layer materials, it is obvious that the vibration film and the insulating layers are the most charged when the insulating layer is silicon nitride, and it is the greatest influencing factor, while the vibrating film is the silicon nitride insulating layer. The most obvious charge is when the silicon dioxide is used, and the second is when the insulating layer is silicon nitride. Compared with the first three, when the vibrating diaphragm and the insulating layer are both silicon, the charging is minimal, that is, in the CMUT, the silicon dioxide material is less charged than the silicon nitride material.
In addition, the increase in the thickness of the diaphragm will increase the charging. When designing the CMUT, the thickness of the diaphragm should be selected in conjunction with the function of the CMUT. An increase in the height of the cavity increases the charging, so the cavity height can be appropriately reduced without affecting the operation of the CMUT. Increasing the thickness of the insulating layer increases the charging.

4. Conclusion

This paper introduces the non-contact charging and contact charging in the study of CMUT dielectric charging for the first time in combination with the structure and working mode of CMUT. By analyzing the conduction mechanism of dielectric charging, several influencing factors affecting dielectric charging are obtained: diaphragm thickness, insulation thickness, cavity height, diaphragm and insulation material, and temperature. The influence of various influencing factors on charging was analyzed. The charging of the diaphragm and the insulating layer were compared. The results show that in the CMUT, the silicon dioxide material is less charged than the silicon nitride material. Finally, based on the analysis of non-contact charging and contact charging, a method of changing the shape and coverage area of the insulating layer to reduce the dielectric charging is proposed, thereby reducing the charging, enabling the CMUT to work better and prolonging the life.

5. Acknowledgments

This work was financially supported by the Natural Science Foundation of China under Grant [61774055]; the united project for cooperation of enterprise, university and institute from Office of Science and Technology of Henan under Grant [162107000039] and the Nature Science Foundation of Henan under Grant [162300410033].

References

[1] G. J. Papaioannoul, M. Exarchos, V. Theonas, et al. Microw. 2005 IEEE MTT-S, 2005:761-764
[2] G. Papaioannou, N. Tavasolian, C. Goldsmith, Proc. 39th Euro. Microw. Conf., 2009:1752-1755.
[3] M. Koutsoureli, L. Michalas, G. Papaioannou, 2012 IEEE International Conference, 2012:1-5.
[4] P. Zhang, G. Fitzpatrick, W. Moussa, 2010 IEEE IUS Proceedings, 2010:1881-1885.
[5] W. zheng, D. Barlage, P. Zhang, 2011 IEEE IUS Proceedings, 2011:353-356.
[6] A. Kshirsagar, A. Sampaleanu, R. Chee., 2013 IEEE IUS (IUS) Conference, 2013:1728-1730.
[7] G. J. Papaioannou, G. Wang, Proc. 1st Euro. Microw. Inte. Cir. Con. 2006:513-516.
[8] N. Tavassolian, G. Papaioannou, J. Papapolymerou. IEEE MWCL, 2011, 21:592-594.
[9] M. Koutsoureli, L. Michalas and G. Papaioannou. 2011 IEEE IRPS, 2011:290-296.
[10] L. Michalas, M. Koutsoureli, E. Papandreou, FACTA U. Elec.& Energetics, 2015, 28,:113-122.
[11] N. Tavassolian, G. Papaioannou, J. Papapolymerou. IEEE MWCL, 2011, 21:592-594.
[12] L. Michalas, M. Koutsoureli, E. Papandreou, et al., MRR, 2015, 55:1891-1895.
[13] L. Michalas, M. Koutsoureli, E. Papandreou, Microelectronic Engineering, 2012, 90:145-148.
[14] Li Gang, Ph.D thesis, Xiamen, China: Xiamen University, 2009.
[15] T. Zure, S. Chowdhury, Micro and Nanosystems, 2014, 6,55-60.
[16] U. Zaghloul, G. J. Papaioannou, H. Wang, et al. NANO TECHNOLOGY, 2011, 22:1-25