Comparative Studies of Novel Capacitive Transducers with Non-Planar Diaphragms

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ABSTRACT

Novel single-chip fabricated condenser structures with corrugated diaphragms for residual stress releasing have been proposed and simulated. An electrostatic-structural coupling FEM analysis has been performed to fully reveal the nonlinear relationship of output electrical signal with respect to input mechanical change. The influence of various nonlinear effects on the performance of transducers is investigated. Two typical corrugation layouts are studied. Numerical results have shown that the round structure was promising with its potential of high sensitivity, while the squared one was superior in the low-voltage applications. The ill effects of these variations can be reduced by delicate design and adjusting of corresponding processes.

Keywords: corrugation, FEA, couple-field analysis, capacitor, diaphragm

1 INTRODUCTION

Capacitive transducers are favored for their low temperature drift, flat frequency response and low noise level. The development of high-performance diaphragm structures is of critical importance in the successful realization of these transducers. However, the sensitivities of most diaphragm-based capacitive transducers are determined by the diaphragm flexibility, which is greatly reduced by the residual stress in the diaphragm owning to the stress stiffening effect. A good method for releasing the residual stress is the application of corrugated diaphragms[1-4].

Most previously reported work on micromachined corrugated diaphragm has focus on those with continuous circular corrugations. In this case, the capacitors can only be realized as two separate chips. For the two-chip approach, bonding or polymer adhesives are often used to assemble the diaphragm and the substrate, which always involve critical and laborious alignment procedures as well as high temperature treatments that might affect the integrated electronics and change the material properties. In addition, the large parasitic capacitance and electric leakage between the two chips may further deteriorate its performance. It seems that the single chip approach will be more promising.

Novel single-chip fabricated condenser structures with corrugated diaphragms for residual stress releasing have been proposed. These diaphragm-based structures have been realized in one single chip by use of sacrificial layer etching. In the SLE process, the sacrificial layer should be etched through holes leaving a freestanding structure. To maintain the integrity of the substrate, the corrugations must not be self-closed. Therefore, continuous flat "bridges" appears on the diaphragm (as shown in Figure 1), which makes these novel corrugated diaphragms different from those achieved by bonding approach.

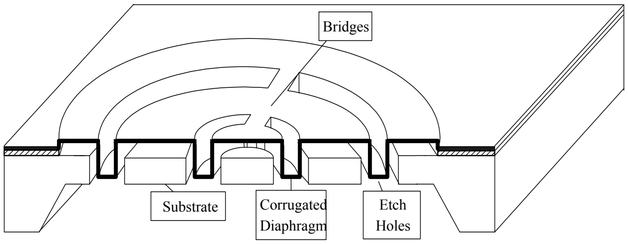

Figure 1. Schematic view of the structure.

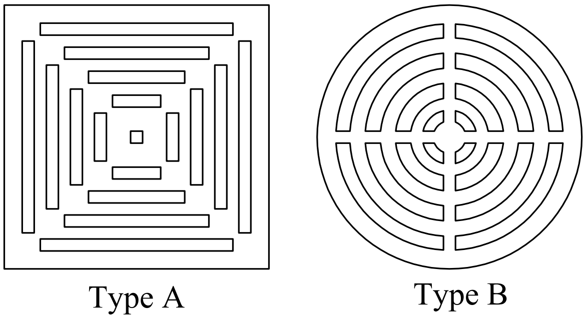

Figure 2. Layout of the corrugations.

The mechanical behaviors of several kinds of corrugated diaphragms under residual tensile stress have been investigated for the maximizing of their mechanical sensitivities; optimum values of design parameters are determined, but the electrostatic-structure interaction has never been taken into account[1,2,5]. For microstructures, mechanical forces developed by electrostatic fields can be significant enough to deform structures. The deformation can also affect the electrostatic field, hence requiring a coupled-field solution. In this paper, an electrostatic-structural coupling FEM analysis of this condenser structure was performed in ANSYS/Multiphysics 5.7.1 for the first time, using the direct method to fully reveal the nonlinear relationship of output electrical signal with respect to input mechanical change. Two typical corrugation layouts are studied, as shown in Figure 2. Numerical results have shown that the round structure was promising with its potential of high sensitivity, while the squared one was superior in the low-voltage applications. The ill effects of these variations can be reduced by delicate design and adjusting of corresponding processes.

2 MODELING

For microstructures, mechanical forces developed by electrostatic fields can be significant enough to deform structures. The deformation can also effect the electrostatic field, hence requiring a coupled-field solution. The simulation is carried out in ANSYS/Multiphysics 5.7.1 using the direct method, which fully coupled the two physics domains within a single element. ANSYS currently offers a direct matrix-coupled formulation in a 1-D transducer element: TRANS126. The element couples structural motion with electrostatic fields, which can be used in a "lumped" or "distributed" environment. In this method, coupling is handled by calculating element matrices or element load vectors that contain all necessary terms.

The capacitor generally serves as a press transducer, with the diaphragm suspended above the fixed substrate. The diaphragm is meshed with four node Shell 93 element, the initial stress is introduced by a "cooling temperature" method with both the large deformation and the stress stiffening effect considered. Zero voltage is applied to the substrate, while a non-zero voltage is applied to the diaphragm. The top and bottom electrodes are separated by air gap, which is modeled using distributed TRANS126 transducer element. To evaluate the capacitor for certain parameter sweep, APDL was used to construct a looping sequence that can be set up using the *DO and *ENDDO commands.

All the geometry parameters must fulfill the fabrication requirements, which is the major consideration of the geometrical design. The distance between the edges of corrugations cannot be too large, if it is too large, the releasing time could increase, and may damage the structure and electronics on the front side of the wafer, in this case, less than 100μm. The area of the diaphragm is $1mm^2$, other design parameters and their constrains are given as follows:

- The frequency of the corrugations: 10
- The distance between corrugations: 100μm according to the frequency
- The mean width of the bridges: 100μm, consistent with the distance of the releasing consideration
- The depth of the corrugations: 14μm.
- The mean width of the corrugations: 15μm.

The material properties of the diaphragm are: Young's modulus E=200GPa, Poisson's ratio $\nu=0.25$ and the density $\rho=2400kg/m^3$. In this analysis, the thickness of the diaphragm and the airgap are 1μm and 2.5μm respectively, the initial stress is set 70MPa.

The zero-pressure center offset, the pull in voltage, the optimal voltage, the electrical sensitivity are the major specifications for the condenser structures. Although the introduction of microelectronics patterning allows definite control of most dimensions, such parameters as the residual stress and the thickness of deposition layer are determined by various process parameters, it is difficult to control accurately. The sensitivities of three process-related parameters (air gap, diaphragm thickness and residual stress) with respect to the design specifications are also our concern. The data were of good quality without further processing.

3 NUMERICAL RESULTS

3.1 Static Deflection

Simulations performed using FEA have shown that the corrugated diaphragms having initial tensile stress exhibit a small deformation under zero pressure and bias voltage. Figure 3 and 4 show typical simulation results of the center area of the diaphragm for the zero-pressure offset. Note that the center portions do not remain flat because of the non-uniformly distributed internal stress, which does not occur for the flat diaphragm. For a planar diaphragm, the internal tensile stress is in-plane, giving rise to in-plane forces. The result of this internal tensile stress is to increase the rigidity of the planar diaphragm, which is so called "stress stiffening" effect. For a non-planar diaphragm, the redistribution of internal tensile stress is non-uniform. The resulting forces do not remain in-plane due to this non-uniform stress distribution. These out-of-plane forces generate bending moments, causing the diaphragm to deflect[3].

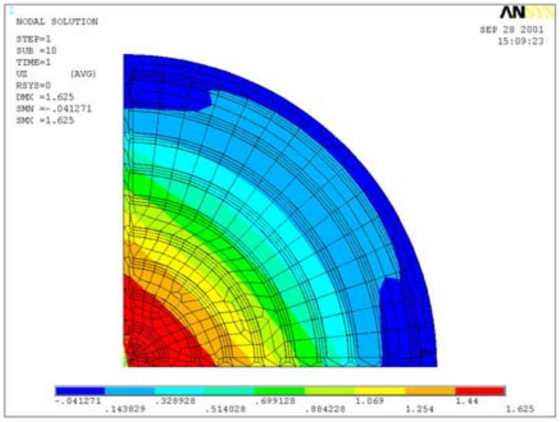

Figure 3. Deflection of round structures.

The offset/bending direction of a corrugated diaphragm depends on the corrugation layout. For the corrugated diaphragms studied here, the circular type shows an "up" offset deflection of center areas, that is, popping away from the substrate, while the squared type takes the opposite direction, as shown in Figure 3 and 4. Although zero-pressure offset is normally unwanted, the upside offset is desirable for diaphragm releasing and can greatly increase the deflection range.

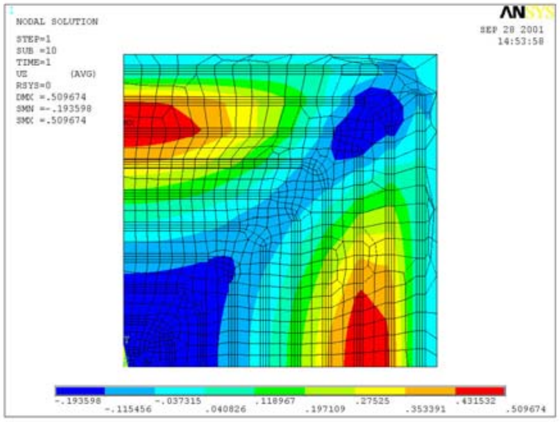

Figure 4. Deflection of squared structures.

3.2 Bias Voltage

The capacitor always works under a DC bias voltage. In fact, the electrical sensitivity increases with the bias voltage. However, the bias voltage cannot be increased without limit. At a certain pull in voltage, the diaphragm collapses to the substrate[1]. In this simulation, the fact that the electrostatic force is not distributed uniformly across the diaphragm was taken into account. A typical relation between the central deflection and the bias voltage of the circular corrugated diaphragm is shown in Figure 5-6.

This curve can be naturally divided into four regions. In the first linear region for small bias voltages, the electrostatic forces are insignificant compared with the pressure load. For intermediate voltage, the electrostatic forces have a notable influence. In the region close to collapse of the structure, the influence becomes significant enough to cause a dependence stronger than exponential and finally the contact occurs. Considering the relation between the distortion and the bias voltage, the working voltage has to be restricted to the linear region. The circular corrugated diaphragms can benefit from its upper offset for greater bias voltage, while their square counterpart can only work on a much lower voltage. In our simulations, the upper limit of the linear range is about 60% of the pull in voltage as listed in Table 1.

Our previous investigations have revealed that all the corrugated diaphragms shown a mechanical sensitivity more than one order larger than that of the flat diaphragm of equal size and thickness, while the sensitivities of circular corrugated diaphragms were two times larger than the square types. However, the electrical sensitivity is of more concern, which is given by the relation between a change in the pressure, dP, and the resulting change in the voltage across the air gap, dV, defined as $S_e=dV/dP$. The electrical sensitivity not only has close relation with the mechanical sensitivity but also influenced by the initial gap, bias voltage and the active capacitance.

For maximal electrical sensitivity, the optimal working voltage is chosen to be the upper limit of the linear range. In this condition, the electrical sensitivity of the round structure is much higher. Furthermore, the upside offset is desirable for diaphragm releasing and can greatly increase the deflection range. The round structure is promising with its potential of high electrical sensitivity, while the squared one is superior in the low-voltage applications.

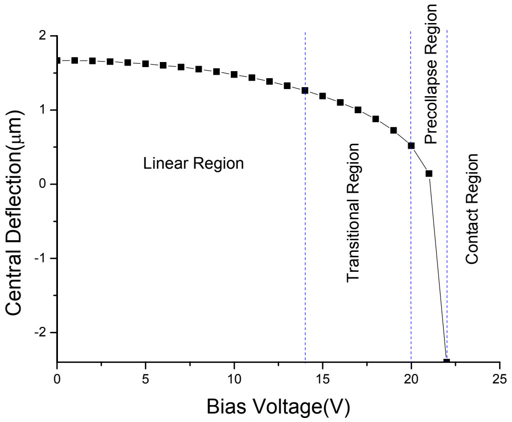

Figure 5. The relation between central deflection and the bias voltage(round).

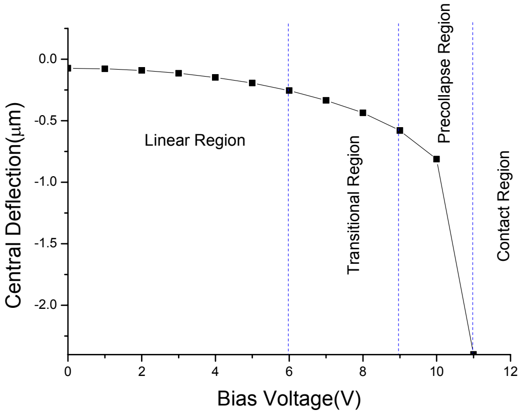

Figure 6. The relation between central deflection and the bias voltage(squared).

When the pressure increases, the nonlinear and non-uniform electrostatic attraction forces between the diaphragm and substrate have influence on the distortion, leading to an asymmetric response. In certain applications requiring a wide dynamic pressure range, a DC bias voltage smaller than the optimum may have to be chosen to keep the distortion within reasonable magnitude.

3.3 Sensitivities of Parameters

The zero-pressure center offset and electrical sensitivities are the two major specifications for the condenser structures, which greatly affect the performance of the capacitive transducer. Although the introduction of microelectronics patterning allows definite control of most dimensions, such parameters as the residual stress and the thickness of deposition layer are determined by various process parameters, it is difficult to control accurately. The run-to-run diversity and the wafer level deviation would cause variations of the transducer's performance.

The sensitivities of three process-related parameters (air gap, diaphragm thickness and residual stress) with respect to the design specifications are shown in Figure 7-8(under a bias voltage of 5V). As shown in these figures, the variations of the parameters result in a considerable deviation of the design specifications, especially for the sensitivity. For the square type, the gradient of the air gap is larger than that of thickness, whereas the influence of thickness is greater than the air gap for the round type. This results from the "down" offset and the enhancement of electrostatic force. Of all these parameters, the residual stress is most difficult to control. As a matter of fact, in both cases, the effect of residual stress is the smallest of all three, which is very favorable in the fabrication.

The air gap is defined by the thickness of the sacrificial layer. PSG and LTO are the most commonly used. The PSG has a very rapid etch rate of 10μm/min in a 10% BHF solution, while the etch rate of LTO can hardly exceed 1μm/min even in a 40% concentrated HF solution. On the other hand, PSG tends to shrink during the following anneal, whereas LTO shows little shrinkage even in a temperature higher than that of deposition. As a result, the thickness of LTO is much easier to control. In the square type, the thickness of air gap plays a greater role, it's better to use LTO as sacrificial material. However, the thickness of air gap is of minor importance in the round type, so PSG can be used to reduce the releasing time.

To reduce the total stress, the diaphragms often takes form of multilayer consisting of compressive stressed polysilicon and tensile stressed nitride. The thickness and the initial stress can be adjusted in this approach. The stress variations can be reduced by delicate design and adjusting of the composite diaphragm, which can be realized with an ANSYS APDL program with the feed back value of in-situ stress measurement structures within several iterations.

4 CONCLUSION

Novel single-chip fabricated condenser structures with corrugated diaphragms for residual stress releasing have been proposed. For the first time, an electrostatic-structural coupling FEM analysis of this condenser structure was performed to reveal the nonlinear relationship of output electrical signal with respect to input mechanical change.

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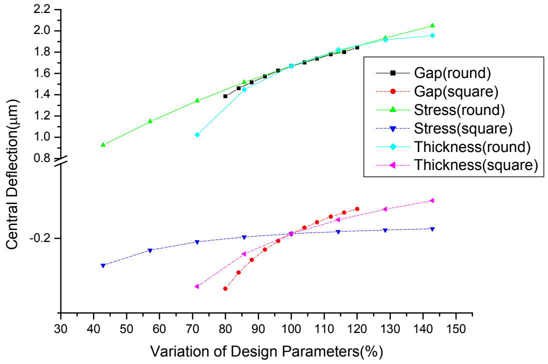

Figure 7. Gradient results of central deflection.

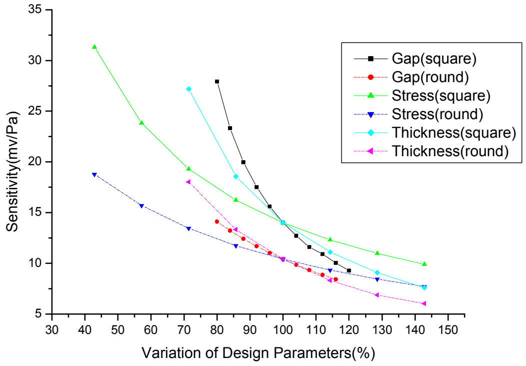

Figure 8. Gradient results of sensitivity.

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