Influence of the Electrode Size and Location on the Performance of a CMUT

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Abstract - **The collapse voltage of micromachined capacitive ultrasonic transducers (CMUT) depends on the size, thickness, type, and position of the metal electrode within the membrane. This paper reports the result of a finite element study of this effect. The program (ANSYS 5.7) is used to model a circular membrane on top of a Si substrate covered by a Si_3N_4 insulation layer. We find that the collapse voltage increases in proportion to the metal thickness for constant membrane thickness. The collapse voltage of a membrane with a thin metal electrode decreases as the metal plate moves closer to the bottom of the membrane; whereas, for electrodes with larger metal thickness, the collapse voltage has a peak intermediate value. Decreasing the outer radius of the metal plate results in an asymptotic increase of the collapse voltage. For a finite metal thickness, an initial decrease in the collapse voltage is seen as the outer radius decreases. The collapse voltages of half-metallized and full-metallized structures are almost equal for typical metal plate thickness. The asymptotic increase of the collapse voltage is seen for ring shaped metal plates as the inner radius is varied from the center to the outer radius. In summary, we find that the influence of the metal electrode on the collapse voltage is a very important parameter in determining optimum performance of a CMUT.**

Index Terms – **Capacitive micromachined ultrasonic transducer, CMUT, collapse voltage.**

I. INTRODUCTION

The performance of the capacitive micromachined ultrasonic transducer (CMUT) [1] [2] is dependent on the operating DC bias, which should be close to the collapse voltage [3]. Hence, determination of the collapse voltage using a detailed model of the fabricated transducer is necessary to accurately characterize the CMUT. Parallel plate approximation assumes constant deflection in the membrane. However, the deflection profile due to the applied voltage changes in the radial direction [4]. It has a peak at the center and deflection decreases to zero at the edge supports. Figure 1. compares the membrane shape calculated with parallel plate approximation and finite element simulation. The gap (g) and membrane thickness (t) are both 1μm for this structure. As seen from the deformed membrane shape, the parallel plate approximation is inadequate for the accurate calculation of the membrane deflection profile. Hence it can be used for the collapse voltage calculation to a limited extent. Moreover it neglects the metal electrode. Finite element simulation is required to determine the influence of the electrode size and location on the performance of a CMUT.

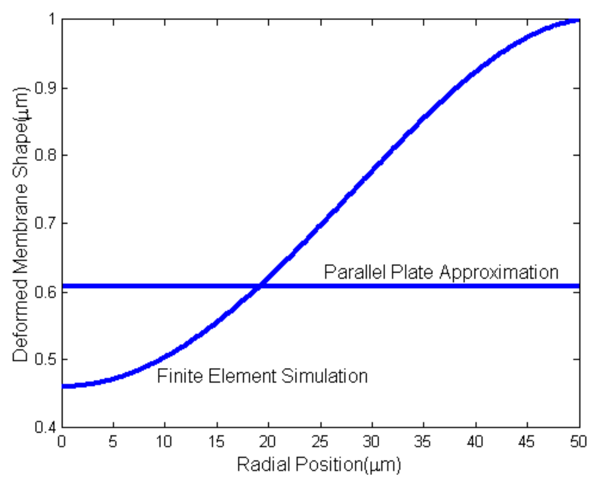

Figure 1. Deformed Membrane Shape

This paper presents the effect of the parameters of the metal electrode on the collapse voltage using finite element simulation of the structure.

II. FEM MODELING AND ANALYSIS

The model of the CMUT includes a silicon substrate, silicon nitride insulation layer, silicon nitride membrane and (Al or Au) metal electrode. Electrode size, location and metal type are variables and their effects on the collapse voltage can be determined by using the finite element analysis. Circular CMUT is represented by axisymmetric 2D model. Figure 2 shows the model and the parameters. Size of the metal plate is defined by inner radius r_{in} and outer radius r_{out}. Thickness and position of the metal are denoted by t_e and d_e, respectively. d_e=0 and d_e=1 places the metal plate at the bottom and the top of the membrane, respectively. Membrane thickness, t, and gap, g, are equal to 1μm. Radius, R, of the

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membrane is 50 µm. Insulation layer thickness, t_i, is set to 0 µm in the analysis. However, it could also be included if desired. The substrate thickness, S, is 1 µm.

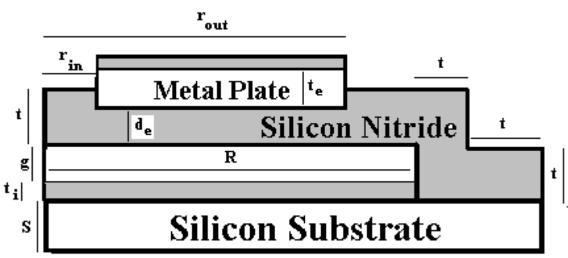

Figure 2. CMUT model and parameters

PLANE82 and PLANE121 element types are used for the structural and electrostatic analysis of the model. Physics environment in ANSYS 5.7 is used for the solution of the sequentially-coupled nature of the problem. Binary search algorithm is used with a relative voltage accuracy of 1% for the collapse voltage convergence. Silicon substrate is supported from the bottom. The center line acts as a symmetry axis with no displacement in the radial direction. The ground electrode is the line between the substrate and the insulation thickness. Voltage is applied to the borders of the metal plate. The material properties that are used in the structural and electrostatic solutions are shown in Table 1. Vacuum is used in only electrostatic solution whereas metal types are only used in the structural solution.

	Si_3N_4	Vacuum	Si	Al	Au
Young's Modulus	3.2E11		1.69E11	6.76E10	8.06E10
Density	3270		2332	2700	19700
Poisson's Ratio	0.263			0.3555	0.4205
Permittivity	5.7	1	11.8		

Table 1. Material properties

III. RESULTS

1) *Effect of Electrode Outer Radius (r_{out})*

First, zero thickness electrode on top of the membrane (d_e=1) is assumed. The electrode radius changes from the center to the radius of the membrane (r_{in}=0, r_{out}: variable).

The collapse voltage increases slightly as the outer radius of the metal plate decreases to half the membrane radius. Further decrease in r_{out} results in rapid asymptotic increase of the collapse voltage. The collapse voltage of half-metallized structure is only 15% greater than that of full-metallized structure.

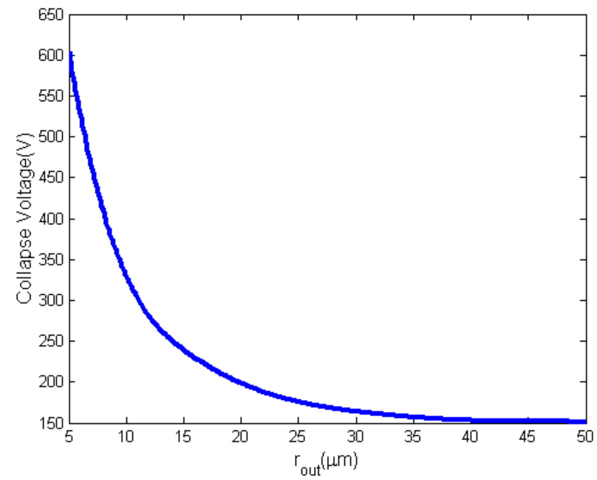

Figure 3. Effect of Electrode Outer Radius (r_{out})

2) *Effect of Electrode Inner Radius (r_{in})*

Collapse voltage change as a function of the electrode inner radius (r_{in}) is shown in Fig. 4. The outer radius is kept constant at the membrane radius. Smooth gradual increase is followed by an asymptotic increase as r_{in} becomes close to membrane radius.

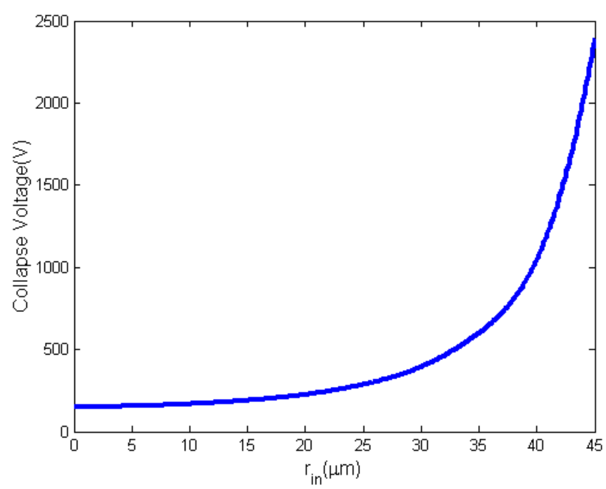

Figure 4. Effect of Electrode Inner Radius (r_{in})

3) *Effect of Electrode Position (d_e)*

Electrode position is changed for a full-metallized structure when the electrode thickness is zero (t_e=0). Collapse voltage increases almost linearly as the metal moves away from the substrate as shown in Fig. 5.

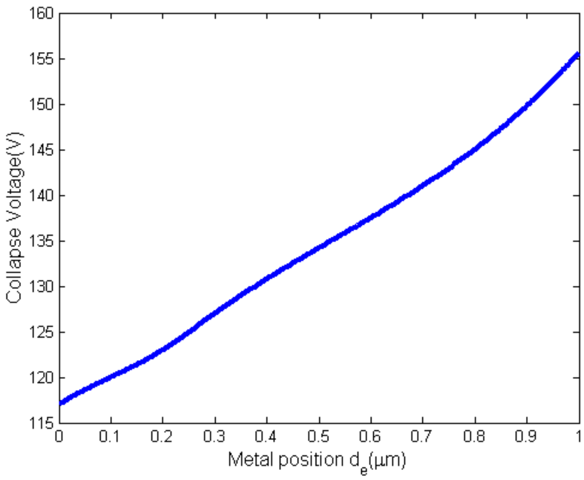

Figure 5. Effect of Metal Position (d_e)

4) Effect of Electrode Thickness (t_e) and Metal Type (Al/Au)

Metal type has no effect in collapse voltage if metal thickness t_e is small with respect to the membrane thickness, and the equivalent Young's modulus of the overall structure is close to that of the silicon nitride. The metal type becomes important as metal thickness is increased. The effect of electrode thickness (t_e) and metal type (Al/Au) is shown in Fig. 6 for full-metallized structure (r_{in}=0, r_{out}=50 µm) with electrode on top (d_e=1). The increase of the collapse voltage is slightly greater for Au since it has larger Young's modulus than aluminum.

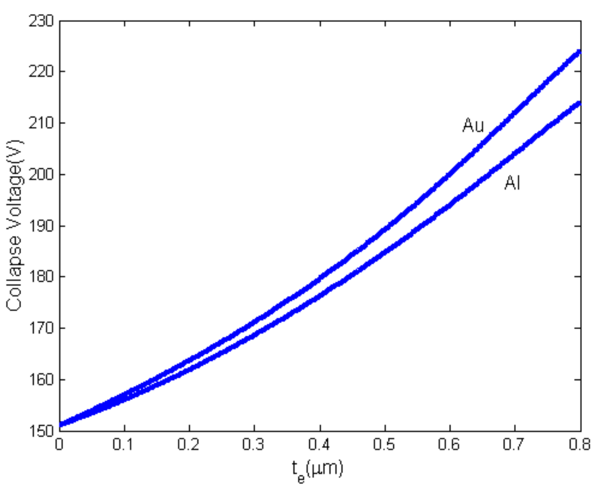

Figure 6. Effect of Electrode Thickness (t_e) and Metal Type (Al/Au)

5) Effect of Electrode Outer Radius (r_{out}) for nonzero metal thickness (t_e)

The effect of electrode outer radius (r_{out}) on collapse voltage for negligible metal thickness (t_e) is described in Fig. 3, and the effect metal thickness (t_e) for a full-metallized structure is shown in Fig. 6. Combination of r_{out} and t_e changes the shape of the collapse voltage curve as shown in Fig 7. Collapse voltages for r_{out}=35µm, r_{out}=30µm and r_{out}=25µm are almost equal to those of the full metallized structure for t_e=0.2µm, t_e=0.5µm and t_e=0.8µm, respectively. As the metal gets thicker, the membrane becomes stiffer. If partial metallization is done, the membrane tends to be less stiff since the non-metallized portion of the membrane still has the original structure. This effect becomes clearer as the curvature of the collapse voltage becomes more convex for considerable t_e. Fig. 8 shows the effect of metal type, which is not significant for the typical metal thickness in fabrication.

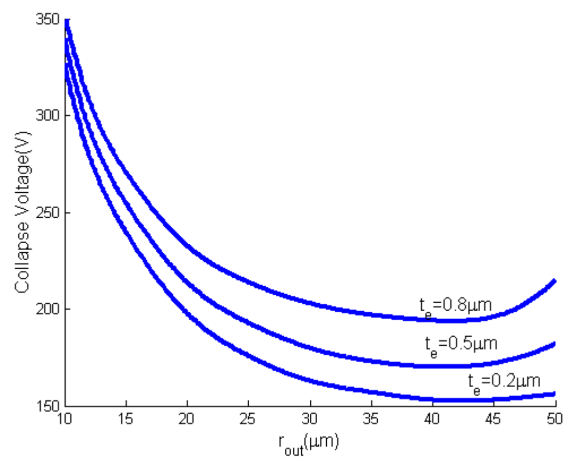

Figure 7. Effect of Electrode Outer Radius (r_{out}) for nonzero metal thickness(t_e)

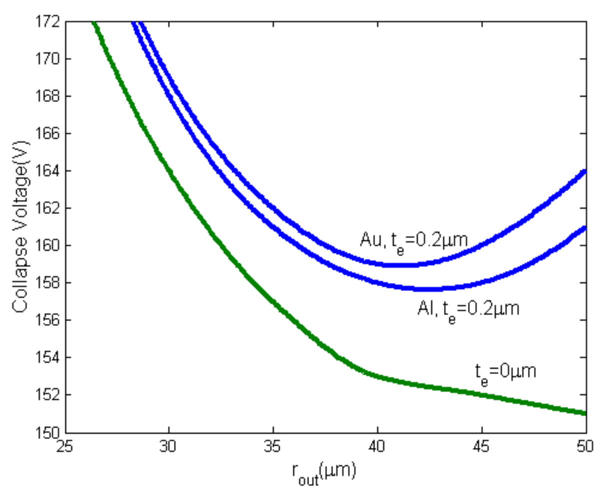

Figure 8. Effect of Electrode Outer Radius (r_{out}) for Al/Au metal type

6) Effect of Electrode Inner Radius (r_{in}) for nonzero metal thickness (t_e)

Combined effect of electrode inner radius (r_{in}) and metal thickness (t_e) is described in Fig. 9. The curvature of the collapse voltage remains unchanged, suggesting an additive shift of the collapse voltage. This is mainly due to the fact that the structural stability is dependent on the metallized parts closer to the edges.

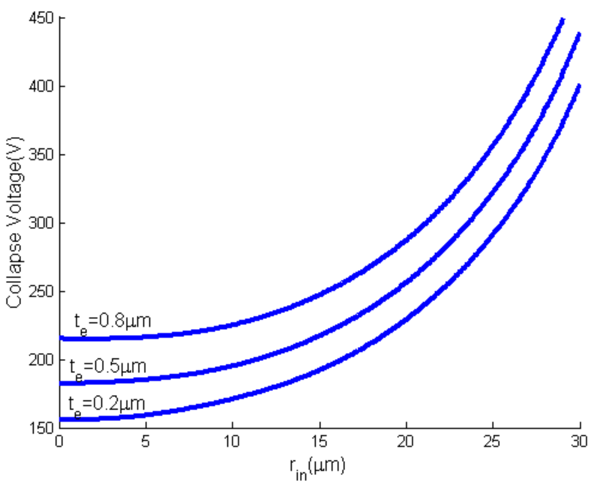

Figure 9. Effect of Electrode Inner Radius (r_{in}) for nonzero metal thickness(t_e)

7) Effect of Electrode Position (d_e) for nonzero metal thickness (t_e)

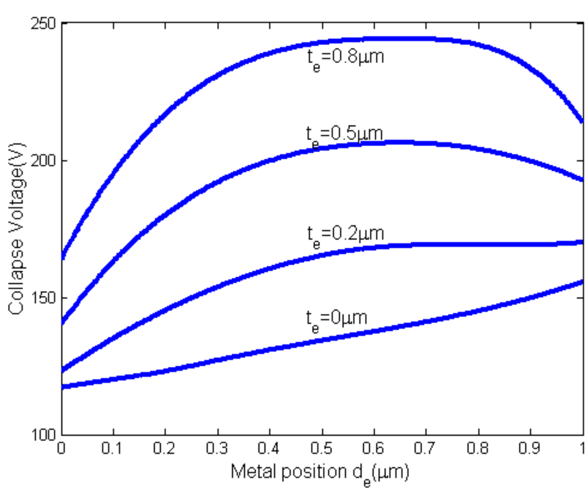

Figure 10. Effect of Electrode Position (d_e) for nonzero metal thickness(t_e)

Metal position d_e increases collapse voltage almost linearly for t_e=0. However, this relation changes significantly when t_e becomes considerable. The stiffness of the membrane structure becomes maximum for d_e~0.6 for t_e~0.6. Further increase in d_e results in smaller collapse voltage as shown in figure 10. So maximum collapse voltage occurs when the metal electrode is positioned in the membrane for nonzero t_e.

IV. CONCLUSION

The collapse voltage of micromachined capacitive ultrasonic transducers (CMUT) depends on the size, thickness, type, and position of the metal electrode within the membrane. This paper presents the effect of each electrode parameter on the collapse voltage. Both the electrostatic and structural properties of the membrane are affected by these parameters and finite element simulations are essential to take these effects into account. Further study will focus on the optimization of the electrode parameters for maximization of transducer coupling efficiency.

ACKNOWLEDGMENT

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