A Low Pull-in SU-8 based Capacitive Micromachined Ultrasonic Transducer for Medical Imaging Applications

Jose Joseph[1], Shiv Govind Singh[2] and Siva Rama Krishna Vanjari[3]

Abstract— **In this paper we present a thorough analysis of a low pull-in voltage Capacitive Micromachined Ultrasonic Transducer (CMUT) using SU-8 as the membrane material. It is designed to operate at 1 MHz frequency that has a wide range of applications including the imaging of deeper organs. We also propose a simple state-of-the-art fabrication methodology for the same. As compared to the standard Silicon Nitride CMUTs, the proposed structure gives the same electromechanical coupling coefficient with lower membrane dimensions and low pull-in voltage which in turn results in reduced area and power consumption. Moreover the proposed fabrication methodology is a low temperature process which makes it CMOS compatible.**

I. INTRODUCTION

Capacitive Micromachined Ultrasonic Transducers (CMUTs) are potential replacements for conventional piezoelectric transducers owing to their high sensitivity, transduction efficiency, and bandwidth [1]. In addition, ease of fabrication of complex device geometries such as two-dimensional (2-D) arrays, has made CMUTs an even more attractive alternative to piezoelectric transducers [2]. One of the critical requirements of CMUTs is to achieve a vacuum sealing which allows these devices to be used in immersion applications as well. Vacuum sealed CMUTs have been fabricated using sacrificial release method or by wafer bonding technique [3]. Though sacrificial release involves simple micromachining processing steps, it has the inherent disadvantage of non-uniformity in the membrane and air gap. Furthermore, single crystal membranes can't be realized with sacrificial release technique. Wafer bonding technique gives good membrane and air gap uniformity in less number of fabrication steps but the processing involves the use of Silicon on Insulator (SOI) wafer which increases the cost of device dramatically. Apart from this, the inherent high temperature bonding process hinders the practical adaptability of this technique for CMOS integration [3]. Typically the pull-in voltage of CMUTs are high, of the order of 100V. The aim of our work is to come up with a low pull-in CMUT which can be fabricated using low temperature processes. The pull-in voltage can be reduced if the membrane is made up of a flexible material instead of a rigid one. SU-8(MicroChem Corp.)[4], a photosensitive polymer is best suited for this application as the structure can be realized with out any significant etching steps [5], [6]. As shown in Table.I, SU-8 is highly flexible and is not brittle. Before fabricating an SU-8 based CMUT it is prudent to accurately model and design the device using well developed, accurate multi-physics models. Existing modeling strategies for CMUTs include the equivalent circuit modeling that predicts the basic response of CMUTs [7], Finite Element Modeling that gives more reliable CMUT operation through numerical computations [2] and analytical models which are either limited to mechanical parts of the device[8], [9]or fully coupled models with only limited cases of solutions [10], [11]

TABLE I

MATERIAL PROPERTIES OF SU-8 AND Si_3N_4

Property	SU-8	Si_3N_4
Young's modulus (E)	5 GPa	310 GPa
Poisson's ratio (ν)	0.22	0.27
Density (ρ)	1200 kg/m^3	3290 kg/m^3
Dielectric Constant (ϵ_r)	4	7.5

In this paper, we adopt well-established analytical models for the static analysis of SU-8 based CMUTs for 1 MHz operation. Critical device parameters such as pull-in voltage, membrane deflection, coefficient of coupling and device capacitance are investigated and are compared with those of CMUTs employing Silicon Nitride membrane. Through our analysis, we found that SU-8 based CMUT results in the reduction of pull-in voltage approximately by 30% and reduction of device dimensions by more than 50% without any significant change in the coupling coefficient, which is regarded as the performance metric of an ultrasound transducer. A low complex, low temperature fabrication process for the realization of SU-8 based CMUTs is also proposed. The target application is the medical imaging of deep organs which requires the frequency of ultrasonic waves in the range of 1 MHz [12].

The paper is organized a follows. Mathematical modeling aspects of the design of SU-8 based CMUT is presented in the section II followed by the comparison of its performance with the standard Si_3N_4 based CMUT in the section III. The final section describes the fabrication procedure of the same and the relevant conclusions are presented in the conclusion section.

II. MATHEMATICAL MODELING

The design is carried out for low frequency (exactly 1MHz) operation which helps in imaging the large or deep organs of a human body [12]. Low frequency ultrasound has

---

[1] Jose Joseph is a Ph.D student in Department of Electrical Engineering, Indian Institute of Technology Hyderabad, India `ee13p1010@iith.ac.in`

[2] Shiv Govind Singh and [3] Siva Rama Krishna Vanjari are associate and assistant professors respectively in Department of Electrical Engineering, Indian Institute of Technology Hyderabad, India [2]`sgsingh@iith.ac.in`, [3]`svanjari@iith.ac.in`

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

lower absorption and greater penetration depth in tissues, which can even pass through bones without much attenuation [13]. The important geometrical and performance parameters are calculated for SU-8 based membrane and are compared with the standard Si_3N_4 based CMUT. In all cases, thickness of the membrane (t) and air gap (d_0)are taken as 1μm each.

A. Radius of the Membrane

From mass-spring theory, the resonance frequency of a membrane can be determined as [14]

$$\omega_0 = \sqrt{\frac{k_1}{m}} = \frac{10.22}{a^2\sqrt{\rho t/D}} \quad (1)$$

Thus the radius of the membrane is:

$$a = \sqrt{\left(\frac{1.626}{f_0}\sqrt{\frac{D}{\rho t}}\right)} \quad (2)$$

Where $f_0 = \omega_0/2\pi$ is the center frequency and D is the flexural rigidity of the membrane.

$$D = \frac{Et^3}{12(1-\nu^2)} \quad (3)$$

For SU-8 CMUT operating at the desired frequency, the radius of curvature can be calculated using eqn.2, eqn.3 and the material properties in table.I

B. Pull-in(Collapse) Voltage

One of the critical parameters of CMUT design is the pull-in voltage. If the applied voltage is less than the pull-in voltage, the membrane deflects to a stable position [14]. On applying a voltage which is greater than pull-in voltage, the force due to the applied electric field overcomes the mechanical restoring force and the membrane collapses to the bottom electrode. Through Elasto-Electrostatic analysis,the pull-in voltage can be calculated using the expression[11]

$$V_{PI} = \frac{5.46}{a^2}\sqrt{\frac{d_0^3 D}{\epsilon_0}} \quad (4)$$

where d_0 is the air gap between the membrane and the substrate and ϵ_0 is the permittivity of air. In deriving the above expression, the membrane is assumed to be conductive. If the membrane is not conductive which is the case in SU-8 based CMUTs, the gap d_0 should be replaced by effective air gap d_{eff} which takes into account the thickness of the insulating layer. The effective air gap d_{eff} is given by

$$d_{eff} = d_0 + \frac{d_t}{\epsilon_r}; \ \ d_t = t + d_i \quad (5)$$

Where d_i is the thickness of the insulator layer above the bottom electrode. It can be neglected if there is no insulation layer above bottom electrode.

C. Membrane Deflection

The classical plate theory with Krichhoff-Love assumption can be used to find the deflection when the ratio of the diameter to thickness of the membrane is very large (> 20). The analytical expression of the deflection as a function of radius is given by [11]

$$w(r) = \frac{Bd_0(a^2-r^2)^2}{64d_0 - 1.524Ba^4} \quad (6)$$

where

$$B = \frac{\epsilon_0 V^2}{2Dd_0^2} \quad (7)$$

Where V is the applied DC voltage. These equations can be adapted to SU-8 membrane by replacing d_0 with d_{eff} and using the material properties of SU-8 as tabulated in table.I

D. Coefficient of Coupling

Coupling coefficient (k_T^2) is the ratio of delivered mechanical energy to the stored total energy. It is one of the most important figures of merit of ultrasound transducers and is given by [15]

$$k_T^2 = 1 - \frac{C^S}{C^T} \quad (8)$$

where C^S and C^T are the fixed and free capacitance of the transducer respectively and are given by

$$C^S = \frac{\epsilon_0 A}{(d_{eff}-x)} + C_p; \ C^T = \frac{\epsilon_0 A}{d_{eff}-3x} + C_p \quad (9)$$

In the above equation C_p represents a parallel parasitic capacitance which can be a fraction of device capacitance without applied DC bias.

E. Capacitance

Another important aspect of the design of CMUT is the device capacitance. On applying a DC bias, the membrane deflects and this causes a change in capacitance. The capacitance of CMUT is obtained by by integrating the capacitance of an elemental ring along the radius [11]. It is a function of applied bias and the expression for the same is given by

$$C = \frac{26.833\pi\epsilon_0\sqrt{B}a^4}{Sd_0} tan^{-1}\left(\frac{1}{60a^2}\sqrt{\frac{5S}{B}}\right) \quad (10)$$

where

$$S = 286Ba^4 - 12012d_0 + \sqrt{N} \quad (11)$$

and

$$N = 144288144d_0^2 - 6870864Bd_0a^4 - 188474B^2a^8 \quad (12)$$

For dielectric membranes, d_0 should be replaced by d_{eff}.

TABLE II
CALCULATED RADIUS AND COLLAPSE VOLTAGE FOR CMUTS WITH SU-8 AND Si_3N_4 MEMBRANES

Material	Radius (μm)	Collapse Voltage (V)
Si_3N_4	68.97	78.09
SU-8	31.34	54.63

III. RESULTS AND DISCUSSION

The radius of membrane is calculated from the equation of natural frequency of operation for both SU-8 and Si_3N_4 based CMUTs and is tabulated in Table II . It can be observed that for the same frequency of operation, radius of CMUT with SU-8 is less than half the radius of CMUT with Si_3N_4. This scaling in radius owes a lot to the material properties of SU-8. Decrease in radius of CMUT membrane enables one to incorporate more cells in a given area or decrease the total area for a fixed number of cells at a particular frequency of operation.The collapse voltage of the two different membranes is also summarized in Table II. The elastic properties of SU-8 are responsible for the decrease in pull-in voltage. Though collapse voltage is inversely proportional to the square of membrane radius, the Youngs modulus of SU-8, which is two orders less than that of Si_3N_4 helps in bringing down the collapse voltage. These calculations prove that CMUT with SU-8 membrane is the best option for low power operation. In addition to this, the variation of collapse voltage with respect to the membrane radius is plotted in fig.1. It can clearly be seen that at lower membrane radius, SU-8 CMUTs offer much lower pull-in voltages as compared to Si_3N_4 CMUTs. Also as the membrane size increases, collapse occurs at very low a voltage which is an added advantage for choosing SU-8 as the membrane material for low frequency CMUTs. The deflection of the plate as a function of applied DC voltage is calculated and plotted till the pull-in voltage in fig.2. SU-8 membrane deflects at early values of applied voltage than Si_3N_4 membrane and this can easily be attributed to the flexibility of SU-8 membrane. Coefficient of coupling is calculated for SU-8 based and Si_3N_4 based CMUTs. It can be noticed that the coefficient of coupling of both the CMUTs are almost equal and the small decrease of the same for CMUT with SU-8 membrane is the lower dielectric constant of SU-8 as compared to Si_3N_4. The parallel parasitic capacitance has been discarded for the sake of simplicity. If it were included, the saturation of coupling coefficient will happen towards the pull-in voltage. At pull-in voltage, the coefficient of coupling reaches its maximum value. Variation of coefficient of coupling with respect to the membrane deflection is portrayed in fig.3 The capacitance of CMUT with SU-8 membrane is found to be lower than that of Silicon Nitride CMUTs. This is because of the lesser radius of SU-8 membrane for a particular frequency and the higher effective gap (d_{eff}). Fig.4 depicts the influence of applied voltage on the device capacitance.

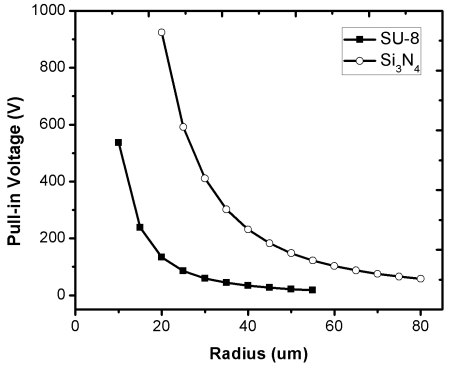

Fig. 1. Change in collapse voltage with respect to membrane radius

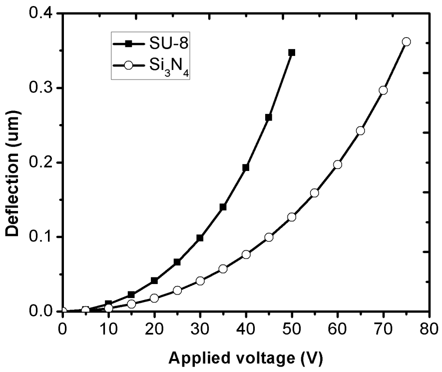

Fig. 2. Influence of applied DC voltage on the membrane deflection

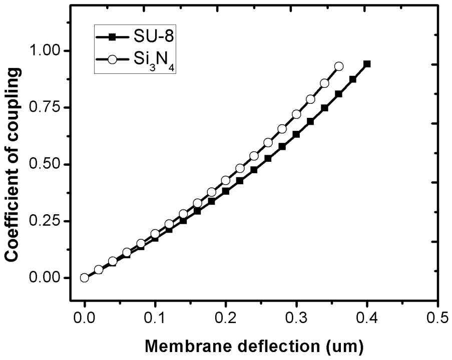

Fig. 3. Variation of coefficient of coupling with respect to membrane deflection

IV. FABRICATION PROCEDURE

In this work, we suggest a novel method to fabricate CMUTs with SU-8 membrane using a low temperature wafer bonding method and is depicted in fig.5. The fabrication starts with SU-8 spinning on a properly cleaned silicon wafer, for a thickness of 1μm (step: a). After pre-bake, the wafer is exposed to UV light through a mask with circular features (step: b). It is then subjected to post exposure bake

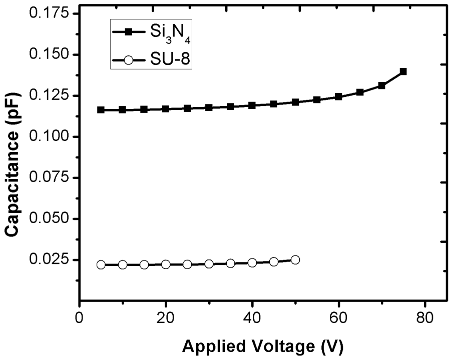

Fig. 4. Change in device capacitance due to the applied voltage

followed by developing in SU-8 developer to get the cavities of desired dimension. The wafer is then hard baked so that the cavities would remain without any deformation (step: c) [4]. A second wafer is taken and is coated with a thin layer of Omnicoat. This helps in peeling off the second wafer easily after the bonding process. [16] (step: e). On the top of Omnicoat film, 1μm of SU-8 is spin coated and is subjected to pre-exposure bake, UV exposure without mask and post-exposure bake (steps: f,g). It is difficult to bond two SU-8 coated surfaces since SU-8 by nature is hydrophobic. To make it hydrophilic, both the wafers are subjected to oxygen plasma of 100W for 30sec (steps: d,h)[17]. These wafers are then bonded in bonding equipment with low temperature ($< 100°$C) and pressure [18] (step: i). After bonding, the structure is immersed in AZ 300 MIF developer and the second wafer is peeled off (step: j)[18]. The electrodes are then formed and characterization can be done (step: k).

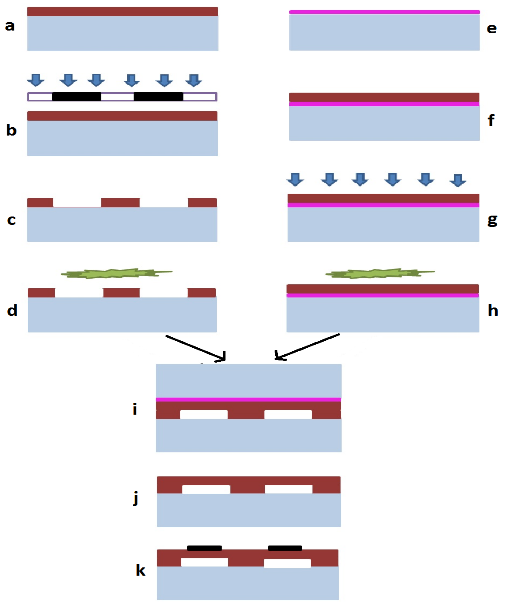

Fig. 5. Fabrication Procedure

V. CONCLUSIONS

A low frequency CMUT with SU-8 membrane for medical imaging application is presented. Analytical modeling of the same is done and the important parameters are figured out and are compared with that of a Silicon Nitride based CMUT. For the same frequency of operation the proposed device gives a pull-in voltage which is about 70% of the pull-in voltage of CMUT with Si$_3$N$_4$ membrane. The radius of CMUT cell with SU-8 is nearly half of that with Silicon Nitride membrane. These advantages will surely push the industry towards adopting the proposed technology as the back bone for next generation CMUTs. A novel fabrication procedure employing wafer bonding is also outlined for the sake of completeness.

REFERENCES

[1] S. Ergun, G. G. Yaralioglu, and B. T. Khuri-Yakub, Capacitive Micromachined Ultrasonic Transducers: Theory and Technology, Journal of Aerospace Engineering, vol. 16, pp. 76-84, 2003.
[2] G. G. yaralioglu, a. s. Ergun, and B. T. Khuri-yakub, Finite-element analysis of capacitive micromachined ultrasonic transducers, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 52, no. 12, pp. 21852198, 2005.
[3] A. S. Ergun, Y. Huang, X. Zhuang, O. Oralkan, G. G. Yaralioglu, and B. T. Khuri-Yakub, Capacitive Micromachined Ultrasonic Transducers: Fabrication Technology, IEEE Trans. Ultrason., Ferroelectr., Freq. Control, vol. 52, no. 12, 2005, pp. 2242-2257.
[4] SU-8 datasheet, MicroChem Corp., USA
[5] Kwang W. Oh, Chong H. Ah, and Kenneth P. Roenker, Flip-Chip Packaging Using Micromachined Conductive Polymer Bumps and Alignment Pedestals for MOEMS, IEEE Journal Of Selected Topics in Quantum Electronics, Vol. 5, No. 1, January/February 1999
[6] A. Patrick, C. Veronique, C. Henri, G. Anne-Marie, and N. Nam-Trung, SU-8 as a structural material for labs-on-chips and microelectromechanical systems, NCBI Electrophoresis, 28(24): 4539, December 2007
[7] I. ladabaum, X. Jin, H. T. soh, a. atalar, and B. T. Khuri-yakub, Surface Micromachined Capacitive Ultrasonic Transducers, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 45, no. 3, pp. 678690, 1998.
[8] S. Ballandras, M. Wilm, and J. Gelly, Theoretical analysis of micromachined ultrasonic transducer using a simple 1-D model, IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, vol. 53, no.1, pp. 209223, Jan. 2006.
[9] H. Oguz, S. Olcum, M. Senlik, V. Tas, A. Atalar, and H. Koymen, Nonlinear modeling of an immersed transmitting capacitive micromachined ultrasonic transducer for harmonic balance analysis, IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, vol. 57, no.2, pp. 438447, Feb. 2010.
[10] G. W. Vogl, and A. H. Nayfeh, A reduced-order model for electrically actuated clamped circular plates, Micromechan. Microeng., vol. 15, pp. 684690, 2005.
[11] B. Ahmad, and R. Pratap, Elasto-Electrostatic analysis of circular microplates used in capacitive micromachined ultrasonic transducers, IEEE sensors journal, vol.10, pp. 1767-1773, November 2010
[12] Samer N. Narouze, Atlas of Ultrasound-Guided Procedures in Interventional Pain Management , Springer, 2010, ch.2
[13] H. Peter, M. Kevin, and T. Abigail, Diagnostic Ultrasound : Physics and Equipment, Cambridge Medicine, 2010
[14] I. O. Wygant, M. Kupnik, and B. T. Khuri-Yakub, Analytically calculating membrane displacement and the equivalent circuit model of a circular CMUT cell, IEEE Ultrasonics Symposium, 2008. IUS 2008. IEEE, Nov. 2008, pp. 2111-2114.
[15] J. Frase,r and P. Reynolds, Finite-element method for determination of electromechanical coupling coefficient for piezoelectric and capacitive micromachined ultrasonic transducers, Joint 140th meeting of ASA/NOISE-CON, 2000.
[16] Omnicoat datasheet, MicroChem Corp., USA
[17] C. Yu-Tzu, and L. Denz, A bonding technique using hydrophilic SU-8, J. Micromech. Microeng. 17(2007) 19781984
[18] AZ 310 MIF developer datasheet, Clariant Corporation, Switzerland