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Design of Ultrasonic Transducer MEMS Model for Distance Measurement using Multiphysics

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Abstract

The technique in artificial ultrasonic transducer using electronics is very bulky and power hungry. We switched over to ultrasonic Micro-Electronics Mechanical Systems (MEMS) which have shown significant importance for miniaturized mechanical system, based on silicon technology. MEMS based acoustic sensing transducers commonly employ the piezo-electric technology to interpret the received ultrasonic reflection. Prior to fabrication of MEMS device design simulations are extensively needed to avoid expensive time and cost. The aim of the present work is to describe the design of different lead free piezoelectric materials based ultrasonic transducer and their performance. COMSOL Multiphysics 4.2a is versatile tool and is used to design and solve the transducer device with 3D partial differential equations. In this paper, 2D axis-symmetry model geometry of piezoelectric transducer was designed with lead free piezoelectric material like Barium Sodium Niobate (Ba2NaNb5O15) which is capable of being used as thin film. The potential of 20 Volts with 140 KHz frequency was applied to the device that was inside geometry of cylindrical air medium. The surface and radial displacement of the transducer structure of the material with pressure and stress were studied in air medium.

Keywords

COMSOL Multiphysics 4.2a, Lead free materials, piezoelectric thin film. MEMS.

1. Introduction

Without seeing some creatures can navigate by using their sense organ, for example bats can navigate for a long time with the help of transducer which is embedded within them. These transducers help them to transmit and receive ultrasonic sound wave. Based upon this principle of operation, the artificial transducers can be effectively used to achieve some of our needs like navigation, distance calculation and internal flaw detection etc [1].

Our target is to imitate such technique for our convenience. The only way to do so is by electronic means, but initially it was very bulky and power hungry. Hence we switched over to ultrasonic Micro-Electro Mechanical Systems (MEMS). Being compatible with CMOS era, it aided the MEMS technology to opt for a big leap. MEMS based acoustic sensing transducers commonly employ the piezo-electric technology to interpret the ultrasonic reflection received [2-3]. For piezoelectric applications, such as making ultrasonic transducers and piezoelectric actuators, it is desirable to have high electromechanical coupling coefficients, relatively large dielectric constant and large piezoelectric coefficient [4]. Large electromechanical coupling coefficient makes the transducer to have a broader bandwidth. Where, larger dielectric constant makes the electric impedance matching between the transducer and its driving power supply which makes it easier for small size transducers, such as MEMS [5]. For this reason, Lead Zirconate Titanate (Pb[ZrxTi1-x]O3), or PZT ceramics has become the dominant material in the ultrasonic transducer industry in the past 40 years. Unfortunately, lead compounds have been recognized as environmentally non-friendly material as contains more than 60 percent lead by weight. Hence, researchers have been searching for a lead-free piezoelectric material which may be used as an alternative to the PZT ceramics. Unfortunately, among the existing lead-free ferroelectric crystals, some have weak piezoelectricity and some have very expensive to fabricate. Suitable lead-free piezoelectric materials are still at developing stage as no single composition has been found comparable to PZT. Main issue that determines the piezoelectric acoustic transducer performance at micrometer scale is the piezoelectric material itself [6]. The piezoelectric material based MEMS have been used in conventional underwater acoustic transducer, but only a few can suitably be deposited as a thin film for micrometer scale design. Earlier, Barium Sodium Niobate (BNN)

(Ba2NaNb5O15) [7], Lithium Niobate (LiNbO3) and Barium Titanate (BaTiO3) (BT) [8] etc. lead free piezoelectric material based ultrasonic MEMS for different applications have been reported.

Barium Sodium Niobate (Ba2NaNb5O15) structure at temperatures below its ferroelectric Curie temperature consists of planar sheets of oxygen atoms in a distorted hexagonal close-packed configuration [8]. As the temperature decreases from the Curie temperature, the elastic forces of the crystal become dominant. For this property it behaves as piezo electric material. Thus, BNN belongs to the broad class of displacement ferroelectrics. BNN has immense importance in many technological applications. However its application is limited due to high cost and difficulty in fabrication. The preparation of powder sample is important to fabricate BNN film devices [9-11].

2. Model geometry of cross section of Ultrasonic Transducer and Boundary conditions

COMSOL Multiphysics 4.2a tool package is used to solve acoustic piezoelectric device using the 3D partial differential equations. Here, using 2D axis-symmetry model of the cross section geometry of piezo acoustic device was designed and simulated for Barium Sodium Niobate (BNN), its properties compared with PZT-5H. Figure-1 shows the 3D model of the ultrasonic transducer. The possible layer structure of ultrasonic transducer MEMS is shown in Figure 2.

In the air domain, the wave equation describes the pressure distribution [12].

$$\frac{1}{\rho_0 C_S^2}\frac{d^2p}{dt^2} + \nabla.\left(-\frac{1}{\rho_0}(\nabla\rho - q)\right) = Q \qquad \text{..... (1)}$$

For this model, assume that the pressure varies harmonically in time as

$p(x,t) = p(x)e^{iwt}$

Hence Equation 1 simplifies to

$$\nabla.\left[-\frac{1}{\rho_0}(\nabla p - q)\right] - \frac{w^2p}{\rho_0 C_S^2} = Q \qquad \text{................ (2)}$$

Because there are no sources present, Equation 2 simplifies further to

$$\nabla.\left[-\frac{1}{\rho_0}(\nabla p)\right] - \frac{w^2p}{\rho_0 C_S^2} = 0 \qquad \text{........... (3)}$$

2.1 Design Method

2D-Axis symmetry model has been chosen from COMSOL

1. 2D-Axis symmetry model has been chosen from COMSOL
2. Choose the Piezoelectric material. (e.g. here two materials have been chosen one after other).
3. The physical parameters have been added to the model geometry to characterize the material.
4. The acoustic pressure distribution is used as Equation (1), (2), (3).
5. The PZT-5H and Ba2NaNb5O15 are established as the sensor and data can be transmit or receive through air medium.

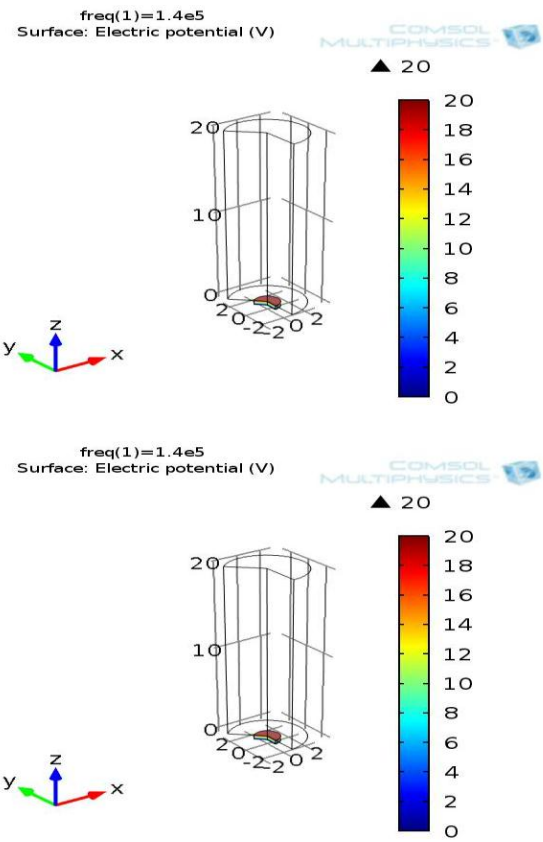

Figure 1: 2D axis-symmetric model geometry of the BNN based ultrasonic transducer

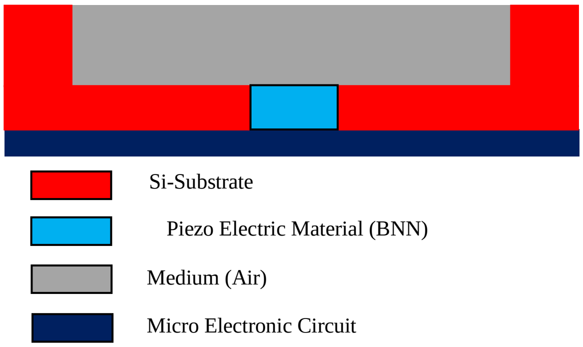

Figure 2: Schematic diagrams of layer structure of the MEMS based Ultrasonic Transducer

The piezoelectric domain is made of the crystal Lead Zirconate Titanate [PZT], which is a common material in piezoelectric transducers. The structural analysis is also time harmonic although, for historical reasons, in structural-mechanics terminology it is a frequency response analysis.

The optimized frequency and voltage was obtained from frequency vs pressure graph. This is shown in Figure 3. The optimized potential of 20 Volts with 140 KHz frequency was applied to the piezoelectric device which was inside the air medium.

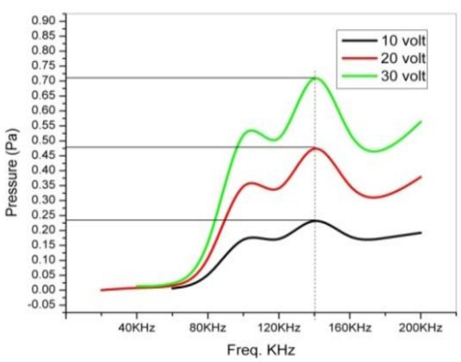

Figure 3: Frequency vs. pressure graph to obtain optimized frequency and voltage.

An AC electric potential of 20 V is applied to the upper part of the transducer, while the bottom part is grounded. At the interface between the air and solid domain, the boundary condition for the acoustics application mode is that the pressure is equal to the normal acceleration of the solid domain.

$$n.\left[\frac{1}{\rho_0}(\nabla p)\right] = \alpha_n \qquad \ldots\ldots\ldots\ldots (4)$$

Where αn is the normal acceleration.

This drives the pressure in the air domain. The solid domain is on the other hand subjected to the acoustic pressure changes in the air domain. Because of the high voltage applied to the transducer, in comparison this load is probably negligible. As the model is in 2D, it is possible to include this load and solve the full model [13].

3. Results and Discussion

After designing the device with Barium Sodium Niobate (Ba2NaNb5O15) we observed the corresponding outputs. From the acoustic plot it is observed how the stress in piezo material exerts pressure in the air domain effectively. We have observed the air domain using BNN. From the Material section BNN was chosen for the same design for air domain.

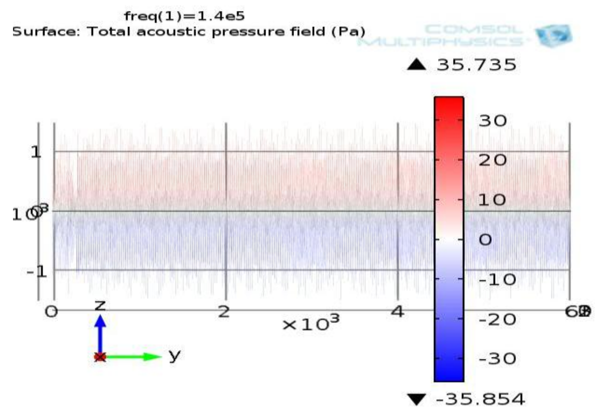

Figure 4: Acoustic pressure of ultrasonic wave plot for transmission in the air domain.

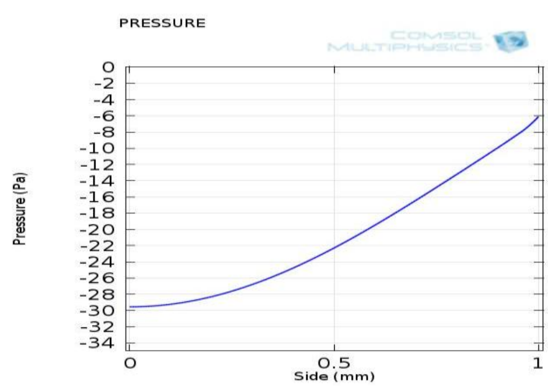

Figure 5: Study of generation and transformation of pressure at the solid-air environment interface.

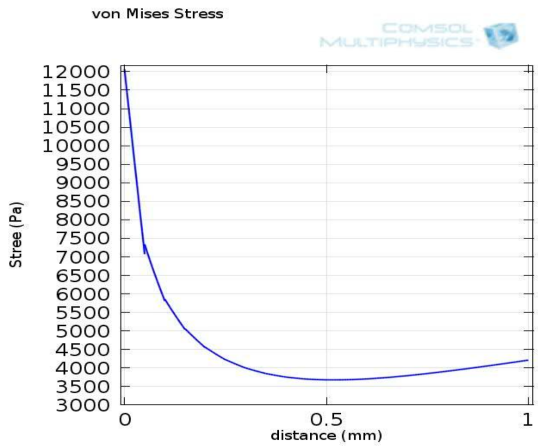

Figure 6: Study of Von-Misses stress produce in BNN while generating ultrasonic wave.

In the layout structure the gold electrodes serve both as contacts to the piezo material and as an encapsulation material which saves the device from the environment. The micro electronic circuit layer just below the substrate is the circuit that would be employed for supplying the input and interprets the output for this study. This microelectronic layer is fabricated separately and assembled using the layer bonding technique.

The plot in Figure 4 shows the propagation of the wave generated by the BNN material at the device and air environment interface. Here we have observed that BNN produces a constant pressure on the environment from the surface. The production and transformation of pressure at the solid-air environment interface was studied. It is found that minimum pressure developed at the edge of the circular dice type device having radius 1 mm and 0.5 mm thickness and gradually it increases as a result of propagation of harmonic waveform, the initial portion of variation of this study is also shown in Figure 5. Likewise, Von Mises stress (criterion for ductile failure) generated by Ba2NaNb5O15 (BNN) material along the solid-air interface is shown in Figure 6. It shows that at any point within the body there is different stress acting in different directions, so the direction and magnitude of stress changes from point to point. According to this study the stress reduces when height of the cylindrical column increases. It is found that air displacement and compliance by PZT is significantly higher than Ba2NaNb5O15 which is shown in Table 1.

Table 1: Comparison of results between PZT and BNN by COMSOL 4.2a

Parameter / Material	Density (Kg/m3)	Dielectric Constant	Compliance Matrix [1/Pa]	Material in Medium	Acoustic pressure Min	Acoustic pressure Max
PZT-5H	7500	2920, 2920, 168	1.65E-11	Air	-18.925	15.41
Ba2NaNb5O15	5300	235, 247, 51	5.30E-12	Air	-35.8	35.7

4. Conclusion

From the property of Ba2NaNb5O15 material air displacement, compliances and polar graph are simulated using software COMSOL Multiphysics 4.2a. Hence it is concluded that Ba2NaNb5O15 as an ultrasonic transducers is not up to the mark compared to conventional PZT material based transducers, but it has an edge over PZT material as Ba2NaNb5O15 is free from lead contain.

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