Studies of Lead Free Piezo-Electric Materials Based Ultrasonic MEMS Model for Bio Sensor

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Abstract: This paper describes the design of an ultrasonic transducer using different lead free piezo-electric materials and evaluates their performance with different glucose levels in the human blood. COMSOL Multiphysics 4.2a is used in this paper for the simulation study where a 2D axis- symmetric model geometry of piezoelectric transducer was designed with lead free piezoelectric materials such as Barium Sodium Niobate ($Ba_2NaNb_5O_{15}$)(BNN), Barium Titanate (BaTiO3)(BT) and Lithium Niobate ($LiNbO_3$) (LN). These piezoelectric materials are capable of being used as thin films. The potential of 10 Volt with 140 KHz frequency was applied to the device. The geometry of the sample container for blood is cylindrical shape of 20 mm dia, and 30mm height. The surface and radial displacement of the transducer structure of the materials with pressure and stress are studied in liquid blood medium. The ultrasonic transducer with these piezo materials was observed showing different transducer response to different blood density and therefore, it can be used to measure the glucose levels in the human blood. However, the BT has shown better performance compared to others. The glucose level of blood samples were also compared with a commercial glucose meter.

Keywords: COMSOL Multiphysics, Lead free materials, piezoelectric thin film. MEMS, Bio sensor.

1. Introduction

To prevent complications in diabetes, accurate monitoring and timely management of blood glucose levels is essential. Diabetes can lead to other health issues such as obesity, blood pressure and heart ailments. As projected by World Health Organization (WHO) in 2011 diabetic people counts up to 346 million worldwide. Millions of people die due to high sugar levels. Regular monitoring of sugar level in patient can alarm any unwanted rise in the level and necessary precautions can be taken at the right time [1-3].

Glucometers are supposed to be a solution for continuous monitoring of sugar level. It is a device that instantaneously determines the approximate glucose concentration in blood. The most common glucometer available in market is electronic glucometer. The cost of such glucometers is substantial due to the cost of the test strips used to collect the blood samples for analysis. Unlike the commercially available glucometers where pricking fingers or other area of the skin is required, a noninvasive method for monitoring blood glucose levels is desired [4].

By using an ultrasonic transducer, the glucose levels of human blood can be determined. The imitation of this biosensor will not become very bulky and power hungry. Hence a Micro-Electronics Mechanical Systems (MEMS) based ultrasonic transducer is studied here. This has got significant importance due to miniaturized system, based on silicon technology. MEMS based acoustic biosensing transducer is based on the piezoelectric technology which exploits the nature and properties of the propagating ultrasonic wave in blood medium of various densities. The biologically sensitive elements are combined with physical transducer to make biosensors, which are mostly used as analytical devices. This is done to discern specific compounds from a biological environment. Improved performance of biosensors is not only important from technological point of view but also important so far as human life is concerned. Using an ultrasonic transducer with which detections can be made through wireless operations the glucose levels of humans can be determined by studying the variation of amplitude with density of blood sample with glucose and it can be calibrated and compared to determine the sugar level. Piezoelectric materials are employed because they offer a high pressure per density ratio for the actuator, high stability in hostile environment and chemically they are very stable. For making ultrasonic transducers and piezoelectric actuators, it is desirable to have high electromechanical coupling coefficients, relatively large dielectric constant and large piezoelectric coefficient [5]. Large electromechanical coupling coefficient makes the transducer to achieve a broader bandwidth, whereas, larger dielectric constant makes the electric impedance matching between the transducer and its driving power supply easier for small sized transducers, such as MEMS [6].

For this reason, Lead Zirconate Titanate ($Pb[Zr_xTi_{1-x}]O_3$), or PZT ceramics become the dominant material in the ultrasonic transducer industry in the past 40 years. The miniaturized piezoelectric ultrasonic transducer based upon PZT material was developed by Tao Li *et al*, [7]. Unfortunately, lead compounds have been recognized as an environmentally non-friendly material which contains more than 60 percent lead by weight [8, 9].

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 are very expensive to fabricate. Suitable lead-free piezoelectric materials are still at a 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 [8, 10, 11].

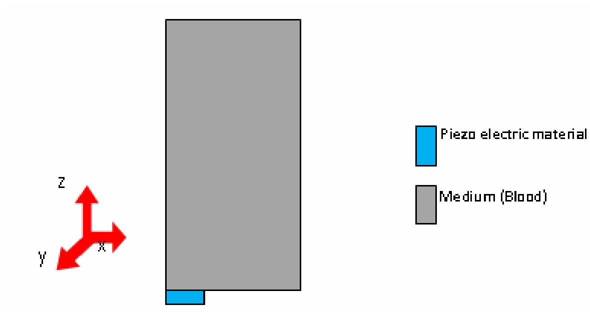
Prior to fabrication of MEMS device, design and simulation are extensively needed to avoid expensive time and cost. The goal of the present work is to describe the design of ultrasonic transducer using different lead free piezo-electric materials and their performance with different density of glucose levels in the human blood. COMSOL Multiphysics 4.2a is a versatile tool and is used to design and solve the transducer device with 3D partial differential equations. In this paper, 2D axis- symmetric model geometry of piezoelectric transducer was designed with different lead free piezoelectric materials like Barium Sodium Niobate ($Ba_2NaNb_5O_{15}$)(BNN), Barium Titanate (BaTiO3)(BT) and Lithium Niobate (LiNbO3) (LN) which are capable of being used as thin film [8,9,12]. The glucose levels of blood samples will be compared with commercial glucose meter to calibrate.

2. Model geometry and boundary conditions of ultrasonic transducer

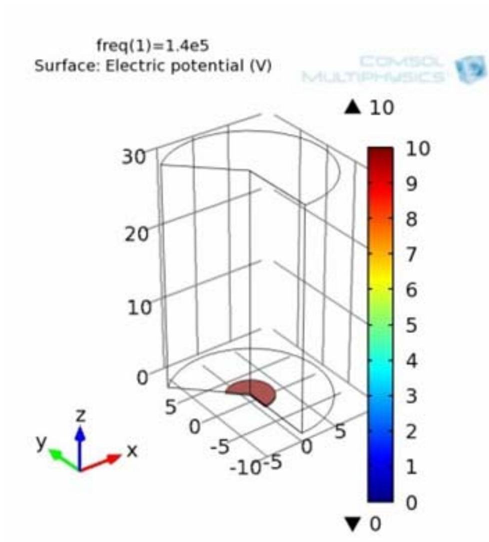
COMSOL Multiphysics 4.2a tool package is used to solve acoustic piezoelectric device using the 3D partial differential equations As we propose our design to be wireless, here we are simulating with blood samples with different concentrations of glucose taken in a cylindrical container, that is the reason for using the 2D axis- symmetric to imitate the device in the blood sample medium.

Here using this model, the cross section geometry of ultrasonic piezoelectric MEMS device was designed and simulated for Barium Sodium Niobate (BNN), Barium Titanate (BT) and Lithium Niobate (LN) piezoelectric materials and their properties were compared. Based upon the documentation of piezoacoustic transducer model in COMSOL Multiphysics 4.2a we have designed and analyzed the parameters [13].

The Figure-1(a) and Figure-1 (b) shows the schematic model of piezoelectric based ultrasonic transducer designed with different glucose concentrations of blood samples as the medium and simulated study of this 2D axis-symmetric geometry structure.



(a)



(b)

Figure 1 (a) Schematic model, (b) 2D axis-symmetric model geometry of the piezoelectric based ultrasonic transducer.

3. Fabrication process of ultrasonic transducer MEMS

In general, MEMS based Ultrasonic Transducer is fabricated using surface micromachining technology, meaning all the processing is done on the surface of the silicon wafer by means of thin-film depositions, thin-film etching, and photolithography. The design, modeling with process fabrication of piezoelectric micro-machined ultrasonic transducers was reported by Belgacem *et.al.* [14] The possible layer structure of MEMS based ultrasonic transducer is shown in Figure 2. 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.

4. Results and discussion

After designing the ultrasonic transducer with different lead free piezoelectric materials device it was kept inside the geometry of cylindrical blood sample medium. The glucose concentrations of the blood sample were then varied. The corresponding outputs were observed. It was observed from the 3D acoustic plots that the stress in piezoelectric material exerts pressure in the blood samples domain effectively. Different lead free piezoelectric materials such as Barium Sodium Niobate (BNN), Barium Titanate (BT) and Lithium Niobate (LN) were used in this study. It was observed that the Barium Titanate (BT) have showed better performance compare to others. Therefore, the acoustic pressure waveform for pure blood sample and blood samples added with different concentrations of glucose are shown in Figure 3.

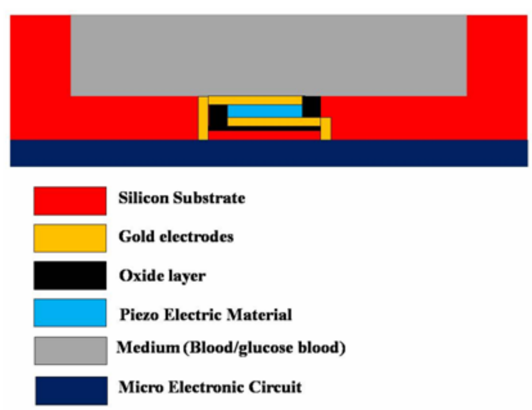


Figure 2. Schematic diagrams of layer structure of the MEMS based Ultrasonic Transducer

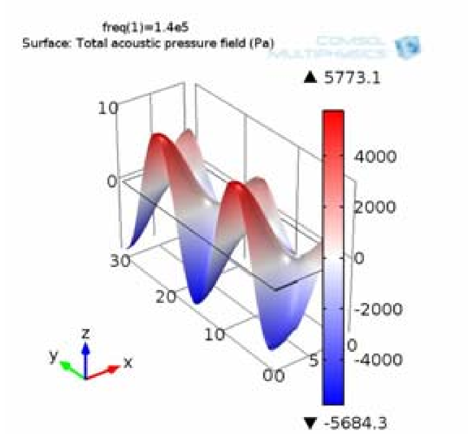


Figure 3(a) Acoustic pressure plot for pure blood sample.

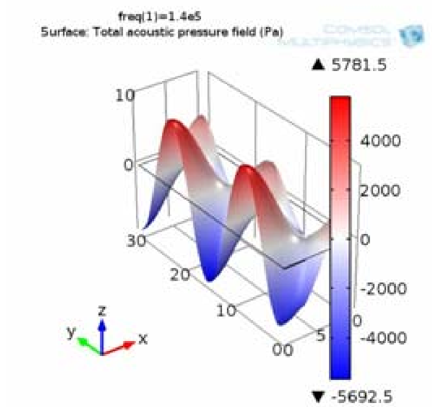


Figure 3(b) Acoustic pressure plot for blood sample (155mg/dL).

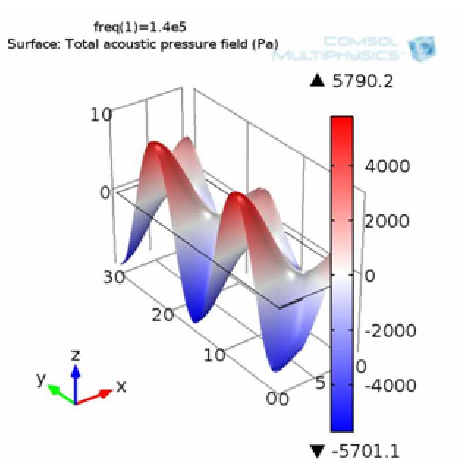


Figure 3(c) Acoustic pressure plot for blood sample (316 mg/dL).

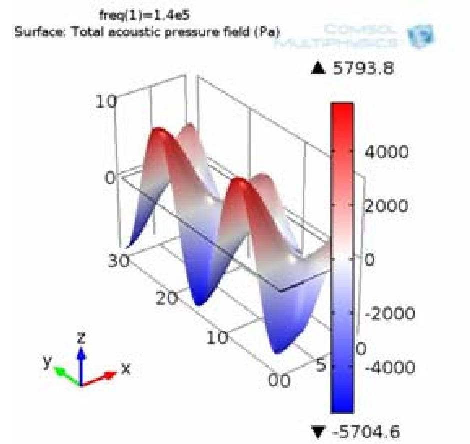


Figure 3(d) Acoustic pressure plot for pure blood sample, (382 mg/dL).

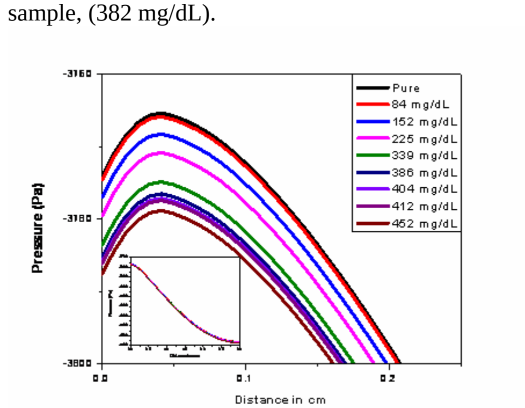


Figure 4 Acoustic pressure verses distance of the medium for different gluclose concentrations of blood sample.

Table 1 Comparison results of Electronic glucometer Pressure data and pressure generated by BT with different concentration of glucose.

Blood sample	Glucose added in blood sample (mg/dL)	Density of Blood sample (Kg/m^3)	Electronic glucometer (mg/dL)	Pressure generated by BT (Pa)
1	0	1050	70	-3765.337914
2	14	1050.14	87	-3765.832407
3	82	1050.82	155	-3768.234204
4	155	1051.55	227	-3770.812553
5	269	1052.69	340	-3774.838906
6	316	1053.16	390	-3776.498856
7	334	1053.34	408	-3777.134575
8	342	1053.42	415	-3777.417116
9	382	1053.82	449	-3778.829811

The different glucose concentrations were added to healthy blood samples was compared with commercial glucose meter to calibrate. Procedure followed for calibration is as follows. The sample contained 0.5 ml of blood and diluted with EDTA anticoagulant to prevent coagulation of blood. Then very small amount of weighted glucose was added to the blood sample to increase the glucose level. The glucose level of this sample was then measured with the help of electronic glucometer. By calculating the density of different blood samples the simulation were done to study the ultrasonic wave propagation in these medium. As the velocity has an inverse relation with the medium, the pressure is also going to decrease inversely as the square of density which is verified by the data obtained in Table 1. The amount of glucose added in blood with corresponding electronic glucometer reading was taken to verify the glucose concentrations in blood. Similarly calculating the density of blood samples by considering the amount of glucose added, the pressure generated by simulation has been calibrated.

The comparative result obtained by taking BNN and LN as piezoelectric materials with different glucose concentrations blood have been shown in Table 2 and BT has showed better performance compare to others.

Table 2 Comparison results of different lead free piezoelectric materials based devices.

Blood sample	Pressure generated by LIN (Pa)	Pressure generated by BNN (Pa)	Pressure generated by BT (Pa)
1	-255.2156377	-1564.508718	-3765.337914
2	-255.2495062	-1564.715697	-3765.832407
3	-255.4140098	-1565.721021	-3768.234204
4	-255.590608	-1566.800254	-3770.812553
5	-255.8663893	-1568.485608	-3774.838906
6	-255.9800878	-1569.180438	-3776.498856
7	-256.0236318	-1569.446543	-3777.134575
8	-256.0429846	-1569.564811	-3777.417116
9	-256.139748	-1570.15615	-3778.829811

5. Conclusion

From the property of different lead free piezoelectric materials with different glucose concentrations blood sample medium displacement, compliances and polar graph are simulated using software COMSOL Multiphysics 4.2a. It was found that BT has shown better performance compare to others. And it has an edge over PZT material as all are free from lead contain which are bio compatible.

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