Alternate glucometer bio-sensor model based on ultrasonic MEMS transceivers

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Abstract: To prevent further complications in diabetes, proper management of blood glucose levels is essential. By using ultrasonic transceivers (both transmit and receive) the glucose level of human blood can be determined. Ultrasonic sensors works on the principle of generating high frequency sound waves by evaluating the echo which is received back by the sensor. By using this ultrasonic technique miniaturized sensors for non-invasive monitoring blood glucose levels. In this paper Barium Titanate (BaTiO3) (BT) thin film was used as a transmitter and receiver. The simulation work using COMSOL Multiphysics software was carried out with this piezoelectric material with a model of blood with controlled density level. The size of BT thinfilm was optimized with respect to its width and thickness to produce maximum transmitting pressure at the transmitting end and maximum voltage at the receiving end. The transmitted was excited by 2 MHz oscillation at 1.6 V. The received potential was found to be varying with the density change of the blood medium. Hence BT can be used as a suitable bio-sensor for glucometer application.

Keywords: COMSOL Multiphysics 4.3, Lead free materials, piezoelectric thin film. MEMS, Bio sensor

1. Introduction

Improved performance of biosensors is not only important from technological point of view but is also important so far as human life is concerned. As projected by World Health Organization (WHO) in 2011 diabetic people counts up to 346 million worldwide. Millions of people die due to sugar level fluctuations. To prevent complications in diabetes, proper management of blood glucose levels is essential. Diabetes causes direct as well as indirect expenses as it is accompanied by many other health issues such as obesity, blood pressure and heart ailments. So a regular self-monitoring of glucose level in diabetic patient is essential which can alarm any unwanted fluctuations in the level thereby ensuring that necessary precautions can be taken at the right time, as opposed to conventional laboratory measurements [1-3].

The cost of commercial glucometer is substantial due to the high cost of the test strips being 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 regular and noninvasive method for monitoring blood glucose levels is desired [4-5]. During the last couple of decades, research work towards the development of a non-invasive glucose monitor has increased significantly among research groups producing motivating results [6].

Non-invasive detection is a fundamental prerequisite for pervasive healthcare system and biosensing. The qualitative review of different technologies of non-invasive glucose sensors each with their advantages and challenges are discussed which mainly covers: spectroscopy-based methods, transdermal extraction-based methods, fluorescence, electromagnetic variations and polarimetry [7].

Using an ultrasonic transceiver, the glucose levels of human blood can be determined but for non-invasive method we need miniaturized structures; hence we focus on ultrasonic Micro-Electronics Mechanical Systems (MEMS) which demonstrate significant importance for miniaturized mechanical system. Ultrasonic MEMS technology has recently emerged as an alternative aiming to offer advantages such as flexible geometries, reduced voltage requirements and mixing of different resonant frequencies for integration with supporting microelectronics circuits. The MEMS based acoustic biosensing transducers commonly employ the piezo-electric technologies to study the various nature and properties of the propagating ultrasonic wave in liquid medium of various densities, to calibrate and compare.

With extensive literature survey it was found that piezoelectric materials can generate ultrasonic waves as it has high electromechanical coupling coefficients, relatively large dielectric constant and large piezoelectric coefficient which enable them to generate and transmit ultrasonic waves into the liquid medium [8]. Large electromechanical coupling coefficient makes the transceiver to have a broader bandwidth; larger dielectric constant makes the electric impedance matching between the transceiver and its driving power supply which is easier for small size transceiver, such as MEMS [9]. For these characteristics, Lead Zirconate Titanate (Pb[ZrxTi1-x] O3), or PZT ceramics become the dominant material in the ultrasonic transducer or transceiver industry for the past 40 years. The miniaturized piezoelectric ultrasonic transceiver based upon PZT material was developed by Tao Li et al. [10]. Unfortunately, lead compounds which contain more than 60 percent lead by weight have been recognized as an environmentally non-friendly material [11]. Hence, researchers have been searching for a lead-free piezoelectric material which may be used as an alternative to the PZT ceramics for biosensor. Fortunately, lead free piezoelectric materials have an advantage for being used in biomedical applications. However, all among the existing lead-free ferroelectric crystal have weak piezoelectricity and some are even very expensive to fabricate. Thus suitable lead-free piezoelectric materials are still at their developing stage.

The acoustic pressure is affected by density of the medium, keeping this concept in mind, depending on the glucose density in blood the ultrasonic wave pressure varies. Therefore the measurement of such wave pressure can give an indication of the glucose density in blood. However, proper selection of piezoelectric material, dimension of the device, the operating voltage and frequency are not yet well studied.

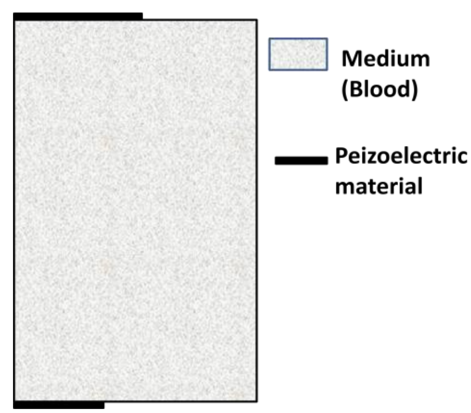
Carrying out experimental work for this is a tedious, expensive and time consuming job. Therefore, simulation study using advanced tools (COMSOL multiphysics 4.3) has been the basis of the present work. In this paper, piezoelectric transducer was designed with lead free piezoelectric material like Barium Titanate (BaTiO3) (BT) which is capable of being used as thin film [5]. The glucose levels of blood samples are compared with commercially available glucose meter for calibration.

2. Model geometry of ultrasonic trance-receiver

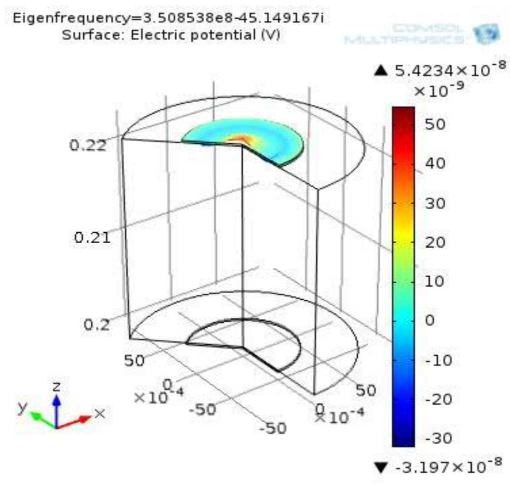
In this simulation study, the blood medium is considered as a cylindrical structure of 1 mm dia, and 10 mm height. A relatively small size piezoelectric film on a silicon substrate is used as ultrasonic wave generator as well as receiver. The thin slice of Barium Titanate (BT) material transmits the ultrasonic wave into the blood medium and a similar thin slice of Barium Titanate (BT) material receives the pressure wave and converts to electric potential. The potential vary based on the concentration of the blood medium.

The 3D partial differential equations and the 2D axis- symmetric configurations of COMSOL Multiphysics 4.3 tool package is used to solve acoustic piezoelectric device and to imitate the device in the blood sample medium [12]. The Barium Titanate (BT) was taken as the lead free piezoelectric material for our sensing device. The potential of 1.6 Volts was applied to the transmitting device.

The piezoelectric based ultrasonic transducer designed based on 2D axis- symmetric geometry structure and the simulating 3D model is shown in Figure 1(a) and (b). Figure 2 (a) and (b) shows the ultrasonic pressure wave with different glucose concentration of blood samples as the medium.

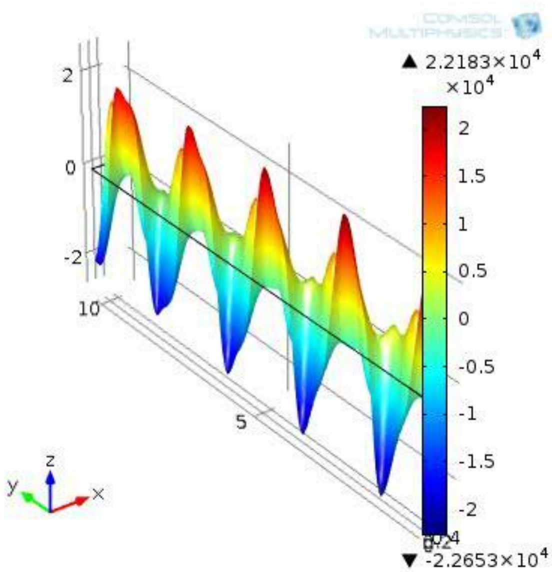


(a)



(b)

Figure 1. (a) 2D axis- symmetric geometry structure with piezoelectric material and blood medium (b) simulating 3D model using COMSOL



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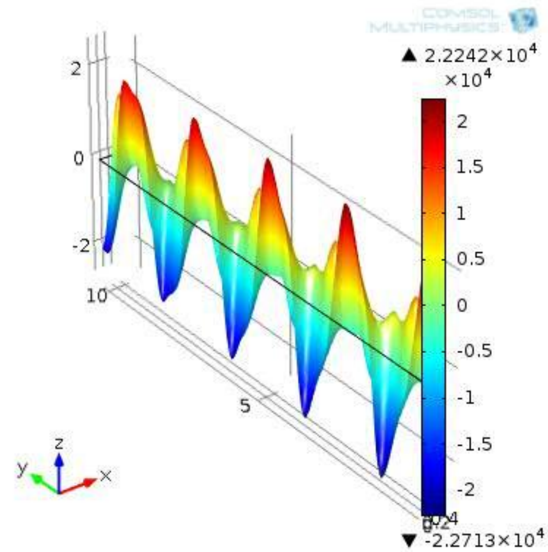
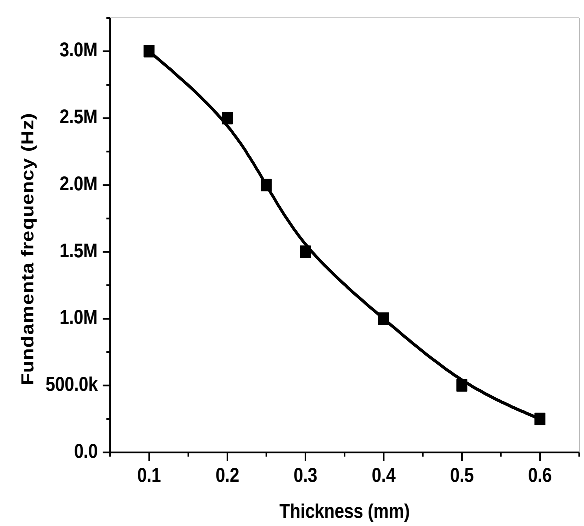


(b)

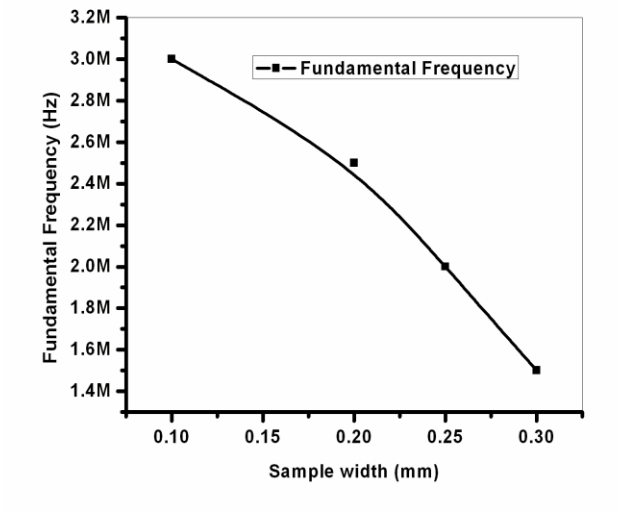
Figure 2. Acoustic pressure plots using BATiO3 based devices (a) pure blood sample, (b) blood sample (glucose added 269 mg/dL),

3. Result and Discussion

3.1 Effect of sample width and thickness on fundamental frequency



(a)



(b)

Figure 3. Piezoelectric sample layer (a) thicknesses (b) width versus fundamental frequency

The piezoelectric ultrasonic device produces an acoustic wave that propagates in the blood medium. In this experiment, to optimize the size of the device, which is frequency dependent, the width and thickness of Barium Titanate (BT) sample in the model was varied from 0.1 mm to 0.3 mm and 0.1mm to 0.6 mm respectively to tune the frequency. Figure 3 (a) and (b) show the variation of resonant frequency obtained from the pressure generation mode of the model with BT with respect to various widths and thickness. It was observed that fundamental frequency dropped significantly with the increase of the sample width and thickness. Nonlinear relationship from the above analysis makes it only suitable for rough estimation of model's fundamental frequency with sample size. The optimized device layer thickness and width at fundamental frequency 2 MHz was considered at 0.275 mm and 0.25mm respectively. The piezoelectric co-efficient is size-dependent due to the strong c-axis orientation. When the film approaches strong c-axis orientation, the piezoelectric co-efficient increases rapidly. Therefore, the piezoelectric coefficient increases with increasing thickness [13]

3.2 Effect of frequency on pressure

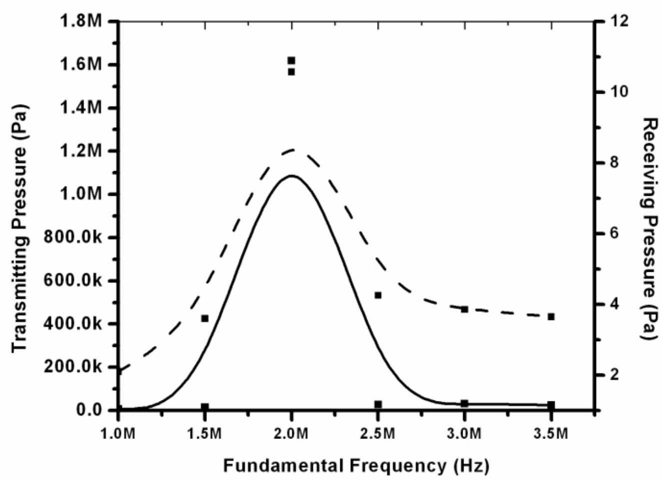


Figure 4. Frequency vs. pressure graph to obtain optimized frequency for BT

After fixing the size 0.275 mm thickness and 0.25mm width (radius) respectively, the exiting frequency is varied from I MHz to 3.5 MHz. The pressure of the ultrasonic wave at the transmitting and receiving ends were plotted in Figure 4. It is found that the sample gives height pressure at 2 MHz. Hence the frequency of 2 MHz is used as the exciting frequency in rest of our experiment.

3.3 Effect of acoustic wave propagation and potential generated on the density of blood

The commercially available glucometers provide the glucose density information in the blood using electrochemical sensors. The proposed sensing method uses a physical sensor using ultrasonic trans-receiver. This experiment was devoted to compare a commercial glucometer reading with the thin-film based piezoelectric trans-receiver pressure generated at transmitting end and also potential generated at receiving end due the glucose density variation in the blood.

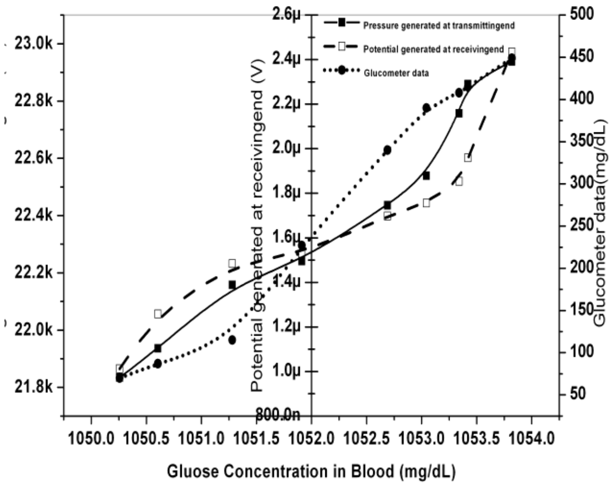


Figure 5. Comparison results of pressure and potential generated by BT with different concentration of glucose in both transmitting end as well as receiving end.

For measurement using the commercial glucometer, 0.5 ml of blood sample was diluted with ethylene-diamine-tetra-acetic acid (EDTA), an anticoagulant to prevent coagulation. Then measured quantities of glucose (from 1050-1054 Kg/m3) were 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 to verify the glucose concentrations in blood. Similarly, in the simulation environment, the glucose density in blood was varied from 1050-1054 Kg/m3 to study the ultrasonic wave propagation in the medium. It was found that the pressure and potential at a point in the blood medium increases with density in this range as it is seen using commercial glucometer reading. The comparison of both the measured data and the simulated data are plotted in Figure 5.

4. Conclusion

The property of BT as a lead free piezoelectric materials with different blood samples of glucose concentrations were simulated by using COMSOL Multiphysics 4.3 software to its performance as the BT can be used as a material for ultrasonic trance-receiver MEMS device. Hence it is environmental friendly and bio safe piezoelectric material to be used as ultrasonic glucose sensor.

5. References

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