Design of Ultrasonic MEMS Temperature Sensor

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Abstract –The attempt has taken to design a ultrasonic Micro Electronics Mechanical System (MEMS) of non-contact temperature sensor. The piezoelectric material is used both transmitter and receiver ends for the miniature device. Prior to fabrication of ultrasonic MEMS device, design and simulation are extensively used to avoid wastage of time and test the workability of a system without much expenditure. COMSOL Multiphysics 4.4 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 is designed with Quartz (SiO_2) which is capable of being used as thin film. By varying thickness of the transmitter as well as receiver; the dimension was optimized to produce maximum transmitting pressure. The proposed device relies on the propagation of 40 kHz ultrasonic waves in air medium and the decreasing density of air with increasing temperature. So it would affect the generated pressure and received potential of both transmitting and receiving end of piezoelectric material with respect to changing temperature. This indicated that by using this principle one can design and fabricate high temperature sensing devices.

Keywords:COMSOL 4.4;ultrasonic; temperature sensor; MEMS; Quartz

1. Introduction

Piezoelectric materials have found wide usage for sensing of various parameters like vibration, chemicals, mass, distance and pressure. However temperature sensing using piezoelectric based ultrasonic transducer is a new approach that relies on the propagation of ultrasonic wave in air medium and thermal property of the used piezoelectric material [1]. There are varieties of thermal sensors employed for high temperature sensing and have dissimilar features on the grounds of their actual application. Some of them have a crucial requirement that needs them to be in physical contact with the object whose temperature is to be measured whereas some others employ radiation and convection to monitor thermal variations for contactless measuring of temperature [2].

High-temperature sensing is indispensable in industrial sectors dealing with material production and processing, aerospace engineering, power plants, automotive, transportation etc. Piezoelectric sensing is acclaimed due to its compact sensor size and low cost [3]. Extensive exploration has previously been done on fiber optics, capacitive sensors and piezoresistive sensors to test their working in high-temperature environment [4-6].

Due to insusceptibility to electromagnetic intrusion, comparatively higher melting point, toughness and resistance to corrosion, optical sensors fiber optic sensors have gained popularity. It has been verified that optical fiber based sensor can operate at elevated temperatures, deprived of any kind of degradations [7]. But a problematical technique of construction and an expensive and perplexing system for signal processing are some of the significant inadequacies restraining their use [8-9].

Optical Pyrometers utilizes objects radiating color due to heat and from that, color passes through an optical system to a detector from which measurement of temperatures takes place and surrenders to obtaining continuous values of temperatures at small intervals. Pyrometers are suited especially to the measurement of moving objects or any surfaces that cannot be reached or cannot be touched. However they have low sensitivity, poor time response and object whose temperature is t be measured must be hot enough to radiate visibly [10].

Generally, piezoresistive materials are less vulnerable to hindrance caused by electromagnetic waves but at temperatures beyond 660 °C the conductor from becomes polluted by impurities present at the metal sheath of the thermometer. On the contrary the integral temperature dependency of materials upon resistivity can lead to imprecisions at high temperatures [11]. Even though capacitive sensors have the benefit of high resolution, small thermal drift and decent noise performance, they lack satisfactory robustness and get easily affected by parasitic capacitance equivalent to that of the sensor [12-14].

Ultrasonic temperature sensing uses piezoelectric material as the active element of the ultrasonic transducer. Transformation of electrical pulses to mechanical vibrations, which is universally termed as piezoelectric effect and transformation of reimbursed mechanical vibrations into electrical signal, which is universally termed as reverse piezoelectric effect is the basis for ultrasonic Sensing [15].

Ultrasound just like normal sound is a sort of mechanical energy which is characterized by vibrating particles contained by a medium. The characteristics of the ultrasound energy are prominently influenced by the medium in which it is propagating. Ultrasound waves communicate the energy in form of motion in the direction of material as soon as it disseminates through it. In an unceasing intermediate, performance of the ultrasound waves has meticulously been linked with equilibrium among the inertial forces and to that of the elastic distortion. The travelling velocity of ultrasonic waves relies on the material property and the form in which medium is and sporadically by the operating frequency.

The sound field is affected by numerous aspects such as the area over which the sound wave is generated, the speed sound waves in that particular medium and operating frequency of the waves. There are multiple points of origination of ultrasonic waves across the surface of the transducer.

In this work the piezoelectric material used is quartz. It has been tested and their performance with respect to temperature has been studied and reported. The charge generated by quartz crystals is dependent on the cut and shape of the crystal [16-17].

The ultrasonic Micro-Electronics Mechanical Systems (MEMS) device technology is used to design an infinitesimal transmitter and receiver. This technology has lately come to prominence as an alternative objective that entails improvements such as a substandard voltage requirement and flexible geometries. It also facilitates mixing of various resonant frequencies for incorporation with the auxiliary microelectronics circuits [18]. The acoustic transducers system relies on the fundamental property of piezoelectric materials. Piezoelectric material is chosen on the grounds of large piezoelectric coefficient, moderately larger dielectric constant and a high electromechanical coupling coefficient. These aforesaid strictures enable the propagation of ultrasonic waves through the air medium. Quartz having a large electromechanical coupling coefficient has a broader bandwidth [19].

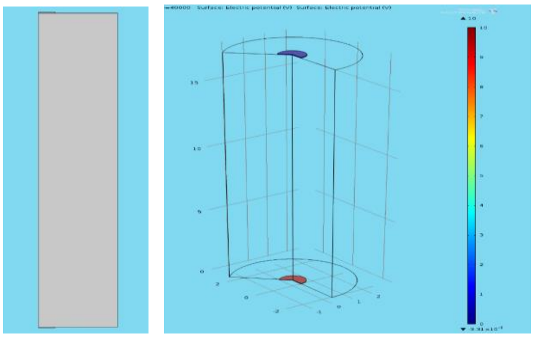
In order to curb the expenses and save time MEMS experiments preferred to be done through a multidisciplinary simulation platform to test the feasibility of the proposed system. The simulation platform used is COMSOL Multiphysics 4.4.

2. Model Geometry of Ultrasonic Transducer

COMSOL Multiphysics is one of the few general-purpose software platforms which provide profusion accuracy, because of its advanced numerical methods, for simulation and modelling of physics-based problems. It is intended for cross-disciplinary development of products with an integrated workflow which not only solution based upon the 3D partial differential equation but also independent of the area of application.

Simulation using computers has now become a critical part of engineering and science as it saves time and resources. It is idyllic to employ a simulation platform that comprises the opportunity to add or remove any peripheral physical effect to the designed model.

For the design and simulation of ultrasonic temperature sensor, the piezoelectric devices module was used in which a parameterized geometry was created along with addition of Predefined materials to the model. The 2D axis-symmetric module of COMSOL Multiphysics 4.4 was utilized for simulation of the device which is shown in Fig. 1(a) and also the 3D view of the model shown in Fig. 1(b). Relatively trivial piezoelectric films are used as ultrasonic transmitter and receiver. The air medium was considered as a cylindrical structure of 5.2 cm diameter and 17.5 cm height. With change the temperature, physical properties of the medium also changes which in turn impacts the propagation of ultrasonic wave.



(a) **(b)**

Figure 1. (a) 2D axis- symmetric model geometry showing the structure of air medium as well as Quartz sample. **(b)** 3D View of the model.

3. Mathematical Analysis (Model)

Ultrasound waves, like normal sound waves travel at a certain velocity in air medium. However, this velocity is dependent on temperature (T) as the speed of sound (c) upsurges with increasing temperature [20]. Sound and heat are forms of kinetic energy. Therefore at elevated temperatures molecules have more energy as a result of which they vibrate rapidly. Due to this faster vibration of molecules, energy transfer between molecules is faster which ultimately leads to faster propagation of sound waves. The speed of sound in air medium at room temperature is 343 m/s which faster compared to that of speed of sound (c_0) at 0 °C which is equivalent to 331.3 m/s. This relation can be represented as

$$c = c_0 * \sqrt{\left\{1 + \left(\frac{T}{273.15}\right)\right\}} \tag{1}$$

This can be written in terms of temperature:

$$T = \left(\left[\frac{c}{c_0}\right]^2 - 1\right) * 273.15 \tag{2}$$

According to ideal gas equation, density of air (ρ) decreases with increase in temperature (T), because the volume usually becomes greater which is shown in Fig. 2.

For air medium obeying the 'perfect gas law' it is straightforward. The fractional increase in density, at constant pressure (P), is equal to fractional in temperature and shown in Fig. 3 [21]. This relation can be represented as

$$\rho = \frac{P}{\{R(273.15+T)\}} \tag{3}$$

This can be written in terms of temperature:

$$T = \left[\frac{P}{\rho R} - 273.15\right] \tag{4}$$

Here 'R' is the ideal gas constant, which is also equivalent to the product of the Boltzmann and the Avogadro constant.

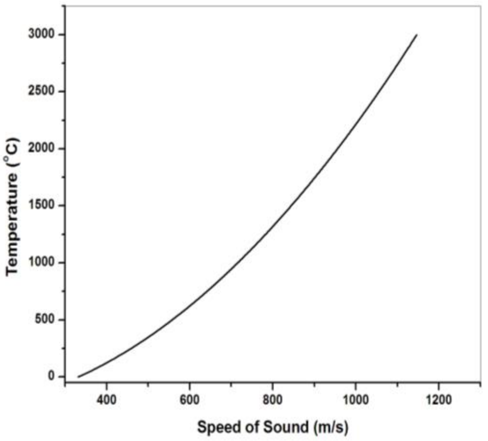


Figure 2. Speed of sound vs. Temperature

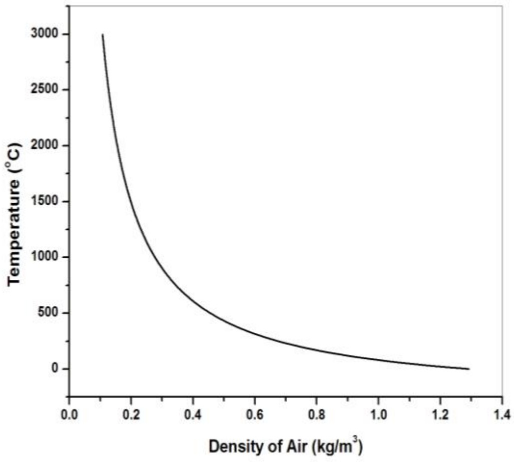


Figure 3. Air Density vs. Temperature

4. Result & Discussion

The acoustic wave produced by the piezoelectric ultrasonic transmitter propagates in the air medium to the receiver. The geometry of the medium significantly impacts the operating frequency for the transmitter and receiver.

4.1 Frequency Optimization

Here the medium and transducer size is kept constant. Also, a constant potential of 10 Volt is supplied to the transmitter. The operating frequency of the transmitter is varied from 20 KHz to 80 KHz. The optimum transmitting pressure and generated voltage obtained at optimized frequency of 40 KHz is shown in Fig. 4 . Hence the operating frequency is kept constant at 40 KHz.

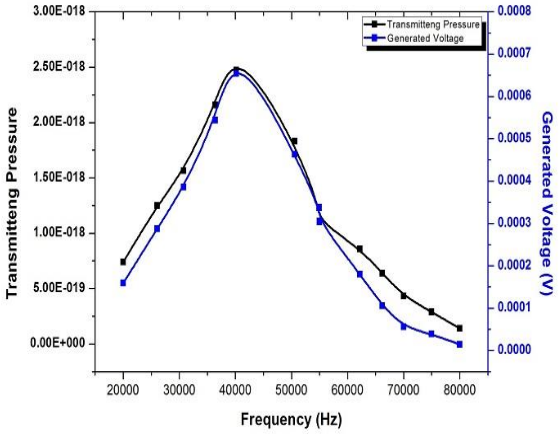


Figure 4. Frequency optimization

4.2 Effect of sample width and thickness on fundamental frequency

After frequency optimization, the thickness of ultrasonic based piezoelectric MEMS device is optimized to get best transmitting pressure from transmitter side and best generated voltage from receiver end.

At 40 KHz optimized frequency and a constant width of 0.5475 cm the thickness of the transmitter and the receiver are varied from 0.01 cm to 0.0885 cm.

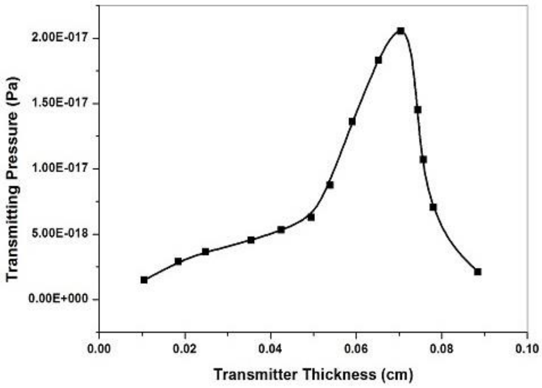


Figure 5. Transmitter thickness optimization

The transmitter is optimized for maximum transmitting pressure and shown in Fig. 5. The receiver is optimized for maximum generated voltage respectively as it can be seen in Fig. 6. The transmitter thickness was fixed at 0.0705 cm and the receiver at 0.0535 cm respectively.

4.3 Study of Receiving Pressure and Generated Voltage at the Receiving End

The axis-symmetrical geometry model of piezoelectric transducers are maintained. But the medium density and speed of sound is varied with changing temperature while keeping the shape and size intact.

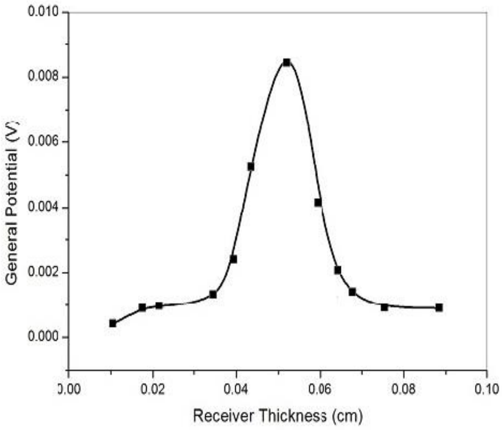


Figure 6. Receiver thickness optimization

When air density decreases as temperature increases, it results in less particles in the medium. This decline in particle density in turn affects the pressure received at the receiver. Fig. 7 shows that the receiving pressure drops when the air density decreases.

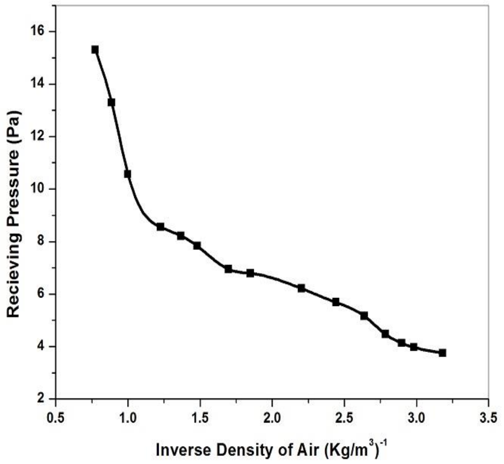


Figure 7. (Air Density)$^{-1}$ vs. Receiving Pressure

Increasing temperature impacts the air density negatively which ultimately leads in decline of pressure received at the receiver. Fig. 8 clearly shows that the receiving pressure is inversely proportional to temperature.

This voltage sensitivity of piezoelectric material varies from sample to sample. Generated Potential (V) is solely dependent on piezoelectric material property such as voltage sensitivity of material (S_v), receiving pressure (P) and thickness of the receiver (t).

$$V = S_v . P . t \quad (5)$$

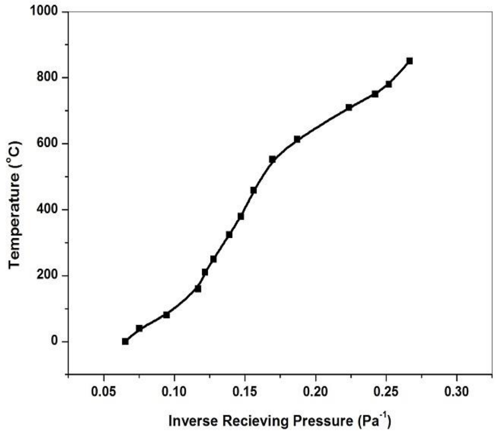


Figure 8. (Receiving Pressure)$^{-1}$ vs. Temperature

As voltage sensitivity and receiver thickness are constant the respective materials, generated potential is directly proportional to receiving pressure which is clearly indicated in graph in Fig. 9.

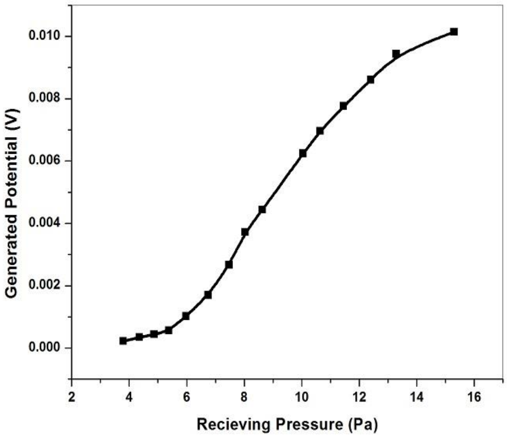


Figure 9. (Receiving Pressure)$^{-1}$ vs. Generated Voltage

By comparing the plots from Fig. 7 through to Fig. 9, it is concluded that the generated voltage at the receiver end decreases as at the temperature rises, which can be seen in Fig. 10. Hence temperature can be calculated from the generated potential.

5. Conclusion

These ultrasonic transducers are designed by using COMSOL Multiphysics 4.4. From results of simulation it is found that the less pressure generates as temperature increases. Quartz has quite significant pressure which can be utilized as an ultrasonic temperature sensor. However it squanders its piezoelectric property around a temperature of 880 °C.

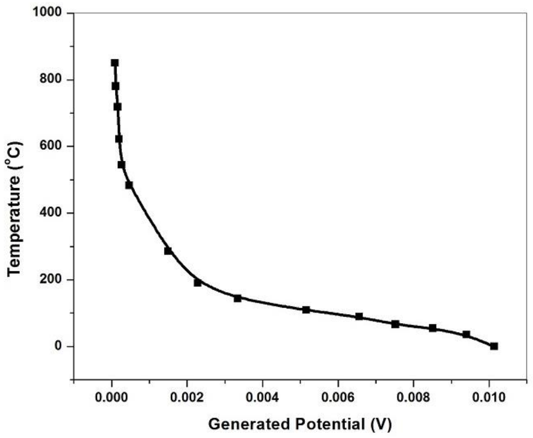


Figure 10. Generated Voltage vs. Temperature

Piezoelectric materials with higher Curie temperature can be used for sensing even higher temperatures. The temperature limitation is not exclusively related to the piezoelectric material's Curie point and for successful design, all materials used in the construction of a device need to be considered. For example, at higher temperatures, transducer delimitation ensues due to strains caused by differential thermal expansion. This leads to degradation of performance and ultimate device failure. For contactless sensing of very high temperature piezoelectric technology is highly efficient.

6. References

1. Yasuchi Hayashi, Koji Numata and Kazutoshi Nishizawa, "Ultrasonic temperature measuring apparatus.' U.S. Patent 5,360,268, issued November 1, (1994)

2. Kienitz, Ulrich, and Christian Schiewe. "Method for the contactless measuring of temperature with a multi-channel pyrometer." U.S. Patent **No. 4** p-821 219 (1989)

3. Jiang, Xiaoning, Kyungrim Kim, Shujun Zhang, Joseph Johnson, and Giovanni Salazar. "High-temperature piezoelectric sensing." Sensors 14, **no. 1** (2013)

4. Pulliam, Wade J., Patrick M. Russler, and Robert S. Fielder. "High-temperature high-bandwidth fiber optic MEMS pressure-sensor technology for turbine engine component testing." In Environmental and Industrial Sensing, pp. 229-238. International Society for Optics and Photonics (2002)

5. Young, Darrin J., Jiangang Du, Christian A. Zorman, and Wen H. Ko. "High-temperature single-crystal 3C-SiC capacitive pressure sensor." Sensors Journal, IEEE 4, **no. 4**,pp. 464-470 (2004)

6. Li, Xin, Qin Liu, Shixin Pang, Kaixian Xu, Hui Tang, and Chensong Sun. "High-temperature piezoresistive pressure sensor based on implantation of oxygen into silicon wafer." Sensors and Actuators A: Physical, **no.179**, pp.277-282 (2012)

7. Wang, Jiajun, Bo Dong, Evan Lally, Jianmin Gong, Ming Han, and Anbo Wang. "Multiplexed high temperature sensing with sapphire fiber air gap-based extrinsic Fabry–Perot interferometers." Optics letters 35, **no. 5**, pp.619-621 (2010)

8. Nguyen, Linh Viet, Dusun Hwang, Sucbei Moon, Dae Seung Moon, and Youngjoo Chung. "High temperature fiber sensor with high sensitivity based on core diameter mismatch." Optics express 16, **no. 15**, pp.11369-11375 (2008)

9. Barrera, David, Vittoria Finazzi, Joel Villatoro, Salvador Sales, and Valerio Pruneri. "Packaged optical sensors based on regenerated fiber Bragg gratings for high temperature applications." Sensors Journal, IEEE 12, **no. 1**, pp.107-112 (2012)

10. Ackerman, Sumner. "Automatic brightness pyrometers." U.S. Patent No. 3,264,931. August 9, (1966)

11. Van Kampen, R. P., and R. F. Wolffenbuttel. "Modeling the mechanical behavior of bulk-micromachined silicon accelerometers." Sensors and Actuators A: Physical 64, **no. 2,** 137-150 (1998)

12. Kasten, Klaus, Jörg Amelung, and Wilfried Mokwa. "CMOS-compatible capacitive high temperature pressure sensors." Sensors and Actuators A: physical 85, **no. 1**, pp.147-152 (2000)

13. Yazdi, Navid, Farrokh Ayazi, and Khalil Najafi. "Micromachined inertial sensors." Proceedings of the IEEE 86, **no. 8**, pp.1640-1659 (1998)

14. Zimmermann, L., J. Ph Ebersohl, F. Le Hung, J. P. Berry, F. Baillieu, P. Rey, B. Diem, S. Renard, and P. Caillat. "Airbag application: a microsystem including a silicon capacitive accelerometer, CMOS switched capacitor electronics and true self-test capability." Sensors and Actuators A: Physical 46, **no. 1**, pp.190-195 (1995)

15. Aindow, Joseph. "Electrical coupling for piezoelectric ultrasound detector." U.S. Patent No. 6,pp.094,988. (2000)

16. Jaffe, H., and D. A. Berlincourt. "Piezoelectric transducer materials."Proceedings of the IEEE 53.10, pp.1372-1386 (1965)

17. Jaffe, Bernard. Piezoelectric ceramics. **Vol. 3**. Elsevier (2012)

18. Hara Prasada Tripathy, Priyabrata Pattanaik, Subrat Kumar Pradhan, and Sushanta Kumar Kamilla. "Simulation Study of ZnO Based Ultrasonic Micro-Electronics Mechanical Systems Model for Blood Glucose Level Measurement." Advanced Science Letters (ASP), **Vol. 22**, **no. 2**, pp.401-404 (2016)

19. Lakin, M., J. Belsick, J. F. McDonald, and K. T. McCarron. "Improved bulk wave resonator coupling coefficient for wide bandwidth filters." In Ultrasonics Symposium, 2001 IEEE, **Vol. 1**, pp. 827-831 (2001)

20. Wong, George SK. "Speed of sound in standard air." The Journal of the Acoustical Society of America, **Vol. 79.5**, pp.1359-1366 (1986)

21. Perry, R.H. and Chilton, C.H., "Chemical Engineers' Handbook", 5th ed., McGraw-Hill (1973)