Journal of New Materials for Electrochemical Systems
Vol. 27, No. 2, June 2024, pp 156-161
Journal homepage: http://iieta.org/journals/jnmes

Performance Evaluation of Capacitive Accelerometer Piezoelectric Energy Harvester Using GaAs Material

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https://doi.org/10.14447/jnmes.v27i2.a07

Received: November 27, 2023
Accepted: June 12, 2024

Keywords:
Accelerometer, Energy harvesting, fabrication, Micro-Electro Mechanical System*, fabrication.*

ABSTRACT

A novel method of obtaining energy from natural sources is MEMS (Micro-Electro Mechanical System) energy harvesting. Being a renewable, nearly endless energy source, it has a lot of potential for wireless sensor applications. A micro energy harvester is a crucial part of the self-sustaining integrated micro-electromechanical systems (MEMS) and microelectronics that will be widely used in the upcoming Internet of Things (IoT) era, or the so-called trillion sensors. GaAs is used in the capacitive accelerometer's design, and the specs are listed below. In this piece. The proof mass of the capacitive accelerometer is 0.5 microns, and its thickness is 2 microns. The distance between its springs is 1 micron, and their overlap is 120 microns. The relationship between acceleration and the sense voltage for various materials namely Si, ZnO, GaAs, Ge has been simulated using COMSOL software. The results show that GaAs give the better performance when compared with the other materials. The acceleration and the total energy are obtained which is shown in the graph. The acceleration is adjusted, and the related capacitance for various materials is examined in order to assess the behaviour of energy harvesting. Hence with different analysis it is identified that GaAs is well suited for applications where a low cost microsensors is required. Thus the work shows that GaAs is the better choice for energy harvesting.

1. INTRODUCTION

Micro-Electro Mechanical System (MEMS) energy harvesting is a new way to extract energy from natural sources. It has a lot of potential in wireless sensor applications because it's a natural, almost in exhaustible energy source. The most important component for self-sustaining integrated MEMS and microelectronics, which will be widely distributed in the coming Internet-of-Things (IoT) era, or the so-called trillion sensors, is a microenergy harvester. Micro energy conversion sciences, as well as design and fabrication technologies for energy harvester products, are critical for realizing anticipated applications, such as wireless sensors for infrastructure monitoring and remote healthcare, and as a result, energy harvesters are becoming a hot topic in the MEMS culture. Vibration sensors, or capacitive accelerometers, depend on the variation of electrical capacitance in accordance with the acceleration.

The schematic diagram for the capacitive accelerometer is shown in figure 1. The variations in the capacitance are caused with the help of plates which are arranged parallel. If the plate distance is varied in proportional with the acceleration applied between the plates. The micro electro mechanical system stands for MEMS which can be used for sensing and other different applications. These methods, which are normally used on silicon, are used to construct different structures which can be used for observing tiny particles also in detail.

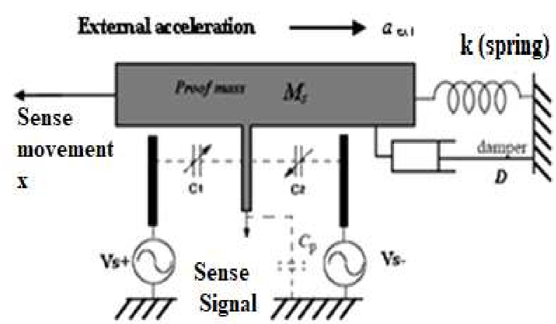

Figure 1. Schematic Diagram of MEMS Capacitive Accelerometer

2. LITERATURE SURVEY

Guruprasad et al., [1] has designed a cantilever MEMS Utilizing surface micromachining, the sensor is created. An omniscient instrument is used to detect VOCs. This analysis examines the detection sensitivity of PVP and 3-APTES to acetone and isopropyl alcohol. It gives a better performance in increasing its sensitivity for measuring volatile organic compounds. Surendran R et al., [2] had analyzed the various performance of the cantilever beam by changing different materials. They also have analyzed the resonant frequencies by altering the thickness of the beams. Yanjue Gong et al., [3] have discussed the principle for designing the cantilever mems optimally.

C. Li et al., [4] has designed an efficient capacitive power sensor which has been dealing with 2 mems cantilever beams and the same has been fabricated with the GaAs.The authors have also analysed the multiple beam cantilever and their caharacteristics. D. Wang et al., [5] has developed, a double MEMS cantilever beam-based in-line microwave power sensing system. It achieves the separation of power detection and sense. The performance of an in-line microwave power detection system based on double cantilever beams is increased compared to the single beam, and a 10% coupling factor can be reached.

A. D. Singh et al., [6] in this work a method is created to determine electromechanical coupling in relation to bias voltage. This electrical model can anticipate how the device will behave before the pull-in instability region starts to develop and can also estimate pull-in voltage. This macro model can be used to highlight the potential benefit of employing this method for enhancing device and system dynamics and is simple to apply in any platform for circuit modelling. Based on the partial load distribution and curling, an analytical formulation for the cantilever's spring constant and pull-in voltage is constructed to achieve equivalency. It makes use of an approach based on a mechanical force-deflection model and nonlinear electrostatic pressure that is approximated by its linearized uniform equivalent.

Y. Liu et al., [7] the author has designed and analyzed the energy harvesters using different beam structures. D. Xie et al., [8] the author has done a model using single cantilever with metal oxide semiconductor. The performances are tested which gives a good linear characteristics.Z. Xin et al., [9] a cantilever beam with 2 channel for power sensor using MEMS has been proposed which will provide sensitivity and power overloading in an optimized level. The performance of the cantilever beam has been studied and tested with 3 different sensors with the variable beam sizes of the cantilever.

A. Mohammadi et al., [10] the harvesting efficiency has been improved for the microfabrication process.the authors have introduced a new approach in the, multiplexing process with the help of time domain concept.M. Mousavi et al., [11] the authors have put forth a new idea in which the interaction force and pressure can be correlated with each other. Hence the results show that whenever there is an increase in pressure at that time the interactive force is also getting increased.

The various analyses [12] can be carried out with the help of MEMS sensor for measuring different parameters namely pressure, acceleration, etc. E. Iranmanesh et al. (2018). The integration of a MEMS variable-capacitance factor into an accelerometer. The detection of acceleration, including that of the metal diaphragm accelerometer, necessitates the use of two capacitive elements and a flexure. The acceleration [13] induces small variations because of which the sensing elements undergo a shift in capacitance R.K Santhanaraj, et al. (2023). Because of the silicon's single-crystal nature [14], the transducer consists of a wider capability as there is a severe reduction in the mechanical joints S. Dran, et al. (2013). At the greater temperature the properties for damping can be improved for a greater temperature. If the central mass displaces, a sequence of grooves and holes in the structure compress gas into the structure. In comparison to silicone oil, a gas's thermal viscosity change is negligible. Currently, capacitive MEMS accelerometers can measure hundreds of g's and have a frequency of minimum kHz. The Accelerometer [15] size will also be reduced with the help of technology using MEMSQ. Wang. Et al. (2019). Built-in electronics in most of the capacitive accelerometers for completing the bridge and conditioning the signal a signal will be added in addition to the element. To provide enough power to the accelerometer, most capacitive sensors need only a normal voltage [16] supply or battery A. Daruwalla et al. (2020).

The ferroelectric materials perform many functions which has gained a great interest in microelectro mechanical systems (MEMS) area, which can give a new and the latest sensing and actuating deals as fine microstructures can be framed with the help of thin films which are integrated using ferroelectric materials. The electromechanical properties are more predominant in piezoelectric material which is one of the necessary properties that prevails in ferroelectric material. MEMS Sensors [17] and Actuators has the most essential property known as piezoelectricity. In order to have the presence of piezoelectric materials into MEMS, they must first be prepared as thin films that can be micro fabricated using photolithography. There are many applications in piezoelectric [18] MEMS and one of the most important is the Vibration energy harvesters (EHs). A simple structure of cantilever [19] is used for generating a great electric power with the help of piezoelectric thin films. There are many technical issues which has to be solved for manufacturing great energy efficient and reliable piezoelectric [20] MEMS. The properties and deposition [21] of thin film piezoelectric films are analyzed. Lead has a greater impact in the environment. The reason for the lead free ceramics which contains piezoelectric [22] thin films has been investigated to a greater.

Accelerometers are one of the most fundamental but often utilised micro-electromechanical systems (MEMS) [23]. In the car industry, as well as in computer and audio-video technology [24 & 25], they were in dispensable [26] Dadi, et al. (2024). Micromachined accelerometers are a versatile enabler with a lot of business potential. They provide sensing that is low-power, light weight, and reliable. In order to have correct data and for analyzing the multi axis sensors it is very much important to have many sensors. A MEMS based capacitive accelerometer can be designed based upon the model which has been designed for the purpose. It's crucial to figure out whether you're trying to calculate motion or vibration before choosing an accelerometer. Motion measurement is concerned with the rigid body's speed or displacement, as opposed to vibration measurement, which is concerned with the vibratory responses of the force under examination. It's crucial to make sure that there are no zero offset errors in the derived acceleration data when utilising an accelerometer to accurately estimate motion.

After numerical integrations, even a little amount of zero offset in the acceleration output results in significant amounts of velocity or displacement inaccuracies. Existing authors recommend against using piezoelectric-based accelerometers for motion measurements since they produce zero offset errors while attempting to track a sluggish motion.

A high-precision bulk micro machined sensing element and an ultra-low noise CMOS integrated readout-IC are both components of a capacitive, MEMS-based accelerometer. The resulting accelerometer is appropriate for seismic measurements that demand noise levels much below 1 g/Hz, reaching an acceleration equivalent noise of only 200 ng/Hz. The given sensor system is also appropriate for high-frequency measurements, for example, in predictive maintenance applications for rotating machinery, thanks to a high bandwidth of more than 5 kHz that was attained. In-depth design information for the sensing lement and readout IC is supplied, and measurement results are presented to show the sensor system's effectiveness**.**

A dome can be raised which is present at the bottom of the MEMS accelerometer that can beheated with the help of a small heater. The place where the hot air is to be reached is determined by the thermocouple which is present on the dome and the acceleration applied is measured using the deflection off the Centre. The vast majority of micromechanical accelerometers are present in thesame plane, meaning they are only sensitive to directions parallel to the plane of the die. A two devices are connected which is perpendicular and present in the single die is a two-axis accelerometer. If three axes has to be measured then an extra plane is added which is out of the plane. After packaging, the misalignment error is also much smaller when three discrete versions are combined. The measurement scales for a MEMS based accelerometers are available for a greater scales which ranges from a few hundreds to many. Thus there should be balance maintenance between the adaptation and full acceleration.

3. PROPOSED SYSTEM

A dome can be raised which is present at the bottom of the MEMS accelerometer that can be heated with the help of a small heater. The place where the hot air is to be reached is determined by the thermocouple which is present on the dome and the acceleration applied is measured using the deflection off the Centre. The vast majority of micromechanical accelerometers are present in the same plane, meaning they are only sensitive to directions parallel to the plane of the die. A two devices are connected which is perpendicular and present in the single die is a two-axis accelerometer. If three axes has to be measured then an extra plane is added which is out of the plane. After packaging, the misalignment error is also much smaller when three discrete versions are combined. The measurement scales for a MEMS based accelerometers are available for a greater scales which ranges from a few hundreds to many. Thus there should be balance maintenance between the adaptation and full acceleration.

In the figure 2 the substrate is suspended with the help of GaAs springs which allows thesensor's body to move in the direction of X and Y. The proof mass is getting deflected from its centre position because of the acceleration. Along the radial fingers are the 32 sets of radial fingers. These fingers are sandwiched between two plates that are adhered to the substrate. The differential capacitance measures the proof mass deflection. The differential capacitance is used to measure the deflection of the proof mass. The differential capacitor is composed of each finger and a pair of fixed plates. An accelerometer is the primary sensor used to gauge inertial acceleration, or the change in velocity over time. Mechanical accelerometers, quartz accelerometers, and MEMS accelerometers are only a few of the several types of accelerometers available. Essentially, a MEMS accelerometer is a mass held in place by a spring. The mass is called the proof mass, and the axis on which it is free to move is called the sensitivity axis. When subjected to a linear acceleration along the sensitivity axis, an accelerometer will move to one side, with the amount of movement being proportional to the acceleration. Suppose the accelerometer is now turned so that the sensitivity axis is parallel to the gravity vector. Gravity in this situation causes the proof mass to deflect downward. This means that the accelerometer can measure both the linear acceleration brought on by motion and the fictitious acceleration brought on by gravity.

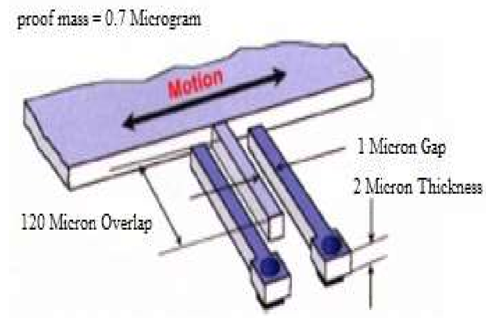

Figure 2. Capacitive Accelerometer

Using COMSOL software, it has been simulated that for a variety of materials, including Si, ZnO, GaAs, and Ge, the link between acceleration and the sensing voltage exists. In comparison to other materials, the data demonstrate that GaAs performs better. As can be seen in the graph, the total energy and acceleration are obtained. Analysis of the associated capacitance for various materials is done while varying the acceleration to assess how energy harvesting behaves. Figure 3 shows Switch 1(3) = GaAs - Gallium Arsenide acceleration (5)=50 Volume: Electric field norm (V/m). Comsol software is used for the design and simulation processes. The acceleration forces are measured with the help of an electromechanical system made up of an accelerometer. These forces may be static, such as gravity's relentless pull on your feet, or dynamic, such as those induced by shifting or vibrating the accelerometer.

The piezoelectric energy harvesting using capacitive accelerometer is studied with its basic fundamental principles and the analysis is performed. The fundamental operation of the MEMS piezoelectric energy harvesting sensor has been studied. A detailed survey on various MEMS pressure sensors, its significance, application and the materials used in MEMS system were discussed. The study of the piezoelectric capacitive accelerometer includes theoretical and computational investigation of MEMS capacitive accelerometer. The sense voltage activity versus Acceleration of different materials is investigated. Silicon, Zno, GaAs and Ge were used in the study.

The properties of these materials are considered, and an investigation of different displacement behaviour is carried out. The acceleration is varied and corresponding sense voltage is noted for the different materials. It is observed that GaAs has a good value when compared with the other materials. It has been shown on figure 4.

The total energy stored versus acceleration has been analyzed for different materials namely Si, ZnO, GaAs and Ge. The behavior of these materials are analyzed and they are plotted graphically. Amongst all materials compared GaAs is giving better performance than all other materials. So the material selected is GaAs for the capacitive accelerometer piezoelectric energy harvesting.

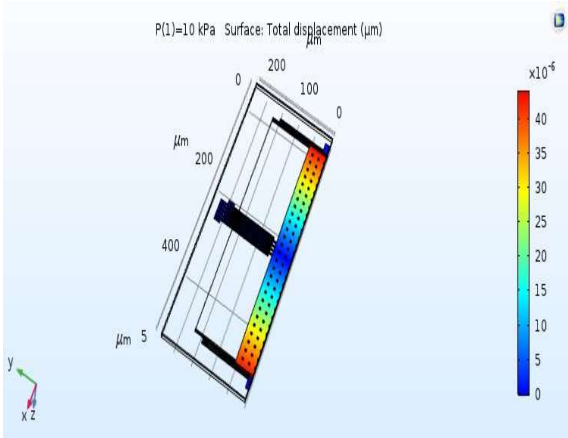

Figure 3. Switch 1(3)=GaAs - Gallium Arsenide acceleration(5)=50 Volume: Electric field norm (V/m)

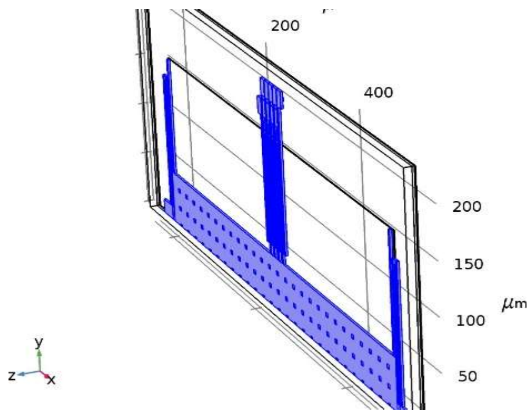

Figure 4. Accelerometer view

The acceleration is varied for all the materials and the energy stored for each material is observed out of which GAAs suits well for energy storage which is shown in figure 5.

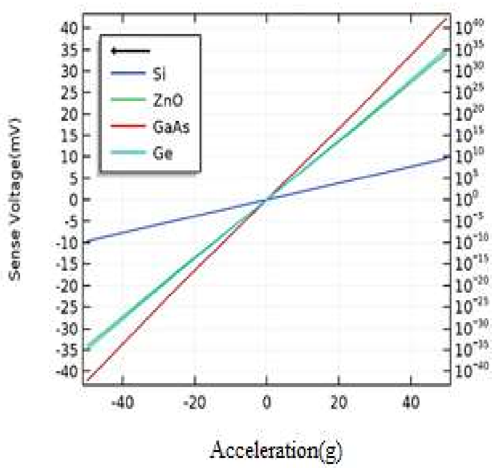

Figure 5. Sense Voltage Vs ACC

With a length of 120 micrometres, a thickness of 2 microns, and a material of GaAs, the displacement of the accelerometer sensor increases as pressure increases, and the displacement lineally changes due to normal blood pressure values (120/80 mmHg) as reference results. The deflection of the fingers of the has been found to differ linearly with pressures in the 10[kPa] to 20[kPa] range. As a result, when the highest applied pressure is used, the mass displacement nearly doubles. It has been found that as pressure rises, the displacement rises as well which is shown in figure 6.

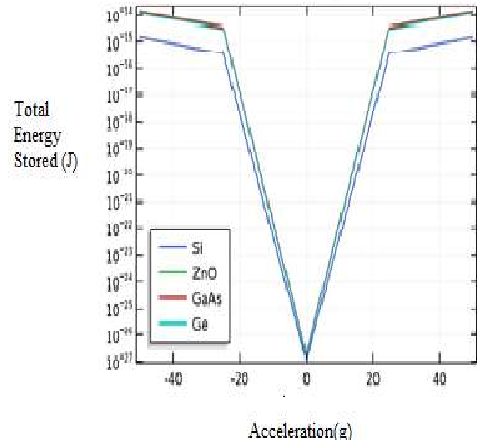

Figure 6. Total Energy stored

The proof mass (and the moving electrodes attached to it) shifts by around 0.5 micrograms which has been clearly observed in figure 7.

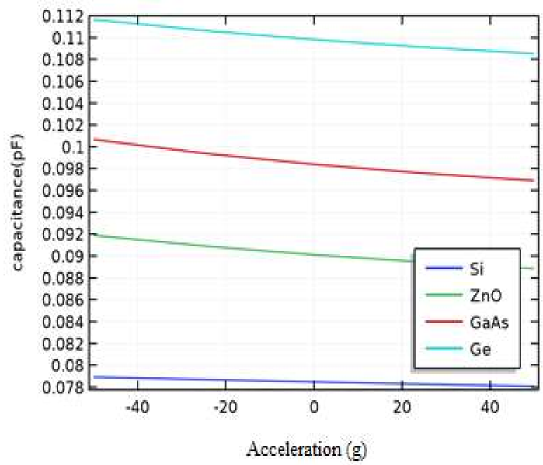

Figure 7. Acceleration versus Capacitance

The sensitivity of the pressure sensor can be increased by optimizing the design parameters. The proof mass is moved from 10[kPa] to 20[kPa] by sweeping the applied pressure from 10[kPa] to 20[kPa] and computing the displacement. The displacement of GaAs domains when the applied pressure is seen in Figure 8 (Displacement Vs pressure 2D surface). Due to their friction, the anchored spring bases and fixed electrodes shift very little. The linear graph Dis Vs P depicts the linear relationship between displacement and applied pressure.

The displacement is determined by the capacitive connection between the moving and fixed sense electrodes. When the proof mass moves as a result of the pressure, an alternating voltage in proportion to the displacement is induced due to the capacitive coupling between the fixed and moving electrodes. The figure 9 clearly shows the energy storage with respect to pressure.

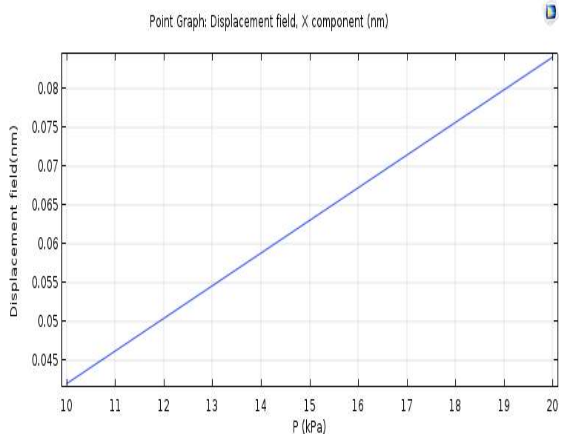

Figure 8. Pressure versus total Displacement

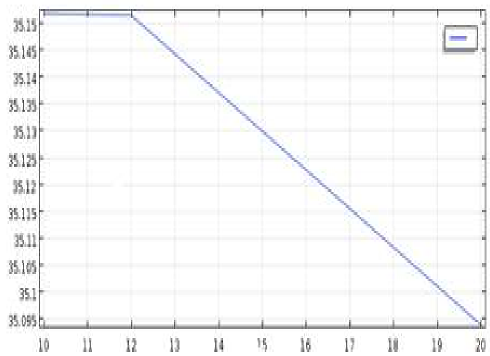

Figure 9. Pressure versus Displacement

A capacitive accelerometer was simulated using GaAs and the specified specifications. In this work, a capacitive accelerometer with a thickness of 2 microns and a proof mass of 0.5 microns was built with spring spacing of 1 micron. The relationship between acceleration and the sensing voltage has been studied using COMSOL software for a number of different materials, including Si, ZnO, GaAs, and Ge. The statistics show that GaAs performs better when compared to other materials. The total energy and acceleration are determined, as shown in the graph. In order to analyse the behaviour of energy harvesting, the associated capacitance for different materials is examined while the acceleration is varied. Energy stored details are shown in the figure 10. Table 1 is display the design Specifications.

Table 1. Design Specifications

S.No	Material Properties	Value
1	Proof mass	0.5 microgram
2	Overlap	120micron
3	Gap	1 micron
4	Thickness	2 microns

Utilizing GaAs and the requirements listed below, a capacitive accelerometer was created. With a proof mass of 0.5 microns and a spacing of 1 micron between the springs, a capacitive accelerometer with a thickness of 2 microns has been constructed in this study.

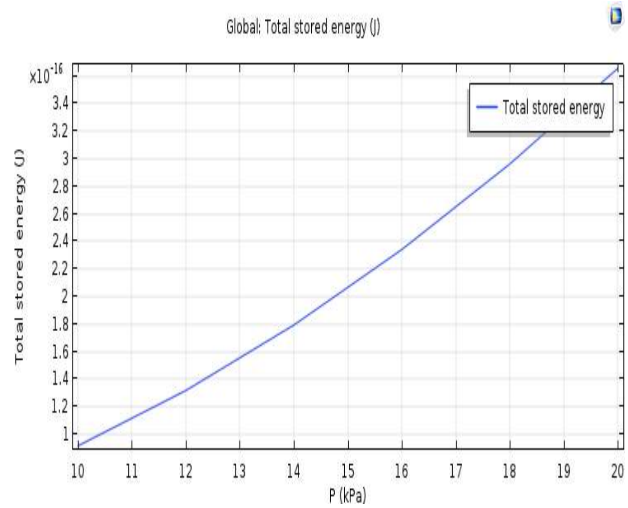

Figure 10. Energy stored

4. CONCLUSIONS

MEMS accelerometers are very efficient and effective devices which are used for meeting the various challenges in the sensing field with a reduction in size, greater efficiency and it can be used for different integrated applications. Intelligent sensor accelerometers provide enhanced integration and accuracy, as well as application-specific data, functionality, which also reduces the testing time during production of the device and it reduces the cost for calibrating the various functionalities. MEMS will undoubtedly play a significant role in standardizing manufacturing, testing, and packaging. A MEMS component's relatively long and costly development cycle is a barrier that must be overcome, and a less expensive micro fabrication method than photolithography must be followed. Utilizing GaAs and the requirements listed, a capacitive accelerometer was simulated. With a proof mass of 0.5 microns and a spacing of 1 micron between the springs, a capacitive accelerometer with a thickness of 2 microns has been constructed in this study. Using COMSOL software, it has been simulated that for a variety of materials, including Si, ZnO, GaAs, and Ge, the link between acceleration and the sensing voltage exists. In comparison to other materials, the data demonstrate that GaAs performs better. As can be seen in the graph, the total energy and acceleration are obtained. Analysis of the associated capacitance for various materials is done while varying the acceleration to assess how energy harvesting behaves. GaAs is thus found to be well suitable for applications that call for low-cost microsensors through various analyses. The research demonstrates that GaAs is a superior material for energy harvesting.

REFERENCES

[1] B. Guruprasad, M.G. Veena, Analysis of MEMS cantilever sensor for sensing volatile organic compounds, Micro and Nano Engineering, Volume 16, 2022, 100143, ISSN 2590-0072, https://doi.org/10.1016/j.mne.2022.100143

[2] R. Surendran, and B. KeerthiSamhitha, 2014. Energy aware grid resource allocation by using a novel

negotiation model. Journal of Theoretical and Applied Information Technology, 68(3).

[3] Yanjue Gong, Li Zhang, Fu Zhao, Chunling Meng and Liang Lv, "Design optimization of cantilever Beam MEMS switch," 2009 International Conference on Industrial Mechatronics and Automation, Chengdu, 2009, pp. 28-31, doi: 10.1109/ICIMA.2009.5156552.

[4] C. Li, J. Xiong and D. Wang, "A Novel Capacitive Microwave Power Sensor Based on Double MEMS Cantilever Beams," in IEEE Sensors Journal, vol. 22, no. 12, pp. 11803-11809, 15 June15, 2022, doi: 10.1109/JSEN.2022.3174556.

[5] D. Wang, X. Gu, J. Zhao, L. Jin and X. Ji, "An In-Line Microwave Power Detection System Based on Double MEMS Cantilever Beams," in IEEE Sensors Journal, vol. 20, no. 18, pp. 10476-10484, 15 Sept.15, 2020, doi: 10.1109/JSEN.2020.2994149

[6] A. D. Singh and R. M. Patrikar, "Development of Nonlinear Electromechanical Coupled Macro Model for Electrostatic MEMS Cantilever Beam," in IEEE Access, vol. 7, pp. 140596-140605, 2019, doi: 10.1109/ACCESS.2019.2943422.

[7] Y. Liu et al., "Design and Performance of ScAlN/AlN Trapezoidal Cantilever-Based MEMS Piezoelectric Energy Harvesters," in IEEE Transactions on Electron Devices, vol. 68, no. 6, pp. 2971-2976, June 2021, doi: 10.1109/TED.2021.3072612.

[8] D. Xie, D. Chen, S. Peng, Y. Yang, L. Xu and F. Wu, "A Low Power Cantilever-Based Metal Oxide Semiconductor Gas Sensor," in IEEE Electron Device Letters, vol. 40, no. 7, pp. 1178-1181, July 2019, doi: 10.1109/LED.2019.2914271.

[9] Z. Xin, H. Sun and D. Wang, "A High-Performance Dual-Channel MEMS Microwave Power Sensor With Cantilever Beam," in IEEE Sensors Journal, vol. 23, no. 11, pp. 11540-11546, 1 June1, 2023, doi: 10.1109/JSEN.2023.3269035.

[10] A. Mohammadi, S. Sadrafshari, C. R. Bowen and M. R. Yuce, "Time Domain Multiplexing for Efficiency Enhanced Piezoelectric Energy Harvesting in MEMS," in IEEE Electron Device Letters, vol. 41, no. 3, pp. 481-484, March 2020, doi: 10.1109/LED.2020.2965143.

[11] M. Mousavi, M. Alzgool and S. Towfighian, "A MEMS Pressure Sensor Using Electrostatic Levitation," in IEEE Sensors Journal, vol. 21, no. 17, pp. 18601-18608, 1 Sept.1, 2021, doi: 10.1109/JSEN.2021.3091665.

[12] E. Iranmanesh, A. Rasheed, W. Li and K. Wang, "A Wearable Piezoelectric Energy Harvester Rectified by a Dual-Gate Thin-Film Transistor," in IEEE Transactions on Electron Devices, vol. 65, no. 2, pp. 542-546, Feb. 2018, doi: 10.1109/TED.2017.2780261.

[13] R.K. Santhanaraj, S. Rajendran, C.A.T. Romero. and S.S. Murugaraj, 2023. Internet of Things Enabled Energy Aware Metaheuristic Clustering for Real Time Disaster Management. Comput. Syst. Sci. Eng., 45(2), pp.1561-1576.

[14] S. Dran, and P. Varthini, 2013. Detecting power systems failure based on fuzzy rule in power grid. Przegląd Elektrotechniczny, 89(8), pp.172-177.

[15] Wang, Q. et al.: A Universal High-Sensitivity Area-Variation Capacitive Displacement Transducer (CDT) Based on Fringe Effect. IEEE Access, vol. 7, pp. 153650-153659, (2019), doi: 10.1109/ACCESS.2019.2947570.

[16] Daruwalla, H. Wen, Gong, M., Ayazi, F.: High-G and High-Bandwidth Bulk Acoustic Wave (BAW) Accelerometers Using a Metal-Less AlN-HARPSS Process With 95nm Gaps. IEEE Sensors Letters, vol. 4, no. 8, pp. 1-4, (2020), Art no. 2501004, doi:10.1109/LSENS.2020.3011642.

[17] Yesner, G., Jasim, A., Wang, H., Basily, B., Maher, A., Safari, A.: Energy Harvesting and Evaluation of a Novel Piezoelectric Bridge Transducer. Sensors and Actuators A: Physical, (2019) DOI: https://doi.org/10.1016/j.sna.2018.11.013.

[18] Amini, S., Johns, D.A.: A Normalized Figure of Merit for Capacitive Accelerometer Interface Circuits. In: IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 67, no. 1, pp. 19-22, (2020), doi: 10.1109/TCSII.2019.2901851.

[19] Maity, R., Maity, N. P., Baishya, S.: An Efficient Model of Nanoelectro mechanical Systems Based Ultrasonic Sensor with Fringing Field Effects. In: IEEE Sensors Journal, vol. 20, no. 4, pp. 1746-1753, (2020), doi: 10.1109/JSEN.2019.2948795.

[20] Gomez, J.M., Bota, S.A., Marco, S., Samitier, J.: Force-balance interface circuit based on floating MOSFET capacitors for micro-machined capacitive accelerometers. In: IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 53, no. 7, pp. 546-552, (July 2006), doi: 10.1109/TCSII.2006.875315.

[21] Reverter, F., Casas, Ò.: Interfacing Differential Capacitive Sensors to Microcontrollers: A Direct Approach. In: IEEE Transactions on Instrumentation and Measurement, vol. 59, no. 10, pp. 2763-2769, (Oct. 2010), doi: 10.1109/TIM.2009.2036500.

[22] Tez, S., Aykutlu, U., Torunbalci, M. M. Akin, T.: A Bulk-Micromachined Three-Axis Capacitive MEMS Accelerometer on a Single Die. Journal of Microelectro mechanical Systems, vol. 24, no. 5, pp. 1264-1274, (Oct. 2015), doi: 10.1109/ JMEMS.2015.2451079.

[23] Colombo, L., Kochhar, A., Vidal-Álvarez, G., Piazza, G.: High-Figure-of-Merit X-Cut Lithium Niobate MEMS Resonators Operating Around 50 MHz for Large Passive Voltage Amplification in Radio Frequency Applications. In: IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 67, no. 7, pp. 1392-1402, (July 2020), doi:10.1109/TUFFC.2020.2972293.

[24] Isobe, A. et al.: Design of Perforated Membrane for Low-Noise Capacitive MEMS Accelerometers. In: IEEE Sensors Journal, vol. 20, no. 3, pp. 1184-1190, (February, 1 2020, doi:10.1109/JSEN.2019.2948172.

[25] E. Iranmanesh, W. Li, A. Rasheed and K. Wang, "A Piezoelectric-Transducer-Biased 3-D Photosensitive Thin-Film Transistor as a Dual-Mode Wearable Energy Harvester," in IEEE Electron Device Letters, vol. 41, no. 9, pp. 1368-1371, Sept. 2020, doi: 10.1109/LED.2020.3009685.

[26] Dadi, P.S., Meera, R., Rajkumar, K. and Surendran, R., 2024, April. Enhance Energy Efficiency based Automobile Wheels by using Piezoelectric Energy Harvesting Technology and Sustainable Power Generation. In 2024 2nd International Conference on Networking and Communications (ICNWC) (pp. 1-9). IEEE.