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Simulation and Comparison of Average Harvested Power for Lead Zirconate Titanate and Quartz on Silver Substrate based MEMS Piezoelectric Energy Harvester

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ABSTRACT

Aim: The aim of the research work is to simulate and compare the average harvester energy and natural frequency for lead zirconate titanate (PZT) and quartz on a silver substrate based MEMS piezoelectric energy harvester with a thickness varying from 80 µm to 800 µm. **Materials and Methods:** There are 25 samples for each device obtained with an error rate of 0.05 and a sample pre test power of 80%. **Results and Discussion:** The natural frequency, average harvested power and power density were obtained for quartz on silver and PZT-5H on silver. The mean value of average harvested power of PZT-5H based piezoelectric energy harvester (1.60E-08) is significantly higher than the quartz based piezoelectric harvester (1.39E-06) significance value of 0.0001 ($p < 0.005$). **Conclusion:** The average harvested power of the PZT-5H based MEMS harvester is significantly better than the quartz based MEMS harvester.

Keywords: Novel piezoelectric material, lead zirconate titanate (PZT-5H), quartz, silver substrate, MEMS technology, energy harvesting, vibrational energy.

INTRODUCTION

MEMS technology paves the way for energy harvesting applications. The MEMS piezoelectric based energy harvesting sensor is a MEMS sensor which converts wasted mechanical energy for conversion into usable electrical energy [1]. The importance of such devices uses the principle of direct piezoelectric effect to convert the energy of the vibrating surface to electrical current. The principle of the piezoelectric effect is shown in Fig. 1. These vibrational energy harvesters are more apparent due to the versatility provided for the low-power micro generators. PZT-5H and Quartz have superior power efficiency than existing piezoelectric materials because the thickness of the piezoelectric material is reduced. [2]. The applications of the piezoelectric energy harvester is low output power efficiency and is used in bio-medical devices like pacemakers [3], internal organ defibrillators [4], neural stimulators, pressure level monitors and pressure sensors [5].

There are more than 900 articles published on MEMS piezoelectric energy harvesters in the past five years in Google Scholar database. Most cited articles are listed as follows. The experimental results demonstrate an ultra-low natural frequency of 98Hz [2], [6]. The reduction of the thickness of the piezoelectric material leads to a decrease in the frequency and power density. To report a Ag nanowire array primarily based nanogenerator for the first time to reap mechanical energy [7]. However, the output of the device is sort of restricted for use due to the low electricity constant of the Ag nanowires [7], [8]. Because PZT-5H has a twenty-fold greater electricity constant than Quartz, a multifunctional PZT-5H ribbon energy harvester on a polyimide substrate is said to harvest energy from the motions of animal hearts, lungs, and diaphragms [9]. Recently, it has been reported that a breathing-driven established triboelectric energy harvester can in vivo power a pacemaker [7], [8], [10].Previously our team has a rich experience in working on various research projects across multiple disciplines[11]–[21]

When the thickness of a piezoelectric material is increased, the power increases, which is a disadvantage in low-power applications [9], [22]. For the desired power generation, it must be replaced with a novel piezoelectric material and selection of the substrate is important [23]. The main aim of the paper is to design, simulate, and compare power generation through vibrational analysis for lead zirconate titanate and quartz on silver substrate based MEMS piezoelectric energy harvesting.

MATERIALS AND METHODS

The work setting is carried out at the Semiconductors laboratory, Department of Electronics and Communication Engineering, Saveetha School of Engineering, using the Nano hub online simulation tool. Two groups were compared with a sample size of 25, assigned to each group. The clincalc application is used to determine the minimum sample size value. Simulations of the groups were based on the MEMS configuration with pre-test power of 80% used for testing.

In the sample preparation group 1, the quartz on Ag is used as the piezoelectric structure by varying the thickness of the piezoelectric layer. Ag is used as a substrate; the thickness of the Ag substrate is kept constant. Now the thickness of the novel piezoelectric material is varied from 80 µm to 800 µm and the resultant average harvested power and natural frequency is analysed.

In the sample preparation group 2, PZT-5H which is a novel piezoelectric material is used to enhance the harvester structure with a varying thickness. Ag is used as a substrate; the thickness of the Ag substrate is kept constant. Now the thickness of the piezoelectric material is varied from 80 µm to 800 µm and the resultant average harvested power and natural frequency is analysed.

The power reduction reduced the actual power to low power. The temperature change occurs along with the power reduction. High power will be produced. For calculating the sample size group 1, PZT-5H on a silver (Ag) substrate and for sample size group 2 Quartz on silver (Ag), varying the thickness of the piezoelectric material and silver substrate will be constant along with temperature at 273 K. Quartz on silver (Ag) has low power compared to the PZT-5H on silver. Nanohub simulation tool used for the simulation of the substrate and piezoelectric materials.

The simulation is provided by the testing procedure, which employs the DFT tool. In Nanohub, launch the DFT simulation tool. Then, from the tag menu, choose MEMS Piezoelectric Vibrational Energy Harvesting Lab [24]. From the list of resources, choose MEMS piezoelectric vibrational energy harvester lab. Select the launch tool. To keep the material silver, choose PZT-5H or Quartz in the beam set, the thickness of the piezoelectric material, and mechanical properties (Ag). Then run the simulation and record the results. As the thickness of the novel piezoelectric material is varied, the results are recorded in excel sheets. DFT and SPSS statistical software, which can calculate the mean and significance of the collected data, are used for data collection and comparison.

Statistical Analysis

The data collection includes the tabulation of the 25 samples obtained for each group. The total samples were 50 which possessed the simulation and evaluation of the materials. The Quartz on Ag and PZT-5H on Si-based MEMS devices were compared by the data collected from the DFT software. The SPSS tool is used as statistical software [25], [26]. The datasets were imported here. The graphs that resulted were plotted, and a comparison was made. The thickness of piezoelectric materials varies from 80 µm to 800 µm and is an independent variable. The dependent variables were the thickness of the substrate and the temperature, which were varied in relation to thickness values. As the thickness of the piezoelectric material decreases, the natural frequency and average power gradually decrease. The analysis is carried out by comparing the two groups' average harvested power and natural frequency values to their respective graphs.

RESULTS

The quartz on Ag substrate MEMS energy harvester significantly has greater average harvested power than PZT-5H on Ag substrate [2], [27]. Natural frequency, average harvested power, peakpower, and power density are the results of the DFT simulation. The layers of MEMS devices are depicted in Fig. 2. The electrodes are supporting layers and the top layer is made of piezoelectric material [28]. On the basis of the thickness of the piezoelectric material, PZT-5H and Quartz have a high thickness (800 µm). It has been demonstrated that the output power's efficiency has been flexibly reduced [29]. To increase the multimode energy harvester's operating frequency bandwidth while maintaining constant power efficiency. The thickness of the MEMS energy harvester ranges between 80 µm and 800 µm were simulated. The output power varies as well, from high to low frequency [30].

Table 1 shows the electrical properties of quartz on Ag and Table 2 provides for the PZT-5H MEMS energy harvesters. For both quartz and PZT-5H materials, the natural frequency, average harvested power, peak power, power density, and efficiency are shown. The output power of both piezoelectric materials is reduced as the thickness of the piezoelectric materials is reduced. When comparing the power efficiency of the two materials for ultra-low-power medical applications, the quartz material has the edge in biomedical applications.

The increase in the thickness of the piezoelectric material leads to an increase in the natural frequency. This power is used in low-power medical applications here. As a result, the thickness of the piezoelectric material is reduced. The piezoelectric materials used in low-power micro generators are quartz and PZT-5H.

Figure 3 shows that when the thickness of the piezoelectric material decreases, the power decreases. When quartz and PZT-5H materials are compared, both the piezoelectric material quartz on silver is the best material to use in biomedical applications.We can observe that quartz on silver has low average harvested power compared to PZT-5H material. Figure 4 shows that as there is a decrease in the thickness of the piezoelectric material, it reduces the power. When comparing the two piezoelectric materials, quartz on silver emerges as the best option for biomedical applications. When compared to PZT-5H material, quartz on silver has a lower peak power.

Natural frequency, average harvested power, peak power, and power density were obtained from the calculations. As shown in Fig. 5, the natural frequency in quartz on silver is lower at an 80µm thickness. At the low thickness of the piezoelectric material, the average harvested power, peak power, and power density are also low. Table 3 provides the comparison of group statistics for both sample groups in SPSS software providing mean, standard deviation and standard error mean for 25 samples. The mean value of average harvested power of PZT-5H based piezoelectric energy harvester (1.60E-08) is significantly better than the quartz based piezoelectric harvester (1.39E-06). Table 4 shows the average harvested power's mean and significance using SPSS software. SPSS is a statistical data analysis programme that is used to calculate the mean and significance between two groups in a variety of studies.

Figure 6 shows that the PZT-5H material has a high power compared to quartz on silver (Ag). Quartz is the best piezoelectric material to use in biomedical applications. In the vibrational analysis, the start frequency (400 Hz) and the end frequency (600 Hz) are also kept constant when varying the thickness of piezoelectric material to obtain the natural frequency.

DISCUSSION

The novel piezoelectric material PZT-5H and the conventional piezoelectric material quartz on silver MEMS piezoelectric energy harvester for low-power micro generators were analysed and compared [31]. Here, it is observed that quartz/Si has a better power than PZT-5H/Ag with respect to the average harvested power and natural frequency [1]. The average harvested power and natural frequency were dependent on the thickness, where the average harvested power and natural frequency is reduced with respect to the thickness of the piezoelectric material [32].

The factors that affect the thickness of Quartz/Ag in MEMS devices and PZT-5H/Ag in MEMS devices in this research work are piezoelectric material thickness and substrate thickness [1]. The other factors are kept constant and simulations are carried out by varying thickness of piezoelectric material [33]. Natural frequency is decreased with respect to the thickness of piezoelectric material. Temperature and vibrations influence the generation of power which is agreed by literature [34]. Piezoelectric materials have the mean differences, quartz/Ag has the highest mean with 2567.9 and PZT-5H has the lowest mean 1326.3. In standard deviation quartz/Si has the lowest standard deviation with 2.23E-06, PZT-5H/Ag has the highest standard deviation with 3.19E-02. In standard error mean quartz/Ag has the lowest error mean with 4.46E-7 and PZT/5H has the highest error mean with 6.39E-3.

The limitations were due to change in thickness and temperature. Better results in average harvested power have been obtained if temperature is varied instead of thickness. There is a restriction in thickness but for temperature there will be more number of values and the comparison can be done effectively. The future scope of this work can be extended in order to decrease the thickness of the substrate by decreasing the thickness and temperature values which strive to reduce natural frequency and average harvested power. In order to achieve more significant performance the materials have to be used in various fields.

CONCLUSION

The power generation through vibrational analysis for lead zirconate titanate (PZT-5H) and quartz on the silver substrate-based MEMS piezoelectric energy harvester for low-power micro-generators. The piezoelectric materials such as PZT-5H and Quartz were taken on Ag substrate for the low-power micro-generators. The silver MEMS energy harvester for low-power applications has been designed and characterized.

DECLARATIONS

Conflict of interests

No conflict of interests in this manuscript

Authors Contributions

Author KCDK was involved in data collection, data analysis, and manuscript writing. Author CRAJC was involved in conceptualization, data validation, and critical review of manuscript.

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FIGURES AND TABLES

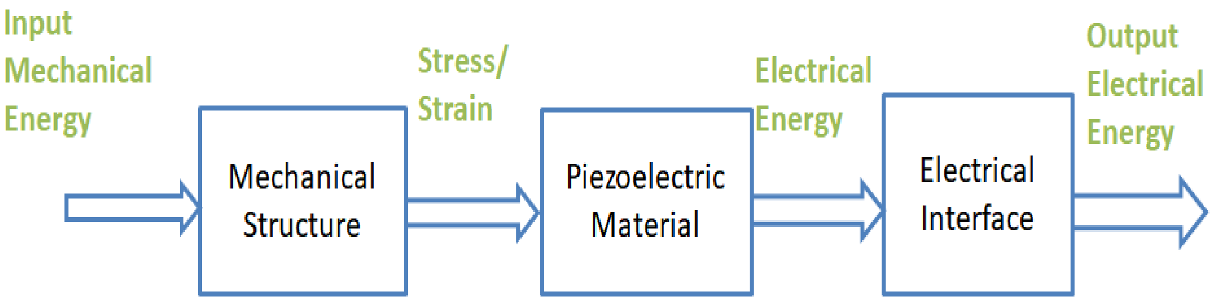

Fig. 1. Principle of piezoelectric energy harvesting

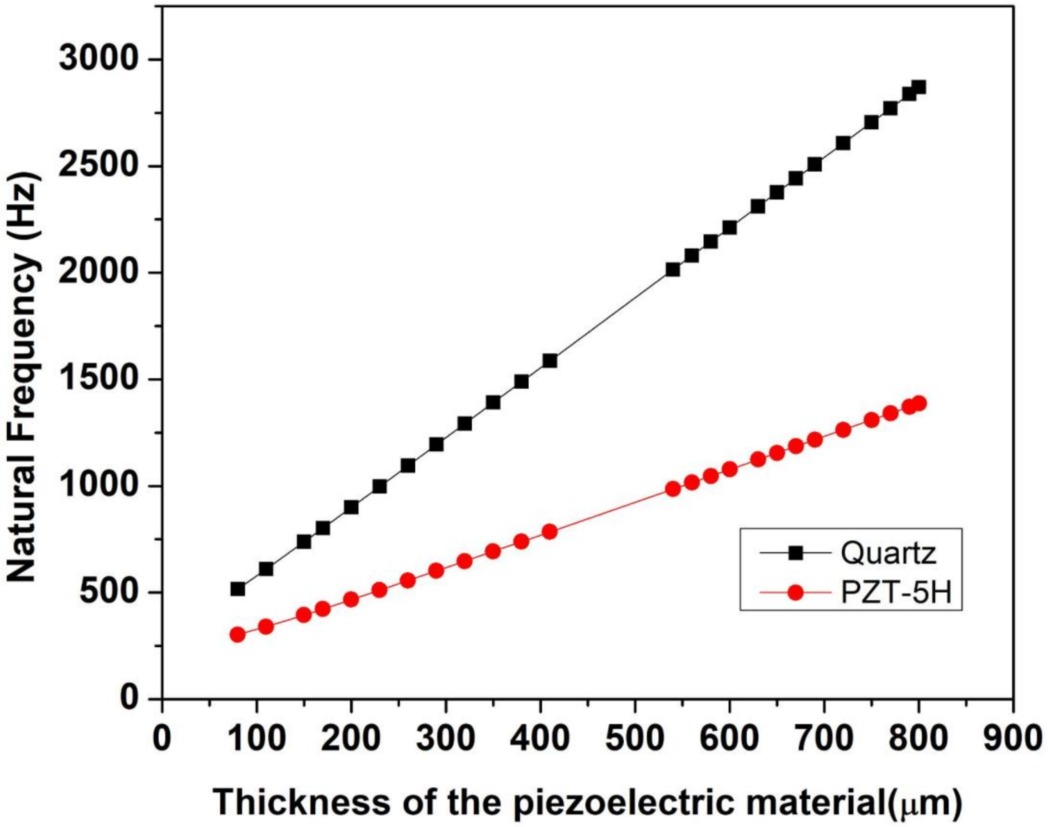

Fig. 2. Comparison of the plot providing thickness of the piezoelectric material vs natural frequency of Quartz/Ag and PZT-5H/Ag. Thickness ranging from 80 µm to 800 µm.

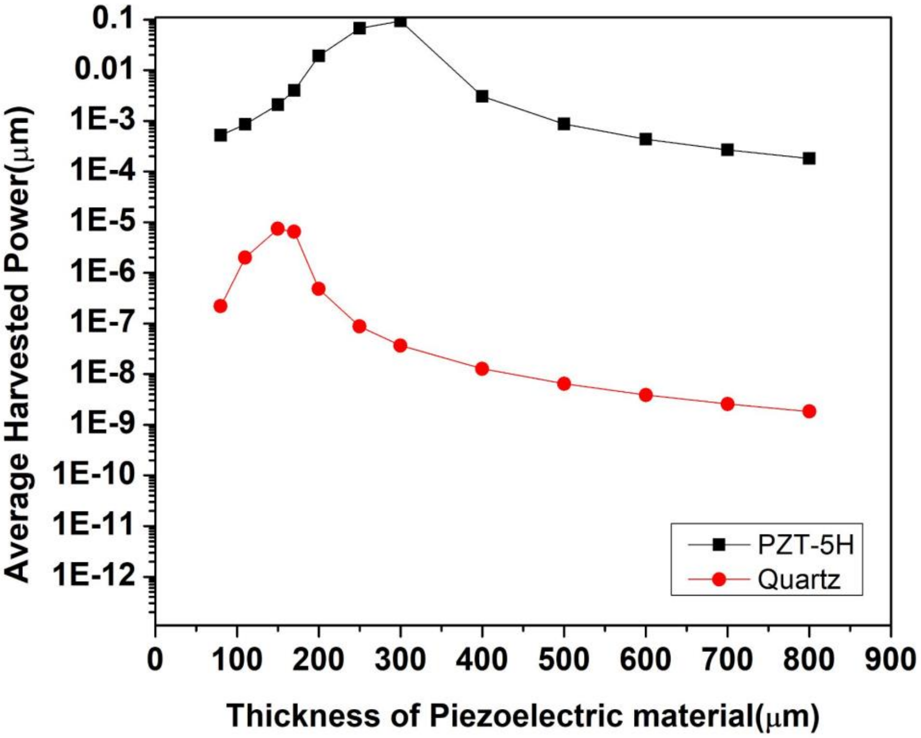

Fig. 3. Comparison of the plot providing thickness of the piezoelectric material vs the average harvested power of Quartz/Ag and PZT-5H/Ag. Thickness ranging from 80 µm to 800 µm.

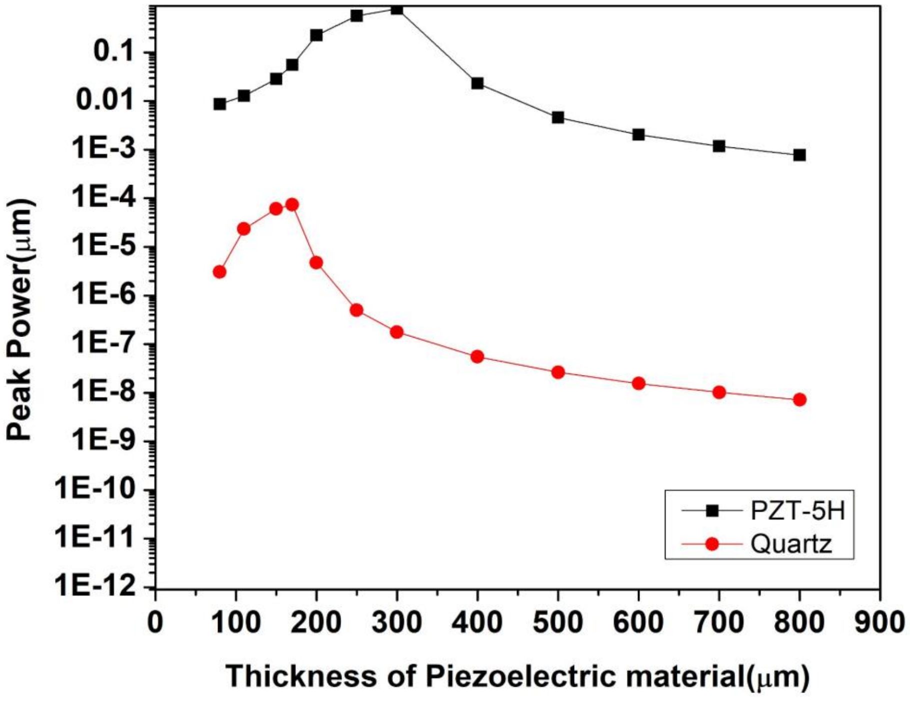

Fig. 4. Comparison of the plot providing thickness of the piezoelectric material versus the peak power of Quartz/Ag and PZT-5H/Ag. Thickness ranging from 80 µm to 800 µm.

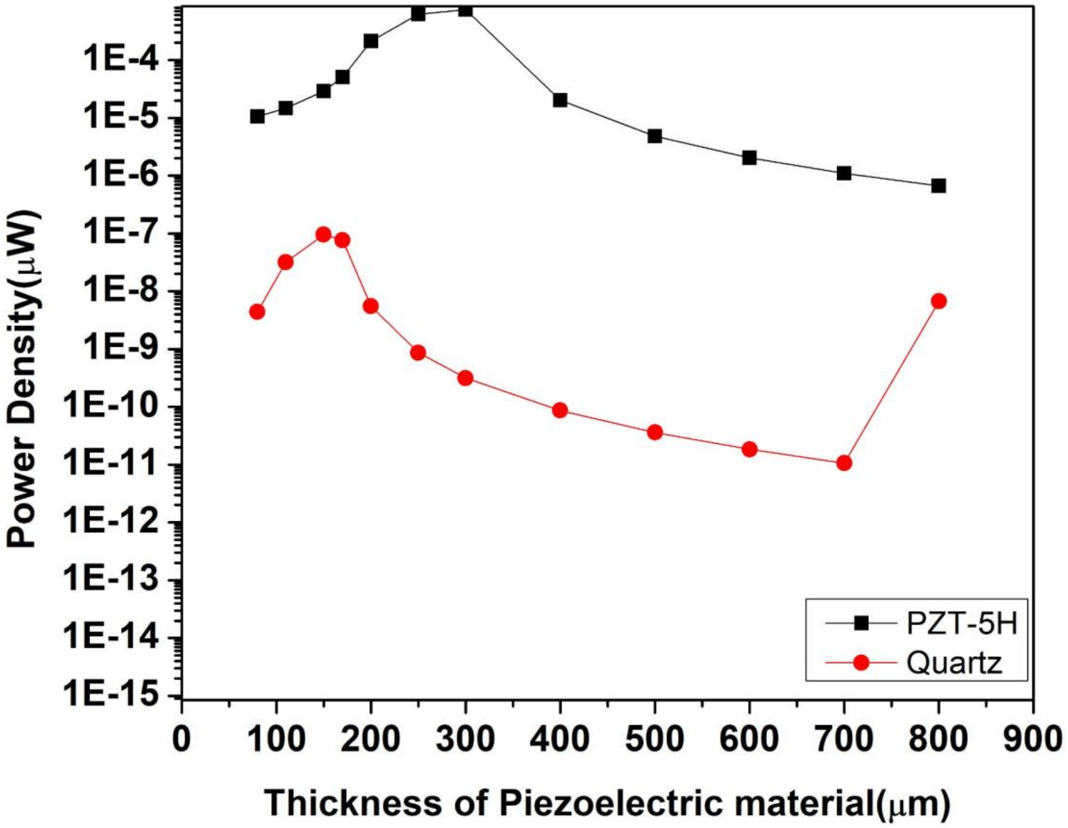

Fig. 5. Comparison of the thickness of the piezoelectric material versus the power density of Quartz/Ag and PZT-5H/Ag. Thickness ranging from 80 μm to 800 μm.

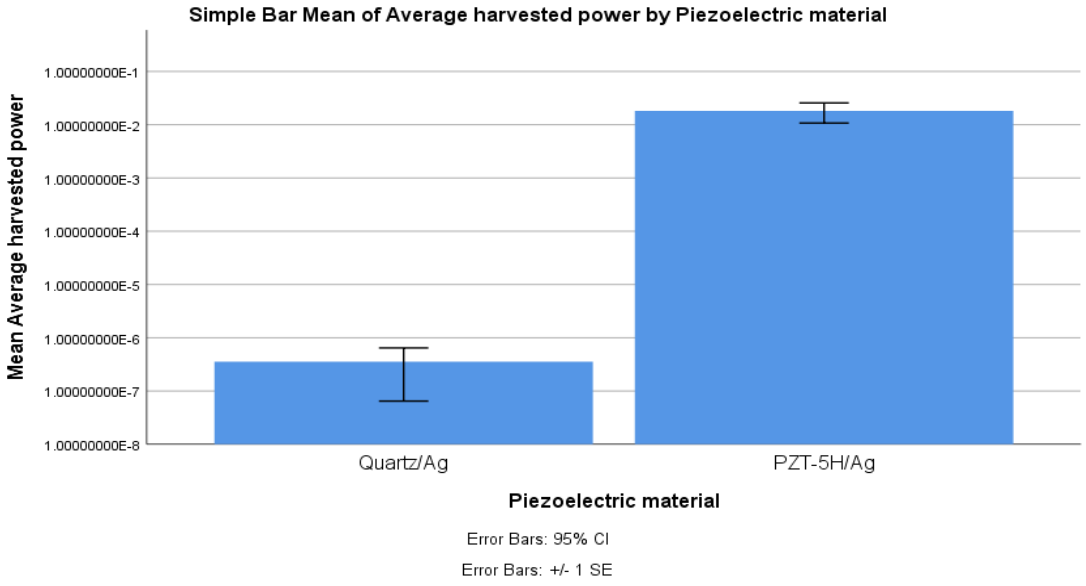

Fig. 6. Bar chart comparing the mean (±1SD) of the statistical analysis of Quartz/Ag and PZT-5H/Ag were the x-axis: Piezoelectric materials (groups) and y-axis: Mean average harvested power

Table 1. The average harvested power, natural frequency, peak power and power density for Quartz on Silver substrate.

S. No.	Substrate	Piezoelectric material	Thickness of piezoelectricmaterial (μm)	Natural frequency (㎐)	Average harvested power (μW)	Peak power (μW)	Power density (μW/m^2)
1	Ag	Quartz	800	2567.9	1.83E-09	7.17E-09	6.69E-09
2			700	2244.3	2.57E-09	1.02E-08	1.06E-11
3			500	1601.5	6.47E-09	2.65E-08	3.60E-11
4			200	663.98	4.80E-07	4.74E-06	5.51E-09
5			80	314.82	2.20E-07	3.06E-06	4.43E-09

Table 2. The average harvested power, natural frequency, peak power and power density for PZT-5H on Silver substrate.

Sl. no.	Substrate	Piezoelectric material	Thickness of piezoelectricmaterial (μm)	Natural frequency (㎐)	Average harvested power (μW)	Peak power (μW)	Power density (μW/m^2)
1	Ag	PZT-5H	800	1326.3	1.81E-07	7.17E-08	6.64E-07
2			700	1171.4	2.61E-07	1.70E-08	1.10E-06
3			500	861.64	4.33E-06	4.62E-07	4.83E-06
4			200	398.29	1.92E-06	2.24E-06	2.11E-06
5			80	215.73	5.15E-05	8.64E-04	1.05E-05

Table 3. Comparison of group statistics for both sample groups in SPSS software providing mean, standard deviation and standard error mean for 25 samples.

	Piezoelectric material	N	Mean	Std. Deviation	Std. Error Mean
Average Harvested Power	PZT-5H	12	1.60E-08	3.10E-08	8.94E-09
	Quartz	12	1.39E-06	2.65E-06	7.65E-07

Table 4. Independent sample t - test provides significance, mean difference and 95% confidence interval of the difference of the average harvested power and natural frequency. There is a significant difference between the two groups p<0.05 (Independent Sample T-Test).

Independent Samples Test										
Levene's Test for Equality of Variances				**t-test for Equality of Means**						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Average Harvested Power	Equal variances assumed	15.329	0.001	-1.798	22	0.086	-1.38E-6	7.65E-07	-2.96E-06	2.11E-07
	Equal variances not assumed			-1.798	11.003	0.1	-1.38E-6	7.65E-07	-3.06E-06	3.09E-07