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The application of piezoelectric materials to convert kinetic energy into electrical energy

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ABSTRACT

Purpose: The main goal was to determine the efficiency of converting kinetic energy into electrical energy in piezoelectric materials. The article presents research results regarding the relationship between the number of piezoelectric transducers, the generated voltage, and the relationship between the pressure force and the induced voltage.

Design/methodology/approach: Experimental research began with determining whether the voltage generated by piezoelectric transducers connected in series is proportional to their number. The spacers were then applied to see if this increased the performance of the test platform. The latest tests were carried out at the author's measurement station.

Findings: The authors of the work researched electricity generation by piezoelectric materials, confirming their potential but showing limitations related to the brittleness of the materials. The work suggests the possibility of improving the efficiency of these materials by examining the influence of the pressure frequency on the obtained value of the generated voltage.

Research limitations/implications: The main limitation was the need to develop an optimal test platform design that would effectively use the piezoelectric potential of the transducers while preventing their damage. The results were not entirely satisfactory; therefore, future research is intended to optimise the parameters of transducers and the test platform to maximise efficiency in converting mechanical energy into electrical energy.

Practical implications: A practical application of the obtained results may be using energy produced using piezoelectric membranes in renewable energy, for example, to power streetlamps, road signs, or other low-power devices.

Originality/value: The main originality of the research is the possibility of its practical application. Research on such many piezoelectric membranes connected in series is rare, which makes this configuration original.

Keywords: Smart materials, Electrical properties, Piezoelectric materials, Energy harvesting

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PROPERTIES

1. Introduction

Piezoelectric materials convert mechanical energy, such as vibrations or pressure, into electrical energy. Such property makes them valuable in various applications where harvesting energy from mechanical movements is essential. Such innovative materials have been studied for nearly a century now. Their properties are being enhanced to be used in novel applications. In the paper [1] Habib et al. present an overview of piezoelectric materials divided into three classes: ceramics, polymers, and composites. The materials under each class were examined and compared, with a concentration on their linear piezoelectric response.

Piezoelectric materials have a vast set of applications, including medicine (as a power source for pacemakers [2,3] similarly to TPU-based nanocomposites filled with halloysite nanotubes, they are used in regenerative therapies after oncological surgery [4,5]), sonar technology whether renewable energy technology (for example a system of plates from Pavagen that convert kinetic energy generated by people into electricity [6-8]). Both piezoelectric materials and organic waste in composites [9] can be seen as elements of sustainable technologies. Piezoelectric materials can help produce electricity from mechanical energy, which can be used to power electronic devices. At the same time, using organic waste as fillers in composites can help reduce waste and minimise environmental impact. Piezoelectric materials can also generate electricity from the oscillations or vibrations of motorcycle riding. The energy can be used to charge the motorcycle's battery, which, together with optimising the weight of its frame [10,11], could significantly reduce its price. In the paper, Gadgay et al. [12], propose a model that utilises human strolling, hopping, and running as a spring of electrical energy. Also, in [13,14] Somashekhar et al. and Bhatele et al. describe research on using piezoelectric materials to convert the force generated by human footsteps into a useful form of electricity. Researchers have shown that mounting one piezoelectric plate (piezotile) can create a maximum of 5-8 volts. They concluded that installing many piezotiles would generate high voltage but did not support it with research.

The article's authors researched to determine the relationship between the number of piezoelectric sensors and the generated voltage, as well as the relationship between the pressure force on the original test platform and the induced voltage.

2. Materials and methods

2.1. Designed test platform

Figure 1 shows the designed test platform, which consists of 48 piezoelectric transducers connected in a series—this method of connecting the transducers allowed for summing the voltage values of the generated current.

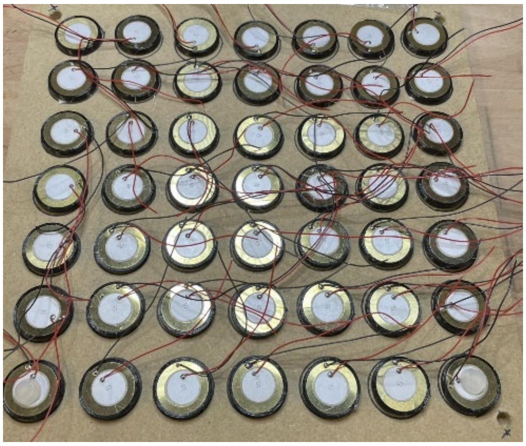

Fig. 1. Designed test platform

To convert alternating current into direct current, the Graetz diode bridge was used, which allowed the generated energy to be stored in the battery, as shown in Figure 2. One of the parameters characterising the diode bridge is the switching time. The parameter should be interpreted as the time parameter when the diode bridge changes from conducting to non-conducting. The faster the switching time, the quicker the alternating current will be rectified into direct current. The aspect is crucial when obtaining energy from piezoelectric materials because they produce an electric charge on their surface when deformed. However, when the piezoelectric materials are not deformed, these transducers return to their original form. During the process, the polarisation of the electric charge changes. This should be interpreted to discharge the energy accumulated on their surface. Therefore, severe energy losses may occur if the current is rectified for too long. For this reason, the Graetz diode bridge was made of four Schottky diodes [15-16].

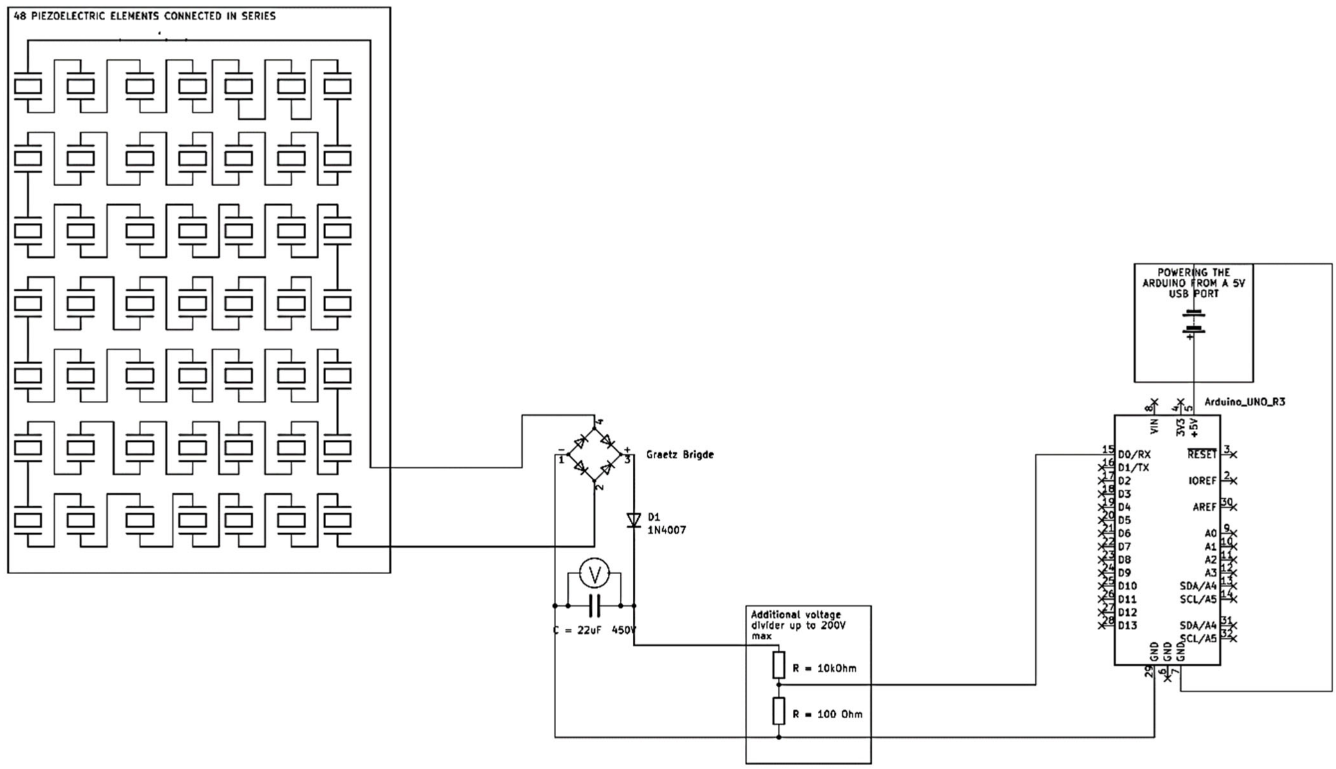

Fig. 2. Electrical diagram of the platform for testing the electrical properties of piezoelectric membranes

To avoid the risk of damaging the piezoelectric transducers under the influence of a point load, a plate attached to the linear motor was used as the type of pressure on the piezoelectric materials, as shown in Figure 3. The purpose of the system was to simulate the pressure of a human foot under conditions that provide a constant surface on which the pressure is exerted [17].

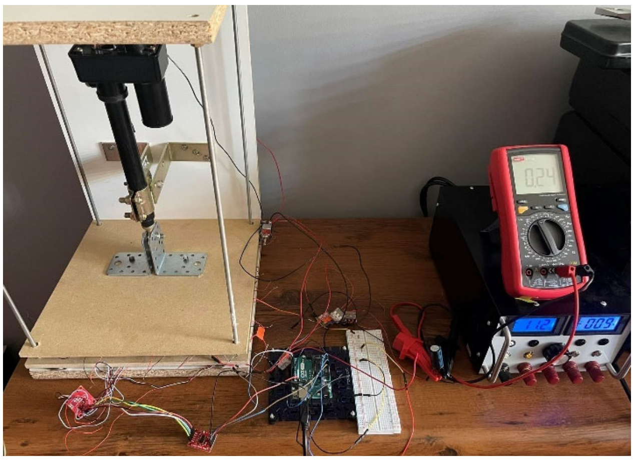

Fig. 3. Author's measurement station

The actuator was controlled using a lever switch, as shown in Figure 4.

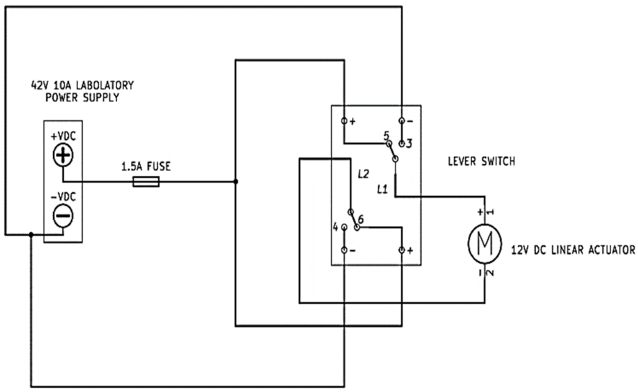

Fig. 4. Diagram of the actuator control system

2.2. Measurement methodology

The main goal of the research was to determine the relationship between the voltage value of the generated current and the value of the pressure force. In addition, the amount of generated electricity was determined. For this purpose, a capacitor was used as an energy store [18,19]. Knowing that the energy E stored in a capacitor with capacity C and the applied voltage V is equivalent to the work done by the battery to transfer the charge Q to the capacitor, the relationship can be determined:

$$E = \frac{1}{2} \cdot Q \cdot V = \frac{1}{2} \cdot C \cdot V^2 \tag{1}$$

where:
E – energy stored in the capacitor, in J,
C – capacity of the capacitor, in F,
V – applied voltage, in V,
Q – charge accumulated in the capacitor, in C.

Using the formula (1), the amount of energy generated by the test platform was determined.

Strain gauge sensors were used to measure the pressure force on the test platform. The diagram of their connection with the HX711 amplifier and microcontroller is shown in Figure 5.

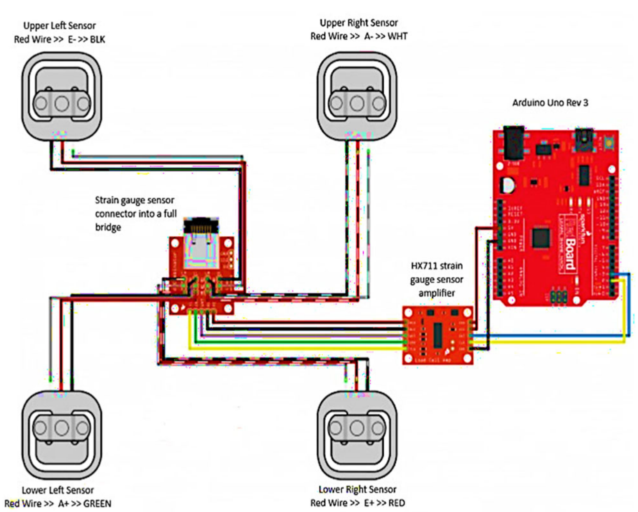

Fig. 5. The actual model of the test platform

3. Results of experimental studies

Based on the literature study [20-23], a research problem was formulated to determine the influence of the number of series-connected piezoelectric transducers on the amount of generated voltage. For this purpose, preliminary tests were carried out to verify whether the voltage increase in the system in which piezoelectric transducers are connected in series is cumulative.

The research was divided into two stages. The first determined the value of the alternating voltage initially generated by the piezoelectric transducer. In the second case, the value of the direct voltage after connecting to the rectifier bridge system was checked. First, the value obtained by a single piezoelectric transducer was measured, and then the value was summed for the assumed number of piezoelectric transducers. The values are presented in Table 1. Then, the output voltage for the series-connected piezoelectric transducers was measured. The obtained results are shown in Table 2.

Table 1.
The theoretical voltage values

No of piezo	DC voltage, V	AC voltage, V
1	0.67	13
2	1.34	26
4	2.68	52
8	5.36	104

Table 2.
The experimental voltage values

No of piezo	DC voltage, V	AC voltage, V
1	0.67	13
2	0.71	29.8
4	0.88	49.7
8	0.96	61.4

It is known from the literature study, including those described in [24-26], that piezoelectric transducers used to generate electricity need adequate space to deform their structure freely. The results presented in Tables 1 and 2 were performed on a substrate where the transducers had small spaces for free deformation. Therefore, in the next part of the research, appropriate spacers provided optimal space for the transducers. The spacers are presented in Figure 6.

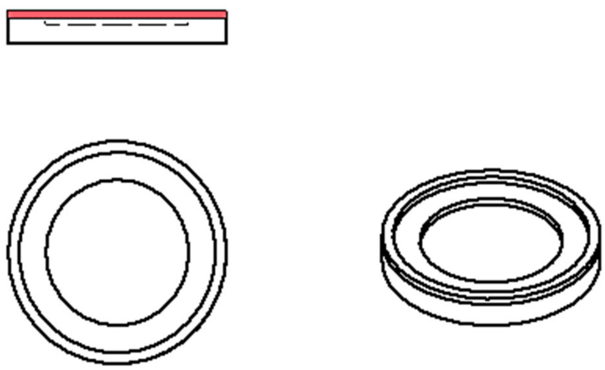

Fig. 6. The spacer

Figure 4 shows the position of the transducer relative to the spacer, which is marked in red. The dashed line shows the recess that allows the transducer to deform freely. The results of the measurements performed using spacers are presented in Table 3.

Table 3.
The experimental voltage values – platform test with spacers

No of piezo	DC voltage, V	AC voltage, V
1	0.70	52
2	0.97	70.8
4	0.92	81.7
8	0.95	87

The results obtained from preliminary tests indicate that with the increase in piezoelectric transducers connected in series, the value of the generated voltage increased. However, this relationship was not linear. Based on the results presented in Tables 1 and 2, with the increase in the number of transducers, the increase in the obtained voltage was smaller and smaller. The use of spacers significantly improved the efficiency of piezoelectric transducers. The voltage value obtained for one transducer increased 4 times and eight – 1.5 times.

The following research stage was to determine the relationship between the pressure force on the test platform (Fig. 1) and the voltage generated by the piezoelectric transducers. The tests were carried out at the author's measuring station (Fig. 3). A capacitor with a capacity of 22 μF and a maximum voltage of 450 V is connected to the system (Fig. 2). Its charge level was checked using a multimetre. Before each measurement series, the capacitor was discharged. Figure 7 presents the graphs of the dependence of the generated voltage on the pressure force for three representative series.

Based on the graphs presented in Figure 7, the relationship between the generated voltage and the pressure force is not linear. In the case of the first series, the maximum generated voltage was 192 V with a pressing force of 923 N. For the second series, it was 153.1 V at 859 N; for the third series, it was 150 V at 987 N. In the case of the first two measurement series, it was observed that after exceeding the pressure force of 600 N, the increase in the generated voltage was significant. However, in the case of the last series, a substantial increase in the induced voltage occurred after exceeding the pressure force of 85 N. At a value of approximately 100 N, it increased less dynamically.

The capacitor power was determined for the results of three series. The results are presented in Table 4.

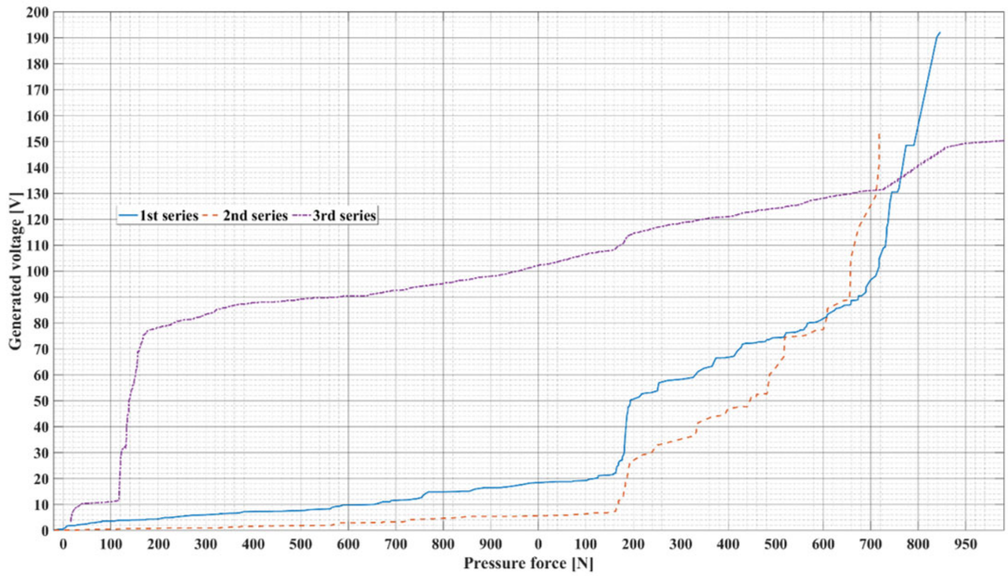

Fig. 7. Graph of the dependence of the generated voltage on the pressure force

Table 4.
The power accumulated in the capacitor

	1st series	2nd series	3rd series
The capacitor charge level, V	12.6	3.74	45.1
The power accumulated, μJ	1746.36	153.87	22374.11

The lowest power generated by the test platform was 153.87 µJ. In the case of the most extended measurement cycle, a power of 0.0223 J was developed.

4. Conclusions

The authors of the work make a significant contribution to research on using piezoelectric materials to generate electricity. Their experiments and analysis of the results may contribute to developing sustainable energy technologies. The work is an original approach to the topic. It suggests that further research and experiments may lead to more effective solutions using piezoelectric materials to convert kinetic energy into electrical energy.

The main conclusions resulting from the research discussed in the article are:

1. Confirmation of the ability of piezoelectric materials to generate electricity: The experiments proved that piezoelectric materials could generate electricity by exerting pressure on them.
2. Limitations of Piezoelectric Materials: Research has shown that piezoelectric materials such as lead zirconate titanate (LZT) are brittle and susceptible to failure under too much pressure. Determining the maximum pressure that can be safely applied to these materials is crucial.
3. Benefits of using spacers: Experimental results showed a beneficial effect of specially designed spacers on the energy generated. It may provide a practical solution to improve the performance of systems based on piezoelectric materials.
4. Total voltage increases in the series connection of piezoelectric elements: Although the results did not confirm the thesis, it is worth continuing the research, considering uniform pressure on the transducers.

The research results indicate the need for their continuation, among others, to examine the effect of the frequency with which we apply pressure on piezoelectric materials on the amount of voltage generated. Although the work has not achieved practical effectiveness, it provides a valuable knowledge base for further sustainable technology development. The possibilities of using piezoelectric materials in various practical applications are worth exploring.

Additional information

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References

[1] M. Habib, I. Lantgios, K. Hornbostel, A Review of Ceramic, Polymer and Composite Piezoelectric Materials, Journal of Physics D: Applied Physics 55/42 (2022) 423002. DOI: https://doi.org/10.1088/1361-6463/ac8687

[2] N. Li, Z. Yi, Y. Ma, F. Xie, Y. Huang, Y. Tian, X. Dong, Y. Liu, X. Shao, Y. Li, L. Jin, J. Liu, Z. Xu, B. Yang, H. Zhang, Direct Powering a Real Cardiac Pacemaker by Natural Energy of Heartbeat, ACS Nano 13/3 (2019) 2822-2830. DOI: https://doi.org/10.1021/acsnano.8b08567

[3] L. Dong, C. Jin, A.B. Closson, I. Trase, H.C. Richards, Z. Chen, J.X.J. Zhang, Cardiac Energy Harvesting and Sensing Based on Piezoelectric and Triboelectric Designs, Nano Energy 76 (2020) 105076. DOI: https://doi.org/10.1016/j.nanoen.2020.105076

[4] M. Mrówka, J. Lenża-Czempik, A. Dawicka, M. Skonieczna, Polyurethane-Based Nanocomposites for Regenerative Therapies of Cancer Skin Surgery with Low Inflammatory Potential to Healthy Fibroblasts and Keratinocytes In Vitro, ACS Omega 8/41 (2023) 37769-37780. DOI: https://doi.org/10.1021/acsomega.3c01663

[5] M. Chomiak, Reuse of polyester-glass laminate waste in polymer composites, Journal of Achievements in Materials and Manufacturing Engineering 107/2 (2021) 49-58. DOI: https://doi.org/10.5604/01.3001.0015.3583

[6] T. Jintanawan, G. Phanomchoeng, S. Suwankawin, P. Kreepoke, P. Chetchatree, C. U-viengchai, Design of Kinetic-Energy Harvesting Floors, Energies 13/20 (2020) 5419. DOI: https://doi.org/10.3390/en13205419

[7] Pavegen, Every Step Generates a Powerful Connection. Available from: https://www.pavegen.com/ (access in: 01.09.2023)

[8] R. Chmielewski, A. Baryłka, J. Obolewicz, The impact of design and executive errors affecting the damage to the floor of the concert hall, Journal of Achievements in Materials and Manufacturing Engineering 104/2 (2021) 49-56. DOI: https://doi.org/10.5604/01.3001.0014.8488

[9] M. Mrówka, D. Franke, M. Ošlejšek, M. Jureczko, Influence of Citrus Fruit Waste Filler on the Physical Properties of Silicone-Based Composites. Materials 16/19 (2023) 6569. DOI: https://doi.org/10.3390/ma16196569

[10] K. Stencel, M. Jureczko, Optimal Design of Electric Motorcycle Tubular Frame using Topology Optimization, WSEAS Transactions on Applied and

Theoretical Mechanics 18 (2023) 150-160. DOI: https://doi.org/10.37394/232011.2023.18.14

[11] C. Bala Manikandan, S. Balamurugan, P. Balamurugan, S. Lionel Beneston, Weight reduction of motorcycle frame by topology optimization, Journal of Achievements in Materials and Manufacturing Engineering 91/2 (2018) 67-77. DOI: https://doi.org/10.5604/01.3001.0012.9664

[12] B. Gadgay, D.C. Shubhangi, H. Abhishek, Foot Step Power Generation Using Piezoelectric Materials, Proceedings of the IEEE International Conference on Computation System and Information Technology for Sustainable Solutions "CSITSS", Bangalore, India, 2021, 1-5. DOI: https://doi.org/10.1109/CSITSS54238.2021.9682844

[13] G.C. Somashekhar, K.H. Anu Reddy, M. Bini, L. Prateeka, Energy Generation from Footsteps Using Piezoelectric Sensors, International Journal of Computer Sciences and Engineering 9/6 (2021) 54-58. DOI: https://doi.org/10.26438/ijcse/v9i6.5458

[14] P. Bhatele, S. Mali, A. Mali, M. Chrungoo, A. Mali, R. Makode, Energy Generation Via Footsteps Using Piezoelectric Sensor, International Research Journal of Engineering and Technology 9/12 (2022) 647-650.

[15] S. Chand, J. Kumar, Evidence for the Double Distribution of Barrier Heights in Pd_2Si/n-Si Schottky diodes from I - V - T measurements, Semiconductor Science and Technology 11/8 (1996) 1203. DOI: https://doi.org/10.1088/0268-1242/11/8/015

[16] S. Chand, S. Bala, Analysis of Current-Voltage Characteristics of Inhomogeneous Schottky Diodes at Low Temperatures, Applied Surface Science, 252/2 (2005) 358-363. DOI: https://doi.org/10.1016/j.apsusc.2005.01.009

[17] A.C. Redmond, J. Crosbie, R.A. Ouvrier, Development and Validation of a Novel Rating System for Scoring Standing Foot Posture: The Foot Posture Index, Clinical Biomechanics 21/1 (2006) 89-98. DOI: https://doi.org/10.1016/j.clinbiomech.2005.08.002

[18] S.M. Al-Jaber, I. Saadeddin, Theoretical and Experimental Analysis of Energy in Charging a Capacitor by Step-Wise Potential, Journal of Applied Mathematics and Physics 8 (2020) 38-52. DOI: https://doi.org/10.4236/jamp.2020.81004

[19] A. Bezryadin, A. Belkin, E. Llin, M. Pak, E. Colla, A. Huber, Large Energy Storage Efficiency of the Dielectric Layer of Graphene Nanocapacitors. Nanotechnology 28/49 (2017) 495401. DOI: https://doi.org/10.1088/1361-6528/aa935c

[20] T.-B. Xu, 7 - Energy Harvesting Using Piezoelectric Materials in Aerospace Structures, in: F.-G. Yuan (ed), Structural Health Monitoring (SHM) in Aerospace Structures, Woodhead Publishing, Sawston, Cambridge, 2016, 175-212. DOI: https://doi.org/10.1016/B978-0-08-100148-6.00007-X

[21] B. Zhao, F. Qian, A. Hatfield, L. Zuo, T.-B. Xu, A Review of Piezoelectric Footwear Energy Harvesters: Principles, Methods, and Applications, Sensors 23/13 (2023) 5841. DOI: https://doi.org/10.3390/s23135841

[22] M. Safaei, H.A. Sodano, S.R. Anton, A review of Energy Harvesting Using Piezoelectric Materials: State-of-the-Art a Decade Later (2008–2018), Smart Materials and Structures 28/11 (2019) 113001. DOI: https://doi.org/10.1088/1361-665X/ab36e4

[23] M.C. Sekhar, E. Veena, N.S. Kumar, K C.B. Naidu, A. Mallikarjuna, D.B. Basha, A Review on Piezoelectric Materials and Their Applications, Crystal Research and Technology 58/2 (2022) 2200130. DOI: https://doi.org/10.1002/crat.202200130

[24] C. Covaci, A. Gontean, Piezoelectric Energy Harvesting Solutions: A Review, Sensors 20/12 (2020) 3512. DOI: https://doi.org/10.3390/s20123512

[25] Y. Cao, F. Zhang, A. Sha, Z. Liu, J. Li, Y. Hao, Energy harvesting performance of a full-pressure piezoelectric transducer applied in pavement structures, Energy and Buildings 266 (2022) 112143. DOI: https://doi.org/10.1016/j.enbuild.2022.112143

[26] A. Aabid, M.A. Raheman, Y.E. Ibrahim, A. Anjum, M. Hrairi, B. Parveez, N. Parveen, J.M. Zayan, A Systematic Review of Piezoelectric Materials and Energy Harvesters for Industrial Applications, Sensors 21/12 (2021) 4145. DOI: https://doi.org/10.3390/s21124145