ANALYSIS OF PIEZOELECTRIC MATERIALS FOR IMPLANTABLE DEVICES

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Keywords: piezoelectric material, energy harvesting, pacemaker, ANSYS

Abstract: *The article deals with the analysis of piezoelectric materials and their possible application as alternative sources of electrical energy in implantable devices. Materials composed of GaN, ZnO, CdS and PZT-4 were considered under this study. The samples had three fundamental geometry which was a circle, square and rectangle with maximum area of 20 mm² and thickness of 0.1 mm. After considering the criterion for biocompatibility an analysis was done in software ANSYS which output voltage values. The most suitable piezoelectric material was found to be Gallium Nitride with a circular shape.*

1 INTRODUCTION

The term energy harvesting or energy scavenging refers to the process of obtaining ambient energy from the environment. The energy obtained by current methods for energy harvesting occurs in the range of small values, therefore the classical energy sources, such as fossil fuels, coal and nuclear power are still in use. However, energy harvesting systems can be used for small autonomous wireless and wearable devices, for instance: sensors, wrist watches, mobile phones, medical devices, etc. 90% of electronics are power by batteries. These batteries make devices bulky, heavy, take a lot of space, and must be replacement or recharge. It is now possible to apply solar radiation, thermal energy, magnetic field or mechanical energy, to replace batteries in generating energy for electronics with small power consumption. [1]

The piezoelectric effect occurs in the dielectric areas of materials with symmetric and asymmetric crystalline structure. It is a coupling between the material's mechanical and electrical behavior. When a mechanical stress is applied, an electrical charge is generated. This is called the direct piezoelectric effect which is used in sensors. The reverse piezoelectric effect is used in motors or actuators, where the applied electrical field causes deformation of the structure. [1] There exist several types of piezoelectric materials: ceramics, crystals, polymers, composites, etc. Ceramics are the most applicable materials used in industry and are represented mainly with different types of lead zirconate titanate (PZT). Their biggest advantage is that ceramics polarize after production and therefore can be modified according to demands. Rochelle salt, quartz, zinc oxide, etc. are amongst the group of crystal materials used. [2]

Describing the relationship between mechanical and electrical behavior, constitutive equations are used. These constitutive equations must be combined together as follows:

$$S = s_E \cdot T + d \cdot E \quad (1)$$

$$D = d \cdot T + \epsilon_T \cdot E \quad (2)$$

Where D represents the charge density, ϵ is the permittivity, E refers to electric field, S represents mechanical strain, s is compliance and T describes the stress, d is the vector of the piezoelectric coupling properties. Other coefficients and constants which describe piezoelectric materials are the piezoelectric charge constant d . The piezoelectric effect can occur in all possible directions therefore as subscript to the coefficients and constants are given numbers in accordance to the applied electrical field or mechanical displacement/force. [2]

This article deals with the application of piezoelectric materials for implantable devices. The aim is to design a generator suitable for a pacemaker. Each heart has its own internal electrical system which controls the rate and rhythm of the heartbeat. With each beat, the electrical discharge goes through the electrical system of the heart. The electrical system consists of a SA (sinoatrial) node, AV (atrioventricular) node, His Bundle, right and left Bundle branches and Purkinje fibers. The SA node provides the frequency by which the heart beats. The goal of cardio stimulation is to obtain correct rhythmic function of the heart. Defects which can be treated by a pacemaker or implantable defibrillator are bradycardia (heartbeat below 60 beats per minute - bpm), tachycardia (heartbeat above 100 bpm), fibrillation (quivering heart) or premature contraction (early heartbeat). [3]

The atria and ventricles beat with natural frequencies, which is 1 Hz and 0.8 Hz, respectively. According to heart disease there exist about 20 types of pacemakers location of the defect, type of programmable functions and mode of response. All these types are denoted by NBG code. [4] Pacemaker consists of a pulse generator, leads (electrodes) and battery. Average dimensions of the pacemaker are 42 x 51 x 6 mm and weight is 21 g. The overall size of the pacemaker, 2/3 is taken by the battery. Currently, the main emphasis is to minimize the size, weight and increase the working life of the battery. The average lifetime of a Lithium ion battery, which is used in the pacemakers, is 10 years maximum. After ten years the patient must undergo surgery to replace the battery of the pacemaker. These problems can be solved by applying an energy harvesting system using piezoelectric material. [3]

2 ANALYSIS AND SYNTHESIS OF MODELS

Material properties are described by the piezoelectric matrix (stress/strain), compliance matrix/stiffness matrix, density and permittivity. Strain matrix e is typically associated with stiffness matrix c^E . According to IEEE standard 176-1987 the matrices are transformed as seen in fig. 1.

$$\text{ANSYS}[c]E = \begin{matrix} & \begin{matrix} x & y & z & xy & yz & xz \end{matrix} \\ \begin{matrix} x \\ y \\ z \\ xy \\ yz \\ xz \end{matrix} & \begin{bmatrix} c_{11} & & & & & \\ c_{21} & c_{22} & & & & \\ c_{31} & c_{32} & c_{33} & & & \\ c_{61} & c_{62} & c_{63} & c_{66} & & \\ c_{41} & c_{42} & c_{43} & c_{46} & c_{44} & \\ c_{51} & c_{52} & c_{53} & c_{56} & c_{54} & c_{55} \end{bmatrix} \end{matrix} \quad \text{ANSYS}[e] = \begin{matrix} & \begin{matrix} x & y & z \end{matrix} \\ \begin{matrix} x \\ y \\ z \\ xy \\ yz \\ xz \end{matrix} & \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \\ e_{61} & e_{62} & e_{63} \\ e_{41} & e_{42} & e_{43} \\ e_{51} & e_{52} & e_{53} \end{bmatrix} \end{matrix}$$

Figure 1: *IEEE (176-1987) stiffness matrix and piezoelectric strain matrix, respectively [1]*

The materials under the study were Cadmium Sulfide, Gallium Nitride, Zinc Oxide and PZT – 4, in Tab.1 material properties are given.

Table 1: *Material properties*

Material/ Properties	ρ [kg/m ³]	e_{31} [m/V]	e_{33} [m/V]	e_{15} [m/V]	C_{11}^E [m s ² /kg]*E10	C_{33}^E [m s ² /kg]*E10	C_{12}^E [m s ² /kg]*E10	C_{13}^E [m s ² /kg]*E10	C_{44}^E [m s ² /kg]*E10	C_{66}^E [m s ² /kg]*E10	$\epsilon_{11}^S/\epsilon_0$ (E-10)	$\epsilon_{33}^S/\epsilon_0$ (E-10)	ϵ_0 [F/m]*E-12
CdS	5684	-0,22	0,46	-0,21	9,07	9,38	5,81	5,09	1,63	1,50	0,80	0,84	8,85
GaN	6150	-0,33	0,65	-0,30	39,00	39,80	14,50	10,60	12,20	10,50	0,02	-5,10	8,85
PZT-4	7500	-5,20	15,08	12,72	13,92	11,50	7,78	7,43	3,06	2,56	67,50	58,70	8,85
ZnO	5680	-0,57	1,32	-0,48	21,00	21,10	12,10	10,50	4,42	4,24	0,76	0,90	8,85

For the piezoelectric analysis in ANSYS, the appropriate element type must be chosen, which can combine the mechanical and electrical behavior of the model. PLANE and SOLID elements were used in analysis. The element was given degrees of freedom (DOF) in the form of VOLT or CURR, in order to calculate electric potential or current.

The design of possible generators was chosen to be the simplest for technological production, therefore circular, rectangular and square shape was selected. These areas were extruded along the normal in 0.1 mm increment:

- Square cross section area of 4 x 4 mm
- Circle with radius 2.25 mm
- Rectangle cross section area of 2 x 8 mm

These configurations can be seen in fig. 2. The harvester must not impede the heart beating action or action of the lungs during breathing, therefore the dimensions must be as small as possible.

Figure 2: *Models of material configurations*

The idea of replacing or recharging the batteries is based on the fact, that the piezoelectric material is charged by the hearts own operation. This means that the generator is loaded by harmonic pressure. The function representing the harmonic load is as follows:

$$p = p_0 \cdot \sin(\omega \cdot t)$$

(3)

The pacemaker or implantable cardio defibrillator is programmed depending on the heart condition. Therefore it is necessary to store the generated energy in a capacitor and then use it at a time when the heart needs stimulation. Classical implantable devices don't have such storages of energy because they run on batteries. This function can be seen in fig. 3 below.

Figure 3: Pacemaker charged by heart (1-heart, 2-implantable device, 3-piezoelectric material, 4-heart beat action, 5-processing computer)

Tab. 2 represents simulation of analysis described above, where time of simulation was 10 seconds and results are in 10E-14 volts. Starting values at time 1 second are very low and during the simulation the values oscillate around the equilibrium position which is zero. The square model was not sufficient; the rectangular and circular model returned better results.

Table 2: *Voltage generated within 10 seconds*

Material	Model	Time of simulation [s]/ Output voltage [1E-14V]									
CdS		1	2	3	4	5	6	7	8	9	10
	CIRCLE	0,07	0,15	-1,91	0,29	2,50	-3,82	6,91	0,59	-5,73	5,00
	SQUARE	0,03	0,05	-0,65	0,10	0,85	-1,30	2,36	0,20	-1,95	1,70
	RECTANGLE	0,10	0,20	-2,56	0,39	3,35	-5,11	9,25	0,79	-7,67	6,69
PZT-4											
	CIRCLE	-0,01	-0,02	0,21	-0,03	-0,28	0,42	-0,77	-0,07	0,64	-0,55
	SQUARE	0,00	0,00	0,06	-0,01	-0,08	0,13	-0,23	-0,02	0,19	-0,17
	RECTANGLE	-0,01	-0,02	0,25	-0,04	-0,32	0,49	-0,89	-0,08	0,74	-0,64
ZnO											
	CIRCLE	0,06	0,12	-1,59	0,24	2,07	-3,17	5,73	0,49	-4,76	4,15
	SQUARE	0,02	0,04	-0,55	0,09	0,72	-1,11	2,00	0,17	-1,66	1,45
	RECTANGLE	0,08	0,17	-2,17	0,33	2,84	-4,34	7,85	0,67	-6,51	5,68
GaN											
	CIRCLE	0,09	0,19	-2,41	0,37	3,16	-4,82	8,72	0,74	-7,24	6,31
	SQUARE	0,02	0,03	-0,43	0,07	0,56	-0,85	1,54	0,13	-1,28	1,12
	RECTANGLE	0,07	0,14	-1,80	0,28	2,36	-3,60	6,51	0,56	-5,40	4,71

3 CONCLUSION

The human body offers a great source of ambient energy which can be transformed to electrical energy and potentially power small devices such as pacemakers, ICD, deep brain neurostimulators, insulin pumps, etc. Currently the focus is to make medical devices wireless, long lasting, small and light. These demands can be fulfilled by application of piezoelectric materials as a generator for powering a pacemaker or any other implantable device.

Figure 4: *Results of analysis*

After analyzing 3 fundamental generator shapes made from 4 different materials, it can be concluded that Gallium Nitride with the circular model and PZT-4, Cadmium Sulfide and Zinc Oxide with rectangular model were the most efficient which we can see in fig. 4.

The most voltage was produced by Cadmium Sulfide, Gallium Nitride, Zinc Oxide and PZT-4, respectively. The aim is to implant such a generator into the human body; therefore the model needs to meet the criterion for biocompatibility. Even though Cadmium Sulfide obtained the best results after applying the load, it is sadly a heavy metal and cannot be used in body. The Second most efficient model was made of Gallium Nitride in a circular shape which meets the criterion of biocompatibility. Zinc Oxide, which is currently utilized in the biomedical industry produced the third most electricity while the least voltage was generated by PZT – 4 and moreover PZT – 4 contains lead which is toxic.

The shape of the generator must also be taken into consideration. There are two shapes which show promise for voltage generation. The disadvantages of rectangular model are sharp edges. The generator cannot hurt the muscle of heart, therefore after all conditions which were described in the text, it can be concluded that the most suitable generator is made of Gallium Nitride in a circular configuration.

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