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Study on Waste Heat Energy Harvestingusing Pyroelectric Ceramics

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ABSTRACT

Waste thermal energy harvesting is becoming a popular area of research because of the continuously diminishing of conventional energy resources. Waste thermal energy comes from the sun, exhaust emissions, and waste oil/water exiting manufacturing and power plants. Particularly energy harvested in terms of micro/milli watts has gained more attention for low-power electronics. Energy requirements for self-powered wireless devices can be covered with these waste energy resources. Pyroelectric materials have been extensively explored for such kind of energy harvesting applications. These materials generate electrical current on the expense of input thermal energy. Pyroelectric devices have many advantages such as high sensitivity, high response time, high reliability, and low cost. This study explore the knowledge about the thermal energy harvesting potential of Pyroelectric material.

Keywords:Ferroelectric, Pyroelectric and Thermal energy harvesting, Olsen Cycle.

I INTRODUCTION

Ferroelectric oxide ceramics are used in a very broad range of functional ceramics and form the materials base for the majority of electronic applications like sensors, actuators, buzzers, medical ultrasonic transducers, etc. These materials have excellent piezoelectric properties, pyroelectric properties, figure of merits (FOMs) and good temperature stability [1-3]. Pyroelectric materials are a subclass of piezoelectric materials as in fig. 1. These are 10 point symmetry group exist in 32 non cento-symmetric piezoelectric materials, which display spontaneous polarization in the absence of an electric field. In addition to having piezoelectric characteristics, these materials demonstrate a change of polarization on exposure to a transient temperature gradient. Pyroelectric materials possess spontaneous polarization due to their non-cento-symmetric crystal structure. This creates permanent dipole moment along the material’s crystal axis. In multi-crystalline sample, dipoles are aligned in preferential direction to create surface polarization [4-5].

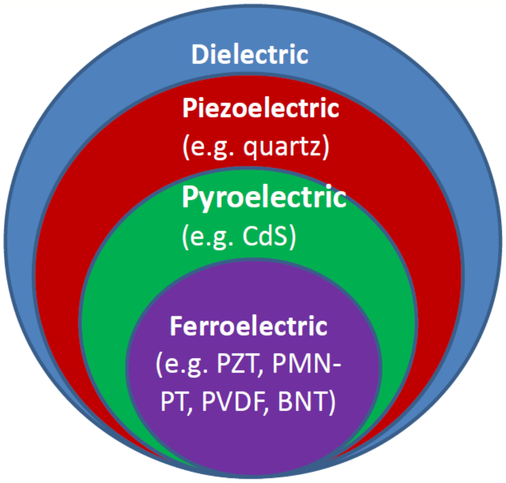


Figure 1: Functional hierarchy of ferroelectric materials

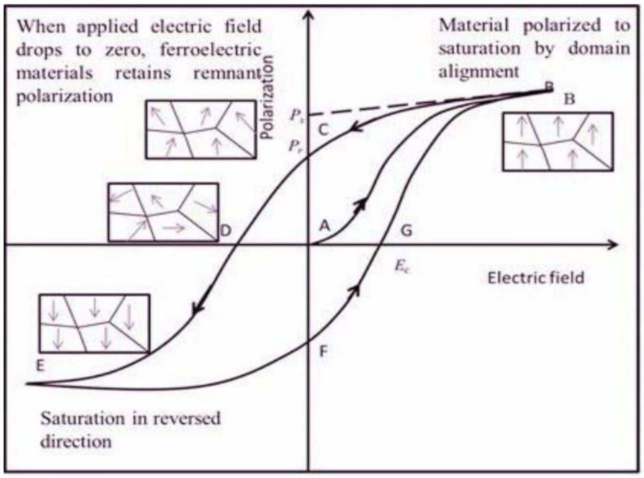


Figure 2: P-E hysteresis loop for ferroelectric materials

Material surface attract free charge of opposite nature in order to maintain electrical charge neutrality. When a temporal temperature gradient is applied to these materials, the dipoles become randomly oriented due to thermal agitation. Accordingly, the polar vector decay and electrical imbalance is produced on the material surface. In this condition if surfaces are kept insulated an electrical potential is developed. Further, if conducting surfaces are connected through a conducting medium, a flow of charge takes place which is known as pyroelectric current. As the temperature is decreased, the dipoles are restored to their initial orientation. On heating and cooling of material, the movement of the atoms from their equilibrium location results in the pyroelectric effect. This forms the basis of pyroelectric energy harvesting and conversion [6-9].

Ferroelectric materials are categorized by remnant polarization in the absence of electric field. Thispolarization is switchable reversibly on application of suitable electric field. A polar vector with different orientation may cohabit within a ferroelectric material. The region of such polar vectoris known as ferroelectric domains. Domains are regions within the crystal separated by domainwall. Dipoles within these regions are aligned in specific direction. In case of polycrystallinematerials these domains are randomly aligned in different direction causes for diminishing netpolarization. Poling of ferroelectric materials can facilitate alignment of all domains in onedirection there by providing material with net polar vector.Further, when the applied electric field decreases depolarization process alters form its originalpath and polarization decreases with low rate. Whereas after complete removal of electric field(E=0), material possess some polarization (C) known as remnant polarization. As the direction ofelectric field is reversed, remnant polarization decreases and attains zero value at specific electricfield (D) termed as coercive electric field (*Ec*).Further increase in electric field, the polarization attains saturation in reverse direction (E).Correspondingly, as the applied electric field direction is changed similar behavior is observedcompletion of all process from E-F-G-B results in a symmetric hysteresis (*P-E*) loop. Thespontaneous polarization (±Ps) is defined as the extrapolation of maximum polarization on y axisas shown in figure 2. Ps is often found to be higher in polycrystalline materials due for resistanceto formation of reversed domains during decrease in the electric field to zero however, in singlecrystal material Pr and Ps is almost same and it can be close in single crystals. Ferroelectricmaterials possess a spontaneous electric polarization which is reversible under applied electricfield.

Energy resources such as batteries and fuel cells are used in power electronics devices [10-11]. However, they have many disadvantages such as high maintenance costs and frequent recharging issues. Many researchers have investigated scavenging energy from the environment for prolonged operation of miniature devices such as wireless sensor networks. There are many ways of harvesting waste thermal energy such as solar photovoltaic, thermoelectric, and solar thermal power plants in shown in fig. 3.

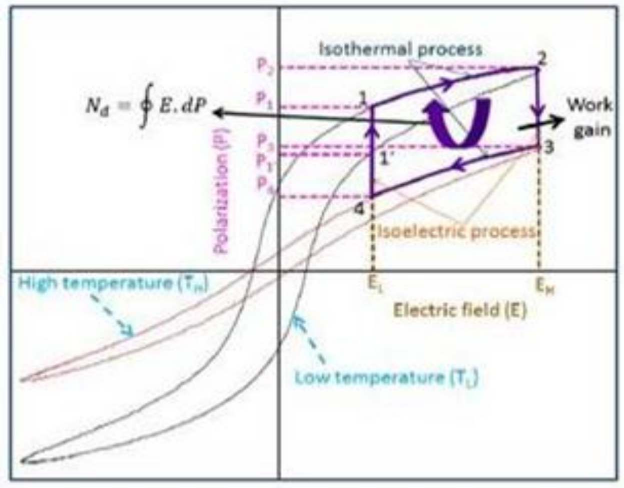


Figure 3:Application areas for Pyroelectric Figure 4: Thermal energy harvesting cycle materials

To harvest energy using thermoelectric materials, a large spatial temperature difference needs to be maintained, which is difficult to achieve in specific applications, and the devices have low efficiencies. On the other hand, thermal energy harvesting using the pyroelectric effectis becoming a prominent area of research. Pyroelectric ceramics such as $LiNbO_3$, $LiTaO_3$, $Sr_{0.5}Ba_{0.5}Nb_{0.5}O_6$, $Ca_{0.2}(Sr_{0.5}Ba_{0.5})0.8Nb_{0.5}O_6$, and $Pb(Zr_{0.5}Ti_{0.5})O_3$ are promising materials. There are few research groups who have attempted to achieve thermal energy harvesting using the pyroelectric effect. Energy harvesting through the pyroelectriceffect requires a continuous temporal thermal gradient. To attain this continuous temporal temperature gradient, several methods have been reported [12-14].

II WORKING PRINCIPLE

The pyroelectric effect is a phenomenon originating from non-centro symmetric materials that generates an electrical potential from temporal temperature changes in the materials. Such materials retain spontaneous polarization because of their non-centro symmetric crystal structure. The unit cells of pyroelectric materials contain permanent dipole moments, and these dipoles contribute towards the spontaneous polarization. An electric current can be generated by temporal temperature fluctuations using two parallel surfaces of pyroelectric material with electrodes connected to an external circuit. For a temperature gradient of zero on a pyroelectricmaterial (dT/dt=0), the spontaneous polarization remains constant, which results in no electric current flow to the external circuit. Similarly for a positive temporal temperature gradient (dT/dt>0), the spontaneous polarization of the material decreases. This causes the redistribution of surface charge on the electrodes, which results in current flow in the external circuit.Upon cooling (negative temporal temperature gradient), the spontaneous polarization increaseswhich causes an increase in surface charge. The direction of current flow in the external circuit reverses during heating/ cooling cycles. These cycles can be repeated using a pyroelectric material for thermal energy harvesting. The relations for the pyroelectric current and electrical charge can be written as:

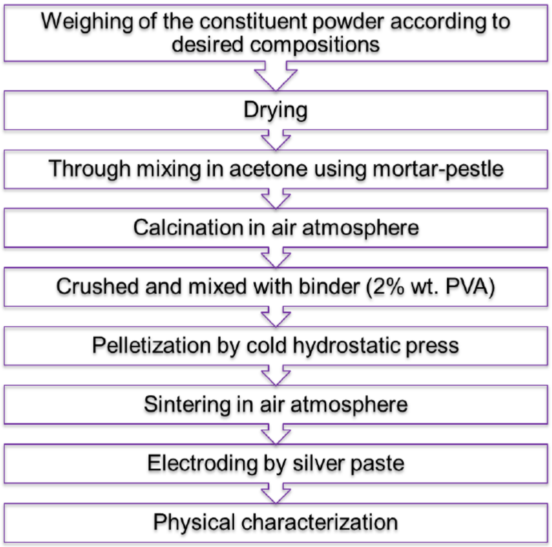
$$I_{\mathrm{P}} = pA_{\mathrm{m}}\frac{\mathrm{d}T}{\mathrm{d}t} \text{ and } Q = pA_{\mathrm{m}}\mathrm{d}T \qquad (1)$$

for which I_P is the generated pyroelectric current, Q is charge generated, A_m is the surface area of the pyroelectricmaterial perpendicular to the polar vector, p is the coefficientof pyroelectricity, and dT/dt is the temporal temperaturegradient.

In figure 4, it is recorded that the reversible polarization can be made to get a clockwise loop in the middle of two different temperatures. This cycle is known as Olsen cycle, which basically is used to convert thermal energy into electricity. This cycle have two isothermal and two iso-electric field processes. The processes 1-2-3-4-1 represent the electric analog of the Olsen cycle, whereas corresponding embedded area shows the maximum electric energy conversion per unit volume per cycle.The area enclosed (1-2-1-1) represents the hysteresis loss when Olsen cycle is operated in bipolar P–E loop. However, in the unipolar P–E loop, hysteresis loss is very small. So, for unipolar condition hysteresis loss, these can be neglected and the enhanced energy conversion is expressed by the shifted loop (1-2-3-4-1), which is considered in the current study. Process 1-2 is performed at a constant lower temperature (T_L) as electric field increases from lower limit (E_L) to higher limit (E_H), and correspondingly material polarization also increases. In process 2-3, heat (Q_S) is given to the material, which increases the temperature and produces lattice vibration. Therefore, material depolarizes at constant electrical field E_H. So, this develop a large depolarization current, which can be used or stored for powering electronic equipment using suitable circuit. Moreover, temperature of the material increases from lower temperature (T_L) to higher temperature (T_H). In the process 3-4, the electric field reduces from E_H to E_L at constant temperature T_H. Therefore, the polarization also decreases due to lack of electric field, which developed a weak depolarization current. Finally, in process 4-1, extraction of heat from the system at constant electric field (E_L) is done so that the materialreaches to its initial state andfinish the cycle. Energy density (N_D) per unit volume of the material can be estimated [15-16].

III FABRICATION TECHNIQUE

Ferroelectric ceramics can be fabricated using a wide variety of methods (solid oxide route, sol-gel, co-precipitation, hydrothermal, combustion and their combinations). However, the vast majority of ferroelectric ceramics are produced by solid oxide reaction route. The important steps that are involved in fabrication and characterization of ferroelectric ceramics used during current investigations are depicted in fig. 5 in the flowchart.



A flowchart depicting various steps involved in the fabrication of ceramics

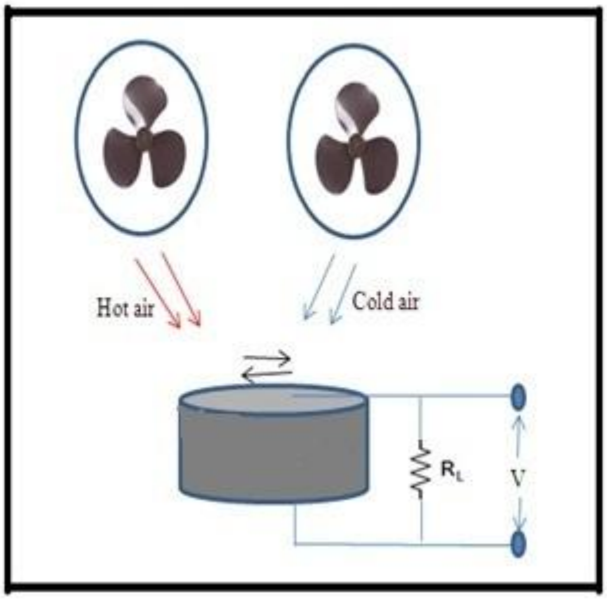


Figure 5: Flowchart for fabrication of ceramics Figure 6: Electrical energy generationset up using pyroelectric ceramics

In order to measure the pyroelectric signal in the composition under study, the pyroelectric material was poled in silicon oil. Figure 6 shows the typical schematic of the electrical energy generation from pyroelectric ceramics. The poled sample was alternatively placed in front of hot and cold air to generate continuous temperature gradient. Upon exposure to a transient thermal gradient, the pyroelectric material generates continuous electrical signal.

IV CONCLUSIONS

Energy recycling from the by-products of energy conversion devices is a topic of prime concern for effective utilization of resources. In this context, we have done the study of efficient conversion of heat energy into electric signal by using pyroelectric material .These materials also explored for energy harvesting applications. This property of these materials propounds ample possibilities for harnessing energy from the thermal by-products of many energy conversion and commercial electronic devices such as internal combustion engines, refrigerator, microwave oven, laptop, television, and other domestic appliances. This study will provide the various inputs to design a system for energy harvesting applications.

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