ENERGY HARVESTING FROM BICYCLE VIBRATIONS USING FLEXIBLE LEAD-FREE PIEZOELECTRIC MATERIALS

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Abstract
A piezoelectric flexible patch, based on $(K_{0.5}Na_{0.5})(Nb_{0.85}Sb_{0.05}Ta_{0.1})O_3$ doped with 0.5 mol% $GdMnO_3$ piezoelectric ceramic was studied. The ferroelectric and piezoelectric measurements performed shows good material properties of the studied compound. The application considered is an electric energy harvester from the rotation of a bicycle wheel. A maximum output power of 4.522 mW was obtained, sufficient to light a LED or charge a rechargeable battery.

Introduction
Perovskite ferroelectric materials are considered nowadays very interesting, due to their extraordinary piezoelectric proprieties, with application in the field of sensors, actuators and transducers. $(K,Na)NbO_3$ perovskite ferroelectric materials are considered promising materials as alternative environmental friendly piezoelectrics [1, 2, 3], envisioned to replace current lead based materials based on $Pb(Zr,Ti)O_3$. The latest finding shows that $(K,Na)NbO_3$ piezoceramics can reach a value for the charge coefficient of d_{33} = 490 pC/N [4], superior to some lead based compositions.
Current renewable energy technologies are based on wind power or solar energy. A new field that recently emerged is based on recovering energy from different sorts of vibration. The conversion of mechanical energy into electrical energy can be done by electromagnetic induction, electrostatic induction or by direct piezoelectric effect, using piezoelectric materials [5]. The piezoelectric materials used for electric energy harvesting can be ceramics, polymeric or composite. Functionally, there are two types of piezoelectric materials: monolithic, with one active part and bimorph, with two active components (the piezoelectric material and a metal or plastic substrate). Structurally, a bimorph can be fabricated using a polymeric material (such as PVDF [6]), a ceramic material or a mixture of piezoelectric ceramics (particles or fibers) and polymers, known as composite materials [7].
The purpose of this work is to fabricate and characterize a flexible piezoelectric materials based on $(K_{0.5}Na_{0.5})(Nb_{0.85}Sb_{0.05}Ta_{0.1})O_3$ doped with 0.5 mol% $GdMnO_3$ ceramics. The energy harvesting application proposed consists of a bicycle, where a flexible piezoelectric patch was mounted on the wheel. The AC voltage obtained was converted into DC using an electronic converter, and then the electric energy is stored in a rechargeable battery.

Experimental
A flexible piezoelectric electric energy harvester was obtained based on $(K_{0.5}Na_{0.5})(Nb_{0.85}Sb_{0.05}Ta_{0.1})O_3$ doped with 0.5 mol% $GdMnO_3$ (noted KNNST-0.5GM) piezoelectric ceramics. A solid state reaction was used to obtain the intended compound, starting from K_2CO_3 (99%; Scharlau), Na_2CO_3 (99%; Scharlau,), Nb_2O_5 (99%; Merck), Gd_2O_3 (99%; Fluka), Mn_2O_3 (99%; Sigma-Aldrich), Sb_2O_5 (99%; Merck) and Ta_2O_5 (99%; Merck). The samples were first calcined at 880º C for five hours, then mixed with a 5 mass% PVA binder, cold pressed at 200 MPa into disk samples of 10 mm in diameter and 0.5 mm thickness, and sintered at 1090°C for 3 hours. Flexible piezoelectric patches were obtained by

metal soldering a rectangular shaped piezoelectric ceramic to a thin metal plate, and then glue bonded to a large flexible fiber glass substrate. X-ray diffraction was obtained using a PanAnalytical X'Pert Pro MPD diffractometer (Netherlands). The temperature dependence of the dielectric constant and dielectric loss was obtained 1 kHz, using an Impedance/LRC meter TEGAM model 3550 (Geneva, OH, USA). The hysteresis loop was obtained at 100 Hz, using a Sawyer-Thomson capacitive voltage divider, coupled with an Atten ADS 1152CML digital storage oscilloscope (Helmond, Netherlands). The piezoelectric properties were measured using the resonance method with an impedance analyzer Agilent E5100A (Amstelveen, Netherlands).

Results and discussion

Figure 1 shows the X-ray diffraction pattern of $(K_{0.5}Na_{0.5})(Nb_{0.85}Sb_{0.05}Ta_{0.1})O_3$ – 0.5 mol% $GdMnO_3$ sintered ceramics. The pattern obtained was indexed as pure perovskite using the JCPDS-ICDD file number 01-071-2171, with a mixture of orthorhombic and tetragonal crystalline structure at room temperature, identified from the splitting of [200] and [020].

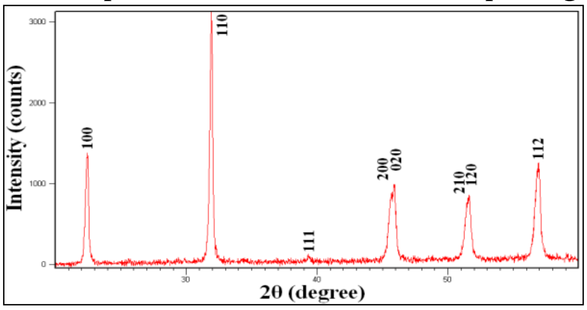

Figure 1. X ray diffractions of KNNST-0.5GM

The variation of dielectric constant and dielectric loss for KNNST-0.5GM ceramics, in terms of temperature, is presented in figure 2. The dielectric spectroscopy measurements were performed from room temperature up to 430º C, at 1 kHz. From X-ray diffraction we have concluded that the system crystallize in a mixture of orthorhombic and tetragonal phases at room temperature. At 60º C, the system re-crystallizes in tetragonal symmetry, than at 260º C, the Curie temperature of the composition, the system distorts to cubic symmetry. All phase transitions are marked by inflexions points in figure 2. Similar behavior was observed for the dielectric loss variations. At room temperature a small dielectric dissipation factor was measured, of 0.09, where at high temperature, the factor increases exponentially up to 0.22.

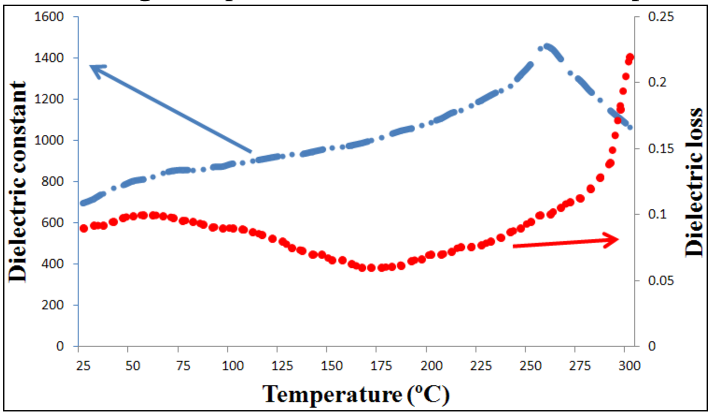

Figure 2. Temperature dependence of the dielectric constant and dielectric loss

KNNST doped with 0.5 mol% $GdMnO_3$ shows good ferroelectric properties, as proved in figure 3. The remnant polarization measured was 14.5 $\mu C/cm^2$, with a polarization saturation value of 28 $\mu C/cm^2$. Also, for a maximum electric field applied of 50 kV/mm, the coercive field measured was 14 kV/cm

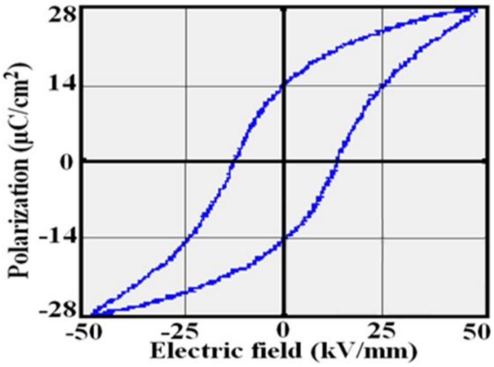

Figure 3. Room temperature hysteresis loop of KNNST-0.5GM ceramics.

After poling in silicon oil at room temperature, for 30 minutes at 4 kV/mm, the samples were aged for 1 day.For a complete determination of piezoelectric coefficients from resonance and anti-resonance curves, both radial mode and length mode oscillations were used. The piezoelectric properties are presented in table 1.

Table 1. Piezoelectric properties of KNNST-0.5GM.

Q	k_{31}	k_p	S^E_{11} [10^{-12} m^2/N]	S^E_{12} [10^{-12} m^2/N]	S^D_{11} [10^{-12} m^2/N]	d_{31} [10^{-12} C/N]	g_{31} [10^{-3} Vm/N]	k_{33}	d_{33} [10^{-12}C/N]	g_{33} [10^{-3} Vm/N]	S^D_{33} [10^{-12} m^2/N]	S^E_{33} [10^{-12} m^2/N]
102	0.18	0.41	10.5	4.6	9.98	52.3	7.3	0.43	147	10.8	11.9	13.6

In order to obtain a flexible piezoelectric patch a thin disk of 0.5 mm thick was obtained. Than it was cut into a rectangular shape and silver bonded to a thin metal sheet, serving as reinforcement for the ceramic. This subassembly was finally glue bonded to a flexible carbon fiber substrate. The length of the substrate was chosen in such a way that the transversal oscillation applied to the piezoelectric material do not produce cracks (figure 4).

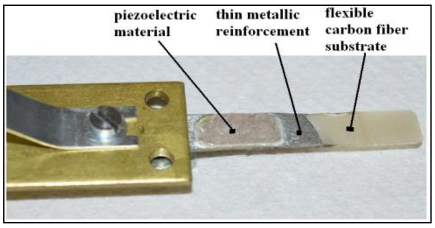

Figure 4. Flexible piezoelectric patch.

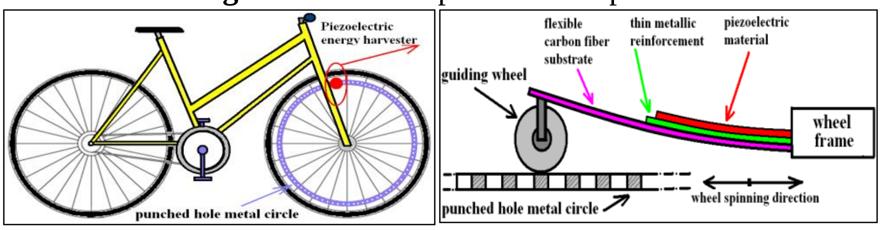

Figure 5. Design of a bicycle piezoelectric harvester

In order to obtain the vibrations needed for the patch to generate electric energy, a system based on a force cantilever was proposed, as seen in figure 5. The patch is initially compressed; the guiding wheel attached to one end of the piezoelectric patch has the possibility to roll across a fixed punched whole metal circle clamped to the wheel on the bicycle. While passing through a whole, the patch will be decompressed and the resulting internal deformation of the piezoelectric material will produce an alternative current voltage signal. The electric current obtained can be directly used to light a LED, or guided through a diode bridge to recharge a direct current battery.

The output voltage generated by the piezoelectric harvester, measured with an digital oscilloscope is presented in figure 6. Three wheel rotational speeds were considered, for which the output power was calculated in table 2. The maximum output power obtained was 4.522 mW for the highest rotational speed. As a LED requires at optimum operation conditions around 25 mW, the output power obtain by the proposed flexible piezoelectric harvester show that lead free materials based on KNN can be successfully considered for energy harvesting, along with solar power and wind power.

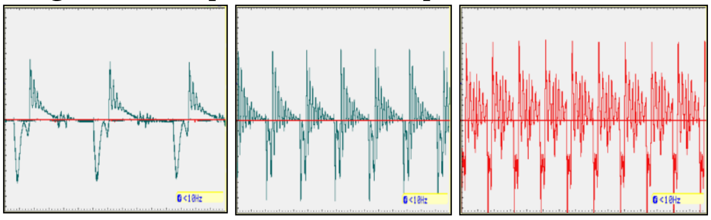

Figure 6. Mesured output voltage of the piezoelectric patch, at three wheel rotational speeds.

Table 2. Power output measured for three wheel rotational speeds.

Speed	Voltage (V)	Current (mA)	Power output (mW)
I	5.8	0.042	0.2436
II	7.4	0.180	1.332
III	10.3	0.439	4.522

Conclusion

A flexible piezoelectric patch was obtained based on $(K_{0.5}Na_{0.5})(Nb_{0.85}Sb_{0.05}Ta_{0.1})O_3$ doped with 0.5 mol% $GdMnO_3$ piezoelectric ceramics. The pattern obtained from X-ray diffraction shows a mixture of orthorhombic and tetragonal phases at room temperature, results confirmed by dielectric spectroscopy. A good ferroelectric behavior was observed, along with good piezoelectric properties. The piezoelectric harvester was mounted onto to a bicycle wheel and was able to produce a maximum power output of 4.522 mW.

References

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