MODELLING AND TRIALS OF PYROELECTRIC SENSORS FOR IMPROVING ITS APPLICATION FOR BIODEVICES

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Abstract: Active or "Intelligent" Materials are capable of responding in a controlled way to different external physical or chemical stimuli by changing some of their properties. These materials can be used to design and develop sensors, actuators and multifunctional systems with a large number of applications for developing medical devices.

Pyroelectric materials, with thermoelectrical properties coupling, can be used as temperature sensors with applications in the development of several biodevices, including the combination with other thermally active materials, whose actuation can be improved by means of precise temperature registration. This paper makes an introduction to pyroelectricity and its main applications in the development of biodevices, focusing also in the pyroelectric properties of polyvinylidene fluoride or PVDF and presenting some results related with sensors' behaviour modelling and characterization.

1 INTRODUCTION TO PYROELECTRICITY

Pyroelectricity is the ability of certain materials to generate an electrical potential when they are heated or cooled. As a result of this change in temperature, positive and negative charges move to opposite ends through migration (the material becomes polarized) and, therefore, an electrical potential is established.

This kind of phenomenon appears in dielectric materials with spontaneous polarizations due to dipole orientation within their structure. These effects have been known to mankind even since Antiquity, especially regarding ceramic materials and metallic oxides.

The name of pyroelectricity was given by Brewster in 1824. But investigations on polymer pyroelectricity are more recent, starting around 1955 with some initial results, which were not commercially promising.

New attention was given to this property with the discovery of pyroelectric effects in polyvinylidene fluorides (PVDF and copolymers) by Bergman in 1971, after the discovery of piezoelectricity in these materials by Kawai in 1969.

During the last decades important progress has been made in creating artificial pyroelectric materials, usually in the form of a thin film, out of gallium nitride (GaN), caesium nitrate ($CsNO_3$), polyvinylidene fluorides (PVDF and copolymers), derivatives of phenylpyrazine cobalt phthalocyanine and other materials.

The main applications developed so far of these materials in biomedical devices are explained below, before paying attention to pyroelectricity in polymers, modelling, signal conditioning and trials.

2 PYROELECTRIC MATERIALS AND POTENTIAL BIODEVICES

The main industrial applications are related with the development of temperature sensors, presence sensors, humidity and leakage sensors and for measuring other processes which mean a temperature change. It can also be applied in biological or medical context as explained in the following examples.

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Infrared Thermography Cameras. Infrared Thermography is a technique for carrying out inspections and non-destructive tests which has multiple applications in the development of machines and products, equipment and facilities maintenance, and troubleshooting.

Since all bodies emit (according to their temperature) infrared radiation, which increases in intensity as the temperature rises, variations in this intensity can be detected by using infrared sensors.

Thermal cameras can detect radiation in the infrared range of the electromagnetic spectrum (usually between a 900 and 14000 nm wavelength, instead of operating in the visible range of 450 to 750 nm) and can produce images of this radiation.

These cameras are fitted with a sensor matrix (called microbolometer) that can be developed using pyroelectric materials. Depending on the intensity of the radiation more or less current is sent to the camera's control electronics, which with the aid of specific software enables temperature maps to be obtained.

Some of the fundamental advantages of the technique are its speed and ease of use, easy to interpret temperature map-based results and the fact that it is a non-destructive technique that does not damage the systems under study (Schindel, 2007, Maldague, 2001).

Apart from these applications, its use as a support tool for developing medical devices, especially those based on the use of thermal materials has also been proposed (Paumier, 2007).

Biometric Systems. Pyroelectric materials can also be used as part of complex biometric systems for real-time recognition of people inside a building or room with security purposes, or in the medical field for evaluating the progress of injuries that limit the mobility of patients (Fang, 2007).

Aided Surgery. These materials have also been proposed and tested for measuring blood temperature during surgeries, such as coronary stent placements, with the purpose of relating temperature profile with the blood velocity field and using this comparison as a method of controlling the surgical procedure (Mochi, 2004).

Flow Sensors. Dymedix Co. has developed nasal flow sensors using PVDF, that besides being piezoelectric has also pyroelectric properties and can be used as temperature sensor. This products allow an active management of pathologies such as sleep apnea or sudden death in children. Such devices are placed adjacent to the nostrils and patient breath induces charges to the sensor, with a typical and recognisable pattern. When breathing ceases, the pattern changes and the microcontroller detects such problem and activates an alarm to alert both the patient and his or her relatives.

X-Ray Intensity Sensors. Based on corporal heating due to absorption of X-Ray (during radiological explorations) pyroelectric sensors can be used, so as to make an estimation of the dosage received and in order to avoid risk situations. The phenomenon has been proved "in vivo" during mammography scans with positive results according to precision and sensitivity (De Paula, 2005).

3 PVDF PYROELECTRIC POLYMER SENSORS

Polyvinylidene fluoride or PVDF $-(CH_2-CF_2)-_n$ and its co-polymers such as poly(vinilydenefluoride-trifluoroethylene) or P(VDF-TrFE), are the polymers of this kind with the largest number of industrial applications. They posses partial crystalinity with an inactive amorphous phase and an elastic modulus close to between 1 and 10 GPa.
The ferroelectric structure makes this polymer both piezoelectric and pyroelectric, which increases its applications, not only as temperature and pressure sensor, but also as actuator. Its use as actuators is limited by the need to apply high electric fields (around 20 V/μm for a 3% deformation), but their use as pressure sensors is taking the place of traditionally used piezoelectric ceramic materials.

Regarding pyroelectricity its important value of pyroelectric coefficient, together with its greater resistance and sensitivity is displacing the use of pyroelectric ceramics.

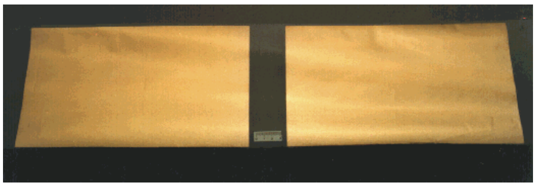

Figure 1: Metallized PVDF sheets. Piezotech S.A..

To make the sensors, we took PVDF 40 μm thick sheets from Piezotech S.A. with Au-Pt coated electrodes. These sheets were cut, joined to the connecting wires and suitably encapsulated into flexible polyurethane layers to protect them.

The sensors obtained and the main properties of the PVDF used, along with some alternatives of the same materials' family, are shown below.

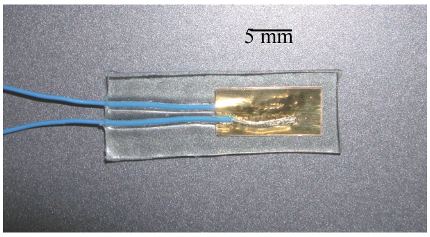

Figure 2: PVDF pyroelectric polymer sensor for fluidic applications with polyurethane protecting layer.

Table 1: Pyroelectric polymers' main properties.

	d_{33} pC/N	d_{31} pC/N	d_{32} pC/N	ε F/m	p3 $\mu C/m^2 \cdot {}^oC$
Uni-ax. PVDF	-20	18	3	$1{,}1 \cdot 1^{-10}$	25
Bi-ax. PVDF	-24	7	7	$1{,}1 \cdot 1^{-10}$	25
P(VDF -TrFE)	-24	7	7	$0{,}9 \cdot 1^{-10}$	25

The sensors' behaviour due to combined piezoelectric and pyroelectric properties can be studied in first approximation using the following equations.

Figure 3 a) shows the sensor layout. The charge displacement (produced when a force of temperature change is applied to the piezoelectric sensor) can be represented using the equivalent electric circuit depicted in Figure 3 b).

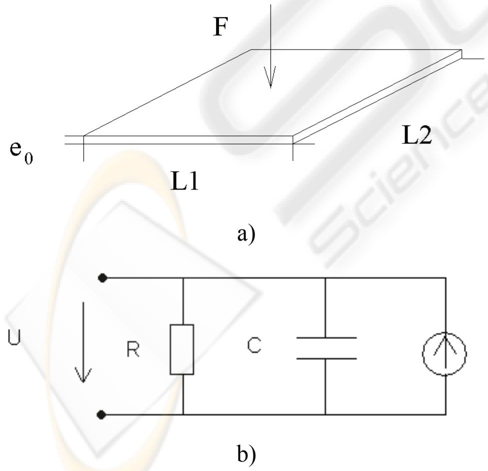

Figure 3: a) Piezoelectric Sensor. b) Electrical behaviour circuit diagram of the piezoelectric sensor.

Force F on the sensor acts as a generator of intensity powering a C capacity condenser. Ec (1).

$$C = C(F) = \varepsilon \cdot (L_1 \cdot L_2) / e \quad (1)$$

Where:

ε.- The dielectric constant of the sensor.

$L_1 \cdot L_2$.- The effective area of the sensor.

e.- The thickness of the sensor.

The thickness of the sensor, e, depends on the initial thickness, e_0, on the pressure applied, $\sigma = F / (L_1 \cdot L_2)$, and the Young modulus of the material, E, using the following expression Eq. (2):

$$e = e_0 \cdot (1 - \sigma / E) \quad (2)$$

Current intensity, I, generated by applying force, F, depends on the transversal piezoelectric coefficient of sensor d33 according to Eq. (3).

$$Q = d33 \cdot F \rightarrow I = dQ / dt = d33 \cdot dF / dt \quad (3)$$

Current intensity, I, generated by applying temperature chages, ΔT, depends on the pyroelectric coefficient p_3 and can be expressed as:

$$Q = p_3 \cdot (L_1 \cdot L_2) \cdot \Delta T \rightarrow$$

$$I = dQ / dt = p_3 \cdot (L_1 \cdot L_2) \cdot dT / dt \quad (4)$$

The total amount of current intensity can be obtained as addition of Eq. (3) and (4).

When the sensor is connected to an external circuit, as is shown in Figure 3 b), it discharges in accordance with the equivalent R resistance of this external circuit (i.e. oscilloscope, charge amplifier). The intensity is given by Eq. (5).

$$I = d33 \cdot dF / dt = U / R + C \cdot dU / dt \quad (5)$$

The effect of thermal expansion has to be taken also into account when the deformations produced due to important temperature changes become relevant, as consequence of the thermo-electro-mechanical coupling in these materials.

Similar equations have been used to model and simulate the behaviour of this kind of materials as part of more complex devices. They can be used not only for design purposes, but also as a way of estimating adverse effects due to piezo and pyro effects coupling, in applications that are intended to use these materials only as pressure sensors or only as temperature sensors.

In case of willing to obtain positive voltages when using this sensors for measuring compressive stresses a polarity change in the connections is enough, but then temperature increases lead to decreasing voltages (as happens in our PVDF trials explained below).

Following chapter shows some characterization trials of the pyroelectric behaviour of PVDF sensors and the influence of parameter changes for its applicability.

4 TRIALS WITH PVDF PYROELECTRIC SENSORS

For proving the pyroelectric response of PVDF sensors a charge amplifier for signal conditioning was designed. It has typical impedance for such conditioning circuits of 10 TΩ and includes a voltage supply of 3.7 V.

The trial bench includes an additional Measurement Computing LS1208 data acquisition card, connected via USB to a personal computer.

The trials were carried out by introducing the sensor from room temperature (26 ºC) into a water vase with temperature control.

Several trials were made, changing water temperature, before introducing the sensor into it, so as to study the influence of ΔT on the speed response of the sensor, which can be measured as a function of the origin slope of the function V(t).

The main results are shown below. Figure 4 represents the trials made using a sensor with just one polyurethane protecting layer. Figure 5 was obtained by using a sensor with three protecting layers and shows a slower response, due to the effect of thermal isolation produced by the polyurethane.

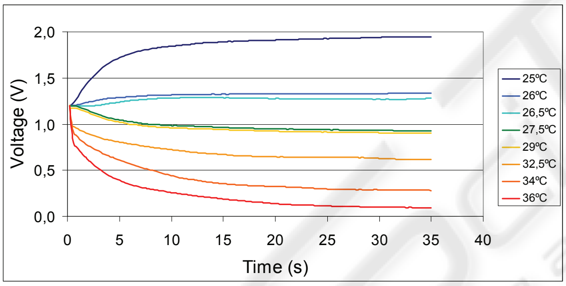

Figure 4: Voltage changes due to introduction of the PVDF sensors in water at different temperatures. (One protecting layer).

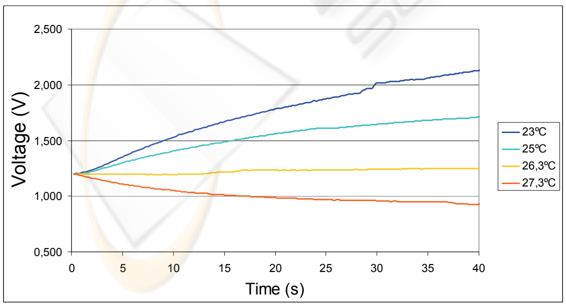

Figure 5: Voltage changes due to introduction of the PVDF sensors in water at different temperatures. (Three protecting layers).

These trials help to show the sensitivity of PVDF as temperature measuring material, due to its pyroelectric properties. The fact that temperature changes can be detected, even using a 4.5 mm thick polyurethane protecting layer, is important for increasing the number of applications of such materials, which can be used not only as surface sensors, but also for measuring surface temperature changes from the inside of a biodevice.

5 CONCLUSIONS

The work presented shows an introduction to pyroelectricity and its main applications in the development of biodevices, focusing also in the pyroelectric properties of polyvinylidene fluoride or PVDF.

Additionally, some results related with sensors' behaviour modelling, signal conditioning and characterization trials are presented.

This type of materials can also be applied to medical devices in combination with other active materials, especially those based on thermal activation.

Thus pyroelectric sensors could be used as a way of monitoring temperature and optimising activation of the active part of the device.

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