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Pyroelectric Effect in PZT Thick Films for Thermal Energy Harvesting in Low-Power Sensors

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Abstract

Thermal-electrical energy converters based on pyroelectric effect are investigated for energy harvesting and possible use in ultra-low-power sensor modules. Different elements based on thick films of lead zirconate titanate (PZT) sandwiched between metal electrodes deposited on alumina substrate were fabricated and characterized. The charge extracted was stored into a capacitor comparing performances offered by different rectifying circuits. Results show that the harvested energy can be compatible with use in autonomous sensors working in low-duty-cycle switched-supply mode.

Keywords: Energy harvesting; pyroelectric effect.

1. Introduction

Networks of autonomous sensors are in constant expansion. To be fully autonomous, it is necessary that the sensors carry their power supply. Batteries provide a finite amount of power supply, therefore the lifespan of the system is limited. For this reason, the harvesting of electrical energy by conversion from freely-available ambient sources is generally considered as a very promising alternative for wireless sensors.

From a somewhat different perspective, the present work more specifically investigates the issue of energy harvesting for ultra-low-power battery-less autonomous sensors with short-range communication capability. Such devices can find many applications while posing significant challenges in terms of power budget, requiring tailored design strategies and in-depth consideration of the predominant energy source, albeit of limited intensity, available to supply the module. When thermal energy is considered and spatial thermal gradients are present, thermoelectric devices can be used [1-2]. When thermal fluctuations are present, the pyroelectric effect can be considered [3-5]. The aim of this paper is to investigate the feasibility to use pyroelectric devices as energy harvesting sources able to power autonomous sensors working in low-duty-cycle switched-supply mode.

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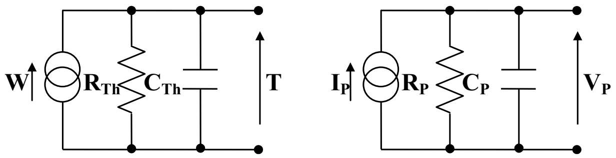
2. Pyroelectric effect

The pyroelectric effect is the property of selected dielectric materials with polar point symmetry which show a spontaneous electrical polarization as a function of temperature. A change in the temperature of the material with respect to time, i.e. thermal fluctuations, causes a correspondent variation in the induced charge thereby producing a pyroelectric current $I_P = S\lambda(dT/dt)$ where S is the electroded surface and λ the pyroelectric coefficient of material. Typically, the pyroelectric coefficient for PZT (lead zirconate titanate) thick films is in the order of 10^{-4} C/(m^2°C) [6]. The Fig. 1 shows a lumped-parameter equivalent circuit of a pyroelectric converter, where W is the thermal power, I_P the generated current, V_P the open-circuit output voltage and C_{Th}, C_P, R_{Th}, R_P are the thermal and electrical capacitances and resistances respectively [3].

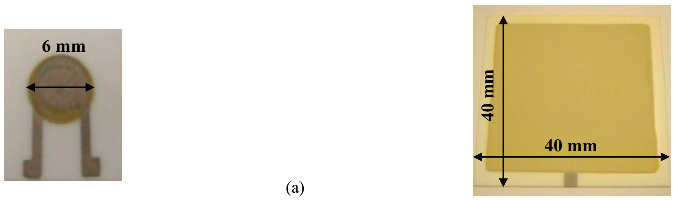


$$I_P = S\lambda \frac{\partial T}{\partial t}$$

Fig. 1. Equivalent thermoelectrical circuit of an homogeneous pyroelectric converter. The pyroelectric element is modelled as a current source in parallel with the internal resistance R_P and the capacitance C_P.

3. Fabrication of pyroelectric elements

Different pyroelectric samples were fabricated in thick-film technology on an alumina substrate, according to the following steps: screen printing of a 10 µm layer of PdAg for the bottom electrode, drying at 150 °C and firing at 950 °C; screen printing of a layer of ferroelectric paste, prepared dissolving a PZT powder (Piezokeramika 856) with a ratio 4:1 in a mixture of terpineol (96 %) and ethyl cellulose (4 %), drying at 150 °C and firing at 950 °C; deposition of top electrode in the same way as the bottom electrode; poling of the PZT with a field of 4 MV/m at 150 °C. Four samples with different geometry and thickness, as listed in Table 1, were manufactured and tested. Pictures of the realized devices are reported in Fig. 2.



(b)

Fig. 2. Pictures of the pyroelectric devices (a) samples 1÷3; (b) sample 4.

4. Experimental results

4.1. Characterization of the fabricated elements

For the characterization of the fabricated devices, an experimental set-up was assembled, including a Peltier cell, two temperature sensors to drive and monitor temperature profiles and a PC-based acquisition system, as shown in Fig. 3a. The Peltier cell and the relative controller was used in order to produce time fluctuations of temperature dT/dt. Since the temperature could not be uniform across the PZT layer, it was estimated by taking the average between the temperature at the interface of the Peltier cell with the alumina substrate (T_1) and on the top electrode

(T_2), as shown in Fig 3a. The pyroelectric current I_P was measured by a transresistance amplifier with gain of 12 MΩ. The output voltage was measured with a multimeter (Fluke 8840A) connected to the acquisition system. The electrical capacitance C_P and the resistance R_P of the different pyroelectric devices were measured with an impedance analyzer (HP 4194A) at 100 Hz, and the results are reported in Table 1.

Table 1. Measured electrical parameters C_P and R_P and the experimental pyroelectric coefficient of the samples.

Sample label	Surface S [mm^2]	Thickness [µm]	C_P [nF]	R_P [MΩ]	Experimental pyroelectric coefficient λ [C/(m^2°C]
1	28	80	0.92	217	$1.1 \cdot 10^{-4}$
2	28	180	0.42	411	$1.8 \cdot 10^{-4}$
3	28	200	0.36	973	$2.1 \cdot 10^{-4}$
4	1600	100	37.75	3.4	$0.5 \cdot 10^{-4}$

Fig. 3b and Fig. 4a show the measured current I_P, the temperature T over the time for sample #1 and #4 respectively. The temperature rates dT/dt were numerically calculated from measured data of temperature T. It can be observed that the measured thermal fluctuations dT/dt and the corresponding generated current I_P(t) have the same behavior as expected. The maximum value for current I_P generated by the sample #4 with a sinusoidal thermal fluctuation dT/dt of 1.8 °C/s peak was about 140 nA. From the data of Fig. 4a the pyroelectric current was plotted versus the temperature rate in Fig. 4b and the pyroelectric coefficient λ was calculated as 5 10^{-5} C/(m^2°C) for sample #4. Higher values were obtained for smaller samples as reported in Table 1.

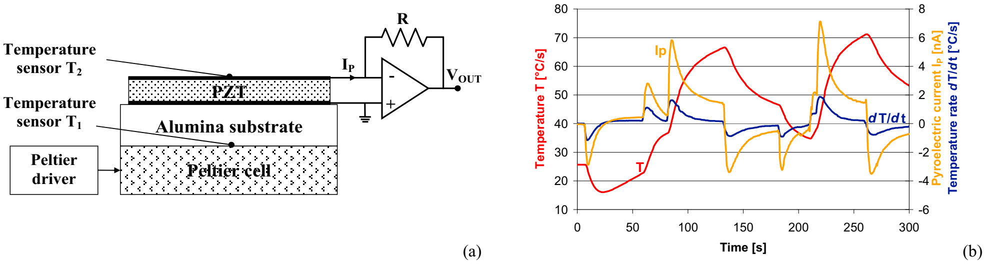


Fig. 3. (a) Schematic diagram of the pyroelectric harvester and experimental set-up; (b) Measured temperature rate dT/dt and pyroelectric current I_P over the time for sample #1.

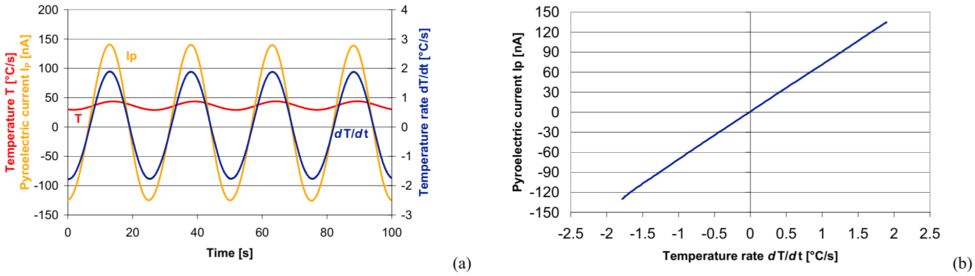


Fig. 4. (a) Measured temperature T, temperature fluctuation dT/dt and pyroelectric current I_P over the time; (b) Relationship between temperature rate dT/dt and current I_P for sample #4.

4.2. Energy storage

The power extracted from a pyroelectric element is typically too low and/or discontinuous to guarantee a continuous operation of low-power autonomous sensors, so the converted energy can be accumulated into a storage capacitor C_S by proper power-management techniques, and then transferred to the load during time intervals of relatively short duration. The harvested charge was accumulated into a 10 µF capacitor using either the full-wave rectifier circuit or the Schenkel doubler circuit as depicted in Fig. 5a. With respect to the Schenkel doubler, the full-bridge rectification provides faster charging although to a lower voltage level. Despite the small thermal fluctuations imposed, the stored energy after few tens of cycles is adequate to intermittently power a battery-less autonomous sensor module [7] as schematized in Fig. 5b. The converters are presently tested to this purpose.

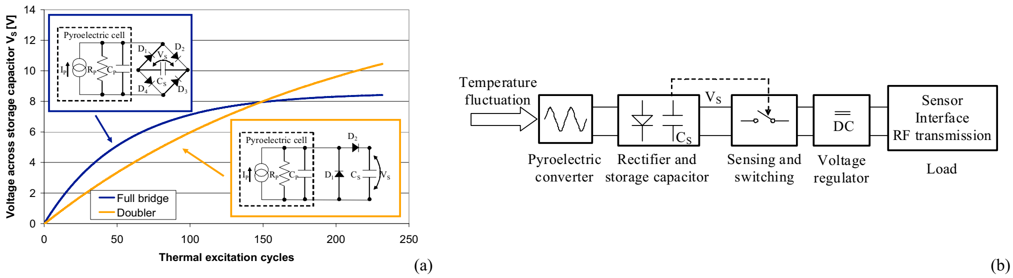


Fig. 5. (a) Voltage across a 10 µF storage capacitor for full-wave bridge and Schenkel doubler for sample #4 excited with a sinusoidal temperature rate of 1.8 °C/s peak; (b) Block diagram of the switched-supply battery-less autonomous sensor module powered by the pyroelectric converter.

5. Conclusion

Pyroelectric elements based on PZT films were fabricated in thick-film technology and characterized as thermal energy harvester in order to supply low power autonomous sensor system. The charge extracted from the energy converter was stored into a capacitor using different rectifying circuits. Results show that the harvested energy can be compatible with use in autonomous sensors working in low-duty-cycle switched-supply mode for measurement and transmission operations.

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