Thermal Energy Harvesting for Low-Power Autonomous Sensors

Simone Dalola, Vittorio Ferrari, Daniele Marioli
University of Brescia - Italy
Department of Information Engineering

simone.dalola@ing.unibs.it

Introduction

Extensive diffusion of sensing nodes (automotive, automation, entertainment, environment monitoring, security systems,…)

Number of nodes ↑

Size

Price ↓

Limiting factor: *power supply*

Standard power supply

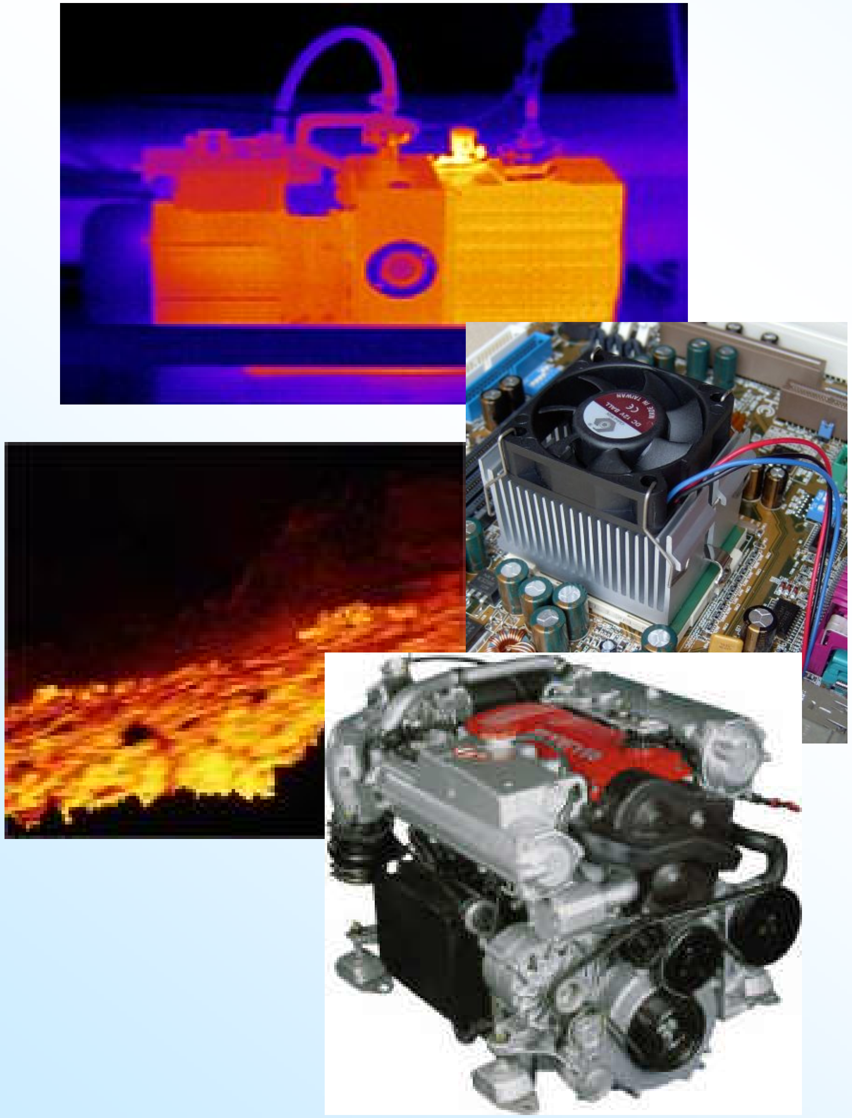
- battery
- rechargeable battery
- fuel cells
- ….

Energy harvesting

Environment

- ✓ Solar energy
- ✓ Mechanical vibrations
- ✓ **Heat**
- ✓ …

Energy from heat



Thermal gradients $\Delta T = \mathrm{T_h} - \mathrm{T_c}$

Thermoelectric conversion

$$\mathrm{V_g} \propto \Delta T$$

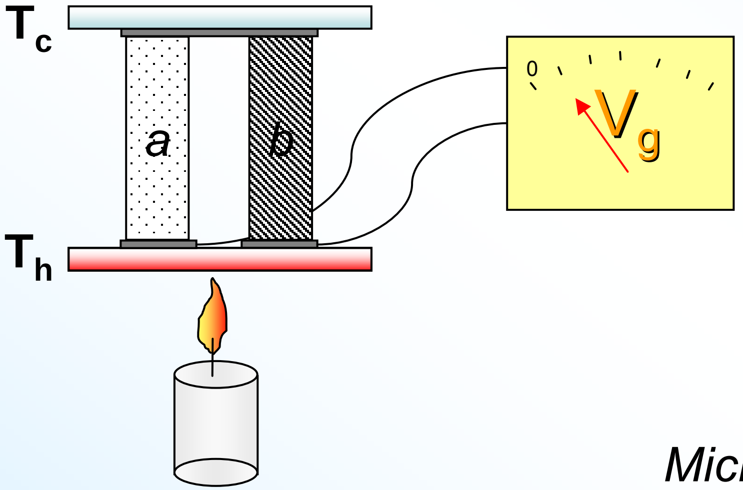
Temperature time-variations $\dfrac{\partial \mathrm{T}}{\partial \mathrm{t}}$

Pyroelectric conversion

$$\mathrm{I_g} \propto \frac{\partial \mathrm{T}}{\partial \mathrm{t}}$$

Thermoelectric effects

Seebeck effect (1821)



$$V_g = \boldsymbol{\alpha}_{a,b}\left(T_h - T_c\right) = \boldsymbol{\alpha}_{a,b}\Delta T$$

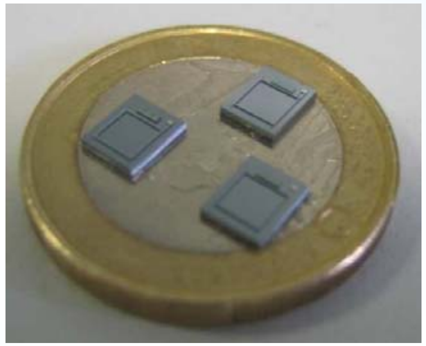
- $\alpha_{a,b}$: Seebeck coefficient
- f.e.m. proportional to ΔT
- reversible effect

Thermocouple/thermogenerator

Cooling device

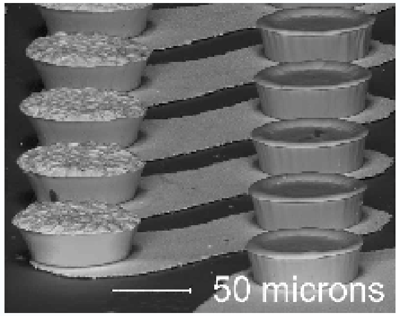
Microdevice

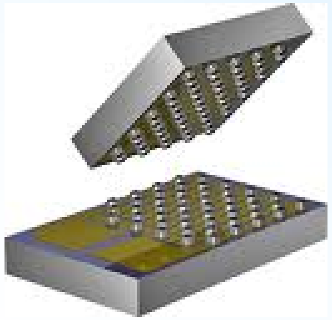
Micromachining device



Thermoelectric generators (TEG)

- **Development of materials**
- **Design of micromachined devices**



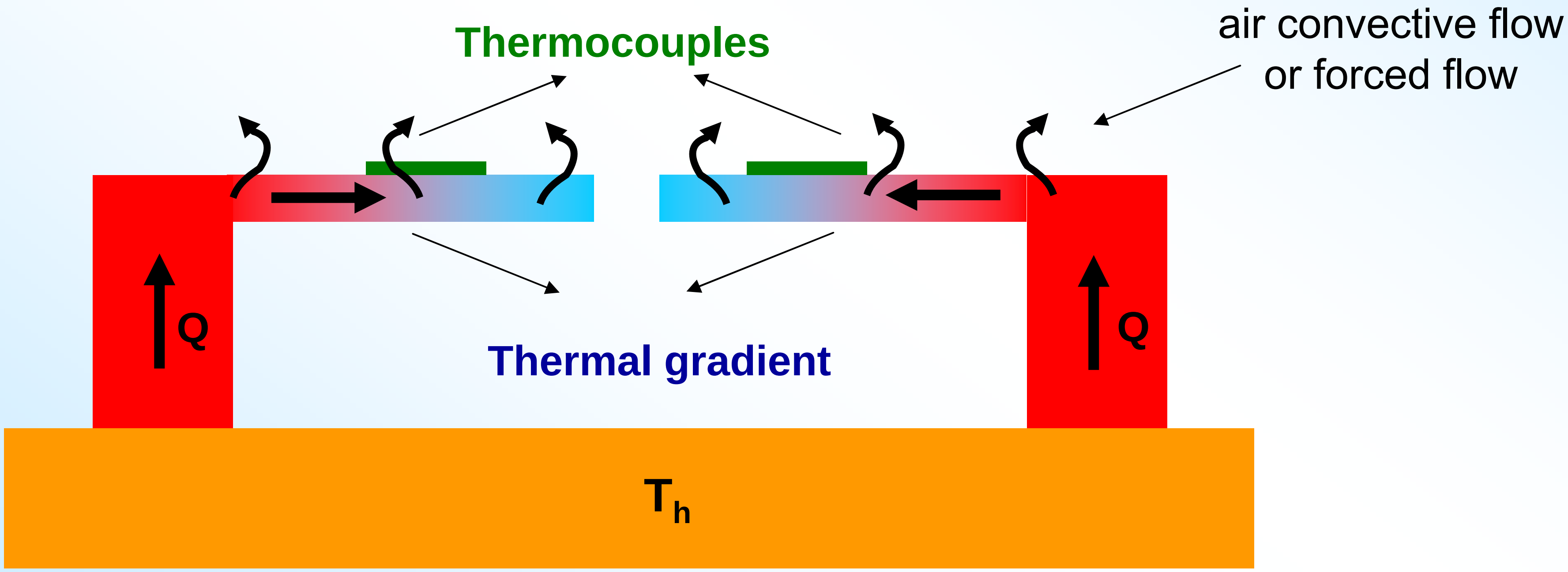


www.micropelt.com

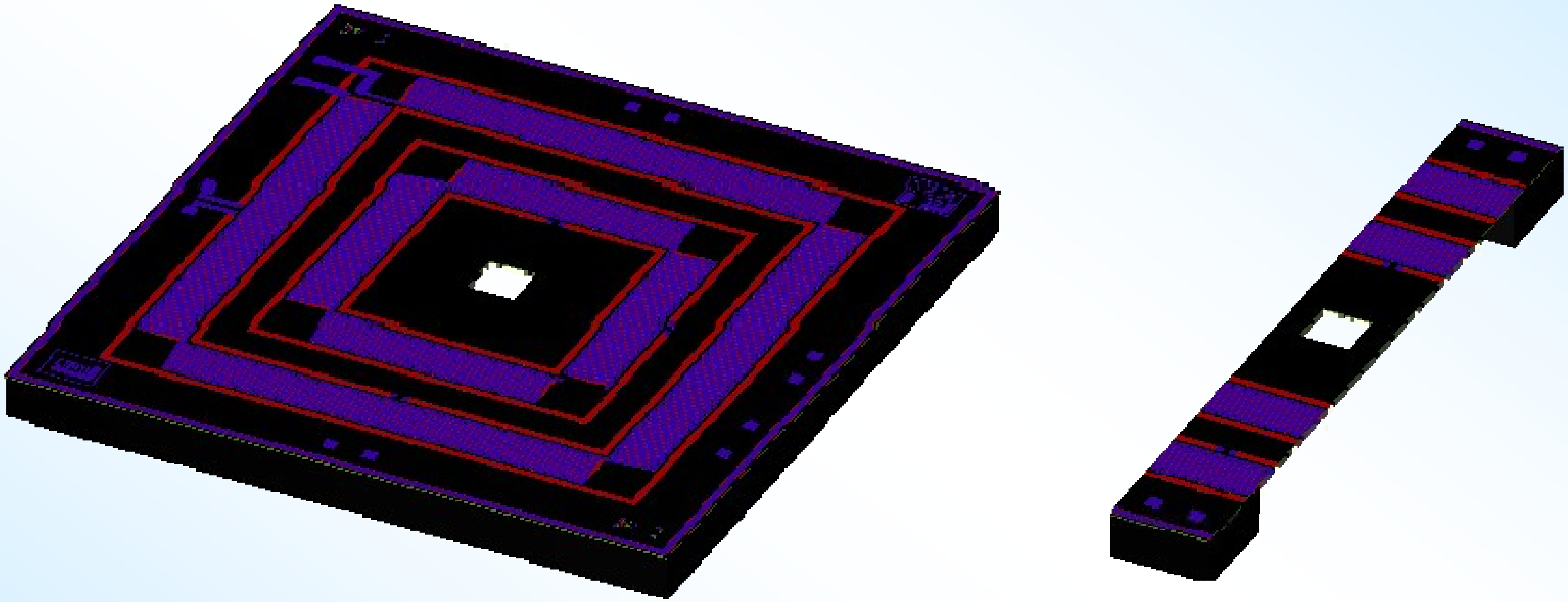
- **Investigate of the feasibility of micromachined thermoelectric generators for energy harvesting application using really available MEMS technologies**
  - Technology
  - Available thermoelectric materials for fabrication process
  - Structural configuration → planar thermocouples

Design of a MEMS TEG

- **At microscale can be difficult to apply or keep thermal gradients**
- **The idea is to use thermal gradient in the MEMS due to heat flow in elements with different thermal resistances**

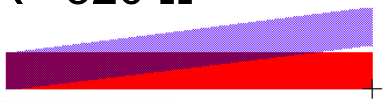


Design of a MEMS TEG

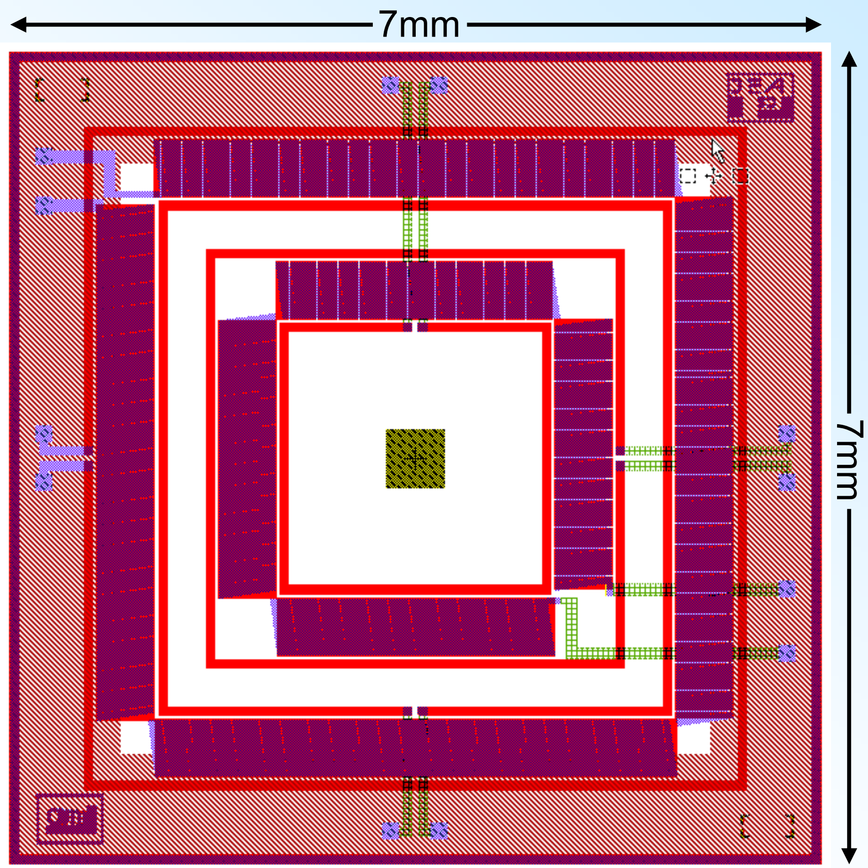


Design of a MEMS TEG

- Planar thermocouple made in polysilicon - aluminum
  - 500 µm x 50 µm
  - $\alpha_{a,b} \approx 100\mu V/°C$
  - R= 320 Ω

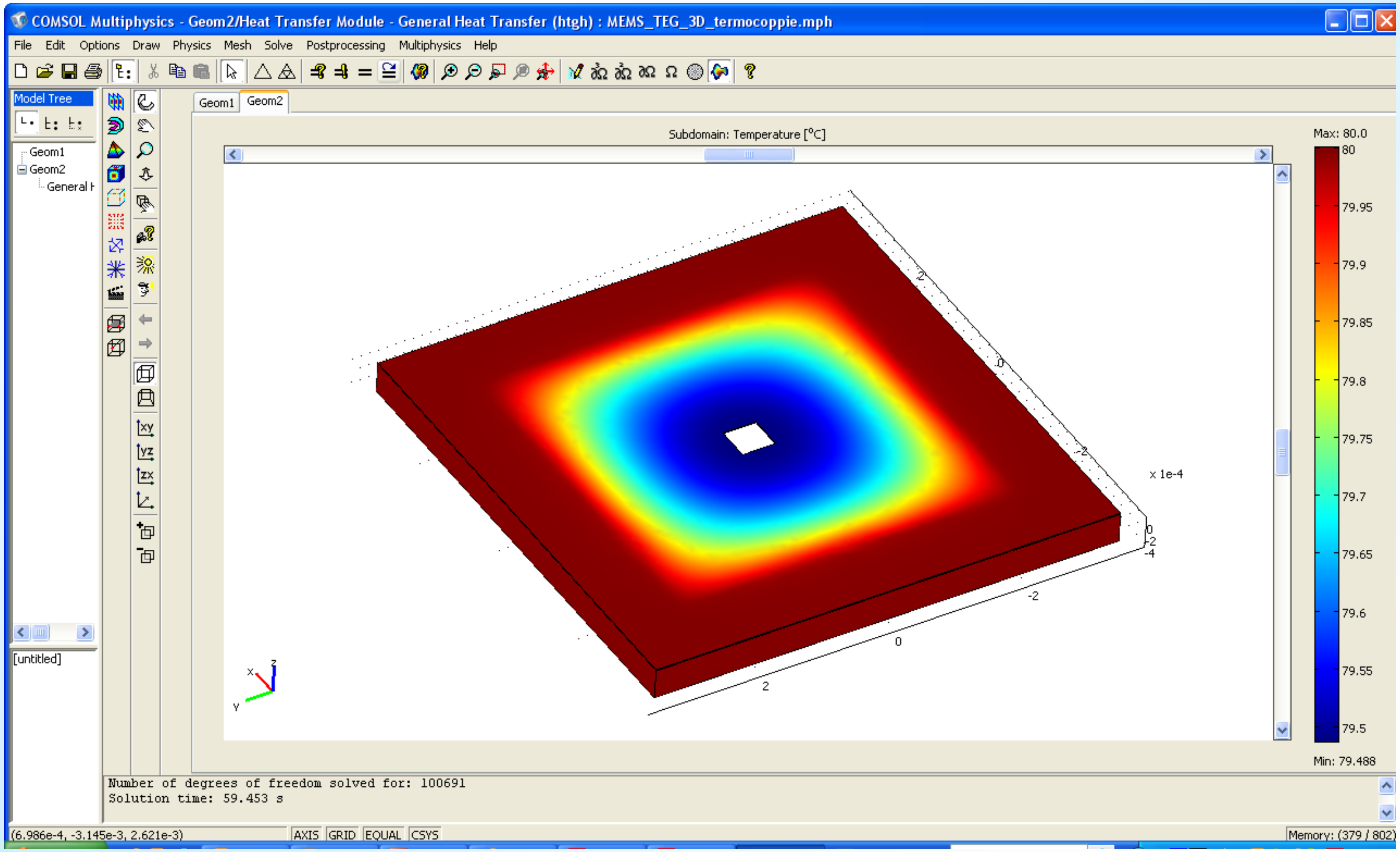


- Two arrays of thermocouples:
  - External: 300 elements (75x4)
  - Internal: 160 elements (40x4)
- Four polysilicon resistors for:
  - Heating
  - Temperature detection
- Electrical resistance:
  - R_{ext}: 96 kΩ
  - R_{int}: 51 kΩ
- Central hole (0.5 mm x 0.5 mm)



Design of a MEMS TEG

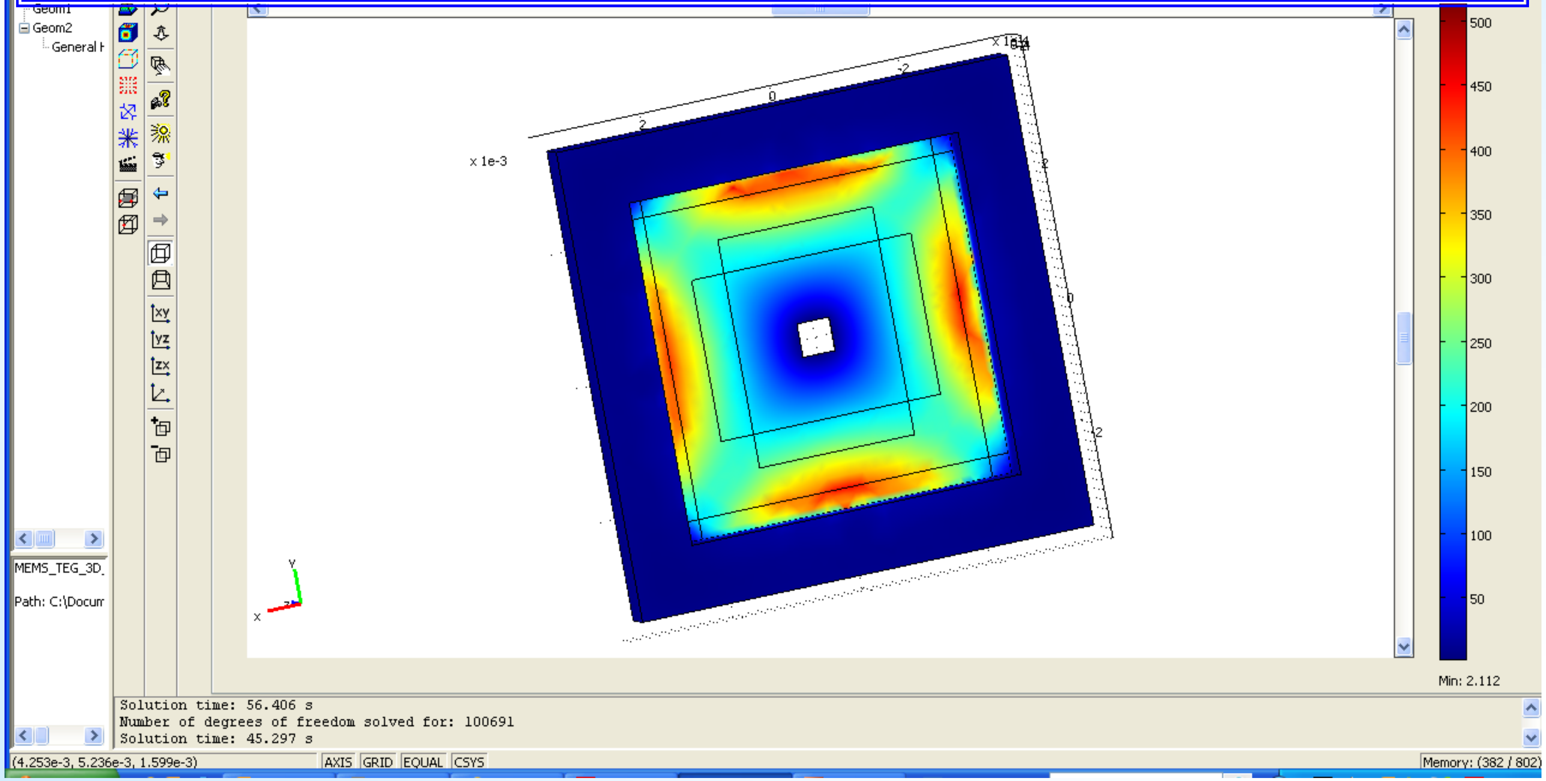
- FEM simulation of the behaviour of MEMS
- T_h = 80°C:



Design of a MEMS TEG

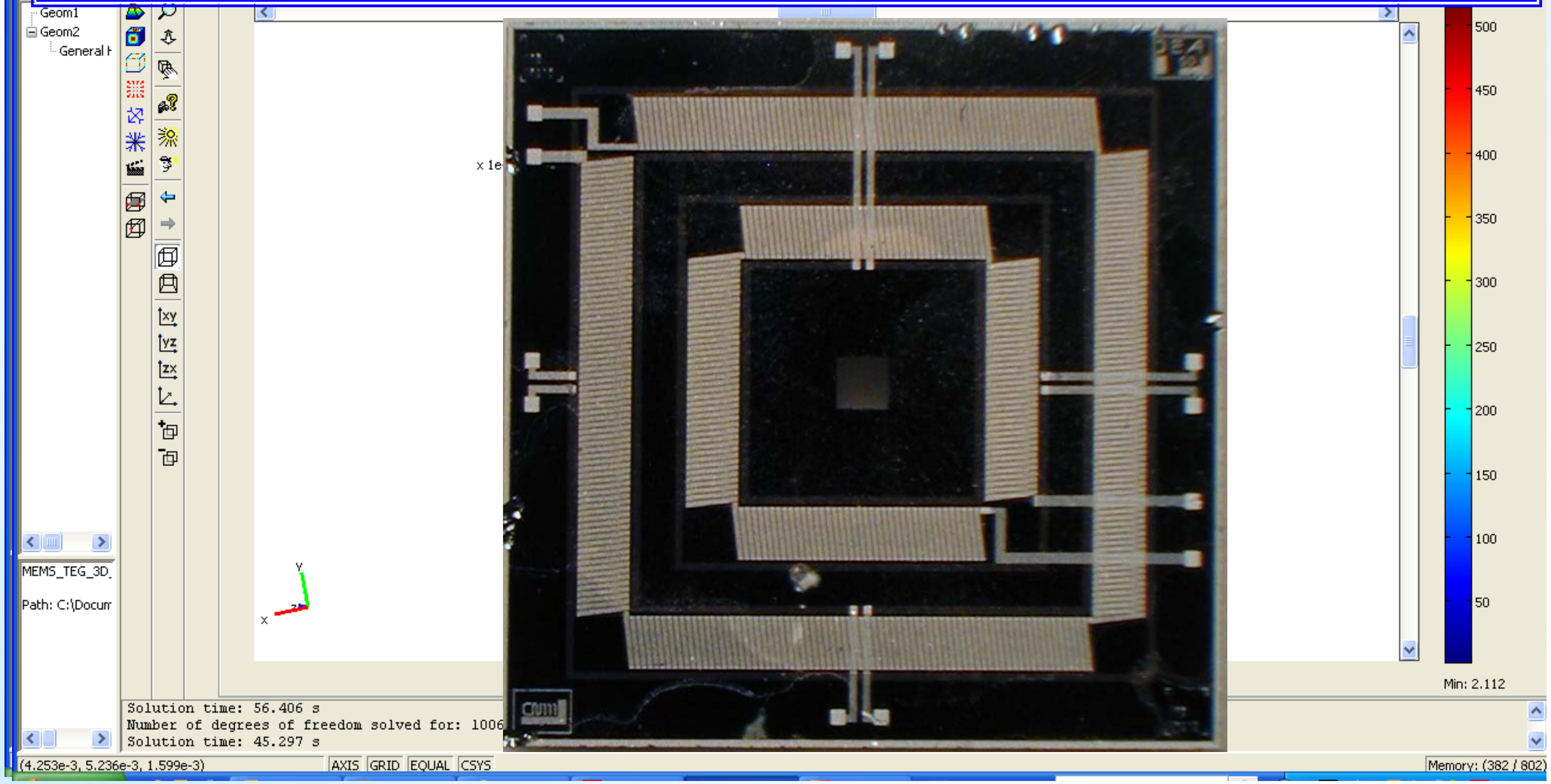
- FEM simulation of the behaviour of MEMS
- T_h = 80°C:

❑ $\Delta T_{ext} \approx 350°C/m*500\mu m \approx 0.17\ °C \rightarrow Vg= N\alpha\ \Delta T \approx 5.1\ mV$
❑ $\Delta T_{int} \approx 200°C/m*500\mu m \approx 0.10\ °C \rightarrow Vg= N\alpha\ \Delta T \approx 1.6\ mV$

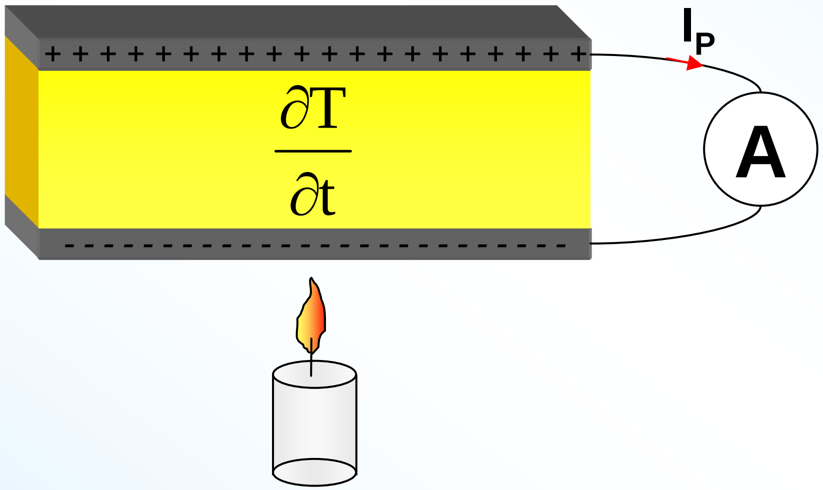


Design of a MEMS TEG

- FEM simulation of the behaviour of MEMS
- T_h = 80°C:
  - ❑ $\Delta T_{ext} \approx 350°C/m*500µm \approx 0.17\ °C \rightarrow Vg= N\alpha\ \Delta T \approx 5.1\ mV$
  - ❑ $\Delta T_{int} \approx 200°C/m*500µm \approx 0.10\ °C \rightarrow Vg= N\alpha\ \Delta T \approx 1.6\ mV$

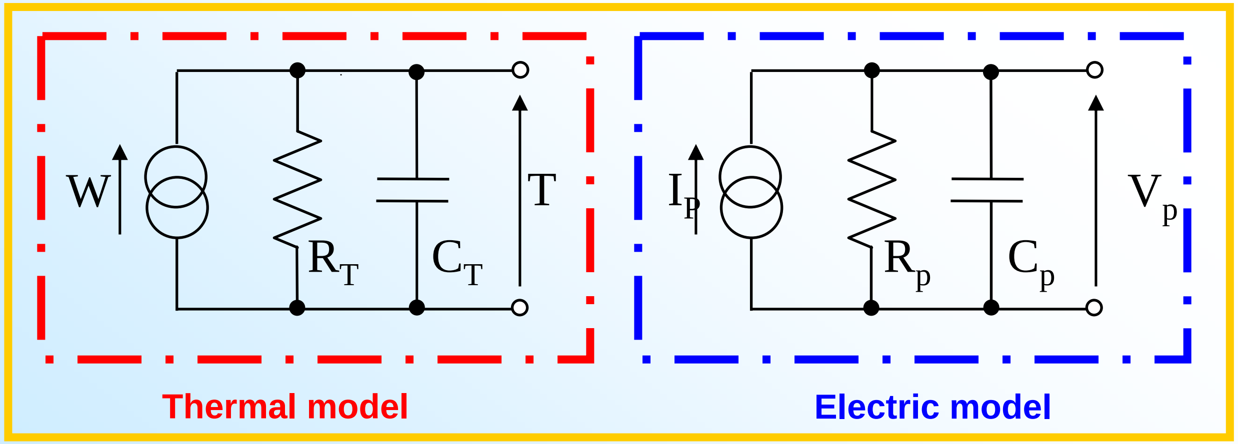


Pyroelectric effect



❑ Property of some dielectric materials with a polar point symmetry which exhibit a spontaneous electrical polarization that is a function of temperature.
❑ A time variation of the temperature causes a correspondent variation in the induced charge, which develops a current if contacting electrodes are placed on the material faces normal to the polar axis.

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

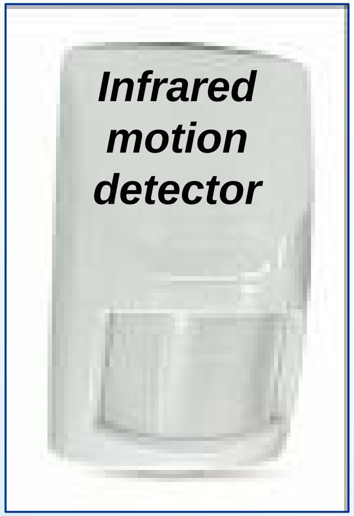


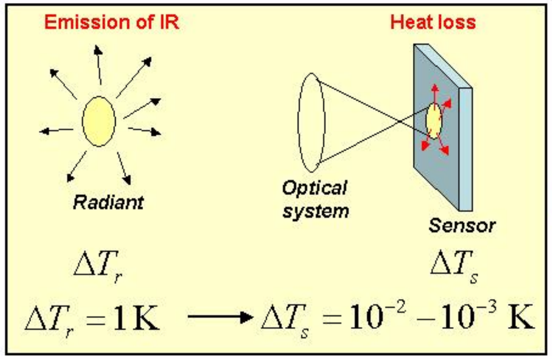
- S: Electrode area
- λ: Pyroelectric coefficient

Energy harvesting from temperature fluctuations

- *Low power generation*
- *Low conversion efficiency*
- *Temperature fluctuations*

- *Low cost*
- *A lot of thermal sources*





Estimation:

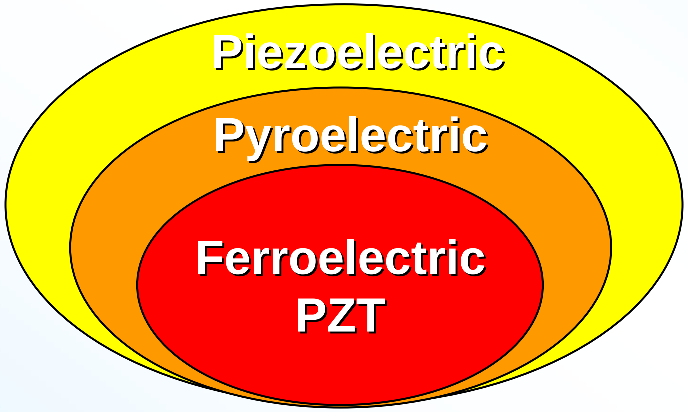
S= 10 cm^2

λ= 10^{-4} Cm^2/°C

dT/dt= 10 °C/s

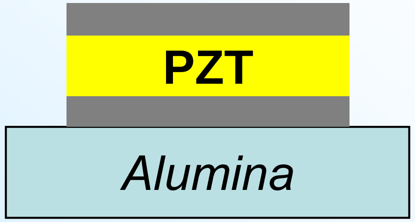
$\boxed{I = 1\ \mu A}$

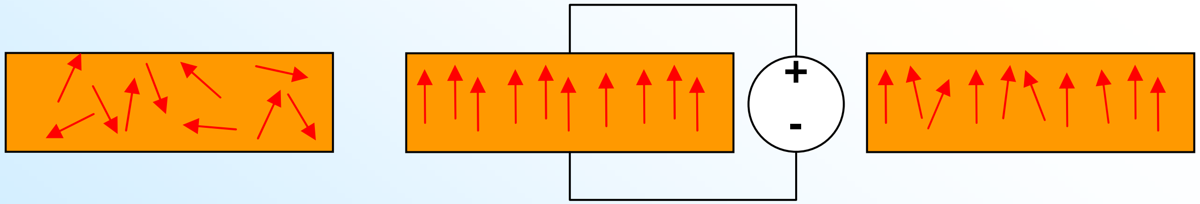
Fabrication of PZT pyroelectric elements



Fabricated in thick-film technology on alumina substrate:

- 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 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.



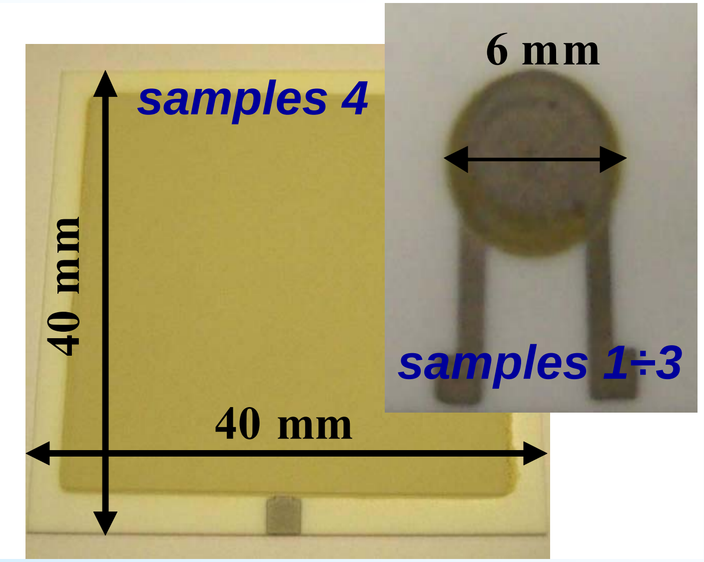


1) Random orientation of dipoles

2) E_{pol}: Orientation of the dipoles

3) Residual polarization

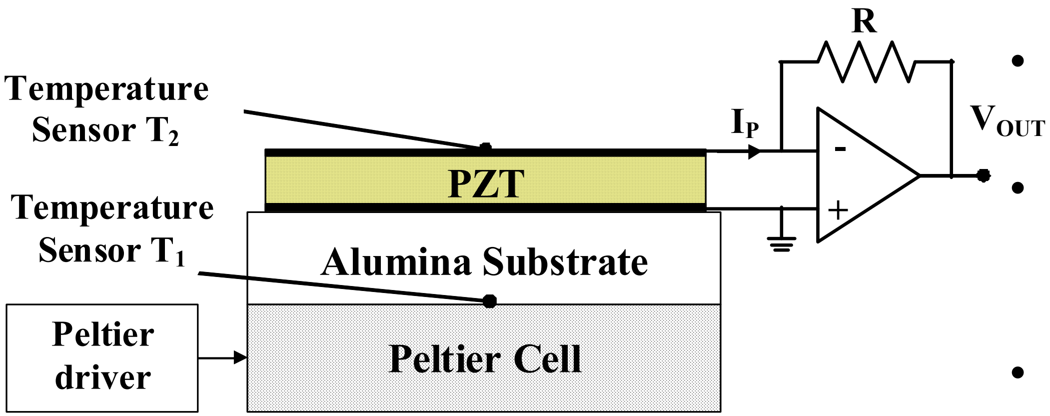
Realized devices



Sample ID	Surface S [mm^2]	Thickness [μm]
1	28	80
2	28	180
3	28	200
4	1600	100

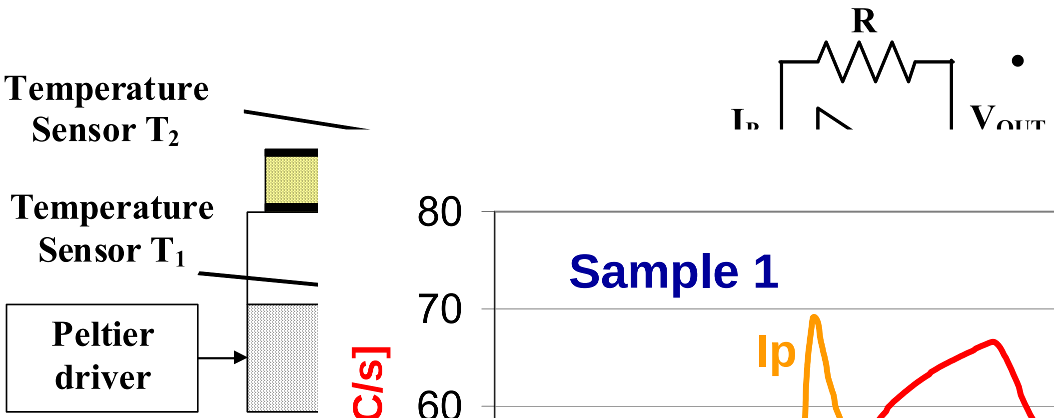
S. Dalola et at. Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

Characterization of pyroelectric samples

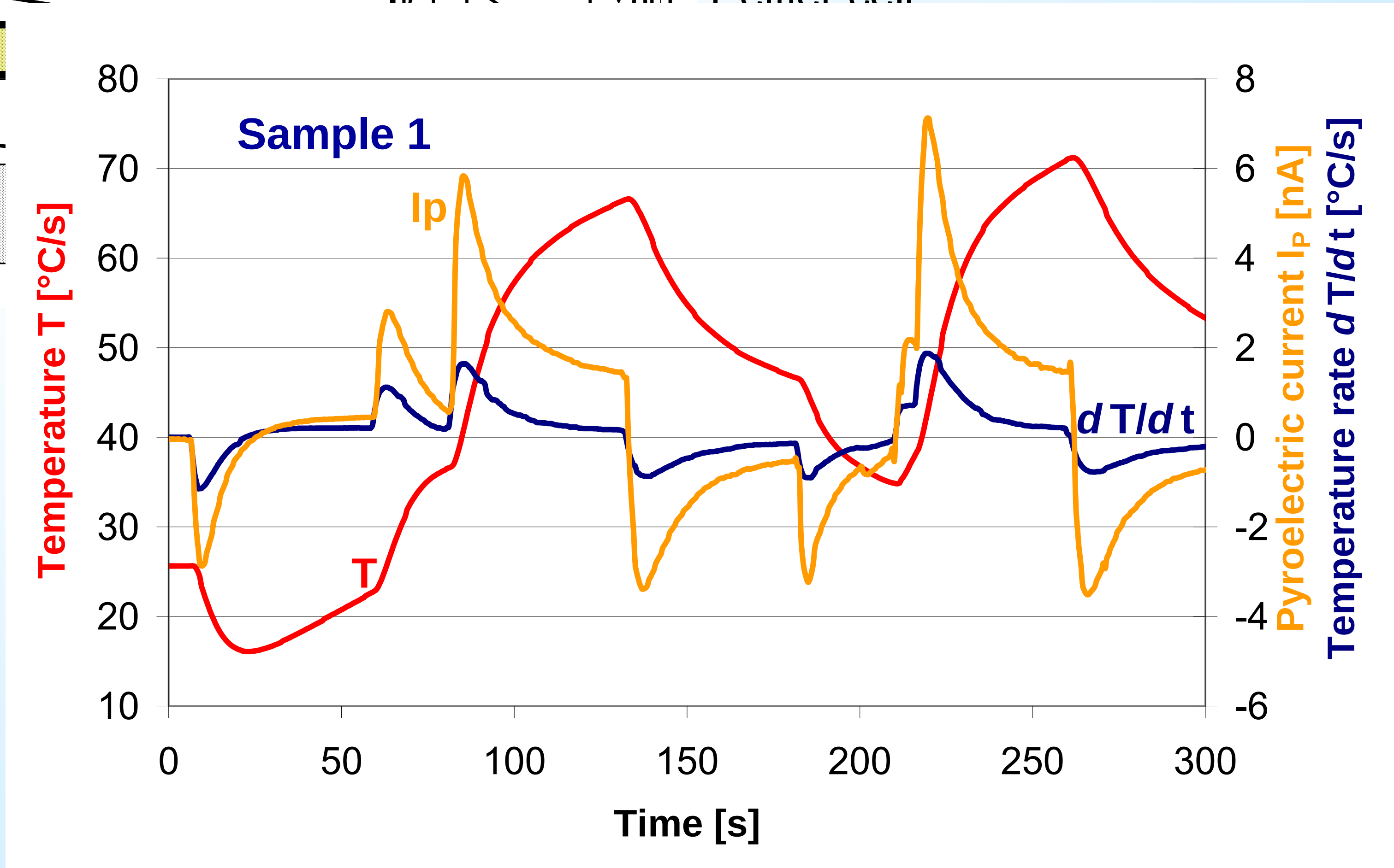


- Thermal profile applied by means of Peltier cell
- Temperature T of the PZT layer estimated by taking the average between the temperatures T_1 and T_2
- Measurement of current I_P

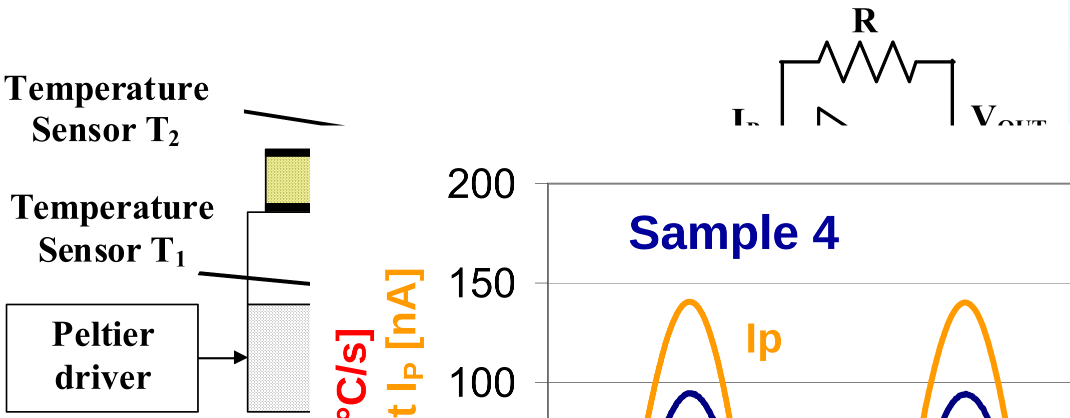
Characterization of pyroelectric samples



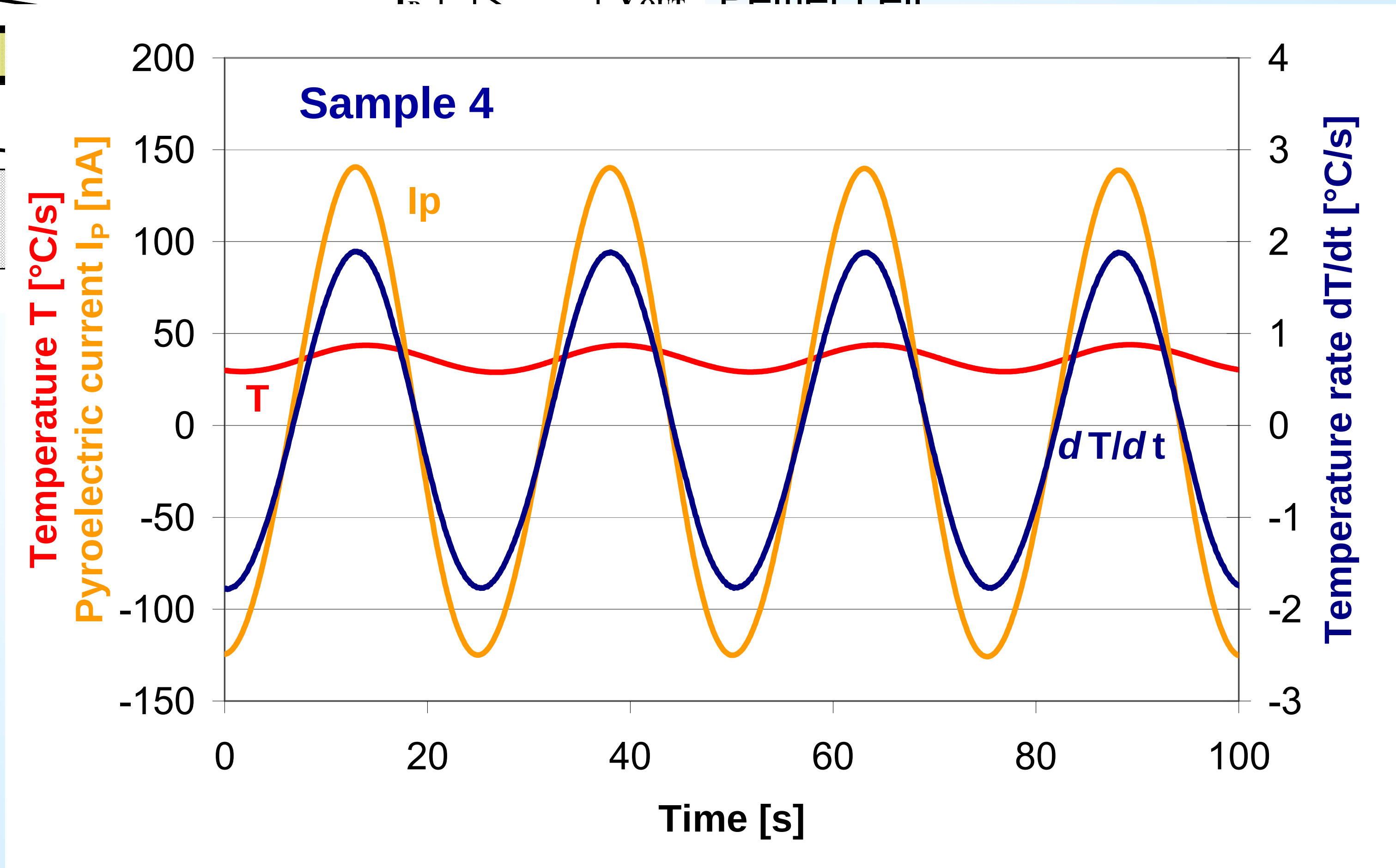
- Thermal profile applied by means of Peltier cell



Characterization of pyroelectric samples

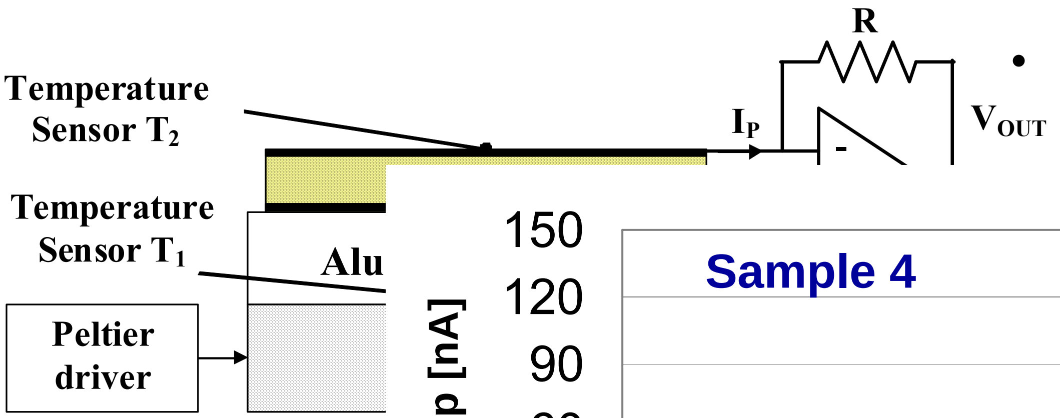


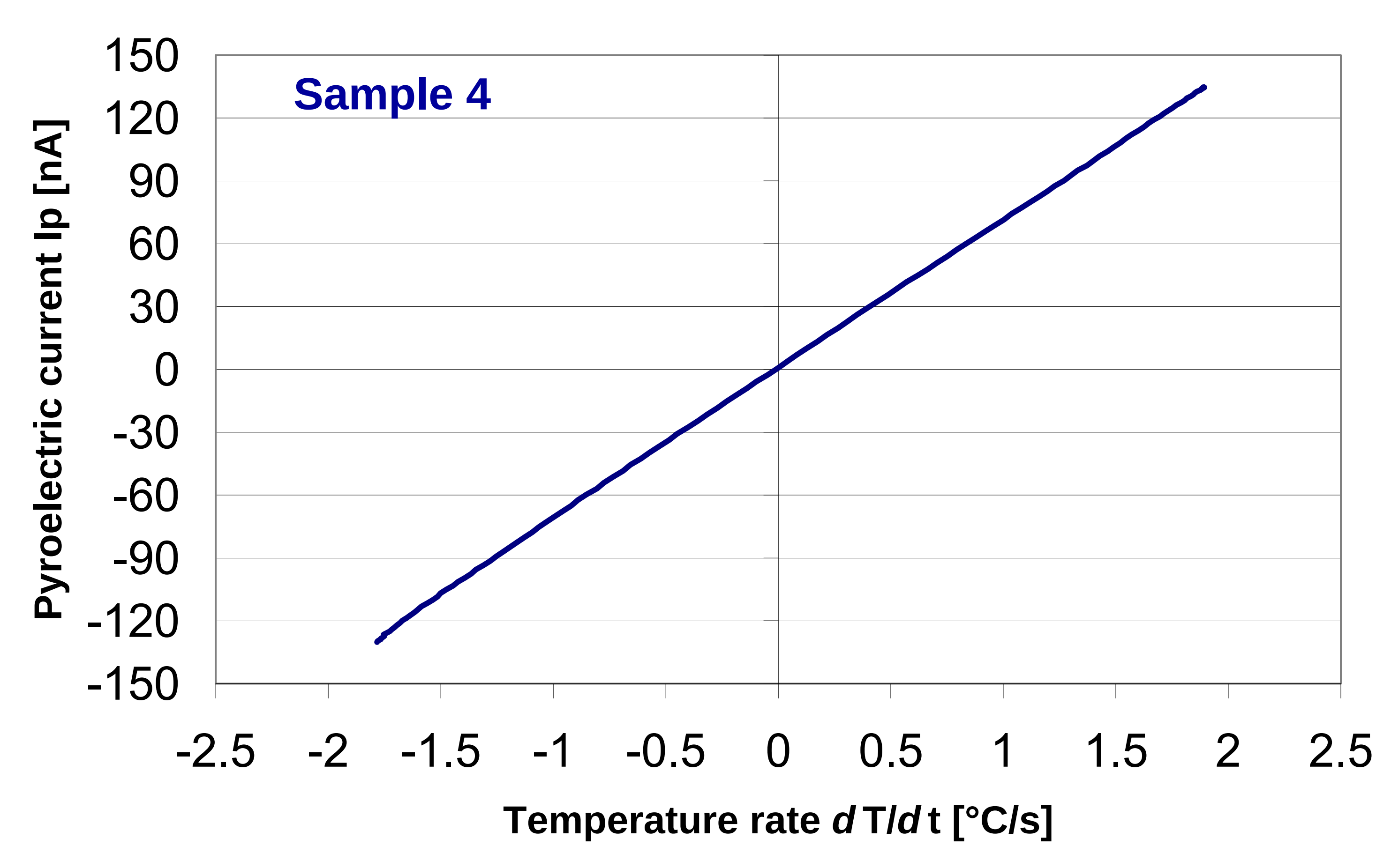
Thermal profile applied by means of Peltier cell



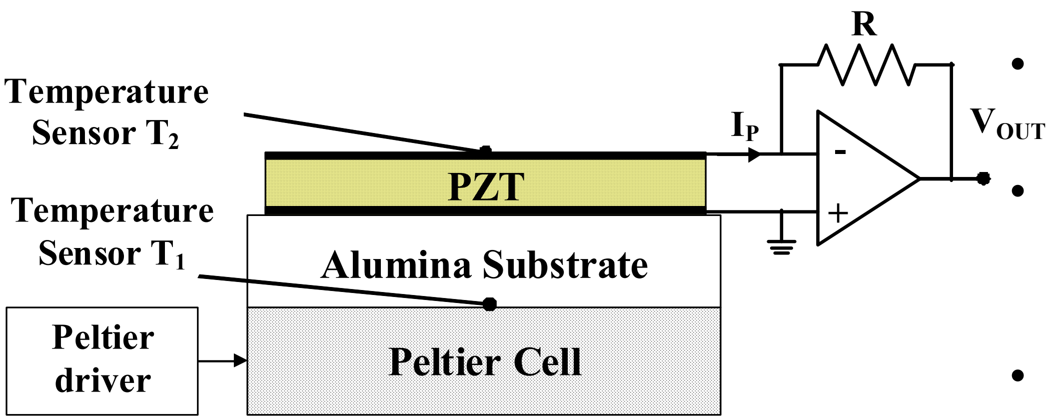
Characterization of pyroelectric samples

- Thermal profile applied by means of Peltier cell





Characterization of pyroelectric samples



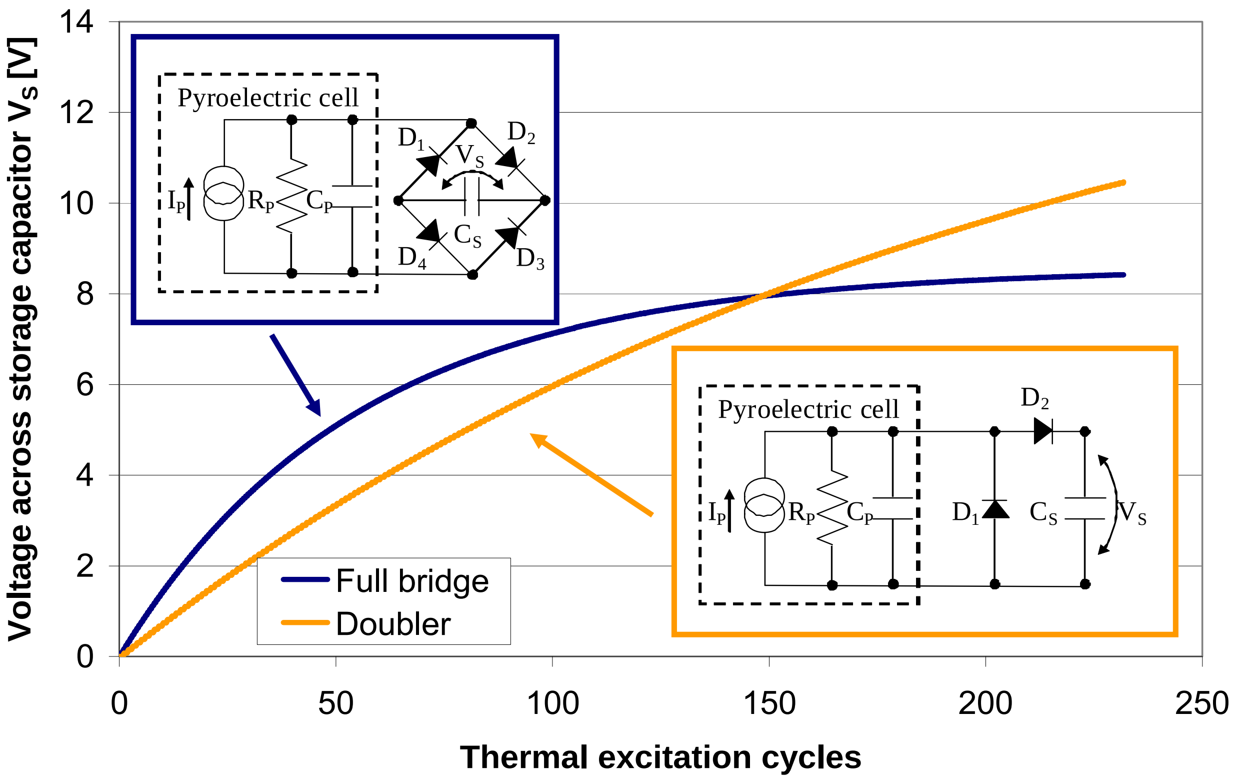
- Thermal profile applied by means of Peltier cell
- Temperature T of the PZT layer estimated by taking the average between the temperatures T_1 and T_2
- Measurement of current I_P

Sample ID	C_P [nF]	R_P [MΩ]	Experimental pyroelectric coefficient [C/(m²°C]
1	0.92	217	1.1·10-4
2	0.42	411	1.8·1.0-4
3	0.36	973	2.1·10-4
4	37.75	3.4	0.5·10-4

Characterization of pyroelectric samples

The pyroelectric current need to be rectified

- Full-wave bridge rectifier
- Schenkel doubler

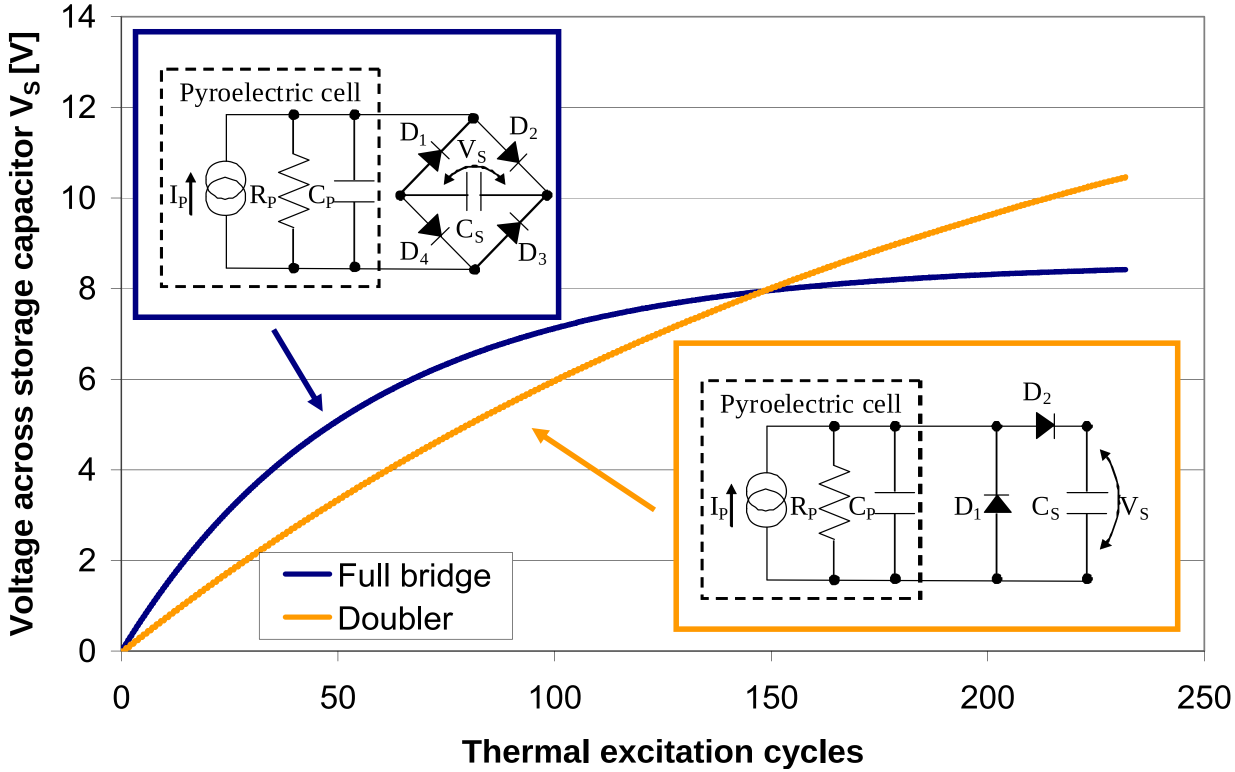


Voltage across a 10 μF storage capacitor for full-wave bridge and Schenkel doubler for sample #4 excited with a sinusoidal temperature rate of 1.8 °C/s peak

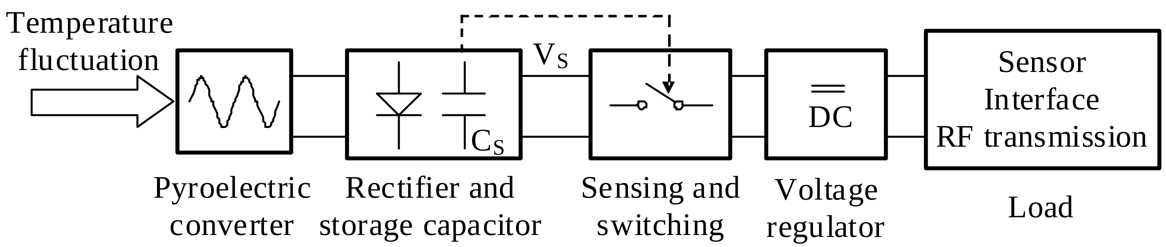
Characterization of pyroelectric samples

The pyroelectric current need to be rectified

- Full-wave bridge rectifier
- Schenkel doubler

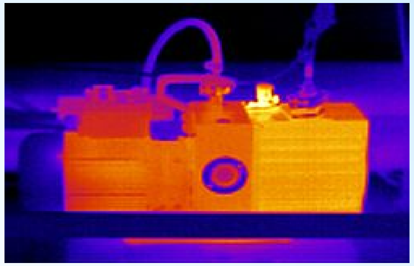


Experimental results demonstrate that the harvested energy can be compatible with use in autonomous sensors working in low-duty-cycle switched-supply mode for measurement and transmission operations

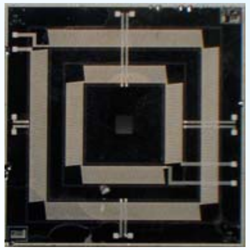


Conclusions

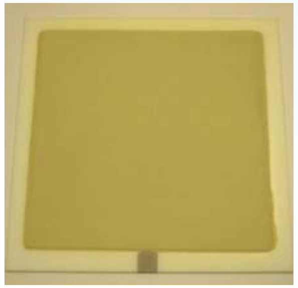
- **Two different principles for thermal energy harvesting:**
  - **Thermoelectric effect (Seebeck)**
    - Spatial thermal gradient ΔT
  - **Pyroelectrical effect**
    - Temperature time-variation dT/dt



- **Investigate the feasibility of micromachined thermoelectric generators for energy harvesting application using really available MEMS technologies**



- **Design, fabrication and characterization of thick-film PZT pyroelectric devices as energy harvesting sources able to power autonomous sensors**




Thank you
for your attention