Pyroelectric conversion: Harvesting Energy from Temperature Fluctuations

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COLLABORATIONS

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- Instrumentation, Sensors and Interfaces Group Castelldefels School of Technology
  - Dr. Gasulla, Dr. Pallàs

INTRODUCTION

Thermal energy

- Present everywhere
- Thermodynamical restrictions

Sources
- Sun
- Fire

- Industry
- Hot Pipes
- Engines

Thermal to electrical conversion

- Thermoelectricity: thermal gradients
- Pyroelectricity: from thermal time-dependent fluctuations

OUTLINE

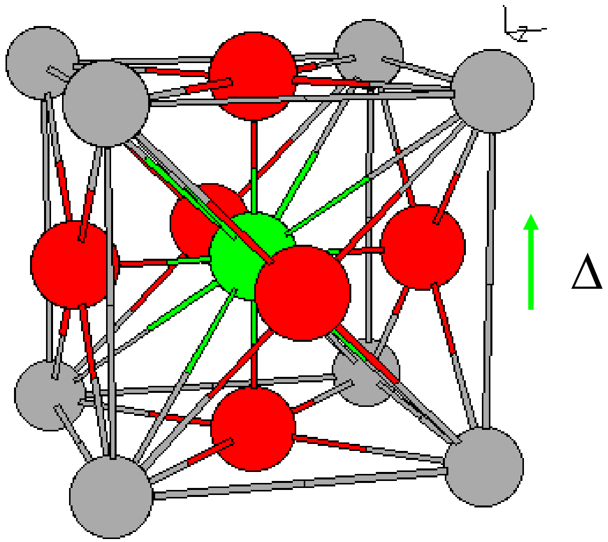
- History
- Pyroelectric Effect
- Materials
- Applications: Sensors and Harvesters
- Experimental harvesters
- Conclusions

HISTORY

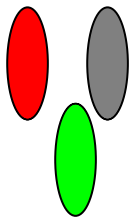
- Phenomenon observation
  - Classic Greeks: Theophrastus (314 BC)
  - XVIIIth and XIXth: phenomenon observation
- Description and quantification
  - Classical explanation: Lord Kelvin
  - Quantical explanation: Born
- Researchers:
  - Schrödinger, Röntgen and P. Curie, among others
- Applications:
  - Sensors: Yeou Ta…
  - Harvesters investigated by Olsen et al., Ikura…

PHYSICAL DESCRIPTION

- Crystalline structures



Cubic structure

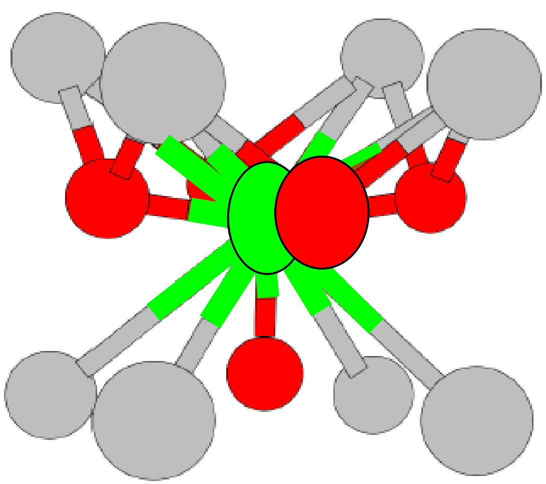


Cations (Pb,Ti,Ca,Ta…)

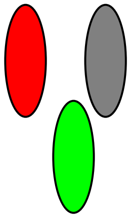
Anions (O)

PHYSICAL DESCRIPTION

- Crystalline structures
- Point symmetry



Tetragonal structure



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PHYSICAL DESCRIPTION

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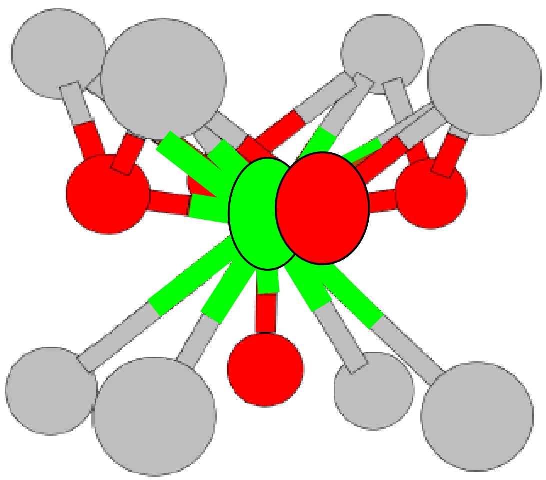
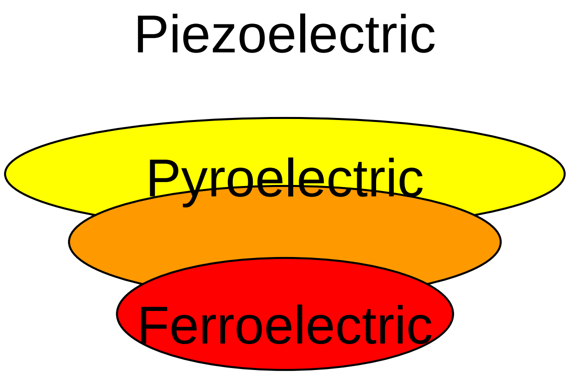
- Point symmetry

Structure
Deformation Δ

- Mechanical stress
- Thermal stress
- Electrical stress



Tetragonal structure



PHYSICAL DESCRIPTION

UPC

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Structure Deformation Δ

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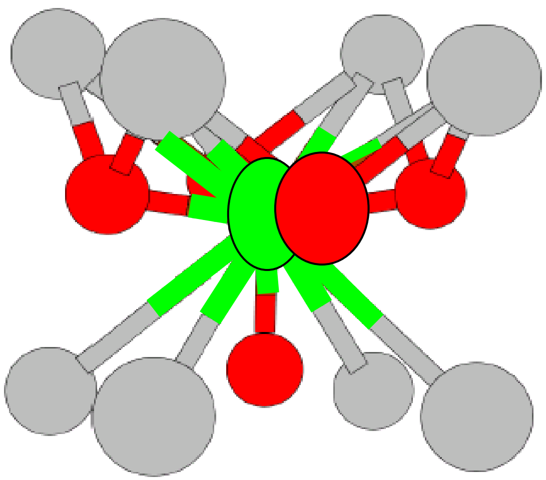
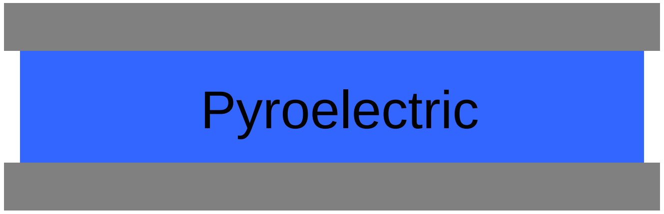


Tetragonal structure



PHYSICAL DESCRIPTION

- Crystalline structures
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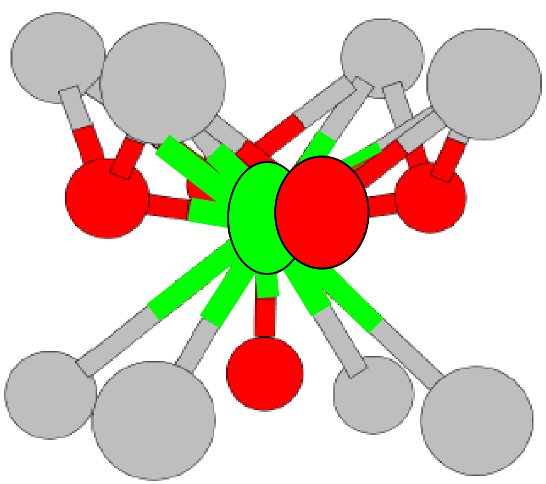
Structure Deformation Δ
- •Mechanical stress
- •Thermal stress
- •Electrical stress



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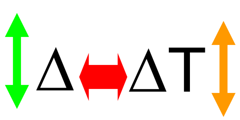
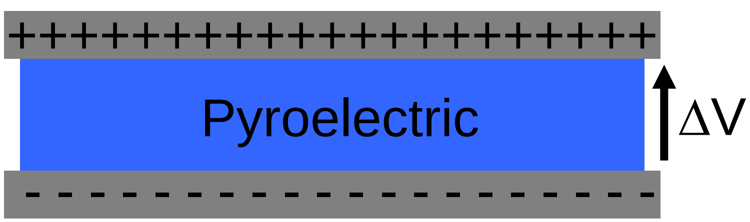




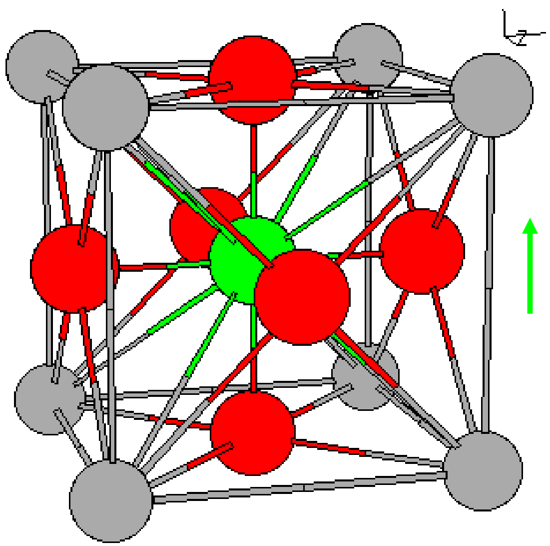
Ion displacement due to ΔT →

Induced charge

PHYSICAL DESCRIPTION

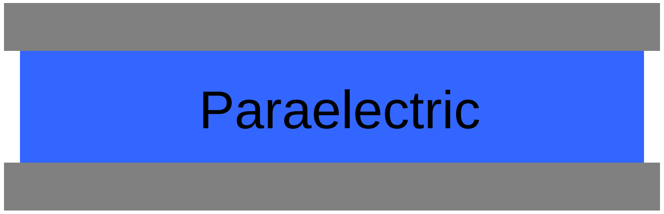
- Crystalline structures
- Point symmetry

Structure Deformation Δ
- Mechanical stress
- Thermal stress
- Electrical stress



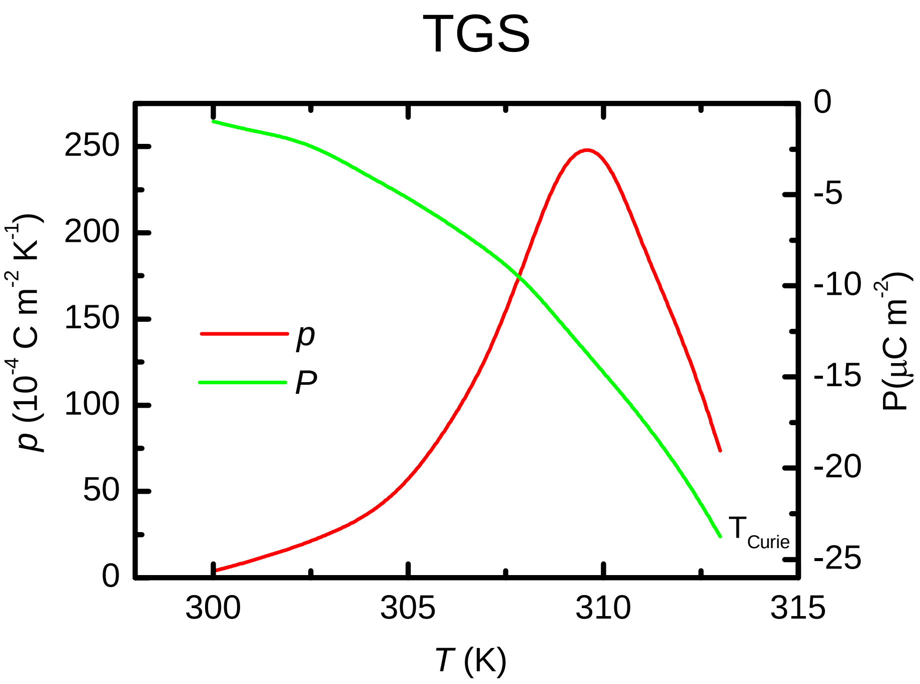
$T>T_C$

Cubic structure



Ion symmetry → no induced charge

PYROELECTRIC EFFECT



- Temperature increase
  - Polarization
  - Dependence of *p* on T $p_s = \frac{dP_s}{dT}$
- Maximum temperature → Curie temperature, phase transition
- Induced current as a function of T

$$I = \frac{dQ_s}{dt} = \frac{dP_s}{dt} = Sp_s\frac{dT}{dt}$$

PYROELECTRIC MATERIALS

- Crystal materials
  - $CaTiO_3$,$LiTaO_3$,$PbTiO_3$
  - Triglycine sulfate (TGS)
  - Growth methods: Czochralki, water dissolution
- Ceramics
  - PZT - Lead zirconate titanate
  - Growth methods: Screen printing
  - Poling
- Polymers
  - PVDF-Polyvinylidene Difluoride
  - Growth methods: Chemical processing

$LiTaO_3$

TGS

MATERIALS DESCRIPTION

- Pyroelectric coefficient (*p*)
  - Thermal energy conversion to electrical conversion
- Thermal capacitance (c_V)
  - Thermal energy stored in the lattice
- Electrical permittivity ($\varepsilon = \varepsilon_0 \varepsilon_r$)
  - Electrical energy stored in the lattice
- Figure of Merit $$FoM = \frac{p}{c_V \, \varepsilon_0 \, \varepsilon_r}$$

Material	p (10^{-4} C m^{-2} K^{-1})	ε_r (1 kHz)	T_C (ºC)	c_v (J cm^{-3} K^{-1})
TGS	3.5	35	49	2.5
$LiTaO_3$	2.3	46	665	3.2
PZT	1.6	1350	320	
PVDF	0.3	12	80	2.4

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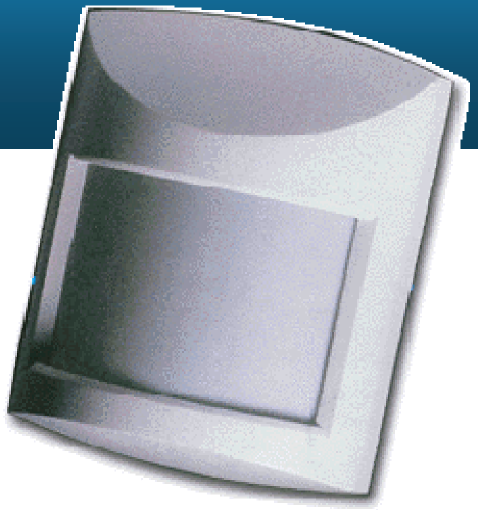
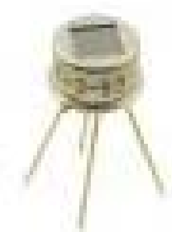
APLICATIONS: SENSORS

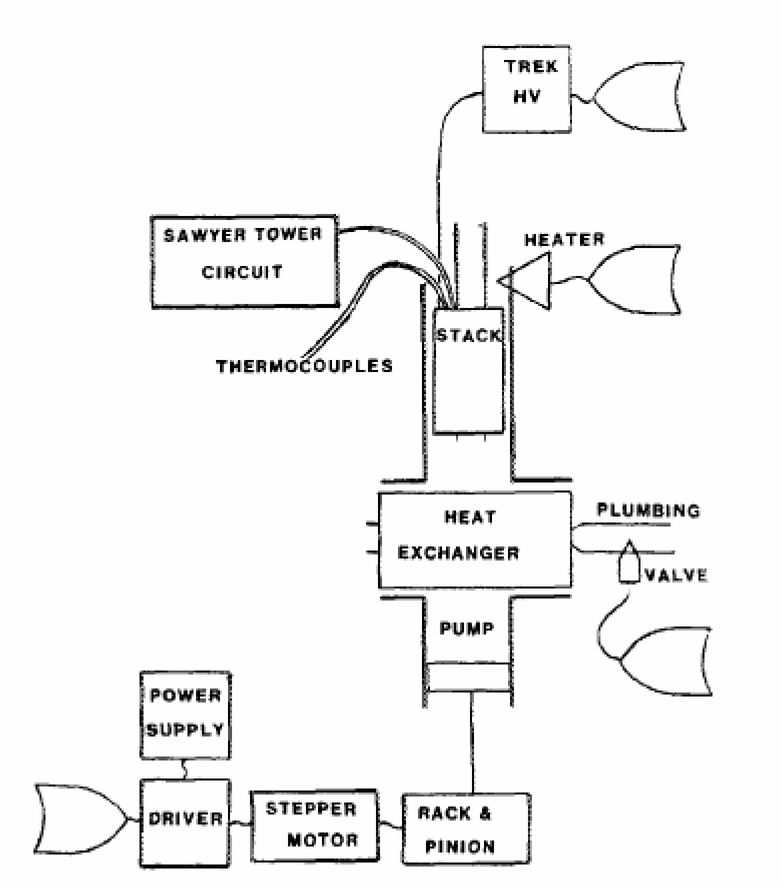


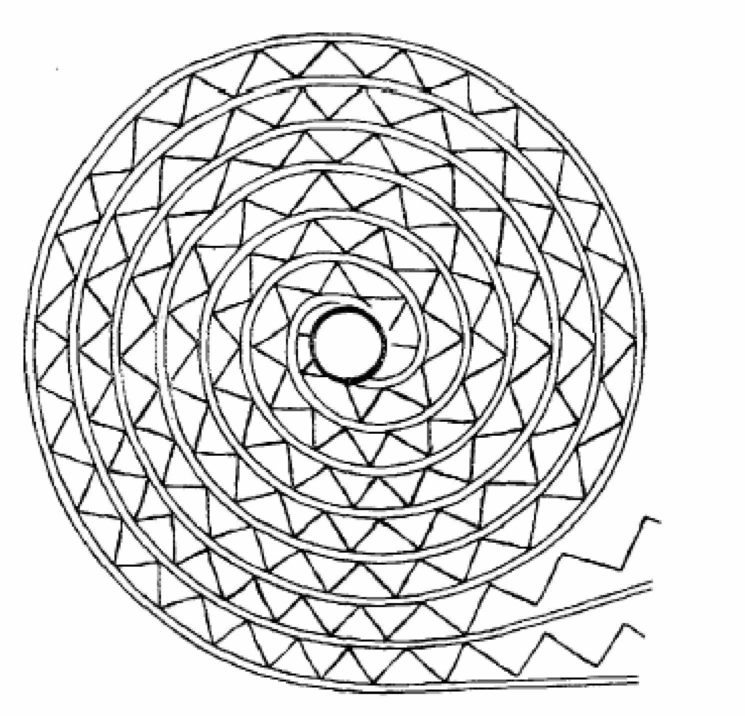
- Proposed by Yeou Ta in 1938
- Application: IR sensors, burglar alarms
- Advantages
  - Wide thermal and electromagnetic sensitivity
  - Fast response (0 to 10 Hz)
  - Low-cost
  - Good signal to noise ratio
  - Work at ambient temperature



- Scientific and commercial development

APPLICATIONS: HARVESTERS





R. B. Olsen, D. A. Bruno, and J. M. Briscoe,

"Pyroelectric Conversion Cycles," *J. Appl. Phys.* 58 (1985) 4709

PYROELECTRICITY: YES OR NOT?

NOT?

- Low power generation
- Low conversion efficiency
- Temperature fluctuations

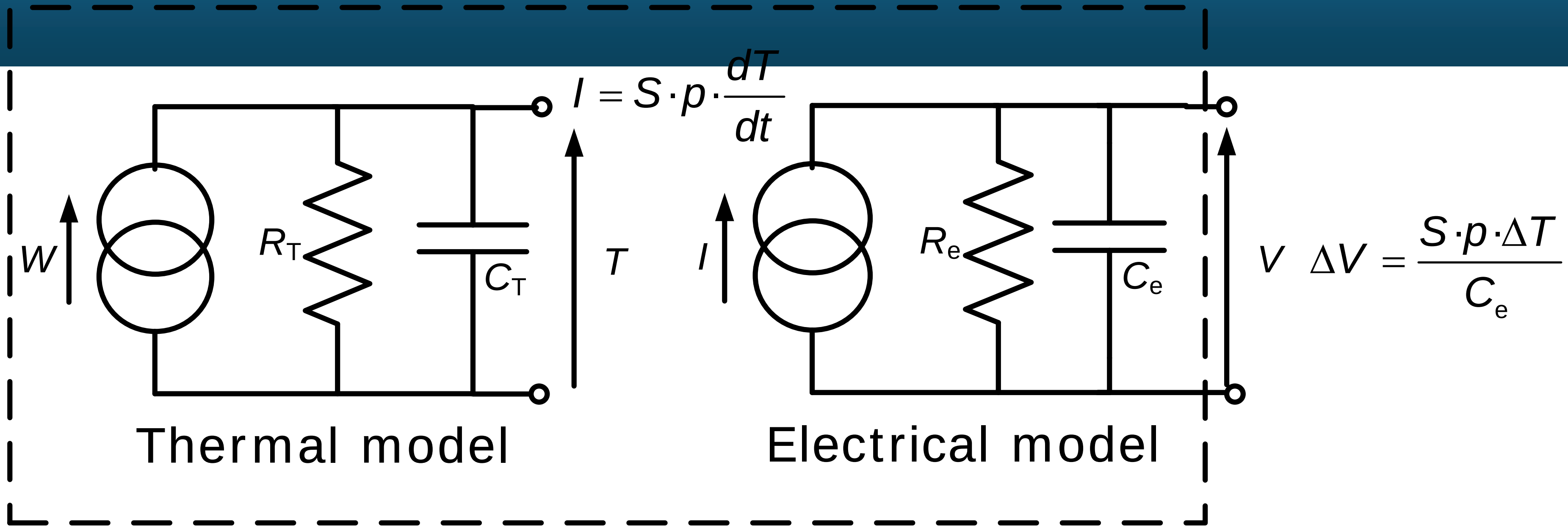
YES?

- Low cost
- Infinite thermal sources

Estimation:

$$\left.\begin{aligned} S &= 10\ \text{cm}^2 \\ \lambda &= 10^{-4}\ \text{C m}^{-2}\text{K}^{-1} \\ dT/dt &= 10\ \text{K s}^{-1} \end{aligned}\right\} \Rightarrow \quad I = 1\ \mu\text{A}$$

MODELING CONVERSION



Harvester critical parameters

R_T and C_T : thermal conductivity and thermal capacitance

R_e and C_e : electrical losses and electrical capacitance

Efficiency (< 1 %)

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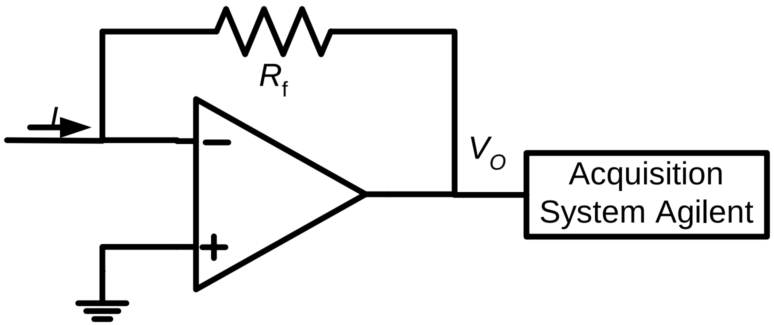
EXPERIMENTAL SETUP

Heating

- 298 K to 370 K
- Warm air
- Halogen lamp

Current Measurement



Thermal measurement

•SMD Thermistor

•Fast thermal response

•Sensitivity up to 0.01 K

Voltage measurement

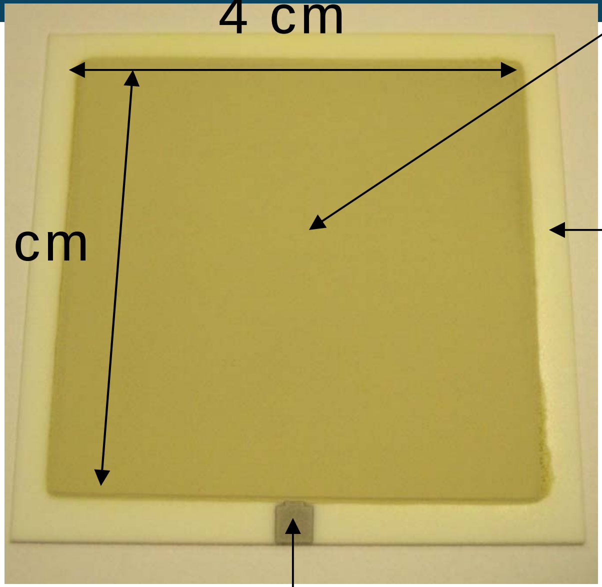
Electrometer Keithley 616

Resistance measurement

Electrometer Keithley 616

R up to 10^{14} Ω

PZT STUDIED HARVESTERS

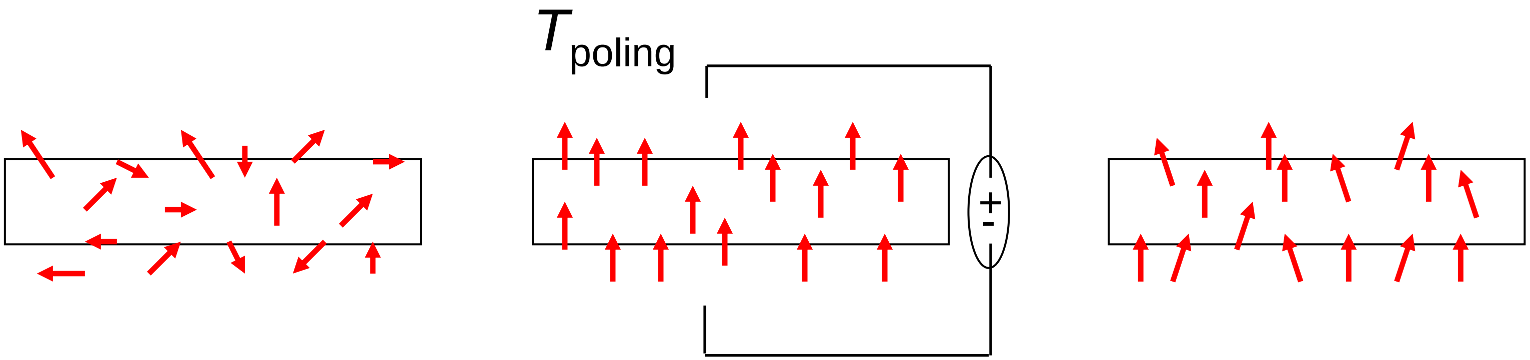


Technology

- Ceramic powder
- Screen printing.
- Firing
- Poling

Sample ID	Target Thickness (μm)	Poling Field (MV/m)
1	60	5
2	60	7
3	100	5
4	100	7

PZT FORMATION



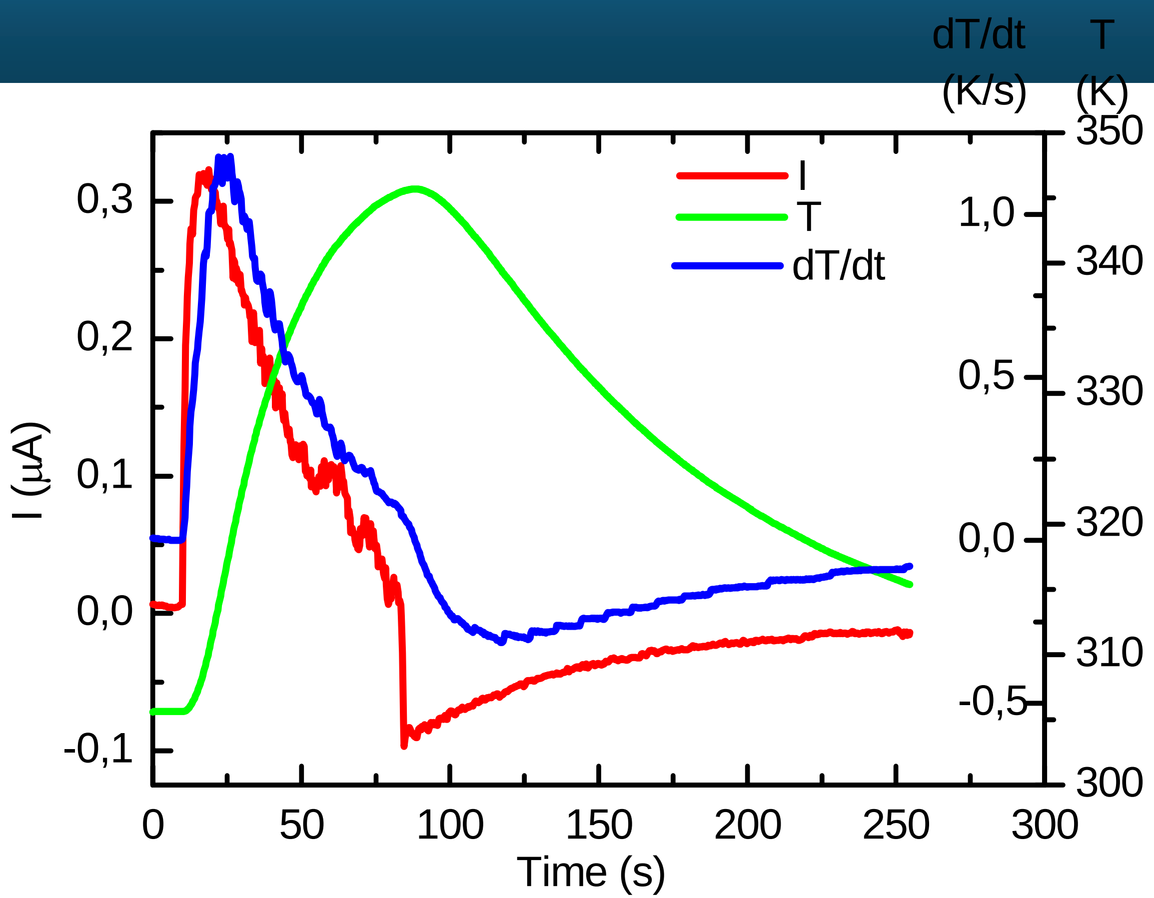
Random orientation of dipoles

DC field application: poling

Remanent polarization

Dipole orientation

PZT CONVERTERS



Air Heating:

- Step function
- Large thermal inertia

Pyrocurrent follows dT/dt

I_{max} = 0.3 mA

Generated charge density

Q = 0.75 C·cm^{-2}

PZT CONVERTERS

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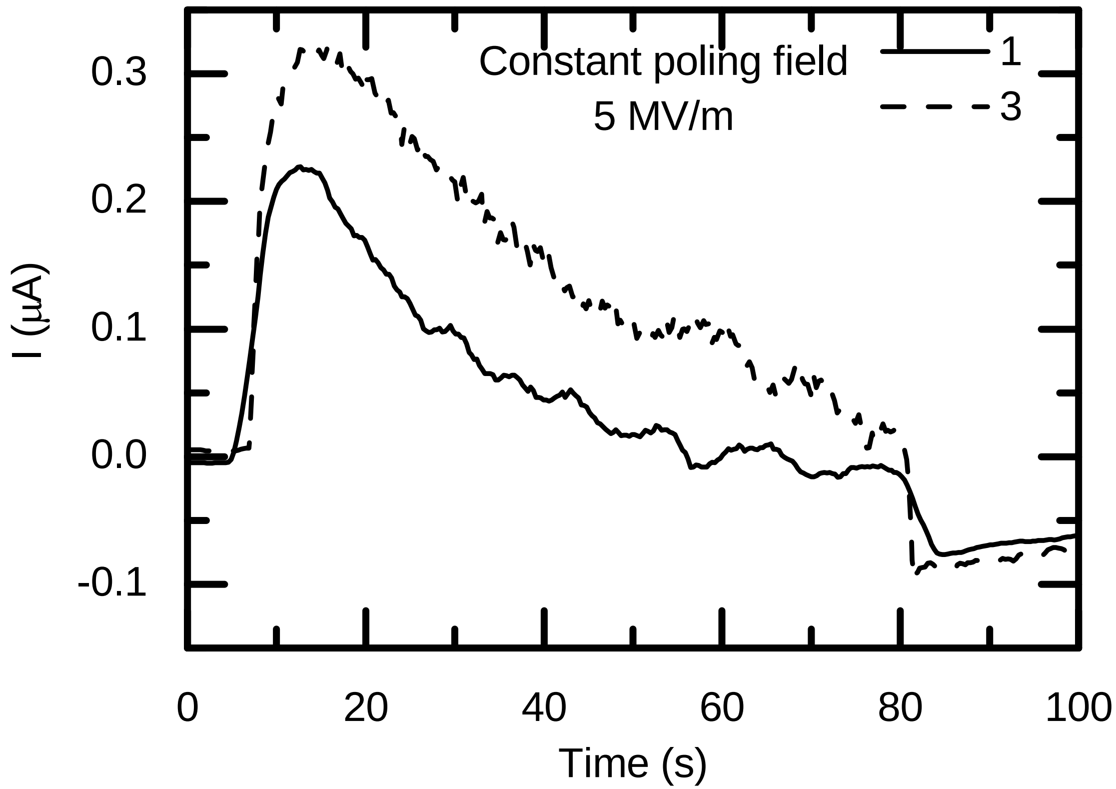
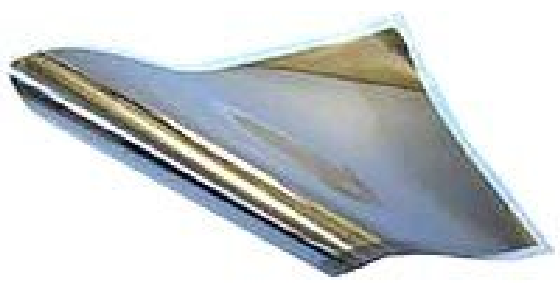


Technological dependence:

- Poling Field
- Thickness

Optimized design

PVDF CONVERTERS



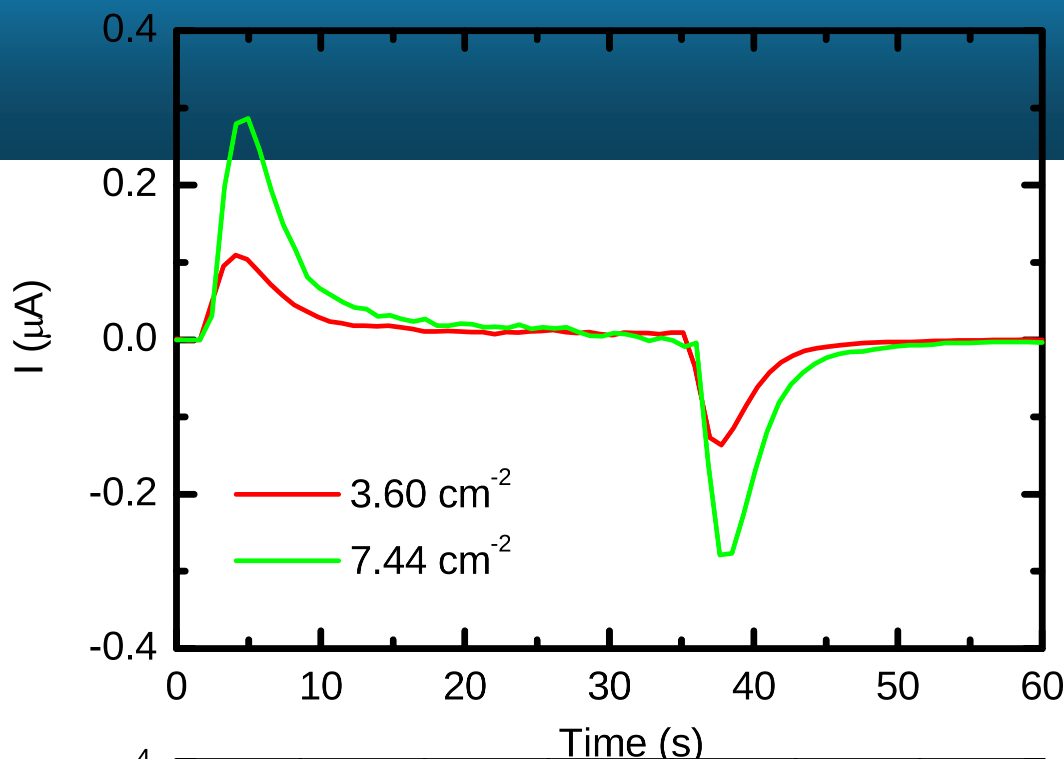
Measurement Specialties Inc.

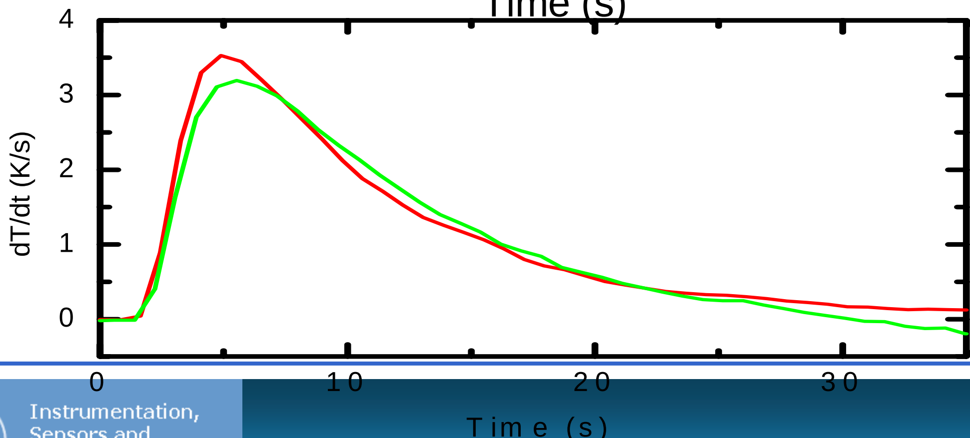
Piezoelectrical Film

PVDF large area technology

Sample ID	Thickness (μm)	Area (cm^{-2})	C (nF)
A1	70	3.6	0.740
A2	40	7.44	2.78

PVDF CONVERTERS





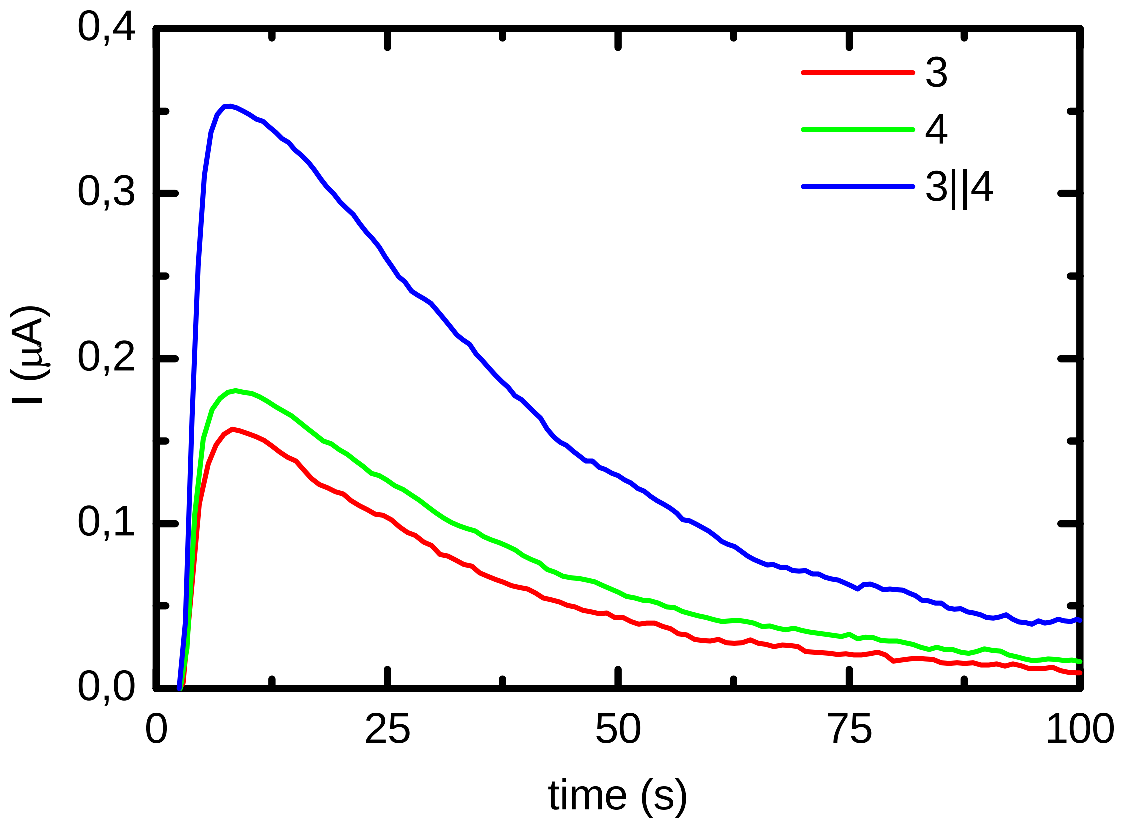
- Warm air flow/fan
- Temperature fluctuation (298 K → 335 K)
- Peak current
- Generated Charge density

  $Q = 0.24\ C{\cdot}cm^{-2}$
- Symmetry in heating and cooling

IMPROVING HARVESTERS

- Cell association
- Energy storage
- Thermal cycling

PARALLEL ASSOCIATION

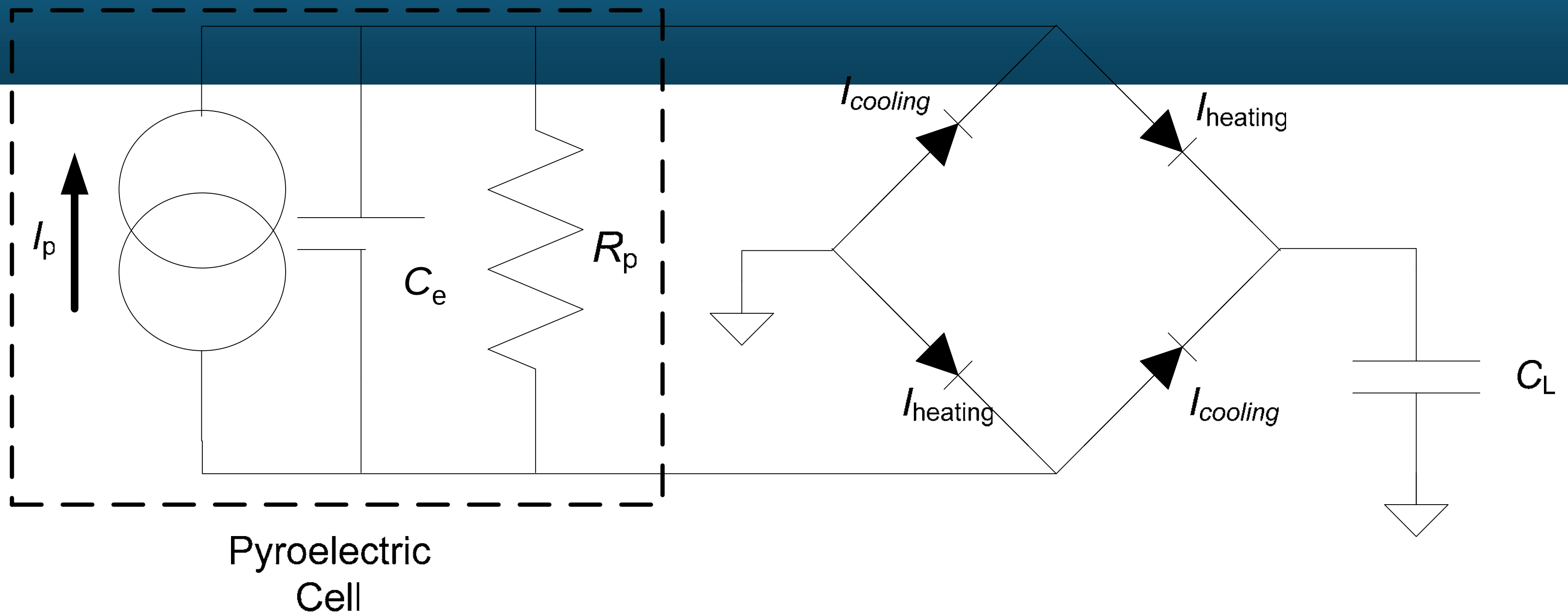


Parallel Cell Association

Current addition

Stacked structures

ENERGY STORAGE

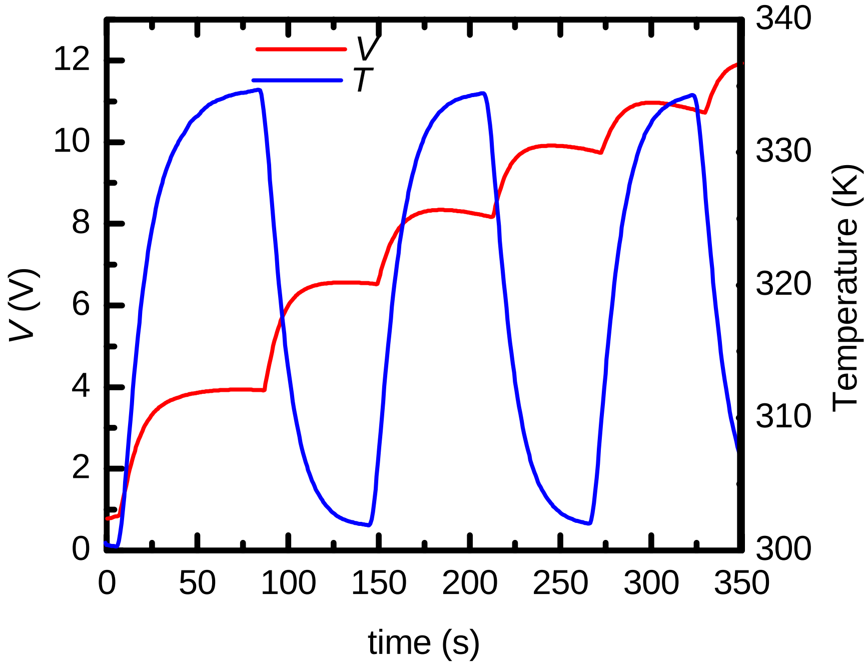


- Impedance matching overcome
- Energy loss at diodes
- Capacitor charge

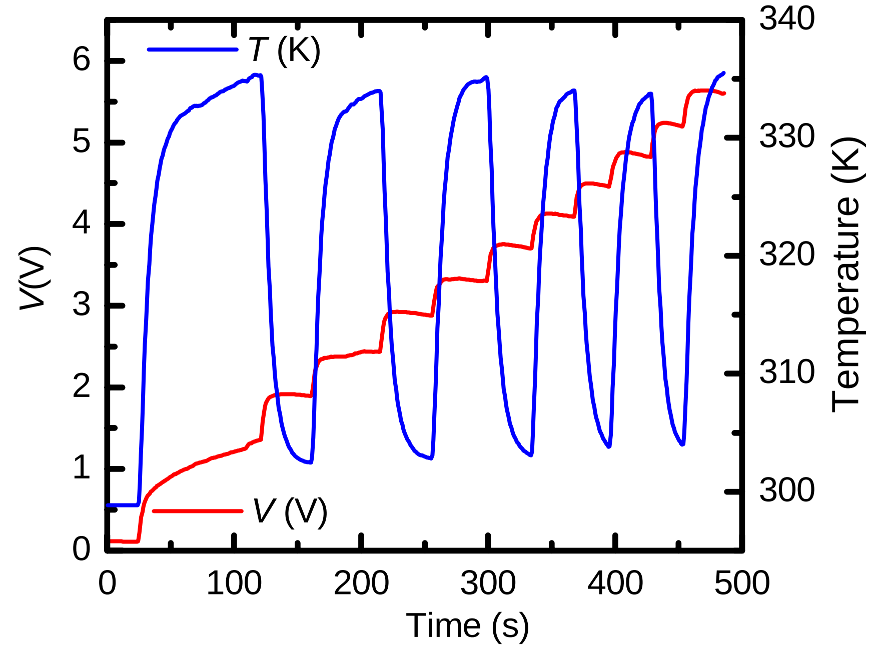
- Low power systems strategy
- Rectification + storage

THERMAL CYCLING

PZT



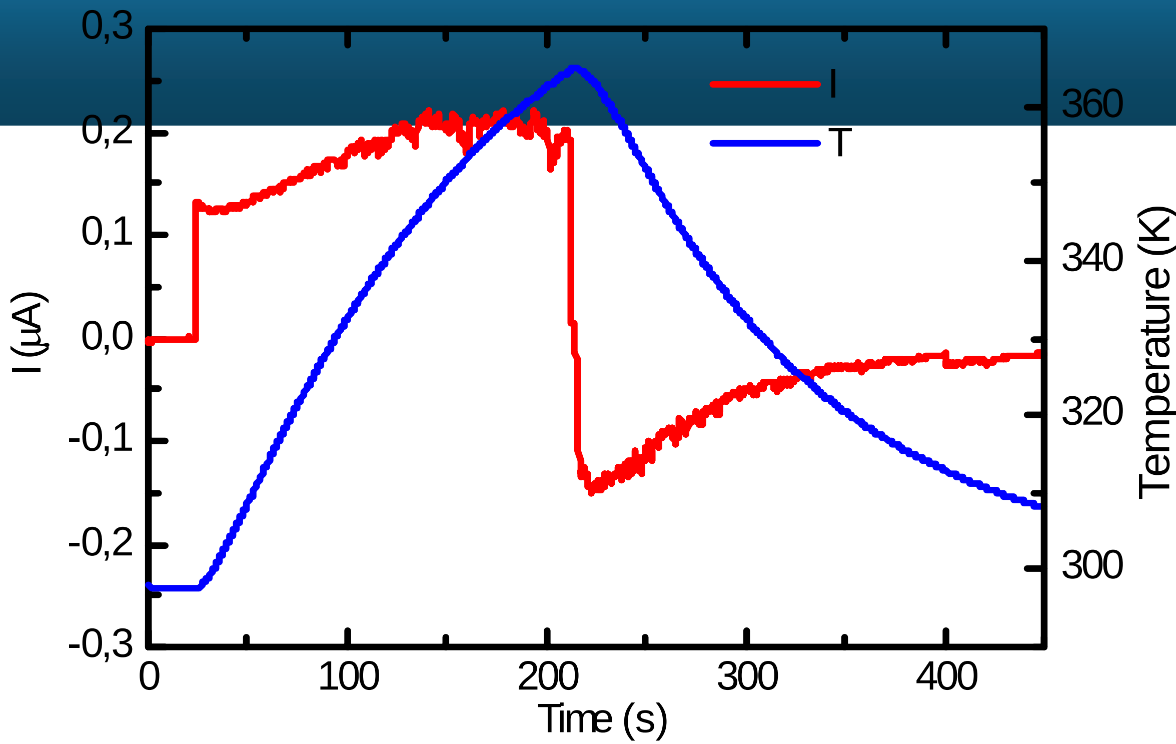
PVDF



$$V_o(N) = \frac{Q_S}{2C_e}\left[1-\left(\frac{C_L - C_e}{C_L + C_e}\right)^N\right] = \frac{S \cdot p \cdot \Delta T}{2C_e}\left[1-\left(\frac{C_L - C_e}{C_L + C_e}\right)^N\right]$$

$$V_{o,\max}(N \to \infty) = \frac{S \cdot p \cdot \Delta T}{2C_e}$$

BEYOND PYROELECTRICITY



- Materials sensitive to external influences.
- Generated current from a PZT when illuminated.
- Current is not proportional to dT/dt.

- Combination of different effects in a single harvester
  - Piezoelectrical response – when undergo mechanical stresses
  - Semiconductor – heated with light

CONCLUSIONS

- Pyroelectricity has been revisited
- PZT and PVDF cells have been developed and modeled.
- Parallel association increases the current.
- Energy can be effectively transferred and stored in capacitors.
- Further research in order to effectively power low power systems.

QUESTIONS?

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