Nanostructured Thermoelectrics

Activities on Nanotechnology for Power Generation and Storage

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ESTEC - Tuesday 16th October 2012

My Talk

National Physical Laboratory

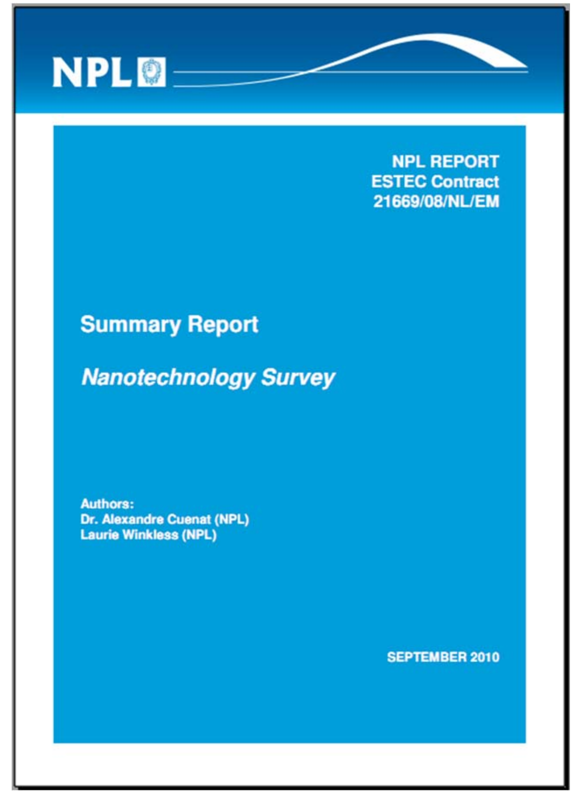
- Intro to the National Physical Laboratory (NPL)
- Thermoelectrics – introduction, applications, challenges
- What are NPL doing in nanostructured thermoelectrics?
- Energy Storage – introduction, applications, challenges
- What are NPL doing in energy storage?
- Summary
- Conclusions

National Physical Laboratory

Founded in 1900

~ 500 scientists

NPL is the UK's national standards laboratory
- ensures accuracy, consistency and innovation in physical measurement and metrology



NPL

NPL REPORT
ESTEC Contract
21669/08/NL/EM

Summary Report

Nanotechnology Survey

Authors:
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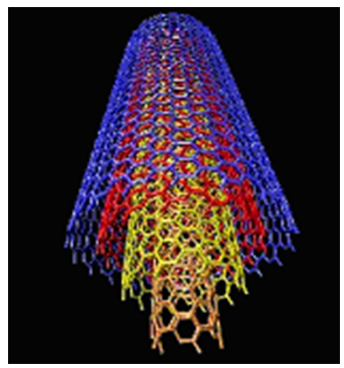
SEPTEMBER 2010



History of working with ESA
– e.g. **Nanotechnology Strategy** (published 2010)

Thermoelectrics

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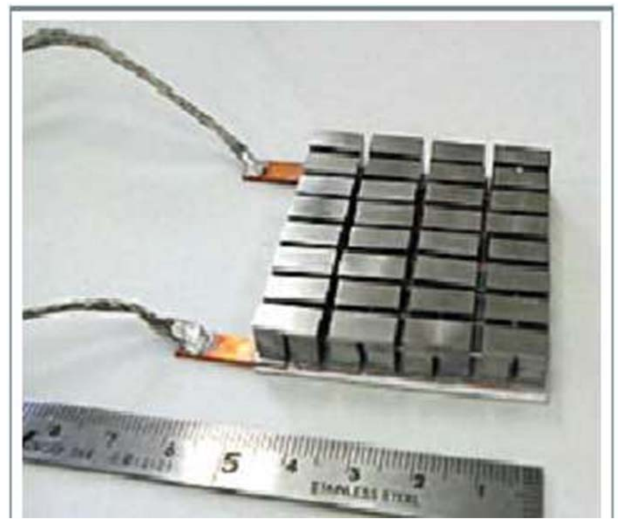
Thermoelectric (TE) Materials can capture heat and transform some of it into electrical power.

You need to maintain a **temperature difference** to "drive" the device



More than 70% of the energy produced by a typical car engine is completely wasted, and most of that in the form of heat

Space Application

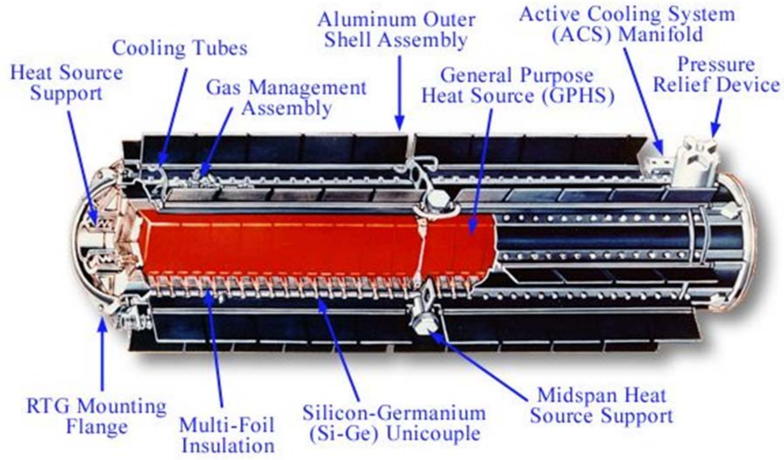
Radioisotope Thermoelectric Generator (RTG)


Apollo 14 (1971)

Lifetime: Up to 1000 years

Issues: Reliability, Maximum Power

Temp Range: ~absolute zero to +500 ° C



Thermoelectricity

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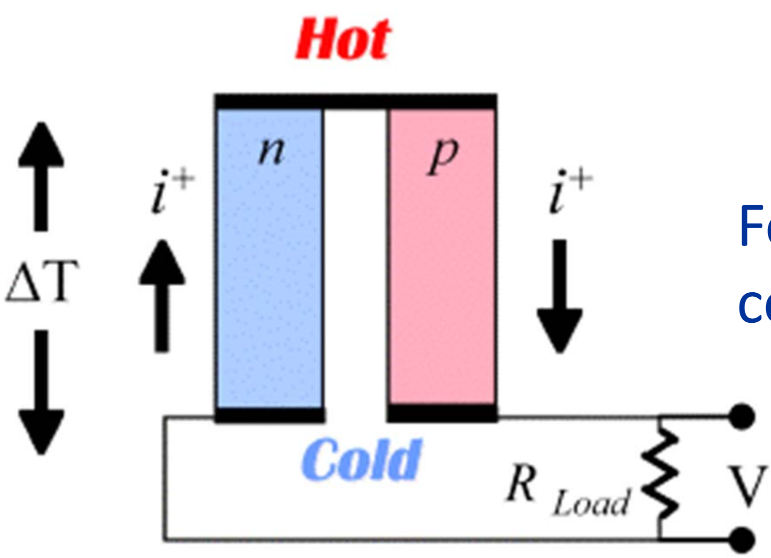
- Traditionally, the term *thermoelectric effect* or *thermoelectricity* encompasses three separately identified effects, the **Seebeck effect**, the **Peltier effect**, and the **Thomson effect**
- What about **Joule heating**? The Peltier–Seebeck and Thomson effects are **reversible**, whereas Joule heating is not
- Figure of Merit (ZT)

$$ZT = \frac{\alpha^2 \sigma T}{\kappa}$$

Power Factor = $\alpha^2\sigma$

α = Seebeck coefficient
κ = thermal conductivity
σ = electrical conductivity



For **power generation**, connect p-n couples and the output voltage is

$$V = \alpha \Delta T - I R_{TEG}$$

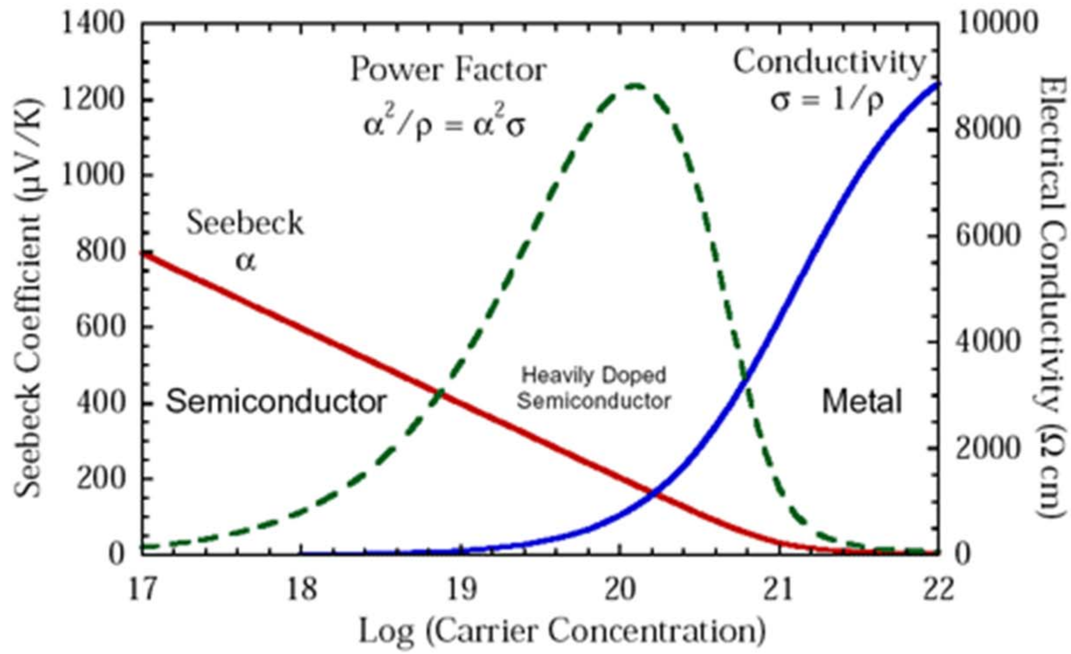
Maximise efficiency when $R_{TEG} = R_{Load}$

Thermoelectricity

- So, for practical power generation from thermoelectric materials, we need **high electrical** conductivity but **low thermal conductivity**
- The thermoelectric **power factor** maximizes between a metal and semiconductor

$$ZT = \frac{\alpha^2 \sigma T}{\kappa}$$

Good thermoelectric materials are typically **heavily doped semiconductors** with carrier concentration of 10^{19} to 10^{21} carriers/cm^3



http://www.its.caltech.edu/~jsnyder/thermoelectrics/index.html

Thermoelectricity

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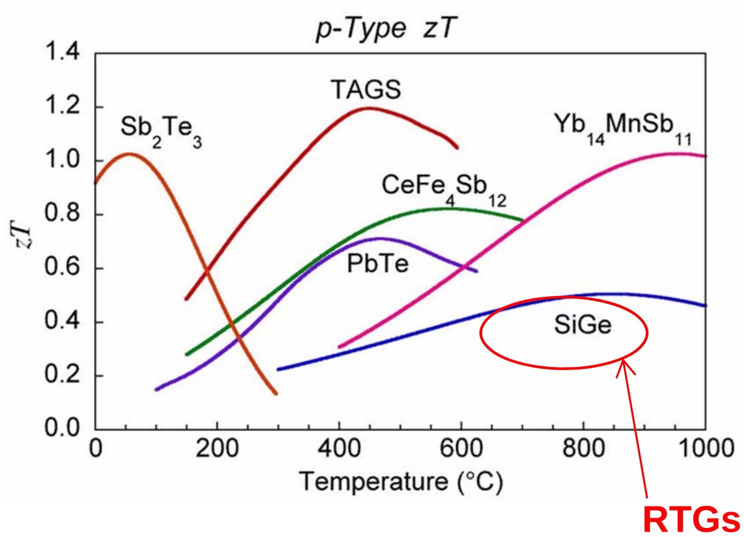

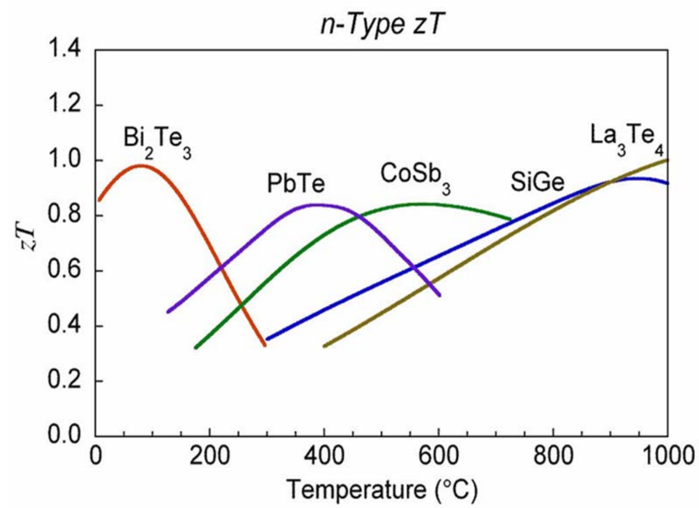

$$ZT = \frac{\alpha^2 \sigma T}{\kappa}$$

$$\eta = \frac{T_{hot} - T_{cold}}{T_{hot}} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + {T_{cold}}/{T_{hot}}}$$

- ZT is a property of the **material** used
- Efficiency improves asymptotically with ZT

- The ZT of a material is proportional to the efficiency of the device
- Each material has an optimum temperature range
- Measurements of ZT / efficiency are **conceptually simple** but results vary considerably. Total uncertainty in Z lies between **25 to 50%** !

Thermoelectrics: Challenges

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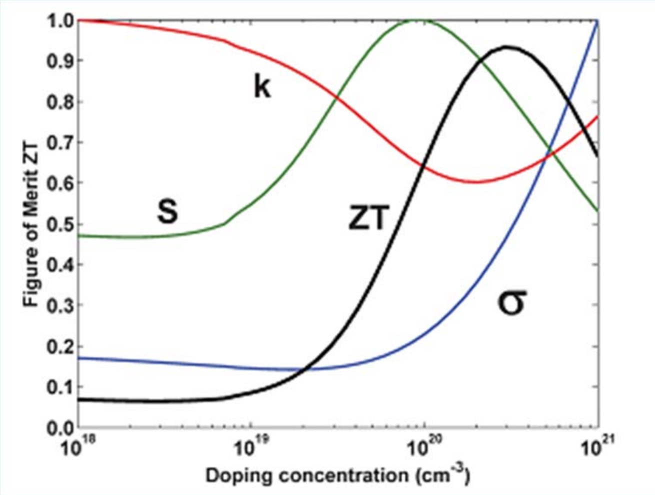
In general

- Low efficiency of TEGs and TE materials – less than 5% efficient in general – can this be improved?
- TE materials are expensive and some are toxic – what are the alternatives?
- Maximum power vs. maximum efficiency – where should we focus?

For space

- Radioactive source
- Need higher efficiency TE materials
- Materials appropriate for the environment (e.g. SiGe)



Nanostructured TE

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- The goal is to increase the ZT of the material – there are generally two options
  - Decrease thermal conductivity
  - Increase thermopower / electrical conductivity

$$ZT = \frac{\alpha^2 \sigma}{\kappa} T$$

- Nanostructured materials have been shown to have reduced thermal conductivity compared to the bulk [REF]

  Bulk PbTe κ = 2.4 W/m.K

  Nano-PbTe (with 2% Sb) κ = 0.8 W/m.K [Poudeu et al 2006]

- Increasing the electrical conductivity (while keeping α and κ at reasonable levels) is more challenging

What are NPL doing - TE?

- Focus on both **materials** and **systems**
- Work with device manufacturers - improve their product
- Close links to end-users from the car, electronics and energy industries – bringing thermoelectrics to market
- Characterisation and **nanometrology** of thermoelectric materials
- We can measure the operating efficiency of a **thermoelectric generator** reliably and repeatably
- EMRP Project
- NexTEC Project
- Focus on high-temperature (800 ° C +) thermoelectric devices

There are NO EXISTING STANDARDS for thermoelectric materials or devices – NPL is leading the effort to develop these standards

TE Projects

- Two EU-funded projects
- NexTEC: ***Next Generation Nano-engineered Thermoelectric Converters – from concept to industrial validation***
- EMRP **Metrology for Energy Harvesting**

NexTEC: NPL Achievements

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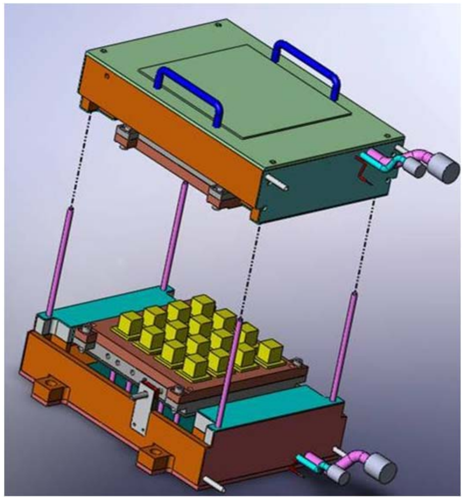
- Low-temperature (RT – 200 °C) test rig
- High-temperature (up to 700 °C) test rig
- Measurement of the **thermal conductivity** of a commercial TE module (7.5 % accuracy)
- New facility to measure Seebeck coefficient on small samples
- New facility to measure TE module efficiency by **electrical spectroscopy**
- **Round-robin** of Seebeck coefficient measurement
- A realistic three-dimensional COMSOL model of thermoelectric module
- The consortium has developed a **new nanostructured TE material**, suitable for use at high temperatures.
- Initial results show a superior performance to bulk Bi_2Te_3 and can be produced at low cost



EMRP: NPL Achievements

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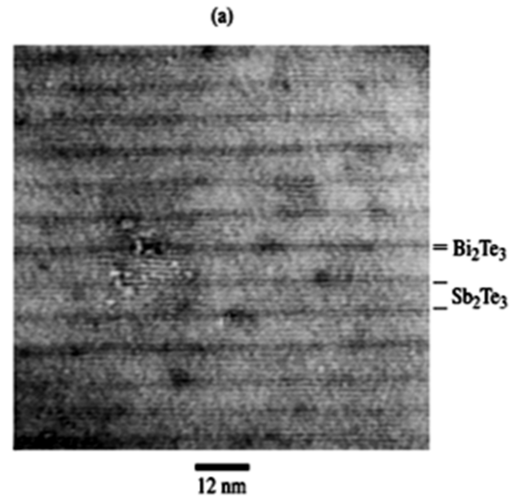
Transport properties measurement in **nanostructured materials**

- Electrical transport on TE materials at the nanoscale and in ultra-high-vacuum
- Nanoscale temperature measurements on metals and insulators

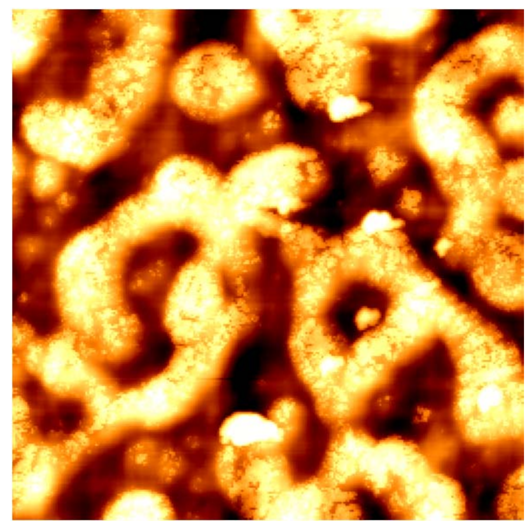


Reliable energy conversion efficiency measurement **at the nanoscale**

- Electrical characterisation of TE materials
- Thermal characterisation of TE materials

(a) ZT ~ 2.4 @ 300 K p-type, Bi_2Te_3/Sb_2Te_3

(b) Nanostructured polymer PV



New methods for traceable efficiency measurement for nanostructured TE materials

Energy Storage: Challenges

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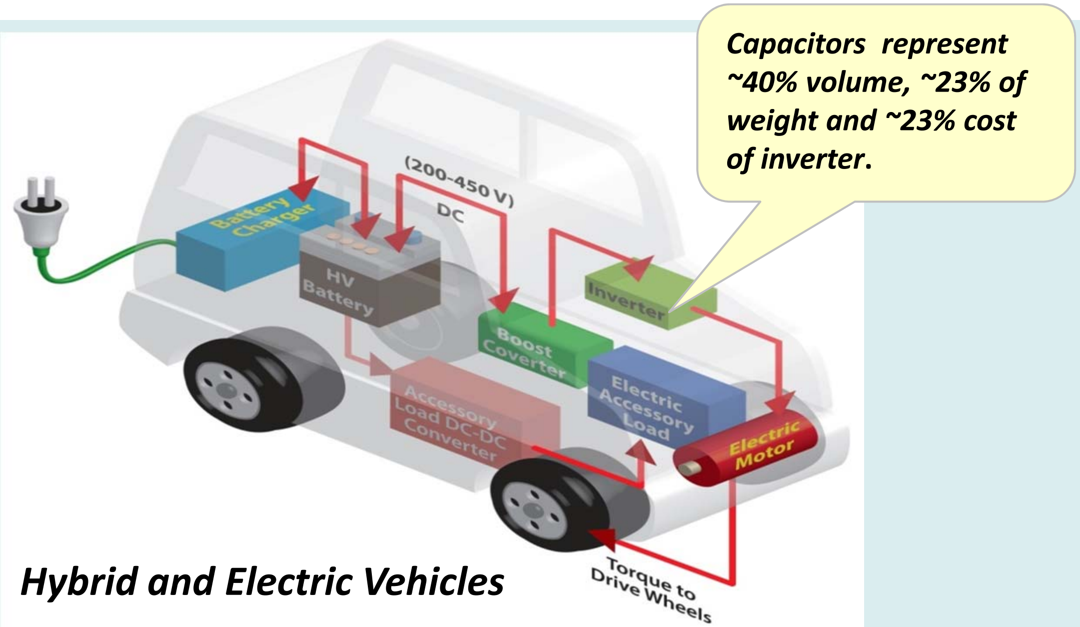

Hybrid and Electric Vehicles

- High temperature operation (>140 ° C)
- High voltage (600 V)
- Temperature and voltage stability
- High energy density
- Mechanically robust

Spacecraft power systems

- Operate under convection or forced-air cooling, and thus higher temperatures than terrestrial environment
- Vibration insensitive

Energy Storage: Challenges

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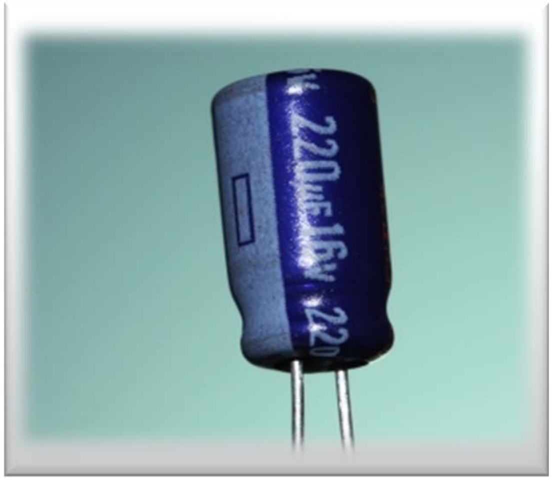
Electrolytic

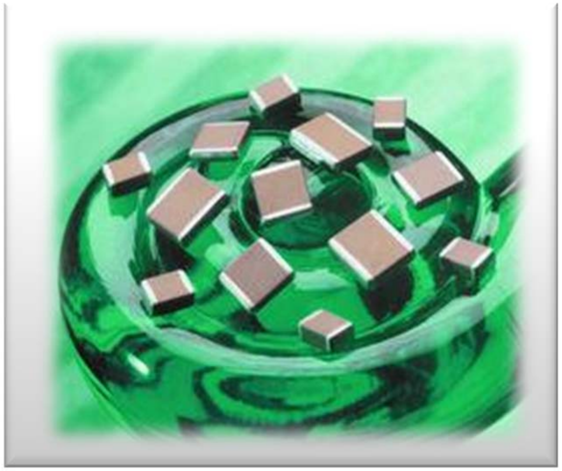


- High energy density

But….

- Low thermal stability
- Low voltage rated
- Short life time

Ceramics



- Vibration robust
- Cost-effective
- Long life-time

But….

- **Low energy density**
- **Capacitance varies with T**

What are NPL doing in Storage?

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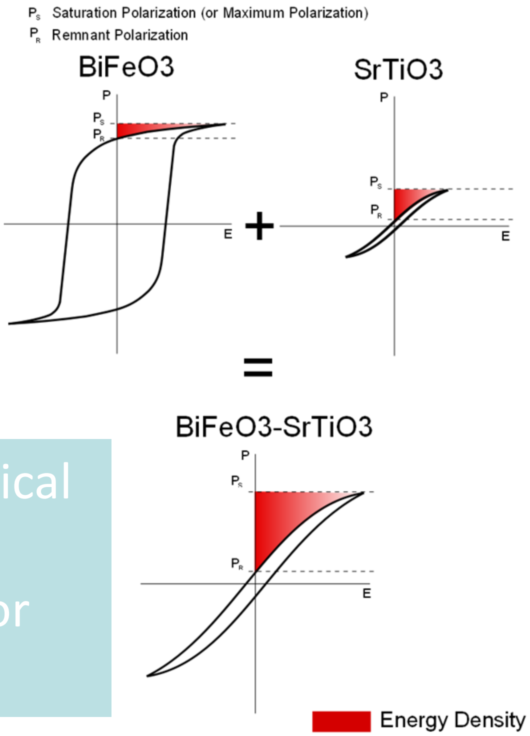
Develop a new generation of high temperature stability, high energy density lead-free capacitors

http://www.aixacct.com

*Enable **power electronics** to operate at significantly higher temperatures - up to (or above) 200 ° C*

Electrical and electro-mechanical characterisation of **ceramic multilayer actuator devices** for device qualification



What are NPL doing in Storage?

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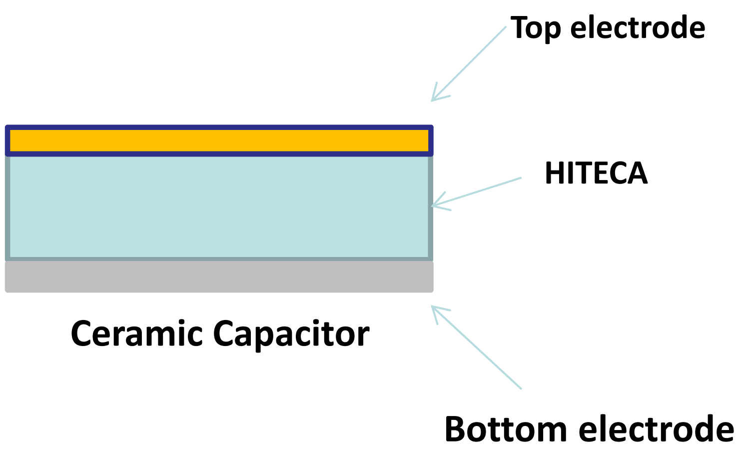
HITECA Capacitor: The key enabler – *UK patent pending*

- Lead-free ceramic
- Energy density 25 J/cc at 1200 kV/cm (2.5J/cc at 500 V)
- High temperature stability (15% of room temperature performance up to 220 ° C)
- High voltage stability
- Low ESR (equivalent series resistance)
- High breakdown voltage



Conclusions

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Thermoelectrics

- Need to develop new, high efficiency devices
- NPL focus is on the validation and metrology of both materials and devices at high-ΔT
- Working closely with end-users (i.e. automotive, space and electronics industry) and partners across Europe
- Emphasis on describing the nanostructure of TE materials

Energy Storage

- Developing a new generation of high temperature stability, high energy density lead-free capacitors
- NPL focus is on the metrology necessary to validate these new capacitors
- Expertise in electrocaloric, multiferroic and piezoelectric materials

Thank you for your attention

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