Metrology for Energy Harvesting

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Energy Harvesting from Mechanical Sources

- Introduction
- Energy harvesting measurements – general considerations
- Energy harvesting: macro, MEMS to nanoscale
- The future for energy harvesting metrology
- Conclusions

EMRP Metrology for Energy Harvesting

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PTB
CMI
INRIM
LNE
MIKES
NPL
SIQ

Metrology for **energy harvesting**

European Metrology Research Programme

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

National Measurement System

Piezo INSTITUTE
The European Institute of Piezoelectric Materials and Devices

http://projects.npl.co.uk/energy_harvesting

Importance of Metrology

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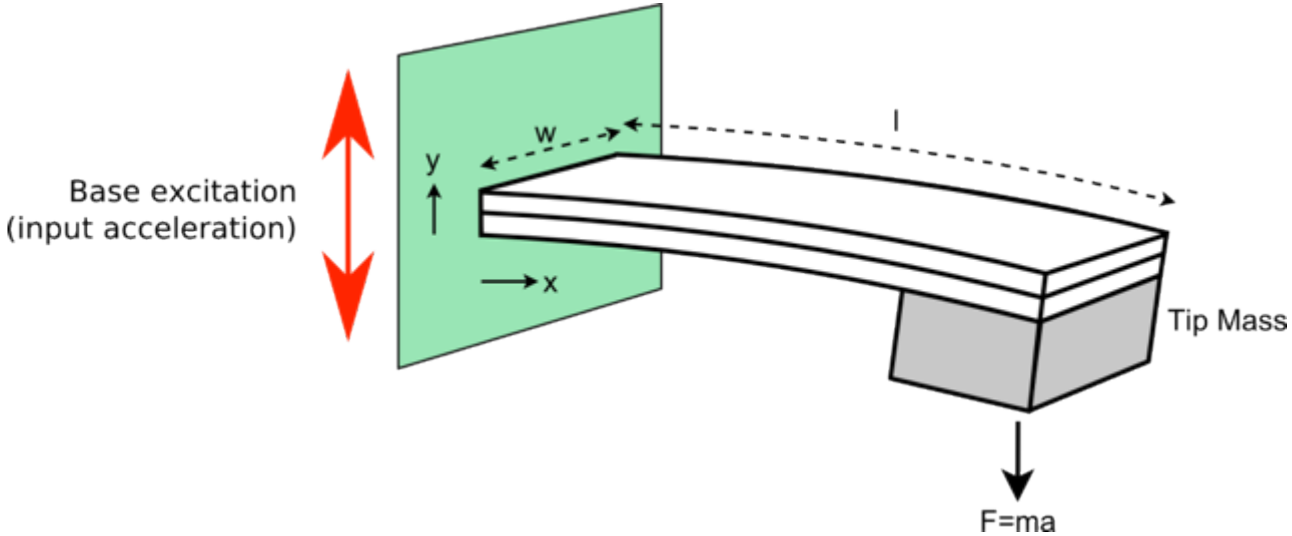
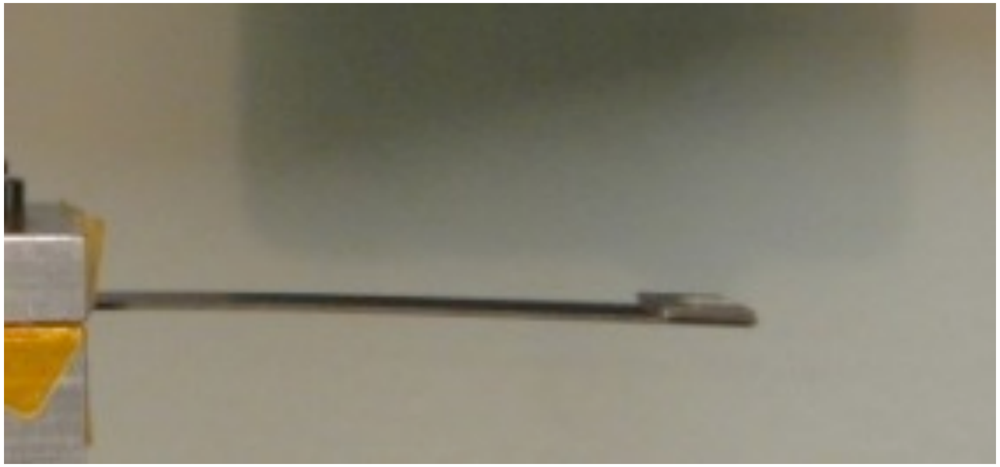
- Facilitates communication between suppliers and users – you know what you're going to get.
- Helps develop "level playing field" for meaningful comparisons
- Reliable measurement builds confidence in new technologies
- Metrology accelerates research and innovation by providing reliable data and solutions to difficult measurement problems
- Metrology forms the basis of standards which help develop emerging markets. Solidifying best practice into standards is a powerful means of dissemination.

Piezoelectric Cantilever





Performance Mapping

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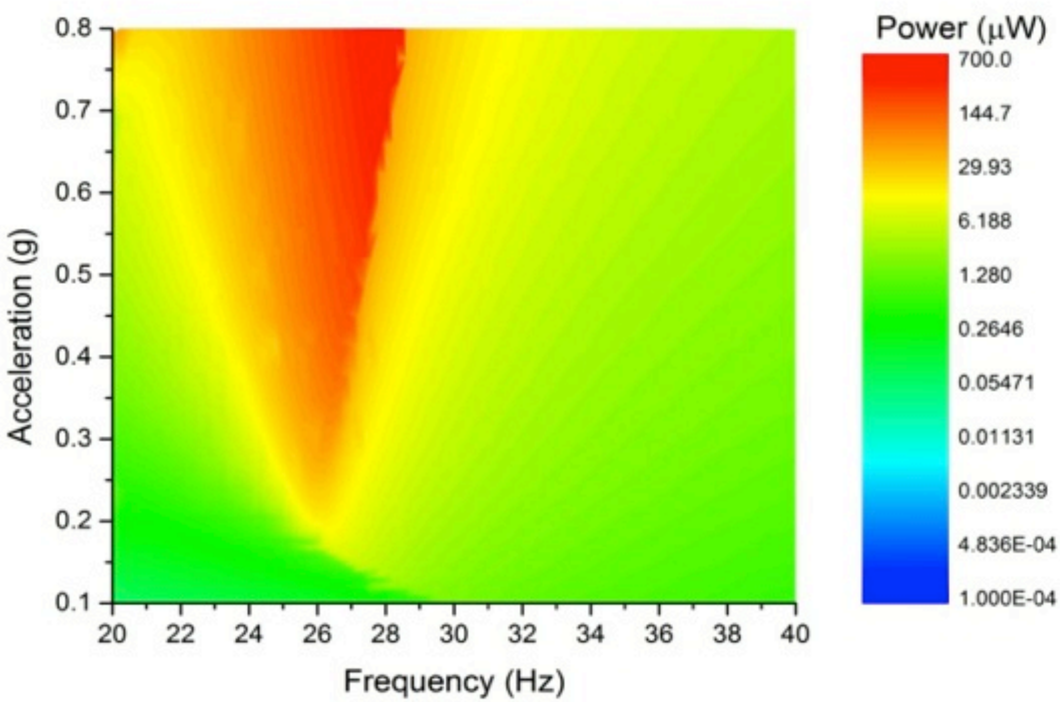
"Simple case": Piezoelectric bimporph with tip mass, sinusoidal vibration, resistive load



- Vibration amplitude
- Vibration
- At resonant frequency do a sweep of electrical load resistance
- Repeat frequency sweep with matched load resistance to get maximum harvester output

BUT peak frequency shifts with acceleration

Piezoceramic bimorph cantilever , clamped with 54mm free length, 1.07g tungsten tip mass.

Power and Efficiency

Power: Need to know the electrical power output that can be expected under conditions of use. This is the main consideration where the harvester loading is insignificant

BUT

- The supplied energy is not always "waste" or "free". The energy harvester increases the power consumed by the source. This can be important e,g, human or vehicle powered applications.
- Impulse excited harvesters e.g. pacemaker or frequency converting systems – efficiency is a direct performance metric.
- Direct strain harvesting can be source energy limited so efficiency matters.
- Efficiency can directly relate to power output in space limited resonators e.g. high Q MEMS resonators where amplitude is limited by power harvested [1].

[1] Renaud et al. J. Micromechanics and Microengineering, 2012, 22, 105030

Efficiency Measurement - Impulse

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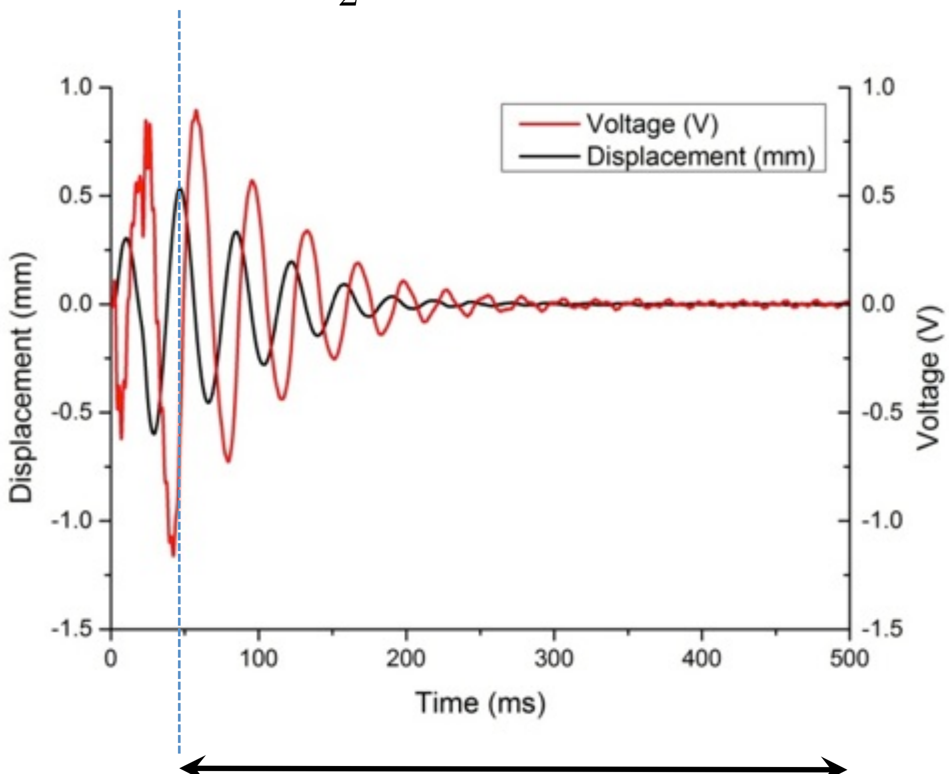
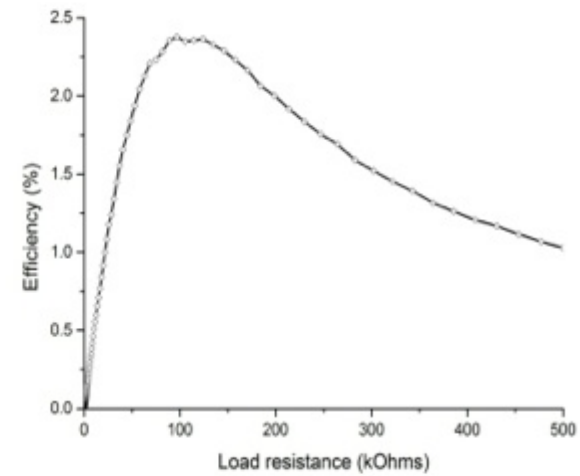
$$E_{mech} = \frac{1}{2} k\, d_0^2$$



$$E_{elec} = \int \frac{V^2}{R}\, \mathrm{d}t$$

Efficiency $\eta = \frac{E_{elec}}{E_{mech}}$



- Efficiency maximum 2.4%

Piezoceramic bimorph cantilever , clamped with 54mm free length, 1.07g tungsten tip mass.

Efficiency Measurement - Continuous

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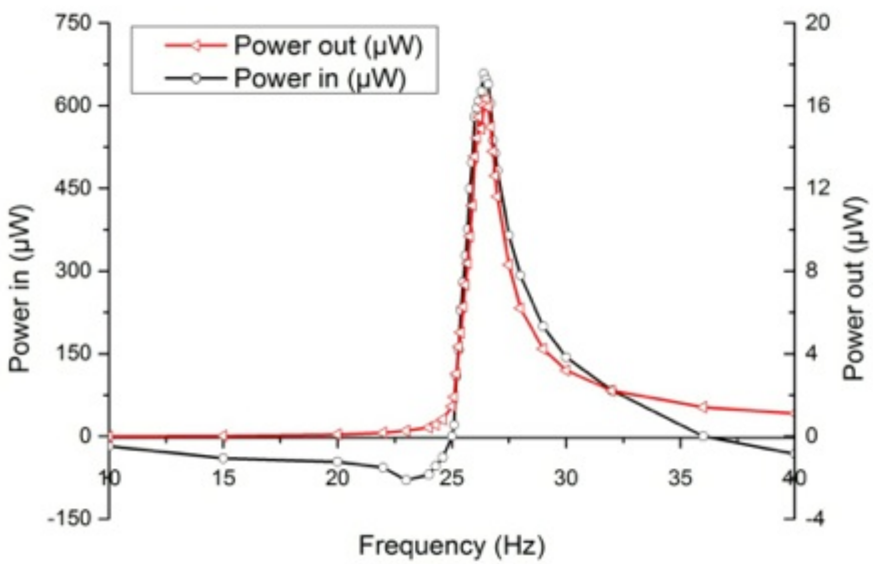
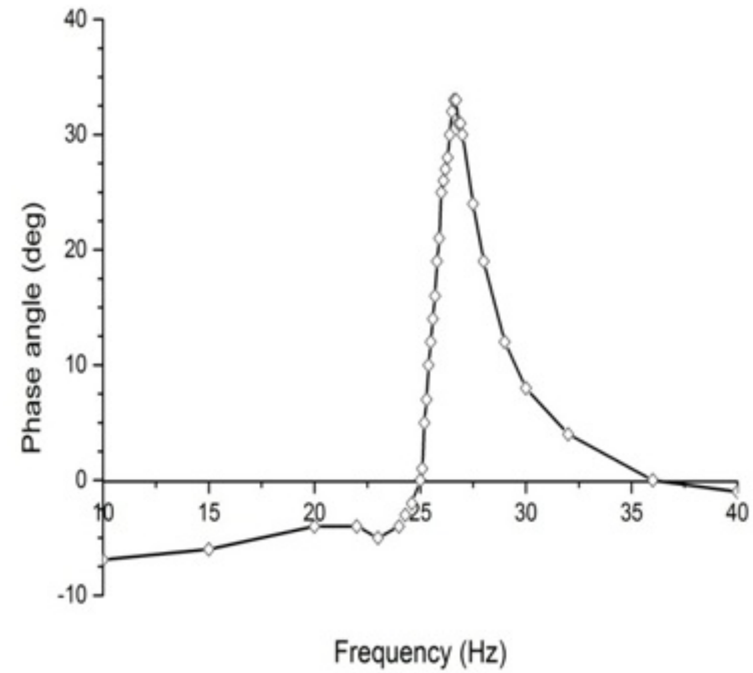
$$P_{mech} = \frac{1}{\tau}\int_0^\tau F \times v\,\mathrm{dt} = \frac{1}{2}F_0\,v_0\,Cos(\phi_v) = \frac{1}{2}F_0\,v_0\,Sin(\phi_d)$$

$$P_{elec} = \frac{1}{\tau}\int_0^\tau I \times V\,\mathrm{dt} = \frac{1}{2}\frac{V_0^2}{R}$$

$$\text{Efficiency} \quad \eta = \frac{P_{elec}}{P_{mech}}$$

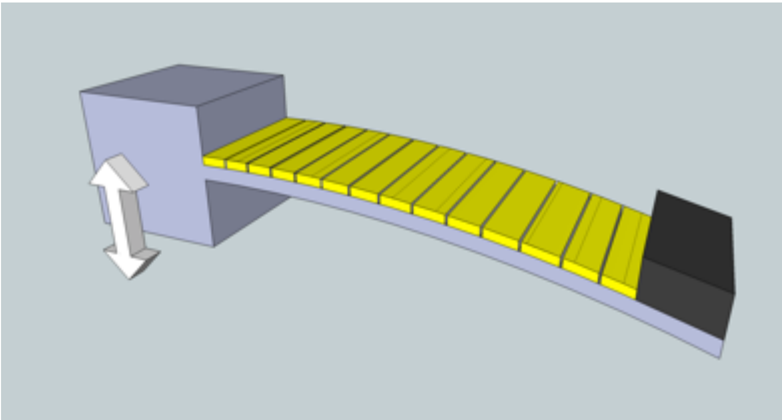


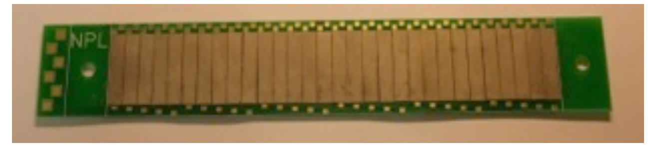


- Efficiency at peak 2.4%

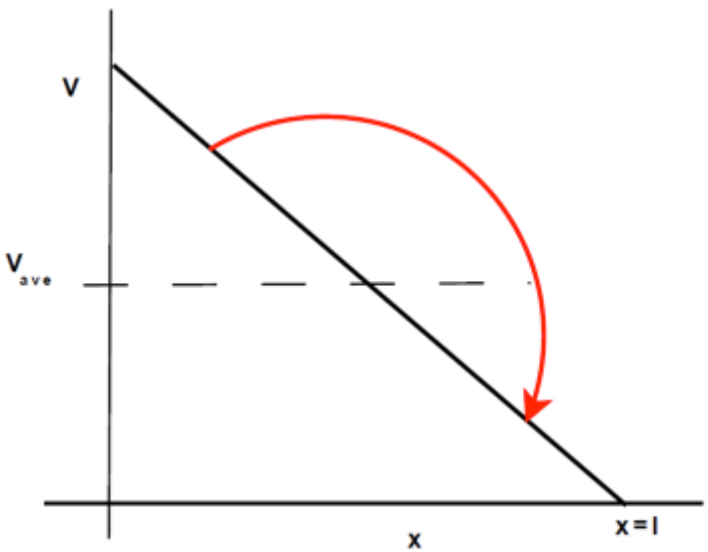
- Higher efficiency at higher frequency
- Vacuum packaged MEMS for max efficiency

Losses

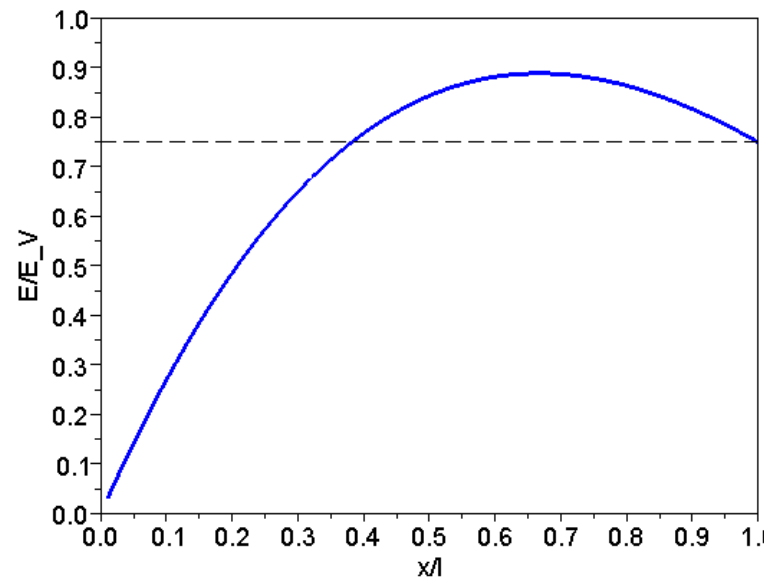




30 element cantilever to investigate the effect of the coverage of the beam with piezoelectric elements



o/c voltage decreases along the beam



Optimum 2/3 coverage

Stewart, M.; Weaver, P. M. & Cain, M. "Charge redistribution in piezoelectric energy harvesters" Applied Physics Letters, 2012, 100, 073901

Energy Harvesting Measurement System

Power IN = $\frac{1}{\tau}\int_0^{\tau} F\, v\, dt$ Power OUT = $\frac{1}{\tau}\int_0^{\tau} I\, V\, dt$

Vibration Energy Harvesting Rig

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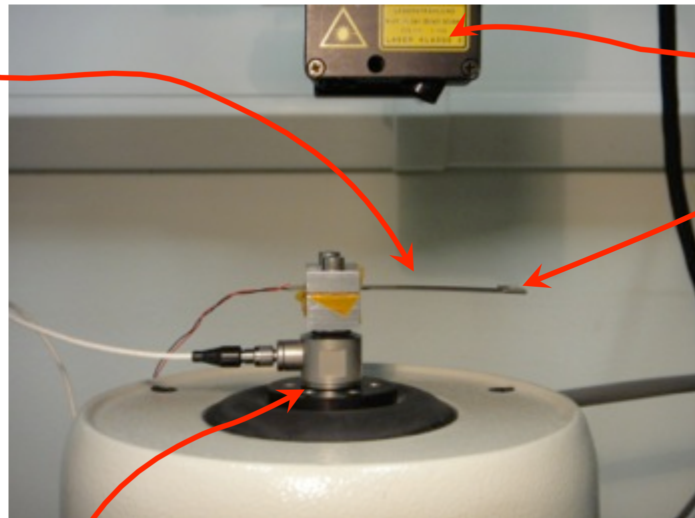
Piezoelectric cantilever

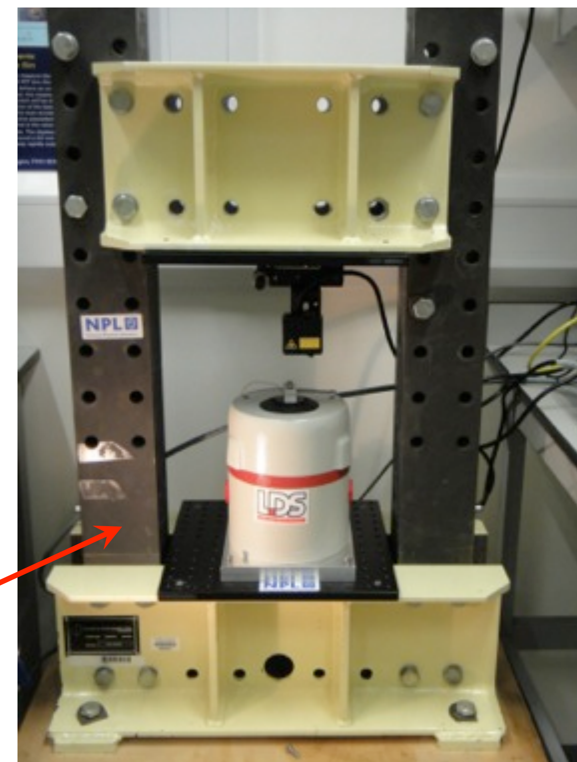
Laser displacement sensor / LDV

Tip mass



Force sensor

Vibration motor



Rigid frame

Vibration Source

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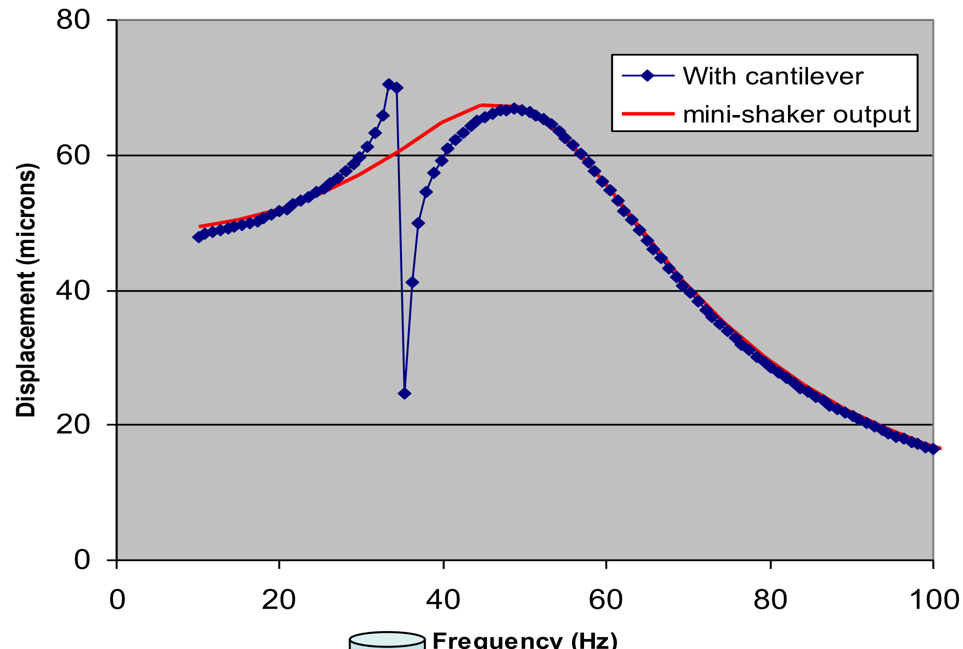
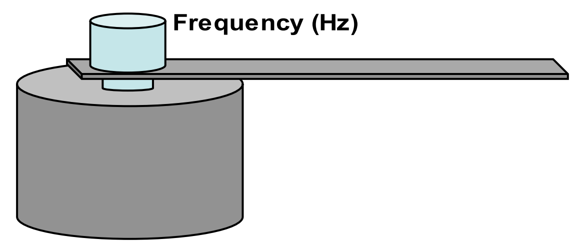
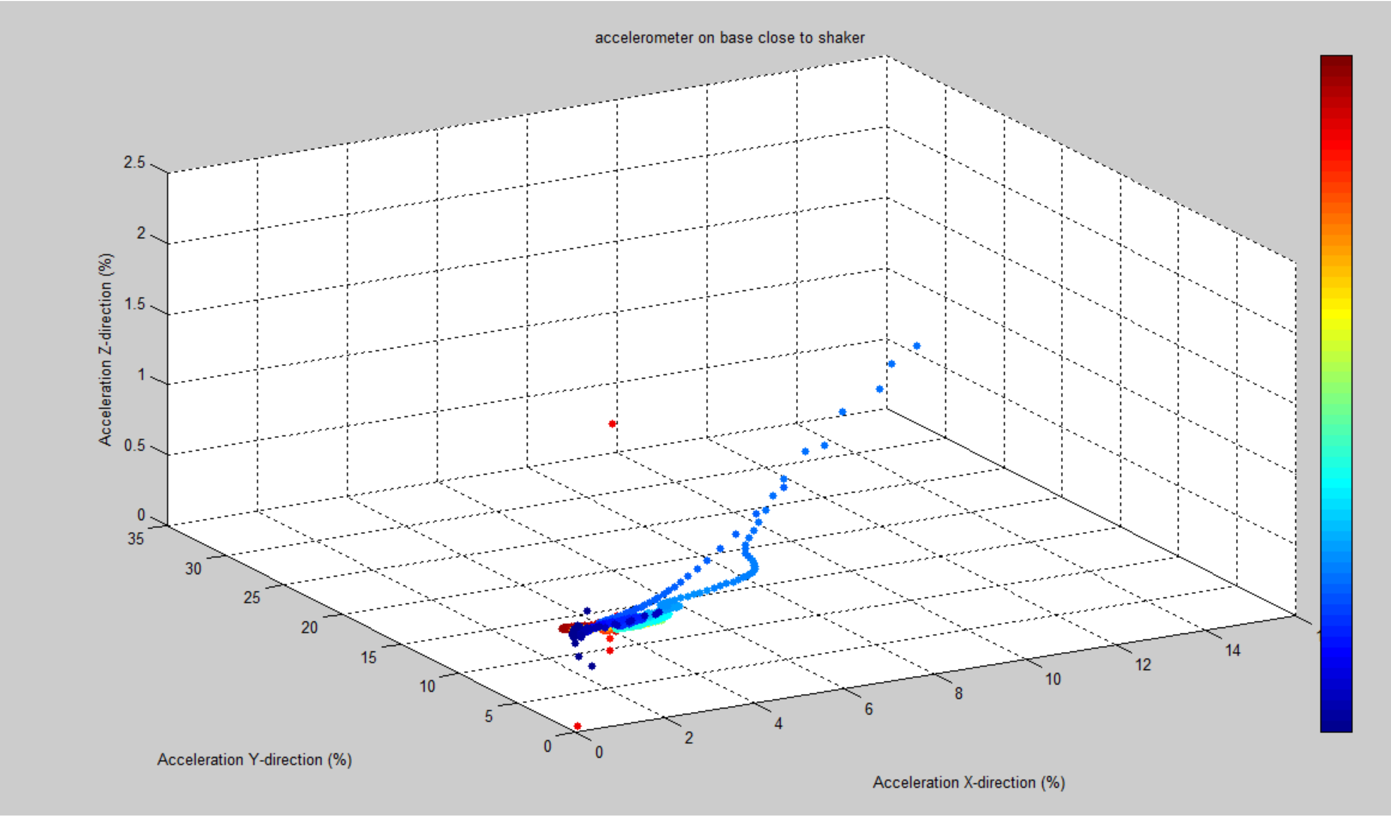
The shaker table needs to be powerful enough to not be significantly affected by the cantilever vibration. Feedback control is usually required to maintain constant amplitude of vibration.





Vibration Source

Resonances in the mounting structure can lead to significant errors!



X vibration >10% of Z vibration measured on lab bench

Scale indicate frequency

15 Hz 1000 Hz

Vibration Source

- Feedback required to stabilise amplitude
- For arbitrary "real vibration" waveforms need amplifier motor combinations with sufficient bandwidth
- Electromagnetic shakers can have stray magnetic fields, could give systematic errors
- Orientation - gravity

Electrical Measurements

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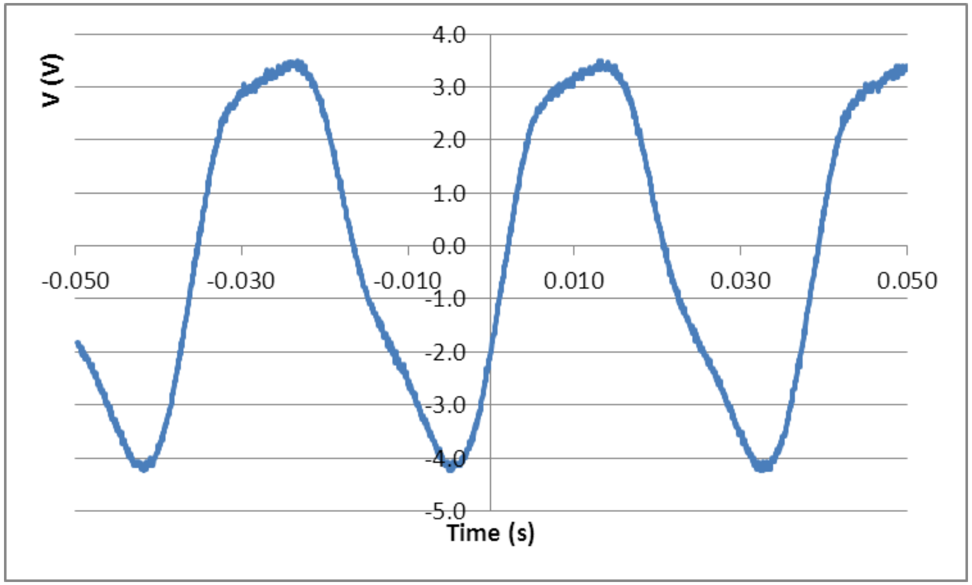
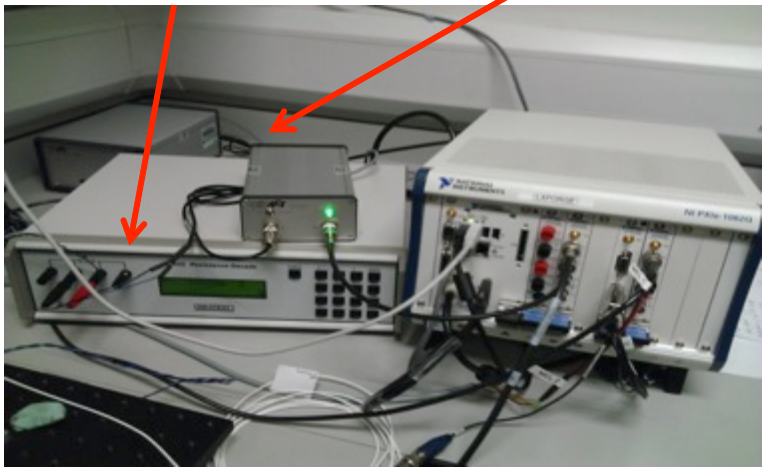
- Simplest load - programmable resistance load.
- Scope/DAQ loading can be significant
- Need to integrate for non-linear or non-sinusoidal waveforms. Sampling rate and bandwidth of the detector can limit accuracy.
- Requires a high (GOhm) input impedance of the voltage measurement.
- Input impedance correction required otherwise.



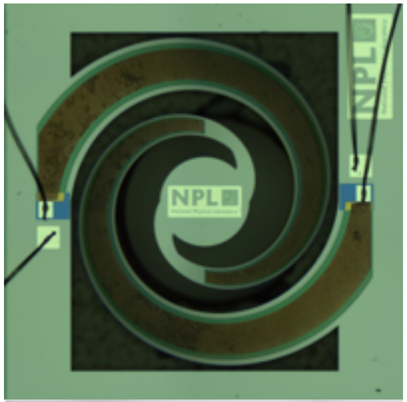
Non-linear waveform from a piezoelectric cantilever resonator under sinusoidal excitation

Programmable Resistance

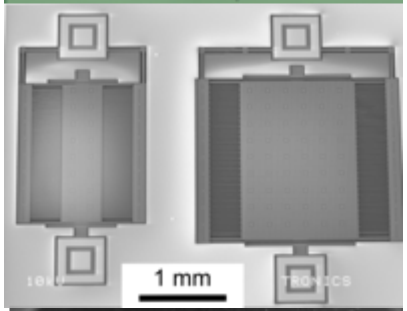
Buffer amplifier



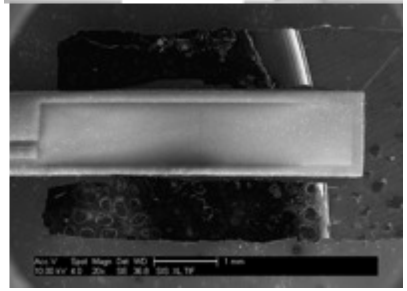
Micro-scale Energy Harvesting



AlN piezoelectric MEMS device from NPL



Electrostatic MEMS. Si finger electrodes are suspended by flexible blade springs. They are constructed using an industrial SOI process.
LNE – A. Bounouh A. CPEM2012, Washington 2012



Silicon micro-cantilevers with integrated proof masses created using low temperature thick film processing
Cranfield University – R.A. Dorey, IEEE TUFFC 54 2462 2007

Analysis of Mechanical Response

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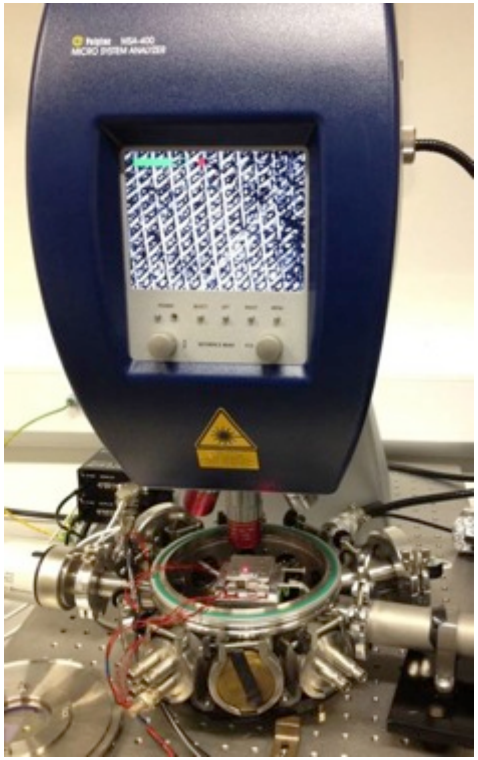
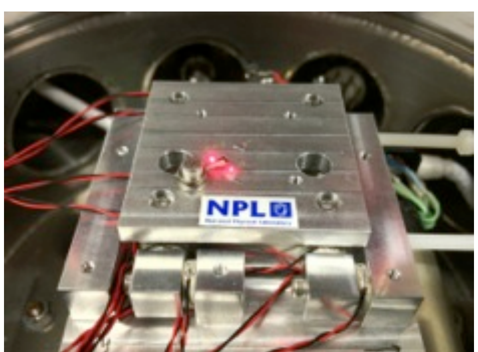
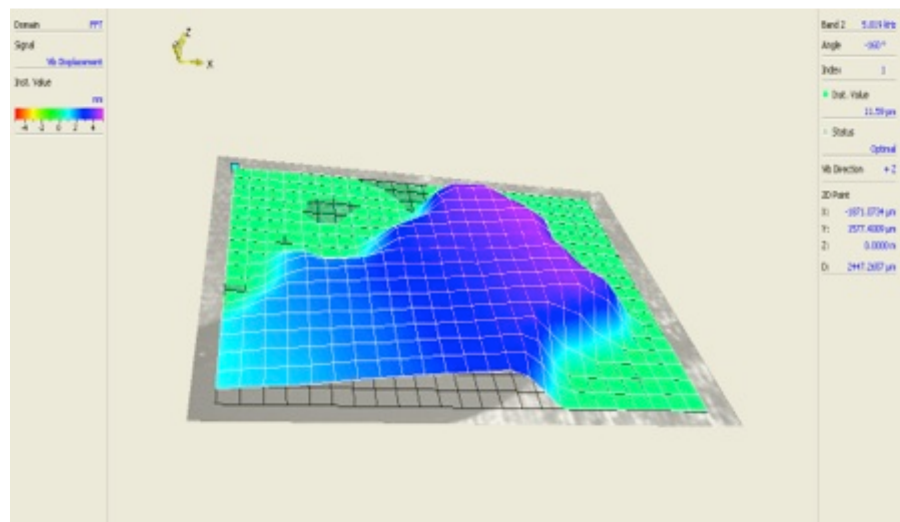
Three-axis broadband shaker for MEMS device testing

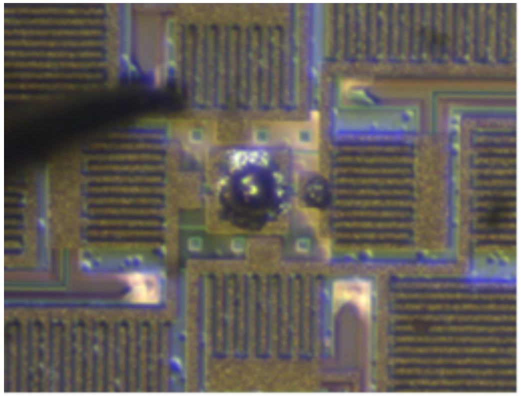




- Integrated with LDV for scanning mechanical response and resonant behaviour
- Wide frequency range (1g at 1kHz)
- Controlled atmosphere or vacuum

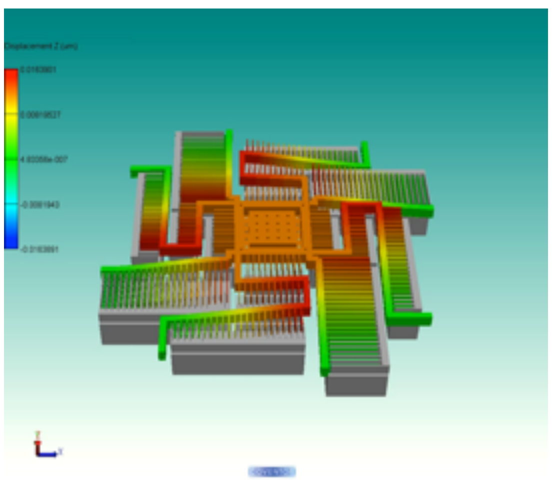


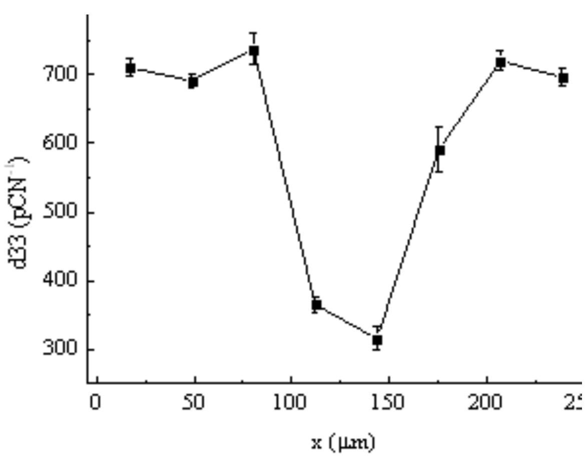
Microscale Piezoelectric Measurements



MEMS Berlincourt measurement tool measures coupling at the micro-scale applied as scanning method to piezoelectric materials used for energy harvesting
Micro-sphere diameter 100 μm

Vertical levitation electrostatic comb drive actuators have been developed to measure the direct piezoelectric effect in micro-scale systems. Forces of ~10μN are applied to the test sample. The charge measurement on the DUT has a 10 AC resolution – measurements of d_{33} of >10pC/N are possible.
Wooldridge, Jet al. J. Micromechanics and Microengineering, 2013, 23, 035028





Nanoscale Piezoelectric Measurements

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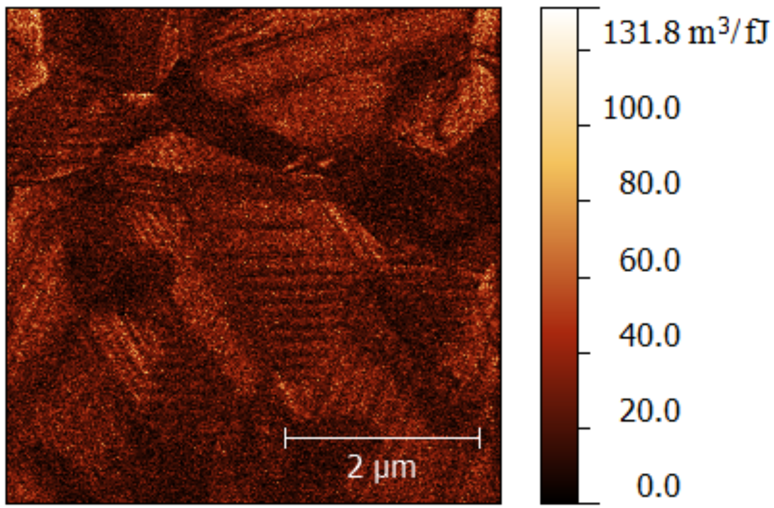
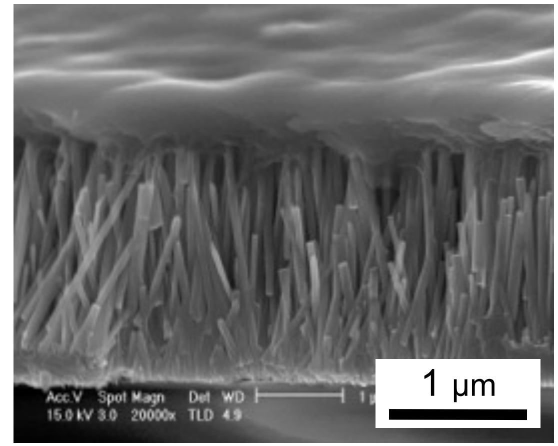
$d_{33} \times g_{33}$



Maximum energy per cycle: $\frac{c}{ab} d_{33} g_{33} F^2$

Piezo-Force response Microscopy (PFM) applied to measurement of energy product $d_{33} \times g_{33}$ at the nanoscale – shows variation of energy coupling between and within grains



Metrological approach to performance characterisation of nano-generators. Collaboration with researchers at Queen Mary College, London led to 100x improvement in power output.

Briscoe, J.; Jalali, N.; Wolliams, P.; Stewart, M.; Weaver, P.; Cain, M. & Dunn, S. Measurement techniques for piezoelectric nanogenerators Energy Environ. Sci., 2013, 3035

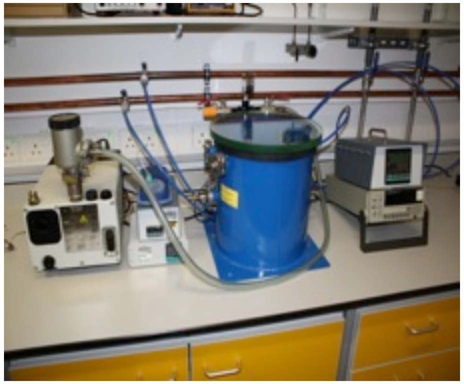
Queen Mary University of London

Thermoelectric metrology

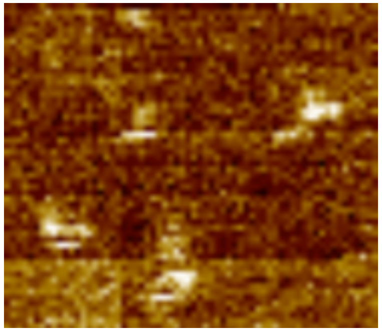
1. Nanoscale thermoelectric measurements
Scanning probe methods for measurement of electrical conductivity, thermal conductivity, and Seebeck coefficient at the nanoscale

2. Thermoelectric generator systems in realistic conditions
Traceable and accurate characterisation of thermoelectric modules – efficiency and maximum power output in operating conditions up to 700 °C

3. Reference materials and electrical traceability



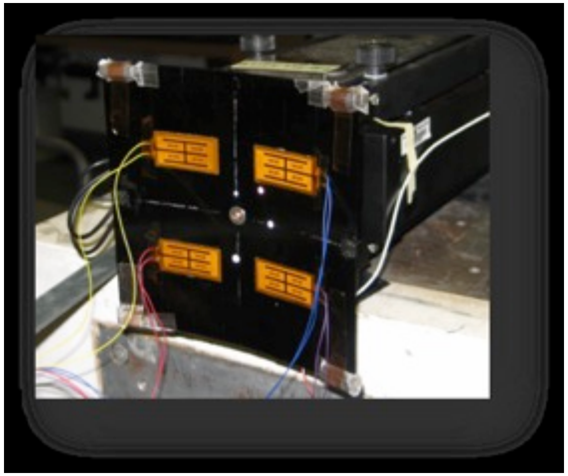
NPL module and materials characterisation plateform



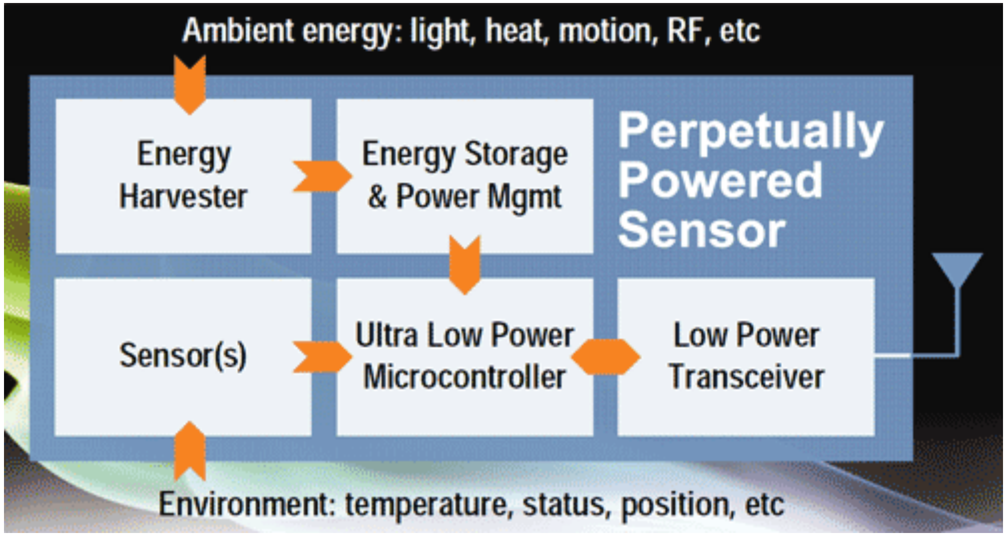
4x 4 μm, Nanoscale scanning spreading resistance measurement of Bi2Te3,

Metrology Challenges

- Energy Harvesting as part of a *system*
- Out of the lab and into the “Real World”
- Non-linear and broadband energy harvesters
- Flexible and conformable harvesters
- MEMS and nanoscale harvesting
- Standards



Non-linear broadband energy harvester from Bath University



www.ti.com/energyharvesting.

Summary

- Metrology is key for enabling timely innovation, developing the market, and establishing performance metrics and standards.
- Energy harvesting systems are complex, and performance can be measured in many different ways.
- Performance measurement needs to be related to actual conditions of use.
- Measurement system needs careful controls to ensure reliable data.
- Interaction of the energy harvesting transducer with the wider system needs further research
- Evaluation of performance under realistic conditions of use - complex vibrational environment, non-linear behaviour, BUT ALSO assessment of degradation, lifetime, and effects of harsh environments

Questions and contact

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Any Questions?