INTERPLAY BETWEEN PHONONIC BANDGAPS AND MICROSTRUCTURED MATERIALS FOR ENERGY HARVESTING AND EFFICIENCY IN TRANSPORTATION

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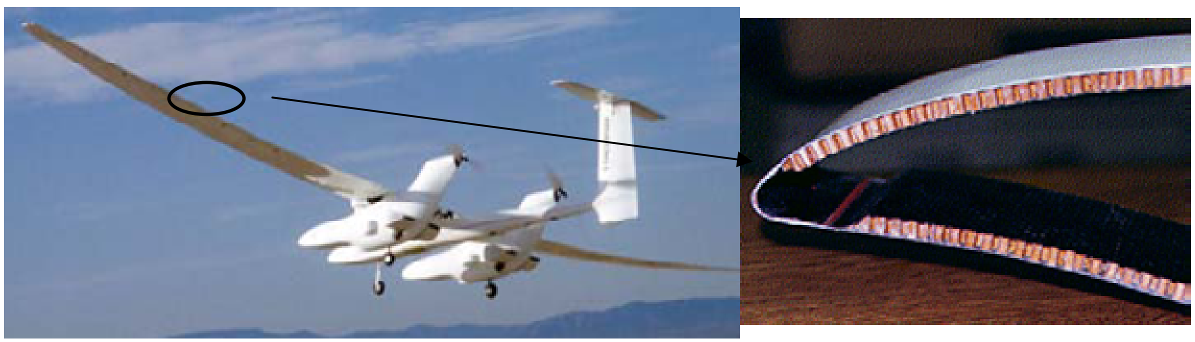
References:

Gonella, To and Liu, J. of Mech. and Phys. of Solids, 2009
Kim, Liu, & Lee, Multi-scale solid oxide fuel cell materials modeling, Comp Mech 09
Qian and Liu, Concurrent Quantum/Continuum Coupling Analysis of Nanostructures, CMAME, 08

MOTIVATION

• Multifunctional structures and material systems are appealing to many engineering applications where multiple capabilities are simultaneously pursued in the design



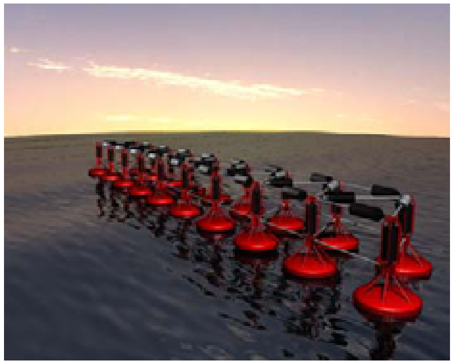
NASA Aurora Flight Sciences UAV

Use of honeycomb sandwich plates in the design of skins for airfoils:
- LIGHT WEIGHT
- LOAD BEARING COMPLIANCE
- ENERGY HARVESTING

Research in Energy harvesting devices has grown in response to:

1) Demand for **portable electronics and wireless sensors**;
2) **On-line structural health monitoring system** for real-time detection of structural damage;
3) **Biomedical devices**, such as drug delivery systems, pace makers, etc.

Current Energy Harvesting Applications



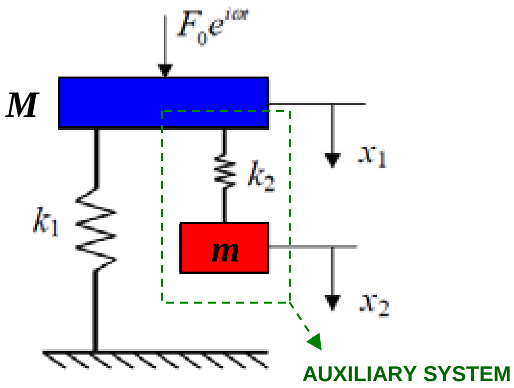
Heelstrike generator

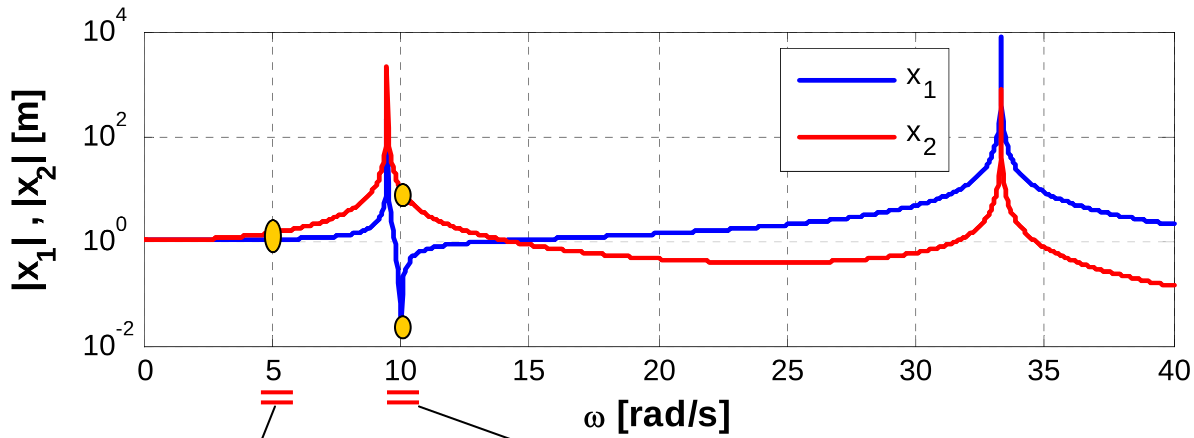
Wave & Tidal Power Generator

Middle and right: Novel Wave-Powered Generators Deployed in Sea Trials off Florida Coast
Source SRI International (www.sri.com/news/imagebank/EPAMGenerator.html)

Microstructures, Antiresonances, Phononic Bandgaps, and Energy Harvesting in Dynamic Systems

- <u>Effects of microstructures on global behavior of dynamic systems</u>





The secondary/auxiliary mass *m* acts as a microstructure for the primary system:

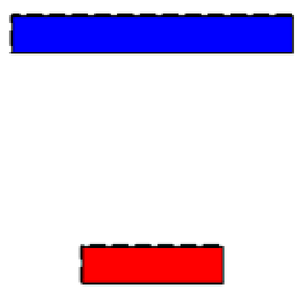
<u>ω = 5 rad/s</u>

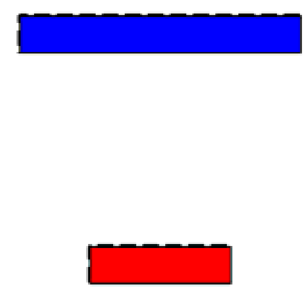
<u>ω = 10 rad/s</u> **(ANTIRESONANCE POINT)**

Primary mass barely displaces. Secondary mass undergoes large oscillations **(LOCALIZATION)**

- Utilize the “microstructure” for energy transfer and localization (phononic bandgap).

- Microstructural properties can be tuned to target performance requirements





While acoustic propagating modes are prohibited within the phononic bandgap, the kinetic energy can be strongly localized. **Goal:** convert the localized vibration into electric voltage.

Multifunctional Vibration-Based Energy Harvesting Devices

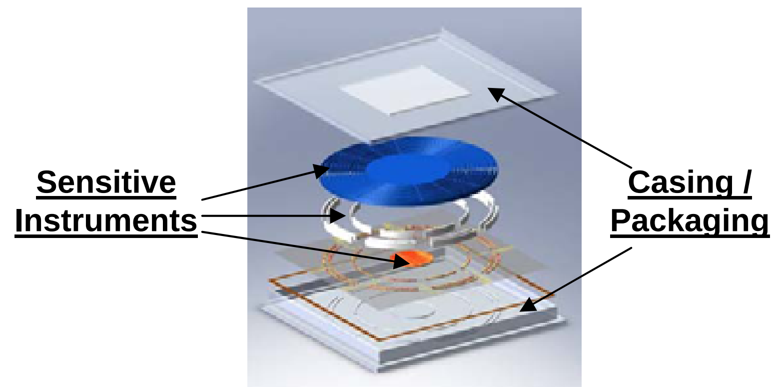
Substrates with Vibration Isolation Capabilities – Power Sources / Additional Batteries

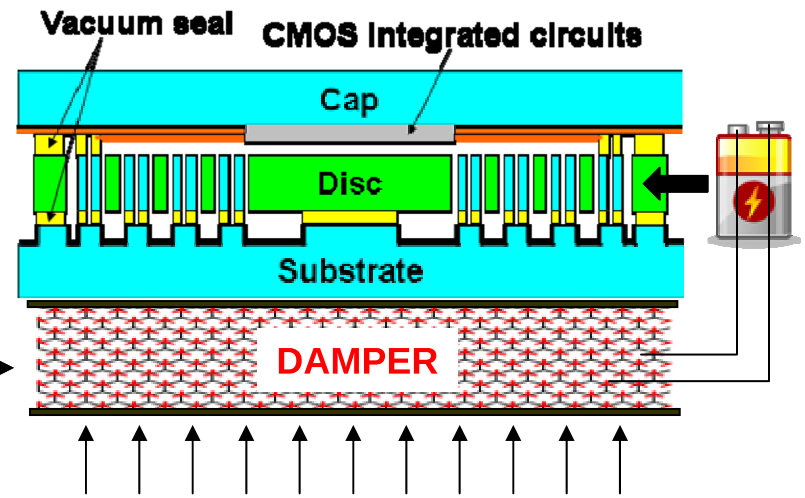
-- Wireless sensors and portable microsystems need power supplies
.
-- Conventional batteries have shortcomings (limited lifespan, hard to replace and maintain).

Energy Harvesting Devices

Truss-core honeycomb sandwich beam or plate with microstructures consisting of beam resonators coated with piezoelectric materials

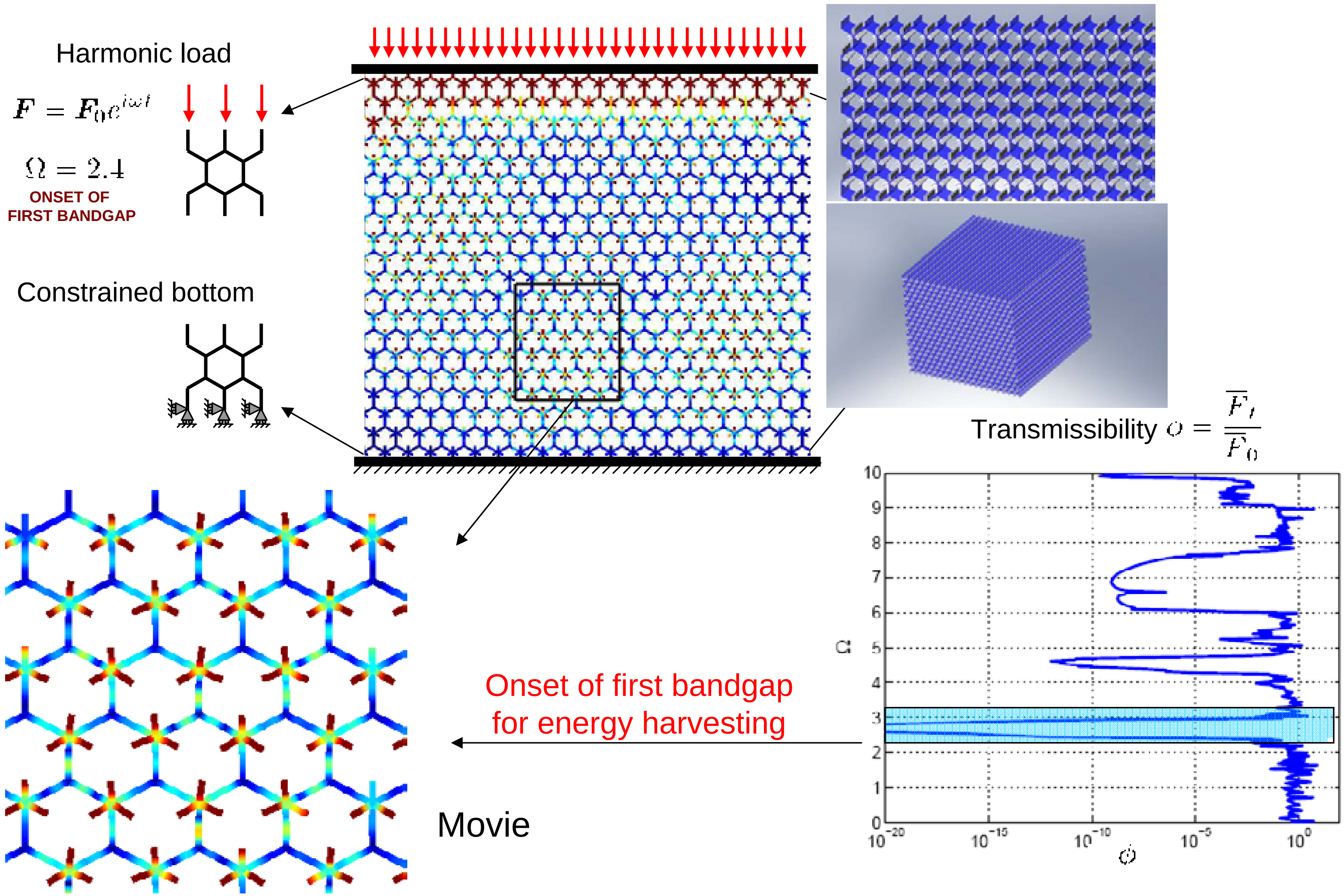
Self-Powered Microsystems





Disturbance (shocks and vibrations) from environment: Structures and engines

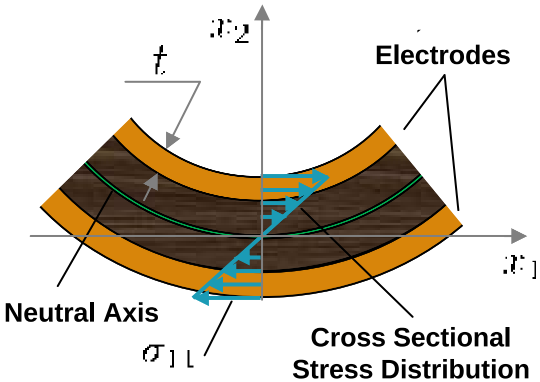
Bandgaps and Localized Oscillatory Phenomena



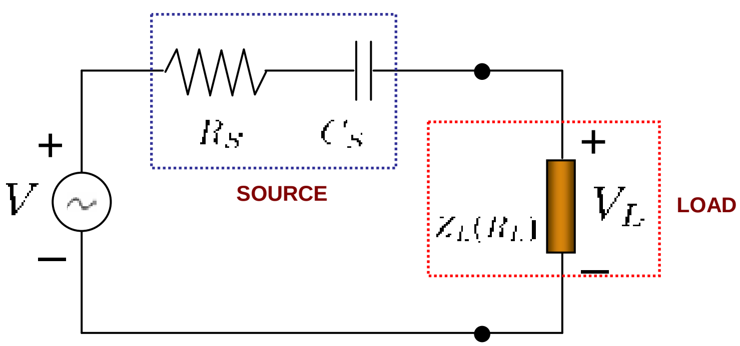
Gonella, To and Liu, J. of Mech. and Phys. of Solids, 2009

Estimation of Power Generation

• The <u>voltage</u> and <u>power outputs</u> for each electrode are estimated from cross sectional stresses

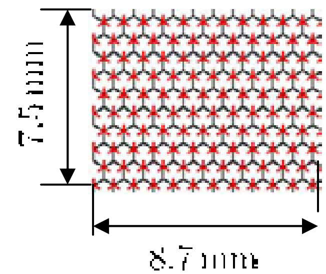


$$\boxed{V = g_{31}\, t\, \overline{\sigma_{11}}}$$



$$\boxed{P_{max} = \frac{\hat{V}^2}{4R_S}}$$

<u>MEMS honeycomb</u> $L = 250\,\mu m$



<u>**Excitation:**</u>

$F_0 = 25\,N$

<u>**Damping:**</u>

$E^* = E(1 + i\eta)$

<u>**Circuit:**</u>

$R_S = R_L = 330000$ ohms

$g_{31} = -9.5 \cdot 10^{-3}\ Vm/N$

$\Omega = 2.37$ **(below band gap)**

η	Power output (μW)	Power density (μW/mm^2)
Undamped	22.8	3.5×10^{-1}
10^{-4}	16.0	2.5×10^{-1}
10^{-3}	2.1	3.2×10^{-2}
10^{-2}	0.4	5.7×10^{-3}

$\Omega = 2.98$ **(above band gap)**

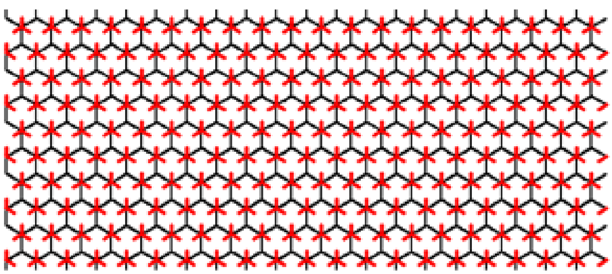
η	Power output (μW)	Power density (μW/mm^2)
Undamped	769.9	1.2×10^{1}
10^{-4}	587.6	9.0×10^{0}
10^{-3}	115.0	1.7×10^{0}
10^{-2}	10.8	1.7×10^{-1}

Gonella, To and Liu, J. of Mech and Phys. of Solids, 2009

Multifunctional Materials and Structural Design

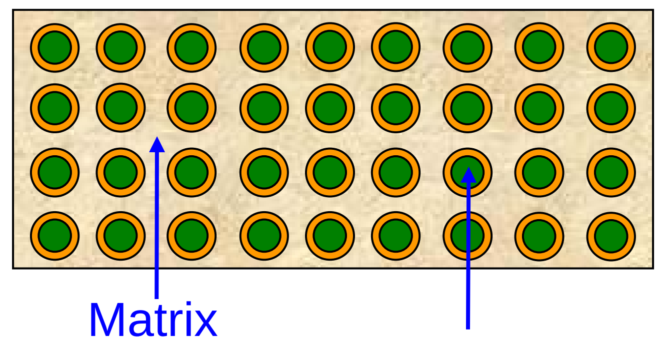
Novel multifunctional design for advanced structures and materials featuring superior mechanical vibration absorption and insulation, while achieving considerable energy harvesting together with embedded sensing and actuation capabilities.

Advanced Honeycombs With Stiff Resonating Structural PZT Elements



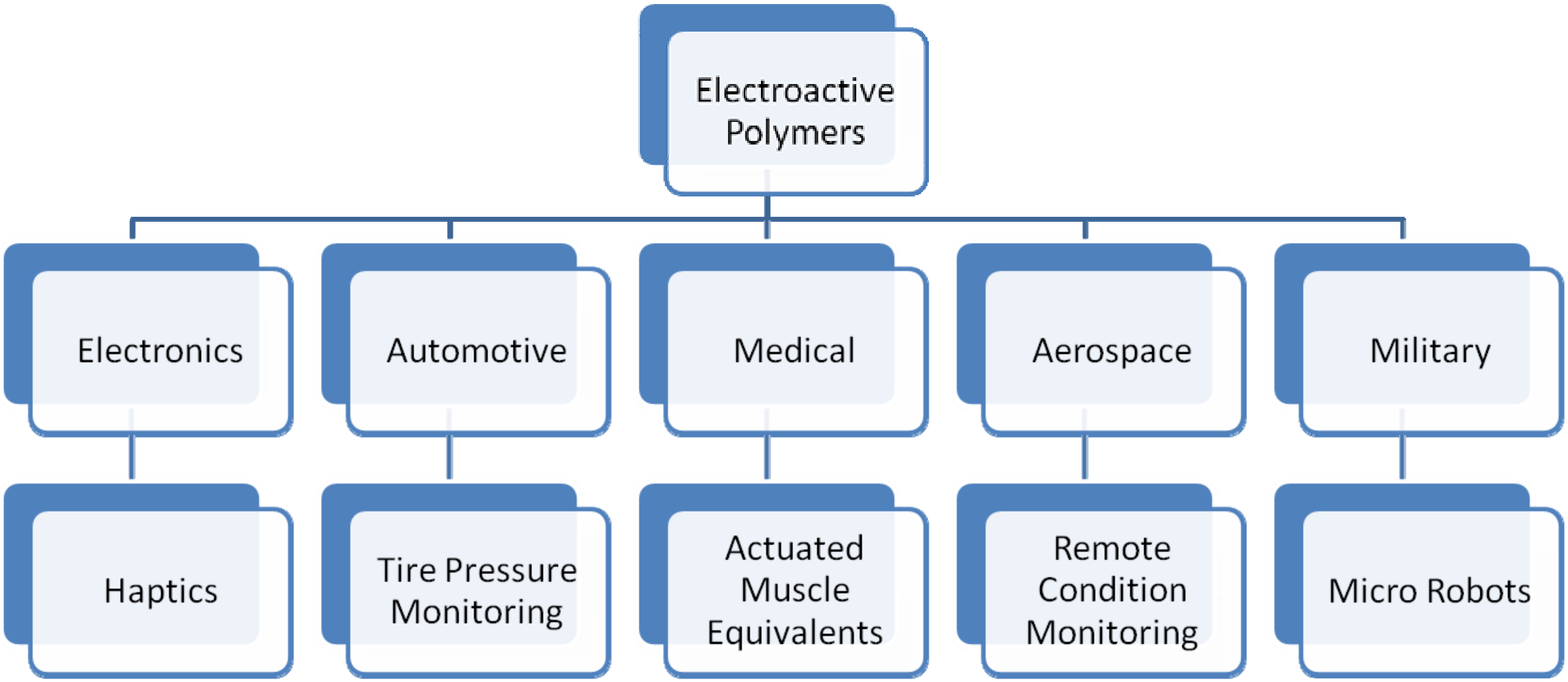
Gonella, To and Liu, J. of Mech. and Phys. of Solids, 2009

Design of Disordered Composites Based on Locally Resonant Sonic Crystals



Liu Z., Zhang X., Mao Y., Zhu Y.Y., Yang Z., Chan C.T. and Sheng P., "Locally Resonant Sonic Materials", *Science*, vol. 289, 2000

Applications of Electro-Active Polymers (EAPs)



New and innovative applications of EAPs are beginning to emerge with increased frequency and vigor as the limits are pushed on current technologies. Every major sector, both commercial and military, is pursuing new ways to utilize this emerging technology.

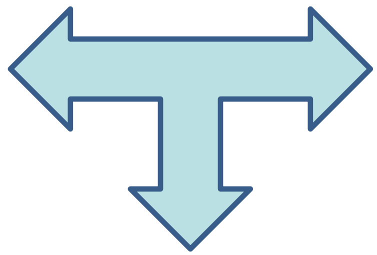
Bar-Cohen, Yoseph. *Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential, and Challenges*. Bellingham, Wash.: SPIE, 2004.

Electroactive Polymer Actuators and Devices. 2009.

Applications of EAPs

Self sustaining applications

Printable electronics



Battery-less machines

Muscle-like actuators

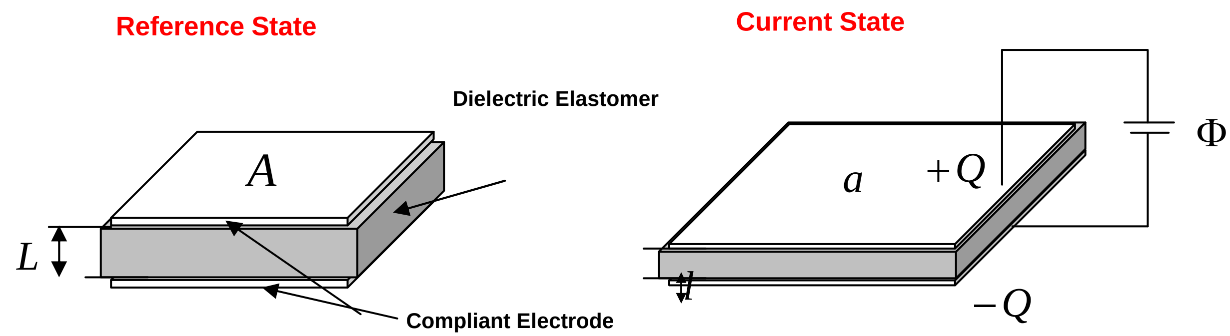
Robotic hand (Photographed at JPL)
Courtesy of Dr. Graham Whiteley, Sheffield Hallam U., UK.

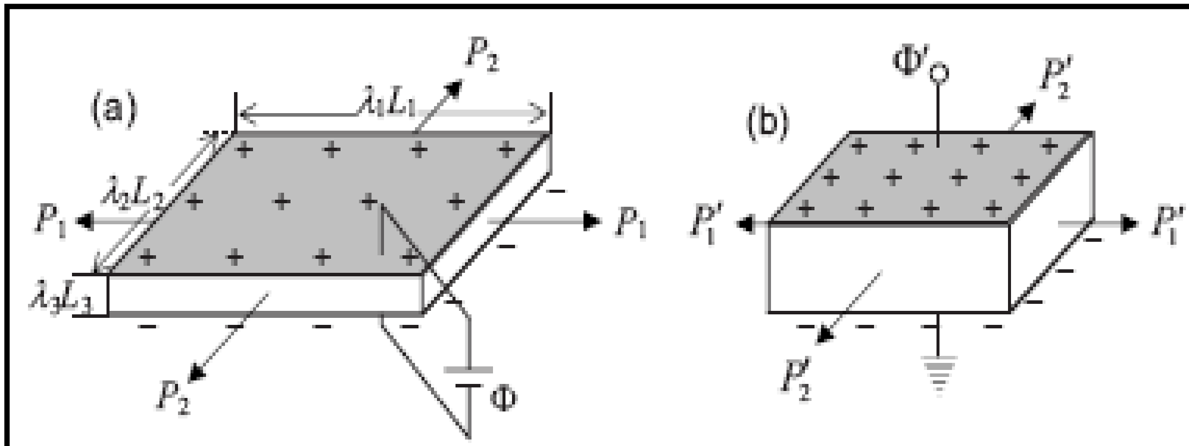
Working Principle of Dielectric Elastomers

• **Basic architecture**: a film of a dielectric elastomer coated on both sides with compliant conductive electrodes.

• When voltage is applied to the two electrodes, a Maxwell pressure is created upon the dielectric layer.

• The Maxwell pressure causes the dielectric film to become thinner, making it expands in the planar directions.



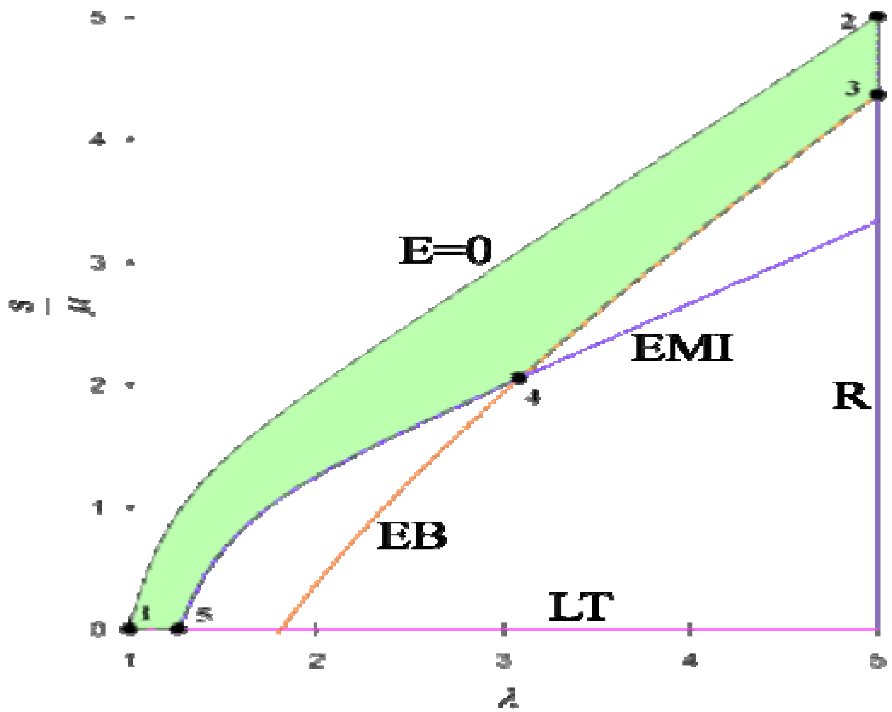


Courtesy of Zhigang Suo

Pelrine, Kornbluh, Pei, Joseph
High-speed electrically actuated elastomers with strain greater than 100%.
Science 287, 836 (2000).

•Toupin (1956), Eringen (1963), Tiersten (1971),...
•Goulbourne, Mockensturm, Frecker (2005)
•Dorfmann, Ogden (2005)
•McMeeking, Landis (2005)
•Suo, Zhao, Greene (2008)

Soft Materials are Superior Than Ceramics and Metals



6 J/g, Elastomer (theory)
0.4 J/g, Elastomer (experiment)

Koh, Zhao, Suo, Appl. Phys. Lett. 94, 262902 (2009)

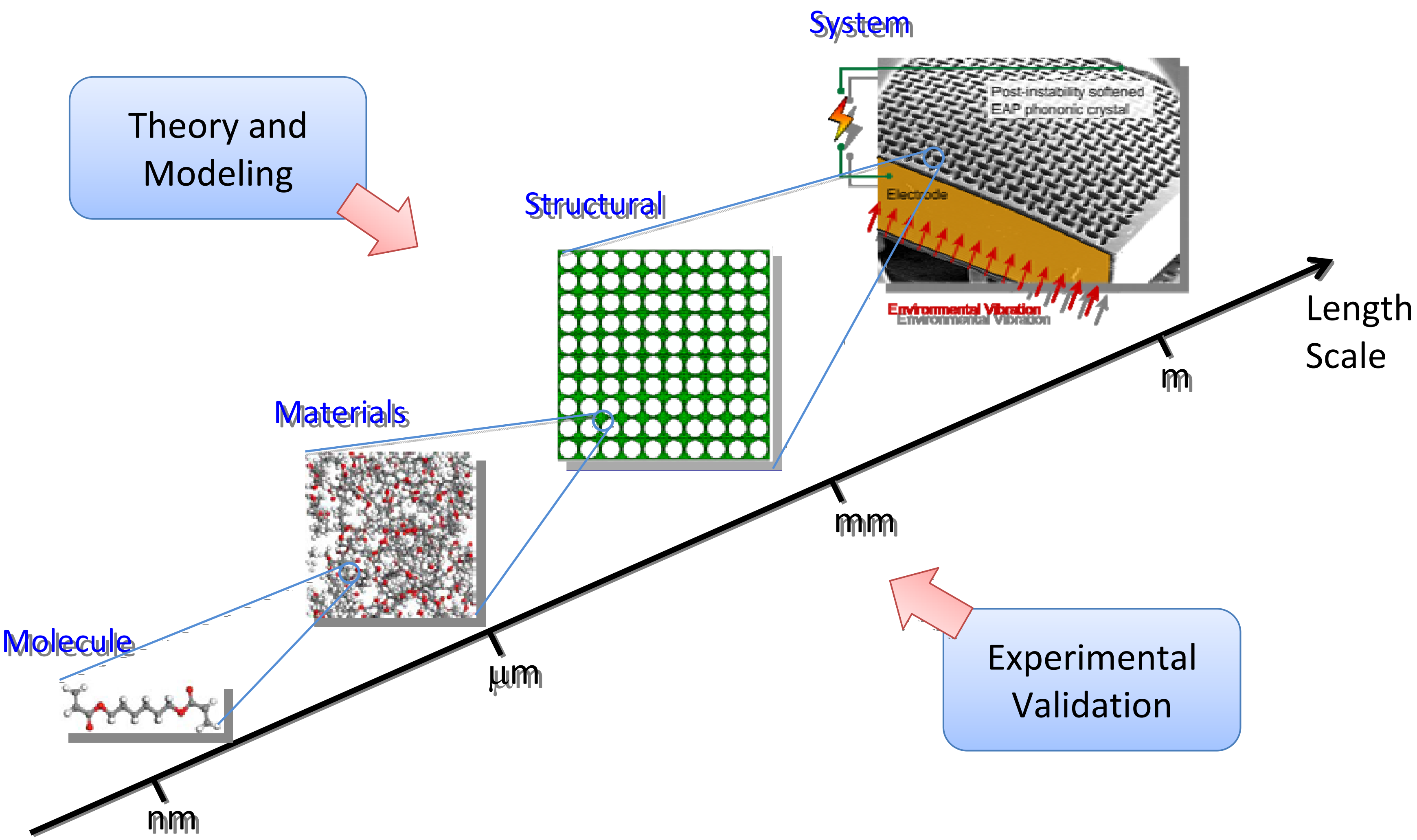
Hydrophobic nanoporous silica particles immersed in water.
Average pore size: 10 nm.
Specific pore volume: 0.6 cm3/g.
Specific surface area is ~500 m2/g.
Energy absorption: 150 J/g

Private conversation (Ling Liu, Columbia)

COMPARISONS
0.01 J/g Ceramics
0.1 J/g of Ti-Ni alloy,
1-10 J/g of composites

In addition, polymer based soft materials
- Manufacturing process are "Environmentally Benign"
- Can be bio/environmentally degradable

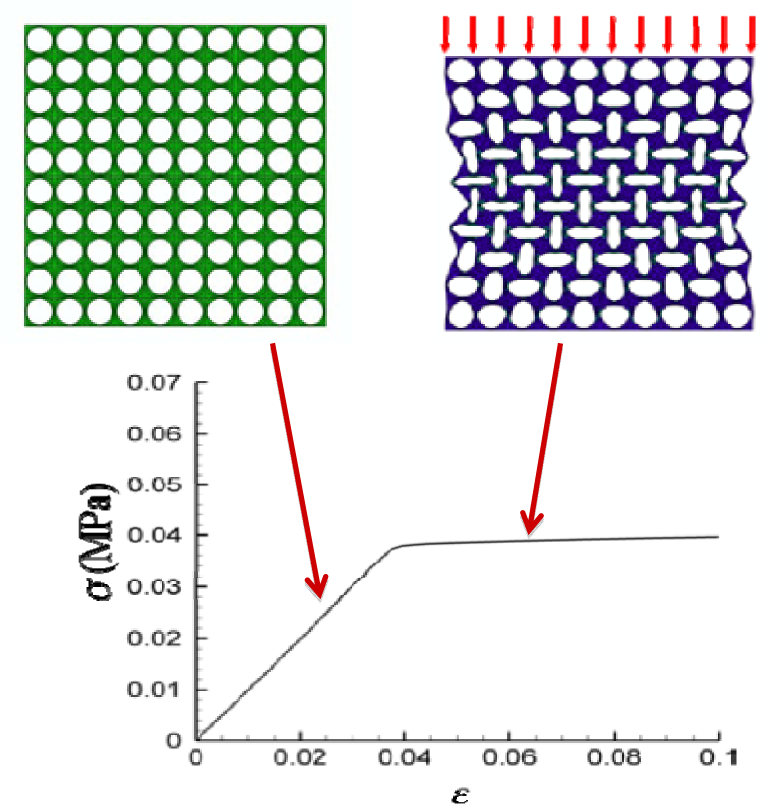
A Multiscale Science-Based EAP Engineering Problem



Environmentally Benign Design of Electro-Active (EAP) Polymer materials

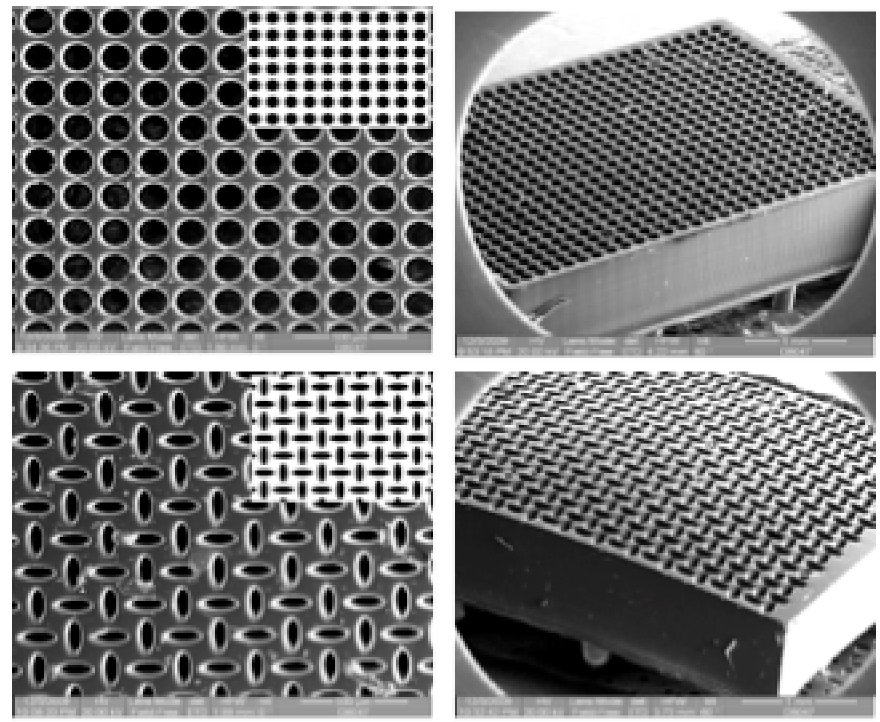
Microstructured EAP Materials for Energy at Continuum Scale

Vibration isolation and energy harvesting often requires materials response at frequencies lower than 300 Hz, which are not available from natural materials.



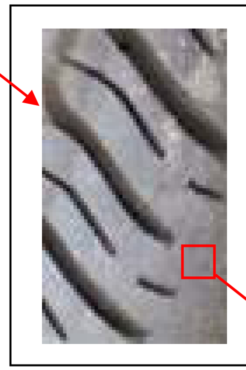
The lowest natural resonance frequency reduced by HALF!

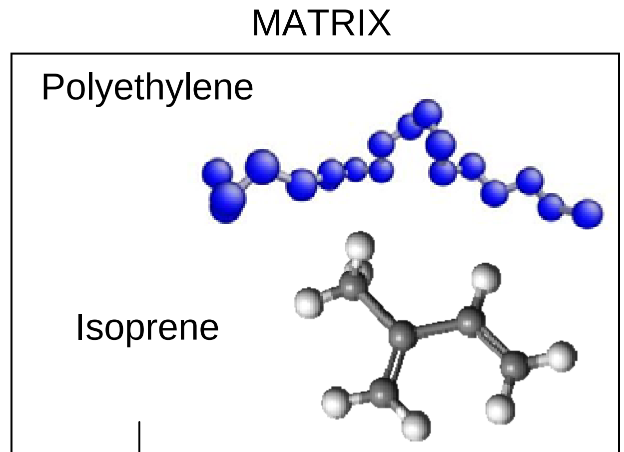
Device Prototype

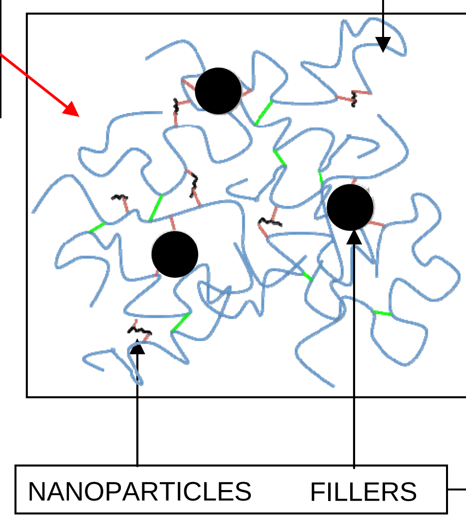


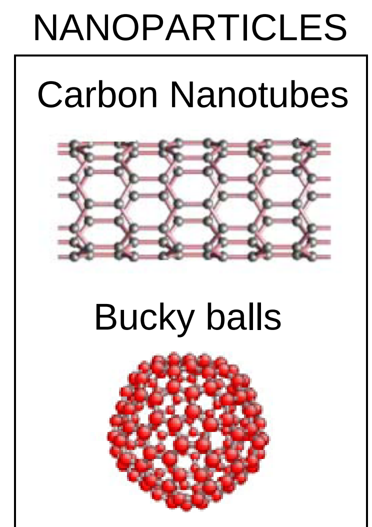
Polymer Nanocomposites for Energy-Efficient Transportation

- <u>Composition of polymer composite</u>









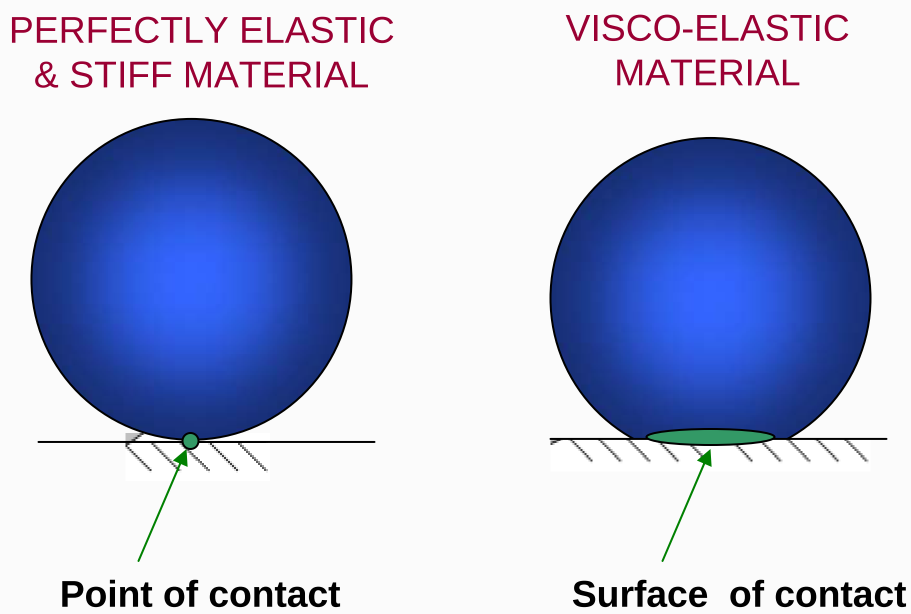
- Properties of Polymer
  - Chain Stiffness
  - Cross-linked Density
- Properties of Fillers
  - Filler Size
  - Filler-Filler Interactions
  - Cluster Size
  - Cluster Morphology
- Properties of Fillers
  - Cluster-Polymer Interactions
  - Filler-Matrix Matrix Interface
  - Filler-Polymer Interphase region

Friction and Drag of Rolling Bodies

Rolling resistance, sometimes called **rolling friction** or **rolling drag**, is the resistance that occurs when a round object rolls on a flat surface.

The Transportation Research Board estimates that if tire rolling resistance were reduced by 50%, 10 billion gallons of fuel (8% of our total national fuel expenditure) could be saved per year.

In addition, if the **WEIGHT of passenger and light truck TIRES** could also be reduced by 50%, as much as an **additional 1.1 billion gallons of fuel** could be saved annually.

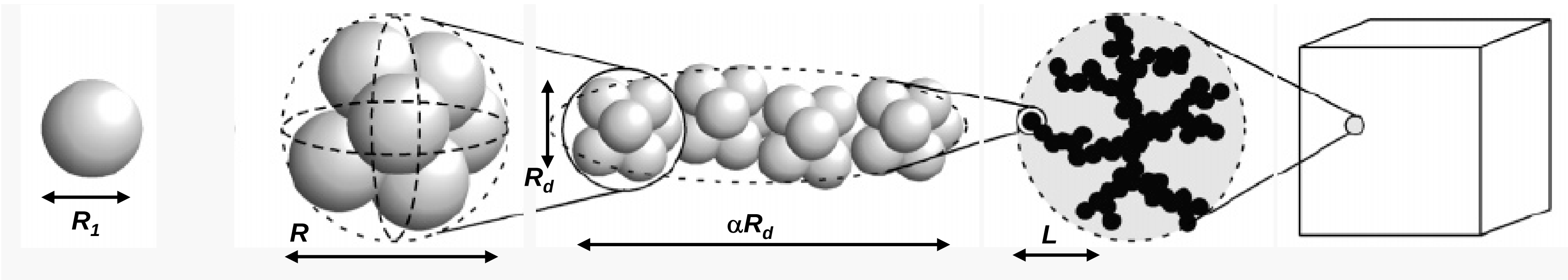


Low-rolling tires are designed to improve fuel-efficiency of a car by minimizing the energy wasted as heat as the tire rolls down the road. Approximately 5–15% of the fuel consumed by a typical car is used to overcome rolling resistance.

Controlling rolling resistance of tires is an effective and realistic way to reduce fuel consumption and reduce polluting greenhouse gas emissions.

Nanofillers: Structural Factors and Dispersibility

Hierarchical Structures of Nanoparticles in the Polymer Matrix



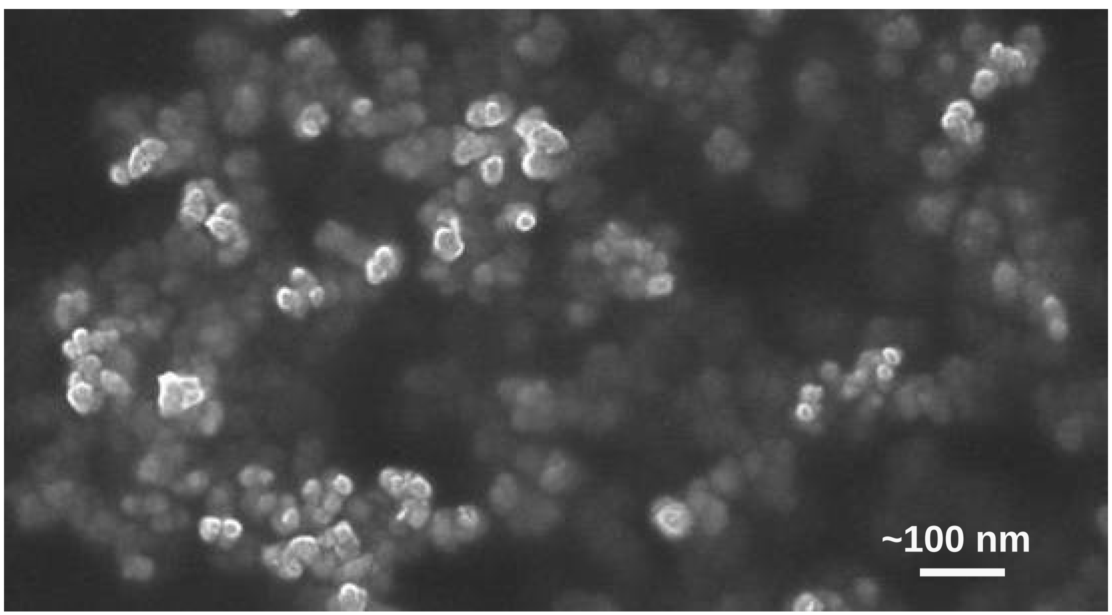
Primary particle
(i) radius: R_1 = X nm's
(ii) standard deviation: σ = X nm
(iii) specific surface area (SAS)

Aggregate
(*N* fused primary particles)
(i) R = XX nm's
(ii) specific surface area

Agglomerate (level 1)
(dispersible unit)
(i) R_d = XX nm's, αR_d = *XXX nm's*
(ii) radius of gyration: R_g = XXX nm's

Agglomerate (level 2)
(mass-fractal structure)
L = XX μm's

Dispersion of Agglomerate in macroscopic polymer



Structure Factors of Dispersible Units of Carbon Black Filler in Rubbers
Koga et all., *Langmuir* 2005, *21,* 11409-11413

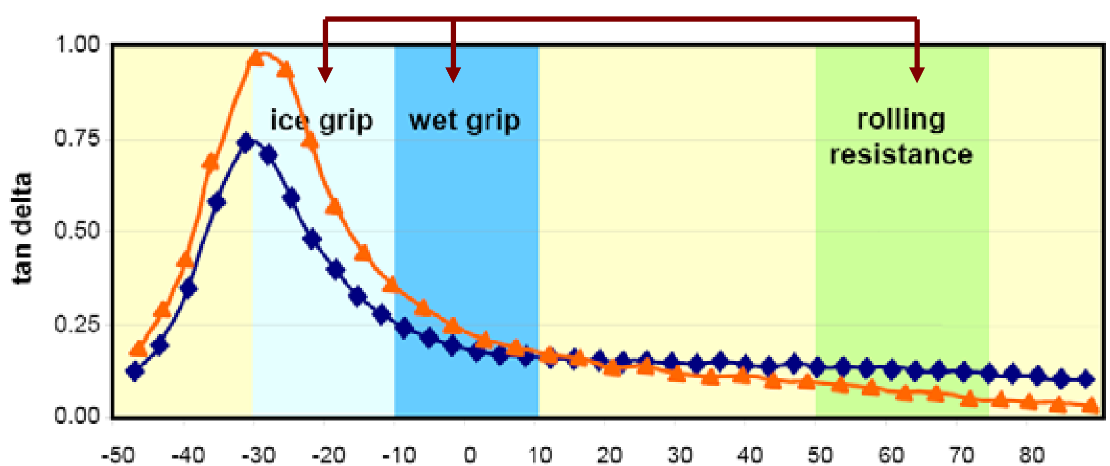
Effects of Micro and Nanostructures on Tire Performance

$$E^* = E' + iE'' \rightarrow \tan(\delta) = \frac{E''}{E'}$$

STORAGE LOSS

Defines:
- the lag of deformation with respect to an applied load
- the viscosity and damping of the material

CRITICAL PERFORMANCE SCENARIOS



Niedermeier and Froelich,
Effect of Rubber Reinforcement by Active Fillers on Viscoelastic Properties, 2008

- Ice and wet grip: high viscosity (high tan delta) is desirable as it improves the grip
- Rolling resistance: low viscosity (low tan delta) reduces the coefficient of rolling resistance

GOAL: Design microstructures to achieve given level of performance and prescribed reduction in FUEL CONSUMPTION (tan(δ) = performance metric)

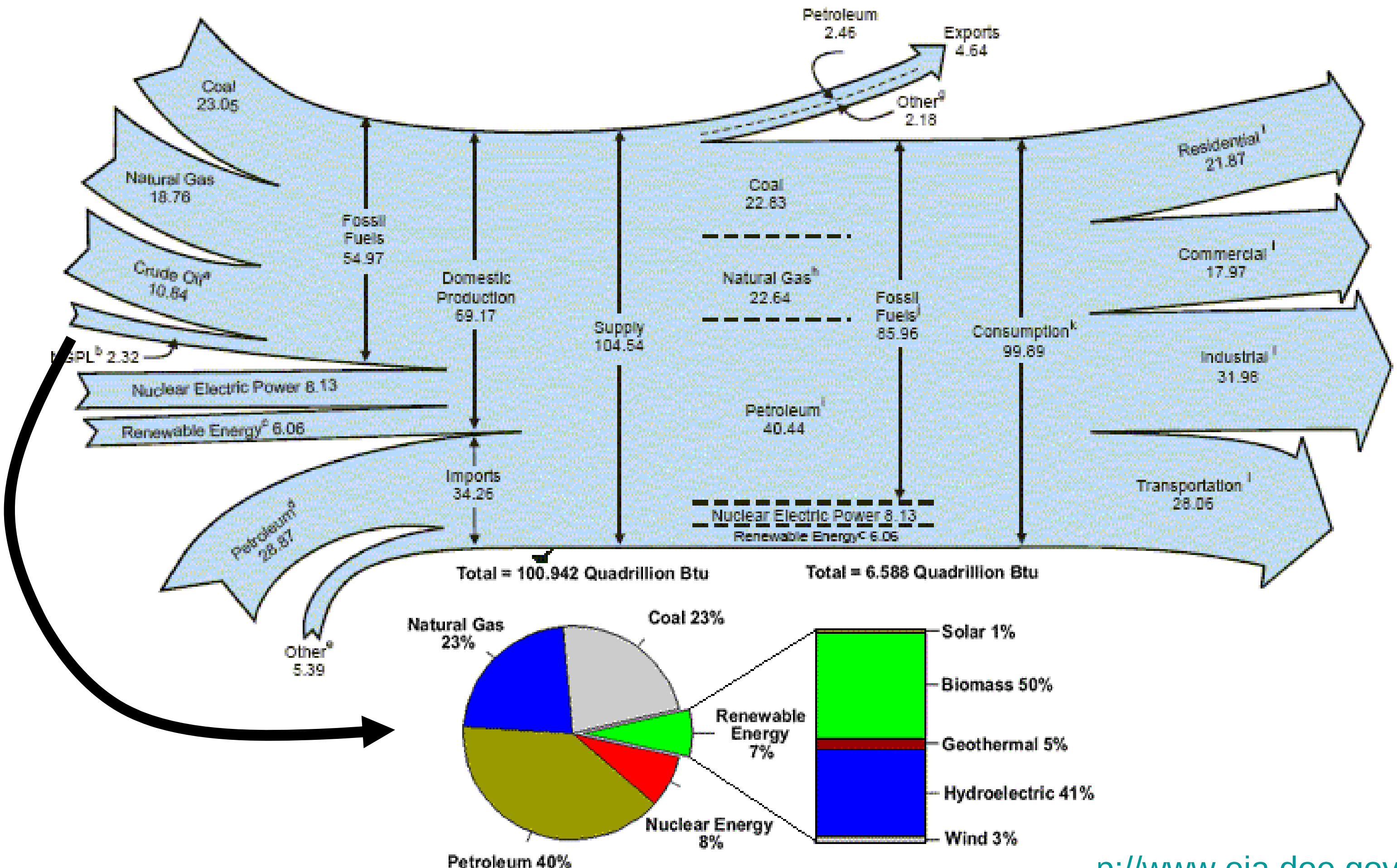
$$\boxed{\tan(\delta)} = \boxed{f}(\text{matrix}, \text{microstructure}, T, \omega)$$

DESIGN VARIABLES

OPERATION CONDITION

- **MULTIRESOLUTION CONTINUUM THEORY**
  (Vernerey, Liu, et al., *JMPS, 2007*)
- **DIRECT NUMERICAL SIMULATION OF MICROSTRUCTURES**
- **MOLECULAR DYNAMICS OF NANOSTRUCTURES**
- **DESIGNED EXPERIMENTS AT MULTIPLE SCALES**

U.S. Energy Flow, 2006



p://www.eia.doe.gov/emeu/aer/

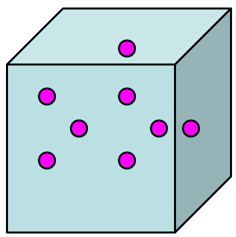
~65% of energy becomes waste heat

~10% conversion to useful forms can have huge impact on overall energy utilization

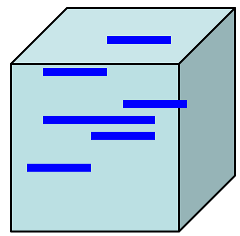
Thermoelectric (TE) Materials Design & Applications

Qian and Liu, Concurrent Quantum/Continuum Coupling Analysis of Nanostructures, CMAME, 08

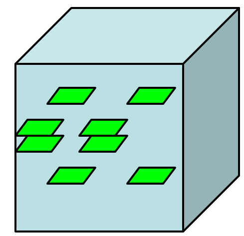
- **Nano-structured mateial systems** reveal **excellent electronic conductivities**



nanoparticles



Nanowires/tubes



Nanosheets

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

Figure-of-Merit

- The large surface-to-volume ratio at small scale may lead to much enhanced phonon scattering and reflection, which is the key to **reduced thermal conductivity**

- The excellent physical properties of nanomaterials may also enhance the **bulk material properties (strength and stiffness, fracture toughness,…..)**

TE Applications

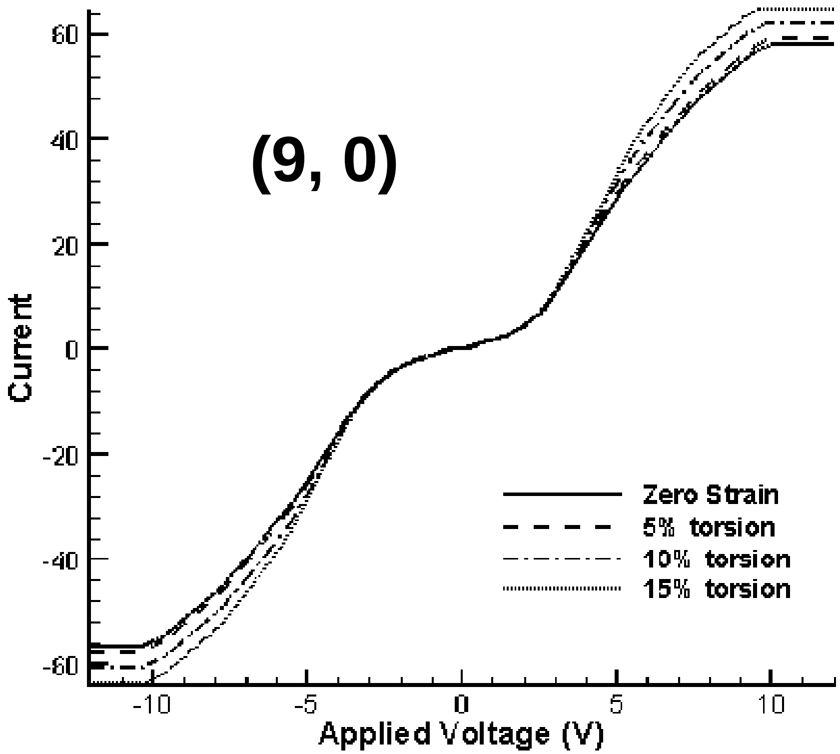
(1) Waste heat recovery
- Automobiles
- Over the road trucks
- Utilities
- Chemical plants

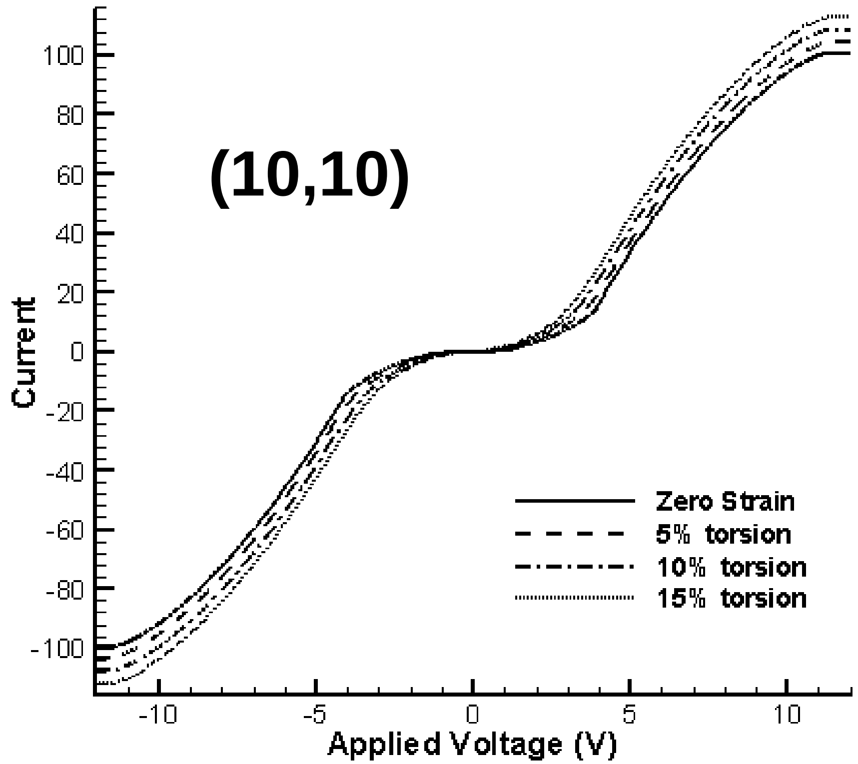
(2) Space power
(3) Remote Power Generation
(4) Solar energy
(5) Direct nuclear to electrical

~65% of energy becomes waste heat
~10% conversion to useful forms - huge impact on overall energy utilization

http://www.eia.doe.gov/emeu/aer/

Current-voltage relation for two different tubes at 0%, 5%,10% and 15% of torsional strain, chiralities: (a) (9,.0), (b) (10,10).





Qian and Liu, Concurrent Quantum/Continuum Coupling Analysis of Nanostructures, CMAME, 08

Conclusions

- INTERPLAY BETWEEN PHONONIC BANDGAPS AND MICROSTRUCTURED METAMATERIALS FOR ENERGY HARVESTING: offer society the potential for massive economic savings and significant stress reduction on the environment.

- If the weight of an automotive tire can be reduced 30% and its rolling resistance can be decreased 50%, multi-billion dollar savings will be realized through reduced fuel consumption.

- Thermal Electrics may be used in automotive, aerospace, or solar energy applications where 65% of energy becomes waste heat. If we can convert just 10% of this waste heat to electric energy, billions of dollars in energy loss can be saved.

- Design of structures and material systems for self-powered and electrically-driven medical devices

✓ Design of thin patches of piezoelectric polymer for drug-delivery systems

Ho et al., 2008