The Compliant Capacitor

David R. Clarke

School of Engineering and Applied Sciences
Harvard University
clarke@seas.harvard.edu

Partial support from National Science Foundation

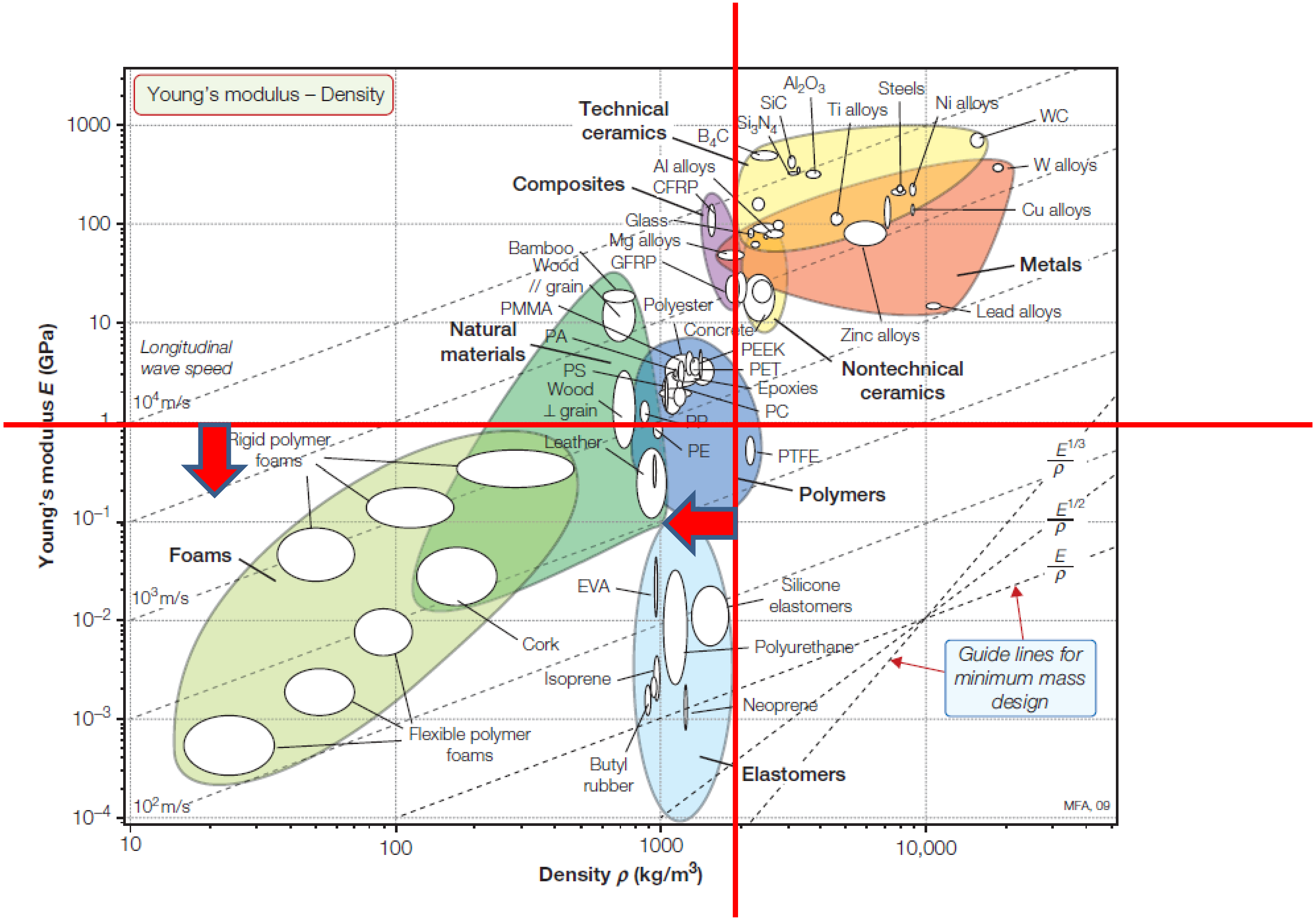
KAUST , February 2015

Materials Design for Compatibility with the Human Body

- Most materials development has been driven by human needs
  - Shelter, defense, transportation, entertainment .....
  - Strong, stiff, unyielding, hard .....
- Some materials have been developed for replacing structural body parts
  - Artificial teeth, hip implants.....
- Only now are materials being developed that are compatible with humans and extending their capabilities

➢ soft, compliant, conformable, capable of a range of motion........

The Human Compatibility Materials Space

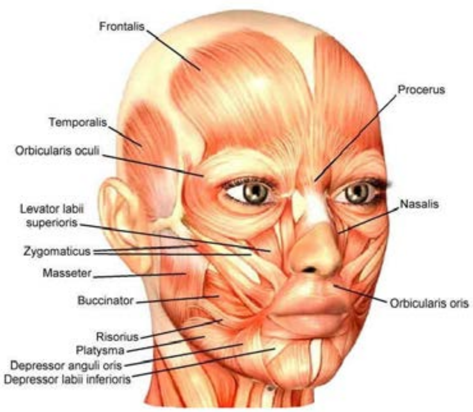


NB. Strictly, skin is a viscoelastic material not elastic so it has no true elastic modulus. But one can speak about instantaneous modulus

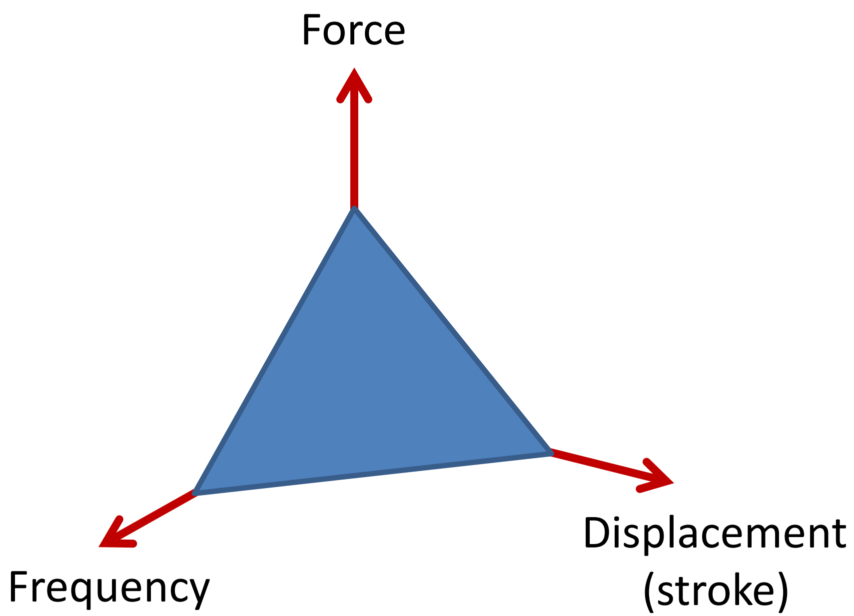
Muscles and Actuators

We use muscles for

- walking and running
- dancing
- swimming
- getting up and sitting down
- moving our eyes
- swinging our arms
- turning our head
- gripping, holding and letting go
- …….



<u>Actuator Capabilities</u>

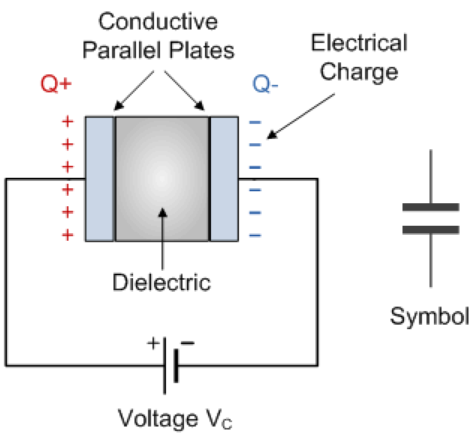


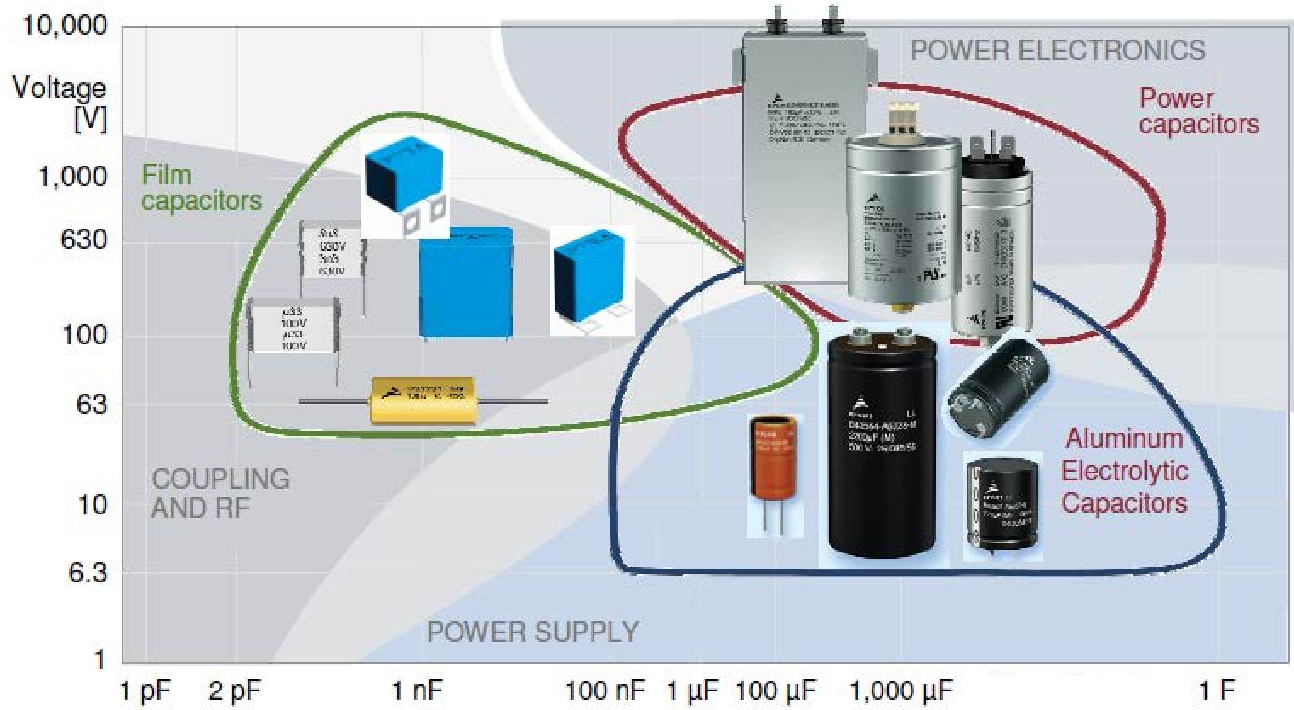
Approximate Range of Characteristics of Existing Mechanical Actuators

actuator type	maximum actuation strain $\epsilon_{\max}[-]$	maximum actuation stress $\sigma_{\max}$ (MPa)	modulus E (GPa)
low strain piezoelectric	5×10^{-6}–3×10^{-5}	1–3	90–300
high strain piezoelectric	5×10^{-5}–2×10^{-4}	4–9	50–80
piezoelectric polymer	2×10^{-4}–1×10^{-3}	0.5–5	2–10
thermal expansion (10 K)	9×10^{-5}–3×10^{-4}	20–50	70–300
thermal expansion (100 K)	9×10^{-4}–3×10^{-3}	200–500	70–300
magnetostrictor	6×10^{-4}–2×10^{-3}	90–200	40–200
shape memory alloy	7×10^{-3}–7×10^{-2}	100–700	30–90
moving coil transducer	1×10^{-2}–1×10^{-1}	4×10^{-3}–5×10^{-2}	4×10^{-5}–5×10^{-3}
solenoid	1×10^{-1}–4×10^{-1}	4×10^{-2}–1×10^{-1}	3×10^{-4}–1×10^{-3}
muscle	3×10^{-1}–7×10^{-1}	0.1–0.4	5×10^{-3}–2×10^{-2}
pneumatic	1×10^{-1}–1×10^{0}	0.5–0.9	5×10^{-4}–9×10^{-4}
hydraulic	1×10^{-1}–1×10^{0}	20–70	2–3

Huber et al., Proc. R Soc. A453 2185 (1997)

The Humble Capacitor



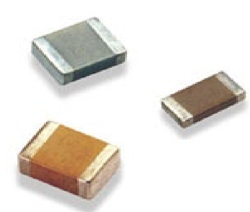


Capacitors

What they do:
These store and release electrical energy. They are widely used to absorb electronic noise and detect signals of set frequencies.

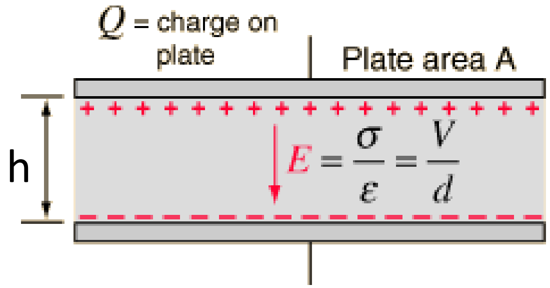
Size: 0.4mm x 0.2mm to 1mm x 0.5mm
Number per phone: 700

Notes: Numbers per smartphone are approximate. S
Source: Murata Manufacturing



The Humble Capacitor: The Essential Physics

A capacitor is usually used to store electrical energy so it requires a large dielectric constant and large area. Electrical energy stored is:



$$U_{electrical} = \frac{\varepsilon\varepsilon_o V^2 \, A h}{2h^2}$$

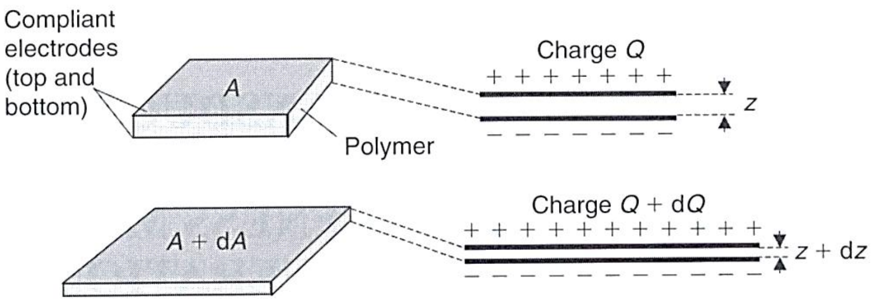
Capacitance: $$C = \frac{Q}{V} = \frac{\sigma_S \, A}{E \, h} = \varepsilon \, \varepsilon_O \frac{A}{h}$$

Attractive force between opposite charges is: $P_C = \frac{1}{2} \varepsilon \, \varepsilon_O \, E^2$

induces electrostrictive strain that for most dielectrics is ppm, ie nanometers

Freeing the Capacitor -- The Compliant Capacitor

Applying a voltage to a capacitor produces opposite charges in the electrodes across the dielectric.



Coulombic attraction between the charges creates a Maxwell force that compresses the dielectric (equivalent to electrostatic actuator in MEMS)

$$P = \sigma_z = \varepsilon\,\varepsilon_o\,E^2 = \varepsilon\,\varepsilon_o\left(\frac{V}{h}\right)^2$$

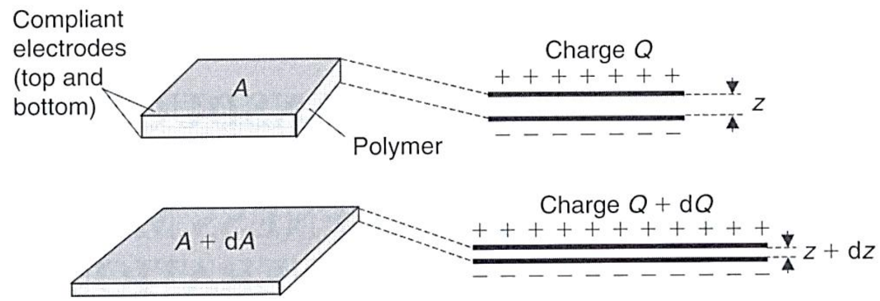
produces strain $s_z = -\dfrac{\sigma_z}{Y}$

Elastomers are incompressible, ie volume change = O. So, if reduce thickness, expands laterally

$$\Delta V = 0 = s_x + s_y + s_z \quad : \quad s_x = s_y = \frac{P}{2Y} = \varepsilon\varepsilon_o\,\frac{V^2}{2Y\,h^2}$$

Freeing the Capacitor -- The Compliant Capacitor

Applying a voltage to a capacitor produces opposite charges in the electrodes across the dielectric.



Coulombic attraction between the charges creates a Maxwell force that compresses the dielectric (equivalent to electrostatic actuator in MEMS)

$$P = \sigma_z = \varepsilon \varepsilon_o E^2 = \varepsilon \varepsilon_o \left(\frac{V}{h}\right)^2$$

produces strain $s_z = -\frac{\sigma_z}{Y}$

Elastomers are incompressible, ie volume change = O. So, expands laterally

Actuation stretch $\lambda \approx \frac{P}{2Y} \approx \varepsilon\varepsilon_o \frac{V^2}{2Y h^2}$

Voltage

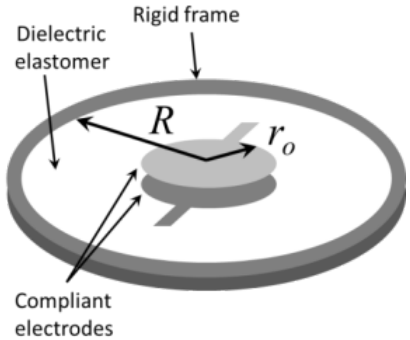
Thickness

Stiffness

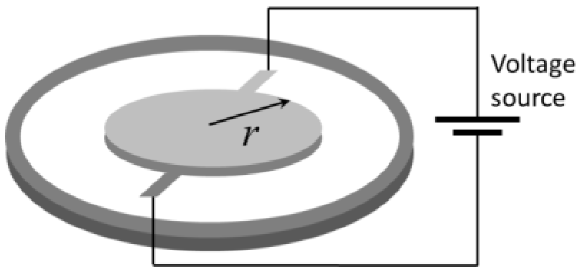
(million times smaller than standard capacitors)

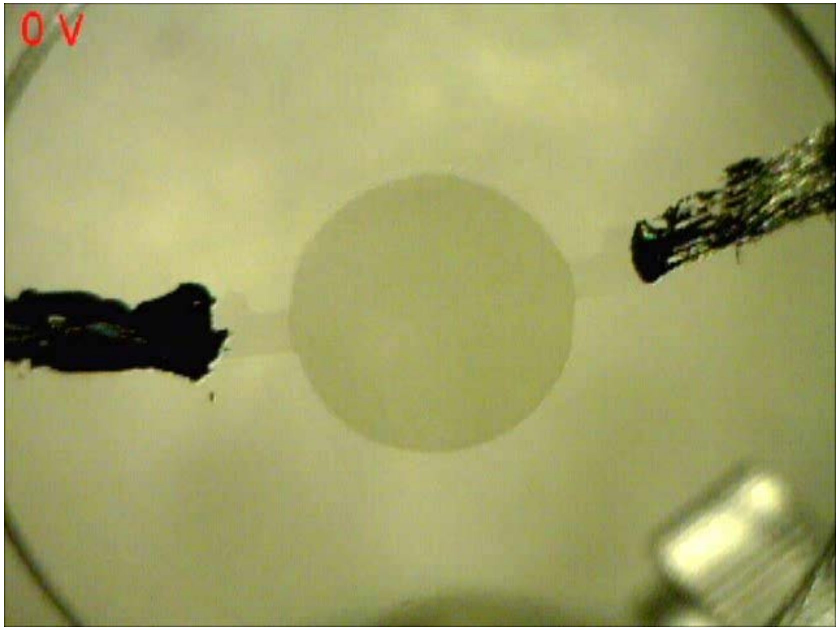
Replacing a ceramic dielectric with an elastomer leads to a million times greater strain !

How much can the compliant capacitor stretch ?



VHB 4905 elastomer
(Acrylic-based)
Prestretched to 250%





12x speed

Carbon nanotube electrodes

Quantify actuator deformation, stretch, λ

$$\lambda = \frac{r}{r_o}$$

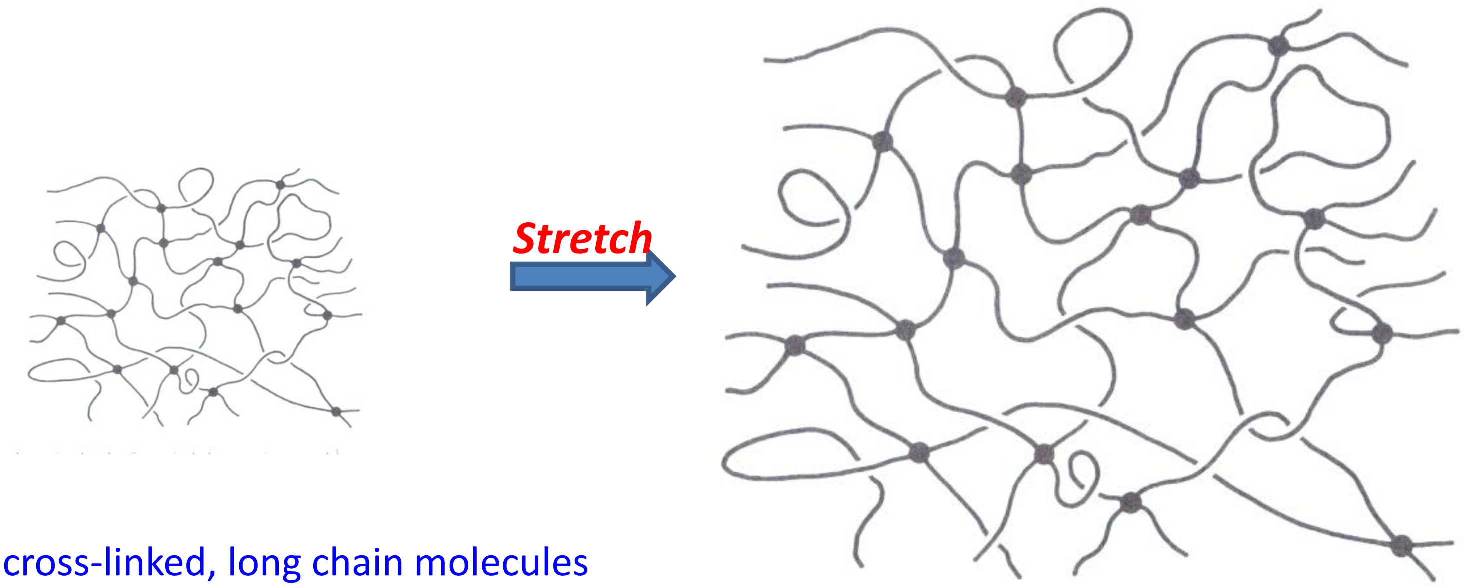
As elastomers are incompressible, so

$$\lambda^2 = H / h$$

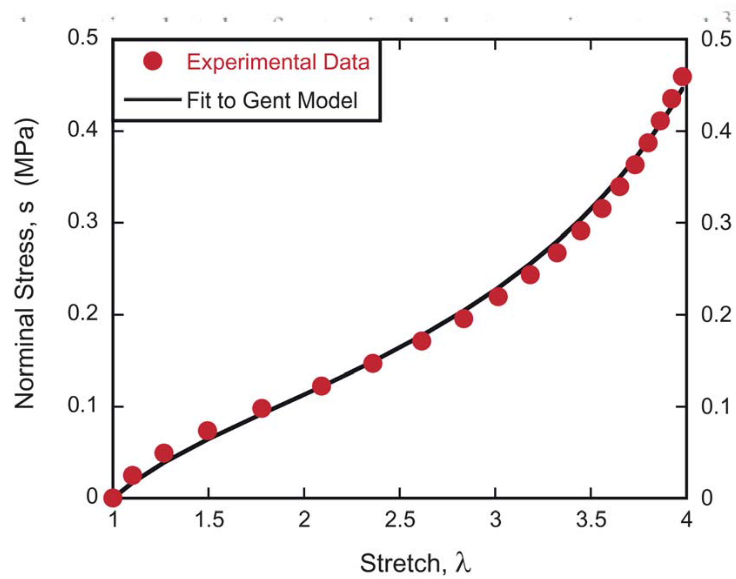
During actuation, the voltage increased at a rate of 20 V/s until electrical breakdown.

$$\lambda = \frac{r}{r_o} \approx 2$$

The Molecular Structure of Elastomers



- Loosely cross-linked, long chain molecules
- Transparent materials
- Highly insulating
- Dielectric constant ~ 2.6
- On stretching – chains straighten
- Huge, nonlinear strain capabilities
- Incompressible – Poisson ratio 0.5



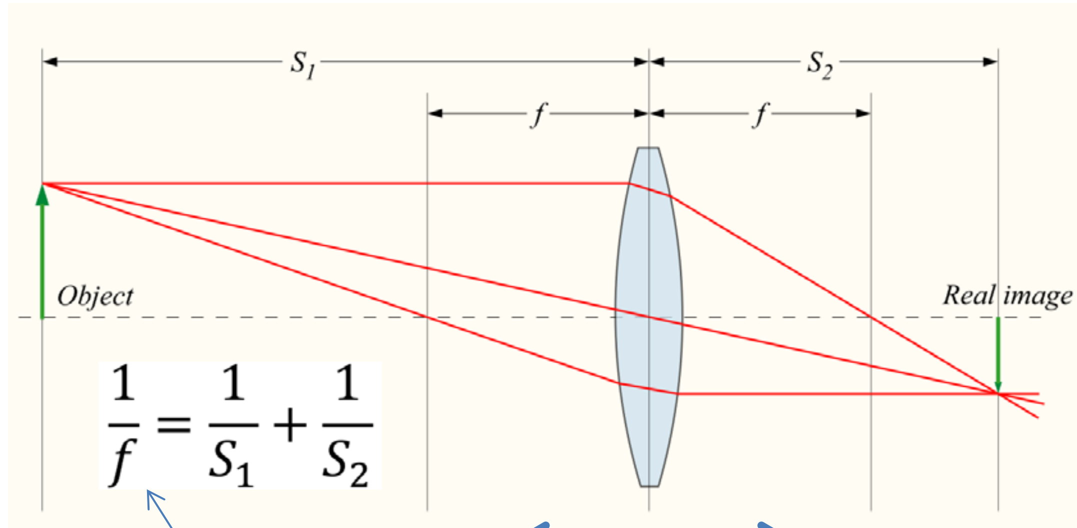
Typical elastomers:

- Natural rubber (latex)
- PDMS
- Arcylic (3M VHB 7905)
- Polyurethane

Compliant capacitor as an electrically driven artificial muscle

A Conventional Electrically Focusing Camera

Canon EF 50mm

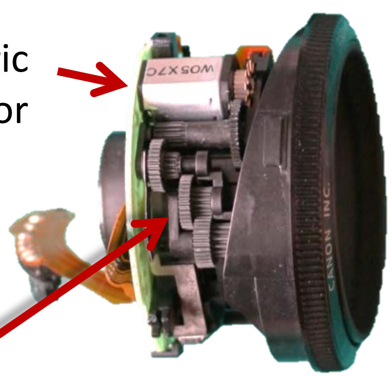


$$\frac{1}{f} = \frac{1}{S_1} + \frac{1}{S_2}$$

Focal length is constant

Focusing by moving lens

Electric Motor



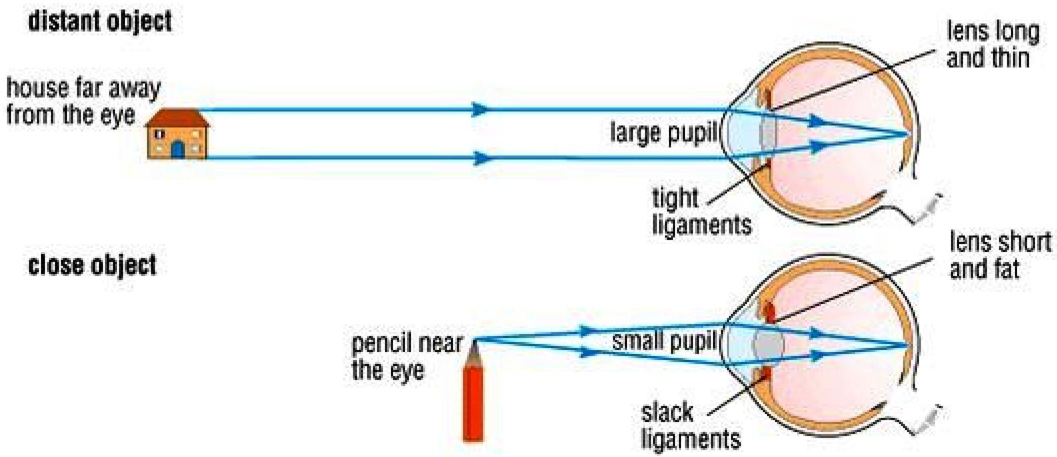
Gear Assembly

http://www.flickr.com/photos/doegox/2750019800/

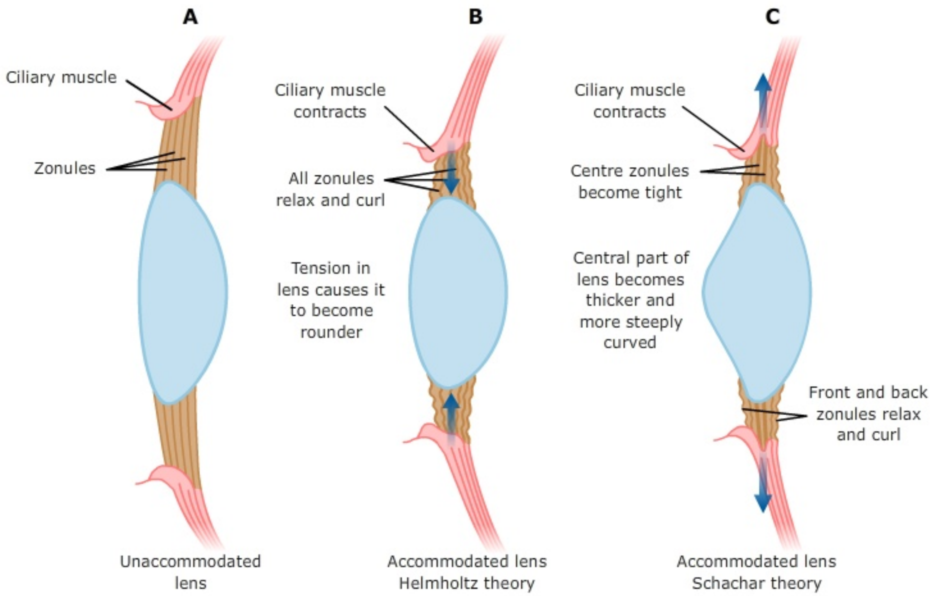
Limitations of traditional lenses:

- Bulky
- Slow
- Complicated design, multiple gears
- Noisy
- Limited focusing range

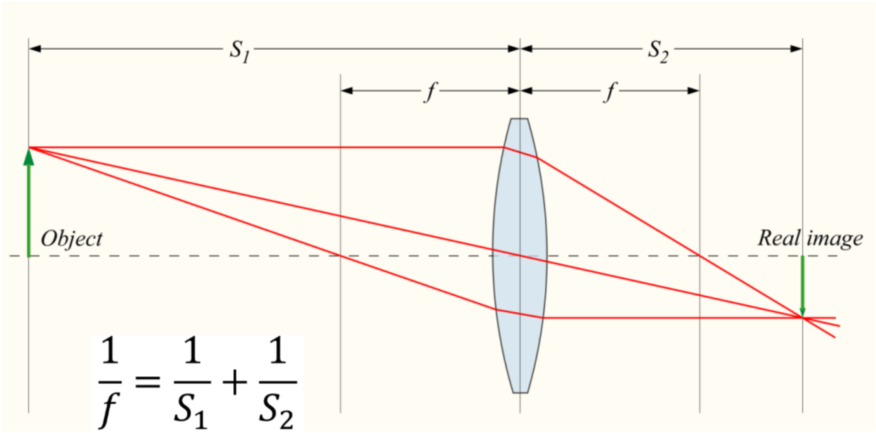
The Human Eye: Focusing

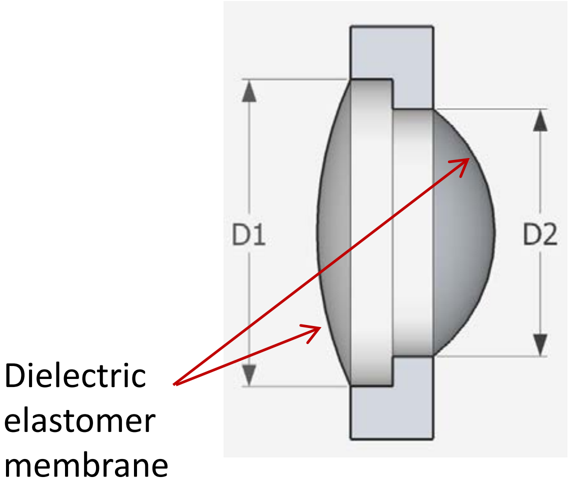


Focusing is associated with change in shape of the ocular lens



An Electrically Tunable, Adaptive Lens





An alternative approach:

Change focal length of the lens by changing its curvature

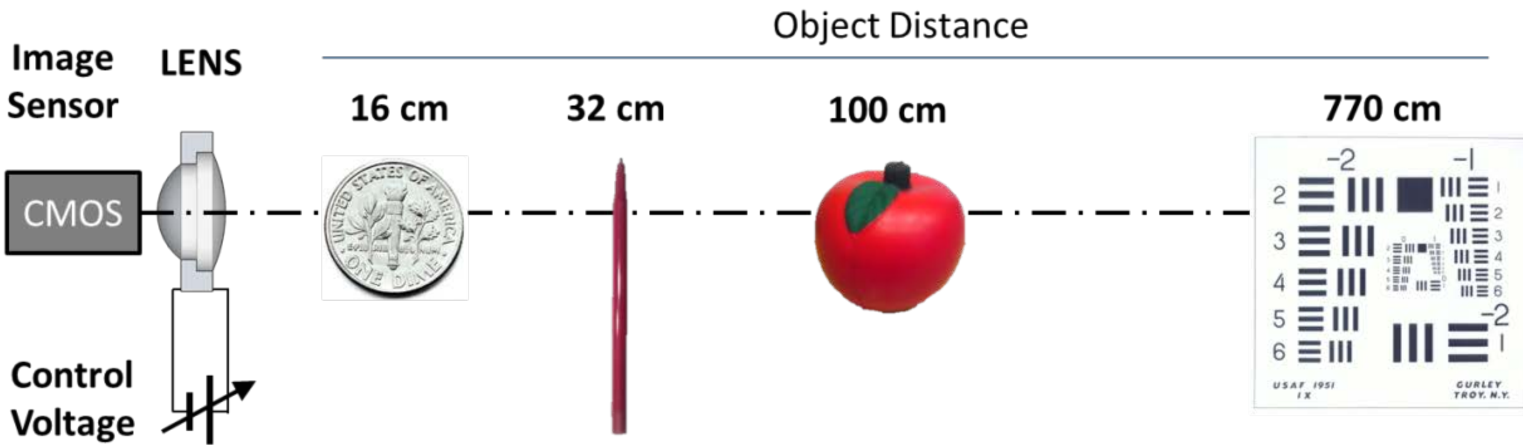
Solution:

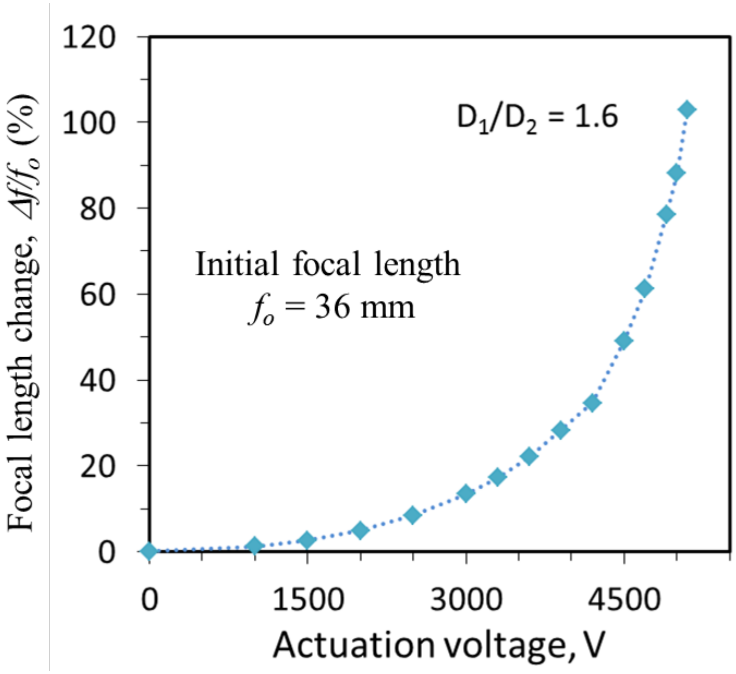
Constant volume liquid droplet contained between transparent sheets whose areas can be altered with an applied voltage.

Requires:

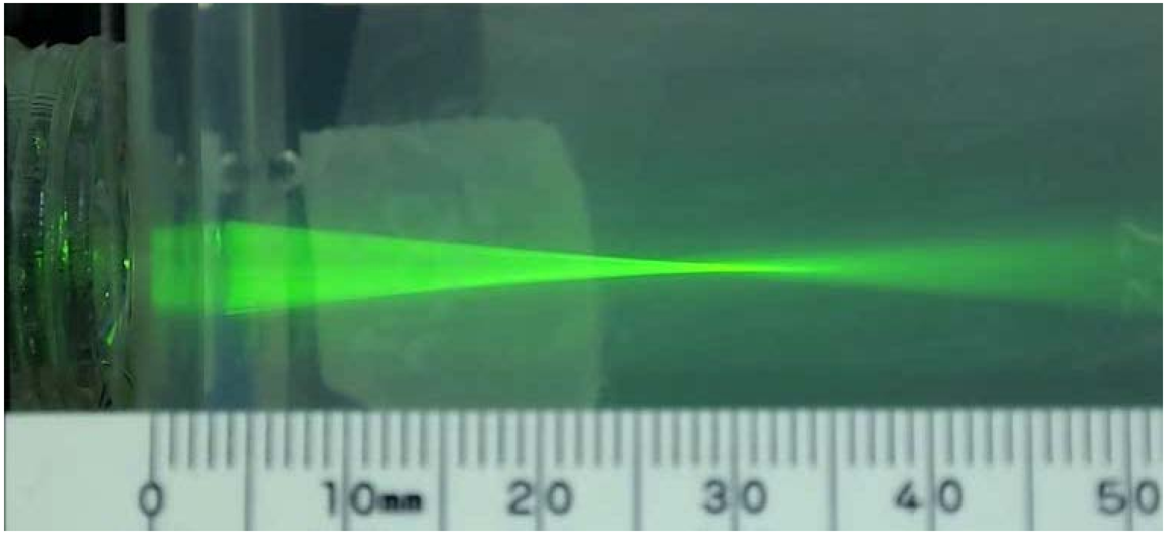
Transparent, compliant electrodes

Demonstration of a Tunable Lens

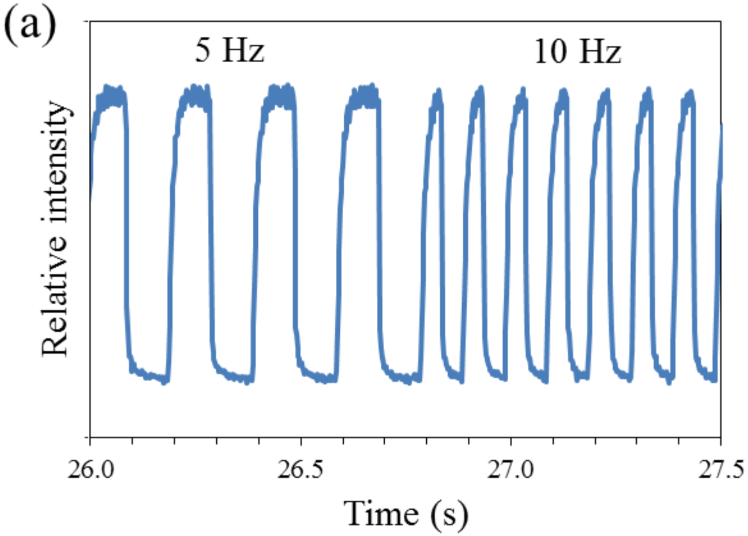


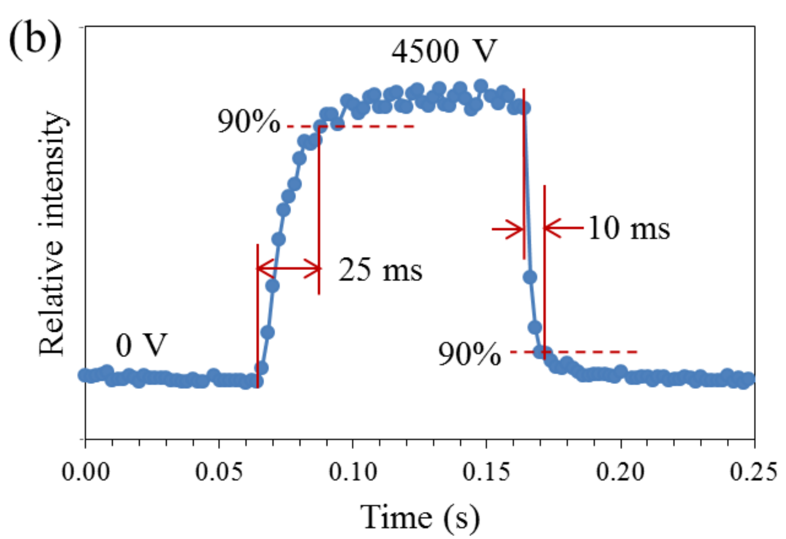


High Speed Response



0 V and 4.5 kV
The scale is in mm.



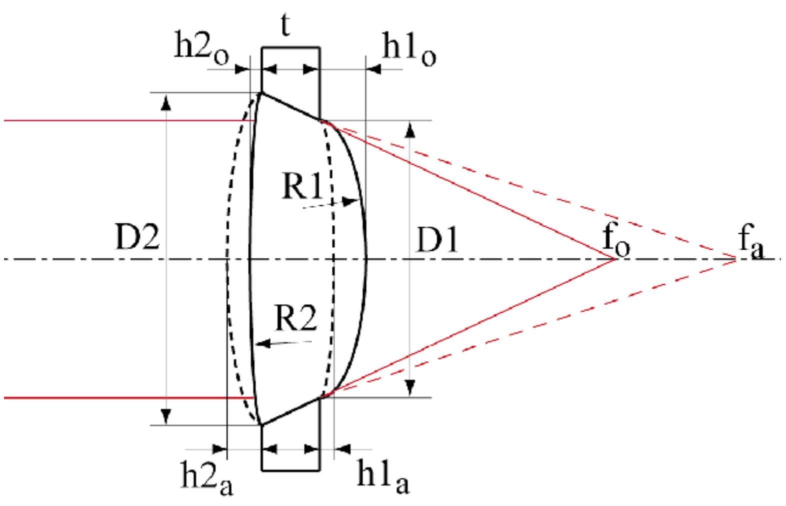


Dynamic Focal Range

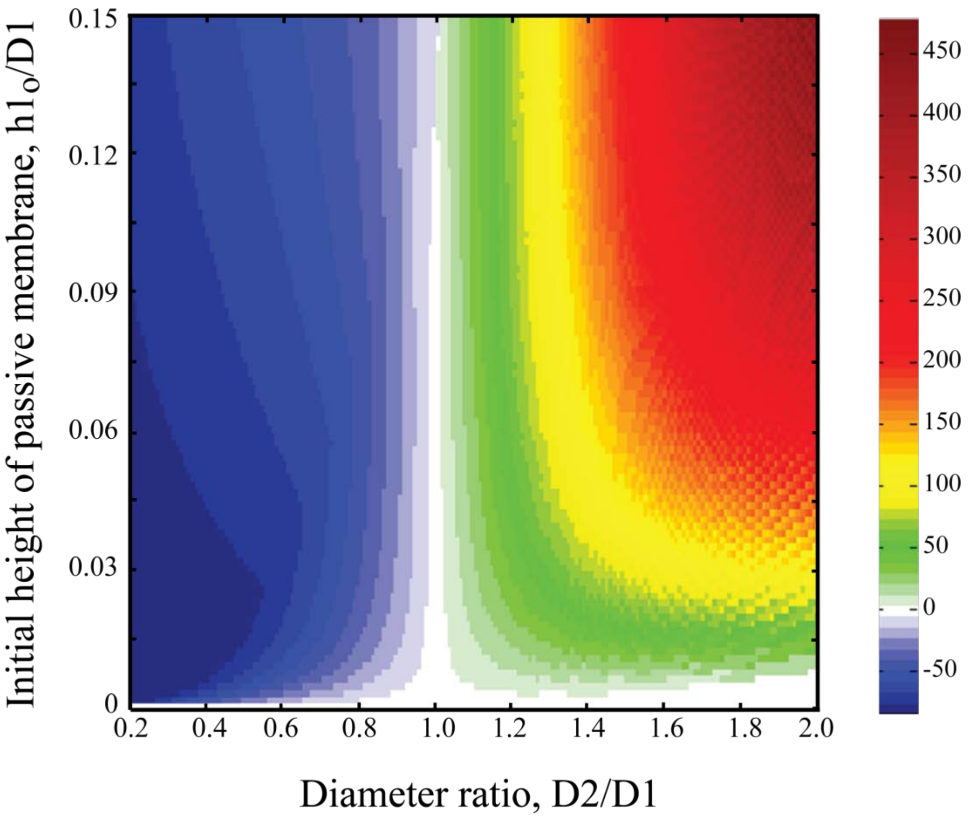
Calculating the dynamic range of focal length:

- Constant volume
- Spherical curvature, h/a < 0.25
- DEA membrane, D2 → curvature decrease
- Passive membrane, D1 → curvature increase

$$\Delta f_{max} = \frac{f_{max} - f_o}{f_o} x\ 100\%$$

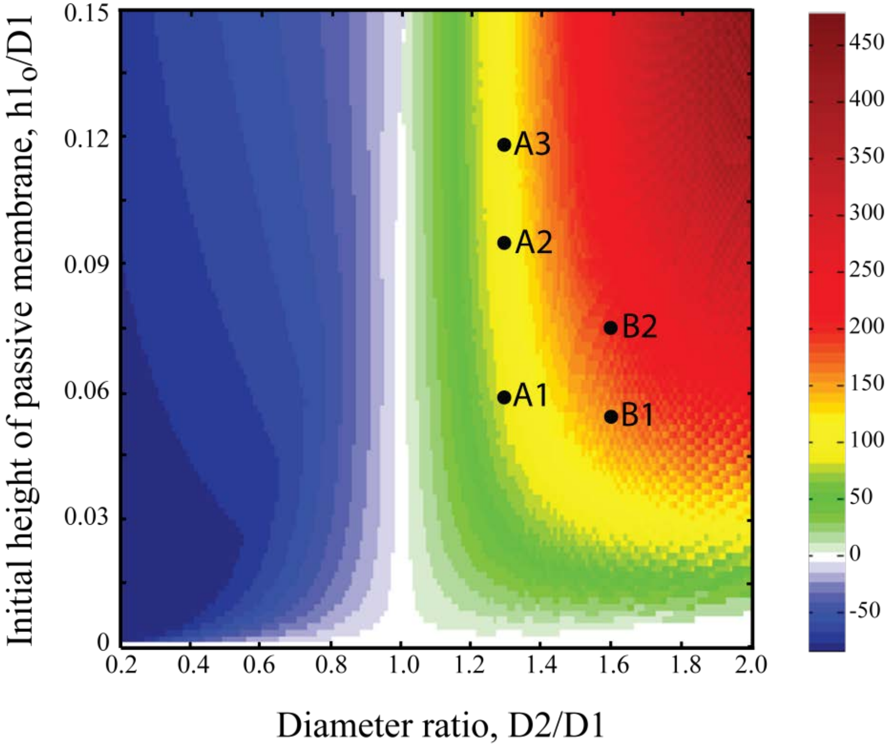


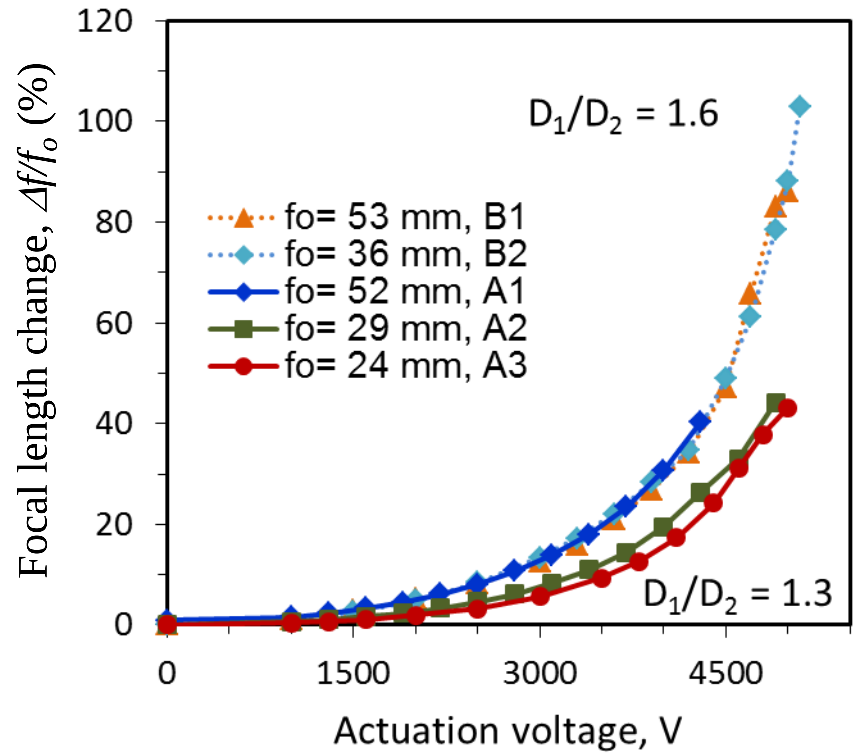
Color indicate maximum focal change



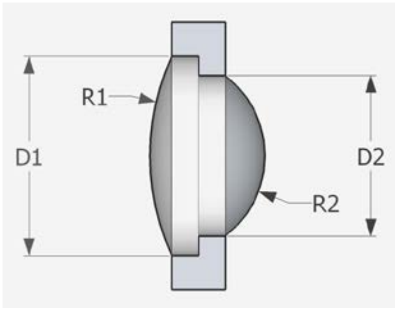
Dynamic Focal Range Depends on Diameter Differences

Color indicate maximum focal change





The maximum focal length variation (Δf_{max}) depend on relative diameter of the membranes (D_1/D_2), but independent of the refractive index.



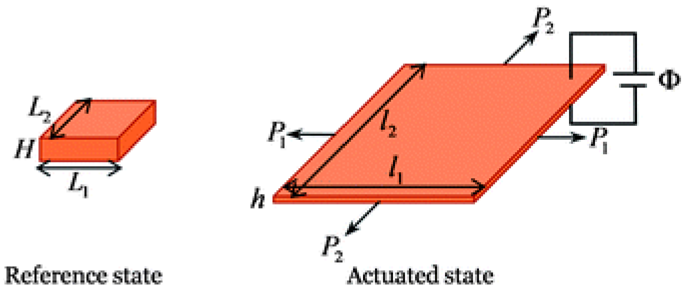
The Compliant Capacitor as a Machine Element

Machine Elements of Soft Robotics

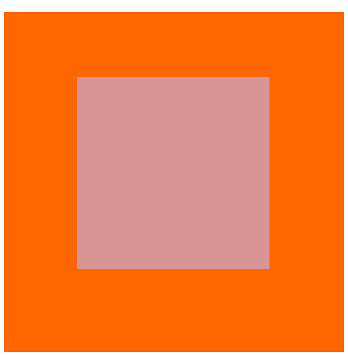
- Actuators
  - Linear actuators
  - Biaxial actuators
- Rotary drives
- Soft clamps
- …………..

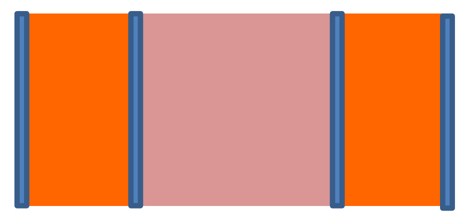
Devising A Uniaxial Actuator

Complaint capacitor creates a biaxial strain.



How do we use it to create uniaxial strain ?

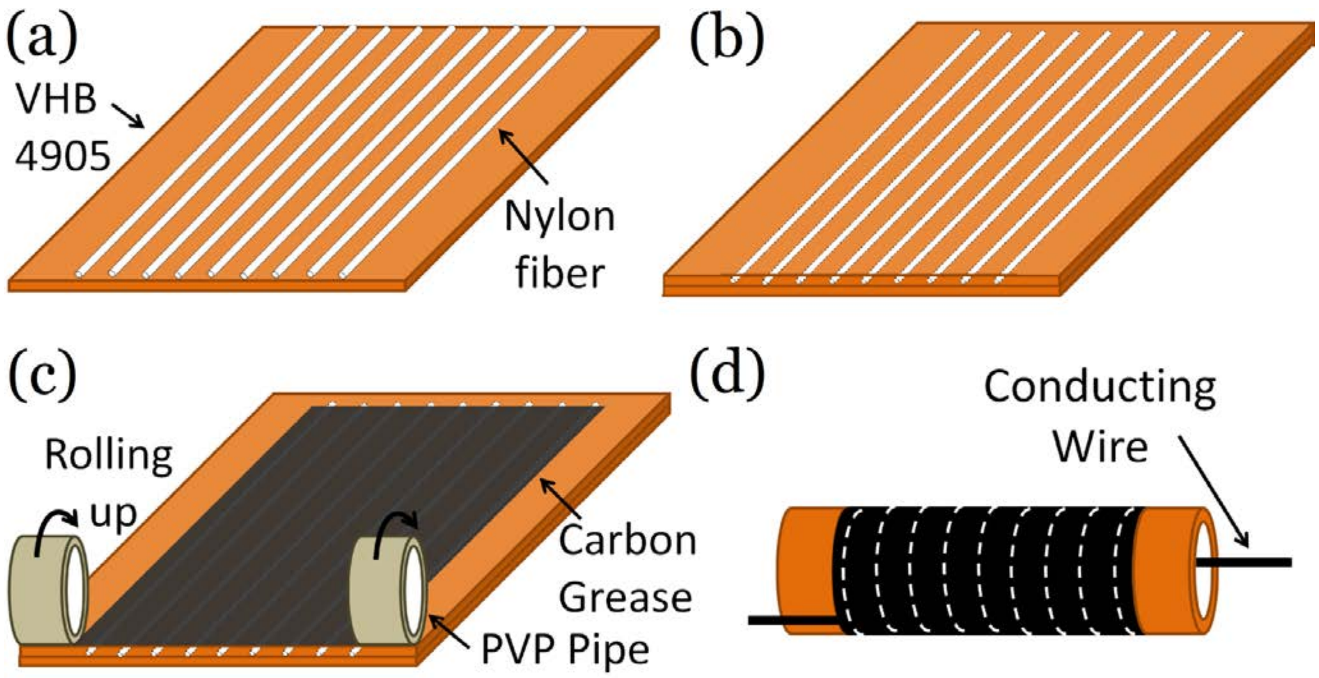




Apply through thickness electric voltage.
Equi-biaxial strain

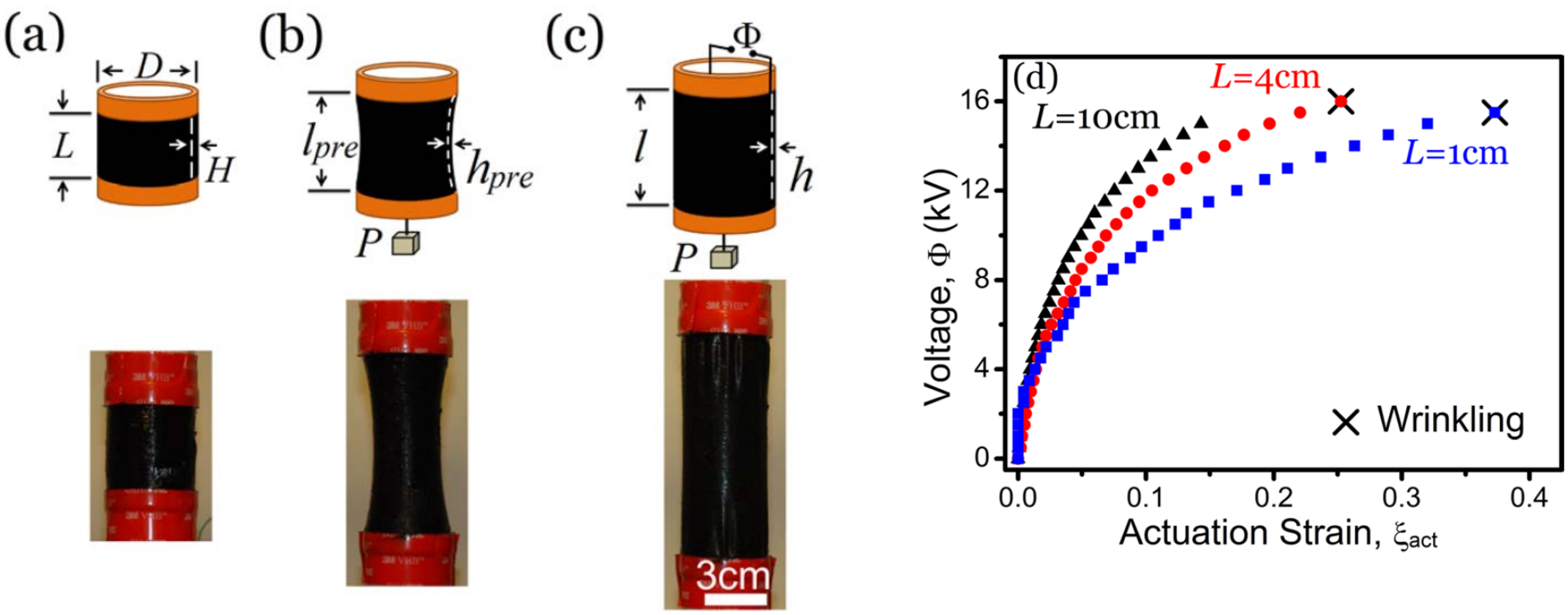
Insert aligned and parallel stiffeners
Apply electric voltage
Elongation perpendicular to stiffeners

Uni-axial Fiber Stiffening of Dielectric Elastomer

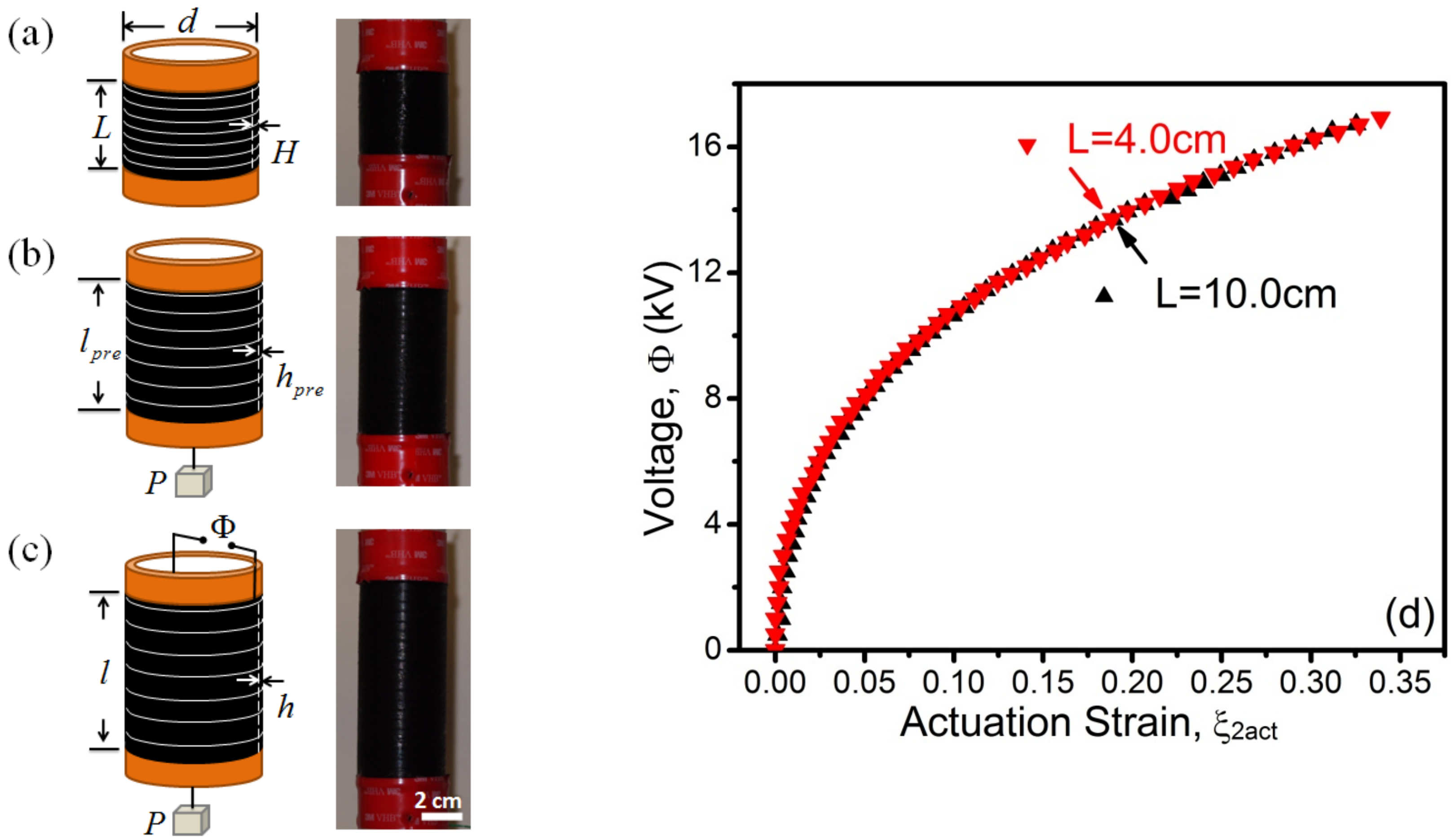


Cylindrical geometry chosen to minimize electrical breakdown at edges

Uni-axial Actuator with no Stiffening



Cylindrical Actuator Using Fiber Stiffened Elastomer

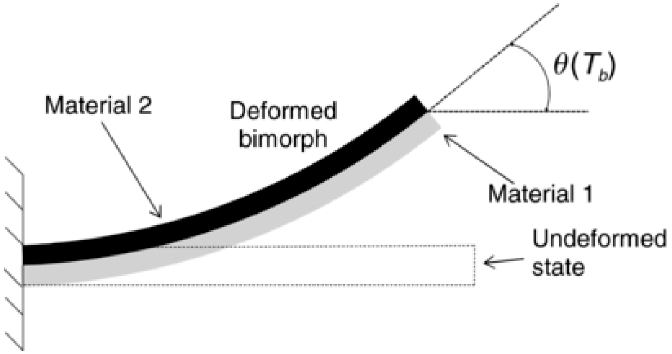


Uniaxial Actuator

Mimicking Finger Action

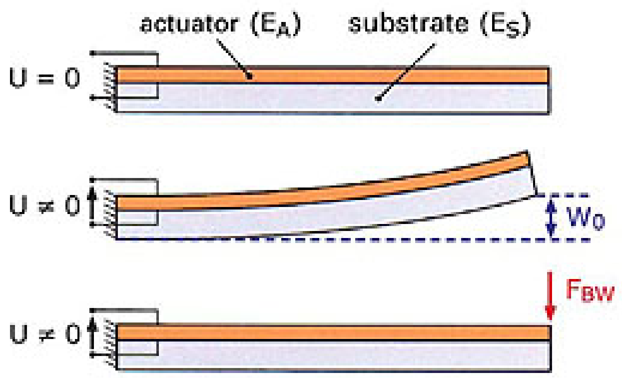
Fingers gripping an object

Fingers striking piano keys



Mechanical element analog:
unimorph or bimetallic strip

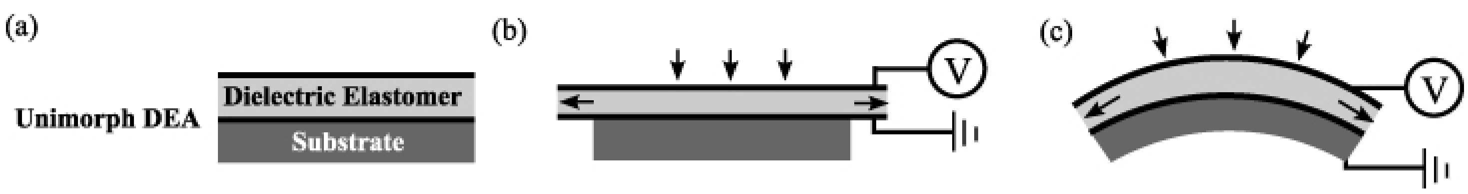
The Simplest Robotics Element: The Unimorph



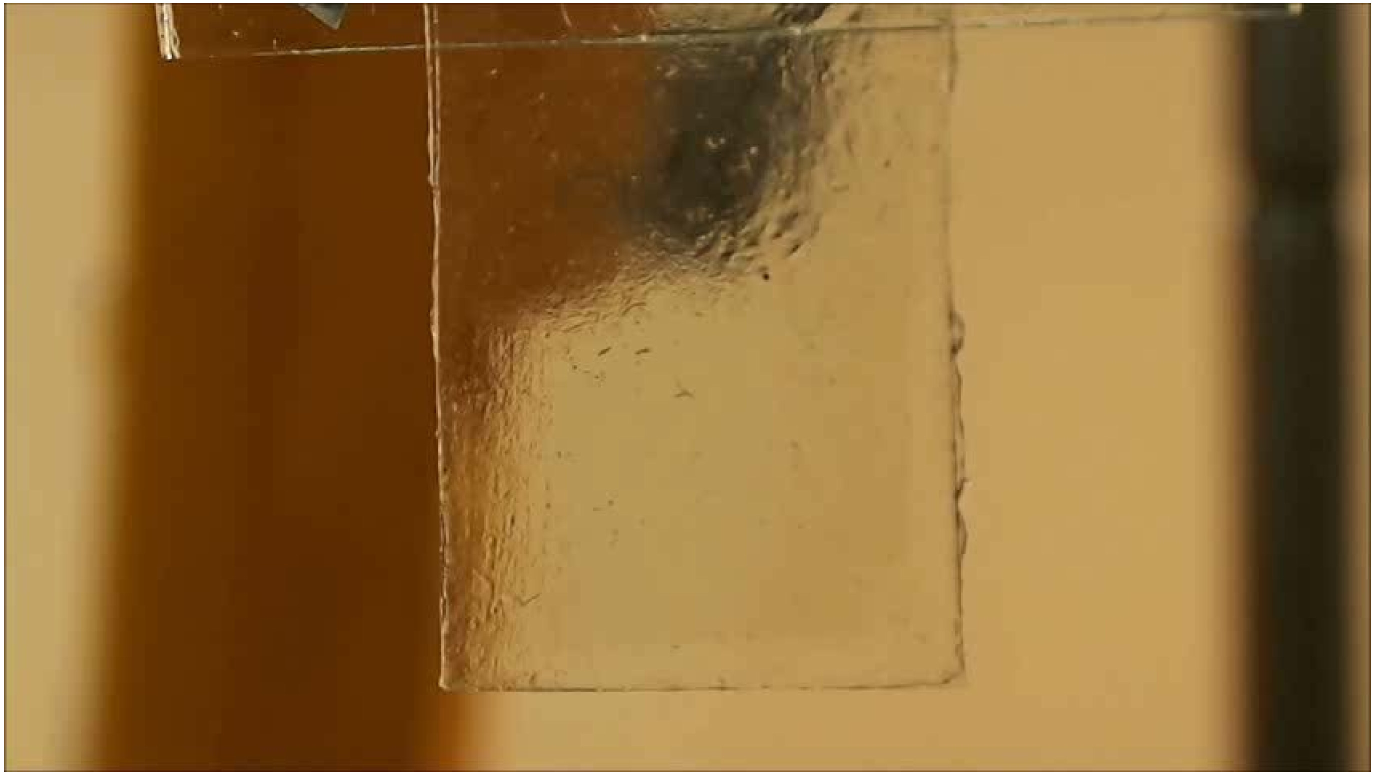
End deflection

Blocking force

–



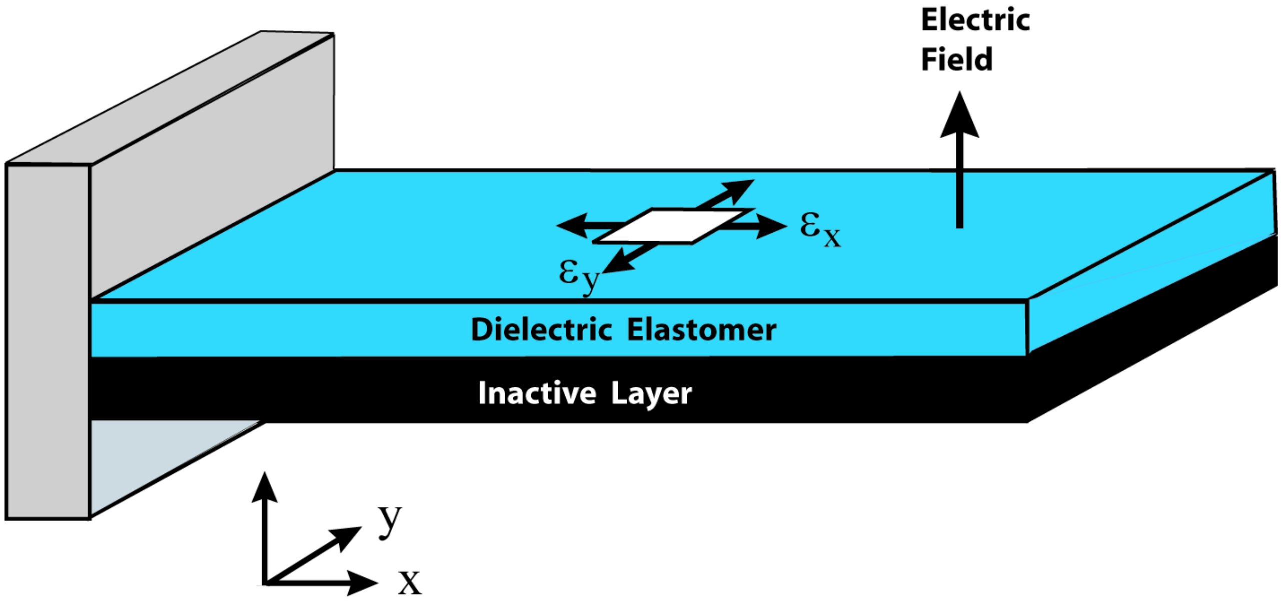
Dielectric Elastomer Unimorph Actuation



NB. Transparent electrodes

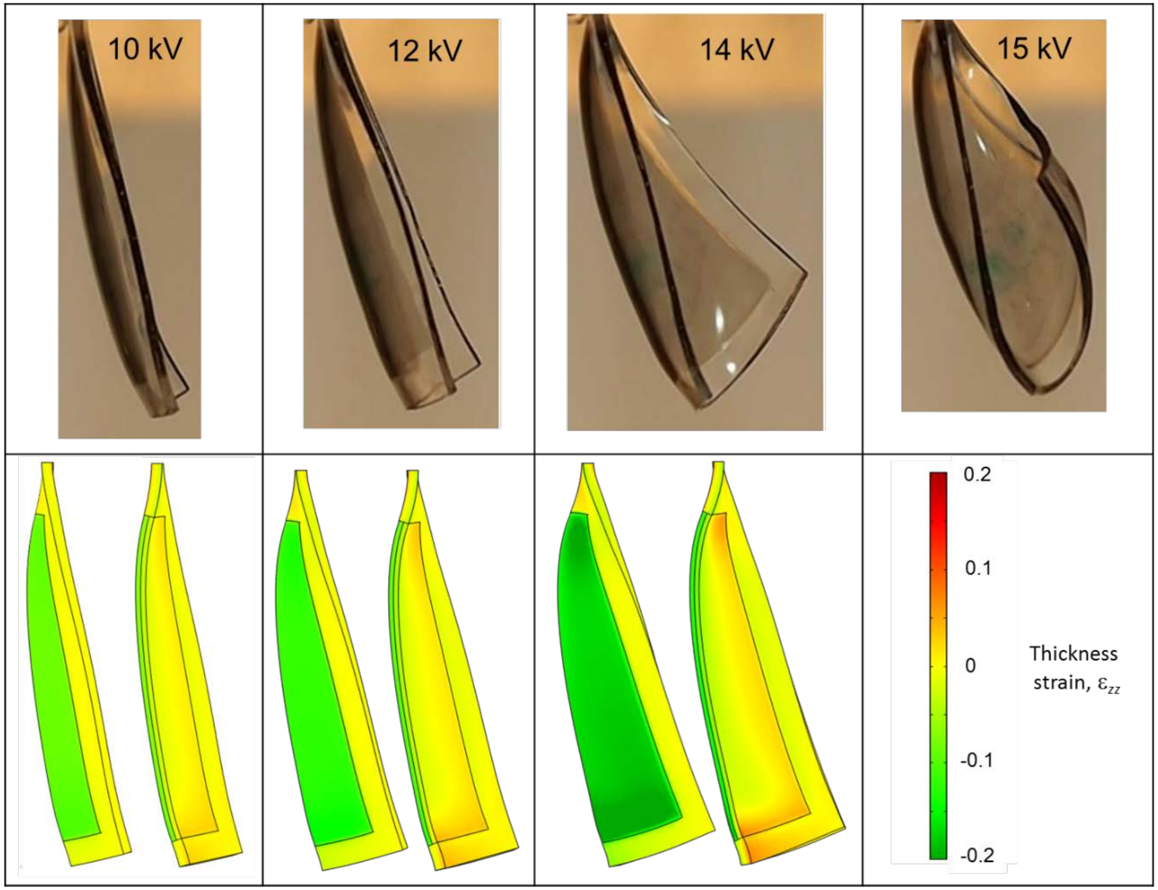
Curling instability due to field induced curvature in two mutually perpendicular directions

The Dielectric Elastomer Based Unimorph



Expansion parallel and perpendicular to beam axis, causes bending in two perpendicular directions. As the strains can be large, the out-of-plane bending can be large.

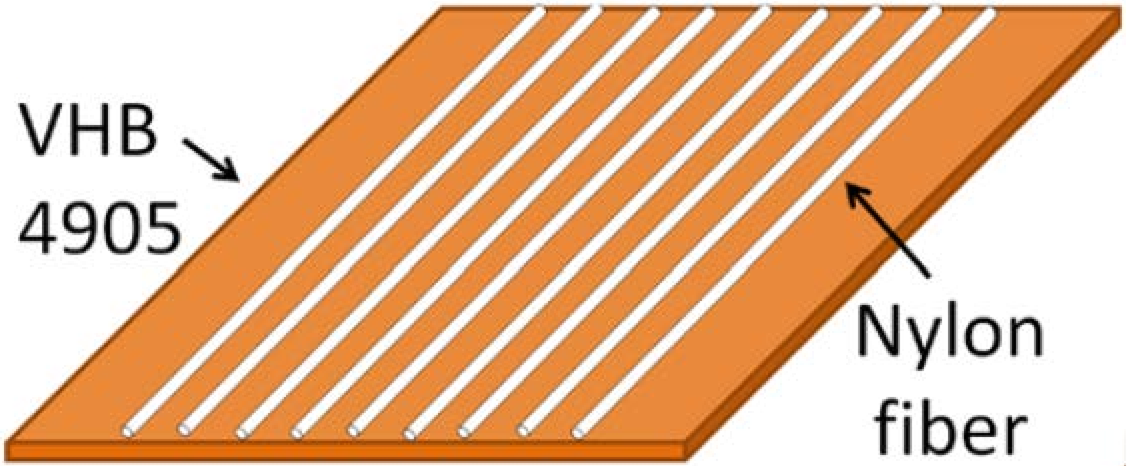
Unimorph Actuation



Observations

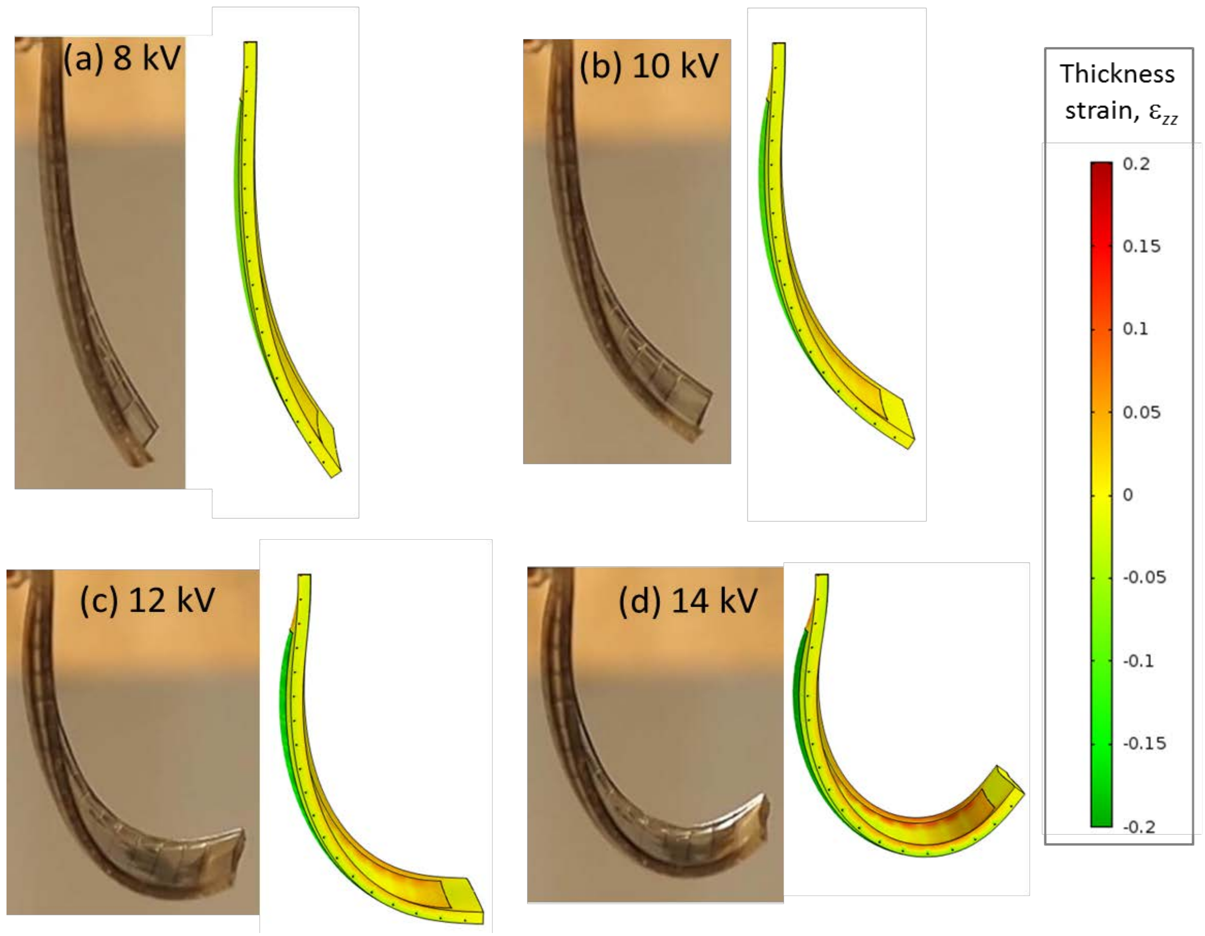
Finite element computations

Aligned, Parallel Fibers Introduce Anisotropic Stiffness

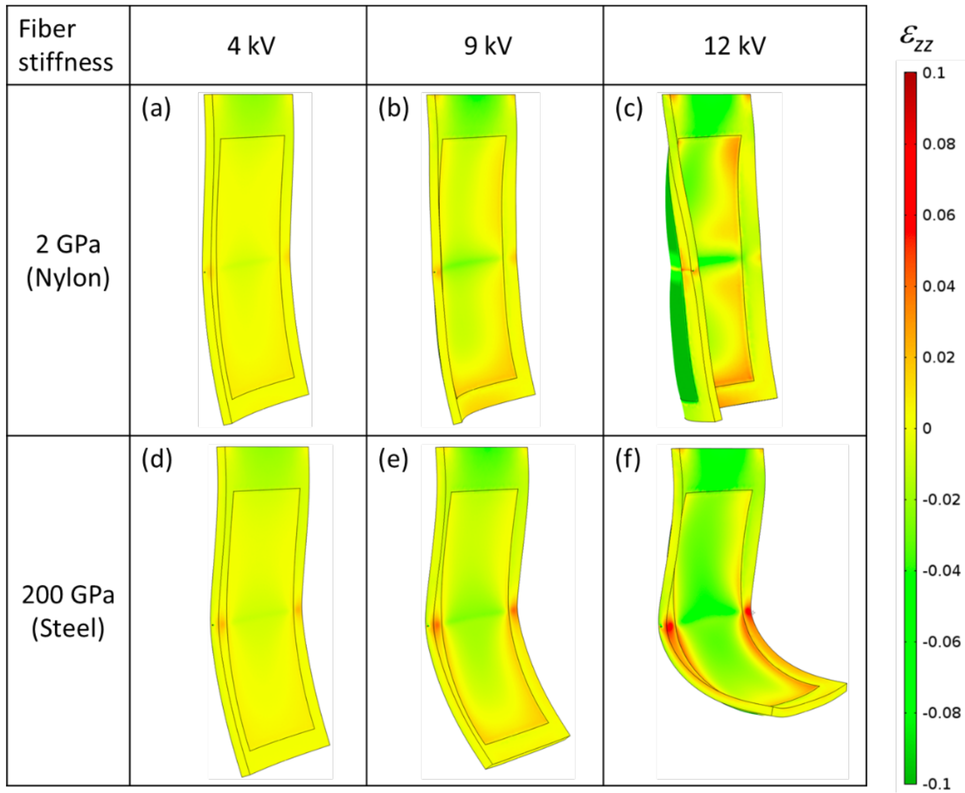


Aligned fibers produces higher stiffness parallel to fibers than perpendicular to them. $E_{nylon} >> E_{VHB.}$ This breaks the flexural deformation response symmetry of the beam

Simulations Show Suppression of Curling



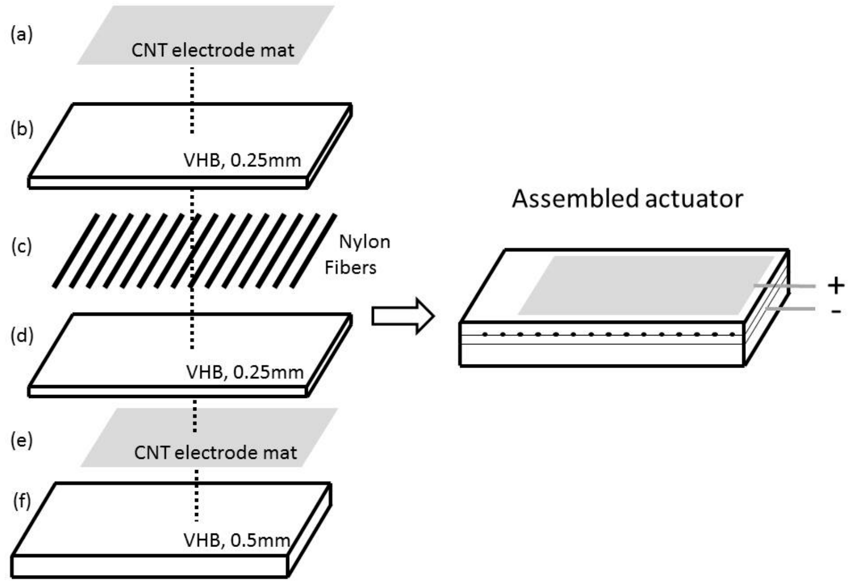
Simulations Show Suppression of Curling



A single fiber can be sufficient to break deformation symmetry

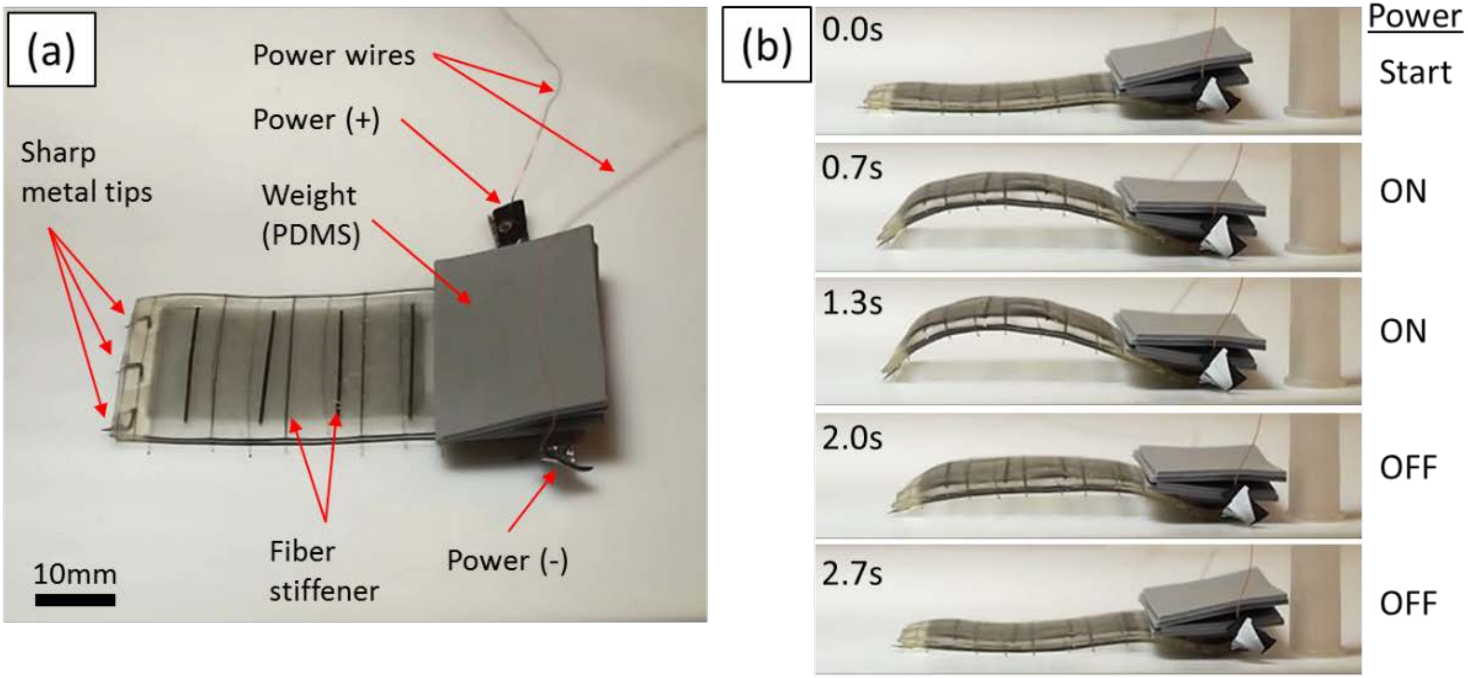
Fiber Stiffened Dielectric Elastomer Based Unimorph

Fabrication:



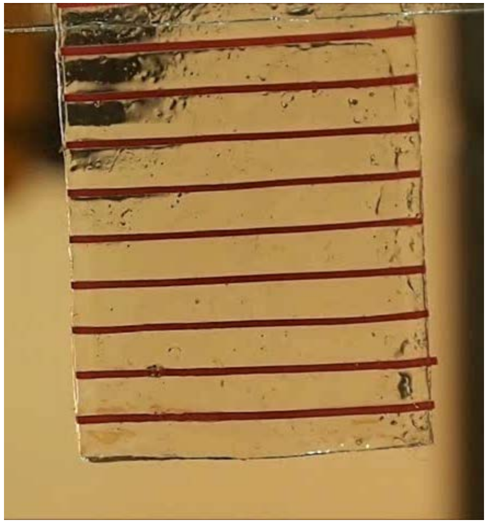
Optical
Micrograph:

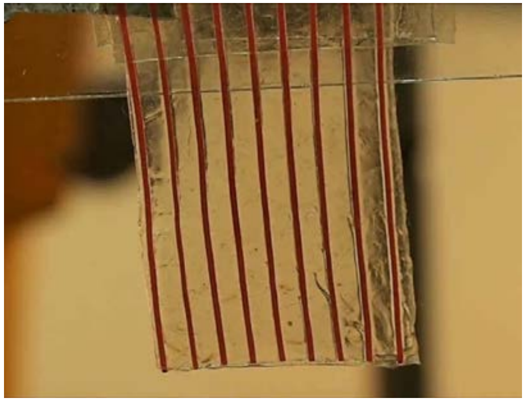
An Inchworm Based on Fiber Stiffened Unimorph

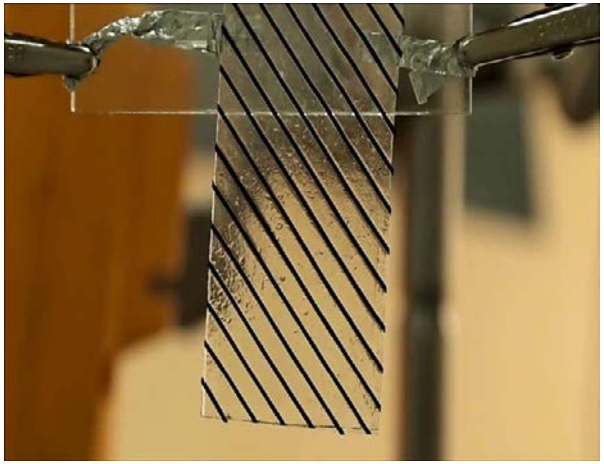


Effect of Elastic Anisotropy in Unimorphs

Low volume fraction of aligned fibers create elastic anisotropy and alters response







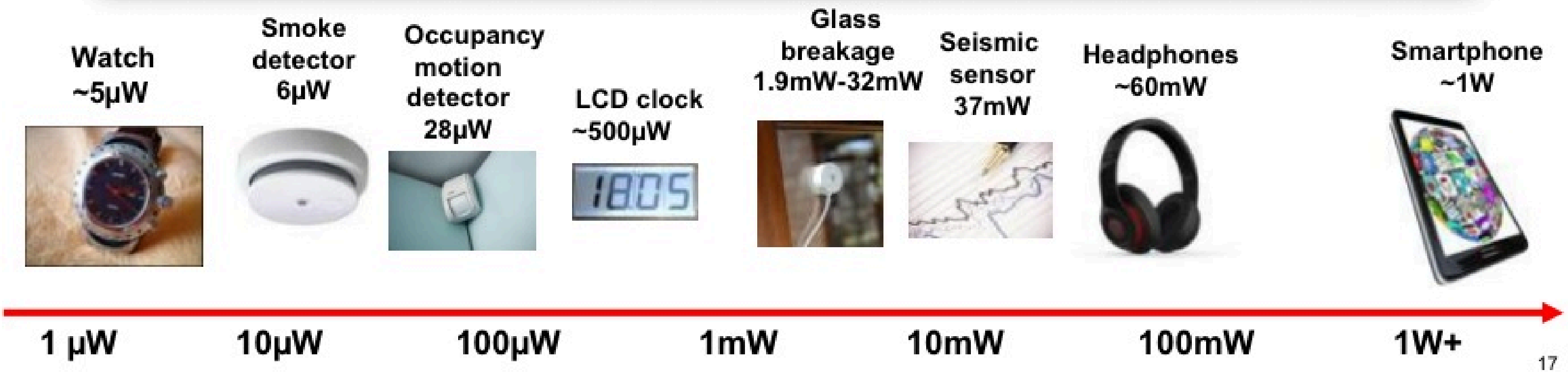
A Simple Soft Robotics Component: The Gripper

Mechanical Energy Harvesting

with a Compliant Capacitor

Energy Harvesting Schemes

Energy Source	Characteristics	Harvested Power
Light	Outdoor Indoor	100 mW/cm^2 100 μW/cm^2
Thermal	Human Industrial	60 μW/cm^2 ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	~4 μW/cm^3 ~800 μW/cm^3
RF	GSM 900 MHz WiFi	0.1 μW/cm^2 0.001 μW/cm^2



Small-Scale Energy Harvesting

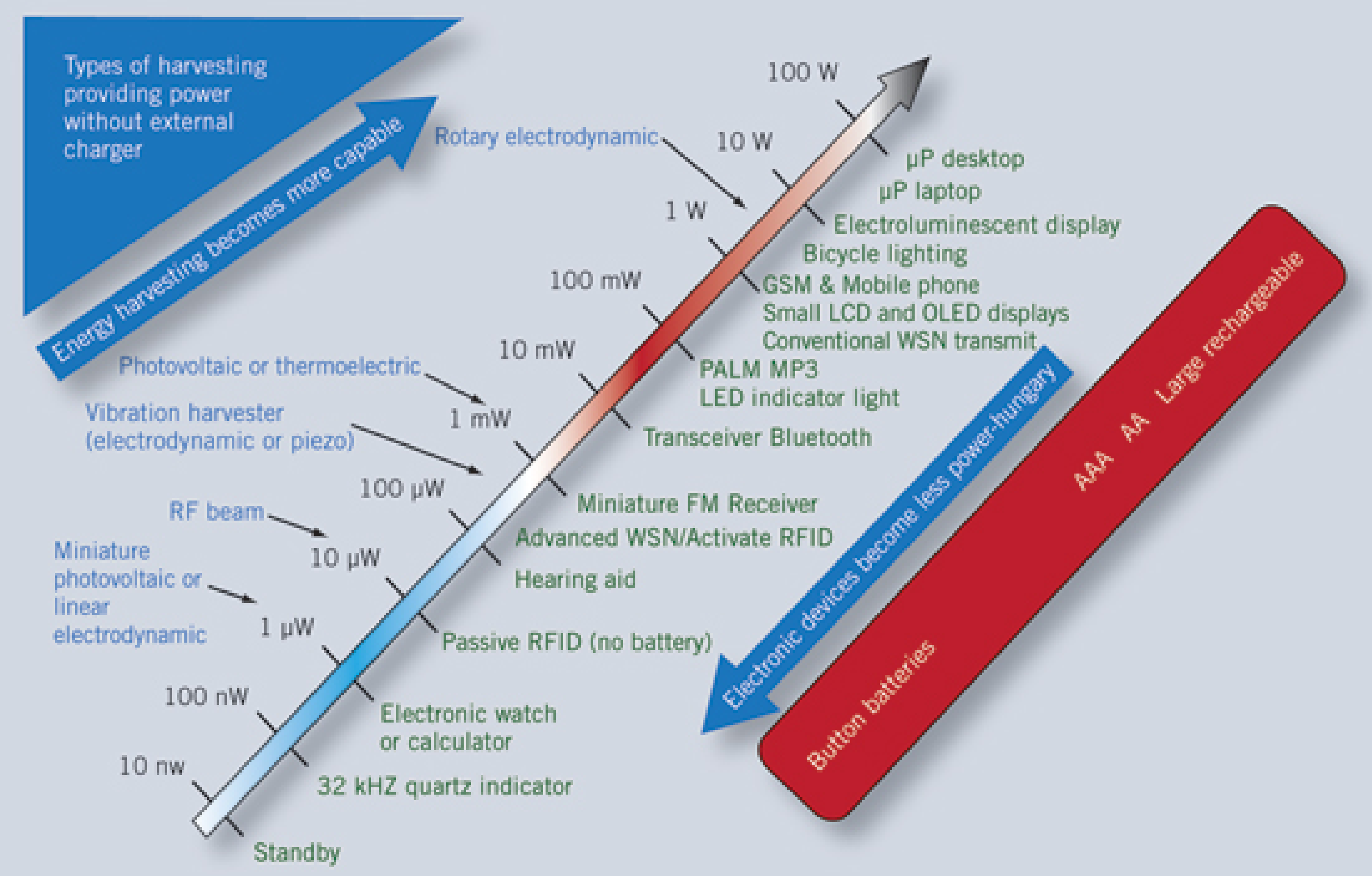
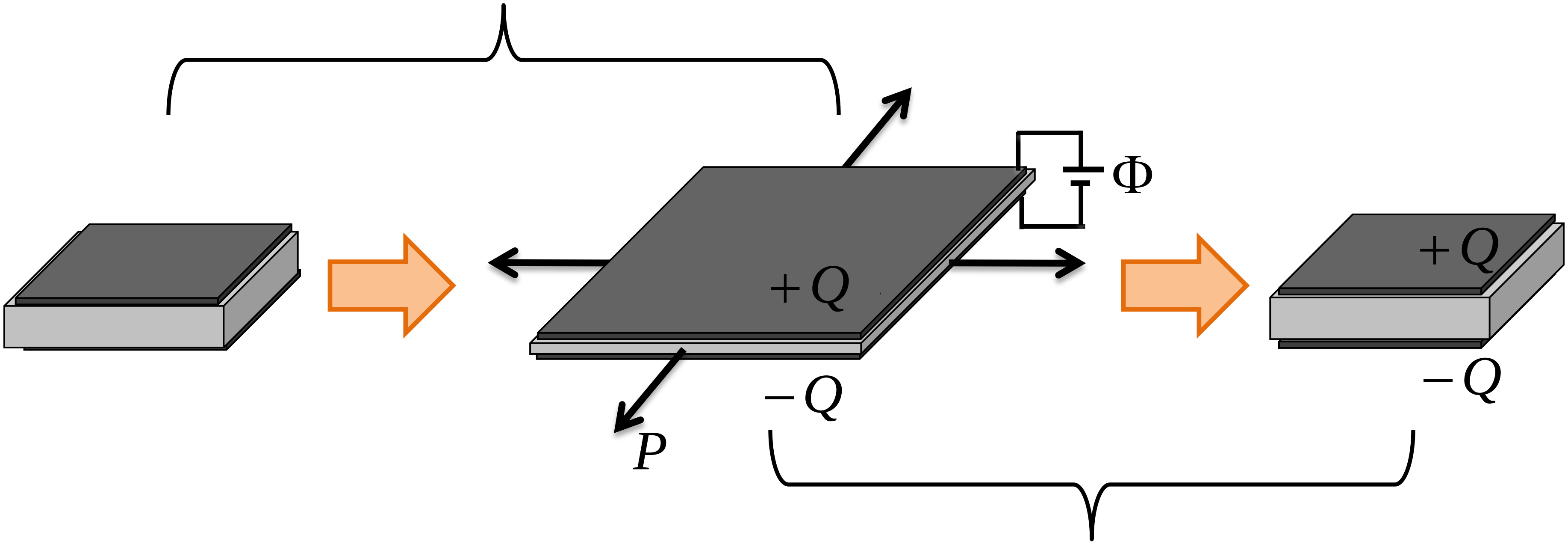


Fig. 2. Shrinking IC chip line geometries and lower power consumption levels come at a time when energy-harvesting devices are becoming more effective and practical. (Source: IDTechEx).

Harvesting Electrical Energy Through Mechanical Work

Convert mechanical energy to elastic energy



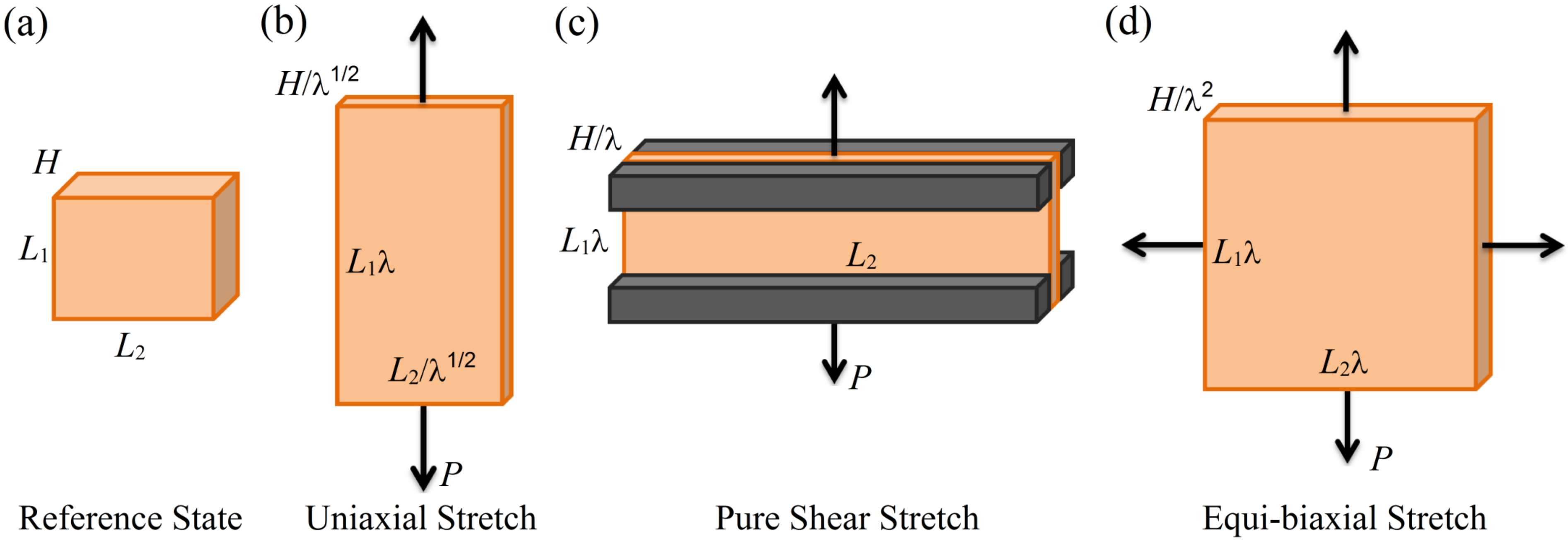
Change in stored elastic energy: $\Delta E_M = \oint P\, dL$

Convert elastic energy energy to electric energy through change in capacitance

Recall: Electrical energy of a capacitor is: $E_{electrical} = \frac{\varepsilon \varepsilon_o V^2}{2h^2} = \frac{CV^2}{2}$

Essentially a device for transferring charge from a low to high voltage – A voltage Step-Up Transformer

What is Optimum Mechanical Loading Configuration ?



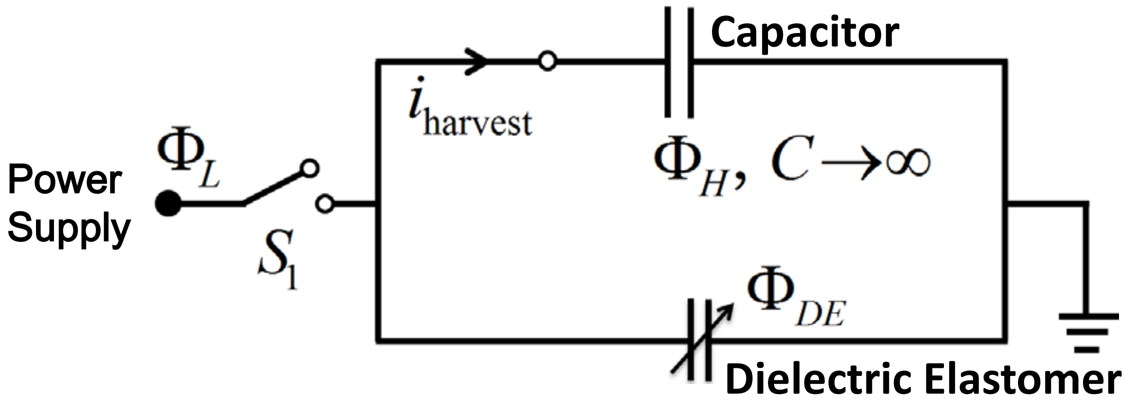
Capacitance Change

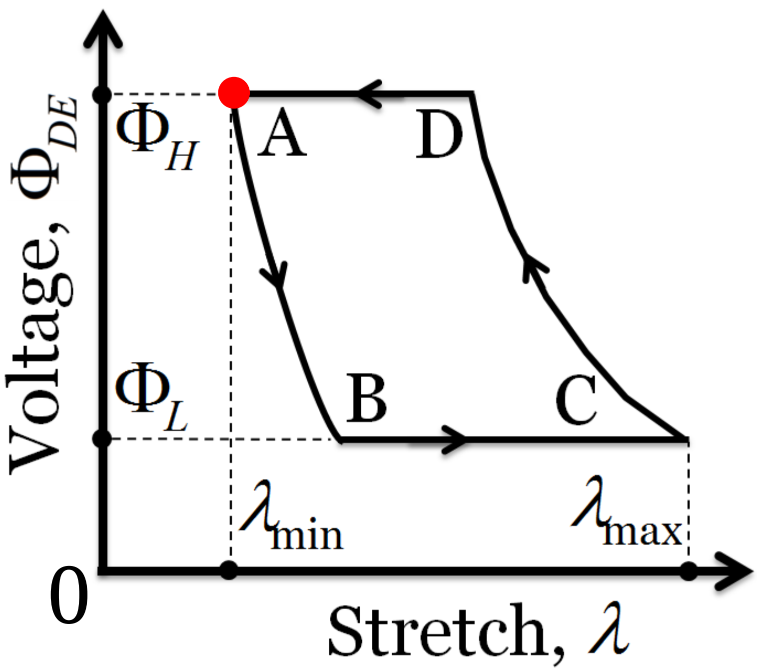
$$C \propto \frac{\lambda(1/\sqrt{\lambda})}{(1/\sqrt{\lambda})} = \lambda$$

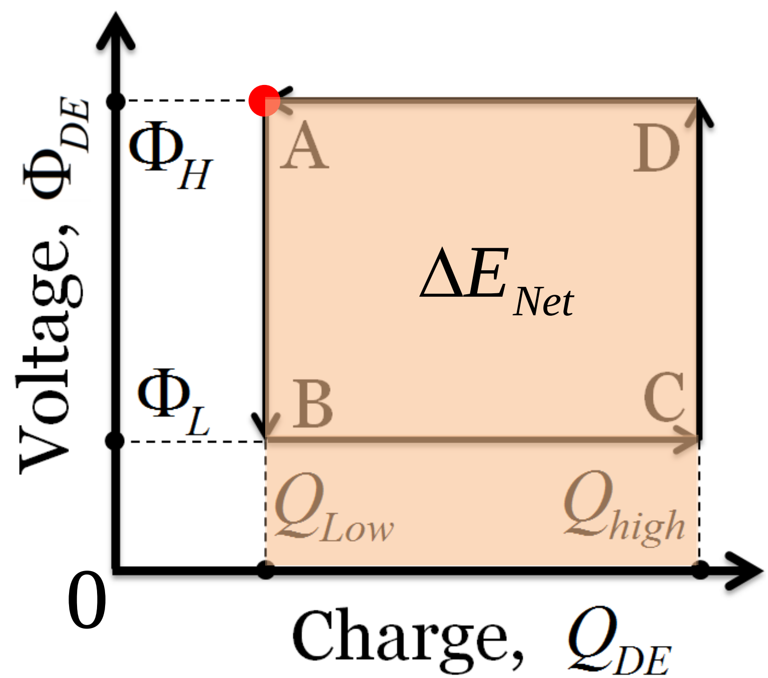
$$C \propto \frac{\lambda}{(1/\lambda)} = \lambda^2$$

$$C \propto \frac{\lambda\lambda}{(1/\lambda^2)} = \lambda^4$$

Harvesting Mechanical Energy: Energy Cycle

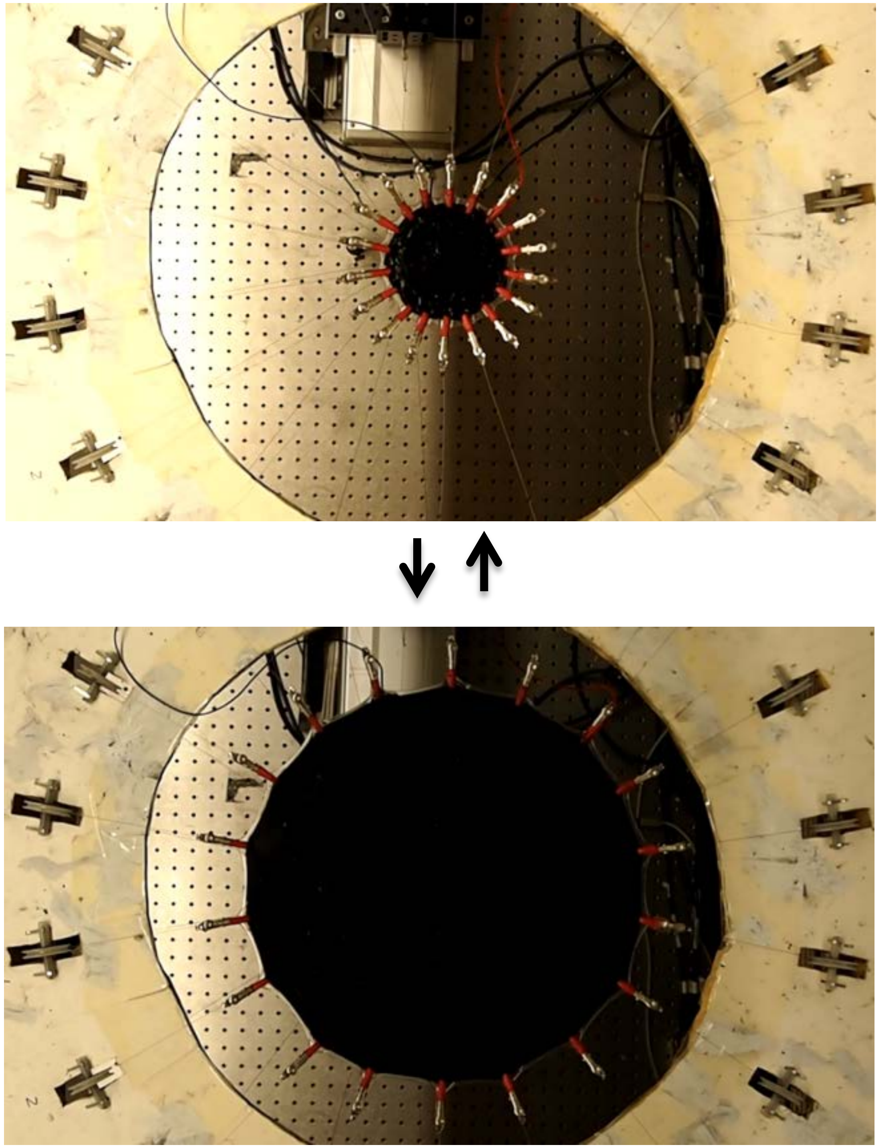


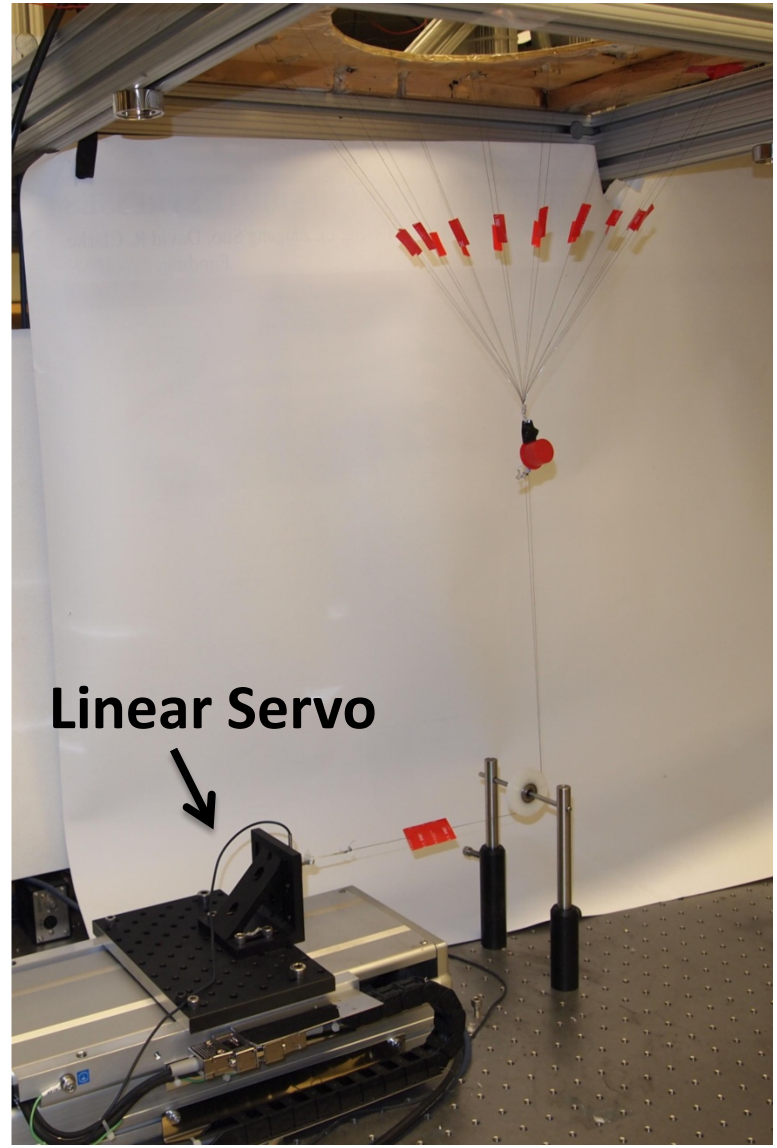




Energy density : $E_{Density} = \Delta E_{Net} / M$

Equi-biaxial Mechanical Loading Configuration

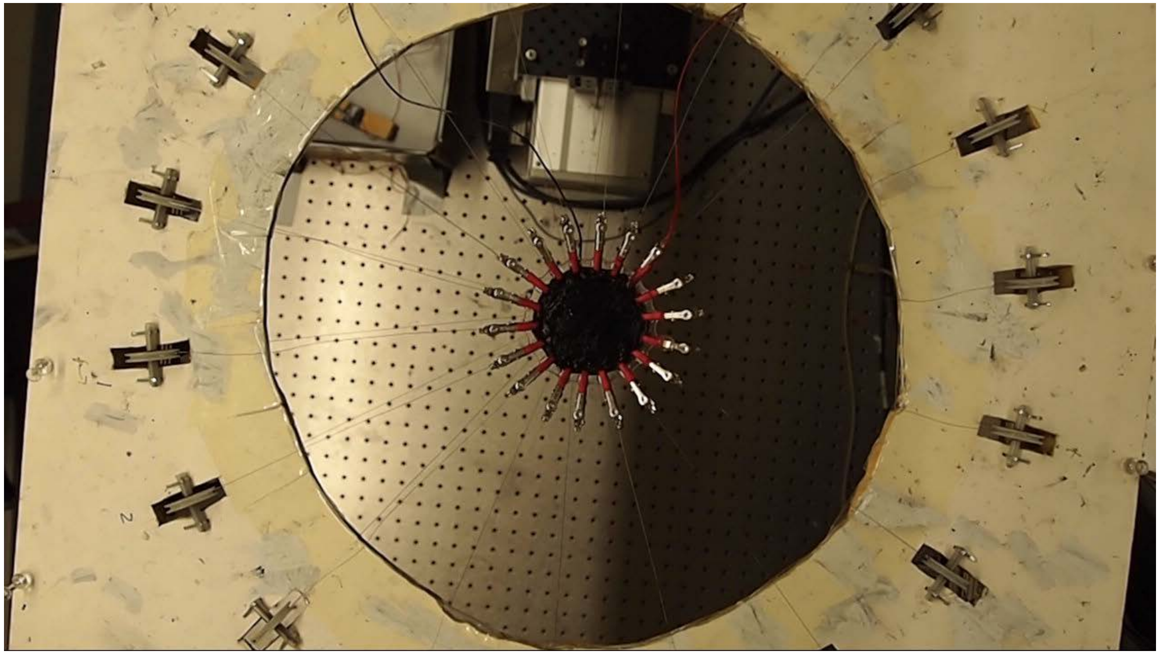




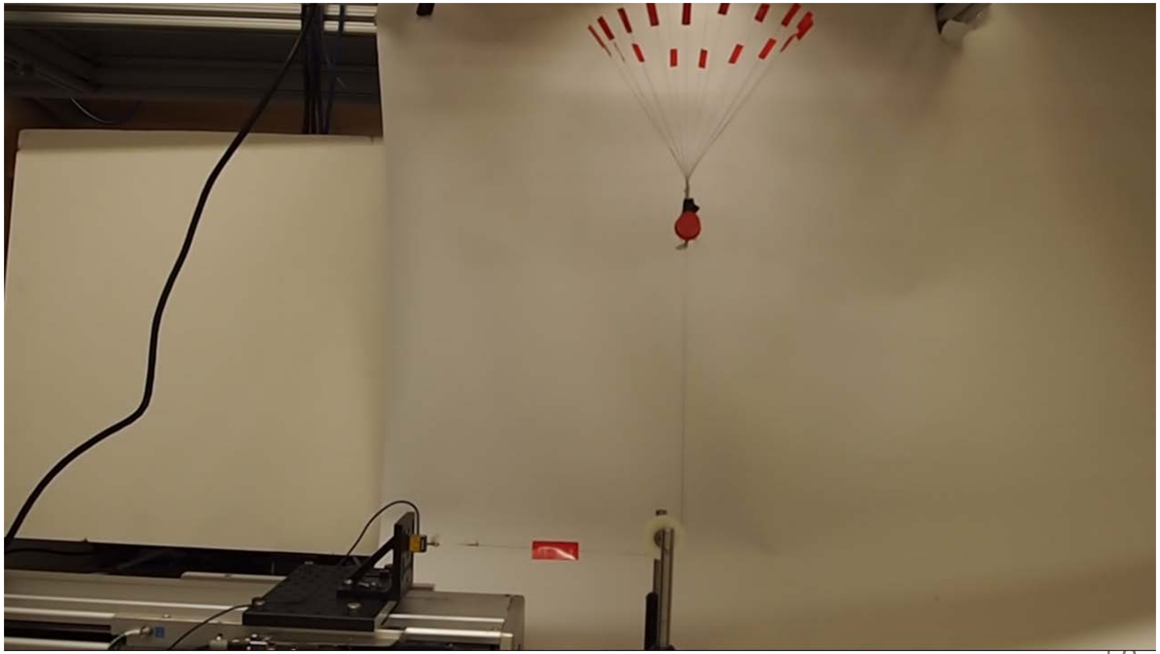
In our experiments, λ changes in the range from 1.2 to 5.4.

Movie

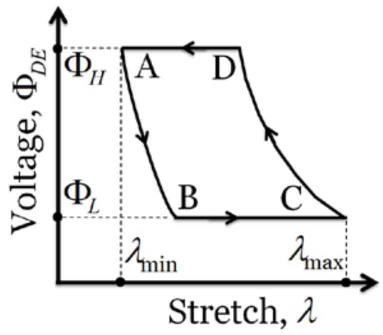
Top down View:



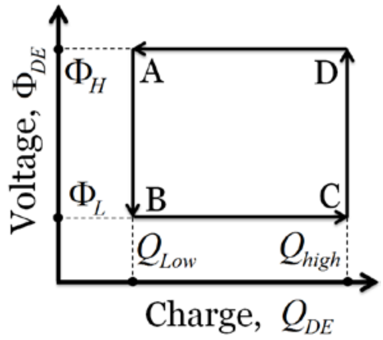
Side View:

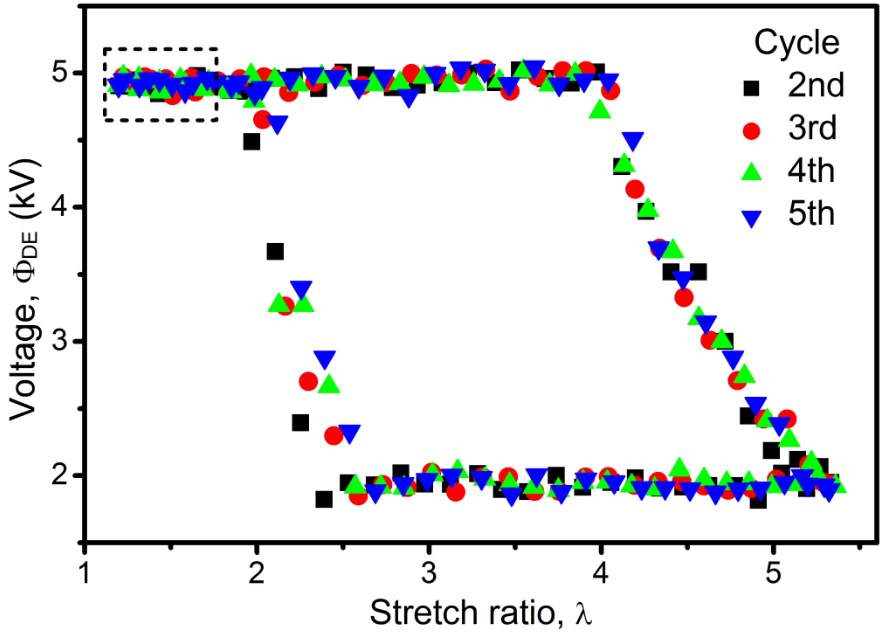


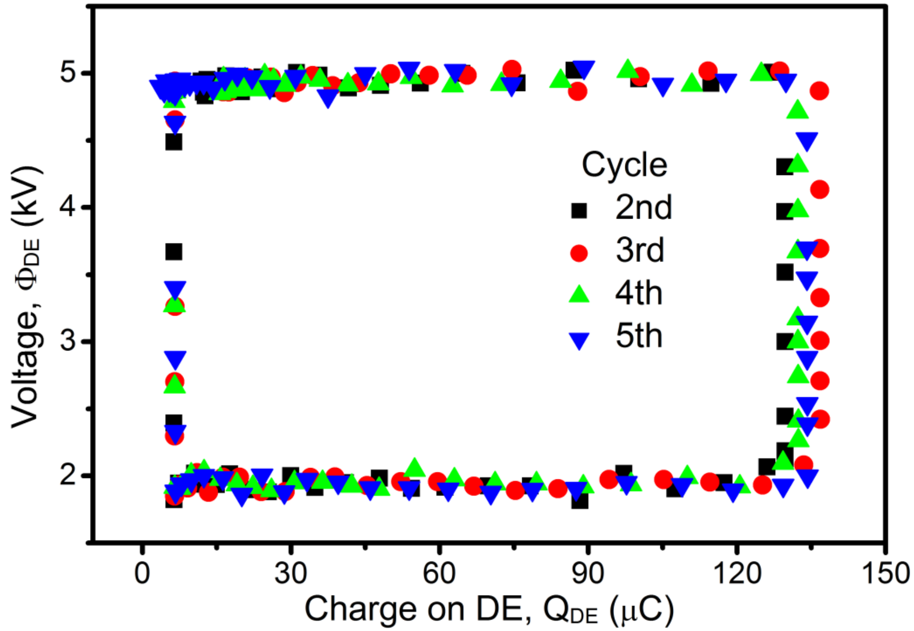
Measured Energy Harvesting Cycles



Schematic





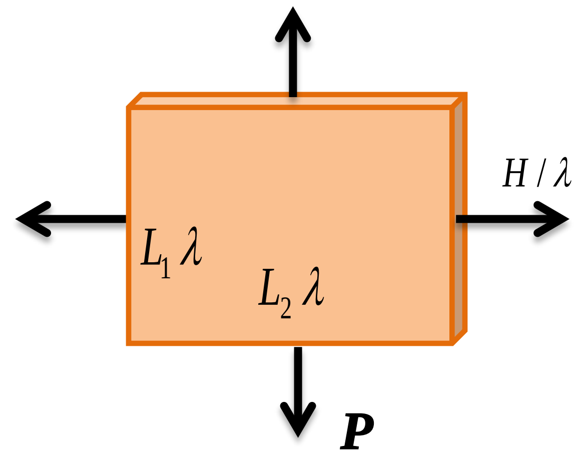


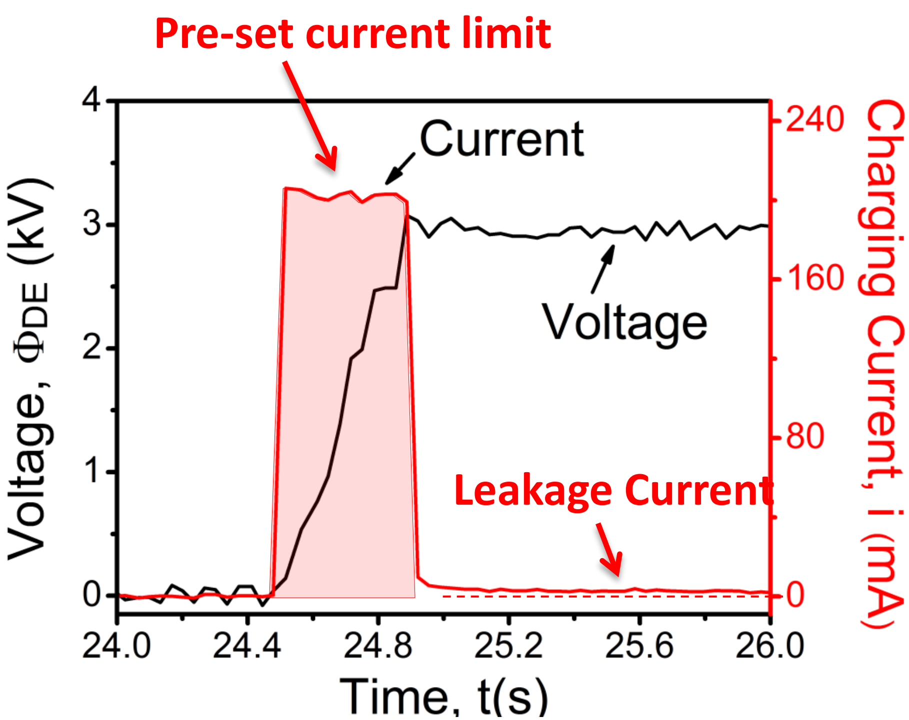
0.5 Hz cycles

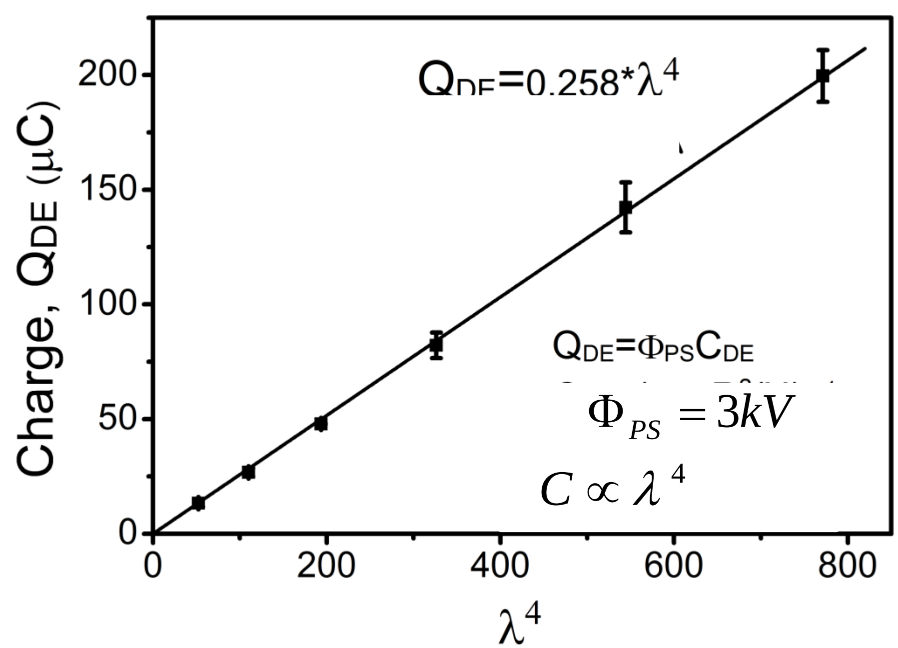
Verification of Stretch Scaling

Model indicates that capacitance scales with fourth-power of stretch under biaxial loading

$$C \propto \lambda^4$$

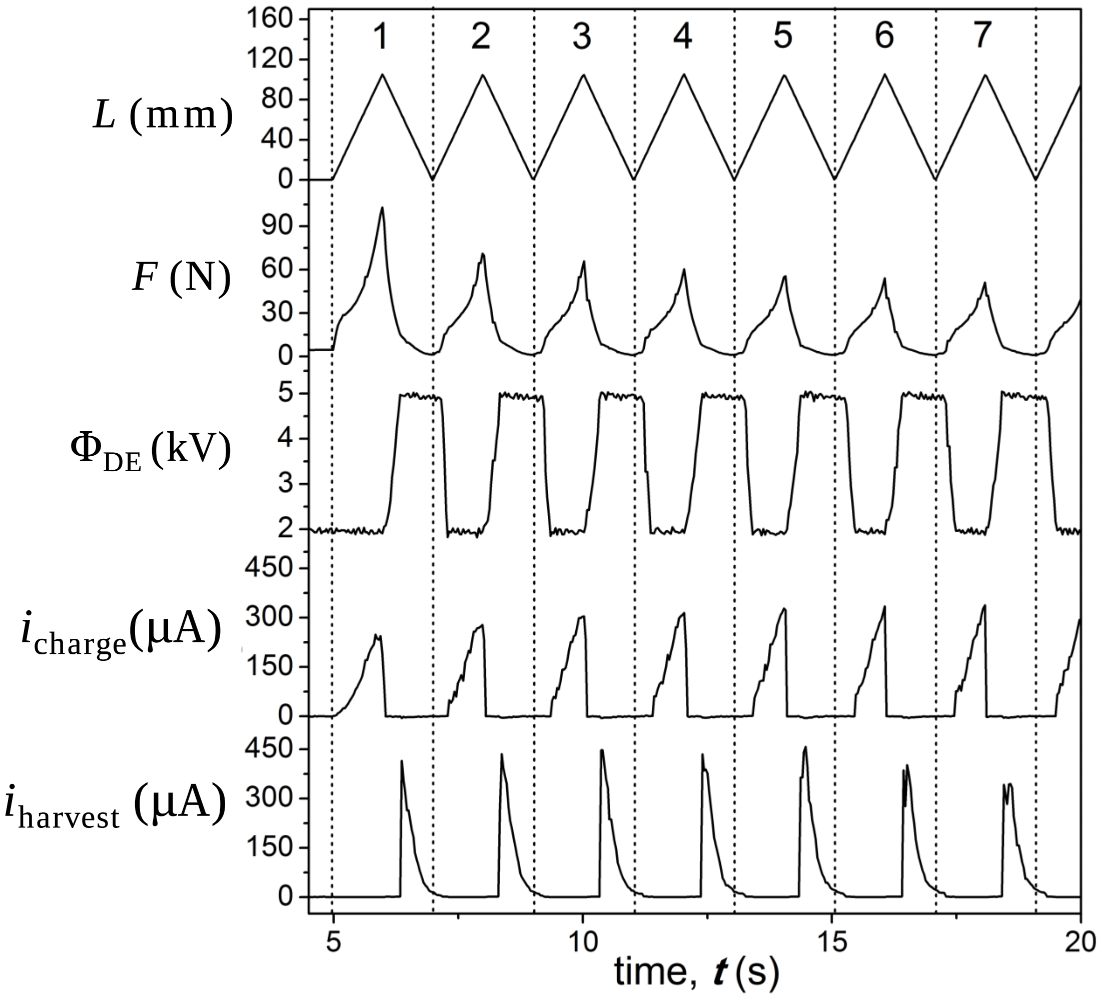






Max stretch is 4.25

Representative Generator Cycles



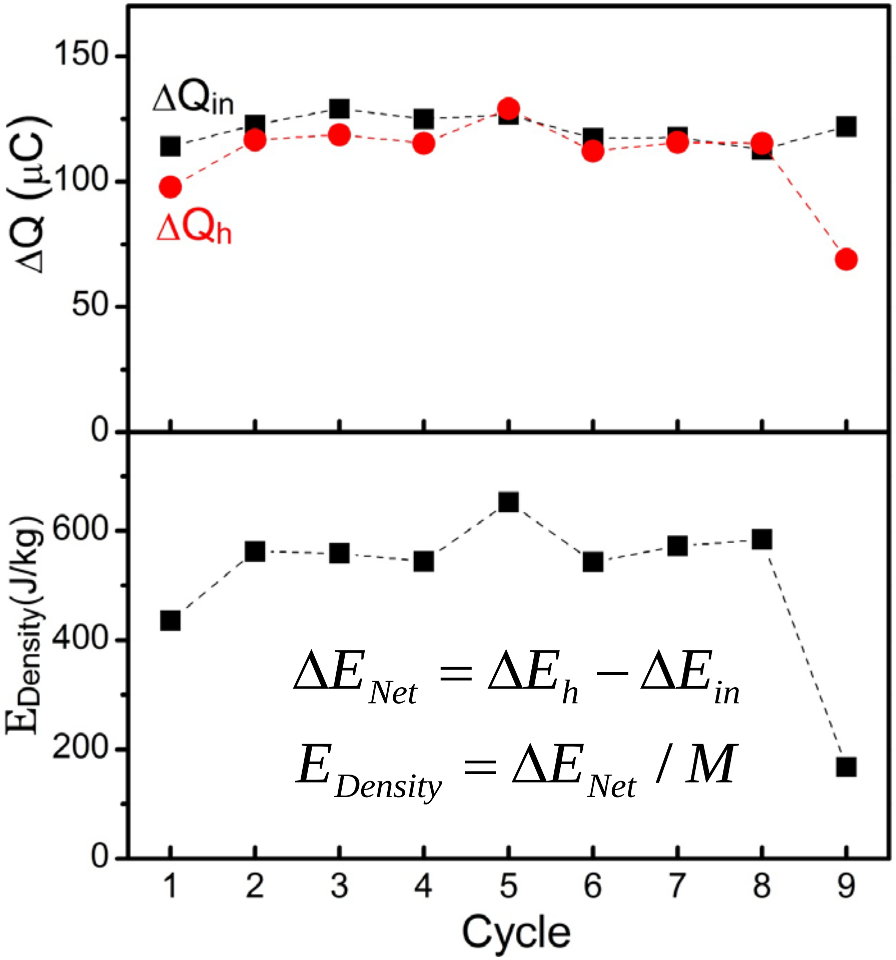
Electrical Energy from Power Source:

$$\Delta E_{in} = \Phi_L \Delta Q_{in} = \Phi_L \int_{T0}^{T+T0} i_{\text{charge}} dt$$

Electrical Energy Harvested:

$$\Delta E_h = \Phi_H \Delta Q_h = \Phi_H \int_{T0}^{T+T0} i_{\text{harvest}} dt$$

Energy density with cycle number

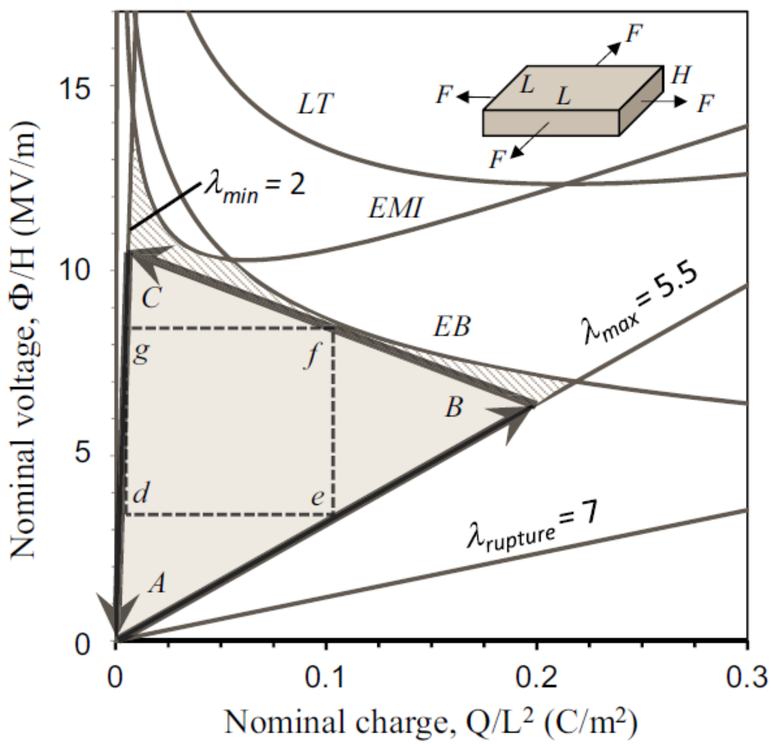


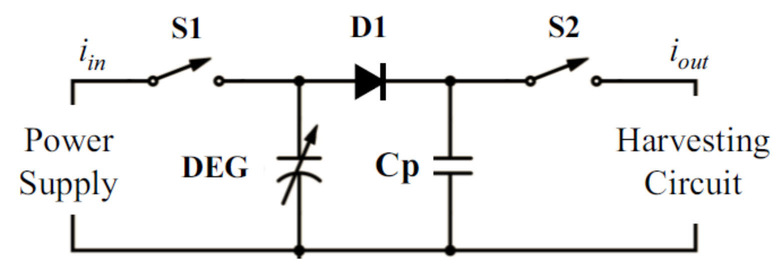
$$\Delta E_{Net} = \Delta E_h - \Delta E_{in}$$

$$E_{Density} = \Delta E_{Net} / M$$

The average energy density of the first eight cycles is **560J/kg** with a power density of **280W/kg**.

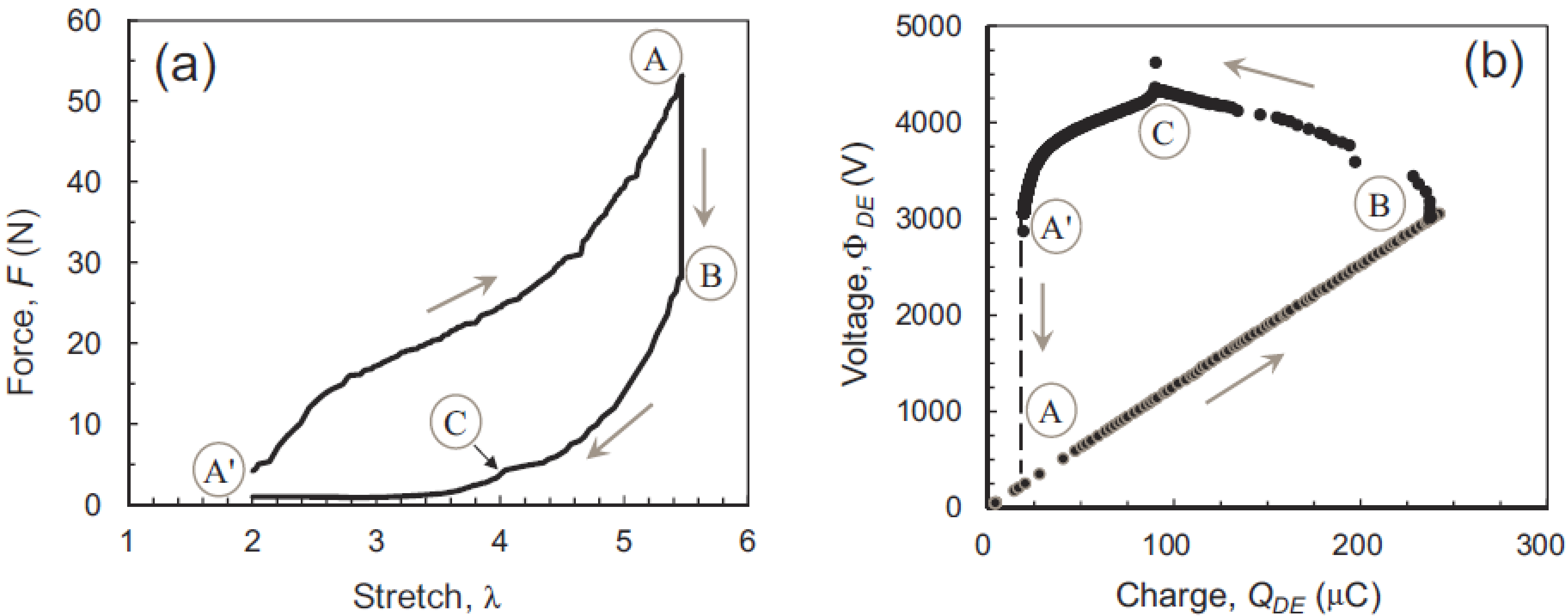
Improved Harvesting Cycle ?





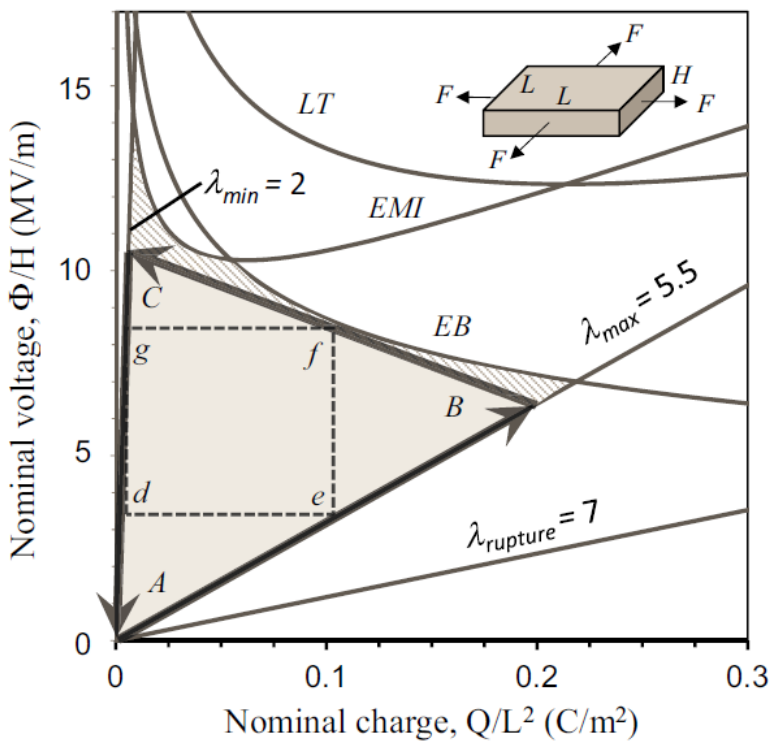
Shian et al., *Adv. Mater.* **2014**, DOI: 10.1002/adma.201402291

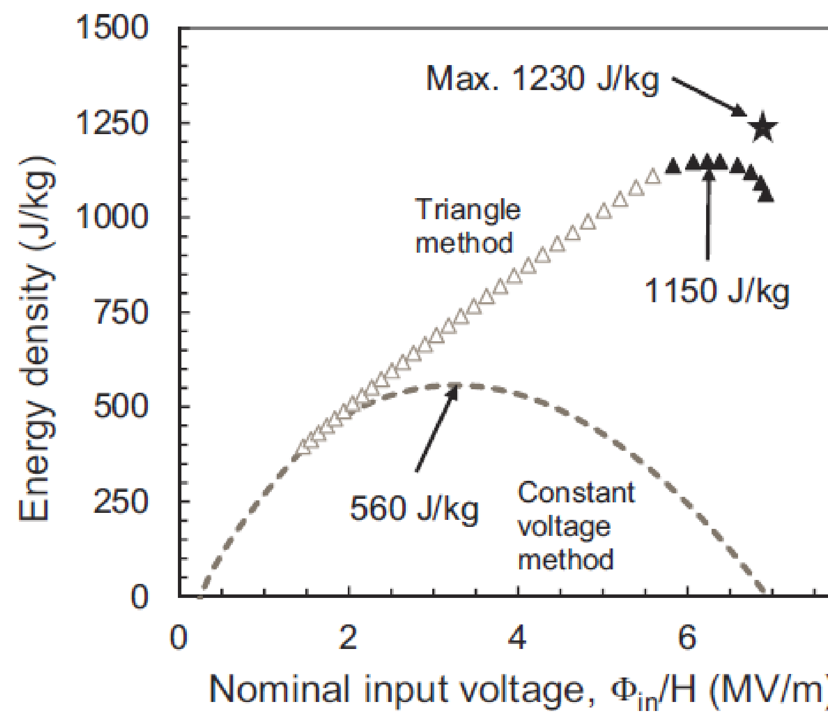
Representation in two conjugate work planes



NB. Mechanical energy storage is separated from the subsequent energy conversion so can occur non-uniformly or even intermittantly while energy conversion can occur over a shorter time.

Improved Harvesting Cycle

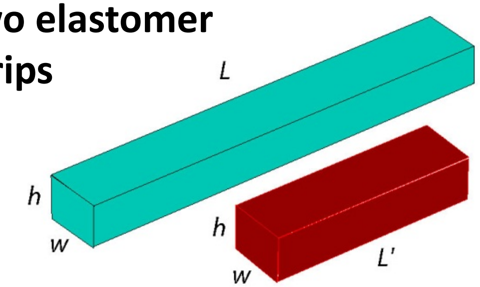




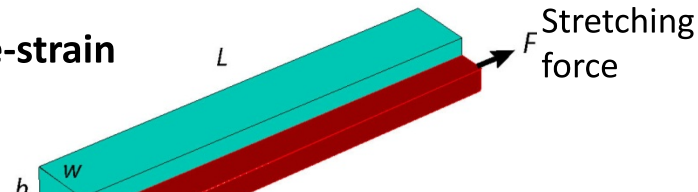
Shian et al., *Adv. Mater.* **2014**, DOI: 10.1002/adma.201402291

Complex Shapes From Bi-strips: Pre-straining, Joining and Release Operation

1. Two elastomer strips



2. Pre-strain

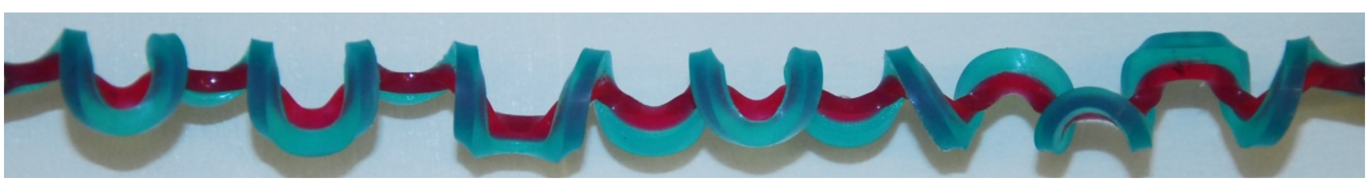


Pre-strain :

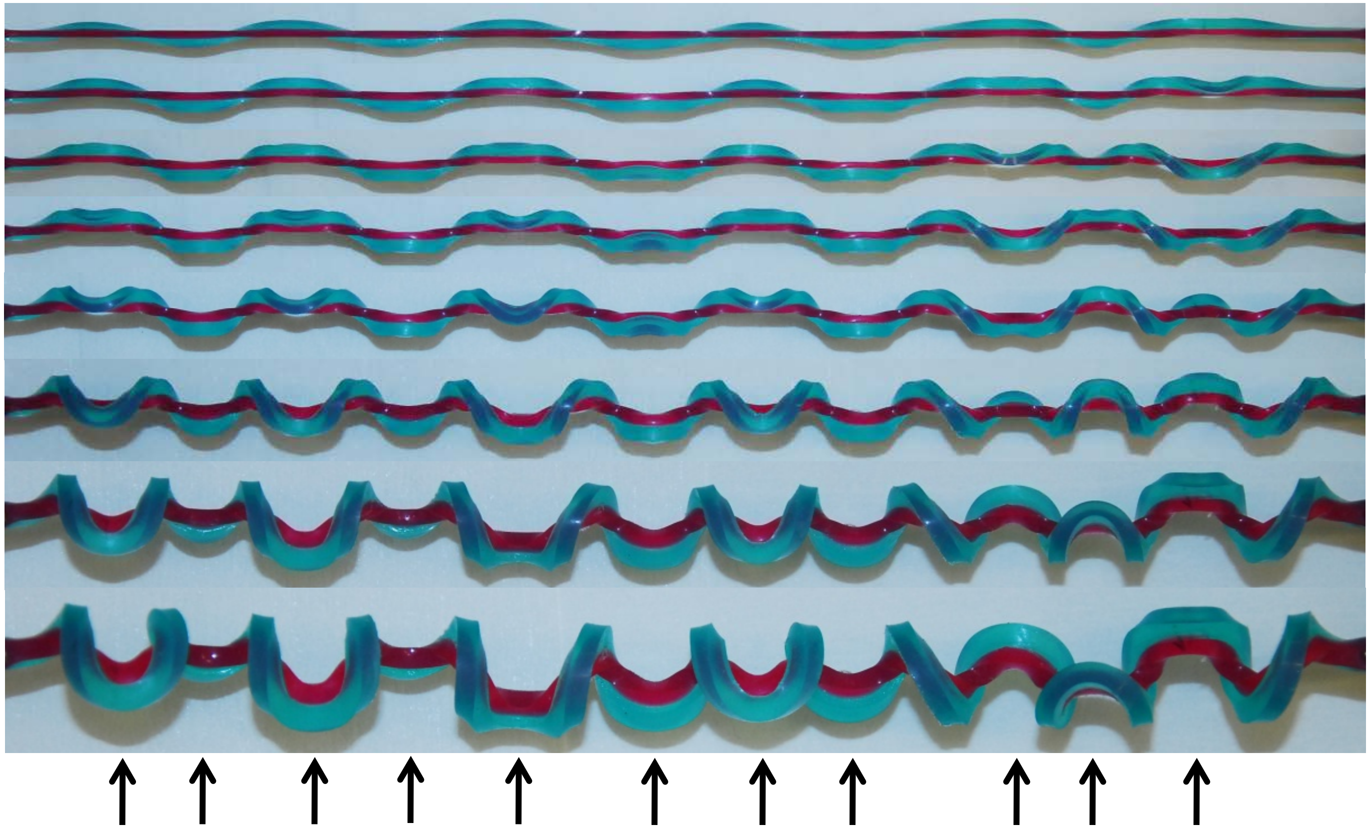
$\chi = (L - L') / L'$

3. Join strips side-by-side.

4. Release stretching force



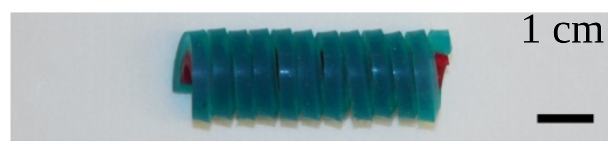
Release of a narrow bi-strip to form a Hemi-helix



44 cm
42 cm
40 cm
37 cm
34 cm
28 cm
22 cm
18 cm

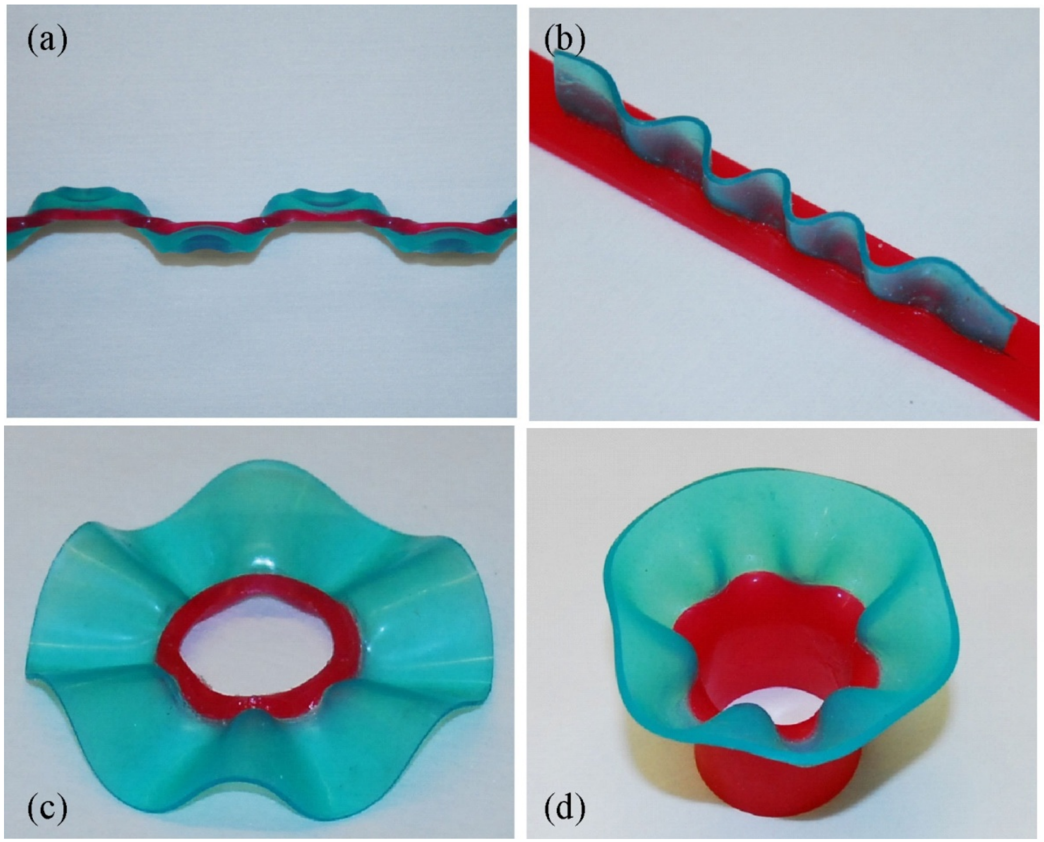
Perversions

After release



After release and rotating one end
---- a regular helix

Examples of Morphological Shape Transitions



Elastomers Offer Opportunities For New Machines and Devices

- Elastomers are soft, compliant, stretchable
- Elastically compatible with humans
- Ideal for Soft Robotics
- Shape changes can be electrically actuated
- Large scale elastic effects
- Transparent but can be colored
- Combination ideal for new optic and mechanical devices
- Elastomer sheets are mass produced