

A Review

Electrostrictive Graft-Elastomers (G-Elastomers)

-Materials, Devices and Applications-

Ji Su

Advanced Materials and Processing Branch
NASA Langley Research Center, Hampton, VA 23681, USA
(ji.su-1@nasa.gov)



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Hampton University
Hampton, Virginia





Electroactive Polymers (EAP)

ELECTRONIC EAP

Electroactive Semi-crystalline Polymers

Ferroelectric and piezoelectric polymers

Poly (vinylidene-fluoride) (PVDF) and its copolymers

Odd-numbered nylons

Electroactive Elastomers

Polyurethane (PU)

Dielectric Elastomers (DE)

Electrostrictive Graft Elastomers (G-elastomers)

Electro-Viscoelastic Elastomers (EVE)

Liquid Crystal Elastomers (LCE)

Electroactive Papers

Carbon Nanotubes(CNT)

IONIC EAP

Conductive Polymers(CP)

Electro Rheological Fluids (ERF)

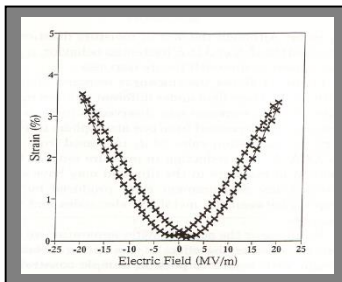
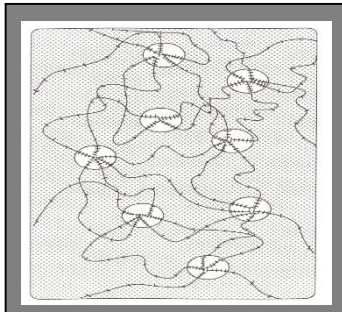
Ionic Polymer Gels (IPG)

Ionic Polymer Metallic Composite (IPMC)



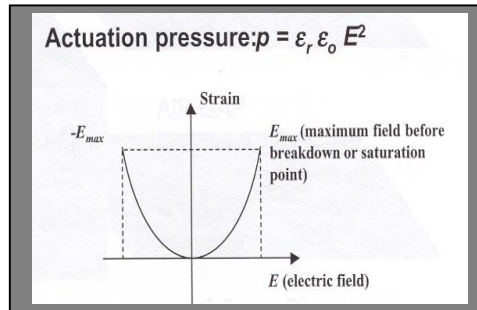
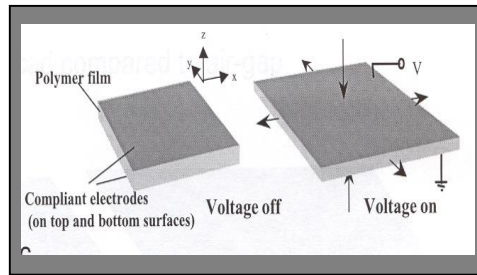
Electromechanically Functional Elastomers

Polyurethane elastomers



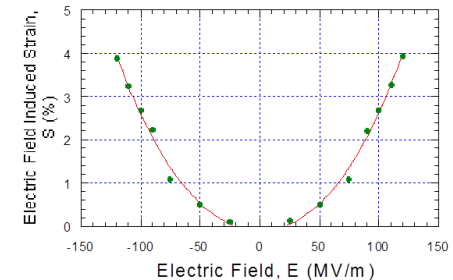
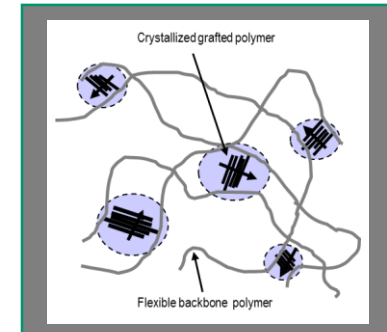
Physically cross-linked (hydrogen bonds) elastomers that offer field-induced strain by a combined mechanism.

Electrostatic/dielectric elastomers



Chemically cross-linked soft elastomers that can offer a large field-induced strain due to the Maxwell Stress effect.

Electrostrictive graft elastomers



Physically cross-linked (formed crystal domains) elastomers that offer field-induced strain by primarily electrostriction.

Ref.: Z. Ma, et al. p. 2721, Vol.32, Journal of Polymer Science: Part B, Polymer Physics (1992)

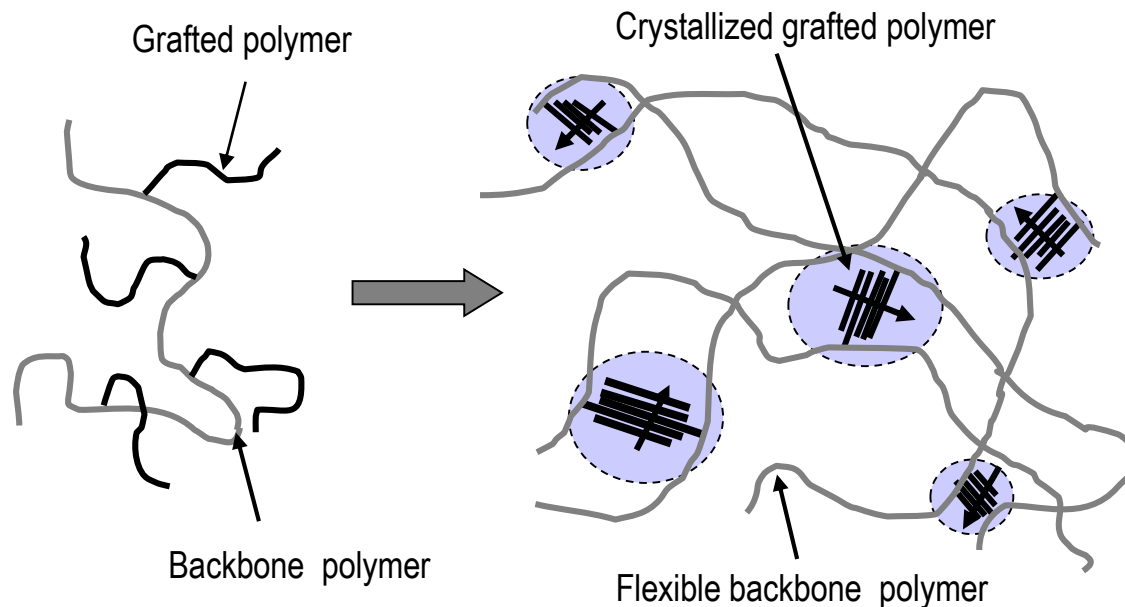
Ref.: "Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential and Challenges" by J. Bar-Cohen (SPIE, 2003).



Electrostrictive Graft Elastomers (G-elastomers)

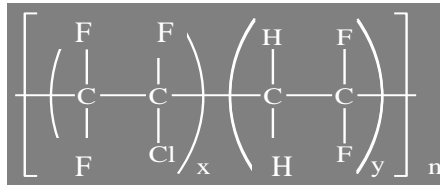
A Two Constituent System

- 1) Flexible backbone polymer that functions as a main contributor for elastomeric three-dimensional molecular network
- 2) Grafted polymer that can crystallize (a) to form physical cross-linking sites for elastomeric three-dimensional network and (b) to produce polar domains that are electric-field responsive.





Structures and Functions of the Constituent Polymers



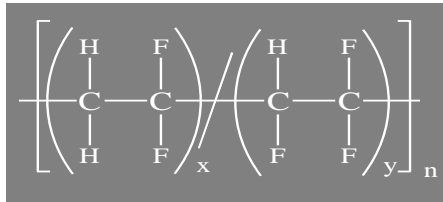
Backbone Polymer

chlorotrifluoroethylene-vinylidene fluoride copolymer

Nature: non-crystalizable and flexible

Functions

- (a) to be the main contributor to three-dimensional elastomeric molecular network and
- (b) to provide space for dimensional change and adjust stiffness of the 3-D network.



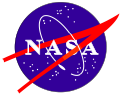
Grafted Polymer

trifluoroethylene-vinylidene fluoride (VDF-TrFE) copolymer

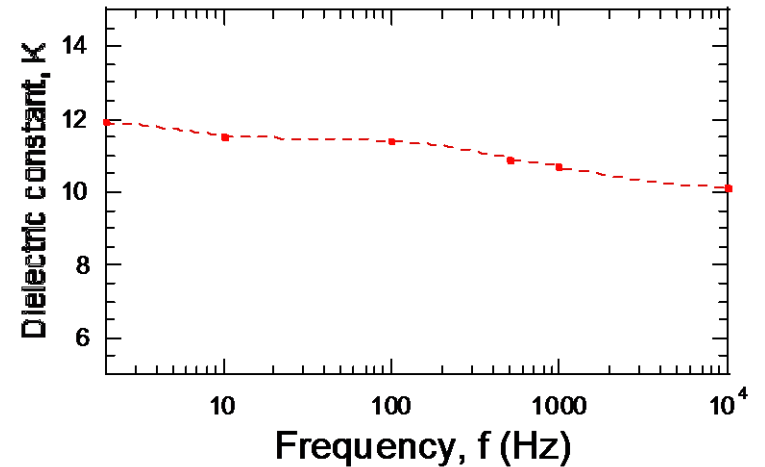
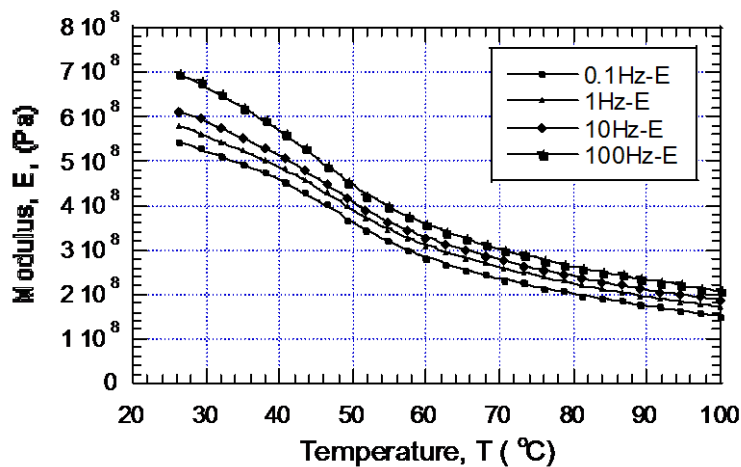
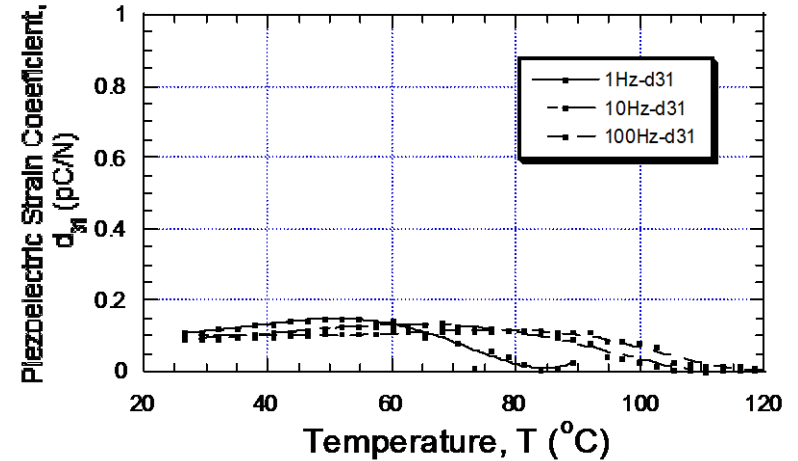
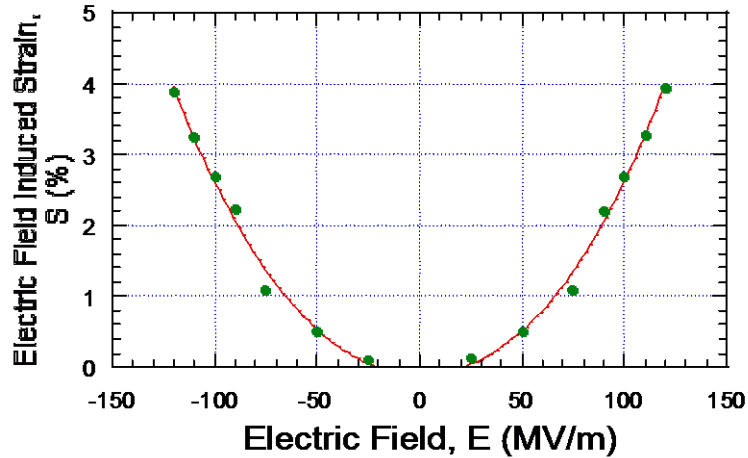
Nature: crystallizable and polar

Functions

- (a) to form physical cross-linking sites for elastomeric three-dimensional network and
- (b) to provide polar domains that are electric-field responsive and drive dimensional change.



Important Properties of the Electrostrictive Graft Elastomers





Mechanisms of Electric Field-induced Strain in Elastomers

Mechanisms

Electrostriction
Maxwell effects

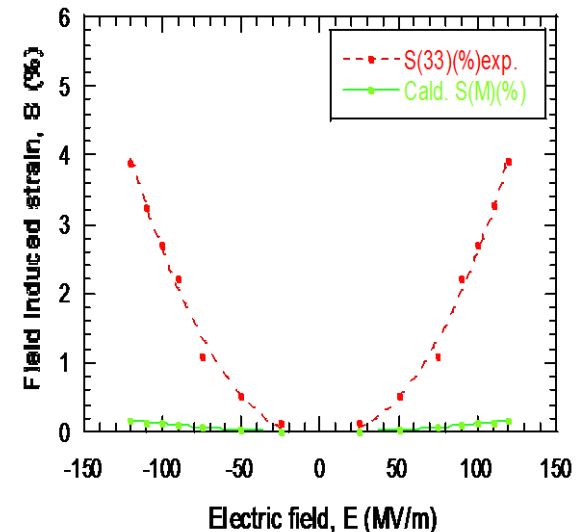
$$S_E = -Qe_0^2 (K-1)^2 E^2$$
$$S_M = -se_0KE^2 / 2$$

Contributions of Different Mechanisms

Materials	Maxwell Effect	Electrostriction
Graft elastomers	<5	>95
Polyurethane	35	65
Dielectric elastomers	100	0

Advantages of Electrostriction Mechanism

Increase both the field-induced-strain and the mechanical modulus simultaneously





Morphology-Property Control of Electrostrictive G-Elastomers

Molecular selection of backbone and graft polymers (amplitude of dipole moment and dimensional parameters of the crystal unit of grafted polymers; molecular weight of graft polymers for optimized crystal size; flexibility of the backbone polymers).

Fraction of the two constitutes (optimization of dielectric constant, mechanical properties, and electromechanical properties such as field induced strain, actuation power, and efficiency).

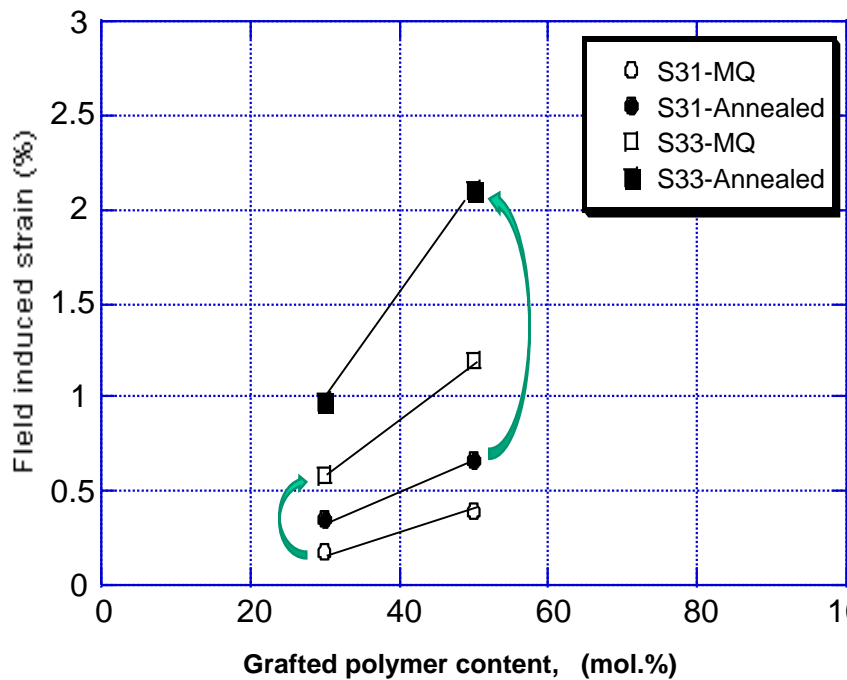
Processing of materials utilizing thermal, mechanical, and electrical processing techniques (control of molecular morphology and optimization of electric, mechanical, and electromechanical properties of electrostrictive graft elastomers).

- The electromechanical properties of the electrostrictive G-elastomers depend on the fraction of the grafted polymer and the crystallinity formed by the polar grafted polymers.
- The fraction of the grafted polar polymers can be controlled through synthesis and the crystallinity can be controlled by thermal treatment and other processing.
- Molecular engineering and morphological control can be employed to tailor and optimize the electromechanical properties of electrostrictive graft elastomers.

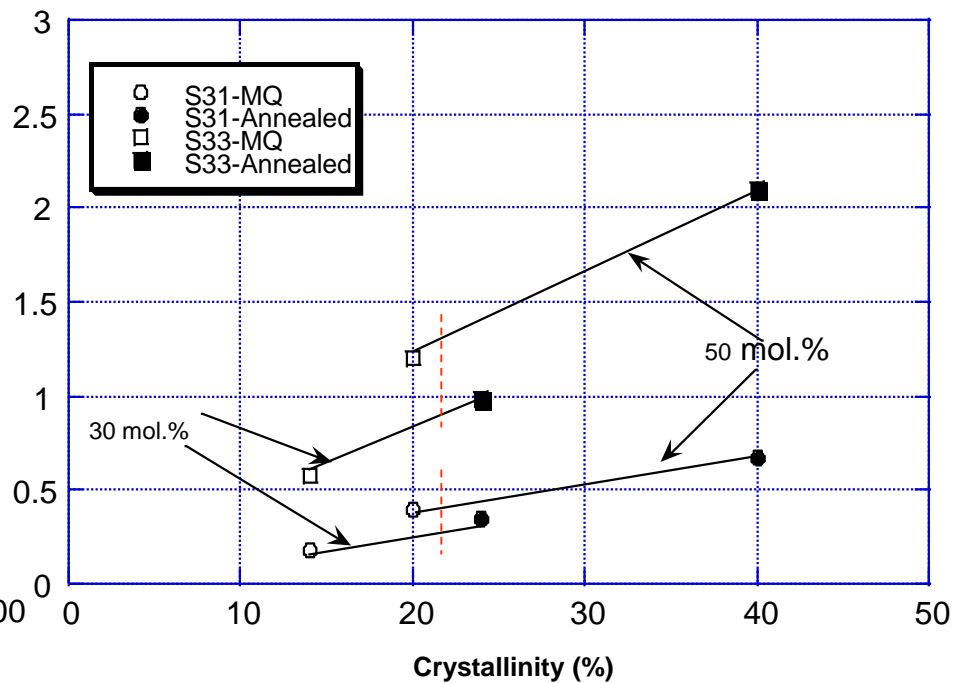


Effects of the Content and Crystallinity of the Grafted Polymer on Field-induced Strain of Electrostrictive G-Elastomers

Effects of the Content



Effects of Crystallinity





Comparison of Electromechanical Properties of Some Representing Electroactive Materials

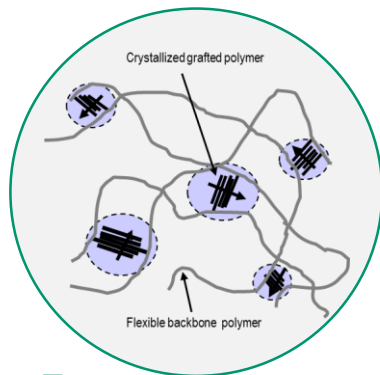
Materials	Strain (s) (%)	Modulus (Y) (MPa)	Output Force (YS) (Mpa)	Salient Features
LaRC G-elastomer	4	580	23	conformable, high strain, lightweight
Polyurethane	4	20	0.8	high strain, low force
PVDF	0.3	1600	4.8	low strain
PZT	0.3	6400	192	brittle, heavy

Some Advantages of Electrostrictive G-Elastomers

- Large electric field-induced strain.
- Light weight and high output power density.
- Two constituent system with adjustable composition and morphology to optimize mechanical, electrical, and electromechanical properties.
- Excellent process-ability for low cost fabrication and device requirements in shape complexity.
- Excellent compatibility with other electroactive polymers for hybrid molecular systems offering multi-functions.



Electrostrictive G-elastomers Related Research



Developed electrostrictive G-elastomer-based sensing-actuating dual functional polymers

Developed electrostrictive G-elastomer-based nano-fibers (mats and oriented fibers)

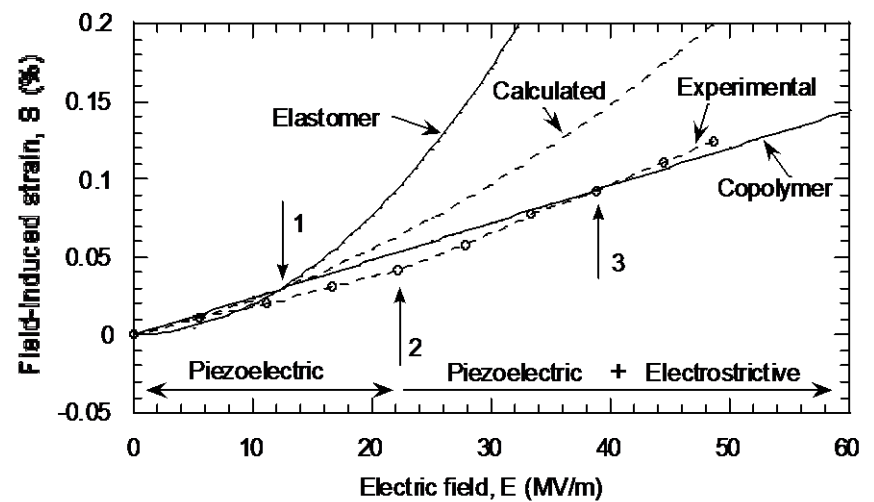
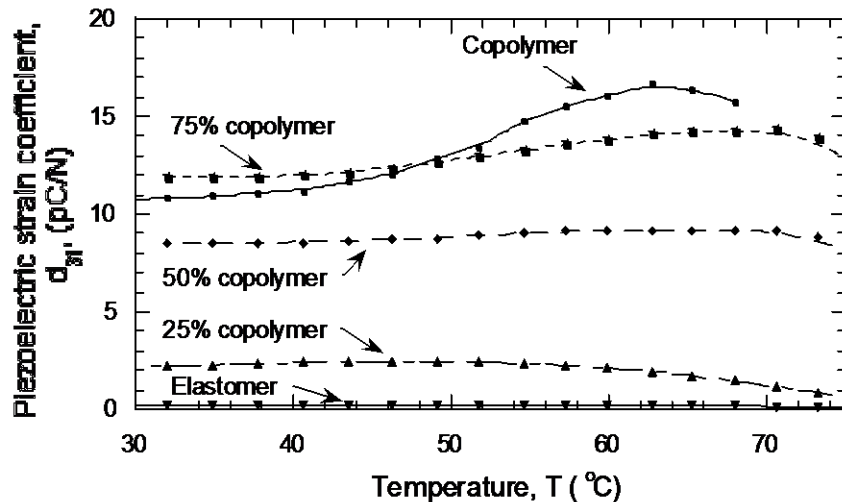
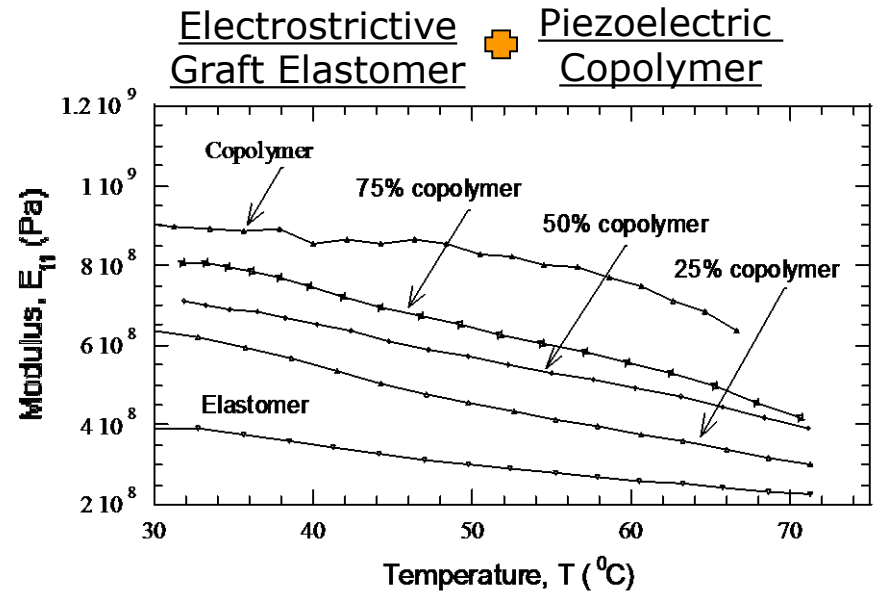
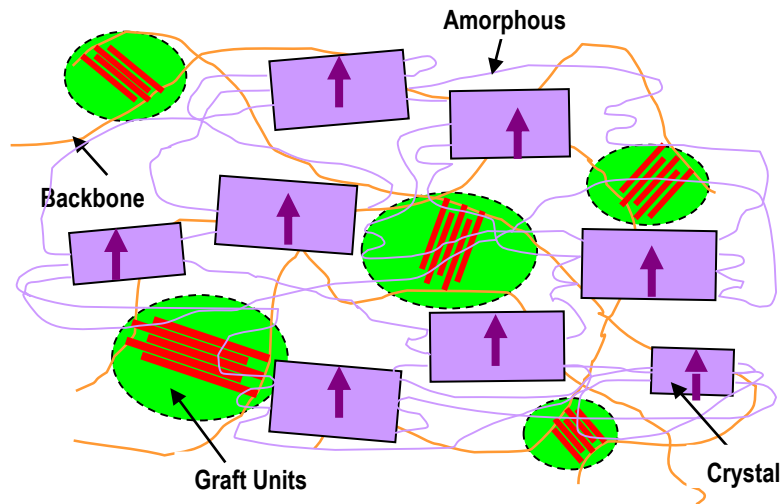
Developed electrostrictive G-elastomer-based devices: bending actuators and hybrid actuators

Applied hybrid concept proven by the hybrid ctuators in development of a series of high performance actuators, transducers, and energy harvesters

Conducted computational study on mechanism of electrostrictive G-elastomer and guidance for optimizing electrostrictive G-elastomers via molecular engineering route



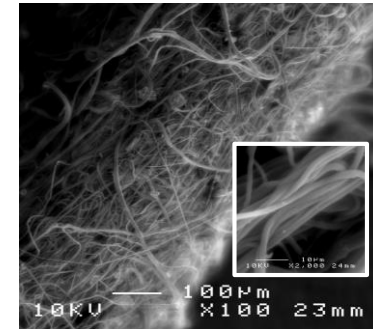
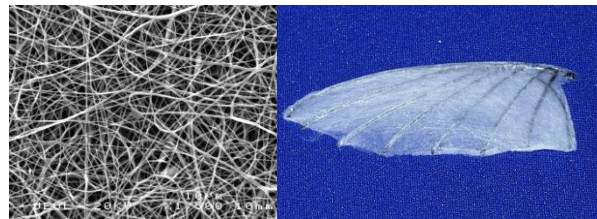
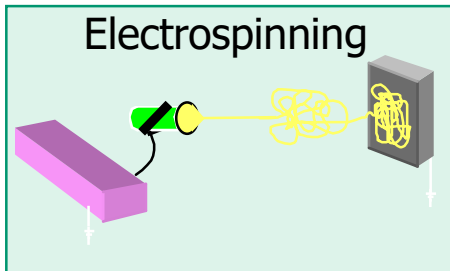
Sensing-Actuating Dual Functional Polymer Blends



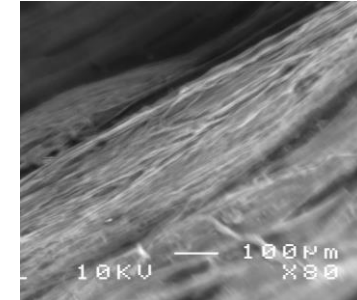
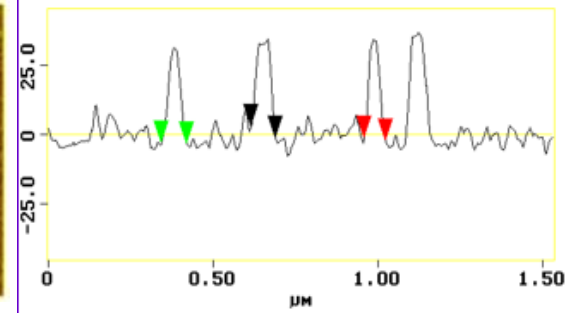
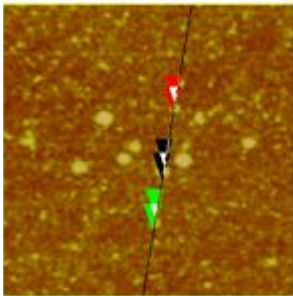
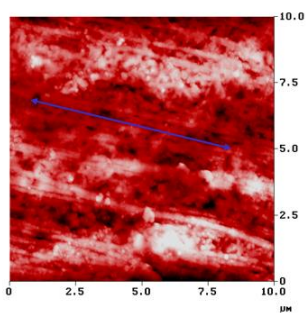


Electrostrictive G-elastomer Nano-fibers

Nano-fibers and Mats by Electrospinning



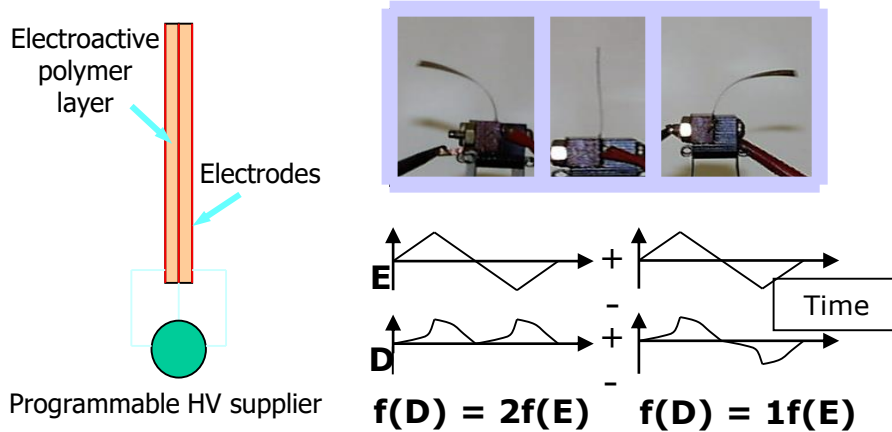
Highly Aligned Nano-fibers by Dynamic Precipitation



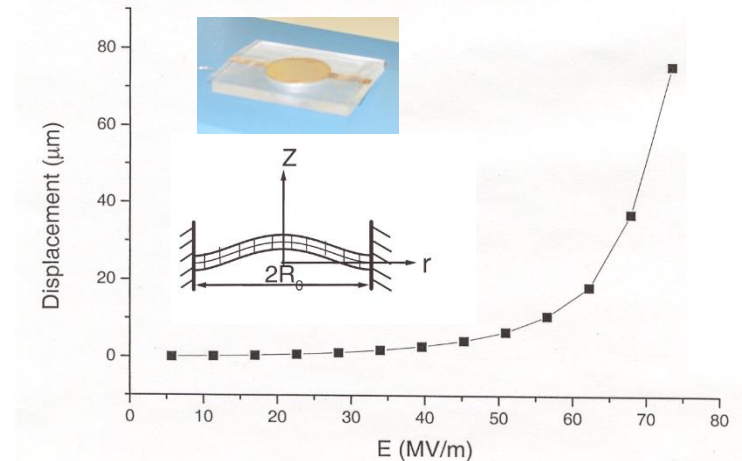


Actuators Using Electrostrictive G-Elastomer

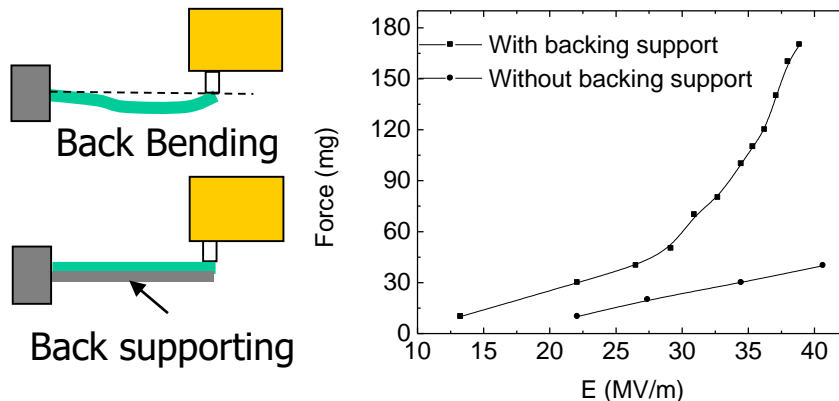
Two Direction Bending Actuator



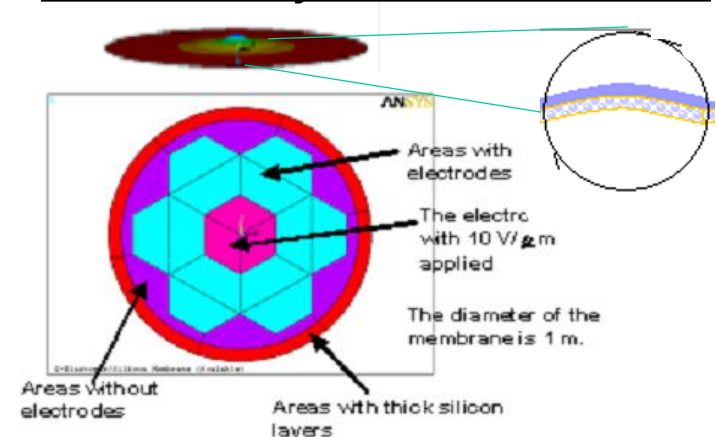
Circular Actuator



Backed Bending Actuator



Actuator Array for Reflector Control

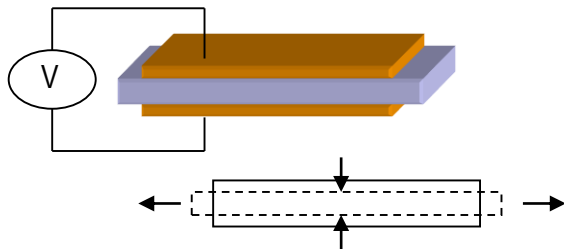




Hybrid Electromechanical Actuators

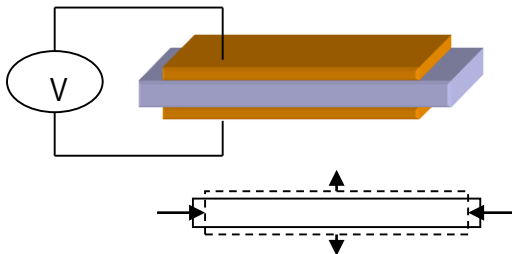
Electric Field-induced Strain

Electroactive polymer



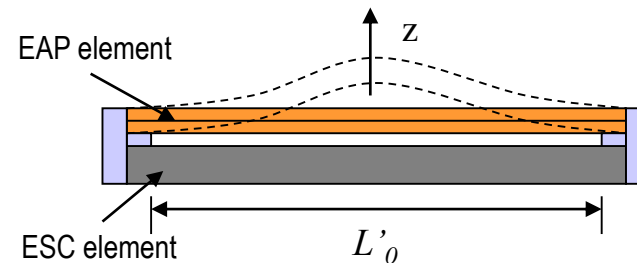
Longitudinal strain: **Negative**
Transverse strain: **Positive**

Electroactive Ceramics



Longitudinal strain: **Positive**
Transverse strain: **Negative**

Hybrid Actuator



EAP: Electrostrictive G-elastomer
ESC: Electroactive single crystal

The HYBRid Actuation System (HYBAS) utilizes the characteristics of the electromechanical response of the two electroactive constituents cooperatively to achieve significantly increased displacement for actuation under one electric excitement source.

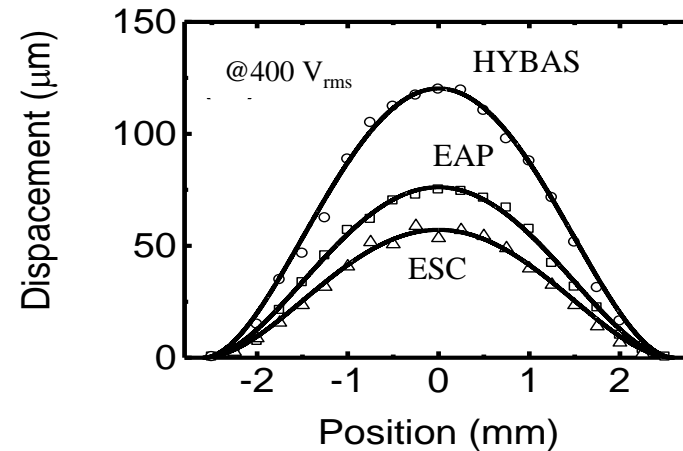
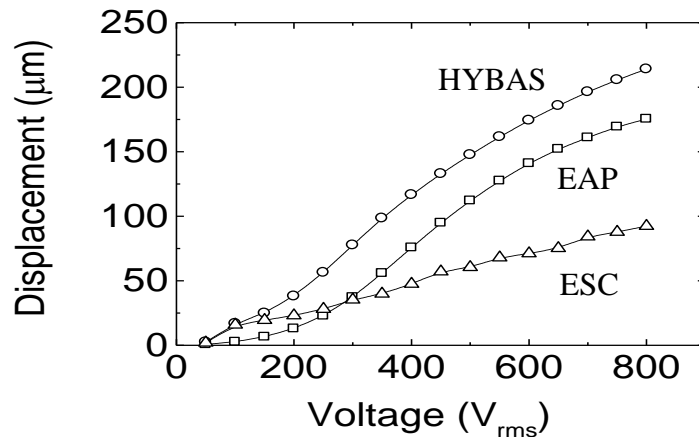


Performance of the Hybrid Electromechanical Actuators

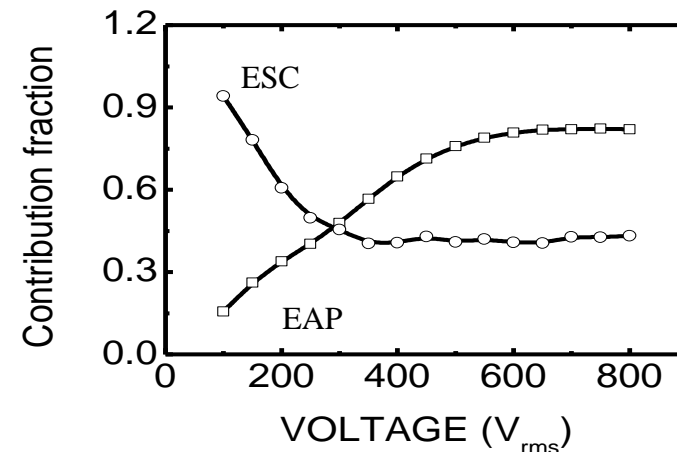
Significantly increased displacement

Proven hybrid concept
for advanced electromechanical devices

Comparison of Displacement of HYBAS and Its
Constituents (at center)



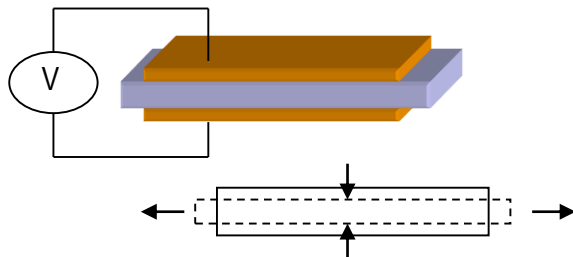
Voltage Dependence of Contributions of
Each Constituent





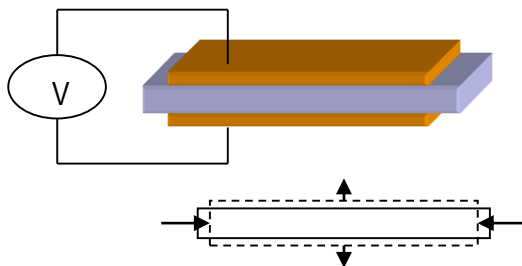
Generalization of Hybrid Concept and Its Extended Application

Active Constituent 1



Longitudinal strain: **Negative**
Transverse strain: **Positive**

Active Constituent 2



Longitudinal strain: **Positive**
Transverse strain: **Negative**

Design and Selection of Active Constituents

Purpose: to make the two active constituents respond in opposite directions when a driving electric field is applied.

Single Material:

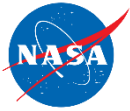
ceramics, polymers, single crystals, etc.

Composites:

ceramics/polymer, polymer/polymers, single crystal/ceramics, single crystal/polymers, etc.

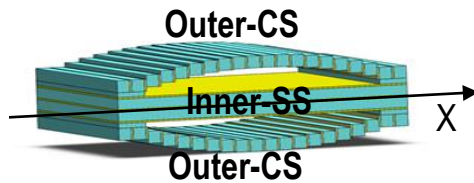
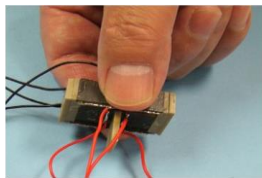
Multilayer/stacks:

single material, composites, single material-based laminates, stacks, etc.



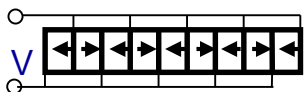
A Successful Sample: HYbrid Piezoelectric Energy Harvesting Transducer System (HYPEHT)

The Energy Harvester

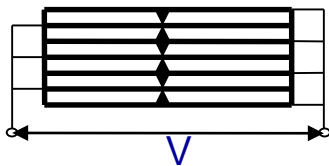


Dimensions: 30 mm (l) × 15 mm (w) × 11 mm (h)
Weight: 21 gram

Active Constituents



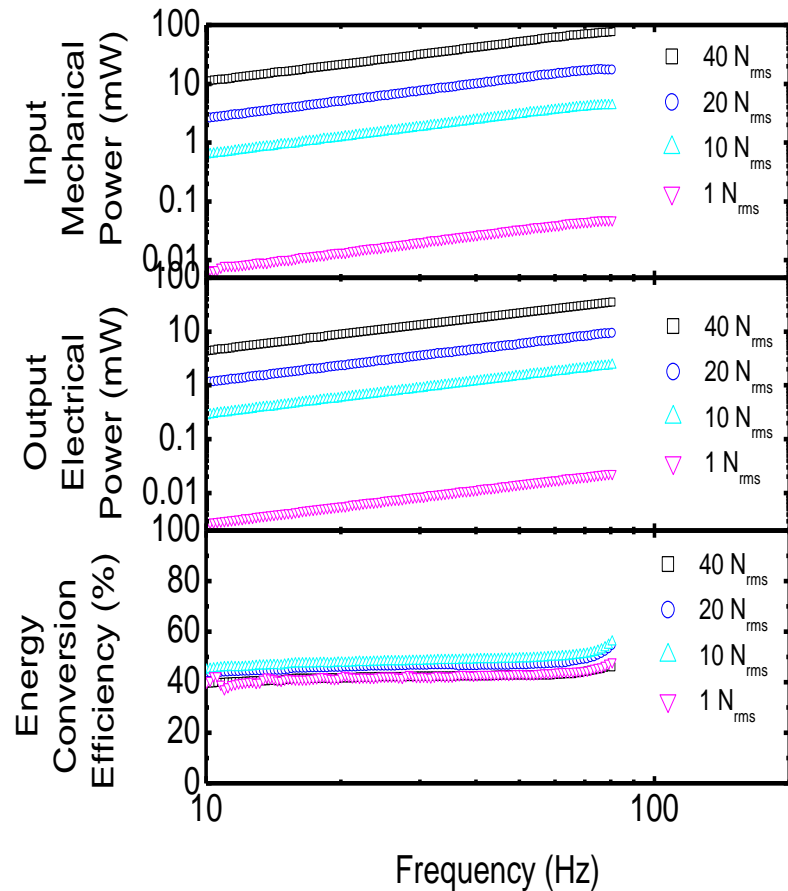
Outer Constituent:
Multi-stacked
 d_{33} effect in x-direction

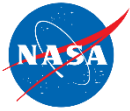


Inner Constituent:
Multi-layered
 d_{31} effect in x-direction

Conversion Efficiency: >40%

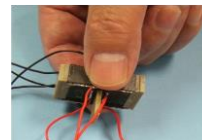
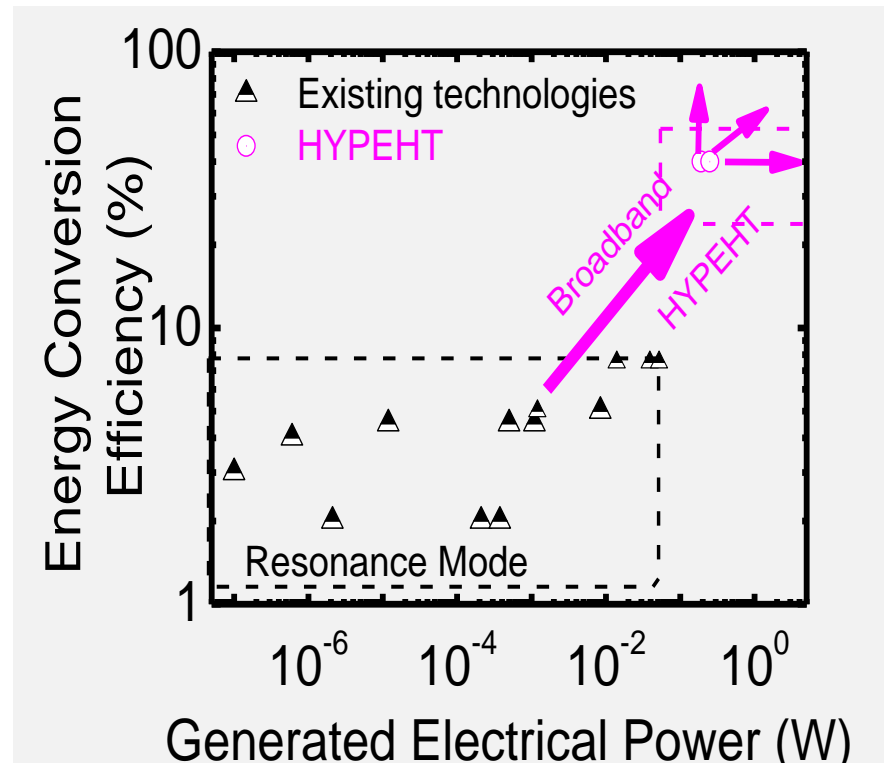
Performance





Recognition of the HYPEHT Energy Harvesting Technology

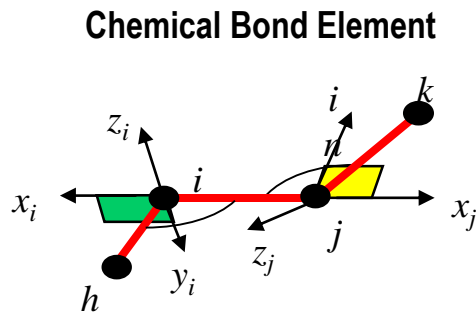
- A proven hybrid concept for advanced electromechanical devices has been successfully applied to both actuation and broadband energy harvesting transducers.
- Innovative of multidisciplinary approaches
 - 1) to capture one order of more mechanical energy into piezoelectric structure,
 - 2) to increase energy conversion efficiency, and
 - 3) to enhance energy charging/storage performance.
- More than 40% mechanical to electrical energy conversion efficiency can be achieved.
- HYPEHT is a broadband harvester at both off-resonance frequencies and resonance frequency.



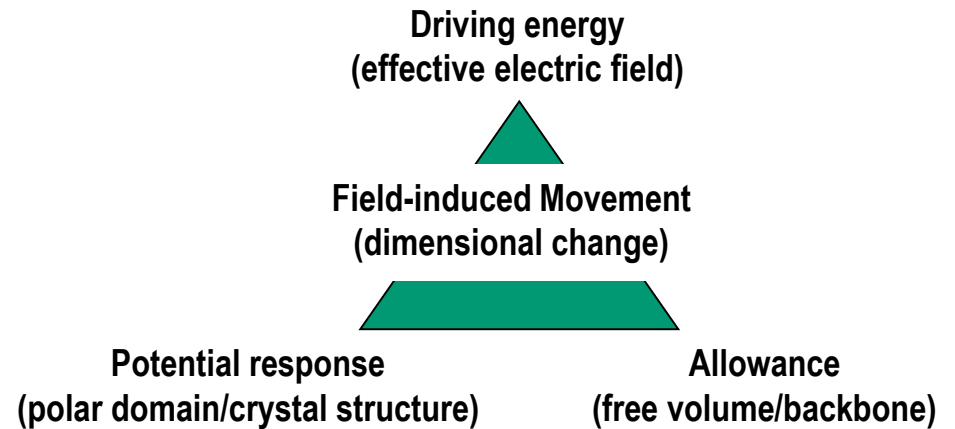


Computational Study of Mechanisms of G-elastomers

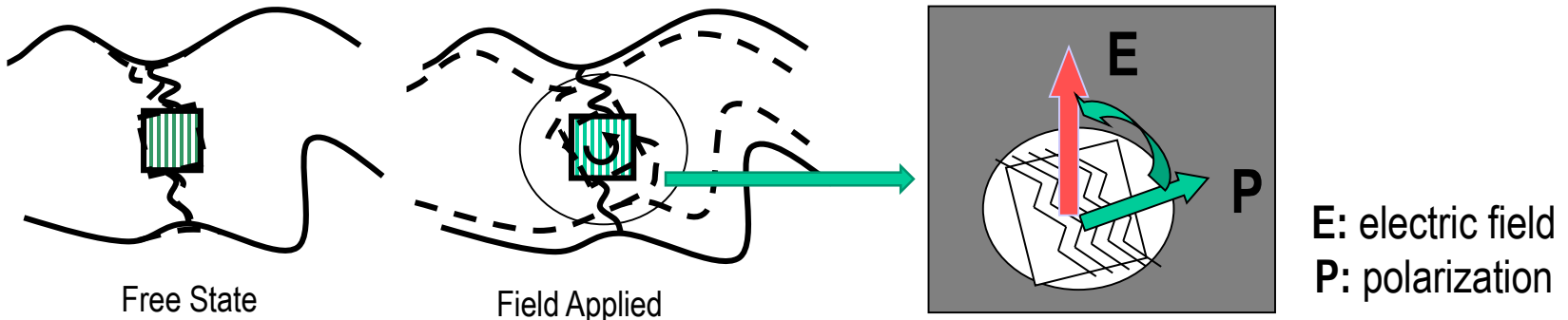
Formation of Element for the Model



Key Parameters Considered



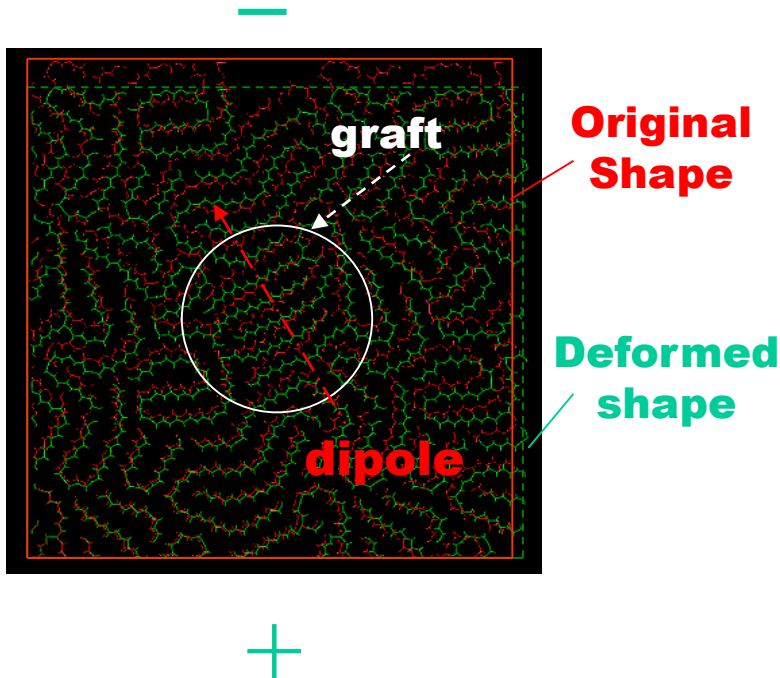
Deformation Mechanisms



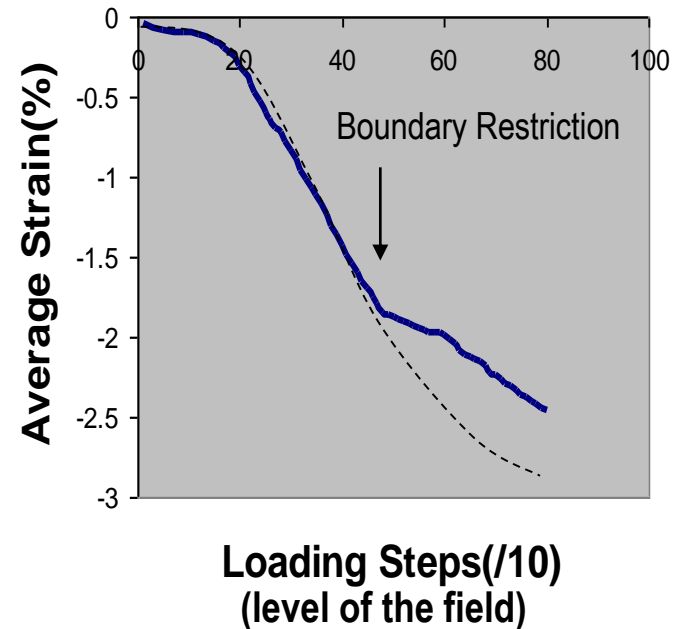


Comparison of Simulated Deformation of Electrostrictive G-elastomers and Experimental Results

Simulated Deformation

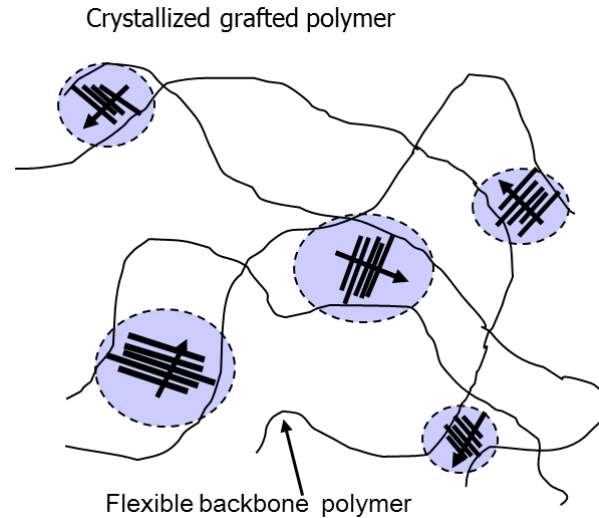
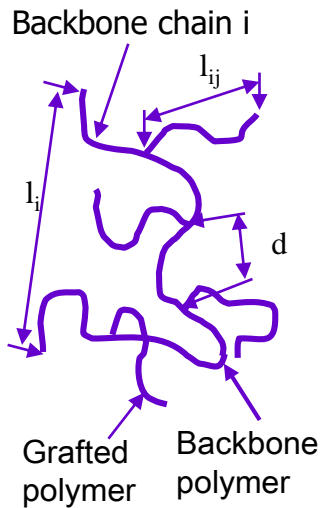


Comparison





Molecular Engineering for Property Control of Electrostrictive G-elastomers



Fraction of a grafted polymer

$$F = S_i S_j l_{ij} / (S_i l_i + S_j l_{ij})$$

Average length of a grafted polymers

$$l = S_j l_{ij} / N_{ij}$$

Average interval distance between the grafting sites

$$d = l_i / N_{ij}$$

Total amount of field responsive grafts

↪ Fraction of grafted polymer $F = S_i S_j l_{ij} / (S_i l_i + S_j l_{ij})$

Crystal size and size distribution

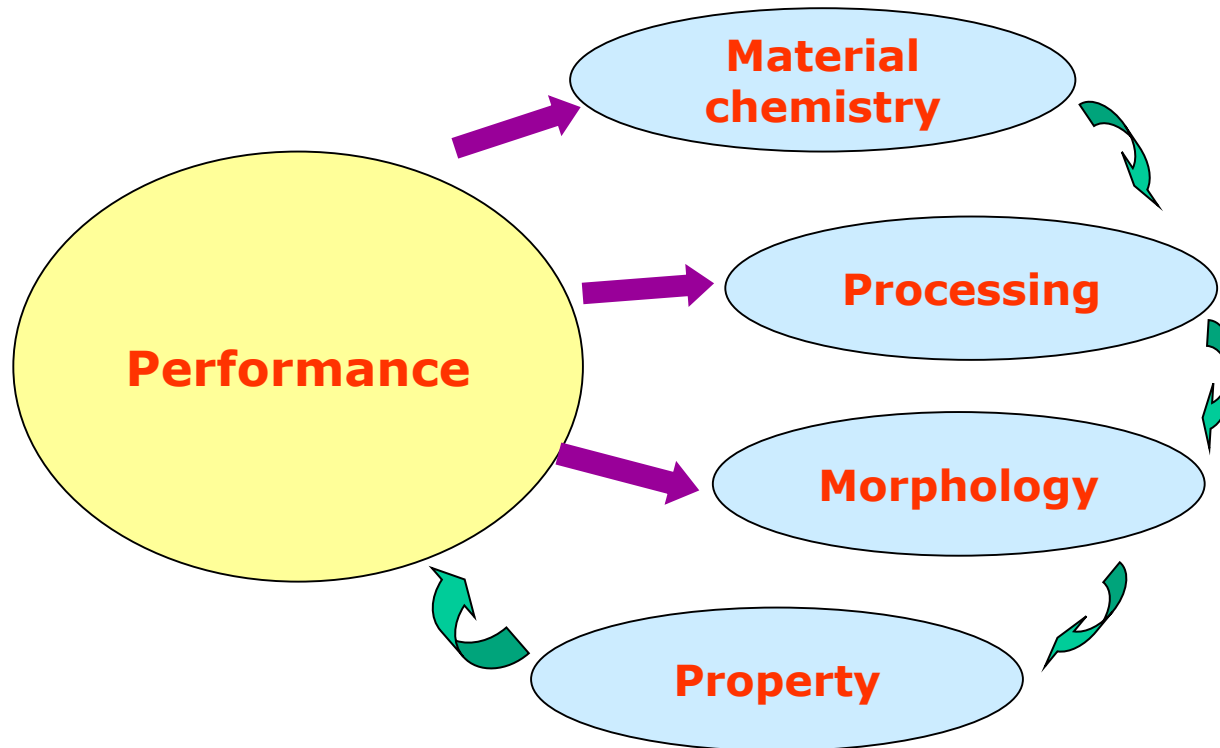
↪ Average length of grafted polymers $l = S_j l_{ij} / N_{ij}$

Cross-linking density and free volume

↪ Average interval between grafting sites $d = l_i / N_{ij}$



The Route to the Desired Electroactive Polymers





Challenges and Opportunities

As a new class electroactive polymers, **Electrostrictive G-Elastomers** have demonstrated promising electromechanical properties with some advantages over other electroactive polymers. A device using the G-elastomer has proven a Hybrid Concept that provides a new route of developing high performance electromechanical devices.

Challenges

- Low voltage operation
- Flexible, durable and low constraint electrode
- High conversion efficiency
- Low dielectric loss
- Low mechanical loss
- Thermal stability
- Electric leaking

Opportunities

Challenges are opportunities

The ways to take the opportunities are to develop better materials. Researchers are trying to develop composites, hybrid system, blends, new polymers, etc. for desired electroactive polymers (EAPs). Different materials have different advantages and disadvantages. One material may be used for a particular application while others for some other particular applications. In order to make EAPs that may be used in many possible applications, the electroactivities need to be **intrinsic**. Molecular Engineering should be one of the ways to achieve the goal.



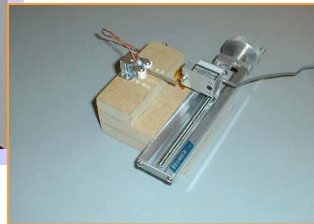
Some Applications in NASA Research Activities

Aerodynamic control Passive optics
Deformable mirror array Tunable antennas
Acoustic transducers

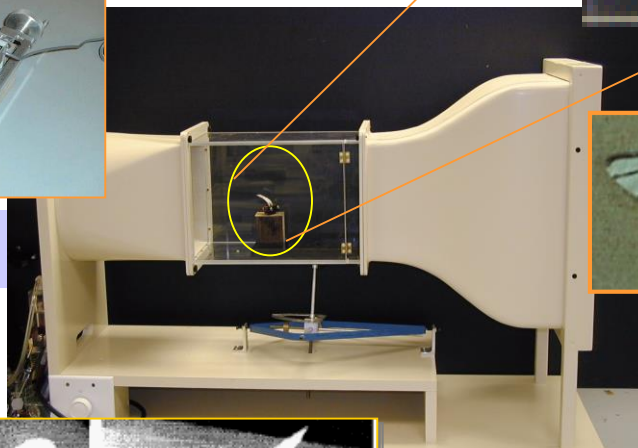
Bending actuators



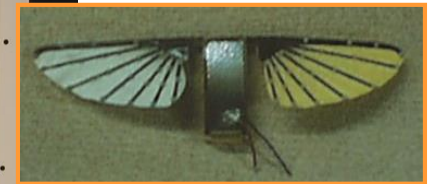
Force-test



Wind-tunnel test



Air flow

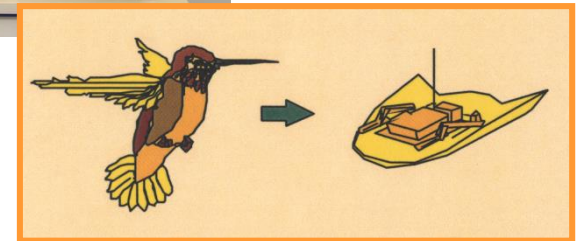
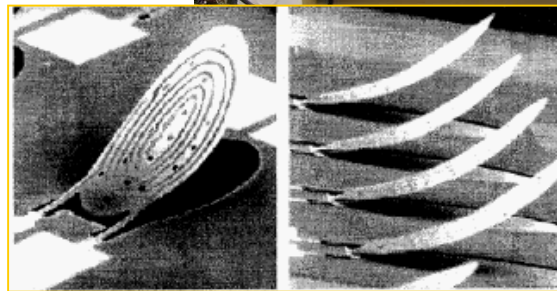


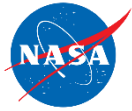
Biomimetic
Micro-Air Vehicle

Sensor/actuator array



Self-sensing actuator array





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Dr. Peter Lellihi
NASA Langley Research Center
Dr. Emilie Siochi
NASA Langley Research Center
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