

# **Electrostrictive Graft-Elastomers (G-Elastomers)**

## **-Materials, Devices and Applications-**

### **A Review**

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**SPIE Smart Structures and Materials**  
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# 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)

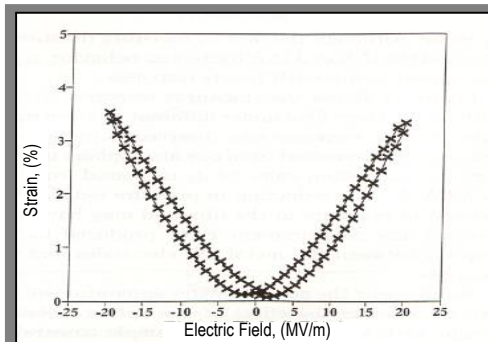
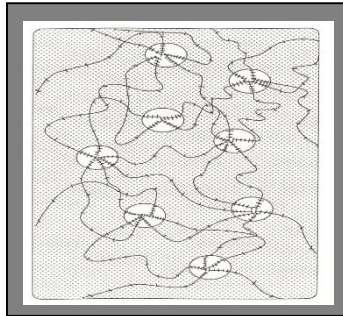
### Ionic Polymer Gels (IPG)

### Ionic Polymer Metallic Composite (IPMC)



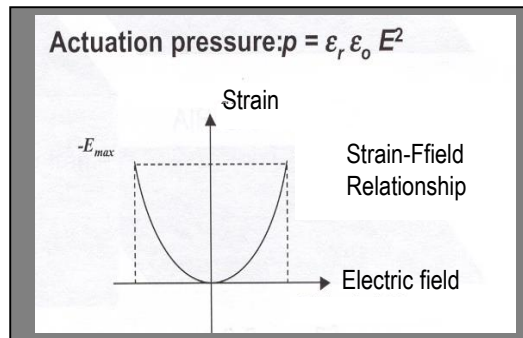
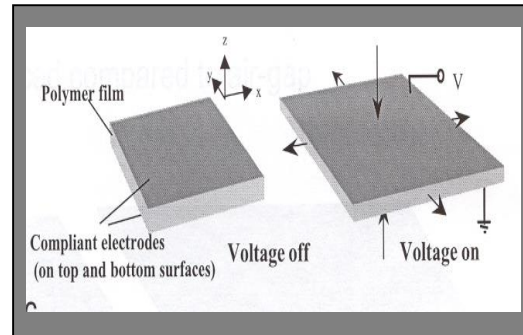
# Electromechanically Functional Elastomers

## Polyurethane elastomers



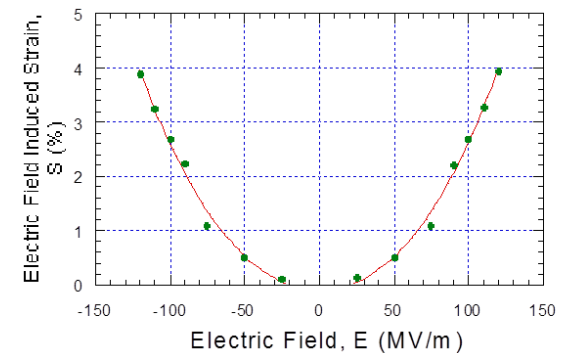
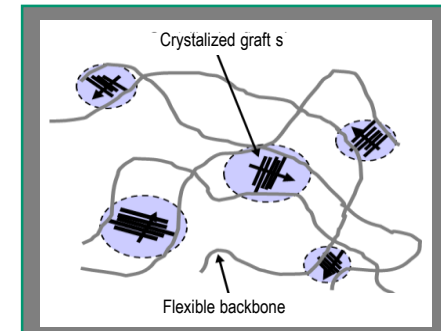
Physically cross-linked (hydrogen bonds) elastomers that offer field-induced strain by a combined mechanism.

## Electrostatic/dielectric elastomers



Chemically cross-linked soft elastomers that can offer a large ffield-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, etc. p. 2721, Vol.32, Journal of Polymer Science: Part B, Polymer Physics (1992)

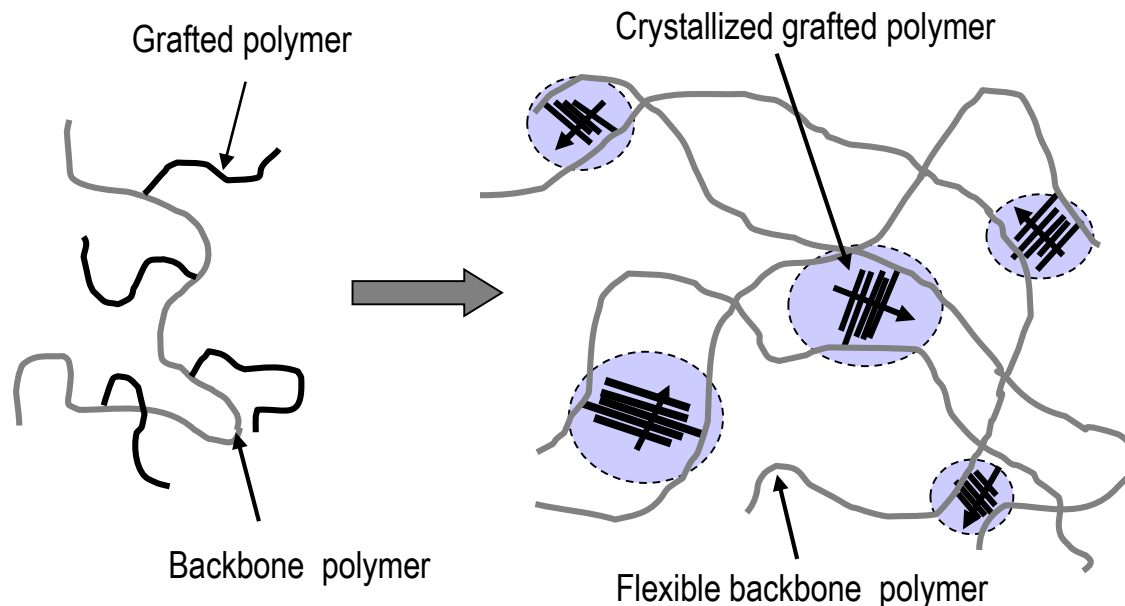
Ref.: "Electroactive Polymer (EAP) Actuators as Artificial Muscles: Reality, Potential and Challenges" by J. Bar-Cohen (SPIE, 2003).



# Electrostrictive Graft Elastomers (G-elastomers)

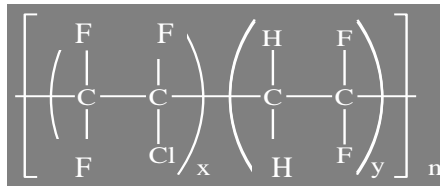
## A Two Constituent System

- 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



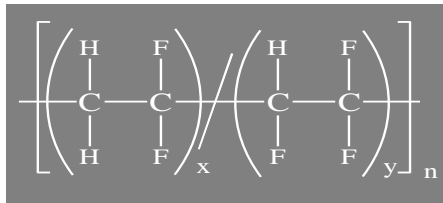
### Backbone Polymer

chlorotrifluoroethylene-vinylidene fluoride copolymer

Nature: non-crystallizable and flexible

### Functions

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



### Grafted Polymer

trifluoroethylene-vinylidene fluoride (VDF-TrFE) copolymer

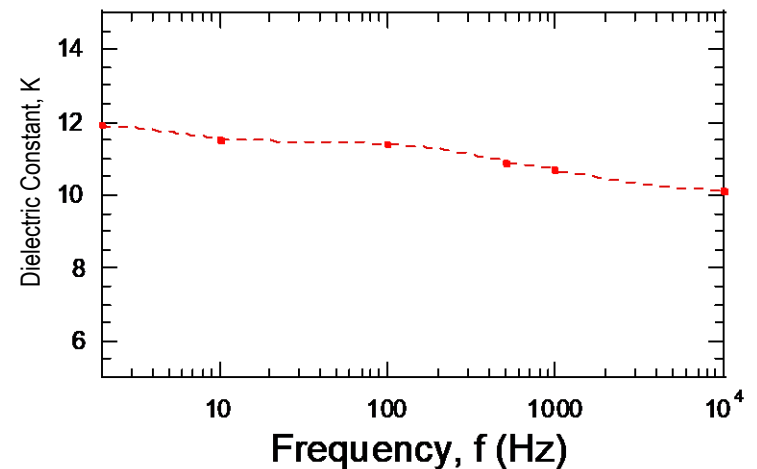
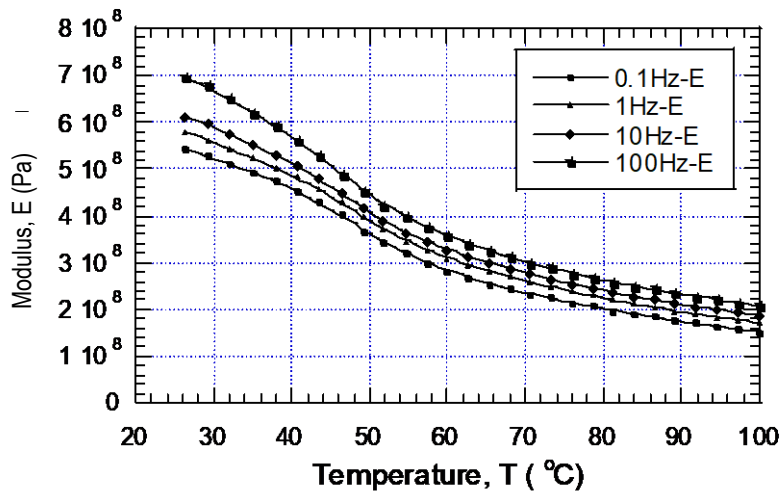
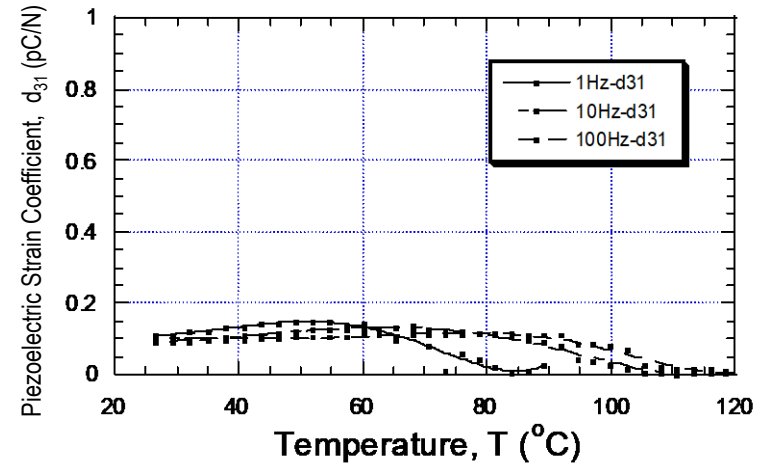
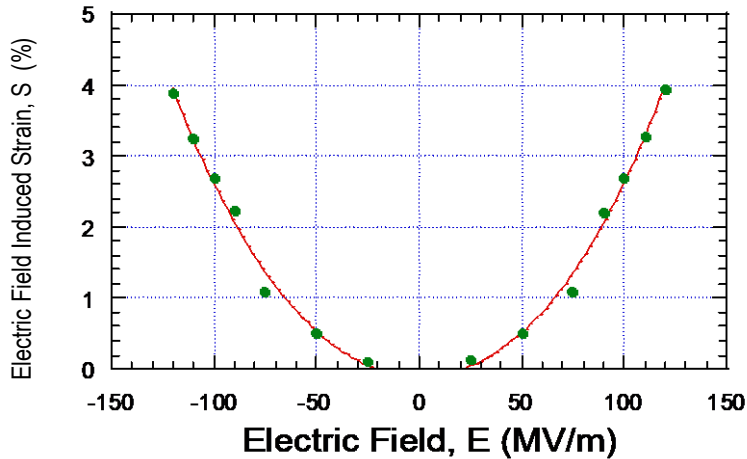
Nature: crystallizable and polar

### Functions

- (a) to form physical cross-linking sites for elastomeric three-dimensional network
- (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

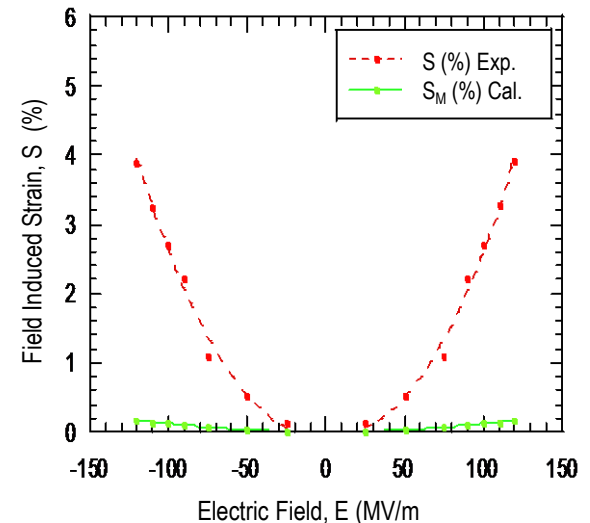
$$S_E = -Qe_0^2 (K-1)^2 E^2$$
$$S_M = -se_0 K E^2 / 2$$

## 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 flexible backbone and crystalized graft polymers  
(dipole moment, crystal unit and crystal size as well as flexibility of the backbone polymers).

**Fraction** of the two constitutes (dielectric constant, mechanical properties, and electromechanical properties).

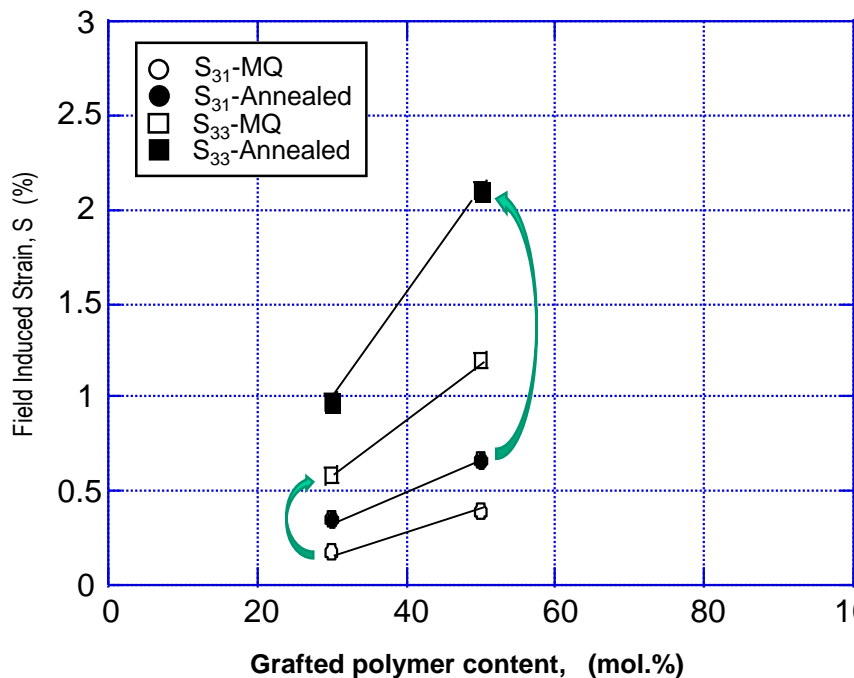
**Processing** of materials utilizing thermal, mechanical, and electrical processing techniques (morphology control and optimization of electric, mechanical, and electromechanical).

- 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.

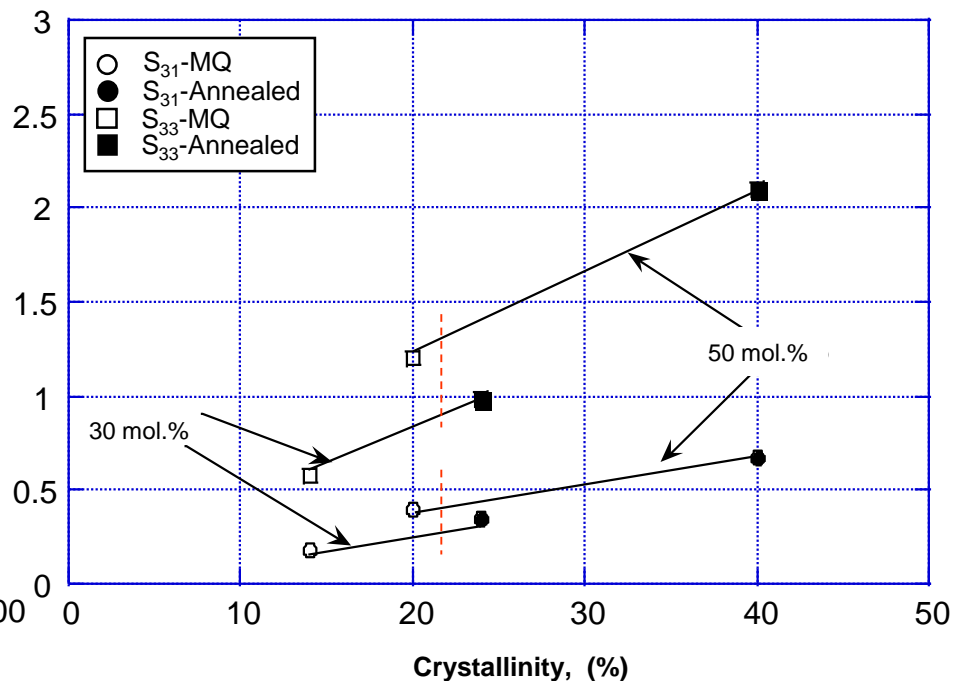


# Effects of the Content and Crystallinity of the Grafted Polymer on Field-induced Strain of Electrostrictive G-Elastomers

Effects of the Content



Effects of Crystallinity





## Comparison of Electromechanical Properties of Some Representative Electroactive Materials

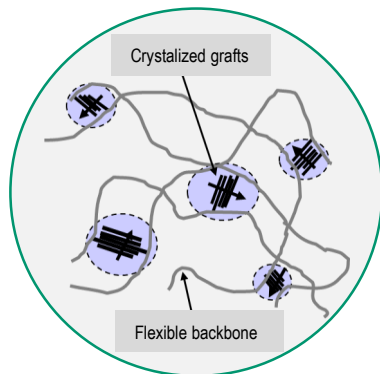
Materials	Strain (s) (%)	Modulus (Y) (MPa)	Output Force (YS) (Mpa)	Salient Features
LaRC G-elastomer	4	580	23	conformable, high strain, lightweight
Polyurethane	4	20	0.8	high strain, low force
PVDF	0.3	1600	4.8	low strain
PZT	0.3	6400	192	brittle, heavy

### 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.



## Research on Electrostrictive G-elastomers



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

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

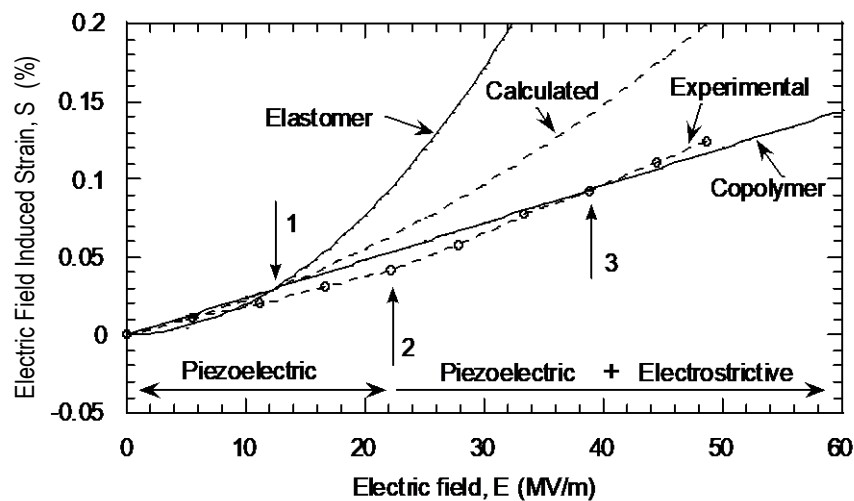
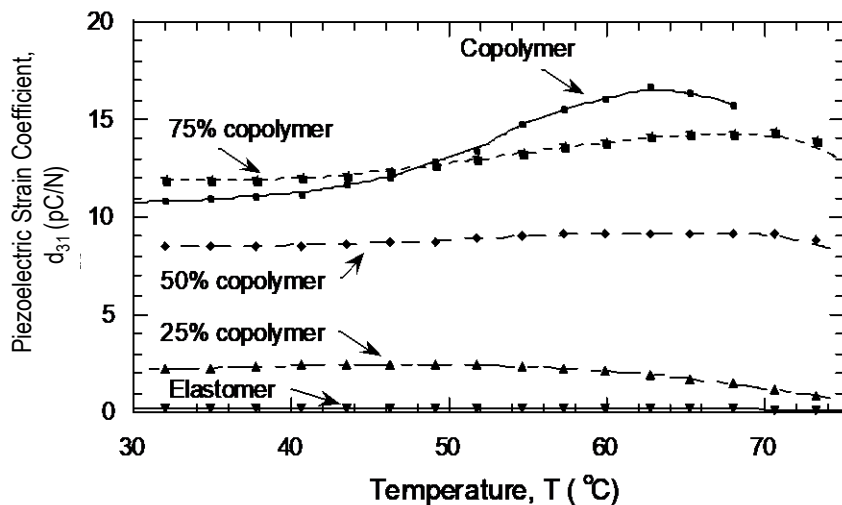
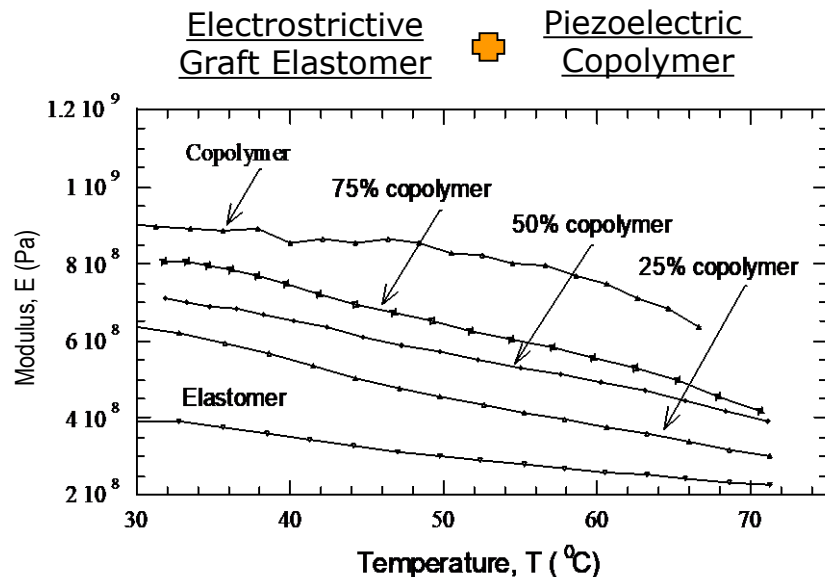
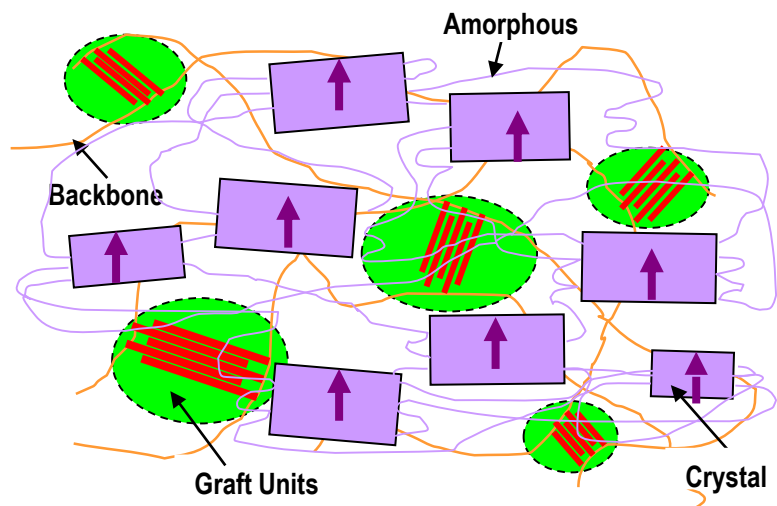
Developed electrostrictive G-elastomer-based devices: bending actuators and hybrid actuators

Applied hybrid concept proven by the hybrid actuators 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



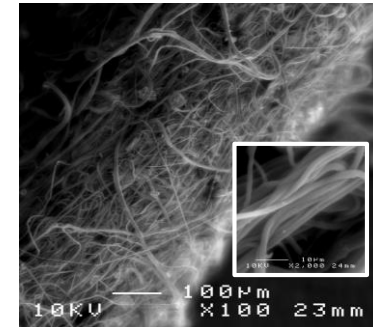
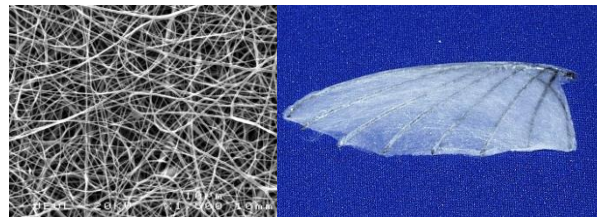
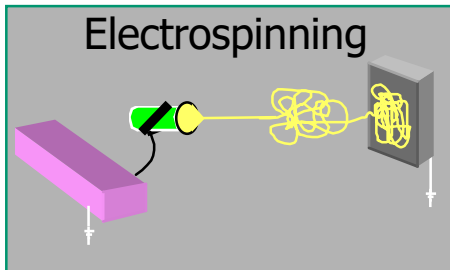
# Sensing-Actuating Dual Functional Polymer Blends



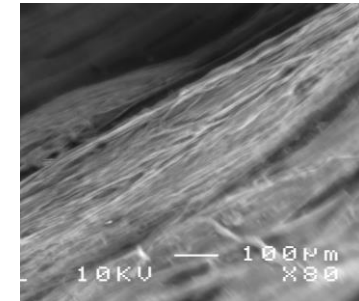
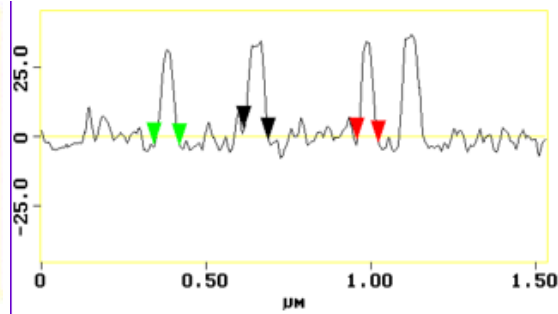
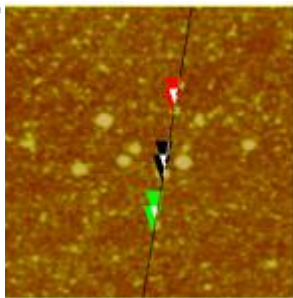
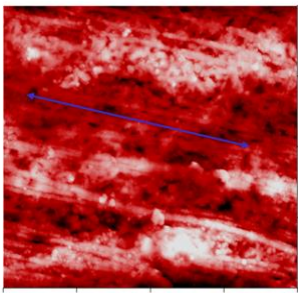


# Electrostrictive G-elastomer Nano-fibers

## Nano-fibers and Mats by Electrospinning



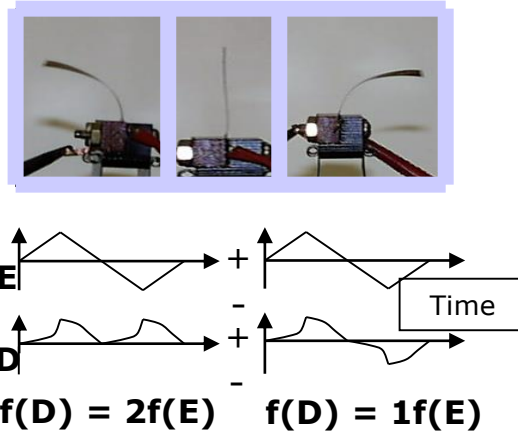
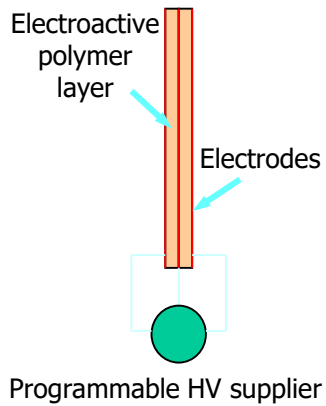
## Highly Aligned Nano-fibers by Dynamic Precipitation



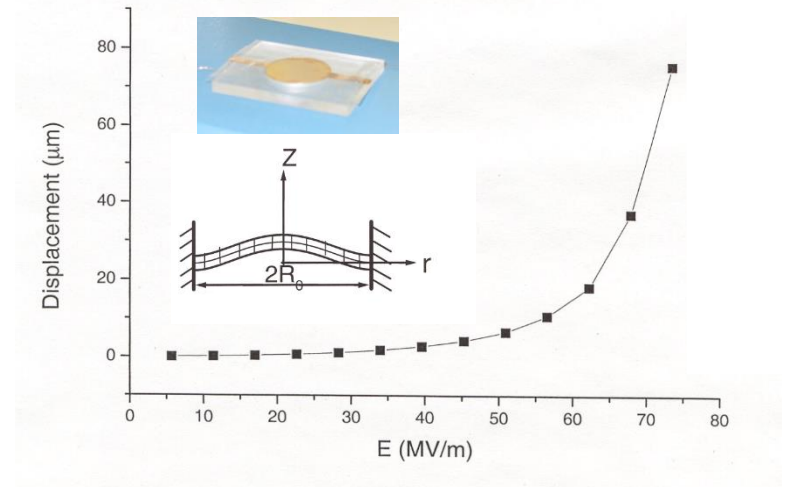


# Actuators Using Electrostrictive G-Elastomer

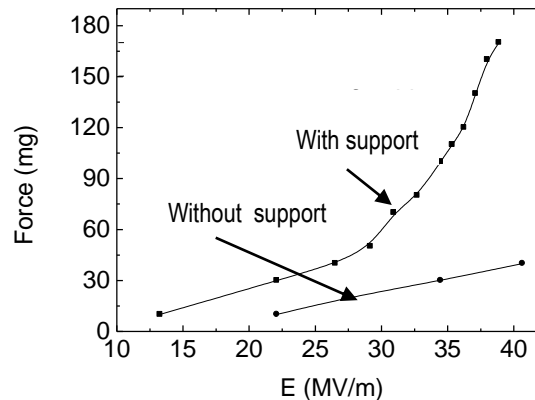
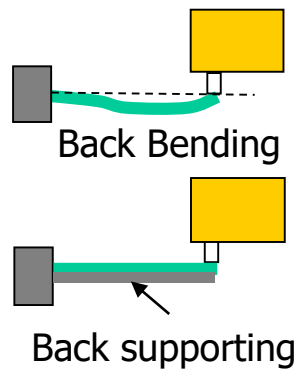
## Two Direction Bending Actuator



## Circular Actuator



## Backed Bending Actuator

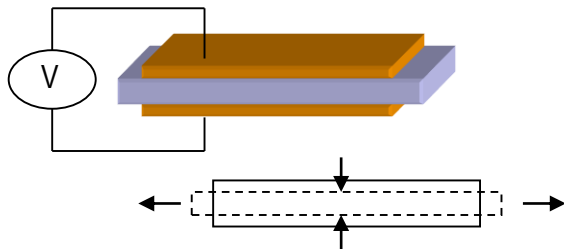




# Hybrid Electromechanical Actuators

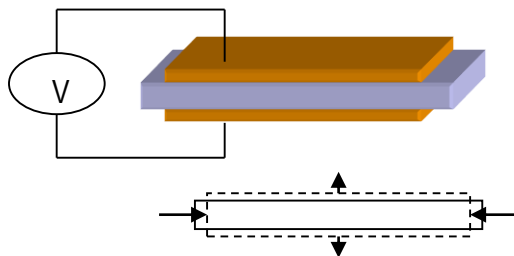
## Electric Field-induced Strain

### Electroactive polymer



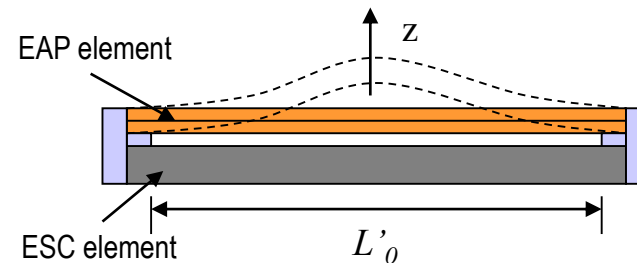
Longitudinal strain: **Negative**  
Transverse strain: **Positive**

### Electroactive Ceramics



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

## Hybrid Actuator



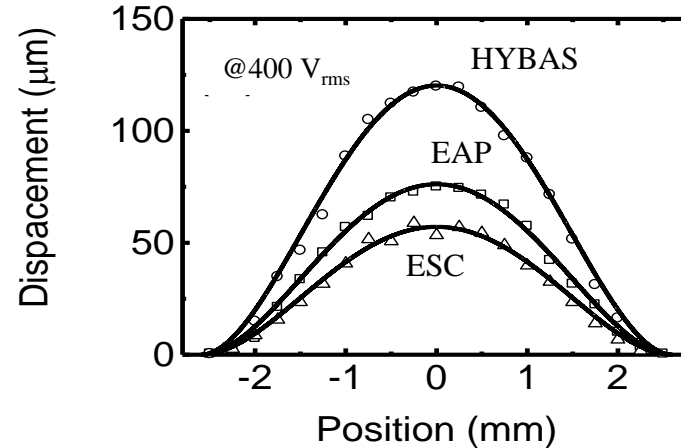
EAP: Electrostrictive G-elastomer  
ESC: Electroactive single crystal

**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.

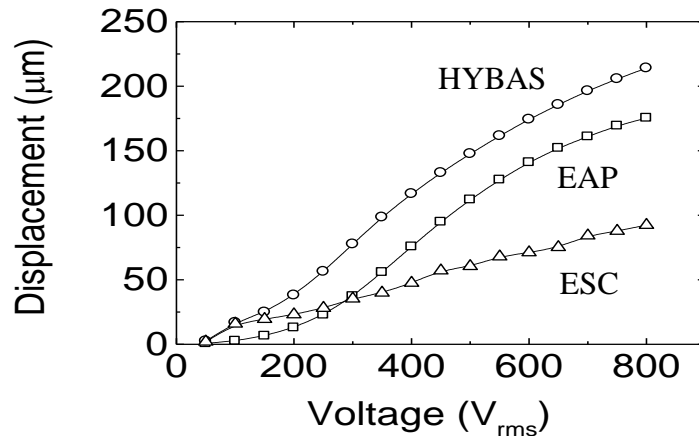


# Performance of the Hybrid Electromechanical Actuators

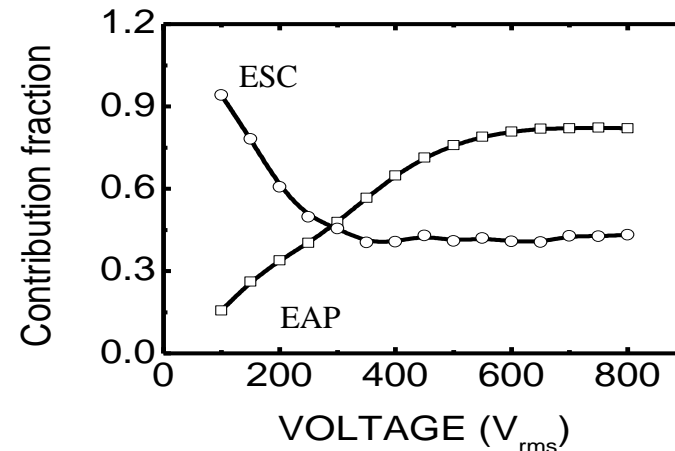
Significantly increased displacement  
Proven hybrid concept  
for advanced electromechanical devices



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



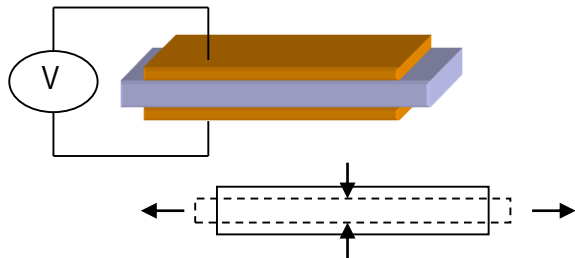
Voltage Dependence of Contributions of Each Constituent





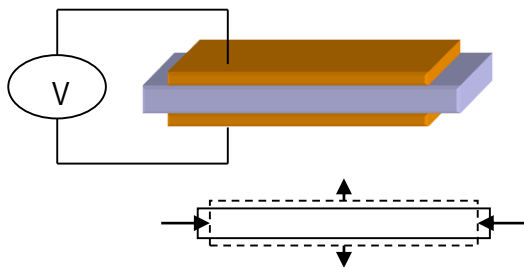
# Generalization of Hybrid Concept and Its Extended Application

## 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.

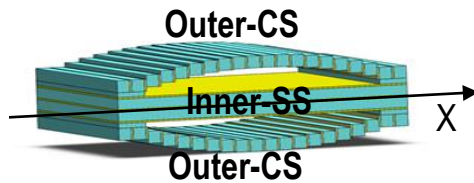
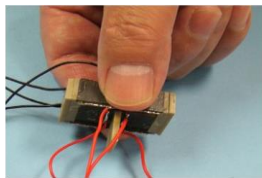
### Multilayer/stacks:

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



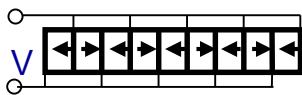
# A Successful Sample: HYbrid Piezoelectric Energy Harvesting Transducer System (HYPEHT)

## The Energy Harvester

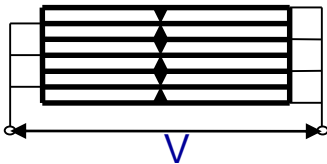


Dimensions: 30 mm (l) × 15 mm (w) × 11 mm (h)  
Weight: 21 gram

## Active Constituents



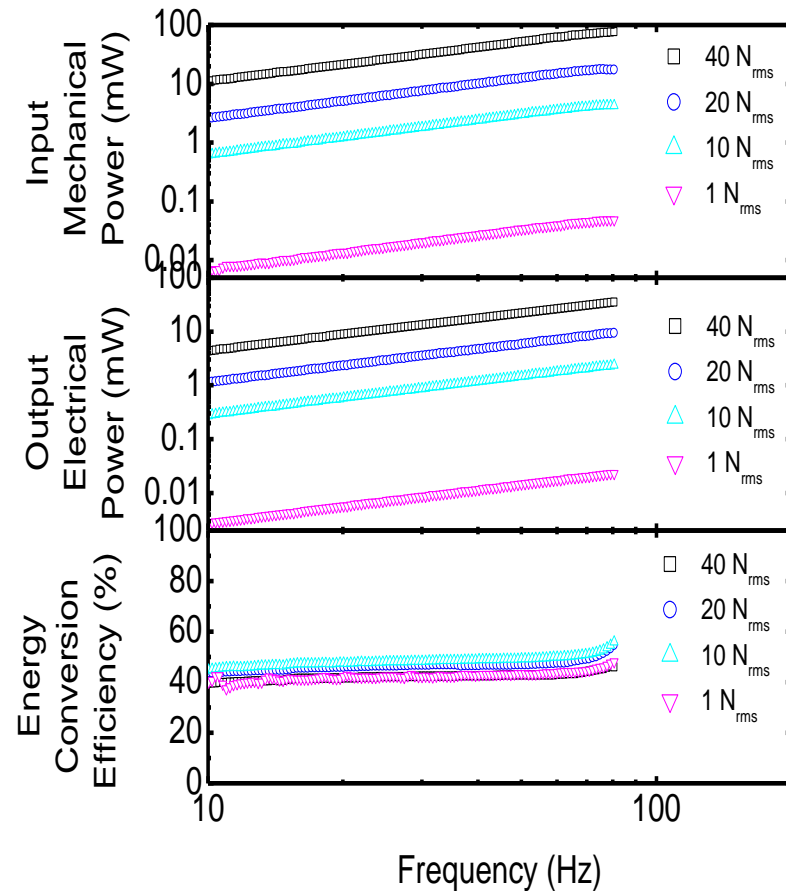
**Outer Constituent:**  
Multi-stacked  
 $d_{33}$  effect in x-direction



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

**Conversion Efficiency: >40%**

## Performance



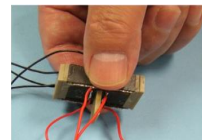
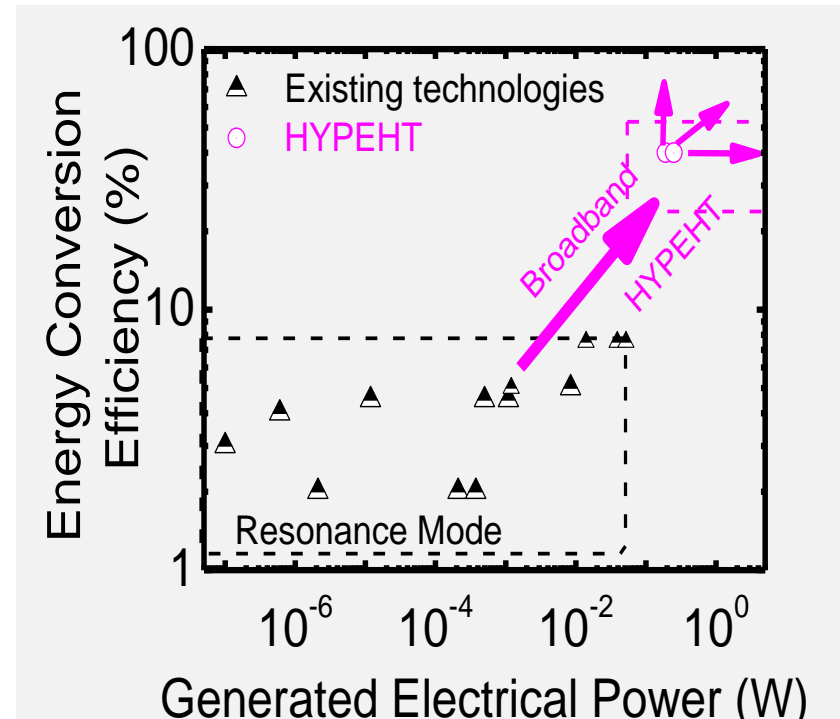


## Recognition of the HYPEHT Energy Harvesting Technology

- A proven hybrid concept for advanced electromechanical devices has been successfully applied to both actuation and broadband energy harvesting transducers.
- Innovation through multidisciplinary approaches
  - 1) to capture one order of magnitude more mechanical energy into piezoelectric structure
  - 2) to increase energy conversion efficiency
  - 3) to enhance energy charging/storage performance

More than **40%** mechanical to electrical energy conversion efficiency can be achieved.

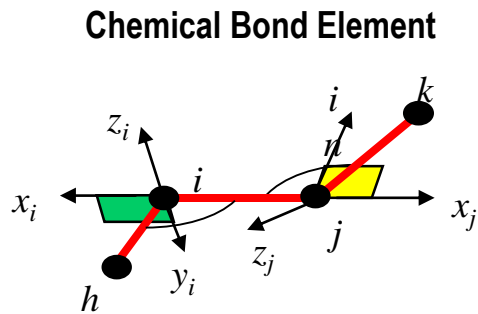
- HYPEHT is a broadband harvester at both off-resonance frequencies and resonance frequency.



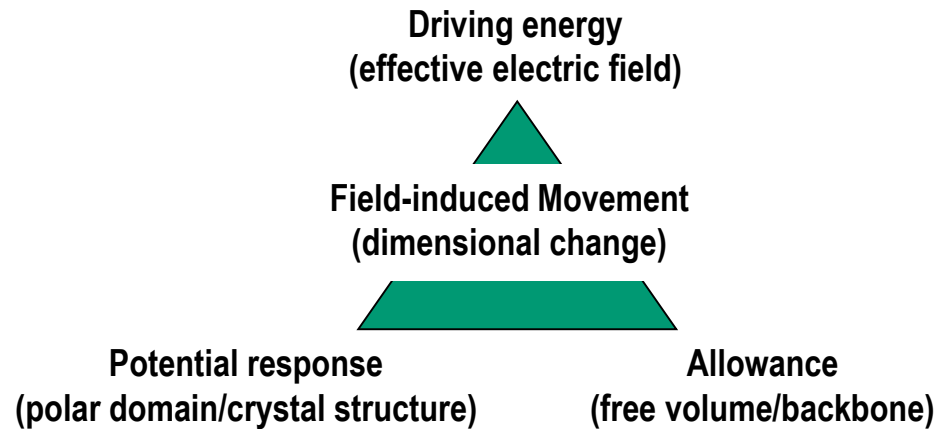


# Computational Study of Mechanisms of G-elastomers

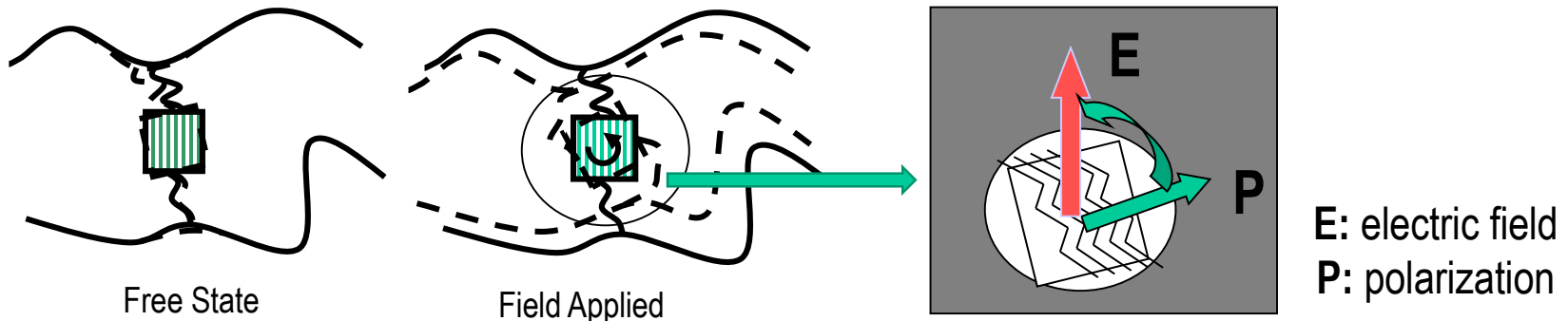
## Formation of Element for the Model



## Key Parameters Considered



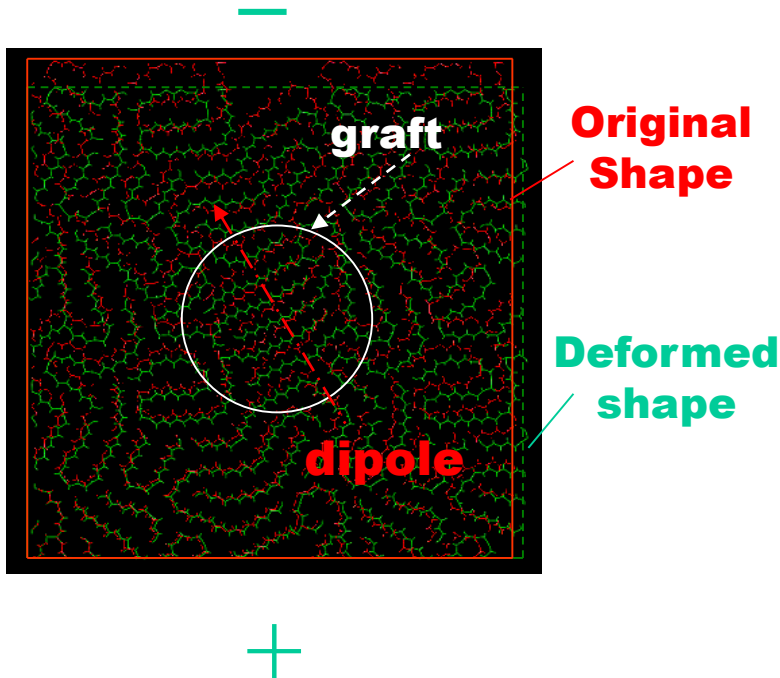
## Deformation Mechanisms



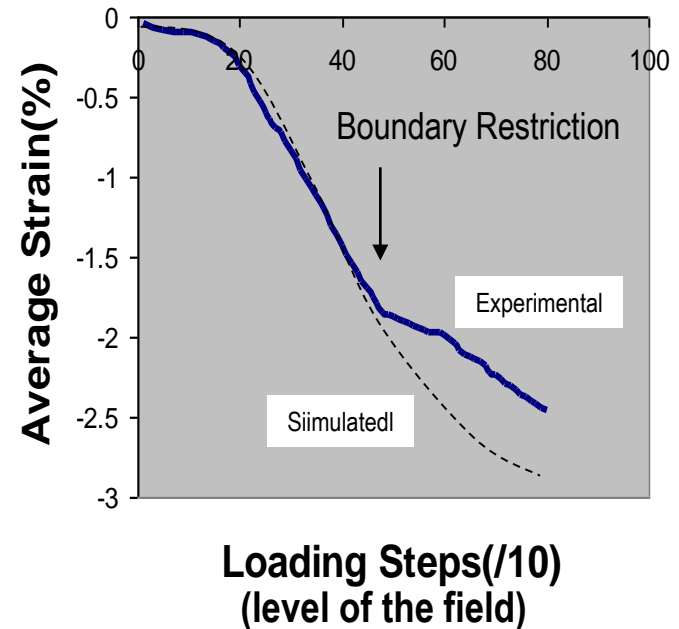


# Comparison of Simulated Deformation of Electrostrictive G-elastomers and Experimental Results

Simulated Deformation

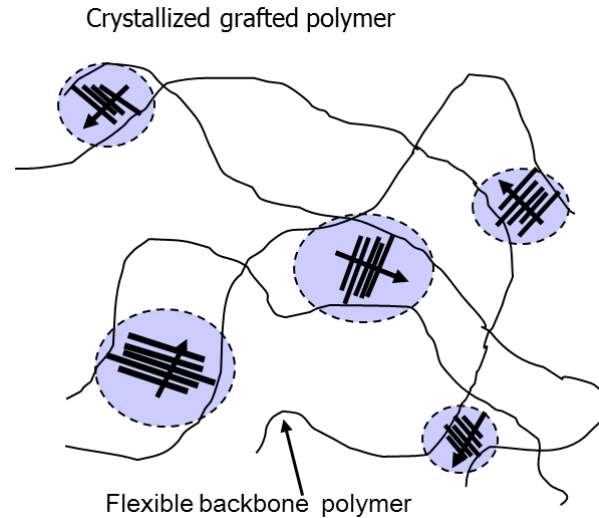
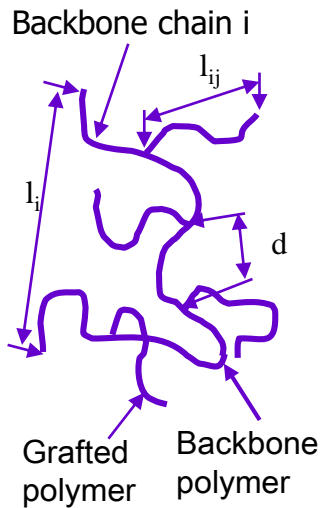


Comparison





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

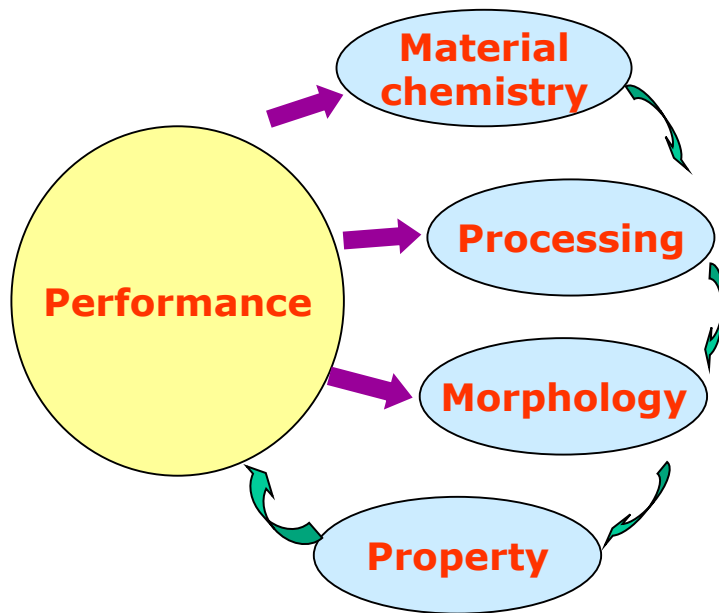
Cross-linking density and free volume

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

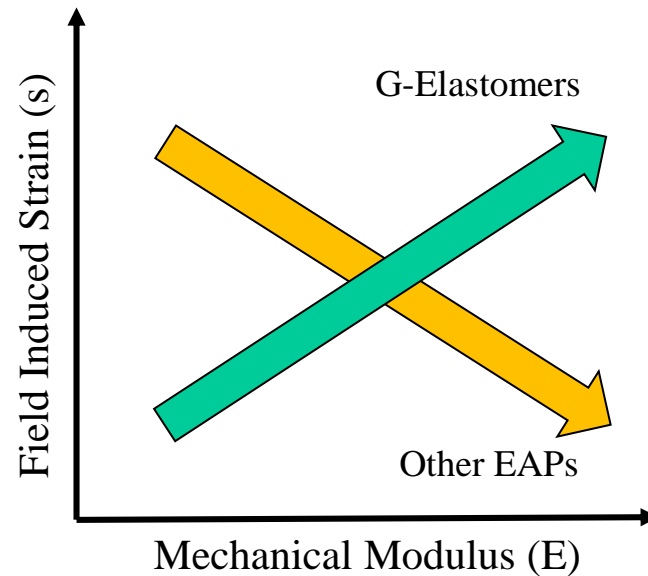


## The Route to the Desired Electroactive Polymers

A Route for Materials Development



Induced Strain vs. Mechanical Modulus



Machine Learning?



## Summary, Challenges and Opportunities

### Summary

-As a new class of 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.

-Computational study demonstrated the key factors that control the electromechanical properties of the G-elastomers

### Challenges

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

### Challenges = Opportunities

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.



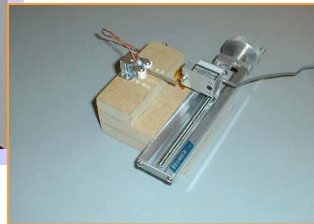
# Some Applications in NASA Research Activities

Aerodynamic control      Passive optics  
Deformable mirror array      Tunable antennas  
Acoustic transducers

Bending actuators



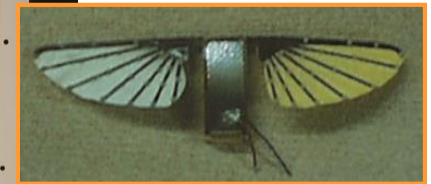
Force-test



Wind-tunnel test



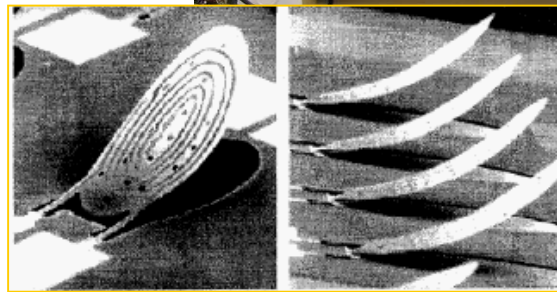
Air flow



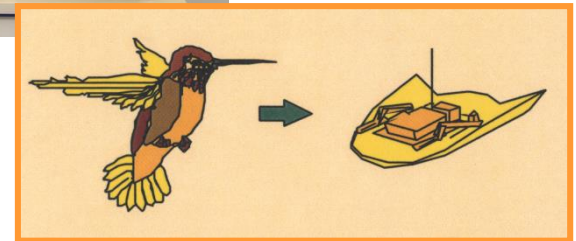
Sensor/actuator array



Self-sensing actuator array  
(NASA-LaRC)



Biomimetic  
Micro-air vehicle





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