

Electrostrictive Graft-Elastomers (G-Elastomers)

-Materials, Devices and Applications- A Review

Ji Su

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



November 5, 2018
Lawrence Livermore National Laboratory
Livermore, CA



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)

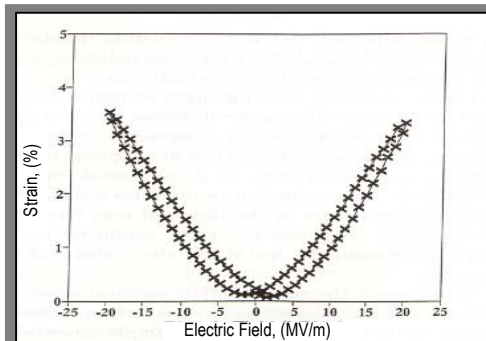
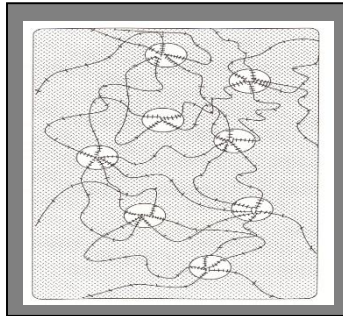
Ionic Polymer Gels (IPG)

Ionic Polymer Metallic Composite (IPMC)



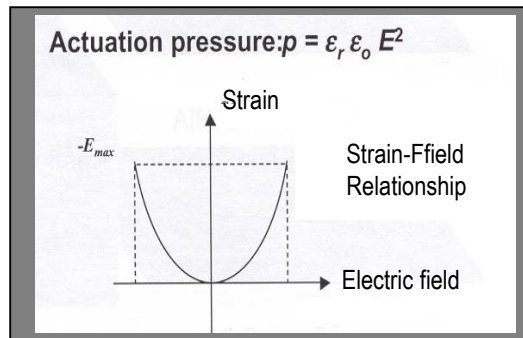
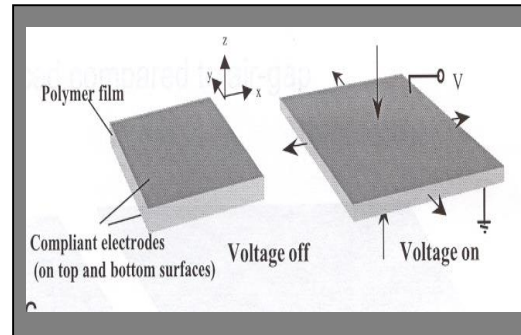
Electromechanically Functional Elastomers

Polyurethane elastomers



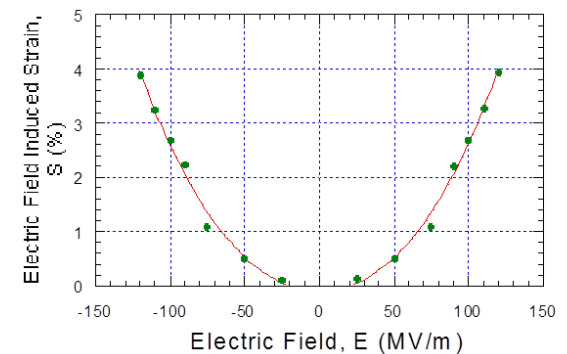
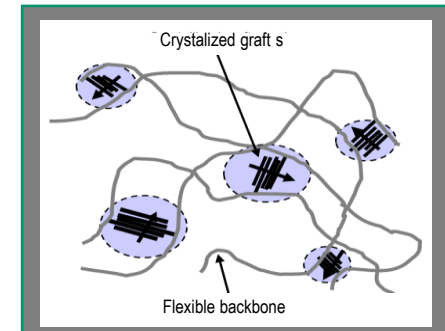
Physically cross-linked (hydrogen bonds) elastomers that offer field-induced strain by a combined mechanism.

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



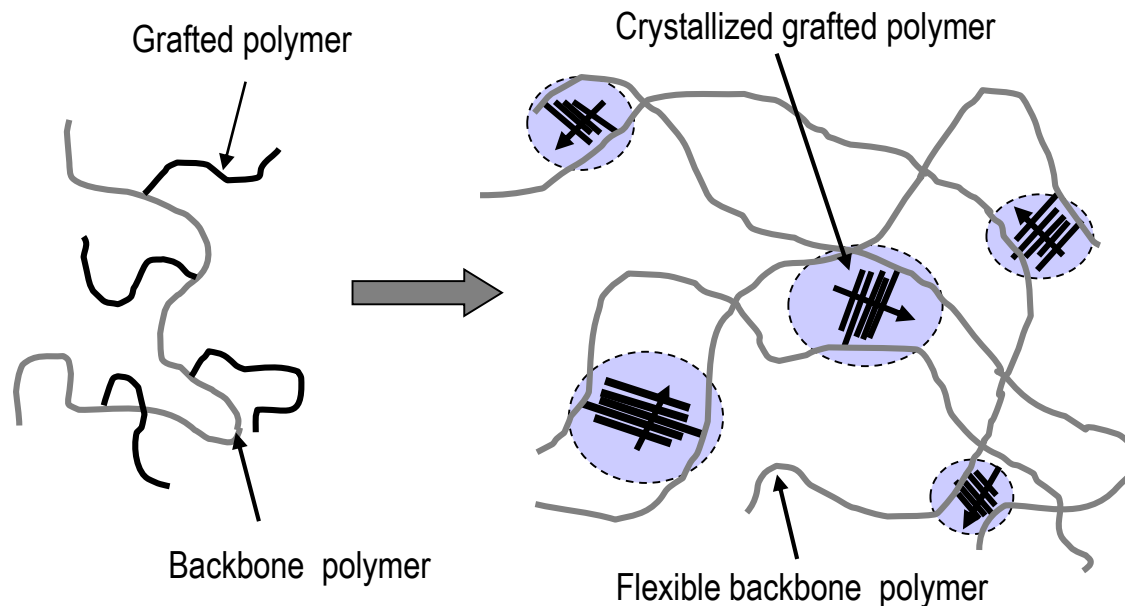
Physically cross-linked (formed crystal domains) elastomers that offer field-induced strain by primarily electrostriction.



Electrostrictive Graft Elastomers (G-elastomers)

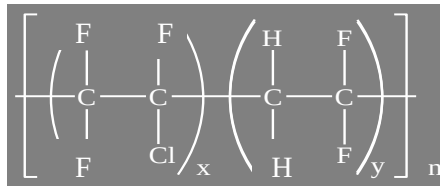
A Two Constituent System

- 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



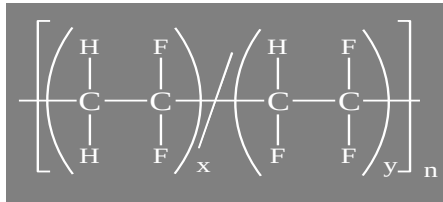
Backbone Polymer

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

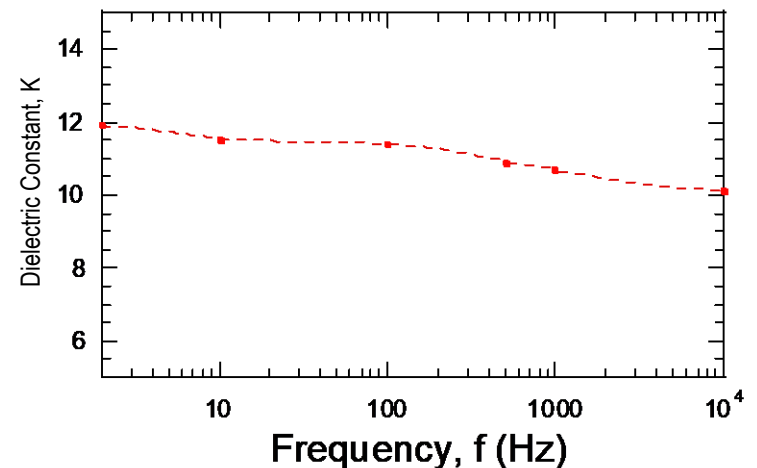
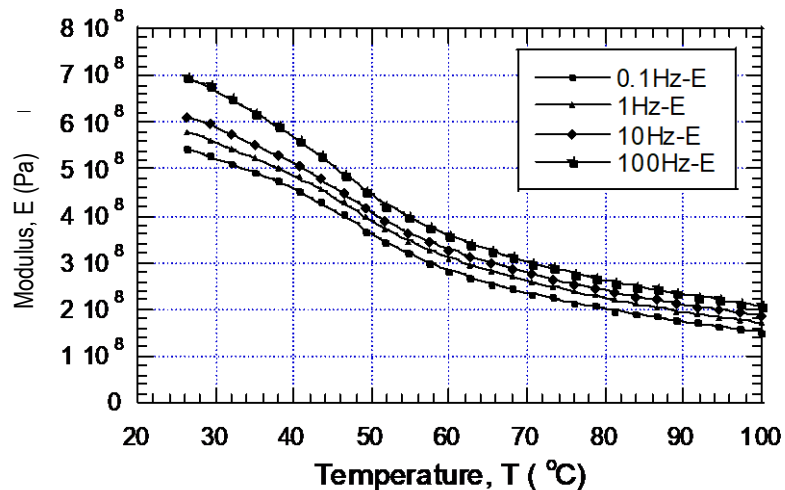
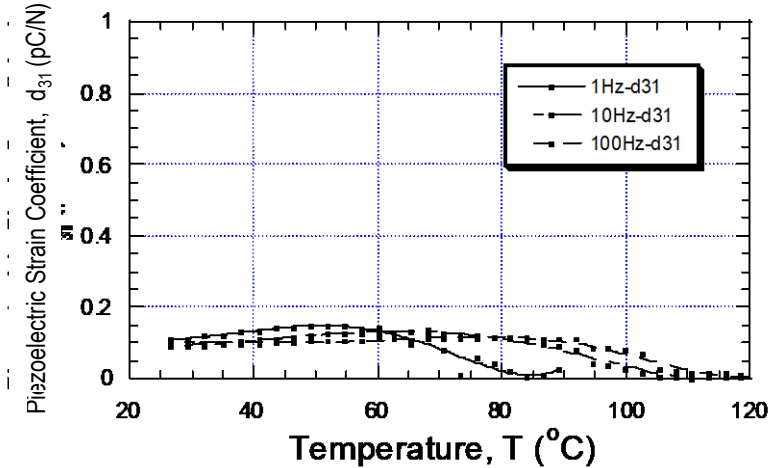
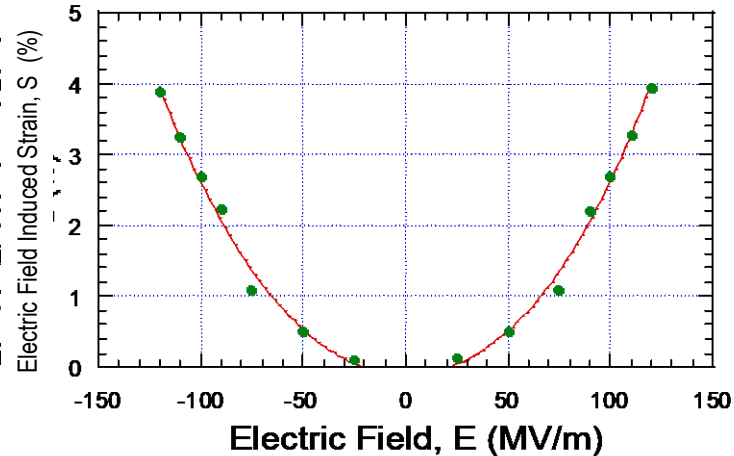
Nature: crystallizable and polar

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

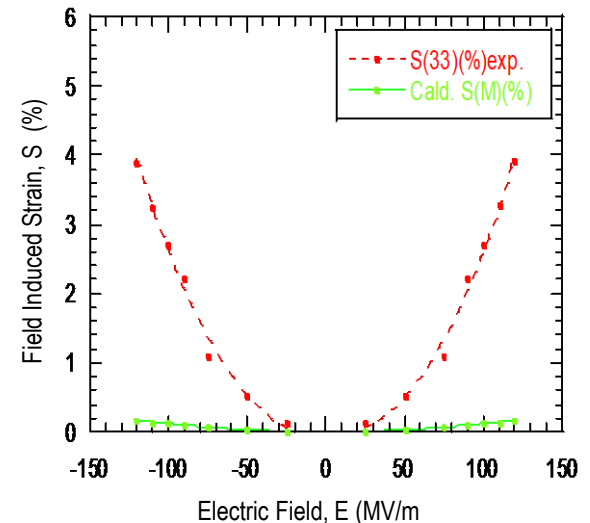
$$S_E = -Qe_0^2 (K-1)^2 E^2$$
$$S_M = -se_0 K E^2 / 2$$

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).

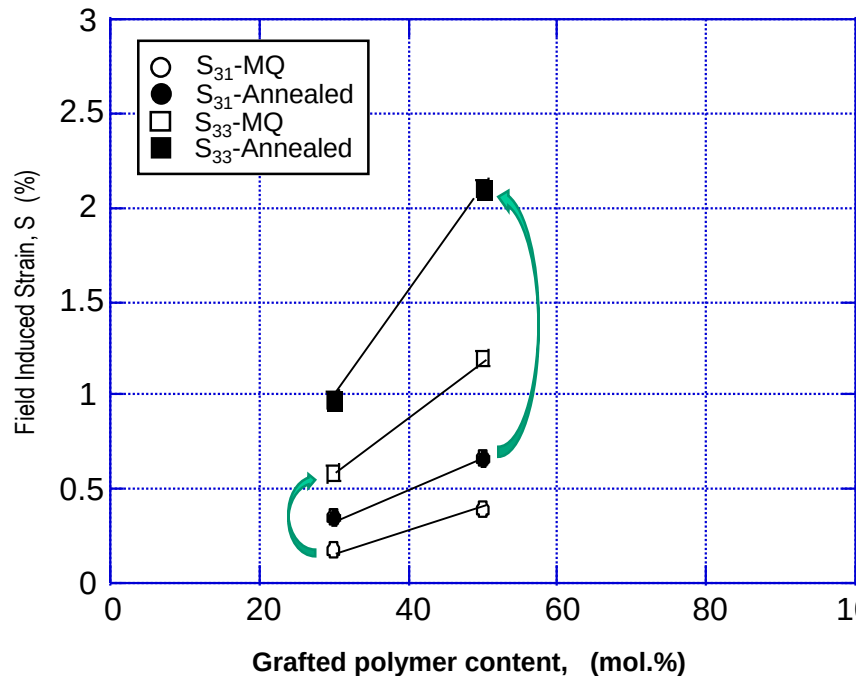
Processing of materials utilizing thermal, mechanical, and electrical processing techniques (morphology control and optimization of electric, mechanical, and electromechanical).

- 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.**

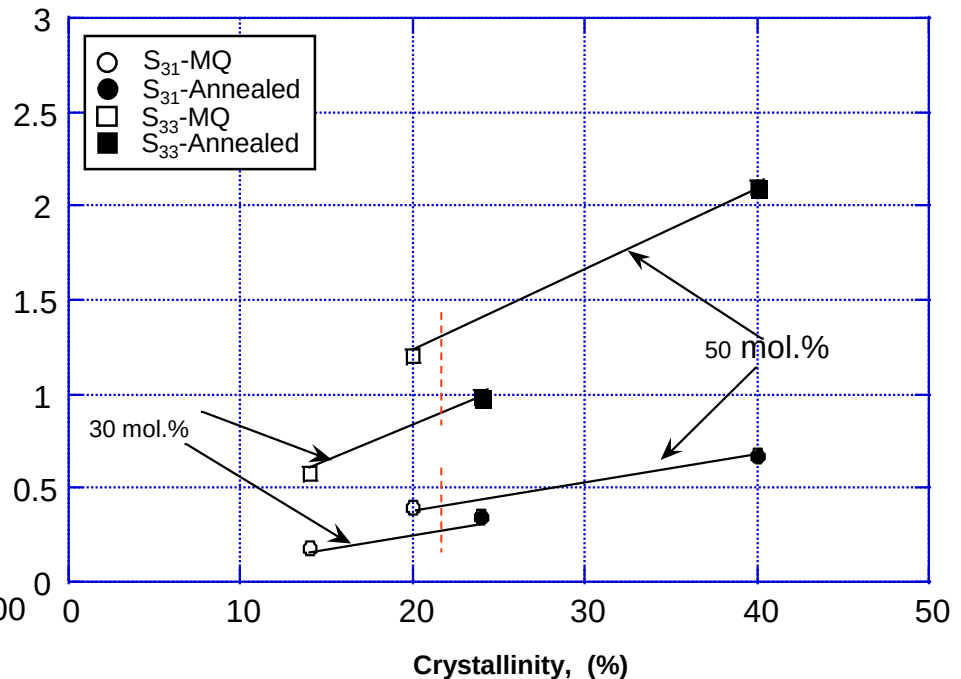


Effects of the Content and Crystallinity of the Grafted Polymer on Field-induced Strain of Electrostrictive G-Elastomers

Effects of the Content



Effects of Crystallinity





Comparison of Electromechanical Properties of Some Representative Electroactive Materials

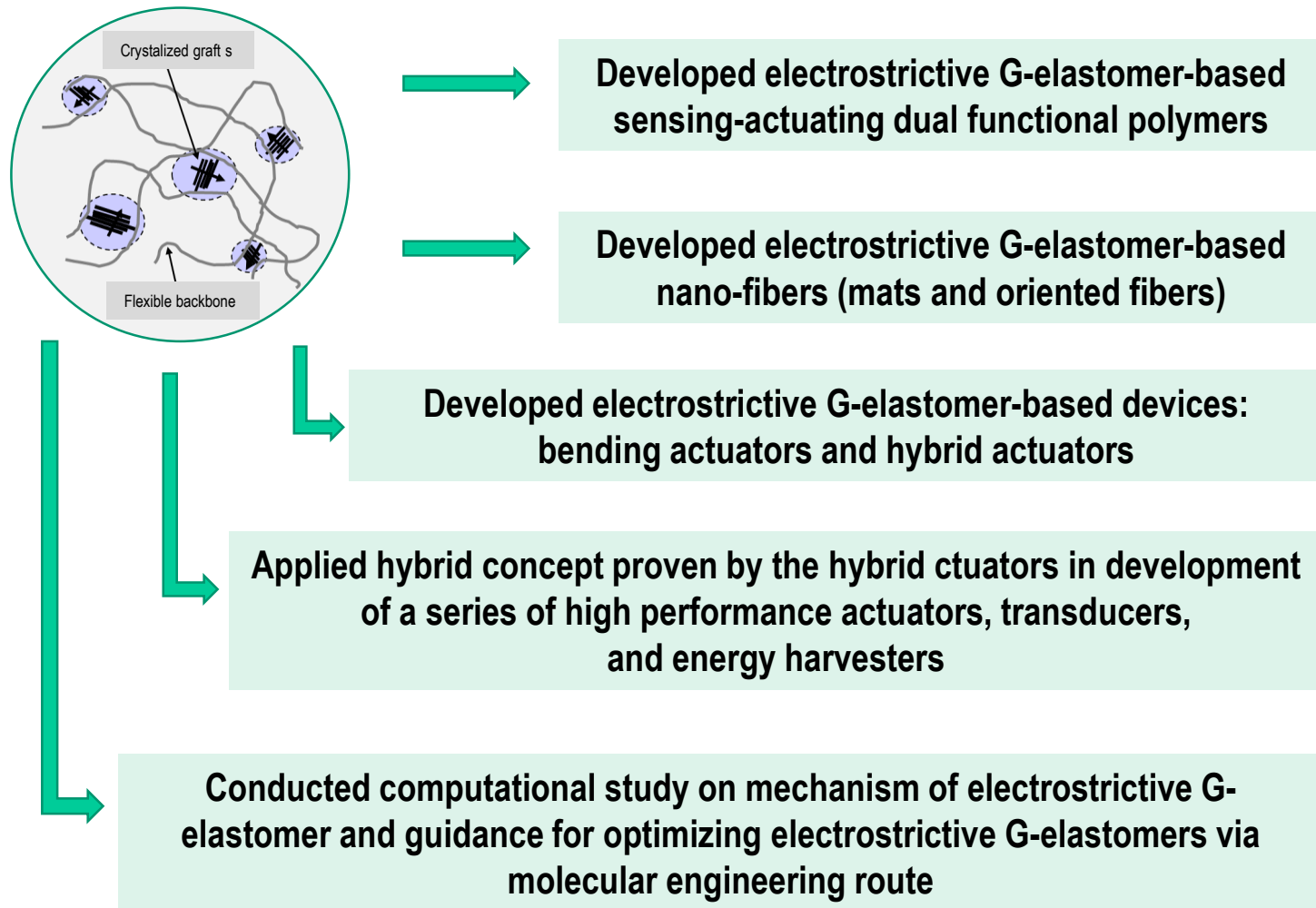
Materials	Strain (s) (%)	Modulus (Y) (MPa)	Output Force (YS) (Mpa)	Salient Features
LaRC G-elastomer	4	580	23	conformable, high strain, lightweight
Polyurethane	4	20	0.8	high strain, low force
PVDF	0.3	1600	4.8	low strain
PZT	0.3	6400	192	brittle, heavy

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.

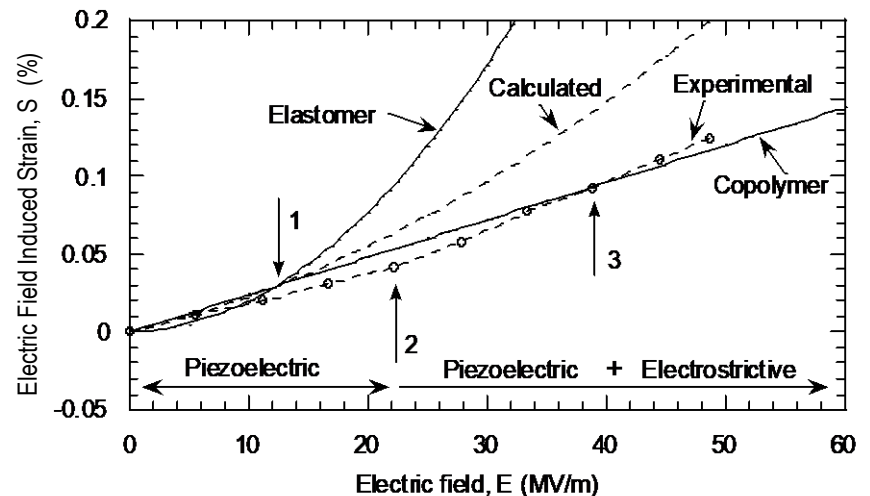
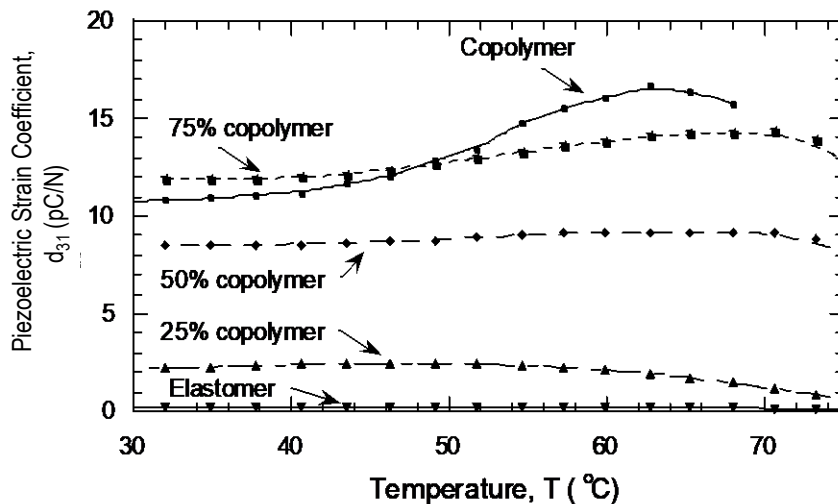
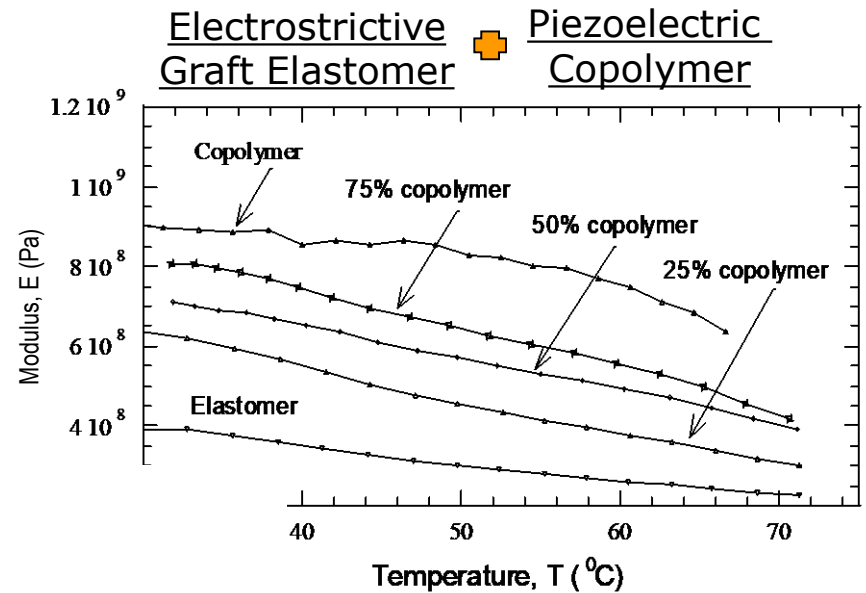
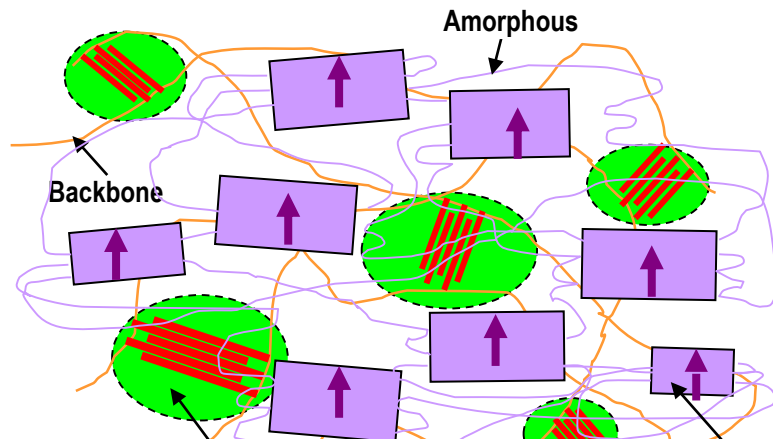


Research on Electrostrictive G-elastomers





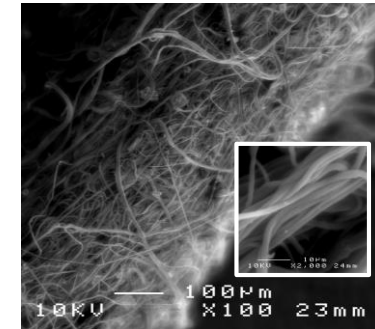
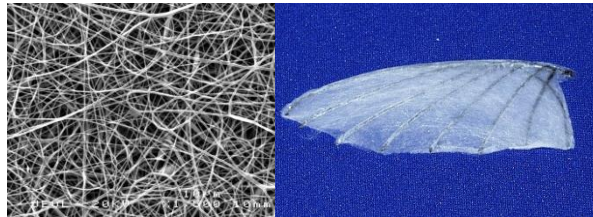
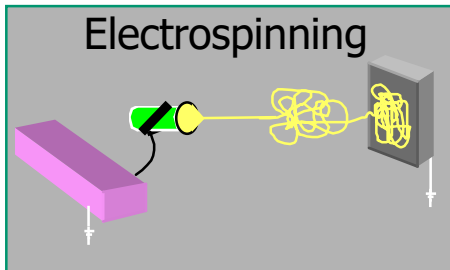
Sensing-Actuating Dual Functional Polymer Blends



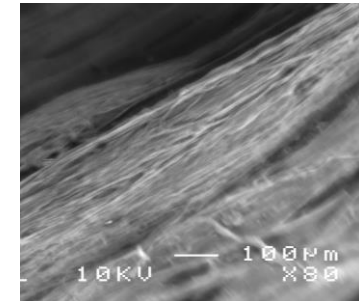
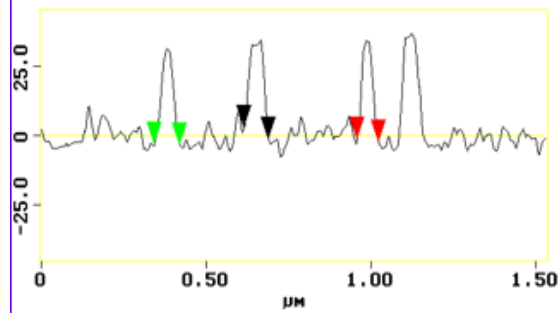
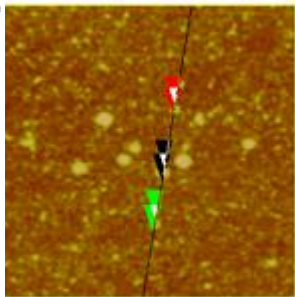
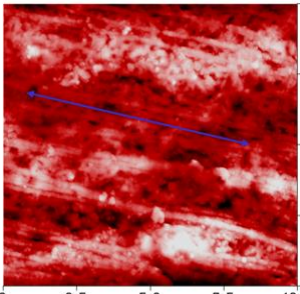


Electrostrictive G-elastomer Nano-fibers

Nano-fibers and Mats by Electrospinning



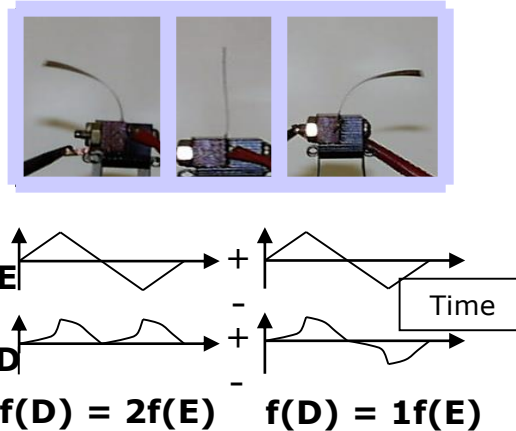
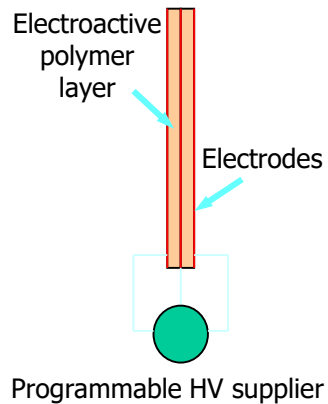
Highly Aligned Nano-fibers by Dynamic Precipitation



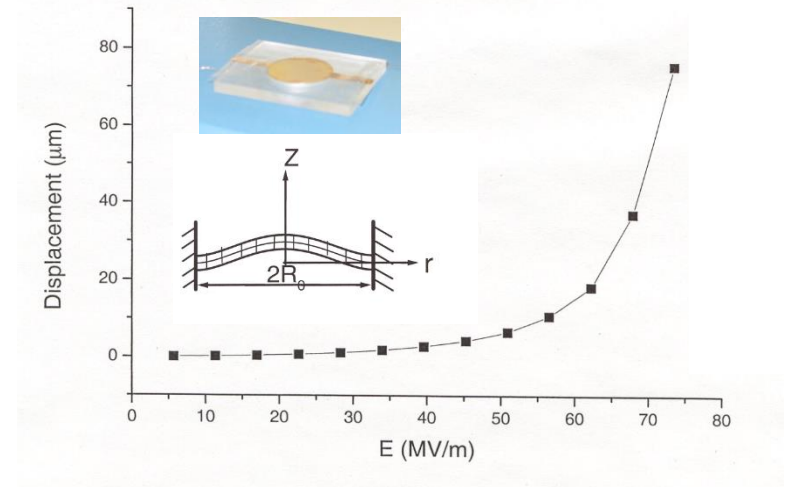


Actuators Using Electrostrictive G-Elastomer

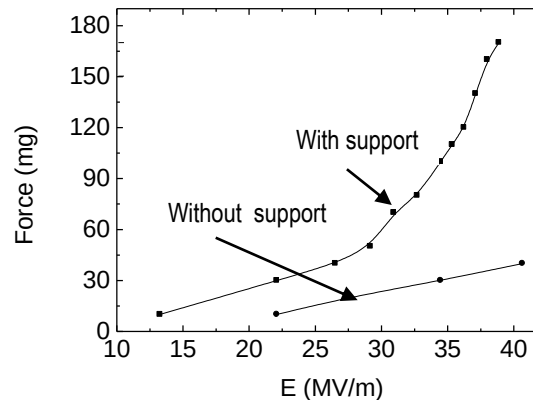
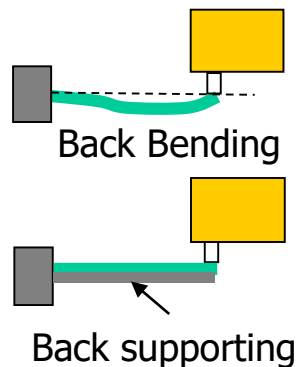
Two Direction Bending Actuator



Circular Actuator



Backed Bending Actuator

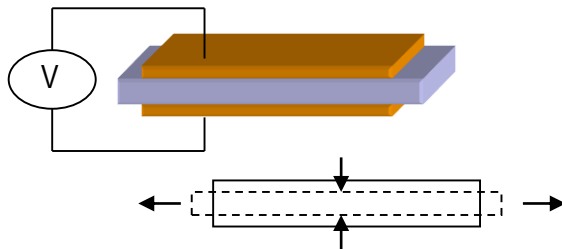




Hybrid Electromechanical Actuators

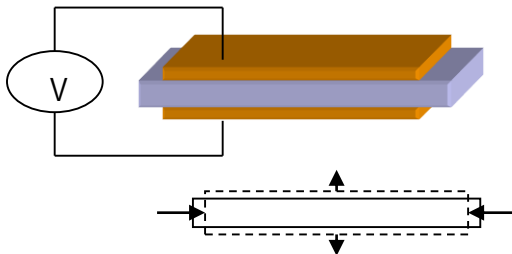
Electric Field-induced Strain

Electroactive polymer



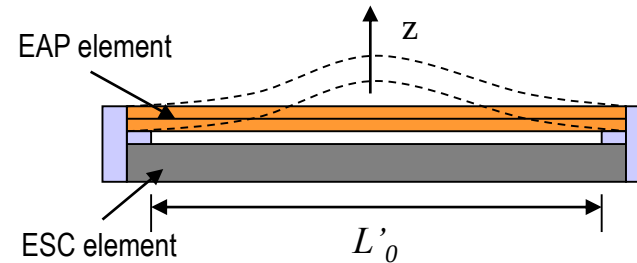
Longitudinal strain: **Negative**
Transverse strain: **Positive**

Electroactive Ceramics



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

Hybrid Actuator



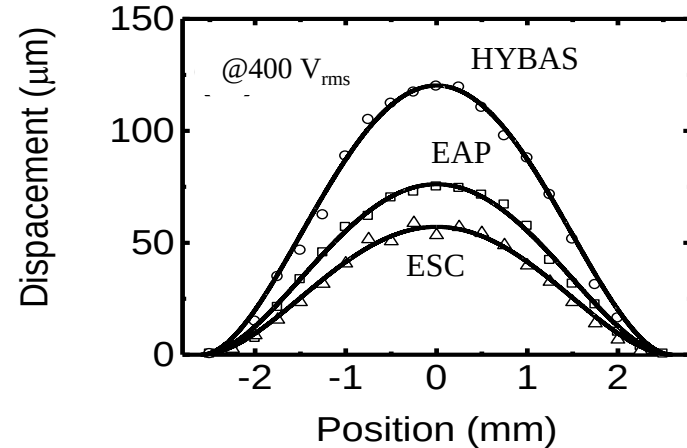
EAP: Electrostrictive G-elastomer
ESC: Electroactive single crystal

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.

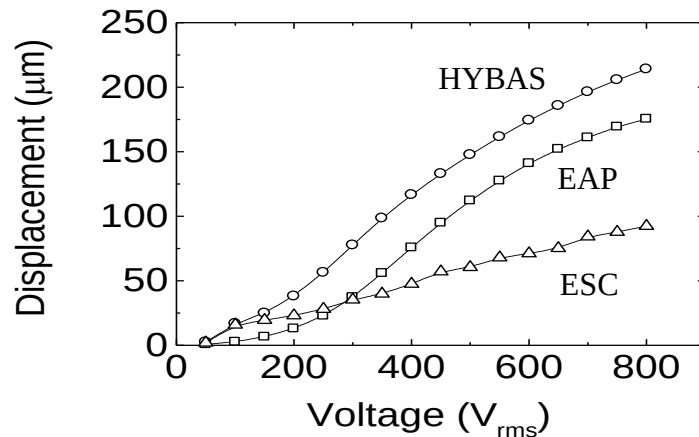


Performance of the Hybrid Electromechanical Actuators

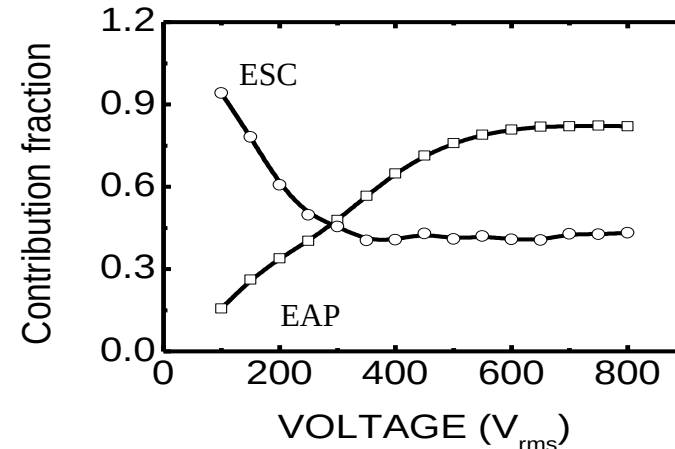
Significantly increased displacement
Proven hybrid concept
for advanced electromechanical devices



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



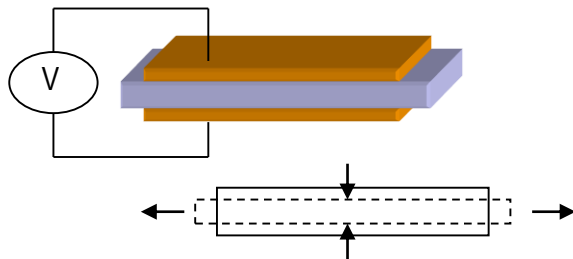
Voltage Dependence of Contributions of Each Constituent





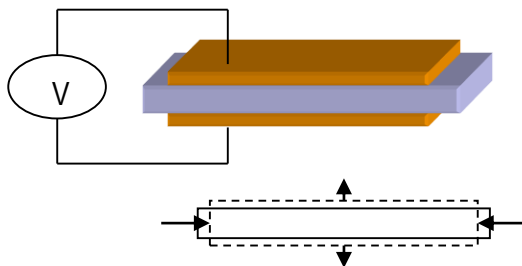
Generalization of Hybrid Concept and Its Extended Application

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:

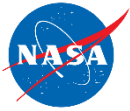
ceramics, polymers, single crystals, etc.

Composites:

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

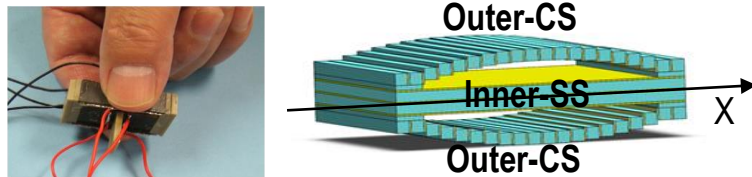
Multilayer/stacks:

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



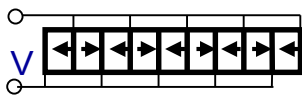
A Successful Sample: HYbrid Piezoelectric Energy Harvesting Transducer System (HYPEHT)

The Energy Harvester

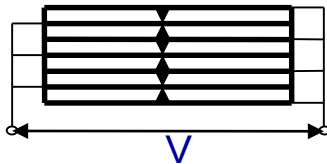


Dimensions: 30 mm (l) × 15 mm (w) × 11 mm (h)
Weight: 21 gram

Active Constituents



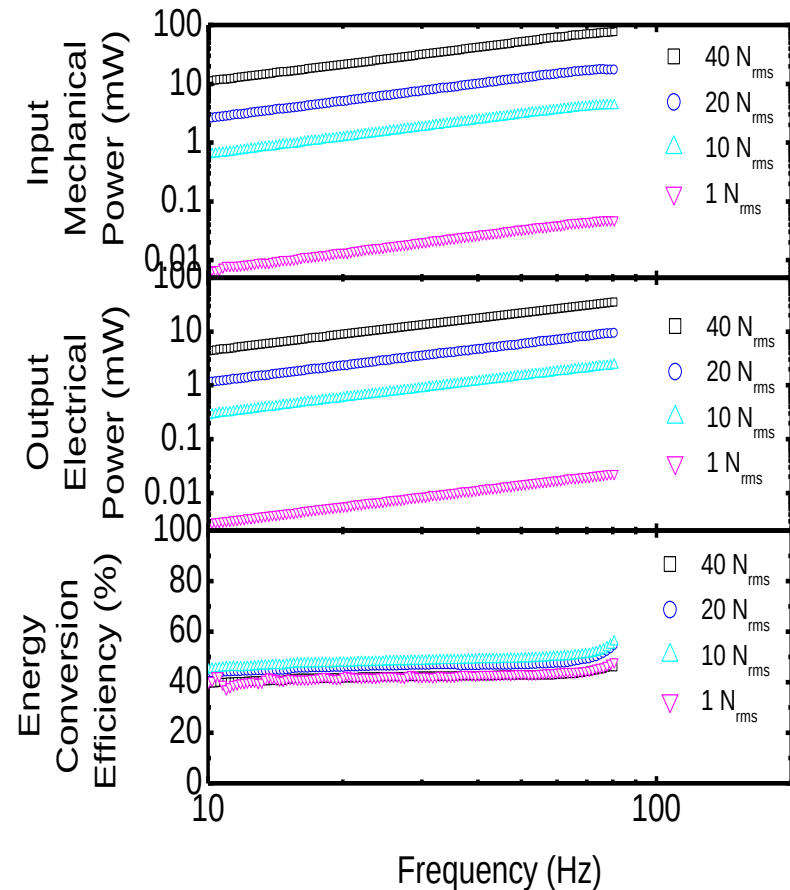
Outer Constituent:
Multi-stacked
 d_{33} effect in x-direction



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

Conversion Efficiency: >40%

Performance



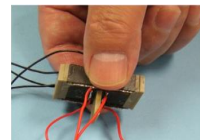
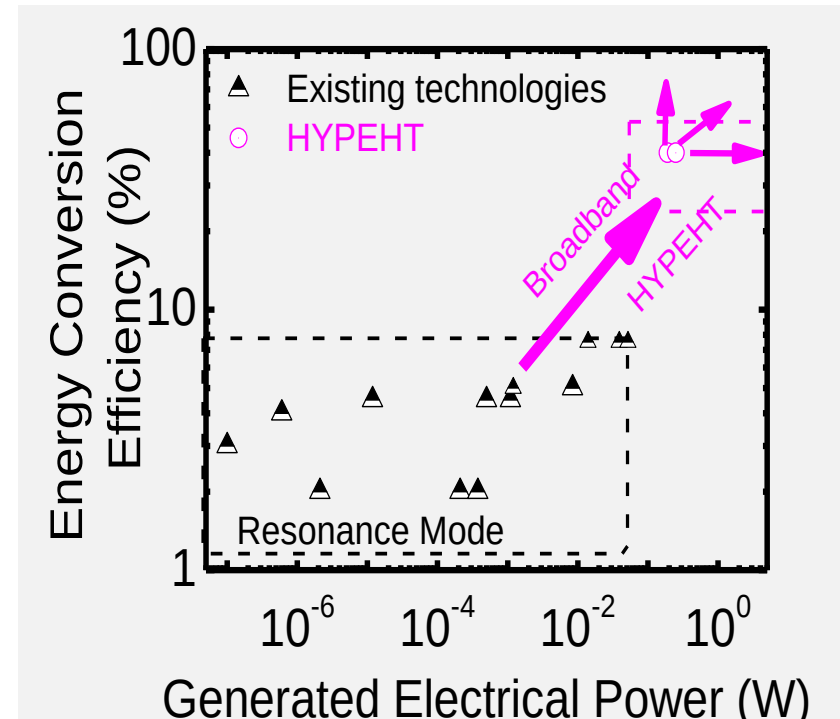


Recognition of the HYPEHT Energy Harvesting Technology

- A proven hybrid concept for advanced eletromechanical 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.

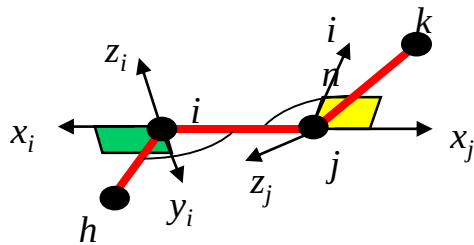




Computational Study of Mechanisms of G-elastomers

Formation of Element for the Model

Chemical Bond Element



Key Parameters Considered

Driving energy
(effective electric field)



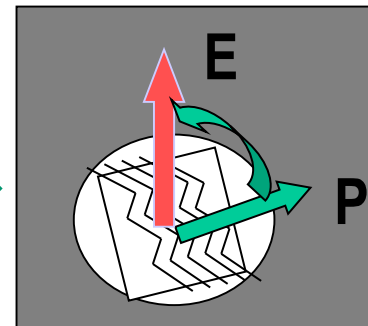
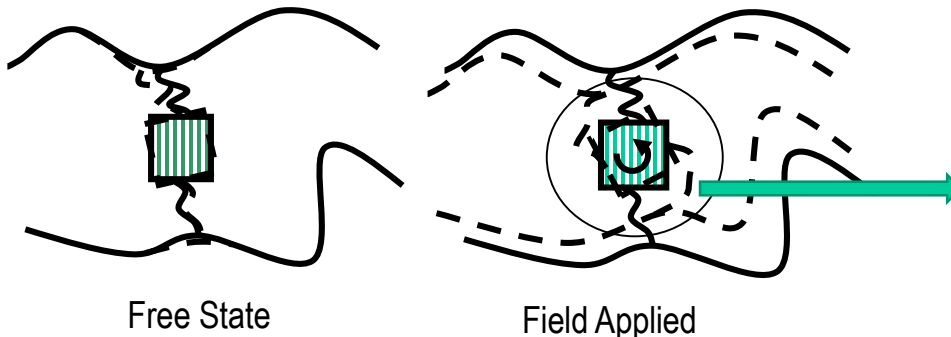
Field-induced Movement
(dimensional change)



Potential response
(polar domain/crystal structure)

Allowance
(free volume/backbone)

Deformation Mechanisms

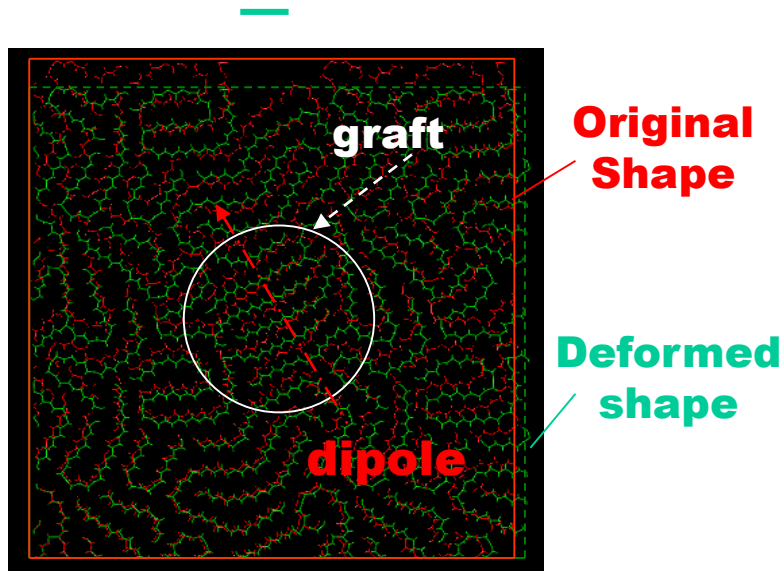


E: electric field
P: polarization

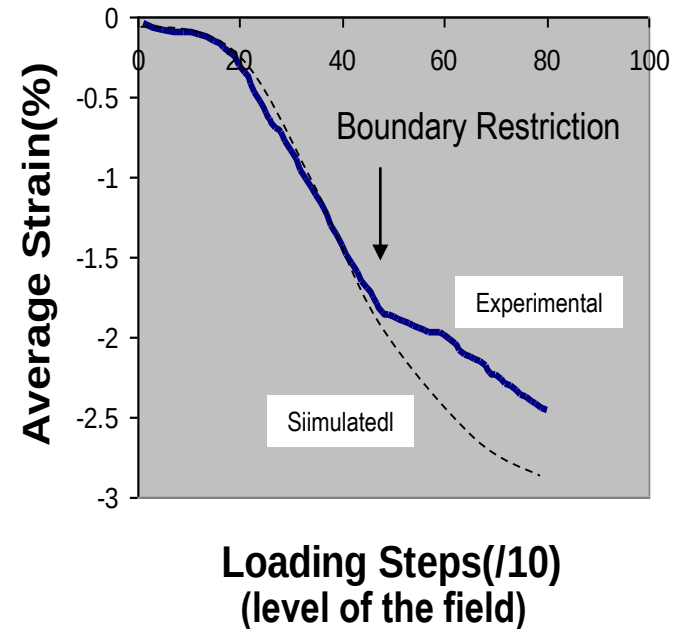


Comparison of Simulated Deformation of Electrostrictive G-elastomers and Experimental Results

Simulated Deformation

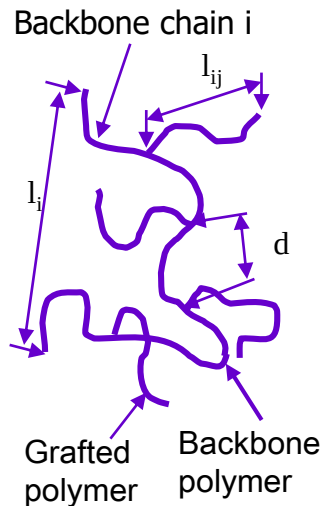


Comparison





Molecular Engineering for Property Control of Electrostrictive G-elastomers



Fraction of a grafted polymer

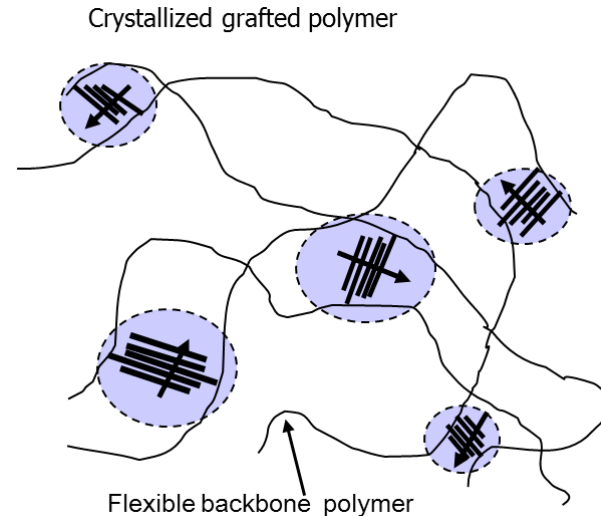
$$F = S_i S_j l_{ij} / (S_i l_i + S_j S_j l_{ij})$$

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

Crystal size and size distribution

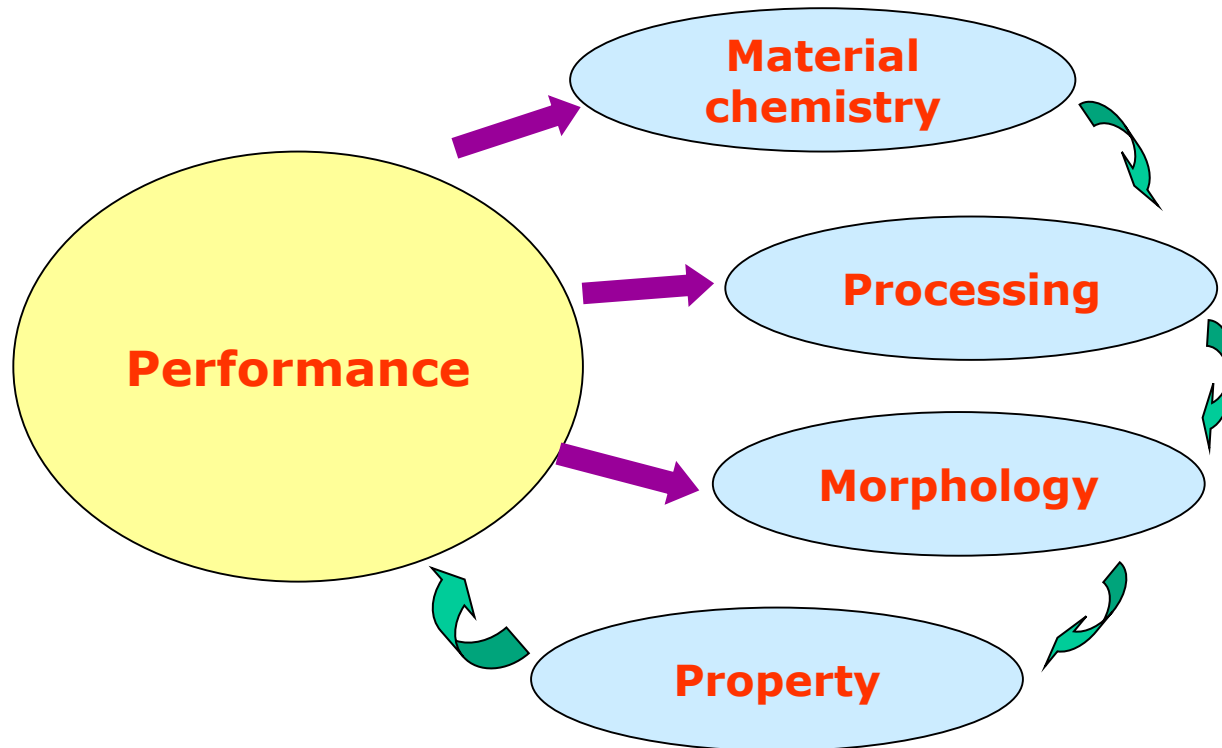
➡ Average length of grafted polymers $l = S_j l_{ij} / N_{ij}$

Cross-linking density and free volume

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



The Route to the Desired Electroactive Polymers





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

Opportunities = Challenges

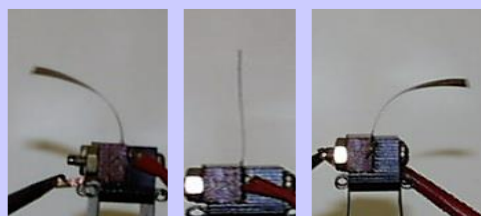
In order to make EAPs that may be used in many possible applications, the electroactivities need to be **intrinsic**. Molecular Engineering should be one of the ways to achieve the goal.



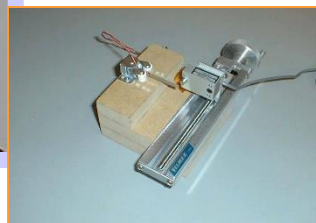
Some Applications in NASA Research Activities

Aerodynamic control Passive optics
Deformable mirror array Tunable antennas
Acoustic transducers

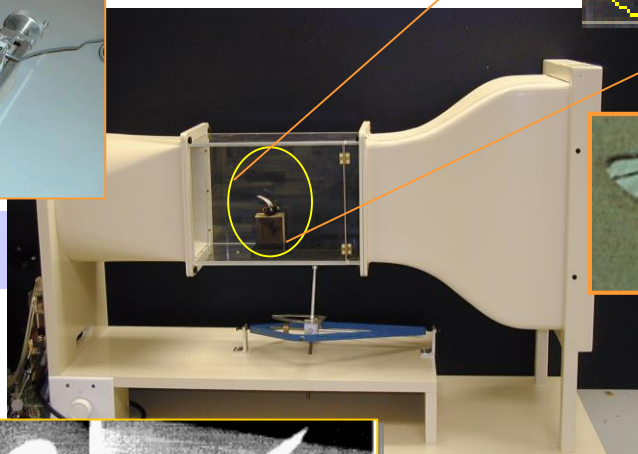
Bending actuators



Force-test



Wind-tunnel test



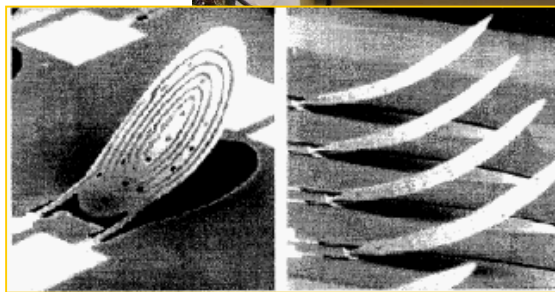
Air flow



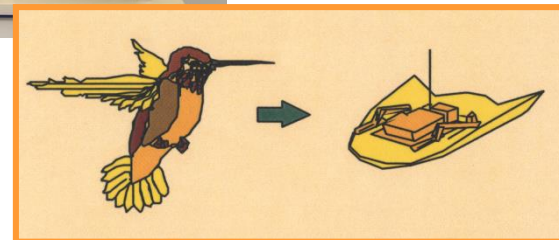
Sensor/actuator array

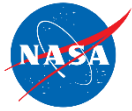


Self-sensing actuator array



Biomimetic
Micro-air vehicle





Acknowledgements

Dr. Tian-Bing Xu

National Institute of Aerospace (NIA)

Prof. Xiaoning Jiang and Laura Tolliver

NC State University

Prof. Lei Zuo and Dr. Wanlu Zhou

Virginia Tech

Drs. Shihai Zhang and Shan Wu

PolyK Technologies, LLC

Paul W. Rehrig

Saint-Gobain Innovative

Dr. Wesley S. Hackenberger

TRS Technologies

Dr. Muralidharan S. Nair

National Science Foundation

Dr. Qiming Zhang

Dr. Zoubeida Ounaies

Pennsylvania State University

Dr. Jerry I Scheinbeim

Rutgers University

Dr. Roy Kornbluh

SRI International

Dr. Joycelyn Harrison

Air Force Research Office

Dr. Yoseph Bar-Cohen

Jet Propulsion Laboratory

Dr. Peter X. Ma

University of Michigan

Dr. Peter Lellihi

Dr. William Cooks

Rheal Turcotte

Dr. Emilie Siochi

Dr. Kristin Pawloski

Dr. Terry St. Clair

NASA Langley Research Center

Ray Baughman

Lockhead Martin Corp

Dr. Changjie Sun

Dr. Chongjian Zhang

Dr. Youqi Wang

Kansas State University