

# Electroactive Polymer Actuators and Sensors

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Guest Editors

## Abstract

Polymers are highly attractive for their inherent properties of mechanical flexibility, light weight, and easy processing. In addition, some polymers exhibit large property changes in response to electrical stimulation, much beyond what is achievable by inorganic materials. This adds significant benefit to their potential applications.

The focus of this issue of *MRS Bulletin* is on polymers that are electromechanically responsive, which are also known as electroactive polymers (EAPs). These polymers respond to electric field or current with strain and stress, and some of them also exhibit the reverse effect of converting mechanical motion to an electrical signal.

There are many types of known polymers that respond electromechanically, and they can be divided according to their activation mechanism into *field-activated* and *ionic* EAPs. The articles in this issue cover the key material types used in these two groups, review the mechanisms that drive them, and provide examples of applications and current challenges. Recent advances in the development of these materials have led to improvement in the induced strain and force and the further application of EAPs as actuators for mimicking biologic systems and sensors. As described in this issue, the use of these actuators is enabling exciting applications that would be considered impossible otherwise.

## Introduction

Electroactive polymers (EAPs) are materials that respond mechanically to electrical stimulation. Their electromechanical response, exhibiting large strain when subjected to electrical stimulation, makes them the human-made actuators that most closely emulate natural muscles. For this ability, EAP materials have earned the name “artificial muscles.”<sup>1</sup> There are many polymers that are considered EAPs, and there are several different mechanisms that determine their response to electrical stimulation. Some of the leading types of EAP materials are covered in the six articles included in this special issue of *MRS Bulletin*.

Impressive advances in improving the actuation strain capability of EAPs are attracting the attention of engineers and scientists from many different disciplines. These materials are particularly attractive in biomimetics, since they can be used to mimic the movements of humans, ani-

mals, and insects for making biologically inspired mechanisms.<sup>2</sup> Increasingly, engineers are able to develop EAP-actuated mechanisms that were previously imaginable only in science fiction.

The electromechanical properties of some EAP materials enable them to serve as both actuators and sensors. When they are stimulated to respond with shape or dimensional changes, they can be used as actuators, while if they exhibit the inverse effect, they can be used as sensors or even power generators.

The polymer base of EAP materials allows many attractive properties and characteristics including low weight, fracture tolerance, and pliability. Further, they can be configured into almost any shape, and their properties can be tailored to suit a broad range of requirements.

For many years, it was known that certain polymers can be stimulated by electric, chemical, pneumatic, light, tem-

perature, or magnetic activation to change shape or size. However, the convenience and the practicality of electrical stimulation and the recent improvement in capabilities have made EAPs one of the most attractive among the mechanically responsive polymers.

## History and Currently Available EAP Materials

The field of EAPs can be traced back to an 1880 experiment conducted by Roentgen using a rubber strip with one end fixed and the other attached to a mass that was subjected to an electric field across the rubber band.<sup>3</sup> The strip responded to the stimulation with an elongation. Sacerdote<sup>4</sup> followed this experiment with a formulation of the strain response to electric-field activation. A subsequent progress milestone was recorded in 1925, with Eguchi's discovery of a method for making an electret by solidifying carnauba wax, rosin, and beeswax under a dc bias field.<sup>5</sup> Electrets are insulators—today typically made of polymer materials—that can hold a charge after being polarized in an electric field, similar to the way an iron bar is magnetized by exposure to a magnetic field. Electrets generate voltage when subjected to stress and deform when voltage is run across them. However, their strain and work output is generally too low to be applicable as actuators, and therefore their use has been limited to sensors. After the 1969 observation of substantial piezoelectric activity in poly(vinylidene fluoride) (PVDF),<sup>6</sup> investigators started to examine other polymer systems, and a series of effective EAP materials have emerged.<sup>7–12</sup> Polymers with significant mechanical response began to emerge at the beginning of the 1990s. Such EAP materials as dielectric elastomers were demonstrated to generate strains of more than 100% with a relatively fast response speed (<0.1 s).<sup>1,13,14</sup>

The key EAP material types known today and their activation mechanisms are illustrated in the articles in this issue. These material types are divided into two major groups: *field-activated* and *ionic* EAPs.

*Field-activated* EAPs are driven by the Coulomb interaction (electrostatic force) produced by the electric field created between the coating electrodes on films or by charge on a local scale. Strain manifests from molecular, microscopic, or macroscopic phenomena in response to an applied electric field (see Tables I and II as well as Figures 1 and 2). An applied electric field may induce a molecular conformation change as the dipoles are aligned

**Table I: Summary of the Leading Ionic and Field-Activated EAP Material Types.**

| EAP Material Types                                     | Principle  | Reported Materials   |
|--|--|--|
| <b>Field-Activated EAPs</b>                            |  |  |
| Ferroelectric polymers                                 | These polymers exhibit spontaneous polarization that can be switched by external electric fields. They can exhibit piezoelectric response when poled and electrostriction in nonpolar phase. Recent introduction of defects in PVDF-TrFE copolymer crystalline structure by electron irradiation or copolymerizing with a third bulky monomer dramatically increased the induced strain. | <ul style="list-style-type: none"> <li>■ Electron-radiated poly(vinylidene fluoride trifluoroethylene)</li> <li>■ PVDF-TrFE-based terpolymers</li> </ul>   |
| Dielectric EAPs or electrostatically stricted polymers | Coulomb forces between the electrodes squeeze the material, causing it to expand in the plane of the electrodes. When the stiffness is low, a thin film can be shown to stretch more than 100%.  | <ul style="list-style-type: none"> <li>■ Silicone</li> <li>■ Polyurethane</li> </ul>   |
| Electrostrictive graft elastomers                      | Electric field causes molecular alignment of the pendant group made of graft crystalline elastomers attached to the backbone.  | <ul style="list-style-type: none"> <li>■ Modified copolymer–PVDF-TrFE</li> </ul>   |
| <b>Ionic EAPs</b>                                      |  |  |
| Ionic gels   | Application of voltage causes movement of hydrogen ions in or out of the gel. The effect is a simulation of the chemical analogue of reaction with acid and alkaline.  | <ul style="list-style-type: none"> <li>■ Poly(vinyl alcohol) gel with dimethyl sulfoxide</li> <li>■ Poly(acrylonitrile) with conductive fibers</li> </ul>  |
| Ionomeric polymer–metal composites (IPMCs)             | The base ionomers provide channels for cations to move in a fixed network of negative ions on interconnected clusters. Mobile cations from the anode are responsible for the bending actuation.  | <p>Base ionomers:</p> <ul style="list-style-type: none"> <li>■ Nafion® (perfluorosulfonate, made by DuPont)</li> <li>■ Flemion® (perfluorocarboxylate, made by Asahi Glass, Japan)</li> </ul> <p>Cations: tetra-<i>n</i>-butylammonium, Li<sup>+</sup>, and Na<sup>+</sup></p> <p>Metal: Pt and Gold</p> |
| Conductive polymers (CPs)                              | Materials that swell in response to an applied voltage as a result of oxidation or reduction, depending on the polarity, causing insertion or de-insertion of (possibly solvated) ions.  | <ul style="list-style-type: none"> <li>■ Polypyrrole, poly(ethylene dioxythiophene), poly(<i>p</i>-phenylene vinylene)s, polyaniline, and polythiophenes</li> </ul>  |
| Carbon nanotubes (CNTs)                                | The carbon–carbon bond of nanotubes (CNTs) suspended in an electrolyte changes length as a result of charge injection that affects the ionic charge balance between the CNTs and the electrolyte.  | <ul style="list-style-type: none"> <li>■ Single- and multiwalled carbon nanotubes</li> </ul>   |

with the field. Examples include a piezoelectric strain concomitant with a ferroelectric response at crystalline phase, and a bulk elastic strain from local field changes at nonuniform material features and trapped space charges. Field-activated EAPs are covered in the article by Cheng et al. in this issue. Since the actuation does not involve diffusion of charge species, they respond quite fast ( $<10^{-3}$  s). This type of EAP can be made to hold the induced displacement while activated under a dc voltage without consuming electrical energy, making these EAPs highly efficient for robotic applications. These materials have a high mechanical energy density. However, generating a large deformation requires a high activation field of 100 V/ $\mu\text{m}$  or more, which may be close to the electric breakdown level. From a basic energy-conservation point of view, the required high activation

field is the result of the low dielectric constant in the polymer, which is typically  $<10$ . Substantially raising the dielectric constant of the activated polymer while maintaining a high electric breakdown strength is a challenge and a worthy research area to further advance field-activated EAPs. The performance of these EAPs may also be improved by employing multilayer structures with film thicknesses of  $<1 \mu\text{m}$ , to generate a high field with low voltage.

In contrast to the field-activated EAP materials, *ionic* EAPs are materials that involve drifting or diffusion of ions. They consist of an electrolyte between two electrodes. Examples of ionic EAP materials include ionic polymer–metal composites (IPMCs) (covered by Park and co-authors in this issue), conductive polymers (covered by Smela), and gels (covered by Calvert). Because of the actuation mecha-

nism (ionic motion) and their mechanical properties, carbon nanotube actuators (covered by Qu and co-authors) are also classified as ionic EAP materials.

Conductive polymers exhibit volume constriction as water and anions leave an oxidized polymer during reduction, and ionic polymer–metal composites with a stationary anionic framework have directional volume expansion as hydrated cations move toward one electrode. Gels show volume expansion as water forms at the anode and flows toward a cathode in a cell, and sheets of carbon nanotubes bend as carbon–carbon bond lengths change and cation surface charges interact with the applied field. One unique advantage is that the activation of the ionic EAP can be done by as low as 1–2 V. On the other hand, high current density is required in order to make up for the electrical energy input in actuation. The macroscopic

**Table II: Advantages and Disadvantages of the Two EAP Groups.**

| EAP Group            | Advantages  | Disadvantages   |
|----------------------|---|---|
| Ionic EAPs           | Low-voltage operation   | Slow response (fraction of a second)<br>The material bends with a relatively low actuation force<br>Low efficiency<br>In aqueous-based systems, the material sustains hydrolysis at >1.23 V |
| Field-activated EAPs | Room-temperature operation for a long time<br>Rapid response (ms)<br>Induce relatively large actuation forces | Require high fields (as much as 200 V/ $\mu\text{m}$ )  |

motion of charged species, responsible for the actuation, results in low actuation speed (on the order of seconds). Their disadvantages are the need to maintain wetness (electrolytes) and their low efficiency (~1%).

An emerging field in EAPs is molecular motors (Figure 3), which are organic molecules displaying huge shape change under electric excitation (covered by Huang in this issue). Recent advances in this field of EAPs have led to strains of 40%–60% and energy densities at the molecular level of ~50 J/cm<sup>3</sup>. Having such energy density values make these motors potentially able to perform significant manipulation tasks at micron scales. Integrating such molecular EAP materials into nanoscale and mesoscale devices, although a great challenge, can potentially

lead to exciting new applications in the EAP field.

Despite the enormous progress that has been made in recent years, EAP materials are still far from being considered the actuator material of first choice by engineers and designers. Some of the current limitations of EAP materials include their low durability and performance reproducibility, as well as the lack of established databases and standard products. To reach the required level of maturity, there is a need for establishing scientific and engineering foundations. Improving understanding of the basic principles that drive the various EAP material types, designing effective computational chemistry models and electromechanical analytical tools, developing comprehensive knowledge of the related materials sci-

ence, and enhancing materials processing techniques are required. To address the materials limitations and lay further groundwork in the field, studies are under way. This research will provide pathways to gain better understanding and characterization of the parameters that control the force and deformation response of EAP materials. Meanwhile, efforts are being made to develop effective processes for synthesizing, fabricating, electroding, shaping, and handling these materials. Databases are being established to support users of these materials.

### Applications of EAPs

The properties of EAP materials, which include resilience, fracture tolerance and operation similarity to biological muscles, make them very attractive for a wide variety of biomimetic, robotic, and engineering applications. In recent years, there has been significant progress in the field of EAPs toward making practical actuators, and commercial products are starting to emerge. Successful devices that have been reported use the ability of such EAPs as the IPMC to bend significantly under low-voltage activation as well as dielectric elastomers to produce large strain. Some reported EAP-actuated devices include audio speakers, focus control for cameras in cellular telephones, miniature manipulators and grippers, active diaphragms for pumps, and a dust wiper for a rover in a space application.<sup>1</sup>

At the end of 2002, an EAP-actuated product was announced by Eamax, Japan,

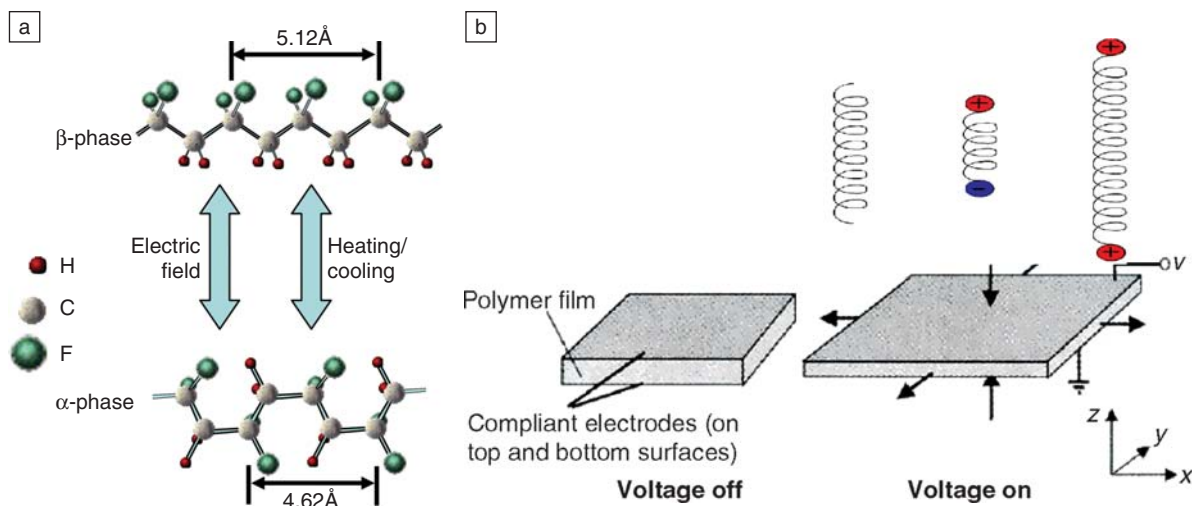


Figure 1. Illustration of the drive mechanisms of the field-actuated electroactive polymer (EAP) materials covered in this issue. Further details are covered in the article by Cheng et al. (a) Blue and red circles represent oppositely charged side groups in poly(vinylidene fluoride). Applying an electric field causes molecular shape change associated with changes in dipolar density and induces large strain in the polymers. (b) Electrostatic force can generate large deformation on soft polymers with high electric breakdown strength. The figure shows a polymer before and after application of an electric field. The presence of opposite charges at the electrodes that coat the polymer give rise to compression. The deformation is related to the softness of the spring (soft polymers) and the amount of charge at the electrodes.

and it is a biomimetic device in the form of a robot that looks and acts like a fish in an aquarium. The operation of a large EAP actuator was demonstrated in March 2007, during the SPIE's EAP-in-Action conference. Dielectric elastomer EAP strips were used to bend fins of a 3-m-long blimp made by EMPA, Switzerland, steering it inside the conference room. Furthermore, various organizations are considering mechanisms that are applicable to aerospace, automobiles, medicine, robotics, exoskeletons, articulation mechanisms, entertainment, toys, clothing, haptic and tactile interfaces, noise control, transducers, power generators, and smart structures. The use of EAPs for medical applications is being considered in an effort to produce either smart prosthetics or assistive devices that are external or internal to the human body as well as effective medical tools such as a steering mechanism for catheters. While still far from practical, making effective prosthetics that are lightweight and that perform like natural limbs can be one of the benefits of having robust EAPs that generate large strain and force.

Generally, the application of EAP materials as actuators for driving manipulation, mobility, and robotic devices involves disciplines that include materials science, chemistry, electromechanics, control and computer algorithms, and electronics. To minimize the complexity associated with the need for a broad range of expertise, efforts are being made to establish databases and commercial EAP products (see links for initiatives of databases at <http://eap.jpl.nasa.gov/>).

Space applications are among the most demanding in terms of the harshness of the operating conditions (extreme temperatures, high pressure or vacuum, radiation effects, and very high reliability and durability requirements). Space applications are in great need of materials that can operate in a wide temperature range, between nearly absolute zero up to hundreds of degrees Celsius. The EAP materials today are not applicable to handle the related challenges.

Another challenge in aerospace is the need for large-scale EAPs in the form of films and fibers. The required dimensions can be as large as several meters or kilometers, and in such dimensions, they can be used to produce large gossamer structures such as antennas, solar sails, and various large optical components. Biomimetic capabilities using EAP material will potentially allow space agencies to conduct missions on other planets using robots that emulate human operation.

In an effort to promote the realization of the potential of EAP materials, one of the

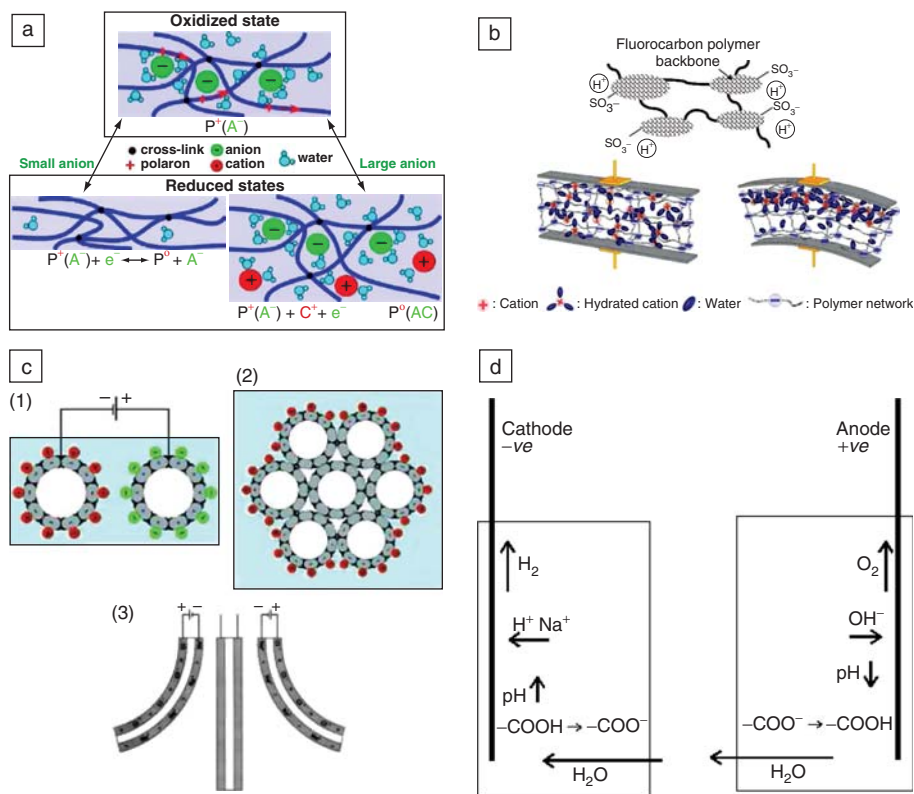


Figure 2. Illustration of the actuation mechanisms of the ionic EAP materials covered in this issue. (a) The movement of either anions or cations during oxidation and reduction generates a volume change in a conducting, conjugated polymer (covered in Smela's article). (b) Ionic polymer metal composites bend in response to an electric field as volume increases at one electrode and decreases at the other (covered in the article by Park et al.). (c) Application of a voltage on single, bundled, or sheets of carbon nanotubes in an electrolyte generates charged surfaces in the materials. Accompanying changes in carbon-carbon bond lengths allows controlled bending (covered in the article by Qu et al.). (d) Application of voltage causes bending in salt-free acidic hydrogel, since water uptake and swelling occurs near the embedded cathode (left) and water loss and shrinkage near the embedded anode (right) (covered in the article by Calvert).

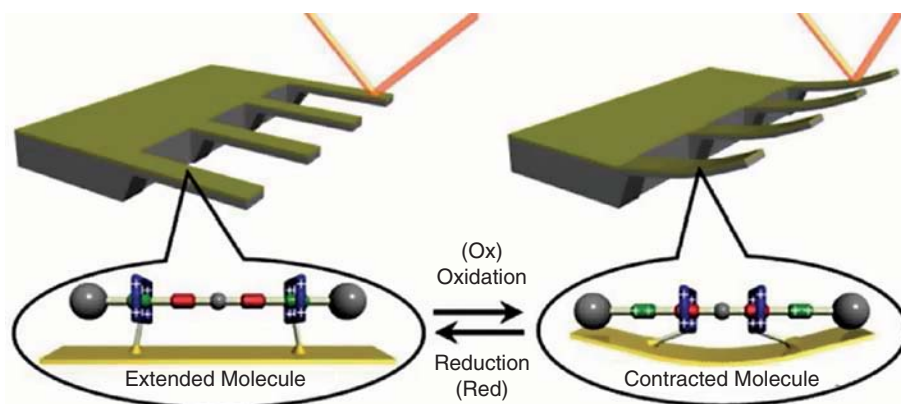


Figure 3. Molecular motors, where shape change on the molecular level is used to form an actuator (covered in Huang's article). Principle: An artificial molecular muscle called bistable [3]rotaxane is composed of a symmetrical dumbbell component with two rings interlocked onto the dumbbell. The distance between the two rings contracts and extends upon oxidation and reduction. These molecular muscles, when self-assembled on microcantilever beams, are capable of bending and stretching the beams upon oxidation and reduction.

guest editors of this special issue posed an arm-wrestling challenge: human versus EAP-actuated robotic arm.<sup>15</sup> Success in developing materials and controlling them in devices to robotically arm-wrestle against a human will enable additional capabilities that are currently considered impossible. It would allow applying EAP materials to improve many aspects of our life, including more effective implants and prosthetics, active clothing, and realistic biologically inspired robots, as well as fabricating products with unmatched capabilities and dexterity.

## Summary and Outlook

For many years, electroactive polymers received relatively little attention, due to their limited actuation capability at the level of a fraction of a percent of strain and the small number of available materials.

Since the early 1990s, a series of new EAP materials have emerged that exhibit large strain levels from 4% to more than 100% and elastic energy density exceeding 1 J/cm<sup>3</sup> in response to electrical stimulation. This capability of the new EAP materials made them attractive as actuators for their operational similarity to biological muscles, particularly their resilience, damage tolerance, and ability to induce large actuation strains (stretching, contracting, or bending).

Even though the actuation performance of existing EAP materials and their robustness require further improvement, there have already been reported successes in the development of EAP-actuated mechanisms. Most of the considered applications are still far from being practical. While there are many potential applications, if EAP materials are developed to operate internal organs inside a human body, this

technology can have a tremendously positive impact on many human lives.

To make the *field-activated* EAP materials applicable for commercial devices, it is necessary for them to produce large strain using dramatically lower voltages than currently needed. This may be achieved by increasing the polymer dielectric constant using support fillers to form effective composite EAP materials. Meanwhile, advancing the *ionic* group of EAP materials requires increasing their response speed and lifetime and developing new materials that can be operated in “dry” environments by adding an effective protective coating layer or working with solvents of near-zero vapor pressure. Addressing these challenges to improving the capability and performance of EAP materials requires a better understanding of their operation mechanism along with improved fabrication and characterization techniques.

The field of EAPs is far from mature; however, the number of researchers and engineers who are pursuing careers in EAP-related disciplines is steadily increasing, which is helping to address the challenges in the field and enhance the capabilities of the materials. In order to exploit the highest benefits from EAPs, multidisciplinary cooperative efforts need to grow among scientists and engineers, including such experts as chemists, materials scientists, roboticists, computer and electronic engineers, and medical professionals. Advances are needed in developing a better understanding of the material behavior. Effective sensors and control algorithms are needed to address the unique and challenging requirements for practical EAP actuators.

Despite their limitations, EAPs have unique properties that could fit niche actuation, sensing, and biomimetic appli-

cations. The materials community continues to develop devices and applications that take advantage of the current state of the art of EAPs.

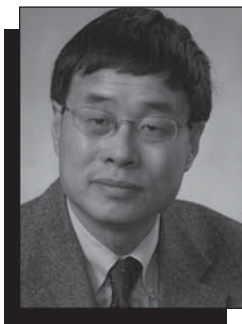
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Bar-Cohen is a fellow of SPIE and the American Society for Nondestructive Testing. He has received NASA Honor Awards for exceptional engineering (2001) and technology achievements (2006), SPIE Lifetime Achievement

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Fitzsimmons</b><br/>Los Alamos National Laboratory<br/>tel. 505-665-4045<br/><a href="mailto:fitz@lanl.gov">fitz@lanl.gov</a></p> <p><b>Young-Chang Joo</b><br/>Seoul National University<br/>tel. 82-2-880-8986<br/><a href="mailto:yjoo@snu.ac.kr">yjoo@snu.ac.kr</a></p> <p style="text-align: center;">***</p> <p>For Additional Information,<br/>visit the MRS Web site at<br/><a href="http://www.mrs.org/meetings/">www.mrs.org/meetings/</a></p> <p>or contact:</p> <p><b>Member Services</b><br/>Materials Research Society<br/>506 Keystone Drive<br/>Warrendale, PA 15086-7573<br/>tel. 724-779-3003<br/>fax: 724-779-8313<br/><a href="mailto:info@mrs.org">info@mrs.org</a></p> | <p><b>Electronics, Photonics, and Magnetism</b></p> <p>A: Performance and Reliability of Semiconductor Devices<br/>B: Transparent Conductors and Semiconductors for Optoelectronics<br/>C: Theory and Applications of Ferroelectric and Multiferroic Materials<br/>D: Rare-Earth Doping of Advanced Materials for Photonic Applications<br/>E: Materials and Technologies for 3-D Integration<br/>F: Low-Cost Solution-Based Deposition of Inorganic Films for Electronic/Photonic Devices<br/>G: Organic and Hybrid Materials for Large-Area Functional Systems<br/>H: Physics and Technology of Organic Semiconductor Devices<br/>I: Reliability and Properties of Electronic Devices on Flexible Substrates<br/>J: Material Science for Quantum Information Processing Technologies<br/>K: Magnetic Nanostructures by Design<br/>L: New Materials with High Spin Polarization and Their Applications</p> <p><b>Energy and the Environment</b></p> <p>M: Energy Harvesting—Molecules and Materials<br/>N: Next-Generation and Nano-Architected Photovoltaics<br/>O: Structure/Property Relationships in Fluorite-Derivative Compounds<br/>P: Photovoltaic Materials and Manufacturing Issues<br/>Q: Scientific Basis for Nuclear Waste Management XXXII<br/>R: Materials for Future Fusion and Fission Technologies<br/>S: Solid-State Ionics<br/>T: Mobile Energy<br/>U: Advanced Intermetallic-Based Alloys for Extreme Environment and Energy Applications</p> <p><b>Engineered Materials and Modeling</b></p> <p>V: Materials, Devices, and Characterization for Smart Systems<br/>W: Computational Materials Design via Multiscale Modeling<br/>Y: Biomineral Interfaces—From Experiment to Theory</p> <p>Z: Mechanics of Biological and Biomedical Materials<br/>AA: Materials for Optical Sensors in Biomedical Applications<br/>BB: Polymer-Based Smart Materials—Process, Properties, and Application<br/>CC: Design, Fabrication, and Self Assembly of “Patchy” and Anisometric Particles<br/>DD: Materials in Tissue Engineering</p> <p><b>Nanoscience</b></p> <p>EE: Nano- and Microscale Materials—Mechanical Properties and Behavior under Extreme Environments<br/>FF: Nanofunctional Materials, Structures, and Devices for Biomedical Applications<br/>GG: Microelectromechanical Systems—Materials and Devices II<br/>HH: Advances in Material Design for Regenerative Medicine, Drug Delivery, and Targeting/Imaging<br/>II: Bio-inspired Transduction, Fundamentals, and Applications<br/>JJ: Nanotubes, Nanowires, Nanobelts, and Nanocoils—Promise, Expectations, and Status<br/>KK: Transport Properties in Polymer Nanocomposites<br/>LL: Nanowires—Synthesis, Properties, Assembly, and Application<br/>MM: Applications of Group IV Semiconductor Nanostructures</p> <p><b>Synthesis and Characterization</b></p> <p>NN: <i>In-situ</i> Studies across Spatial and Temporal Length Scales for Nanoscience and Technology<br/>OO: Grazing-Incidence Small-Angle X-Ray Scattering<br/>PP: Solid-State Chemistry of Inorganic Materials VII<br/>QQ: Synthesis and Processing of Organic and Polymeric Functional Materials for a Sustainable Energy Economy<br/>RR: Artificially Induced Grain Alignment in Thin Films<br/>SS: Selecting and Qualifying New Materials for Use in Regulated Industries<br/>TT: Local Structure and Dynamics in Amorphous Systems</p> <p><b>General Interest</b></p> <p>X: Frontiers of Materials Research</p> | <p><b>Symposium Tutorial Program</b></p> <p>Available only to meeting attendees, the symposium tutorials will concentrate on new, rapidly breaking areas of research.</p> <p><b>Exhibit</b></p> <p>A major exhibit encompassing the full spectrum of equipment, instrumentation, products, software, publications, and services is scheduled for December 2-4 in the Hynes Convention Center. 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