Electroactive Polymer Actuators and Sensors

Yoseph Bar-Cohen and Qiming Zhang, 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.”

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, animals, and insects for making biologically inspired mechanisms. Increasingly, engineers are able to develop EAP-actuated mechanisms that were previously unimaginable 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, temperature, 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. The strip responded to the stimulation with an elongation. Sacerdote 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. 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), investigators started to examine other polymer systems, and a series of effective EAP materials have emerged.

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).

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...
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 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 µm, 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 mechanism (ionic motion) and their mechanical properties, carbon nanotubes are classified as ionic EAP materials.

Conductive polymers exhibit volume contraction 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
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/cm³. 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 science, 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, electrodoping, 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 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. 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.

At the end of 2002, an EAP-actuated product was announced by Eamax, Japan.
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 data-bases 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 changes 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.\textsuperscript{13} 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 life, including more effective implants and materials to improve many aspects of our impossible. It would allow applying EAP against a human will enable additional them in devices to robotically arm-wrestle developing materials and controlling.

**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\(^3\) 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 applications. The materials community continues to develop devices and applications that take advantage of the current state of the art of EAPs.

**References**


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**Yoseph Bar-Cohen**

Yoseph Bar-Cohen, Guest Editor for this issue of MRS Bulletin, is a senior research scientist and

**Qiming Zhang**

group supervisor at the Jet Propulsion Laboratory (JPL). He received his PhD degree in physics from the Hebrew University of Jerusalem in 1979.

In the Nondestructive Evaluation and Advanced Actuators (NDEAA) Technologies laboratory, established by Bar-Cohen in 1991, he leads the development of many novel methods and mechanisms. He initiated the SPIE Conference on Electroactive Polymer Actuators and Sensors (EAPAD) and has been chair of this conference since 1999. In April 2003, Business Week named Bar-Cohen as one of five researchers who are “Pushing Tech’s Boundaries.” To demonstrate the properties of EAPs, he staged arm-wrestling matches between an EAP-driven robotic arm and a human in 2005 and 2006. 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 Awards for nondestructive evaluation (2001) and smart materials and structures (2005), and many other honors. Bar-Cohen has authored or co-authored more than 320 publications and holds 19 registered patents. He is the editor or co-author of four books and has chaired or co-chaired 37 international symposia and conferences. Bar-Cohen can be reached at the Advanced Technologies Group and NDEAA Laboratory, Jet

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Ray H. Baughman

Paul Calvert

Zhongyang Cheng

Liming Dai

Tony Jun Huang

Pyrotechnion Laboratory, MS 67-119, 4800 Oak Grove Dr., Pasadena, CA 91109 USA; tel. 818-354-2610 and e-mail yosi@jpl.nasa.gov.

Qiming Zhang, Guest Editor for this issue of MRS Bulletin, is a Distinguished Professor of Electrical Engineering and Materials Science and Engineering at the Pennsylvania State University. He is a graduate of Nanjing University in China and obtained his PhD degree in 1986 from Penn State. Zhang worked at Brookhaven National Laboratory after his graduate study. His research interests include fundamentals and applications of electronic and electroactive polymers (EAPs) and nanocomposites. Research activities in Zhang’s group cover EAP actuator and sensor materials, transducers, dielectrics and charge storage devices, polymer thin films and polymer MEMS, and electro-optic and photonic materials and devices. He has authored or co-authored more than 270 publications and nine patents in these areas. He is a fellow of IEEE.

Zhang can be reached at 187 Materials Research Laboratory, the Pennsylvania State University, University Park, PA 16802 USA; tel. 814-863-8994 and e-mail qzzi@psu.edu.

Ray H. Baughman is the Robert A. Welch Professor of Chemistry and director of the NanoTech Institute at the University of Texas at Dallas. He holds a BS degree in physics from Carnegie Mellon University and a PhD degree in materials science from Harvard University.

Upon graduation, Baughman joined Allied Chemical, which later became AlliedSignal and Honeywell. He was a corporate fellow of Honeywell/AlliedSignal until joining UT–Dallas in 2001, receiving technical achievement awards for developing new products in the areas of time-temperature indicators, polyamine compositions and applications, and sonar hydrophones.

Baughman is a member of the National Academy of Engineering; a fellow of the American Physical Society and the World Innovation Foundation; an academician of the Russian Academy of Natural Sciences; and an honorary professor at three universities in China. He serves on the editorial or advisory boards of Science, Synthetic Metals, the International Journal of Nanoscience, and the Encyclopedia of Nanoscience and Nanotechnology.

Baughman holds 57 U.S. patents and has more than 280 publications, with over 11,000 citations. He has recently received the New Materials Innovation Prize of the Avantex International Forum (2005), two Nano 50 Awards (2006 and 2007), the Scientific American 50 List recognition, Australia’s NanoVic Prize (2006), the Alumni Distinguished Achievement Award from Carnegie Mellon University, and the Kapitza Medal from the Russian Academy of Natural Sciences (2007). Baughman can be reached at the NanoTech Institute, University of Texas at Dallas, Richardson, TX 75083 USA; e-mail ray.baughman@utdallas.edu.

Paul Calvert is a professor in the Materials and Textiles Department at the University of Massachusetts Dartmouth. He studied materials science at the University of Cambridge and the Massachusetts Institute of Technology.

Calvert then joined the School of Molecular Sciences at Sussex University in 1972, where he taught polymer science. In 1988, he joined the Department of Materials Science and Engineering at the University of Arizona.

In 2003, Calvert went to University of Massachusetts Dartmouth as chair of what was the Textile Sciences Department. In this position, he oversaw the department’s conversion into a materials department with a focus on soft materials.

Calvert’s research interests have migrated through polymer crystalization, composite materials, crystal-induced joint diseases, ceramics processing, biomimetic materials, and processing. His current research is focused on methods to print soft electronics and biological materials.

Calvert can be reached at the Department of Materials and Textiles, Rm. 213, University of Massachusetts Dartmouth, 285 Old Westport Rd., North Dartmouth, MA 02747 USA; tel. 508-999-8355 and e-mail pcalvert@umassd.edu.

Zhongyang Cheng is an associate professor in the Materials Research and Education Center and the Department of Mechanical Engineering at Auburn University.

Cheng received his BS degree in applied physics, his MS degree in electronic materials and components, and his PhD degree in electronic engineering from Xi’an Jiaotong University, China. After graduation, Cheng went to Heinrich Hertz Institute in Germany, where he was a visiting scientist. He then worked as a post-doctoral research associate at the University of Puerto Rico. Prior to joining Auburn University in 2002, Cheng was a research associate at the Pennsylvania State University for four years.

Cheng’s research interests include various smart materials (ferroelectric, piezoelectric, and dielectric ceramics and polymers, magnetostrictive alloys, ceramic–polymer composites) and their applications in actuators, transducers, sensors, and biosensors.

Cheng can be reached at 275 Wilmore Laboratory, Materials Engineering, Auburn University, Auburn, AL 36849 USA; tel. 334-844-3419 and e-mail chengzh@eng.auburn.edu.

Liming Dai is the Wright Brothers Institute endowed Chair Professor of Nanomaterials in the Department of Mechanical Engineering at Auburn University.

Dai has a BS degree in chemical engineering (1988) from Xi’an Jiaotong University and a PhD degree in polymer science from the University of Illinois at Urbana-Champaign (1993). Dai has authored or co-authored more than 280 publications and nine patents in these areas. Dai is a fellow of the American Physical Society, member of the Materials Research Society, and guest editor of the MRS Bulletin. Dai has served on the editorial boards of the Journal of the American Chemical Society, Langmuir, and the Journal of Polymer Science.

Dai holds 13 patents and has been awarded the R&D 100 Award for Marangoni Films and 2007 Nano 50 List recognition. Dai’s research interests include polymer nanocomposites, polymer thin films and coatings, and electronic materials.

Dai can be reached at the Department of Materials Science and Engineering, Auburn University, 285 Old Westport Rd., North Dartmouth, MA 02747 USA; tel. 508-999-8355 and e-mail lxdai@auburn.edu.
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Chemistry and the University of Dayton Research Institute.

Dai’s expertise ranges across several fields, including synthesis, chemical modification, and device fabrication of conjugated polymers, fullerene-containing polymers, and carbon nanotubes. He has authored or co-authored approximately 200 peer-reviewed journal articles, review papers, and book chapters. Dai also has published a research monograph on intelligent macromolecules and an edited book on carbon nanotechnology and holds roughly 20 registered or provisional patents.

He has received several awards, including the 2006 Sigma Xi George B. Noland Research Award and the 2006 Outstanding Engineers and Scientists Award from the Affiliate Societies Council of Dayton.

Dai can be reached at the Department of Chemical and Materials Engineering, School of Engineering, University of Dayton, 300 College Park, Dayton, OH 45469 USA; tel. 937-229-2670 and e-mail ldai@udayton.edu.

Tony Jun Huang is the James Henderson Assistant Professor of Engineering Science and Mechanics at the Pennsylvania State University.

He received a PhD degree in mechanical and aerospace engineering from the University of California, Los Angeles, in 2005, and his BS and MS degrees in energy and power engineering from Xi’an Jiaotong University in China in 1996 and 1999, respectively.

Huang’s research interests include biomedical nano-electro-mechanical systems (bio-NEMS), molecular mechanics, nanomaterials and nanodevices, and microfluidics. He has received honors such as the 2006 Rustom and Della Roy Innovation in Materials Research Award from Penn State and “one of the five most intriguing articles in the third quarter of 2005” by CAS Science Spotlight.

Huang can be reached at the Department of Engineering Science and Mechanics, the Pennsylvania State University, 212 Earth-Engineering Sciences Bldg., University Park, PA 16802 USA; tel. 814-863-4209 and e-mail junhuang@psu.edu.

Kwangmok Jung is a postdoctoral scholar in the Department of Mechanical Engineering at the University of Nevada, Reno.

He graduated from Yonsei University, South Korea, in 1997 and received his MS and PhD degrees from Inha University in Korea, and his PhD degree in mechanical engineering from the University of Nevada, Reno.

Jung’s main research interests include electrochemical analysis and metallization for various applications. He also has five years of industrial experience, specializing in electrochemistry.

Jung can be reached by e-mail at kwang@unr.edu.

Doyeon Kim is a principal engineer at FormFactor Inc. in Livermore, California. He received his BS and MS degrees in chemical engineering from Inha University in Korea, and his PhD degree in mechanical engineering from the University of Nevada, Reno.

Kim’s main research interests include electrochemical analysis and metallization for various applications. He also has five years of industrial experience, specializing in electrochemistry.

Kim can be reached at FormFactor Inc., 7005 SouthFront Rd., Livermore, CA 94551 USA; tel. 925-290-4000.

Kwang J. Kim is professor and chair of the Mechanical Engineering Department and director of both the Active Materials and Processing Laboratory and the Advanced Energy Laboratory at the University of Nevada, Reno.

He graduated from Yonsei University, South Korea, in 1987 and received his MS and PhD degrees from Arizona State University in 1989 and 1992, respectively. Afterward, Kim completed his postdoctoral study at the University of Maryland.

Kim was a senior research engineer at Thermal Electric Devices Inc. from 1995 to 1997 and chief scientist at Environmental Robots Inc. in Albuquerque, N.M., from 1997 to 2001. He was also an adjunct professor at the University of New Mexico from 1996 to 2001. He joined UNR as an assistant professor in 2001, becoming a full professor in 2007.

Kim’s research interests are in a broad spectrum of active materials, sensors, and renewable energy systems. He has authored and co-authored more than 200 technical papers, including over 90 refereed jour-

Sang-Mun Kim is a doctoral student in the Department of Mechanical Engineering at the University of Nevada, Reno.

Kim received his MS degree in ceramic engineering at Yonsei University in 2004 and his BS degree in materials science and engineering at Kunsan National University in 2001. He worked as a student researcher on optical thin-film materials, including a 3D electromagnetic simulation based on semiconducting processes at the Korea Institute of Science and Technology.

Kim’s current research interests at the UNR
Electroactive Polymer Actuators and Sensors

Qiang Peng

Liangti Qu

Elisabeth Smela

Geoffrey M. Spinks

Gordon G. Wallace

Active Materials and Processing Laboratory include development and applications of electroactive-polymer-based artificial-muscle-driven biorobotic actuators.

Park can be reached at the Mechanical Engineering Department, University of Nevada, Reno, Reno, NV 89577 USA; e-mail ilseok@unr.nevada.edu.

Il-Seok Park is a postdoctoral research scholar in the Active Materials and Processing Laboratory at the University of Nevada.

Park received his PhD degree in ceramic engineering from Yonsei University, South Korea, in 2005, and his MS and BS degrees in aviation materials engineering from Korea Aerospace University in 1997 and 1995, respectively. His research experience includes an internship and a student researcher position at the Korea Institute of Science and Technology.

He has published 38 technical papers and holds five Korean patents with two pending. Park’s research is based in biomaterials (all-ceramic dental crowns, artificial hip joints, and ceramic implants) and electronic components. His current research interests are in artificial-muscle materials and hydrogen energy systems.

Park can be reached at the Mechanical Engineering Department, University of Nevada, Reno, Reno, NV 89577 USA; e-mail ilseok@unr.edu.

Qiang Peng is a postdoctoral researcher in Liming Dai’s group at the University of Dayton, Ohio. Peng received his PhD degree in organic chemistry from Sichuan University in China in 2004. Through August 2006, he held a Singapore Millennium Foundation postdoctoral fellowship in the Department of Chemical and Biomolecular Engineering at the National University of Singapore.

Peng’s research areas include the synthesis and characterization of organic/polymer optoelectronic materials, nanomaterials, and devices.

Peng can be reached at the Department of Chemical and Materials Engineering, School of Engineering, University of Dayton, Dayton, OH 45469 USA; e-mail pengqian@notes.udayton.edu.

Liangti Qu is a member of professor Liming Dai’s research group at the University of Dayton. Qu received his PhD degree in chemistry from Tsinghua University in Beijing, China, in 2004. Afterward, he joined professor Dai’s group at the University of Dayton. His current work focuses on the preparation of ordered carbon-based nanomaterials, including aligned single-walled and multivalled carbon nanotubes, and their selective functionalization with inorganic and organic nanocomponents for various applications.

Qu can be reached at the Department of Chemical and Materials Engineering, School of Engineering, University of Dayton, Dayton, OH 45469 USA; e-mail quliangz@notes.udayton.edu.

Elisabeth Smela is an associate professor in the Department of Mechanical Engineering at the University of Maryland.

She received her BS degree in physics from the Massachusetts Institute of Technology and completed her PhD degree in electrical engineering at the University of Pennsylvania. Smela then worked at Linköping University in Sweden and at Risø National Laboratory in Denmark.

In 1999, she joined the startup company Santa Fe Science and Technology in New Mexico as vice president of research and development. Her research interests are in polymer MEMS and bioMEMS and more generally in combining organic materials with conventional inorganic materials to make new microscale devices.

Smela is a recipient of the Presidential Early Career Award for Scientists and Engineers, the DuPont Young Professor Award, the Clark School’s E. Robert Kent Outstanding Teaching Award for Junior Faculty, and UM’s Outstanding Invention of the Year Award in 2004. She has published more than 50 journal papers, of which three have appeared in Science. Smela can be reached at the Department of Mechanical Engineering, University of Maryland, 2176 Glenn L. Martin Hall, College Park, MD 20742 USA; tel. 301-405-5265, e-mail smela@eng.umd.edu, and URL www.wam.umd.edu/~smela.

Geoffrey M. Spinks is a professor of materials engineering at the University of Wollongong, Australia.

His original training was in the mechanical properties of polymers. More recently, he has conducted research into the mechanical properties and processing of conducting polymers. His work has included substantial research on the development and characterization of electromechanical actuators using conducting polymers and carbon nanotubes. Spinks has co-authored one book and more than 100 journal articles and conference papers and serves as a member of the editorial board for Progress in Organic Coatings.

In 1997, Spinks was awarded the Polymer Science and Technology Achievement Award from the Polymer Division of the Royal Australian Chemical Institute for outstanding research in polymers.

Spinks can be reached by e-mail at IPR, University of Wollongong, Northfields Ave., Wollongong, NSW 2522 Australia; e-mail gspinks@uow.edu.au.

Gordon G. Wallace is research director of the Australian Research Council (ARC) Centre of Excellence for Electromaterials Science. He holds a DSc degree from Deakin University.

In 1990, Wallace was appointed professor at the University of Wollongong. He was awarded an ARC Queen Elizabeth II Fellowship in 1991 and an ARC Senior Research Fellowship in 1995. In 2002, Wallace was appointed to an ARC Professorial Fellowship and then
received an E.T.S. Walton Fellowship from the Science Foundation Ireland in 2003. He is a fellow of the Australian Academy of Technological Sciences and Engineering, the Royal Australian Chemical Institute (RACI), and the Institute of Physics (U.K.). In 2006, he was awarded an ARC Federation Fellowship. He received the inaugural Polymer Science and Technology Achievement Award from RACI in 1992 and RACI’s R.H. Stokes Medal for research in electrochemistry in 2004. Wallace has published more than 380 refereed publications and a monograph on inherently conducting polymers for intelligent materials systems.

Wallace can be reached at IPRI, University of Wollongong, Northfields Ave., Wollongong, NSW 2522 Australia; e-mail gordon_wallace@uow.edu.au.