REVIEW

Theory progress and applications of dielectric elastomers

Liwu Liu*, Yanju Liu** and Jinsong Lengb*

aDepartment of Astronautical Science and Mechanics, Harbin Institute of Technology (HIT),
No. 92 West Dazhi Street, Harbin 150001, P.O. Box 301, China; bCentre for Composite Materials,
Science Park of Harbin Institute of Technology (HIT), No. 2 YiKuang Street, Harbin 150080, P.O.
Box 3011, China

(Received 18 July 2013; final version received 16 September 2013)

This paper summarizes the research progress of dielectric elastomer (DE) and its
composite materials, including the introduction of materials, theoretical research
development, and typical applications. First of all, the DE composite materials are intro-
duced. Then, the theoretical research development of DEs is summarized. Finally, some
applications as well as research prospects about DEs are listed.

Keywords: dielectric elastomers; composites; theory progress; applications

1. Introduction

Electro-active polymer (EAP) is a kind of intelligent multifunctional material. When sub-
jected to an external electric field, EAP reduces its thickness and expands its area. But
after the electric field is revoked, it can restore to its original shape. This can be used to
design and fabricate intelligent transition devices such as actuators, transducers, and energy
harvesters [1–6]. Based on different mechanisms, EAP is mainly divided into two kinds:
the electronic type and the ionic type [4–6]. The electronic-type EAP materials mainly
include dielectric elastomer (DE), ferroelectric polymers, liquid crystal elastomers, elec-
троstrictive graft elastomers and so on, while the ionic-type EAP materials mainly include
the ionic polymer–metal composites (IPMC), carbon nanotube, electro rheological fluids,
ionic polymer gels, and conductive polymers [3–6].

Electronic-type EAP materials require high-driving electric field (>100 V/µm) to
obtain certain electrically induced deformation which is close to the breakdown electric
field of the material [3,4]. The ionic-type EAP material is composed of electrolyte and elec-
trodes. The surface and environment of this kind of EAP must be kept moist to work well
[5,6]. This kind of material can produce a stabilized response of extension, contraction, or
bending [6].

DE is a kind of typical EAP. This paper summarizes the research progress of DE and its
composites. First of all, the working mechanism, common DE materials, and the influence
of the pre-stretch of DE are introduced. Then, the theoretical research progress of DEs is
summarized. Finally, we list some applications of DEs and look into the future of research
on DEs.

*Corresponding authors. Emails: yj_liu@hit.edu.cn; lengjs@hit.edu.cn (Jinsong Leng)
2. DEs and their composites

2.1. The working mechanism of DEs

When subjected to electric field, DE can produce large deformation. What’s more, it possesses the advantages of high elastic energy density, super-short response time, high electromechanical conversion rate, excellent flexibility, light weight, etc. [1–3].

DE can be taken as a flexible and changeable capacitance; its working mechanism is demonstrated by Figure 1. It contains two faces of the elastomer with uniform compliant electrodes. When voltage is applied to the electrodes, the opposite charges on opposite electrodes attract each other while the like charges on the same electrodes repel each other. Thus, the DE decreases in thickness and expands in area for the effect of Maxwell stress. DEs can work as electromechanical energy transducers [1,2]. When the DE is on the actuating mode, the electrical energy will change into mechanical energy. DE can be used to fabricate actuators and sensors at this circumstance; while on the electricity generating mode, mechanical energy can be converted into electrical energy. DEs can be used to fabricate energy-harvesting devices in this way.

2.2. Basic DE materials

From 1990 to 2000, a large amount of soft materials including silicone rubber, thermoplastic, acrylic, etc. were taken as DE materials [3,5,6]. By contrast, the acrylic material produced by 3M Company was in common use for its excellent strain property. For example, after pre-stretch, the maximal area stretch of the 4910 type acrylic DE can be up to 380% [2]. But the viscoelasticity and the glass-transition temperature limited its practical application. Polyurethane has a relatively large output force and high permittivity. It can work under low electric field. However, the disadvantage that it cannot obtain large strain makes researchers pay no more attention to it. By contrast, the silicone rubber DEs have many advantages. On 70% pre-stretching, it can reach more than 100% stretching ratio in area; although it is smaller than acrylic elastomers, the smaller viscoelasticity property enlarged its application prospect [3,6].

We can choose different DE materials for different requirements. For an example, in order to obtain a large deformation, the material’s modulus of elasticity cannot be too high to obtain a larger driving force. High dielectric strength is acquired for DE materials [3,4]. To reduce the driving voltage, we need to fabricate much thinner DE films.

Figure 1. Schematic diagram of voltage-driven DEs [1,2].
2.3. **DE composite materials**

DE material is a kind of smart material with huge development potential, some of the advantages have already been listed above. However, the required driving electric field of the DE is very high so that its practical application is greatly affected. Therefore, reducing the driving voltage of DE becomes an urgent problem. The researchers have come up with the idea to fabricate DE composites to meet the application requirements [7,8]. At the time, the research of DE composites is mainly divided into two types: the first type involves selecting silicone rubber as the major substrate material and using the physical blend method to make particle-filled composites; the second type involves selecting acrylic acid as the substrate material and using the chemical cross-linking method to prepare interpenetrating polymer networks.

2.3.1. **Particulate filled type DE composite materials**

Gallone et al. investigated the dielectric and mechanical properties of $[P_b(M_{g1/3}N_{b2/3})O_3]-[P_bT_iO_3]$ (PMN-PT)-filled silicone rubber elastomer composites [7]. The composite material added at most 30 vol% PMN-PT. When the frequency was about 10 Hz, the relative dielectric constant increased to 32 and the elastic modulus of the material increased too. When the content of PMN-PT reached 30%, the elastic modulus increased by 100%. Moreover, the composite material still showed good hyperelasticity.

2.3.2. **DE interpenetrating polymer network**

In order to eliminate the influence of the rigid framework on acrylic materials and thus to improve the effective energy density, Ha et al. fabricated the DE interpenetrating polymer networks [8]. The used 1,6-hexandiol diacrylate (HDDA) or trimethylolpropane trimethacrylate (TMPTMA) monomers as additives of the polymer. The preparation process of the interpenetrating polymer network is to implant the network structure to very high bond (VHB) DE thin film with pre-stretching. When the VHB film is removed from the rigid framework, the new network architecture will enable the VHB thin film to keep the pre-stretch.

2.4. **The influence of pre-stretching**

Pre-stretching can improve electrically induced deformation and dielectric strength of the DE materials. It can reduce the thickness of the DE and voltage needed at the same time, while it can also improve DE’s electrical breakdown strength and electromechanical stability. Normally speaking, the DE materials will produce unavoidable minor defects while fabricating and the breakdown strength will reduce in this way and then lead to the damage of the material. Pre-stretching will make the polymer molecule chain vertical to the added electric field, and then the material’s premature damage is avoided. Pre-stretching can also improve the frequency response speed of DE thin films. Experiments showed that the decrease with frequency in electrically induced deformation of acrylic thin films seldom happens.

Thin film, after pre-stretching, has its disadvantages too. A stiffness frame or other supporting structure is needed to maintain the tensile force of the DE film, which lowers the effective energy density and limits the materials’ larger electrically induced deformation.
Stress relaxation and fatigue of the DE thin film after pre-stretching will take place as time goes by, which will reduce its working life.

3. **The theoretical research progress of DEs**

The DE possesses material nonlinearity and geometrical large deformation. What’s more, its load is multi-field-coupled. The two major research topics of stability and large deformation of the DEs have aroused widespread interest of researchers. Revolving around these two themes, DEs have been studied comprehensively by researchers on the constitutive relations of multi-physics coupling fields, electromechanical stability, and electrically induced deformation [1,9–54].

### 3.1. The constitutive theory research progress of DEs

In 2000, Pelrine et al. created a simple model to describe the mechanical properties of the DEs subjected to electric field. Based on the classic Maxwell theory, the relationship between stress and the applied electric field as well as the dielectric constant was deduced. It opened the prelude of the research for the constitutive theory of DEs [2]. The research for the constitutive theory of DEs mainly includes the following three representative methods [9–13]. The first method is based on the super-elastic or viscoelastic theory, combined with the phenomenological method to establish the constitutive relation of the DE [14,15]. The second research method is based on the classical continuum mechanics and Maxwell–Faraday electromagnetic theory to establish the basic theoretical framework of the electromechanical coupling system of DEs and then to obtain the constitutive relations. The third method is based on the theory of thermodynamics to establish the framework of the thermodynamic theory of deformable dielectrics. The representative research group is the group of Professor Zhigang Suo from Harvard University. They proceed from the point of energy, considering the electromechanical coupling effect to establish the system’s free energy function combined with elastic strain energy and electric field energy, and then deduce the constitutive relation of the DE to study its mechanical behavior [11]. Here, the free energy is written directly in the form of a simple summation of elastic energy and electric fields without considering the coupling between the two kinds of energy. That is because the mechanical response and the electrical response differ for several orders of magnitude on the response time. The coupling exists in the expression of electric field energy and geometric relations.

### 3.2. The electromechanical stability research progress of DEs

DEs will lead to the system’s instability under the coupling effect of mechanical force field and electric field. The study for electromechanical stability of DE began in 2007 [16]. Zhigang Suo revealed the process and mechanism of the DE from the mechanical and electrical stability to instability based on the study of literature [17]. Coating flexible electrodes on the two opposite surfaces of the DE homogeneously, ignoring the resistance of the flexible electrode, and assuming that the deformation of flexible electrodes and elastomer coordinate with each other, after the electric field is applied, due to the electrostatic interactions, the materials will shrink along the direction of the electric field and extend in the direction perpendicular to the electric field at the same time. The thickness of the elastomers reduces and this lead to higher electric field strength; this irreversible process continues. When the applied electric field exceeds the critical electric field, the breakdown of DE occurs. This is called the DE electromechanical instability [16].
The electromechanical instability of DE has been observed in experiments by Plante et al. [14], suffering particular voltage, some regions of the deformed DE film are smooth, while the other parts are wrinkled. The smooth area of the film is relatively thick with small planar stretch, while the wrinkled area is relatively thin with large planar stretch. The two states coexist. Moreover, the spread of electromechanical instability region of the DE thin film can also be obviously observed in the experiment [18].

Zhigang Suo et al. came up with the idea that we can use arbitrary free energy to analysis the electromechanical stability of DE [16]. Taken the neo-Hookean model as an example, they depicted the relation between the nominal electric displacement and the nominal electric field of DEs to study the stability behavior [14,16]. Based on this, the nonlinear electromechanical stability analysis of DE electromechanical coupling system becomes more and more comprehensive and specific [16–31].

Liu et al. analyzed the electromechanical stability of DEs using the Mooney–Rivlin elastic strain energy model with two material constants. The introduced material constant ratio $k$ can be fit to DEs of different types and structures. When $k$ is increasing, the electromechanical stability of DEs of different types and structures is strengthened obviously. These theoretical results are helpful in guiding design or fabrication of DE actuators [22].

Norrisa analyzed the stability behavior of DE using Ogden strain energy model, and the relation of critical real electrical field, nominal stress, and stretch is formulated accurately [24]. Zhou et al. studied the instability spread of DE [18]. They studied the electromechanical stability of DE undergoing inhomogeneous deformation [25,26]. Xu et al. studied the electromechanical stability of DE using full stress theory [27]. The object in the above research is all ideal DE.

Large deformation and electromechanical stability of DE with linear or nonlinear electrostrictive change have been studied comprehensively [28–32]. The permittivity of DE undergoing large deformation depends on its own deformation [15,19,32]. Zhao et al. fitted dielectric constant to a linear function that depended on the stretch and studied the large deformation and stability of DE [28]. Based on the experimental research of Gofod et al. [32], Liu et al. proposed that dielectric constant is a nonlinear function of stretch and studied the electromechanical stability of the system comprehensively both in analytical expression and numerical simulation [29–31].

3.3. The electrically induced deformation research progress of DEs

Researchers studied the electrically induced deformation of the elastomer experimentally and theoretically at the same time [2,33–38]. Experiments showed that in order to obtain large induced deformation of the DE, there are several different ways as follows: the pre-stretched DEs [2], the interpenetrating DE networks [33], applying the solvent swelling effect of elastomers [34], and the charge-driven DEs [35], etc. In 2000, Pelrine et al. reported that after 300% equal biaxial pre-stretch the acrylic acid can produce 100% electrical induced deformation [2]. Ha et al. did experiments to prove that if we bring in the second kind of DE network, the inner pre-stretch of the elastomer will increase and then the electrically induced deformation increases too [33]. In addition, the application of charge-driven DE, instead of voltage-driven elastomer, can induce it to produce electrically induced deformation larger than 100%. This is because the application of charge-driven DE can effectively inhibit or avoid the occurrence of electromechanical instability [35].

Xuanhe Zhao and Zhigang Suo established the theory of the DE which can produce large electrostriction deformation. According to the different locations relation of voltage-stretching curve and the electrical breakdown-stretching curve, three kinds of DEs
with different electromechanical response characteristics were put forward. The theory predicted that more than 500% of the electrically induced deformation can be reached by selecting and designing proper voltage deformation response [35]. Koh et al. depicted a large electrical-induced deformation of DE with pre-stretch or DE composites with short chains and explained the mechanism of super-large deformation of DE considering pre-stretch, strain hardening, and the length of polymer chain theoretically [38].

4. Applications of DEs

4.1. DE actuators

DEs can be used to fabricate various types of actuators. A single DE film can be regarded as an actuator. But the deformation of actuators in one particular direction usually needs to be controlled precisely and large enough in actual applications. Thus, the structure of actuators should be designed and optimized. A simple way of large actuator deformation is to superpose the deformation of several DE films. Such actuators include stack-like (Figure 2(a)), helical (Figure 2(b)), and folded (Figure 2(c)) types [39]. For a more linear deformation, a well-designed framework is required. The common types are diamond (Figure 3(a)), bow tie (Figure 3(b)), cone (Figure 3(c)), spider (Figure 3(d)) actuators, and so on [40,41]. DE actuators have many promising applications in intelligent bio-robots, airship rudder, energy harvesters, and Braille tactile displays [43, 55–59].

4.2. Artificial muscles

Figure 4(a) shows an artificial arm based on DE rolled actuators. It can play arm wrestling match with humans; the fabricated artificial muscle arms can support and resist human arms for nearly 26 s, which is an important milestone. It demonstrates EAP’s great potential in the field of bionics [43]. As Figure 4(b) demonstrates, the simulated face expression robot Einstein fabricated by Hansen robot company revealed different expressions of happiness, sadness, and anger, which aroused wide attention and huge response among the participating representatives of the conference [43].

4.3. Robot insects

To get an idea of bionic properties, materials used to make artificial muscles must possess the important property of natural muscles, such as actuation form, actuation stress,
response speed, and efficiency. In 1995, National Aeronautic Space Administration of America started the research program of light muscle actuators. Figure 5(a) and 5(b) show the bionic robot based on acrylic acid DE rolled actuators. Figure 5(c) is the self-perception intelligent robot designed and manufactured by the University of Southern Denmark. The sensors on its arms and legs are made by DEs [43]. In addition, the PhD research group of Yoseph Bar-Cohen of jet propulsion laboratory promoted the research for robot arms actuated by DEs. The Stanford Research Institute of America signed the DE-based mini-robot research program with Japan [43]. In 2007, the Swiss Confederation laboratory of material testing and research put forward that we can control the free turning of an airship using DE to fabricate actuators for the airship rudder [56].

4.4. Energy harvester and Braille tactile display

Based on the electromechanical effect of DEs, we can design and fabricate energy harvesters. Figure 6(a) and 6(b) showed the mechanical energy produced by wave vibration changing into electrical energy via energy harvester. The traditional repeatable Braille
devices are all made by piezoelectric elements with a complex structure and expensive cost. As Figure 6(c) and 6(d) showed, Harbin Institute of Technology designed and fabricated a Braille tactile display based on DE actuators. After users input English letters or words through the man–machine interface, the program converts the letters to electrical signals according to the corresponding Braille representation and then outputs a signal via a single-chip microprocessor to control the cutoff of six relays; in this way, we can control the deformation of the dielectric actuators and then display information on the touch screen.

5. Conclusions and outlooks
In recent years, although DEs developed rapidly, the majority are limited in laboratory applications now and business applications are facing enormous challenges. The constraints include: easy failure and damage, low driving force, and unsatisfactory electrostrictive deformation in practical use. Therefore, it is urgently required to study the mechanical properties of the DE and its structure comprehensively, and thereby to guide the design and optimization of the materials and devices. In addition, for the DE composites or structures within the characteristics of geometric large deformation and material nonlinearity on mechanics, they possess the feature of multi-physical field coupling (mechanical force field, electric field and thermal field etc) in the response mechanism and working environment. Researching the mechanics and structures of such materials is of very important value.

Acknowledgments
This work is supported by the National Natural Science Foundation of China (Grant No.11225211, No.11272106, No.11102052), China Postdoctoral Science Foundation (Grant No. 2012M520032),
International Journal of Smart and Nano Materials

Heilongjiang Postdoctoral Fund (Grant No. LBH-Z12091), and the Fundamental Research Funds for the Central Universities (Grant No.HIT.NSRIF.2013030).

References

[1] Z.G. Suo, Theory of dielectric elastomers, Acta Mech. Solidia Sin. 23 (2010), pp. 549–578.
[2] R. Pelrine, R. Kornbluh, and Q. Pei, High-speed electrically actuated elastomers with strain greater than 100%, Science 287 (2000), pp. 836–839.
[3] P. Brochu and Q.B. Pei, Advances in dielectric elastomers for actuators and artificial muscles, Macromol. Rapid Commun. 31 (2010), pp. 10–36.
[4] T. Mirfakhrai, J. Madden, and R. Baughman, Polymer artificial muscles, Materials Today 10 (2007), pp. 30–38.
[5] A. O’Halloran, F. O’Malley, and P. McHugh, A review on dielectric elastomer actuators, technology, applications, and challenges, J. Appl. Phys. 104 (2008), p. 071101.
[6] J.D. Madden, N. Vandesteg, P.G. Madden, A. Takshi, R. Zimet, P.A. Anquetil, S.R. Lafontaine, P.A. Wierenga, and I.W. Hunter, Artificial muscle technology: physical principles and naval prospects, IEEE J. Ocean. Eng. 29 (2004), p. 706.
[7] F. Carpi, G. Callone, F. Galantini, and D. Derossi, Silicone-poly(hexylthiophene) blends as elastomers with enhanced electromechanical transduction properties, Adv. Funct. Mater. 18 (2008), pp. 235–224.
[8] S.M. Ha, W. Yuan, Q. Pei, R. Pelrine, and S. Stanford, Interpenetrating networks of elastomers exhibiting 300% electrically-induced area strain, Smart Mater. Struct. 16 (2007), pp. S280–S287.
[9] A. Dorfmann, V. Austria, and R.W. Ogden, Nonlinear electroelasticity, Acta Mech. 174 (2005), pp. 167–183.
[10] N.C. Goulbourne, E.M. Mockensturm, and M.I. Frecker, A nonlinear model for dielectric elastomer membranes, J. Appl. Mech. 72 (2005), pp. 899–906.
[11] Z.G. Suo, X.H. Zhao, and W.H. Greene, A nonlinear field theory of deformable dielectrics, J. Mech. Phys. Solids 56 (2008), pp. 467–468.
[12] R.M. Mcmeeking and C.M. Landis, Electrostatic forces and stored energy for deformable dielectric materials, J. Appl. Mech. 72 (2005), pp. 581–590.
[13] C. Trimarco, On the Lagrangian electrostatics of elastic solids, Acta Mech. 204 (2009), pp. 193–201.
[14] J.S. Plante and S. Dubowsky, Large-scale failure modes of dielectric elastomer actuators, Int. J. Solids Struct. 43 (2006), pp. 7727–7751.
[15] M. Wissler and E. Mazza, Electromechanical coupling in dielectric elastomer actuators, Sens Actuat A Phys. A138 (2007), pp. 384–393.
[16] X.H. Zhao and Z.G. Suo, Method to analyze electromechanical stability of dielectric elastomers, Appl. Phys. Lett. 91 (2007), p. 061921.
[17] K.H. Stark and C.G. Garton, Electric strength of irradiated polythene, Nature 176 (1955), pp. 1225–1226.
[18] J.X. Zhou, W. Hong, X.H. Zhao, Z. Zhang, and Z.G. Suo, Propagation of instability in dielectric elastomers, Int. J. Solids Struct. 45 (2008), p. 3739.
[19] Y.J. Liu, L.W. Liu, Z. Zhang, and J.S. Leng, Dielectric elastomer film actuators: characterization, experiment and analysis, Smart Mater. Struct. 18 (2009), p. 095024.
[20] W. Hong, Modeling viscoelastic dielectrics, J. Mech. Phys. Solids 59 (2011), pp. 637–650.
[21] X.H. Zhao, S.J. Adrian Koh, and Z.G. Suo, Nonequilibrium thermodynamics of dielectric elastomers, Int. J. Appl. Mech. 3 (2011), pp. 203–217.
[22] Y.J. Liu, L.W. Liu, Z. Zhang, L. Shi, and J.S. Leng, Comment on “Method to analyze electromechanical stability of dielectric elastomers” [Appl. Phys. Lett. 91, 061921, 2007], Appl. Phys. Lett. 93 (2008), p. 106101.
[23] Y.J. Liu, L.W. Liu, S.H. Sun, Z. Zhang, and J.S. Leng, Stability analysis of dielectric elastomer film actuator, Sci. China Ser E Technol. Sci. 52 (2009), pp. 2715–2723.
[24] A.N. Norrisa, Comment on “Method to analyze electromechanical stability of dielectric elastomers [Appl. Phys. Lett. 91, 061921, 2007]”, Appl. Phys. Lett. 92 (2007), p. 026101.
[25] T.H. He, X.H. Zhao, and Z.G. Suo, Equilibrium and stability of dielectric elastomer membranes undergoing inhomogeneous deformation, J. Appl. Phys. 106 (2009), p. 083522.
[26] T.H. He, L.L. Cui, C. Chen, and Z.G. Suo, Nonlinear deformation analysis of a dielectric elastomer membrane-spring system, Smart Mater. Struct. 19 (2010), p. 085017.
[27] B.X. Xu, R. Mueller, M. Classen, and D. Gross, On electromechanical stability analysis of dielectric elastomer actuators, Appl. Phys. Lett. 97 (2010), p. 162908.
[28] X.H. Zhao and Z.G. Suo, Electrostriction in elastic dielectrics undergoing large deformation, J. Appl. Phys. 104 (2008), p. 123530.
[29] J.S. Leng, L.W. Liu, Y.J. Liu, K. Yu, and S.H. Sun, Electromechanical stability of dielectric elastomer, Appl. Phys. Lett. 94 (2009), p. 211901.
[30] Y.J. Liu, L.W. Liu, S.H. Sun, and J.S. Leng, Electromechanical stability of Mooney-Rivlin-type dielectric elastomer with nonlinear variable dielectric constant, Polym. Int. 59 (2010), pp. 371–377.
[31] Y.J. Liu, L.W. Liu, K. Yu, S.H. Sun, and J.S. Leng, An investigation on electromechanical stability of dielectric elastomers undergoing large deformation, Smart Mater. Struct. 18 (2009), p. 095040.
[32] G. Kofod, P. Sommer-Larsen, R. Kronbluh, and R. Pelrine, Actuation response of polyacrylate dielectric elastomers, J. Intell. Mater. Syst. Struct. 14 (2003), p. 787.
[33] S.M. Ha, W. Yuan, Q.B. Pei, R. Pelrine, and S. Stanford, Interpenetrating polymer networks for high-performance electroelastomer artificial muscles, Adv. Mater. 18 (2006), pp. 887–891.
[34] R. Shankar, T.K. Ghosh, and R.J. Spontak, Mechanical and actuation nanostructured polymers as tunable actuators, Adv. Mater. 19 (2007), pp. 2218–2223.
[35] C. Keplinger, M. Kaltenbrunner, N. Arnold, and S. Bauer, Röntgen’s electrode-free elastomer actuators without electromechanical pull-in instability, Proc. Nat. Acad. Sci. 107 (2010), pp. 4505–4510.
[36] R.E. Pelrine, R.D. Kornbluh, and J.P. Joseph, Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation, Sens Actuat A Phys. 64 (1998), pp. 77–85.
[37] X.H. Zhao and Z.G. Suo, Theory of dielectric elastomers capable of giant deformation of actuation, Phys. Rev. Lett. 104 (2010), p. 178302.
[38] S.A. Koh, T.F. Li, J.X. Zhou, X.H. Zhao, W. Hong, J. Zhu, and Z.G. Suo, Mechanisms of large actuation strain in dielectric elastomers, J. Polym. Sci [B] 49 (2011), pp. 504–515.
[39] F. Carpi and D. De Rossi, Contractile folded dielectric elastomer actuators, Proc. SPIE. 6524 (2007), p. 65240D.
[40] J.S. Plante, Dielectric elastomer actuators for binary robotics and mechatronics. Massachusetts Institute of Technology, Cambridge, MA, 2006.
[41] R. Pelrine, P. Sommer-Larsen, R. Kornbluh, R. Heydt, G. Kofod, Q.B. Pei, and P. Gravesen, Applications of dielectric elastomer actuators, Proc. SPIE. 4329 (2001), pp. 35–349.
[42] J.S. Plante, L.M. Devita, and S. Dubowsky, A road to practical dielectric elastomer actuators based robotics and mechatronics: discrete actuation, Proc. SPIE. 6524 (2007), p. 652406.
[43] Y. Bar-Cohen, Biologically inspired technology using electroactive polymers (EAP), Proc. SPIE. 6168 (2006), p. 616803.
[44] L. Liu, Y. Liu, and J. Leng, Voltage induced deformation in dielectric. J. Appl. Phys. 112 (2012), p. 033519.
[45] L. Liu, Y. Liu, X. Luo, B. Li, and J. Leng. Electromechanical stability and snap-through stability of dielectric elastomers undergoing polarization saturation. Mech. Mater. 55 (2012), pp. 60–72.
[46] L. Liu, Y. Liu, B. Li, and J. Leng. Theoretical investigation on polar dielectric with large electrocaloric effect as cooling devices. Appl. Phys. Lett. 99 (2011), p. 181908.
[47] L. Liu, Y. Liu, J. Leng. Electromechanical stability of compressible dielectric elastomer actuators. Smart. Mater. Struct. 20 (2011), p. 115015.
[48] L. Liu, Y. Liu, B. Li, K. Yang, T. Li, and J. Leng. Thermo-electro-mechanical instability of dielectric elastomers. Smart. Mater. Struct. 20 (2011), p. 075004.
[49] Z. Zhang, L. Liu, Y. Liu, J. Leng, and S. Du. Effect of mechanical force field on the electromechanical stability of dielectric elastomers. Sci China Ser G: Phys. Mech. Astron. 58 (2011), pp. 94–101.
[50] Y. Liu, L. Liu, S. Sun, and J. Leng. Electromechanical stability of Mooney-Rivlin-type dielectric elastomer with nonlinear variable dielectric constant. Polym. Int. 59 (2010), 371–377.
[51] L. Liu, Y. Liu, Z. Zhang, B. Li, and J. Leng. Electromechanical stability of electro-active silicone filled with high permittivity particles undergoing large deformation. Smart. Mater. Struct. 19 (2010), p. 115025.
[52] Y. Liu, L. Liu, L. Shi, S. Sun, and J. Leng. *Comment “on electromechanical stability of dielectric elastomers [Appl. Phys. Lett. 93, 101902, 2008]”*. Appl. Phys. Lett. 94 (2009), p. 096101.

[53] L. Liu, Y. Liu, K. Yu, and J. Leng. *Thermoelectromechanical stability of dielectric elastomer undergoing temperature variation*. Mech. Mater. (2013). doi: 10.1016/j.mechmat.2013.05.013.

[54] B. Li, L. Liu, and Z. Suo. *Extension limit, polarization saturation, and snap-through instability of dielectric elastomers*. Int. J. Smart. Nano. Mater. 2 (2011), pp. 59–67.

[55] Y. Bar-Cohen. WW-EAP News. 7 (2005), pp. 1–26.

[56] Y. Bar-Cohen. WW-EAP News. 13 (2011), pp. 1–13.

[57] Y. Bar-Cohen. WW-EAP News. 10 (2008), pp. 1–17.

[58] Y.J. Liu, L.W. Liu, and J.S. Leng, *Analysis and manufacture of energy harvester based on Mooney-Rivlin type dielectric elastomer*, Europhys. Lett. 90 (2010), p. 36004.

[59] Y. Bar-Cohen, WW-EAP News. 12 (2010), pp. 1–19.