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Increasing the performance of dielectric elastomer actuators: A review from the materials perspective

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A B S T R A C T

Electro-active polymers (EAPs) are emerging as feasible materials to mimic muscle-like actuation. Among EAPs, dielectric elastomer (DE) devices are soft or flexible capacitors, composed of a thin elastomeric membrane sandwiched between two compliant electrodes, that are able to transduce electrical to mechanical energy, actuators, and vice versa, generators. Initial studies concentrated mainly on dielectric elastomer actuators (DEAs) and identified the electro-mechanical principles and material requirements for an optimal performance. Those requirements include the need for polymers with high dielectric permittivity and stretchability and low dielectric loss and viscoelastic damping. Hence, attaining elastomeric materials with those features is the focus of current research developments. This review provides a systematic overview of such research, highlighting the advances, challenges and future applications of DEAs.

Contents

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Nomenclature

A	Area
C	Capacitance
e	Energy density
E	Electric field or nominal electric field
M_w	Molecular weight
p	Electrostatic pressure
$\tan(\delta)$	Dielectric loss factor or loss tangent
T_c	Curie temperature
U	Electrostatic energy
V	Voltage
Y	Young's modulus
z	Film thickness
ε_0	Vacuum permittivity
ε	Dielectric permittivity
ε'	Real part of the complex dielectric permittivity, dielectric permittivity
λ	Pre-stretch ratio
BN	Boron nitride
BR	Butadiene rubber
BT	Barium titanate $BaTiO_3$
CB	Carbon black
CCTO	Calcium copper titanate $CaCu_3Ti_4O_{12}$
CNTs	Carbon nanotubes
CPs	Conducting polymers
CR	Chloroprene rubber
CuPc	Copper-phthalocyanine
DBSA	Dodecyl benzene sulfonic acid
DE	Dielectric elastomer
DEAs	Dielectric elastomer actuators
DEGs	Dielectric elastomer generators
DOP	Dioctyl phthalate
EAPs	Electro-active polymers
EGEs	Electrostrictive graft elastomers
EPR	Ethylene-propylene rubber
ETAS	Ethyltriacetoxysilane
EVA	Ethylene-vinyl acetate
FGS	Functionalised graphene sheets
HNBR	Hydrogenated acrylonitrile butadiene rubber
HPU	Hyperbranched polyurethane
IIR	Polyisobutylene-co-isoprene
IPGs	Ionic polymer gels
IPMCs	Ionic polymer-metal composites
IPN	Interpenetrating polymer network
LCEs	Liquid-crystal elastomers
LDPE	Low density polyethylene
MWCNTs	Multiwall carbon nanotubes
NBR	Acrylonitrile butadiene rubber
NR	Natural rubber
PANI	Polyaniline
PDA	Polydopamine
PDMS	Poly(dimethylsiloxane)
PHT	Poly(3-hexylthiophene)
PMMA	Poly(methylmethacrylate)
PMN-PT	Lead magnesium niobate–lead titanate
PSF	Polysulfone
PTFE	Poly(tetrafluoroethylene)
P(TrFE)	Poly(trifluoroethylene)
PU	Polyurethane
PVDF	Poly(vinylidene fluoride)
P(VDF-TrFE)	Poly(vinylidene fluoride-trifluoroethylene)
PZT	Lead zirconate titanate
SBR	Styrene-butadiene rubber
SEBS	Styrene-ethylene-butadiene-styrene rubber
SEBS-g-MA	Styrene-ethylene-butylene-styrene-grafted maleic anhydride
SWCNTs	Single wall carbon nanotubes
TEOS	Tetraethoxysilane

1. Introduction

Electro-active polymers (EAPs) that respond to an electrical field by changing their shape have the potential to mimic muscle-like behaviour enabling the development of lightweight, energy efficient and silent actuators, motors and force and strain sensors [1,2]. Among the different EAPs, soft dielectric elastomers (DEs) have attracted much interest in recent years due to their outstanding deformation strains, in some cases greater than 100%. Such interest has not been restricted to the academic world and a number of enterprises [3–5] are already commercialising devices based on this technology.

The first investigations on the effect of electrical field on solids go back to the late 18th century when Italian scientist Alessandro Volta mentioned in a letter [6] that researcher Felice Fontana had observed volume changes in Leyden jars (the first electrical capacitors) [7,8]. Subsequent work on a pre-stretched natural rubber band by Willem Röntgen [9], best known for the discovery of X-rays that earned him the Nobel prize in 1901, showed length changes of several centimetres. Since then, further isolated work can be found on the strain response of dielectric materials to applied fields. However, it was not until 2000 when researchers from Stanford Research Institute reported for the first time large strains in dielectric elastomer in a paper published in *Science* [10]. Since that pivotal work, DEs are recognised to provide the best combination of electrical