Elastomeric materials for energy and harvesting applications

IOM3: Elastomer use in sustainable energy generation

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Dielectric elastomers

Need to maximise strain:

\[ s_z = \frac{-\varepsilon_0 \varepsilon_r E_{\text{breakdown}}^2}{Y} \]
Applications

Soft actuators
Tang et al. IEEE, DOI: 10.1109/IROS.2017.8206054

Energy harvesting

Soft sensors
Zoltán Rácz et al. / Procedia Eng., 2016, 168, 721.

Stretchable capacitors
Yun et al. Chem Eng J 2020 387 124076

\[ \varepsilon_{\text{biaxial}} = \frac{(l' - l)}{l} \]
Applications of interest

ACS Appl. Mater. Interfaces 2018, 10, 38438 with University of Warwick

Dr. Chaoying Wan, Prof. Tony McNally

Intrinsic Tuning of Poly(styrene–butadiene–styrene)-Based Self-Healing Dielectric Elastomer Actuators with Enhanced Electromechanical Properties

Christopher Ellingford, Runan Zhang, Alan M. Wemyss, Christopher Bowen, Tony McNally, Łukasz Figiel, and Chaoying Wan

Matter 2020, 3, 989

Perspective
Self-Healing of Materials under High Electrical Stress

Yan Zhang, Hamideh Khanbareh, James Roscow, Min Pan, Chris Bowen, and Chaoying Wan

Electrical and Mechanical Self-Healing in High-Performance Dielectric Elastomer Actuator Materials

Yan Zhang, Christopher Ellingford, Runan Zhang, James Roscow, Margaret Hopkins, Patrick Keogh, Tony McNally, Chris Bowen, and Chaoying Wan

Adv. Funct. Mater. 29, 1808431 2019
Figure 1. Mechanisms of Electric Breakdown in a Dielectric Elastomer

**A**
High electric field
Defect
Pristine polymer under high E

**B**
Conductive electrode
Carbon deposit
Dielectric breakdown (Timescale: ns to μs)

**C**
Self clearing
(Timescale: ns to μs)

**D**
Electrical treeing
(Timescale: s to hrs)
Self-clearing: inc. capacitors for energy storage

Gradual decay in capacitance

Mechanical properties?
Self-healing elastomer (Dr Chaoying Wan)

- Methyl thioglycolate (MG) was grafted to the butadiene block via a one-step thiol-ene “click” reaction under UV at 25 °C.
- UV photo-polymerisation
  Room temperature, 5-20 mins
- Grafting ratio ~98%
- Up-scalable

Wan et al., ACS Appl. Mater. Interfaces 2018, 10, 38438
Self-healing MGSBS elastomer

- Push two pieces together
- Holds its own weight
- Can be physically stretched
- Cut samples tested

**Strain at Break Recovery (%)**

<table>
<thead>
<tr>
<th>Time</th>
<th>Immediate</th>
<th>5 mins</th>
<th>15 mins</th>
<th>30 mins</th>
<th>1 day</th>
<th>3 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

**Tensile Strength Recovery (%)**

- MGSBS (98.5%)
- MGSBS (98.5%) reused

**Elongation at Break Recovery (%)**

- MGSBS (98.5%)
- MGSBS (98.5%) reused
Self-healing MGSBS elastomer

Low-field electrical properties (1V)
Dielectric breakdown / healing high field properties

Adv. Funct. Mater. 29, 1808431 2019
Recovery of **high-field** properties (4kV)

Original material

Fine – needle at 24 hrs healing after breakdown
Dielectric breakdown modelling

**Propagation of breakdown defect**
Blue = Dielectric elastomer
Red = Conductive phase (i.e. electrode, elastomer post-breakdown)

**Electric field contour plots**

- Complete breakdown

- Electric field magnitude, kV/mm
  - 0
  - 36.9
  - 46.7
  - 74.2

- Top view
  - 50 μm
Recovery of mechanical damage/cuts

(A)

(B)

5min

2hrs

4hrs
Actuator healing

(A) Breakdown site
(B) Healed site
(C) Cut & healed site
(D) Breakdown site after cut & heal
(E) Graph showing radial actuation strain vs. driving voltage for different healing conditions and voltages.
### DEG energy harvesting cycle

#### Low C, higher V

\[ Q = CV \]

#### Low C, no V

#### High C, high V

#### High C, no V

\[ C = \varepsilon_r \varepsilon_0 \frac{A}{t} \]

\[ \text{harvested energy} \quad \frac{\text{volume}}{\text{}} = \frac{1}{2} \varepsilon_0 \varepsilon_r E_{\text{max}}^2 \left[ 1 - \frac{A_{\text{min}}^2}{A_{\text{max}}^2} \right] \]
Electrical circuit for energy harvesting Voltage input is 1.5 kV (i.e. $\Phi_L = 1.5$ kV). Diode D1 allows the measurement of harvested voltage at voltmeter V3; D2 is an assembly of Zener diodes in series to establish a constant harvesting voltage of $\Phi_H = 2.4$ kV and allows measurement of the harvested current across a resistor R2 at voltmeter V2.
Harvesting cycle. Pressure ($P$), flow ($Q_a$), $V$ ($\Phi$), $I$
Self-healing of DEGs: High strain & electric field!

(A) 

(B) 

Self-Healing Dielectric Elastomers for Damage-Tolerant Actuation and Energy Harvesting

Christopher Ellingsford, Runan Zhang, Alan M. Weymss, Yan Zhang, Oliver B. Brown, Honghao Zhou, Patrick Kneih, Christopher Bowen, and Chaoying Wan

ACS Appl. Mater. Interfaces 2020, 12, 7595
Variation on MGSBS (Dr Chaoying Wan)

Commercial material

SBS

MGSBS

Electrostatic interactions

(a)

OH-groups, permittivity & healing

Longer dangling side chain – increased flexibility

(b)

M3M SBS

Increase graft chain length

Dual groups for permittivity, mech. props. & healing

Enhanced intermolecular interactions enabled self-healing function

MG/TG SBS

Additional hydrogen bonding
Elastomer design for energy generation applications:

Adaptation of commercial materials for:

- Mechanical properties (Y, elastic strain, visco-elastic)
- Dielectric properties (permittivity, loss)
- Self-healing functionality (dielectric/mechanical damage)

Dielectric generators
Energy storage (capacitors, flexible electronics)

Less on tribo-electric and piezo-electric systems

Parida et al., Adv Mat 2017, 29, 1702181
The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement no. 320963 on Novel Energy Materials, Engineering Science and Integrated Systems (NEMESIS).