A soft and conductive PDMS-PEG block copolymer as a compliant electrode for dielectric elastomers

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Publication date:
2015

Document Version
Peer reviewed version

Citation (APA):
A soft and conductive PDMS-PEG block copolymer as a compliant electrode for dielectric elastomers

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Annual Polymer Day 2015
Motivation

Principle of dielectric elastomer (DE) as an actuator:

Requirement of compliant electrodes: 1) Inherently soft 2) Conductivity
Stereotypes of electrodes

1) A conductive material is generally non-stretchable.

2) A stretchable material is usually non-conductive.

Our goal: soft-conductive polymer
Conventional electrodes for DEs

1) **Losse carbon black**
   - Samuel Rosset (EPFL)
   - Helmut Schlaak (University of Darmstadt)

2) **Carbon grease**
   - Samuel Rosset (EPFL)

**Alternative electrodes:**
1) Ionic conductor (hydrogel)
2) Silver nanowires
3) Conductive rubber
PDMS3-PEG copolymer

1. Hydrosilylation reaction of PDMS-PEG copolymer:

\[ \text{PDMS}3\text{-PEG} \rightarrow \text{Stiff} \]

2. Conductivity (PDMS-PEG copolymers)\(^1\)

\[ \text{PDMS3-PEG} \rightarrow \text{high conductivity (10}^{-8} \text{ S/cm)} \]

3. Linear viscoelasticity-LVE (PDMS-PEG copolymers)\(^1\)

\[ \text{PDMS3-PEG} \rightarrow \text{Stiff} \]

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Chain-extended PDMS3-PEG copolymer

1. To obtain a soft-conductive polymer → Chain extended PDMS-PEG copolymer

\[
\begin{align*}
&\left[\begin{array}{c}
H_3C \\
CH_3 \\
CH_3 \\
\end{array}\right]_n \text{Si-O-} \left[\begin{array}{c}
\text{CH}_3 \\
\text{Si-O-} \\
\text{Si-O} \\
\text{Si-O} \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\text{CH}_3 \\
\end{array}\right]_m \text{CH}_3 \\
\end{align*}
\]

PDMS - PEG (vinyl terminated)

\[
\begin{align*}
&\left[\begin{array}{c}
\text{CH}_3 \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
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\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\end{array}\right]_m \text{CH}_3 \\
\end{align*}
\]

PDMS232 (hydride terminated)

\[
\begin{align*}
&\left[\begin{array}{c}
\text{CH}_3 \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
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\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\text{Si-O} \\
\end{array}\right]_m \text{CH}_3 \\
\end{align*}
\]

Crosslinked copolymer:

Chain-extended PDMS-PEG copolymer + 15-functional vinyl crosslinker + 30 ppm Pt catalyst

\[\text{Mn} = 38 \text{ kg/mol}\]
Multi-walled carbon nanotubes (MWCNTs)

1. ↓ conductivity (PDMS3-PEG) → add conductive nanofillers (MWCNTs)

2. Obstacle → MWCNTs entangle

Fig. 1

SEM image of pure MWCNTs showing entanglements.

3. Dispersion methods:

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Mechanical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation process by acid e.g. HNO₃ &amp; solution of H₂O₂/NH₄OH</td>
<td>1) Probe sonicator 2) Ball milling</td>
</tr>
<tr>
<td>Drawback: intrinsic properties of MWCNTs are destroyed due to structural defects</td>
<td>Drawback: rupture MWCNTs into smaller lengths</td>
</tr>
</tbody>
</table>

4. Non-covalent physical treatment

Mechanism of flocculation of CNTs via surfactant molecules.

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Multi-walled carbon nanotubes (MWCNTs)

- Dispersion of MWCNTs $\rightarrow$ Rastogi et al.\(^1\), Geng et al.\(^2\) and Goswami et al.\(^3\)

1. Stability versus time for a reference method (MWCNT/NMP/Triton X-100) dispersed by a mechanical shaker at 23 °C: a) Immediately b) 5 min c) 30 min d) 60 min.

2. Stability versus time for MWCNT/NMP/Triton X-100 dispersed by water-bath ultrasonication at 23 °C for 6 hours: a) Immediately b) 5 min c) 30 min d) 60 min.

3. Optical microscope image of this film containing MWCNTs (0.07 phr) in PDMS-PEG matrix.

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Conductivity & permittivity

![Graph showing conductivity vs. frequency for different samples]

- 0CNT Si3PEG_H25
- 1CNT Si3PEG_H25
- 2CNT Si3PEG_H25
- 3CNT Si3PEG_H25
- 4CNT Si3PEG_H25
- LR 3162

Conductivity (S/cm) vs. Frequency (Hz)
Modulus

![Graph showing storage modulus and modulus loss factor as a function of frequency for different samples. The x-axis represents frequency (Hz) on a logarithmic scale, ranging from $10^{-2}$ to $10^2$, and the y-axes represent storage modulus (Pa) and modulus loss factor on logarithmic scales. The graph includes data points for 0CNT Si3PEG_H25, 1CNT Si3PEG_H25, 2CNT Si3PEG_H25, 3CNT Si3PEG_H25, 4CNT Si3PEG_H25, and LR 3162.](image-url)
Stress-strain plots

- Compliant electrodes
- PDMS-PEG
- MWCNTs
- Dielectric properties
- Rheology
- Stress-strain
Conclusion

• The cross-linked conductive PDMS-PEG copolymers were successfully prepared with addition of different MWCNT concentrations.
• The conductivity of the chain-extended elastomers increases nearly to $10^{-3}$ S/cm;
  - $< \text{LR3162} = 10^{-1}$ S/cm
• The mechanical properties of chain-extended PDMS-PEG copolymers with MWCNTs ($< 3$ phr) indicate soft networks with low modulus losses.
• Future work:
  – The conductivity can be improved by adding silver nanoparticles in the system if properly designed.
  – Measure the conductivity of samples in “stretch” mode.
Acknowledgement