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

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

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Motivation

Principle of dielectric elastomer (DE) as an actuator:

Requirement of compliant electrodes: 1) Inherently soft  2) High 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:

   \[
   \text{PDMS3-PEG} \rightarrow \text{Stiff} \quad \text{at} \quad 60 \, ^\circ \text{C}
   \]

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

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

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

   PDMS3-PEG \(\rightarrow\) Stiff

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Chain-extended PDMS3-PEG copolymer

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

\[
\begin{align*}
\left( \begin{array}{c}
\text{PDMS - PEG (vinyl terminated)} \\
\end{array} \right) + \\
\left( \begin{array}{c}
\text{PDMS232 (hydride terminated)} \\
\end{array} \right)
\end{align*}
\]

23 deg. C \[ Pt^{2+} \]

\[
\begin{align*}
\left( \begin{array}{c}
\text{(PDMS - PEG) - PDMS232 (hydride terminated)} \\
\end{array} \right)
\end{align*}
\]

2. Crosslinked copolymer:
Chain-extended PDMS-PEG copolymer + 15-functional vinyl crosslinker + 30 ppm Pt catalyst

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

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

2. Obstacle → MWCNTs entangle

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.¹

Multi-walled carbon nanotubes (MWCNTs)

- Dispersion of MWCNTs → 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

Fig. 1

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

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

Retest with normal force = 10N
Modulus

![Graph showing storage modulus and modulus loss factor against frequency.](image)

**Legend:**
- ★ 0CNT Si3PEG_H25
- □ 1CNT Si3PEG_H25
- ◯ 2CNT Si3PEG_H25
- △ 3CNT Si3PEG_H25
- ▲ 4CNT Si3PEG_H25
- ○ LR 3162
Stress-strain plots

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

![Stress-strain plot](image)

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

Y = 1.17 MPa
Y = 0.92 MPa
Y = 0.70 MPa
Y = 0.47 MPa
Y = 0.26 MPa
Y = 0.23 MPa
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