COMPOSITE ELECTRETS:
MATERIALS COMBINATIONS
WITH ENHANCED PROPERTIES

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1. Polymer-matrix micro- and nano-composites:
   Combining advantages, avoiding shortcoming

2. Composite materials: The connectivity concept

   - Piezo-, pyro- and ferroelectric particles in
     piezo-, pyro- and ferroelectric polymer
   - Magnetostrictive particles in
     piezoelectric polymer (inverse effect)
   - Liquid-crystalline electro-optic particles in
     space-charge electret polymer

4. Conclusions and outlook
Surface and bulk charges (left), frozen-in and ordered dipoles (right) in a polymer electret

Surface charges

Frozen-in dipoles
(amorphous phase)

Bulk charges

Stable dipoles
(crystalline phase)

Electrode charges

+ + + + + + + + + + + +

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Dipole-density effect as basic mechanism for piezo- & pyroelectricity in polymer electrets

Electrode

Oriented dipoles

Electrode

Expansion

Compression

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Preparation of 0-3 ceramic-polymer composites with ferroelectric or dielectric properties

(after Dias and Das-Gupta 1999)

mixing and hot rolling

hot pressing

aluminium evaporation

corona poling

conventional poling (AC or DC)

field=25MV/m

silicone oil @100°C
Model of a composite with spherical ceramic inclusions embedded in a polymer matrix

(after Furukawa and Fukada 1976 as well as Dias and Das-Gupta 1999)
Schematic views of connectivity patterns in two-phase composites

0-0  0-1  0-2  0-3
1-1  1-2  1-3  2-2
2-3  3-3  two opposite views  3-3

by rotating 180° around the z axis

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Connectivities and typical examples of practical composites (not all of them electrets)

<table>
<thead>
<tr>
<th>Index</th>
<th>Matrix</th>
<th>Filler</th>
<th>Examples</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0</td>
<td>particles</td>
<td>particles</td>
<td>sintered powders</td>
<td>both phases only particles</td>
</tr>
<tr>
<td>0-3</td>
<td>continuous</td>
<td>particles</td>
<td>concrete, paint, etc.</td>
<td>particles in matrix</td>
</tr>
<tr>
<td>1-1</td>
<td>rod-like</td>
<td>rod-like</td>
<td>fibre bundle</td>
<td>e.g. two types of fibres</td>
</tr>
<tr>
<td>1-3</td>
<td>continuous</td>
<td>fibres/rods</td>
<td>fibre reinforcement</td>
<td>rod length $\approx$ thickness</td>
</tr>
<tr>
<td>2-2</td>
<td>layers</td>
<td>layers</td>
<td>sandwich panel</td>
<td>layers continuous</td>
</tr>
<tr>
<td>2-3</td>
<td>continuous</td>
<td>2-D grid</td>
<td>reinforced concrete</td>
<td>2-D tensional strength</td>
</tr>
<tr>
<td>3-3</td>
<td>continuous</td>
<td>continuous</td>
<td>&quot;filled sponge&quot;</td>
<td>interwoven networks</td>
</tr>
</tbody>
</table>

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Photorefraktivität: Optische und elektrische Gitter

Lichtintensität

\[ I(z) \]

Ladungsdichte

\[ \rho_{SC}(z) \]

Elektrisches Feld

\[ s'(z) \sim E_{sc}(z) \sim \int \rho_{sc}(z) \, dz \]

Brechungsindex

\[ \Delta n(z) \sim -E_{sc}(z) \]

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Model of a double-layer electret (soft + hard layer)

(after R. Kacprzyk et al., J. Electrostat. 39 (1997))

\[
\begin{array}{c}
\text{d}_1 & \text{\varepsilon}_1, \text{E}_1 \\
\hline
\text{"HARD"} & 1 \\
\hline
\text{d}_2 & \text{\varepsilon}_2, \text{E}_2 \\
\end{array}
\]

Response: \( r_{33} = -\sigma \frac{\varepsilon_1 \varepsilon_2 d_1 d_2}{(\varepsilon_2 d_1 + \varepsilon_1 d_2)^2} \left( \frac{1}{E_2} - \frac{1}{E_1} \right) \)

with the charge density \( \sigma \) and the thicknesses \( d_i \), relative permittivities \( \varepsilon_i \) and elastic (Young’s) moduli \( E_i \) of the hard (1) and soft (2) layers
Double-layer electret transducer with charged PTFE film and non-woven PP fabric

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Two-layer arrangements with (D) 40 $\mu$m and (E) 80 $\mu$m thick porous PTFE films

<table>
<thead>
<tr>
<th>Film sequence in stack</th>
<th>$\sigma$ (mC/m²)</th>
<th>$r_{33}$ (pC/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15$\mu$m</td>
<td>1.2</td>
<td>11</td>
</tr>
<tr>
<td>“HARD”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40$\mu$m</td>
<td>2.4</td>
<td>18</td>
</tr>
<tr>
<td>“SOFT”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15$\mu$m</td>
<td>1.2</td>
<td>5.2</td>
</tr>
<tr>
<td>“HARD”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80$\mu$m</td>
<td>2.4</td>
<td>7</td>
</tr>
<tr>
<td>“SOFT”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>15.5</td>
<td></td>
</tr>
</tbody>
</table>

Twice the soft-layer thickness $\Rightarrow$ Half the response

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Composite with poled particles and/or poled matrix
(after Ploss et alii 2000)
Pyroelectric coefficients of matrix, particles and both

(after Ploss et alii 2000)
Electric polarization & magnetoelectric coefficient in a 2-layer Terfenol/PVDF composite

(after Mori and Wuttig 2002)

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Field- and composition-dependent magnetoelectric coefficients of Terfenol/PZT/PVDF composites

(after Nan et alii 2002)
Schematic view of a polymer-dispersed liquid crystal
(after Kitzerow 1994)
Electret (memory) effect in the polymer matrix of polymer-dispersed liquid crystals

(after Cupelli, Nicoletta, de Filpo, and Chidichimo 2001)

\( +--+ \) = ion impurities
\( \gamma \) = disordered polymer chains
\( \parallel \) = aligned polymer chains
\( \bigcirc \) = Liquid Crystal

MEMORY STATE \hspace{2cm} NO MEMORY STATE

\( \vec{E}_{\text{int}} \neq 0 \)

\( \vec{E}_{\text{int}} = 0 \)

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