Short-Term Dielectric Performance Assessment of BOPP Capacitor Films: A Baseline Study

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Outline

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   - Dielectric spectroscopy
   - Thermally stimulated depolarization current
   - DC conductivity
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Motivation and background

GRIDABLE, a EU Horizon 2020 project:
“Plastic nanocomposite insulation material enabling reliable integration of renewables and DC storage technologies in the AC energy grid”

Target:
To connect renewable energy sources to the energy grid in a more efficient way through innovative polypropylene (PP) nanocomposites that aim to improve reliability at operating voltages in DC cable insulation and in power capacitors.

Consortium:
Motivation and background

Biaxially oriented polypropylene (BOPP) in film capacitors:

- Current state-of-the-art dielectric medium in both high-energy metallized film capacitors and oil-impregnated film-foil capacitors.
- Superior dielectric strength (small-area DC DBS ~700 V/µm), very low dielectric loss (\(\tan \delta < 2 \times 10^{-4}\)) and excellent self-healing breakdown capability in metallized form.

Capacitor BOPP today:

- High-isotactic base PP with optimized molecular weight distribution and stabilization
- Minimum residual catalyst and impurity contents
- Film thickness homogeneity, controlled surface roughness, optimized heat shrinkage etc.
- Film thicknesses to date can reach <2 µm!

The purpose of this study:
Short-term reliability evaluation of state-of-the-art BOPP capacitor films for reference purposes of the GRIDABLE project.
1. Motivation and background
2. Materials and sample preparation
3. Methods and main results
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   - Dielectric spectroscopy
   - Thermally stimulated depolarization current
   - DC conductivity
4. Conclusions
Film specifications

Two types of commercial tenter BOPP films were studied:

- Non-metallized (base) films; 5 µm & 10 µm
- Zn-Al metallized films; 5 µm & 10 µm

All films manufactured using the same base polymer (a capacitor-grade iPP homopolymer with high purity and low ash content).

Properties (10 µm base film):

- Melting temperature $T_m$ of $\sim 167.9$ °C
- Glass-transition temperature $T_g$ of approx. $-5.4$ °C
- Initial crystallinity $X_{DSC}$ of $\sim 61$ % ($\alpha$-form)
- Smooth film surfaces with shallow crater-like structures (mean area surface roughness $\sim 24$ nm)
Electrode preparation

For dielectric spectroscopy, conductivity and TSDC measurements:

- Electrodes (⌀ 22 mm) were deposited on both sides of the sample films by e-beam evaporator inside a clean room facility:
- Deposited materials: **Ni + Au (10+100 nm)** or **Al (100 nm)**
- Samples were short-circuited and stored in vacuumed desiccator for several days prior to electrical measurements.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Rate (nm/s)</th>
<th>P (mbar)</th>
<th>Current (mA)</th>
<th>Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>0.05</td>
<td>&lt; 1×10^{-6}</td>
<td>~59</td>
<td>10</td>
</tr>
<tr>
<td>Au</td>
<td>0.2</td>
<td>&lt; 1×10^{-6}</td>
<td>~150</td>
<td>10</td>
</tr>
<tr>
<td>Al</td>
<td>0.15</td>
<td>&lt; 1×10^{-6}</td>
<td>~85</td>
<td>10</td>
</tr>
</tbody>
</table>

Distance between source and substrate: ~50 cm
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Experimental methods

1. Dielectric breakdown strength
   - Voltage form (DC, AC)
   - Area-dependence
   - Temperature dependence

2. Dielectric permittivity and loss
   - Frequency, temperature and field* dependence

3. Thermally stimulated depolarization current
   - High field, high temperature

4. DC conductivity
   - Temperature and field dependence

* Not presented here
**Dielectric breakdown strength: Measurement specifications**

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Voltage form</th>
<th>T (°C)</th>
<th>Active area (cm²)</th>
<th>N</th>
<th>Total film area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large-area multi-breakdown</td>
<td>DC</td>
<td>RT</td>
<td>81</td>
<td>20</td>
<td>1620</td>
</tr>
<tr>
<td>1</td>
<td>Large-area multi-breakdown</td>
<td>DC</td>
<td>100</td>
<td>81</td>
<td>6</td>
<td>486</td>
</tr>
<tr>
<td>2a</td>
<td>Small-area single-breakdown</td>
<td>DC</td>
<td>RT</td>
<td>1</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>2b</td>
<td>Small-area single-breakdown</td>
<td>AC</td>
<td>RT</td>
<td>1</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

*RT (room temperature conditions): $T = 23.7^\circ C \pm 0.6^\circ C$, RH = 33.5% $\pm 10.7%$*

**Extensive short-term breakdown strength characterization was made:**

- Large-area self-healing breakdown measurement using metallized films as electrodes\(^1\).
- Conventional small-area single-breakdown measurement according to IEC-60243.

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Dielectric breakdown strength: Weibull results

- DC breakdown strengths (Weibull $\alpha = 650–770$ V/µm) in similar or higher range in comparison to literature values for high-quality BOPP.

- Some weak points observed for the non-metallized films (100-400 V/µm range).

- At 100 °C: Approx. 13–20 % decrease in DC breakdown strength.

- Small-area AC breakdown strength data (peak AC voltage) in similar or slightly lower range in comparison to the DC data—consistent with literature on thin films.

Shaded areas: 90 % confidence bounds

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Relative permittivity and dielectric loss

Relative permittivity:
- In the expectable range for BOPP (2.2–2.3 at RT, 1 kHz).
- Slight decrease (~5 %) with increasing temperature (from −50 °C to 100 °C).

Dielectric loss:
- Very low dielectric loss characteristics ($\tan \delta < 2 \times 10^{-4}$ at room temperature, 1 kHz).
- Broad relaxation peak above glass transition temperature (−5 °C to 60 °C).
- An increase of $\tan \delta$ at low frequencies and high temperature → Release of trapped charge; increase of DC conductivity...

Charge originates from the electrode evaporation process? Difficult to remove…

Inset: Room temperature conditions
Thermally stimulated depolarization current (TSDC): Procedure

**Procedure:**

1. Sample is heated ($T_p = 80 \, ^\circ C$).
2. DC voltage is applied for $t_p = 40 \, \text{min}$ (charging).
3. Temperature is rapidly decreased to $T_0 = -50 \, ^\circ C$ (voltage still on).
4. Voltage is removed, sample is short-circuited.
5. Linear heating at $\beta=3 \, ^\circ C/\text{min}$.

**TSDC** is a useful technique for studying charge storage and decay processes in dielectrics. Information on e.g. charge trap depth and density distributions.

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**Diagram:**

- **Voltage on:** $U_p = 1000 \, \text{V}$, $t_p = 40 \, \text{min}$
- **Current:** $100 \, \text{V/\mu m}$
- **Temperature:** $T_p = 80 \, ^\circ C$
- **Cooling:** $dT/dt = -15 \, ^\circ C/\text{min}$
- **Linear heating:** $dT/dt = +3.0 \, ^\circ C/\text{min}$
- **$T_{max} \approx 125 \, ^\circ C$**

**Measurement of TSDC**
Thermally stimulated depolarization current (TSDC): Results

Shallow traps were observed in the ~0.75 eV range, and deep traps were observed in the ~1.08 eV range.

- Impurity states?
- TSC intensity in the shallow trap region was relatively low in proportion to the strong peak in the high-temperature region (deep traps).
- Space charge effects (deep traps) were observed in the high temperature region (anomalous TSDC).

DC conductivity: Measurements

- Temperature 30–100 °C
- DC fields of 30–250 V/µm
- Poling time 20–24 h

At each temperature, the sample was subjected to progressively increasing electric field. The sample was let to relax at the set temperature between each electric field application.
DC conductivity: Results

After 20–24 h of poling at each E-field:

- Conductivity in the $10^{-16}...10^{-17}$ S/m range.
- No clear dependence on electric field in the range studied (up to 200 V/µm). Rather, a slowly decreasing and saturating trend was observed.

Low shallow trap density + large amount of deep traps $\rightarrow$ Suppression of charge hopping between shallow traps and blocking of further charge injection due to formation of homocharge layer near BOPP-electrode interface?
Conclusions

- Short-term reliability and dielectric properties of commercial capacitor BOPP films were thoroughly characterized for reference purposes of GRIDABLE project.

- Overall, the studied BOPP films exhibited very high short-term dielectric performance:
  - High dielectric strength
  - Low dielectric loss
  - Low conductivity

- Further studies are needed to elucidate the role of electrodes and charge trapping in the observed dielectric phenomena.
Thank you!

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