Introduction to electrets: Principles, equations, experimental techniques

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Overview

Principles
Charges
Materials
Electret classes

Equations
Fields
Forces
Currents
Charge transport

Experimental techniques
Charging
Surface potential
Thermally-stimulated discharge
Dielectric measurements
Charge distribution (surface)
Charge distribution (volume)
Electret charges

- Dielectric
- Surface charges
- Space charges
- Metal electrode
- Dipolar (or displaced) charges
- Compensation charges
Energy diagram and density of states for a polymer
**Electret materials**

**Polymers**
- Fluoropolymers (PTFE, FEP)
- Polyethylene (HDPE, LDPE, XLPE)
- Polypropylene (PP)
- Polyethylene terephtalate (PET)
- Polyimide (PI)
- Polymethylmethacrylate (PMMA)
- Polyvinylidene fluoride (PVDF)
- Ethylene vinyl acetate (EVA)
- Cellular PP
- Porous PTFE

**Anorganic materials**
- Silicon oxide ($\text{SiO}_2$)
- Silicon nitride ($\text{Si}_3\text{N}_4$)
- Aluminum oxide ($\text{Al}_2\text{O}_3$)
- Glas ($\text{SiO}_2 + \text{Na, S, Se, B, ...}$)
- Photorefractive materials
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# Charged or polarized dielectrics

<table>
<thead>
<tr>
<th>Category</th>
<th>Materials</th>
<th>Charge or polarization</th>
<th>Properties</th>
<th>Applications</th>
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</thead>
<tbody>
<tr>
<td>Real-charge electrets</td>
<td>FEP, SiO₂</td>
<td></td>
<td>0.1 - 1</td>
<td>External electric field and force</td>
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<tr>
<td>NLO materials</td>
<td>PMMA / DR₁, glasses</td>
<td></td>
<td>0.1 - 10</td>
<td>Electrooptic and NLO effects</td>
</tr>
<tr>
<td>Ferroelectric materials</td>
<td>PVDF, PZT</td>
<td></td>
<td>10 - 100</td>
<td>Piezo- and pyroelectricity</td>
</tr>
<tr>
<td>Porous or cellular electrets</td>
<td>PP, PTFE</td>
<td></td>
<td>1</td>
<td>strong longitudinal piezoelectric effect</td>
</tr>
</tbody>
</table>

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Principles
- Charges
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- Forces
- Currents
- Charge transport

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- Charge distribution (surface)
- Charge distribution (volume)
Equations 1:
Fields of an electret

Surface charges only:
\[ \sigma = \sigma_r + \Delta P_p \]

Volume charges only:
\[ \rho(x) = \rho_r(x) + \rho_p(x) \]

External field \( E_2 \) from Eq. (2) with \( \sigma = \hat{\sigma} \)

\[ E_1 = -\frac{\sigma d_2}{\varepsilon_0 (\varepsilon d_2 + d_1)} \]  
(1)

\[ E_2 = \frac{\sigma d_1}{\varepsilon_0 (\varepsilon d_2 + d_1)} \]  
(2)

\[ \hat{\sigma} = \frac{1}{d_1} \int_0^{d_1} x\rho(x)dx \]
Equations 2: 
Force of an electret on an electrode

\[ F = \frac{1}{2} \varepsilon_0 E_2^2 \]
Equations 3: Currents in an electret

\[ E(x,t) \quad P_p(x,t) \quad i_c(x,t) \]

Current density

\[ i(t) = \frac{\partial (\varepsilon_0 \varepsilon E + P_p)}{\partial t} + i_c \]

\[ i_c = (\mu_+ \rho_+ + \mu_- \rho_-) E \]
Equations 4: Charge transport equations

Current Equation:
\[ \varepsilon \frac{\partial E(x,t)}{\partial t} + \mu \rho_f(x,t) \cdot E(x,t) + I(x) = I_0 \] (1)

Poisson Equation:
\[ \varepsilon \frac{\partial E(x,t)}{\partial t} = \rho_f(x,t) + \rho_t(x,t) \] (2)

Poisson Equation:
\[ \frac{\partial \rho_t(x,t)}{\partial t} = \frac{\rho_f(x,t)}{\tau} \cdot \left[ 1 - \frac{\rho_t(x,t)}{\rho_m} \right] \] (3)

Parameters of Model:
- \( I(x) \): current
- \( \mu \): free-carrier mobility
- \( \tau \): free-carrier lifetime
- \( \rho_m \): trap density

\( e^- \)
Measured and calculated location of charge peak in electron-beam charged FEP (Sessler 2004)
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Charging methods

CORONA

ELECTRON BEAM (Vacuum)

THERMAL

surface charge (and polarization)

volume or surface charges and polarization

surface and volume charges and/or polarization

~10kV

~200V

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Surface potential measurement

- Determination of charge stability of different electret materials by isothermal discharging at elevated temperatures

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Thermally-stimulated discharge (TSD)

Heating chamber

Linear temperature increase

Separation of surface and volume traps
Activation energies
Trap densities

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Measurement of activation energy $A$: Initial-rise-method

\[
\frac{d(\ln i)}{d\left(\frac{1}{T}\right)} = -\frac{A}{k}
\]
TSD for electron beam charged FEP
(v. Seggern 1981)
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Kelvin probe force microscope (KFM)
(Jacobs et al 1997)

Measures lateral potential distribution
KFM images of charge distribution on PMMA
(Jacobs et al 2001)
**Thermal pulse method**
*(Collins 1975)*

\[
\frac{\bar{r}}{d} = \frac{V(t_2)}{V(t_1)}
\]

![Diagram of the thermal pulse method](image)

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Thermal wave method
(Bauer 1996)

Measures charge distribution close to surface

\[
penetration\ depth \quad \frac{1}{k} = \sqrt{\frac{2D}{\omega}}
\]
Laser-Induced Pressure Pulse (LIPP) method

\[ I(t) \propto (\gamma + 1) \left( \rho - \frac{dP}{dx} \right) - \frac{de}{dx}, \quad x = ct \]
Charge distribution in e-beam irradiated FEP
(Sessler et al 1983)
Evolution of charge distribution in LDPE measured with Pulsed ElectroAcoustic (PEA) method (Hozumi et al 1998)
CV-method for measuring charge centroid location

- Electrostatic Voltmeter (field compensation principle)
- Capacitance - Voltage measurements

Measures location of charge centroid and total charge

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Charge drift in double layers of SiO$_2$ (300 nm) and Si$_3$N$_4$ (150 nm) (Zhang et al 2002)

[Graph showing the normalized units of surface potential, mean charge depth, and integrated charge density as a function of annealing time at 400°C.]
Scanning Electron Microscope (SEM) method
SEM pictures of cross section of charged cellular PP
(Hillenbrand et al 2000)
Summary:
New aspects of electret research

Electret materials
- NLO materials
- Cellular polymers
- Tailored polymers
- Silicon materials

Theoretical approaches
- Charge transport models with dispersive transport
- Generation-recombination models
- Radiation effects

Experimental methods
- Pressure pulse and thermal methods
- Atomic force microscopy
- Scanning electron microscopy
- CV-method
- Dielectric method

Better understanding of
- Charging and charge transport in irradiated polymers, cellular polymers, etc.