Micro/Nano Mechanical Systems
Lab – Class#22

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Outline

◆ Reviews
ME 138/238
Flexible Mechanical-Electrical Transducers for Self-Powered Systems

Dr. Junwen Zhong
Supported by Prof. Liwei Lin

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Mechanical-Electrical Energy Conversion

Flexible Transducers

Electromagnetic

Piezoelectric

Electrostatic Induction

Z. L. Wang, et al, EES, 2015, 7, 426
Comparison for 3 Principles

Electromagnetic
Ad: Large outputs, Mature technology
DisAd: Non-flexible, Heavy

Piezoelectric
Ad: Flexible, Miniaturize, wearable
DisAd: Little outputs, toxic

Electrostatic
Ad: Flexible, Relative large outputs
DisAd: Bad stability, Abrasion
Electrets

An electret is a piece of dielectric material exhibiting a quasi-permanent electric charge

- **Surface Potential (kV)**
  - Time (Day)
  - Even hundreds of years

- **Lifetime $\tau$ [years]**
  - Conductivity $G$ [S/m]
  - Experimentally observed lifetimes of Teflon® electrets
  - Non-charged Teflon® film

J. A. Malecki, *PRB* 1999, 59, 9954
Electrets

Electret material: Teflon (PTFE)

Dielectric strength: 20-200 MV/m
Relative permittivity: 1.90-2.2
Volume resistivity: $10^{16}$-$10^{19}$
Melting Point: 327°C - 342°C
Charge density: $-5.0 \times 10^{-4}$ C/m²

G. M. Sessler, Electrets (2nd ed), Berlin: Springer-Verlag, 1987
Surface Charge Density Detection

(1) According to Gauss law:
\[-E_1 + \varepsilon_r E_r = \sigma_1 / \varepsilon_0\]
\[-\varepsilon_r E_r + E_2 = \sigma_2 / \varepsilon_0\]

(2) According to Kirchhoff's second law:
\[E_1 d_1 + E_r d_0 + E_2 d_2 - U = 0\]
Working Mechanism of Flexible Electrostatic Transducer

\[ d_1 + \sigma + \sigma_2 = 0 \]

\[ \sigma_2 = -\frac{\sigma d_1}{d_2 \varepsilon_{r-e} + d_1} \]

Original

Pressing

Releasing
Simulation Results

equivalent circuit

\[ \begin{align*}
E^+ & \quad Q(t) \quad C_1 \quad E_1 \quad - \\
-Q(t) & \quad T-Q(t) \quad C_2 \quad E_2 \quad + \\
\end{align*} \]

\[ \begin{align*}
Q_T & \quad R_x \quad + \quad Q_E \quad d_0 \\
+ & \quad \downarrow \quad d_A \\
- & \quad \uparrow \\
\end{align*} \]

Original \quad \leftrightarrow \quad Releasing

Pressing \quad \leftrightarrow \quad Equilibrium

\[ \begin{align*}
\text{Current (\muA)} & \quad \begin{array}{c}
0.5 \\
0.0 \\
-0.5 \\
-1.0 \\
6 \quad 7 \quad 8 \quad 9 \quad \text{Time (s)}
\end{array}
\end{align*} \]
Surface Potential Detection

PTFE

0.1-1 mC/m²

PE

PET

PP
Lab Experiment: Arch-Shaped Flexible Generator

Question

◆ How to Improve the Output and Stability?
◆ What’s the Advantage and Disadvantage?
◆ Other application for the Transducer?
Electrostatic Self-excited Actuators for Micro Robots

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Electrostatic Self-excited Actuators

• Franklin bells

To lightning rod

Ball

To ground

Gordon’s idea
Electrostatic Self-excited Actuators

• Working principle

1. The ball is attracted by the electrode due to electrostatic induction;
2. The ball impacts the electrode;
3. The ball is charged and repelled by the electrode (same type of charge);
4. The ball goes to the opposite electrode and repeats the process.
Electrostatic Self-excited Actuators

- We find a similar vibration in micro world.

1 – 5 Hz

Big vibration
50 – 500 Hz
Electrostatic Self-excited Actuators

• Summary of advantages
  – Simple structure
  – Low power consumption
  – Easy to drive by DC voltage
  – Large vibration

Micro flying robots
Micro crawling robots
Micro cleaning robots
Micro Crawling Robots

- Directly use the impact between the beam and electrode to generate forward-driven force

**Working principle**

**Structural design**
Micro Crawling Robots

• Propulsion principle

Creeping forward (Top view)
Micro Crawling Robots

• Fabrication

- single layer of carbon fiber
- two orthogonal layers of carbon fiber
- carbon fiber + tinfoil
- Plastic membrane (PET, Nalifilm Company)

(a) Laser machining

(laser cutting + apply heat)

(laser cutting + apply heat)

(cutting)

supporting structure

cantilever beams

ceramics capacitor (10nF, 3kV, Yageo)

electrodes

additional mass

NiTi beams

beams

legs

(b) Manual assembly
Micro Crawling Robots

- Use a mold to assemble the electrodes

A. Mold
   - Place the supporting beams in the mold

B. Mold
   - Get some glue (edge only)

C. Mold
   - Keep pressure

D. Mold
   - The longer side
Micro Crawling Robots

- Insert the electrodes into the **supporting plates**

- **Insert**

- **Glue, adjust, and wait**
Micro Crawling Robots

- Glue **legs** for the robot

**G**
Insert anther two supporting beams for legs

**H**
Glue, adjust, and wait
Micro Crawling Robots

- Moving on different kinds of surfaces
Micro Crawling Robots

- Measure the operating current
  - Calculate the frequency and power consumption
Micro Crawling Robots

- Evaluate the performance
  - Operating frequency and forward velocity

**Graph (a)**
- Applied DC voltage ↑
- Frequency ↑
- Velocity ↑

**Graph (b)**
- Tip mass ↑
- Frequency ↓
- Velocity ↑
Thanks!
Micro/Nano Mechanical Systems Lab – Review of Lab #3

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Outline

◆ Micro/nano technologies for energy storage
  • Lithium ion battery
  • Supercapacitor
◆ Lab #3: Supercapacitors based on Laser Induced Graphene
Lithium ion battery

◆ Li ion path:
  • Solid-state diffusion – liquid diffusion/migration – solid-state diffusion

◆ Electron path:
  • Active material – collector – outer circuit – collector – active material
Supercapacitor (I)

◆ Working principle
  • Electrochemical double-layer effect

Electrochemical Double Layer

Typical Electrode: Porous Carbon, Carbon nanotube, Graphene…

\[ C \approx \frac{A_{\text{interface}} \varepsilon \varepsilon_0}{d} \]

http://en.wikipedia.org/wiki/Supercapacitor
Supercapacitor (II)

- Design of nanostructures for supercapacitors
  - High energy density: High Surface area
  - High power density: Fast transport paths for ions and electrons

http://wiki.seg.org/wiki/Carbon
Supercapacitor (III)

- Comparison

<table>
<thead>
<tr>
<th></th>
<th>Current Commercial Devices</th>
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</thead>
<tbody>
<tr>
<td><strong>Batteries</strong></td>
<td><strong>Supercapacitors</strong></td>
</tr>
<tr>
<td>Energy (Wh/kg)</td>
<td>10 - 300</td>
</tr>
<tr>
<td>Power (W/kg)</td>
<td>100 – 1,000</td>
</tr>
<tr>
<td>Charge time</td>
<td>Hours</td>
</tr>
<tr>
<td>Cycle life</td>
<td>~1,000</td>
</tr>
<tr>
<td>Safety</td>
<td>Flammable Corrosive Toxic</td>
</tr>
</tbody>
</table>

Liwei Lin, University of California at Berkeley
Lab #3 (I)

- Supercapacitors based on laser induced graphene
- Reduction from polymer by laser
Lab #3 (II)

- **Design considerations**
  - Voltage (>2V)
  - Energy (Proportional to electrode area)
  - Power (Related to internal resistance)
ME138/238 Spring 2018 Lecture

Quick “Review Session”: Microfluidics!

Eric Christopher Sweet | PhD Candidate

The Liwei Lin Lab
Department of Mechanical Engineering
University of California, Berkeley

Thursday April 5th, 2018
Microfluidics Background

• What are microfluidics?
  ◦ *Interdisciplinary field*: engineering, physics, chemistry, biochemistry, nanotechnology, and biotechnology
  ◦ “Study and manipulation of fluids at sub-millimeter length scales”
  ◦ Scaling-down fluid processes: *micro-scale resolution (~μm→mm) devices*
    ◦ **Volume (~L³)** → reduce L
      → *three-fold reduction in volume!*

Microfluidics Motivation

• Why scale down?
  - **Low fluid volumes**: fL (μm³), pL, nL, μL (mm³) << mL (cm³)
  - **Confined reactions**: precise control, faster, higher sensitivity, compact
  - **Biological scale**: single cell culture, analysis, observation, manipulation
  - **Unique micro-scale physical phenomena**
    - Different forces dominate fluids at micro-scale: gravity, inertia \(\rightarrow\) viscosity (surface energy), capillary forces

Walling et al., *Chem Soc Rev* (2011)
## Microfluidics Principles

- **Dimensionless Numbers**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Expression</th>
<th>Category</th>
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</thead>
<tbody>
<tr>
<td>Re</td>
<td>Reynolds</td>
<td>$\frac{\rho U_0 L_0}{\eta}$</td>
<td>inertial/viscous</td>
</tr>
<tr>
<td>Pe</td>
<td>Péclet</td>
<td>$\frac{U_0 L_0}{D}$</td>
<td>convection/diffusion</td>
</tr>
<tr>
<td>Ca</td>
<td>capillary</td>
<td>$\frac{\eta U_0}{\gamma}$</td>
<td>viscous/interfacial</td>
</tr>
<tr>
<td>Wi</td>
<td>Weissenberg</td>
<td>$\frac{\tau_p \dot{\gamma}}{\gamma}$</td>
<td>polymer relaxation time/shear rate time</td>
</tr>
<tr>
<td>De</td>
<td>Deborah</td>
<td>$\frac{\tau_p}{\tau_{flow}}$</td>
<td>polymer relaxation time/flow time</td>
</tr>
<tr>
<td>El</td>
<td>elasticity</td>
<td>$\frac{\tau_p \eta}{\rho h^2}$</td>
<td>elastic effects/inertial effects</td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof</td>
<td>$\rho U_b L_0$</td>
<td>Re for buoyant flow</td>
</tr>
<tr>
<td>Ra</td>
<td>Rayleigh</td>
<td>$\frac{U_b L_0}{\eta}$</td>
<td>Pe for buoyant flow</td>
</tr>
<tr>
<td>Kn</td>
<td>Knudsen</td>
<td>$\frac{\beta}{L_0}$</td>
<td>slip length/macroscopic length</td>
</tr>
</tbody>
</table>

Jean-Baptiste Salmon, (Mass) transport phenomena in microfluidic devices, PDF
Microfluidics Principles

- **Reynold’s Number**: relative importance of inertial to viscous $F$

  \[
  Re = \frac{(\rho U^2)}{\left(\frac{\mu U}{L}\right)} = \frac{\rho UL}{\mu}
  \]

  momentum transported by convection

  momentum transported by viscous diffusion

Laminar flow: $Re < 2300$

Turbulent flow: $Re > 4000$
Microfluidics Principles

- **Peclet Number**: relative importance of convection to diffusion

\[
P_{e} = \frac{L u}{D}
\]

- Low Peclet Number → diffusion-dominant mixing
  → Complete mixing: long time, long distances

Con: *(intentional) mixing is really hard!*
Pro: membrane-less filtering (H-filter)

Stokes-Einstein Equation

\[
D = \frac{k_{B}T}{6\pi \eta R}
\]
Microfluidics Principles

• Improve mixing in conventional microfluidics
  ✷ Large microchannels
  ✷ Higher flow rates
  ✷ Inter-channel geometries
  ✷ “3D” microchannels (compact length)
Fabrication Techniques

**Micromachining and Thermoplastic Processing**
- Lithography/patterning (glass, quartz, silicon, ceramics, paper)
- Hot embossing, injection molding (polymers)

**Soft Lithography**
- Lithography → silicon wafer
- Elastomer (PDMS) casting

**Microfluidics**

**Additive Manufacturing**
- FDM, SLA, Polyjet
- 3D printed molds
Fabrication Techniques

**Micromachining & Thermoplastic Processing**

- **Lithography** (glass, Si, etc.)
  - Chemically stable materials
  - Scalable manufacturing
  - Highest resolution (~1’s μm)

- **Hot embossing & injection molding** (polymers)
  - Cheap materials, recyclable
  - Simple & scalable processing
  - Biocompatible & stable
Fabrication Techniques

**Soft Lithography**
- Mold → lithography
- PDMS casting
  - Gas permeable
  - Flexible, transparent
  - High quality transfer of features
  - Reusable molds, 10-100’s devices
  - Major limitations:
    - Planar feature complexity
    - Bonding & manual assembly issues
Fabrication Techniques

• Why 3D print microfluidics?
  ◦ Single-step fabrication
  ◦ No bonding issues
  ◦ High-throughput prototyping

◊ Novel 3D geometries

Microfluidics

Additive Manufacturing

• FDM, SLA, Polyjet

FDM

PolyJet

SLA
Fabrication Techniques

- Alternative to soft-lithography
- Truly rapid prototyping!
  (3D print mold + cast PDMS ~ 1 day)
- No mask or wafer fabrication needed (i.e. lithography)