Capacitive Micro Force Sensors
Manufactured with
Mineral Sacrificial Layers

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What is it all about?

A **capacitive microforce sensor**
made with
**mineral sacrificial paste**

- 2 mN full scale
- resolution ~20µN
Goal: to develop a capacitive microforce sensor

1. Introduction – capacitive force sensors

2. Sensor design – electric layout and variants

3. Sacrificial paste – setup and dissolution

4. Results – prototype performance

5. Conclusions & outlook
1. Introduction

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5. Conclusions & outlook
1. Motivations

Existing force sensor: the *MilliNewton*
- up to 400-2000[mN], resol. 1% FS
- piezoresistive

Goal: **up to ~2 [mN]** full scale
- strain measurement inadequate
- \( \Rightarrow \) displacement measurement
- \( \Rightarrow \) capacitive sensor
- active feedback possible

Long-term: to pave the way for LTCC
- inlays in **Mineral Sacrificial Paste (MSP)**
- composition and dissolution well controlled
- shrinkage matching

Examples of mismatched shrinkage of MSP on LTCC
1. State of the art

Pioneering in early 1980’s
- at Bosch by G. Stecher et al.
- already in TF on alumina
- **complex** successive steps of depositions
- involved $\text{N}_2$ and air firing
  $\Rightarrow$ no large-scale manufacturing

In our lab (Laboratoire de Production Microtechnique)
- Dr. Hansu Birol experiments on LTCC
- MSP mix of $\text{B}_2\text{O}_3$ (melts 450°C) and CaO (refractory)
- **strong deformations** due to low shrinkage (7-8%)
- films remained porous

  $\Rightarrow$ we made new attempts, but on alumina
- replacement of boric oxide ($\text{B}_2\text{O}_3$) by Borax ($\text{Na}_2\text{B}_4\text{O}_7$)
- study of paste compatibilities
- improvement of dissolution selectivity
2. Sensor design

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2. Physical principle

- electrodes embracing MSP
- MSP dissolved after firing
- force bends cantilever
  - top electrode moves
  - capacity increases
- capacity = f (force)

\[
C(F_a) = \frac{\varepsilon_0 \varepsilon_r \cdot A}{F_a} \quad \frac{r_0 - \frac{F_a}{k}}
\]

Legend
- \( d, A \) displacement, area
- \( r, r_0 \) gap between electrodes (initial)
- \( F_r = -k \cdot d \), mech. force of recall
- \( F_a \) applied force to measure
- \( F_e \) electrostatic counter force (opt.)
- \( \varepsilon_0, \varepsilon_r \) diel. constant, rel. air permittivity
2. Electrical layout

• 4 electrodes:
  - reference
  - measurement
  - GND
  - (active compensation)

Al₂O₃ base with Ag electrodes

Dielectric cantilever with electrodes

Legend
- top
- bottom
2. Electrical layout

- 4 electrodes:
  - reference
  - measurement
  - GND
  - (active compensation)
2. Electrical layout

- **4 electrodes:**
  - reference
  - measurement
  - GND
  - (active compensation)

Legend:
- + top
- - bottom

(Active compensation)
2. Geometry variants

• 2 cantilever types:
  - single
  - bridge

• openings in cantilever:
  - with / without
  - variable size
2. Sandwich variants

8 printing variants, varying:
- dielectric thickness (1 or 2 L)
- electrode location (bottom, mid)
- top electrode type (Ag, Au, R)

Legend
- **Sub**: 96% Al₂O₃ substrate, 0.635mm
- **Ag**: silver-palladium AgPd, *ESL 9635B*
- **MSP**: mineral sacrificial paste
- **Diel**: dielectric, *ESL 4913*
- **Au**: gold, *DuPont 5744*
- **R**: resistor paste, *DuPont 2031*
3. Sacrificial paste

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3. From boric oxide to borax

- Originally:
  CaO (skeleton) + B₂O₃ (sintering binder) ⇒ porous MSP 😞

- Idea:
  to replace B₂O₃ with Borax Na₂B₄O₇, vitreous flux

- Experiments:
  - preparation of mix with varying borax content
  - ball grinded + 3-roll-milled with organic vehicle

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [g]</th>
<th>Mass [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tepineol C₁₈H₃₈O</td>
<td>32.00</td>
<td>64.5</td>
</tr>
<tr>
<td>Fluka 86480, anhydrous</td>
<td>16.00</td>
<td>32.2</td>
</tr>
<tr>
<td>Dibutylcarbitol Aldrich 99+%, 20,562-1</td>
<td>32.00</td>
<td>64.5</td>
</tr>
<tr>
<td>Ethyoxe llulose Aldrich 300 [cps], 20,065-4</td>
<td>1.64</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Borax volume fraction %
range 10%-80%
### 3. Initial paste experiments

<table>
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<th>Borax [vol. fraction %]</th>
<th>Results</th>
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</table>
| < 40                   | • powdery, degrades with humidity  
⇒ **unusable** |
| 40 - 50                | • transition from powdery to vitreous state  
• relatively stable and slightly reactive  
⇒ **interesting zone** |
| > 50                   | • vitreous, resistant to mech. constraints  
• strongly reacts with other layers  
⇒ **unusable** |
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                         • strongly reacts with other layers  
                         | ⇒ **unusable** |
3. Final paste: 50% borax

• best pastes are 40% and 50% of borax
• paste 40% decomposed in a few days ☹️ ⇒ let’s go with paste 50%
• paste with 60 wt% powder mix + 40 wt% organic vehicle

<table>
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<tr>
<th>Component</th>
<th>Mass proportions</th>
<th>Used quantity [g]</th>
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<tr>
<td>Borax</td>
<td>24.8%</td>
<td>7.81</td>
</tr>
<tr>
<td>CaO</td>
<td>35.2%</td>
<td>11.06</td>
</tr>
<tr>
<td>Organic binder</td>
<td>40.0%</td>
<td>12.58</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>34.82</td>
</tr>
</tbody>
</table>

…but at posteriori, it was a mistake ☹️:

• paste 50% proved difficult to dissolve
• better to use 40%, but immediately to avoid destruction by moisture
3. Sacrificial paste dissolution

- Very difficult to achieve good selectivity – not yet controlled
- First with HCl (too strong), then in H$_3$PO$_4$ (better selectivity)
- **Best results**: 30 hours in 80-90°C H$_3$PO$_4$, then thoroughly rinsed (DI H$_2$O for 1-8 hrs, IPA) and air dried at 100°C
4. Results

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4. Pastes compatibilities

- Resist-diel (V3, V7, V8) and MSP-Au-diel (V6): bubbles ⇒ unusable 😞
- Black stains around MSP for resistor paste variants (no other impact)

- Au variants (V2, V4): overall best results
4. Design considerations

- Few tests carried out, due to few healthy offspring however:
  - Layouts single/bridge:
    - both proved to be relatively good mechanically
    - single layout easier to dissolve than bridge
  - Variants with very long cantilevers and long inner cuts:
    - twist and tear easily $\Rightarrow$ unusable
  - Both sandwich and asymmetric cantilever designs were successful
4. Measuring setup

Demo-board of **Analog Devices AD7746EB**
- 2 channels (#1 measurement, #2 reference)
- chip range: ±4 pF (or 0-8 pF, displaceable up to +17 pF)
- remarkable performance
4. Prototype performance

Achieved performance:
- force range \( \sim 2 \) mN
- resolution \( \sim 1\% \) of FS (remarkable for passive measurement!)
- 1\(^{st}\) estimation inaccurate, based on theoretical values
- 2\(^{nd}\) estimation adapted to actual dimensions \( \Rightarrow \) fits reality well
4. Other considerations

• Absolute or differential measurement:
  • little differences
  • in differential, humidity affects the reference electrodes too...
  • humidity (breath) has a strong effect on measurement
    ⇒ contamination with sodium
    ⇒ could be a humidity sensor or alcohol test 😊

• Active measurement with electrostatic counteraction:
  • has not yet been implemented ☹
  • possible, electrodes already implemented
5. Conclusions & outlook

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5. Conclusions

- Capacitive microforce sensor with mineral sacrificial layers:
  - possible on alumina in thick-films
  - not yet possible on LTCC (shrinkage mismatch)

- Paste incompatibilities:
  - resistor-dielectric + MSP-Au-dielectric
  - best results with Au

- Selective dissolution very difficult:
  - best results with 80-90°C H₃PO₄ for 30 hours
  - hindered by MSP-sodium reaction with electrodes

- Various designs successful
  - single cantilever easier to dissolve but more fragile

- Active electrostatic counteraction:
  - not yet tested, but electrodes implemented
5. Outlook

• Recent tests with reduced sodium / alkali content:
  • promising solution
  • paste 60% vol. CaO, 15% Borax and 25% H$_3$BO$_3$ or B$_2$O$_3$

• To suit LTCC, shrinkage has to be increased (from 7-8 to 15%):
  • e.g. by adding bismuth borate
  • known to melt at 726°C (congruent)
The end

Thank you for your attention!