Fabrication, response and stability of miniature piezoresistive force-sensing thick-film cantilevers

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Outline

1. Introduction
2. Manufacturing
3. Thermal drift
4. Force response & signal stability
5. Conclusions & outlook
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Typical thick-film piezoresistive sensor

**Typical elements**
- Sensing bridge
- Offset trim
- TCO trim
- Differential amplifier

**Typical values (±)**
- Offset ~30 mV/V
- Response ~2-3 mV/V
- TCO ~1 μV/V/K
  (50 K : ~0.05 mV/V, ~2% F.S.)

**For 0.1% F.S.:**
- Offset reduction ~10'000×
- Stability (bridge) ~2-3 ppm
Cantilever force cell – principle

- Piezoresistive bridge
- Thick-film resistors
- Gauge factor $K_L \sim 12$
Cantilever force cell – distances

Geometry
- $L$ : for stress
- $d^+$ : positive signal (avg.)
- $d^-$ : positive signal (avg.)
- $d$ : signal (overall)
- $b$ : cantilever width
- $h$ : cantilever thickness

$$d = \frac{1}{2} \left( d^+ - d^- \right)$$

Nominal stress:  Effective sensor strain:  Response (signal / supply):

$$\sigma = \frac{6}{b \cdot h^2} \cdot L \cdot F \quad \varepsilon_r = \frac{6}{b \cdot h^2 \cdot E} \cdot d \cdot F \quad r = K_L \cdot \varepsilon_r$$

($E$ = substrate elastic modulus; $K_L$ = piezoresistive longitudinal gauge factor)
Classical cantilever

\[ \frac{d}{L} = 75\% \]

\[ L = 8 \text{ mm} \]

Pros
- Full active bridge
- Little thermal drift

Cons
- Double-side, complex fabrication
- More difficult resistor matching (separate prints)
- Layers on top side
- Sensitive to horizontal forces

\[ R_2^+ - R_1^+ - R_2^- + R_1^- = +6 \text{ mm} \]

\[ d^+ = +6 \text{ mm} \]

\[ d^- = -6 \text{ mm} \]
Single-side cantilever (type 1)

Pros

- Single-side, simple
- Good resistor matching (single print)
- Blank top side
- Little thermal drift

Cons

- Half bridge, less sensitive
- Sensitive to horizontal forces

\[ \frac{d}{L} = 40\% \]

- \( L = 6 \text{ mm} \)
- \( d^+ = 0 \text{ mm} \) (no stress)
- \( d^- = -4.75 \text{ mm} \)
Single-side cantilever (types 2/3)

\[ \frac{d}{L} = 34\% \]

Pros
- Single-side, simple
- Good resistor matching (single print)
- Blank top side
- Horizontal force compensation

Cons
- Half bridge, sensitivity further reduced by "retrograde" resistors
- Buried conductors?

Bottom (w/o diel.)
- \[ L = 8.08\, \text{mm} \]
- \[ d^+ = -1.25\, \text{mm} \]

Bottom (with diel.)
- \[ d^- = -6.75\, \text{mm} \]
Substrates (blank) – static fatigue

- Very good performance for ZrO2:Y (YSZ) & ZTA
- Glassy (Al2O3 96% & LTCC) : poorer
Substrates (load cell) – static fatigue

- Strong degradation of high-strength substrates (ZrO$_2$ & ZTA)
- ZrO$_2$ & ZTA better with single-side cantilevers (blank top side)
Substrates (load cell) – static fatigue

- Strong degradation of high-strength substrates (ZrO$_2$ & ZTA)
- ZrO$_2$ & ZTA better with single-side cantilevers (blank top side)
LTCC structured cantilever

Pros
- Single-side
- Good resistor matching
- Higher signal by structuration
  - Concentration of compression
  - In practice ~2x
- Horizontal force compensation

Cons
- LTCC process critical for thin, sensitive cantilevers (shrinkage matching, warpage)
- Resistor compatibility
- Drift???
LTCC cantilever – drift?

- Moderate, consistent signal
- No apparent drift
LTCC cantilever – drift?

1 - Introduction

- Abnormally high signal
- Strong variations between samples
- Significant drift
YSZ cantilevers – drift?

Anelasticity in YSZ
- Ferroelasticity
- Problematic for elastic substrate...

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## Substrates

<table>
<thead>
<tr>
<th>Code</th>
<th>Substrate material</th>
<th>Thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3YSZ (Kerafol)</td>
<td>45</td>
</tr>
<tr>
<td>B</td>
<td>3YSZ (Kerafol)</td>
<td>90</td>
</tr>
<tr>
<td>C</td>
<td>Al₂O₃ 96% (Kyocera A-476)</td>
<td>400</td>
</tr>
<tr>
<td>D</td>
<td>Al₂O₃ 96% (CeramTec Rubalit 708S)</td>
<td>150</td>
</tr>
<tr>
<td>E</td>
<td>ZTA (CeramTec Rubalit HSS 2-14-02-004)</td>
<td>250</td>
</tr>
<tr>
<td>F</td>
<td>ZTA (CeramTec Rubalit HSS4-38/3 S2)</td>
<td>320</td>
</tr>
<tr>
<td>G</td>
<td>LTCC (Heraeus CT700)</td>
<td>470 / 710</td>
</tr>
<tr>
<td>H</td>
<td>LTCC (Heraeus Heralock HL2000)</td>
<td>180 / 270</td>
</tr>
<tr>
<td>I</td>
<td>LTCC (DuPont 951)</td>
<td>270 / 410</td>
</tr>
</tbody>
</table>

### Tested substrates
- All pre-fired
- Not structured, same layout
**Tested layouts**

1) Short cantilever, half-bridge
2) Long cantilever (no tracks under resistors)
3) Long cantilever (tracks under resistors)
Fabrication

- Resistors (DP 2041) on dielectric:
  - 3YSZ : ESL 4931 (for steel -> CTE ~ YSZ)
  - Others : ESL 4913 + 4917 (low CTE)
- 3YSZ : 45 µm critical, 90 µm OK
- Al₂O₃ / ZTA : OK down to 150 µm (ZTA recommended)
- LTCC : flatness critical (DP951 ≥ HL2000 > CT700)
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A – 45 µm 3YSZ – layout 3

- Very low heat conductance (45 µm thick, \( k \sim 2-3 \) W/m/K)
- Thermal drift max \(~1\%\) (for 2'000 ppm F.S.)
B – 90 µm 3YSZ – layout 2

- Same material, 2x thickness
- ½ thermal drift
D – 150 µm alumina – layout 2

- Very low thermal drift even for thinnest Al₂O₃
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A – 45 µm 3YSZ – layout 3

- High signal level, consistent
- No visible drift (<±5 ppm)
- Linear signal, ~43 ppm/mN
B – 90 µm 3YSZ – layout 2

- High signal level, quite consistent
- Linear signal, ~20 ppm/mN
- Slight drift?
B – 90 µm 3YSZ – layout 2 (loading)

- High signal level, quite consistent
- Linear signal, ~20 ppm/mN
- Slight drift?
B – 90 µm 3YSZ – layout 2 (unloading)

- High signal level, quite consistent
- Linear signal, ~20 ppm/mN
- Slight drift?
B – 90 µm 3YSZ – layout 3 (unloading)

- Apparent drift similar for both layouts
D – 150 µm Al₂O₃ – layout 2

- Expected magnitude vs 90 µm YSZ (B) & 400 µm Al₂O₃ (C)
- Very clean signal
Expected magnitude vs 90 µm YSZ (B) & 400 µm Al₂O₃ (C)

Very clean signal
- High signal, large variations
- Visible zero drift (not anelastic) – damage ?
- No apparent dependence on layout
H2 – 180 μm LTCC HL2000 – layout 3

- High signal, large variations
- Visible zero drift (not anelastic) – damage?
- No apparent dependence on layout
- Thicker: mostly similar behaviour
- Some "clean" samples
- Thicker: mostly similar behaviour
- Some "clean" samples
Different LTCC: similar behaviour
Different LTCC: similar behaviour
I2 – 270 µm LTCC DP951 – layout 2

- Different LTCC: similar behaviour
I2 – 270 µm LTCC DP951 – layout 2

- Increase of drift with apparent signal -> anomalous
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Conclusions

- Thin cantilevers on many substrates, including LTCC

- Same manufacturing process:
  - Post-fired, single-side
  - Two-layer, piezoresistors on thick-film dielectric
  - Resistors allowed above buried tracks (variant 3) or not (variant 2)

- Results:
  - Al₂O₃ / ZTA: clean signal, thermal drift not a problem
  - 3YSZ: possibly slight anelastic drift & thermal effects due to very low thermal conductance of cantilever
  - LTCC: signal mostly unstable (some clean samples)
    - Cause? Low thermal expansion?
Outlook

- Elucidate drift mechanism on LTCC
  - Perform progressive loading tests
  - Check for resistor damage
  - Try on LTCC with high CTE – should avoid instabilities

- Extended analysis of new design
  - Performance & economics vs existing cantilever
  - Sensitivity to side loads
  - Lowest practical force ranges (deflection, manufacturing…)
The end

Thank you for your attention!