Modeled Electroformed MEMS Variable Capacitor for Cobalt Iron Alloy Magnetostriction Measurements

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Electrodeposited Magnetostrictive CoFe

Previous work:

Our work:

Expression du Tremolet de Lacheisserie and Peuzin

$$\lambda_{eff} (D_{sat}) = \frac{2(D_{\parallel} - D_{\perp})E_s t_s^2 (1 + \nu_f)}{9E_f L^2 t_f (1 + \nu_s)}$$

Need a method for measuring $\lambda$ to obtain fundamental performance metrics $\lambda_s$ and $d_{33,m}$ for magnetostrictive materials.
Optical Lever

- Strain resolution (nε)
- Incompatible with electrodeposition

Laser Doppler Vibrometer (LDV)

- Strain resolution (± 5με)
- Not good for thin films
- Film adhesion poor


Staruch, M., NRL, communications

Resistive Strain Gauge

- Strain resolution (pε)
- Compatible with electrodeposition
- Torsional effects
Both magnetoelastic and electrostatic models were created. Only magnetoelastic model will be presented.
Design Features

**Advantages**
- Chip-scale (5mm (W) X 10mm (L))
- Orthogonal (patterned by photolithography)
- Parallel sensors possible (boosts signal)
- Less prone to torsional effects (improves accuracy)
- Reduced instrumentation complexity

**Disadvantages**
- Complex fabrication (Sandia is good at this!)

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Agilent 4284A 20Hz-1MHz Precision LCR Meter

Single orthogonal pair  Custom PCB

Triple orthogonal pair
Simulation – Physics Interfaces and Mesh

**Solid Mechanics (solid)**

1) \[ 0 = \nabla \cdot S + F_v \]

\( S = \) stress tensor
\( F_v = \) body force per volume

2) \[ \varepsilon_{me} = \frac{3 \lambda_s}{2 M_s^2} \text{dev}(M \otimes M) \]

\( \lambda_s = \) saturation magnetostriction
\( M_s = \) saturation magnetization

I.C.’s: \( u = (0, 0, 0) \) m
\( \delta u/\delta t = (0, 0, 0) \) m/s

B.C.’s: cantilever anchor

**Magnetic Fields (mf)**

2) \[ B = \nabla \times (A_b + A_r) \]

\( A_b = B \cdot y = \) vector potential

I.C.’s: \( A = (0, 0, 0) \)

B.C.’s: \( n \times A = 0 \) (mag insulation)

**Magnetostriction (pzm1)**

Coupling Type: Fully Coupled

Initial B-H curve (measured)

User controlled mesh with free tetrahedrals of size “Normal”. 

Air

IED’s
Simulation – Study and Results

Stationary Study
- Parametric sweep: $\lambda_S = 50-100 \text{ ppm} @ B = 1 \text{ T}$
- Intent: magnetically saturate film without touching bottom plate
- Parametric sweep: $B = 0 \text{ to } 1 \text{ T}$

$\text{3D surface displacement plot (MEMS Cap 1)}$

$C = \sum_{i=0}^{n} \alpha \varepsilon_0 \text{depth} \int_{0}^{\text{width}} \frac{dx}{1 + w}$

$n = \text{number of block types used}$
$\alpha = \text{symmetry (2)}$
$\text{depth} = \text{block dimension (y-axis)}$
$\text{width} = \text{block dimension (x-axis)}$
$w = \text{z-displacement}$
Sensitivity and Range

<table>
<thead>
<tr>
<th>Device</th>
<th>Quasilinear Range (B = 0.01 to 0.1 T)</th>
<th>Sensitivity (μm/pF)</th>
<th>$\lambda_s$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS Cap 1</td>
<td>0.14 to 0.57 μm 1.3 to 2.2 pF</td>
<td>0.48</td>
<td>100</td>
</tr>
</tbody>
</table>

MEMS Cap 1 sensitivity plot
Conclusions

• New method for measuring magnetostriction in electroplated CoFe alloy films needed → MEMS variable capacitors.
• Sensitivity of 0.48 μm/pF was achieved with the MEMS Cap 1 design.
• Capacitor was designed to measure films with saturation magnetostriction values ranging from $\lambda_S = 1$ to 100 ppm.
• Alternative designs under consideration.
• 1st pass capacitors under development.
Acknowledgements:

- Individuals for their support and contributions to the vision of this work: Dianna Blair, (Project Manager), Keith Ortiz, Wahid Hermina.
- Metglas Inc. for providing free samples of magnetostrictive alloy ribbon used for calibration of our magnetic test equipment.
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Independent verification of magnetostriction in Sandia bimorph CoFe/Copper cantilevers confirmed by Margo Staruch, Ph.D., Naval Research Labs (NRL).
Measurement Apparatus: (MPMS-7) superconducting quantum interference device (SQUID) magnetometer.

Quantum Design Magnetic Property Measurement System (MPMS) probe assembly

Agilent 4284A 20Hz-1MHz Precision LCR Meter

Custom PCB
# Plating Bath

<table>
<thead>
<tr>
<th></th>
<th>Chemicals</th>
<th>H$_3$BO$_3$</th>
<th>Co(H$_2$SO$_3$)$_2$</th>
<th>TMAB</th>
<th>Sorbitol</th>
<th>Na Saccharin salt</th>
<th>Ascorbic acid</th>
<th>Fe(NH$_4$)$_2$(SO$_4$)$_2$ · 6H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CoFe</strong></td>
<td>Conc. (mol/L)</td>
<td>0.5</td>
<td>0.4</td>
<td>0.1</td>
<td>0.01</td>
<td>0.05</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td><strong>Chemicals</strong></td>
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<tr>
<td></td>
<td>Neutronex 309i Gold – 2.4 troy oz gold/gal, 40 ppm thallium</td>
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<td></td>
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<tr>
<td><strong>Au</strong></td>
<td>Conditions</td>
<td>700 Hz pulse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 mA/cm2</td>
</tr>
</tbody>
</table>

*CoFe: Bath pH=2.0; Bath temperature=50°C  
Au: Bath pH=9.5; Bath temperature=50°C
Contact Pads 2 \( \mu \text{m} \) Cu

Capacitor Top Plate (Movable) 9 \( \mu \text{m} \) Cu

CoFe/Au Bimorph Cantilever 2 \( \mu \text{m} \) CoFe/9 \( \mu \text{m} \) Cu

Electrostatic Actuator 75 nm Pt, evaporated

Capacitor Bottom Plate (Fixed) 2 \( \mu \text{m} \) Cu

*Model courtesy of Adam Thorpe, Sandia National Laboratories*