MEMS Packaging Techniques for Silicon Optical Benches

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Introduction

Why MEMS for optoelectronic packaging?

• high precision required: ±0.5 micron, ±0.7°
• towards parallel assembly
• avoid expense of nanomanipulator
Introduction

Why rapid prototyping?

• many new materials
• mechanical design hard
**Introduction**

Why rapid prototyping?

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- mechanical design hard

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**Laser beam**
- 3ns pulses @ 50Hz
- 0.6mJ/pulse
- 355nm or 532nm
- 50μm-diameter spot

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**Pulsed laser source**
**Optical microscope**
**Sample table**
**X-y stage**
**Computer control for laser and stage**

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New Wave
www.new-wave.com
Introduction

Why rapid prototyping?

- many new materials
- mechanical design hard

Laser beam
3ns pulses @ 50Hz
0.6mJ/pulse
355nm or 532nm
50μm-diameter spot

sample (moves)

plan
section

substrate

parasitic undercut

SiN$_x$ cantilever
Introduction

Previous MEMS packaging work: passive

Journal Micromechanics Microengineering 8, 343-360 (1998)
Introduction

Previous MEMS packaging work: out of plane

- polysilicon multi-layer processes (e.g. SUMMiT, Sandia)
Introduction

Previous MEMS packaging work: out of plane

- polysilicon multi-layer processes (e.g. SUMMiT, Sandia)
- surface tension: self-assembly

self-assembled inductor

Imperial College http://www.ee.ic.ac.uk/optical/Microsystems.html
Outline

Laser micromachining: characterisation

Extracting mechanical properties

Analysis + concepts

Silicon-on-insulator clamps: bistable, thermal

Thin film microclips

Inflatable MEMS

- hinged SOI
- bistable clamp
- substrate
- rubber film
- component
- thermal bimorphs
- applied pressure
Outline

Laser micromachining: characterisation

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Characterising laser ablation of silicon nitride

3ns-pulse
3.5eV (UV),
50Hz, 10μms⁻¹

0.1mm

3ns-pulse
2.3eV (Green),
50Hz, 10μms⁻¹

0.1mm

3ps-pulse
1.2eV (IR),
50kHz, 10mms⁻¹
Lumera Laser

0.1mm
Characterising laser ablation of silicon nitride

SiN (2μm)
SiN (0.2μm)
ta-C(0.1μm)
Bare silicon threshold
Characterising laser ablation of silicon nitride
Characterising laser ablation of silicon nitride
Characterising laser ablation of silicon nitride

Pulse power density

Film remains

Good region

2 μm

EHT = 8.00 kV
WD = 28 nm
Mag. Detect
Photo No. = 75

EHT = 8.00 kV
WD = 28 nm
Photo No. = 70

EHT = 8.00 kV
WD = 28 nm
3 μm
Photo
Characterising laser ablation of silicon nitride

Optical micrograph
Characterising laser ablation of silicon nitride

Film thickness = 2 μm

Sample surface

Film thickness = 2μm

Profilometer trace

Optical micrograph
Characterising laser ablation of silicon nitride

Use ablation to create shallow microfluidic channels?
Outline

- Laser micromachining: characterisation
- Extracting mechanical properties
- Silicon-on-insulator clamps: bistable, thermal
- Thin film microclips
- Inflatable MEMS

Analysis + concepts
Extracting Young’s Modulus of thin films

- resonance frequency measurement\(^1\)
- electrostatic pull-in\(^2\)
- microbeam deflection with nanoindenter\(^3\)

Extracting Young’s Modulus of thin films

- resonance frequency measurement\(^1\)
- electrostatic pull-in\(^2\)
- microbeam deflection with nanoindenter\(^3\)
- scanning profilometer along microbeam

Extracting Young’s Modulus of thin films

\[ Z = F \left\{ \frac{(x-x_0-L_u)^3}{3EI} + \frac{(x-x_0-L_u)^2 L_u}{EI_u} + \frac{(x-x_0-L_u)L_u^2}{EI_u} + \frac{L_u^3}{3EI_u} \right\} \]
\[ = \frac{Fx^3}{3EI} + O(x^2) \]
Extracting Young’s Modulus of thin films

Fitting range

Vertical deflection, $z$

$Z = F \left\{ \frac{(x-x_0-L_u)^3}{3EI} + \frac{(x-x_0-L_u)^2 L_u}{EI_u} + \frac{(x-x_0-L_u) L_u^2}{EI_u} + \frac{L_u^3}{3EI_u} \right\}
= \frac{Fx^3}{3EI} + O(x^2)$
Extracting Young’s Modulus of thin films — additional problems

- anticlastic curvature affects effective stiffness
- stylus force varies with deflection
- local indentation
- beam twisting
Extracting maximum stress of thin films
Outline

- Laser micromachining: characterisation
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- Silicon-on-insulator clamps: bistable, thermal
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Analysis + concepts
## Problem abstraction

<table>
<thead>
<tr>
<th>Linear DoF</th>
<th>Angular degrees of freedom</th>
<th>0</th>
<th>1</th>
<th>2+</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>filter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1*</td>
<td>plane mirror</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>detector$$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>spherical lens</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### Notes:
- $\theta, x, y$: in plane
- $z, \phi, \psi$: out of plane
- * $x$ or $y$
- ** includes $\theta$
- $\$ translation in $x$
or $y$, plus $z$
- # positioning in $x$ and $y$
**Specification**

1. Alignment precision: 0.1dB coupling loss requires 0.5µm and 0.7° but throw must be larger

2. Components to be held sub-millimetre: lenses, mirrors and fibres

3. Slop: component dimension tolerances up to 10%

4. Up to 2 linear and 3 angular degrees of freedom or *vice versa*

5. Power and area budgets: debatable
Outline

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- Extracting mechanical properties
- Analysis + concepts
- Thin film microclips
- Inflatable MEMS

Silicon-on-insulator clamps: bistable, thermal
DRIE structure
Lens manipulator
DRIE structure
Lens manipulator
Out-of-plane bistable clamps

Passes: 5 4 3 2 1

SEM cross-section of SOI thinning experiment
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Thin film microclips

component

thermal bimorphs
Proposed microclips

When a component is inserted, the microcantilevers deflect and hold the component in static equilibrium.

Fabrication

1. deposit thin film on to wafer
2. photolithography or laser micromachining to define cantilevers
3. anisotropic etch through wafer
Proposed microclips

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Deflection of Microbeams

- A thin beam subject to a tip displacement constraint assumes a shape that minimises energy.
- To obtain a minimum energy state we must vary the shape function of the cantilever until the integral energy function reaches a stationary point.

Discretisation
- The integral expression can be approximated by a series expression.
- The system effectively becomes a series of rigid members joined by torsional springs whose spring constant gives the same bending rigidity per unit length as the continuous bar.
Deflection of Microbeams

- Excel contains an optimisation plug-in called Solver. This allows us to
  - Minimise an objective function
  - By changing a set of variables
  - Subject to constraints

Stored Energy
Bar Angles ($\theta_0...\theta_n$)
Tip Displacement + segment angle

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Processing variations and probabilistic design

- For optical benches components must be precisely aligned in the vertical plane.
- Process variability can lead to component misalignment.

Investigate the effect of each error and build a distribution of vertical alignment.

[Graph showingForce vs Clearance/clip length and Energy vs Clearance/clip length]
Processing variations and probabilistic design

within specification
Towards ‘active’ clips

Thicknesses $a_1, a_2$
Thermal expansivities are $\alpha_1, \alpha_2$
Moduli $E_1, E_2$
Increase in temperature $\Delta T$

$$\frac{E_1}{E_2} = n$$
$$a_1 + a_2 = t$$
$$a_1/a_2 = m$$
$$K = 6(1 + m)^2/ [3(1 + m)^2 + (1 + mn)(m^2 + 1/mn)]$$

Thermal curvature is given by:

$$\kappa = K(\alpha_2 - \alpha_1)\Delta T/t$$
Extending energy simulation to 4 thermal clips

No misalignments
Extending energy simulation to 4 thermal clips

No misalignments

Local energy minimum with antisymmetric clip orientations

rotation $\psi = -11.5^\circ$
Extending energy simulation to 4 thermal clips

No misalignments

20 μm front-to-back misalignment...

rotation $\psi = -2.1^\circ$

$x \approx 0$
Extending energy simulation to 4 thermal clips

No misalignments

20 μm front-to-back misalignment...

rotation \( \psi = -2.1^\circ \)

\( x \approx 0 \)

... countered by 20K temp increase in red clip.

(150nm Ni/SiN\(_x\))

rotation \( \psi = 0.4^\circ \)

\( x \approx 0 \)
Extending energy simulation to 4 thermal clips

No misalignments

50K temperature increase in clips 1 and 2

rotation $\psi \sim 2^\circ$

$x \sim -5 \mu m$
Inflatable MEMS

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Thin film microclips

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Inflatable MEMS

rubber film
substrate
applied pressure
Why consider inflatable MEMS?

- sharp edges unstressed
- films in tension mean larger holding forces
- inherent damping
- fluid could solidify

Explore the possibilities of making inflatable microballoons from elastic films, either welded together or spun on to a rigid substrate.
Conclusions

*Laser micromachining*
- cutting slow / refinement fast
- material damage can probably be controlled
- UV/silicon nitride combination ideal

*Modulus extraction*
- target accuracy better than 20%
- noise in data remains largest problem

*Deep reactive ion etching*
+ strong  + well-characterised  – large footprint

*Thin-film microclips*
+ simple  + compact  – max. stress high

*Inflatable MEMS*
+ manipulate and fix in one step
+ strength from inflation not high modulus  – unproven