MEMS Packaging Techniques for Silicon Optical Benches

Hayden Taylor

David Moore, Mohamed Boutchich, Billy Boyle,
Johnny He, Graham McShane, Richard Breen, Rob Wylie

CAMBRIDGE UNIVERSITY ENGINEERING DEPARTMENT

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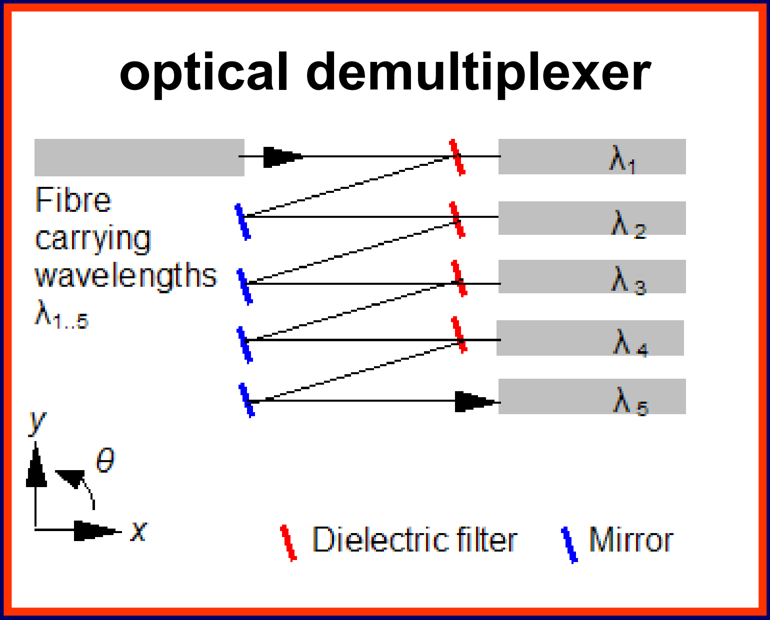
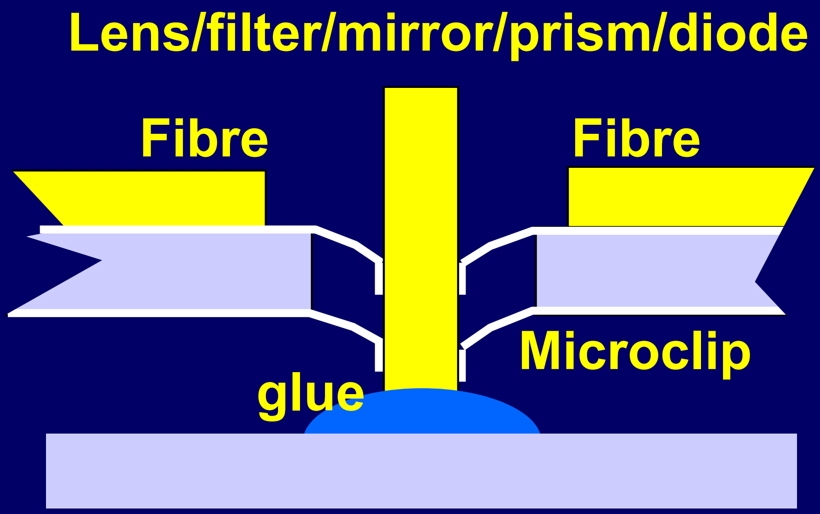
Introduction

Why MEMS for optoelectronic packaging?

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


optical demultiplexer

cross-section



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Why rapid prototyping?

- many new materials
- mechanical design hard

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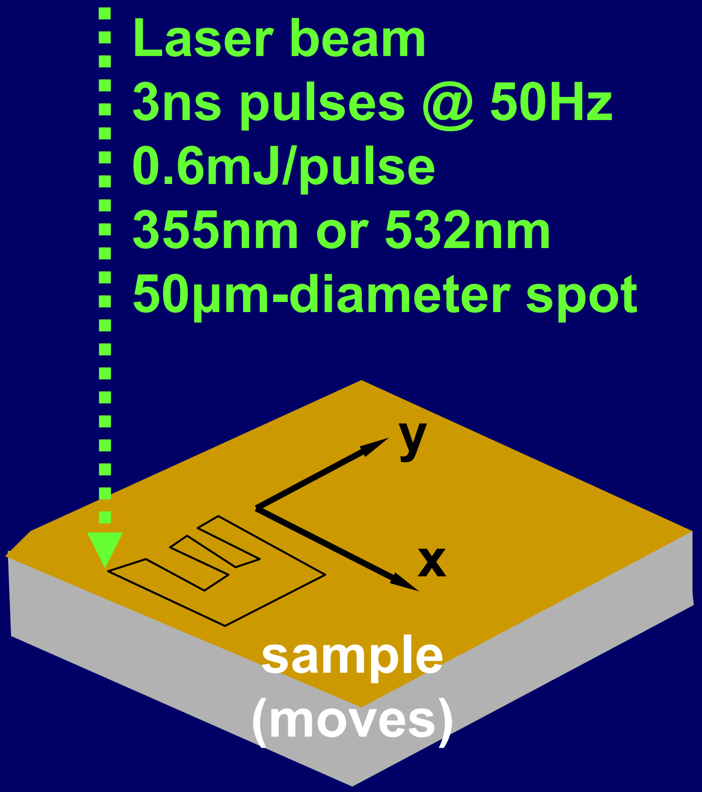
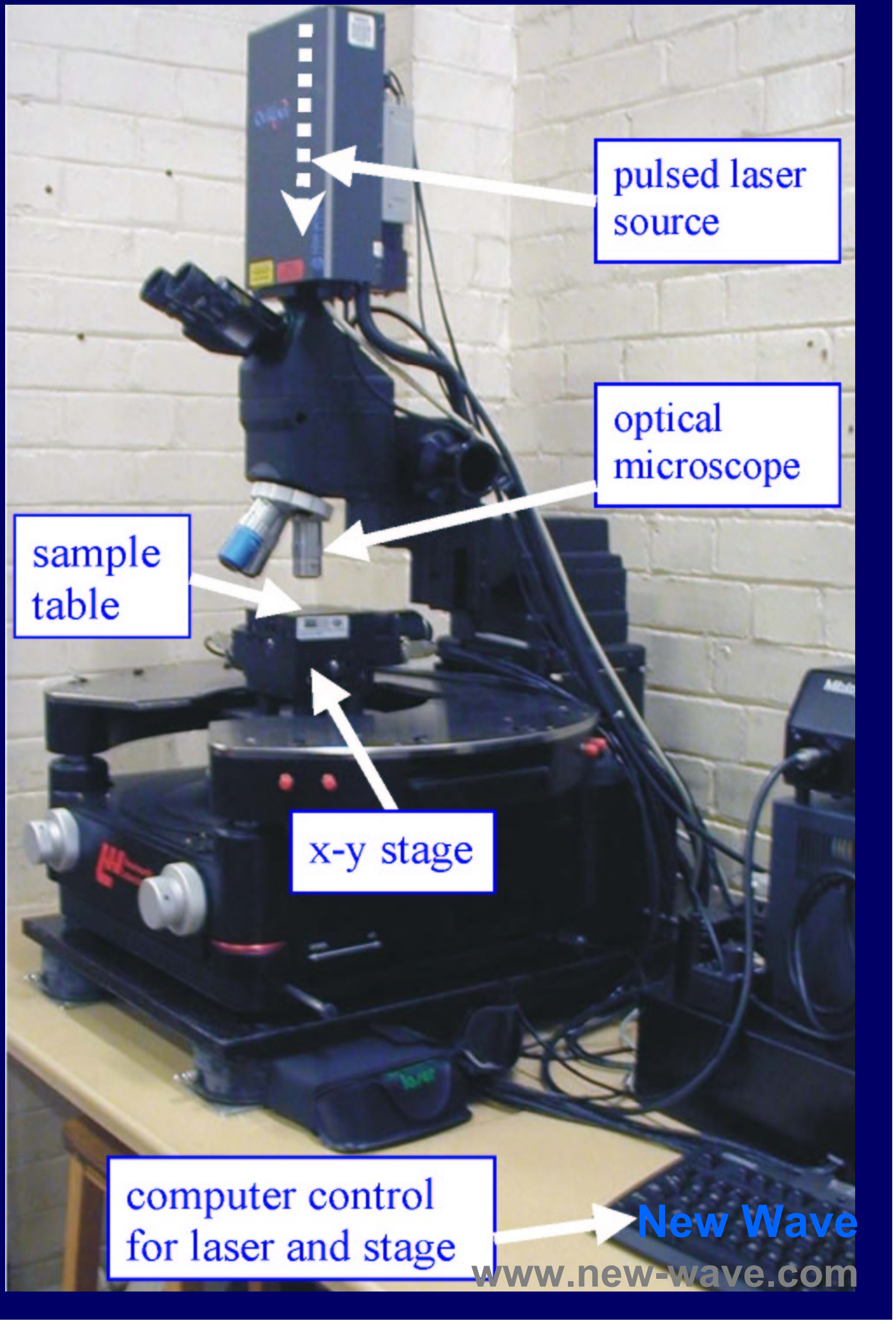


Laser beam
3ns pulses @ 50Hz
0.6mJ/pulse
355nm or 532nm
50µm-diameter spot



pulsed laser source

optical microscope

sample table

x-y stage

computer control for laser and stage

New Wave
www.new-wave.com

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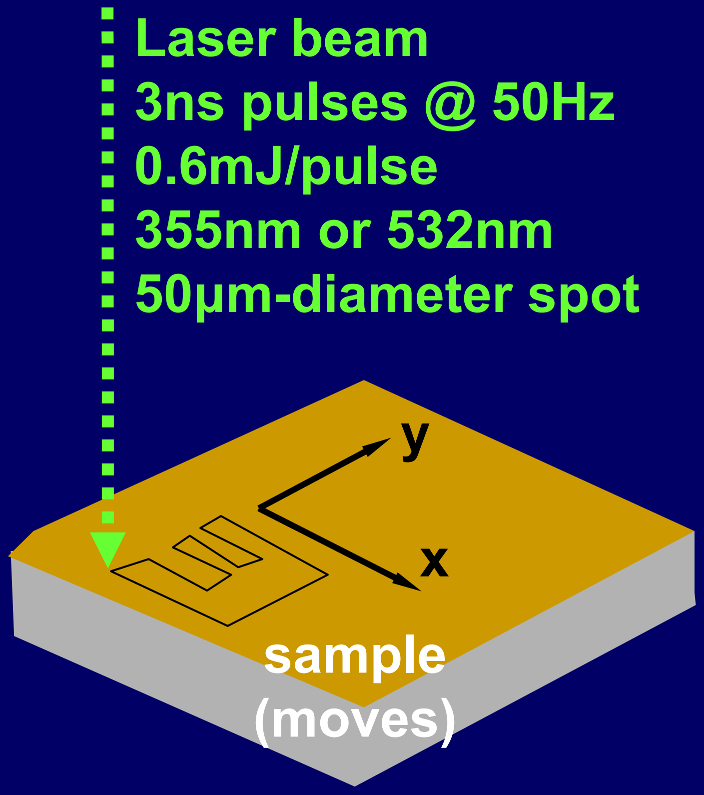

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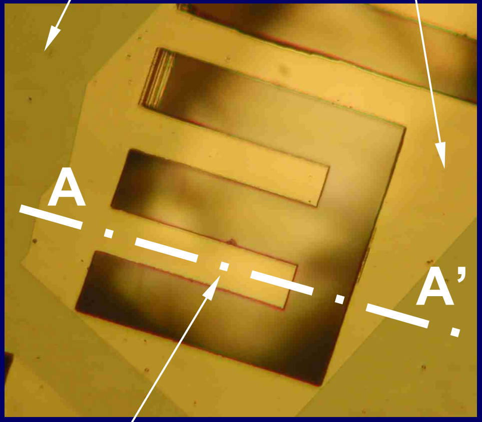

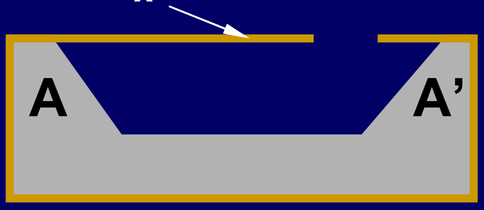

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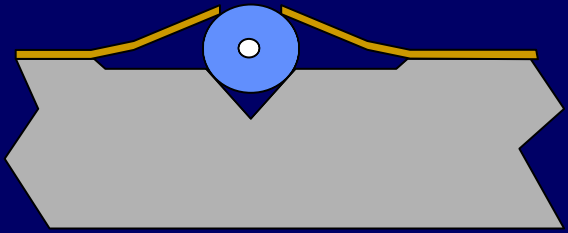
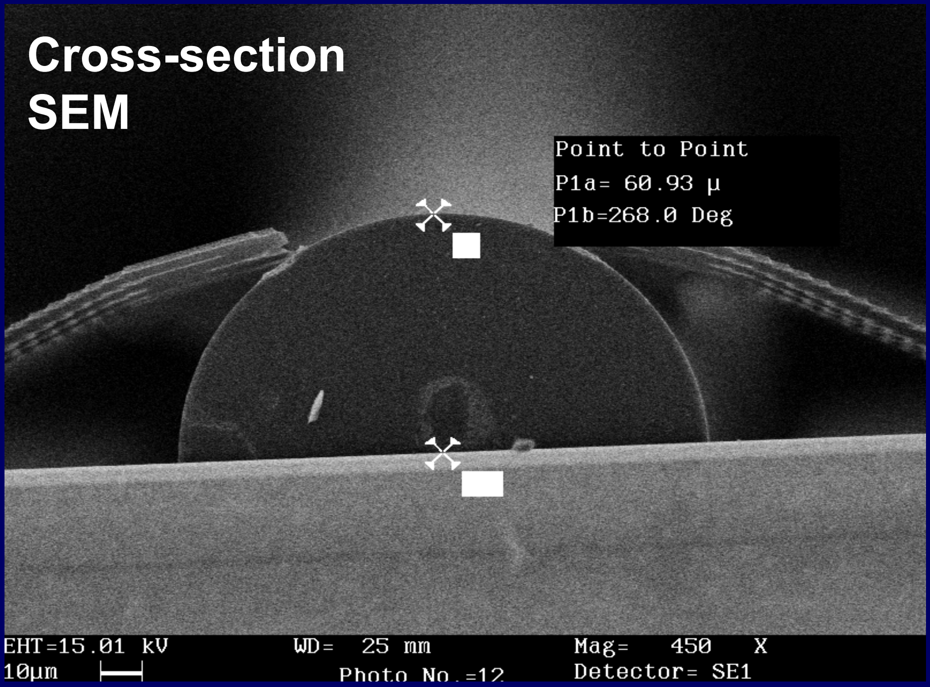
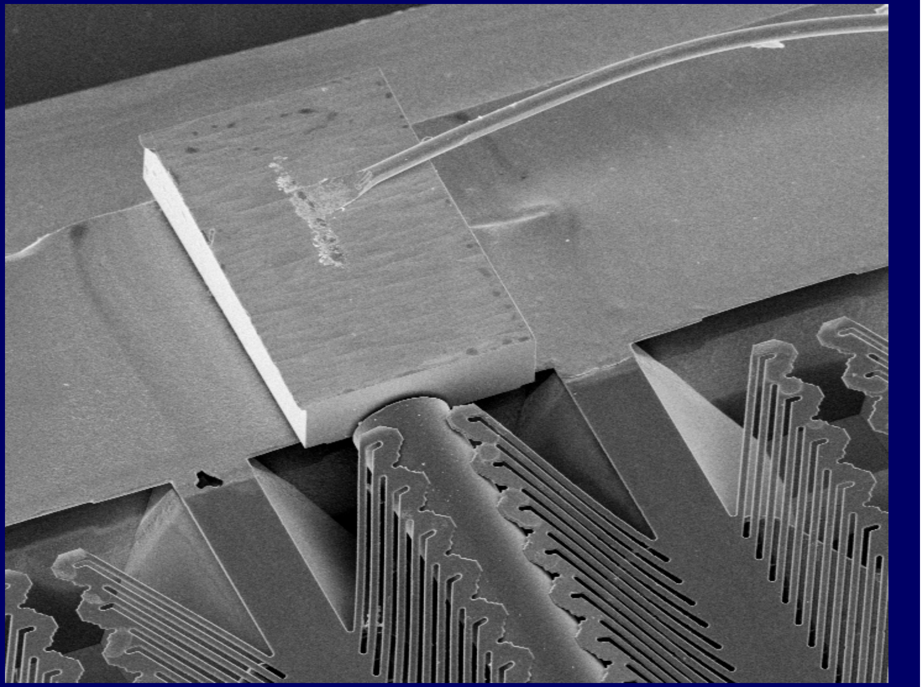
Previous MEMS packaging work: passive



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



Cross-section SEM



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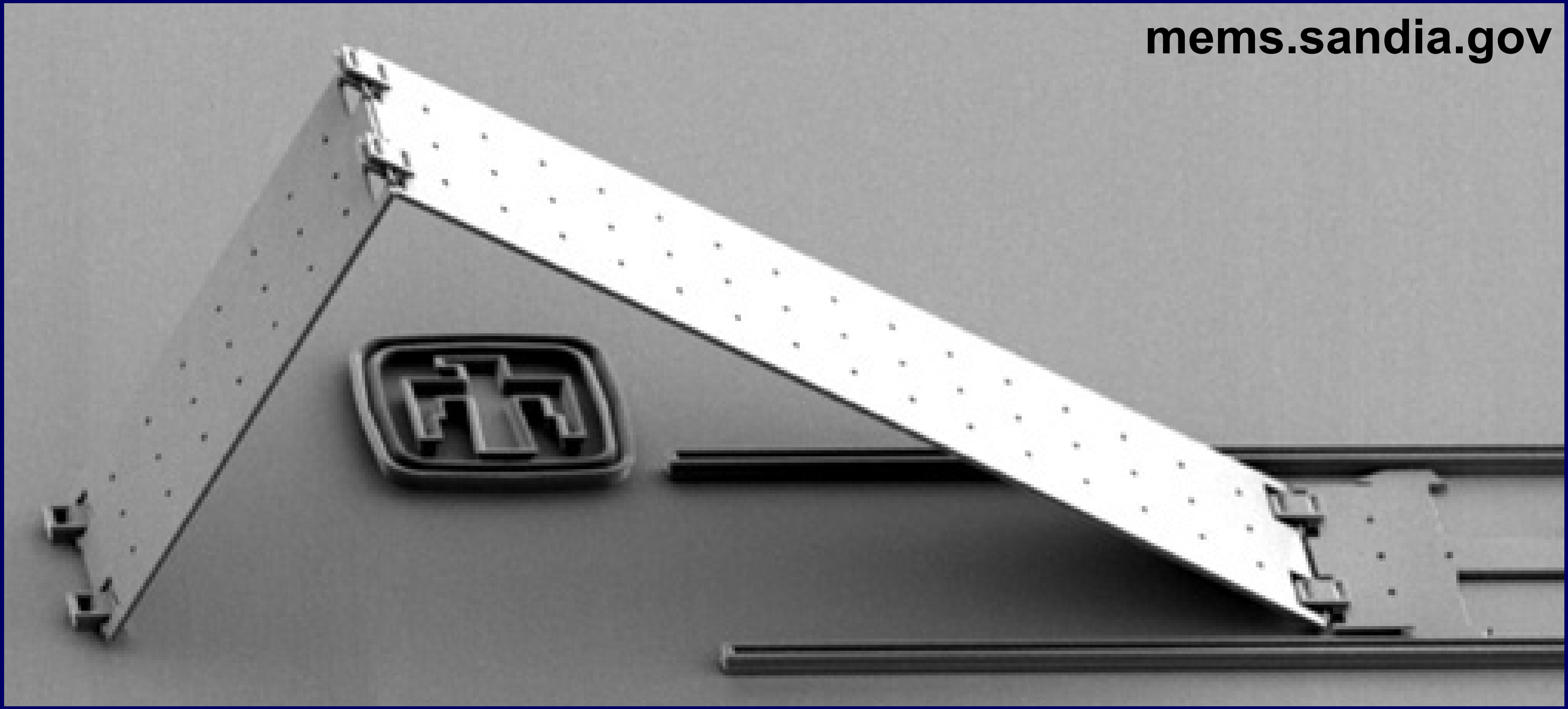
Previous MEMS packaging work: out of plane

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



mems.sandia.gov

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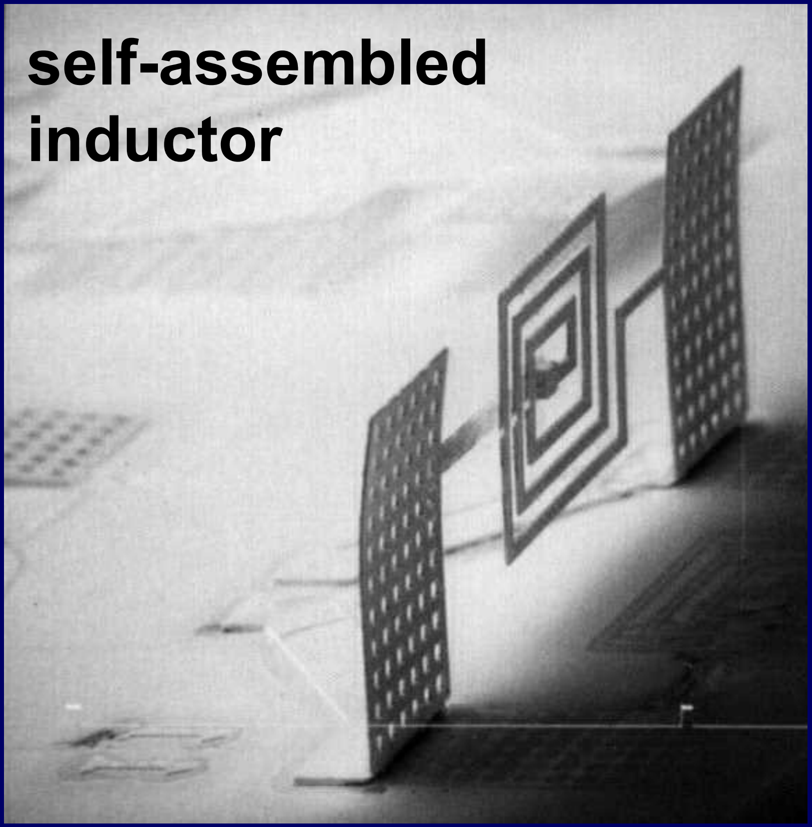
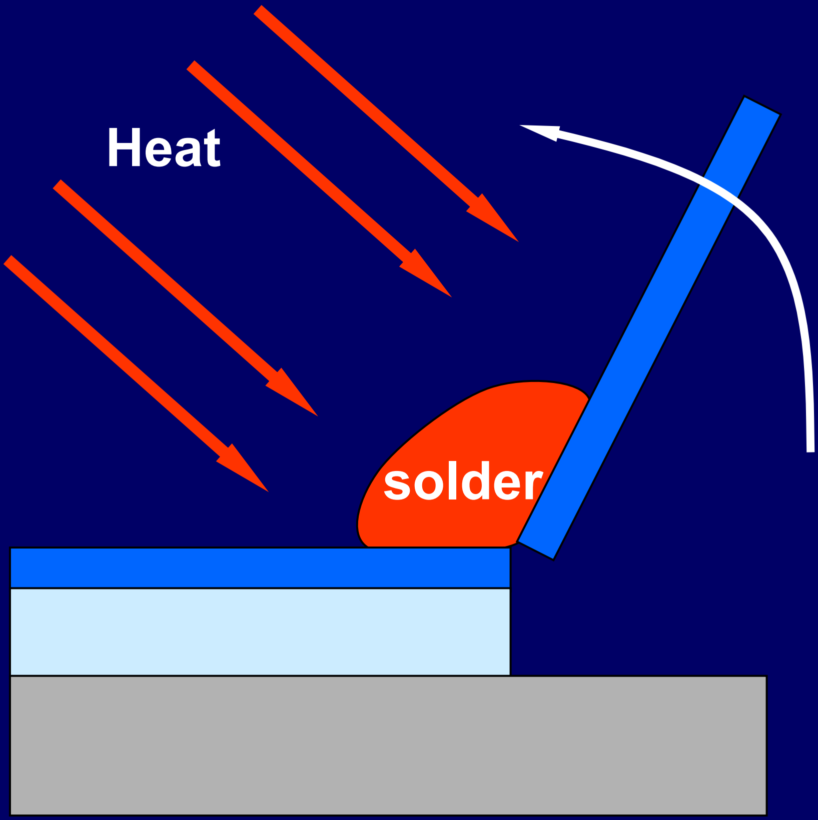
Previous MEMS packaging work: out of plane

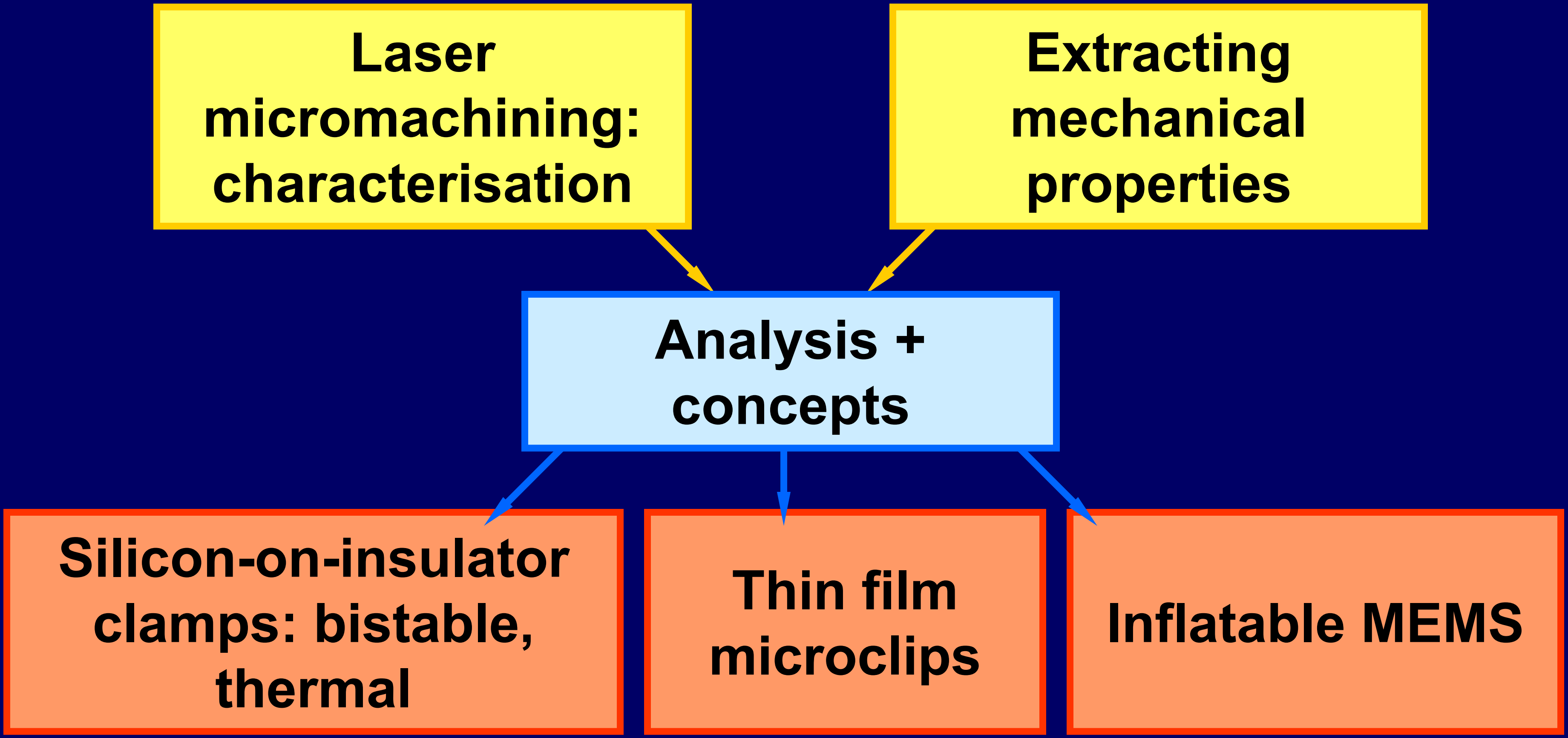
- polysilicon multi-layer processes (e.g. SUMMiT, Sandia)
- surface tension: self-assembly





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

Outline



Laser micromachining: characterisation

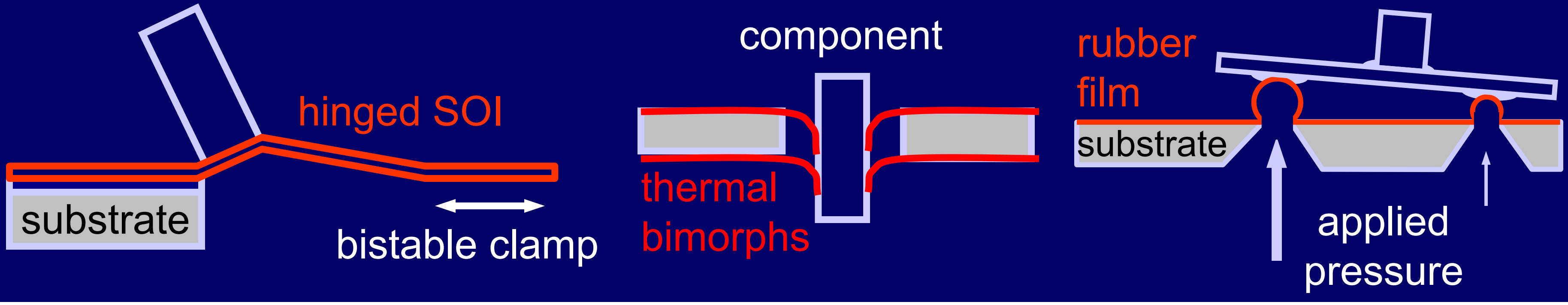
Extracting mechanical properties

Analysis + concepts

Silicon-on-insulator clamps: bistable, thermal

Thin film microclips

Inflatable MEMS



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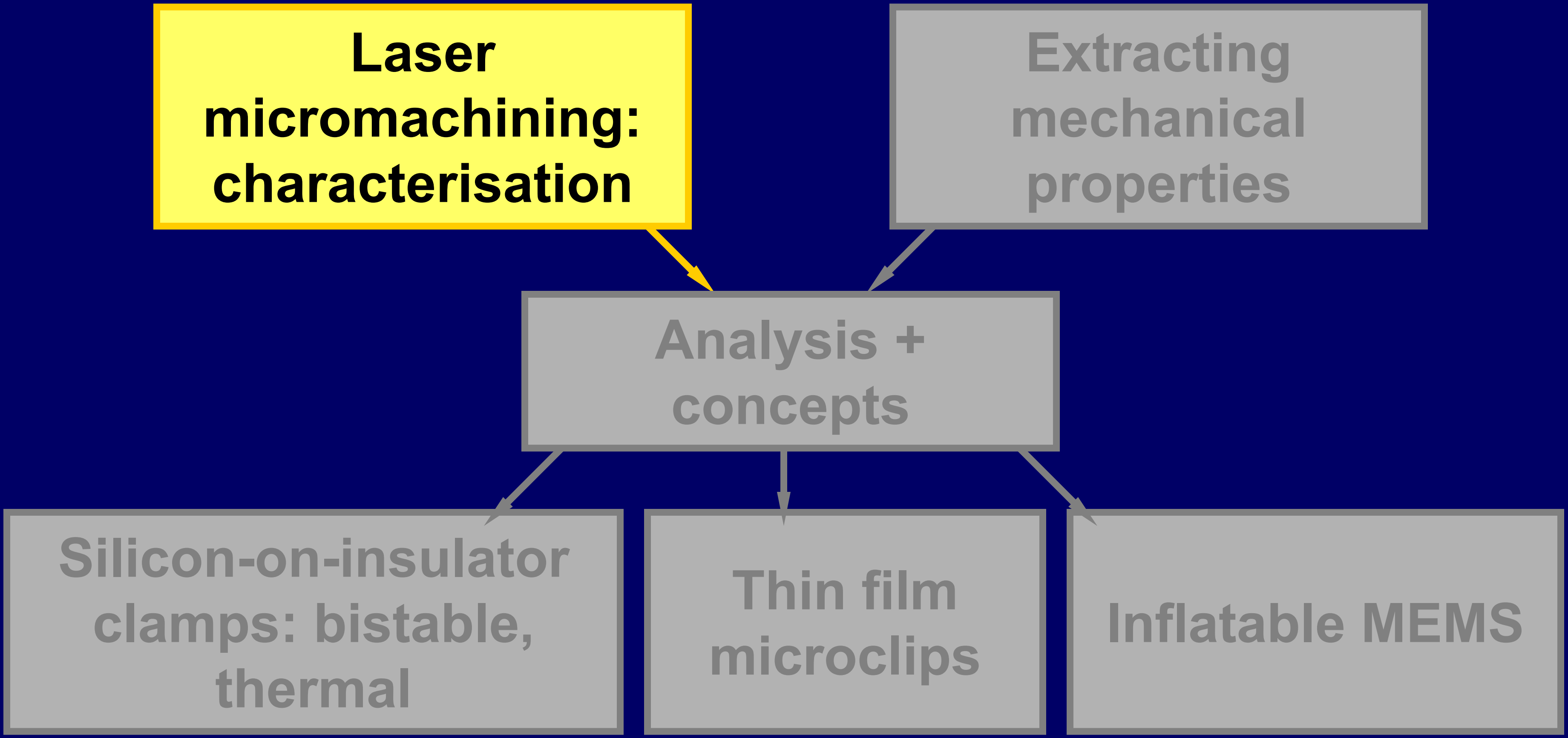

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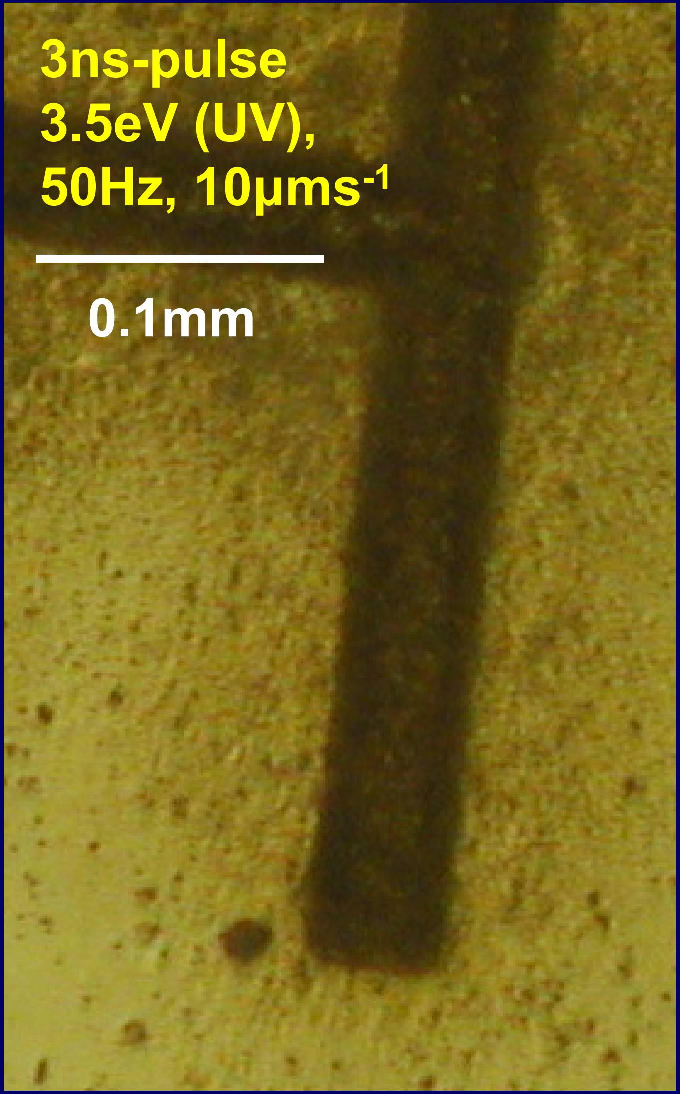
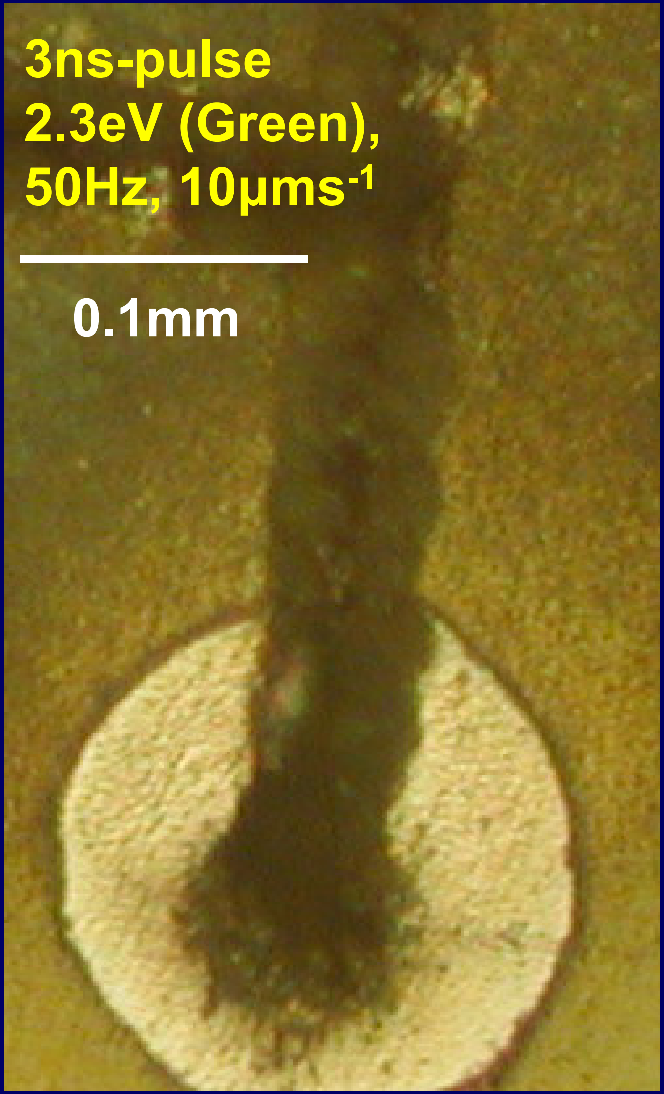
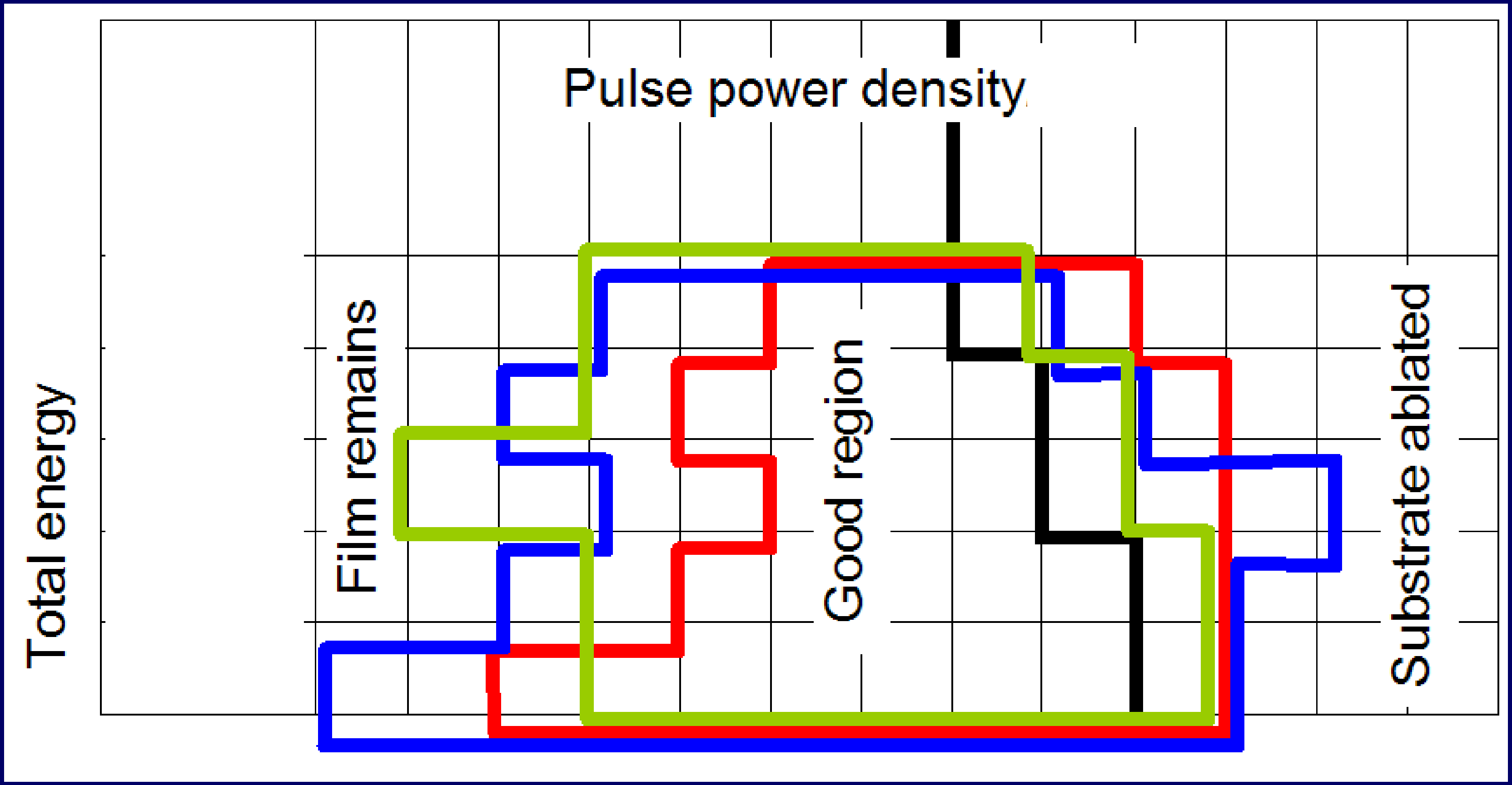
Characterising laser ablation of silicon nitride


3ns-pulse
3.5eV (UV),
50Hz, 10μms^{-1}


3ns-pulse
2.3eV (Green),
50Hz, 10μms^{-1}

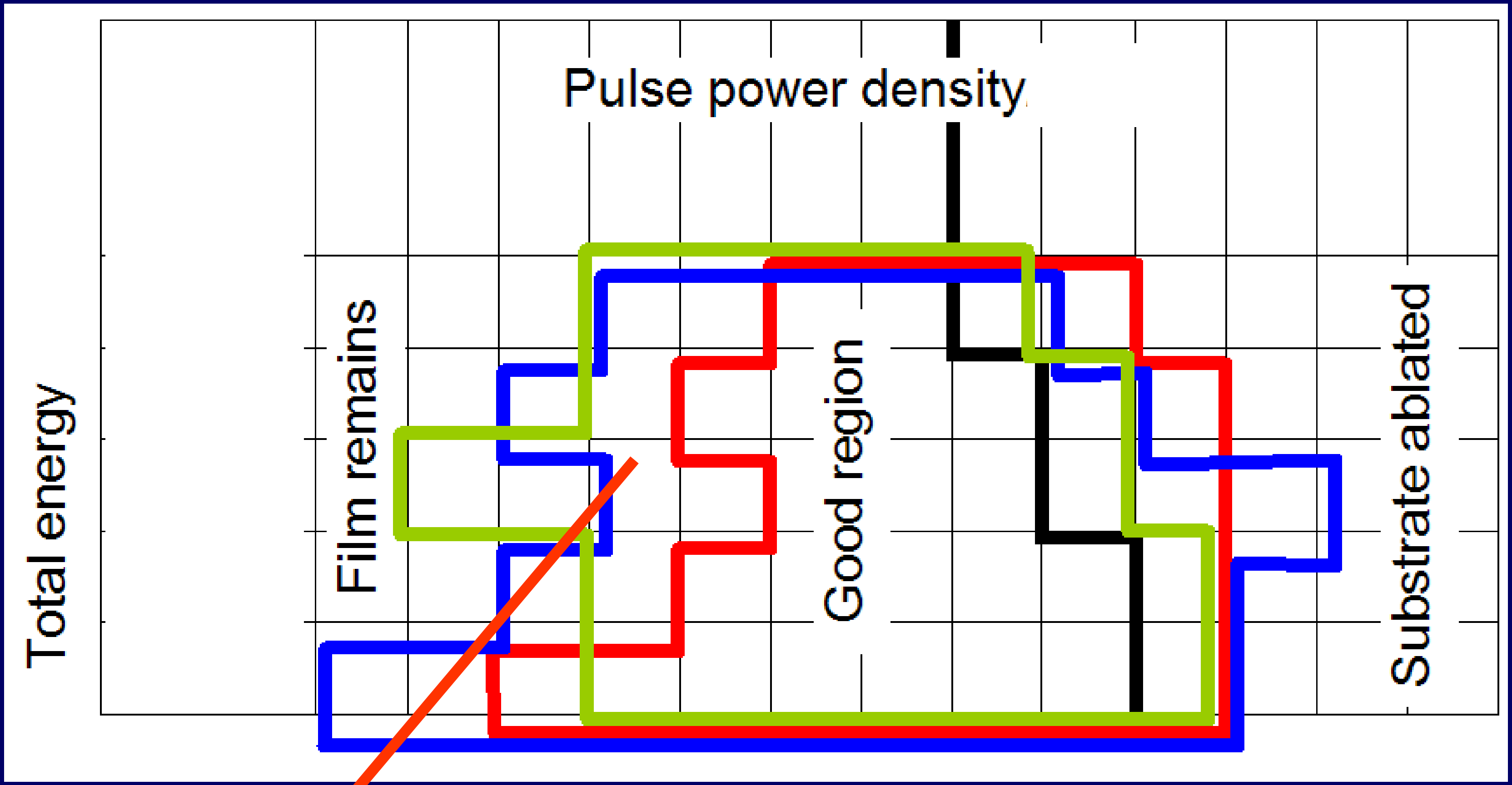

3ps-pulse
1.2eV (IR),
50kHz, 10mms^{-1}
Lumera Laser

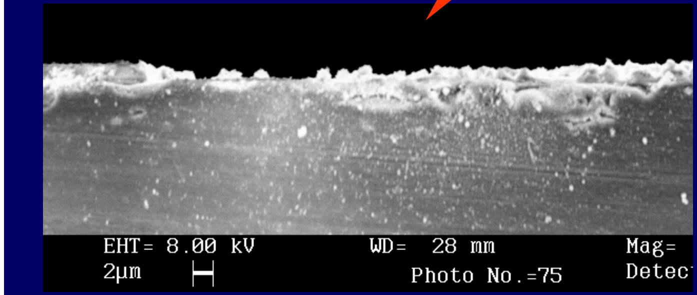
Characterising laser ablation of silicon nitride



SiN (2μm)
SiN (0.2μm)
ta-C(0.1μm)
Bare silicon threshold

Characterising laser ablation of silicon nitride





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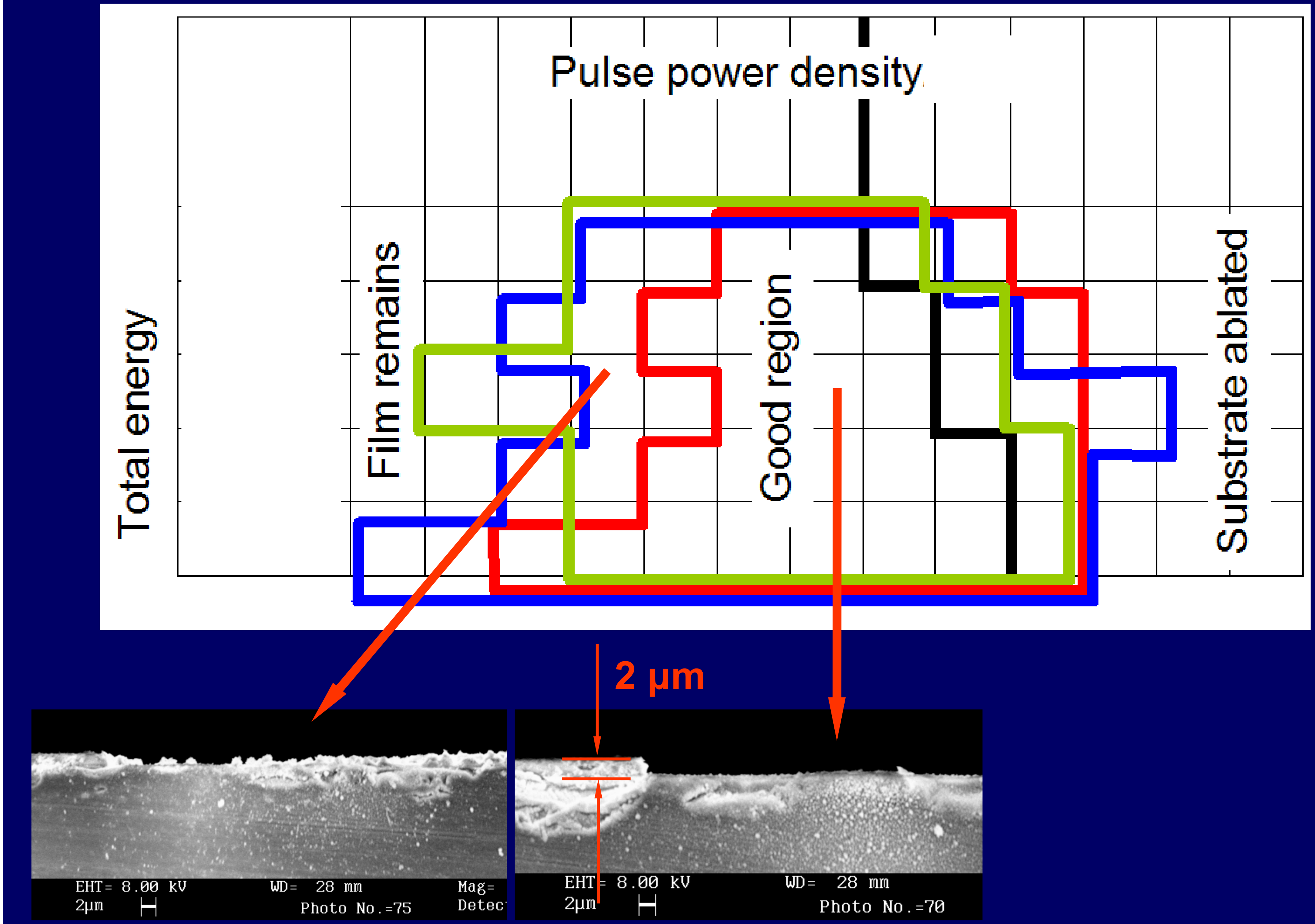

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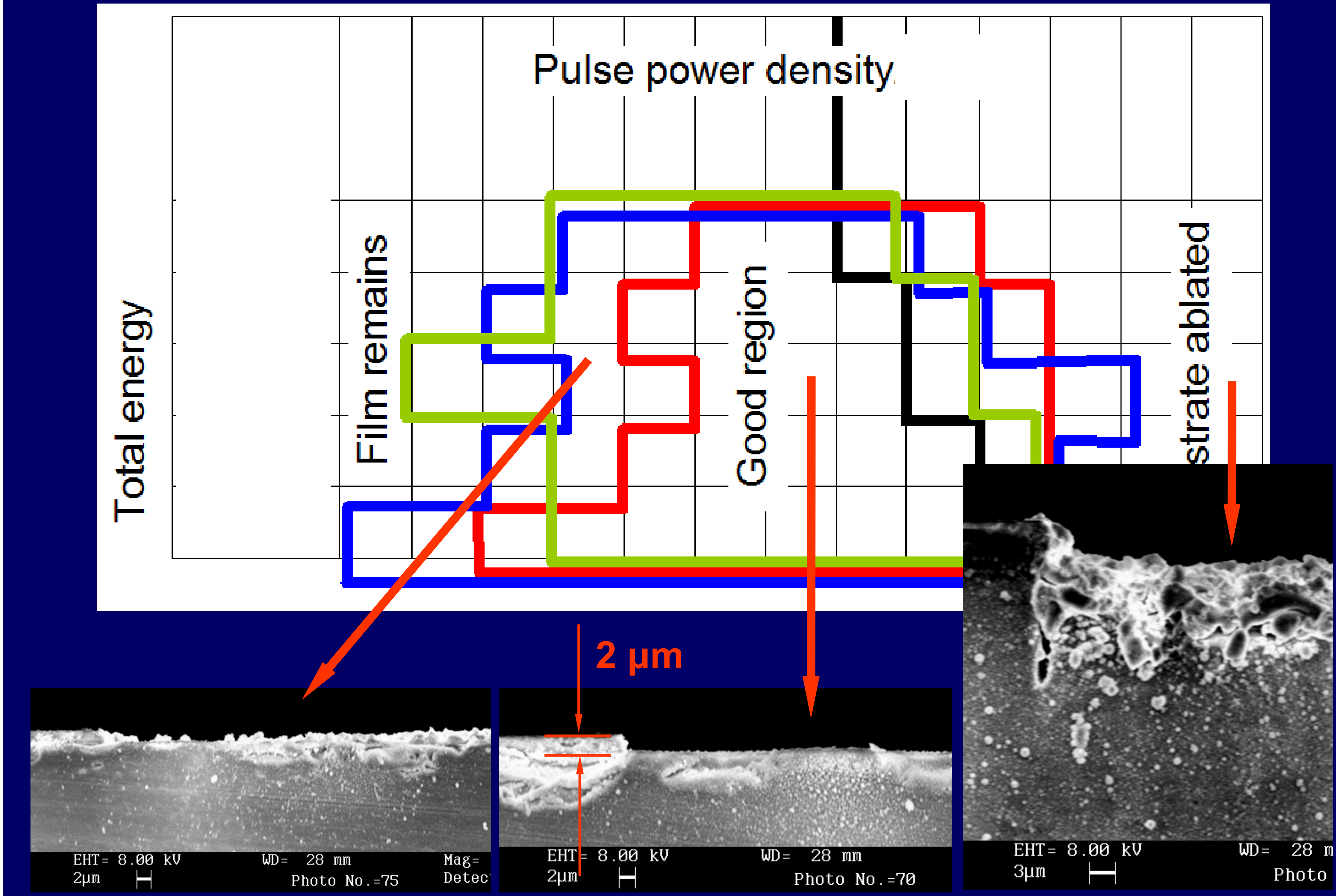

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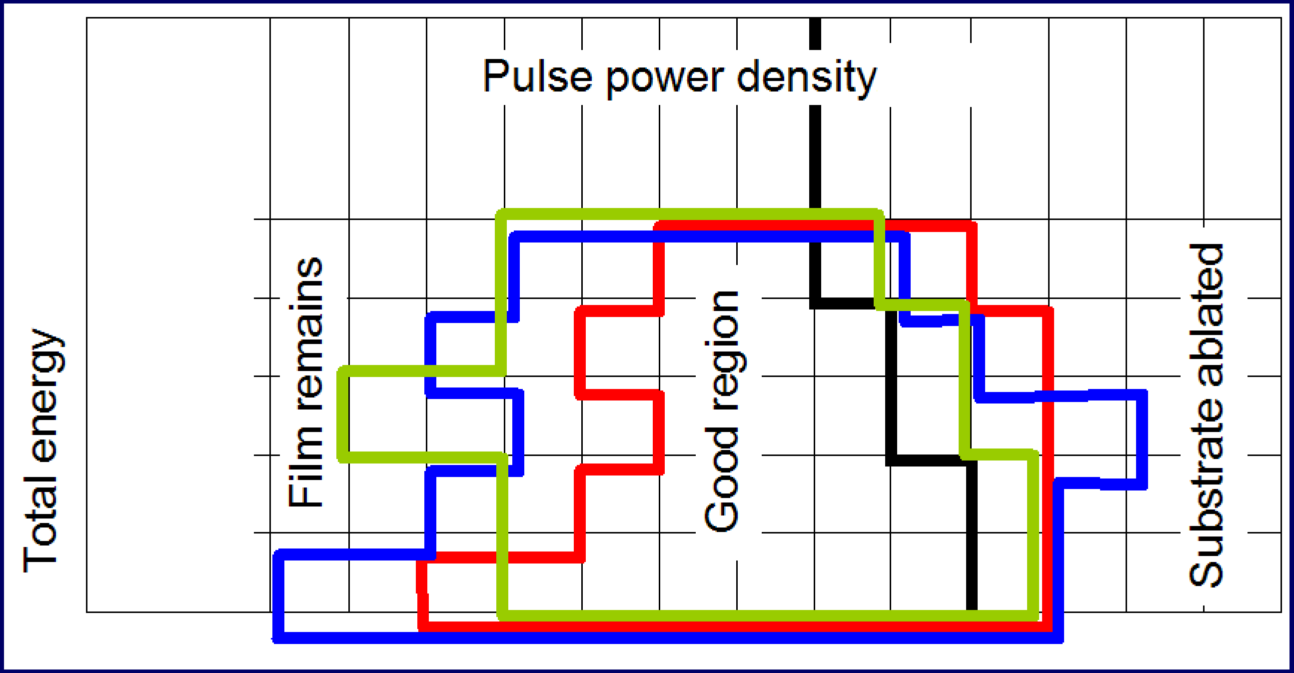
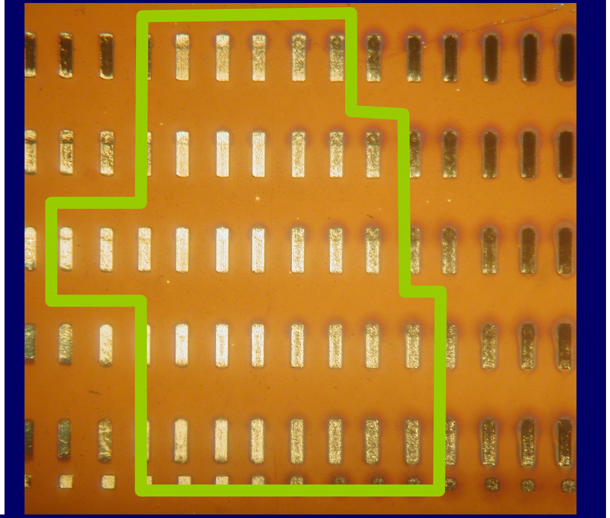


Optical micrograph



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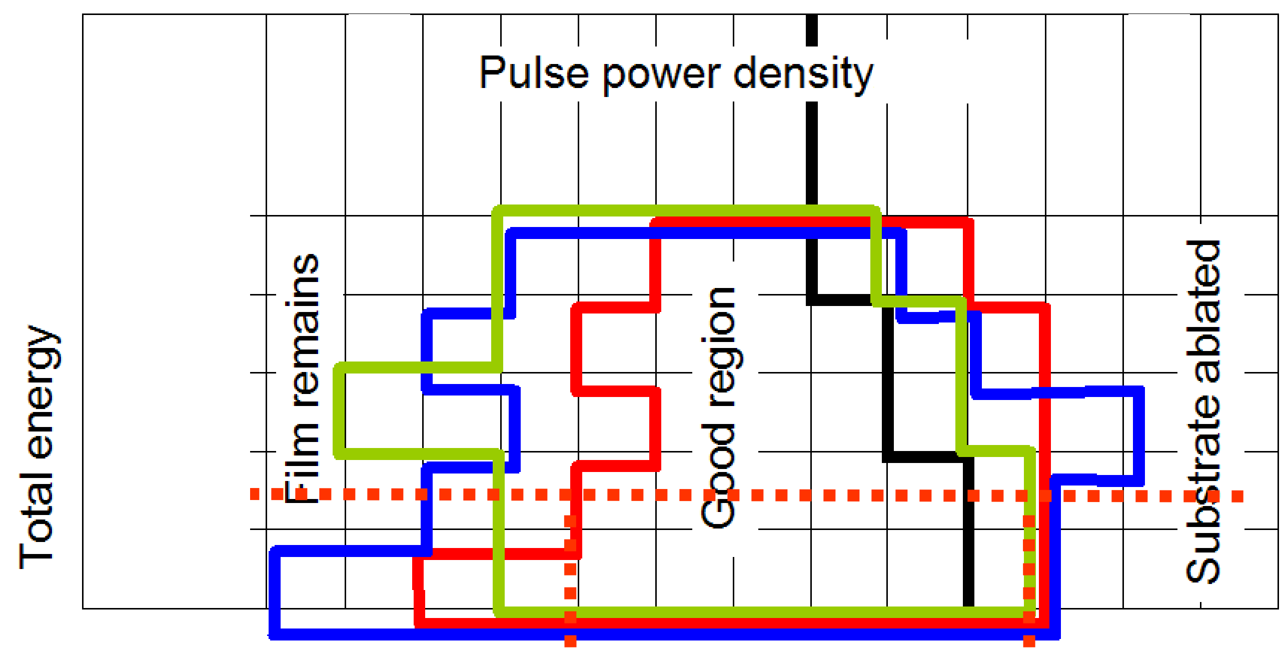
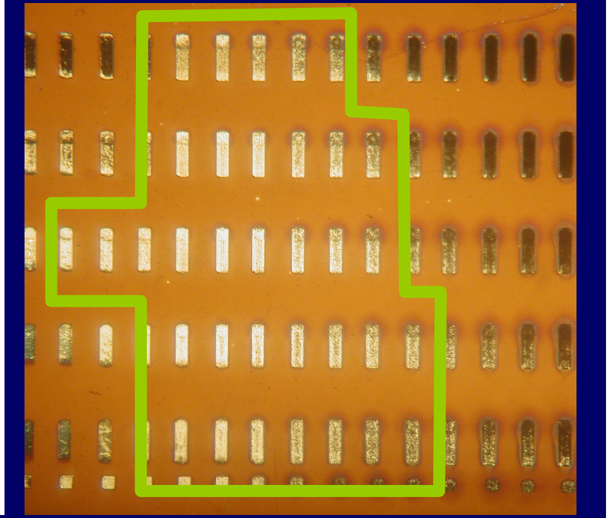
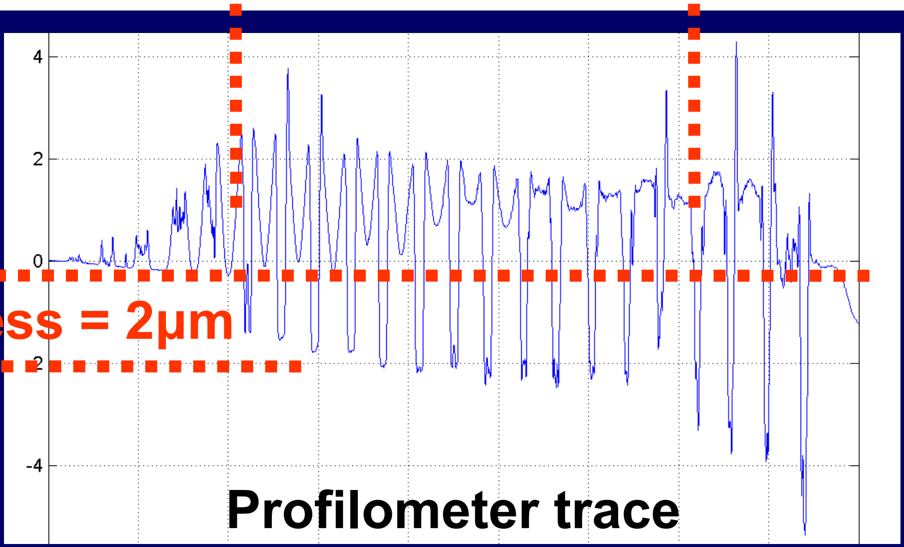


Optical micrograph



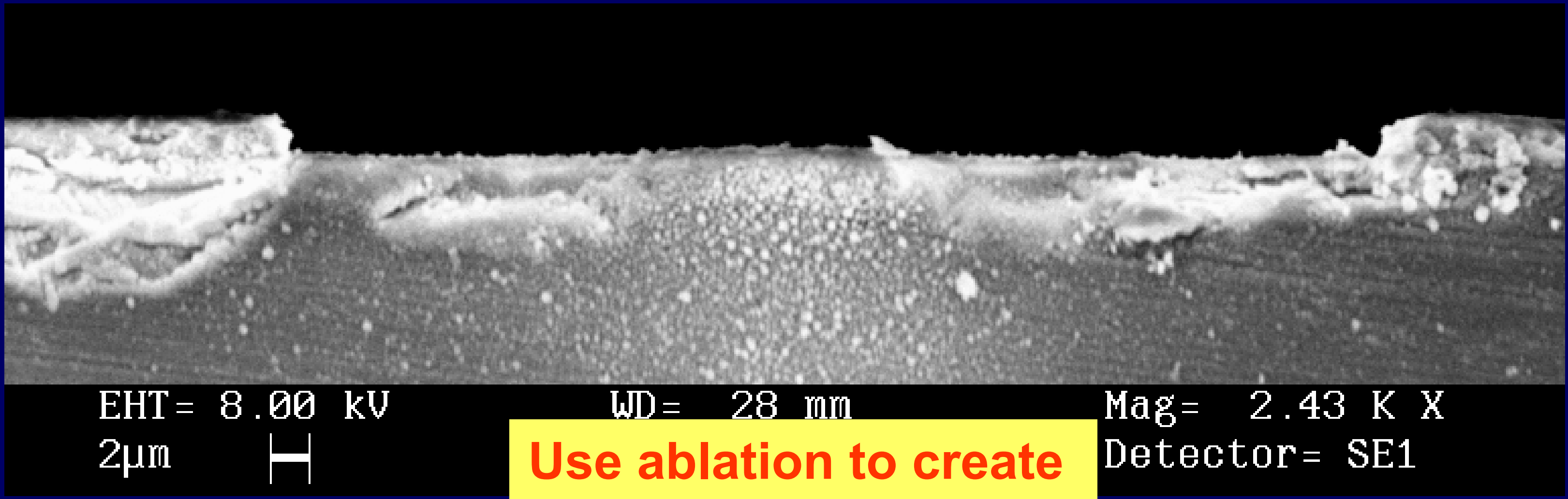
sample surface



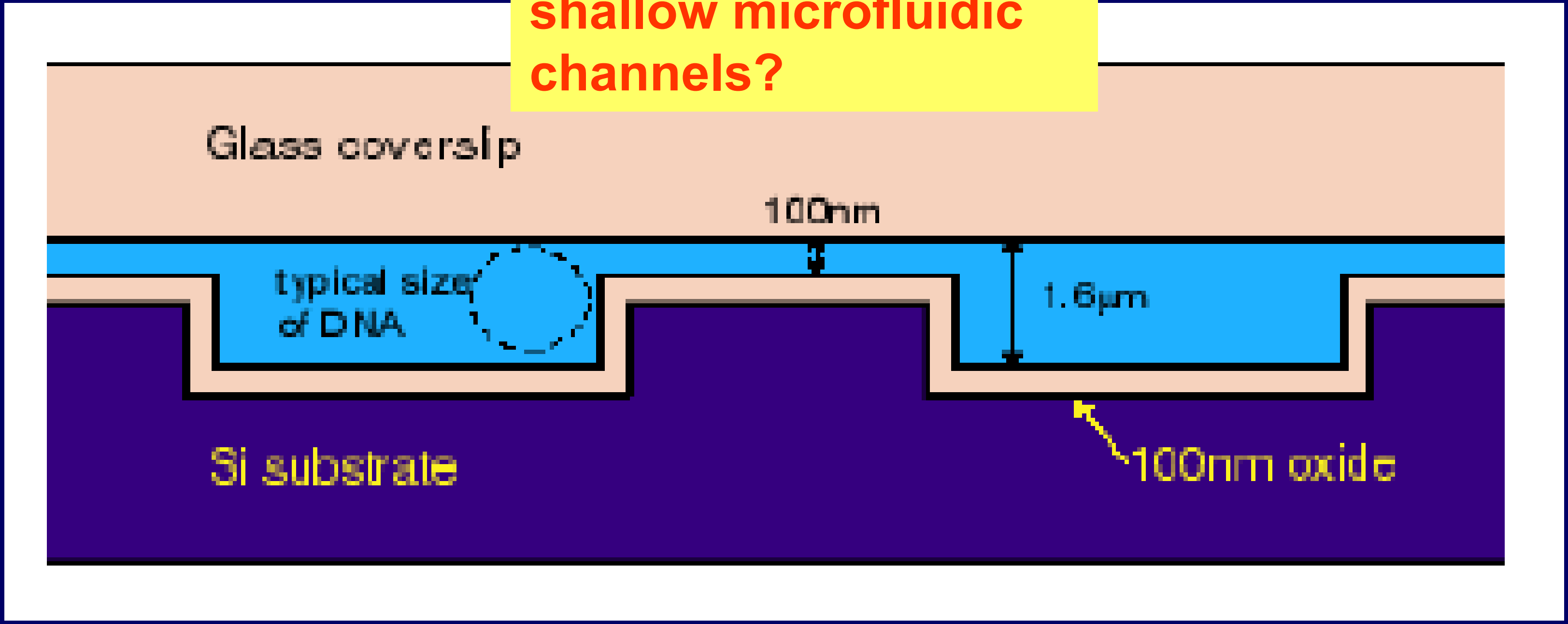
Film thickness = 2µm

Profilometer trace

Characterising laser ablation of silicon nitride



Use ablation to create shallow microfluidic channels?



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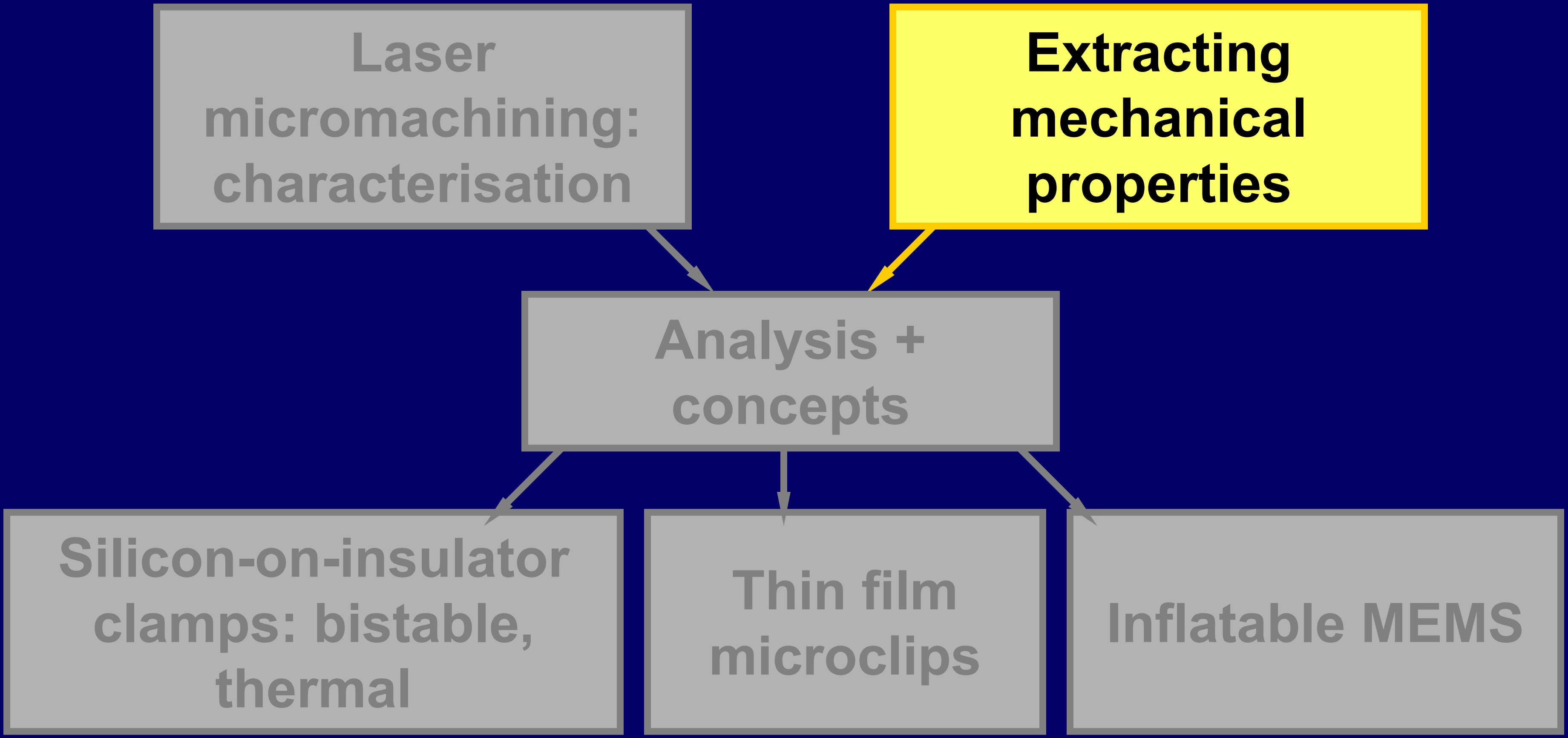

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Extracting Young's Modulus of thin films

- resonance frequency measurement[1]
- electrostatic pull-in[2]
- microbeam deflection with nanoindenter[3]

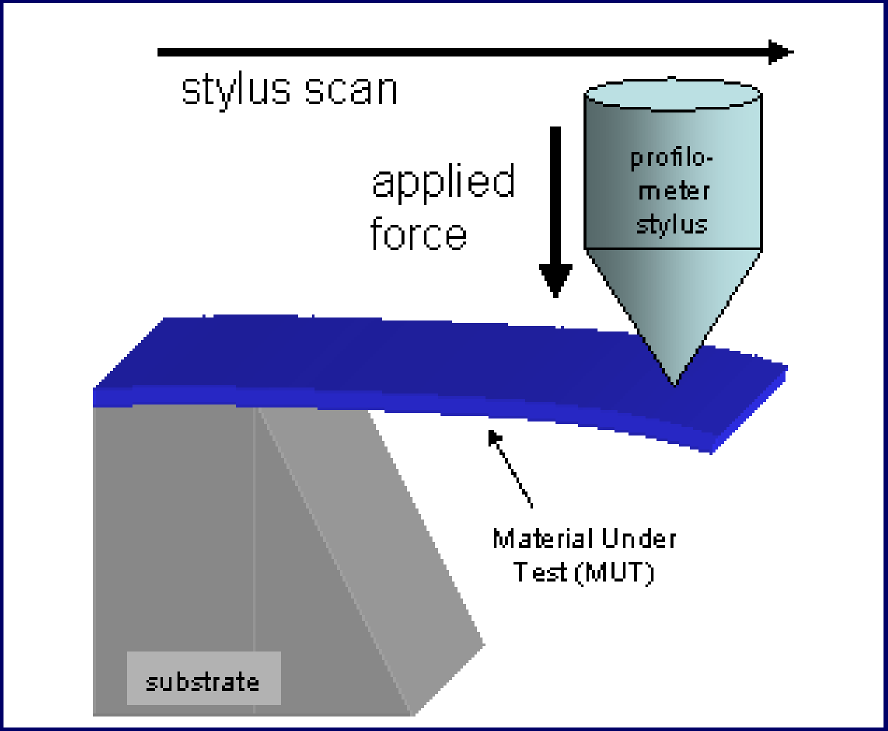
[1] M Madou: Fundamentals of Microfabrication, p270

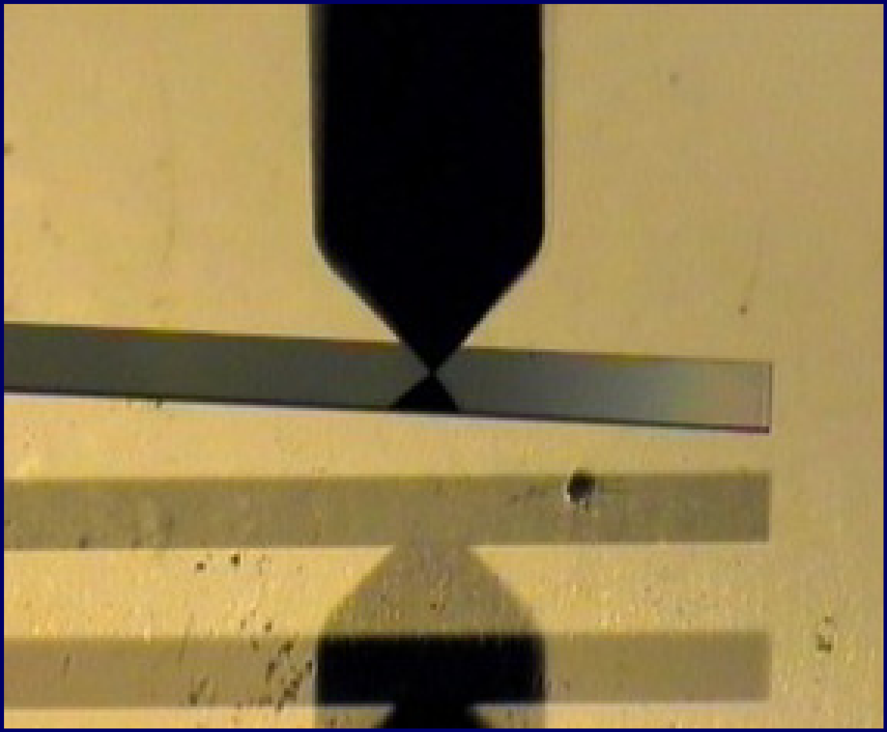
[2] *Journal MEMS*, **6** 2 1997 pp107–118

[3] WD Nix: *Measurement of Mechanical Properties in Small Dimensions by Microbeam Deflection,* Stanford

Extracting Young's Modulus of thin films

- resonance frequency measurement[1]
- electrostatic pull-in[2]
- microbeam deflection with nanoindenter[3]
- scanning profilometer along microbeam





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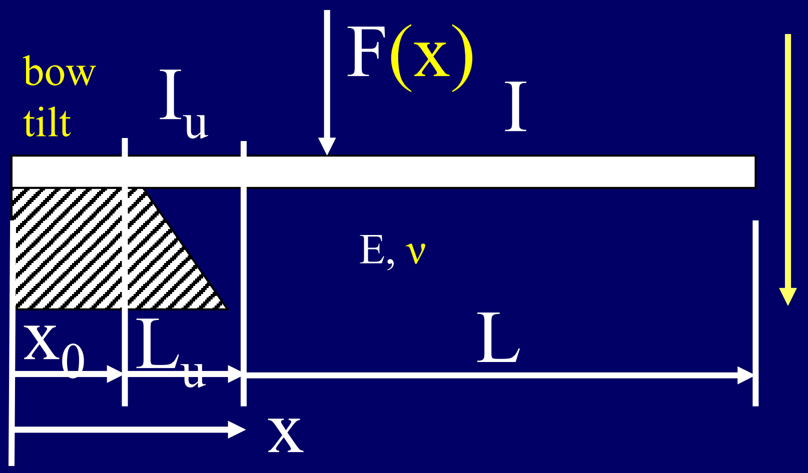
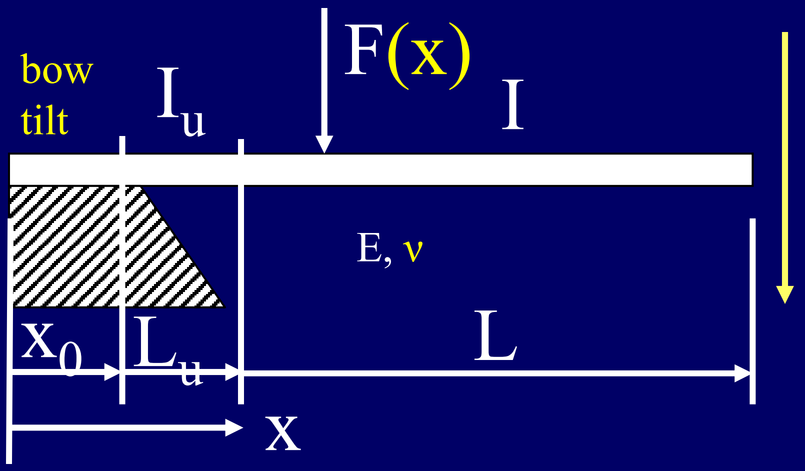


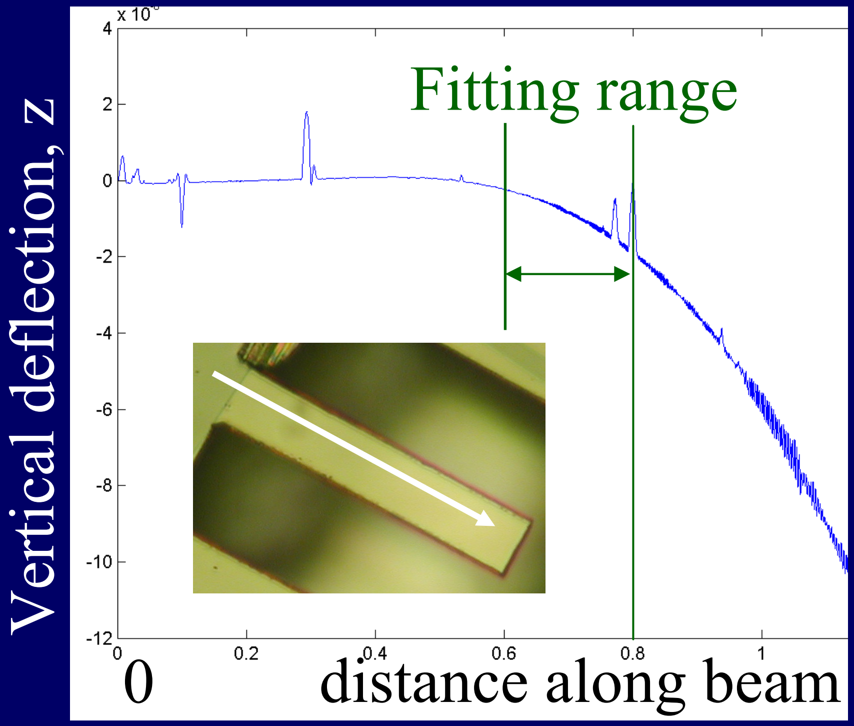
$$
\begin{aligned}
Z &= F\{(x-x_0-L_u)^3/3EI + \\
&\quad (x-x_0-L_u)^2 L_u/EI_u + \\
&\quad (x-x_0-L_u)L_u{}^2/EI_u + \\
&\quad L_u{}^3/3EI_u)\} \\
&= Fx^3/3EI + O(x^2)
\end{aligned}
$$

Extracting Young's Modulus of thin films



$$Z = F\{(x-x_0-L_u)^3/3EI + (x-x_0-L_u)^2L_u/EI_u + (x-x_0-L_u)L_u^2/EI_u + L_u^3/3EI_u)\}$$

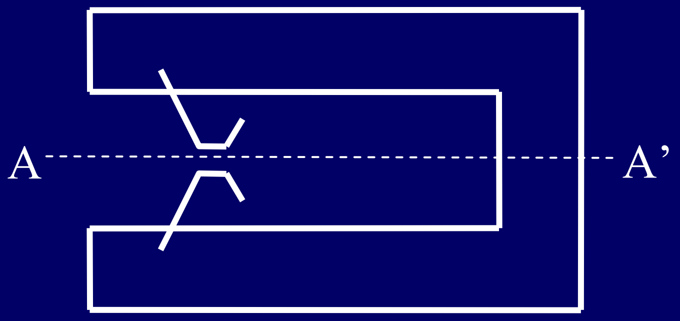
$$= Fx^3/3EI + O(x^2)$$

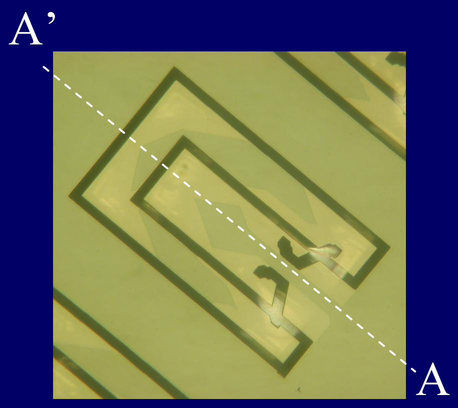


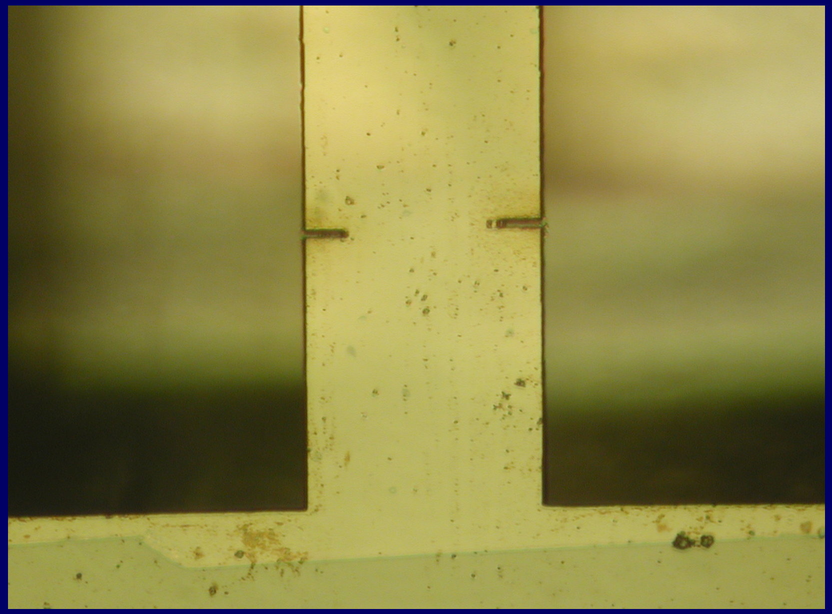
Extracting Young’s Modulus of thin films — additional problems

- anticlastic curvature affects effective stiffness
- stylus force varies with deflection
- local indentation
- beam twisting

Extracting maximum stress of thin films







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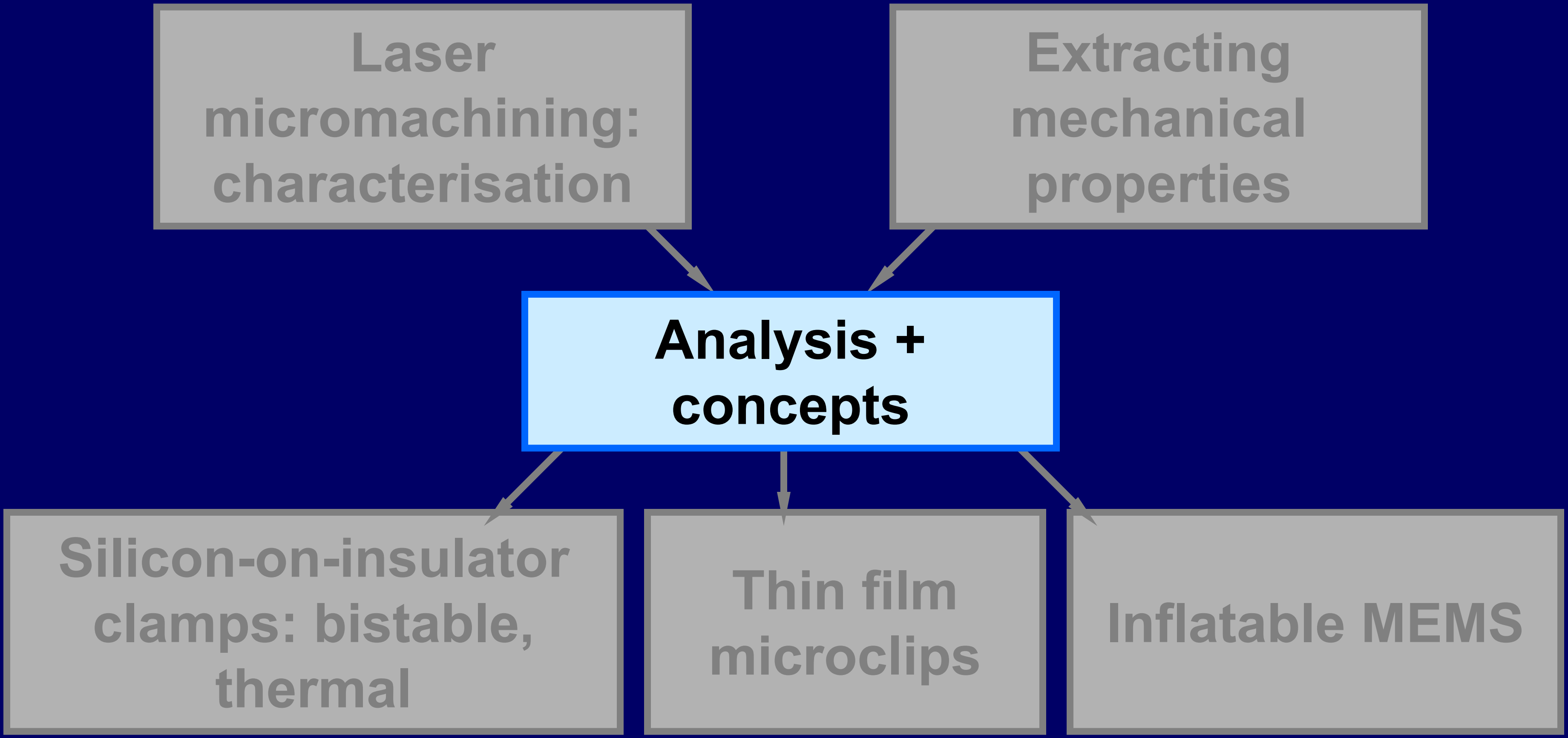

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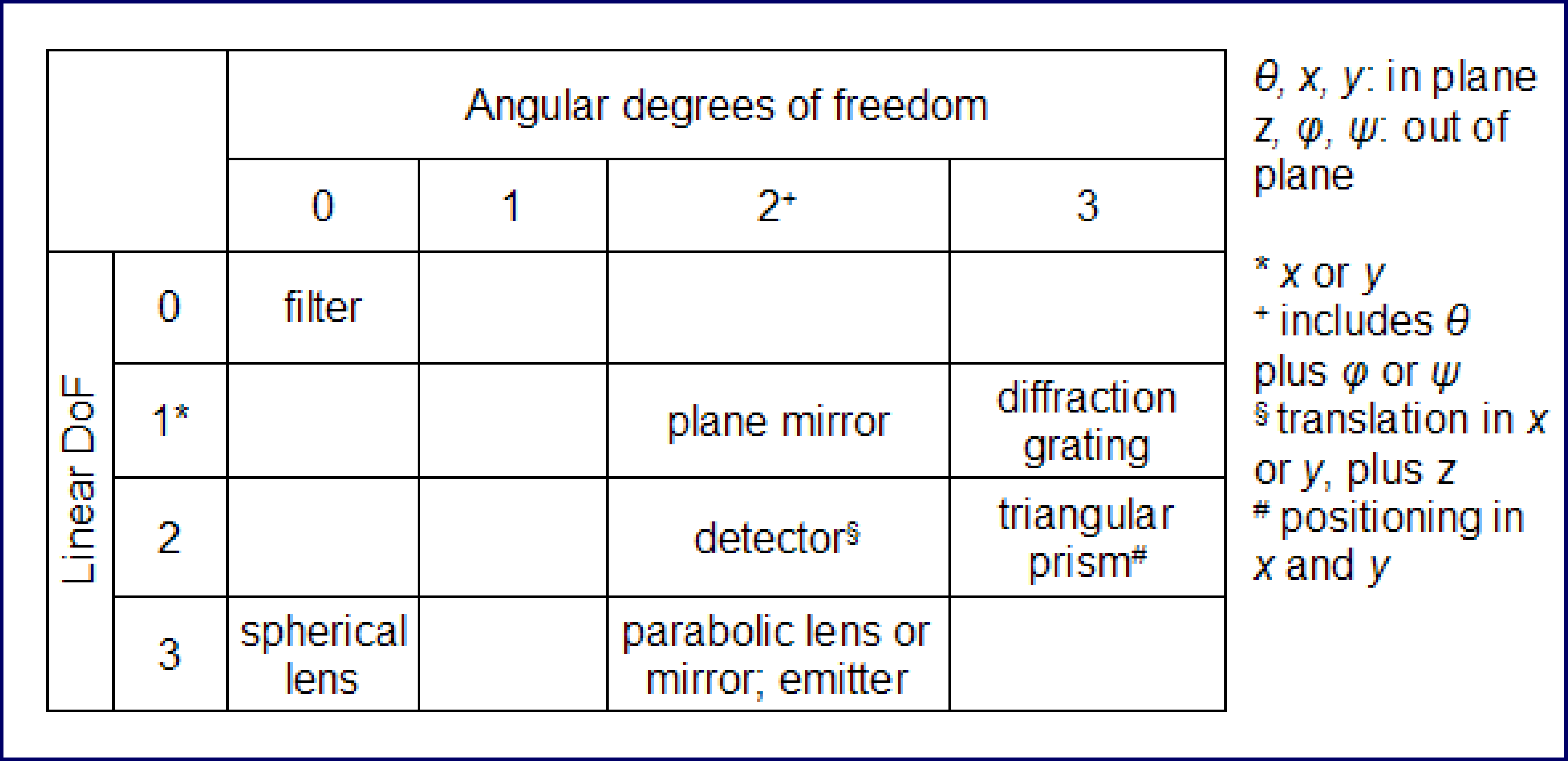
Problem abstraction



		Angular degrees of freedom			
		0	1	2^+	3
Linear DoF	0	filter			
	1^*			plane mirror	diffraction grating
	2			detector§	triangular prism$^{\#}$
	3	spherical lens		parabolic lens or mirror; emitter	

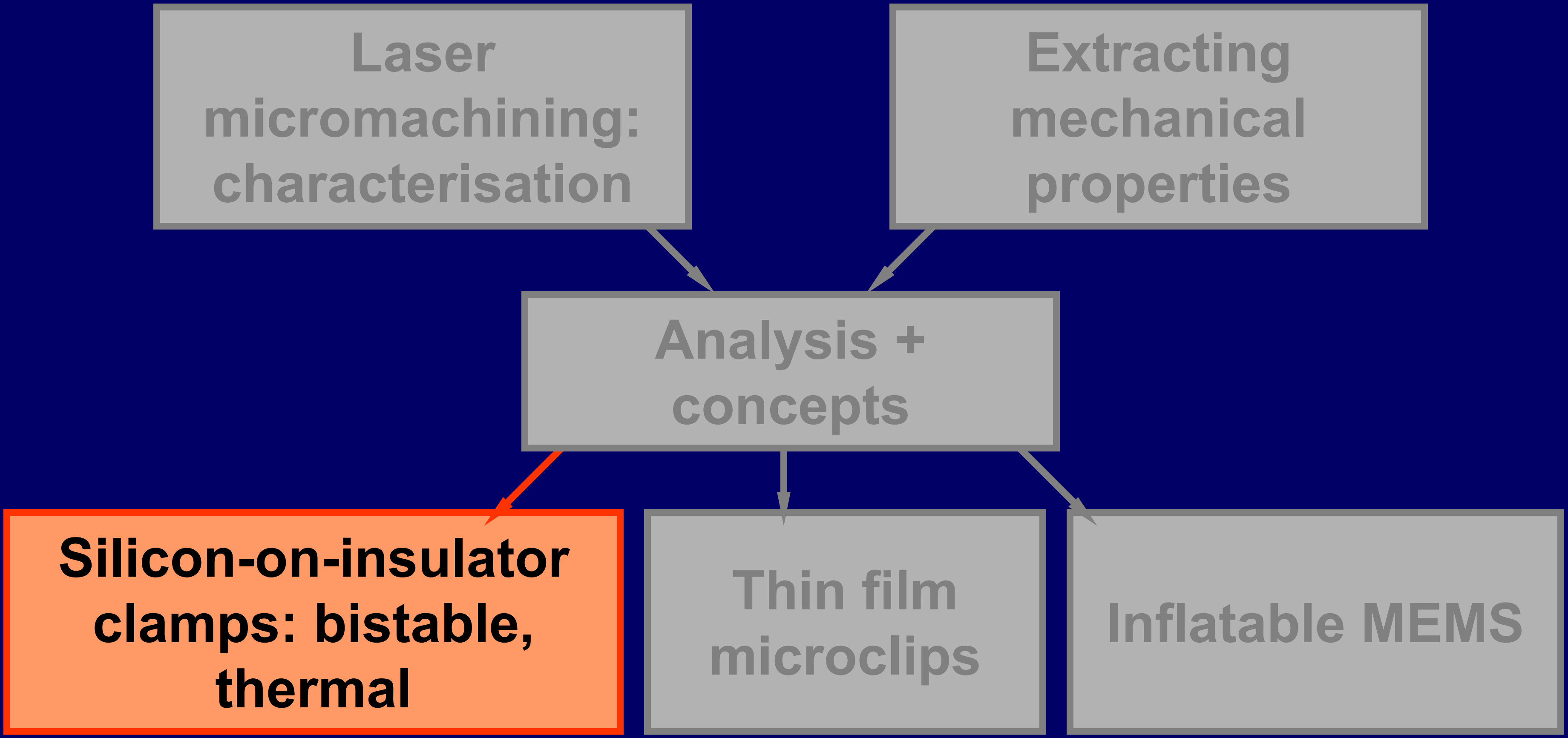
θ, x, y: in plane
z, φ, ψ: out of plane

* x or y
$^+$ includes θ plus φ or ψ
§ 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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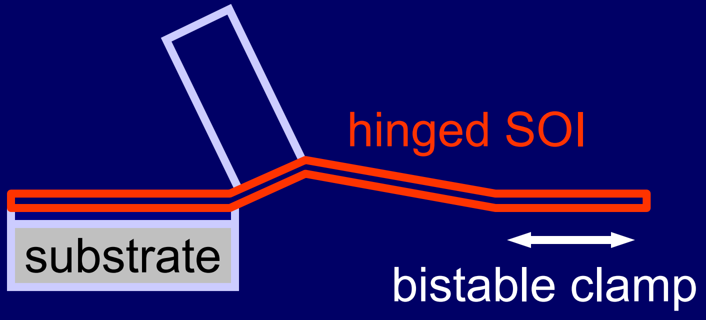
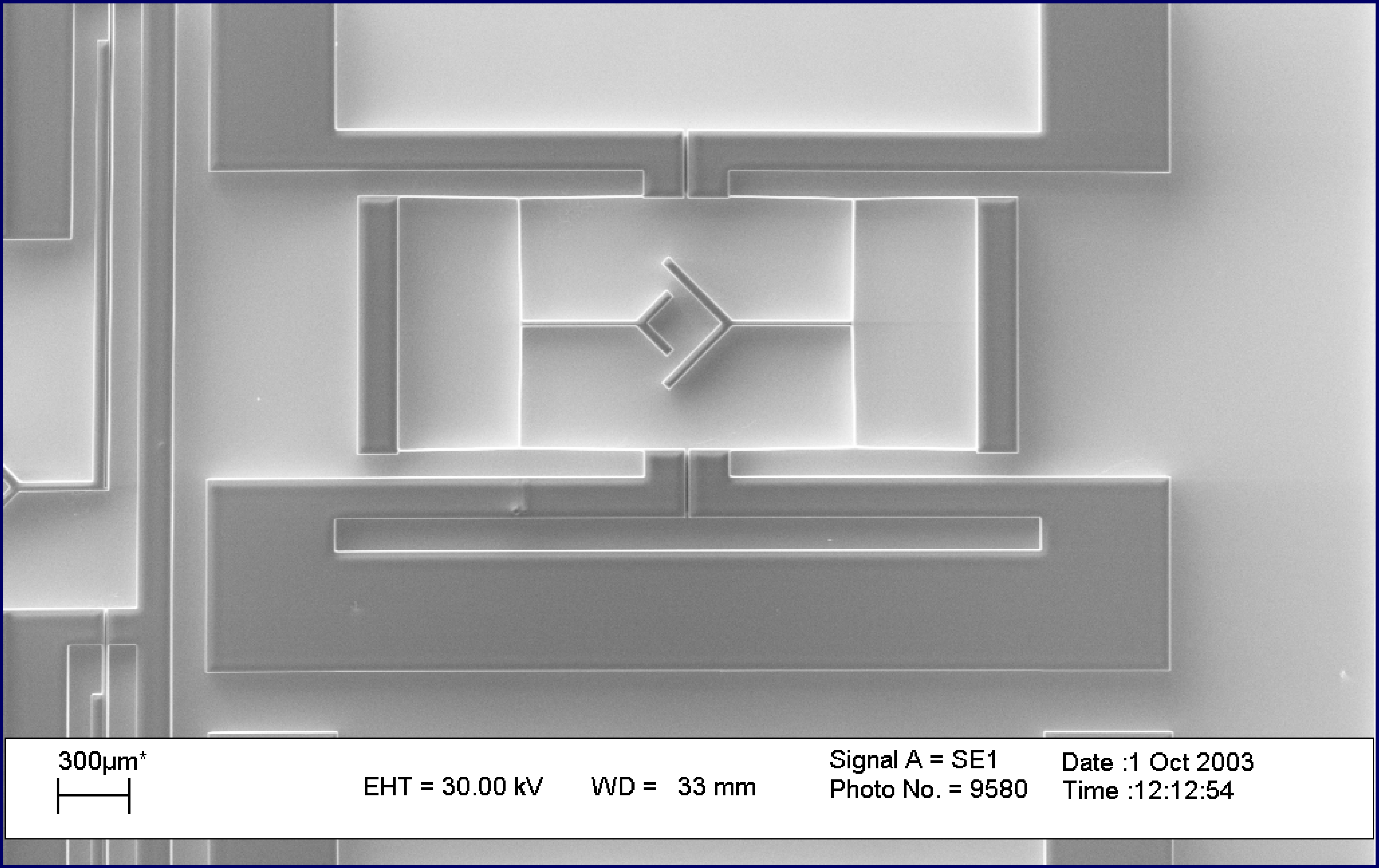


DRIE structure
Lens manipulator



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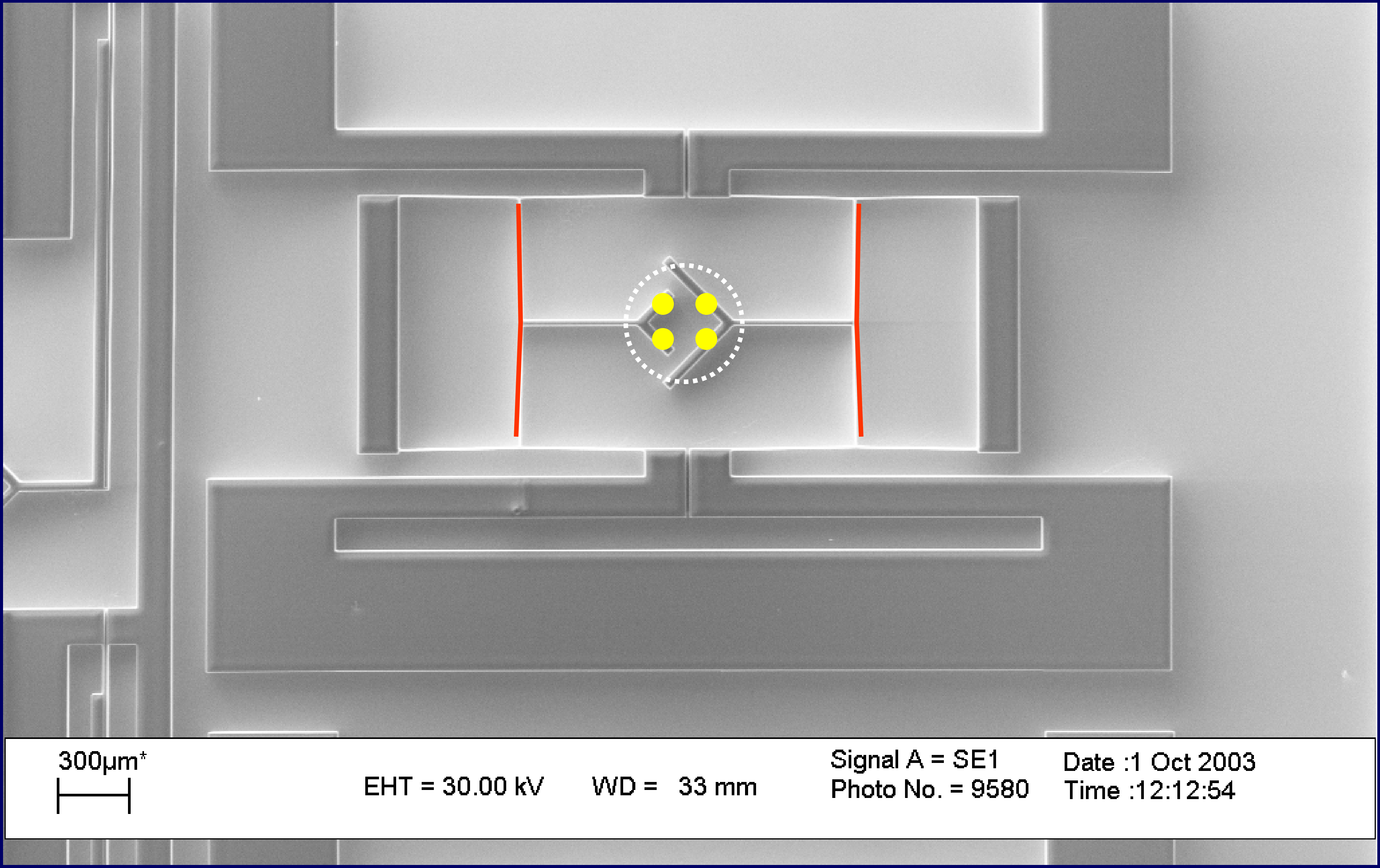
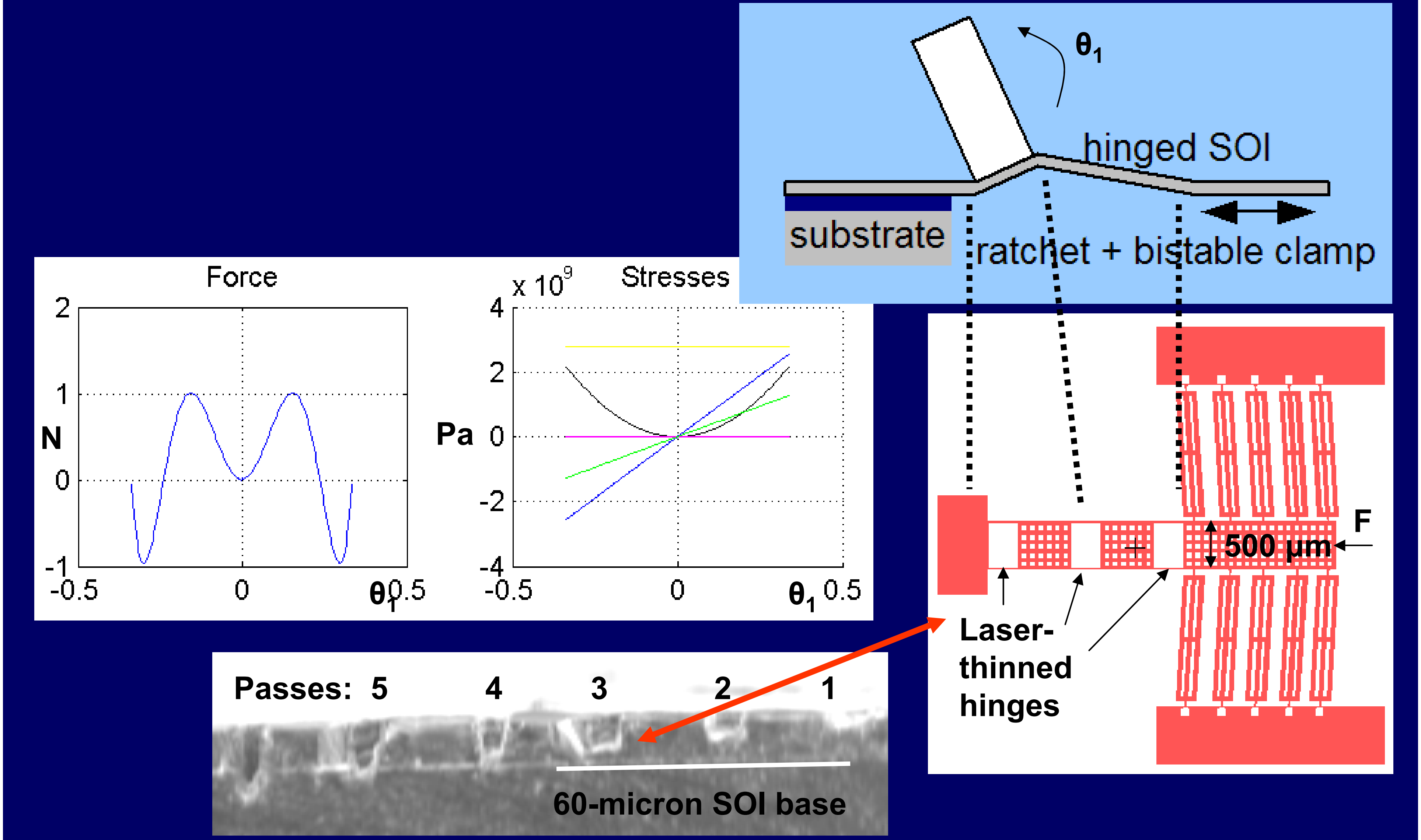
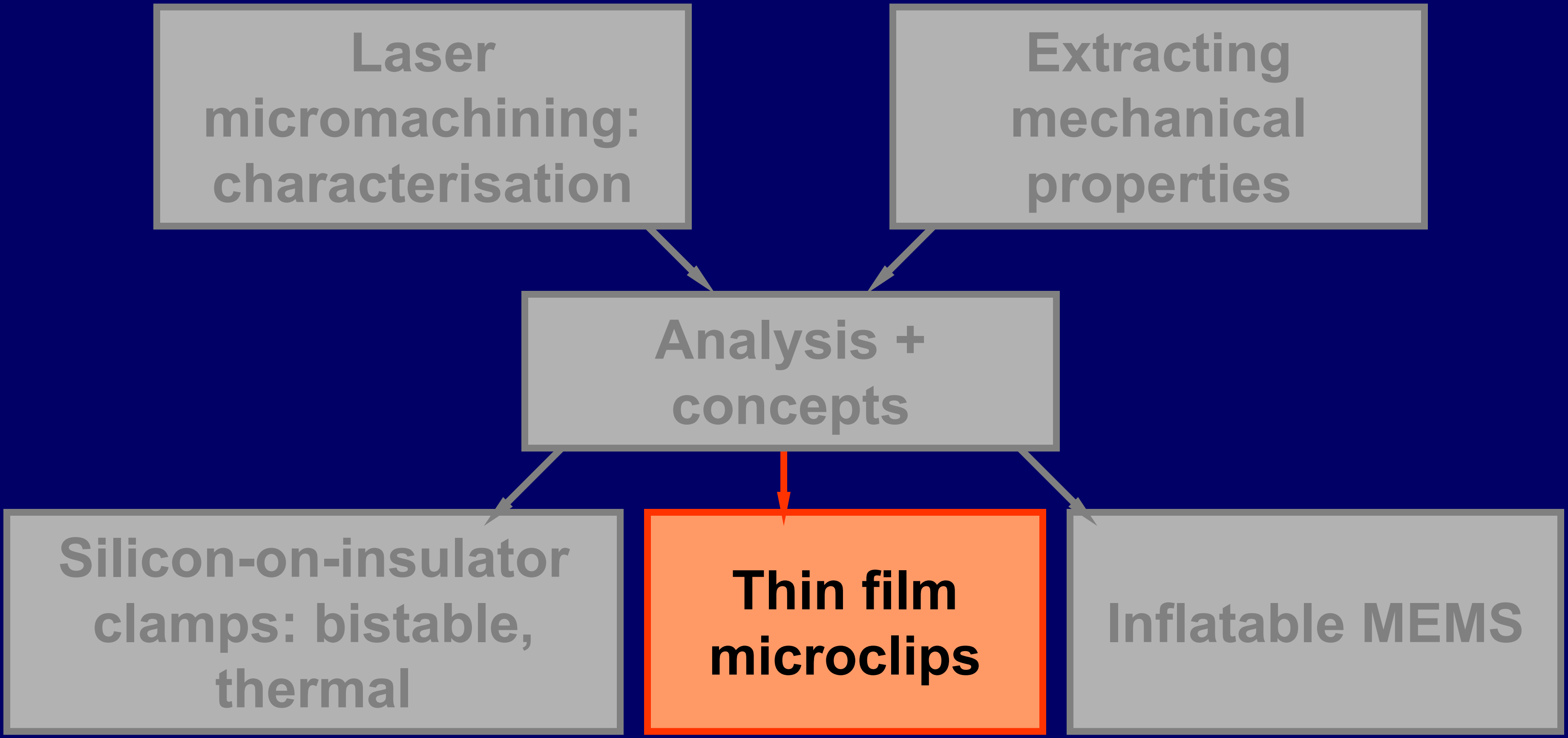


Out-of-plane bistable clamps



SEM cross-section of SOI thinning experiment

Outline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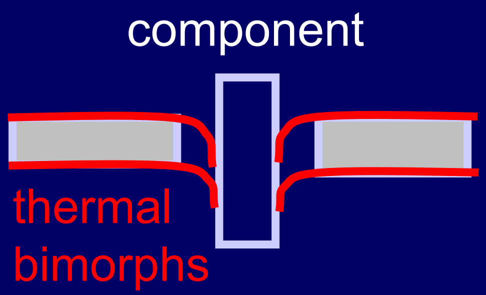
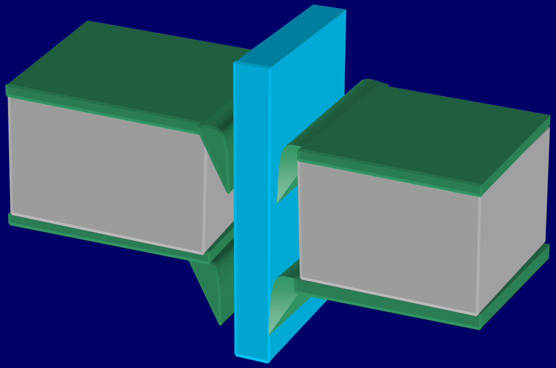


Proposed microclips

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

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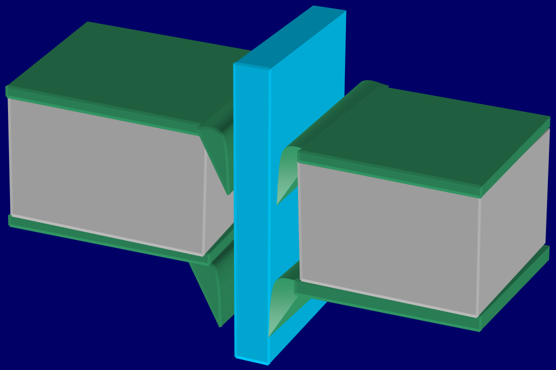

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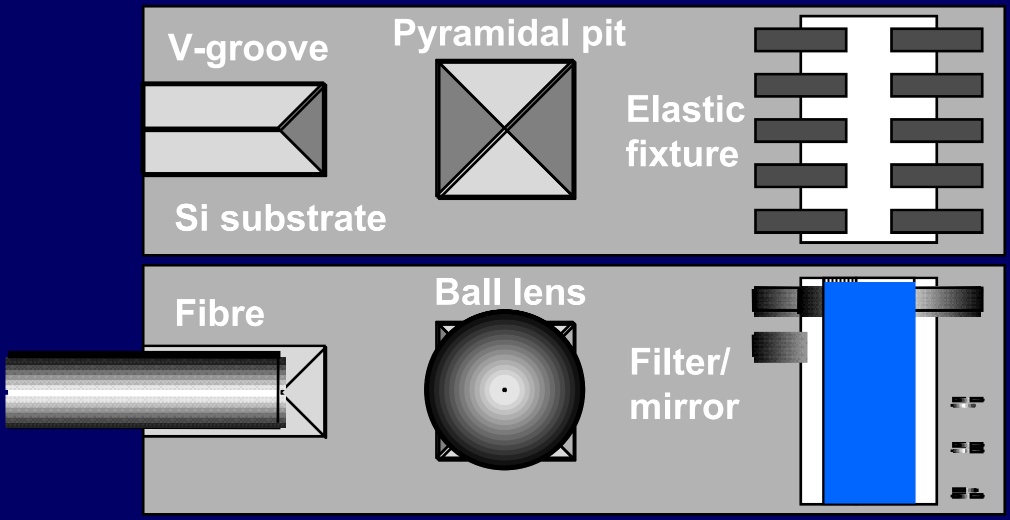
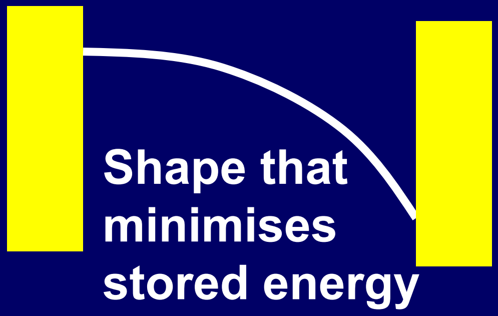


Deflection of Microbeams

- 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.



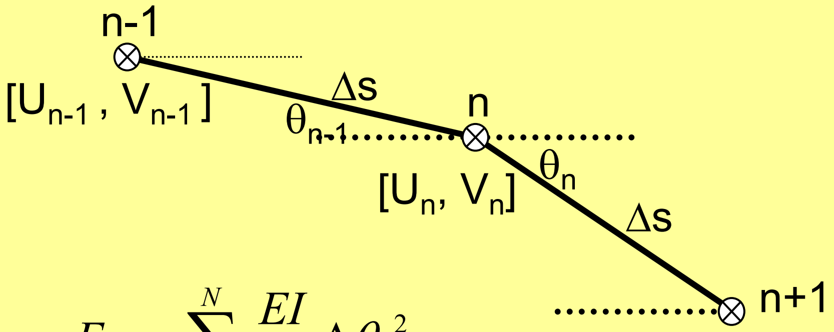
Shape that minimises stored energy

$$E = k\int_0^L F\left(y, \frac{dy}{dx}, x\right)dx$$

$$E_{tot} = \int M\kappa\, ds$$

Discretisation

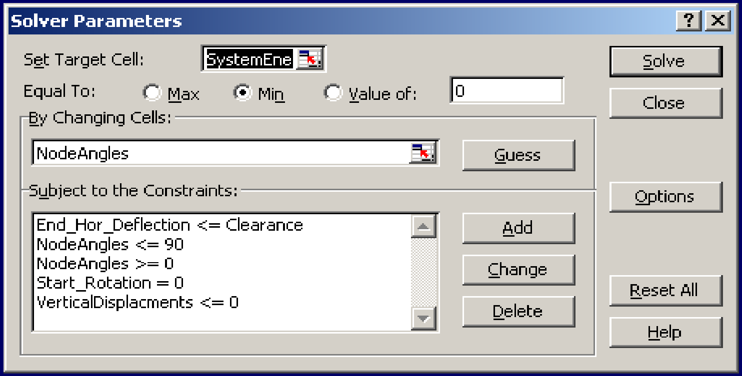
- The integral expression can be approximated by a series expression.
- The system effectively becomes a series of rigid members joined by torsional springs whose spring constant gives the same bending rigidity per unit length as the continuous bar.



$$E_{tot} = \sum_{n=0}^{N} \frac{EI}{2\Delta s}\Delta\theta_n^{\,2}$$

Deflection of Microbeams

- Excel contains an optimisation plug-in called Solver. This allows us to
  - Minimise an objective function — Stored Energy
  - By changing a set of variables — Bar Angles ($\theta_0 \ldots \theta_n$)
  - Subject to constraints — Tip Displacement + segment angle



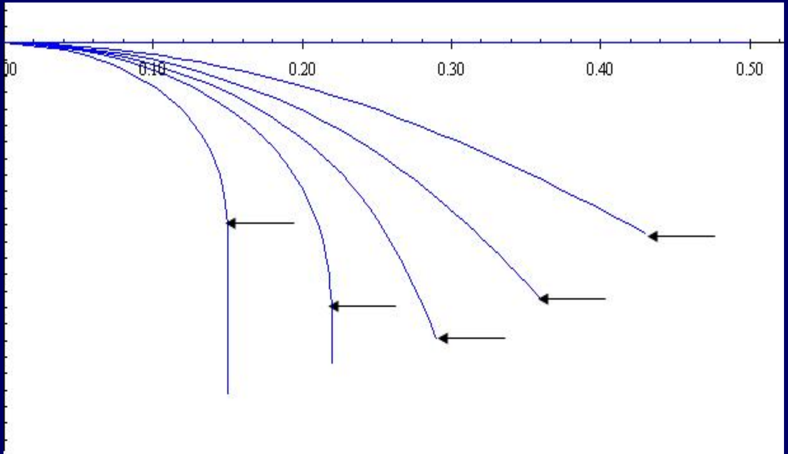
Set Target Cell: SystemEne

Equal To: ○ Max ● Min ○ Value of: 0

By Changing Cells: NodeAngles

Subject to the Constraints:

End_Hor_Deflection <= Clearance
NodeAngles <= 90
NodeAngles >= 0
Start_Rotation = 0
VerticalDisplacments <= 0

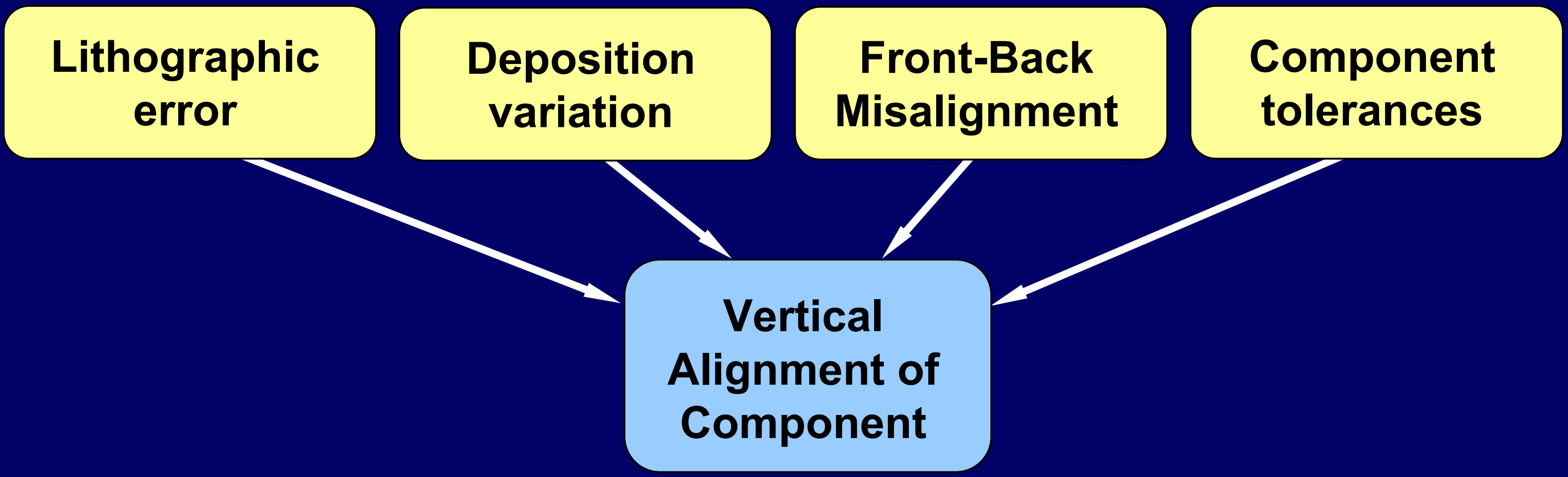


Node	θ degrees	θ radians	U_n	V_n	$\Delta\theta_n$	Energy
0	0.00	0	0.00	0.00		
1	1.32	0.0230469	0.03	0.00	0.0230469	4.46E-03
2	2.64	0.0460318	0.07	0.00	0.0229848	4.44E-03
3	3.95	0.0688915	0.10	0.00	0.0228598	4.39E-03
4	5.25	0.0915638	0.13	-0.01	0.0226723	4.32E-03
5	6.53	0.1139874	0.17	-0.01	0.0224236	4.22E-03
6	7.80	0.1361017	0.20	-0.02	0.0221143	4.11E-03
7	9.04	0.1578469	0.23	-0.02	0.0217453	3.97E-03
8	10.27	0.1791647	0.26	-0.03	0.0213178	3.82E-03
9	11.46	0.1999985	0.30	-0.03	0.0208338	3.65E-03
10	12.62	0.2202919	0.33	-0.04	0.0202934	3.46E-03
11	13.75	0.2399913	0.36	-0.05	0.0196994	3.26E-03
12	14.84	0.2590443	0.39	-0.06	0.0190529	3.05E-03
13	15.89	0.2774013	0.43	-0.07	0.018357	2.83E-03
14	16.90	0.2950133	0.46	-0.08	0.017612	2.61E-03
15	17.87	0.3118345	0.49	-0.09	0.0168212	2.38E-03
16	18.78	0.3278219	0.52	-0.10	0.0159874	2.15E-03
17	19.65	0.342934	0.55	-0.11	0.0151121	1.92E-03
18	20.46	0.3571318	0.58	-0.12	0.0141977	1.69E-03
19	21.22	0.370379	0.62	-0.13	0.0132472	1.47E-03
20	21.92	0.3826425	0.65	-0.14	0.0122636	1.26E-03
					Σ Energy	6.345E-02

IEEE 2002 Electronics Components and Technology Conference, San Diego, U.S.A., s19p3, pp. 1-7 (2002)

Processing variations and probabilistic design

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



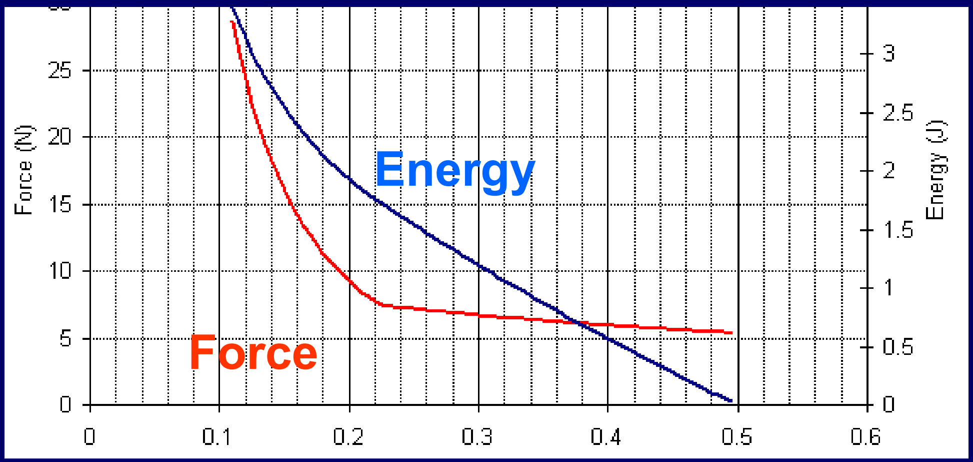
Lithographic error

Deposition variation

Front-Back Misalignment

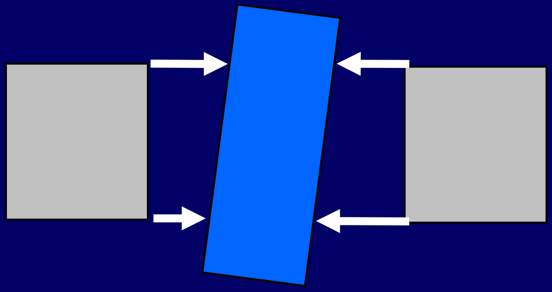
Component tolerances

Vertical Alignment of Component

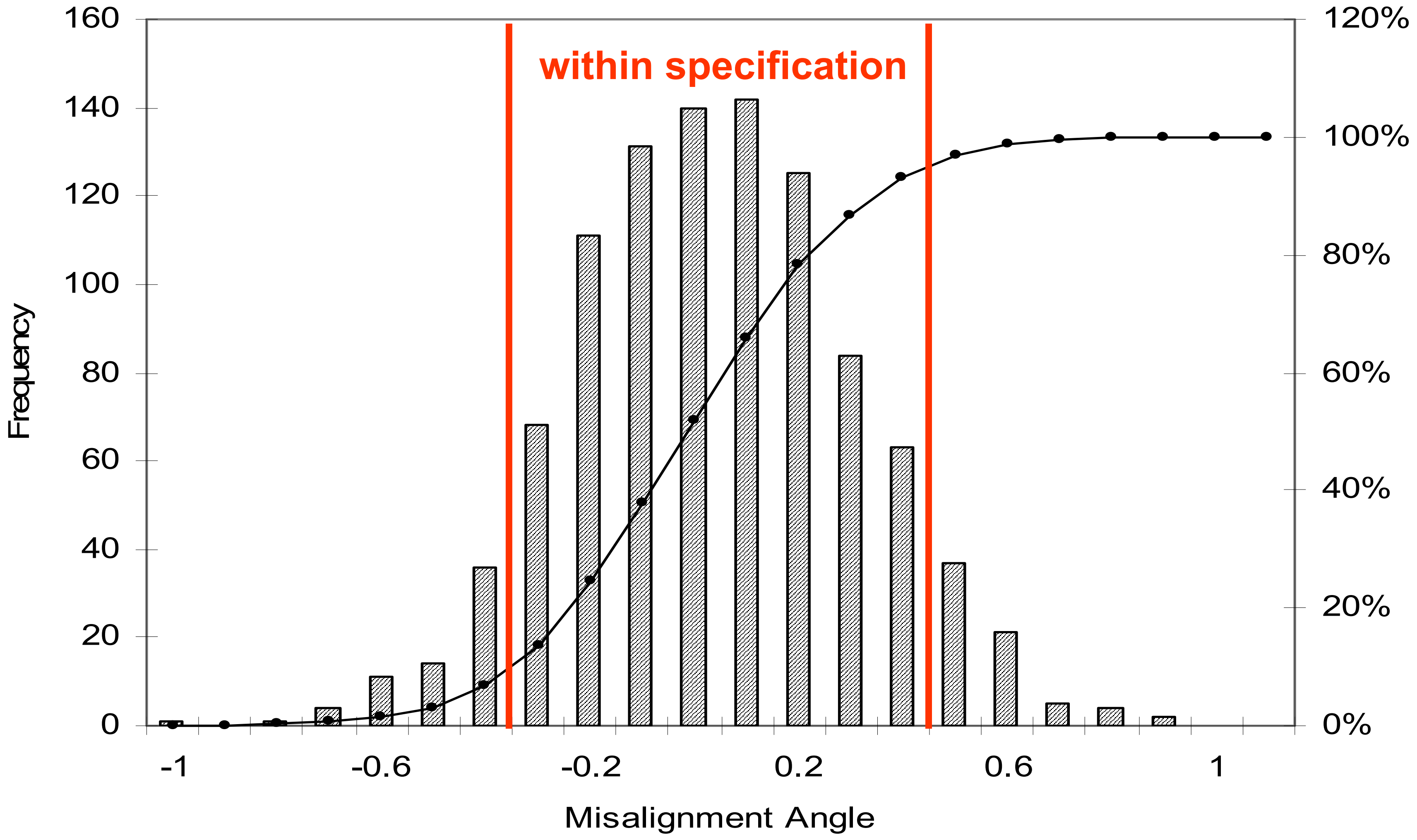


Clearance/clip length

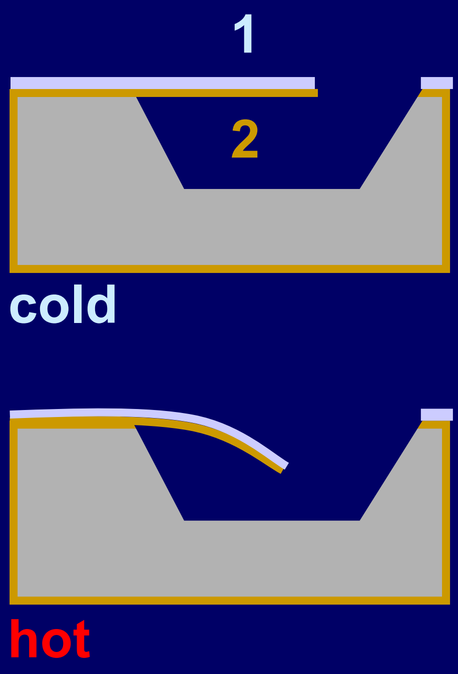
Investigate the effect of each error and build a distribution of vertical alignment.



Processing variations and probabilistic design



Towards 'active' clips



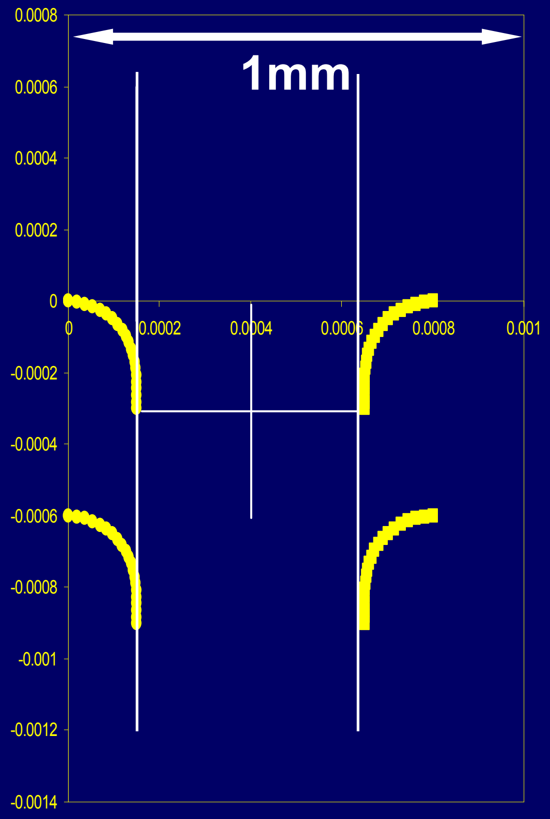
Thicknesses a_1, a_2
Thermal expansivities are α_1, α_2
Moduli E_1, E_2
Increase in temperature ΔT

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

Thermal curvature is given by:

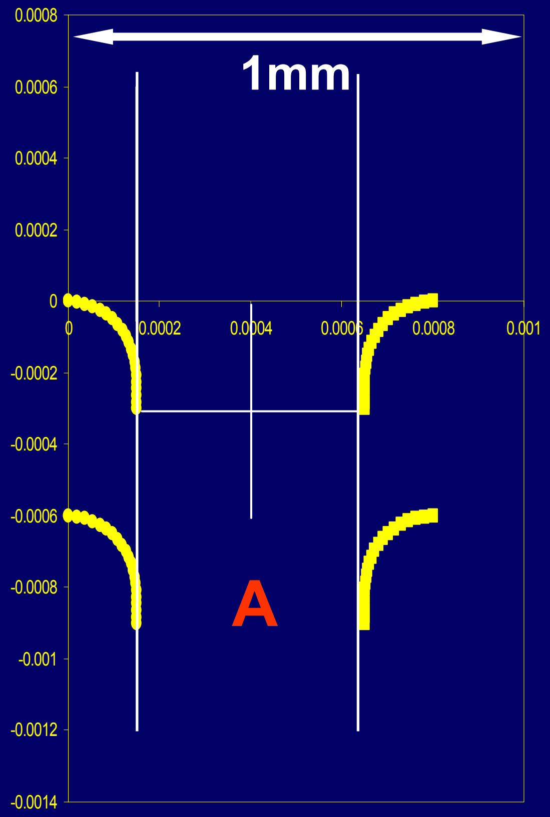
$$\kappa = K(\alpha_2 - \alpha_1)\Delta T/t$$

Extending energy simulation to 4 thermal clips

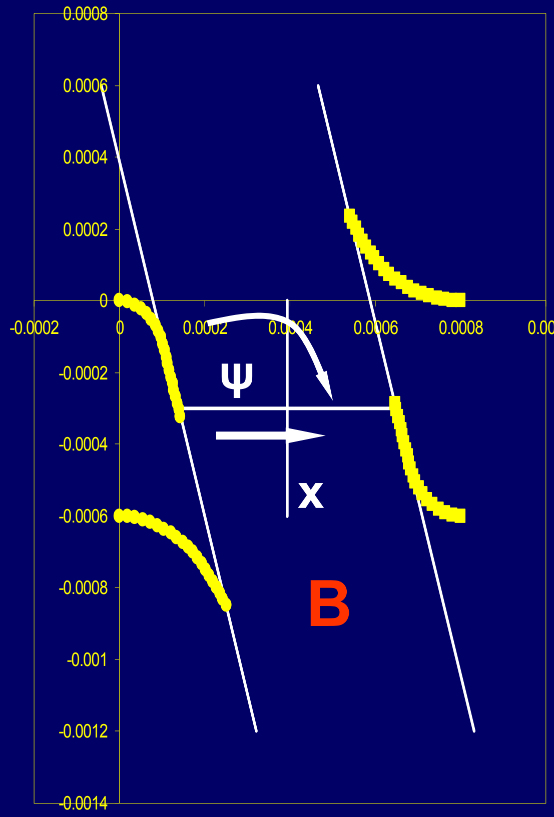


No misalignments

Extending energy simulation to 4 thermal clips

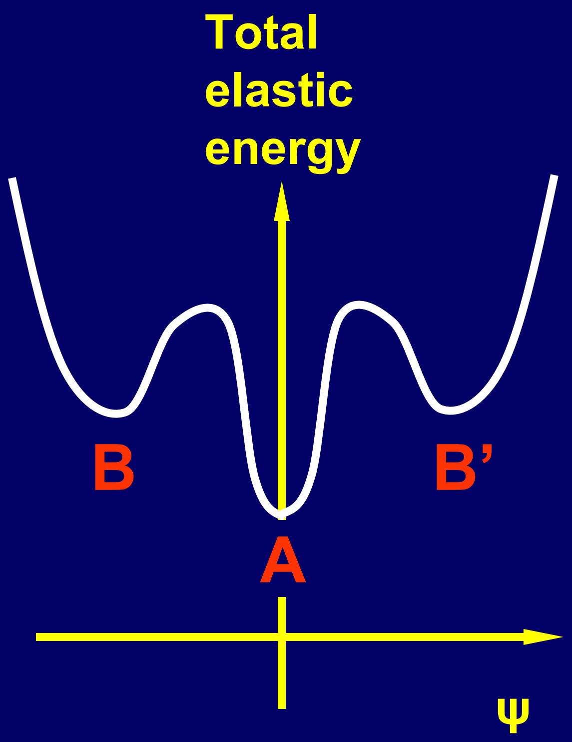


No misalignments

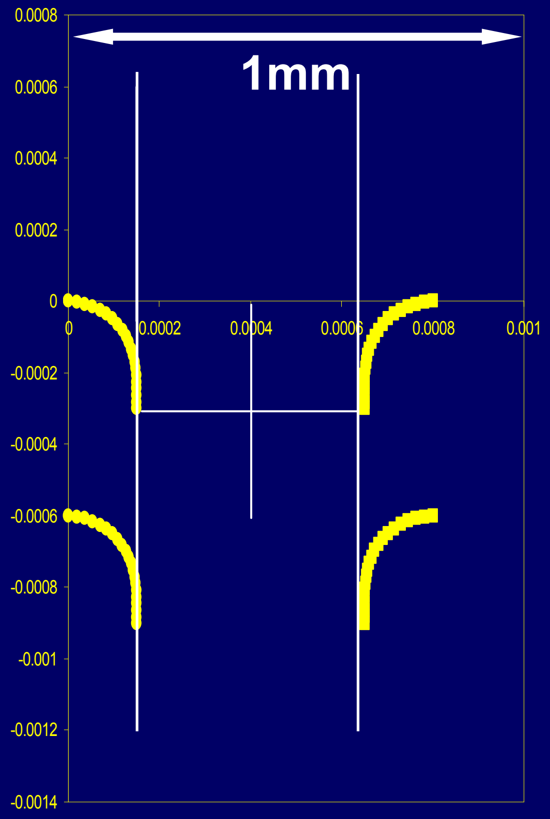


Local energy minimum with antisymmetric clip orientations

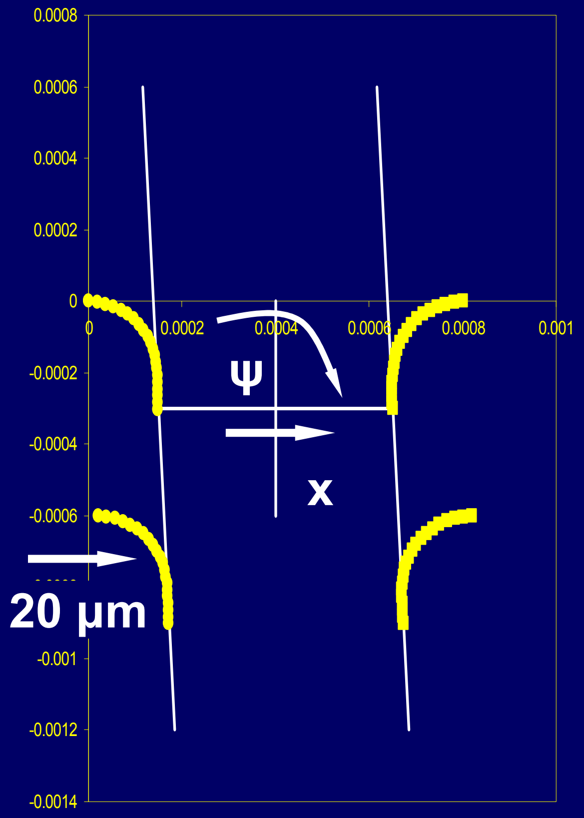
rotation ψ = –11.5°



Extending energy simulation to 4 thermal clips



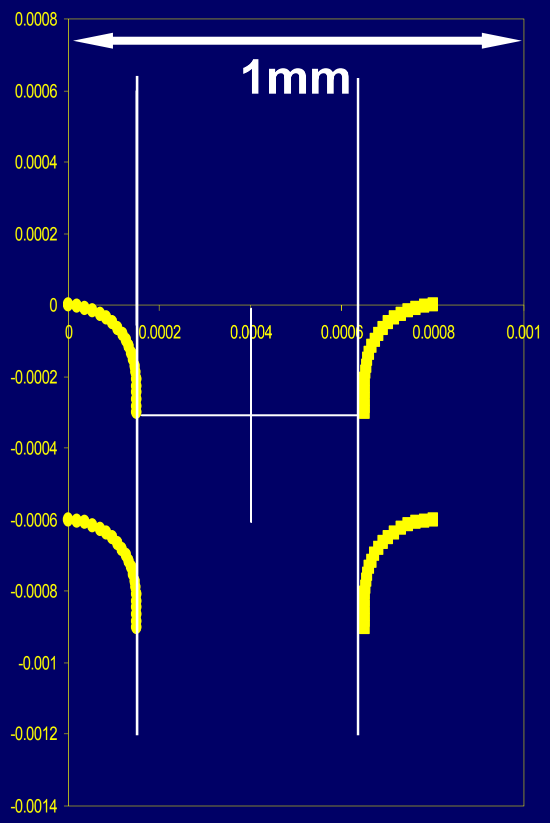
No misalignments



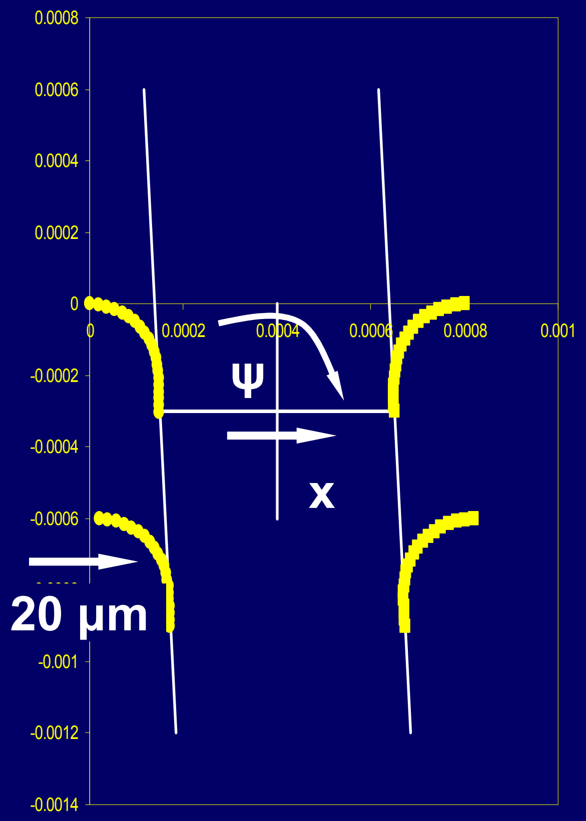
**20 µm
front-to-back
misalignment…**

**rotation $\psi = -2.1^\circ$
$x \approx 0$**

Extending energy simulation to 4 thermal clips

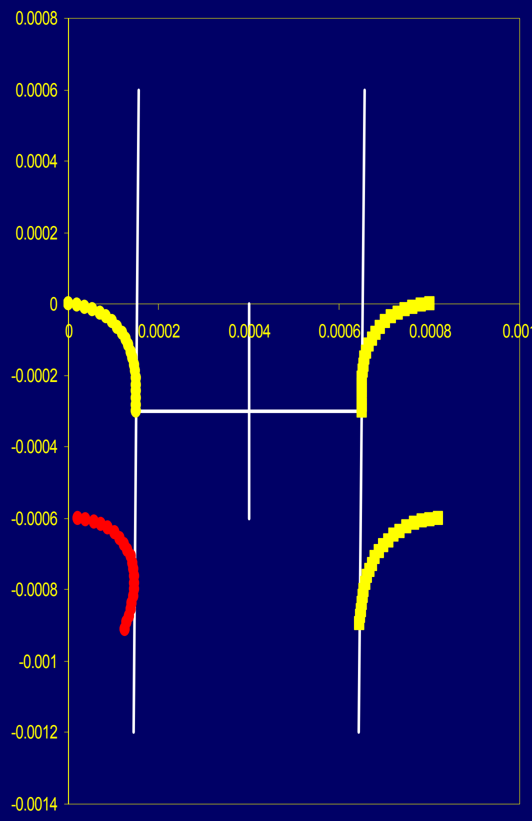


No misalignments



20 μm
front-to-back
misalignment…

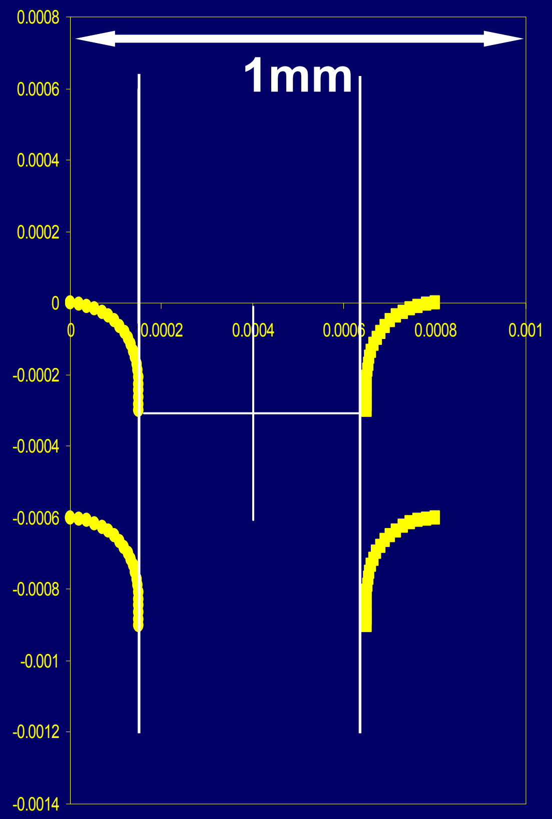
rotation $\psi = -2.1°$
$x \approx 0$



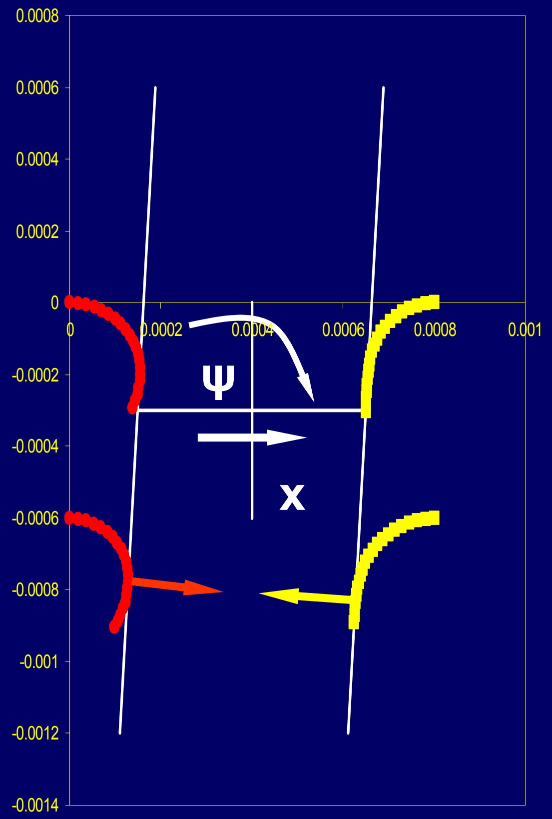
… countered by
20K temp increase
in red clip.
(150nm Ni/SiN_x)

rotation $\psi = 0.4°$
$x \approx 0$

Extending energy simulation to 4 thermal clips



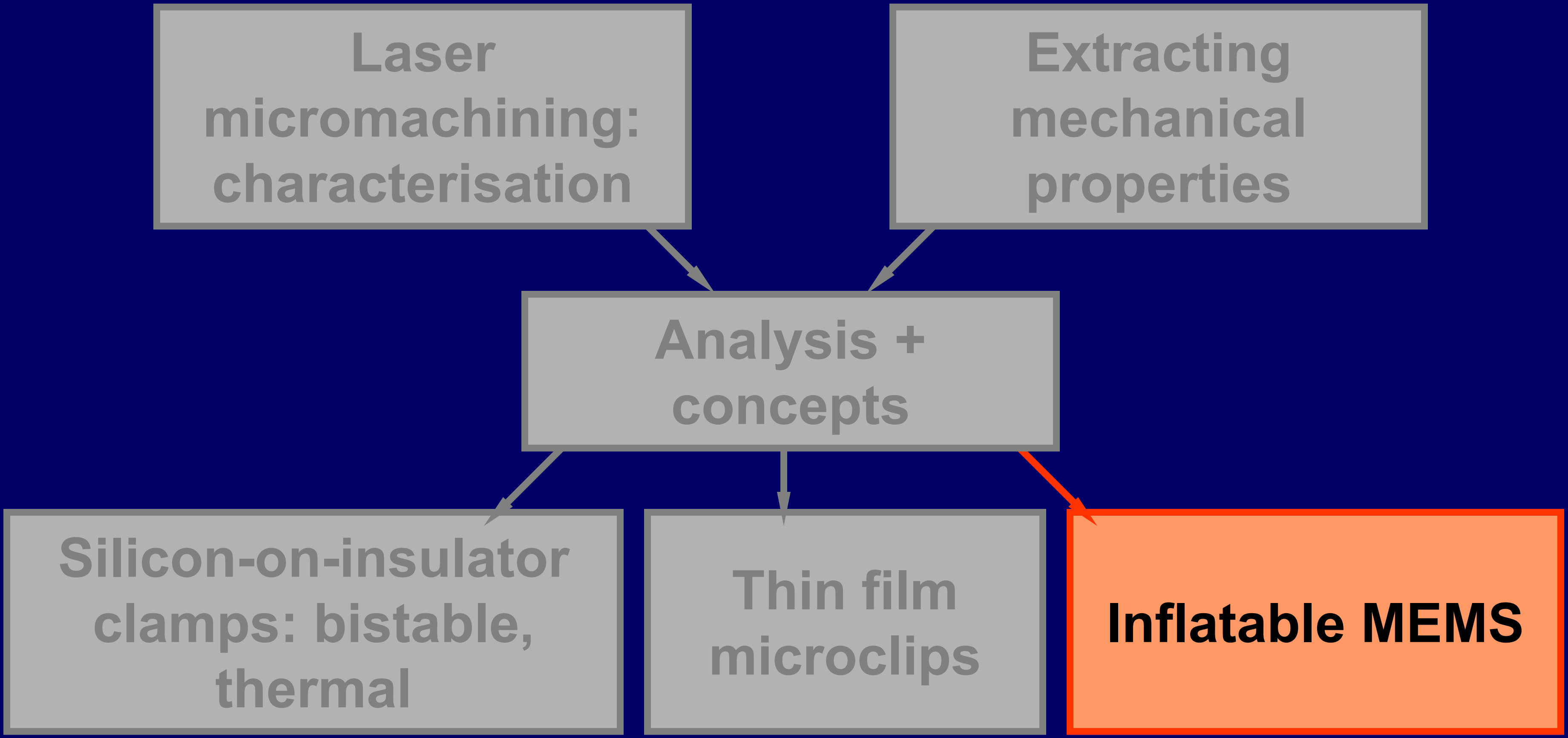
No misalignments



50K temperature increase in clips 1 and 2

rotation ψ ~ 2°
x ~ –5 μm

Outline



Laser micromachining: characterisation

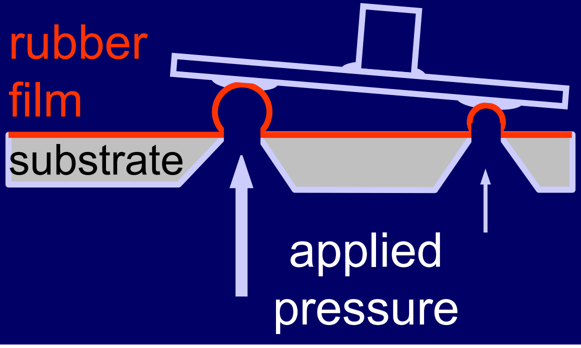
Extracting mechanical properties

Analysis + concepts

Silicon-on-insulator clamps: bistable, thermal

Thin film microclips

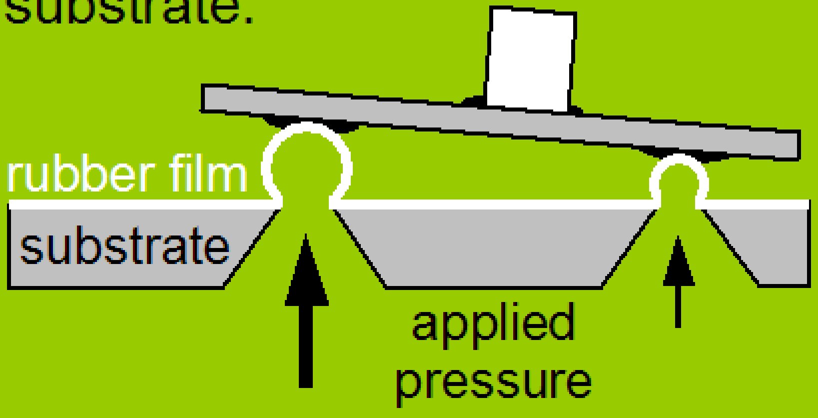
Inflatable MEMS

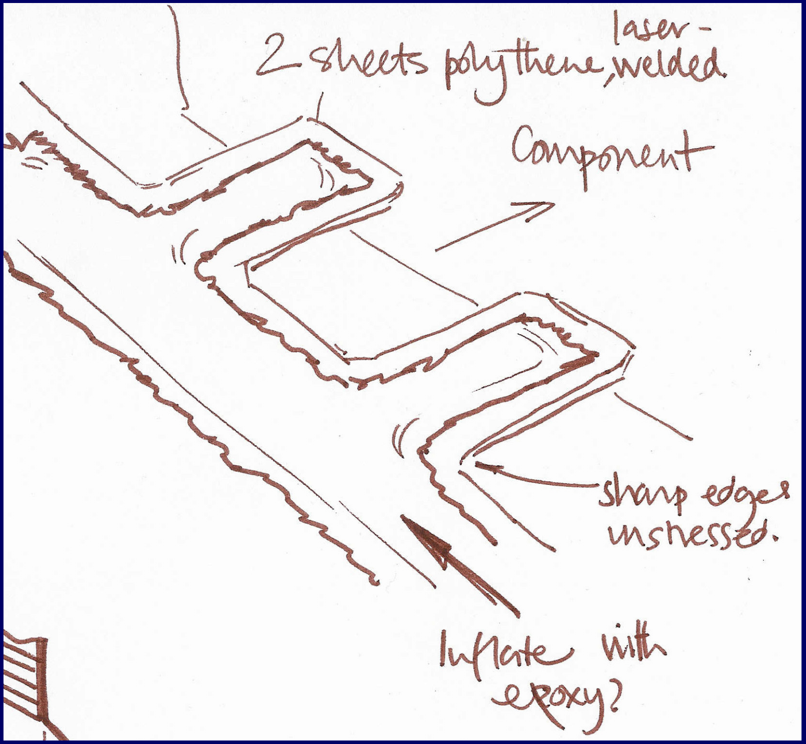


Why consider inflatable MEMS?

- 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