Temperature Homogenization of Co-Integrated Shape Memory – Silicon Bimorph Actuators

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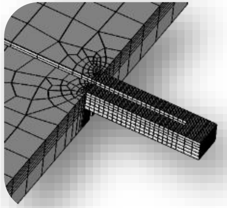
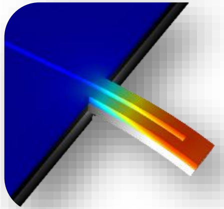
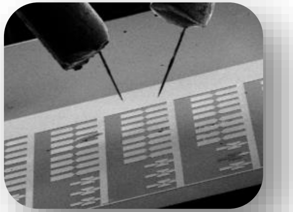
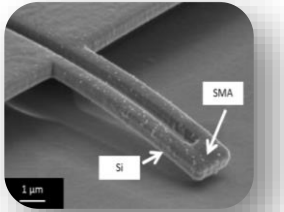
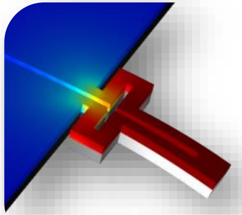










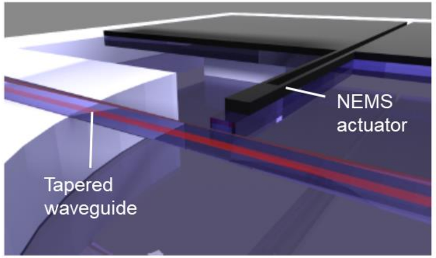
1st International Electronic Conference on Actuator Technology: Materials, Devices and Applications (IeCAT 2020)

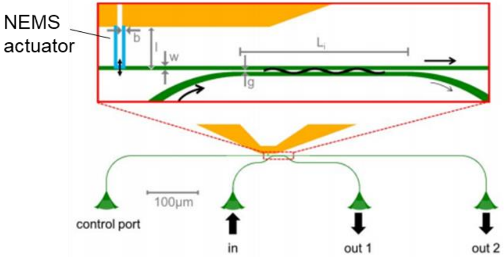
Session: Cooperative Micro-Actuator Systems
November 23rd – 27th 2020

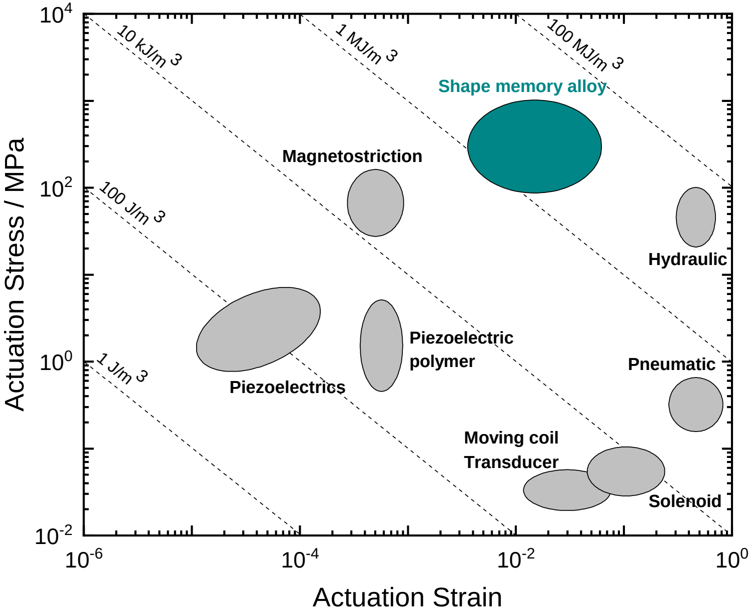
Motivation

- Shape memory alloy
  - Beneficial downscaling (footprint of 1 x 1 µm^2)
  - Strong mechanical effects and high work density
  - Compatibility with semiconductor technology

- Applications
  - Co-integration with Si mechanical structures
  - Optical switching and tuning
  - Cooperative actuators systems



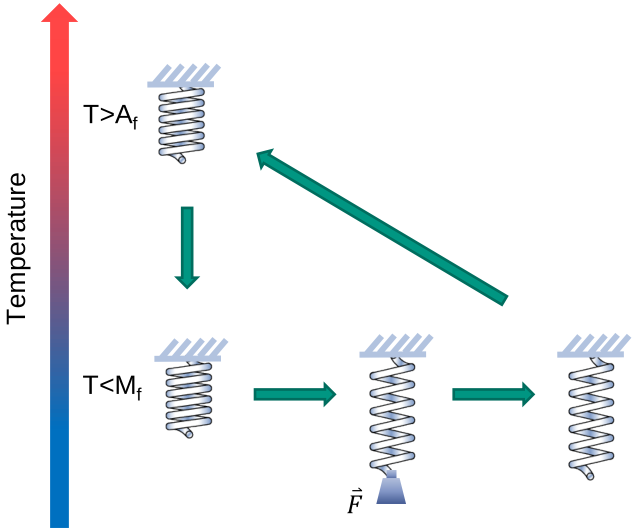




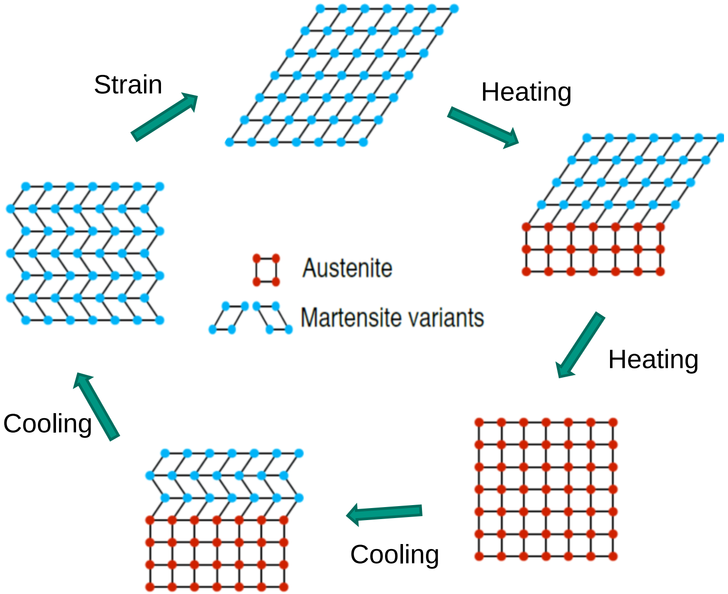
Work density for different actuation principle [1]

Background

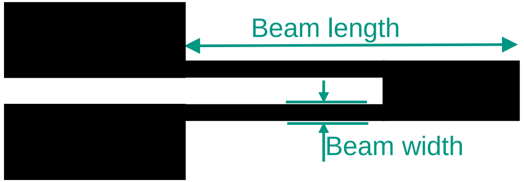
- Shape memory effect - Overview

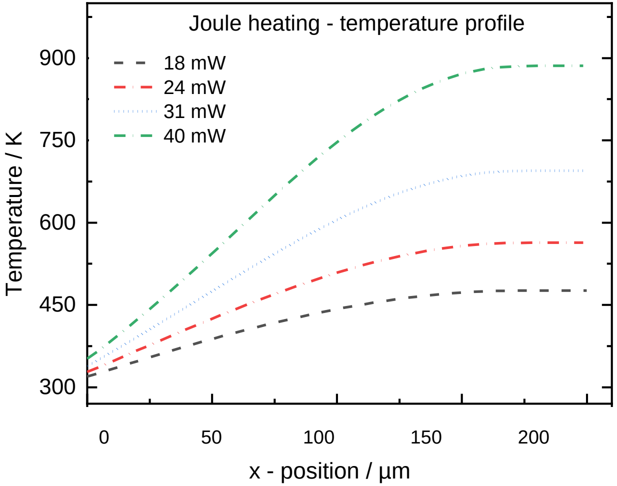


- Phase transformation



Challenge: Temperature profile





- SMA/Si bimorph cantilever
  - 20 µm / 200 µm of beam width/length
  - SMA/Si each of 2 µm thickness

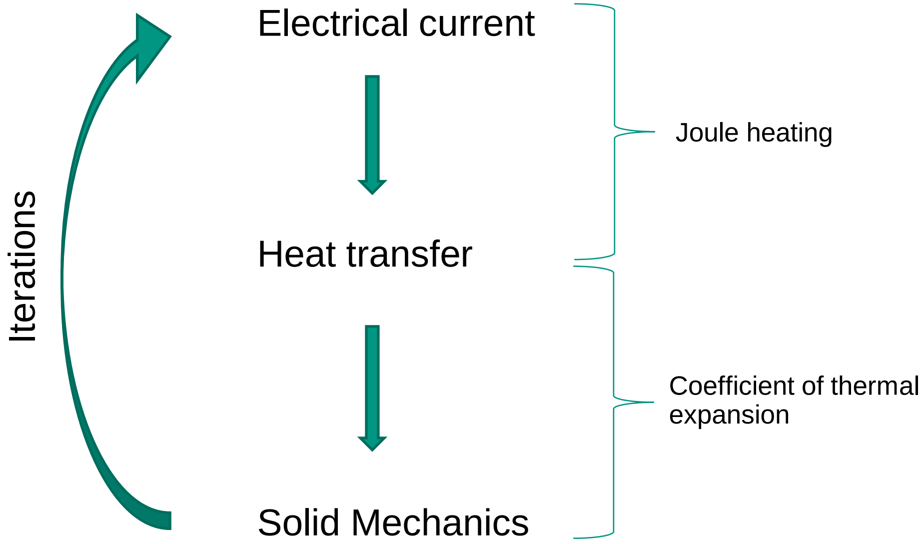
- Simulation of T-profile – thermal conductivity of materials [3]

$$\kappa_{SMA}(T) = L_0 \cdot \sigma_{SMA}(T) \cdot T$$

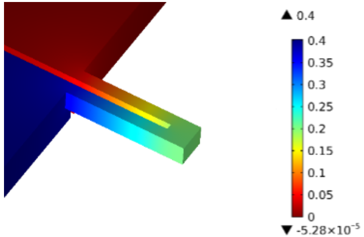
$$\kappa_{Si}(T) = \frac{5.0105 \times 104 \, \frac{W}{m}}{T} - 19.24 \, \frac{W}{mK}$$

- Large temperature gradients along the cantilevers
- Major effect on downscaling

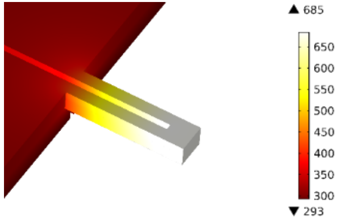
Coupled Multiphysics simulation



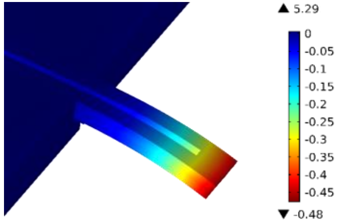
Electric potential, Φ



Surface temperature, ΔT

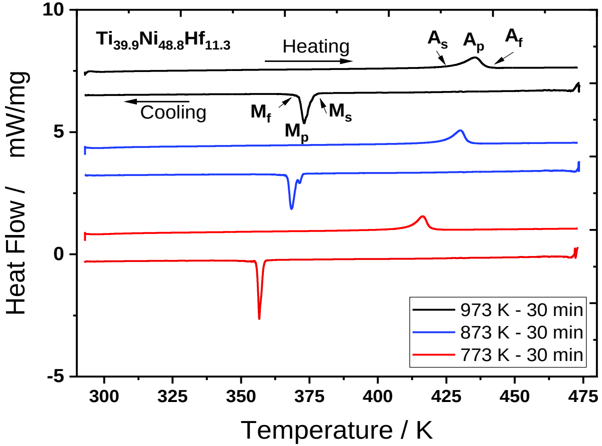


Out-of-plane deflection, ΔS

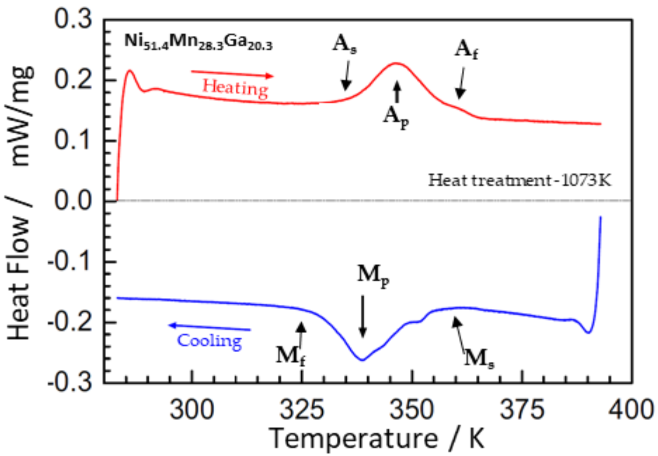


SMA – DSC measurement

TiNiHf



NiMnGa



Material	Annealing Information	Af (K)	As (K)	Ms (K)	Mf (K)
TiNiHf	773 K – 30 min	419.0	412.1	357.9	356.1
	873 K – 30 min	432.9	425.1	370.7	367.1
	973 K – 30 min	439.7	428.9	376.0	371.2
NiMnGa	1073 K – 600 min	355	337	360	326

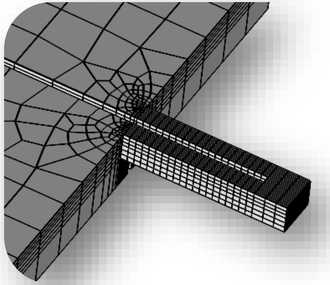
Modelling and material properties

Tanaka-type model

$$\sigma_{SMA}(T) = \left(1 - \xi_M(T)\right) \cdot \sigma_A + \xi_M(T) \cdot \sigma_M$$

$$\alpha_{SMA}(T) = \left(1 - \xi_M(T)\right) \cdot \alpha_A + \xi_M(T) \cdot \alpha_M$$

ξ_M - martensite volume fraction ($0 < \xi_M < 1$)

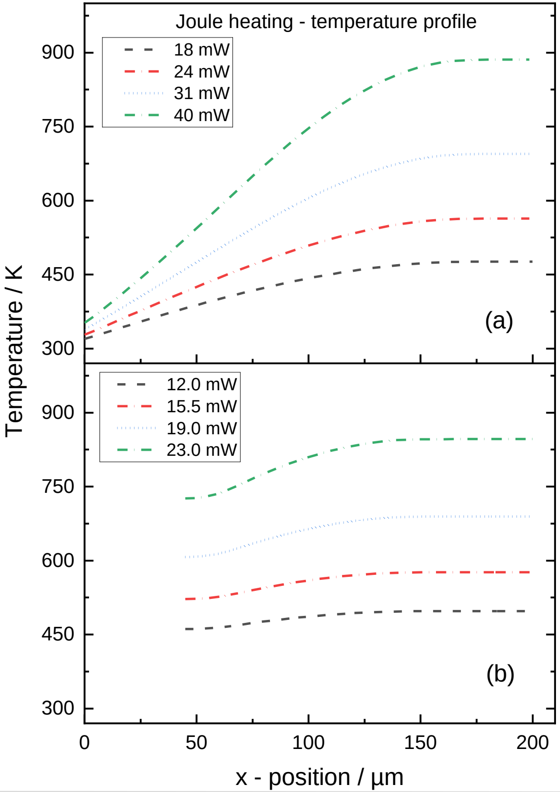


Meshing – double beam cantilever

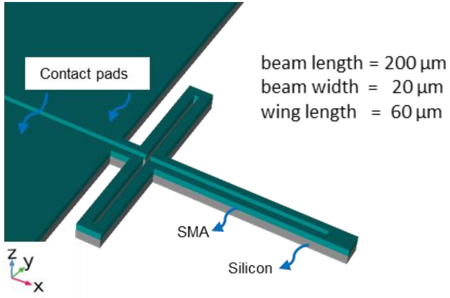
Material properties of SMA and Si

	Si	NiMnGa	NiTi(Hf)
Electrical conductivity β_{SMA}, S/m	10	$\beta_{NiMnGa}(T)$	$\beta_{NiTi}(T)$
Thermal expansion coefficient α, 1/K	$\alpha_{Si}(T)$	$\alpha_A = 23 \times 10^{-6}$ $\alpha_M = 33 \times 10^{-6}$	$\alpha_A = 11 \times 10^{-6}$ $\alpha_M = 6.6 \times 10^{-6}$
Young's modulus E, GPa	169	E = 100	E = 87
Poisson's ratio ν	0.22	0.33	0.39

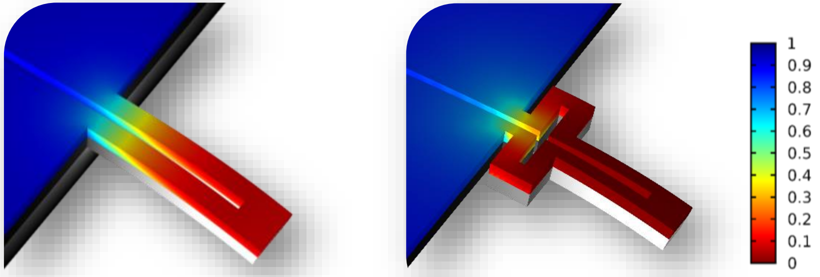
Challenge: Temperature profile



- Design challenges
  - Homogeneous T-profile
  - Deflection should not be affected
  - Power consumption
- Solution: Wing like folded structures
  - Homogeneous T-profile
  - Uniform phase transformation

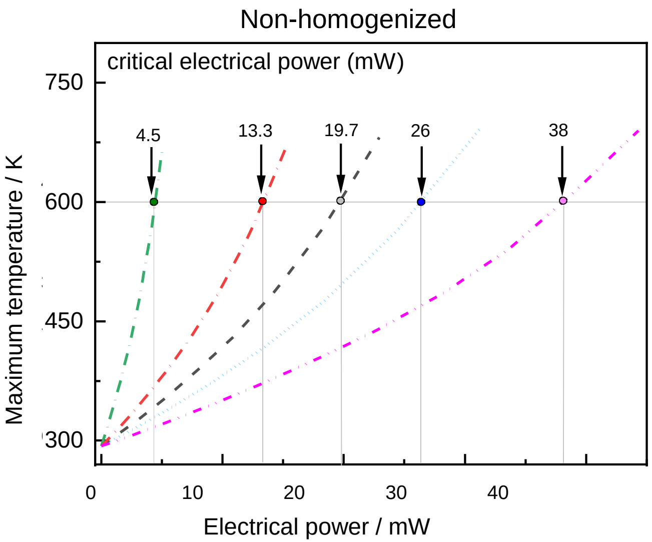


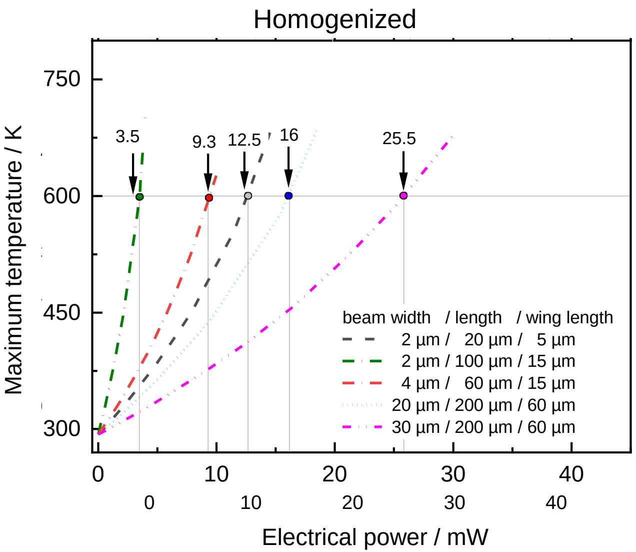
beam length = 200 µm
beam width = 20 µm
wing length = 60 µm



Phase fraction of Martensite

Critical Electrical Power

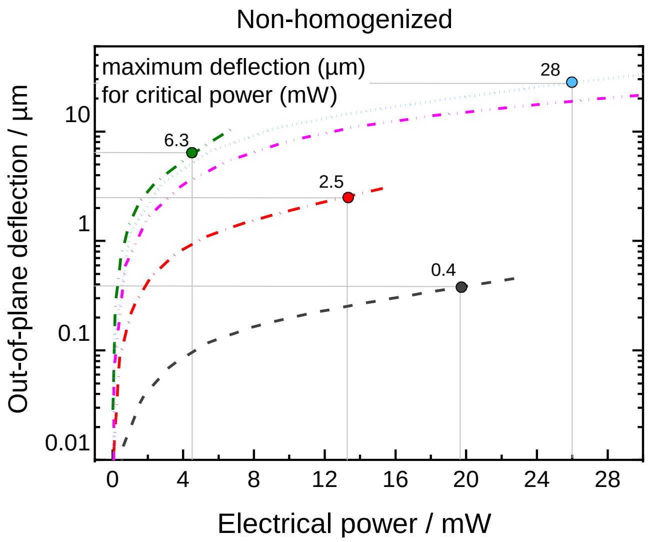


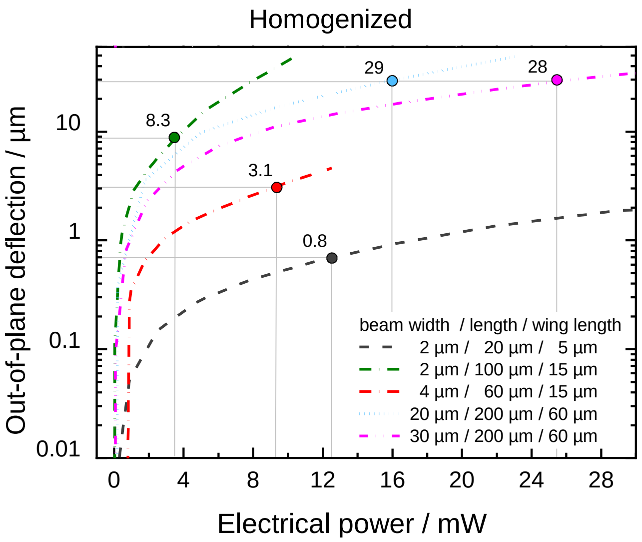


- Reference temperature of 600 K (operational limit of the device)
- Beam width ↑ - needs ↑ electrical power (#4 and #5)
- Beam length ↑ - needs ↓ electrical power (#1 and #2)

- With folded beam structure, less power is required to achieve maximum temperatures
- Nearly 35 % reduction in power consumption

Maximum Displacement

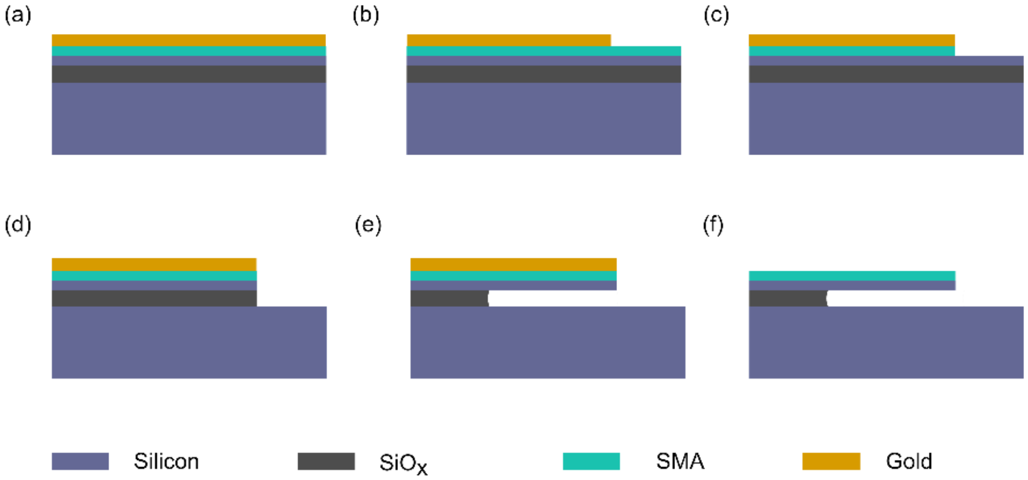




- Maximum displacement for the critical power (at the beam tip)
- Beam width – no significant change
- Beam length ↑ – deflection ↑

- Folded beam structure achieves larger deflection at lower power in all variants
- Deflection improved by factor of 2 with 2 µm/20 µm of width/length

Fabrication Process



(a) SOI wafer with SMA and Au layer

(b) Lithography of beam structure (EBL* for nanostructures)

(c) Wet-etching of SMA

(d) RIE* process of Si using HBr

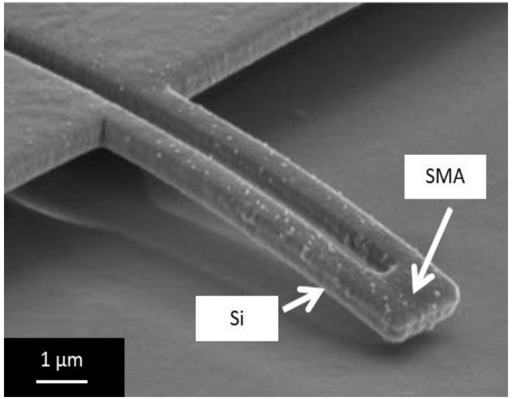
(e) Isotropic HF etching of SiO_2

(f) Free-hanging bimorph structure

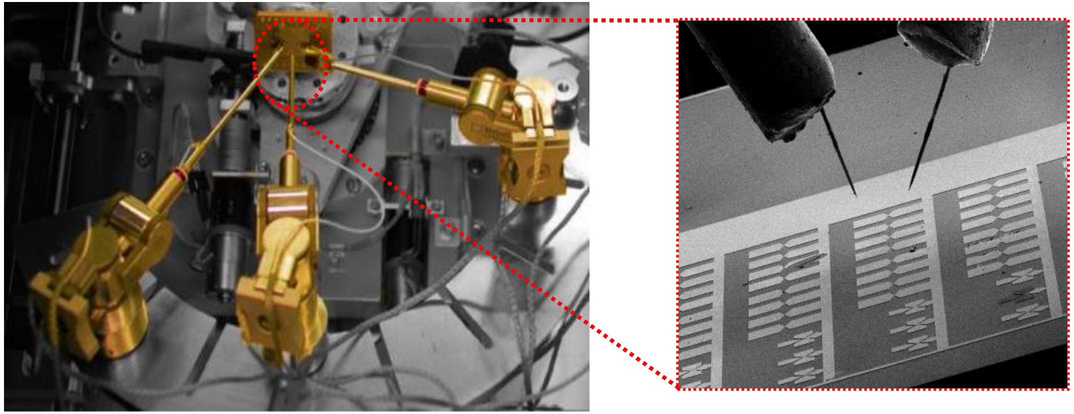
*EBL – Electron Beam Lithography
RIE – Reactive Ion Etching

Characterization

In-Situ Mechanical Characterization



SEM image of freestanding SMA-Si bimorph actuator



Nanomanipulators

Summary

- Temperature homogenization – phase transformation ↑
- Reduction of power consumption by nearly 35 %
- For beam width/length of 2/20 µm variant – deflection ↑ by factor of 2

References

[1] F. Lambrecht, I. Aseguinolaza, V. Chernenko, and M. Kohl. (2016). Integrated SMA-based NEMS actuator for optical switching. IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS). pp. 79–82; doi: 10.1109/MEMSYS.2016.7421562.

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[3] R. Fechner, C. Chlub, E. Quandt, and M. Kohl. (2018) .A Shape Memory Alloy 1×2 Optical Waveguide Switch. IEEE 18th International Conference on Nanotechnology (IEEE-NANO). pp. 1–3; doi: 10.1109/NANO.2018.8626320.

[4]. M. Kohl, M. Schmitt, A. Backen, L. Schultz, B. Krevet, and S. Fähler. (2014). Ni-Mn-Ga shape memory nanoactuation. Applied Physics Letters, vol. 104, no. 4, p. 043111; doi: 10.1063/1.4863667.

Thank you for your attention!

SPP 2206 Cooperative Multistage

Multistable Microactuators Systems

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Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation