SHAPE MEMORY ALLOYS IN THIN STRUCTURES

Doctoral Thesis – Summary

for obtaining the scientific title of Doctor at
Politehnica University of Timișoara
in the doctoral field of **Materials Engineering**

author ing. **BOLOCAN Vlad-Marius**
scientific supervisor Prof.univ.dr.ing. **CRĂCIUNESCU Corneliu Marius**

month **07,** year **2026**

Table of Contents

1. Introduction…… 2
2. Studies on shape memory alloys and their use in microelectromechanical systems……3
3. Studies and research on the use and development of experimental methods employed for the fabrication and characterization of thin structures based on shape memory alloys……7
4. Contributions to the fabrication of shape memory alloy films by magnetron sputtering……11
5. Research on the fabrication of microactuators with shape memory alloy films — modelling and experimental results……15
6. Final conclusions, original contributions and future research directions……29
7. Selected bibliography……33

1. Introduction

Context.

The development of modern technologies has led to a significant increase in interest in materials and structures capable of responding in a controlled manner to external stimuli. The integration of mechanical, electrical and thermal functionalities into miniaturized devices has become a major direction in contemporary research, both in materials engineering and in micro and nanotechnologies. Thin structures and multilayer architectures have acquired an essential role in this context, due to their versatility, miniaturization potential and compatibility with advanced manufacturing processes. Smart materials, particularly those that modify their properties or shape under the action of an external stimulus, represent an especially important category for the design of modern functional systems.

Motivation.

The interest in functional thin structures is driven by the need to obtain materials and devices with high performance, operational stability and the capacity for integration into complex systems. Varying the composition, thickness, deposition sequence or applied treatments allows fine control of the properties of multilayer structures and thin films. At the same time, increasingly strict requirements regarding energy efficiency, precision and reliability call for advanced fabrication and characterization methods. The motivation of the thesis stems from the need to integrate, within a coherent framework, the fabrication processes, characterization methods and predictive models associated with functional thin structures, with the aim of underpinning the development of optimized architectures for advanced applications.

Objectives.

The general objective of the thesis is the investigation of the fabrication, characterization and modelling processes of smart thin cantilever beam structures composed of shape memory alloy films deposited on substrates by sputtering, with the aim of understanding and optimizing their behaviour in simple and multilayer architectures. The specific objectives include: the development and use of experimental methods for film fabrication, commissioning of the necessary equipment, application of appropriate heat treatments, structural, microstructural, compositional and functional characterization of thin structures, analysis of phase transformations by Differential Scanning Calorimetry, development of methods for evaluating electrical and mechanical behaviour, modelling of film-substrate, bimorph and trimorph systems, identification of influencing factors and optimization through compositional variations and multilayer architectures.

Thesis structure.

The thesis is organized into six chapters, following a progression from the analysis of the current state of the field (Chapter 2), through the experimental methods and equipment (Chapter 3), the contributions regarding film fabrication (Chapter 4), the research on simulating the behaviour of shape memory alloy cantilevers deposited on substrates (Chapter 5), to the final conclusions, original contributions and future research directions (Chapter 6).

2. Studies on shape memory alloys and their use in microelectromechanical systems

The chapter presents a synthesis of the specialized literature on microelectromechanical systems, the active materials used in these systems and, in particular, shape memory alloys, with emphasis on the martensitic transformation, on sputtering deposition parameters and on the main directions of application.

Microelectromechanical systems and active materials.

Microelectromechanical systems (MEMS) integrate mechanical, electrical and signal processing components at the micrometer scale, enabling the fabrication of devices with complex functionality and reduced dimensions. Actuation in MEMS can be achieved through various principles — electrostatic, piezoelectric, thermal, magnetic — each with specific advantages and limitations. Shape memory alloys stand out for their high energy density and superior actuation forces compared to other alternatives, which makes them particularly suitable for microactuators requiring large displacements and high loads at reduced dimensions.

Shape memory alloys - general aspects.

Shape memory alloys are materials that, after deformation, return to their original shape upon application of an external thermal stimulus [1]. The one-way shape memory effect, two-way shape memory effect and super elasticity represent the main functional manifestations of these materials [2]. Practical applications exploit either the force generated upon recovery, the displacement produced, or the combination of sensing and actuation, which confers remarkable versatility to shape memory alloys in engineering.

Martensitic transformation.
The functional behaviour of shape memory alloys is governed by the reversible thermoelastic martensitic transformation between the high-temperature phase (austenite, B2 phase) and the low-temperature phase (martensite, B19 or B19’ phases) [3].

The shapes memorized by the material are in fact the shapes it has in the martensitic and austenitic states respectively. The transformation takes place in a different manner compared to the classical martensitic transformation known from steels. In the case of shape memory alloys, the transformation occurs not through the breaking of atomic bonds but through the sliding of atomic layers against each other. A characteristic aspect is that in the case of shape memory alloys the transformation is reversible, which is not possible in the case of steels. The martensite in shape memory alloys may also be referred to as thermoelastic martensite.

By cooling the austenite, twinned martensite is obtained, formed from two martensite variants. An external force will cause the favorably oriented martensite variant to grow in volume relative to the unfavorably oriented variant, resulting in detwinned martensite with a single variant. Detwinned martensite is associated with the deformed material, and the return to the original shape, i.e., to austenite, is achieved by heating (Figure 2-1).

The transformation occurs in two distinct thermal ranges, characterized by four points: Ms (Martensite start) and Mf (Martensite finish) on cooling, and As (Austenite start) and Af (Austenite finish) on heating, as presented in Figure 2-2. The presence of thermal hysteresis, different for NiTi systems compared to NiTiCu, determines the actuation behaviour over complete heating-cooling cycles. The transformation is associated with changes in the thermomechanical, electrical and optical properties of the material, which allows its detection through multiple characterization techniques.

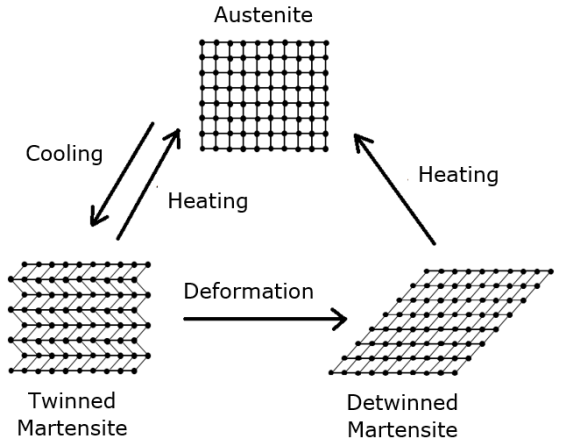


Figure 2-1 Mechanism of the martensitic transformation, adapted from [3].

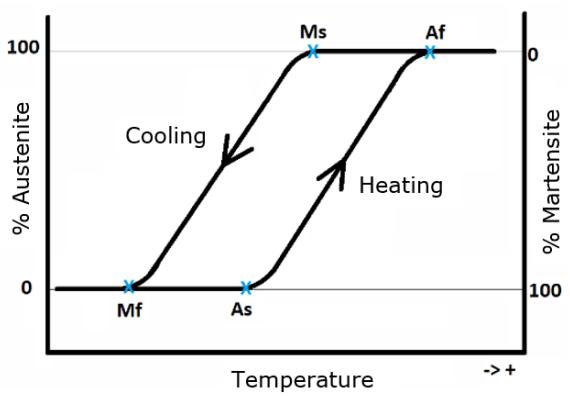


Figure 2-2 Hysteresis and characteristic points of the martensitic transformations.

Applications of shape memory alloys.

The main directions of application concern connectors (controlled interference joints)[4], actuators (generation of thermally controlled displacements), medicine (stents, orthopedic clamps, endoscopic instruments) [5], [6], [7], [8]; precision robotics and MEMS [9], [10], [11]. In the field of microactuators, bimorph cantilever structures with SMA film deposited on a rigid substrate [12] represent the most frequently studied configuration, due to the simplicity of fabrication and the predictability of the actuation behaviour. Multilayer architectures extend the possibilities for actuation control, enabling the generation of successive plateaus or sequential actuation over extended thermal ranges.

Obtaining films by plasma sputtering deposition technique.

Sputtering is a process of bombardment and ejection of atoms from a source material by ions of an inert gas and their deposition onto a substrate. The process takes place inside the evacuated chamber of the sputtering equipment, which contains the anode and cathode of an electrical circuit. The substrate onto which the film is to be deposited is mounted on the anode, while the source material is mounted on the cathode. An inert gas, typically Ar, is introduced into the chamber, with the role of sustaining the sputtering process (Figure 2-3 a). Once the cathode is negatively charged, all free electrons in the chamber are accelerated away from it and in their path collide with Ar atoms. As a result of the collision, the Ar atom loses an electron and becomes a positive ion (Figure 2-3 b), which will be strongly attracted towards the cathode (Figure 2-3 c), where, once again, a collision will take place, but this time with the source material from which atoms will be ejected (Figure 2-3 d). The ejected atoms will travel through the chamber towards the anode and will be deposited onto the substrate (Figure 2-3 e). The free electrons find their way to rejoin the Ar ions, at which point the latter become atoms once again and

release the energy gained from electron recapture in the form of photons (Figure 2-3 f), this being the reason why the chamber is "illuminated" during sputtering (Figure 2-3 g).

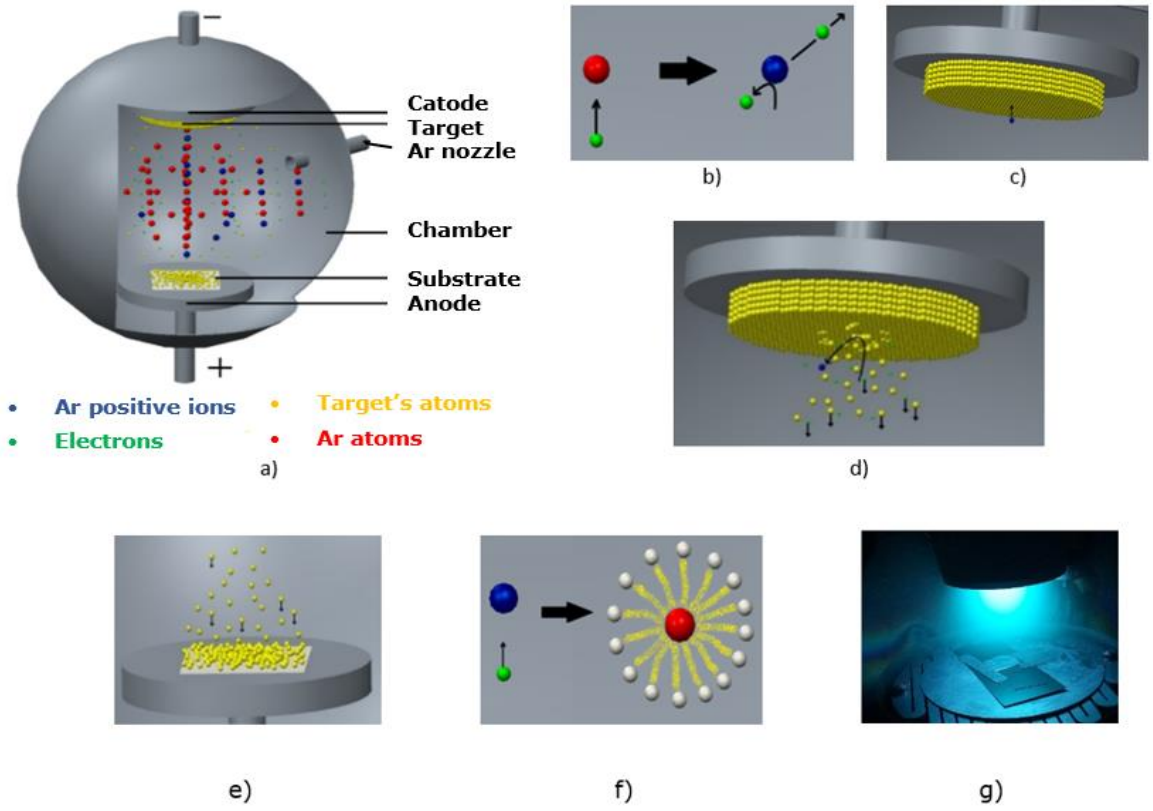


Figure 2-3 General sputtering process.

Deposition parameters and their influence.

Magnetron sputtering deposition allows the obtainment of thin films with controllable thicknesses, compositions and microstructures through variation of the process parameters: sputtering power [13], working gas pressure [14] or substrate temperature. The deposition temperature [15], [16] decisively influences the degree of crystallinity of the films and, through this, the transformation temperatures and functional properties. Deposition at low temperatures produces amorphous or partially crystalline films, which require subsequent heat treatment to activate the martensitic transformation.

Applications of SMA films

SMA thin films find application in several categories of devices, a selection of applications being presented below through examples from the specialized literature.

- Microsensors. The thermally activated phase transformation produces changes in SMA properties — light reflectance, electrical resistivity — which can serve as input signals in logic control systems.
- Micropumps and microvalves. The difference between the "hot" shape and the "cold" shape of the film allows the design of elements that obstruct an orifice in one state and

release it in the other. The films can also function as membranes which, mounted over a cavity, pump or draw in a fluid depending on the direction of concavity (**Error! Reference source not found.**).

- Microgrippers. They operate on the basis of two states (open/closed) corresponding to the cold shape and the hot shape respectively (Figure 2-5). SMA properties can be exploited directly, with the gripper made entirely from active material, or indirectly, through mechanisms actuated by SMA.

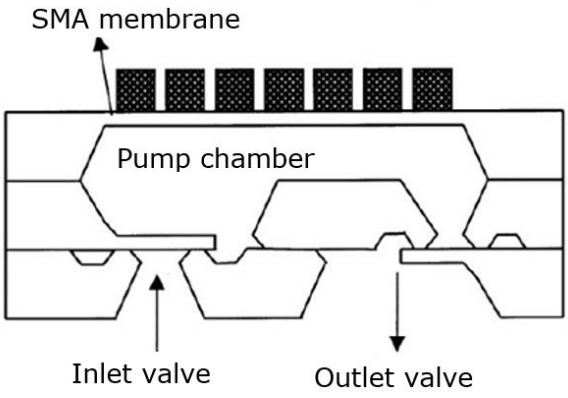


Figure 2-4 Operating principle of a micropump. Adapted from [17], with permission from Elsevier.

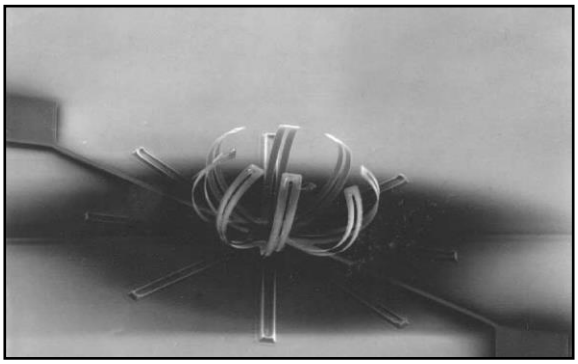


Figure 2-5. SMA microwrapper [10], reproduced with permission from Elsevier.

Chapter conclusions.

The analysis of the specialized literature has shown that shape memory alloys represent the material of choice for MEMS microactuators requiring large forces and displacements. The deposition temperature and alloy composition are the factors with the greatest impact on the functional properties of thin films, while multilayer architectures open significant prospects for the control of the actuation profile.
The applications of SMA thin films (microsensors, micro-switches, micropumps, microvalves, microgrippers and microelectrodes for the acquisition of neurological signals) illustrate the versatility of these structures and confirm their relevance for integration into complex functional systems at the micrometer scale.

These conclusions underpinned the experimental and modelling directions addressed in the following chapters.

3. Studies and research on the use and development of experimental methods employed for the fabrication and characterization of thin structures based on shape memory alloys

The chapter describes the experimental infrastructure used in the thesis, the methods for thin film fabrication and the structural, microstructural, thermal and functional characterization techniques applied.

The fabrication and characterization of thin structures based on shape memory alloys requires following a well-defined methodological chain, in which each stage conditions the quality and interpretability of the subsequent results. From the selection and preparation of substrates, continuing with the deposition of films under controlled conditions and through to their structural, compositional and functional characterization, each step involves specific equipment and methods whose particularities must be known and mastered. The logical diagram presented in Figure 3-1 summarizes this methodological sequence, highlighting the connections between stages and the role of each one within the research process.

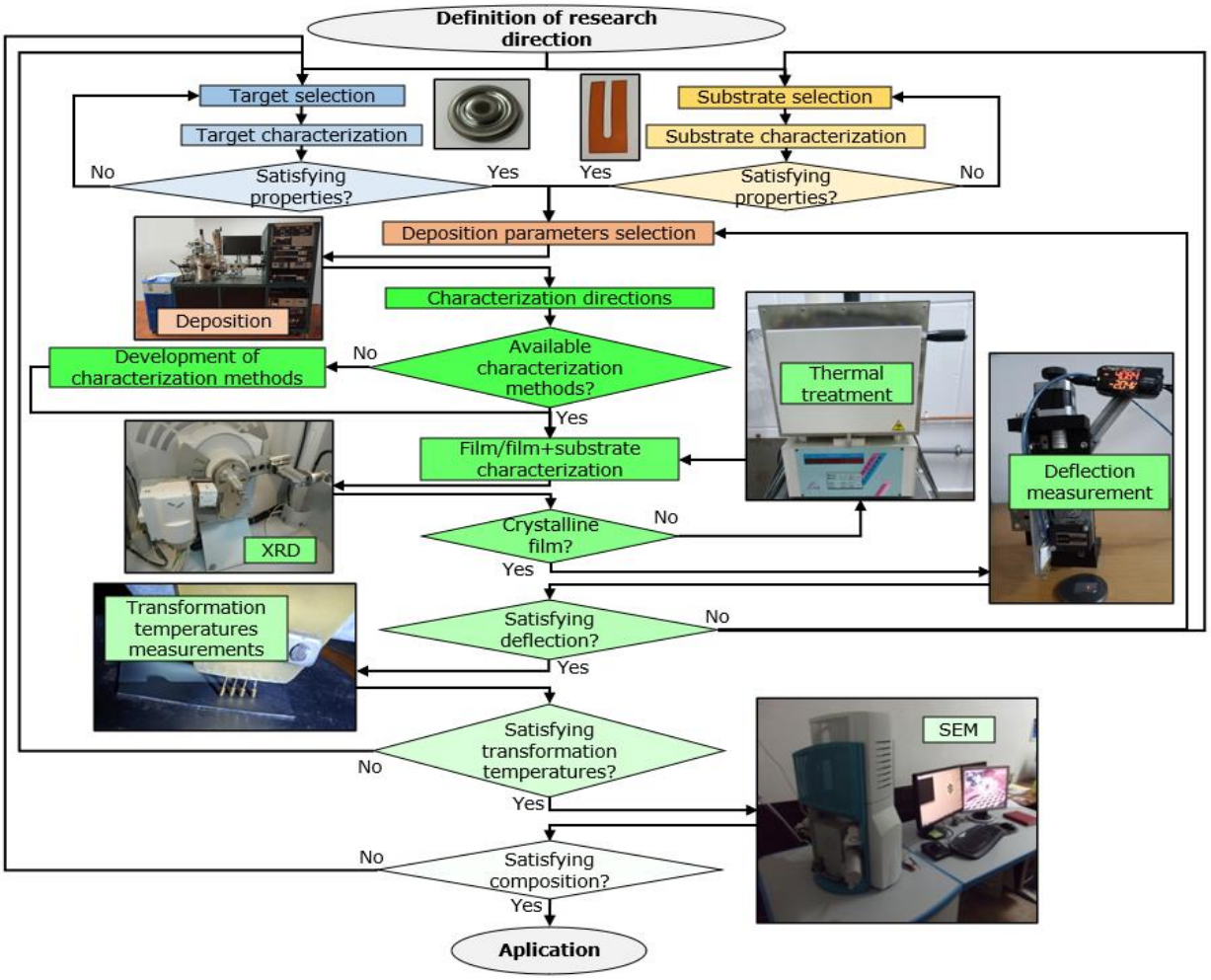


Figure 3-1 Logical diagram applied in the concept-fabrication-characterization process of the films.

Thin film deposition by magnetron sputtering.

The thin films were fabricated by magnetron sputtering. Two pieces of equipment were used: a system built within the Department of Materials and Manufacturing Engineering at Politehnica University of Timișoara (UPT) (Figure 3-2) and a commercial AJA International ORION 8 system (Figure 3-3), equipped with four sputtering guns and automated substrate temperature control. The main deposition parameters: the power applied to the target, the working gas pressure (argon), the substrate temperature and the deposition time were systematically controlled and varied in order to investigate their influence on the properties of the obtained films.



Figure 3-2 DC Magnetron sputtering equipment.

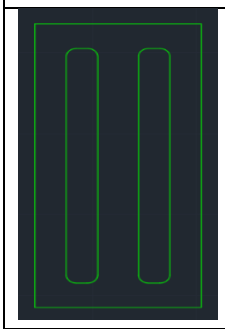
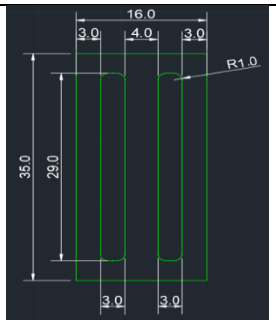
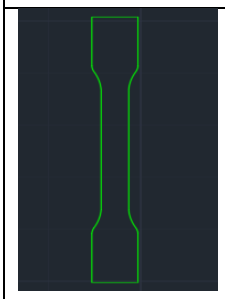
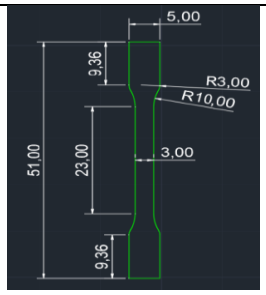
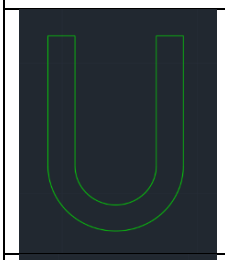
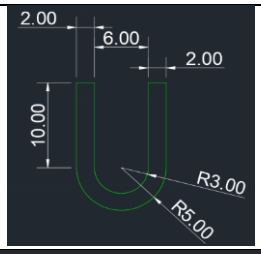
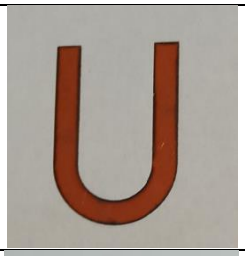
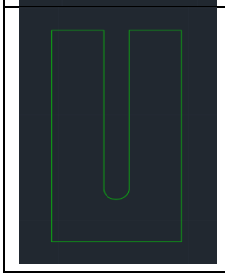
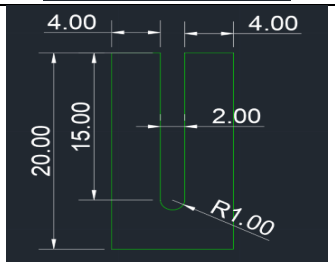
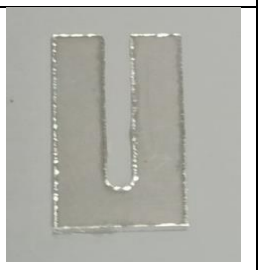


Figure 3-3 ORION 8 DC Magnetron sputtering equipment.

Substrate preparation.

The substrates used were made of silicon (Si), polyimide (Kapton), Upilex, Mo, Mica, glass and others. The cutting of substrates (Kapton, mica and other materials suitable for a low-power laser) to the desired dimensions was carried out using the Trumpf TruMark Station 5000 laser marking and cutting equipment, fitted with a Trumpf TruMark 3230 laser with a power of 7W and a wavelength of λ=532 nm (Green LASER), focal spot diameter dr=24 µm, focal length f=160 mm, working distance A=212 mm, objective height B=36 mm, objective diameter C=91.4 mm, marking field D x D=110 mm x 110 mm, and uses an F-Theta lens and a vacuum table for workpiece fixation. In Table 3-1 some substrates cut by this method are presented.

Table 3-1 Examples of LASER-cut substrates.

Model	Sketch	Kapton	Mica
			-
			
			-
			

Structural characterization by X-ray diffraction.

The structural analysis of the films and target materials was carried out by X-ray diffraction (XRD), using the PANAlytical X'Pert³ diffractometer. The obtained diffractograms allowed the identification of the crystalline phases present — the body-centered cubic B2 phase (austenite), the monoclinic martensite B19' and the orthorhombic martensite B19 — and the evaluation of the degree of crystallinity of the deposited films. The interpretation of the diffractograms was supported by simulations performed with the VESTA crystal structure visualization and analysis software.

Microstructural and compositional characterization.

The microstructure and chemical composition of the films and target materials were investigated by scanning electron microscopy (SEM), using the Tescan Vega 3LM microscope. Quantitative compositional analysis was carried out by Energy Dispersive X-ray Spectroscopy (EDX), using the Bruker

Quantax 200 system integrated into the electron microscope. The electron microscopy images allowed the identification of grain morphology, growth mechanisms and local compositional variations.

Differential Scanning Calorimetry.

The characteristic temperatures of the martensitic transformation — the start and finish temperatures on cooling (Ms and Mf) and on heating (As and Af) — were determined by Differential Scanning Calorimetry (DSC), using the Perkin-Elmer DSC 7 equipment. The measurements were carried out over complete heating and cooling cycles, also allowing the extraction of the martensite fraction profile m(θ) as a function of temperature, subsequently used in the actuation models.

Profilometry.

The thickness of the deposited films was determined by contact profilometry, on stepped samples obtained by partial masking of the substrate during deposition. The profilometer provided quantitative data on film uniformity and on the deposition rate under the experimental conditions used.

Development of the integrated functional characterization system.

An essential infrastructural contribution of the thesis is the development and validation of an integrated system (Figure 3-4) that allows the recording of two functional quantities as a function of temperature: electrical resistivity, by the four-point probe method, and the deflection of the free end of the cantilever, by the OMRON ZX2-LD50 point laser sensor. The sample temperature is controlled by Peltier effect modules, and the data are acquired by computer. The system allows the detection of phase transformations based on resistivity variation and the simultaneous quantification of the thermomechanical actuation capacity, offering the possibility of direct comparison with the predictions of the models developed in the thesis.



Figure 3-4 Device for measuring deflection and electrical resistivity in films deposited on substrate.

Chapter conclusions.

The experimental infrastructure commissioned covers the entire chain from film deposition through to their structural, microstructural, thermal and functional characterization. The integrated functional characterization system represents an original tool, validated on multiple film-substrate configurations, which underpinned all the experiments carried out.

4. Contributions to the fabrication of shape memory alloy films by magnetron sputtering

The chapter presents the compositional, microstructural and structural characterization of the target materials used in sputtering and of the thin films obtained from them, together with the analysis of the phase transformations identified in the films.

Characterization of shape memory alloy targets.

The most frequently used target materials were alloys from the Nickel-Titanium (Ni-Ti) family, in titanium-rich and nickel-rich variants respectively, including a superelastic variant, and a target from the Titanium-Nickel-Copper (Ti-Ni-Cu) family.

Ti-rich NiTi target. X-ray diffraction analysis confirmed the presence of monoclinic B19' martensite through the succession of peaks located around 2θ = 40° (Figure 4-1). Scanning electron microscopy analysis revealed the microstructural aspects of the surface topography, with identification of martensite variants in two distinct zones of the target surface.

Ni-rich NiTi target. Compositional analysis of the Ni-rich NiTi target shows a composition characteristic of the austenitic state. X-ray diffraction analysis reveals predominantly the austenitic peak characteristic of the B2 crystal structure (Figure 4-2), confirmed as the dominant phase in this target.

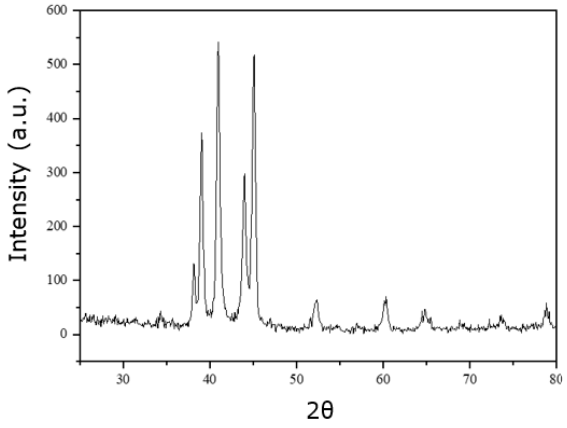


Figure 4-1 X-ray diffraction analysis of the Ti-rich NiTi target in the martensitic state.

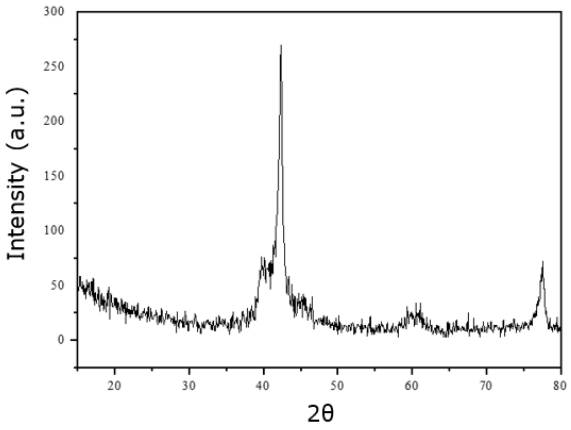


Figure 4-2 X-ray diffraction analysis of the Ni-rich NiTi target in the austenitic state.

TiNiCu target. The microstructure of TiNiCu alloys is influenced by composition; since the substitution of Ni by Cu can occur over a wider compositional range, the segregation of secondary phases is not uncommon. The transformation temperatures of these alloys are more stable with respect to the Ni/Cu composition compared to the NiTi system, where the Ni/Ti ratio has a much more pronounced effect. The microstructure of the TiNiCu target exhibits polyhedral grains individualized by well-defined boundaries, with dimensions ranging between 40 and 60 µm. Ti-rich precipitates are identified, and EDX compositional analysis shows significant

variations between grains and grain boundaries Figure 4-3. X-ray diffraction recorded at high temperature reveals the presence of the austenitic B2 phase (Figure 4-4).

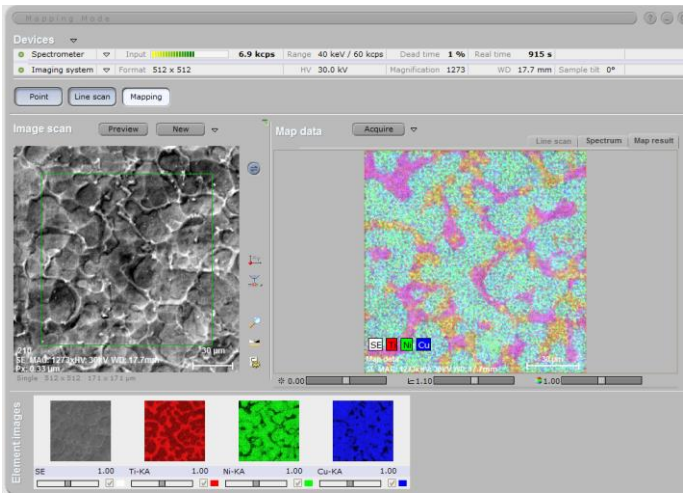


Figure 4-3 Microstructure and compositional map of the Ti-Ni-Cu target.

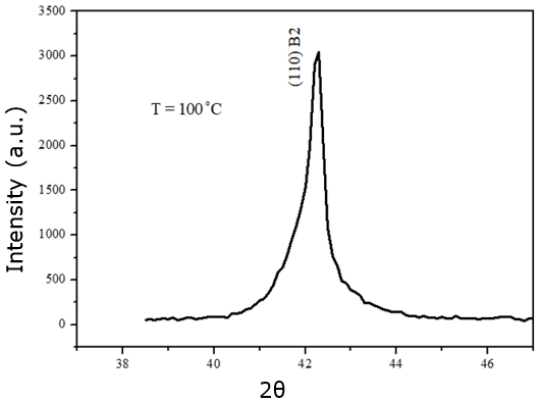


Figure 4-4 XRD analysis of the Ti-Ni-Cu target.

Characterization of targets after use in sputtering.

Repeated use of the targets in the magnetron sputtering process produces characteristic annular erosion patterns, specific to the geometry of the magnetic field, visible on the surface of all investigated targets. The annular zone with maximum erosion shows a higher Ti concentration compared to the nominal composition (Figure 4-5). This compositional redistribution has direct consequences on the stoichiometry of the deposited films and, consequently, on the transformation temperatures of the films. The practical conclusion is that the film stoichiometry does not always correspond to the nominal composition of the target and that compositional variations between film batches can be partly attributed to the progressive wear of the target.

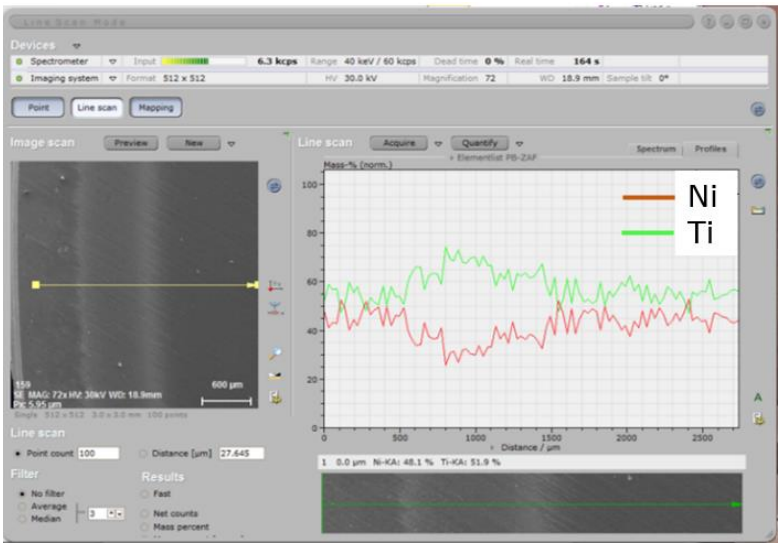


Figure 4-5 Compositional analysis of the superelastic NiTi target.

Compositional analysis of the deposited films.

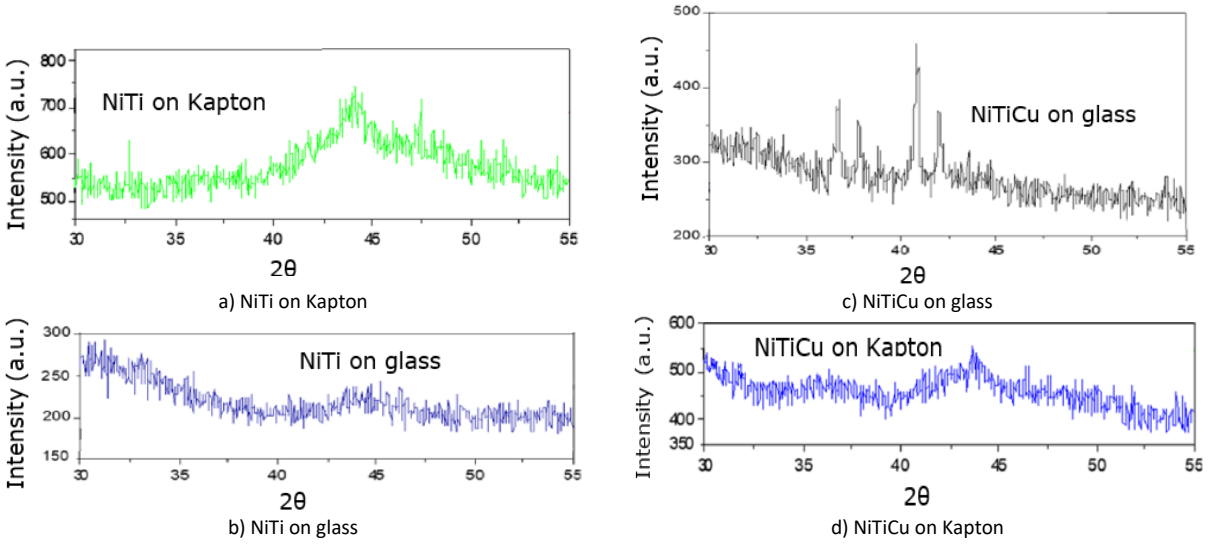
The composition of the TiNiCu films was determined by EDX analysis and compared with that of the corresponding target materials. A systematic decrease in Ti content in the film relative to the target was observed, associated with the different sputtering yield of the constituent elements (Table 4-1).

Table 4-1 Comparative analysis of the composition of the Ti-Ni-Cu target and film.

Element	Ti		Ni		Cu	
	at%	wt%	at%	wt%	at%	wt%
Target	59.32	53.65	26.77	29.64	13.91	16.71
Film	52.28	46.58	33.34	36.41	14.38	17.01

Structural characterization by X-ray diffraction of the deposited films.

Structural analysis by X-ray diffraction, carried out using the PANAlytical X'Pert³ MRD equipment in the UPT laboratory, showed that the degree of crystallinity depends on the type and composition of the substrate. NiTi films deposited on Kapton (Figure 4-6 a) or glass (Figure 4-6 b) showed no peaks characteristic of the martensitic transformation either on heating or on cooling. In contrast, NiTiCu films deposited on glass (Figure 4-6 c) clearly exhibited martensitic peaks, while for films deposited on Kapton (Figure 4-6 d) the phase transformation was not as evident, with only partial crystallization being observed.



a) NiTi on Kapton
c) NiTiCu on glass
b) NiTi on glass
d) NiTiCu on Kapton

Figure 4-6 XRD analysis of films deposited on glass and Kapton.

Microstructure of the deposited films.

The growth of films deposited by sputtering results in the formation of a dense structure, whose cross-sectional morphology is revealed in the form of columnar grains (Figure 4-7).

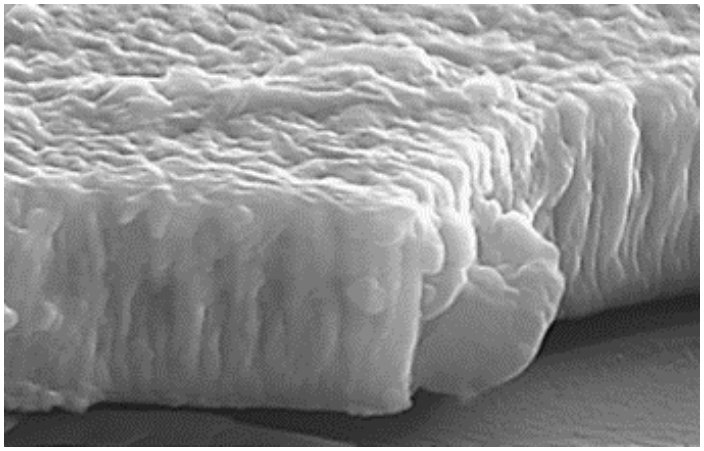


Figure 4-7 Columnar grains of films deposited on substrate.

Chapter conclusions.

The microstructural and compositional characterization of the targets and deposited films revealed a series of particularities determined by the nature of the alloy, the deposition parameters and the interaction between the film and the substrate. The analysis of the phases present, the surface morphology and the growth mechanisms allowed the correlation of the processing conditions with the structural properties of the obtained films, providing essential information for understanding their functional behaviour in the studied architectures. The main observations are summarized below:

- The Ti-rich NiTi target showed a B19' martensitic structure, confirmed by XRD and DSC.
- The Ni-rich NiTi target proved to be austenitic, with the B2 phase stable at ambient temperature.
- The Ti-Ni-Cu target exhibited well-defined polyhedral grains, but with compositional variations at the boundaries and Ti-rich segregations.
- After magnetron sputtering, the targets underwent annular erosion and local compositional changes, leading to stoichiometry differences in the films.
- The deposited films remained amorphous at low temperatures, but crystallized at elevated temperatures, revealing the B2, B19 and B19' phases.

5. Research on the fabrication of microactuators with shape memory alloy films — modelling and experimental results

The chapter constitutes the core of the original contributions and brings together eight published studies on the modelling, optimization and experimental characterization of cantilever-type microactuators with shape memory alloy (SMA) films, as well as other unpublished experiments and research, organized in subsections corresponding to each paper.

Establishing the influencing factors.

The research presents the alloy composition and the thickness of the active film as factors influencing the actuation behaviour of bimorph structures. The variation of these two factors is considered while keeping the substrate thickness and material, the deposition temperature and the cantilever length fixed. On the basis of the parametric analysis, it was established that the variation of the deposited film thickness or the alloy composition plays an important role in actuator design, showing that small variations in Ni content (between 48% and 51%) lead to visible differences in the position of the transformation range and in the deflection amplitude, with the critical range being 50–51% Ni: here the largest differences in actuation temperature and deflection occur, which confirms the high sensitivity of the material to compositional refinement. The film thickness (df) influences the deflection amplitude, but the general trend remains the same: the curves show a sharp increase in the martensite–austenite transformation zone. The graphical results are presented below in Figure 5-1, Figure 5-2 and Figure 5-3.

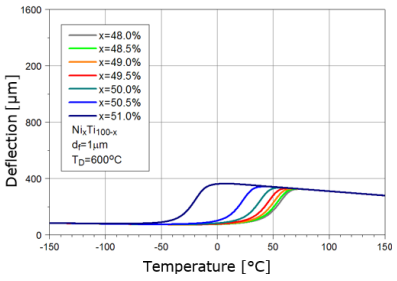


Figure 5-1 Influence of composition (x) on the transformation temperature for df=1µm.

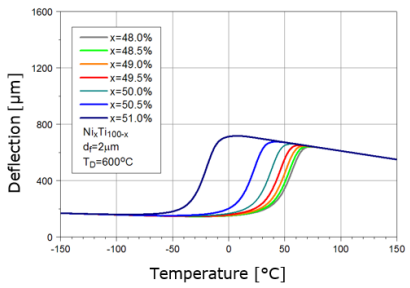


Figure 5-2 Influence of composition (x) on the transformation temperature for df=2µm.

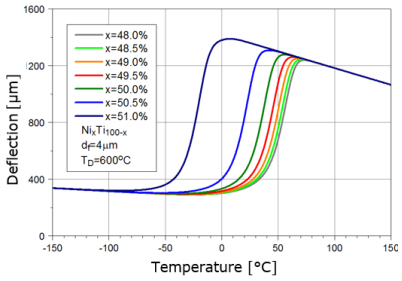
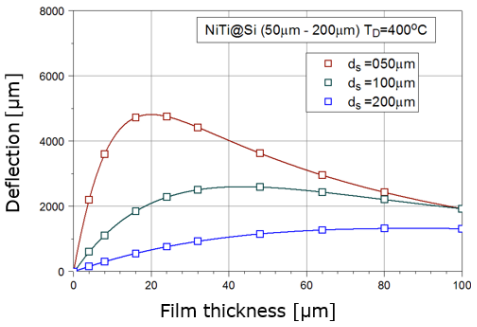


Figure 5-3 Influence of composition (x) on the transformation temperature for df=4µm.

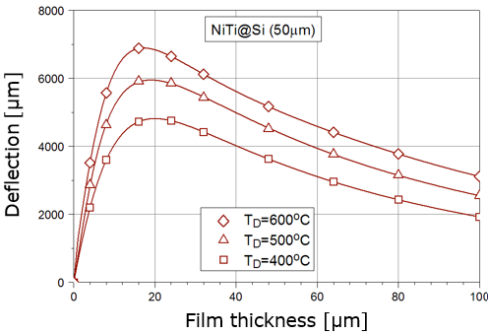
Optimization of the exploration system for extending innovative research.

This research presents a systematic parametric analysis of the factors influencing the deflection amplitude of NiTi bimorph cantilevers on silicon (Si) substrates, carried out through series of numerical modelling. The varied parameters were: substrate thickness (ds = 50, 100 and 200 µm), deposited active film thickness (df), deposition temperature (TD = 400, 500 and 600°C) and cantilever length (L = 1–25 mm). Four main conclusions emerged from the analysis of the obtained results. Firstly, the deposition temperature directly influences the deflection amplitude: films deposited at 600°C produce larger maximum deflections compared to those deposited at 400°C, the effect being more pronounced for thinner substrates. Secondly, there is an optimal film thickness at which the deflection reaches a maximum; further increase in thickness stiffens the structure and diminishes the actuation effect.

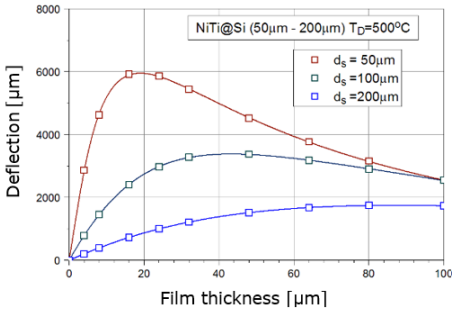
Thirdly, thinner substrates (50 µm) allow larger deflection amplitudes compared to thick substrates (200 µm), which limit the deformation. The results are represented graphically in Figure 5-4.



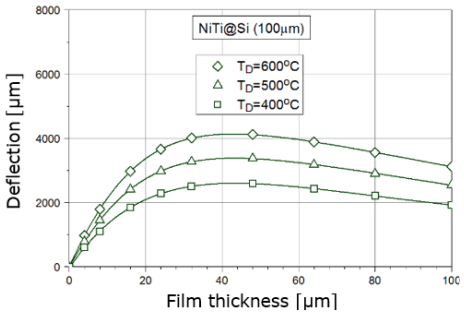
a) Influence of substrate thickness on deflection for films deposited at TD=400°C.



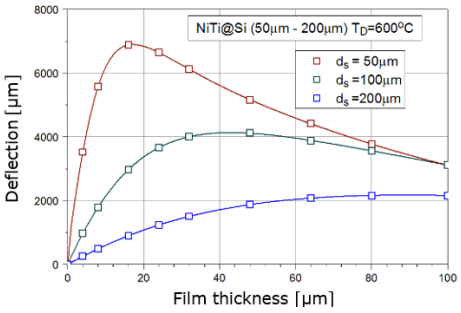
b) Influence of deposition temperature on deflection for films deposited on substrate with ds=50µm.



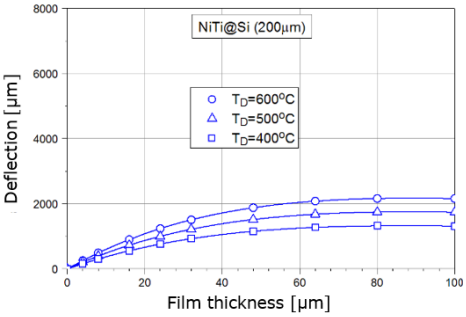
c) Influence of substrate thickness on deflection for films deposited at TD=500°C.



d) Influence of deposition temperature on deflection for films deposited on substrate with ds=100µm.



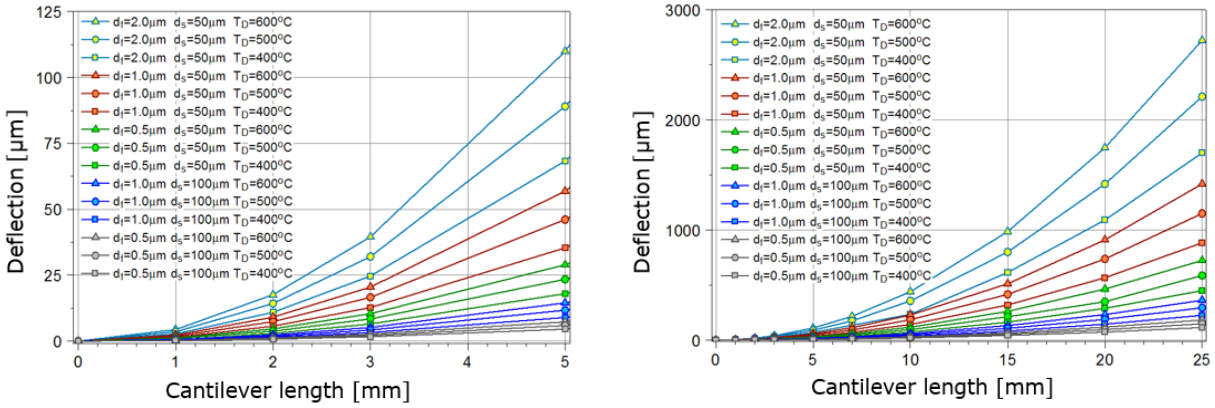
e) Influence of substrate thickness on deflection for films deposited at TD=600°C.



f) Influence of deposition temperature on deflection for films deposited on substrate with ds=200µm.

Figure 5-4 Influence of film thickness, substrate thickness and deposition temperature on the deflection amplitude during the martensitic transformation.

Fourthly, the deflection amplitude increases with cantilever length, as shown in Figure 5-5, where it can be observed that regardless of the deposition temperature, film thickness or substrate thickness, an increase in length leads to an increase in deflection.



a) For cantilever lengths ranging between 0 and 5 mm.

b) For cantilever lengths ranging between 0 and 25 mm.

Figure 5-5 Dependence of the deflection amplitude during the martensitic transformation on different film thicknesses, different substrate thicknesses and different deposition temperatures.

The models constructed in this stage, developed for the NiTi system but adaptable to any alloy system by modifying the input data, lay the foundations for the systematic investigation of the actuation capacity as a function of composition and deposition parameters.

Material optimization through thin film compositional spreads.

The paper introduces the methodology of compositional libraries realized by simultaneous sputtering from elemental targets, which allows the rapid exploration of a large number of compositions within a single deposition process. The method was applied to the Titanium-Niobium (Ti-Nb) and Titanium-Niobium-Platinum (Ti-Nb-Pt) systems. In the case of the TiNb system, the compositional distribution over a length of 90 mm allows the identification of compositionally unique points, starting from an approximate Ti:Nb ratio of 9:1 and ending with a ratio of approximately 1:9 (Figure 5-6). Figure 5-7 shows a mini-library of the TiNbPt system whose electrical resistivity is directly influenced by the elemental ratio.

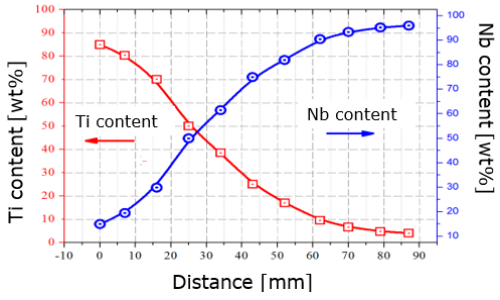


Figure 5-6 Graphical representation of the Nb and Ti distribution.

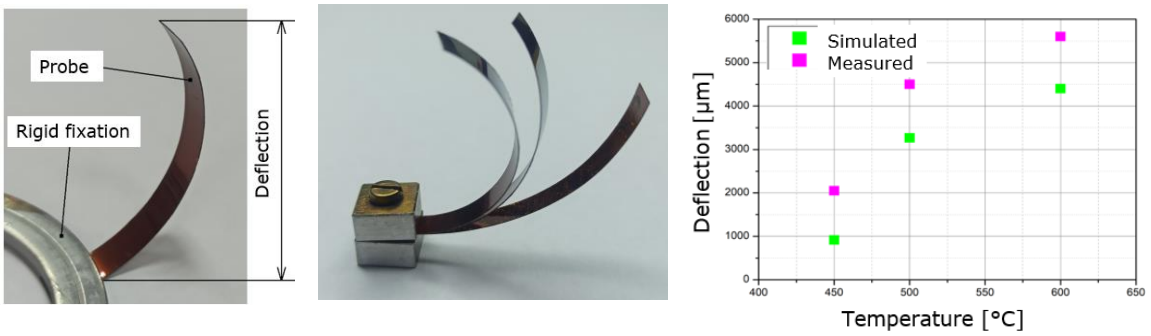
Ti gradient [wt%]	2,31	3,8	6,38	8,41	18,44
Nb gradient [wt%]	8,63	10,56	18,61	27,25	38,81
Pt gradient [wt%]	89,06	85,64	75,01	64,35	42,75
Resistance [Ω]	0,0493	0,0385	0,035	0,0474	0,0633

Figure 5-7 Mini-library in the Ti-Nb-Pt system.

Experimental validation of the prediction model.

The actuation model was validated by comparing the predictions with measurements carried out on physical samples: bimorph cantilevers with Ni-Ti alloy films deposited on polyimide (Kapton) substrates at temperatures of 450, 500 and 600°C (Figure 5-8). The close agreement obtained between the

simulated and measured values confirms the applicability of the model for microactuator design and significantly reduces the experimental effort required for optimization.



a) method of measuring deflection on the sample.

b) presentation of the three measured samples.

c) comparative graph between the measured and modelled values.

Figure 5-8 Comparison of measured and modelled deflection.

Micro-actuation systems based on phase transformation films. [18]

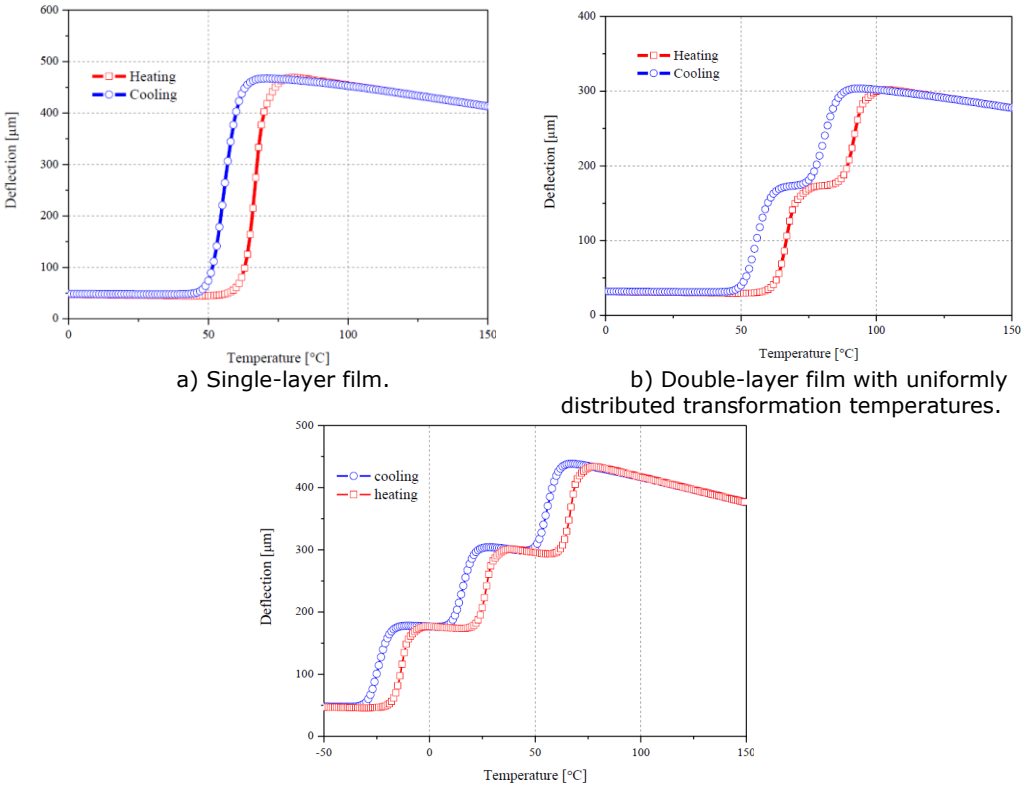
The paper synthesizes the design principles of bimorph microactuators with shape memory alloy films. Once the austenitic films begin to transform into martensite, a variation in the deflection of the free end of the cantilever occurs. The deposition temperature significantly influences the deflection amplitude, with films deposited at elevated temperatures generating larger variations compared to those deposited at room temperature. Varying the composition of the Ti-Ni alloy allows control of the thermal position of the transformation range, offering the possibility of adapting the actuation to specific temperature domains. The modelling results demonstrate the importance of the thermoelastic properties of the film in generating actuation in cantilever-type microactuators based on shape memory alloy films.

Actuation based on phase transformations in microlayered architectures. [19]

The paper extends the analysis from single-layer structures to bi-layer and tri-layer architectures with different transformation temperatures. Using the parameters from Table 5-1, deflection behaviour modelling was carried out for multilayer actuators and it was demonstrated that through the design of the layering, distinct actuation plateaus or sequential actuation distributed over extended thermal ranges can be generated (Figure 5-9).

Table 5-1 Parameters of the NiTi/Si cantilever-type microactuators used in the simulation, considering that the deposition was carried out at the same temperature for all films.

Cantilever	Substrate thickness [µm]	Layer 1		Layer 2		Layer 3		Figure
		Thickness [µm]	Ms [°C]	Thickness [µm]	Ms [°C]	Thickness [µm]	Ms [°C]	
Single-layer	100	1	60	-	-	-	-	Figure 5 9 a
Double-layer	100	0.5	60	0.5	80	-	-	Figure 5 9 b
Triple-layer	100	0.333	60	0.333	20	0.333	-20	Figure 5 9 c



a) Single-layer film.

b) Double-layer film with uniformly distributed transformation temperatures.

c) Triple-layer film with uniformly distributed transformation temperatures.

Figure 5-9 Deflection–temperature simulations for bimorph structures with shape memory alloy film deposited on a non-transforming substrate.

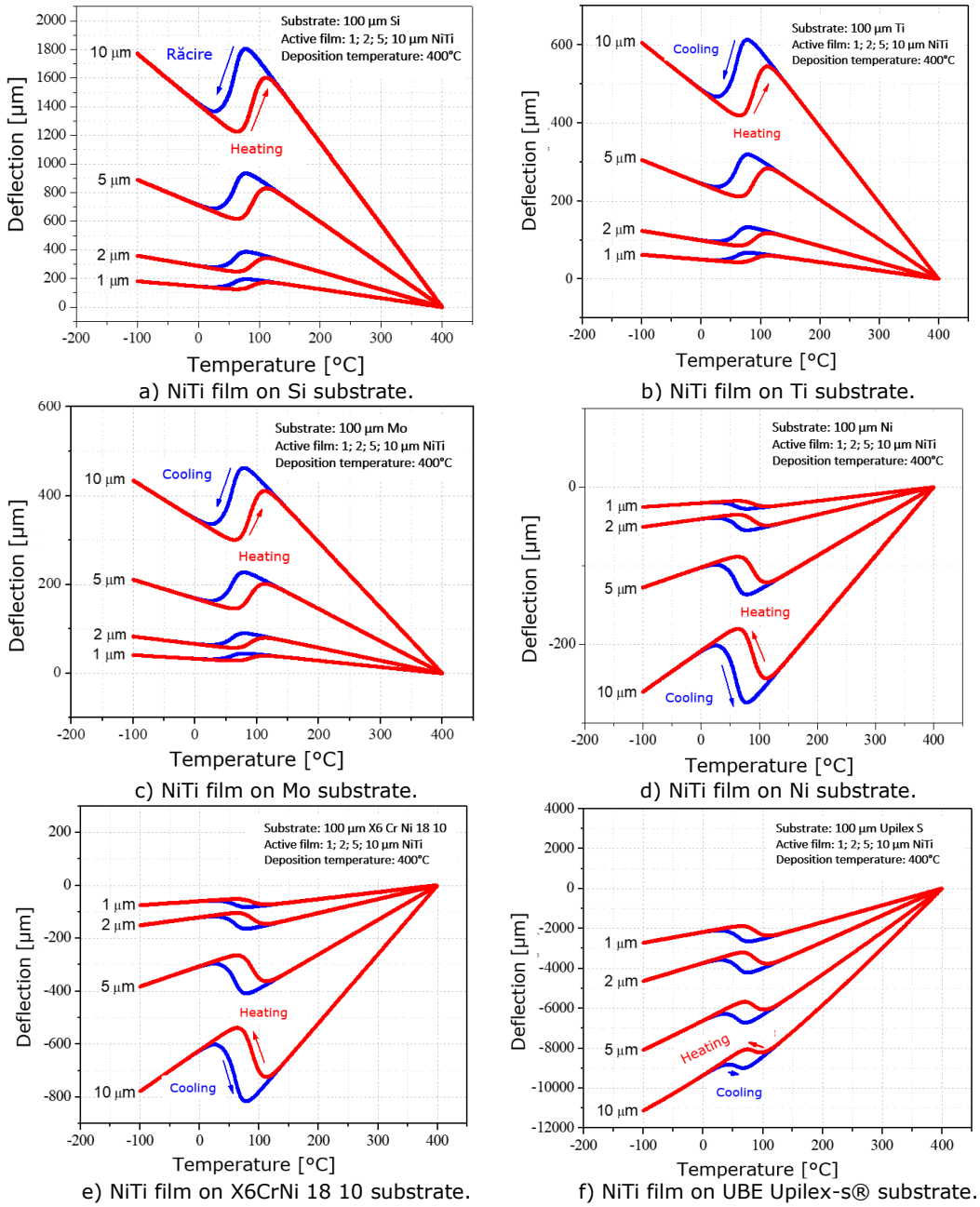
Study of the influence of substrate characteristics on the deflection of bimorph actuators. [20]

The paper systematically investigates the influence of the thermoelastic properties of the substrate — Young's modulus and the coefficient of thermal expansion — on the thermal deflection of bimorph cantilevers with Ni-Ti film, with the aim of maximizing the actuation amplitude through appropriate selection of the substrate material.
For the purposes of modelling, a bimorph cantilever-type actuator with the following characteristics was defined: 20 mm length, 100 µm substrate thickness and 4 mm width, with the deposition temperature considered to be 400°C. In order to analyze the optimizations for a specific micro-actuation application, the influence of thermoelastic properties on actuation was studied for several cases, such as:

- Thermal expansion coefficient of the SMA film smaller than that of the substrate (αSMA<αS). NiTi film deposited on Si or polyimide substrate.
- Thermal expansion coefficient of the SMA film equal to that of the substrate (αSMA≈αS). NiTi film deposited on Ti and Ni substrate.
- Thermal expansion coefficient of the SMA film greater than that of the substrate (αSMA>αS). NiTi film deposited on stainless steel 304 or Mo substrate.

The results obtained from the modelling are presented in Figure 5-10. As expected, a steady increase in actuation during the phase transformation is observed with increasing NiTi film thickness. The magnitude of the deflection is also influenced by the mismatch between the thermoelastic constants of the SMA film and the substrate.

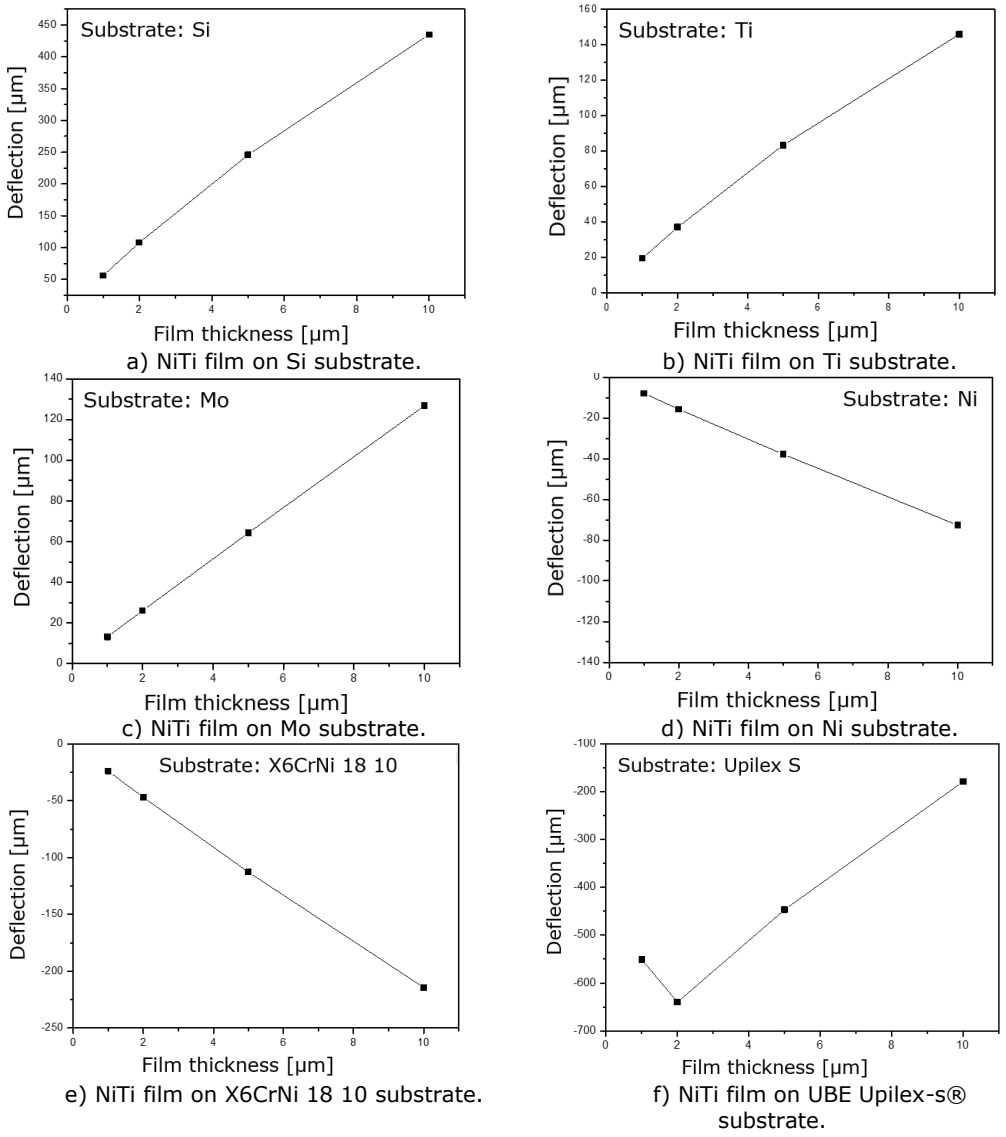
The film deposited at 400°C on a Si substrate exhibits significantly greater actuation compared to that deposited at the same temperature on a Ti substrate, while the film deposited on Mo is in a range close to that deposited on Ti. The difference between the thermoelastic parameters of Si and those of NiTi is the largest, whereas the difference between those of Ti and those of NiTi is the smallest.
In the case of actuators with a substrate having a thermal expansion coefficient greater than that of the film, the deflection will be achieved by displacement of the cantilever tip towards the film. In the case where the thermal expansion coefficient is greater in the film than in the substrate, the cantilever tip will be displaced towards the substrate.



a) NiTi film on Si substrate.
b) NiTi film on Ti substrate.
c) NiTi film on Mo substrate.
d) NiTi film on Ni substrate.
e) NiTi film on X6CrNi 18 10 substrate.
f) NiTi film on UBE Upilex-s® substrate.

Figure 5-10. Modelling of deflection for NiTi films deposited at 400°C in thicknesses of 1, 2, 5, 10 µm on substrates of 100 µm thickness.

From the modelling results presented in Figure 5-10, information regarding the maximum deflection of each cantilever type as a function of the deposited film thickness can be extracted. Thus, Figure 5-11 presents the maximum deflection values of the previously presented cantilevers as a function of the film thickness deposited on each substrate type.



a) NiTi film on Si substrate.
b) NiTi film on Ti substrate.
c) NiTi film on Mo substrate.
d) NiTi film on Ni substrate.
e) NiTi film on X6CrNi 18 10 substrate.
f) NiTi film on UBE Upilex-s® substrate.

Figure 5-11 Maximum deflection for the modelling of cantilevers with NiTi films deposited at 400°C in thicknesses of 1, 2, 5, 10 µm on substrates of 100 µm thickness.

The results show that the selection of the substrate material is a design tool just as important as the composition of the active film (Figure 5-12). The Upilex substrate exhibits a special behaviour: the large difference between the elastic modulus of the film and that of the substrate leads to twisting of the cantilever at large deflections, apparently reversing the direction of deflection (Figure 5-13). The transition from a Si substrate to a Kapton substrate results in a reversal of the direction of curvature, a phenomenon confirmed both experimentally and through modelling.

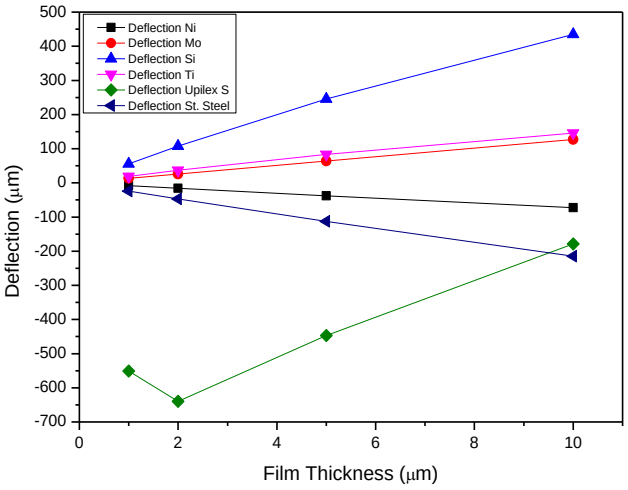


Figure 5-12. Comparative graph of maximum deflections for different substrate materials and deposited film thicknesses.

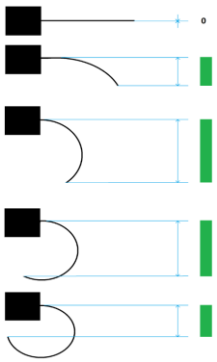


Figure 5-13 Specific deflection behaviour for a bimorph cantilever with Es<<Ef.

Design of shape memory micro-actuator modules with sequential actuation. [21]

The paper proposes and analyses, through modelling, the concept of microactuator blocks with sequential actuation, composed of cantilevers with Ni-Ti films having a Ni content ranging between 48.5% and 51%. As presented in Figure 5-14, each of the 6 cantilevers in the block has a NiTi film deposited with a Ni content of 48.5%, 49.0%, 49.5%, 50.0%, 50.5% and 51.0% respectively; the film thickness is 1.2 μm, the substrate is considered to be Si with a thickness of 100 μm, and the cantilever dimensions are 20 mm length and 4 mm width. The deposition temperature of the films on the substrate is also considered to be 500°C. A first conclusion is that the characteristic temperatures — As, Af, Ms, Mf — are directly influenced by the Ni content of the deposited film. Figure 5-15 shows the influence of Ni content on the phase transformation temperatures. For films with a Ni content of 48.5%, 49.0% and 49.5%, the temperatures differ very little, whereas for films with 50.0%, 50.5% and 51.0% Ni content, the differences begin to increase.

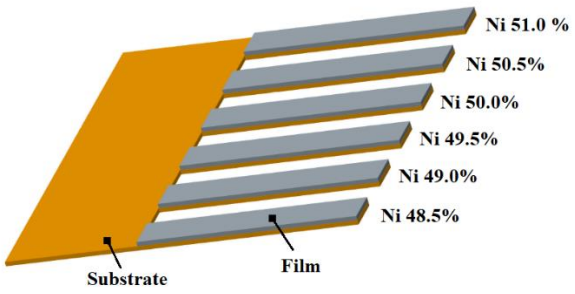


Figure 5-14 Modelled actuator block [21] – V. Bolocan-coauthor.

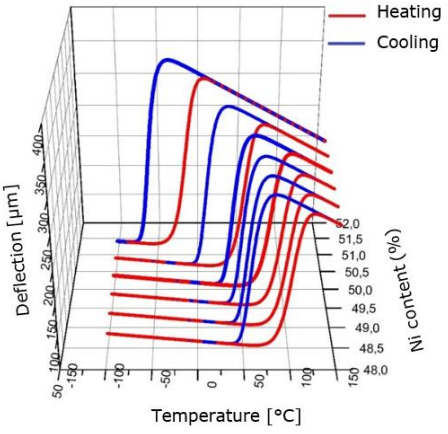
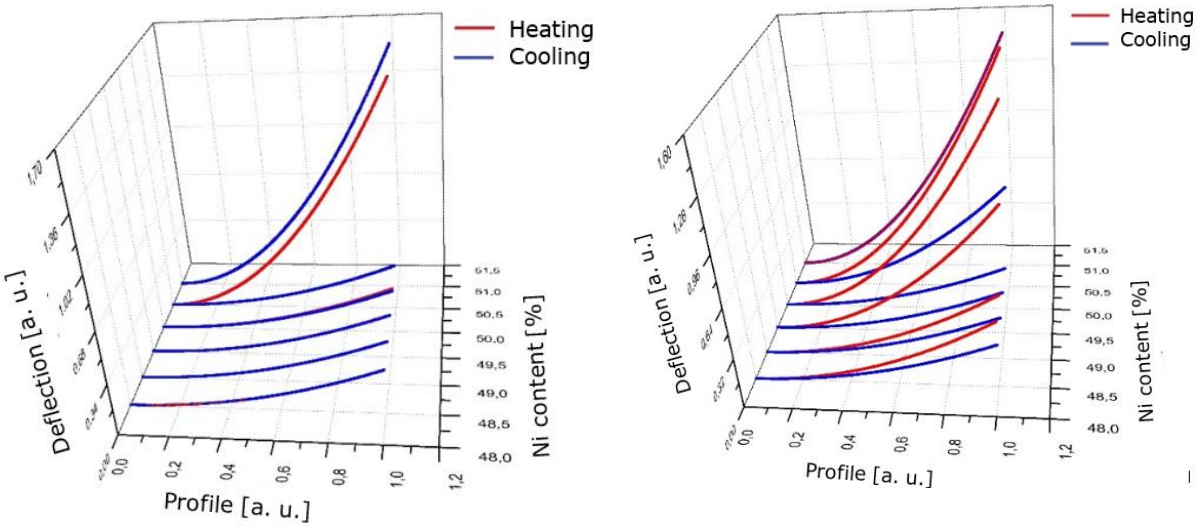


Figure 5-15 Graphical representation of actuator deflection, with the aim of highlighting the influence of Ni content on the phase transformation temperatures [21] – V. Bolocan-coauthor.

Another approach of this research was to establish the actuation profile of each cantilever in the block at a constant temperature. Thus, simulations and graphical interpretations were carried out for the actuator block at temperatures of 25°C (Figure 5-16, a) and 50°C (Figure 5-16, b). The obtained results show that at 25°C, films with 48.5% Ni–49.5% Ni are in the martensitic state and no difference in deflection is observed between the heating and cooling cycles; a very small difference in deflection between the temperature cycles is recorded for the film with 50% Ni; the film with 50.5% Ni is the only one undergoing transformation at 25°C, exhibiting the characteristic hysteresis between the heating and cooling cycles; and the film with 51% Ni is in the austenitic state at this temperature. At 50°C, with the exception of the film with 51% Ni, which is still in the austenitic state, all films exhibit hysteresis between the temperature cycles.



25°C. 50°C.

Figure 5-16 Actuation profile of the block cantilevers at temperatures of: a) 25°C, b) 50°C [21] – V. Bolocan-coauthor.

Starting from the previously modelled block, the individual behaviour of each cantilever was also simulated in the case of exposure to different temperatures, while considering that all films have the same composition $Ni_{50}Ti_{50}$. Thus, Figure 5-17 shows graphically the deflection profiles of the 6 cantilevers of the block, considering them exposed to temperatures of 20°C, 40°C, 60°C, 80°C, 100°C and 120°C.

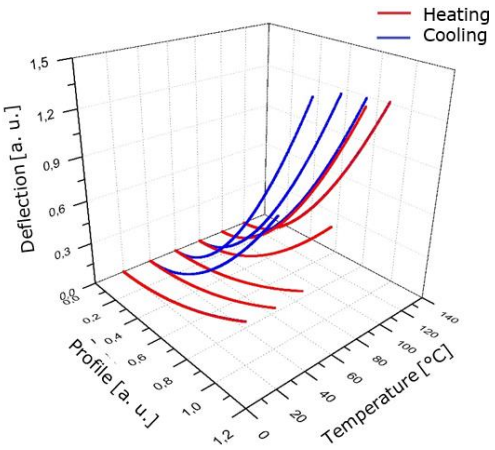


Figure 5-17 Actuation profile of the block cantilevers at different temperatures [21] – V. Bolocan-coauthor.

It was demonstrated that the compositional range of 50–51% Ni determines the largest variations in transformation temperature and that each element of the block activates independently at its specific transformation temperature, without disturbing the neighboring elements.

Modelling of sequential actuation through the use of multilayer films with different properties. [22]

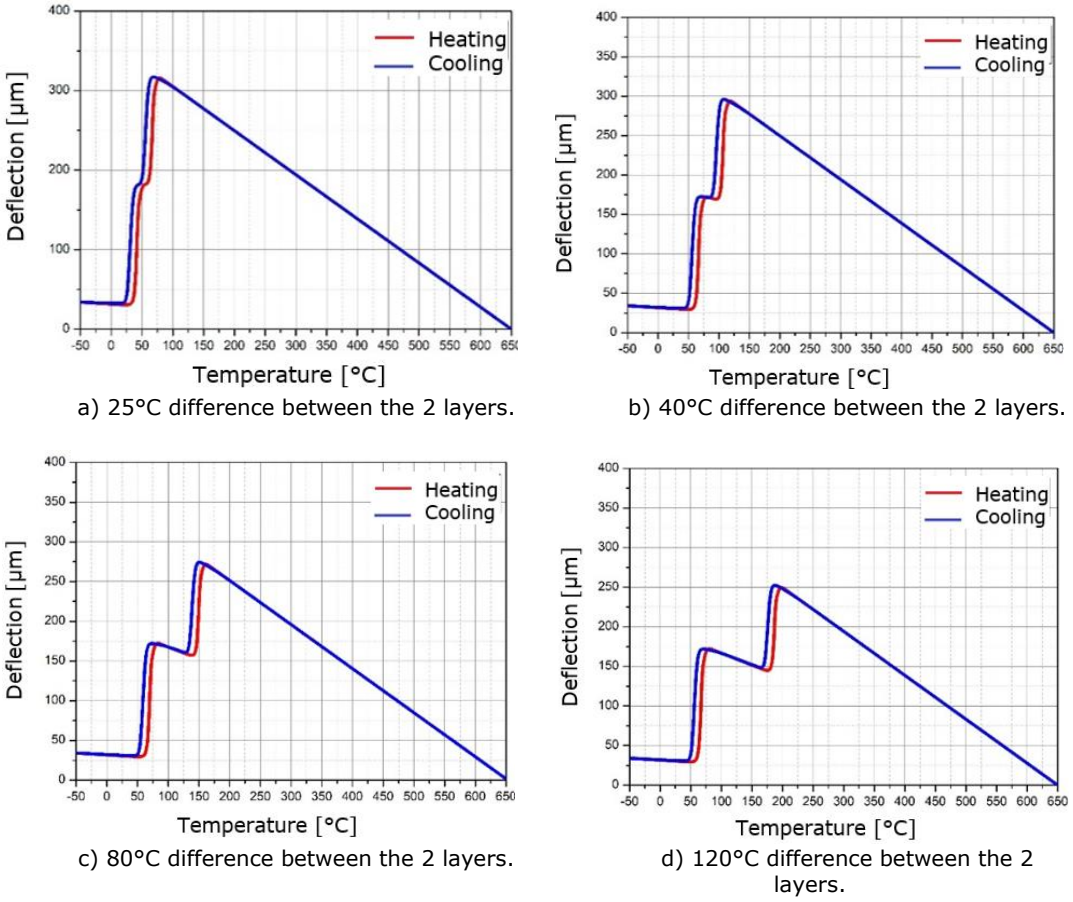
The paper analyses the behaviour of bimorph cantilevers with a length of 20 mm, composed of a Si substrate with a thickness of 100 µm and shape memory alloy films, with variations in transformation temperatures and thicknesses.

The simulation results for four distinct situations, in which the martensitic transformation ranges of the two film layers differ by 25°C, 40°C, 80°C and 120°C, are presented in Figure 5-18. In the case of the actuator in which two SMA films were deposited with a martensitic transformation temperature difference of 25°C (Figure 5-18a): the general behaviour of the cantilever closely resembles that of a homogeneous film. The deflection of the free end does not exhibit major variations, but only small inflections in the slope of the actuation curve within the transformation range. The total deflection value is slightly smaller than in the case of the homogeneous film, because the transformation in one layer begins immediately after the transformation in the other layer ends, which causes the effects to partially overlap and not to be clearly distinguished.

When the difference between the transformation temperatures of the two layers increases to 40°C (Figure 5-18b): the deflection versus temperature curve changes visibly. A plateau appears between the two transformations: the first layer exhausts its actuation capacity, while the second has not yet begun to transform. In this intermediate zone, the behaviour resembles that of a classic bimetal, until the initiation of transformation in the second layer. At the same time, the total deflection decreases further, because the internal stresses in the actuator influence the response, and the bimetallic contribution modifies the stress distribution.

For even larger differences of 80°C and 120°C (Figure 5-18c and Figure 5-18d): the previously observed phenomenon is amplified. The total deflection is considerably reduced, and the actuation curve becomes more fragmented, with distinct sequences corresponding to each layer. In practice, each layer

contributes separately to the actuation, and the overall effect is a succession of steps rather than a continuous increase.



a) 25°C difference between the 2 layers.
b) 40°C difference between the 2 layers.
c) 80°C difference between the 2 layers.
d) 120°C difference between the 2 layers.

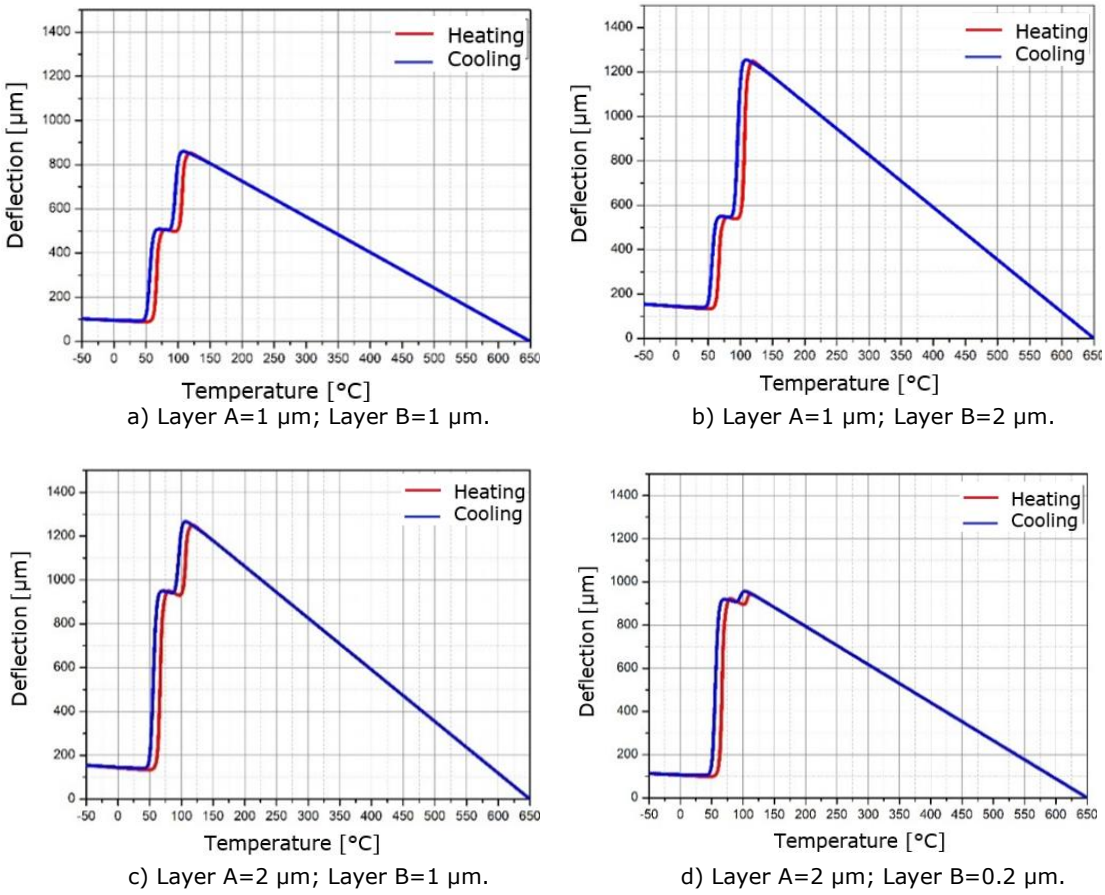
Figure 5-18 Deflection simulation graphs for bimorph actuators with double SMA layer with different martensitic transformation temperatures.

Another essential aspect that influences the behaviour of the double-layered actuator is the thickness of the deposited layers. To highlight this effect, simulations were carried out for a cantilever in which the difference between the martensitic transformation temperatures of the two layers is 40°C. In these simulations, the first layer was designated Layer A and the second Layer B.
In the situation where Layer A and Layer B have equal thicknesses (Figure 5-19a), of 1 µm each, the deflection of the free end is distributed almost uniformly between the two transformations. At different temperatures, each layer contributes similarly to the total actuation, and the deflection curve exhibits two steps of comparable amplitude. In practice, the overall response resembles that of a homogeneous film, but with two distinct transformation ranges.

When Layer A has a thickness of 2 µm and transforms at a higher temperature, while Layer B has a thickness of 1 µm and transforms at a lower temperature (Figure 5-19b), the behaviour changes visibly. On cooling, Layer A is the first to transform and, due to its greater thickness, releases a much larger amount of stress. This translates into a pronounced deflection within its transformation range. Subsequently, Layer B contributes a smaller deflection, completing the total response.

In the reverse scenario, when Layer A has a thickness of 1 µm and transforms at a higher temperature, while Layer B has a thickness of 2 µm and transforms at a lower temperature (Figure 5-19c), the maximum deflection is recorded within the transformation range of Layer B. The thin layer (A) has a limited effect, and the overall response is dominated by the thick layer (B), which actuates strongly at lower temperatures.

An extreme situation arises when Layer A has a thickness of only 0.2 µm and transforms at a higher temperature, while Layer B has a thickness of 2 µm and transforms at a lower temperature (Figure 5-19d). In this case, the contribution of Layer A is almost negligible: the generated deflection is very small, and the significant response appears only when Layer B begins to transform. In practice, the behaviour of the actuator is dictated almost exclusively by the thick layer, while the thin layer plays only a secondary role.



a) Layer A=1 µm; Layer B=1 µm.

b) Layer A=1 µm; Layer B=2 µm.

c) Layer A=2 µm; Layer B=1 µm.

d) Layer A=2 µm; Layer B=0.2 µm.

Figure 5-19 Deflection simulation graphs for bimorph actuators with double layer with different SMA layer thicknesses.

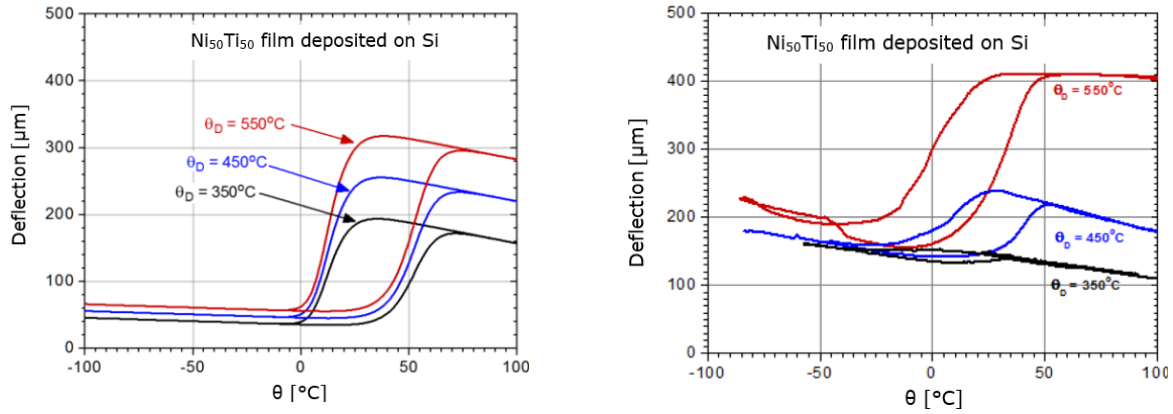
The analysis carried out demonstrates that through careful design of the layering — the choice of composition, deposition temperatures and thicknesses — the response of the actuator can be controlled and adjusted. This opens up the possibility of developing sequential micro-actuations, adapted to applications requiring multiple or modular responses.

Modelling and characterization of the actuation of bimorph structures with TiNiCu film deposited by magnetron sputtering. [23]

The paper is a continuation of previous studies that dealt predominantly with binary alloys and presents the characterization of ternary TiNiCu targets and films, while also retaining NiTi alloys, deposited on Si, glass and Kapton substrates, in parallel with the use of simulation models existing in the specialized literature.

Ni-Ti and Ti-Ni-Cu thin films were deposited by magnetron sputtering on silicon, Kapton® HN and glass substrates, obtaining film/substrate bimorph structures intended for the study of thermal actuation.

An important aspect observed was that in the case of NiTi films deposited at different temperatures, films with low crystallinity (deposited at lower temperatures) were capable of a much smaller deflection compared to the model prediction used, which means that the model does not account for the degree of crystallinity of the film but instead considers it to be fully crystalline regardless of the deposition temperature. The comparative analysis is represented graphically in Figure 5-20.



a) Modelled data. b) Experimental data.

Figure 5-20 Deflection as a function of temperature of actuators with NiTi films deposited on Si substrate at different temperatures (θD=350°C; 450°C; 550°C). [23] – V. Bolocan-coauthor.

Research on the fabrication and characterization of bimorph structures with shape memory alloy films. [24]

The paper investigates the deposition of TiNiCu films on glass substrates by magnetron sputtering at room temperature. The cross-sections of the films reveal thicknesses of approximately 1 µm and a dense structure. X-ray diffraction confirmed that the films are partially crystalline, exhibiting reflections corresponding to orthorhombic B19 martensite. Heat treatment by annealing at 370°C did not lead to significant changes in the degree of crystallinity, indicating that higher temperatures are required for complete crystallization of films deposited at room temperature (Figure 5-21).

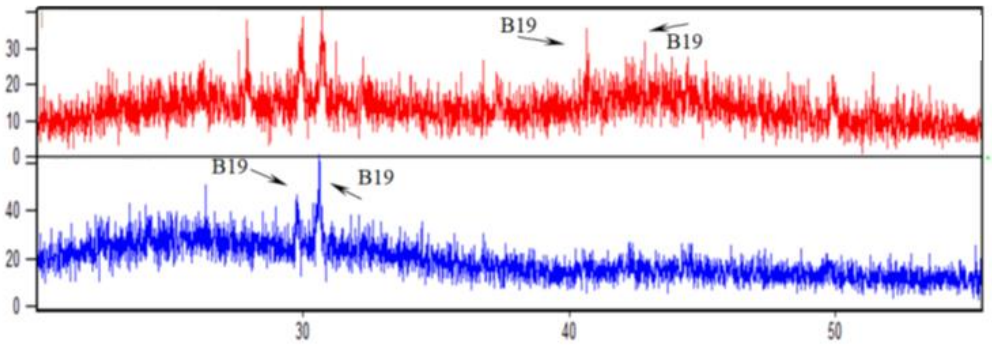


Figure 5-21 X-ray diffraction profiles for Ti-Ni-Cu films deposited at room temperature (top) and subsequently annealed at 370°C (bottom). [24] – V. Bolocan-coauthor.

Chapter conclusions.

The functional performance of bimorph microactuators with shape memory alloy (SMA) films is governed by the complex interaction between the properties of the film, the substrate and the processing conditions. The experimentally validated prediction models confirm that the deflection depends simultaneously on the alloy composition, the film and substrate thickness, the deposition temperature and the cantilever length. Multilayer architectures allow the modulation of the actuator response through the generation of actuation plateaus and sequential actuation over extended thermal ranges, compared to the abrupt actuation characteristic of single-layer films. The thermoelastic properties of the substrate decisively determine both the amplitude and the direction of curvature, with the selection of the substrate material constituting a design tool just as important as the composition of the active film. Microactuator blocks with films of different compositions on the same substrate demonstrate the feasibility of independent sequential actuation. The TiNiCu alloy has been confirmed as a viable alternative to classical NiTi, with a narrower thermal hysteresis and adjustable transformation temperatures. Combinatorial exploration through compositional gradient libraries accelerates the identification of optimal compositions through a single deposition process, with the note that internal stresses and the difficulty of extrapolating results to bulk structures represent limitations that must be taken into account.

6. Final conclusions, original contributions and future research directions

Final conclusions

The thesis investigated the behaviour of thin structures based on shape memory alloys deposited by magnetron sputtering, with the aim of understanding and optimizing the thermomechanical actuation response in bimorph and multilayer architectures. The research integrated the bibliographic analysis of the field, the development of experimental methods, the characterization of the obtained films and the predictive modelling of the actuation behaviour.

The bibliographic analysis confirmed that metallic shape memory alloys represent a preferred material for MEMS microactuators, due to their high energy density, superior actuation forces compared to piezoelectric and magnetostrictive alternatives, and compatibility with microfabrication processes. The thermoelastic martensitic transformation, with its reduced hysteresis and four characteristic transformation points, constitutes the physical mechanism underlying the functional behaviour studied.

Regarding film fabrication and characterization, the deposition temperature represents the dominant factor in controlling the crystallographic structure: films deposited at low temperatures remain amorphous or partially crystalline, while deposition or annealing at elevated temperatures leads to crystallization and the appearance of the B2, B19 and B19' phases. NiTiCu films deposited at room temperature proved to be partially crystalline, exhibiting orthorhombic B19 martensite, and heat treatment by annealing up to 370°C did not lead to significant changes in the degree of crystallinity. Target characterization revealed annular erosion patterns that introduce local compositional variations in the plane of the target, with direct consequences on the stoichiometry of the deposited films and, consequently, on the transformation temperature. The growth mechanisms identified — Volmer-Weber for NiTi films and Johnson-Mehl for NiTiCu films — explain the distinct morphologies observed, columnar and tessellated structures respectively.

The modelling studies demonstrated that the deflection of bimorph cantilevers depends simultaneously on several interconnected factors: the alloy composition, the film and substrate thickness, the deposition temperature and the cantilever length. The thermoelastic properties of the substrate decisively influence both the amplitude and the direction of cantilever curvature, and the choice of substrate material constitutes a design tool just as important as the film composition. In the case of the Upilex substrate, the large difference between the elastic moduli of the film and the substrate leads to twisting of the cantilever at large deflections. The reversal of the direction of curvature upon transition from a Si substrate to a Kapton substrate, confirmed both experimentally and through modelling, demonstrates that substrate selection has a direct effect on the direction of actuation. The models were validated by comparing the simulated results with measurements carried out on physical samples, the agreement obtained confirming their applicability for future designs.

Research on multilayer architectures showed that bi-layer and tri-layer structures with different transformation temperatures allow the modulation of the thermal response of the actuator through the generation of actuation plateaus and the extension of the thermal operating range. Small differences between the transformation temperatures of the layers produce behaviour similar to that of a homogeneous film, while large differences generate distinct sequential actuations with a reduced total amplitude compared to the equivalent single-layer film. The layer with the greater thickness dominates the overall response of the actuator. Microactuator blocks with films of different compositions

deposited on the same substrate demonstrated the feasibility of independent sequential actuations, with each cantilever activating at its specific transformation temperature. The TiNiCu alloy confirmed that it represents a viable alternative to classical NiTi, with a narrower thermal hysteresis due to the transition from the B2 phase to the B19 phase and with transformation temperatures adjustable through composition, and the characterization of the films confirmed the agreement between the experimental behaviour and the model predictions.

Original contributions

The original contributions of the thesis are structured along two main directions: the development of the experimental infrastructure required for the fabrication and testing of SMA thin films, and the published research on the modelling, fabrication and characterization of microactuators based on such films.

Regarding the experimental infrastructure, a DC magnetron sputtering system built within the Department of Materials and Manufacturing Engineering at UPT was commissioned and optimized, to which a computerized substrate temperature control and recording system was added by connecting an Omron e5cn controller. The procedures for the preparation of Kapton and Mica substrates by LASER cutting using the Trumpf TruMark Station 5000 equipment were established and optimized, with identification of the optimal parameters for each material. An integrated functional characterization system was developed and validated, allowing the simultaneous recording of electrical resistivity by the four-point probe method and of deflection by a point laser sensor, as a function of temperature, over a thermal range controlled by Peltier modules. The system was successfully used both on CuZnAl and TiNiCu alloy ribbons and on thin films deposited on Kapton substrates.

The contributions materialized through papers published in international journals and the proceedings of international conferences are presented below, in the order in which they are addressed in chapter 5.

- The paper "Material optimization through thin film compositional spreads" (Solid State Phenomena), co-authored with B. Gavre, D. D. Vâlsan and C. M. Crăciunescu, introduced and validated the combinatorial exploration methodology through compositional gradient libraries realized by simultaneous sputtering from elemental targets, applied to TiNb and TiNbPt systems. The paper demonstrates that this approach allows the rapid investigation of a large number of compositions through a single deposition process, with the identification of systematic variations in electrical resistivity as a function of the local film composition.
- The paper "Micro-actuation systems based on phase transformation films" (AIP Conference Proceedings, Vol. 2843, 2023), co-authored with D. Vâlsan, A. Ercuța and C. Crăciunescu, synthesized the design principles of bimorph microactuators based on SMA films. The paper demonstrated that the deposition temperature influences both the actuation potential and the thermal range over which it occurs, and that the bimorph structure ensures superior reproducibility compared to SMA films not connected to a substrate.
- The paper "Actuation based on phase transformations in microlayered architectures" (Journal of Engineering Sciences and Innovation, Vol. 8, No. 1, 2023), co-authored with D. D. Vâlsan and C. M. Crăciunescu, extended the analysis from single-layer architectures to bi-layer and tri-layer structures with different transformation temperatures. The paper demonstrates that through the design of the layering, actuation plateaus or sequential actuation over extended thermal ranges can be generated, and that the thickness of the layers directly controls the amplitude of the contribution of each layer to the total deflection.
- The paper "Optimization of thermal deflection in NiTi-based bimorph microactuators" (Materials Today: Proceedings, Vol. 45, 2021), co-authored with D. Vâlsan, Gh. Chilnicean and A. Novac,

systematically analyzed the influence of the thermoelastic properties of the substrate on the thermal deflection of bimorph cantilevers with NiTi film. The paper highlighted the particular behaviour of the Upilex substrate, where the large difference between the elastic moduli of the film and the substrate leads to twisting of the cantilever at large deflections, and demonstrated that the selection of the substrate material and the control of the active film thickness represent essential tools for the optimization of the amplitude and direction of actuation.

- The paper "Design of shape memory micro-actuator modules with sequential actuation" (Solid State Phenomena, Vol. 332, 2022), co-authored with D. D. Vâlsan, A. Novac and G. A. Chilnicean, proposed and analyzed the concept of microactuator blocks with sequential actuation, composed of cantilevers with NiTi films of compositions ranging between 48.5 and 51% Ni, deposited on Si substrates. The paper demonstrates that the compositional range of 50 to 51% Ni determines the largest variations in transformation temperature and that each element of the block activates independently at its specific transformation temperature.
- The paper "Micro-actuation in bi-layered shape memory alloy structures" (Materials Today: Proceedings, Vol. 78, 2023), co-authored with D. D. Vâlsan, A. Ercuța and C. M. Crăciunescu, comparatively analyzed the behaviour of bimorph actuators with bi-layer film for transformation temperature differences between layers of 25, 40, 80 and 120°C and for different layer thicknesses. The paper demonstrated that small differences produce behaviour similar to that of a homogeneous film, that large differences generate sequential actuations with reduced total amplitude, and that the thicker layer dominates the overall response of the actuator.
- The paper "Actuating Bimorph Microstructures with Magnetron-Sputtered Ti-Ni-Cu Shape Memory Alloy Films" (Nanomaterials, Vol. 12, 2022), co-authored with D. Vâlsan, A. Ercuța and C. M. Crăciunescu, presented the structural, compositional, thermal and functional characterization of TiNiCu films deposited by magnetron sputtering on Si and Kapton substrates. The paper confirmed that the TiNiCu alloy represents a viable alternative to classical NiTi, with a narrower thermal hysteresis due to the transition from the B2 phase to the B19 phase, and demonstrated the agreement between the experimental behaviour of the bimorph structures and the model predictions, including the reversal of the direction of curvature upon transition from a Si substrate to a Kapton substrate.
- The paper "Shape Memory Alloy Films Manufactured by Magnetron Sputtering" (IOP Conference Series: Materials Science and Engineering, Vol. 418, 2018), co-authored with R. Sprîncenatu, A. Novac, G. Chilnicean and C. Crăciunescu, investigated the deposition of NiTiCu alloy thin films on glass substrates by DC magnetron sputtering at room temperature. The paper showed that the deposited films are partially crystalline, exhibiting orthorhombic B19 martensite, and that heat treatment by annealing up to 370°C does not lead to significant changes in the degree of crystallinity.

Future research directions

The results obtained raise a number of aspects that could not be fully addressed within the scope of the thesis and which constitute natural directions for the continuation of the research.

A first direction concerns the experimental validation of the actuation prediction models for trimorph architectures and for reinforced cantilevers, treated in the thesis exclusively theoretically. The extension of experiments towards these configurations would allow the verification of the limits of applicability of the models and the identification of additional influencing factors not included in the current modelling.

A second direction relates to the study of the behaviour of films under repeated thermal cycling. The thesis focused on the characterization of the response during the first actuation cycles; however, the long-term behaviour, thermomechanical fatigue, the evolution of the transformation temperature with the number of cycles and the stability of film adhesion to the substrate represent essential aspects for

the evaluation of the reliability of microactuators under real operating conditions.
A third direction consists of a more detailed investigation of the influence of the deposition process parameters — sputtering power, working gas pressure and substrate temperature — on the stoichiometry of the films and the transformation temperature. The results from chapter 4 showed that the compositional variations generated by the non-uniform erosion of the targets have direct consequences on the actuation behaviour, and more precise control of these parameters would allow predictable adjustment of the functional properties of the films.
A fourth direction concerns the extension of the modelling and experimental validation to architectures with more than three layers, with different properties and thicknesses. The thesis demonstrated that bi-layer and tri-layer structures generate controllable sequential behaviours, and architectures with a larger number of layers could extend the thermal operating range and would offer an additional degree of freedom in the design of the actuator response.

7. Selected bibliography

1. Elahinia, Mohammad. Effect of System Dynamics on Shape Memory Alloy Behavior and Control. 2004.

2. Crăciunescu, Corneliu Marius. Micro și Nanoingineria Aliajelor cu Memorie a Formei. Timișoara: Editura Politehnica, 2005. 973-625-216-7.

3. T. W. Duerig, K. N. Melton, D. StÖCkel, C. M. Wayman. Engineering Aspects of Shape Memory Alloys. s.l.: Butterworth-Heinemann Ltd, 1990. 0-750-61009-3.

4. www.aerofit.com. [Online] AeroFit. [Cited: 14 01 2020.] http://www.aerofit.com/sma-cryofit-couplings/.

5. Fixation of a frontozygomatic fracture with a shape-memory staple. Z. Laster, A. D. MacBean, P. R. Ayliffe, L. C. Newlands. 2001, British Journal of Oral and Maxillofacial Surgery, Vol. 39, pp. 324-325.

6. Scoliosis correction with shape-memory metal: results of an experimental study. D. J. Wever, J. A. Elstrodt, A. G. Veldhuizen, J. R. v Horn. s.l.: Springer, 2002, Eur Spine, Vol. 11, pp. 100-106.

7. Modulation of scoliotic spine growth in experimental animals using intelligent metal bars. J.M. Sánchez-Márquez, F.J. Sánchez Pérez-Grueso, N. Fernández-Baíllo, E. Gil-Garay, S. Antuna-Antuna. 2013, Revista Española de Cirugía Ortopédica y Traumatología.

8. Fusionless Scoliosis Correction Using a Shape Memory Alloy Staple in the Anterior Thoracic Spine of the Immature Goat. J. T. Braun, J. W. Ogilvie, E. Akyuz, D. S. Brodke. 18, 2004, Spine, Vol. 29, pp. 1980-1989.

9. SMA microgripper system. M. Kohl, B. Krevet, E. Just. 2002, Vols. 97-98, pp. 646-652.

10. Manufacturing issues of thin film NiTi microwrapper. John J. Gill, David T. Chang, Leslie A. Momoda, Greg P. Carman. s.l.: Elsevier Science B.V., 2001, Sensors and Actuators, Vol. 93, pp. 148-156.

11. A Three-Dimensional Shape Memory Alloy Microelectrode with Clipping Structure for Insect Neural Recording. Shoji Takeuchi, Isao Shimoyama. 1, s.l.: 2000 IEEE, March 2000, JOURNAL OF MICROELETROMECHANICAL SYSTEMS, Vol. 9, pp. 24-31.

12. A practical microgripper by fine alignment, eutectic bonding and SMA actuation. Abraham P. Lee, Dino R. Ciarlo, Peter A. Krulevitch, Stacy Lehew, Jimmy Trevino, M. Allen Northrup. Elsevier Science S.A., 1996, Sensors and Actuators A54, pp. 755-759

13. Effect of sputtering power on surface topography of dc magnetron sputtered Ti thin films observed by AFM. Yongzhong Jin, Wei Wub, Li, Jian Chen, Jingyu Zhang, Youbing Zuo, Jun Fu. s.l.: Elsevier, 2009, Applied Surface Science, Vol. 255.

14. The effect of argon pressure on the structural and photocatalytic characteristics of TiO2 thin films deposited by d.c. magnetron sputtering. K. Eufinger, E.N. Janssen, H. Poelman, D. Poelman, R. De Gryse, G.B. Marin. s.l.: Elsevier, 2006, Thin Solid Films, Vol. 515, pp. 425-429.

15. Effect of temperature on the properties of Al:ZnO films deposited by magnetron sputtering with inborn surface texture. Weimin Li, Huiying Hao. s.l.: Springer, 2012, Mater Sci, Vol. 47, pp. 3516-3521.

16. Effects of deposition parameters on tantalum films deposited by direct current magnetron sputtering. Y.M. Zhou, Z. Xie, H.N. Xiao, P.F. Hu, J. He. s.l.: Elsevier, 2009, Vacuum, Vol. 83, pp. 286-291.

17. Characteristics and fabrication of NiTi/Si diaphragm micropump. D. Xu, L. Wang, G. Ding, Y. Zhou, A. Yu, B. Cai. 2001, Sensors and Actuators, Vol. 93, pp. 87-92.

18. Micro-actuation systems based on phase transformation films. V. Bolocan, D. Vâlsan, A. Ercuța, C. Crăciunescu. 2023, AIP Conf. Proc., Vol. 2843.

19. Actuation based on phase transformations in microlayered architectures. V-M. Bolocan, D. D. Vâlsan, C-M. Crăciunescu. 1, 2023, Journal of Engineering Sciences and Innovation, Vol. 8, pp. 53-62.

20. Optimization of thermal deflection in NiTi-based bimorph microactuators. Vlad Bolocan, Dragos Vâlsan, Gheorghe Chilnicean, Andrei Novac. [ed.] Elsevier. 2021, Materials Today: Proceedings, Vol. 45, pp. 4216-4220.

21. Design of shape memory micro-actuator modules with sequential actuation. V. Bolocan, D-D. Vâlsan, A. Novac, G. A. Chilnicean. 05 2022, Solid State Phenomena, Vol. 332, pp. 67-72.

22. Micro-actuation in bi-layered shape memory alloy structures. Vlad Bolocan, Dragoș-Dumitru Vâlsan, Aurel Ercuța, Corneliu-Marius Crăciunescu. 2023, Materials Today: Proceedings, Vol. 78, pp. 282-286.

23. Actuating Bimorph Microstructures with Magnetron-Sputtered Ti-Ni-Cu Shape Memory Alloy Films. V. Bolocan, D. Vâlsan, A. Ercuța, C. M. Crăciunescu. 12, 2022, Nanomaterials.

24. Shape Memory Alloy Films Manufactured by Magnetron Sputtering. V. Bolocan, R. Sprincenatu, A. Novac, G. Chilnicean, C. Craciunescu. s.l.: IOP Publishing, 2018. IOP Conference Series: Materials Science and Engineering. Vol. 418.