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Technical note

TRIMORPH ACTUATION BASED ON SHAPE MEMORY ALLOYS

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Trimorph and bimorph martensitic actuators have been designed and produced by sputter-depositing NiTi shape memory alloys films on one or both sides of heated Si cantilever-type substrates. The phase transformation temperatures and specific sequence of the shape memory alloy films was induced by appropriately selecting the deposition temperature. Thus, the deflection of the trimorph cantilever recorded as a function of temperature reflects the phase transformation associated features of the corresponding films. Various actuation signals obtained by selecting the composition and the deposition temperatures of the films are discussed and models for the behavior of such trimorphs have been proposed.

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1. Introduction

Shape memory alloys (SMA's) are promising materials for the development of micro-actuators [1-3]. Bimorphs consisting of thin SMA films deposited on a substrate show a considerable actuation when the martensitic phase transformation takes place in the film. In the range of the transformation temperatures, the austenite (A) – the high temperature phase – transforms into martensite (M) – the low temperature phase - during a reversible process. As a result of the difference in the elastic properties of the two phases a stress change develops in the film associated with the phase transformation. The deflection of the free end of a bimorph cantilever can be used for experimental detection for adequate film / substrate ratio (frequently 1:100 for SMA film / silicon substrate).

Roytburd et al. [4] have defined bimorph and trimorph architectures based on Kim's results [5] and have studied the martensitic transformation in bimorph films. Accordingly, a bimorph can be obtained when the film is deposited on one side of the substrate (Fig. 1a), while a trimorph can be constructed by depositing films on both sides of the substrate (Fig. 1b).

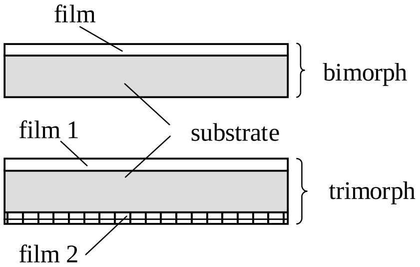

Fig. 1. Basic architectures generated by depositing films on one (bimorph) or booth sides (trimorph) of a substrate (adapted after Roytburd et al. [4]).

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Several papers have considered bimorph architectures based on the martensitic transformation that occurs in SMA's. Su et al. [6] have analyzed bimorph $Ni_{50}Ti_{50}$ films deposited on (100) Si substrates. Winczeck et al. [7] have studied the influence of the substrate in Ni-Ti-Pd films deposited at room temperature (RT) and annealed at 700 °C, Wuttig et al. [8] have characterized the dynamic properties of Ni-Ti/Si bimorphs deposited on heated substrates.

Ingenious trimorphs for microrobotics have been designed and produced using NiTi and NiTiHf shape memory alloy films with embeeded transformations deposited on metal substrates and leading to wave-like transportation systems or robotic legs [9].

Recently it has been observed that - depending on the deposition temperatures -different transitions, with different thermal characteristics occur in Ni-Ti/Si [10] or NiTiCu / Si [11] bimorphs. Therefore if SMAs films of the same composition, but with different transformation characteristics are deposited on each side of a substrate, each film will have its own transition, hence its own stress change during the phase transition.

This paper reports on new experimental results for Ni-Ti trimorph martensitic actuators with films deposited out of the same target on substrate heated at different temperatures during the deposition of each film. It will be shown how the stresses in the films deposited at different temperatures interact to give a new type of response to thermal stimuli for SMA trimorph actuators.

2. Experimental techniques

Nominally $Ni_{50}Ti_{50}$ targets were used to sputter-deposit films on one (a) or both sides (a and b) of heated (100) Si cantilever-type substrates (Fig. 2). The cantilevers were manufactured using the lithography technique (see also [12]) and the surface of the cantilevers was oxidized at 1100 °C in air. The depositions were made using a dc magnetron sputtering system and the following parameters: 100 W power, 10^{-6} preliminary vacuum, 10 mTorr Ar pressure. The Si cantilevers were attached to a heating plate and the films were deposited on one side of the substrate at a time. Two sets of actuators have been made, with specific features described in Table 1. Bimorph-type cantilevers (B) have the film deposited on only one side of the cantilever, while trimorph-type cantilevers (T) have films deposited on both sides of the cantilever. For all cases the first deposition was made on side (a) of the cantilever.

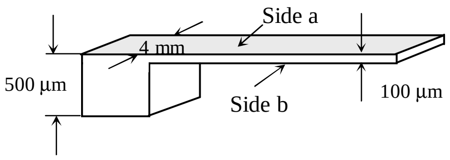

Fig. 2. Silicone cantilever used for manufacturing bimorphs (film deposited on side a) and trimorphs (films deposited on side a and b respectively).

Table 1. The parameters used for the deposition of bimorph and trimorph actuators.

Actuator Type	Code	Target/ Deposition Temperature / Film Thickness	
		First deposition /(side)	**Second deposition /(side)**
Bimorph (with one transforming film)	B1	Ni-Ti /385 °C/2 µm /(a)	-
	B2	Ni-Ti /250 °C /2 µm /(a)	-
Trimorph (with two transforming films)	T_{t1}	Ni-Ti /385 °C /1 µm /(a)	Ni-Ti /250 °C /1 µm /(b)
	T_{t2}	Ni-Ti /250 °C /1 µm /(b)	Ni-Ti /385 °C /1 µm /(a)

The main difference between (T_{t1}) and (T_{t2}) trimorph cantilevers is related to the sequence of the deposition temperature of the corresponding films. For example, the manufacturing process for T_{t1} trimorphs was initiated by heating the cantilever at 385 °C (the limit of the deposition system), followed by deposition of the NiTi film. Before the deposition of the second film, the deposition chamber was opened and the cantilever was turned with the undeposited side toward the sputtering gun and reattached to the heating plate. The trimorph T_{t1} architecture resulted after heating at 250 °C and the deposition of the second film.

Several techniques have been used to investigate the behaviour of the bimorf and trimorph architectures, produced following the sequences described in Table 1.

The thickness of the films was measured with a stylus profiler on witness samples deposited under the same conditions as the films. Parts of the witness sample have been masked by coating, in order to reveal the heigth difference between substrate areas with and without film.

The composition of the films was determined by wavelength dispersive spectroscopy (WDS) and showed, as expected [13], the depletion of Ti, thus making the Ni-Ti films Ni-rich. X-ray spectra of the films deposited on the substrates were recorded at room temperature using a Rigaku X-ray diffractometer and CuKα radiation.

The actuation - reflected by the bending of the bimorph and trimorph cantilevers - was determined as a function of temperature, using the clamped free-reed vibration method [14], which also allowed the measurement of the damping and the modulus defect. A heterodyne circuit was used to excite the fundamental mechanical resonance of the SMA/Si cantilevers. The bending of the cantilever was quantified by measuring the variation of the carrier frequency of the vibrating-reed apparatus. The measurement method is described in Fig. 3. First the cantilever was gradually forced to bend toward the electrode. This caused a variation of the capacitance between the cantilever and the electrode and therefore a change in the carrier frequency. The bending was measured and the corresponding carrier frequency was recorded. Then the cantilever was thermally cycled in the temperature range corresponding to the transformation of the film(s). The heating/cooling rate was 1°C/min. The carrier frequency data recorded during the thermal processing was converted into the displacement of the free end of the cantilever using the relationship previously established. The damping was determined by free decay, allowing the verification of the relationship between the macroscopic behavior of the cantilever and the phase transition that occurs in the films. Details of the damping measurements have been given elsewhere [12].

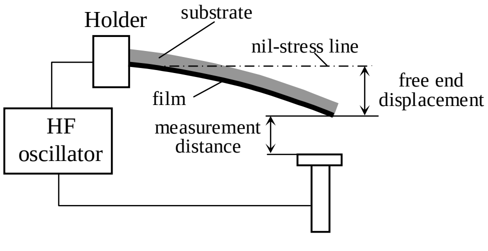

Fig. 3. Schematic representation of the Vibran - type experimental set-up used for the measurement of the characteristics of bimorph and trimorph architectures (see also [14]).

3. Experimental results

While bimorph and trimorph actuators are expected to exhibit different actuation behaviour, some of the characteristics of the martensitic transformation of the films are influenced by the state of stress in the corresponding architecture. Therefore, the aspects related to the film transformations are described for the bimorph architectures, while the actuation is the main issue considered for trimorphs.

Fig. 4 describes the features of bimorph cantilevers with films deposited at 250 and 385 °C respectively. The deflection of the free-end of the cantilever (or the bimorph actuation) is in close relationship with the deposition temperature, as it can be seen in Fig. 4 a.

Both films reveal a typical martensitic transformation, however the transition range is slightly lower for the film deposited at 250 °C compared to those deposited at 385 °C. The shape of the 250 °C displacement vs. temperature dependence is also different, suggesting that not only stress-related factors are directly involved. In fact, the X-ray spectra of the film (Fig. 4c) shows not only that the films are both crystalline in the as-deposited state, but also that a different transition occurs in the films, depending on the deposition temperature. This supposition is also confirmed by mechanical spectroscopy (Fig. 4 b, c) data.

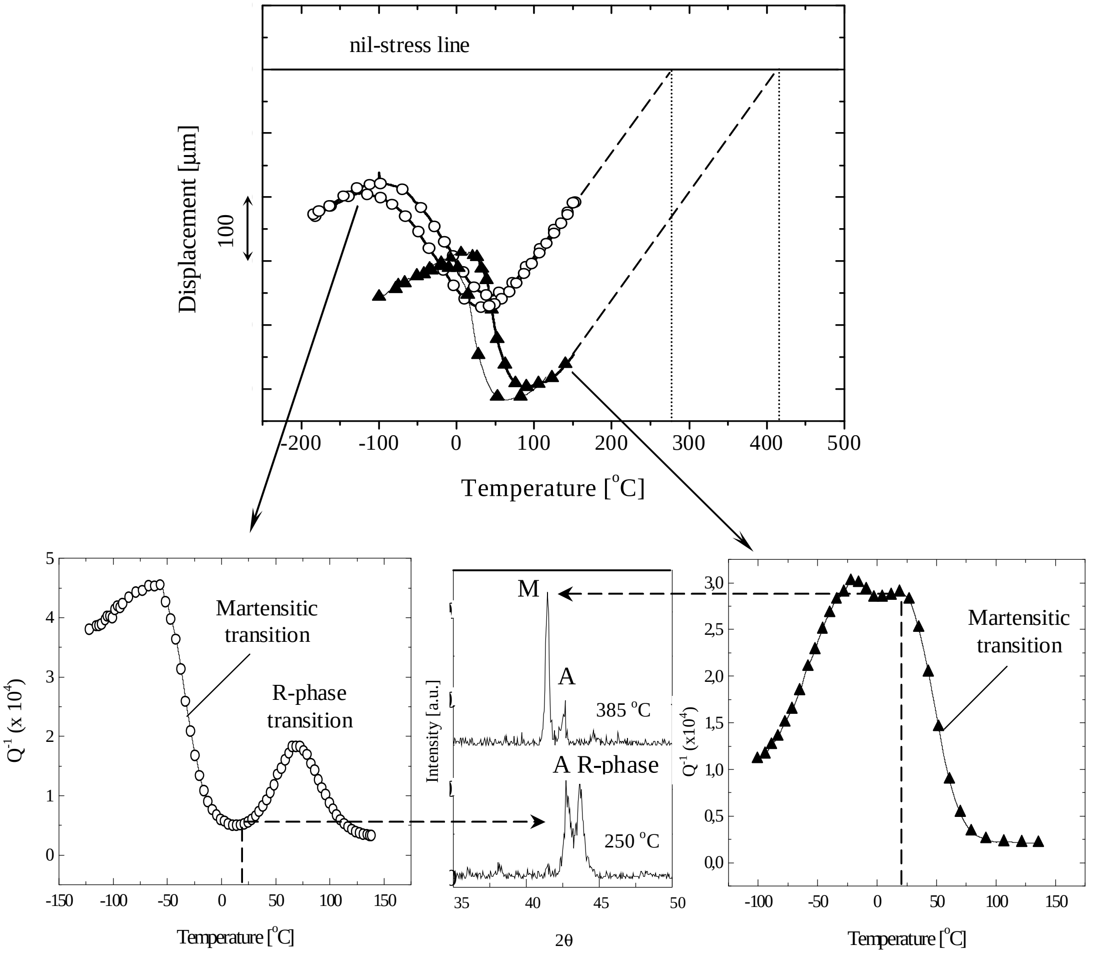

Fig. 4. Summary of experimental results on NiTi bimorphs (see also text for details): a. cantilever free-end deflection recorded on cooling for bimorphs with films deposited at 250 and 385 °C respectively. The extrapolation of the graphs toward the nil-stress line is also depicted. b. internal friction vs. temperature dependence for (B1) bimorphs with films deposited at 250 °C. c. X-ray diffraction spectra of the NiTi constrained films (in bimorph architectures) deposited at 250 and 385 °C respectively. The 250 °C spectrum reflects the R-phase transition, while the 350 °C one shows typical martensitic (M) and austenitic (A) peaks. d. internal friction vs. temperature dependence for (B2) bimorphs with films deposited at 250 °C.

The internal friction of the films deposited at 250 °C shows a peak related to the R-phase transition, while the films deposited at 385 °C shows only a typical monoclinic-related transition (see also ref. [15]).

The case of trimorphs actuation by temperature control, described in Fig. 5 shows significant behavioral differences between the two architectures, when the deposition sequence for the films is reversed. For T_{t1} type trimorphs (first film deposited at high temperature), there is a step change in the displacement. A two-step change in the displacement curve vs. temperature has been observed for T_{t2} type trimorphs (first deposition made at low temperature).

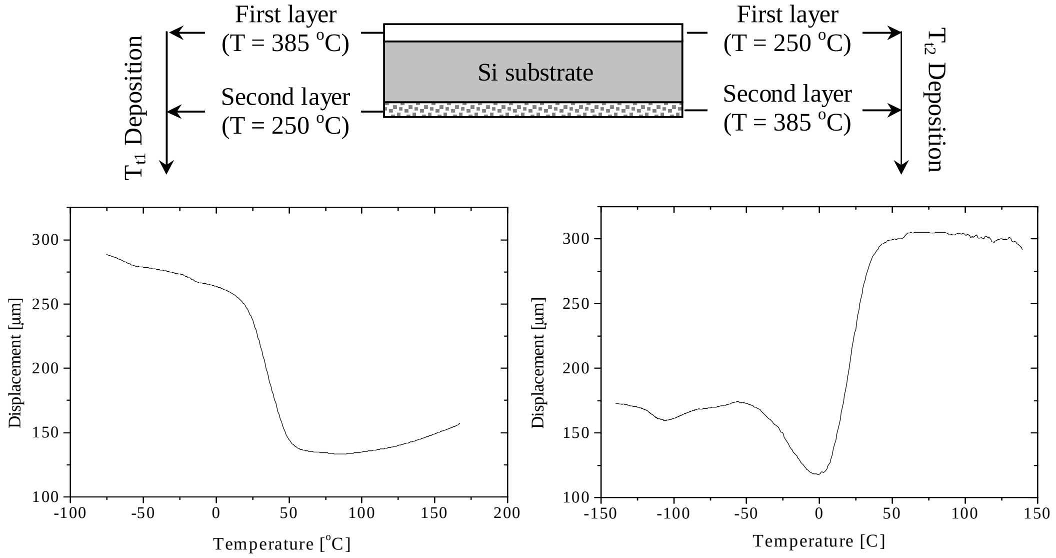

Fig. 5. Experimental results describing NiTi trimorphs behaviour (see also text for details): a. features of the two particular trimorph architecture manufactured by depositing films in a specific order on the sides of the cantilever-type substrate. b. the response on thermal activation of a (T_{t1}) trimorph actuator with NiTi films deposited successively at 385 and 250 °C, respectively. c. the response on thermal activation of a (T_{t2}) trimorph actuator with NiTi films deposited successively at 250 and 385 °C, respectively.

The difference between the trimorphs actuation occurs in the temperature range where the phase transition has been detected in the bimorph films, i.e. (+50) ... (-50) °C.

4. Discussion

The state of stress of bimorph and trimorph cantilevers is reflected by the deflection of the free-end (see also the well-known Stoney equation in ref. [16]). The stress is built on cooling the architecture from the deposition temperature, when the films have different expansion coefficients than the substrates. The amount of the stress is directly proportional to the difference between the deposition and the testing temperature, providing that no phase transformation occurred in the film or the substrate. During the phase transition in the shape memory alloy films, a stress relief occurs, because the austenite and the martensite have different properties and, the martensite can adapt and relieve the stress in the bimorph [4]. Since the deflection of the cantilever is a measure of the stress in the films composing the trimorph architecture, it is considered interesting to detail a model proposed to explain the behaviour of trimorphs based on the behaviour of simple bimorphs with shape memory alloy films.

It was shown in Fig. 4 that the state of stress in the film at the beginning of the phase transformation affects the sequence of transformation. An austenite → B19' martensite transition occurs when the stress is high at the onset of the transformation (such as the one that develops on cooling from the 385 ^{o}C deposition temperature) and an austenite → R-phase → B19’ martensite transition appears when the stress is low at the onset of the transformation (corresponding to a 250 ^{o}C deposition). Such sequences of transformation are known to occur in bulk NiTi alloys and have been also reported in films [10].

The issue of internal friction of shape memory films is a complex one because it involves simultaneously distinct aspects related to film / substrate composite architectures and internal friction, respectively.

The dynamical mechanical properties of thin film / substrate bimorphs has been addressed [17, 18] - and the same principle has been used in this paper - with relationship established for the resulting composite damping [19,20].

The internal friction is known to be influenced by the microstructure and the presence and mobility of crystalline defects [21] leading to the conclusion that the issue of shape memory alloys is a complex one because it involves a thermoelastic phase transformation associated with the presence of mobile interfaces between martensite and austenite or between martensitic variants.

In Ni-rich bulk NiTi alloys the internal friction allows to differentiate between two distinct transitions that occur, i.e. austenite (the high temperature phase) successively transforms on cooling into an R-phase (rombohedral) and martensite (B19’ monoclinic) respectively, and a similar transition but in reverse order occurs on heating. The internal friction vs. temperature dependence is known to individualize the peaks related to each transformation, i.e. austenite to R-phase and R-phase to martensite [22]. A trend similar to the one observed for bulk has been reported for NiTi shape memory alloy films deposited on Si substrates, with similarity related to the occurrence of the phase transition under constraint [10], and the stress-related sequences of transformation [15]. The internal friction peaks of the R-phase and martensitic transitions in constrained Ni-rich NiTi films, as the ones shown in Figs. 4 b and d can be considered as an additional proof that different deposition temperatures are associated with different sequences of transformation. Since each transition is also associated with a stress relief, but at different temperatures (as shown in Figs. 4 a and b) it follows that one could use the differences to generate trimorph actuations.

The actuation of trimorphs shows a clear difference related to the sequence of deposition and the transitions that occurs in each film. When the first film is deposited at 385 ^{o}C and the second one at 250 ^{o}C, the combination of the stresses in the corresponding films leads to one step change in the actuation that suggests as a leading factor the stress change in the 385 ^{o}C film.

A more interesting case is the one with the films deposited in a reverse order and leading to the two step transition. This complex case is the base for the model proposed to describe the thermal actuation of trimorphs with films deposited at different temperatures.

Figs. 6 a and b show the stress in the bimorph and trimorph cantilevers deposited at two different temperatures (T_1 and T_2 respectively) on heated substrates. The Stoney equation can be used to calculate the stress based on the dispalcement of the cantilever. This is possible because the cantilever bends as a result of the interaction between one film and the substrate. By comparison, this equation cannot be used to calculate directly the stress of the trimorphs. If the expansion coefficients of the films deposited in trimorph architectures are equal, there will be no bending data to be used and the Stoney equation does not apply (it is only valid for bimorphs). In this case, the stress in the films results from adding the stresses that would have occurred in the corresponding bimorphs. The following different regions can be considered for the films deposited at two different temperatures T_1 and T_2:

- a_1, b_1 – growth of thermoelastic stresses in the corresponding bimorphs due to the difference in the thermal expansion between the NiTi films in austenitic state and the Si substrate; The corresponding slope α and β are influeced by the thermal expansion of the films.
- a_2, b_2 – stress relief in the bimorphs as result of the martensitic transformation;
- a_3, b_3 – growth of thermoelastic stresses in the bimorphs due to the difference in the thermal expansion between the NiTi film in martensitic state and the substrate;
- t_1 – the deflection of the free-end of the cantilever at a given temperature depends on the difference between the a_1 and b_1 stresses. The (a_1) stress is usually higher than (b_1) leading to a slight slope oriented toward bimorph I;

- t_2 – the onset of the transformation in bimorph I (a_1) is associated with a change in the curvature. The trimorph tends to adopt a curvature similar to the one of bimorph II
- t_3 – the transition in bimorph I is complete and its stress tends to increase (a_3), leading to an equilibrium with the stress generated in bimorph II (b_1). The trimorph actuation shows an intermediary plateau.
- t_4 – the onset of the transformation in bimorph II (b_2) leads to a similar result as the one observed during (t_1) stage, but in opposite direction.
- t_5 – the transitions in both films is complete and the stresses in the corresponding bimorphs is increasing (a_3, b_3). The trimorph tends to bend toward the higher stressed film.

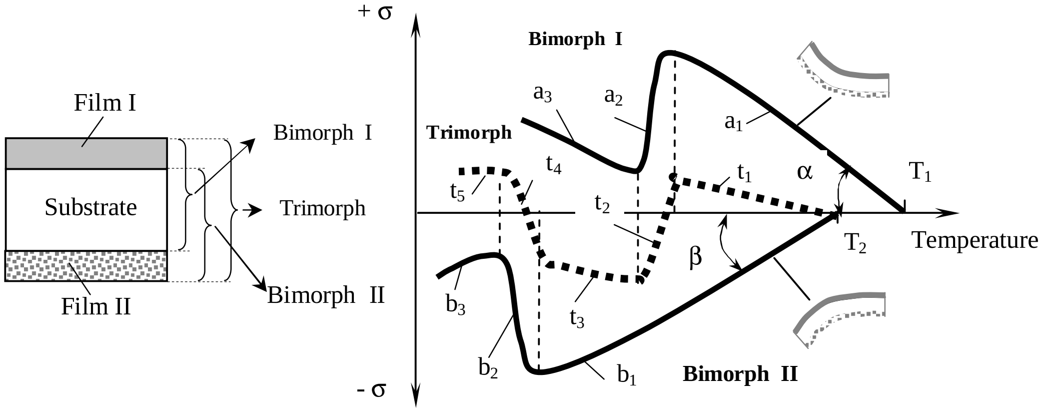

Fig. 6. Model for stress-temperature dependence for trimorph shape memory alloy architectures, compared to bimorph ones. In NiTi/Si bimorphs, the film is under tensile stress when cooled from the deposition temperature and leads to the bending of the cantilever toward the film. In trimorph architectures the bending of the two bimorphs in opposite directions is balanced by the initiation of the phase transition in each film ($a_2 \rightarrow t_2$ and $b_2 \rightarrow t_4$).

Different actuation curves can be designed using the model described before. The actuation can be adjusted through the composition of the films, the transformation temperatures or the width and the relative position of the films hysteresis.

The order of deposition for the films in the trimorph architecture is another important factor that influences the output of the trimorph actuator. The order is basically influencing the state of stress in the films, however further research needs to be carried out in order to fully understand the influence of the deposition sequence. For the specific case analized in this paper, if the first film is deposited at low temperature (250 °C) and at zero stress, it will be under compression when the so produced bimorph is heated to 385 °C for the deposition of the second film. If the succession of the depositions is reversed, then the high temperature film (385 °C) is deposited at zero stress and subsequently, when the 250 °C film is deposited, the 385 °C film will be under tension. These observations explain the differences in the behavior for the T_{t1} and T_{t2} trimorphs.

The examples presented in this paper show the possibility for increasing the range of response for the SMA actuators. The output of such actuators can be improved and diversified by selecting the type of actuator (bimorph or trimorph), the nature of the films (transforming or non-transforming) and the deposition temperatures. Additional factors can also be modified to obtain the desired actuation. The chemical composition of the films (NiTiPd films show transitions at higher temperatures [23, 24], NiTiCu films show higher actuation and lower hysteresis [23, 11], etc.), or the substrate (different substrates have different thermal expansion coefficients influencing the thermal stresses that are built in the structures).

5. Conclusions

Trimorphs architectures based on shape memory alloys are a class of actuators with extended capabilities as compared to known bimorph actuators, due to the fact that they can combine the specific properties of two films, in order to generate the actuation. Compared to bimorphs their response can be modulated in a larger range due to the interaction between films that takes place throughout the substrate.

The experiments made with films deposited out of the same NiTi alloy target, but deposited at different temperatures showed one-step and two-step actuations, depending on the order of deposition for the films. The model proposed describes how the actuator characteristics can be predetermined based on the known behavior of the shape memory bimorph actuators.

Several factors have been identified as a source for designing thermal actuation signals, such as: the composition of the films, the transformation temperatures or the width and the relative position of the films hysteresis. Such a type of actuators can provide a better response to specific needs of the current and future trends in micro-techniques.

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