Thin film shape memory alloys and microactuators

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Abstract: For Micro-electro-mechanical System (MEMS) applications, TiNi-based thin film Shape Memory Alloys (SMAs) possess many desirable properties, such as high power density, large transformation stress and strain upon heating and cooling, superelasticity and biocompatibility. In this paper, recent development in TiNi-based thin film SMA and microactuator applications is discussed. The topics related to film deposition and characterisation is mainly focused on crystal nucleation and growth during annealing, film thickness effect, film texture, stress induced surface relief, wrinkling and trenches as well as Temperature Memory Effect (TME). The microactuator applications are mainly focused on microvalve and microcage for biological applications, micromirror for optical applications and data storage using nanoindentation method.

Keywords: shape memory; TiNi; thin films; MEMS; micro-electro-mechanical system.

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1 Introduction

Shape Memory Alloy (SMA) is a metal that can 'remember' its geometry, that is, after a sample of SMA has been deformed from its original shape, it regains its original geometry by itself during heating (shape memory effect) or, simply during unloading at a higher ambient temperature (superelasticity). These extraordinary properties are due to a temperature dependent martensitic phase transformation from a low-symmetry (martesnite) to a highly symmetric crystallographic structure (austenite) (Otsuka and Ren, 2005). Shape memory effects have been found in many materials, such as metals, ceramics and polymers. Among all these materials, TiNi-based alloys have been extensively studied and found many commercial applications (Humbeeck, 1999; James and Hane, 2000). For Micro-electro-mechanical System (MEMS) applications, thin film based SMAs possess many desirable properties, such as high power density (up to 10 J/cm^3), the ability to recover large transformation stress and strain upon heating and cooling, Pseudoelasticity (PE) (or superelasticity) and biocompatibility (Kahn et al., 1998; Krulevitch et al., 1996a,b; Miyazaki and Ishida, 1999; Wolf and Heuer, 1995). The work output per volume of thin film SMA exceeds those of other microactuation mechanisms. The phase transformation in SMA thin film is also accompanied by significant changes in the mechanical, physical, chemical, electrical and optical properties, such as yield stress, elastic modulus, hardness, damping, shape recovery, electrical resistivity, thermal conductivity, thermal expansion coefficient, surface roughness, vapour permeability and dielectric constant, etc. Fu et al. (2001, 2004a,b). These changes can be fully made use of the design and fabrication of microsensors and microactuators (Winzek et al., 2004). The main potential problems associated with TiNi thin film MEMS applications include:

1. low energy efficiency, low dynamic response speed and large hysteresis
2. non-linearity and complex thermomechanical behaviour and ineffectiveness for precise and complex motion control and force tracking
3. potential degradation and fatigue problems.

Even with the above disadvantages, TiNi thin film is still considered as a core technology for actuation of some MEMS devices, where large force and stroke are essential and in conditions of low duty cycles or intermittent operation, and in extreme environment, such as radioactive, space, biological and corrosive conditions. In this paper, recent research on the TiNi-based SMA thin films and their microactuator applications have been discussed.

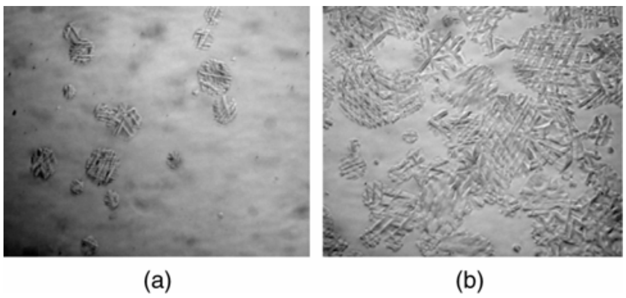
2 TiNi thin film processing and characterisation

TiNi-based films are the most frequently used thin film SMA materials and they are typically prepared using sputtering method (Fu et al., 2004a,b; Miyazaki and Ishida, 1999; Wolf and Heuer, 1995). Transformation temperatures, shape memory behaviours and superelasticity of the sputtered TiNi films are sensitive to metallurgical factors (alloy composition, contamination, thermomechanical treatment, annealing and aging process, etc.), sputtering conditions (targets and power, gas pressure, deposition temperature, etc.) and the application conditions (loading conditions, ambient temperature and environment, heat dissipation, heating/cooling rate, strain rate, etc.) (Cho et al., 2005; Miyazaki and Ishida, 1999; Quandt, 2004). Precise control of Ti/Ni ratio in the TiNi films is of essential importance. The intrinsic problems of different sputtering yield for Ti and Ni targets can be solved by cosputtering of TiNi target with another Ti target or using two separate single element (Ti and Ni) targets (Fu et al., 2004a,b; Krulevitch et al., 1996a,b) or adding titanium plates on TiNi target (Ohta et al., 2000). High deposition rate is important for MEMS application. Normally, the deposition rate is about 1 micron per hour, which is quite low. Different strategies have been proposed to increase the deposition rate (Ishida et al., 2005; Zhang et al., 2006). One problem for the compatibility with MEMS technology is that TiNi films are needed to anneal at high temperatures (between 400 and 600°C) for crystallisation. This could cause problems in the application to some substrates, such as glass or polymer materials. Martensitic transformation and superelasticity of TiNi films are sensitive to post-annealing and/or aging temperature and duration (Lehnert et al., 2002; Surbled et al., 2001), thus post-sputtering annealing should be handled with care. Detailed information about sputtering deposition of TiNi-based films can be found in Miyazaki and Ishida (1999), Fu et al. (2004a,b) and Winzek et al. (2004).

Recently the nucleation and growth mechanisms of the TiNi thin films have been systematically studied using in situ TEM technique (Lee et al., 2005) or in situ optical microscopy analysis (Wang and Vlassak, 2006). During annealing of amorphous TiNi films, crystalline grains nucleate randomly and homogeneously at the surface, grow isotropically and laterally as the parent amorphous phase is consumed (see Figure 1(a)). Growth occurs continuously as new crystals form in the amorphous matrix and the nucleated crystals continuously grow laterally until impingement with each other or until they touch the substrate (see Figure 1(b)). From both (Lee et al, 2005; Wang and Vlassak, 2006), the kinetics of crystallisation have been found to follow a Johnson-Mehl-Avrami-Kolmogorov model:

$$\phi = 1 - \exp\left(-kt^n\right) \tag{1}$$

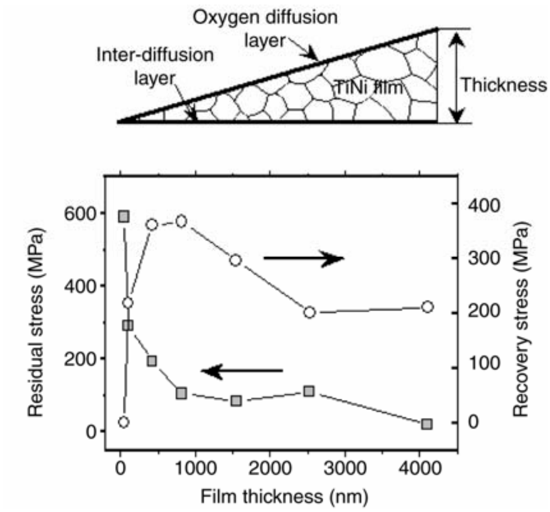
Figure 1 Optical image showing nucleation and growth of crystals within amorphous matrix during annealing (a) initial nucleation of crystals in amorphous matrix and (b) growth and coalescence of crystals



in which ϕ is the fraction of the crystallised material, K is a temperature dependent constant, n is the Avrami component, t is the holding time at a certain temperature.

Effects of film thickness on shape memory effect have been investigated by several groups recently (Fu et al., 2006a,b; Ishida and Sato, 2003; Wan and Komvopoulos, 2005). TiNi films usually undergo a high temperature between 400 and 650°C (during deposition or post-annealing). At these temperatures, the surface oxidation and interfacial diffusion between the film and substrate could significantly affect the phase transformation behaviour if the film is too thin. It is important to know how thin the TiNi-based film can go or how small the TiNi structure can be without losing the shape memory effect. In Fu et al. (2006a,b), the stress-temperature evolution for the TiNi films with different thickness was measured using the curvature method. The stress-temperature response of a 50 nm film is linear, that is, this film experiences only thermal effect (due to the difference in thermal expansion between film and substrate) with no apparent phase transformation. Thicker films (up to 4 microns thick) undergo stress/temperature hysteresis loops, demonstrating shape memory effects. During heating, the stress increases significantly due to phase transformation from martensite to austenite. During cooling, martensitic transformation occurs and the tensile stress relaxes significantly due to formation and alignment of twined martensite (Fu and Du, 2003a,b). Figure 2 shows the measured residuals stress and recovery stress of these films. Recovery stress, defined as the difference between the maximum and minimum stresses during phase transformation, is an indication of shape memory actuation ability during application. With increase of film thickness, the residual stress decreases sharply and then remains a low value, whereas the recovery stress increases significantly and reaches a maximum at a film thickness of 820 nm before it gradually decreases with further increase in film thickness.

Figure 2 Residual stress and recovery stress for TiNi films with different film thickness calculated from the stress-temperature curves by wafer curvature method (Fu et al., 2005a)



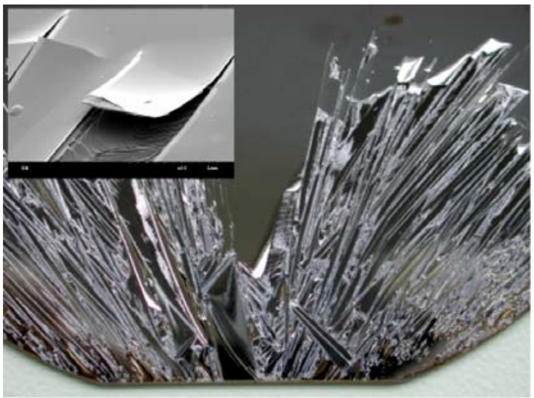
From Figure 2, it is clear that a minimum thickness (about 100 nm) is necessary to guarantee an apparent shape memory effect in the TiNi films. Surface oxide and oxygen diffusion layer as well as interfacial diffusion layer are dominant in the films with thickness of tens of nanometers (Fu et al., 2004a,b, 2006a,b). The combined constraining effects from both surface oxide and interfacial diffusion layers in a very thin film will be detrimental to the phase transformation. As the film thickness increases above a few hundred nanometers, the effects of the surface oxide, oxygen diffusion layer and interdiffusion layer become relatively insignificant. Therefore, phase transformation becomes significant and the recovery stress increases as thickness increases. Due to the significant phase transformation effect, thermal and intrinsic stresses in the films are drastically relieved, resulting in significant decreases in residual stress as shown in Figure 2. With the further increase in film thickness, more and more grain boundaries form in the films (see Figure 2). The grain boundaries are the weak points for generation of large distortion and twinning processes. Therefore, as the film thickness increases, the constraining effect from the neighbouring grains becomes more and more significant, causing decreases in recovery stress.

Shape memory and mechanical properties of the TiNi films depends significantly on the orientation of the crystal grains. Deposition conditions, film composition and post-deposition thermomechanical treatment could have important consequences on formation and evolution of the film texture. A strong film texture may lead to anisotropic shape memory effect since the recoverable strain and deformation behaviour is highly dependent on the film crystallographic orientation (Gall and Sehitoglu, 1999; Liu et al., 2005; Shu and Bhattacharya, 1998). The post-annealed crystallised TiNi films normally have a strong texture along austenite A (110) (Miyazaki et al., 2000). Whereas at room temperature, martensite (200) and (022) peaks become dominant. Hassdorf et al. deposited a TiNiCu film on the SiO_2 substrate using Molecular Beam Epitaxy (MBE) technology (Hassdorf et al., 2002), and found the film has a distinct austenite (200) diffraction peak. The crystallites are oriented within $\pm 3^{o}$ along the film plane normal. The authors pointed out that an intermediate Ti_2Ni layer is crucial for the formation of (200) texture.

Effect of film texture on shape memory effect has not been experimentally clarified yet. Under tensile load, [100] orientation is characterised as ‘hard’ since it demonstrates small uniaxial transformation strain levels and begins transforming at a significant higher stress (Gall and Sehitoglu, 1999). The film with (100) texture has a highest transformation stress compared with [111] and [110] texture. The [111] orientation is characterised as ‘soft’ since it demonstrate large uniaxial transformation strains and low critical transformation stress levels. In Shu and Bhattacharya (1998) and Miyazaki et al. (1984), based on a theoretical model, the author also showed that the recoverable strain of the TiNi film is much higher with A (111) texture, than that with the commonly observed (110) texture. However, so far, (111) dominant texture in TiNi-based films is difficult to achieve. It is clearly indicate an opportunity to improve shape memory effects of the films by targeting special textures using novel processing technique.

Residual stress and stress evolution in the films could pose potential problems in applications, as it may influence not only adhesion between film and substrate, but also deformation of MEMS structure, mechanics and thermodynamics of transformation and superelasticity effects, etc. Craciunescu et al. (2003). Large residual stress could lead to either film cracking or decohesion under tension, or film delamination and buckling under compression, with one film cracking morphology shown in Figure 3. Deposition conditions, post-deposition thermomechanical treatment and composition of the TiNi films could have important consequences with respect to the development of residual stress (Fu and Du, 2002; Grummon and Zhang, 2001). These have been studied in details and reported in Fu et al. (2003a,b). In the crystalline TiNi films, large tensile stress is generated during heating due to the phase transformation from martensite to austenite, while during cooling, the martensitic transformation occurs and the tensile stress drops significantly due to the formation and alignment of twins. The stress generation and relaxation behaviours upon phase transformation are significantly affected by film composition, deposition and/or annealing temperatures, which strongly control the formation and evolution of intrinsic stress, thermal stress and phase transformation behaviours (Fu et al., 2003a,b).

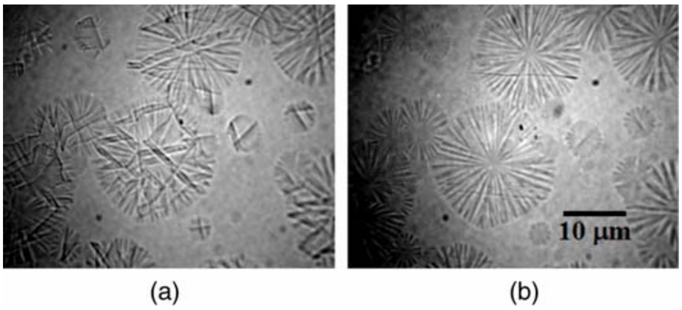
Figure 3 Fracture and cracking of TiNi films on Si wafer after annealing due to large tensile stress (see online version for colours)



Note: Inset figure shows cracks propagation in Si substrate, rather than at the film/substrate interface.

The stress evolution could have significant effect on the film surface morphology evolution. Significant surface relief (or surface upheaval), caused by the displacive martensitic transformation, is commonly observed in TiNi bulk materials and has recently also been reported in the sputtered TiNi thin films (He et al., 2004). During the martensitic transformation, the atomic displacement introduces stacking faults that lead to surface relief morphology on the film surface. A flat surface in austenite transforms to twinned martensite upon cooling and becomes rough, without a macroscopic shape change, and vice versa. Fu et al. (2006a,b) reported a phenomenon of film surface morphology evolution between wrinkling and surface relief during heating/cooling for a sputtered TiNiCu thin film. In situ optical microscopy observation with substrate heating up to 100°C revealed that the interweaving martensite plate structure (shown by the surface relief in Figure 4(a)) disappeared. However, many radial surface wrinkles form within the original martensitic structure as shown in Figure 4(b). Further heating up to 300°C did not lead to much change in these wrinkling patterns. On subsequent cooling to room temperature, the twinned martensite plates or bands reform exactly within the wrinkling patterns as those before thermal cycling. Normally on a TiNiCu film, there is an oxide and diffusion layer (Fu et al., 2005a,b). Once the nucleated crystalline TiNiCu forms, the large compressive film stress will apply on the thin surface oxide layer, surface wrinkling would occur by the elastic buckling of the elastic oxidation layer on top of crystallised TiNiCu. The wrinkles can grows radially along with the growth of crystals. During cooling, the martensitic transformation occurs and significant surface relief occurs inside these wrinkles. During heating and cooling between room temperature and 100°C, surface morphology evolution occurs between surface relief and wrinkling (Fu et al., 2006a,b).

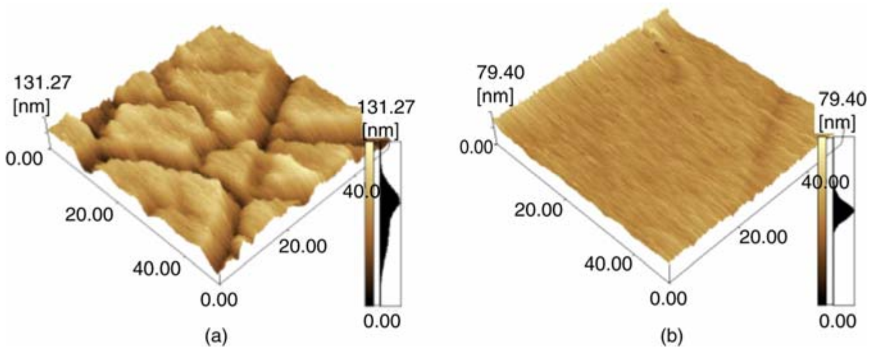
Figure 4 Evolution of surface morphology between surface relief and wrinkling patterns during heating/cooling (a) heating to 40°C and (b) heating to 55°C



Source: Fu et al. (2006a,b).

After post-annealing of a partial crystallised TiNiCu films at 650°C, optical microscopy (at room temperature) revealed an interconnected network structure of trenches on the film surface (Wu et al., 2006). In situ observation using optical microscopy, interferometry and AFM during heating/cooling showed that these trenches (see Figure 5(a)) gradually disappear on heating, and the film surface becomes smooth and featureless (reflective and shiny, see Figure 5(b)). On subsequent cooling the trenches reappear, with almost the identical surface morphology as present before heating and the surface becomes slightly opaque and cloudy. However, the exact mechanisms have not been clarified yet. These trenches should not be surface cracks since during heating they fully disappear. The formation of surface trenches could be explained using stress induced surface wrinkling with the consideration that large stress in annealing exerts in a thin oxide layer on the TiNiCu film.

Figure 5 Surface morphology of TiNiCu film from AFM analysis (a) trenches at room temperature (20°C) in martensite state and (b) smooth and featureless morphology at 90°C in austenite state (see online version for colours)

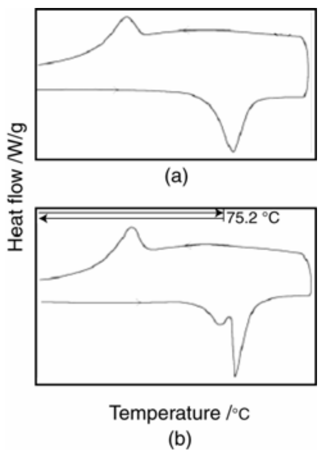


Source: Wu et al. (2006).

Adhesion of the TiNi films on different substrates is one concern for their successful MEMS applications. TiNi film adheres well to silicon substrate provided it is clean. TiNi films deposited on a glass substrate can be easily peeled off, which is quite useful to obtain free-standing films. In MEMS processes, there is a need for an electrically and thermally insulating or sacrificial layer. Thermally grown SiO_2 is often used as this sacrificial layer. However, the adhesion of TiNi film on SiO_2 layer is poor owing to the formation of a thin intermixing layer and the formation of a fragile and brittle TiO_2 layer (Fu et al., 2003a,b). In a significant deformation or during a complex interaction involving scratch, this layer is easily broken, thus peel off. Fu et al. (2004a,b) reported that the addition of Si_3N_4 interlayer between film and Si substrate did not cause much change in phase transformation behaviour as well as adhesion properties. There is significant interdiffusion of elements and formation of Ti-N bond at the Si_3N_4/TiNi interlayer. If compared with poor adhesion results of TiNi films on SiO_2 interlayer, Si_3N_4 interlayer seems a good choice for an electrically insulating and diffusion barrier layer in respect of adhesion properties. Adhesion of TiNi films on polysilicon and amorphous silicon layers is also quite good.

A new phenomenon, Temperature Memory Effect (TME), has also been reported in the TiNi-based films (Wang and Zu, 2005). An incomplete thermal cycle upon heating in a SMA (arrested at a temperature between austenite transformation start and finish temperatures, A_s and A_f) induced a kinetic stop in the next complete thermal cycle (Zheng et al., 2004), and the kinetic stop temperature is a 'memory' of the previous arrested temperature (see Figure 6) (Wang et al., 2005). If a number *N* of incomplete heating with different arrested temperatures is performed with decreasing order, *N* temperatures can be memorised. TME can be eliminated by appropriate complete transformation heat cycle. During the partial reverse transformation, only part of the martensite transforms into the parent phase, with the rest of the martensite, M1, remaining. With further decreasing the temperature below martensitic transformation finish temperature, the parent phase transforms back to martensite and the newly formed martensite is called M2. M1 and M2 have different orientation structures and different elastic energies between martensitic variants, which cause the different transformation temperatures of M1 and M2 into austenite during the next heating process. On the contrary, if a partial austenite to martensite transformation is performed by an incomplete cycle on cooling, the next complete austenite to martensite transformation does not show any evidence of kinetic interruptions. During heating, interruptions in both thermally and external-stress induced transformations exhibit TME.

Figure 6 DSC results of (a) TiNiCu4 film and (b) TME of same sample with a single incomplete cycle on heating at 75.2°C



Source: Wang et al. (2005).

3 Microactuator applications of TiNi films

Free-standing films usually show intrinsic ‘two-way’ shape memory effect, with large displacement. This is applicable in microsensors, microswitches or micropositioners. The origin of the two-way shape memory effect observed in the TiNiCu films can be attributed to the difference in sputtering yields of titanium and nickel, which produces a compositional gradient through the film thickness (Gill, 2002; Gyobu et al., 2001). The film layer near the substrate is normally nickel rich, and no shape memory effect is observed, but the material may possess superelasticity. As the Ti/Ni content changes through the film thickness, the material properties change from being superelastic to having a shape memory. A stress gradient is generated due to the changing microstructure and composition as a function of thickness. The bottom layer of material is under a compressive stress relative to the higher layers and so the film layer extends dramatically upon release from the substrate, causing free-standing structures to bend upward. When heated, the film layer returned to flat position due to shape memory effect. Figure 7 shows some examples of simple structure which can be actuated by heating/cooling through this two-way shape memory effect.

Figure 7 Free-standing TiNi-based film structures (a) a microtweezer structure which have both horizontal and vertical movement due to both shape memory and thermal effects, (b) microstent which can be opened by heating, (c) a micromirror structure which can be actuated by four arms when electrically heated, (d) microfinger which can operate both horizontally and laterally, and can be designed and integrated into a walking robotics, (e) microcage structure with fingers opening/closing by two-way effect and (f) microspring structures

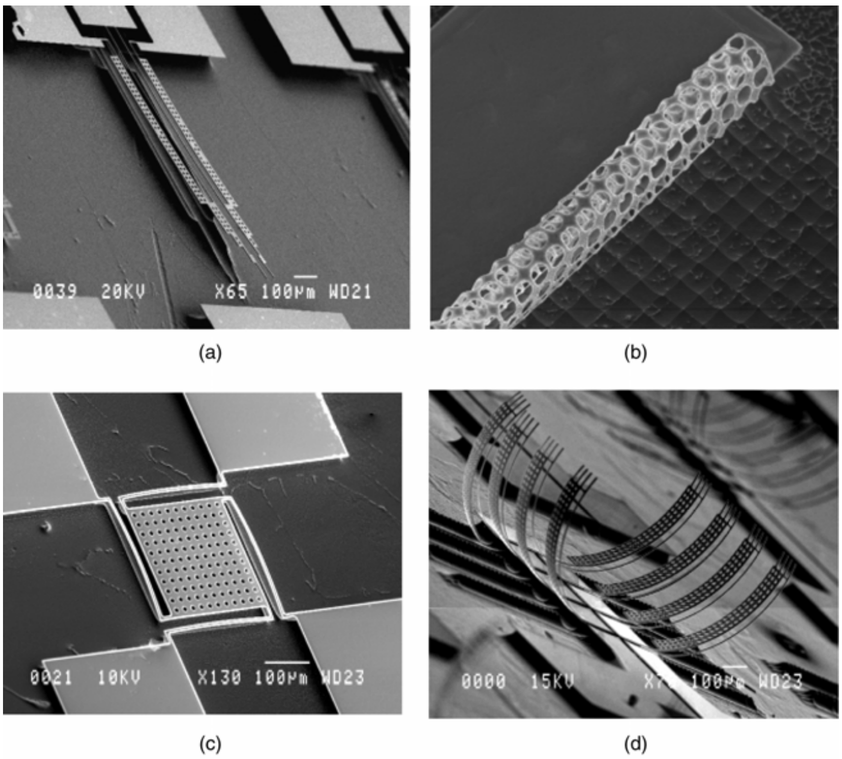
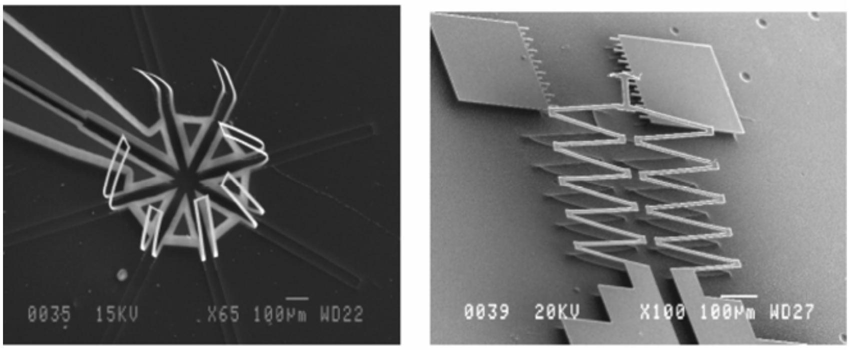


Figure 7 Free-standing TiNi-based film structures (a) a microtweezer structure which have both horizontal and vertical movement due to both shape memory and thermal effects, (b) microstent which can be opened by heating, (c) a micromirror structure which can be actuated by four arms when electrically heated, (d) microfinger which can operate both horizontally and laterally, and can be designed and integrated into a walking robotics, (e) microcage structure with fingers opening/closing by two-way effect and (f) microspring structures (continued)



(e) (f)

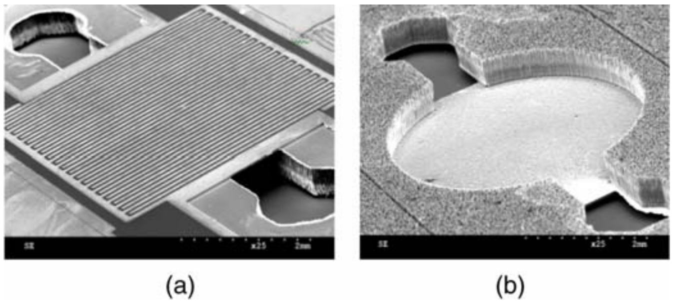
Problems associated with the free-standing films include limited force in actuation and potential degradation in performance. The constrained film/substrate (bimorph) actuators could provide large actuation force, although sacrifice the deflection (or strain). The substrate may act as an effective biasing force, thus creating a mechanical 'two-way' shape memory effect. Since TiNi films can provide large forces for actuation and large displacement, therefore, most applications of TiNi films in MEMS are focused on microactuators, such as micropumps, microvalves, microgrippers, microcage, etc.

MEMS-based micropumps and microvalves are attractive for many applications such as implantable drug delivery, micro on-chip chemical analyser and analytical instruments, etc. MEMS-based microfluidic device differs from the conventional macroscale devices. The dominance of surface tension forces in liquids requires the device to have large force and stroke to achieve acceptable flow rates, and TiNi thin films are promising for these applications. There are different designs for TiNi film based micropumps or microvalves, and most of them use TiNi/Si membrane (or diaphragm, microbubble, etc.) for actuation (Benard et al., 1998; Kohl et al., 1999; Liu et al., 2004; Makino et al., 2001). The advantages of using TiNi/Si membrane as the driving diaphragm include (Xu et al., 2001):

1 large actuation force
2 simplicity in process and no special bias structure needed because the silicon substrate can provide bias force
3 no isolating structure is needed because silicon structure can separate the working liquid from SMA film completely.

Figure 8 shows a simple valve fabricated based on a membrane structure. The pump is of a simple reciprocating nature, with a TiNi/Si bimorph diaphragm and inlet and outlet to ensure unidirectional flow. The TiNi/Si bimorph diaphragm is flat at room temperature, and turns to concave when the TiNi electrode is electrically heated. The reduced chamber pressure causes the fluid to flow into pump chamber from one inlet. When the current is turned off, the bimorph diaphragm will be cooled and the TiNi/Si membrane will be pulled back to its original shape under the structure bias force, thus the fluid in the chamber will be pressed and squeezed out of the chamber.

Figure 8 TiNi microvalve fabricated with TiNi electrode on silicon membrane structure (a) top view of membrane and TiNi electrode and (b) bottom view



Wireless Capsule Endoscope (WCE) is a new diagnostic tool in searching for the cause of obscure gastrointestinal bleeding. A WCE contains video imaging, self-illumination, image transmission modules and a battery (Iddan et al., 2000; Waye, 2003). The indwelling camera takes images and uses wireless radio transmission to send the images to a receiving recorder device that the patient wears around the waist. However, there are two drawbacks for the current WCE:

1 lack of ability for biopsy

2 difficulty in identifying the precise location of pathology.

Without tissue diagnosis, it is often difficult to differentiate inflammatory lesions from tumour infiltration. The former may require only medical treatment while the latter may need surgical solution. Therefore, there are two potential microactuator applications in capsule endoscopy:

1 microgripper for biopsy or tissue sampling

2 microclipper or pin tagging device, to firmly attach to the tissue.

SMA thin film based microactuators are promising for these applications.

For these biological applications, microgripper has been widely studied (Gill, 2001; Huang et al., 2004; Sugawara et al., 2006; Takeuchi and Shimoyama, 2000). One common design for microgripper is out-of-plane bending mode, mostly with two integrated TiNi/Si cantilever (or other substrates, such SU-8 or polyimide, etc.) with opposite actuation directions (Lee et al., 1996; Seidemann et al., 2002). The force and displacement generated can be very large. Another gripper design is in-plane mode, in which the deformation of two arms (using free-standing TiNi films or TiNi/Si beams) is within a plane realised by compliant structure design (Wang et al., 2002). The problems associated with this design include: small force generated and out-of-plane bending caused by intrinsic film stress.

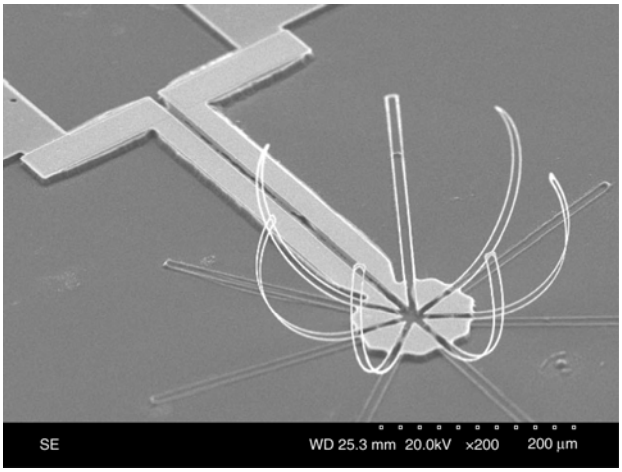
Compared with the conventional microgrippers or tweezers, a microcage captures the microobject by confining or trapping it without applying a force directly on the object, thus avoiding a potential damage to the ‘captive’. There are some successful studies on fabrication of microcage based on nickel and DLC bimorph structure (Luo et al., 2005). A highly compressively stressed DLC lifts the DLC/metal fingers upwards once they are released from the substrate, forming a closed microcage. By electrically or thermally heating, the microcage can be opened to capture objects. Based on the similar idea, a microcage based on the bimorph TiNi/DLC structures have been fabricated as shown in Figure 9. After released from Si substrate, the opening of the microcage tips can be controlled by changing thickness ratio of the two layers, the finger length and stress state in both TiNi and DLC layers. During thermal cycling, the opening/closing performance of the microcage is mainly determined by:

1 thermal effect, that is, temperature change and the difference in the Coefficients of Thermal Expansion (CTE) of the two materials

2 shape memory effect.

Based on thermal and shape memory effects, there are two possible changes. When heated to about martensitic start transformation temperature, martensite (loose structure) changes to austenite (a dense structure), causing the closing of the microcages to capture the microobject. Release of the microstructure can be realised either by decreasing the temperature or by further increasing in temperature to cause the gradual opening of the microfinger (thermal effect).

Figure 9 TiNi/DLC bimorph microcage structure



TiNi film can be used as a lever to move optical lens up or down (instead of left or right), thus forming an out-of-plane microactuator for optical switches (Fu et al., 2004a,b). Figure 10 shows morphologies of multicantilevers of TiNi/Si_3N_4 bimorph structure. At room temperature, these cantilevers bend up due to the bimorph effect. When thermally or electrically heated, the cantilevers show shape memory effect and they become flat. The potential areas of micromirror applications include field emission flat panel displays technology, in which TiNi film based microactuators can erect a large number of micromachined spacers between the pixels. Figure 11 shows a *V*-shaped cantilever-based structure with a square Si cap (40 µm thick) as the top mirror (Fu et al., 2005a,b, 2008). In operation, electrical current will be applied to the TiNi electrodes, resulting in an increase of temperature in the TiNi beam. Transformation from martensite to austenite causes the generation of large tensile stress, resulting in the bending of the *V*-shaped beam and thus the mirror cap. The TiNi/Si beams will be flat at room temperature, and bent up after applying voltage on TiNi electrodes, thus causing the angle changes of micromirror. The estimated maximum angle change was about 15–20°. The maximum frequency response detected by the naked eye was about 20–30 Hz.

Figure 10 Micromirror made of TiNi/Si_3N_4 bimorph multicantilevers (a) room temperature and (b) at high temperature of 100°C (see online version for colours)

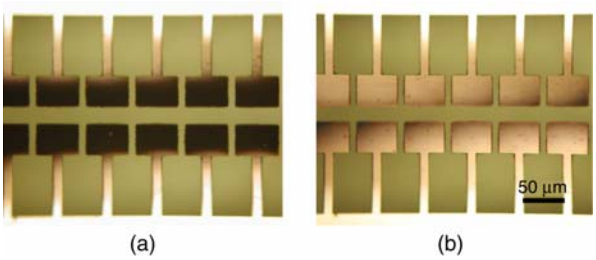
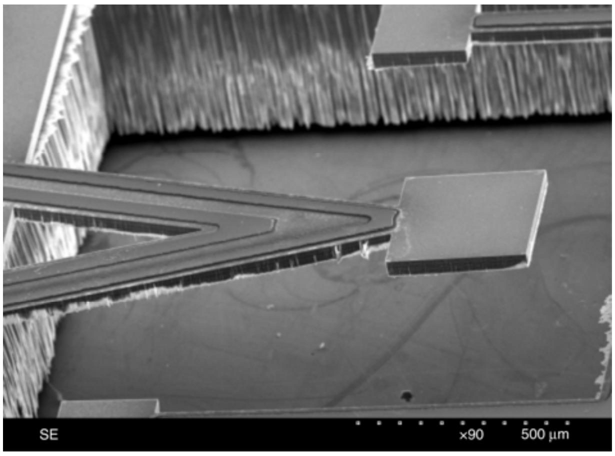


Figure 11 Cantilever-based micromirror structure with a square Si cap as the mirror



Source: Fu et al. (2005a,b).

Nanoindentation testing with or without changes of temperature could reveal the different elastic and plastic deformation behaviours of austenite and martensite, thus is promising for characterisation of superelasicity, phase transformation, shape memory effect and mechanical properties of the constrained thin films (Ni et al., 2002; Shaw et al., 2003). During loading and unloading in nanoindentation, there is large force hysteresis, that is, large energy dissipated during loading/unloading in the TiNi-based thin films. During the reverse phase transformation, the martensite variants must overcome the internal stress generated during phase change in order to shrink back to the parent austenite matrix. Therefore, energy is dissipated as friction heat due to the imperfect austenite matrix and the martensite. The energy dissipation associated with the pseudoelastic behaviour contributes to the high vibration damping capacity of the TiNi films.

Nanoindentation test is one promising method for characterisation of nanoscale PE (Ma and Komvopoulos, 2003). The PE behaviour of the TiNi-based thin films demonstrates their intrinsic capacity to undergo large deformations without permanent surface damage, or called self-healing behaviour (Ma and Komvopoulos, 2003; Ni et al., 2002). However, using a sharp tip, it is difficult to obtain pseudoelastic behaviour, since the plastic deformation due to dislocation movement is dominant than the phase transformation (Zhang et al., 2005). Therefore, spherical-shape tips have been widely used recently to characterise the nanorange superelasticity behaviour of TiNi and thin films. Indentation using a spherical indenter could avoid large plastic deformation if the indentation force is not too high. During nanoindentation of SMA thin film using a spherical indenter, Yan et al. (2006) found that there exist two characteristic points, the bifurcating point and the returning point in one indentation loading/unloading curve, which reply much on the forward transformation stress and the reverse transformation stress. They proposed a method to determine the transformation stresses of SMA film based on the measured bifurcating and returning forces (Yan et al., 2006).

Nanometer scale indentations in TiNi thin films, for example, less than 100 nm in depth can be fully recovered on further heating due to thermally induced martensitic transformation (Shaw et al., 2003). Using spherical indentation method, surface protrusions can be made on TiNi shape memory surfaces, and then the indented surface can be planarised to restore a flat surface. Upon heating, reversible circular surface protrusions can be produced due to two-way shape memory effect (Zhang et al., 2006). SMAs with shape relief ability can find more optical and mechanical applications for their greater load bearing capacity and/or better durability than normally used polymers.

Information storage technology has undergone a revolution for the past years, however, the magnetic storage is reaching to a fundamental limits of about 100 Gbit/in^2 (or 6500 nm^2 bit^{-1}) (Chikazume, 1997). The reason is that with the shrinkage of the size of magnetic domains, the fluctuation in temperature could easily cause the randomly changing of the moments of the magnetic domains, thus lose the stored data. Recently, nanoindentation method has been proposed to use for high-density mechanical storage applications (Shaw et al., 2005). The storage devices with capacities 1 Tbit/in^2 can be expected to achieve. The write-read or erase-rewrite operations can be performed with a nanoindenter and atomic force microscope. Information was written into the martensite thin film with mechanically forming nanoindentation on a TiNi film with probe tips. The indentation was then scanned and heated using the nanoindentation tip in situ to cause shape memory effect, thus erasing the data recorded. Subsequent rewriting can be performed using the indentation process. For this application, the use of shaper probes than the relatively blunt or spherical diamond indenter could increase storage density. However, as already pointed out in Shaw et al. (2005), there are some drawbacks with this mechanical storage method: slow speed, strong dependence on film planarity (and roughness) and tip wear.

4 Summary

Some important issues pertaining to the preparation of high performance shape memory TiNi films using sputtering methods and their MEMS applications were discussed in this paper. The issues related with film deposition and characterisation are mainly focused on crystal nucleation and growth during annealing, film thickness effect, film texture, stress induced surface relief, wrinkling and trenches and TME. The microactuator applications are mainly focused on microvalve and microcage for biological applications, micromirror for optical applications and data storage using nanoindentation method. TiNi film-based micoractuators will find potential applications in medicine, aerospace, automotive and consumer products, especially for medical microdevices and implantable applications.

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