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Thin film shape memory alloys for optical sensing applications

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Abstract. Based on shape memory effect of the sputtered thin film shape memory alloys, different types of micromirror structures were designed and fabricated for optical sensing application. Using surface micromachining, TiNi membrane mirror structure has been fabricated, which can be actuated based on intrinsic two-way shape memory effect of the free-standing TiNi film. Using bulk micromachining, TiNi/Si and TiNi/Si_3N_4 microcantilever mirror structures were fabricated.
Keywords: TiNi, film, shape memory, sputtering, micromirror

1. Introduction

Shape memory alloy (SMA) is a metal that can "remember" its geometry, i.e., after a sample of SMA has been deformed from its original shape, it regains its original geometry during heating (shape memory effect) or, simply during unloading (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) [1]. Shape memory effects have been found in many materials, such as metals, ceramics, and polymers. Among all these materials, TiNi based alloys have been extensiviely studied and found many commercial applications. For micro-electro-mechanical system (MEMS) applications, thin film based shape memory alloys (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, peudoelasticity (or superelasticity) and biocompatibility [2-5]. The large surface to volume ratio of the TiNi thin films results in higher frequency response than that of bulk SMA. The work output per volume of thin film SMA exceeds those of other micro-actuation mechanisms. The phase transformation in SMA thin film is also accompanied by significant changes in the mechanical, physical, chemical, electrical and optical

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properties [2-4]. These changes can be fully made use of the design and fabrication of microsensors and microactuators.

So far, MEMS applications of the TiNi films have been focused on microactuators, such as microgrippers, micropump or microvalves [2-7]. TiNi film based structures are promising for optical applications. When the TiNi film undergoes a phase transformation, both its surface roughness (corresponding to light scattering) and its refractive index change [8,9]. The reflection coefficient of the austenite phase is higher than that of the martensite phase by more than 45%, thus it is possible to use TiNi films as a light valve or on-off optical switch for spatial light modulators. Apart from surface relief morphology, there are other types of surface morphology changes, which can show significant change in surface roughness, for example, surface wrinkling [10] and surface trenches [11]. However, as reported in the ref [11], the change in the surface roughness or refractive index in the film is rather limited, and also it is strongly dependent on the film composition and performance. For optical applications, the TiNi film can be used as a lever to move optical lens up or down, forming an out-of-plane microactuator for optical switches. Actuation can be realized by electrically local heating or using external heating sources, such as laser beam or infrared. In this paper, using both surface and bulk micromachining techniques, different types of micromirror structures were designed, fabricated and characterized for optical applications.

2. Optical application based on free-standing TiNi film

TiNi films with thickness of 3.5 microns were deposited on Si (100) substrate by co-sputtering an equiatomic TiNi target (RF, 400W) and a Ti target (DC, 70W) using an R.F. magnetron sputtering equipment. An Ar gas pressure of 0.8 mTorr was used in sputtering. After the deposition, the films were annealed at a temperature of 600°C in a vacuum at 1×10^{-7} Torr. Film composition determined by energy dispersive X-ray microanalyzer (EDX) is Ti: 50.3 at.%, and Ni, 49.7 at.%. Micro-devices were fabricated by photolithogaphically patterning 4.8 μm thick layers of AZ4562 photoresist on top of the TiNi films. $HF:HNO_3:H_2O$ (1:1:20) solution was employed to etch the TiNi films and form the micro-actuator patterns. The etch rate for the TiNi film is about 0.6 μm/min. The silicon substrate beneath the TiNi patterns was isotropically etched by SF_6 plasma until the free-standing TiNi structures were released. Etch rate of the Si substrate is about 0.8 μm/min.

Fig. 1 shows cantilever based micromirror structures which can be actuated through the intrinsic two-way shape memory effect of the free-standing film. The actuation performance of the released micro-actuators was demonstrated by simply heating the structure on a hot plate up to a maximum temperature of 100°C. Vertical displacement of about two hundred micrometers can be achieved. Figure 2(a) shows another design of TiNi micromirror structure based on the free-standing TiNi film. The micromirror is composed of a TiNi membrane cap as the mirror and four flexible beams with the corresponding TiNi electrical circuits and pads. The flexible beams are designed as the arms to support the cap, guide the out of plane motion and actuate the mirror. In operation, electrical current will be applied to the thermal element (TiNi electrodes), causing the increase in temperatures in TiNi. The TiNi microbeams will bend up at room temperature due to the film intrinsic gradient stress, and becomes flat after applying current in TiNi electrodes and causing the angle changes of micromirror, as is clearly shown in Fig. 2(b) and (c).

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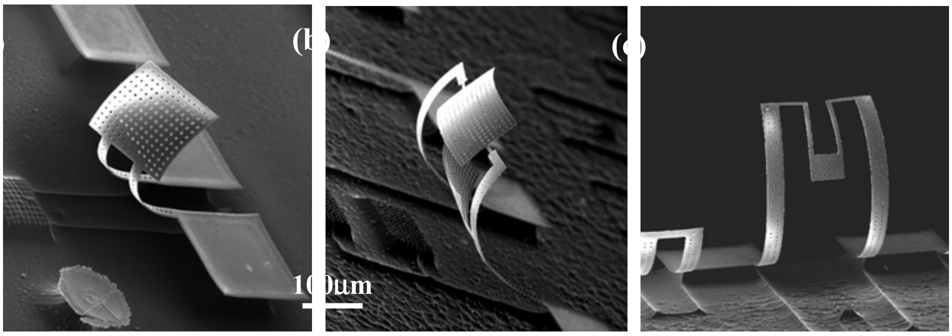

Figure 1. *Cantilever based micromirror structure which can be actuated through the intrinsic two-way shape memory effect of the free-standing film*

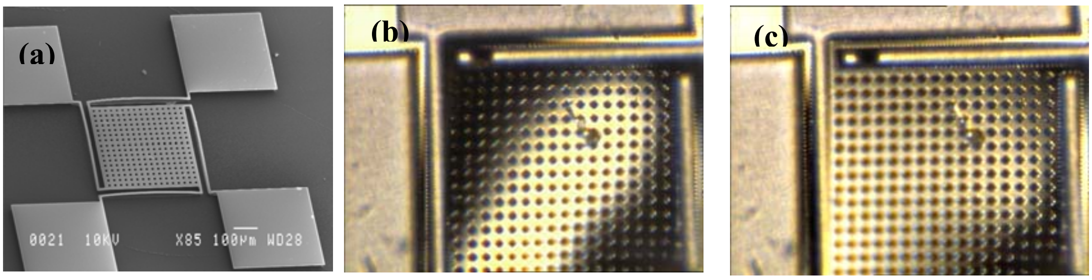

Figure 2. *TiNi micromirror structure actuated by four flexible beams (a) SEM morphology; (b) and (c) micromirror actuation through electrically heating in the arm beams*

Fig. 3 shows another design of the micromirror structure. The device consists of four arms with complaint spring structures to actuate the micromirror. Each arm is made up of two beams, one of which is wide and another is narrow. When a current is passed through each arm, the higher current density in the narrow beam causes it to be heated up more than the wide beam, leading to both vertical (shape memory effect) and horizontal (thermal effect) movement through a simple difference in thermal expansion between the two beams. It should be pointed that in Fig. 3, the micromirror cap did not fully released from the Si substrate yet in the figure.

3. TiNi/Si micro-mirror structure

The bimorph TiNi/Si cantilevers were fabricated to demonstrate the bending performance. The advantage of using SMA/Si beams as the driving force is that no special bias structure is needed because the silicon beam can provide bias force for pulling back to its original shape after removing the electrical current. Fig. 4 shows the MEMS process of the patterned TiNi electrode on Si cantilever. A 3.5 μm thick TiNi film was sputtering-deposited onto the Si_3N_4/ Si substrate. The TiNi films were photolithographically patterned using the first mask, then a mixture of HF:HNO_3:H_2O (1:1:20) was used to etch the TiNi film and the electrode patterns were obtained. The second mask was used to define the cantilever structure. The Si_3N_4 layer and the beneath Si substrate were further etched up to about 50 microns using deep reactive-ion-etching (DRIE). The backside nitride layer was patterned and etched using RIE with CF_4+O_2 (9/1) plasma. DRIE was used to etch through the Si, until the

TiNi/Si bimorph cantilever was obtained as shown in Fig.5.

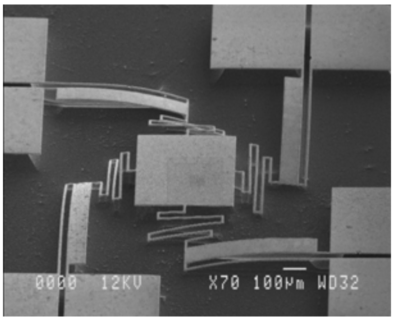

Figure 3. *Micromirro design consisting four arms with complaint spring structures to actuate the micromirror*

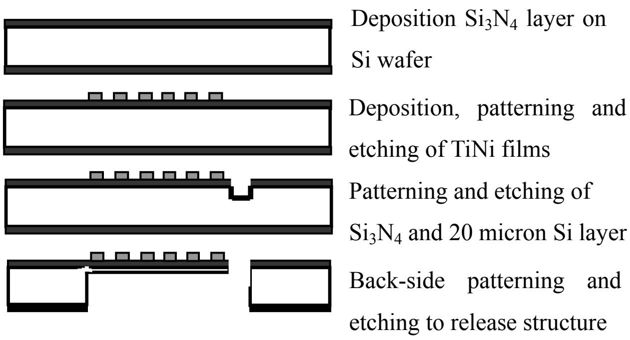

Figure 4. *MEMS processing of the TiNi/Si cantilever with TiNi as electrodes*

The actuation performance of the micro-actuators was evaluated by passing a current through the patterns and resistively heating the film. The current was provided by a Keithley 224A voltage/current power supply generating a square-wave voltage signal and this allowed actuation as a function of frequency. Fig. 6 shows the measured tip displacement produced by passing a current through the electrodes as a function of the voltage amplitude and frequency signal applied. It is clearly seen that a higher voltage could results in a high bending up displacement, due to the higher energy input. For frequencies below ~60 Hz, the tip displacement increases with applied voltage. However, at a frequency larger than ~60 Hz, the displacement decreases with increasing frequency for all applied voltages, indicating that delay time is required to cool the microstructure due to the thermal capacity of the system.

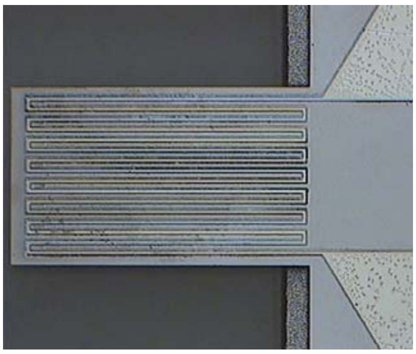

Figure 5. *TiNi/Si cantilever structure with patterned electrodes*

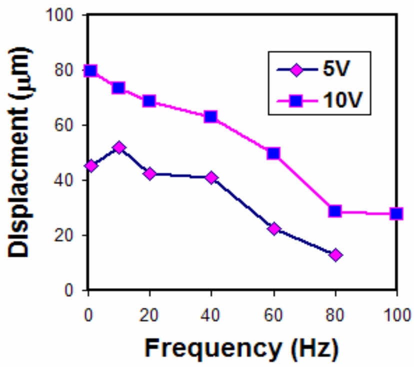

Figure 6. *Tip displacement of micromirror as a function of the voltage and frequency*

Fig. 7 shows another design of the TiNi/Si bimorph micromirror, which uses a square Si cap (40 µm thick) as the top mirror. A V-shaped TiNi/Si beam structure (40 µm thick) acts as the actuating element. The MEMS process is similar to that shown in Fig. 4. Figures 7(b) and (c) are optical microscopic images of the micromirror structures before and after an electrical current is applied, and significant tilting for the TiNi/Si micromirror structures can be observed. The deformation of the beam tip was measured using a CCD camera connected to a computer under different temperatures. Fig. 8 shows the estimated deflection of TiNi micromirror tip with the application of different powers with fixing voltage of 5 V and gradually increasing the current. When the current is less than 30 mA, the tip deflection does not show much change. With further increase in currents, the tip deflection increases significantly (due to phase transformation and shape memory effect) until above a current of 90 mA. Further increase in the current results in the slight decrease in tip deflection. Above a current of 140 mW, optical observation on TiNi surface reveals that the film color gradually changes, indicating the oxidation or deterioration of the film properties. The estimated maximum angle change is about 15^{o}. The maximum frequency response detected by the naked eye in this study is about 30 Hz. However, it is observed that the higher the frequency, the smaller the deflection of beams.

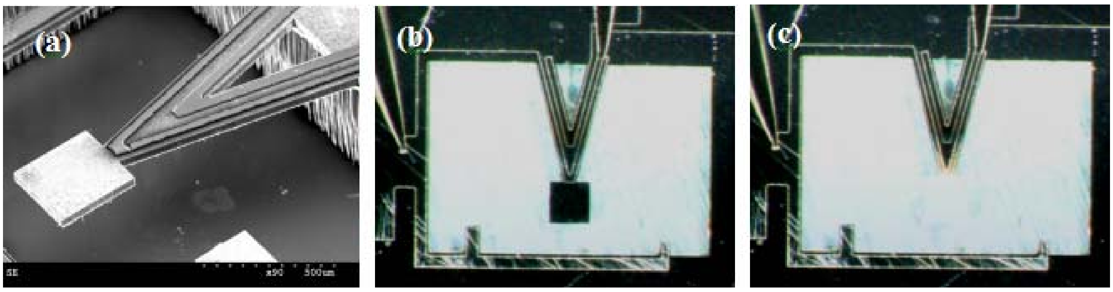

Figure 7. *Cantilever-based micromirror structure with a square Si cap as the mirror (b) without electrical current and (c) after applying electrical current*

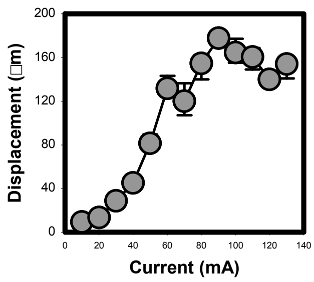

Figure 8. *Tip displacement as a function of current for TiNi/Si micromirror shown in Fig. X*

4. TiNi/Si_3N_4 microcantilever

Micromirror structures were fabricated with bimorph TiNi/Si_3N_4 system. Low stress Si_3N_4 layer of 2 microns was deposited on Si wafer, then patterned into cantilever mirror structure and etched using RIE process. The beneath Si have been etched using KOH until the free-standing Si_3N_4 structures obtained. The fabricated TiNi/Si_3N_4 mirror is shown in Fig. 9. TiNi film was deposited on the Si_3N_4 cantilever. After deposition, the cantilever beams bend down significantly due to large compressive stress in the amorphous TiNi film. After annealing the films at 650^{o}C for one hour for crystallization, the bimorph structure bends up due to bimorph thermal effect as shown in Fig. 9. When heated using a hot plate, the cantilevers show shape memory effect, and they become flat as can be seen clearly in Fig. 10, forming a micromirror design.

5. Conclusions

Different types of TiNi based optical micromirror structures including free-standing TiNi films, TiNi/Si, TiNi/ Si_3N_4 bimorph structures were designed and fabricated in this study. The microbeams are either bending up or flat at room temperature, and then becomes flat or bends up with either heating the structure above 80°C or applying voltage in TiNi electrodes (due to phase transformation and shape memory effect), thus causing the changes in angles of micromirror.

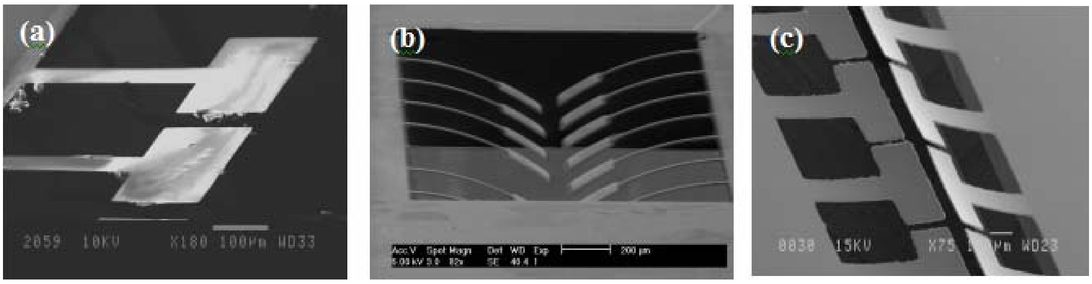

Figure 9. Bimorph TiNi/Si_3N_4 micromirror; (a) free-standing Si3N4 cantilever; (b) bending down of TiNi/Si3N4 bimorph structure after amorphous TiNi film deposition; (c) cantilever bending up after crystallization

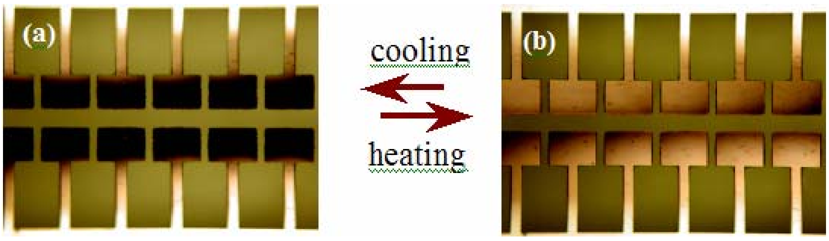

Figure 10. *Observation of micromirror structure bending when heated using a hot plate up to 100°C*

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