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A Comparative Study of PZT-Based & TiNi- Shape Memory Alloy Based MEMS Microactuators

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Abstract:

In this paper, we are interested in drawing a comparison between PZT & TiNi shape memory alloy (SMA) thin films using microelectromechanical systems (MEMS). Also, we present a new hybrid heterogeneous structure. Different characteristics are investigated in this comparative study. Based on the comparison made, it was shown that TiNi-SMA based microactuators can serve higher flow rates in fluid systems and at low operating voltages in comparison with that provided by PZT-Based microactuators. Another concluded result indicates that the fast response and the high operating frequencies are provided by PZT-based microactuators, but displacement is relatively small, whereas TiNi-SMA has a slow response frequency and a large force-displacement. By combining TiNi and PZT films, we proposed in our paper a new hybrid heterogeneous structure that can utilize the unique properties of the individual bulk materials and present large displacement and multiple responses.

Keywords : PZT films; TiNi films; MEMS; Piezoelectric Thin Films; Shape Memory Alloy(SMA); Composite; Smart Material.

1. Introduction

Microelectromechanical systems (MEMS) are the core of the technology of miniature chip device, which integrates mechanical elements, sensors, actuators and electronics. MEMS are components between 1 to 100 micrometers in size, and MEMS devices range in size from 20 micrometers to a millimeter. MEMS were used in 1980s in USA, but they were commercially used in the early 1990s in automotive industry [1].

Over the last decade, this field has been growing daily with a motivation to make smaller and smaller MEMS. They are not only smaller, but also cheaper and more functional with fast response times. A weather station that measures temperature, humidity and barometric pressure can be built on a single chip. Conditions inside living bodies can be monitored, using implanted sensors and tiny submarines that can travel through the bloodstream. Different commercially applications of MEMS are found in automotive, military, telecommunications and aerospace industries. MEMS devices act as impact sensors in the accelerometers of automobile airbags. They also act as micronozzles in commercial inkjet printers [1].

MEMS microstructures are manufactured either through surface micromachining in which successive layers of material are deposited on a surface and then etched to shape or through bulk micromachining where the substrate itself is etched to produce a final product. Different challenges are found in designing MEMS devices, such as finding skilled engineers with an adequate knowledge of micromechanical systems, materials and target manufacturing processes. Another challenge is transferring data between separate electronic and mechanical design teams who handle system and component-level development. Efforts are extending to optimize performance and improve the reliability of MEMS.

The world has gone through two material ages: the plastic age and the composite age, and a new area has developed in between, which is called smart materials. Smart materials are materials that receive, transmit, or process a stimulus and respond by producing a useful effect that may include a signal upon which the materials act. The action of receiving and responding to stimuli to produce a useful effect must be reversible [1]. Although a few materials that possess these capabilities are available so far, there are some materials that have multi-functions, such as shape memory alloys and piezoelectric materials [2].

SMA possesses the unique ability to recover their shape against strong deformations. They, particularly, exhibit an extremely interesting mechanical behavior as a function of temperature; they get deformed at low temperature since they will stay deformed until heated above some threshold temperature when they spontaneously return to the original

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shape, with a mechanism involving large mechanical strengths [3]. SMA has been seen as a plighting and high performance material in MEMS applications, since standard lithography techniques can be used to pattern in batch process. Also, thin film SMA has a very small amount of thermal mass, thus the response time is reduced and speed of operation is increased significantly.

Piezoelectric materials are very important functions. Multiphase piezoelectric composites were developed for their synergetic effect between the piezoelectric activity of monolithic ceramics and the low density of nonpiezoelectric polymeric materials. One of the developed classes is the smart tagged composites. These piezoelectric composites are PZT-5A particles that are embedded into an unsaturated polyester polymer matrix and are used for structural health monitoring [1].

Section Two deals with literature review and available applications. Material characteristics of PZT and TiNi-SMA thin films are presented in Section Three, followed by aspects of comparison in Section Four concerning preparation and fabrication techniques in 4-1, operating conditions in 4-2, applications of TiNi-SMA and PZT based MEMS in subsection 4-3, and finally obstacles and challenges in Section Five. The proposed new hybrid heterostructure is presented in Section Six. Finally, conclusions and recommendations are summarized in Sections Seven.

2. Literature Review and Available Applications

Yongqing Fu. et al. in [4] discussed preparation, characterization, considerations, residual stress and adhesion, frequency improvement fatigue and stability, and modeling of behavior as well as composite thin films. A comparison of TiNi-SMA microactuation was made with other microactuation methods (High performance) TiNi-based films were deposited at a relatively high temperature (about 400°c). An AFM based in-situ testing method have been used to characterize phase transformation behavior of the deposited films. They concluded that TiNi actuators at micro-scale, out-performs other actuation mechanisms in work/volume vatio, large deflection and force but with a relatively low frequency (less than 100 Hz) and efficiency as well as non-linear behavior.

Yongoing Fu et al. in [5] designed and fabricated new types of TiNi thm film based microactuators, such as microgrippers, microvalues and micromirror using MEMS techniques. TiNi films were etched at room temperature using HF:HNO3:H2O (1:1:20). AZ 9620 positive photoresist with thickness of 10 μm was used as a mask. They concluded that miniature TiNi actuated devices based on sputtered TiNi films are ready for huge manufacturing market and for medical microdevices implantable into the human body.

A. Camposeo, N. Puccini et al. in [3] combined TiNi-SMA with pulsed laser deposition (PLD) to produce films with shape memory effect onto Si-based substrates. PLD deposition technique was performed using Si/SiO2 (450nm) wafers and Si3N4 triangular cantilevers at a rate of the order of 0.3-0.4A per laser shot. Temperature of substrate was 520-600ºc with a 20-40min in situ high-vacuum annealing at the same temperature, followed by free cooling to room temperature. TiNi pellet (51:49) was used as a target. Deposited samples were analyzed using an ad hoc setup, employing a temperature controlled Peltier stage and a tilt/twist measurement system based on an optical lever method. The attainment of shape memory effect was demonstrated to confirm PLD as a new technique for deposition of SMA films. MEMS prototypes with a wide range of possible applications can be fabricated by PLD in a simple, clean and congruent process.

Shuren Zhang, Jingsong Liu and Chengtao Yang in [6] investigated the growth mechanism of grains and the size effect on the coercive field. ULVAC Ferroelectric thin film deposition system was used to fabricate PZT on Pt/Ti/SiO2/Si (100) structured substrates, then these films were annealed using ULVAC-RIKO Rapid Thermal Annealing (RTA) system, with a heating rate of 50ºc /s. A two-step-warm-up method was designed to obtain different grain sizes. Lateral grain size was measured using scanning force microscopy (SPM), film crystal phase was identified using Bede DI multi-function X-Ray diffractometer (XRD), and the electrical properties were measured using the Radiant Precision LC Materials Analyzer. It was demonstrated that PZT thin films with different grain sizes were fabricated by controlling the nucleation process time and growth process time. Electrical properties and polarization has a great dependence on grain size, which was found to be 70nm as a critical value for the domain structure transition.

D.F.L.Jenkins, W.W.Clegg et al. in [7] optimized d31 coefficient to maximize actuation efficiency. d31coefficient was measured for different PZT thin films and their effectiveness as microactuators was compared and evaluated. PZT thin films, with a (Zr/Ti) ratio equal to (54/46) were deposited on Si substrate at room temperature or the substrate temperature between 500-550ºc by R.F. magnetron sputtering. Two thermal treatments have been used: conventional and rapid thermal process. It was shown that PZT films were extremely effective as micro-actuators and were able to operate efficiently over a wide bandwidth. d31 coefficient was found to be -12, -1.3 and -0.05 for the 110, 100 and 111 films, respectively, and was significantly increased by poling at elevated temperatures of around 120ºc. Actuation was increased by application of D.C. bias field, with up to 5.9μm of actuation being possible for a 110 film being driven with 10V a.c. with 5V D.C. bias voltage.

P. Delobelle et al. in [8] used nanoindentation technique to measure the transverse biaxial elastic modulus and hardness of piezoelectric ceramic films (PZT), and the true biaxial elastic modulus to describe the mechanical properties of these films having various grain size. Morphotropic PZT films Zr/Ti=54/46 were deposited by RF magnetron sputtering from cold pressed powder targets. Substrates were platinized silicon. Post-deposition annealing was applied to samples in a conventional furnace in air at 625ºc. Thicknesses of synthesized films in the range 0.3 to 2.0μm with varying grain diameters in the range 0.1 to 4.0μm. Nanoindenter was used for measuring the transverse elastic modulus and hardness. They concluded that there exists a relation between grain size and elastic behavior; hardness measurement also confirmed that these sputtered films possess a hard mechanical behavior.

Romain Herdier, M.Detalle et al. in [9] compared the electric, ferroelectric and piezoelectric properties of two different PMN-PT composition, along with those of PZT of the same thickness. PMN-PT and PZT thin films have been grown by R.F. magnetron sputtering on Pt(111)/TiOX/SiO2/Si substrates. Titanium oxide and platinium bottom electrode were deposited with thicknesses of 15 and 120nm, respectively. The thickness of the PMN-PT and PZT films were 800nm. X-ray diffraction analysis was performed using a Siemens D5000 diffractometer. Piezoelectric coefficient was determined using a homemade Laser Doppler vibrometry. They concluded that 0.7PMN-0.3PT and PZT are good candidates for MEMS actuators, but PZT is superior and simpler to grow compared to PMN-PT. An important advantage for PZT material is the possibility to introduce dopants and improve the piezoelectric properties of PZT.

Sibei Xiong et al. in [10] evaluated the piezoelectric coefficient e31 of PZT thin film by measuring the tip displacement of PZT-coated cantilevers of the dimensions 50mm long, 4mm wide and 0.3mm thick. Micro-machined ultrasonic sensors, in which PZT-coated membrane functioned as sensing element, were fabricated and their properties were characterized. Pb(Zr0.52Ti0.48)O3(PZT) piezoelectric thin films with thickness of 0.7-2.2µm were prepared on Pt/Ti-coated SiO2/Si(0.5µm) substrates by the sol-gel method. Fabrication procedures are reported in details in the paper, and piezoelectric coefficient was measured by observing the actual deflection of PZT-coated cantilevers under applied voltage. It was concluded that the effective piezoelectric transverse coefficient e31 of PZT thin film was -12.5+0.3c/m2. The prepared PZT films demonstrated excellent piezoelectric properties and had been applied in MEMS ultrasonic sensors. The sensitivity of the micro-sensors reached 500µv/Pa.

S. Srinivasan, J. Hiller and B. Kabius in [11] integrated and demonstrated low voltage piezoactuated hybrid of PZT and UNCD films as a high performance platform for advanced MEMS/NEMS devices. Material integration involves growth of 1µm thick Ultra nanocrystalline diamond (UNCD)layer on si(100)substrate, fabrication of UNCD cantilevers, growth of an 10nm thick TaAl barrier layer on the UNCD film, growth of 180nm thick Pt layer on top of the TaAl barrier, growth of 70 nm thick PbZn0.47 Ti0.53 O3 piezoelectric layer via sputter deposition at 600°c in 100 mTorr of oxygen and growth of the top s o nm thick Pt layer to complete the capacitor like structure needed for piezo actuation via voltage application between the top and bottom Pt electrode layers. X-ray diffraction analysis showed preferential (001) orientation and this PZT layer yielded capacitors with well-saturated polarization in the 5-97 range. Another conclusion is that PZT/UNCD cantilevers can be fabricated using industrial processes, involving photolithography in conjunction with reactive ion etching in oxygen plasmas to produce large arrays of PZT/UNCD structures for high performance MEMS/NEMS piezoactuated devices.

F. Dauchy.R.A. Dorey in [12] described the fabrication and structuring of multilayer thick film piezoelectric structures (PZT) using composite sol-gel techniques and wet etching. PZT films of 10 and 40µm thick are produced by repeated layering and infiltration with embedded thin (100nm thick) metal electrodes. Signal and multilayer structures were demonstrated. A crack free surface finish of a 28-µm- thick film reveals the adaptability of spin coating technique to fabricate thick films. Wet etching technology revealed the possibility of great adaptability to pattern and shape innovative devices such as bars 10µm wide of 21µm PZT thick film. Byung –Moon Jin, SE-Hwan Bae and others in 2005[13] tested PZT/PZ multi-layered films and measured fatigue effects of PZT/PZ series and normal PZT films by applying AC 10 volts. Sol-gel technique was used to fabricate PZ/PZT multi-layered thin films. Different kinds of films with 250nm thick for each by using PZ and PZT precursors. Substrates for these were the same as Pt/Ti/sio2/si.Piezoelectric Loops were measured by a standardized ferroelectric Tester System +10 volt saw type pulse and the pulse period of 1.000*10-3second were used for measurement. It was found that the best fatigue effect is in the sample that is made by 3PZT layers after 3PZ layers. The values of switch polarization and switch remant polarization in this sample are reduced within the 10% of the initial values up to 108 cycles and this film is a good candidate for FeRAM application. A. Kumar, M. R. Alam and others in 1999 [14] synthesized and characterized TiNi films from crystallographic point of view by using X-ray diffractometer(XRD) and atomic force microscope (AFM) techniques. A deposition process was carried out in the "Materials Research Laboratory" at the university of south Alabama. A buffer Layer of BaTio3 was deposited at 600ºc in 100m Torr oxygen environment. After depositing approximately 4000ºA of BaTio3 at 10Hz repetition rate, TiNi films of nearly 600ºA were deposited on the top of the buffer layer in the presence of 15m Torr nitrogen environment at various deposition temperatures (50,300,500ºc). For TiNi/PZT films on si(100) substrates, first a PZT buffer layer was deposited at 600ºc in a 200m Torr oxygen environment with the same previous deposition conditions. Also TiNi films were deposited on si(100)substrates without any buffer layer at various deposition temperatures in presence of 15m Torr nitrogen atmosphere. X-ray diffractometer was used to characterize these films, and AFM analysis was done by a digital Nanoscope. TiNi deposited films at lower temperatures have amorphous type structure but films at higher temperatures have crystalline quality thin films. Also buffer layers of BaTio3and PZT have improved the crystalline of TiNi films deposited at higher temperatures. The TiNi/BaTio3 film was less uniform than TiNi/PZT film due to the differences in grain structure, and TiNi/PZT film has smaller diameter columns than the TiNi/BaTio3 film due to differences in deposition parameters.

All the above studies were concerned with deposition and analysis of single or double layered thin films for MEMS applications. Researchers studied PZT thin films and analyzed their mechanical behavior; others studied TiNi-SMA films. Others studied the possibility of integration of PZT an UNCD film to provide high performance platform for advanced MEMS devices. Another study described fabrication and structuring of multi-layer thick film piezoelectric structure using composite sol-gel techniques and wet etching ones. PZ and PZT multi-layered thin films were also testified.

Microactuators based on PbZr1-xTixO3(PZT) and TiNi-SMA are compared using MEMS. Operating frequencies pressures, pumping rates, design and fabrication are all studied and investigated. Also, a new hybrid heterostructure of TiNi and PZT films is proposed having superior static and dynamic properties.

3. Material Characteristics

Piezoelectric and Shape memory materials in thin film form can provide reasonable displacements that are suitable for microactuators, and, therefore, they were developed for MEMS applications [17]. Piezoelectric materials can be defined by dividing the word into piezo and electric. Piezo is from the Greek word piezoin, which means "to press tightly or squeeze," when combined into piezoelectric it means "squeeze electrically." Piezoelectric phenomenon was discovered by Jacques Curie and Pierre Curie in1880 [17].

Lead zirconate titanate (PZT), PbZrx(Ti1-x)O3; $0<x<1$ are polar dielectric which exhibits a high degree of piezoelectric activity. Sol-gel PZT structures were crack free and had good crystallinity[16], and being widely used in MEMS actuators. When a piezoelectric material is subjected to a mechanical stress, an electric charge is generated across the material. Piezoelectric materials are also pyroelectric. As they undergo temperature change, an electric charge is generated. When temperature is increased, a voltage develops with the same orientation of polarization voltage, whereas a positive orientation to the polarization voltage is produced when temperature is decreased. In Rigaku RINT2000X-ray diffractometer (XRD), typical peaks were observed associated with perovskite-type PZT phase, and preferential (100), (110) and (111) orientations were dominant in the PZT. Dielectric constant and dielectric loss value were measured with a HIOKI 3532 LCR hitester. Dielectric constant and loss were over 300 and 0.03, respectively[16].

Shape memory materials possess different and desirable properties such as large power-density, scalable character, hence the ability to recover large transformation stress and strain upon heating and cooling, because of the molecular rearrangement of the metal that it constitutes of, high damping capacity, super elasticity, good chemical resistance and biocompatibility. Shape memory alloys can be patterned with standard lithography techniques and fabricated in batch process. They have a very small amount of thermal stress to heat or cool, consequently response time is reduced and the speed of operation is increased significantly[4].

Nickel-titanium alloys Ni/Ti(49/51) are the most widely used shape memory material, known as Nitinol after the laboratory where this material was first observed (Nickel Titanium Naval Ordinance Laboratory). As this alloy is cooled below a critical temperature, the crystalline structure enters into the Martensitic phase. During this stage, the material can be easily deformed through large strains with a little change in stress. As the temperature is increased above the critical temperature, it drives the molecular rearrangement of the alloy, and Martensite is now transformed into the cubic Austenite phase, accordingly the material regains its high strength and modulus and behaves normally. As a result, the material shrinks during the change from the Martensitic to the Austenitic phase. This behavior (shape memory effect) is considered a unique property of shape memory alloys. Different kinds of shape memory effect can be reported but the most common memory effects are the one-way shape memory and the two-way shape memory. With the one-way effect, cooling from high temp. does not cause a macroscopic shape change, but with the two-way shape memory effect the material remembers two different shapes: one at low temperatures, and one at the high temperature shape, even without the application of an external force. Such behavior is attributed to training, in which a shape memory can learn to behave on a certain way. Under normal conditions, a shape memory alloy remembers its high temperature shape, but upon heating to recover the high temp. shape, immediately forgets the low temperature shape. However, it can be trained to remember to leave some reminders of the deformed low temperature condition in the high temp. phase. Pseudo-Elastic behavior is another unique property for shape memory alloys when the alloy is completely composed of Austenite. Unlike the shape memory effect, pseudo-elasticity occurs without a change in temperature. The load on SMA is increased until the Austenite becomes transformed into Martensite simply due to the loading. The loading is absorbed by the softer Martensite, but as soon as the loading is decreased the Martensite begins to transform back to Austenite and the material returns back to its original shape.

4. 4. Aspects of Comparison

4.1. Preparation & Fabrication Techniques

TiNi thin films are prepared using Laser ablation, plasma spray and flash evaporation, but with some problems such as non-uniformity in composition and film thickness, low deposition rate, non-batch processing and incompatibility with MEMS process. To overcome these difficulties, an alternative method mostly used is sputtering. However, transformation temperatures, shape memory behaviors and super elasticity of sputtered TiNi films are sensitive to sputtering conditions, metallurgical factors and the application conditions, this sensitivity provides flexibility in engineering a combination of properties for different applications. TiNi films were deposited either at room or high temperatures. Sputtering at room temperature necessitate post-sputtering annealing(higher than 450ºc) to generate films of crystalline structure with shape memory effect. Films deposited at high temp.(about 400ºc) were crystallized in crystalline form, so there was no need for post-annealing. Localized laser annealing was used for TiNi films [4] due to its precision in selection of the areas to be annealed as small as micrometer, non-contact and efficiency, free of restrictions on design and processing, ease in integration in MEMS processes and ease in cutting of the final structure using the laser beam.

PZT thin films can be prepared using different techniques, but these techniques are not practical because they need highly specialized equipment and have low compatibility with conventional IC/MEMS processes. Sol-gel technique was used as an alternative technique, which only requires simple and low temp. process. PZT precursor solution 0.8M with molar ratio of Pb:Zr:Ti=1.2:0.53:0.47 of high concentration, high boiling point and low carbon content, based on the acetic acid-based method with "inverted mixing order(IMO)" of alkoxides, was prepared. Fabrication processes include the following:

First, wafer was preheated with the wet gel then Vacuum deposition of Pt(100nm)/Ti(30nm) bottom layers on a silicon wafer (thickness: 250µm). A layer of SU-8 25 of thickness 50µm was patterned to form circular apertures with 40µm, 80µm and 180µm diameters, respectively. Second, PZT solution was dispensed on the SU-8 layer, filtered with 0.2µm syringe filter. The wafer is dried in a sealed container at room temp. to gelatinize the sol. Third, PZT wet gel is prebaked at 140 ºC prior to lapping. Fourth, the wafer is lapped using a urethane foam pad. Isopropyl alcohol was used as solvent and lubricant. Fifth the gel is fired on a hotplate at 350ºc for 10 min. The gel transforms into amorphous solid of PZT and SU-8 layer Separates from the PZT structures. Then the wafer was heat treated. At last, annealing is applied at 600ºc for 20 min [16].

4.2. Operating Conditions

The actuation mechanism of TiNi films is as straightforward as that for PZT-based microactuation. TiNi SMA-based microactuation operates at low voltages, which allows easier integration with electronic devices, and high output pressures which are required to overcome flow resistance associated with complicated flow paths. TiNi SMA-actuated microvalve that is capable of operating pressures of 200KPa under an operating voltage of 3.5V has been reported [18]. A large pumping volume per stroke can be achieved due to the high recoverable strain of TiNi SMAS that is generated by the ferroelastic deformation that occur in the low temperature Martensitic phase. The low operating frequencies reduce the flow rate of TiNi micropumps and microvalves below the expected values, and are limited by the necessary cooling of the microactuation and is in the range of tens of Hz or lower. Patterned TiNi films have been developed to reduce thermal mass, however, the power consumption is still in the range of hundreds of milliwatts [17].

PZT-based actuation operates at high frequencies due to the large actuation forces; stresses of up to 100MPa and operating frequencies of up to 10KHz have been reported, which provided high operating pressures and pumping rates up to100KPa[19] and 2300µ1/min[20], respectively. PZT actuators can be operated at their primary natural frequencies and multi-layered piezoelectric components can be used to avoid high voltages since some tens of volts are usually required for actuation. It was demonstrated that although operating at high voltages, the power consumption of PZT-based microactuators was not excessive.

4.3. Applications of TiNi-SMA & PZT Based MEMS

Shape memory alloys are used in many fields, in bio-engineering as mending bones and opening the clogged arteries. Other applications such as in antiscalding protection, coffee pot thermostat, fire security and protection systems, eyeglass frames and super elastic glasses. Most applications of TiNi films in MEMS are focused on micro-actuators, such as microgrippers, springs, micropumps and microvalves. Several requirements for microgrippers such as large gripping force, sufficient opening distance for assembling works, in which TiNi films are promising. Two types of TiNi film based microgripper designs are available. The popular design is out-of -plane bending mode with two integrated TiNi/Si cantilever with opposite actuation directions as shown in Figure1 below.

Figure 1. the popular design of TiNi film based microgripper

The other type, shown in Figure2, is the patterned TiNi electrodes on silicon cantilevers. The cantilever bends up when the electrodes are electrically heated, due to the shape memory effects of TiNi films, consequently generating gripping force.

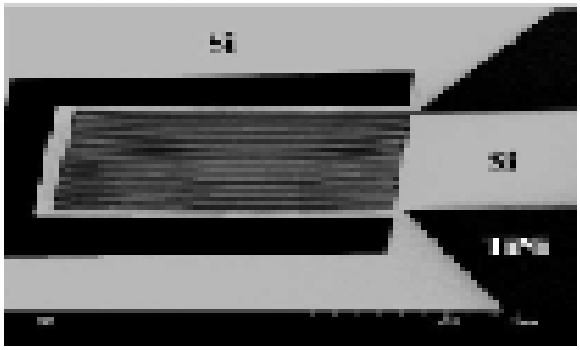

Figure 2. the patterned TiNi electrodes on silicon cantilevers

Both gripper designs need further bending process to combine two cantilevers to form gripping movement. A novel micro-wrapper was fabricated using freestanding TiNi films with out-of-plane movement as shown in Figure (3) [4].

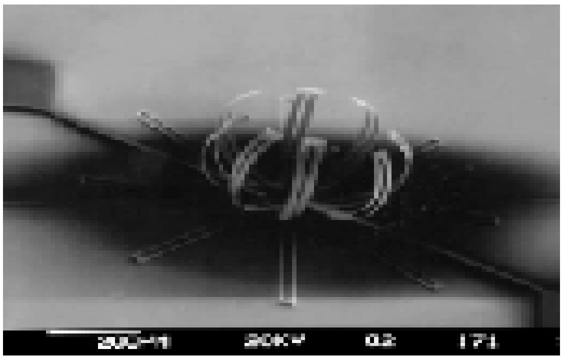

Figure 3. A novel micro-wrapper using freestanding TiNi films

It can be used in invasive surgery to remove anomalies such as tumors. The overall dimension of the micro-wrapper arms is 100µm. A small current passes through it to maintain the flat shape, whenever the current is removed, the small arms close to form a cage.

Piezoelectric materials were first applied in Sonar Devices then in piezoelectric filters, piezo buzzers, transducers and lighters. There are different applications of TiNi films in MEMS such as being used in Cantilever fabrication. PZT films were prepared using the sol-gel method. The precursor solution of PZT (52/48) was supplied by the Mitsubishi Materials Corporation. PZT films were then prepared on Pt/Ti-coated SiO_2/silicon wafers by multiple spin-coating and annealing. Each layer was fabricated by spin coating the solution precursor on the lower electrodes and was pyrolized at 350ºcfor 10min. After the fabrication of every four single layers, the PZT thin films were thermally annealed at 650ºc for 10min using the RTA furnace in flowing oxygen. Heating rate in RTA was 8ºC/s. As film thickness of single coating is about 58nm, 12single layers were coated to form 0.7-µm-thick PZT films.

The size of the cantilever was 50mm long, 4mm wide and 0.3mm thick. Fabrication process can be described as follows:

Pt(100nm)/Ti(10nm) bottom electrode layer was deposited on SiO2/Si substrates at RT by RF-sputtering. Pt/Ti bottom electrode layer was patterned by ion milling technology. PZT thin film was deposited by sol-gel method. Piezoelectric PZT thin film was patterned using wet-etching method to form contact holes. The etchant for PZT was a diluted solution of HF & HNO_3. Au/Cr films deposited by evaporation, and patterned to form the top electrode by lift-off, at last the Si wafers were diced into $50*4*0.3mm^3$. Figure 4 shows a photograph of the prepared PZT cantilever and the measurement setup.

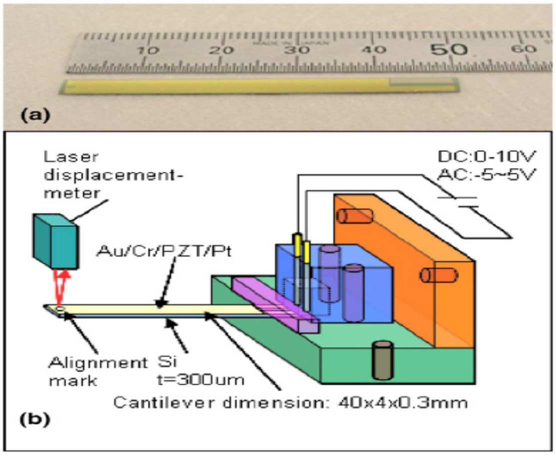

Figure 4. a) The prepared PZT cantilever, b) and the measurement setup of the microactuator.

One end of the cantilever was clamped by a plastic vise and the other end was left free. Piezoelectric vibration was generated by applying a sine wave voltage between the top and bottom electrode, and the tip displacement was measured using a laser displacement meters. The laser spot position was adjusted precisely to coincide with the alignment mark near the free end of the cantilever. Elastic contact of the bottom and top electrode was obtained using a pair of needles through the plastic vise.

Another application is the PZT microactuator. Its fabrication includes micromachining of the silicon diaphragm, depositions of PZT thin film with its electrode layers. Diaphrams were fabricated by wet etching of silicon. Oxide layer (500nm) was grown followed by LPCVD deposition of (100nm) silicon nitride.

Nitride layer was patterned by RIE with a positive photoresist layer as a mask and the oxide layer was patterned in 6:1 BOE using the same photoresist mask layer. Etching of silicon was performed in 45% KOH solution. Three or four stages of etching were carried out to obtain 10-15µm thickness range. Then the nitride layer was stripped in hot phosphoric acid. The oxide layer was etched in 10: 1 BOE to 200nm thickness. At last, diaphragms of uniform thickness were obtained.

For the bottom electrode layer, Pt and Ta layers (100 and 10nm) were deposited using e-beam evaporation and patterned using the lift-off method. PZT film(118/52/48) in 10% PZT-E solution was deposited on the bottom electrode layer using the sol-gel technique. Five layers were applied, then the film was patterned using a positive photoresist for masking. The patterned PZT layer was annealed at 650ºcfor 90minin a RTA furnace. These procedures were repeated until a 600nm-thickPZT thin film was obtained. Finally, metal films of Cr and Ag were deposited using e-beam evaporation and patterned using the lift-off technique to form the top electrode layer.

5. Obstacles and Challenges

Functional materials such as PbZr1-xTixO3(PZT) and TiNi shape memory alloy (SMAs) in thin film form can provide reasonable displacements that are suitable for microactuators, and have, therefore, been developed for MEMS applications. The main advantages of these materials are their high work density and ease of implementation, due to their relatively straightforward actuation mechanisms.

One of the major obstacles to commercializing PZT-based microactuation for MEMS is the lack of serviceable deposition techniques compatible with Si processing. Physical vapor depositions are not appropriate. Screen-printing and sol-gel deposition techniques have been reported. In contrast, Si compatible deposition and microfabrication techniques for TiNi films were developed in the past decade. However, they have not received much attention in the MEMS technology as is the case with other microactuator technologies.

Different challenges are found in designing MEMS devices, such as finding skilled engineers with an adequate knowledge of micromechanical systems, materials and target manufacturing processes and transferring data between separate electronic and mechanical design teams who handle system and component-level development. On the other hand, measuring the mechanical properties of these films is a difficult task because these films are clamped by their substrates, thus nanoindentation technique was chosen to characterize transverse mechanical properties of the films[21]. Biaxial elastic modulus and hardness were measured for PZT thin film using this advanced technique. Also, it does not require any complex modeling in order to extract the parameter values. However, few measurements, relating to mechanical characterization of ferroelectric films such as PZT, are published.

One of the main problems of particular concern is to elaborate novel interfacial technology to connect dissimilar components. To accomplish a multi-layered interface which provides durability, mechanical stability, dynamical coupling, chemical and physical compatibility, will be the key. The next problem is understanding and modeling the potential emergent properties of the complex systems with the non-linear integration effects of the components, and specifically understanding the phase transformation characteristics under constraints exerted by coupled components via the interface. Phase stability, degradation and transformation hysteresis under certain circumstances have not been understood very well yet.

6. The New Hybrid Structure

Multi-layer, composite or functionally graded TiNi-based, films can be designed in order to improve the properties of TiNi films. Different designs were modeled for the functionally graded TiNi thin films. One of them was through the gradual change in composition (Ti/Ni ratio), crystalline structures, and residual stress through film thickness and transformation temperatures. Material properties could change from pseudo-elastic to shape memory, and integration of both characteristics reveals a two-way reversible actuation, since residual stress variations in thickness will enable biasing force to be built inside the thin film.

Functionally graded TiNi films can be prepared by changing the target powers during deposition. Another way is to change the target temperature during sputtering. To optimize functionally graded TiNi thin films for MEMS application, it is necessary to characterize, model and control the variations in composition, thermomechanical properties and residual stress in these films. Another design includes materials and functions other than TiNi films. Functionally graded TiN/TiNi layer was deposited to achieve this objective (4), in which an adherent and hard TiN layer(300nm) on TiNi film(3.5μm) formed a good passivation layer, and improved the overall hardness, load bearing capacity and tribological properties without sacrificing the shape memory effect of the TiNi film. TiN layer is able to restore elastic strain energy during heating and to reset the martensite phase on subsequent cooling, forming a two-way SMA effect. As a result a functionally graded Ti/TiNi/Ti/Si graded layer was proposed to improve biocompatibility and adhesion of TiNi films.

A new functionally graded design is proposed in this paper which includes the combination of TiNi films with piezoelectric (PZT) thin films. It was found that the response time of PZT films is fast while the displacement is relatively small, while TiNi film has a large force-displacement, with slow response frequency. Upon coupling both of these a new hybrid heterostructure is generated in order to tune the static and dynamic properties of TiNi films, which produce a larger displacement than conventional piezoelectric thin films, and improve dynamic response compared with that of single layer TiNi films. TiNi films can be prepared by sputtering and PZT film by sol-gel methods. Either one of these films can be the bottom layer.

To integrate and hybridize such materials lead to composite materials with intrinsic mechanisms for sensing, control and response. A hybrid structure with embedded sensors or actuators and controlled by an external processor is named an adaptive structure rather than an intelligent material. The sensing, actuating and information-processing capabilities of an intelligent material stem from its intrinsic composition and microstructure. These structures can provide massive actuation stress, tolerable strain, high speeds and reasonable efficiency. One of the major problems encountered is to develop novel interfacial technology to bind dissimilar components. Also understanding the phase transformation characteristics for SMA-based composites exerted by coupled components via the interface. Detailed informations will be presented and validated in a future work. Amazing results will overtake the vested interest of workers and researchers in this field.

7. Conclusions and Recommendations

TiNi-SMA thin films were able to operate at low frequencies and generate a large force displacement, whereas PZT thin films were able to operate at high operating frequencies and generate a relatively small displacement. Low power consumption was attained using PZT films compared to that using TiNi-SMA which was in the range of hundreds of miliwatts although patterned TiNi films have been developed to reduce thermal mass. Also TiNi films were capable to operate at low voltage and high flow rates, while PZT-thin films operated at high operating voltages and low strains produced.

Different preparation and fabrication methods were optimized for both microactuation techniques. Sputtering technique was used to fabricate TiNi thin films to achieve high uniformity in composition, film thickness, high deposition rate and batch processing and compatibility with MEMS process. Sol-gel technique was optimized to fabricate PZT thin film, which only requires simple and low temperature process.

Different applications for both films were discussed and they seem to be promising for more accurate and complex applications in the future. Different difficulties were encountered, such as lack of a robust deposition technique compatible with Si processing for PZT thin films. In contrast, different Si compatible deposition and microfabrication techniques have been developed for TiNi-SMA thin films.

New hybrid heterostructure is proposed to tune the static and dynamic properties of TiNi thin films, which generate a larger displacement than conventional piezoelectric (PZT) thin films, and have an improved dynamic response compared with that of single layer TiNi films. It is promising to fabricate nano-scale SMA thin film structures, since shape memory effect still occur in films of nanometer grains. Physical actuation techniques at nano-scale may be achieved using these structures.

It is also recommended that TiNi and PZT films be coupled experimentally, to create a new hybrid heterogeneous structure composite. This new hybrid can tune the static and dynamic properties of TiNi thin films, which produce larger displacement than conventional piezoelectric thin films, and have an improved dynamic response compared with that of single layer TiNi films. Sputtering technique is proposed to prepare TiNi film and sol-gel method to prepare PZT thin film. Fabrication processing, adhesion, dynamic coupling of dissimilar components can all be considered for this new hybrid.

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