Shape Memory Alloy and Elastomer Composite MEMS Actuators

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ABSTRACT

A process for fabrication of shape memory alloy MEMS actuators on a elastomeric polymer substrate is described. These actuators are designed for use on innovative soft body robots. Patterned shape memory alloy (nitinol) is sputter deposited on a polyimide mesh structure. The mesh substrate acts as a bias spring to de-twin the shape memory alloy in the martensite phase. Significant portions of the structure have been fabricated, but the nitinol anneal has not been successful, nor has the shape memory effect been demonstrated. Refinement of the fabrication process is ongoing.

Keywords: shape memory alloy, nitinol, actuator, elastomer, polyimide

1 INTRODUCTION

The majority of robots currently built are constructed of rigid members, limiting the capacity of these robots to move through oddly shaped and confined spaces. A new focus in robotics has been the design of soft body robots. Advantages over rigid body robots of comparable size and shape including the capacity to expand and contract upon demand to facilitate movement through and over complex environments environment. Soft bodied robots composed of a soft silicone elastomer material are under developement at Tufts [1]. These soft bodied robots are modeled after the *Manduca sexta* tobacco hornworm caterpillar, which can grow on the order of 10,000 fold during its lifetime [2]. It is of significant interest to develop small scale models of these existing soft body robots. To provide movement to such robots, one option is actuation derived from resistive heating of patterned nitinol, a nickel and titanium shape memory alloy. Previous research has shown the use of nitinol actuators for MEMS devices [3]–[5]. Such actuators develop high forces and strains, and can be fabricated in into flexible sheets, but tend to require relatively high power. The paper describes fabrication of nitinol MEMS actuators.

2 SHAPE MEMORY ALLOY

Shape memory alloys exhibit the phenomenon of shape recovery during phase transitions. Various types of shape memory alloys have been discovered, though for the purpose of this research only nitinol (nickel-titanium) was used. When in a cooled state nitinol displays a martensite crystal structure. When nitinol is heated above its transition temperature it changes to an austenite crystal structure. Nitinol can be trained in one position by raising the temperature of the alloy above its transition temperature while restraining the sample in the desired position. The sample is then cooled while still being restrained and the nitinol shifts to a twinned martensite structure [6]. Once this cooling step is complete the nitinol will revert back to its trained position upon subsequent heating, provided the nitinol has undergone 6-8% strain to de-twin the martensite [7].

For the purposes of this research, a transition temperature greater than air temperature is required. Small shifts in the composition of the alloy can lead to dramatic changes in the transition temperature [8]. As such, an alloy composition of 50% nickel and 50% titanium by atomic weight percentage is desired where the transition temperature is near $100°$ C. The transition temperature of a specific alloy can be determined through differential scanning calorimetry.

The actuating devices were microfabricated using sputter deposition. Separate nickel and titanium targets were used to co-sputter the nitinol. When determining the processing conditions, the power supplied to the DC magnetron guns must be given special consideration. Initial settings were determined from a literature search [9], [10]. Inductively coupled plasma (ICP-OES) - optical emission spectroscopy (The M&P Lab, Schenectady, NY) was then utilized to analyze the percent composition of a number of samples. Figure 1 shows the results of the elemental analysis. For the desired 50% nickel and titanium by atomic percentage, powers of 70 W and 200 W must be applied to the nickel and titanium targets, respectively.

When nickel and titanium are co-sputtered, the resulting nitinol film is in an amorphous state [3]. For the shape memory effect to be possible, the film must be in a crystalline state. The transition from the amorphous to crystalline state is achieved through an anneal of the film at $480°$ C for 30 minutes [5]. The precise annealing temperature and time depend on the conditions present during the co-sputtering of the film. The anneal must
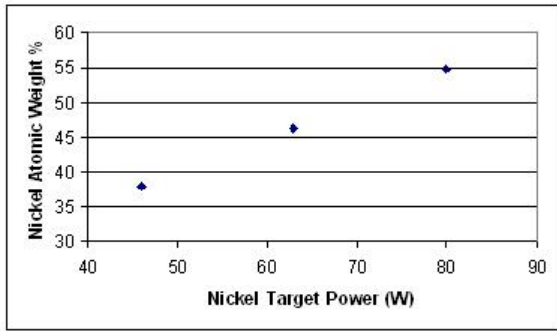
Figure 1: Composition as a function of DC magnetron gun power (Ti gun power = 200 W).

be conducted in an inert atmosphere as the nitinol will oxidize during the anneal if it is completed in air. The transition of the crystal structure can be examined with x-ray diffraction.

3 DESIGN

In order for the nitinol to exhibit its shape memory effect, it must first be strained to de-twin the martensite crystal structure. It is also desirable to laminate or affix the shape memory alloy onto the wall of the soft body robot. The polymer must also be able to survive the high temperature anneal of the nitinol. To accomplish these three things, an elastomeric polymer substrate, HD Microsystems 4100 series photodefinable polyimide, was used. This polyimide was chosen because it does not decompose until a temperature of 600° C is reached, so it can withstand the high nitinol anneal temperature. While polyimide is not the ideal elastomer, it is one of the most chemically and thermally resistant polymers available, making it effective for use as a substrate for nitinol.

A series of devices were designed to examine the effect of various changes in the nitinol wires and the polyimide substrate. A mesh structure was developed for the polyimide layers to make them more compliant than a full sheet. The nitinol meanders across the polyimide mesh structure in an attempt to model a three dimensional spring in two dimensions. The devices range in overall size. The largest are 22 mm long and 10 mm wide layers and the smallest are 7.75 mm long and 3.5 mm wide layers. The nitinol patterned on the polyimide is 1 μm thick and varies in width from a maximum of 0.8 mm to a minimum of 0.1 mm. Representative microscope images are shown in Figures 2 and 3.

4 FABRICATION

Figure 5 outlines the process. A 0.5 mm thick, 100 mm diameter, < 100 > oriented silicon wafer with a 1 μm thermal oxide layer is the starting substrate. To
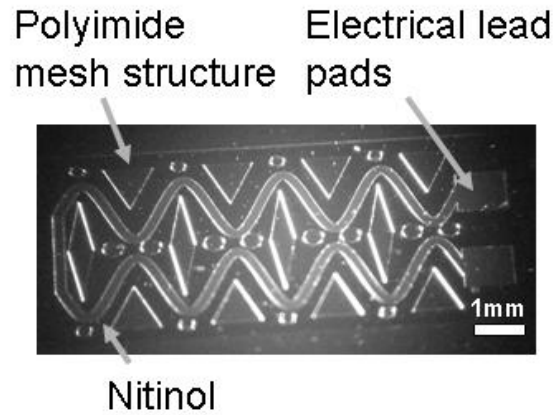

Figure 2: Microscope image of a particular device design prior to the release from the sacrificial layer.
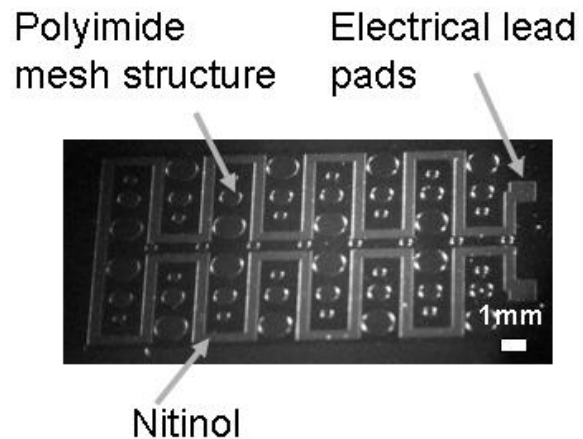

Figure 3: Microscope image of a particular device design prior to the release from the sacrificial layer.

enhance adhesion between the oxide and the polyimide a 100 nm layer of Titanium was sputter deposited (Nanomaster NSC-3000 DC Magnetron Sputter Tool) onto the wafer. The titanium was sputtered at a process pressure of 5 mTorr and a magnetron gun power level of 150 watts. A base pressure of at least $5x10^{-5}$ torr must be met for a quality film. Base pressures above this level resulted in stresses significant enough to cause macro scale cracking in the deposited films, as seen in figure 4.

On top of the adhesion layer a 6 μm layer of polyimide was patterned. This layer of polyimide was spun at 3800 RPM, patterned with photolithography, and cured for 30 minutes at 200° C and 60 minutes at 375° C.

Photoresist (SPR 220-3.0 series) was spun at 2000 RPM and patterned with photolithography (MF CD-
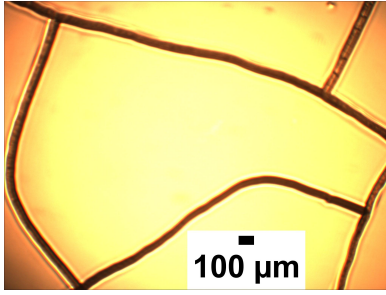
Figure 4: Macro-scale cracking resulting from deposition at a high base pressure.

26 developer). 1 μm of nitinol was sputter deposited. Nickel and titanium targets were co-sputtered at 70 and 200 watts respectively. An acetone and isopropanol liftoff of the nitinol was then performed.

A 6 μm upper layer of polyimide was spun, patterned, and cured with the same conditions as the lower layer. At this point another thick layer of photoresist is spun and patterned with photolithography. The pattern allows for deposition and liftoff of 50 nm chromium adhesion layer and a 300 nm layer of gold for connection of electrical leads.

The devices were then annealed in a nitrogen ambient oven at 480° C. A hydroflouric acid etch of the thermal oxide layer and Ti adhesion layer was performed to release the devices.

5   CONCLUSIONS

The process for the fabrication of shape memory alloy MEMS actuators has been described. The fabrication process has been successfully performed, though shape memory effect has not yet been demonstrated. The devices would be greatly enhanced with a more thermally resistant polymer substrate. Most of the issues with the fabrication process are related to the polyimide mesh not surviving the anneal required to set the crystal structure of the nitinol.

Future work will include a refinement of the fabrication process to achieve a successful demonstration of the shape memory effect. The focus of this effort will be the development of an affective annealing process. Characterization of the devices will also commence once the shape memory effect is demonstrated.

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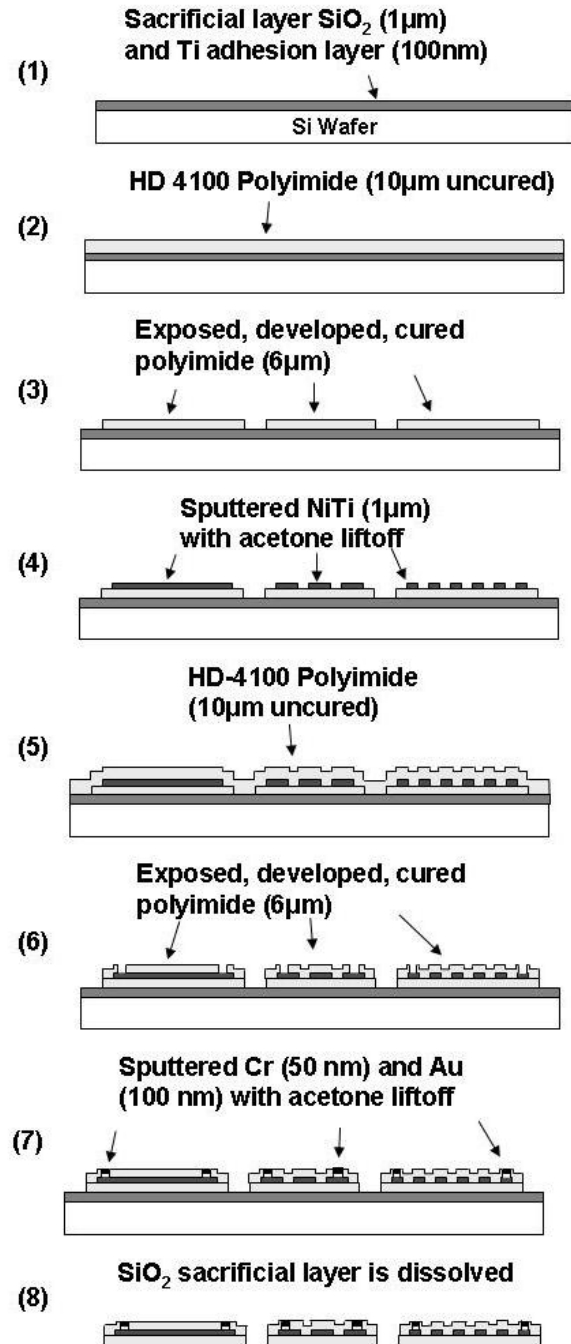
Figure 5: Microfabrication process for producing SMA-elastomer actuator patches.

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