Thermal Energy Conversion using a Microfabricated Shape Memory Alloy Structure

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Abstract:
In this paper we present the conversion of fluctuations in ambient temperature to mechanical energy (strain energy). The design is based on the phase transformation of shape memory alloy (TiNi; e.g. Nitinol). Ambient temperature fluctuation instead of current is used to drive the alloy. Compared with aluminum/polysilicon bimorphs, which are based on the difference between the thermal expansion coefficients of Al and polysilicon, larger displacement can be achieved by a free standing TiNi/polysilicon bimorph with in-plane motion. Optimization analysis of the geometry is applied and optimal scaling is determined with consideration of fabrication limitations. A novel fabrication process and low-cost but reliable mask making method are also described.

Introduction:

A conventional bimorph consists of two different materials bonded together. As the temperature changes, both materials undergo different strains. Therefore, a large deflection is achieved by the difference between the thermal expansion coefficients of two materials.

A shape memory alloy (SMA) bimorph consists of a layer of TiNi film bonded with a supporting structure (polysilicon), which acts as a bias spring. At low temperature, the TiNi film is easily deformed. Upon heating over the austenitic transformation temperature A_s, the TiNi film recovers its memorized shape and transforms to austenite phase. When cooled below the martensitic transformation temperature M_s, the TiNi film transforms to martensite phase and the bimorph returns to original shape.

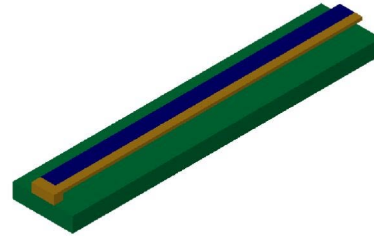

Fig.1 Bimorph Layout

Commonly used bimorphs are layer-by-layer structure, which means the actuator layer is on the top of the bias layer. Therefore the motion is restricted only at out of plane. In order to achieve in plane motion, a side-by-side design is necessary(1). In this paper we present a novel side-by-side SMA bimorph that can convert of fluctuations in ambient temperature to mechanical energy (strain energy).

Geometry Optimization:

The SMA bimorph can be modeled as follows(2):

$$\delta = \frac{3 \cdot \sigma_{rec}/E_b \cdot (t_a + t_b)}{t_b^{\,2} \cdot KI} \cdot l^2 \qquad (1)$$

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where the effective stiffness factor KI is given by:

$$KI = 4 + 6 \cdot \frac{t_a}{t_b} + 4\left(\frac{t_a}{t_b}\right)^2 + \frac{E_a}{E_b} \cdot \left(\frac{t_a}{t_b}\right)^3 + \frac{E_b \cdot t_b}{E_a \cdot t_a} \qquad (2)$$

where t_a and t_b are the thickness of the two materials; E_a and E_b are the Young's moduli of the bias spring and austenitic TiNi; and l is the length of the bimorph;

$\frac{\sigma_{rec}}{E_b}$ is the recoverable strain; (recoverable stress σ_{rec}, measured by substrate curvature, we set 200MPa, divided by the Young's modulus of austenitic TiNi)

Table 1 shows that a 0.529µm deflection is achieved by an Al/polysilicon bimorph with a 40K temperature fluctuation, but 1.75µm deflection is achieved by a SMA bimorph of the same size. The major advantage of a SMA bimorph over a normal thermal bimorph is the large deflection for small temperature changes.

	Al / Polysilicon	TiNi / Polysilicon
Temperature Difference	40K	N.A.
Thickness of two materials	20µm both	20µm both
Bimorph Length	200µm	200µm
Young's Moduli	77GPa / 165GPa	83GPa / 165GPa
Thermal Expansion Coefficients	23×10^{-6}/ °C; 4.7×10^{-6}/ °C	N.A.
Recoverable Stress	N.A.	200MPa
Tip Displacement	0.529µm	1.75µm

Table 1 Comparison of Al/polysilicon bimorph with TiNi/polysilicon bimorph

From equations (1) and (2) above, we understand that the tip deflection is the function of multiple parameters, like the thickness of two layers, Young's moduli of two materials, length of the bimorph and the recoverable strain. Due to the fabrication factors, the following parameters are fixed: Young's moduli of TiNi and polysilicon. Therefore only three parameters can be modified to achieve the maximum tip deflection.

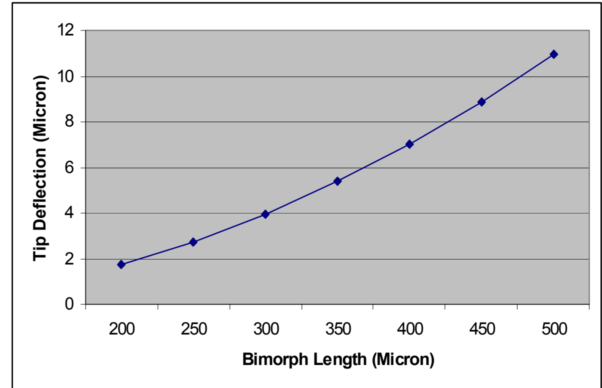

Fig.2 Tip deflection Vs. Bimorph length

We fix the thickness of TiNi and polysilicon at 20µm, and increase the length of bimorph from 200µm to 500µm. Fig.2 indicates clearly that greater tip deflection increases while the bimorph is getting longer.

We fix the bimorph length at 200µm and thickness of polysilicon at 20µm. Meanwhile we increase the thickness of TiNi from 1µm to 40µm. Fig.3 indicates that the tip deflection will reach maximum when the ratio of thickness of TiNi to polysilicon is around 0.675.

We fix the bimorph length at 200µm and the thickness ratio at 0.675 and increase the thickness of TiNi from 2µm to 40µm. From Fig.4 we understand that the tip deflection decreases while the material layers are getting thicker.

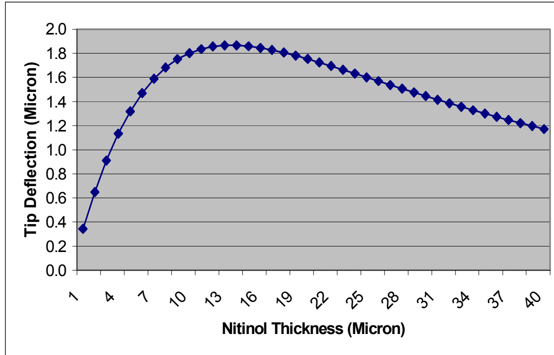

Fig.3 Tip Deflection Vs. Thickness Ratio

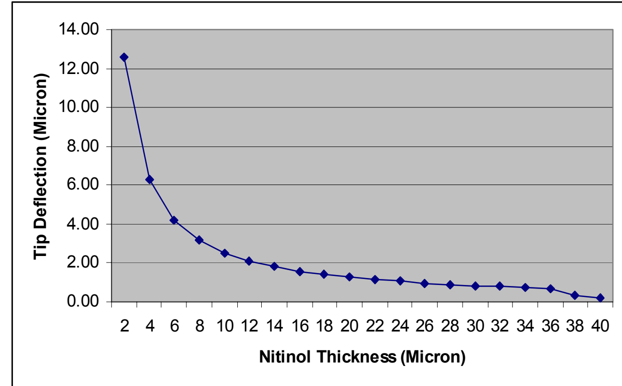

Fig.4 Tip Deflection Vs. Thickness at Fixed Ratio

Actually due to the fabrication limitations, we cannot make a structure with an optimal thickness ratio. Structure widths below 20µm are beyond our current facility capacity. Therefore we design the thickness of material at 20µm.

Fabrication Process:

In this paper, a new surface micromaching process is designed for fabricating the side-by-side bimorph. In a normal SMA bimorph, the SMA depositions were made by blanket depositions on top of the bias spring, which was in line with the deposition and patterning. In order to make side by side effect, one more patterning of the bias spring before the deposition of SMA is necessary. Fig.5 shows the cross section and top view at different stages of our process. (1) A 0.5µm silicon nitride is deposited on the silicon substrate as the protection layer. A 2µm sacrificial silicon dioxide layer is deposited onto the silicon nitride. (2) The sacrificial layer is patterned to make the anchor of bimorph. (3) A 2µm polysilicon is deposited as the structure layer. (4) The polysilicon is patterned to make the bias spring. (5) A SMA blanket deposition is sputtered and then patterned by photolithography. The alloy on the bias spring is etched away by SMA etchant and the alloy beside the bias spring is left. (6) Finally the whole structure is released from the substrate.

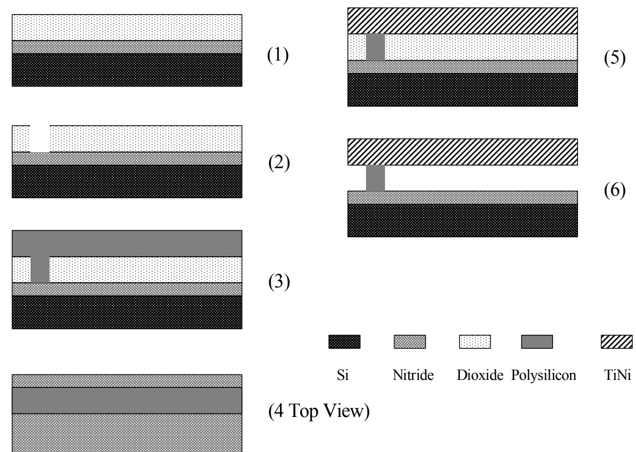

Fig.5 Fabrication Process Chart

Mask Making:
In previous papers, several alternatives to standard chrome masks have been discussed(3)(4). In this paper, the mask pattern has been printed on transparency films using a high-resolution printer first. Then the pattern on the transparency films will be transferred to the soda-lime glass through contact lithography. A commercially available polished soda-lime glass coated with iron oxide (4×4 inch, Nanofilm, CA) has been used. Prior to mask making, the soda-lime glass must be cleaned by acetone, methanol, isopropanol and DI water consecutively. A Karl Suss mask aligner and the standard procedure of AZ5214 has been used. The iron oxide was etched by a 3HCl:1H_2O etchant.

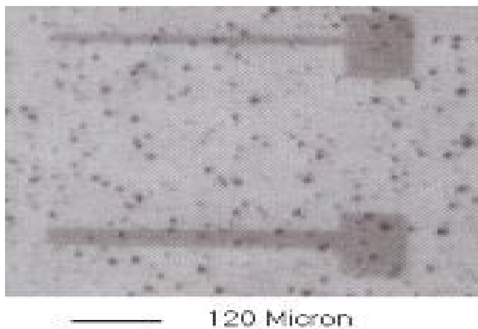

Fig.6 Pattern on the Transparency Film

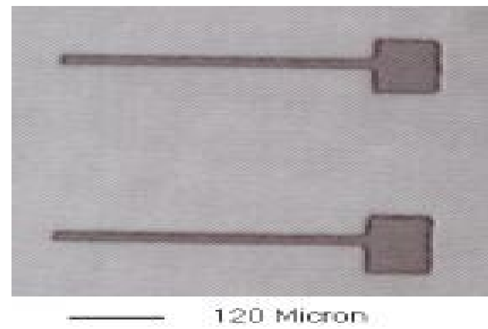

Fig.7 Pattern on the Soda-lime Glass

From Fig.6 and 7 we observe that most dust and ink dots on the transparency film can be removed via the photolithography process. Finally the iron oxide has the permanent mask pattern. Therefore a satisfactory hard mask can be made reliably and inexpensively through this method. This will be used in contact photolithography to pattern the structures designed to verify TiNi/polysilicon bimorphs, together with finite element simulations.

Conclusion:
Larger tip deflection can be achieved by using a SMA bimorph rather than normal Al/polysilicon bimorph from theoretical calculations. Geometry optimization has been discussed. A novel surface micromachining has been designed to fabricate side-by-side bimorph. A reliable and low cost mask making method has been proved by experiment.

References:

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