Development of patterned SMA strips as self-heating resistors

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ABSTRACT

A way to develop the pattern of shape memory alloys (SMA) titanium-nickel (TiNi) strips for improving the actuation performance of membrane microactuator is described in this paper. The patterned SMA strips serve not only as structural parts but also as heating resistors. Two different kinds of pattern designs are proposed and comparatively analyzed with finite element analysis (FEA) software ANSYS. Thermal-structural analysis is performed on the basis of maximum deflection potential. Coupled electro-thermal analysis is performed to investigate the effect of patterning of the SMA strips especially on the characteristics of temperature behavior. The planar pattern of the SMA strips for nonuniform heat generation rate are suggested so as homogeneous temperature variations can be obtained in the SMA thin films allowing an optimized use of the shape memory effect.

Keywords: MEMS, Membrane microactuator, Micropump, Shape memory effect, Finite element analyses

1 INTRODUCTION

Micropumps are essential devices in microfluidic systems. In the last years, various kinds of actuation mechanisms of micropumps have been suggested. The membrane micropumps are more practicable among them, where membrane microactuator draws most attentions. To meet the demands for actuation membrane with high deflection and large force, shape memory alloys TiNi thin films turn out to be a promising candidate in the design of microactuator [1,2]. To date, several efforts have been made yet all these designs are with complicated biasing force structural parts [3,4].

We have developed a novel membrane microactuator prepared for micropump, which only consists of membrane silicon substrate with TiNi thin films sputtered on [5]. The recovery of stresses upon heating in TiNi thin films is employed to deform the membrane. And the shape memory alloy thin films are patterned for self-heating. The micropump driven by this actuator is with excellent performance although its structural design is fairly simple [6].

For further improving performances, simulations are urgently needed in order to understand the effect of pattern and its structural parameters on the actuation behavior. In this paper, thermal-structural analysis is performed firstly on the basis of maximum deflection potential. Coupled electro-thermal analysis is followed to investigate the effect of pattern design of the resistor strips especially on the characteristics of temperature variation.

2 DESCRIPTION OF DESIGN

The composite membrane microactuator is shown in the Figure 1. Its outer configuration dimension is 6×6×0.45 mm^3. TiNi thin film of 5 μm are sputtered on the (100)-silicon substrate and then crystallized. Later on, the silicon substrate of 3×3 mm^2 lateral size has been back etched to 18 μm to establish a composite membrane.

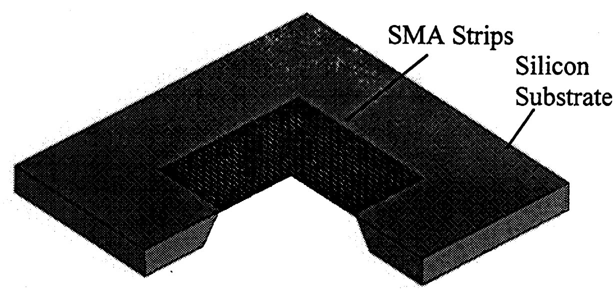

Figure 1: Cross-section of the membrane microactuator.

The operation of the composite membrane microactuator is based on the relaxation and recovery of stresses in TiNi thin films. When TiNi thin films are heated up to reverse martensitic transformation start temperature As, stresses redevelop to deform the membrane through the shape memory effect. However, when it cools down to martensitic transformation start temperature Ms, the stresses begin to relax. Mechanical spring forces in the actuator and fluidic pressure act to restore the membrane to the flat position. Here, the elasticity of silicon substrate membrane acts as the structure yielding biasing force against the deformation generated by the SMA.

In order to bring the principle into practice, mainly two requirements have to be met: temperature in TiNi varies above and below the transformation temperature; amplitude of temperature variation must be sufficiently large.

The reverse martensitic transformation can be induced by direct electric current heating. In order to simplify the structure, the TiNi thin films are patterned into strips, which can serve as self-heating resistors. Here besides the power supply modes, the dynamic temperature distributions of the TiNi strips will depend strongly on the pattern design and its dimensions. Unfortunately, in the specific design of the pattern of the strips, little guidance was found in the literatures. However, obviously improvement on performance can be made when satisfying the following conditions: the actuation voltage need to elevate the TiNi strips to requisite temperature is compatible with integrated circuits; requisite heating and cooling time are shortened so that high work frequency attained; temperature contours vary uniformly allowing an optimal use of the shape memory effect.

On one hand, for an optimal use of the shape memory effect, temperature variations large enough is required for a given power load. The temperatures should come up sufficiently high above austenitic transformation start temperature As, and go down large enough below martensitic transformation start temperature Ms. On the other hand, high response requires short heating and cooling time in a cycle. Both contradictory requirements should be taken into consideration simultaneously.

3 FINITE ELEMENT ANALYSES

Two patterns, square strips and spiral strips, are proposed as shown in Figure 2.

The selected material properties used in the analysis are listed in Table 1.

Material properties	Si	TiNi
Mass density (kg/m^3)	2300	6450
Thermal conductivity (W/mK)	157	20.9
Specific heat (J/kgK)	705	460
Young's modulus (GPa)	127.6	116
Thermal expansion coefficient (10^{-6}/K)	3.6	15.4
Poisson's ratio	0.27	0.33

Table 1: Material properties used in the FEM analysis

3.1 Thermal-Structural Analysis

From the working principle, we can see that although SME make the actuator work, however, the bimorph effect controls the maximum deflection potential. It is obvious that deformation behavior of different patterns are different even if the temperature variations in TiNi are the same. The geometric patterns mean a lot to deflection. In our effects under above considerations, several pattern designs are proposed and studied comparatively. In this part, qualitative analyses of two patterns are performed without taking partial transformation under considerations.

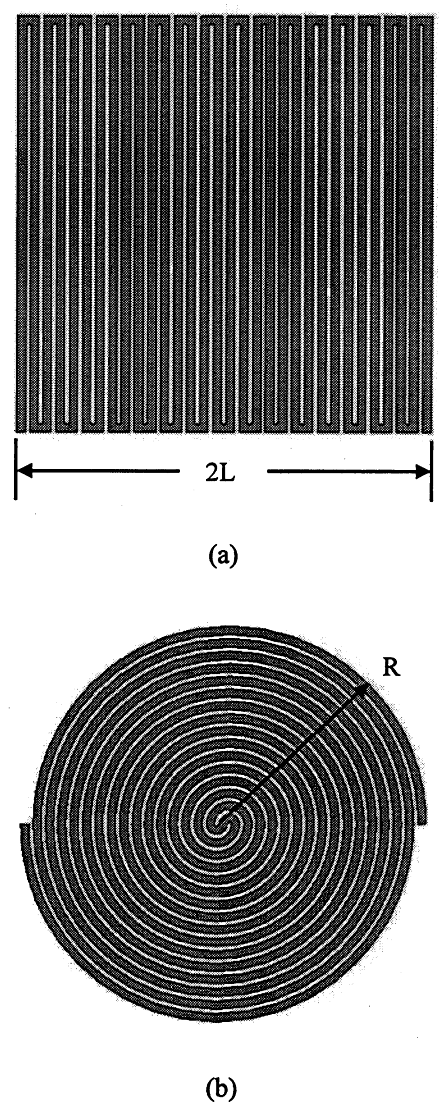

Figure 2: Two kinds of pattern arrangements (a) square and (b) spiral.

Three-dimensional 8-node structural brick solid element SOLID45 for the SMA resistor strips and 20-node element SOLID95 for the silicon membrane and frame were selected in the analysis. We take annealing temperature 823 K as nominally stress-free temperature. At this stage, uniform constant temperature distributions are imposed. Clamped boundary condition option was used for constraint condition.

The redeveloped stresses originate from thermal residual stresses, which arises due to the difference in expansion coefficients between TiNi and Si when the composite membrane cools down from the high annealing temperature. Thermal buckling occurs when structures are constrained and temperatures are decreased. The relationship between the normal displacement and the pattern can be obtained from the thermal-structural analysis. Figure 3 shows the calculated central deflection of the diaphragm dependent of the area size of TiNi patterns. As can be seen that for both patterns, there are optimal sizes of L and R at which the resulted deflections approach their maxima. The simulated optimal values of L and R are approximately 1.1 mm for the half side length of the square and the radius of the disc. In the further temperature distribution analysis, we take these results as the structural parameters.

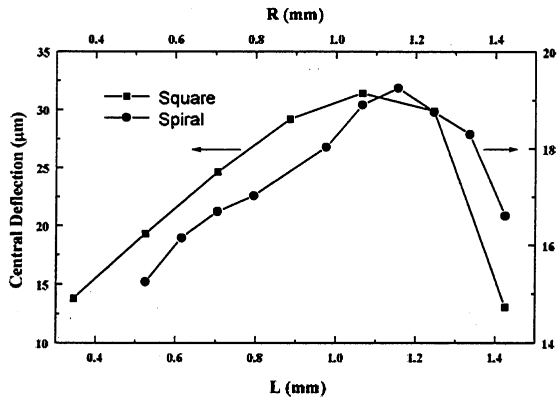

Figure 3: Central deflection dependent of SMA pattern size. (L and R are as shown in Figure 2)

3.2 Temperature Distribution

For improvement of the work output, the basic idea of optimization is to design the pattern of active SMA parts in such a way that spatially homogeneous temperature profiles are obtained for a given power supply mode. Thus a maximum volume fraction of SMA material is used for actuation and force due to stresses is maximized.

Heat generation rate can be converted from applied voltage and applied as body loads in the case of uniform values. However, as to the complicated patterns, it doesn't work. Thus three-dimensional 8-node thermal-electric solid element SOLID69 is selected for TiNi strips and 20-node three-dimensional thermal solid SOLID90 is selected for silicon structure to do the electro-thermal analysis.

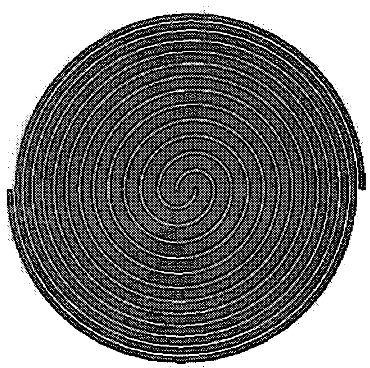

Figure 4: Variable width arrangement of spiral strips.

For constant resistivity, the heat generation induced by electric current is proportional to the cross-section of the strips, that is the width of the strips since thickness is homogeneous. Primary results show that most of heat dissipates through the conduction of silicon substrate which make inhomogeneous temperature distributions in the TiNi thin films. In order to compensate for different heat loss at different area, a design concept with variable width of strips as shown in Figure 4 is suggested and nonuniform heat generation rate was obtained as demonstrated in Figure 5. Much more heat generates on the fringe of the pattern, thus efficient thermal compensation take place between regions of different widths.

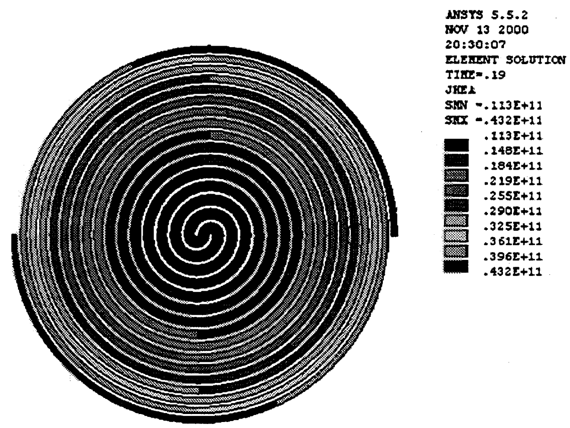

Figure 5: Heat generation rate with applied voltage 8V.

In comparison, Figure 6 and Figure 7 shows the peak temperature contours at stable dynamic working state with constant and variable width strips respectively under the

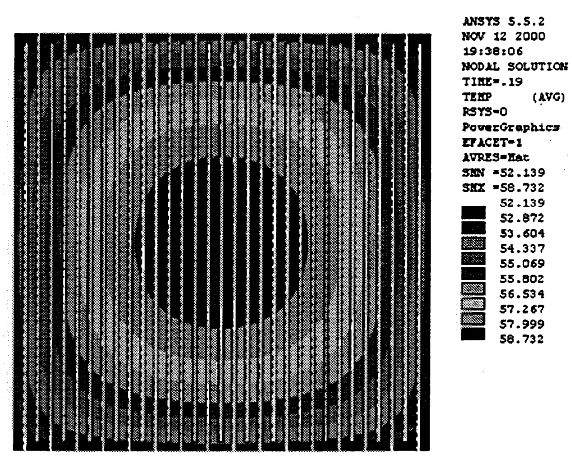

Figure 6: Temperature contours at peak value with uniform strip widths.

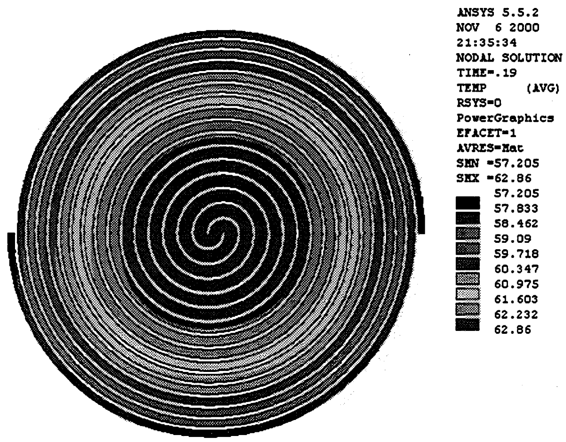

Figure 7: Temperature contours at peak value with variable strip widths.

same power supply mode. It can be seen that the fraction of high temperature zone in Figure 7 is larger than that in Figure 6. To shows it more clearly, a path across the area of TiNi pattern is defined. Figure 8 shows the peak value and valley value of these two designs simultaneously along this path under dynamic work condition in one graph. Solid lines stand for variable width design while segmented lines stand for constant one. In the case of Figure 7, a sufficiently homogeneous temperature distribution occurred, we can clearly see that there exist a temperature flat zone in the central part. Moreover, larger magnitude of temperature variation is obtained which implies more sufficient transformation thus higher deflection and larger force.

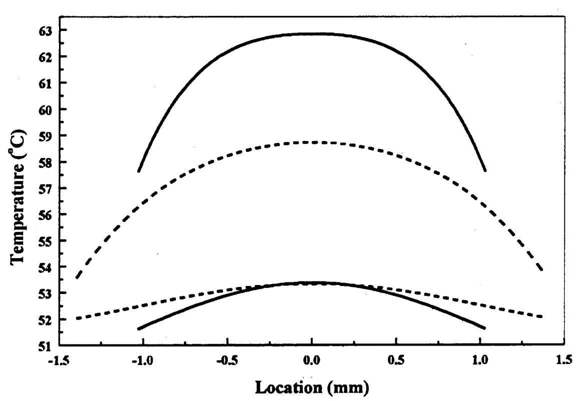

Figure 8: Temperature profiles along the path across SMA thin films.

4 CONCLUSIONS

Two design concepts, square and spiral, are proposed and analyzed with FEM software ANSYS comparatively. Variable widths of strips are suggested for heat compensation for inhomogeneous heat dissipation rate. Knowledge on the relation between temperature distributions and pattern arrangement allows for the optimization of the design. It can be expected the performance of the diaphragm will be improved after the optimized design.

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