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Ti–Ni–Cu/polyimide composite-film actuator and simulation tool

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ABSTRACT

Polyimide/$Ti_{49}Ni_{33}Cu_{18}$ composite films were fabricated by the sputtering of an alloy target. The composite films could be used as a simple actuator by cutting an appropriately shaped piece out of an as-sputtered films with scissors and then connecting it to a battery. In order to investigate the design parameters for the composite-film actuators, Ti–Ni–Cu films with various thicknesses (0.8–13 μm) were deposited on two kinds of polyimide films (Kapton EN and H) with various thicknesses (25–175 μm). The force and stroke of the composite-film actuators were found to vary largely with changes in various parameters such as the thickness ratio of Ti–Ni–Cu and polyimide films and the coefficient of thermal expansion of the polyimide films. A simulation tool based on a simple deformation model for a shape memory alloy was developed, and the effects of dimensional parameters (thickness, length, and width) and material parameters (Young's modulus, elastic strain limit, and transformation strain) on the actuation properties (force and stroke) of the composite-film actuators were systematically investigated on the basis of the simulation results. The simulation results revealed that composite-film actuators allow for various combination of force and stroke. Optimized actuators exhibited a long actuation stroke, a high response speed of 3 Hz, and a large force of 0.4 N.

1. Introduction

Shape-memory-alloy (SMA) thin films formed by sputtering are attractive candidates as actuators in microelectromechanical systems, such as microvalves, microfluid pumps, and micromanipulators, owing to their large force and displacement [1–9]. Several types of thin-film SMA actuators have been reported. Fig. 1 shows some of the typical actuators that have so far been reported [10]. Bridge- and diaphragm-type actuators were reported for microvalves [3,8] and micropumps [9], respectively. Because these actuators operate in tensile mode, they produce a large force without a long stroke. On the contrary, because cantilever-type actuators operate in bending mode, they produce a long stroke, but not a large force. The cantilever-type actuators were employed for micromanipulators [7].

The SMA films shown in Fig. 1 were deposited on Si wafers. These films are typically amorphous and require crystallization above 773 K. Such a high-temperature heat-treatment prevents the fabrication of an SMA-based composite film on a temperature-sensitive substrate, such as a polymer. However, we recently demonstrated that a crystalline Ti–Ni–Cu film can be directly deposited on a polyimide film by heating the substrate at 543 K during deposition [11]. This polyimide/SMA composite film could be used as a simple actuator by cutting out an appropriately shaped piece with scissors and then connecting the two edges of this piece to a battery. An 8-μm-thick $Ti_{48}Ni_{29}Cu_{23}$ film deposited on a polyimide (Kapton 100H) film could move the 0.18 g wing of a toy dragonfly up and down [11]. In a successive paper [12], the microfabrication of Ti–Ni–Cu films on a polyimide film was performed successfully in the same manner as they were fabricated on a Si wafer. The additional deposition of Cu onto a Ti–Ni–Cu film, but not the actuator parts, reduced the power consumption and hence the response time. Furthermore, an 8-μm-thick $Ti_{48}Ni_{29}Cu_{23}$ film on a polyimide (Kapton 500H) film could lift 13.5 g coins. These previous studies demonstrated the feasibility of Ti–Ni–Cu/polyimide composite films as a new-type of actuator, but the parameters controlling the actuation properties of the composite films had not been clarified. The shape memory behavior of Ti–Ni–Cu thin films has been intensively investigated in the last decade [13]. However, the performance of the thin-film SMA actuators in Fig. 1 have been known to strongly depend not only on material parameters, but also on the actuator dimensions [10]. Therefore, information on the parameters of Ti–Ni–Cu/polyimide composite actuator is essential to optimize the actuator design for applications.

In the present study, Ti–Ni–Cu films with various thicknesses were deposited on two kinds of polyimide films (Kapton EN and H) with various thicknesses. The deposition was performed using a conventional sputtering apparatus with an alloy target (Fig. 2)

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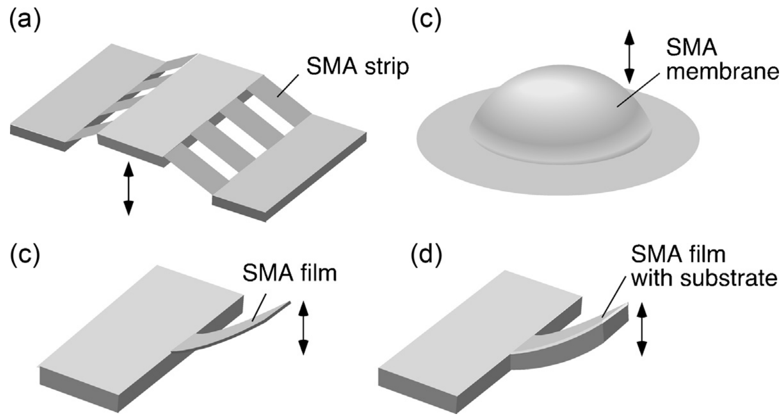

Fig. 1. Various types of SMA thin-film actuators formed on silicon substrates: (a) bridge type, (b) diaphragm type, (c) cantilever (free-standing) type and (d) cantilever (bimorph) type (after [10]).

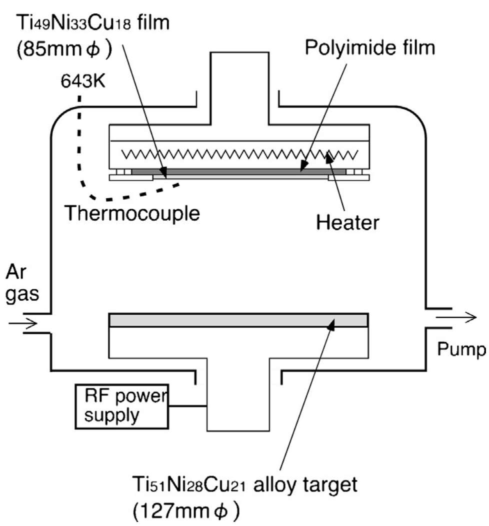

Fig. 2. Schematic of sputtering apparatus.

instead of the carrousel-type multi-element sputtering apparatus used in the previous study [11]. The actuation properties of the composite films were examined and a simulation tool was developed to predict the actuation properties. The fabrication and evaluation of thin-film SMA actuators with dimensions ranging from microns to centimeters is difficult. The simulation tool can overcome this difficulty and will be helpful in designing an actuator before fabrication. In the present paper, the effects of dimensional parameters (thickness, length, and width) and material parameters (Young's modulus, elastic strain limit, and transformation strain) on the actuation properties (stroke and force) of the composite-film actuators are discussed on the basis of experimental and simulation results.

2. Experimental procedure

$Ti_{49}Ni_{33}Cu_{18}$ films with thicknesses of 0.8–13 μm were sputter-deposited on two kinds of polyimide substrates (Dupont-Toray Kapton H and EN) with thicknesses of 25–175 μm by using a 5-in $Ti_{51}Ni_{28}Cu_{21}$ alloy target. The sputtering conditions were as follows: substrate temperature, 643 K; Ar gas pressure, 0.37 Pa (base pressure, 5.2×10^{-5} Pa); rf power, 800 W; substrate-to-target distance, 80 mm; deposition time, 15–70 min; and sputtering rate, 0.11 μm/min. To simplify the process, baking and reverse-sputtering of the polyimide films were omitted, although they were performed in a previous study [11]. The compositions of the films and target were determined by inductively coupled plasma atomic emission spectroscopy. To characterize the Ti–Ni–Cu films, X-ray diffraction (XRD) and differential scanning calorimetry (DSC) measurements were conducted on the films.

The composite-film actuators showed two types of actuation: two-way and one-way. The two-way actuation properties of the composite films were evaluated by measuring the curvature change during heating and cooling, whereas the one-way actuation properties of the composite films were evaluated by varying an applied load. The shapes of the test samples used for evaluating the two- and one-way actuation properties were a rectangle (14 mm × 3 mm) and a two-beam shape (beam portion: 10 mm × 9 mm), respectively. As described later, some of as-sputtered films did not show a shape change owing to lateral warpage that was unintentionally introduced during the sputtering process. To eliminate this effect, test samples for the two-way actuation measurement were wound on a stainless steel pipe with a diameter of 7 mm such that the polyimide side was on the inside. The samples were then annealed at 523 K for 20 min under the constraint before the measurement. This treatment was effective in modifying the initial shape of the composite films.

3. Results and discussion

3.1. Formation of Ti–Ni–Cu/polyimide composite film

Fig. 3 shows the XRD patterns of an as-sputtered $Ti_{49}Ni_{33}Cu_{18}$ film, measured at 423 K and room temperature. This film shows a crystalline diffraction pattern. TiNi (B2) and $Ti(NiCu)_2$ phases are identified at 423 K, and the B2 phase is found to completely transform into the B19 phase at room temperature. The film shows a strong 110 texture, since no other reflections were detected. XRD patterns were obtained at various distances of 5, 15, 25, and 35 mm from the center, and all the patterns show almost the same features except that the peak height of $Ti(Ni,Cu)_2$ decreases slightly with the distance from the center, as shown in Fig. 3(a) and (b). This suggests that the Ti content increases slightly with the distance from the center.

Fig. 4 shows the DSC curves of the as-sputtered $Ti_{49}Ni_{33}Cu_{18}$ film. The martensitic transformation peak temperature (M^*) is sufficiently greater than room temperature, and the temperature hysteresis is approximately 10 K. DSC curves were measured at different positions of the film, and the transformation peak temperatures are plotted in Fig. 5. These temperatures decrease slightly with the distance from the center. According to Fig. 3, the Ti content increases slightly with the distance from the center. Therefore, the decrease in the transformation temperature cannot be attributed