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Fabrication of magnetostrictive actuators using rare-earth (Tb,Sm)-Fe thin films (invited)

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A new concept is proposed for the microactuation based upon magnetostriction. Magnetostrictive bimorph cantilever actuators and a traveling machine, composed of the magnetostrictive amorphous Tb-Fe and Sm-Fe thin films on a polyimide substrate, were fabricated. These actuators moved without power supply cables. The 3-mm-long cantilever actuator exhibited the large deflection above 100 μm in as low a magnetic field as 300 Oe and above 500 μm at resonant frequency in an alternating magnetic field of 300 Oe. Such unique characteristics suggest that magnetostriction is useful as the driving force of the microactuator.

I. INTRODUCTION

A high-performance microactuator is required for the microelectromechanical system (MEMS). Several driving principles for the microactuator such as electrostatic force, electromagnetic force, piezoelectric effect, thermal expansion, and shape memory effect have been proposed up to now. In principle, electrostatic force devices are favorable for the μm-size actuators,[1] but some practical applications require larger mechanical forces than those obtained by electrostatic forces.

On the other hand, the electromagnetic force, which is predominant in a macroworld, had been considered to be unsuitable for the microactuator because it is a body force; however, recent developments of the three-dimensional micromachining techniques have enabled magnetic microstructures having enough volume to generate large mechanical forces. As a result, some magnetic microactuators have been demonstrated.[2,3] In the future, the magnetic microactuator is expected to play an important part of the MEMS.

In this article we propose a new concept for the microactuation based upon magnetostriction. The advantages of the magnetostrictive actuator are as follows: (1) The combination of a positive magnetostrictive material and a negative one enables a large deflection; (2) no power supply cable is required for its actuation because it is driven by external magnetic fields.

In spite of these advantages, only an in-pipe mobile robot made of a "bulk" magnetostrictive material has so far been reported.[4] Taking account of miniaturization and integration with other microelements, a magnetostrictive "thin film" should be used for the microactuator. In order to develop such thin-film actuators, we needed magnetic thin films with large magnetostriction in low magnetic fields. Here we used amorphous Tb-Fe thin films having positive magnetostriction and amorphous Sm-Fe thin films having a negative one. Both films exhibited a large magnetostriction of above 10^{-4} in low magnetic fields.[5,6]

In this article we fabricated two kinds of magnetostrictive "bimorph" cantilever actuators of different sizes and a traveling machine using the Tb-Fe and Sm-Fe thin films. We examined their basic properties and discussed their merits for the microactuators.

II. MAGNETOSTRICTIVE MATERIALS

The magnetostriction of the conventional materials such as Ni, Fe-Al, and amorphous Fe-Si-B is only $30-40\times10^{-6}$. On the other hand, some of rare-earth–transition-metal (RE-TM) crystalline alloys have very large magnetostriction above 10^{-3}. In particular, $TbFe_2$ has the largest positive magnetostriction and $SmFe_2$ has the largest negative one;[7] however, they have very large magnetocrystalline anisotropies and in general need large magnetic fields to saturate the magnetostriction. In order to reduce the magnetocrystalline anisotropy, two methods can be used: One is to alloy positive and negative magnetocrystalline materials such as

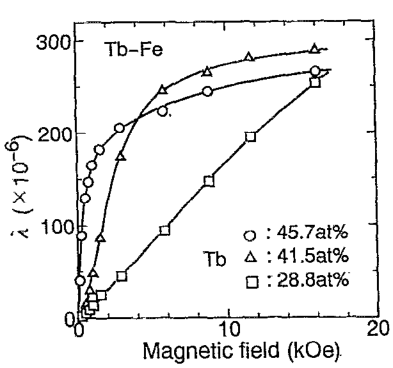

FIG. 1. Applied magnetic-field dependence of the magnetostriction for Tb-Fe thin films.

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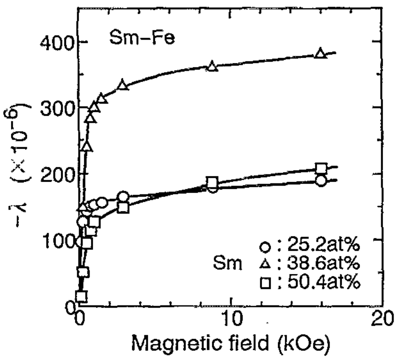

FIG. 2. Applied magnetic-field dependence of the magnetostriction for Sm-Fe thin films.

(Tb,Dy)Fe_2 and the other is to prepare amorphous state materials. In our study we applied the latter, because amorphous RE-TM thin films are easily obtained by a sputtering technique.

Details of the magnetic properties of the amorphous Tb-Fe and Sm-Fe thin films have been already reported in our previous articles.[5,6] In this section, we explain the outline.

Figure 1 shows the applied magnetic-field dependence of the magnetostriction for the Tb-Fe thin films having different compositions. The magnetostriction at 16 kOe exhibited large values above 250×10^{-6} in a wide composition range for 28–46 at. % Tb; however, the low-magnetic-field characteristics largely depended on the film composition because of the composition dependence of the magnetic anisotropy.

The films with 18–40 at. % Tb content had perpendicular magnetic anisotropy and needed high magnetic fields to saturate in-plane magnetization. On the other hand, the films with above 45 at. % Tb content had in-plane magnetic anisotropy. In this case, the in-plane magnetization increased rapidly in low magnetic fields, and accordingly the magnetostriction increased in the same manner. The saturation magnetostriction decreased with increasing Tb content above 50 at. % Tb; therefore, we used the 45–50 at. % Tb-Fe thin films for further examinations.

Figure 2 shows the applied magnetic-field dependence of the magnetostriction for the Sm-Fe thin films having different compositions. The magnetostriction increased rapidly in low fields regardless of Sm content because Sm-Fe thin films always had in-plane magnetic anisotropy. The maximum absolute values of $250–300\times10^{-6}$ at 1 kOe and 300–400 $\times10^{-6}$ at 16 kOe were obtained at 30–40 at. % Sm. In this experiment we chose the 30–40 at. % Sm-Fe films for the fabrication of actuators.

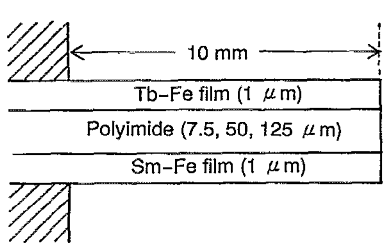

FIG. 3. Side view of the cantilever actuator.

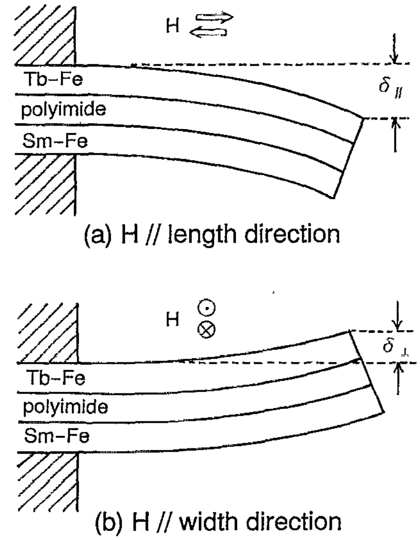

FIG. 4. Actuation behavior of the magnetostrictive bimorph cantilever.

III. DEVICE CONCEPT

Figure 3 shows the side view of the magnetostrictive bimorph cantilever. On a surface of a polyimide substrate, which has low elastic stiffness and high thermal stability, the Tb-Fe film is sputtered and on the opposite surface the Sm-Fe thin film is sputtered.

Figure 4 shows the actuation behavior of the magnetostrictive bimorph cantilever. When a magnetic field is applied along the cantilever length direction, the Tb-Fe film expands and the Sm-Fe film contracts in the length direction and as a result the cantilever deflects downward [Fig. 4(a)]. Next, when a magnetic field is applied along the cantilever width direction, the Tb-Fe film contracts and the Sm-Fe film expands in the length direction and then the cantilever deflects upward [Fig. 4(b)].

A bending behavior for the cantilever with composite structure such as a thermally excited bimetal cantilever[8] and a piezoelectric bimorph cantilever[9] has been analyzed using a classical method. Therefore, we applied this theory to the magnetostrictive cantilever and described below.

For the cantilever of total thickness h and length L, let the z direction be the thickness dimension and a neutral axis be located at $z=0$. We defined n $(0<n<1)$ to satisfy the condition that the upper surface and the lower one are located at $z=nh$ and $z=(n-1)h$, respectively. The neutral axis can be found from

$$\int_{(n-1)h}^{nh} E(z)z\,dz=0, \tag{1}$$

where $E(z)$ is Young's modulus as a function of thickness. In this article we assume that Tb-Fe and Sm-Fe films have the

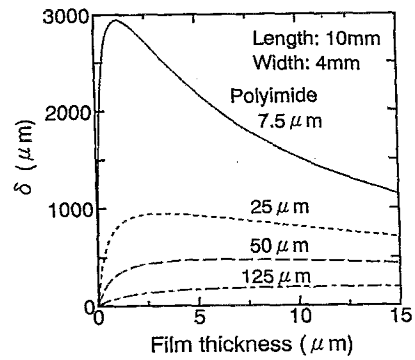

FIG. 5. Calculated deflection of magnetostrictive bimorph cantilevers as a function of thickness of each magnetic layer.

same Young's modulus and thickness; therefore, the neutral axis is located in the geometric center for a bimorph structure, that is, $n=0.5$.

When a magnetic field is applied along the length direction, the radius of bending curvature R caused by magnetostriction can be expressed by

$$R=\frac{\int_{(n-1)h}^{nh}E(z)z^2\,dz}{\int_{(n-1)h}^{nh}E(z)\lambda(z)z\,dz}, \tag{2}$$

where $\lambda(z)$ is the strain in the length direction caused by magnetostriction as a function of thickness and magnetic field. The tip deflection of the cantilever δ is

$$\delta=R[1-\cos(L/R)]. \tag{3}$$

In our study, R is much larger than L. Therefore, Eq. (3) can be approximated by

$$\delta=L^2/2R. \tag{4}$$

This equation indicates that the deflection decreases strongly with decreasing the cantilever length.

Next, when a magnetic field is applied along the width direction, we approximated that the strain in the length direction by magnetostriction is $-\lambda(z)/2$. Accordingly, the cantilever deflects in the opposite direction and the tip deflection is a half of that expressed in Eq. (4). When the cantilever is driven in rotating in-plane magnetic fields, the total deflection is the sum of the deflection caused by a magnetic field along the length direction and that by a magnetic field along the width direction.

Figure 5 shows the calculated tip deflection for the bimorph cantilever with a length of 10 mm as a function of thickness of each magnetic film layer when it is driven in a rotating in-plane magnetic field. In this calculation, we assumed the magnetostriction values of $\lambda_{\text{Tb-Fe}}=150\times10^{-6}$ for Tb-Fe films and $\lambda_{\text{Sm-Fe}}=-250\times10^{-6}$ for Sm-Fe films. These are typical experimental values obtained at 1 kOe on a glass substrate. The calculated deflection increases with decreasing the substrate thickness and that each substrate has the optimum thickness of the magnetic film to exhibit the maximum deflection. This calculation excludes the stress and strain in the width direction and the magnetic torque described later, but is effective to estimate the brief operation of the cantilever.

IV. FABRICATION

The amorphous Tb-Fe and Sm-Fe thin films were prepared by the rf magnetron sputtering method. They were deposited to a thickness of 1 μm on each surface of a rectangular polyimide substrate. The sputtering target used was composed of a pure Fe plate (3 in. diameter) and small Tb or Sm chips. The film composition was 45–50 at. % Tb for the Tb-Fe films and 30–40 at. % Sm for the Sm-Fe films as mentioned above. rf input power was 200 W, and Ar gas pressure was 4–10 mTorr for the Tb-Fe films and 10 mTorr for the Sm-Fe films. During sputtering, the substrate was water cooled. In order to prevent the oxidation of the magnetostrictive thin films, SiO_2 films with a thickness of 0.05–0.1 μm were coated on them.

After deposition, we clamped one end of the substrate and then obtained the magnetostrictive cantilever actuators as shown in Fig. 3. In this experiment, we fabricated two kinds of the cantilever actuators. One was a 10-mm-long cantilever using a commercial polyimide film with a thickness of either 7.5, 50, or 125 μm. The other was a microcantilever with a length of 3 mm using a 3-μm-thick polyimide film. This very thin substrate was made from 7.5-μm-thick polyimide by reactive-ion etching (RIE) using O_2 gas. The tip deflection of the cantilever was measured by both a three-terminal capacitance method[10] and direct observation using the optical microscope.

V. RESULTS AND DISCUSSION

A. Magnetic properties on a polyimide substrate

Before fabrication of the actuators, we investigated the magnetic properties of the Tb-Fe and Sm-Fe films sputtered on the polyimide substrate.

Figure 6 shows the magnetization curves of (a) Tb-Fe thin films on the glass substrate, (b) the 50-μm-thick polyimide substrate, and (c) the 3-μm-thick polyimide substrate. The 3-μm-thick substrate was the thinnest for our present techniques. The in-plane magnetization on the glass substrate increased rapidly in low magnetic fields, while that on the 50-μm-thick polyimide required high magnetic fields to saturate. This result suggests that we could not obtain the large magnetostriction in low magnetic fields when the 50-μm-thick polyimide was used. This change of the magnetic properties was caused by the large compressive stress in the Tb-Fe film with large positive magnetostriction. We think that this compressive stress was generated by the difference of the thermal expansion and/or the thermal contraction of the polyimide during sputtering; however, the magnetic properties on the 3-μm-thick polyimide was similar to those on the glass substrate. The stress in the Tb-Fe film from the substrate decreased with decreasing the thickness of the polyimide substrate.

On the other hand, the magnetic properties of the Sm-Fe films were less dependent on the substrate material, compared with those of Tb-Fe films. It seems that the compressive stress hardly influenced the magnetic properties of the Sm-Fe film because of negative magnetostriction.

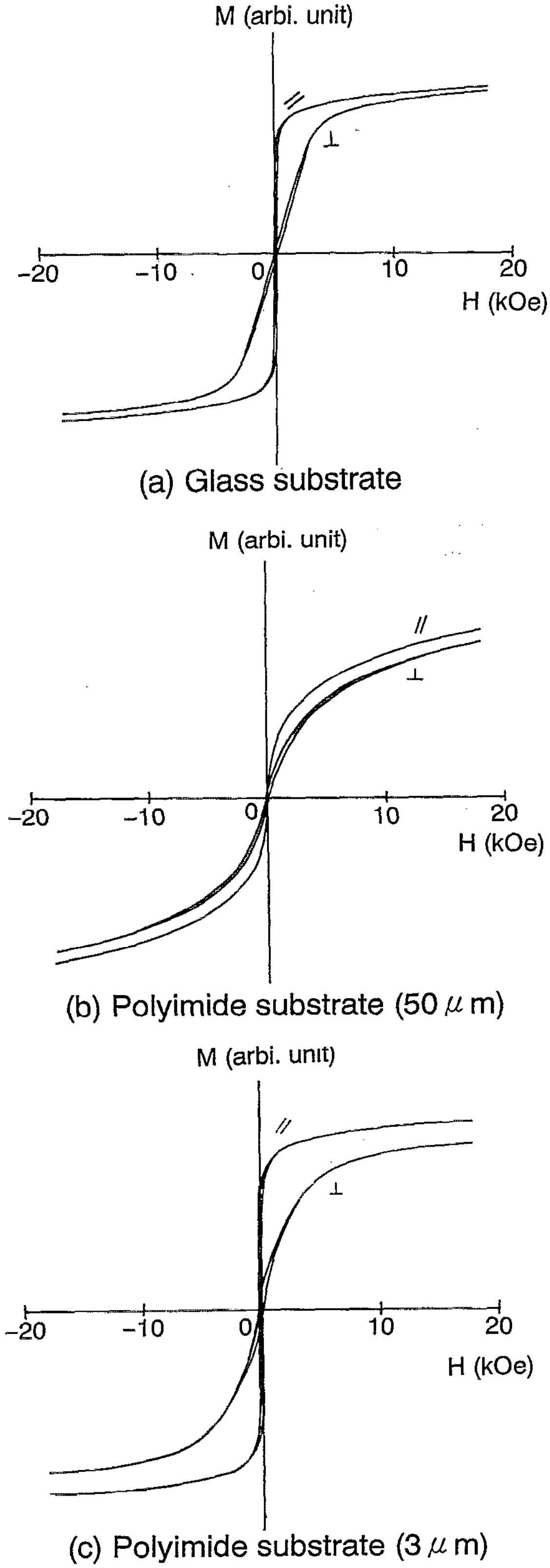

FIG. 6. Magnetization curves of Tb-Fe films

Generally, magnetic properties of the magnetostrictive material are greatly influenced by the stress. It is necessary to pay attention to the stress generated during the deposition and the micromachining process.

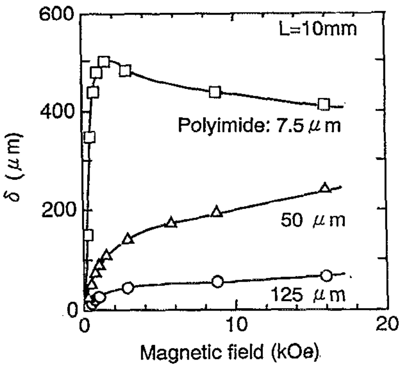

FIG. 7. Applied magnetic-field dependence of the deflection for 10-mm-long cantilevers.

B. 10-mm-long cantilever

In this subsection we examined the basic properties of the magnetostrictive cantilever. The cantilevers were 10 mm long and 4 mm wide.

Figure 7 shows the applied magnetic-field dependence of the deflection, when the cantilevers were driven in a rotating in-plane magnetic field. It is seen that each cantilever exhibited the large deflection in relatively low magnetic fields and that the deflection increased with decreasing the substrate thickness. The deflection of the cantilever using a 7.5-μm-thick polyimide exhibited the maximum value of approximately 500 μm at 1–1.5 kOe.

In the case of using the 7.5-μm-thick polyimide, however, the deflection decreased at high magnetic fields above 2 kOe. This was due to the magnetic torque generated by the large directional difference between the magnetic moment in the films and the applied magnetic field, when a high magnetic field was applied along the length direction as shown in Fig. 4(a). We must design the magnetostrictive actuator, taking account of both the amplitude and the direction of the applied magnetic field.

C. Microcantilever

From the results of the magnetic properties on the polyimide substrate and the 10-mm-long cantilever, we found that a thinner substrate was effective to obtain the large de-

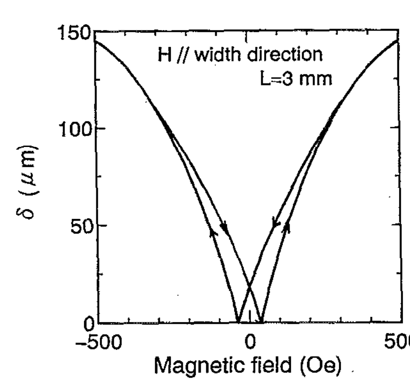

FIG. 8. Applied magnetic-field dependence of the deflection for a 3-mm-long cantilever.

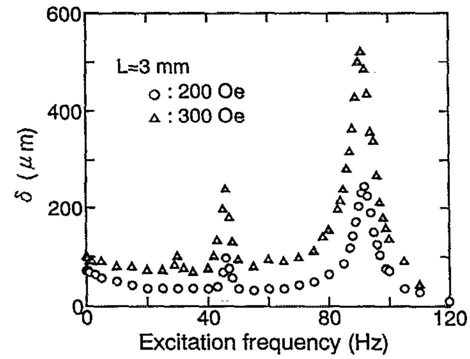

FIG. 9. Excitation frequency dependence of the deflection.

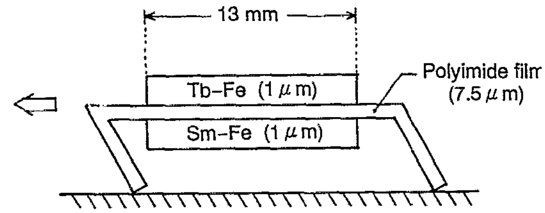

FIG. 11. Schematic view of a traveling machine.

flection. Therefore, we fabricated a trial microcantilever using a 3-μm-thick polyimide substrate. The cantilever was 3 mm long and 0.5 mm wide. In this experiment we examined its hysteresis and dynamic behavior.

Figure 8 shows the hysteresis curve of the tip deflection of the microcantilever when a magnetic field was applied along the width direction, where the deflection was little influenced by the magnetic torque. It exhibited a large deflection above 100 μm at as low a field as 300 Oe. This deflection was equivalent to more than 1 mm of the 10-mm-long cantilever as seen from Eq. (4); besides, this microcantilever had relatively small hysteresis. Such characteristics of the cantilever actuator were suitable for application as a micropositioning device.

Figure 9 shows the excitation frequency dependence of the deflection when alternating magnetic fields of 200 and 300 Oe were applied along the width direction. Note that the vibrational frequency was double the excitation frequency because the cantilever deflected in the same direction for both positive and negative magnetic fields. The cantilever exhibited the maximum deflection above 500 μm at an excitation frequency of 92 Hz, where the vibrational frequency agreed with its mechanical resonant frequency. This maximum deflection was five times as large as that in a static field. Two small peaks observed around 30 and 45 Hz were caused by the harmonics of the vibration.

We describe the future direction of the actuator design on the basis of Eq. (3). Figure 10 shows the calculated deflection of the bimorph cantilever with a length of 1 mm as a function of the substrate thickness when it is driven in a rotating in-plane magnetic field. E_f and E_s are the Young's modulus of the magnetostrictive films and substrate, respectively. Note that the deflection was a function of ratio of E_f/E_s. In our experiment, E_f/E_s is about 12 and the magnetostrictive films were supposed to be 1 μm thick and have magnetostriction as in the case of Fig. 5. The deflection increased gradually with decreasing the substrate thickness, and when substrate thickness is zero, that is, a "bimetal" structure composed of the Tb-Fe film and the Sm-Fe film, the predicted deflection exhibits the maximum value of 225 μm.

D. Traveling machine

We fabricated a traveling machine using the magnetostrictive bimorph actuator with 7.5-μm-thick polyimide as shown in Fig. 11. Its two legs at both ends were inclined so that it could travel in one direction. When an alternating magnetic field was applied, it vibrated and traveled in the arrow direction on disk planes as well as inside a quartz tubes (6.5 mm in diameter).

Figure 12 shows the excitation frequency dependence of the average traveling velocity when an alternating magnetic field of 300 Oe was applied along the machine width direction. The traveling machine needed the excitation frequency

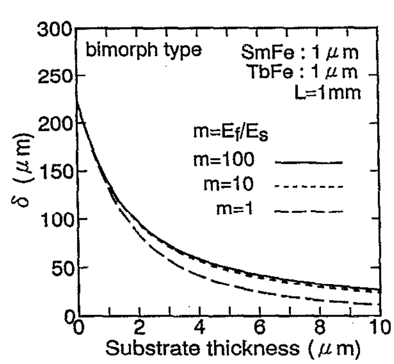

FIG. 10. Calculated deflection of the 1-mm-long cantilever as a function of the substrate thickness.

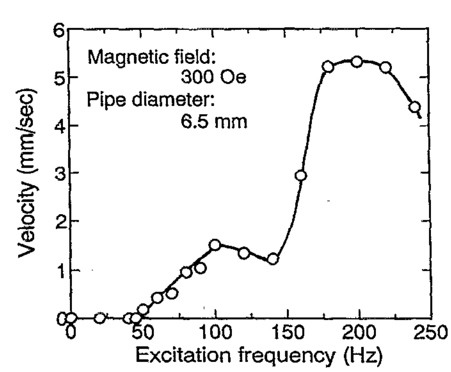

FIG. 12. Excitation frequency dependence of the average traveling velocity.

above 50 Hz to begin to travel and exhibited the maximum speed of approximately 5 mm/s around the mechanical resonant frequency of 200 Hz.

This magnetostrictive traveling machine requires no power supply cables which disturb its actuation in a microworld; therefore, magnetostriction is suitable for the driving force of the traveling micromachine.

VI. CONCLUSIONS

We fabricated cantilever actuators and a traveling machine using magnetostrictive Tb-Fe and Sm-Fe thin films and examined their basic properties. They showed unique characteristics such as large deflection and wireless driving. These results indicate that the magnetostrictive actuation is useful as the driving force of microactuators.

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