Development of Magnetic-Field-Driven Micro-Gas Valve

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Giant magnetostrictive Fe-Pd and Fe-Ga alloys are promising as actuator/sensor materials with high respective velocity and stress created by magnetostriction. To apply them to a micro-gas valve, we developed magnetostrictive actuators, that is, Fe₈₀Ga₄₀/Ni and Fe₇₀Pd₂₉₆/Ni bimorph layers. These cantilever-type actuators can be bent by applying magnetic field parallel to length. An actuator point displaced about 300µm under a low magnetic field of 37kA/m. Small and large actuators were applied to a micro-gas valve. The opening and closing action of a gas valve consisting of magnetostrictive bimorph layers can be controlled remotely by magnetic fields. Gas flow rate can be driven from 50 to 0mL/min by increasing the magnetic field to 40kA/m. The response time to the applied magnetic field is below 0.15s.

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1. Introduction

Giant magnetostrictive Fe-Pd¹,² and Fe-Ga³ alloys are desirable actuator/sensor materials with high respective velocity and stress created by magnetostriction. Recently, we have shown that ferromagnetic shape memory alloy Fe₇₀₄Pd₂₉₆ ribbons prepared by a rapid solidification melt-spinning method with a simple processing technique have a fine columnar microstructure with a highly [100]-oriented texture and exhibit a giant magnetostriction of 1000ppm under a good shape memory effect.⁴,⁵ Moreover, we have applied a melt-spinning method to an Fe₁₋ₓGaₓ (x = 0.13, 0.15, 0.17) alloy with a bcc phase to yield inexpensive, ductile and strong polycrystalline magnetostrictive materials.⁶ These ribbons also had a highly [100]-oriented texture, which induces magnetic anisotropy, and exhibited a large magnetostriction of 270ppm. However, to achieve saturation magnetostriction in these ribbons, a large magnetic field of 800kA/m is required.

To develop a magnetostrictive actuator using a low magnetic field, we investigated magnetostrictive (positive magnetostriction/negative magnetostriction) bimorph layers, that is, rapidly solidified Fe-Ga (146µm)/Ni(14µm) foils.⁷ These cantilever-type actuators can be bent by applying small magnetic field parallel to length, that is, a point of an actuator with a length of 20mm displaced about 440µm under a low magnetic field of 40kA/m.

Micro-valve, which can adjust flow rate, is urgently desired in biomedical instrument and semiconductor manufacturing fields. Micro-valves, which are actuated by micro-fabricated shape memory alloy (SMA: Ti-Ni, Ti-Ni-Cu, Ti-Ni-Pd) thin films, have been investigated.⁸,⁹ These valves were operated by temperature of 303–400K controlled by electric power. For micro-pumps and micro-valves driven by piezo actuators from PZT, typical driving voltages were in the range of −100 to 250V depending on the PZT characteristics and membrane/glue layer thickness.¹⁰–¹² Low voltage multi-layer piezo actuators and piezoelectric thin sheet material with driving voltage of 30V have been developed.¹³,¹⁴ Thus, SMA and piezo actuators have to contact electric power with wire. On the other hand, magnetostrictive actuators can be driven remotely by applied magnetic field. Moreover, the wireless actuator can operate the valve in wide temperature ranges, because curie temperatures Tc for bcc Fe-Ga alloy and Ni are about 720 and 628K, respectively, which are higher than Tc of 400–470K for PZT. Wireless micro-valve actuated by magnetostrictive TbDyFe alloy has been investigated.¹⁵ However, the micro-valve actuated by TbDyFe is operated by large magnetic field of 400kA/m, which is not suitable to application in micro-device.

In this study, a magnetostrictive bimorph-layer actuator, which is driven by low magnetic field, was investigated and applied to a micro-gas valve device. The micro-gas valve can drive the gas flow rate from 50 to 0mL/min by increasing the magnetic field to 40kA/m.

2. Experimental Procedure

Ingots of Fe₈₀Ga₄₀ and Fe₇₀₄Pd₂₉₆ alloys were prepared from electrolytic iron (4N), gallium (5N) or palladium (4N) by arc melting in Ar atmosphere. Fe₈₀Ga₄₀ and Fe₇₀₄Pd₂₉₆ ribbons of 30~120µm thickness and 6mm width were produced from these ingots using an originally designed melt-spinning apparatus with an iron single roll in Ar atmosphere.³

An Fe₈₀Ga₃₀ (120µm)/Ni(50µm) bimorph layer was prepared by gluing an Fe₈₀Ga₃₀ ribbon (120µm thickness) and a Ni foil (50µm) together. On the other hand, an Fe₈₀Ga₃₀ (30µm × 4)/Ni(50µm) bimorph layer was produced from four sheets of Fe₈₀Ga₃₀ ribbon and Ni foil (50µm) using a lap seam weld. Main magnetostrictive bimorph-layers actuators are shown in Table 1.

When magnetic field was applied parallel to length, the bimorph layers bent because the Fe₈₀Ga₃₀ and Fe₇₀₄Pd₂₉₆ ribbons with positive magnetostriction elongated and the Ni film with negative magnetostriction contracted parallel to the magnetic field direction. The displacement of the upper part of these magnetostrictive bimorph-layer actuators was...
measured by a bending cantilever beam method under steady and alternating magnetic fields in a Helmholtz coil.

Figure 1 shows two micro-gas valves and a schematic diagram. The micro-gas valves No.1 and No.2 were prepared for large (width $W = 18$ mm, length $L = 20$ mm) and small ($W = 5$ mm, $L = 17.5$ mm) actuators, respectively. The design of these devices in a solenoid coil is simple. The sides of the devices No.1 and No.2 consist of aluminium and brass, respectively. Ar gas flows through a metal tube with a diameter of 1 mm, and the opening and closing action of the valve, which consists of a magnetostrictive actuator with a rubber, is controlled remotely by low steady magnetic fields. Ar gas flow rate was measured using a digital flow meter with a minimum scale of 1 mL/min.$^{-1}$.

### 3. Results and Discussion

#### 3.1 Magnetostrictive bimorph-layer actuators

Figure 2 shows a photograph of a ribbon (a) prepared by rapid solidification and SEM image of close section of as-spun Fe$_{80}$Ga$_{20}$ (b) and Fe$_{70.4}$Pd$_{29.6}$ (c) ribbons. From these photographs, it is found that the as-spun ribbons consist of fine columnar structures of about 10$\mu$m width.

Figure 3 shows the XRD patterns obtained from the surfaces of (a) Fe$_{70.4}$Pd$_{29.6}$ and (b) Fe$_{80}$Ga$_{20}$ ribbons by Cu K$_\alpha$ radiation. The XRD pattern of ferromagnetic shape memory alloy Fe$_{70.4}$Pd$_{29.6}$ exhibits fct (200), (020) and (002) peaks due to the martensite phase$^2$ and a fcc (200) peak due to the austenite phase. Martensitic twins, which cause large magnetostriction, are observed in Fig. 2(d). It is considered that the ribbons have a highly [100]-oriented texture, because FCT (200), (020) and FCC (200) peaks are very distinct.$^5$

On the other hand, the XRD patterns obtained from the surfaces of as-spun Fe$_{80}$Ga$_{20}$ ribbon and Fe-Ga/Ni bimorph layers exhibit bcc (110), (200) and (211) peaks. The Fe$_{80}$Ga$_{20}$ ribbon also has a highly [100]-oriented texture, because the

<table>
<thead>
<tr>
<th>Bimorph layers</th>
<th>$D/\mu$m</th>
<th>$f$/Hz</th>
<th>$EI/10^{-5}$N·m$^2$</th>
<th>$F$/mN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuator 1</td>
<td>Fe$<em>{80}$Ga$</em>{20}$ (120$\mu$m)/Ni(50$\mu$m)</td>
<td>298</td>
<td>178</td>
<td>13.05</td>
</tr>
<tr>
<td>(glue) 20 mmL × 6 mmW</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Actuator 2</td>
<td>Fe$<em>{80}$Ga$</em>{20}$ (120$\mu$m)/Ni(50$\mu$m)</td>
<td>231</td>
<td>170</td>
<td>35.7</td>
</tr>
<tr>
<td>(glue) 20 mmL × 18 mmW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actuator 3</td>
<td>Fe$<em>{80}$Ga$</em>{20}$ (30$\mu$m × 4)/Ni(50$\mu$m)</td>
<td>87.5</td>
<td>244</td>
<td>73.54</td>
</tr>
<tr>
<td>(seam weld) 20 mmL × 18 mmW</td>
<td></td>
<td></td>
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<tr>
<td>Actuator 4</td>
<td>Fe$<em>{70.4}$Pd$</em>{29.6}$ (40$\mu$m × 4)/Ni(50$\mu$m)</td>
<td>258</td>
<td>210</td>
<td>12.68</td>
</tr>
<tr>
<td>(seam weld) 17.5 mmL × 5 mmW</td>
<td></td>
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Fig. 1 Two micro-gas valves and schematic diagram.
bcc (200) peak obtained from the as-spun Fe₈₀Ga₂₀ ribbon is very distinct.⁶)

The magnetostrictive properties under a low steady magnetic field for the Fe₈₀Ga₂₀/Ni and Fe₇₀.₄Pd₂₉.₆/Ni bimorph layers are shown in Fig. 4. The ordinate axis in Fig. 4 shows the displacement \( D \) of the upper part of these cantilever-type bimorph layers when the magnetic field \( H \) is applied parallel to length. These magnetostrictive bimorph layers almost saturate at a low field of 37 kAm⁻¹ and yield curves exhibiting little hysteresis with increasing and decreasing magnetic field. Moreover, the displacements induced by both positive and negative magnetic fields are almost equal.

The displacements at a field of 37 kAm⁻¹ for the glued actuators 1 (\( W = 6 \) mm) and 2 (18 mm) are 298 and 231 \( \mu \)m, respectively. The displacements decrease with increasing \( W \). On the other hand, the displacement at a field of 37 kAm⁻¹ for the seam welded actuator 3 with \( W = 18 \) mm is 90 \( \mu \)m, which is smaller than those obtained from other actuators.
The mechanical resonance frequency \( f \) in Table 1 was measured under alternating magnetic fields in a Helmholtz coil. Table 1 also shows the displacement \( D \), the binding stiffness \( EI \) and the actuated force \( F \) at \( H = 37 \text{kA m}^{-1} \) for these actuators. \( EI \) and \( F \) are given by

\[
F = \frac{3EI}{L^3} D
\]

and

\[
f_n = \frac{\omega}{2\pi} = \frac{1}{2\pi L^2} (\kappa_n L) \sqrt{\frac{EI}{\rho A}}
\]

where \( E, I, \kappa_n, \rho, \) and \( A \) denote the Young’s modulus, bending moment, constant of natural frequency \( f_n \), density and close section of the bimorph layers, respectively. Moreover, \( EI = E_A I_A + E_0 I_B \) and \( \kappa_n L = 1.875 \) for the first resonance frequency \( f_1 \). The actuated force \( F \) increases with \( W \). Moreover, the small actuator 4 has larger force of 18.2 mN than the actuator 1, which is 14.6 mN. The actuators 3 and 4 were applied to the micro-gas valves No.1 and No.2, respectively.

### 3.2 Micro-gas valves

Figure 5 shows the different setting types of actuators in micro-gas valves, namely, Types A with single actuator, B and C with double actuators, in which the valves open without magnetic field and close with increasing magnetic field. On the other hand, for Type D, the valve closes without magnetic field and opens with increasing magnetic field.

Figure 6 shows the dependences of the gas flow rate \( Q \) on the pressure difference \( P \) between the entrance and exit of the device (a), and magnetic field (b) for Types A, B, C and D. The actuator 3 controls the gas flow rate to zero below 6 kPa for Type A, 16 kPa for Type B, 18 kPa for Type C and 9.9 kPa for Type D. The gas flow rate increases linearly with magnetic field until 21.7 kPa for Type C. The gas flow rate vs magnetic field curves are shown in Fig. 6(b). \( Q \) for Type C can be driven from 50 to 0 mL min\(^{-1}\) at a pressure difference of 21.7 kPa by increasing the magnetic field to 24 kA m\(^{-1}\). However, the \( Q \) obtained by decreasing the magnetic field is not equal to the value obtained by increasing the field. On the other hand, the gas flow rate for Type D can be linearly driven from 0 to 16 mL min\(^{-1}\) at a pressure difference of 9.9 kPa by increasing the magnetic field to 40 kA m\(^{-1}\) and decreases reversibly. From these results, the actuator 3 can control the gas flow rate at pressure differences of 6.7–21 kPa.

Figure 7 shows the response of the actuator 3 to the applied magnetic field. As shown in Fig. 7, the gas flow
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rate for Type C is \( 50 \text{ mL min}^{-1} \) without \( H \). After applying a pulse magnetic field of \( 40 \text{ kAm}^{-1} \), \( Q \) decreases to zero with two steps below 0.15 s. It is considered that this behavior is due to two actuators with different times of response to the applied magnetic field.

Next, we investigate the behavior of the small actuator 4 in the micro-gas valve No.2. Figure 8 shows the dependences of the gas flow rate \( Q \) on the pressure difference (a) and magnetic field (b) for Types A and D. The actuator 4 controls the gas flow rate to zero below 2.6 kPa for Type A and 4.2 kPa for Type D. As shown in Fig. 8(b), \( Q \) for Type A can be driven from 42 to 0 mL min\(^{-1}\) at a pressure difference of 3 kPa by increasing the magnetic field to 20 kAm\(^{-1}\). Moreover, the \( Q \) obtained by decreasing the magnetic field is nearly equal to the value obtained by increasing the field. On the other hand, \( Q \) for Type D can be driven linearly from 0 to 30 mL min\(^{-1}\) at a pressure difference of 4 kPa by increasing the magnetic field to 33 kAm\(^{-1}\) and decreases reversibly. From these results, the small actuator 4 can control the gas flow at pressure differences of \( \sim 4 \text{ kPa} \), which are lower than those in the case of the actuator 3, and exhibits a similar behavior to the actuator 3.

Figure 9 shows a repeat test of a magnetically actuated valve consisting of a small \( \text{Fe}_{70.4}\text{Pd}_{29.6} \) (\( 40 \mu m \times 4 \))//\( \text{Ni}(80 \mu m) \) actuator. The flow rate vs applied magnetic field curves are nearly similar in seven repeat test experiments.

4. Conclusions

For application to a micro-gas valve, we developed magnetostrictive bimorph-layer actuators, that is, \( \text{Fe}_{80}\text{Ga}_{20} / \text{Ni} \) and \( \text{Fe}_{70.4}\text{Pd}_{29.6} / \text{Ni} \). These cantilever-type actuators can be bent by applying magnetic field parallel to length. An actuator point displaced \( \sim 300 \mu m \) under a low magnetic field of \( 37 \text{ kAm}^{-1} \). The opening and closing action of the valve consisting of a magnetostrictive actuator can be controlled remotely by magnetic fields. Gas flow rate can be driven from 50 to 0 mL min\(^{-1}\) by increasing the magnetic field to \( 40 \text{ kAm}^{-1} \). The response time to the applied magnetic field is below 0.15 s. Thus, the magnetostrictive bimorph-layer actuator is useful for applications in microdevices, such as micro-gas valves.

Acknowledgment

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