Miniature piezoelectric motors

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Received 12 July 2002; received in revised form 01 August 2002; accepted 12 August 2002

Abstract

There is great demand for micro- or miniaturized actuators for practical application. However, magnetic coils of electromagnetic motors are an obstacle to such miniaturization because of their complicated construction. Furthermore, electrostatic micro-motors fabricated by IC-processing cannot generate sufficient output power. Piezoelectric motors are promising because of their simple construction and high power density. In fact, some piezoelectric actuators have been or are close to being launched in the market. For their miniaturization, proper fabrication processes including thick deposition methods are important. In this review, various principles of piezoelectric motors are introduced in addition to suitable fabrication processes.

Keywords: Actuator; Micro-motor; Ultrasonic motor; Ferroelectric film

1. Introduction

The demonstrations of micro-electrostatic motors in the later 1980s are worthy to note [1–4]. By utilizing the silicon micro-processing technique, electrostatic motors were miniaturized to a couple of hundred micrometer in diameter and the advantage of an electrostatic force in the micro-field is emphasized by Paschen’s Law [5]. These demonstrations led to a rapid expansion of research in MEMS seeking the practical application of micro-actuators in medical, military, outer space and industrial fields.

Although electrostatic motors played an important role in stimulating MEMS research, their small dimensions and flat shape made it impossible to generate sufficient output force. The output torque of variable capacitive electrostatic micro-motors were around only 10 pNm [6,7]. Fujimoto et al. [8] studied a larger sized electrostatic motor whose diameter was 5.5 mm, although the generating torque was only 10 nNm.

For practical applications, millimeter or sub-millimeter sized motors might be attractive. For example, in micro-surgery, insect scaled robots or micro-positioning stages, actuators less than 1 mm³ might not be required. Instead of small dimensions, higher output power is a critical parameter and some miniature electromagnetic motors have been studied from this perspective [9–11]. Their output torque levels were µNm with a few millimeters in diameter, however the constructions were rather complicated because of their magnetic coils, and their low torque with high speed required a reduction gearbox.

Abbas et al. [12] tried to find a suitable rotational motor for installation into medical catheters. The target diameter was between 1 and 2 mm, however electrostatic and electromagnetic motors were rejected due to their drawbacks and unfortunately, piezoelectric motors were not taken into consideration in their investigation.

Piezoelectric motors, such as ultrasonic motors, can generate a large output torque with very simple constructions. A direct drive and a holding torque contribute a smart system that has no reduction gearbox and no brake mechanism. However, of course, piezoelectric motor also have problems. For miniaturization, to overcome the fragility of piezoelectric ceramics, special fabrication processes, including a thick film deposition process, are required. Moreover, the small strain that can be obtained from the piezoelectric effect proved problematic until researchers proposed the application of various interesting driving principles with a simple construction. Using these intelligent principles, the motors have been operated successfully with a small amplitude or displacement.

This paper reviews various fabrication processes for piezoelectric material and miniature piezoelectric motors.
2. Piezoelectric materials

An advantage of electromagnetic actuators is their high energy density of $4 \times 10^5$ J/m$^3$ with 1 T, $\mu = 1$. Centimeter-sized motors can be fabricated without difficulty so the dominant actuator in conventional use is the magnetic motor at present. However, in smaller sized motors, magnetic coils result in the complicated structure which can be a serious disadvantage.

Electrostatic energy density is quite small ($4 \times 10^6$ J/m$^3$ with $3 \times 10^5$ V/m, $\varepsilon = 1$) compared to electromagnetic energy density. Although, a maximum electrical field with a smaller gap is increased due to Paschen’s Law. For example, an electrical field of $1.7 \times 10^8$ V/m with a 12.5 $\mu$m gap was reported [13] and using SiO$_2$ film, $2 \times 10^8$ V/m was easily realized [5]. With these values, the energy density is calculated to be $2 \times 10^5$ J/m$^3$.

Paschen’s Law is one of the reasons why the electrostatic motor is adaptive as a micro-motor, although the main advantage of micro-electrostatic motor is its superior matching to a silicon fabrication processes.

Between the scale of centimeter-size (electromagnetic motor) and a few hundred micrometer-size (electrostatic motor), there is demand for powerful motors and piezoelectric motors are promising candidates. Before describing the fabrication process and presenting motor examples, the properties of piezoelectric materials are briefly explained.

At present, the most widely used piezoelectric material is lead zirconate titanate, PZT. With additives of doping or acceptor ions, PZT can be modified to soft-type or hard-type PZT.

Soft-type piezoelectric material is utilized to generate a large stroke, in other words it has a large $d$ piezoelectric coefficient. The energy density is expressed as

$$U_{\text{piezo}} = \frac{1}{2} k_{33}^2 \varepsilon_{33} \varepsilon_0 E^2$$

(1)

where $E$ is an electrical field ($1.5 \times 10^6$ V/m), $\varepsilon_{33}$ the permittivity (1700), $k_{33}$ the coupling factor (0.71), is $8.5 \times 10^5$ J/m$^3$ for PZT-5A [14]. This value is not as large compared to an electromagnetic value. Hard-type PZT is applied for resonance-type actuators like ultrasonic motors. Energy density for this type is

$$U_{\text{piezo}} = \frac{1}{2} Q^2 k_{33}^2 \varepsilon_{33} \varepsilon_0 E^2$$

(2)

where $Q$ is a mechanical quality factor. Generally, maximum electrical field is limited to $0.1 \times 10^6$ V/m and a quality factor of ultrasonic motor’s stator is from 100 to 200. Then the energy density for hard-type PZT (PZT-8; $k_{33}=0.64$, $\varepsilon_{33}=1000$ [14]) with the quality factor of 150 is calculated to be $4 \times 10^5$ J/m$^3$. After all, the magnetic and the hard-type PZT’s energy densities are similar, and the soft-type PZT’s energy density is below one order of magnitude.

Recently, relaxor type materials have been thoroughly investigated for their potential as actuators due to their very high dielectric constant and outstanding electromechanical properties. Research on the activities of relaxor materials are well reviewed by Yamashita and Ichinose [15]. Important relaxor materials are Pb(Zn$_{1/2}$Nb$_{1/2}$)O$_3$–PtTiO$_3$ (PZNT) and Pb(Mg$_{1/2}$Nb$_{1/2}$)O$_3$–PtTiO$_3$ (PMNT). Reported parameters for the PZNT (91/9) single crystal [0 0 1] and the PMNT (70/30) single crystal [0 0 1] are listed in Table 1. Their piezoelectric factors $d_{33}$ are more than three times those of soft-type PZT. The large coupling factor, which is very close to 1, indicates almost all input energy can be converted to mechanical energy.

These superior properties of relaxor material might offer a number of benefits for actuator applications. On the contrary, it should be noted that these properties can only be realized with the form of single crystals and the cut angle plays an important factor. The fabrication difficulties and mechanical fragility are disadvantages. However, relaxor materials might be a promising material for film deposition, because epitaxial growth is expected in some cases. Hence, epitaxial growth and thick film deposition for the relaxor material process is being extensively investigated in the field of ferroelectric materials [19].

Table 1 Piezoelectric factor $k_{33}$ and piezoelectric constant $d_{33}$ of relaxor materials with PZT [15]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Feature</th>
<th>$k_{33}$</th>
<th>$d_{33}$ pC/N</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT (soft)</td>
<td>Ceramics</td>
<td>0.71</td>
<td>374</td>
<td>[14]</td>
</tr>
<tr>
<td>PZT (hard)</td>
<td>Ceramics</td>
<td>0.64</td>
<td>225</td>
<td>[14]</td>
</tr>
<tr>
<td>PZNT (91/9)</td>
<td>Single crystal [0 0 1]</td>
<td>0.92</td>
<td>1500</td>
<td>[16]</td>
</tr>
<tr>
<td>PZNT (92/8)</td>
<td>Single crystal [0 0 1]</td>
<td>More than 0.90</td>
<td>2200</td>
<td>[17]</td>
</tr>
<tr>
<td>PMNT (70/30)</td>
<td>Single crystal [0 0 1]</td>
<td>More than 0.90</td>
<td>1500</td>
<td>[18]</td>
</tr>
</tbody>
</table>

3. Fabrication process

3.1. Ceramics

In general, piezoelectric materials are provided as ceramics and their fragile property prevents them from conventional cutting and grinding machining when the dimensions are smaller than 1 mm size. Larger than 1–2 mm sized piezoelectric actuators can be machined with conventional...
grinding. With a conventional grinding process, Morita et al. [23] fabricated a cylindrical stator transducer for a ultrasonic motor, whose dimensions were 2.4 mm in diameter, 1.4 mm in inner diameter and 10 mm long. For further miniaturization, reducing the cutting force is indispensable. Electrolytic in-processing dressing (ELID) [24,25] is a promising machinery process. This technology provides small grinding force by dressing to metal-bonded cutting wheels during the grinding process. This advantage might contribute to the fabrication of micro-parts made of piezoelectric ceramics.

As a cutting process, a YAG laser cutter was studied by Ohara et al. [26] and Li et al. [27]. Fig. 1 shows a SEM photograph of a concentric ring groove PZT. Other complicated patterns, for example, zigzag, triangle and square, can be patterned using this method. This technique was utilized to fabricate a piezoelectric composite, however, it is easily applied to micro-actuator fabrication.

3.2. Thick and thin film fabrication processes

Piezoelectric thin films have been extensively investigated in thin film form for their utility as non-volatile memories. For memory applications, thinner films are recommended to reduce the voltage to write and read record. Fabrication methods, such as ion beam sputtering, RF magnetron sputtering, MOCVD and so forth, are suitable for films thinner than 1 μm. For details of the thin film deposition process, please refer to a distinguished review paper written by Muralt [28].

In order to produce large piezoelectric displacement and force, research on piezoelectric thick film is increasing for application in micro-actuators. Each of these methods has specific advantages and disadvantages. The selection of fabrication process is dictated by the design of the micro-piezoelectric motor. The required features of the fabrication process for piezoelectric parts are as follows:

- Thick and uniform film that can endure higher input voltage without breakdown.
- The quality of piezoelectric coefficients, for example, piezoelectric constant d, coupling factor k and large permittivity ε depend on the chemical stoichiometry. The ratio of the chemical components should be precisely controlled in order to maximize the piezoelectric effect.
- In the thick film fabrication process, a low temperature sintering process is necessary. Mismatch of thermal expansion coefficients between piezoelectric material and substrate results in crack and breakage.
- Silicon process matching is sometimes required when the motors are integrated with a driving circuit and sensors. However, for millimeter-sized motors, this process matching could sometimes be neglected.
- Three-dimensional construction is required to obtain a large output power. Note that the output power of ultrasonic motors is proportional to the weight of the stator transducer.
- Fabrication process should have a batch processing opportunity, in other words mass production, because the motors might be disposable. This property will result in low cost.

Screen-printing method [29–31] is the most widely used technique in the electronic industry for thick film deposition. It is based on the principle of a paste that is forced to pass through a mesh by means of a plastic or rubber squeeze. A major advantage of the screen-printing method is the possibility of low-cost mass production because the patterning can be performed during film deposition. Complicated patterning is possible and electrodes are integrated together with the actuator. A multilayered PZT actuator was fabricated with screen printing and applied to piezoelectric motors by Bexell and Johansson [32].

An arc-discharged reactive ion-plating (ADRIP) method using a triple metal source was studied by Yasuda et al. [33]. Compared with conventional sputtering, dry-etching and plasma-enhanced chemical vapor deposition (PCVD) processes, the plasma density of the arc discharge is 1000 times higher than that of glow discharge. It is expected that the arc-discharged plasma can provide large amount of oxygen radicals, which could be effective for the growth of PZT films. A 1.4 μm thickness PZT thick film was deposited on a silicon wafer with a SiO2, Pt and Ti buffer layer. Using an oriented PZT buffer layer deposited by a chemical solution process, it was confirmed that PZT thick film was also oriented along the [0 0 1] direction.

Various research have been carried out on depositing piezoelectric thin and thick film using the sol–gel method. Target materials are PZT, PMN [19,34], PSN [35] and so forth. In the sol–gel method, the cations of the film are taken up into solution, as metal organic precursors, the solution then being deposited onto the substrate of interest.
by spinning or dipping by a firing stage. This method is very useful for thin film having a thickness below 1 μm, but it takes more time for a thicker film as multiple depositions are required. Also the process tends to be plane arising over a substrate processing, a 3D topography which can be another disadvantage.

The hydrothermal method (Fig. 2) is a promising method for depositing PZT thin film on a titanium substrate. This method was reported by Shimomura et al. [36] and Ohba et al. [37] and improved the reaction conditions to uniform chemical component by Morita et al. [38]. The chemical reaction between titanium substrate and ions in a solution is carried out under conditions of high temperature and pressure. The reaction temperature is from 100 to 200 °C. With chemical process in the solution, a PZT thin film is deposited over the entire surface. This feature is essential to applying the PZT thin film to a three-dimensional structure. The hydrothermal method makes use of a recrystallization reaction, so annealing is not necessary and a thick film can be realized. This technique was applied to fabricate micro-ultrasonic motors [39–41] and tactile sensors [42–44]. The disadvantage of their method is the mismatching to the silicon substrate because a high alkali concentration at high temperature attacks the silicon and melts it.

Jet-molding technology [45] used for PZT-layer deposition is based on gas deposition of ultrafine PZT powder. PZT particles less than 1 μm in diameter have been deposited onto sample surfaces by a high-speed jet stream ejected from a nozzle above the sample surface. As a result, the powder PZT is transformed into a sintered ceramic layer on the sample surface, most likely by transformation of the kinetic energy of the particles into thermal energy during the impact with the surface. By repeated scanning of the nozzle over the substrate, larger areas can be covered, and layer thickness up to 100 μm can be fabricated (Fig. 3).

4. Piezoelectric motors

4.1. Linear motor

As a linear type motor, an inertial drive motor has an advantage due to its simple construction. An additional advantage is the capability of nanometer order positioning faculty. One of the inertial motor categories is an “Impact Drive Mechanism (IDM)” driven by impulse inertial force [46]. The construction of this mechanism consists of the main body, actuator and the inertial weight. Slowly increasing and rapid decreasing input voltage is supplied to the actuator. The static friction surpasses inertial force during slow motion and impulsive inertial force results in slippage by the rapid displacement of an actuator. By modifying the input voltage shape, the moving direction is reversible. Using this actuator, multiple degree of freedom mechanism and micro-manipulator for cell manipulation [47], micro-positioning system for profile measurement system, auxiliary positioning system for STM [48] and AFM and precision automatic assembly systems [49] were developed.

Another inertial drive is a stick slip type that is sometimes called “Smooth Impact Drive Mechanism” (SIDM). In this mechanism, a base plate or bar is driven with rapid expansion and slow shrinkage. The slider on the base slips during rapid motion and follows the base due to frictional force.
After this pulsed excitation, precise driving is possible because the slider can be moved with dc voltage input to the piezo. Thus, this mechanism is effective for practical application that requires a precise positioning property. With the same principle, a self-moving type and a stator excitation type motor are realized as shown in Fig. 4. Using a slip stick mechanism, a micro-parallel link mechanism and X–Y stage for an optical microscope were developed by Breguet and Clavel [50]. They proposed and fabricated many applications including a 6 DOF micro-parallel link as shown in Fig. 5, a sample holder for AFM, Micro-Electric Discharge Machining (EDM) machine, a micro-assembly system and micro-telemanipulation system for biological specimens. This wide variety confirms that such a small motor is in demand for a practical use. Recently, Yoshida et al. [51] reported a smaller driving mechanism (Fig. 6) and this motor is being installed in mobile equipments.

Ultrasonic motors convert vibration energy of a stator transducer to slider or rotor motion energy. In general, bending, longitudinal or torsional vibration modes are used. There are few micro-linear type ultrasonic motors because of the difficulty in the exciting traveling wave in bars or plates as a stator transducer. Kurosawa [52] utilized one of the surface acoustic waves (SAW), Rayleigh wave for the source of an ultrasonic motor. Its driving principle is shown in Fig. 7. Since the vibration energy of the Rayleigh wave concentrates on the surface of the stator transducer, high mechanical power output was realized and the backside can be held firmly without energy loss. It should be noted that the amplitude of the Rayleigh wave is less than 20 nm, which was quite small compared to the bending or longitudinal vibration mode. For successful operation with such small vibration amplitude, a silicon slider can be used that has many 30 μm diameter protrusions on the surface. These protrusions are effective for obtaining a high contact pressure to avoid the influence of a squeeze film of air.

When the size of ultrasonic motors, including linear types and rotational ones, are miniaturized, the driving frequency becomes higher, and the maximum vibration velocity depends on the material and not on the dimensions; hence, the vibration amplitude of the stator transducer is decreased due to miniaturization because of the high driving frequency. The SAW motor operation has shown that even a 20 nm vibration amplitude is sufficient to drive a motor under proper contact condition and with high contact pressure.

4.2. Rotational motor

Inchworm mechanism was utilized for a rotational drive motor [32]. The diameter and height are 4 and 2 mm,
respectively. The stator transducer consists of six multilayered bimorph as shown in Fig. 8. A piezoelectric multilayered bimorph had one intermediate and two external electrodes. With opposite input voltage to each layer, the multilayered bimorph bends by a similar principle to a conventional one. On the other hand, with the same voltage to each layer, it can generate sufficient longitudinal deformation because it is a multilayered structure. Hence, it is possible to activate the electric field in one layer independent of the other. Due to the phase shift between electrical fields to each layer, tips of the bimorph move along an elliptical trajectory. The maximum torque was 1.4 mNm and the maximum speed has been limited to 4 rpm. Recently, it was reported that this mechanism was applied to a multiple degrees of freedom motor [53].

A standing wave type ultrasonic motor has simpler construction than a traveling wave type. An excellent example of the standing wave type was developed by Suzuki et al. [54], whose construction is shown in Fig. 9. Measured starting torque was 3.2 μNm with 2.0 mm diameter transducer. Its principle and construction is quite simple, however a disadvantage of this motor is the non-reversible operation principle. Another example is also categorized as a standing wave type ultrasonic motor, although the motor is reversible by selecting the driving electrodes. This miniature ultrasonic micro-motor was developed by Iino et al. [55]. This motor with a diameter of 8 mm was applied to a vibration alarm, and a smaller one with a diameter of 4.5 mm to a driving source of a calendar mechanism in a watch. The watch and motor construction are shown in Fig. 10. This ultrasonic micro-motor is expected to be of use as a new driving source in a broad range of fields.

These two ultrasonic motor examples were fabricated using a ceramic PZT, although film PZT is indispensable for further miniaturization because of the fragility of PZT bulk ceramics. The first report regarding a micro-ultrasonic motor using a thin film might be the one by Flynn et al. [56]. A 0.3 μm thick PZT thin film was deposited by the sol–gel method and separated eight-electrode patterns was used for excitation. The tiny lens whose diameter was 1.5 mm was substituted for a motor. The principle of this motor is the traveling wave ultrasonic motor. The revolution speed was from 100 to 300 rpm, and the starting torque was 41 pNm. The rotational phenomena were observed, although the reversible rotation could not be observed. It might be assumed that the traveling wave was not excited as designed and an unexpected standing wave resulted in motor rotation.

To excite vibration using a piezoelectric film is rather easy, if the piezoelectric property is reasonable. A different point is how to convert a stator vibration to a rotor driving force. A miniaturization utilizing a rotor with various elastic fins was proposed by Uchiki et al. [57] on a rather larger...
scale. This principle was applied to a standing wave type micro-ultrasonic motor by Muralt and co-workers [58,59] using the sol–gel deposited PZT thin film. The schematic construction is shown in Fig. 11. Measured values for this motor were 1020 rpm and 0.94 µNm with a 5.2 mm in diameter stator transducer [59].

To generate large output power, three-dimensional construction is effective. Most thin film deposition processes are suitable for flat shape, hence such construction was difficult. Although by using a hydrothermal method Morita et al. succeeded in fabricating and operating a cylindrical shaped ultrasonic motor [39–41]. In advance of the PZT film type motor fabrication, a micro-ultrasonic motor composed of bulk PZT was developed. The stator transducer had dimensions of 2.4 mm in diameter and 10 mm length [23]. The maximum revolution speed was 650 rpm and the maximum output torque was 0.22 mNm with the condition of 100 V p-p input voltage. These characteristics surpassed that of an electromagnetic motor of a similar diameter, and the bulk PZT motor was applied to robot hands as shown in Fig. 12. This robot hand was driven in direct drive mode and it did not contain a brake system, thus keeping it very simple. A two-axes hand application was successfully operated with a step motion and carried up to a 10 g load.

For further miniaturization of the motor, PZT film utilization was indispensable. The thickness of a hydrothermal method can be more than 10 µm and with this film a stator transducer whose dimensions were 1.4 mm in diameter and 5.0 mm long was fabricated as shown in Fig. 13. To date, this diameter might be one of the smallest as a stator transducer for an ultrasonic motor. The base substrate of the stator transducer was made of titanium, which is easy to machine. The starting torque was measured to 0.67 µNm, which is very large for a micro-motor. By considering an equivalent circuit of this stator transducer, output torque as a function of motor size was estimated. As can be seen in Table 2 even with 100 µm diameter, the output torque is 27 nNm [41]. This value is quite large compared to a micro-electrostatic motor, bearing in mind that the maximum output torque of an electrostatic motor is 10 nNm with 5.5 mm diameter [8].
5. Conclusions

In this paper, an overview on recent development in the field of miniature piezoelectric motor is given. First, the features of piezoelectric materials were summarized. Relaxor type materials have superior potential for actuator applications in the near future, although some disadvantages due to single crystal, for example a difficulty of fabrication, should be overcome. One of the key points for miniature piezoelectric motor would be an epitaxial process for a thick film deposition.

Next, various fabrication processes were surveyed. An ERID and a laser cutting process are effective to machine piezoelectric ceramics with small grinding or cutting force. For thick piezoelectric film, thin film fabrication processes can be modified in some cases, although requirement for thicker film has brought out interesting technologies. In this review, a screen printing, ADRIP, sol–gel, hydrothermal and jet-printing method were introduced briefly. Amongst them, a jet-molding method and a hydrothermal method are considered to be promising because they can deposit a thick film on a three-dimensional structure. In fact, several actuators and sensors have been fabricated using a hydrothermal deposited PZT.

Finally, linear and rotational piezoelectric motors are described. Some of their dimensions are too large to really be called “a micro-motor”. However, their principles are interesting and their constructions are simple. As mentioned in Section 1, both a small size and effective output power are important factors.

At present, few thick film deposition methods have been applied to micro- or miniaturized motor fabrication and it is certain that the success for miniaturized piezoelectric motors depends on the piezoelectric material fabrication process.

Acknowledgements

The author would like to thank Arvid Bergander of IPR-LSRO in EPFL for his helpful advice and comments.

References


Biography

Takeshi Morita was born in 1970. He received B.Eng., M.Eng. and Dr.Eng. degrees in precision machinery engineering from the University of Tokyo, Japan in 1994, 1996 and 1999, respectively. His PhD thesis was about a cylindrical shaped micro-ultrasonic motor. After about 2 years as a postdoctoral research in RIKEN (the Institute of Physical and Chemical Research), he moved to Switzerland in 2001. For 13 months, he worked on piezoelectric thin films and piezoelectric actuators at the ceramics laboratory of Swiss Federal Institute of Technology (EPFL). Since July 2001, he has been an associate researcher at Tohoku University in Japan. His research interests are ferroelectric material and film, piezoelectric actuator including an ultrasonic motor and control systems.