A novel shape memory alloy microactuator for large in-plane strokes and forces

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Received 3 January 2016, revised 14 March 2016
Accepted for publication 4 May 2016
Published 1 June 2016

Abstract

This paper describes a novel concept for in-plane actuators based on a thin free-standing shape memory alloy (SMA) film. The presented guidelines can be used to design a variety of actuators that can provide a combination of large strokes and forces for linear and rotary motions. A prototype actuator demonstrated a displacement of 45 μm related to 4.5% of the SMA film length, and a force of up to 115 mN related to a stress of 230 MPa in the SMA film without plastic deformations. These capabilities allow the actuator to work against the stiff springs that are essential for the devices’ ability to sustain vibrations, impacts, and accelerations.

Keywords: NiTi, SMA, MEMS, sputtering, thin film, actuator

(Some figures may appear in colour only in the online journal)

1. Introduction

Shape memory alloys (SMAs) are a unique class of materials that exhibit strongly nonlinear thermo-mechanical behavior associated with a martensitic phase transformation. SMA actuators have the highest work-output per unit volume among all other actuation methods [1]; therefore, thin films of NiTi SMA have the potential to be integrated into micro electron mechanical systems (MEMS) for the fabrication of powerful actuators [1–3]. In addition, SMA thin films can be integrated into MEMS devices because they can be patterned with standard lithography techniques and are compatible with standard MEMS processes [4].

The most common concept for SMA based actuators uses a bias force, which acts on the SMA element and induces detwinning deformation in the martensite phase [5]. The latter deformation is recovered upon heating, when the SMA transforms to the austenite phase. In the absence of a mechanism that applies a bias force, the SMA can still exhibit reversible deformation in a process known as a two-way-shape memory effect [6], by which internal stresses in the martensite phase induces detwinning. However, the strain and stresses that the two-way-shape memory effect can apply are much smaller [3].

In bulk actuators, the bias force is usually applied by an external spring, which is pre-stressed by a predefined amount before the operation of the actuator [5, 7, 8]. However, in micro-SMA actuators, fabricated using silicon micromachining processes, a construction of a mechanism for inducing a bias force is a challenging task. In micro-pumps, a bias force is applied on a SMA membrane by the fluid pressure [9–11]. Some micro-actuators used a bilayer (unimorph) structure in which the bias force is applied by an elastic layer attached to the SMA layer [12]. In order to use the full strain capability of the SMA, the SMA layer has to be deformed (detwinned) prior of being connected to the elastic layer. This process is relatively easy when dealing with thick (bulk) layers [5], but is practically impossible when using layers with a thickness at the micro scale. As a result, the strain in micro SMA based unimorph structures is limited to the mismatch strain between the layers (e.g. due to different thermal expansion coefficient) and is much smaller than the detwinning strain capability of SMA.

Almost all micro-SMA based actuators published until now produced out-of-plane motion. Kohl and Skrobanek [13]...
presented a micro actuator for in-plane motion, fabricated by laser cutting. However, this device cannot be integrated, on-chip, with other Si-based MEMS or microelectronic devices. To the best of our knowledge, only one previous publication has reported in-plane actuation using silicon based MEMS devices \[14\]. However, due to the use of the two-way shape memory effect, the strains and stresses applied by this actuator were very small.

In this work, we present a new concept for a MEMS SMA-based in-plane actuator fabricated using silicon micro-machining processes that can provide a large displacement with significant output forces. The actuator is composed of a thin free standing SMA film that is connected in series with a spring made by four silicon folded beams. Before the operation of the actuator, an external translation stage induces a one-time prescribed stretching of the SMA film and springs. Upon heating, the SMA film returns to its original length (except for a small elastic strain), and the silicon springs are stretched further. Then, upon cooling, the silicon springs stretch the SMA film and induce detwinning. These reversible deformations result in a reversible motion of a mass located between the SMA film and the silicon spring. In this mechanism, high output forces can be integrated with stiff springs as a restoring force, hence increasing the robustness of the actuator design. This device can provide an actuation strain of more than 4.5% of the SMA film length and an actuation stress of more than 200 MPa.

2. Operating principle and actuator design

The actuator operating principle is illustrated schematically in figures 1 and 2. The device is based on two masses, labeled as A and B, that are connected together by a released SMA thin film. Each mass is also connected to the rigid frame of the device by silicon springs, which protect the SMA film from rapture due to undesirable external out-of-plane loads and assure a uniaxial in-plane motion of the masses. Before the operation of the actuator, mass A is moved with an aim of applying a controlled initial stretching that defines the detwinning strain in the martensite phase. During the operation of the actuator, mass A is fixed and mass B moves back-and-forth upon heating and cooling.

In the initial stage labeled (a) in figures 1 and 2, the system is at rest and the SMA film is in the lower temperature martensite phase. The only acting forces at this stage are related to the residual stress of the SMA thin film. Next (stage (b) in figure 1 and path (a) to (b) in figure 2), a displacement \(u^A\) of mass A relative to the rigid frame is applied by an external translation stage. This stage is applied only once to induce the desired detwinning strain

\[
\varepsilon_{\text{det}} = \frac{(u^A - u^B)}{L},
\]

where \(u^B\) is the displacement of mass B during this initial stage and \(L\) is the initial length of the released SMA film. A prescribed value of \(\varepsilon_{\text{det}}\) can be applied by measuring \(u^B\) while increasing \(u^A\) until the desired difference between them is reached. After this initial motion, the location of mass A relative to the frame is fixed, and the actuator is ready for operation. In practical applications, the location of mass A can be fixed, for example, by a ratchet mechanism \[15\].

In the actuation stage (figure 1(c)), the temperature of the SMA film is increased to induce a phase transformation from...
the low temperature martensite to the parent austenite phase. The phase transformation is associated with an additional (actuation) displacement \( u_{\text{act}} \) of mass B, such that the overall displacement of mass B is given by

\[
 u_B = u_{\text{int}}^B + u_{\text{act}}^B. \tag{2}
\]

In the austenite phase, the film returns approximately to its original length (except for relatively small elastic strains) such that \( u_B \) is nearly equal to \( u_A \). Due to the force equilibrium with the spring, the strain and stress obtained during this stage follow a straight line, as illustrated by the dashed line from points (b) to (c) in figure 2. As explained below, the slope of the actuation line can be tailored by changing the dimensions of the SMA film and the silicon springs. Finally, upon cooling, the actuator returns to stage (b) and \( u_{\text{act}} \) returns to zero. Thus, reversible heating and cooling results in a reversible change between stages (b) and (c) and in accordance a change of \( u_{\text{act}} \).

A free body diagram of mass B allows the force \( F_{\text{SMA}} \) and stress \( \sigma \) acting on the SMA film to be calculated as follows:

\[
 F_{\text{SMA}} = Ku_B^B, \tag{3}
\]

\[
 \sigma = (Ku_B^B)/(wt). \tag{4}
\]

Here, \( w \) and \( t \) are the width and the thickness of the released SMA film, \( K \) is the spring constant of A and B masses. In addition the strain \( \varepsilon \) in the SMA film is given by

\[
 \varepsilon = (u_A - u_B)/L. \tag{5}
\]

Mathematical representation of the dashed line between points (b) and (c) in figure 2 can be obtained by combining equations (4) and (5):

\[
 \sigma = -\frac{KL}{wt} \varepsilon + \frac{Ku_A}{wt}. \tag{6}
\]

Then, the relationship between the output actuation stress and strain is described by

\[
 \Delta \sigma = -\frac{KL}{wt} \Delta \varepsilon. \tag{7}
\]

According to equation (7), the ratio between the actuation stress and strain can be modified by changing the spring constant or the \( L, w, \) and \( t \) dimensions of the SMA film. The maximum stress value is determined by the yield stress, \( \sigma_y \), and the detwinning strain, \( \varepsilon_{\text{det}} \). According to equation (7), the maximal value of \( \Delta \sigma \) is obtained when \( \Delta \varepsilon = -\varepsilon_{\text{det}} \). According to equation (6), the maximal value of \( \sigma \) is obtained when \( \varepsilon \) is minimal, i.e. when the film is completely at the austenite phase. In the absence of plastic strain the maximal value of \( \sigma \) is approximately given by \( \sigma_{\text{max}} = \frac{Ku_A}{wt} \). This approximation is obtained by substituting \( \varepsilon = 0 \) in equation (6), i.e. by assuming that the elastic strain at the austenite phase is negligible with respect to \( \varepsilon_{\text{det}} \). If the temperature is not high enough to complete the phase transformation, i.e. \( \Delta \varepsilon < \varepsilon_{\text{det}} \), the value of the stress is determined by the temperature approximately in accordance with the Clusius–Clapeyron equation [16]. If \( \sigma > \sigma_y \), the strain \( \varepsilon \) does not return to zero due to the plastic strain. Thus, \( \sigma_{\text{max}} \) is limited by \( \sigma_y \).

Our aim is to exploit the large stress and strain capabilities of NiTi without achieving plastic strains. Because it is difficult to predict \( \sigma_y \) in thin films, we chose the \( \frac{KL}{wt} \) ratio (see equation (7)) so that \( \Delta \sigma \cong 125 \text{ MPa} \) under a strain amplitude of \( \Delta \varepsilon = -5\% \), which is similar to the maximal stroke capability of NiTi [5]. Specifically, to demonstrate relatively large strokes, the chosen released SMA length was 1 mm. To demonstrate a robust actuator, which applies large forces and works against a stiff spring, the thickness and width of the released film were chosen as 3 \( \mu \text{m} \) and 200 \( \mu \text{m} \), respectively. For these dimensions and conditions, the spring constant was designed as 1500 N m\(^{-1} \) according to equation (7).

Another role of the silicon springs is to protect the SMA film from rapture due to undesirable bending and torsion loads and to force the masses to move only along the uniaxial direction of the actuator motion. For this purpose, the springs were designed such that their stiffness along the perpendicular directions is much larger than their stiffness along the axial direction of the actuator motion. In addition, the springs were designed to allow a travel of up to 80 \( \mu \text{m} \) that is related to a strain of 8\% in the SMA film.

### 3. Experimental setup

Actuation tests were conducted at room temperature using a custom-designed experimental setup that was introduced in detail in [17–19]. The experimental setup consists of a piezoelectric linear stage that applies a controllable displacement \( u_A \) to the moving gripper and is connected to mass A (see figure 1) while the rigid frame is held in place by a static gripper. The piezoelectric stage allows a relatively long travel of up to 100 \( \mu \text{m} \) with a nm-scale resolution and is located on a manual translation stage which is used for pre-aligning of the device relative to the static and dynamic grippers. A piezoelectric force sensor, with a full scale of 2 N and a resolution of 50 \( \mu \text{N} \), is located on the static gripper and measures the force applied on the rigid frame by both springs. The displacement, \( u_B \), is measured using an optical encoder that reads the displacement of a micro-grating pattern located on mass B. The measuring range of the encoder is in the mm-scale, while its resolution is approximately 25 nm. The experimental setup is operated, and the measured results are recorded using a designated software and user interface.

Before each test, the following stages are applied: (a) locating the micro device with the actuator in the experimental setup with the gripper pins inside the technical holes. (b) Initial alignment of the position of the gripper pins inside the technical holes using the manual translation stage. At this stage the locations of the gripper pins and the micro device
are observed under a stereoscope. The dynamic gripper is manually moved until a small force is measured in the force sensor indicating that the actuator is aligned inside the experimental setup. 

The force is released to zero by manually moving back the dynamic gripper along the opposite direction. After this stage, the setup is ready for performing a software controlled test.

The force $F_M$ measured by the force sensor can be expressed based on free body diagram and force equilibrium on mass A as follows:

$$F_M = K (u^A + u^B).$$  

(8)

Note that equation (8) is specific for the case in which the springs connected masses A and B to the frame has the same constant $K$. Based on this equation, the spring constant of each device is determined.

Figure 3 presents a general overview of the fabricated device (a) and focuses on the free standing SMA film (b). Each of the masses (A and B) is supported by four folded springs that are connected to the rigid frame of the device and have an overall stiffness of $K$. The released SMA thin film spans between the two masses. The gripping of the device is performed by pins that are inserted into circular holes in mass A and the frame.

Device actuation was designed to be performed by using resistive heating. When electrical current passes through the released SMA thin film, the temperature of the released SMA thin film increases above the austenite finish temperature ($A_f$). Consequently, a phase transformation occurs. The developed heat is proportional to $I^2R$, where $R$ is the resistance of the SMA film and $I$ is the applied electrical current. To minimize the developed temperature in the folded springs during actuation, an aluminum layer was designed for use in all conductors other than the released SMA thin film because the resistivity of aluminum is more than an order of magnitude lower than that of NiTi. In addition, aluminum conductors have been placed on all four folded springs of each mass to decrease the current flow on each folded spring and reduce the temperature in the folded springs.

4. Actuator fabrication

The microfabrication steps are shown in figure 4. First, a 1 $\mu$m silicon nitride layer is deposited by low pressure chemical vapor deposition on both sides of a silicon wafer with a diameter of 100 mm and a thickness of 250 $\mu$m. Then (figure 4(b)), a 3 $\mu$m NiTi film is sputtered from a single 200 mm diameter high purity (99.99%) Ni–Ti target (48 at% Ni–52 at% Ti). The distance between the substrate and the target during sputtering was set at 65 mm. The background pressure in the deposition chamber was $1 \times 10^{-7}$ Torr. The target was sputtered using argon at a pressure of 2 mTorr with a generator power of 1 kW. The substrate holder was rotated at 20 rpm in the horizontal plane to achieve a uniform film thickness and composition. After deposition, the samples were transferred immediately to a high vacuum ($1 \times 10^{-7}$ Torr) furnace for heat treatment at a temperature of 450 °C for 30 min. Measurements of the internal stress in the NiTi film by means of the Stoney method [20] using a Veeco Wyko NT9300 optical profiler provide small values in the range of 10 MPa. Differential scanning calorimetry (TA instruments, Q100) measurements showed that the austenite start and finish temperatures are $A_s = 72$ °C and $A_f = 105$ °C, and that the martensite start and finish temperatures are $M_s = 66$ °C and $M_f = 50$ °C. Comprehensive characterization of the microstructure and transformation phases of the NiTi film have been reported in [21].

The NiTi layer was patterned (figure 4(c)) by lithography and wet etching using an etching solution consisting of HF/HNO$_3$/H$_2$O with a volume ratio of 1:5:25. Then, a 1 $\mu$m aluminum film was deposited by electron beam evaporation and patterned by wet etching using the aluminum type A etchant (figure 4(d)). In the next step (figure 4(e)), the wafer was etched starting from the bottom side using RIE to etch the silicon nitride layer and then deep reactive ion etching for the silicon. Finally (figure 4(f)), the silicon nitride was etched using RIE from the bottom side to release the SMA film. After fabrication, small buckling of the released NiTi film was observed (figure 3(b)) due to the mismatched strains with respect to the silicon.
5. Results and discussion

Figure 5 presents the measured force $F_M$ as a function of $u^A + u^B$. According to equation (8), the slope of the curve is equal to the spring constant $K$, as illustrated in figure 5. In the test presented in figure 5, a linear regression provided $K = 1450 \, \text{N m}^{-1}$. This value agrees well with the designed spring constant of $1500 \, \text{N m}^{-1}$ that was calculated analytically based on beam theory.

Figure 6 presents three stress–strain curves of the same sample at room temperature (i.e., at the martensite phase). The presented strain and the stress were calculated based on equations (2) and (5) respectively. After each test, the film was heated to a temperature larger than the $A_F$ by using an electrical current to return it to zero strain before cooling to room temperature. After each test, a significant residual strain occurred, which is fully recovered by heating the sample, indicating that the residual strain is due to detwinning, i.e., $\varepsilon_{\text{det}}$. Another indication for the detwinning process during the loading is that the average slope during the loading segment is much smaller than that during the unloading segment. The stress during the loading segment gradually increases and does not settle on a plateau as is often observed in bulk SMA samples (see, e.g., [16]). Such a behavior has been previously observed in thin films of SMA [22] and it indicates that the barriers for the detwinning process do not have a single value that can be represented by the detwinning (plateau) stress. This observation is supported by the somewhat jerky behavior of the stress–strain curve during loading, which indicates the non-uniform kinetics of the detwinning [23–25]. From the
technical perspective, a stress of 90 MPa is sufficient for providing a large detwinning strain of $\varepsilon_{\text{det}} = 4.5\%$.

Figure 7 presents several actuation cycles that were applied after moving mass A and fixing it in a position that provides a detwinning strain of $\varepsilon_{\text{det}} = 4.5\%$. Strain, stress and force have been calculated using equations (2)–(5) and (8) and the displacement was measured by the encoder. Actuation cycles were implemented by applying an electrical power of 200 mW through the SMA thin film for several seconds and then letting the SMA film cool for several seconds. The maximal stress reaches approximately 230 MPa, and the actuation strain is approximately equal to the detwinning strain of 4.5%. After each actuation cycle, the stress and strain in the film return to their initial value, indicating that there is no generation of plastic strain.

Figure 8 presents zoomed views of the transition heating and cooling stages during the temperature changes. The transition time related to the martensite to austenite transformation presented in figure 8(a) is slightly shorter than the time between the sampling points, which is 45 ms.

Figure 8(b), shows the response during cooling in the first and in the second cycles. In the first cycle, the austenite to martensite transformation starts with a rapid transition in which approximately 70% of the stroke is obtained during approximately 90 ms. The last 30% of the stroke occurs much more gradually and takes several seconds. In the second cycle, the behavior is similar to that shown for the first cycle, but the first rapid transition in the second cycle provides approximately 90% of the stroke.

Previous studies have shown that the kinetics of martensite and reverse martensite transformations occur at time scales of 0.1 ms [26]. The time period associated with a mechanical resonance of the spring and mass combination is approximately 0.36 ms. Our observed transition times of 45–90 msec are determined by a much slower process, i.e., by the heating and cooling times. The gradual tails in figure 8(b) indicate on an additional much slower process that occurs after the film has cooled to the room temperature. Comparison of the gradual tails in the first and the second or third cycles (figure 8(b)) shows that although the characteristic time associated with this process remains approximately the same in all three cycles, the percentage of transformation associated with this process in the second and in the third cycles is much smaller than in the first cycle. Thus, from a practical point of view, the effect of this process can be decreased after a few training cycles.

6. Conclusions

A novel concept for SMA based in-plane actuators that can provide a combination of large strains and stresses and huge energy density has been demonstrated. A prototype actuator-provided displacement of 45 $\mu$m (4.5% of the SMA film length) under a force of up to 115 mN (related to a stress of 230 MPa in the SMA film) indicated no signs of plastic strain. Integration of the stress with respect to the strain showed that the demonstrated actuator provided a work per volume of $8 \times 10^6$ J m$^{-3}$, which is more than two orders of magnitude larger than the capabilities of the other MEMS actuation methods [1].

Several MEMS actuation principles other than the SMA have been demonstrated in the past for in-plane actuation, including electrothermal, piezoelectric, and electrostatic. Electrothermal actuators can generate a force in the range of several $\mu$N, and to achieve larger forces, the thermal actuators
are linked in an array [27] or use controlled buckling [28]. Piezoelectric thin films actuators are limited by the small strain of the piezoelectric material, which is in the range of 0.1%. In addition, for piezoelectric thin film mechanisms, the obtained actuation force is less than 1 mN [29]. Electrostatic actuators typically provide a small work per volume [1] and to provide actuation forces greater than 1 mN, the overall device dimensions must be very large, e.g., 87 μN mm−2 at 33 V in [30] (see also references therein). Thus, the demonstrated actuator provides a force that is at least two orders of magnitude larger than all other in-plane actuators with similar sizes.

The ability to induce large strokes and forces allows the demonstrated actuator to provide a motion against stiff springs (overall stiffness of 1500 N m−1). This capability is important for several reasons. First, stiff springs increase the overall robustness of the device and, particularly, its ability to sustain vibrations, impacts, and accelerations. Second, for a given mass that must be moved, an increase in stiffness results in an increase in the resonance frequency and a corresponding increase in the bandwidth.

The demonstrated actuator design can be modified to increase the actuation forces by increasing the film thickness and width or by applying several SMA films connected in parallel. The prototype actuator provides linear motion, but the same concept can also be used for applying rotary motion.

References

[1] Knulevich P, Lee A P, Ramsey P B, Trevino J C, Hamilton J and Northrup M A 1996 Thin film shape memory alloy microactuators J. Microelectromech. Syst. 5 270–82

[2] Ishida A 2013 Progress in thin-film shape-memory-alloy actuators Proc. Transducer 2013 (Barcelona, Spain) pp 1573–8

[3] Fu Y, Du H, Huang H W, Zhang S and Hu M 2004 TiNi-based thin films in MEMS applications: a review Sensors Actuators A 112 395–408

[4] Zamponi C, Rumpf H, Schmutz C and Quandt E 2008 Structuring of sputtered superelastic NiTi thin films by photolithography and etching Mater. Sci. Eng. 481–482 623–5

[5] Otsuka K and Wayman C M 1999 Shape Memory Materials (Cambridge: Cambridge University Press)

[6] Liu Y, Liu Y and Hunbeek J V 1999 Two-way shape memory effect developed by martensite deformation in NiTi Acta Mater. 47 199–209

[7] Krevet B, Pinneker V and Kohl M 2012 A magnetic shape memory foil actuator loaded by a spring Smart Mater. Struct. 21 094013

[8] Spaggiari A, Spinella I and Dragoni E 2013 Design equations for binary shape memory actuators under arbitrary external forces J. Intell. Mater. Syst. Struct. 24 682–94

[9] Benard W L, Kahn H, Heuer A H and Huff M A 1998 Thin-film shape-memory alloy actuated micropumps J. Microelectromech. Syst. 7 245–51

[10] Makino E, Mitsuya T and Shibata T 2000 Micromachining of TiNi shape memory thin film for fabrication of micropump Sensors Actuators A 79 251–9

[11] Shin D D, Mohanchandra K P and Carman G P 2005 Development of hydraulic linear actuator using thin film SMA Sensors Actuators A 119 151–6

[12] Gill J J, Chang D T, Momoda L A and Carman G P 2001 Manufacturing issues of thin film NiTi microwrapper Sensors Actuators A 93 148–56

[13] Kohl M and Skrobarek K D 1998 Linear micromachining based on the shape memory effect Sensors Actuators A 70 104–11

[14] Wang R X, Zohar Y and Wong M 2002 Residual stress-loaded titanium-nickel shape-memory alloy thin-film microactuators J. Micromech. Microeng. 12 323–7

[15] Tanner D M, Walraven J A, Barnes S M, Smith N F, Bitsie F and Swanson S E 2001 Reliability of a MEMS torsional ratcheting actuator 39th Annual Int. Reliability Physics Symp. (Orlando, Florida)

[16] Churchill C B, Shaw J A and Iadicola M A 2010 Tips and tricks for characterizing shape memory alloy wire: part 4— thermo-mechanical coupling Exp. Tech. 34 63–80

[17] Ben-David E, Tepper-Farán T, Rittel D and Shilo D 2014 A new methodology for uniaxial tensile testing of free-standing thin films at high strain-rates Exp. Mech. 54 1687–96
[18] Ben-David E, Kanner O and Shilo D 2009 A new method for measuring displacements of micro devices by an optical encoding system Exp. Mech. 49 823–7
[19] Ben-David E, Tepper-Faran T, Rittel D and Shilo D 2014 A large strain rate effect in thin free-standing Al films Scr. Mater. 90–91 6–9
[20] Ohring M 2002 The Materials Science of Thin Films (New York: Academic)
[21] Kabla M, Seiner H, Musilova M, Landa M and Shilo D 2014 The relationships between sputter deposition conditions, grain size, and phase transformation temperatures in NiTi thin films Acta Mater. 70 79–91
[22] Ishida A, Takei A, Sato M and Miyazaki S 1996 Stress–strain curves of sputtered thin films of Ni–Ti Thin Solid Films 281–282 337–9
[23] Benichou I, Faran E, Shilo D and Givli S 2013 Application of a novel bi-stable chain model for the analysis of jerky twin boundary motion in NiMnGa Appl. Phys. Lett. 102 011912

[24] Faran E and Shilo D 2012 Implications of twinning kinetics on the frequency response in NiMnGa actuators Appl. Phys. Lett. 100 151901
[25] Faran E and Shilo D 2014 Dynamics of twin boundaries in ferromagnetic shape memory alloys Mater. Sci. Technol. 30 1545–58
[26] Vollach S and Shilo D 2010 The mechanical response of shape memory alloys under a rapid heating pulse Exp. Mech. 50 803–11
[27] Sinclair M J 2000 A high force low area MEMS thermal actuator 7th Intersociety Conf. Thermal and Thermomechanical Phenomena in Electronic Systems pp 127–32
[28] Cao A, Kim J and Lin L 2007 Bi-directional electrothermal electromagnetic actuators J. Micromech. Microeng. 17 975–82
[29] Conway N J and Kim S G 2004 Large-strain, piezoelectric, in-plane micro actuator IEEE MEMS Conf. pp 454–7
[30] Yeh R, Hollar S and Pister K S J 2002 Single mask, large force, and large displacement electrostatic linear inchworm motors J. Microelectromech. Syst. 11 330–6