Lifetime Studies of Electrothermal Bent-Beam Actuators in Single-Crystal Silicon and Polysilicon

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***Abstract*—Microsystems using electrothermal bent-beam microactuators have been demonstrated for a variety of applications including optical attenuators, RF switches, and micro positioners, thus creating a need for information on the longevity of these devices. This paper reports on the dc and pulse mode lifetime testing of this class of actuators constructed using polysilicon and p^{++} doped single crystal silicon. The relative temperature profile along the top surface of an actuator is experimentally verified by scanning probe microscopy. Displacement measurements are used to explore links between aging behavior and the design variables and operating conditions. At low power levels (which result in average operating temperatures of 300–400 °C) both polysilicon and p^{++} Si devices provide continuous dc operation for >1400 min. in air without change in amplitude. While some types of p^{++} Si devices show monotonic loss of amplitude in pulse tests, others have been operated up to 30 million cycles without degradation. The displacement for polysilicon actuators can either increase or decrease depending on the geometry of the device and operating conditions, both of which are related to temperature and stress of the structural members. Polysilicon grain transformations are observed over extended operation at high temperatures. Performance changes are correlated to material properties using SEM and TEM images. [1682]**

***Index Terms*—Actuator, electrothermal, lifetime, micromachining, polysilicon, in situ annealing.**

I. Introduction

SINCE their introduction, electrothermal actuators have found many applications in microsystems such as optical attenuators and high-precision micropositioners. In particular, bent-beam actuators offer rectilinear displacements with large output force, while operating at a low voltage (typically <12 V) [1]–[6]. These devices are driven by passing current through a V-shaped beam anchored at the two ends, causing thermal expansion by joule heating to push the apex outward (Fig. 1). The displacement of the apex is a function of the beam dimensions and slope, and can be increased by cascading several actuators together. The trade-off between force and displacement is basically linear. Displacements greater than 20 μm with forces >10 mN are routinely achieved. The relatively high spring constant of these actuators can permit high positioning accuracy by reducing Brownian noise. Operating frequencies can exceed 1 KHz. Latching bent-beam actuators can be used in power-sensitive applications or when displacements have to be sustained for long periods of time. Another family of electrothermal microactuators that has been widely investigated is the pseudo-bimorph, which consists of two parallel cantilevers joined at their tips [7], [8]. One of these is wider than the other for most of its length, resulting in lower resistance to electrical current flowing through it and better thermal conductance to the substrate beneath, both of which suppress the temperature elevation in that segment and minimize its longitudinal expansion. The unequal expansion of these two cantilever segments in response to joule heating produces a rotational motion at the distal end of the arrangement. While the displacement is inherently not rectilinear, it tends to be larger than that from bent-beam actuators (albeit with a lower blocking force).

For any class of actuators, information related to the lifetime of the device is important for use in practical applications. Past efforts have included the studies of cyclic fatigue and aging in a variety of ways for devices made from both polycrystalline and single crystal silicon. For example, it was reported in [9] that at low actuation levels (<8 mW input power), polysilicon pseudo-bimorph actuators can operate with <20% amplitude degradation for more than 100 million cycles, and that the number of cycles to failure reduced exponentially with increased input power. (This raises the question of how well bent-beam actuators might behave in similar tests, since the temperature variations and stress concentrations in them tend to be lower.) Further, it has also been established that the polysilicon used in most surface micromachining processes is not stable at elevated temperatures: it tends to show grain growth and re-orientation in subsequent anneals when they are incorporated into the fabrication process [10]. (This raises a question about the impact of elevated temperatures that might result from the actuation itself.) In [11] and [12], it was reported that the fracture strength of polysilicon improves as the size of the specimen is reduced, but remains relatively unchanged with temperature over 0–250 °C. However, the Young's modulus decreases by about 10% at the higher temperatures in that range. In [13], which was a study of boron-doped single crystal silicon

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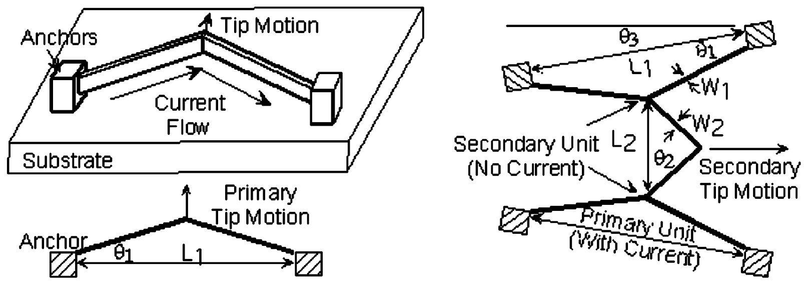

Fig. 1. Structure and operation of a single bent beam actuator (left) and cascaded design (right).

(SCS) cantilevers at room temperature, it was reported that dynamic Young's modulus increases by a few percent as a result of aging. In [14], it was shown that a polysilicon beam that was loaded with 0.6 GPa stress showed strain increasing at about 308 ppm/h, but this rate increased to 61 000 ppm/h at 600 °C.

In this paper, the aging behavior of polysilicon and SCS bent-beam electrothermal actuators under pulsed and dc actuation is reported.[1] Points of distinction from past efforts include the device type, structural design, and materials that were used, as well as the conditions under which the tests were performed. In particular, this effort seeks to explore the impact of inherent thermal and mechanical stress that results from operating bent-beam electrothermal actuators. The failure trends for boron-diffused SCS actuators and polysilicon actuators are separately studied. The grain changes in polysilicon that result from varying levels of actuation are also examined. The results indicate that the behavioral changes in the actuators are due to multiple mechanisms at work simultaneously, especially for the polysilicon actuators. Device fabrication is briefly described in Section II; results of the long-term dc and pulse actuation tests are described in Section III; analysis of these results and further experimental observations are presented in Section IV; and the conclusions are outlined in Section V.

II. Device Fabrication

The SCS devices described in this paper were fabricated by the dissolved wafer process [18], which results in heavily boron doped (p^{++}) Si structures attached to Pyrex™ glass substrates. Single crystal <100> Si wafers are subjected to solid-source boron diffusion, followed by a photoresist-masked reactive ion etching step to define the pattern of the devices. Their faces are then bonded to the glass wafers, and the undoped Si is removed using a wet etch that terminates on the p^{++} Si. The glass is expansion matched to silicon, so the apex position does not drift with changes in ambient temperature. Surface micromachined polysilicon devices were fabricated on Si substrates at Sandia National Laboratories using the SUMMiT IV™ process (Fig. 2). This process permits the deposition of up to four layers of polysilicon that can be separated by layers of sacrificial oxide. The lowest layer of polysilicon is attached to the substrate while the upper three layers are free to move after the removal of the sacrificial oxide. The polysilicon layers can be patterned individually. Thicker structures (up to 4.75 μm) are implemented by concatenating the polysilicon layers without the oxide. Using

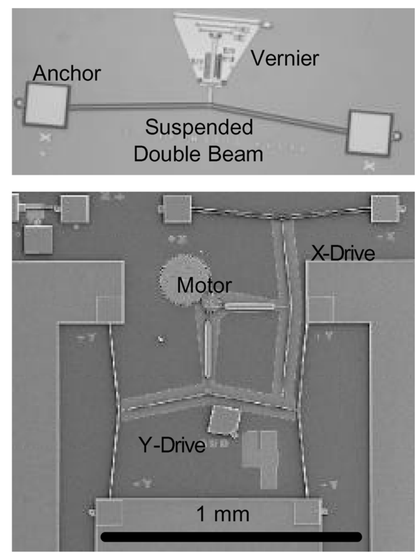

Fig. 2. Fabricated polysilicon microactuators: (a-upper) Optical micrograph of a T4 device, (b-lower) SEM image of a rotary micromotor that used such actuators.

this process, both linear actuators and rotary microengines have been demonstrated in the past [4], [19]. Two separate fabrication runs were performed for the polysilicon actuators. The device geometries used in the polysilicon as the SCS actuators are summarized in Table I.

III. Experimental Results

Actuation amplitudes of fabricated devices were measured by vernier scales integrated on the devices and by calibrated optical imaging. Typical responses are shown in Fig. 3(a) for single-beam actuators and Fig. 3(b) for cascaded actuators. Even under laboratory conditions, the thermal isolation achieved by these devices is typically $10^3 - 10^4$ K/W, and the power consumption is $<$250 mW. The small thermal mass of these devices results in a relatively high bandwidth of about 700 Hz. While this performance is suitable for many applications, it is anticipated that the presence of ambient oxygen and humidity can accelerate crack propagation, particularly since the devices are operating at elevated temperatures [20], [21]. Hence, some of the testing was performed in partial vacuum (as indicated in the caption of Table I.). In vacuum, since the thermal conduction through the air is minimized, the power required to achieve a particular displacement is reduced. However, the elimination of this heat loss mechanism also reduces the bandwidth, as observed in Fig. 4.

[1]Portions of these results have been published in conference abstract form in [15], [16], [17].

TABLE I

DIMENSIONS OF ACTUATORS (IN μm) AS PER FIG. 1, THE ANGLES ARE IN RAD. DESIGNS 1 TO 4 WERE TESTED AT 20–22 °C AMBIENT ROOM TEMPERATURE AND 43–45% AMBIENT RELATIVE HUMIDITY. THE REST OF THE DESIGNS WERE TESTED AT THE SAME TEMPERATURES AND UNDER PARTIAL VACUUM (BELOW 40 KPa.)

Design	Matl	Fab run	Type	T	L1	W1	θ1	L2	W2	θ2
1	SCS	A	Single	5.0	800	13.9	0.2			
2	SCS	A	Single	5.0	800	13.9	0.1			
3	SCS	A	Single	5.0	800	13.9	0.05			
4	SCS	A	Casc.	3.7	800	13.9	0.2	800	13.9	0.2
5	Poly	B	Single	4.25	800	5.7	0.1			
T4	Poly	C	Single	4.25	700	2x3.7	0.1			
T7	Poly	C	Single	4.25	945	5.7	0.06			
4A	Poly	C	Casc.	4.25	700	5.7	0.1	700	3.7	0.2
7A	Poly	C	Casc.	4.25	945	5.7	0.06	945	3.7	0.2

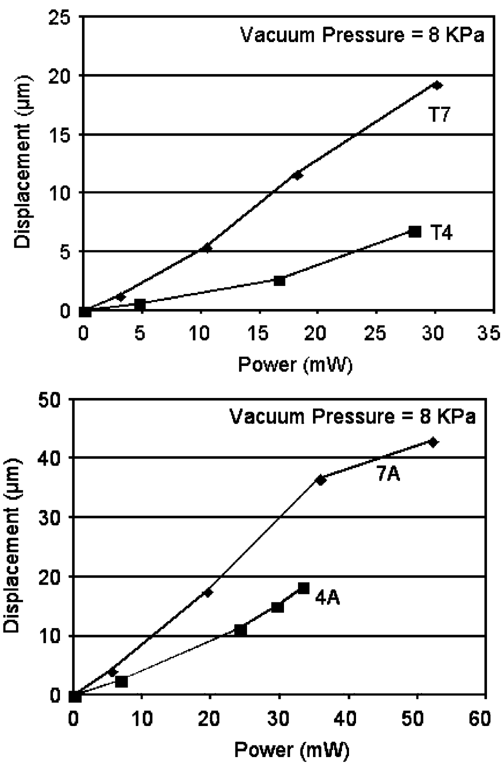

Fig. 3. Measured polysilicon actuator displacement (a-upper) for single and (b-lower) cascaded beam actuator. These results were obtained using dc actuation.

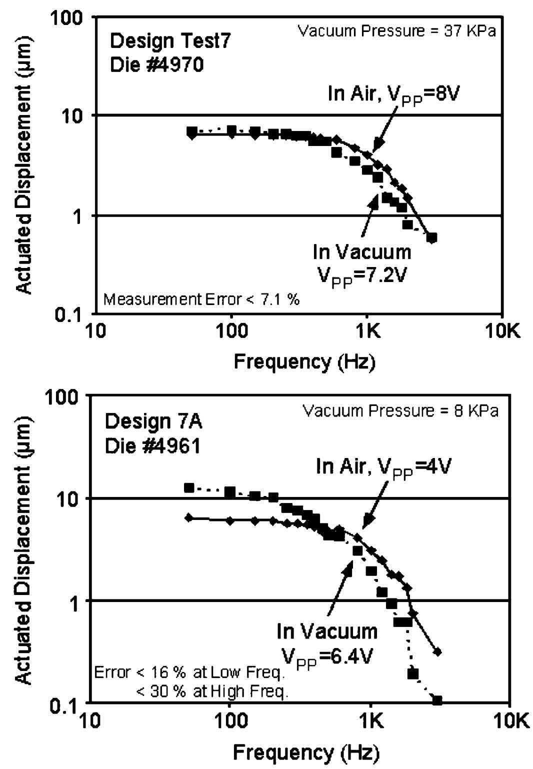

Fig. 4. Measured polysilicon actuator bandwidth (a-upper) for single and (b-lower) cascaded beam designs.

The temperature profile of a bent-beam actuator was measured using a commercial scanning probe thermal microscope. The scan was performed along half the length of the bent-beam (see Fig. 5) since the temperature profile is symmetric about its apex. The scanning thermal probe tip was a Wollaston wire with a 5 μm diameter Pt/Rh alloy wire, the resistance change of which is used to calculate the tip temperature change at different actuation levels that vary in input power. The intent of this experiment was to obtain a relative temperature profile; the true temperature of the actuator beam is higher than the measured tip temperature because the tip cannot be pressed against the cantilevered actuator to provide the intimate thermal contact that would be needed for an absolute measurement. A noteworthy fact is that the hottest location in the actuator was about $2/3$ of the distance from an anchor to the apex. The measured temperature profile resembles the numerical modeling results reported in [22], where a finite-difference method was used to calculate the temperature distribution of a bent-beam actuator.

A. *DC Lifetime Testing of SCS Actuators*

Actuation lifetimes were tested by applying dc power over a period of time while monitoring the location of the apex. The power was periodically turned off to monitor variations in the zero-power location of the apex. A small set of SCS actuators (Table I, #1) was subjected to dc lifetime tests. At 100 mW input power, the net displacement was 4 μm with no change in power-on and power-off positions for 1500 min, at which point the test was stopped. At 180 mW input power, the net displacement was 6 μm. The power-on and power-off positions changed by 1 μm each over a period of 90 min, while the difference between the two positions remained constant. (Note that the SCS devices were designed with relatively wide beams (Table I), and

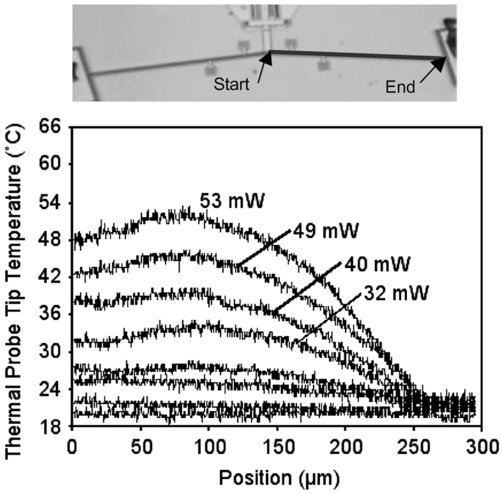

Fig. 5. Temperature profile of a bent-beam obtained using a scanning thermal probe method. The plotted temperature rise is proportional to, but lower than, the actual increase.

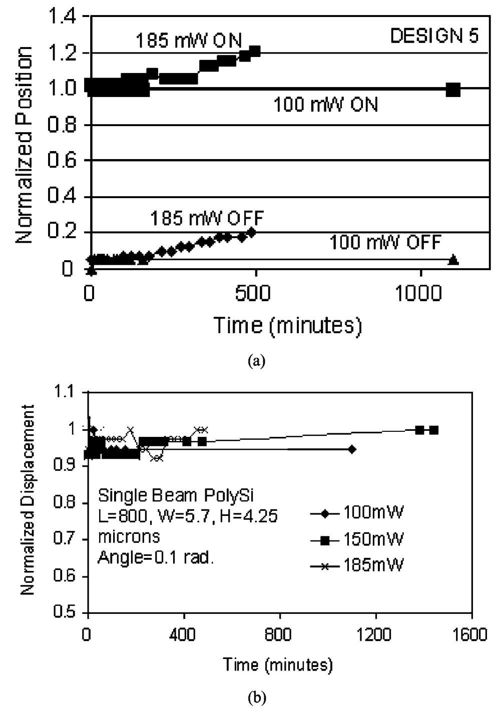

Fig. 6. Measurements of design 5 devices. (a) The power-on and power-off positions normalized to the initial activated position. The plot shows increase by equal amounts over extended periods at high input power. (b) The net displacement, which is the separation between power-on and power-off positions, remains relatively stable.

consequently provided smaller displacements than the polysilicon devices that were used in this study.)

B. DC Lifetime Testing of Polysilicon Actuators

Fig. 6(a) compares the stability of power-on and power-off positions for a single beam polysilicon design (Table I, #5), actuated at 100 mW and 185 mW input power. At the lower power level, small changes were observed in the zero-power position of the apex after the first 10 minutes of operation. However, beyond this time neither the power-off nor the power-on position changed over a cumulative actuation period of ≈1100 min. The same sample was then actuated at the higher level. Over the next 500 min, the power-on and power-off positions gradually increased by 2 μm. The strain associated with these changes is calculated at -524 microstrain using the analytical approach described in [23]. It is notable that despite the change in power-on and power-off positions of the apex, the net displacement remains unchanged at the end of the test period. At 150 mW input power, the behavior was similar to that at 100 mW, with the exception that the separation between the power-on and power-off positions increased by about 6% over 1441 min. of operation. The normalized change in displacement with actuation time is shown in Fig. 6(b). Tests at other power levels confirmed the trends suggested by measurements already described. Although the average and peak temperatures of polysilicon devices may differ from SCS devices tested at comparable power levels because of the different structural materials, fabrication processes, and device dimensions, the qualitative similarity in observed trends raises the possibility that some of the degradation mechanisms may be common to both types of devices. This point is discussed further in Section IV.

C. Pulse Lifetime Testing of SCS Actuators

The SCS devices showed consistent trends after being subjected to repeated actuation. Fig. 7 shows the degradation curves for design 2 at three different average actuation temperatures. (The average temperature was estimated from the fractional change in the resistance of the beam, by utilizing the temperature coefficient of resistance. For the p^{++} Si material used in these experiments, this was separately measured as 1818 ppm/K over the temperature range of interest.) A fresh device was used for each measurement. Clearly, the degradation was more rapid at elevated temperatures, and significant reduction in amplitude is evident within the first 10 million cycles. In contrast, the cascaded sdevice, which can be operated at lower temperatures for the same displacement because of the higher mechanical multiplication, showed no degradation even for 30 million cycles of actuation. These trends are discussed in detail in Section IV.

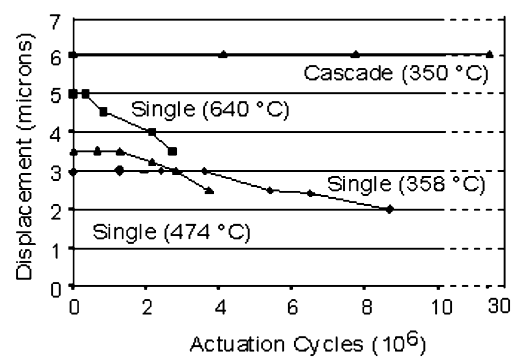

Fig. 7. Pulse activation results for SCS actuators comparing the single beam design 2 at three different temperatures, to the cascaded design 4.

D. Pulse Lifetime Testing of Polysilicon Actuators

Unlike SCS actuators that gradually degrade in amplitude after repeated actuation, polysilicon devices (both single beam

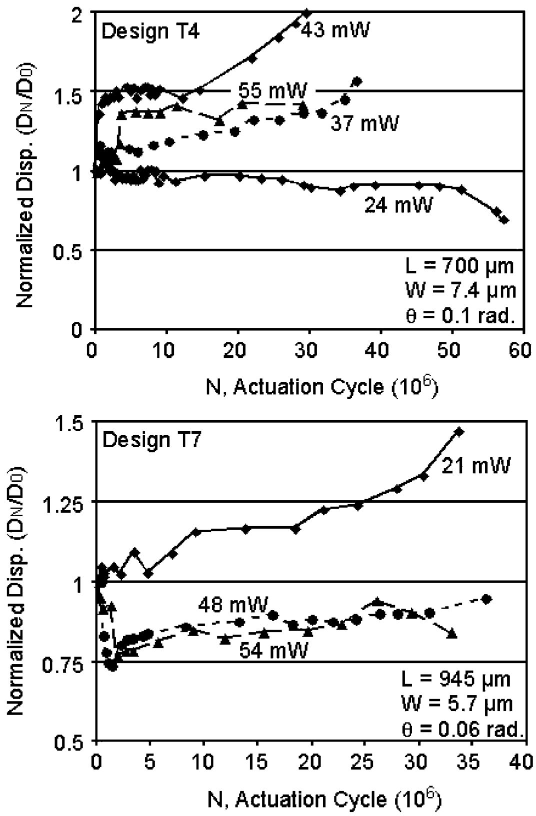

Fig. 8. Displacement variation for polysilicon single-beam designs T4 and T7 at various actuation power levels.

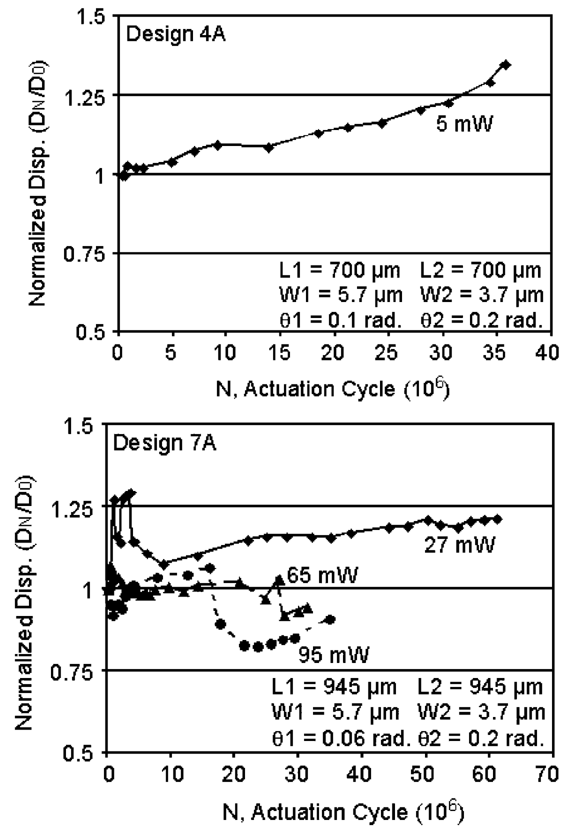

Fig. 9. Displacement variation for polysilicon cascaded designs 4 A and 7 A at various actuation power levels.

and cascaded configurations) may increase or decrease in amplitude, depending on the actuation conditions. The testing results are summarized in Figs. 8 and 9, in which a total of 11 sets of data are presented. It was typical to see large fluctuations in actuator displacement in the first five million actuation cycles for both single and cascaded actuators. After this burn-in period, the displacement changed gradually. For nine of the 11 tested cases, the actuator displacement increased over time, with only two cases showing significant decreasing amplitude (the 95 mW case for design 7 A and the 24 mW case for design T4). For the cases in which amplitude increased, the improvement was as high as 100% during the period of testing. More typically, the improvement was approximately 25% of initial displacement value. Finally, unlike the dc test cases, the off-position (or the zero-position) did not change significantly in pulse testing, but this may be because the pulse tests were conducted at lower power.

IV. Analysis and Discussion

Considering the contradictory trends observed in the long term behavior of bent-beam actuators, it appears unlikely that there is a solitary degradation mechanism at work. While the complete understanding of all the effects and their interplay is beyond the scope of this work, this section explains some of the possibilities and extends some of the analysis.

A. Stress and Microcracks in SCS

One of the physical mechanisms for amplitude degradation under repeated actuation (in which the maximum stress is below the ultimate strength of silicon) is potentially driven by a two-part failure process: the initiation of stress corrosion microcracks and the propagation of microcracks in the devices. The initiation of microcracks mainly occurs during the boron diffusion into the silicon, and results in a dislocation density that is larger than that for weakly doped silicon [13], [24]. The propagation of microcracks, as well as the generation of additional ones, can occur during actuation. The degradation process is expected to depend on peak stress and temperature. Therefore, when comparing devices fabricated from identical structural material, the degradation rates can be correlated to device geometry and operating temperature.

For the SCS actuators, the number of actuation cycles that results in an amplitude degradation of 25% in a device was defined as its Mean Cycles to Failure (MCTF) under the specific environmental and actuation conditions that existed for the test. Fig. 10 shows the MCTF of designs 1–3 as a function of actuation temperature. The data points in this figure represent measurements from previously unused devices from a single batch of wafers. Overall, the MCTF drops from 1.1×10^7 cycles to 1.5×10^6 cycles as the average operating temperature is increased from about 350 °C to just under 800 °C. At much higher temperatures (exceeding 1000 °C), immediate plastic deformation and catastrophic failure of the actuators was observed. For most of our applications the target actuation temperature is about 450 °C, and the MCTF was in the range of 3–7 million cycles for this temperature. In contrast, the cascaded device from the same wafer showed no signs of fatigue up to 30

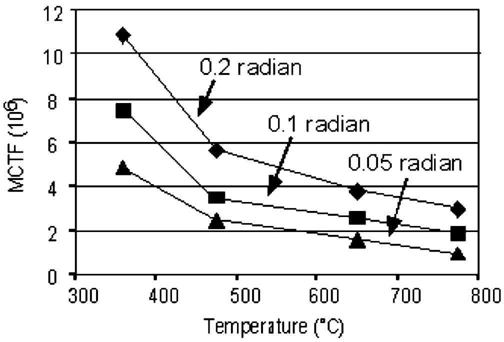

Fig. 10. Mean Cycles to Failure (MCTF) observed for p^{++} Si actuator designs 1–3.

million cycles, at which point the test was terminated. This suggests that at least under some circumstances, device lifetime can be improved by $>5\times$ by selecting cascaded designs.

The inverse relationship between operating temperature and MCTF for each design in Fig. 10 is anticipated by the degradation mechanism outlined above. The measured data also shows that shallower bending angles lead to a smaller MCTF at any given operating temperature. This is not surprising, because actuators with shallower bending angles experience higher stress [23]. Using finite element analysis (FEA), the peak stress at 350 °C in designs 1–3 was determined as 265 MPa, 330 MPa, and 406 MPa, respectively. (For the purpose of these simulations all devices were assumed to be 3.7 μm thick.) For designs 1 and 2, the peak stress occurs along the beam near the anchors, whereas for design 3 it is near the apex. The stress at the anchor of design 3 is 373 MPa, which is also larger than the peak stresses in designs 1 and 2. In contrast to the simple beams, the cascaded device shows a peak stress of 217 MPa midway along the beam of the secondary actuator. Although the exact stress magnitudes are moot because of the inability of the FEA to model the structural imperfections and nonuniformity in any device, the trend inversely correlates lifetime to the peak stress in these devices.

B. Polysilicon Grain Transformation

While it is known that the mechanical properties of silicon and polysilicon vary with temperature [12], [14], the issue of aging is a separate one. Evidence shows that the grain structure of the polysilicon undergoes modification after prolonged dc and pulsed actuation. Changes in the grain structure can affect many of the mechanical, electrical, and thermal properties of the material. Based on a previous study, there are indications that when very large thermal budgets are used in annealing cycles, the preferred post-anneal grain orientation is (111) regardless of the pre-anneal grain distribution, which can vary, but is typically not (111) [10]. While the situation for thermal actuators is somewhat different because the polysilicon layer is suspended while it is being heated and ambient conditions also differ from a furnace, it is possible that grains in the center of the beam favor a similar orientation. Of course, the grain transformations are expected to be different at different locations of the beams because of the temperature profile.

In order to investigate the changes in polysilicon, a focused ion beam was used to cut samples from the section of the beam

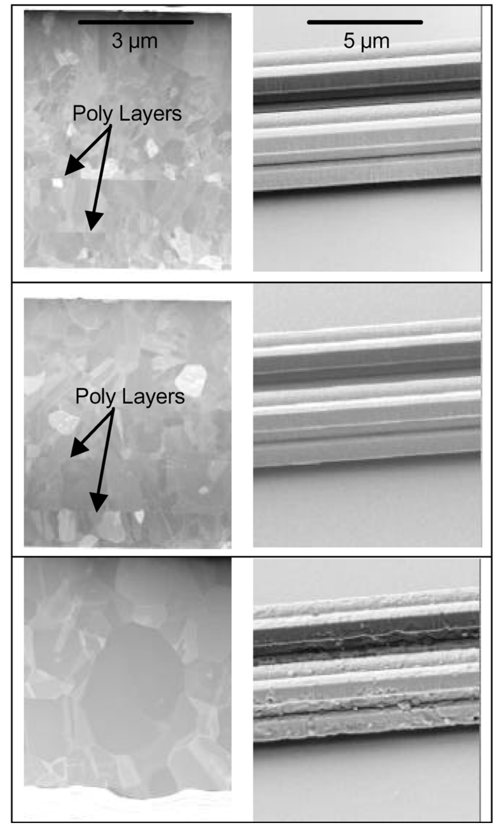

Fig. 11. TEM (left column) and SEM (right column) of bent-beams subjected to different levels of actuation power: (a-top) an unheated section of bent-beam, (b-middle) 58 million cycles at 24 mW, and (c-bottom) 30 million cycles at 43 mW.

that was hottest during actuation (Fig. 5), and from near the anchor, which remained close to room temperature. The grain size and shape in these samples is evident from their TEM images (Fig. 11). In Fig. 11(a), the TEM and SEM of unmodified polysilicon grain structure is shown with the three layers of material distinctly visible. While there are a few grains that are as large as 1.7 μm in diameter, most are smaller than 0.5 μm. Since this is the virgin material as fabricated, it is uniformly distributed along the beam. Fig. 11(b) shows an actuator that had been tested for 58 million cycles at a relatively low actuation power of 24 mW. In the TEM for this case, the polysilicon layers are still distinct; however, the average grain size is observably larger than the unmodified case. The actuator shown in Fig. 11(c) was exercised for 30 million cycles at 43 mW. In this case the heated sample has lost the boundaries between the separate polysilicon layers, which have clearly merged together. The largest grain visible is about 2.1 μm in diameter. While this is a modest gain in size, a more significant observation is that many of the grains are now larger than 1 μm in diameter.

By comparing the SEM images, it is also evident that the surface roughness is larger for the 24 mW case, and more obviously for the 43 mW case. The precise cause of the increased roughness remains to be determined, but it may, in fact, be related to the grain transformation. The possibility of electromigration was ruled out because the rough surface appears in vernier connections which are heated but do not carry any current. (Electromigration is generally observed in metal thin films that sustain

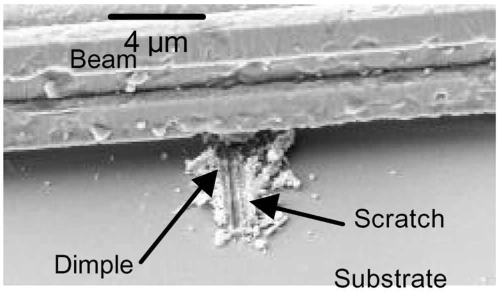

Fig. 12. Dimples that were deliberately formed on the lower surface of the beams to reduce stiction after the sacrificial release during fabrication can rub against the substrate, causing friction.

high current density: physical migration of the metal atoms creates voids in the metal lines, leading to further increase in the local current density, and ultimately failure.)

C. Friction Due to Out-of-Plane Deformation

Some of the inconsistency in the amplitude variation with time may be attributed to friction. Some of the polysilicon devices were fabricated with dimples on their lower surface that were intended to prevent close contact to the substrate. In the wet etch that occurs at the end of the fabrication process, surface forces can otherwise clamp the beam down, rendering the actuator inoperable. However, during actuation, various effects such as asymmetry in the structure or heat loss to the ambient can cause a beam to deform slightly out-of-plane, bringing the dimples into contact with the substrate. Fig. 12 shows that indeed out-of-plane deformation of the electrothermal actuators causes the dimples to rub against the substrate, and the resulting frictional forces might contribute to some of the erratic nature of the behavior displayed in Figs. 8 and 9.

D. Plastic Deformation

Another mechanism that can modify the actuator behavior is the possible plastic deformation of the bent-beam. A change in the shape and slope of the bent-beam structure will change the kinematics of the mechanism and modify its actuation characteristics. As calculated before, the peak stress developed during actuation is much less than the typically used yield strength values for both SCS and polysilicon. However, polysilicon and SCS change from an elastic state at room temperature to a ductile state at elevated temperature and the yield strength can be reduced significantly at sufficiently high temperatures due to strongly thermally activated dislocation glide [25]. In [26], SCS was reported to yield at a stress $\sim$37 MPa at 800 °C and 10 MPa at 1100 °C. As noted earlier, in [14] it was reported that polysilicon shows significant creep at 600 °C for 0.6 GPa stress, but of course Guckel *et al.* had shown in the 1980s that stress in polysilicon can be annealed at such temperatures [27]. Although the experiments in our work do not reach such high temperatures, it does illustrate the significant lowering of yield strength of Si at elevated temperatures and the possibility of plastic deformation at such temperatures.

E. Dopant Diffusion and Redistribution

Over extended periods of activation, it is expected that the dopants may be redistributed by thermally driven diffusion. The as-fabricated device does not have a uniform dopant density through the cross section of the beam. For example, the SCS devices fabricated using a p^{++} Si etch stop technique have a slightly higher boron concentration at the lower side of the beam structure (near the substrate) because of the nature of the gradient created when the Si is doped. The polysilicon devices are comprised of three layers of material which are deposited in separate steps, with the middle layer having 3 mΩ-cm resistivity and the other two having 2 mΩ-cm. (Per convention, since the conductivity of a layer of polysilicon is controlled not only by intra-grain dopant concentration, but also by thermionic emission at grain boundaries, this room-temperature conductivity specification is the measured parameter cited for the fabrication step.) The dopant concentration gradient can cause redistribution at elevated temperatures. One of the effects of the diffusion is a modified current density profile in the cross section of the beam, and it is possible that this may in some way contribute to changes in the temperature profile and device performance.

F. Other Mechanisms

Other than the ones already mentioned, there may exist a number of possible mechanisms that contribute to the actuator behaviors that are observed. These include: surface thermal oxidation and the resulting mechanical/thermal modification, cyclic fatigue and creep in the material, and cross-coupled effects of all the mechanisms already listed. Further studies are needed to reveal much more detail on the modification process.

V. Conclusion

This study shows that while bent-beam electrothermal actuators are suitable for a large number of applications, they can irreversibly change when operated for extended periods of time even at relatively low levels of actuation. The actuation displacement can increase or decrease depending on the operating conditions. Measurements show that at low power levels (which sustain average operating temperatures of 300–400 °C) both polysilicon and SCS devices provide continuous dc actuation for $>$1400 min. and pulse actuation for $>$30 million cycles without any degradation in amplitude. At higher levels of input power the power-on and power-off positions of apex are translated along the locus of motion by a few microns in a manner that suggests the accumulation of compressive stress. Despite this, the amplitude of displacement does not change. Actuation at even higher levels of input power shows increasingly rapid degradation, and eventually, catastrophic failure of the devices.

At elevated actuation levels, the structural material may also undergo modification by mechanisms that affect the surface topology and grain structure of polysilicon, and others that lend to microcrack formation in SCS. It is important to note that the changes in the structural material are not inherently detrimental, and in many cases, the actuator performance is improved over time. Also, if the mechanisms are understood, it may be possible to achieve controllable and predictable performance enhancements. Measured data presented in this paper shows that under proper circumstances, the displacement available from actuators can be increased from 25% to 100%. For example, it is conceivable that a suitable burn-in period can be prescribed for actuators which will maximize the performance and operating life by exploiting the changes in grain size and orientation. Continuing studies are necessary in order to fully use these mechanisms to optimize device behavior. These results also underscore the need for closed-loop control of electrothermal actuation.

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REFERENCES

[1] L. Que, J.-S. Park, and Y. B. Gianchandani, "Bent-beam electro-thermal actuators for high force applications," in *Proc. IEEE Int. Conf. on Micro Electro Mechanical Systems*, Orlando, FL, Jan. 1999, pp. 31–36.
[2] R. Cragun and L. Howell, "Linear thermomechanical microactuators," in *Proc. Microelectromech. Syst. (MEMS)*, Nov. 1999, pp. 181–188. ASME Int. Mechanical Engineering Congress and Exposition.
[3] L. Que, J.-S. Park, and Y. B. Gianchandani, "Bent-beam electrothermal actuators-part I: Single beam and cascaded devices," *J. Microelectromech. Syst.*, vol. 10, no. 2, pp. 247–254, Jun. 2001.
[4] J.-S. Park, L. Chu, A. D. Oliver, and Y. B. Gianchandani, "Bent-beam electrothermal actuators-part II: Linear and rotary engines," *J. Microelectromech. Syst.*, vol. 10, no. 2, pp. 255–262, Jun. 2001.
[5] M. J. Sinclair, "In-plane buckle-beam actuators deliver higher forces in MEMS," *Electron. Eng.*, vol. 73, no. 898, pp. 45–50, Nov. 2001.
[6] L. Chu and Y. B. Gianchandani, "A micromachined 2D positioner with electrothermal actuation and sub-nanometer capacitive sensing," *J. Micromech. Microeng.*, vol. 13, pp. 279–285, 2003.
[7] H. Guckel, J. Klein, T. Christenson, K. Skrobis, M. Laudon, and E. G. Lovell, "Thermo-magnetic metal flexure actuators," in *Proc. Solid-State Sensors and Actuators Workshop*, Hilton Head Island, SC, Jun. 1992, pp. 73–75.
[8] J. H. Comtois and V. M. Bright, "Surface micromachined polysilicon thermal actuator arrays and applications," in *Proc. Solid-State Sensors and Actuators Workshop*, Hilton Head Island, SC, Jun. 1996, pp. 174–177.
[9] R. A. Conant and R. S. Muller, "Cyclic fatigue testing of surface-micromachined thermal actuators," in *Proc. ASME Micro-Electro-Mechanical Systems, ASME Winter International Congress and Exposition*, vol. DSC–66, 1998, pp. 273–277.
[10] Y. B. Gianchandani, M. Shinn, and K. Najafi, "Impact of high-thermal budget anneals on polysilicon as a micromechanical material," *J. Microelectromech. Syst.*, vol. 7, no. 1, pp. 102–105, Mar. 1998.
[11] T. Tsuchiya, O. Tabata, J. Sakata, and Y. Taga, "Specimen size effect on tensile strength of surface-micromachined polycrystalline silicon thin films," *J. Microelectromech. Syst.*, vol. 7, no. 1, pp. 102–105, Mar. 1998.
[12] W. N. Sharpe Jr., M. A. Eby, and G. Coles, "Effect of temperature on mechanical properties of polysilicon," in *Proc. IEEE Int. Conf. Solid-State Sens. Actuators (Transducers'01)*, vol. 2, 2001, pp. 1366–1369.
[13] M. Tabib-Azar, K. Wong, and W. Ko, "Aging phenomena in heavily doped (p+) micromachined silicon cantilever beams," *Sens. Actuators A, Phys.*, vol. A33, pp. 199–206, 1992.
[14] C.-S. Oh and W. N. Sharpe Jr., "Techniques for measuring thermal expansion and creep of polysilicon," *Sens. Actuators A, Phys.*, vol. A112, pp. 66–73, 2004.
[15] L. Que, J.-S. Park, M.-H. Li, and Y. B. Gianchandani, "Reliability studies of bent-beam electro-thermal actuators," in *Proc. IEEE Int. Reliability Phys. Symp.*, 2000, pp. 118–122.
[16] L. Que, L. Otradovec, A. D. Oliver, and Y. B. Gianchandani, "Pulse and DC operation lifetimes of bent-beam electrothermal actuators," in *Proc. IEEE Int. Conf. on Micro Electro Mechanical Systems*, Interlaken, Switzerland, Jan. 2001, pp. 570–573.
[17] L. Chu, D. Nelson, A. D. Oliver, and Y. B. Gianchandani, "Performance enhancement of polysilicon electrothermal microactuators by localized self-annealing," in *IEEE Int. Conf. on Micro Electro Mechanical Systems*, Kyoto, Japan, Jan. 2003, pp. 68–71.
[18] Y. B. Gianchandani and K. Najafi, "A bulk silicon dissolved wafer process for microelectromechanical devices," *J. Microelectromech. Syst.*, vol. 1, no. 2, pp. 77–85, Jun. 1992.
[19] [Online]. Available: http://www.mems.sandia.gov
[20] S. B. Brown, G. Povirk, and J. Connally, "Measurement of slow crack growth in silicon and nickel mechanical devices," in *Proc. IEEE Int. Conf. on Micro Electro Mechanical Systems*, Jan. 1993, pp. 99–104.
[21] C. L. Muhlstein, S. B. Brown, and R. O. Ritchie, "High-cycle fatigue of single-crystal silicon thin films," *J. Microelectromech. Syst.*, vol. 10, no. 4, pp. 593–600, Dec. 2001.
[22] C. D. Lott, T. W. McLain, J. N. Harb, and L. L. Howell, "Modeling the thermal behavior of a surface-micromachined linear-displacement thermomechanical microactuator," *Sens. Actuators A, Phys.*, vol. A101, pp. 239–250, 2002.
[23] Y. B. Gianchandani and K. Najafi, "Bent-beam strain sensors," *J. Microelectromech. Syst.*, vol. 5, no. 1, pp. 52–58, 1996.
[24] J. Washburn and G. Thomas, "Diffusion-induced dislocations in silicon," *J. Appl. Phys.*, vol. 35, p. 1909, 1964.
[25] M. Omri, C. Tete, J. P. Michel, and A. George, "On the yield point of floating-zone silicon single crystals. I. Yield stresses and activation parameters," *Philo. Mag. A*, vol. 55, no. 5, pp. 601–616, 1987.
[26] J. Degli-Esposti, A. Jacques, and A. George, "Dislocation arrangements in single crystalline silicon fatigued in tension/compression," *Mater. Sci. Eng.*, vol. A234-236, pp. 1000–1003, 1997.
[27] H. Guckel, D. W. Burns, C. C. G. Visser, H. A. C. Tilmans, and D. DeRoo, "Fine-grained polysilicon films with built-in tensile strain," *IEEE Trans. Electron Devices*, vol. 35, no. 6, pp. 800–801, Jun. 1988.

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