POLYSILICON GRAIN TRANSFORMATIONS AND PERFORMANCE DRIFT IN ELECTROTHERMAL MICROACTUATORS

Larry Chu[1], Darcee Nelson[1], Andrew D. Oliver[2], and Yogesh B. Gianchandani[1,3a]

[1]Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI, USA
[2]Electromechanical Engineering Department, Sandia National Laboratories, Albuquerque, NM, USA
[3]EECS Department, University of Michigan, Ann Arbor, MI, USA

ABSTRACT

Electrothermal microactuators have been proposed and demonstrated for a variety of applications ranging from micro-optics to positioners for scanning microscopy. This paper reports on polysilicon grain transformations that occur with long term operation of such microactuators. Measurements show that over tens of millions of cycles of pulsed operation, the displacement can either increase or decrease depending on the geometry of the device and operating conditions, both of which are related to the temperature and stress of the members. Performance changes are correlated to material properties using SEM and TEM images as well as deformations in the compliant microstructures that serve as actuators.

I. INTRODUCTION

Electrothermal actuators have drawn increasing interest in recent years for a variety of microsystem applications. They complement electrostatic actuators by providing relatively high forces at moderate voltages, albeit at the cost of higher power dissipation [1-5]. Bent-beam electrothermal actuators [4,5] offer rectilinear non-resonant displacements >20 μm in amplitude with forces >100 μN, drive voltages <30 V, and bandwidths >700 Hz, making them suitable for a wide variety of applications. This paper reports on polysilicon grain transformations that occur with long term operation of such microactuators.

Figure 1 illustrates the operating principle of a bent-beam actuator: when an electric current is passed through a V-shaped beam anchored at the two ends, thermal expansion caused by joule heating pushes the apex outward. 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 of a microactuators is basically linear (Fig. 2).

Surface micromachined polysilicon devices were fabricated on Si substrates at Sandia National Laboratories using the SUMMiT IV™ process (Fig. 3). This permits the deposition of upto four layers of polysilicon which are 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 are implemented by concatenating the polysilicon layers without the oxide. Using this process both linear actuators and rotary microengines have been demonstrated in the past [5,8].

We have previously reported on the DC tests of both polysilicon and single crystal Si microactuators, as well as pulse tests of the latter type [6]. In this effort we report for the first time on pulse tests of polysilicon actuators.

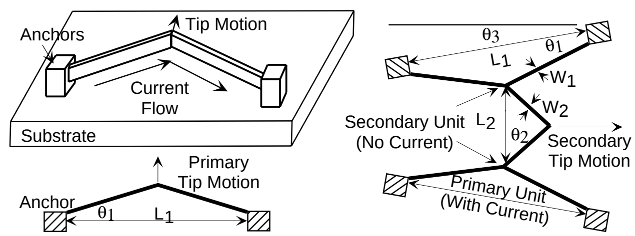


Fig. 1: Structure and operation of a single bent beam actuator (left) and cascaded design (right).

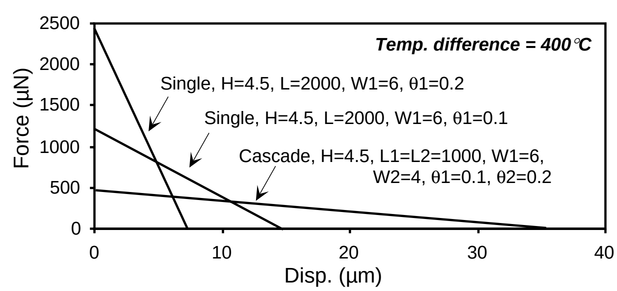


Fig. 2: FEA of tip displacement vs. loading force [4,5].

II. EXPERIMENTAL RESULTS

Various designs of bent-beam and cascaded actuators were used in this study. The dimensional parameters of all devices are listed in Table I. Actuation amplitudes were measured by vernier scales (with a resolution of ±0.25 μm) built into the devices. Displacements that were smaller than ≈2 μm were measured by calibrated imaging for better resolution.

Typical responses of fabricated devices are shown in Fig. 4. Even under ambient 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

[a] Address: 1301 Beal Ave, Ann Arbor, MI 48109-2122, USA; tel: +001 734 615 6407; Fax: +001 734 763 9324; Email: yogesh@umich.edu

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. Hence, much of the testing was performed in vacuum. Under 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.

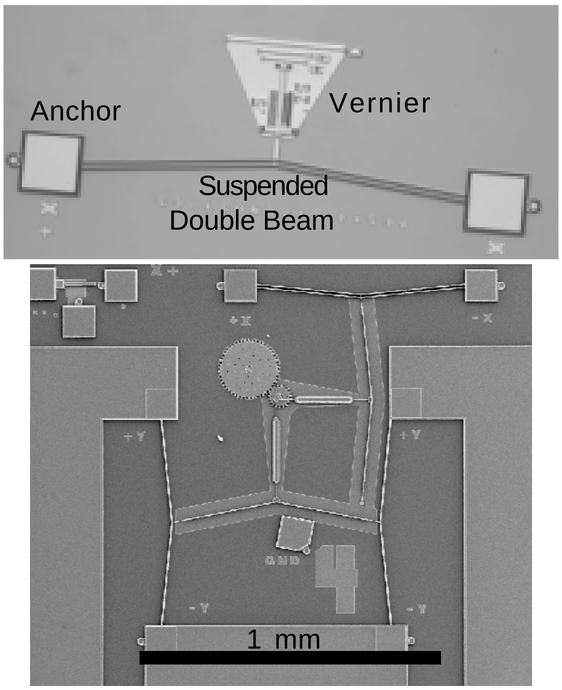
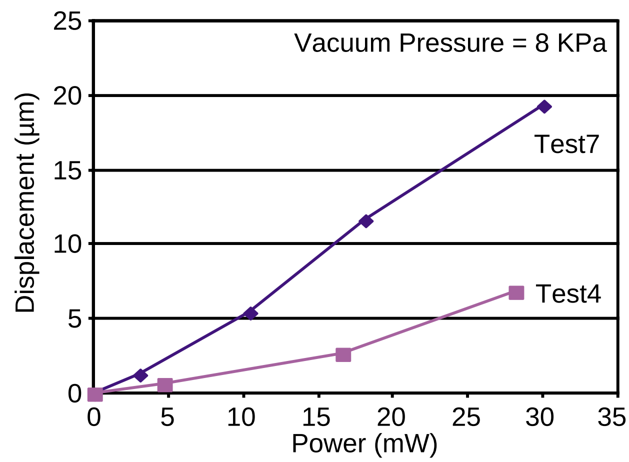


Fig. 3: Image of fabricated polysilicon microactuators. (a-upper) Optical micrograph of device Test 4 that is studied in detail. (b-lower) SEM image of micromotor that used such actuators to generate rotary motion.

Table I: Dimensions of actuators (in µm) as per Fig. 1. The angle is in rad.

ID	L1	W1	θ1
Test4	700	2x3.7	0.1
Test7	945	5.7	0.06

Actuation lifetimes were initially tested by applying DC power over a period of time while monitoring the location of the apex [6]. The power was periodically turned off to monitor variations in the zero-power location of the apex. As shown in Fig. 5a, for a single beam polysilicon device, actuation at 100 mW input power resulted in 5 µm displacement. A change of 0.5 µm was observed in the zero-power position of the apex after the first 10 min. 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 with 185 mW input power, which resulted in a 9 µm displacement. Over the next 500 min., the power-on and power-off positions gradually increase by 2 µm, presumably because of a combination of plastic deformation and changes in the polysilicon grain structure during operation. The strain associated with these changes is calculated at –524 microstrain. It is notable that despite the change in power-on and power-off positions of the apex, the net displacement is unchanged at the end of the test period. Another polysilicon device with similar dimensions was tested at 150 mW input power. In this case the power-off and power-on positions changed by 0.5 µm in the first 75 min., but maintained a 7 µm displacement. The device was tested for a total of 1441 min., and showed no further change in the power-off position, whereas the power-on position increased by an additional 0.5 µm, resulting in a final displacement of 7.5 µm. Tests at other power levels confirmed the trends suggested by measurements already described. The normalized degradation in displacement with actuation time is shown in Fig. 5b.



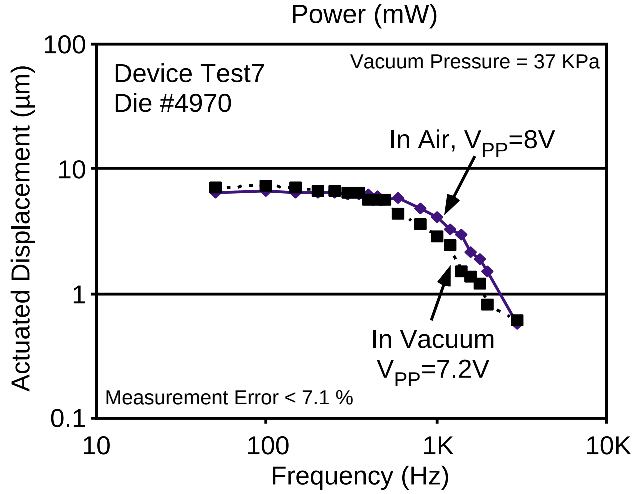


Fig. 4: Measured displacement (a-upper) and bandwidth (b-lower) of polysilicon actuators. Dimensions are listed in Table I.

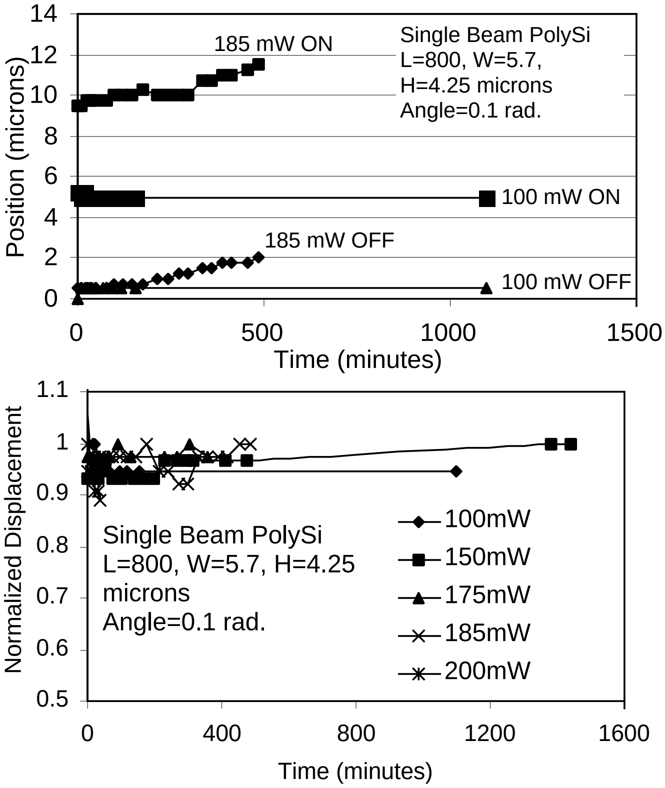


Fig. 5: (a-upper) The power-on and power-off positions increase comparably over extended periods at high input power. (b-lower) The net displacement is relatively stable.

Upon repeated actuation, single crystal Si actuators gradually degrade in amplitude as shown in Fig. 6 [5]. However, polysilicon devices may increase or decrease in amplitude, depending on the actuation conditions (Fig. 7). In order to investigate the changes in polysilicon, a focused ion beam was used to cut samples from near the center of beam, where it is hot during actuation, and from near the anchor, where it is close to room temperature. The grain size and shape in these samples is evident from their TEM images (Fig. 8). In the unheated sample, the three layers of polysilicon are distinctly visible. While there are a few grains that are as large as 3.5 µm in diameter, most are smaller than 1 µm. In contrast, the heated sample has lost the boundaries between the separate polysilicon layers, which are clearly merged together. The largest grain visible is about 4.3 µm in diameter. While this is a modest gain in size, a more significant observation is that most of the grains are now larger than 1 µm in diameter. Figure 9 compares SEM images showing the difference in surface roughness of these two regions. It is evident that the grain transformations change the surface of the material. (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 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.)

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 [7]. 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.

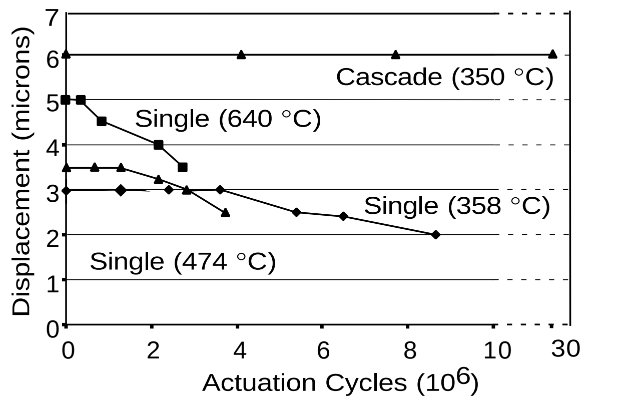


Fig. 6: Displacement degradation for single crystal Si microactuators at various temperatures.

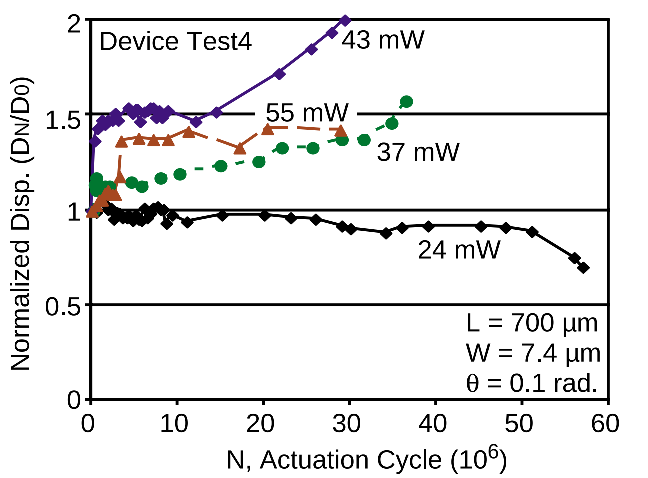


Fig. 7: Displacement degradation for poly Si device Test 4 at various temperatures.

Some of the inconsistency in the amplitude variation with time may be attributed to friction. The devices were fabricated with dimples on their lower surface which were intended to prevent close contact to the substrate. Surface forces (sometime referred to as stiction) can otherwise clamp the beam down rendering it inoperable. Figure 10 shows that indeed minor out-of-plane deformation of the electrothermal actuators causes the dimples to rub on the substrate, and the resulting frictional forces can explain some of the behavior displayed in Fig. 7.

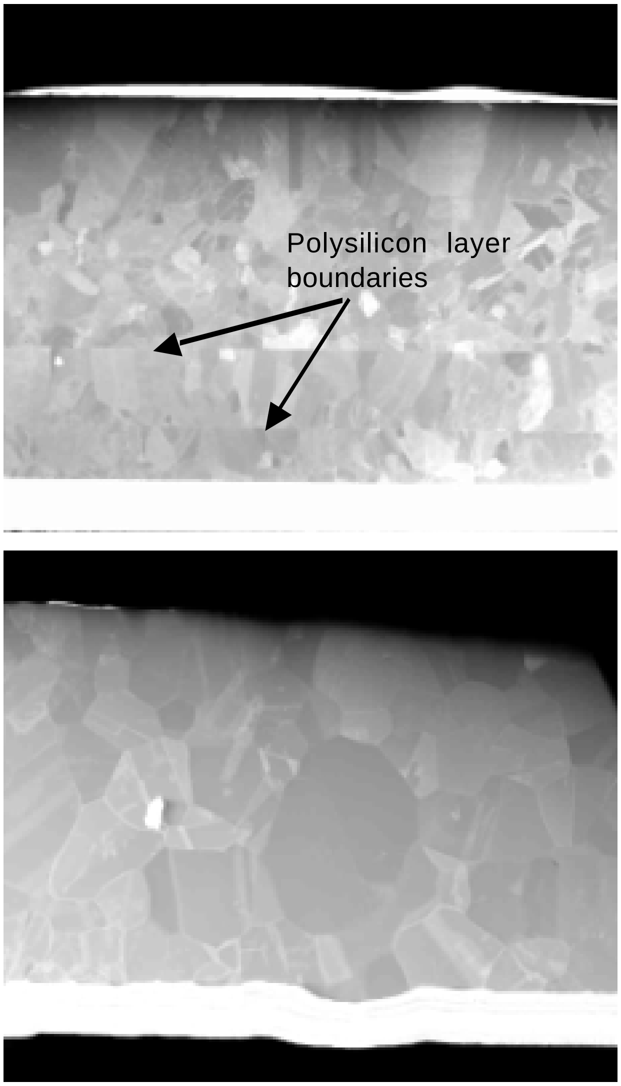


Fig. 8: Transverse electron microscopy (TEM) images of the sections of device Test 4 taken after actuation for about 30 million cycles at 43 mW. (a-upper) Image of an unheated section near the anchor shows boundaries between the three layers of polysilicon. (b-lower) Image of a heated section of the beam shows larger grains and no interlayer boundary. The lateral field of view is 14 µm for both images.

III. CONCLUSIONS

The preceding study has demonstrated that while bent beam electrothermal actuators are suitable for a wide variety of applications, they can irreversibly change if they are driven with an excessive amount of current. These changes include changes in the surface topology, and grain structure as well as changes in displacement. It is also important to note that the changes that take place in these materials are not inherently detrimental if they are *controllable and predictable.* Measured data presented in this paper shows that under proper circumstances, the displacement available from actuators can be *doubled*. For example, it is conceivable that a suitable "burn-in" period can be prescribed for thermal actuators that will increase performance and operating life by exploiting the changes in grain size and orientation that cannot be achieved by conventional deposition and annealing techniques. However, for this possibility to be feasible, continued studies are needed.

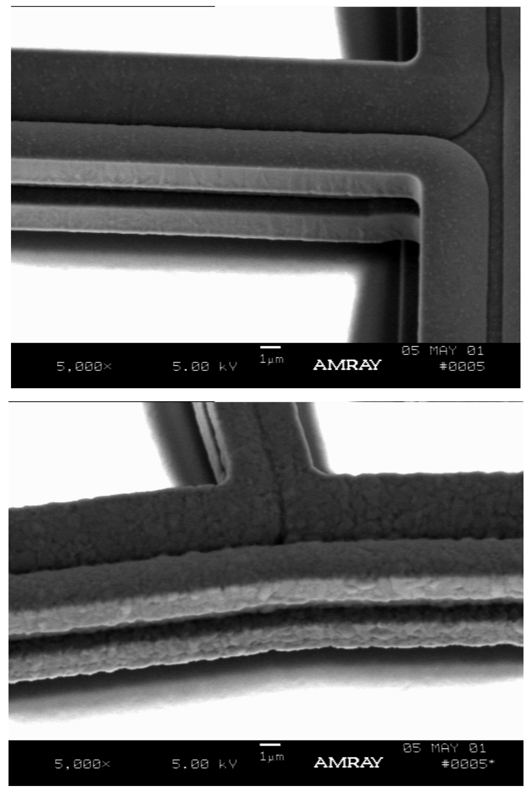


Fig. 9: SEM images showing the difference in surface roughness between the (a-upper) unheated segment near anchor, and (b-lower) heated segment near vernier. The increase in surface roughness for the latter may correspond to the increase in grain size.

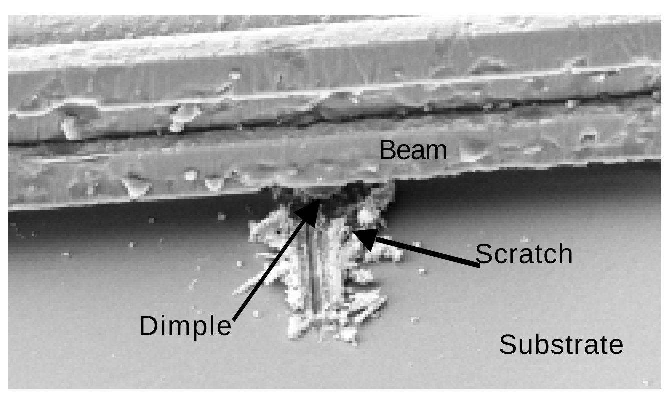


Fig. 10: Dimples formed on the lower surface of the beams can rub against the substrate, causing friction.

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