Performance Enhancement of Polysilicon Electrothermal Microactuators by Localized Self-Annealing

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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 for scanning microscopy, creating an important need for information on the longevity of these devices. This paper reports on the lifetime pulse testing results of polysilicon actuators. Devices have been operated up to 60 million cycles without failure, but over tens of millions of cycles the displacement for a given actuator design 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. In certain cases, actuator displacement increased by more than 50% (up to 100%) of the initial displacement, while for other cases it decreases by more than 25%. Polysilicon grain transformations are observed over extended operation at high temperatures. Performance changes are correlated to material properties using SEM and TEM images.

I. INTRODUCTION

Since the introduction of bent-beam electrothermal actuators in 1999 [1,2], this class of actuators has found many applications in microsystems such as optical attenuators and high precision micro positioners [3]. Bent-beam actuators offer rectilinear displacements with large output force, while operating at a low voltage (<12 V typically). Displacements greater than 20 µm with forces >10 mN is routinely achieved. The higher spring constant of these actuators also allows for microsystems with high positioning accuracy due to reduced Brownian noise. The displacement bandwidth of devices can reach >700 Hz. Latching actuators [4,5] can be used in power-sensitive applications or when large arrays must be actuated simultaneously. These characteristics make bent-beam actuators very versatile.

A bent-beam actuator is 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 [5].

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 upto four layers of polysilicon which 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 are implemented by concatenating the polysilicon layers without the oxide. Using this process both linear actuators and rotary microengines have been demonstrated [5,6].

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 [7,8]. This paper builds upon our previous efforts but focuses primarily on the impact of power and test duration on material changes in the structure.

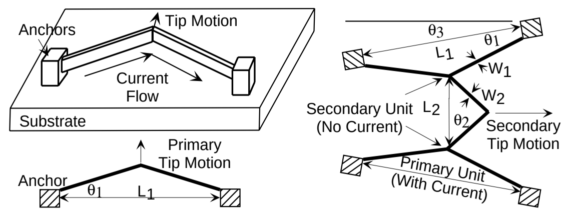

Fig. 1: Structure and operation of a single bent beam actuator (left) and cascaded design (right).

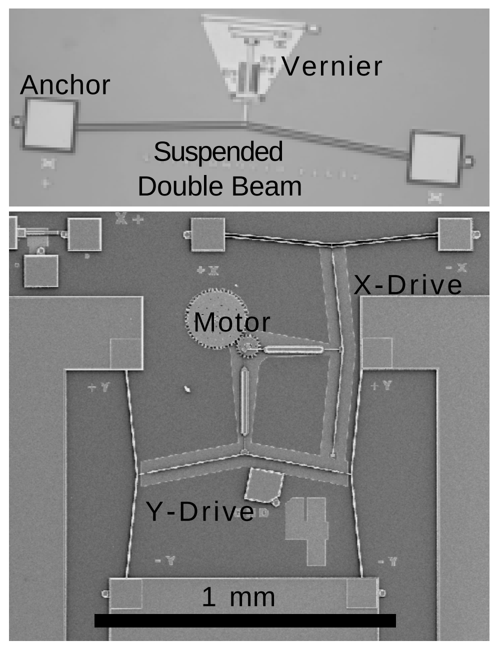

Fig. 2: Fabricated polysilicon microactuators: (a-upper) Optical micrograph of device Test 4, (b-lower) SEM image of a rotary micromotor that used such actuators.

II. EXPERIMENTAL RESULTS

Various designs of bent-beam and cascaded actuators were used in this study (Table I). Actuation amplitudes were measured by vernier scales and calibrated optical imaging. Typical responses of fabricated devices are shown in Fig. 3a. Even under laboratory conditions, the thermal isolation achieved by these devices is typically 10^3-10^4 K/W. The power consumption is <250 mW, with average actuation temperatures of a few hundred degrees Celsius. Since the presence of ambient oxygen and humidity can accelerate crack propagation at these temperatures, much of the testing was performed in partial vacuum. In vacuum,

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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.

Table I: Dimensions of actuators (in µm) as per Fig. 1. The angle is in rad. All devices are 4.75 µm thick.

ID	L1	W1	θ	L2	W2	θ
Test4	700	2x3.7	0.1			
Test7	945	5.7	0.06			
4A	700	5.7	0.1	700	3.7	0.2
7A	945	5.7	0.06	945	3.7	0.2

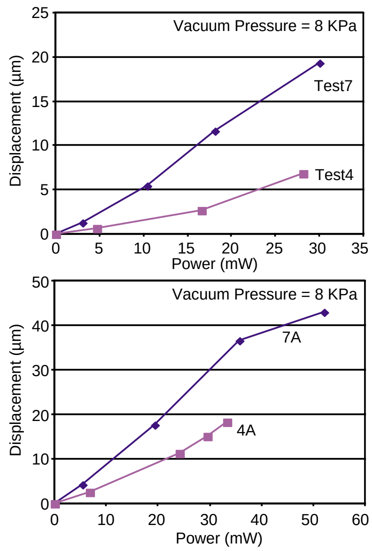

Fig. 3: Measured polysilicon actuator displacement (a-upper) for single and (b-lower) cascaded beam actuator.

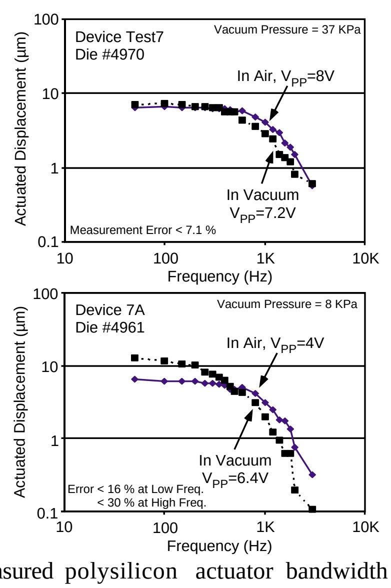

Fig. 4: Measured polysilicon actuator bandwidth (a-upper) for single and (b-lower) cascaded beam actuator.

The temperature profile of a bent-beam actuator was measured using a commercial scanning thermal probe. The scan was performed along half the length of the bent-beam (Fig. 5) since the temperature profile is symmetric about its apex. The scanning thermal probe tip was made of 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. It is important to note that the temperature of the actuator beam is substantially higher than the measured tip temperature; this is because the tip is not in contact with the actuator during the scan. An important observation is that the hottest location in the actuator is about 2/3 of the distance from an anchor to the apex, and temperature of the anchors is relatively unaffected by the input power. The measured temperature profile resembles the numerical modeling results obtained in [10], where a finite-difference method was used to calculate the temperature distribution in a bent-beam actuator.

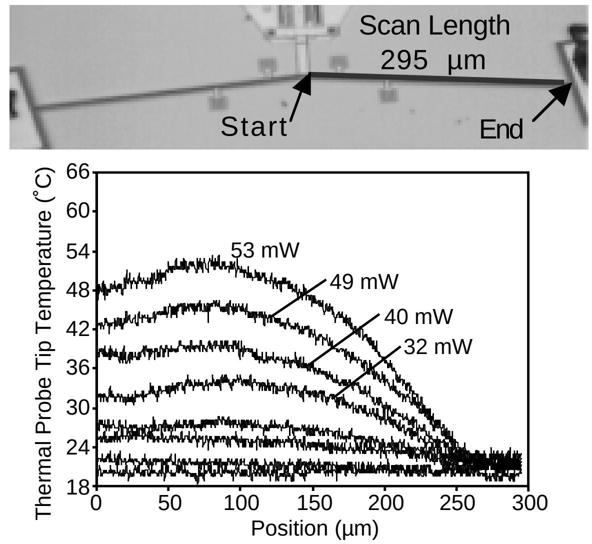

Fig. 5: Temperature profile of a bent-beam obtained using a scanning thermal probe method [9]. The plotted temperature rise is proportional to but lower than the actual increase.

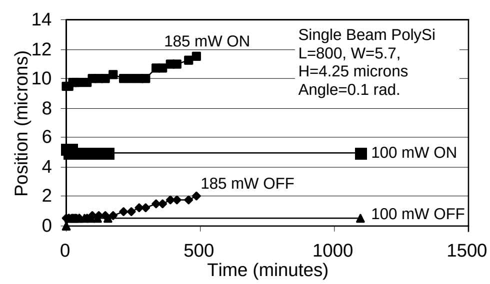

Fig. 6: The power-on and power-off positions increase comparably over extended periods at high input power [7].

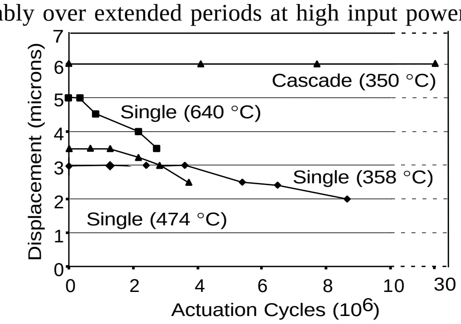

Fig. 7: Displacement variation for single crystal Si microactuators at various estimated average temperatures [7].

Actuation lifetimes were previously tested with DC power applied for long periods of time while monitoring the location of the apex [7]. For a single beam polysilicon device, actuation at 100 mW input power resulted in 5 µm displacement which did not change over a cumulative actuation period of ≈1100 min

(Fig. 6). At 185 mW input power, it resulted in 9 µm displacement, but the zero-position gradually increased by 2 µm over the next 500 min. with no change to the displacement (Fig. 6). Tests at other power levels confirmed the trends suggested by measurements already described. The DC testing of single crystal silicon actuators yields similar findings.

Upon repeated actuation, single crystal Si actuators gradually degrade in amplitude (Fig. 7) [7]. However, polysilicon devices may increase or decrease in amplitude, depending on the actuation conditions for both single beam and cascaded configurations. The testing results are summarized in Fig. 8 and 9, in which a total of 11 sets of data is presented. It is typical to see large fluctuations in actuator displacement in the first 5 million actuation cycles for both single and cascaded actuators, presumably due to surface friction (which is discussed later). After this burn-in period, the displacement changes gradually. For 9 of the 11 tested cases, the actuator displacement increases over time, with only two cases showing significant decreasing amplitude (the 95 mW case for device 7A and the 24 mW case for device Test4). For the increasing amplitude cases, the improvement can be as high as 100% during the period of testing (the displacement amplitude is double of the initial value), while in most cases, the improvement is approximately 25% of initial displacement value. Finally, unlike the DC testing cases, the off-position (or the zero-position) does not change significantly in pulse testing, but this may be because the pulse tests were conducted at lower power.

In order to investigate the changes in polysilicon, a focused ion beam was used to cut samples from the section of the beam that was hottest during actuation (Fig.4), 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. 10). In the unheated sample, the three layers of polysilicon are 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. 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 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. Figure 10 also compares SEM images showing the difference in surface roughness of these two regions. It is evident that the regions which experience grain transformations also experience increased surface roughness. This was observed in samples test at higher vacuum levels of 10^{-5}–10^{-6} Torr as well, ruling out chemical reactions with residual gases as a cause.

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 [11]. 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.

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 (referred to as stiction) can otherwise clamp the beam down rendering it inoperable. Figure 11 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. 8 and 9.

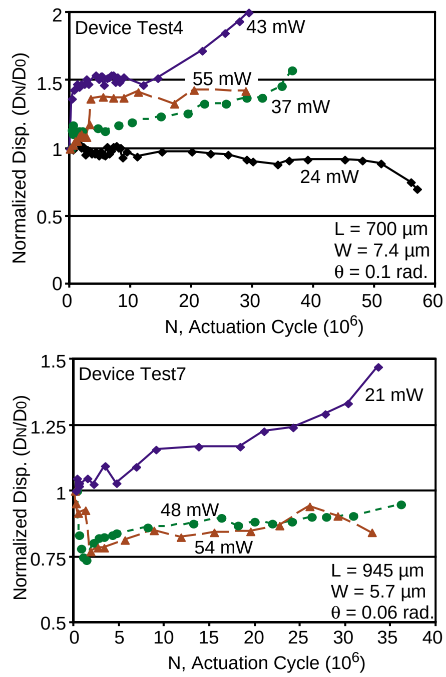

Fig. 8: Displacement variation for polysilicon single-beam device Test 4 and Test 7 at various actuation power levels. D_N and D_0 are the displacements at N and zero cycles, respectively.

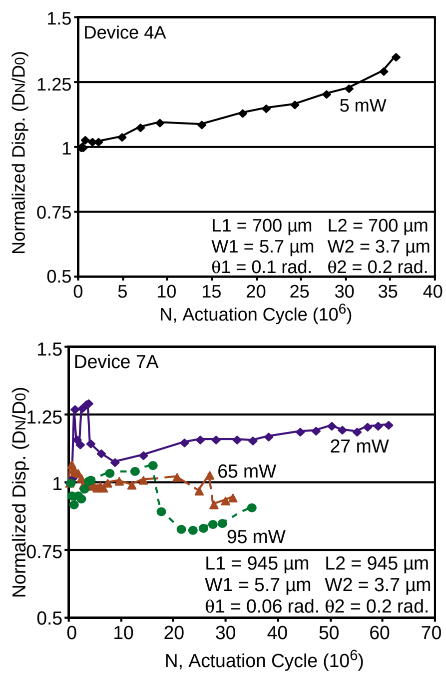

Fig. 9: Displacement variation for polysilicon cascaded device 4A and 7A at various actuation power levels.

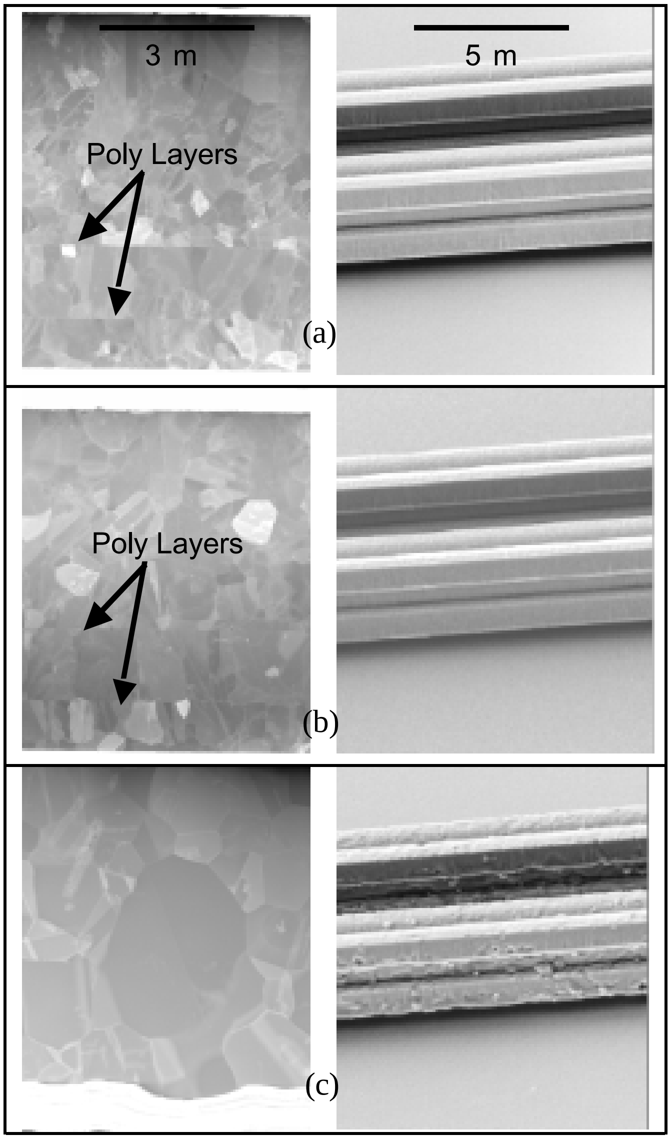

Fig. 10: TEM (left column) and SEM (right column) of bent-beams subjected to different levels of actuation power: (a) an unheated section of bent-beam, (b) 58 million cycles at 24 mW, and (c) 30 million cycles at 43 mW.

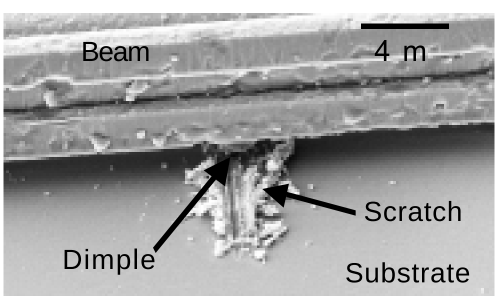

Fig. 11: Dimples formed on the lower surface of the beams can rub against the substrate, causing friction.

III. CONCLUSIONS

This study shows that while bent-beam electrothermal actuators are suitable for a large number of applications, they can irreversibly change when operate for extended periods of time even at relatively low levels of actuation. The actuation displacement can increase or decrease depending on the operating conditions. The structural material also undergoes modification, these include: surface topology and grain structure of polysilicon. It is important to note that the changes in the structural material are not inherently detrimental. In most cases, the actuator performance is improved over time. Also, if the mechanisms are understood, they can provide 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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