Methods for Self-Fabricating Chips

by

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Submitted to the Department of Mechanical Engineering
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Abstract

Current microfabrication systems can achieve resolutions of approximately 0.1\(\mu\)m. This thesis presents physical methods for creating structures with length scales significantly below current fabrication resolutions, as well as below future fabrication resolutions. We present methods for utilizing structures fabricated in conventional, gross-resolution (greater than 2\(\mu\)m) semiconductor facilities and affecting structural change to create features below the lithography limits of the fabrication process. Additionally, the physical methods presented herein open the possibility to achieve resolutions that even future fabrication processes are unable to achieve.

Structural change can come in one of two ways: either the device itself undergoes some physical deformation process, or the device is used to induce structural change in some other system. The physical mechanisms underlying both regimes are presented and device results are presented. Microfabricated fuses are presented capable of undergoing physical change to create devices with separation distances a factor of 20 below the resolution of the process used to fabricate the fuse. Large arrays of thermal actuators are presented which present the possibility of patterning large surfaces in parallel.

Infrastructure has already been constructed to create gross-resolution structures in microfabrication. Novel processes and mechanisms are needed to utilize these resolutions and create structures capable of addressing biological systems, functioning quantum mechanically, use single electrons, or require extreme speeds.

Thesis Supervisor: Joseph M. Jacobson
Title: Associate Professor of Media Arts and Sciences
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Chapter 1

Introduction

State-of-the-art microfabrication equipment is expensive and quickly outdated. Large numbers of fabrication facilities become less-than-cutting-edge and either need to be refurbished or relegated to manufacturing outdated processes. New state-of-the-art fabrication facilities cost billions of dollars [Cor00]. Newer process technology usually means smaller device lengths, particularly gate lengths in semiconductor devices or separation distances between surface-fabricated features. Current production resolution (CMOS) produces gate lengths at 0.125\(\mu\text{m}\) to 0.180\(\mu\text{m}\). Current processes used for fabrication of microelectromechanical systems (MEMS) fabrication have a resolution between 1\(\mu\text{m}\) and 2\(\mu\text{m}\).

These resolutions are well above the separation distances in naturally occurring atoms, molecules, DNA and quantum mechanical devices which require resolutions or features significantly below current resolution for MEMS fabrication, and below current resolution for traditional CMOS fabrication resolution.

As new fabrication technologies come online, the gap between the length scale of interest and the fabrication resolution narrows. However, for all of the devices and phenomena in Table 1.1, the gap is still large. Further, the cost for increasing resolution using conventional fabrication approaches rises exponentially (Moore's second law).

The work presented in this thesis attempts to provide the ability to utilize existing gross-resolution (2 \(\mu\text{m}\)) fabrication processes to create structures which them-
selves are capable of undergoing physical change to yield devices with desired characteristic length scales in the nanometer scale. Physical phenomena widely used in MEMS devices are presented in this thesis as methods for reducing length scales on fabricated devices. Theory and experiment are presented for microfabricated fuses manufactured in traditional 2μm fabrication processes which can be fused to create separation distances well-below 0.5μm. These devices present the possibility of using older-generation fabrication processes and burn-in features on the chip to create structures capable of addressing nanometer-scale phenomenon. Further, sub-micron separation distances may pose possible uses in creating single-electron transistors and quantum logic [PLA+99].

Additionally, actuator arrays are demonstrated. Using mechanical nonlinearities to differentiate devices for addressing, large arrays of thermal actuators can be addressed using a row-column address scheme, where only the device at the row-column cross-point is actuated.

This thesis concludes by presenting a detailed sketch of microfabrication via parallel fabrication systems which themselves were surface micromachined on substrates. These machine systems combine gantries, deposition systems, and patterning methods in a single device.

<table>
<thead>
<tr>
<th>Device</th>
<th>Characteristic Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNA</td>
<td>2nm</td>
</tr>
<tr>
<td>Single Electron Transistor Gates</td>
<td>1nm - 5nm</td>
</tr>
<tr>
<td>Nanoparticles</td>
<td>2nm - 20nm</td>
</tr>
<tr>
<td>Chemical Bonds</td>
<td>1Å- 10 Å</td>
</tr>
<tr>
<td>Proteins</td>
<td>25nm</td>
</tr>
<tr>
<td>Carbon Nanotubes (width)</td>
<td>2nm - 50nm</td>
</tr>
</tbody>
</table>

Table 1.1: Sub-micron length scales
Chapter 2
Physical Methods for Self-Fabricating Chips

The general goal of characteristic length reduction for microfabricated devices can be achieved through a variety of methods, both additive, in which material is deposited onto a surface to create structures which themselves have desired characteristic lengths, and subtractive, in which material is removed from a surface.

The purpose of this chapter is to introduce the reader to the basic physics underlying the mechanisms we propose for either of these systems. Additive processes will require systems to traverse and pattern a surface. Subtractive processes will require physical change of existing devices. The methods presented here will be applied in Chapter 3.

2.1 Heat Equation

Thermal mechanisms are widely used for actuation, control, and sensing of surface-micromachined devices [CBP95, IGLS84]. Voltages necessary to actuate such devices are usually consistent with CMOS outputs. This section presents the physics of thermal heating.
2.1.1 Governing Equations

We restrict our attention to heat transfer through polysilicon beams. In particular, we are interested in the analysis of dog-bone type structures commonly used as fuses in microfabrication [Fed94, Lev99, FCH92].

![Diagram of dog-bone structure with current I applied across the beam.]

Figure 2-1: Schematic of dog-bone structure.

Such a dog-bone structure is shown in Figure 2-1. This structure is commonly fabricated out of thin-film polysilicon vapor deposited onto a substrate. Current is applied across the dog-bone and the temperature in the beam rises. We examine how the way current is applied across a beam influences temperature distribution in the beam.

The governing equation for temperature, $T$, in the beam is:
\[
\frac{dT}{dx} = k \nabla^2 T - h(T - T_0) + GEN
\]  

(2.1)

where \( c_p \) is the heat capacity of the polysilicon beam, \( h \) represents heat transfer at the boundaries of the beam, and \( GEN \) represents heat generation in the beam [IGLS84]. We consider only heat generation due to resistive heating. In that case,

\[
GEN = \rho J^2
\]  

(2.2)

where \( J \) is the current density in passing through the fuse or microbridge.

We restrict our attention to the two-dimensional model. In that case, Equation 2.1 reduces to:

\[
\frac{dT}{dx} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - h(T - T_0) + \rho J^2
\]

The resistivity of the polysilicon, \( \rho \) is given by the functional expression:

\[
\rho(T) = \rho_0 [1 + \zeta (T - T_0)]
\]  

[IGLS84]

where \( \rho_0 \) is the resistivity of the material measured at temperature \( T_0 \). For polysilicon, \( \zeta > 0 \), so there is a slight increase in heat generation as temperature rises. This contributes to an unstable thermal runaway phenomenon.

### 2.1.2 Modeling and Simulation

To analyze the effect of various driving conditions on temperature distribution in the beam, a two-dimensional finite-difference scheme using a backward Euler ODE solver was implemented in Matlab. The solver initializes a temperature matrix to uniform temperature and then iterates to find the next temperature distribution. The simulation considers the four nearest neighbors only. As such, the discretized Equation 2.1 becomes [SH95]:

\[
\frac{dT}{dx} = k \nabla^2 T - h(T - T_0) + GEN
\]
Table 2.1: Physical values used in simulation.

<table>
<thead>
<tr>
<th>Physical Parameter</th>
<th>Value Used</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_0 )</td>
<td>( 3.7 \times 10^{-6} \Omega \cdot m )</td>
<td>[FCH92]</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>( 2.5 \times 10^{-3} )</td>
<td>[KAB00]</td>
</tr>
<tr>
<td>( \sigma_{Si} )</td>
<td>( 32 \text{W/m/K} )</td>
<td>[FCH92]</td>
</tr>
<tr>
<td>( \sigma_{air} )</td>
<td>( 0.051 \text{W/m/K} )</td>
<td>[FCH92]</td>
</tr>
<tr>
<td>( T_0 )</td>
<td>( 27^\circ C )</td>
<td>n/a</td>
</tr>
</tbody>
</table>

\[
\tilde{T}_{i,j}^{n+1} = \tilde{T}_{i,j}^n - 4\sigma_{self}\tilde{T}_{i,j}^n + \sum_{\text{neighbors}} \sigma T + \rho(T)J^2
\]

where \( T_{i,j} \) represents the temperature at a given position, the superscripts denote the time step, and \( \sigma_{self} \) represents thermal capacitance.

The backward solver iterates utilizing a matrix, \( A \) as follows:

\[
\tilde{T}^{n+1} - \tilde{T}^n = c_p A \frac{dt}{dx^2} \tilde{T}^{n+1} + \rho(T)J^2
\]

where \( dt \) is the time step and \( dx \) is the spatial step. and the solution is given by

\[
\tilde{T}^{n+1} = (I - c_p A \frac{dt}{dx^2})^{-1}(\tilde{T}^n - \rho J^2)
\]

The values of physical parameters used in the simulation are summarized in Table 2.1.

Two different driving schemes were simulated. The first applies a large pulse of current across a polysilicon microbridge. The second driving scheme applies a constant current, allows the structure to equilibrate, and then applies an additional current. It simulates a small constant current and a superposed current pulse. In both simulations, 110mA is applied across the dog-bone fuse structure. In the first simulation, a steady 90mA is applied across the structure, and the temperature is allowed to reach steady-state. After reaching steady-state, an additional 20mA is
Figure 2-2: Dog-bone fuse structure showing structure in coordinate axes for temperature plots.
Figure 2-3: Dog-bone fuse structure showing structure for contour plots.
applied to the fuse structure. In the second simulation, 110mA is applied to a fuse structure at room temperature. The model used for the simulation may be seen in Figures 2-2 and 2-3. The first of these figures shows the dog-bone structure necked region. Notice that the necked region is in the center of the plot. In the figures to follow, the region of largest temperature will correspond to the necked region. Figure 2-3 shows a top-down view of the model geometry. This will be helpful for analyzing contour plots of temperature results.

![Temperature Distribution](image)

Figure 2-4: Simulation of constant 90mA current applied to 2 micron dog-bone structure.

Figure 2-4 illustrates the temperature distribution in the dog-bone fuse structure after 90mA steady current is applied. It shows no area of the dog-bone structure with temperature to be above $T_{crit} = 1500C$. This plot shows the steady-state temperature distribution in a $2\mu m \times 2\mu m$ dog-bone fuse structure. At 90mA, no part of the fuse reaches the melting temperature of the material. The thin, or necked, region is the region of highest temperature.
Figure 2-5: Simulation of 110mA current pulse applied to 2 micron dog-bone structure.
Figure 2-5 shows the temperature distribution when 110mA is applied to a fuse at room temperature. Because initially the fuse is all at the same resistance, the thermal runaway effect is less-pronounced and a larger area reaches a critical temperature. Notice that a large region near the center, necked, region is at a temperature above $T_{\text{crit}} = 1500^\circ C$.

The alternative drive scheme allows the polysilicon fuse structure to acclimate at some temperature (which means that heat generated through resistive heating is exactly offset by the heat transfer off the fuse). After reaching steady-state, a short additional burst of current is pulsed through the device. Because of the steady-state temperature profile and the functional form of $\rho(T)$, an exceptionally narrow portion of the fuse structure reaches $T_{\text{crit}}$, corresponding to the critical temperature for fusing. Compared with the minimum pulsed value for fusing, the total fusing area is much less. Experimental results are presented in Chapter 3.

Figure 2-6: Simulation of 90mA steady current with 20mA pulse applied to 2 micron dog-bone structure.
Figure 2-7: Contour plot of temperature distribution in 2 micron dog-bone fuse with 90mA steady current and 20mA pulse applied.
Figure 2-6 shows the simulation when an additional, small current pulse is applied to the solution in Figure 2-4. For this simulation, the temperature vector $\vec{T}$ was initialized to the steady-state solution from the 90mA case. The total region that reaches $T_{crit}$ is substantially less. As will be seen in Chapter 3, the separation distance after fusing can be greater than a factor of 20 smaller.

![Temperature Distribution](image)

Figure 2-8: Simulation of 112.5mA steady current applied to 2 micron dog-bone structure.

To better analyze the difference between the two drive schemes: starting the fuse off at ambient temperature and shocking the device with maximum current, or applying a current bias and allowing the device to reach a steady value before applying the final pulse of current, the simulation was run to determine a steady current value that yields the same maximum temperature as the 90mA bias current plus 20mA pulse. As seen in Figure 2-8, 112.5mA applied to a fuse structure at room temperature yields a maximum temperature of 1679C, the same maximum temperature as in Figure 2-6. The difference in these two drive schemes is more pronounced in a plot.
Figure 2-9: Difference in temperature distribution from simulations of pulsed (90mA + 20mA) and steady-state (112.5mA) current pulse applied to 2 micron dog-bone structure.
Figure 2-10: Contour plot of difference in temperature distribution between 112.5mA current pulse and 90mA steady-state current plus 20mA current pulse.
Figure 2-11: Difference in temperature distribution between 112.5mA steady current and 90mA steady with 20mA pulse, along the centerline.
of the temperature difference (pulsed solution less steady-state plus pulsed solution) as shown in Figures 2-9 and 2-10. Figure 2-11 shows the temperature distributions along the centerline of the fuse dog-bone structure. Notice that the width of the 90mA steady plus 20mA pulse is narrower than the solution for the 112.5mA pulsed solution. This supports the theory that a narrower region of desired temperature can be achieved using this new pulsing method. Further, notice that in Figure 2-11, the entire fuse structure, not just the necked region, reaches substantially elevated temperature, whereas in the steady plus pulsed solution, nearly the entirety of the non-necked region remains below 200°C.

The model itself fails to account for all behavior seen in experiment. This is due to a number of simplifying assumptions made in the model. First, thermal conductivity is usually a loose function of temperature. Second, the discretization size of the model (8 cells per micron) fails to capture much of the behavior near the center of the fuse. Because of the small number of cells, the solution is much smoother near the center than we believe it actually is. That is, sharp temperature rises cannot be seen in the simulation because the thermal mass of each cell is too high. A final source of error are estimates of physical properties for polysilicon used in the model. Literature varies wildly with respect to physical quantities for materials in thin film form.

2.2 Thermoelasticity

This section presents the mechanics of device stress and deformation due to temperature change. Most materials used in microfabrication are deposited at relatively high temperatures [Fed94]. The cooling process imparts significant stress on devices due to differential thermal expansion. That is, substrates tend to be thicker and therefore stiffer than thin film materials. Surface micromachined materials, in particular, tend to have substantial compressive stress after fabrication. Further, temperature rise in beam structures can produce deformation or buckling.

Thermal actuators can be made utilizing this stress-deformation relation [SSNM97, LL98, QPG99]. Many of these actuator devices utilize buckling, which will be pre-
2.2.1 Constitutive Equations

We begin by defining the elastic modulus, $E$, and coefficient of thermal expansion, $\alpha$ of a material. Assume a thin film of material is clamped at both ends as shown in Figure 2-12. Because the beam is constrained, a temperature rise $\Delta T$ results in a stress, $\sigma$, through the beam given by

$$\sigma = E\alpha \Delta T$$  \hspace{1cm} (2.3)

2.2.2 Buckling

The stress deformation relationship is given by [FW94]:

$$EIw_{xxx} + EA(\epsilon - \frac{1}{2L} \int_0^L w_x^2 dx)w_{xx} = 0$$  \hspace{1cm} (2.4)

where $w$ is the beam deflection, $A$ is the beam cross-sectional area, $I$ is the second moment of inertia, $\epsilon$ is the strain, and $L$ is the beam length. The load $P$ applied at the end of the beam is related to $\epsilon$ by:

$$E\epsilon A = P$$
When small deflections of the beam in the deformed shape are assumed, Equation 2.2.2 reduces to:

\[ EIw_{xxx} + EAe w_{xx} = 0 \]

and by applying the boundary conditions of zero deflection and zero slope (because of the nature of the clamped-clamped boundary), the equation yields a critical value of \( P \):

\[ P_{cr} = \frac{4\pi^2 EI}{L^2} = EA\alpha \Delta T \quad (2.5) \]

The solution for the deflection \( w \) as a function of position is given by

\[ w = \frac{\delta}{2} \left( 1 - \cos \frac{2\pi x}{L} \right) \]

Figure 2-13 shows the deflection for the clamped-clamped buckled beam. The plot has been normalized with respect to a deflection of 0.25. These are arbitrary units.

Equation 2.2.2 assumes uniform loading throughout the beam. The solutions to heat distribution in finite beams in Section 2.1 indicate that the temperature distribution is not constant, rather there is a gradient. Rewriting Equation 2.2.1 as follows,

\[ \frac{d\sigma}{dx} = E\alpha \frac{dT}{dx} \]

Combining Equations 2.2.2 and 2.2.2, we have

\[ P_{cr} = 2EA\alpha \int_0^L \frac{dT}{dx} dx \]

27
Figure 2-13: Post buckling shape of beam.
which gives a criteria for the critical temperature gradient required for buckling:

\[ \int_0^L \frac{dT}{dx} dx = \frac{2\pi^2 EI}{\alpha L^2 A} \]

Various authors have presented more detailed analyses of buckling, taking into account the elastic nature of microfabricated supports [MMOK91, MMM93, KDS99, FW94]. While these results present a more accurate solution for Equations 2.2.2 and 2.2.2, the result of Equation 2.2.2 may be applied to their analytic solution.

### 2.2.3 Simulation

The same simulation presented in Section 2.1 was used to simulate thermal stress distribution in a polysilicon beam. The solution of the simulation can be compared against the solution in Equation 2.2.2 to determine the necessary condition for onset of buckling.

This section has developed the theory for microfabricated beam buckling, and more particularly the theory for critical buckling due to temperature gradient.

### 2.3 Resistive Networks

As micromechanical devices become more prominent, emphasis will be placed on efficient methods of driving and controlling large arrays of actuators. Applications such as force-field arrays, micromechanical factories and assembly systems, and high-resolution displays demand high numbers of actuators. However, current fabrication methods of control and drive schemes for these actuators are typically incompatible with fabrication methods for the micromechanical devices themselves. Semiconductor device performance (transistors, diodes, etc.) degrades with extra high temperature processes (deposition steps for MEMS devices) because implanted diffusion. Fabrication of MEMS structures at low temperatures is still a nascent field, and most processes are done at temperatures above 800C [KMHM00].
This section presents a new scheme for driving large arrays of micromechanical devices where a passive matrix array is created using the mechanical nonlinearities of the mechanical device as the nonlinearity for control. This chapter presents the theory for this control scheme, based on resistive networks and the nonlinear phenomenon of buckling in thermally-driven clamped-clamped beams. The next chapter presents preliminary results from creating an arbitrarily-large array of devices. We present a 2X2 array, the minimum array necessary to show extensibility of the drive scheme. We have also fabricated 4X8 and 8X8 devices, although those will not be presented here.

A resistive network is shown in Figure 2-14. In the figure, $R_h$ represents horizontal resistance and $R_v$ represents vertical resistance of the network. At each cross point, there is a device with resistance $R_{d_{i,j}}$, where $i$ and $j$ are the indices of the cross-point. The resistive network shown in the figure is well-suited to fabrication in typical MEMS processes such as the MUMPS process because the required materials set is only a conductor[KMHM00]. In the MUMPS process, for instance, the resistive network
may be fabricated using any of the Poly layers (Poly0, Poly1, or Poly2). Connections may be made via a patterned Metal layer.

For the system in Figure 2-14, we neglect the initial resistances from the pads. The simultaneous state equations for the voltage drop across each of the devices is given by:

\[
\begin{pmatrix}
    V_{1,1} \\
    V_{1,2} \\
    V_{2,1} \\
    V_{2,2}
\end{pmatrix} =
\begin{pmatrix}
    1 & 0 & -1 & 0 \\
    0 & -\frac{R_{1,2}}{R_h+R_{1,2}} & \frac{R_{1,2}}{R_h+R_{1,2}} & 0 \\
    \frac{R_{2,1}}{R_{2,1}+R_v} & 0 & 0 & -\frac{R_{2,1}}{R_v+R_{2,1}} \\
    0 & \frac{R_{2,2}}{R_h+R_{2,2}+R_v} & 0 & -\frac{R_{2,2}}{R_h+R_{2,2}+R_v}
\end{pmatrix}
\begin{pmatrix}
    V_1 \\
    V_2 \\
    V_3 \\
    V_4
\end{pmatrix}
\]

The limiting case results when all resistors are taken to be 0 except for those that constitute the devices themselves. In that case, the voltage drops across each device are given by:

\[
\begin{align*}
V_{1,1} &= V_1 - V_3 \\
V_{1,2} &= V_2 - V_3 \\
V_{2,1} &= V_1 - V_4 \\
V_{2,2} &= V_2 - V_4
\end{align*}
\]

In the usual driving mode, \( V_1 = V, \ V_2 = V_4 = \frac{V}{2}, \) and \( V_3 = 0. \) The voltage drops across each device simplify to:

\[
\begin{align*}
V_{1,1} &= V \\
V_{1,2} &= \frac{V}{2} \\
V_{2,1} &= \frac{V}{2} \\
V_{2,2} &= 0
\end{align*}
\]
We see, then, that the power dissipation in a device depends strongly on the location of the device in the cross-point array. For instance, the power loss in device $d_{1,1}$ is given by

$$P_{d_{1,1}} = \frac{V_{1,1}^2}{R_{d_{1,1}}}$$

which simplifies to

$$P_{d_{1,1}} = \frac{V^2}{R_d}$$

when all device resistances are taken to be $R_d$. Alternatively, the power dissipation in devices $d_{1,2}$ and $d_{2,1}$ is given by:

$$P_{d_{1,2}} = \frac{1}{4} \frac{V^2}{R_d}$$

and

$$P_{d_{2,1}} = \frac{1}{4} \frac{V^2}{R_d}$$

We further note that no power is dissipated through device $d_{2,2}$ as there is no voltage drop.

Hence we have the power dissipation in $d_{1,1}$ is four times the power dissipation in $d_{1,2}$ and $d_{2,1}$. Combining this with Equation 2.2, the heat generated in each device is equivalent to the power dissipation in the device (in reality, there is some efficiency term). That is, the temperature rise in device $d_{1,1}$ is substantially higher than the temperature rise in devices $d_{1,2}$ and $d_{2,1}$. Therefore, if the devices $d_{1,1}$, $d_{1,2}$, $d_{2,1}$, and $d_{2,2}$ were themselves clamped-clamped beams as in Section 2.2.2, the critical temperature rise could be achieved in any of the four devices independently through this row-column, cross-point addressing system. The experimental results from this approach are presented in Chapter 3.
Chapter 3

Devices for Self-Fabricating Chips

Having built a foundation of physical methods for reducing line widths in microfabricated devices, this chapter presents device designs. These devices are of two types: devices with no moving features (herein called Solid-State Devices) and those with moving features (herein referred to as Microfabrication Systems). For both of these types of devices, a mixture of design results and future design recommendations are presented. In all cases, reference is made to the underlying physical phenomenon governing device behavior.

3.1 Solid State Devices

Solid-State Devices, as referred to herein, are any devices that do not contain moving features. Solid-state devices seem well-suited to the task of reducing length scales in microfabricated systems because of their high reliability. The elimination of moving parts eliminates with it the majority of reliability issues (release processes, stiction, etc.). This section presents two devices. The first is a micromachined fuse. This device builds on work presented in [Lev99, Fed94, FCH92] and presents a method for creating sub-micron separation distances in fused devices. The second is a sketch of a solid-state beam steering deposition system, based on thermal evaporation. For this device, experimental results have not yet been achieved.
3.1.1 Fuses

Micromachined fuses have previously been reported to allow structure change on the order of a few microns [Fed94, FCH92, Lev99]. Recent publications have sought to create separation distances significantly below that regime. Electromigration has been shown to allow the creation of gaps of 1nm in shadow evaporated gold films [PLA⁺99]. This section presents experimental results for the creation of sub-micron gaps in polysilicon fuses.

With reference to Section 2.1, it was shown that various drive methods produced substantially different temperature distributions. Because fusing is a combination of phase change and thermal stress (most likely some fracture phenomenon), reduction in the region of the fuse that reaches critical temperature results in smaller gaps after fusing.

![Standard polysilicon fuse blown with large current pulse.](image)

Figure 3-1: Standard polysilicon fuse blown with large current pulse.

Figure 3-1 shows a typical fuse structure after blowing. The separation distance between the two ends is approximately 3μm. Note the sharp edges defining the fused
region. In contrast, Figure 3-2 shows a similar fuse structure blown using the method in Section 2.1. Various devices were tested to determine the fusing current. A bias voltage of approximately 3.75V was applied across the fuse and the device allowed to reach thermal equilibrium. Once that steady-state was reached, an approximately 250mA pulse was applied for anywhere from 2-6μs. For the specific device shown in Figure 3-2, a bias voltage of 3.8V was applied and a 300mA pulse was applied for 2μs. The fuse has blown at the lower necked region. Figure 3-3 shows a close-up image of the fused portion. Note the exceptionally small separation distance between the two edges. Also, note that compared to Figure 3-1, the fused edge is exceptionally jagged. We attribute this to a fusing mechanism that combines local phase change and fracture at the fused surface. These results compare favorably with the model of the previous chapter. The substantial current required to initiate fusing suggests additional mechanisms at work including phase change.

Figure 3-2: Polysilicon fuse blown with current bias and small current pulse.
3.1.2 Solid-State Beam Steering

An alternative method for shape change involves the use of beam steering mechanics. Similar to that used in ink jet systems to determine which drops to dispense, electrostatic or magnetic beam steering may be used to alter the path of evaporated material.

Figure 3-4 shows a sketch of such a device. In the image, electrostatic plates are shown rising from the surface. These can be made from strap-down hinges and raised onto the surface. An alternative method would be to construct a large number of coils on the surface of the substrate and selectively energize those coils in succession to impart a desired velocity on material droplets. This device has not yet been fabricated and tested.


### Table 3.1: Performance figures come from a combination of design and testing of devices and reference publications [CBP95, LHP98]

<table>
<thead>
<tr>
<th>Gantry Type</th>
<th>Maximum Deflection</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comb Drive</td>
<td>10μm</td>
<td>4kHz+</td>
</tr>
<tr>
<td>Heatuator</td>
<td>20μm</td>
<td>2kHz</td>
</tr>
<tr>
<td>Thermal Buckle Beam</td>
<td>4μm</td>
<td>1kHz</td>
</tr>
</tbody>
</table>


## 3.2 Microfabrication Systems

This section presents device designs that replicate traditional clean-room fabrication systems using microfabricated devices. The general method described herein is to create on-chip devices capable of traversing a surface and depositing a material and patterning that material. The patterning step may include deposition through an aperture or mask, or a solid-state burn-in process similar to fusing or electromigration.

### 3.2.1 Gantries

Several types of micromachined mechanical gantries have been fabricated. Three examples are shown in Figures 3-5- 3-7. Both of these devices are fabricated in the 3 layer polysilicon MUMPs process [KMHM00].

Table 3.1 shows device performance results for a large sampling of micromachined actuator types. All devices presented have a range of motion greater than 4μm, and have an effective bandwidth of 1kHz or greater. The largest drawback of these devices is controllability. Each driven device requires separate control connections and separate control electronics. A method for eliminating this requirement is presented in the next section.

### 3.2.2 Actuator Arrays

This section presents results for utilizing mechanical nonlinearities (buckling) and resistive network connections to address actuators at cross-points. This enables the creation of a row-column address system for actuators and greatly reduces the control
Figure 3-8 shows a typical actuator array. The array consists of thirty-two buckle beams connected in a 4X8 matrix. By driving the two nodes that define a cross-point at 4V and ground (0 V), and driving the other nodes at 2V (V/2), individual actuators were driven. Figure 3-9 shows individual cross-point actuation in such an array. The upper-left image shows the upper-left beam actuating; the upper-right image shows the bottom-left beam actuating; the bottom-left image shows the bottom-right beam actuating; the bottom-right image shows the upper-right beam actuating. Deflections are dependent on beam position because of the non-zero resistance found in the row and column electrodes. Maximum displacement was approximately 4 μm.

Figure 3-7 shows a close-up of one of the buckle beam actuators. Geometry can be tailored to induce buckling in a particular direction or have no preference at all. The beam shown in the figure has a slightly greater tendency to buckle in-plane than out-of-plane. The width of the beam may be increased in design to favor buckling out-of-plane. The thickness of the beam may be increased in fabrication process to favor in-plane buckling.

To date, a 2X2 actuator array has been demonstrated. Because of the limitations of the fabrication process, either the rows or columns in the array will have non-zero resistance. The fabrication process only provides for one metallization layer. Therefore, for matrix addressing, one of the dimensions must be fabricated only out of resistive polysilicon (the same material as the actuators themselves). The model in Section 2.3 breaks down. For the devices shown in Figure 3-8, the device resistance is 400Ω, the contact resistance is 30Ω, and the resistance between successive cross-points is 30Ω.

### 3.2.3 Methods for Deposition

Various methods for depositing material onto a substrate may be used. One example is to combine the electrostatic comb drive of Figure 3-5 with a standard fuse structure. Such a device is shown in Figure 3-10. A close-up of the center fuse structure is shown in Figure 3-10. The comb drive gantry structure itself is split so that a potential
may be placed across it to induce current flow in the fuses. As the gantry passes over a surface, the fuses may be activated and some of the material deposits on the surface. Drawbacks to this approach are that control over deposition is not really possible. Precise control over where material is deposited is nearly impossible, as is control over the quality of the material. The deposited material undergoes rapid phase change (from solid, presumably to liquid, and back to solid), which adversely affects the properties. Further, the catastrophic nature of the fusing event surely entrains particulates into the material (local oxidation, carbonization, etc.) before it deposits onto the surface.

An alternative method for depositing material onto a substrate is to replicate the system widely used in thermal evaporation systems for depositing metallic materials on semiconductor substrates. These machines typically have a large resistor that boils material off of a surface. The material itself can pass through an aperture for patterning, or directly hit the target substrate. Such a system is shown in sketch form in Figure 3-12. The resistive heater provides enough energy to boil off particles of material. In reality, all of the material flux from the source does not only move off the substrate. It will have some non-zero velocity parallel to the surface (based on the surface shape prior to boiling). This device has not yet been fabricated or tested.

3.2.4 Methods for Apertures

The basic function of an aperture is to allow material to pass through certain regions and restrict material flow through other regions. The simplest type of aperture is a fixed aperture mask. A sketch of such a mask is shown in Figure 3-13. The drawback of such a system is that as more material passes through various regions, material is certainly going to eventually clog open regions. One solution to this is to raise the temperature of the aperture itself to near melting temperature. Another alternative is to fuse material that clogs openings. Such a system is schematically shown in Figure 3-14. Current can be applied across the halves of the aperture structure. A dielectric stiffener may be used, as shown in the figure, to mechanically connect the two halves of the aperture, while providing electrical isolation. The devices described
here have not been fabricated or tested.

3.2.5 Microfabrication Systems

Finally, we present a sketch of a complete chip-level microfabrication system. This sketch is rudimentary at best. As described previously, the chip-level system contains a means of traversing a surface (a gantry), a deposition means (thermal evaporation head), and some patterning route (aperture). Such a system is shown in Figure 3-15. At least one of the aperture or substrate needs to move. Figure 3-16 shows the operation of such a system. In part a), the evaporator boils off material which passes through the aperture. In part b), the aperture moves and more material is boiled through the aperture. The resultant pattern on the surface is seen in c).

Various combinations of aperture types, gantries and materials may be used. For instance, different material sources can be used with the same evaporation system merely by changing the relative location of the material to the heat source. Different apertures may be moved in and out of use as well. Additionally, the aperture could have moving structures on itself that change the shape of the deposited pattern in real-time.
Figure 3-4: Sketch of solid-state beam steering apparatus. The top system shows two electrostatic plates rising from the substrate. A material droplet comes in. The second image shows the material droplet landing on the surface. The third image shows that, when sufficient voltage is applied between the plates, the material droplet can be made to not strike the substrate.
Figure 3-5: Electrostatic comb drive resonator.

Figure 3-6: Heatuator thermal actuator. Similar to [CBP95].
Figure 3-7: Thermal buckle beam actuators.
Figure 3-8: Thermal buckle beam array.

Figure 3-9: Thermal actuator array showing cross-point actuation.
Figure 3-10: Electrostatic comb drive with five fuse array.
Figure 3-11: Close-up of fuse array on comb drive.

Figure 3-12: Sketch of micro-thermal evaporation system.
Figure 3-13: Sketch of simple aperture.

Figure 3-14: Sketch of aperture capable of reheat.
Figure 3-15: Sketch of chip-level deposition system.
Figure 3-16: Images a), b) and c) show the material deposition process. The aperture system moves to change the pattern of material deposited onto the substrate.
Chapter 4

Conclusion

Current fabrication systems are very costly. If we wish to maximize utilization of existing infrastructure in solving new problems and challenges, thereby benefitting from existing capital outlay, new systems will have to be developed that utilize existing fabrication resolution and yet can create structures of substantially smaller dimension. This thesis presents concepts towards such a system.

Fusing and electromigration will become more commonplace as mechanisms to reduce line width. This thesis has presented a new scheme for the fusing of polysilicon dogbone fuse structures capable of creating separation distances of just tens of nanometers. This thesis also presents a mechanical analogue to passive-matrix addressing. The mechanical non-linearity of the buckling phenomenon in thin-film beams can be utilized to yield cross-point addressing.

This thesis also begins the discussion of what it means to have systems on a chip that are themselves capable of fabrication. Deposition systems are discussed and sketches presented. Alternative solid-state systems are also presented. These utilize beam steering to determine where particles are deposited. Neither can be said to either be viable or useful, yet. More work still needs to be done.

Perhaps the most interesting area for future research based on these results is understanding the phenomenon of fusing at very small scales. The SEM micrographs presented in this document show very rough fusing edges that are inconsistent with smooth profiles for temperature distribution. An additional phenomenon is definitely
seen and understanding this phenomenon holds the key for truly unlocking the power
to create nominal 2 μm structures capable of size reduction to yield desired separation
distances.
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