Micro-Mechanical Switch Array for Meso-Scale Actuation
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ABSTRACT
Traditional MEMS actuators have limited stroke and force characteristics. This paper describes the development of a hybrid actuation solution, which utilizes a micro-machined actuator array to provide switching of mechanical motion of a larger meso-scale piezo-electric actuator. One motivating application of this technology is the development of a tactile display, where discrete mechanical actuators apply vibratory excitation at discrete locations on the skin. Specifically, this paper describes the development fabrication and characterization of a 4 x 5 micro-actuator array of individual vibrating pixels for fingertip tactile communication. The individual pixels are turned ON and OFF by pairs of microscopic thermal actuators, while the main vibration is generated by a vibrating piezo-electric plate. The fabrication sequence and the actuation performance of the array are also presented.

INTRODUCTION
Mechanical actuators are one of the defining features of micro-electromechanical systems (MEMS). Yet due to the increased role of surface forces most moveable structures are free standing attached to the substrate through an elastic hinge. This feature of MEMS presents difficulties in designing actuators with large displacements, since a large displacement would imply large elastic deformation of the hinge and correspondingly significant driving force. Contrary, macroscopic actuators utilize bearings of various kinds in which the frictional forces are negligible in comparison to the driving and inertial body forces. Thus in the field of mechanical micro-actuation large stroke and force is still a significant engineering challenge. The development of thermal micro-actuators for the first time presented a hope for a device with large stroke under reasonable driving voltages. Using poly-crystalline thermal actuators relatively large displacements were easily attainable [1,2]. While these devices had the advantage of ease of integration with on-chip electronics and relatively low power consumption (86mW, [3]), the polysilicon layers were only a few microns thick and brittle, thus limiting the usefulness of the actuator. These limitations have been partially addressed by the advent of actuators made from selectively doped single-crystal silicon [4-5] as well as entirely metallic actuators [6]. Further improvements of the efficiency and available force were achieved by designing V-shaped (also known as “bent-beam”) actuators [7], where the role of the cold arm is performed by the substrate itself. In comparison with the (poly)silicon devices, metallic micro thermal actuators have a larger thermal expansion coefficient and can undergo larger deformations without fracture. Yet due to their higher reactivity and lower melting point the maximum operating temperature is limited to 300-400°C thus reducing the benefit of larger thermal-expansion coefficient. Further in order to develop good quality lateral actuator a high out-of-place stiffness is needed. This can be achieved with a technique known as LIGA [8], where x-ray lithography is used to develop deep trenches in PMMA substrates, later to be filled with metal via electro deposition. The limited access and high cost of this process soon resulted in the development of alternative processes using thick photoresist films. In this paper we describe the development of thermal micro-actuators formed in photoresist mold, which are later released via sacrificial metal seed layer etch. The specific application of these devices is a tactile display, where the actuators perform mechanical switching function [9].

I. DESIGN OF THE THERMAL MICRO-ACTUATOR ARRAY
Vibro-tactile displays are devices utilizing an array of vibrating points in order to stimulate the tactile sensors (Pacianian corpuscles) in the skin and create sensation of touch [10-12]. The required frequency, stroke and force for such stimulation was previously tested and the results are listed in Table 1. As evident from the table the required force and stroke of the actuators is significantly larger than the typical values for MEMS devices. To achieve these requirements we have developed a hybrid solution: (1) meso-scale vibrating plate driven by a set of piezo-actuators is coupled with (2) an array of MEMS mechanical switches (clutches), which re-direct the vibrations of the plate to the individual protruding pins (pixels). The switching of individual pixels is provided by the array of thermal actuators displacing laterally a lock mechanism as illustrated in Figure 1. The MEMS array is mounted on top of the vibrating plate assembly as illustrated in Figure 2. The pixels are turned ON and OFF by pairs of micro-actuators, while the main vibration is generated by a meso-scale vibrating plate as illustrated in Figure 2(left). A 3D close-up view of one such thermal actuator is shown in Figure 2 (right) indicating the need for a second layer of metal rising above the surface of the actuator (arrow).

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Table 1. Settings on Solenoid Tactile Illusion-Producing Device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>No. of vibrations</td>
<td>Total number of protrusions of each solenoid while activated 5</td>
</tr>
<tr>
<td>Required force</td>
<td>More than 10 mN</td>
</tr>
<tr>
<td>Required displacement</td>
<td>More than 20 µm</td>
</tr>
<tr>
<td>Solenoid on-time</td>
<td>Time of core protrusion for each vibration of each solenoid 10 ms</td>
</tr>
<tr>
<td>Solenoid off-time</td>
<td>Time of no active core protrusion for each vibration cycle 10 ms</td>
</tr>
<tr>
<td>Solenoid delay</td>
<td>Time between end of last solenoid vibration and onset of next solenoid vibration = 5 ms</td>
</tr>
</tbody>
</table>

Figure 1. Switching Mechanism: Principle of Operation (left); and Detail of MEMS switch (right).

Figure 2. Vibrating Plate Assembly

II. THERMAL AND MECHANICAL ANALYSIS

The geometry of a typical micro-actuator is shown in Figure 3. There are two types of actuators: thermal bimorphs, in which two different thermal expansion coefficient materials are used, and homogeneous actuators, in which a temperature difference is set between the narrower “hot” and the wider “cold” arm. In both devices, a bending moment is created in the two beams, and the two-arm structure deflects toward the beam with smaller expansion. This actuator consists of two arms with different
cross sections (see Figure 3). When current is passed through the two arms, the higher current density occurs in the smaller cross-section beam and thus generates more heat per unit volume. The displacement is a result of the temperature differential induced in the two arms.

Figure 3. Thermal Micro-Actuator

Coupled field finite element analysis using ANSYS was conducted to predict the steady state displacement and temperature distribution. The analysis was run in two steps. In the first step, the microactuator was discretized with SOLID98 coupled field element with VOLT and TEMP degrees of freedom activated. Voltage was applied to the bonding pads as a boundary condition and the corresponding steady state temperature distribution was obtained. The thermal model assumed that the entire heat flux is dissipated through the bonding pads and the substrate respectively. The material resistivity was considered a linear function of the temperature, which resulted in iterative solution. The current consumption was determined as a nodal reaction solution. Once the temperature distribution was obtained, it was applied as a body force in the consecutive mechanical deflection analysis. Since geometric nonlinearity was required, SOLID92 with UX, UY and UZ degrees of freedom was used. The analysis was performed using the following geometric data: \( l_h = 1368 \mu m \), \( l_f = 415 \mu m \), \( l_c = 953 \mu m \), \( w_h = 17.5 \mu m \), \( w_c = 105 \mu m \), \( w_f = 15 \mu m \) and \( g = 30 \mu m \). The simulations were compared with the experimental results and showed very good agreement (Figure 4).

Figure 4. Simulation results

III. FABRICATION OF THE THERMAL ACTUATOR ARRAY

3.1 Processing Sequence

The thermal microactuator array was fabricated by nickel electroplating in photoresist mold. The chosen thick film photoresist (AZ4903) could be used for plating of structures up to 20\( \mu m \) high and produces very good sidewall profile. Additional benefit of the photoresist is the ease of use and the excellent yield. The process flow is shown in Figure 5, with each step labeled separately. The process starts with an oxidized silicon wafer. A thin seed layer of Ti/Cu is evaporated followed by spin-coating of the one layer AZ4903 approximately 20 \( \mu m \) thick (Steps 1-3). After the photoresist is patterned by UV and developed (Step
4), the freshly exposed seed layer is used to electroplate 20 µm of Ni (Step5). A commercial nickel sulfamate plating bath, Microfab Ni100 (Enthone, RI), was used at 150mA (0.4 amps per square decimeter).

![Image](image_url)

**Figure 5. Processing Sequence**

In order to provide a raised segment of the actuator contacting the vibrating plate, a second layer of photoresist was spun over the first Ni layer and used as a mold to electroplate a second layer of Ni (Steps 6-10). The old photoresist is then removed using acetone and a fresh layer is spun (Steps 11-12) to protect the structure during the back side oxide etch (Step 13) with buffered oxide etch (BOE). Next, the seed layer is removed between the plated structures since it is opaque for the IR used for back-to-front alignment (Steps 14-15). Photoresist is spun on top and bottom of the wafer and the bottom layer is patterned with UV (Steps 16-17). The wafer is then etched with DRIE and the oxide for the etch-stop is removed (Steps 18-19). The final completion of the process includes the etching of the copper seed-layer and the Ti adhesion layer, to achieve electrical conductivity to the devices (Steps 20-21). The selective removal of Cu with respect to the Ni was achieved by using timed wet etching in (NH₄)₂S₂O₈ solution [15]. During this step the wider features are not completely undercut and are therefore fixed to the underlying substrate in order to anchor the device.

![Image](image_url)

**Figure 5. (Cont’d). Processing Sequence**

### 3.2 Fabrication Results

A pair of fabricated devices is shown in Figure 6. The cold arms have release holes allowing for the Cu etchant to undercut them.

![Image](image_url)

**Figure 6. Fabricated Tactile Pixel Switch: (a) Pair of Two Thermal Actuators (b) Close view of the switching end**
IV. ACTUATION EXPERIMENTS

4.1 Thermal Actuator Results
The released actuators were powered by a current source with currents ranging between 110mA and 230mA. The displacement was measured optically by processing images captured by a CCD camera. The current-displacement results are plotted in Figure 4. The displacement was measured at the end of the hot arm and is smaller than the displacement achieved at the tip of the actuator. Summary of all measured parameters at the maximum displacement is compiled in Table 2 below. During the testing, higher steady state deflections of up to 75\( \mu \)m were observed at higher current levels, but the elevated temperature and compression in the hot arm resulted in plastic deformation of the hot arm.

Transient response time of the thermal actuator was also measured. As shown previously [13,14] the bandwidth limiting process in the actuator response in the cooling, which is in the millisecond range. Since the CCD camera has a bandwidth limitation of 33 Hz, we used an indirect technique to measure the transient response of the actuator. The method relies on the variation of the electrical resistance of the actuator due to the temperature changes.

Table 2. Measured Actuator Characteristics for 20 \( \mu \)m Thick Beams

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experimental Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>45( \mu )m</td>
</tr>
<tr>
<td>Length</td>
<td>1368( \mu )m</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>0.3V (per actuator)</td>
</tr>
<tr>
<td>Operating current</td>
<td>0.23A</td>
</tr>
<tr>
<td>Resistance</td>
<td>1.3( \Omega ) (per actuator)</td>
</tr>
<tr>
<td>Power consumption</td>
<td>69mW (per actuator)</td>
</tr>
</tbody>
</table>

The total resistance \( R_{\text{tot}} \) is the sum of constant series resistance \( R_s \) and variable actuator resistance \( R_a (1 + \alpha(T - T_0)) \).

Assuming that the heating and cooling cycles have a thermal time constant \( \tau_{\text{th}} \), the average temperature change during cooling is

\[
T - T_0 = \Delta T e^{-\frac{t}{\tau_{\text{th}}}}, \quad \Delta T = T_{\text{max}} - T_0.
\]

The voltage drop across the thermal actuator is then

\[
\Delta V = I R_{\text{tot}} = I \left( R_s + R_a (1 + \alpha \Delta T) \right) = I \left( R_s + R_a \right) + I \alpha R_a \Delta T e^{-\frac{t}{\tau_{\text{th}}}}
\]

A two-level current source was utilized in this experiment. High current level was used to heat the device to its working temperature and a low current level was used to monitor the change of the resistance during the cooling cycle. Figure 7 shows typical voltage drop across the thermal actuator due to the two-level current excitation. As evident from the figure, the resistance increases during the heating cycle and decreases during the cooling cycle. Since it is always possible to decrease the time for reaching the operating temperature it is important to find the cooling time, which is a function of the system itself and cannot be reduced by any other means. Assuming exponential temperature decay as described by (2), a nonlinear curve fit of the falling edge yields \( \tau_{\text{th}} \approx 6.6 \) ms.

![Figure 7](image_url)

Figure 7. (a) Voltage Drop During Heating and Cooling (b) Exponential Curve Fit
4.1 Actuation Switching Results
The first step towards demonstration of successful actuation switching was to verify that the thermal clutches are properly aligned and could reach over the protruding pixels. Figure 8(a) shows one thermal actuator pair prior to turning the thermal actuators on, where Figure 8(b) shows the pair in final engaged position for 240mA actuation current. As evident from the figure, the actuators have sufficient stroke for the switching.

![Figure 8](image)

Figure 8. (a) Thermal clutches in ‘off’ position (b) Engaged thermal clutches

Next, the assembly depicted in Figure 2 was built and tested. After bonding of the piezo beams and the vibrating plate, the plate vertical displacement was measured to be in the range of 50µm to 60µm. The piezo assembly is shown in Figure 9(a) and the complete stack in Figure 9(b).

![Figure 9](image)

Figure 9. (a) Piezo Assembly (b) Completed assembly stack

During the testing of the stack it was established that the tolerances in the spacer geometry and the piezo beam bonding are larger than the thickness of the second electroplating layer (11µm), making proper alignment and switch demonstration very difficult. In order to test the tactile perception, one actuator pair was deformed plastically above the center of the pixel increasing the effective stroke from 11µm to approximately 30µm and alleviating the alignment problem. For this new protrusion height, distinct tactile perception was produced with the piezo actuators. Therefore, one solution of the alignment problem is to increase the second layer plating thickness to 30µm or more.

V. CONCLUSIONS
A complete design of a micromechanical switch array actuator was presented. The MEMS clutch array and the piezo assembly stack were designed and tested. The measured and simulated properties of the thermal actuator array are in good agreement and allow use in a vibro-tactile display. Using the built piezo actuator assembly, reliable tactile perception was established for protrusion of 30µm.

ACKNOWLEDGMENTS
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