Chapter 6

Testbed Experimental Results

6.1 Introduction

In this section, we present our experimental results for the micromechanical test-bed. We will first discuss the die samples used in the testing, followed by a description of the experimental setup. We have performed characterization of the testbed in air using $\Sigma$-$\Delta$ control of the three modes. Open-loop and closed-loop step response of the plate are compared with simulation. The $\Sigma$-$\Delta$ bitstreams can be combined to produce an acceleration output. Accelerometer functionality is verified by measuring the response to a 1 Hz external vibration input. Static acceleration measurements provide the sensitivity and signal-to-noise ratio, and show mode-coupling of the noise. Last, testing results at low-pressure are presented, where the existence of bounded limit cycles is confirmed.

6.2 Experimental Setup

We have tested the device in air on a wafer probe-station using the custom assembly shown in Figure 6.1. The assembly consists of a zero-insertion-force (ZIF) socket on a printed-circuit board, bolted onto an aluminum chuck. On the bottom-side of the printed-circuit board, signals are routed to 44-pin edge connectors, while the top side is a solid ground plane. Coaxial cables from the edge connectors provide a general interconnection scheme that can be used for many projects. However, the position-sense outputs would be capacitively loaded by the coaxial cable, limiting the bandwidth to less than 1 MHz. For these signals, external buffers are placed close to the testbed chip, on a daughter board.
Figure 6.1: Custom mounting assembly for testing on the wafer probe-station. The testbed DIP is located in the center of the photograph.

attached to the printed-circuit board. Direct wiring to the external buffers reduces the load capacitance to less than 10 pF.

A custom probe card, shown in Figure 6.2, was made for testing devices in our vacuum probe-station. A printed-circuit board with a ground plane is used to route signals through a metal end-cap that seals the vacuum chamber, and out to the edge connectors. The connectors are compatible with the coaxial-cable assembly used in testing on the wafer probe-station.

The experimental test setup is shown in Figure 6.3. The external electronics are housed in a card-cage with most connections made via front-panel BNC connectors. Circuit schematics and the card-cage layout are given in appendix A.2.

6.3 Position-Sensor Characterization

One period of the position sensor waveform, for various reference input values, is shown in Figure 6.4. Tungsten contacts connecting the reference capacitor to the bridge are disconnected, due to HF attack during the microstructure release. The resulting imbalance in the capacitive divider produces a peak-to-peak sensor offset voltage of $-103$ mV. The interconnect leading off-chip has a capacitance value of about 10 pF, limiting the risetime to 424 ns. A source-follower circuit drives the signal off-chip, adding a dc offset of $-0.81$ V. Photocurrent in the diode at the input to the buffer causes the dc bias to shift more negative
Figure 6.2: Custom probe card for testing in the vacuum probe-station (shown in the background).

Figure 6.3: Photograph of the experimental test setup.
when the device is exposed to light. The asymmetric current-voltage diode characteristic is responsible for the output dc bias shift with increasing signal amplitude.

Vertical displacement of the plate is measured by counting fringes using laser interferometry between the top plate and underlying substrate surfaces. Each fringe occurs at multiples of a half wavelength of the He-Ne laser (316.4 nm). In previous work, interferometry with a monochromatic infrared source has been used to measure parallelism of bulk-machined surfaces [96]. The present laser interference technique is used to obtain video confirmation of closed-loop tracking of vertical position and tilt to within ±25 nm and ±0.03°, respectively.

Measured and calculated values of peak-to-peak sensor output voltage versus displacement are compared in Figure 6.5. Sensitivity of the position sensor is 42 mV/μm at zero displacement. Displacement measurement error is ±25 nm; sensor output error is ±1 mV. The measured sensor output values are fitted to Equation (3.178), using |V_m| = 0.3 V, C_{sv0} = 41.4 fF, C_{sf} = 4.0 fF, C_r = 6.8 fF, and C_p' = 173 fF. Interconnect overlap and fringe capacitance account for the reference and fixed sense capacitance. The effective parasitic capacitance value is about 17 times less than the layout value, demonstrating the benefit of the driven shield. As discussed in section 3.6.1.3, most of the parasitic capacitance is due to the diode junction capacitance.
6.4 Capacitive Feedthrough

Capacitive feedthrough between the electrostatic actuators and position sensors can give rise to errors on the sensor outputs. Table 6.1 gives the measured feedthrough between actuators and the sensor in the lower-left quadrant, where each measurement is made with one actuator driven by a 4-V peak-to-peak square wave and the rest grounded\(^1\). Voltage feedthrough between actuators and the sense line is a maximum of \(-61\) dB, with the closest actuators contributing the most feedthrough. Unfortunately, feedthrough to the sensors in the upper quadrants is much larger. In these cases, the sensor high-impedance lines crossover the actuator interconnect, creating a 90 \(\mu\)m\(^2\) overlap, corresponding to a capacitance of about 3 fF, and a feedthrough of \(-38\) dB. For 10 V of actuation voltage, the sensor feedthrough is 130 mV, which is significant when compared with the signal amplitude.

Since the actuator voltage can only switch at the beginning of a sampling period, the position signal and closed-loop control should not be affected. In practice, however, the feedthrough must settle before the signal is sampled. An example waveform of the demodulation output voltage, in Figure 6.6, illustrates the effects of feedthrough during closed-loop operation. Only one actuator voltage waveform is shown; however, feedthrough

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\(^1\)The measured feedthrough value for the upper-left, pull-up actuator is omitted, because the actuator was inadvertently connected to the substrate through a built-in pin-1 connection of the DIP package. We did not correct this problem until after measurements had been taken, however, the feedthrough value should be close to that of the upper-left, pull-down actuator.
<table>
<thead>
<tr>
<th>actuator location</th>
<th>feedthrough [mV]</th>
<th>feedthrough [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>lower-left, pull-up</td>
<td>3.51</td>
<td>-61</td>
</tr>
<tr>
<td>lower-left, pull-down</td>
<td>0.95</td>
<td>-72</td>
</tr>
<tr>
<td>left comb-drive</td>
<td>0.64</td>
<td>-76</td>
</tr>
<tr>
<td>upper-left, pull-down</td>
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<td>-78</td>
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<tr>
<td>right comb-drive</td>
<td>0.11</td>
<td>-91</td>
</tr>
<tr>
<td>upper-right, pull-down</td>
<td>0.10</td>
<td>-92</td>
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<td>upper-right, pull-up</td>
<td>0.09</td>
<td>-93</td>
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<td>lower-right, pull-up</td>
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<td>-95</td>
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<tr>
<td>lower-right, pull-down</td>
<td>0.05</td>
<td>-98</td>
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</tbody>
</table>

Table 6.1: Measured peak-to-peak feedthrough between different actuators and the lower-left testbed sensor. The actuator drive is a 4 V p-p square wave.

Figure 6.6: Waveforms of an actuator voltage and the demodulator output voltage during closed-loop operation with $f_m = 50$ kHz. Cross-marks are placed at times when the comparator is strobed. (The demodulator voltage is scaled to correspond to the peak-to-peak sensor output voltage.)
results from the interconnect overlap capacitance of four different actuators. In Figure 6.6, the actuators do not switch for the first 60 μs, so only residual feedthrough from the external sample-and-hold circuitry is evident. When the actuator voltage switches states, the 8 V step feeds through to the sensor input, and shows up in the demodulator output. During phase $\phi_1$, the sensor voltage with feedthrough is sampled, producing a large spike at the demodulator output. After phase $\phi_2$, the feedthrough is canceled, to first order. The comparator samples the position signal at the times denoted by the cross-marks in Figure 6.6. Operating the testbed above 50 kHz adds more noise to the position signal during actuator switching, because the sample-and-hold cannot accurately acquire the large feedthrough steps. An improvement to the existing electronics would require withholding the $\phi_1$-sampled signal from the demodulator output amplifier until the $\phi_2$-sampled signal is available. As an alternative control scheme, the sense and feedback cycles could be time multiplexed, at the cost of decreasing the sampling rate.

### 6.5 Open-Loop Step Response

Comb-drive levitation force is used to find the open-loop step response at atmospheric pressure. We applied a 30 Hz square-wave voltage with amplitudes ranging from 1 V to 7 V to the combs on both sides of the plate, and measured the demodulator output voltage waveforms shown in Figure 6.7. With no levitation force applied, the demodulator output voltage from the lower-left sensor is around $-0.485$ V, corresponding to a displacement of 380 nm down from the reference position. The plate is slightly tilted, because the lower-right sense pad (the non-working sensor) has a larger offset voltage than the other sense pads. The average plate displacement is around $-310$ nm. At this position, the restoring force of the suspension balances the electrostatic force from the sense capacitors.

Risetime and falltime measurements from Figure 6.7 are tabulated in Table 6.2. The risetime decreases with increasing step height, presumably from a decrease in damping with increasing gap. If we assume that the position dependence of the electrostatic force is important, then we expect to observe shorter falltimes than risetimes, because the offset force increases during the falling (pull-down) step. However, this is not what the measured results indicate; instead, the falltimes are relatively long. In this case, the effects of position dependence are assumed to be negligible compared to the damping effects. When the displacement step is kept small, the risetime approximately equals the falltime, as expected.
Figure 6.7: Open-loop responses to 30 Hz square-wave levitation force varying in amplitude from 1 V to 7 V.

<table>
<thead>
<tr>
<th>$V_{comb}$ [V]</th>
<th>lower $\Delta z$ [nm]</th>
<th>upper $\Delta z$ [nm]</th>
<th>risetime [ms]</th>
<th>falltime [ms]</th>
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<tr>
<td>2</td>
<td>-312</td>
<td>-295</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>-312</td>
<td>-275</td>
<td>2.8</td>
<td>2.7</td>
</tr>
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<td>-312</td>
<td>-240</td>
<td>2.5</td>
<td>3.0</td>
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<td>-312</td>
<td>-197</td>
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<td>3.0</td>
</tr>
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</tr>
<tr>
<td>7</td>
<td>-312</td>
<td>-110</td>
<td>1.8</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 6.2: Open-loop risetime and falltime measurements.
During the rising (pull-up) step, the position dependence of the offset force approximately cancels that of the comb-drive force, resulting in a net force that is independent of position. The risetime and falltime measurements correspond to damping factors between 9 and 16. Open-loop measurements with larger displacements have not been measured, because of lateral comb-drive instability at higher applied voltages.

One other open-loop measurement was made by exciting the parallel-plate feedback actuators with a small square-wave voltage. In this measurement, the displacement is centered around $\Delta z=0$, and the risetime and falltime are both equal to 2.3 ms, corresponding to a damping factor of 12.

The damping factor for a 360 $\mu$m $\times$ 380 $\mu$m solid plate is very large, $\xi_z = 463$, due to the squeeze film of air between the plate and substrate. The testbed plate is not solid, however. Instead, it is perforated with 580, 4 $\mu$m-square holes, spaced 16 $\mu$m apart, and four, 64 $\mu$m $\times$ 24 $\mu$m slots, included to allow room for external probing and manipulation. The holes reduce the squeeze-film damping to about 1/30 times the value for a solid plate. In the simulations presented in this chapter, damping is approximated as a constant value of 16 in air. Although there is a damping dependence on position, we have not needed to add these effects to match simulations to our closed-loop measurements.

### 6.6 Comb-Drive Levitation Force

The comb drives on each side of the plate have 39 fingers, which are 2 $\mu$m wide and have 2 $\mu$m spacing between adjacent fingers. The stationary and movable fingers overlap by 10 $\mu$m, and are suspended above the substrate by $z_o=2.2$ $\mu$m. A two-dimensional finite-element solution of the total comb-drive levitation force, using the Maxwell\textsuperscript{TM} [52] electrostatic field solver, gives

$$F_{\text{comb}} = 1.284 \alpha (1 - 1.596 \Delta z)V_{\text{comb}}^2 \text{[nN/m]}$$

(6.1)

where $F_{\text{comb}}$ and $V_{\text{comb}}$ are the comb-drive force and voltage, respectively, and $\Delta z$ is given in units of $\mu$m. We have included a fitting factor, $\alpha$, to account for differences between the two-dimensional model and any three-dimensional effects or mismatches in the actual geometrical parameters. The spring force is

$$F_{\text{os}} + F_{\text{comb}} = (0.25 \text{ N/m}) \Delta z$$

(6.2)
where the measured parallel-plate offset force, $F_{os}$, is $-77$ nN at $\Delta z = 0.31$ μm. We combine Equation (6.1) and (6.2) to get

$$F_{\text{comb}} = \frac{1.37 V_{\text{comb}}^2}{1 + 0.00756 V_{\text{comb}}^2} [\text{nN}] \quad (6.3)$$

where $\alpha = 0.73$ is selected as a best fit to measured data. A comparison between the measured comb-drive force and Equation (6.3) is made in Figure 6.8. Comb levitation force is measured by differentiating the total spring force before and after the comb-drive voltage is applied. The error bars reflect the ±1 mV uncertainty in the demodulation output voltage measurement. The fitted finite-element calculations and measured data are in good agreement, demonstrating the linear dependence of comb-drive force on vertical position. In contrast, if there was no position dependence, the comb-drive force would rise much more steeply with increasing applied voltage.

### 6.7 Closed-Loop Step Response

Plots of simulated and measured closed-loop response to an 150 Hz square-wave position reference input are given in Figure 6.9. Operation is at atmospheric pressure without

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2The exact dependence of the offset force on displacement has not been determined, because the plate tilt and broken sensor complicate the analysis. For these calculations, we assume that the offset force behaves like a parallel-plate capacitor force.
Figure 6.9: Closed-loop response to an 150 Hz square-wave position reference input. (a) Position reference input voltage, $V_{\text{ref}}$. (b) Simulated peak-to-peak sensor voltage waveform, $V_{pp}$. (c) Measured $V_{pp}$ waveform. (d) Measured quantizer output, averaged over 1024 sweeps and normalized to ±1.
feedback compensation, and with a sampling rate of 50 kHz. Simulated results are generated by using a commercially available program for simulating dynamic systems\cite{11}. Excellent agreement between the measured and simulated peak-to-peak sensor voltage waveforms is obtained. Limit-cycle oscillations, seen in the single-sweep waveform when the position is locked to the reference, have an amplitude of approximately 25 nm. Total open-loop equivalent Brownian noise position in air is 50 times smaller than the limit-cycle amplitude value. The average quantizer output, plotted in Figure 6.9(d), is near zero for both of the controlled plate positions. The actuator force magnitude increases as the actuator gap is reduced, so average quantizer output does not vary linearly with position.

6.8 Accelerometer Testing

The testbed is not specifically designed as an accelerometer, however its sigma-delta digital outputs do provide a measure of external acceleration. An ac acceleration test is performed by manually shaking the device up and down, first along the z-axis and then along a lateral axis. The motion is roughly sinusoidal with a 3 inch amplitude and 1.6 Hz frequency, providing an acceleration amplitude of 0.8 G. Figure 6.10 displays the spectrum of one digital bitstream, which is low-pass filtered and measured with an HP3561 dynamic signal analyzer. Along the z-axis, the measured signal is approximately 1.1 G, based on the full-scale feedback force of 860 nN. No cross-axis signal is detected. The noise floor of about –50 dB is quantization noise passed by the simple one-pole RC filter and aliased to lower frequencies by the dynamic signal analyzer. External angular acceleration about the x-axis and y-axis is also detectable, but no quantitative results are available.

Static acceleration performance is tested in air, with \( f_s = 50 \text{ kHz} \) and \( G_v = 0 \). The digital bitstreams are passed through a \( \text{sinc}^3 \) finite-impulse-response (FIR) filter, decimated by 500, and combined to provide an acceleration output with a signal bandwidth of 50 Hz.

In the static testing, four changes are made to the ideal testbed system. First, the lower-right feedback actuators are grounded, leaving three quadrants in closed-loop operation. Using this configuration, we avoid the over-constrained system created when feedback exists on all four corners of the plate. Second, the spring attached to the lower-right corner of the plate was accidentally broken prior to this test, so the suspension is no longer symmetric. Third, the feedback voltage levels are set to 3.56 V for the pull-down actuator and 7.15 V for the pull-up actuator to compensate for the sensor pull-down force.
Figure 6.10: Spectrum of one digital bitstream, showing the \( \approx 1 \) G acceleration signal at 1.6 Hz. (a) manual shaking along z-axis. (b) manual shaking along lateral axis.
Figure 6.11: Averaged output signals from the three working channels, with the device tilted 90° from horizontal.

Fourth, we adjusted the position references such that the pulse density of the feedback force for all three quadrants is approximately 50%. Precise adjustment of the dc feedback levels is difficult because small changes in the position reference settings produce large shifts in the pulse density and changes in one quadrant couple to the other quadrants. Adequate position settings are: $\Delta z_{ur} = 0.27 \mu m$, $\Delta z_{ul} = 0.54 \mu m$, and $\Delta z_{ll} = 0.25 \mu m$, where the subscripts denote the quadrant (for example, “ul” is upper-left).

An example of the acceleration waveforms from each channel is given in Figure 6.11, where the device is tilted on its side. Full-scale swing of the feedback force is normalized and centered around zero. Signals from the two left quadrants have about 5 times more noise than the upper-right signal. Some interesting mode-coupling effects are seen in the testbed, which would not exist in a single-axis accelerometer design. An enlargement of the signals, in Figure 6.12(a), illustrates that the noise of the left-channel signals is correlated and has a constant spectral density. The equivalent actuator noise accelerations are $\sqrt{a_{eq,ur}^2} = 11$ milli-G, $\sqrt{a_{eq,ul}^2} = 50$ milli-G, and $\sqrt{a_{eq,ll}^2} = 55$ milli-G. We believe that correlated noise originates from the rotational noise torque of the plate, discussed in section 5.6.1. Since the lower-right spring is cut, the actual modes differ from the $z$, $\theta$, and $\phi$ modes assumed in the Brownian noise calculations. The measured noise of the two left channels is about 6 times larger than the calculated equivalent Brownian noise acceleration. By summing these two signals, much of the correlated noise is canceled, producing the lower waveform shown in Figure 6.12(b).
Figure 6.12: Enlargement of the averaged output signals from Figure 6.11. (a) Comparison of the left-channel signals. (b) Comparison of the upper-right signal and the sum of the left-channel signals.
The signal from the upper-right channel (the upper waveform in Figure 6.12(b)) has a correlation to the summed waveform; this noise arises from coupling between the left and right sides. Although this noise can be canceled by subtracting a weighted combination of the two waveforms in Figure 6.12(b), the resulting signal would not yield the total z-axis acceleration.

We have chosen to sum all three channels to obtain the total external acceleration signal. Examples of acceleration signals for differing tilt angles are given in Figure 6.13. From the discrepancy between the results at a 90° tilt and a 270° tilt, we estimate that the actual tilt angle is off by 3.5°. We correct for the tilt error and fit the sensor offset and amplitude to generate the 2-G tilt test results in Figure 6.14. The rms error is 31 milli-G, with a maximum measured error of 71 milli-G. The full-scale range is 55 G, however, we have not tested the acceleration sensing outside of the ±1 G range. Measured noise acceleration is $-86 \text{ dB}/\sqrt{\text{Hz}}$, referenced to the full-scale range of 55 G (0 dB). The previously reported noise value of $-90 \text{ dB}/\sqrt{\text{Hz}}$[97] is obtained by using a weighted sum of the three quadrant signals. In the 50 Hz bandwidth, the measured noise floor is 19 milli-G (-69 dB), about 5 times larger than the Brownian noise calculated in section 5.6.1. The measured noise acceleration is close to the value of quantization noise calculated in section 5.6.4. Quantization noise is dominant, with noise from the rotational modes coupling into the

\[\text{noise} \approx 8.5 \text{ milli-G} \]

\[\text{The quantization noise calculation in section 5.6.4 assumed four actuators are in operation. For three actuators in operation, the total noise acceleration value is 8.5 milli-G.}\]
acceleration output signal and increasing the measured noise value.

### 6.9 Underdamped Operation at Low Pressure

Underdamped system dynamics are investigated by placing the testbed in a vacuum probe-station. Our experiments are constrained to sampling frequencies up to 100 kHz and compensation gain up to 4, because of external circuit limitations. Three of the four feedback channels are activated; the fourth channel has its actuators grounded to avoid the over-constrained instability.

Measured peak-to-peak sensor voltage waveforms are compared with simulation and theoretical results in Figure 6.15, with \( f_s = 100 \text{ kHz} \) and \( G_v = 4 \). Each column of waveform data is taken at three different pressure values, 10 T, 1 T, and 0.1 T, corresponding to estimated\(^4\) quality factors of 2.4, 24, and 240. Simulation results qualitatively match the measured waveform frequency and amplitude. The maximum limit-cycle amplitude given by the theoretical model is also in agreement with the measured data. As the pressure is decreased, damping also decreases, and the limit-cycle amplitude increases. In the \( P = 0.1 \text{ T} \)

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\(^4\)Squeeze-film damping, given by Equation (3.30), is proportional to air viscosity, which is proportional to pressure. In our estimation of \( Q \) values, we assume that \( Q \) is proportional to \( 1/P \) and \( \zeta = 16 \) in air at 760 Torr. However, as indicated in section 3.3, the gas should no longer be treated as a viscous fluid at pressures below 25 Torr. Therefore, the actual \( Q \) values in our experiment may be higher than those stated.
Figure 6.15: Measured, simulated, and theoretical peak-to-peak sensor voltage waveforms during underdamped operation at three different pressure values: 10 T, 1 T, and 0.1 T. The y-axis scales are only supplied once to avoid clutter ($V_{pp}$ in mV on the left, and $\Delta z$ in $\mu$m on the right).
case, actuator nonlinearity and added force from the sensor capacitors distorts the feedback force, and is responsible for the larger measured limit-cycle amplitude than the theoretical value. With lead compensation $G_v < 3$, the underdamped system is unstable and rails to the limit stops, as predicted by the theory.
Chapter 7

Conclusions

In this thesis, we have demonstrated that a complex surface microsystem, the micromechanical testbed, can be modeled with lumped-parameter components that are incorporated into system-level simulation tools, such as SPICE and MATLAB. We have developed analytic models for several components — mass-spring-dampers, parallel-plate and comb-drive electrostatic actuators, and capacitive position sensors — that are used in a broad class of surface microsystems.

The MEMS engineer can use the spring-constant equations in section 3.4 for design of fixed-fixed, crab-leg, folded, and serpentine suspensions. Linear spring constants for almost any other suspension made from slender beams can be derived using the energy method. Implementation of the mechanical equations of motion and the actuator and sensor capacitor models in HSPICE and MATLAB represents a first generation of system modeling.

In chapter 2, we presented theory and experimentally demonstrated a novel form of post-process micromechanical assembly by welding and fusing polysilicon and aluminum structures. Fuses are used as temporary supports for structures, and to configure suspension stiffness. Demonstrated applications include adjustment of the mechanical response in accelerometers and frequency trimming of resonators. Clean, reliable cutting of 2 μm-wide × 12 μm-long × 2 μm-thick polysilicon fuses is obtained by passing about 260 mA of current through the fuse. Cutting of more than four fuses in parallel requires careful matching of low-resistance interconnect. Welding structures provide a relatively large lateral force, on the order of μN’s, which can be used to actively align elements and to pre-stress springs. We have fabricated designs for two welding applications: narrow-gap comb-finger actuators
for increased drive capability, and frequency trim of fixed-fixed resonators.

In chapter 6, we demonstrated digital control of a micromechanical plate for vertical and angular motion. Although the parallel-plate actuator force is highly nonlinear with position and voltage, the \( \Sigma - \Delta \) feedback successfully controls plate position to the mechanical limit stops. Since the maximum sampling rate of the testbed is 100 kHz, accuracy of the position control is limited to \( \pm 25 \) nm in air. Every doubling of the sampling rate results in a 12 dB decrease in the plate chatter. Higher frequency circuitry \( (f_s > 2 \text{ MHz}) \) is necessary to reduce the displacement amplitude below the Brownian noise level of the testbed, which is 0.46 nm in air.

Quantization noise dominates the equivalent noise acceleration of the testbed operating with a sampling frequency of 50 kHz. We have detected correlated quantization noise on the testbed's \( \Sigma - \Delta \) bitstreams, after filtering to a 50 Hz bandwidth. Multi-axis accelerometers and gyroscopes will require proper filtering to remove these extra sources of noise. We have shown experimentally that the integrated testbed can be operated at high-\( Q \), lowering the Brownian noise floor for digital MEMS applications. A limit-cycle model successfully predicts the behavior of the high-\( Q \) system. Other types of micromechanical \( \Sigma - \Delta \) loops, for example, with pulsed feedback or analog compensation, can be analyzed using the limit-cycle theory. Appropriate sampling frequency and compensation can be designed into future systems to obtain a specified maximum limit-cycle amplitude. At higher sampling rates and high-\( Q \) operation, the position-sensor electronic noise limits the acceleration sensitivity. We conclude from our comparison of position-sensing methods that voltage sensing using a unity-gain buffer is superior to displacement-current sensing using a transresistance amplifier. High-frequency modulation of the position signal reduces \( 1/f \) noise from the buffer input diode and transistors to negligible levels. Further improvements in acceleration sensitivity will require reductions in thermal noise of the buffer and the following gain stage.

### 7.1 Future Work

This thesis provides an overview of generic surface microsystem components, but much more work is necessary to create a viable system simulation tool that meets the needs of the MEMS engineer. Eventually, a library of MEMS macro-models for each process technology will exist, which both novices and experts can use to design microsystems right
the first time.

Producing good MEMS models is the key to efficient and useful simulations. Model accuracy can be improved by including higher-order effects, such as axial and shear stress in the spring constant equations. The utility of existing models can be increased by extending their range of applicability. For example, flexure models can be extended to include large deflections and rotations. As another example, parallel-plate electrostatic actuator models should include effects of plate rotation and detailed fringe-field corrections. Development of new models will allow simulation of a wider range of microsystem designs. Experimental verification of models is extremely important and will remain a worthwhile research area for several years. Drop-in test structures for characterization of micromechanical materials, processes, and components must be designed and standardized. With standard tests and models, the MEMS community can share and compare design information easily.

Algorithms for extracting the mechanical equations of motion and model parameters from layout are needed to automate the design process. Once a one-to-one correspondence between models and layout is made, further research will lead to programs that synthesize microsystems from design specifications.

It remains a challenge to reach the surface-micro-accelerometer performance level of 50 $\mu$G in a 1 kHz bandwidth\footnote{This value for the Brownian noise limit is calculated in section 3.6.3.3.}, representing the Brownian noise limit for a 0.5 $\mu$g mass with a 1 kHz resonant frequency and a $Q$ of 80000. The micromechanical $\Sigma$-$\Delta$ architecture used in the testbed is a good candidate for the task. If high-speed, low-noise electronics are used, the Brownian noise limit at $Q = 80000$ is attainable. Control of all mechanical modes with resonant frequencies inside the electrical bandwidth of the system is desirable, and may create a limitation on arbitrary reduction of the fundamental resonant frequency and arbitrary increase of the sampling rate. Eventually, the use of multi-mode control of microstructures will lead to the development of multi-axis accelerometers, angular accelerometers, and gyroscopes.
Bibliography


Appendix A

Testbed Technical Information

Information in the appendices (and elsewhere in this thesis) will be accessible on the World Wide Web (WWW) through a hypertext viewer, such as Mosaic, by specifying the Universal Resource Locator (URL) for the Berkeley Sensor & Actuator Center home page, “http://nitride.eecs.berkeley.edu”. From that location, browse to find the link to my research information (look for "Gary Fedder"). Good luck!

A.1 Testbed Parameter Data
Figure A.1: Layout of the testbed’s micromechanical plate and springs.
Figure A.2: Testbed layout dimensions. Dimensional values are given in Table A.1.
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<td>plate thickness</td>
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<td>2.2 $\mu$m</td>
<td>fabricated air-gap between plate and substrate</td>
</tr>
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<td>$z_{ao}$</td>
<td>2.7 $\mu$m</td>
<td>fabricated air-gap between plate and upper actuators</td>
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</tr>
<tr>
<td>$L_{sxw}$</td>
<td>100 $\mu$m</td>
<td>sensor electrode width in $x$ direction</td>
</tr>
<tr>
<td>$L_{syy}$</td>
<td>100 $\mu$m</td>
<td>sensor electrode width in $y$ direction</td>
</tr>
<tr>
<td>$L_{sx}$</td>
<td>60 $\mu$m</td>
<td>sensor distance from plate’s $x$-axis</td>
</tr>
<tr>
<td>$L_{sy}$</td>
<td>60 $\mu$m</td>
<td>sensor distance from plate’s $y$-axis</td>
</tr>
<tr>
<td>$L_{lxw}$</td>
<td>52 $\mu$m</td>
<td>lower-actuator electrode width in $x$ direction</td>
</tr>
<tr>
<td>$L_{lyw}$</td>
<td>52 $\mu$m</td>
<td>lower-actuator electrode width in $y$ direction</td>
</tr>
<tr>
<td>$L_{uxw}$</td>
<td>54 $\mu$m</td>
<td>upper-actuator electrode width in $x$ direction</td>
</tr>
<tr>
<td>$L_{uyw}$</td>
<td>54 $\mu$m</td>
<td>upper-actuator electrode width in $y$ direction</td>
</tr>
<tr>
<td>$L_{ax}$</td>
<td>150 $\mu$m</td>
<td>actuator distance from plate’s $x$-axis</td>
</tr>
<tr>
<td>$L_{ay}$</td>
<td>150 $\mu$m</td>
<td>actuator distance from plate’s $y$-axis</td>
</tr>
</tbody>
</table>

Table A.1: Testbed geometric parameters.

Figure A.3: Layout of one serpentine spring, showing the 6 fuses that can be cut to set the spring constant.
<table>
<thead>
<tr>
<th>configuration number</th>
<th>configuration cut</th>
<th>$k_z$ [N/m]</th>
<th>$k_x$ [N/m]</th>
<th>$k_y$ [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>none</td>
<td>0.455</td>
<td>1.64</td>
<td>3.72</td>
</tr>
<tr>
<td>2</td>
<td>#1</td>
<td>0.249</td>
<td>0.282</td>
<td>0.946</td>
</tr>
<tr>
<td>3</td>
<td>#1,#2</td>
<td>0.0576</td>
<td>0.0520</td>
<td>0.489</td>
</tr>
<tr>
<td>4</td>
<td>#1,#2,#3</td>
<td>0.0205</td>
<td>0.0170</td>
<td>0.328</td>
</tr>
<tr>
<td>5</td>
<td>#1,#2,#3,#4</td>
<td>0.00937</td>
<td>0.00746</td>
<td>0.247</td>
</tr>
<tr>
<td>6</td>
<td>#1,#2,#3,#4,#5</td>
<td>0.00501</td>
<td>0.00390</td>
<td>0.198</td>
</tr>
<tr>
<td>7</td>
<td>#1,#2,#3,#4,#5,6</td>
<td>0.00357</td>
<td>0.00260</td>
<td>0.169</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>spring configuration number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>----</td>
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<tr>
<td>$z$</td>
</tr>
<tr>
<td>$\theta$</td>
</tr>
<tr>
<td>$\phi$</td>
</tr>
<tr>
<td>$x$</td>
</tr>
<tr>
<td>$y$</td>
</tr>
<tr>
<td>$\psi$</td>
</tr>
<tr>
<td>P</td>
</tr>
<tr>
<td>P</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>spring configuration number</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
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<tr>
<td>----</td>
</tr>
<tr>
<td>$x$</td>
</tr>
<tr>
<td>$z$</td>
</tr>
<tr>
<td>$\phi$</td>
</tr>
<tr>
<td>$\theta$</td>
</tr>
<tr>
<td>$y$</td>
</tr>
<tr>
<td>VS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6</th>
<th>mode</th>
<th>$f_r$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>456</td>
<td>517</td>
</tr>
<tr>
<td>$z$</td>
<td>633</td>
<td>909</td>
</tr>
<tr>
<td>$\phi$</td>
<td>556</td>
<td>854</td>
</tr>
<tr>
<td>$\theta$</td>
<td>2170</td>
<td>3000</td>
</tr>
<tr>
<td>$y$</td>
<td>3260</td>
<td>VS</td>
</tr>
<tr>
<td>VS</td>
<td>11000</td>
<td>LS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7</th>
<th>mode</th>
<th>$f_r$ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>372</td>
<td>436</td>
</tr>
<tr>
<td>$z$</td>
<td>517</td>
<td>909</td>
</tr>
<tr>
<td>$\phi$</td>
<td>854</td>
<td>3000</td>
</tr>
<tr>
<td>$\theta$</td>
<td>2170</td>
<td>15500</td>
</tr>
<tr>
<td>$y$</td>
<td>3000</td>
<td>VS</td>
</tr>
<tr>
<td>VS</td>
<td>8950</td>
<td>LS</td>
</tr>
</tbody>
</table>

| LS | 12100 |

Table A.2: Testbed spring configurations. (a) Static spring constants (four-spring suspension), calculated from linear finite-element analysis (linear and nonlinear finite-element results agree to 4 significant digits). (b) System resonant frequencies, calculated from linear finite-element analysis. Refer to Figure A.3 for definitions of the axes and rotation angles. In the “P” mode, the plate is bending. Springs vibrate laterally in the “LS” mode, and vertically in the “VS” mode.
Table A.3: Capacitance definitions, dimensions and calculated values. Plate displacement, \(\Delta z\), is defined relative to the fabricated spacer gap of 2.2 \(\mu m\). Calculated capacitance values are derived from a combination of parallel-plate, interconnect and etch hole capacitance.

<table>
<thead>
<tr>
<th>capacitor name</th>
<th>symbol</th>
<th>capacitance when (\Delta z = 0)</th>
<th>width (\times) length</th>
<th>spacer gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>sense</td>
<td>(C_s)</td>
<td>41.4 fF</td>
<td>100 (\mu m \times 100 \mu m)</td>
<td>2.2 (\mu m)</td>
</tr>
<tr>
<td>reference</td>
<td>(C_r)</td>
<td>40.7 fF</td>
<td>100 (\mu m \times 100 \mu m)</td>
<td>2.2 (\mu m)</td>
</tr>
<tr>
<td>lower actuator</td>
<td>(C_{\text{down}})</td>
<td>10.8 fF</td>
<td>52 (\mu m \times 52 \mu m)</td>
<td>2.2 (\mu m)</td>
</tr>
<tr>
<td>upper actuator</td>
<td>(C_{\text{up}})</td>
<td>9.2 fF</td>
<td>54 (\mu m \times 54 \mu m)</td>
<td>2.7 (\mu m)</td>
</tr>
</tbody>
</table>

Table A.4: Pin assignments for working testbed chip in a 24-pin dual-inline package.
A.2 External Testbed Electronics

A.2.1 Schematics

Figure A.4: Timing board, schematic #1: digital control logic
Figure A.5: Timing board, schematic #2: voltage references and balanced modulation source.
Figure A.6: Photograph of the timing board, identifying the functional blocks and test points.
Figure A.7: Feedback board, schematic #1: input demodulator (1 of 4). The feedback boards are assigned as follows. Board 1 takes upper-right channel input. Board 2 takes upper-left channel input. Board 3 takes lower-left channel input. Board 4 takes lower-right channel input, or calculates lower-right channel feedback from the other three channels, dependent on the jumper JMP1.
Figure A.8: Feedback board, schematic #2; feedback logic (1 of 4).
Figure A.9: Photograph of one of the feedback boards (board #2), identifying the functional blocks and test points.
Figure A.10: Schematic of the opto-isolation board.
Figure A.11: Photograph of the opto-isolation board.
A.2.2 Card-Cage Layout

Figure A.12: External electronics, housed in a standard card cage. (a) Front view. (b) Rear view. Most connections are made via front-panel BNC connectors. The opto-isolated bitstreams are available from a 9-pin DIN connector. Dials on the front-panel are used to set feedback gains. Power is supplied through banana-jacks.
<table>
<thead>
<tr>
<th>Pin #</th>
<th>Timing Board Front</th>
<th>Timing Board Back</th>
<th>Opto-isolation Board Front</th>
<th>Opto-isolation Board Back</th>
<th>Feedback Board Front</th>
<th>Feedback Board Back</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+5 V</td>
<td>+5 V</td>
<td>+5 V</td>
<td>+5 V</td>
<td>Brds</td>
<td>1,2,3: AGND</td>
</tr>
<tr>
<td>2</td>
<td>DGND</td>
<td>DGND</td>
<td>DGND</td>
<td>DGND</td>
<td>1,2,3: AGND</td>
<td>AGND</td>
</tr>
<tr>
<td>3</td>
<td>VM_ON+</td>
<td>VM_ON+</td>
<td>VM_ON+</td>
<td>VM_ON+</td>
<td>1,2,3: AGND</td>
<td>AGND</td>
</tr>
<tr>
<td>4</td>
<td>SAMPLE1</td>
<td>LATCH</td>
<td></td>
<td></td>
<td>1,2,3: AGND</td>
<td>AGND</td>
</tr>
<tr>
<td>5</td>
<td>SAMPLE2</td>
<td></td>
<td></td>
<td></td>
<td>1,2,3: AGND</td>
<td>AGND</td>
</tr>
<tr>
<td>6</td>
<td>AGND</td>
<td>AGND</td>
<td>REMOTE</td>
<td>REMOTE</td>
<td>Brd 1: V1_PP</td>
<td>V3_PP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GND</td>
<td>GND</td>
<td>Brd 2: V2_PP</td>
<td>V1_PP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GND</td>
<td>GND</td>
<td>Brd 3: V3_PP</td>
<td>V2_PP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D1</td>
<td></td>
<td>Brd 4: V1_PP</td>
<td>V3_PP</td>
</tr>
<tr>
<td>7</td>
<td>VSNS_CAP</td>
<td>AGND</td>
<td>REMOTE</td>
<td>D1</td>
<td>Brd 1: V1_PP</td>
<td>V3_PP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+5 V</td>
<td></td>
<td>Brd 2: V2_PP</td>
<td>V1_PP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brd 3: V3_PP</td>
<td>V2_PP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brd 4: V1_PP</td>
<td>V3_PP</td>
</tr>
<tr>
<td>8</td>
<td>AGND</td>
<td>AGND</td>
<td>D2</td>
<td>D3</td>
<td>AGND</td>
<td>AGND</td>
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<tr>
<td>9</td>
<td>VREF_CAP</td>
<td>AGND</td>
<td>C_CLK</td>
<td>D4</td>
<td>DGND</td>
<td>VFB_UP</td>
</tr>
<tr>
<td>10</td>
<td>VFB_DN</td>
<td>DGND</td>
<td>Z4_HI</td>
<td>Z1_D_UP</td>
<td>DGND</td>
<td>VFB_DN</td>
</tr>
<tr>
<td>11</td>
<td>CLK</td>
<td>DGND</td>
<td>Z1_HI</td>
<td>Z2_D_UP</td>
<td>Brd 1: Z1_HI</td>
<td>Z1_D_UP</td>
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<tr>
<td></td>
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<td></td>
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<td>Brd 2: Z2_HI</td>
<td>Z2_D_UP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brd 3: Z3_HI</td>
<td>Z3_D_UP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brd 4: Z4_HI</td>
<td>Z4_D_UP</td>
</tr>
<tr>
<td>12</td>
<td>DGND</td>
<td>DGND</td>
<td>Z2_HI</td>
<td>Z3_D_UP</td>
<td>Z_SNS</td>
<td>AGND</td>
</tr>
<tr>
<td>13</td>
<td>DGND</td>
<td>DGND</td>
<td>Z3_HI</td>
<td>Z4_D_UP</td>
<td>Z_REF</td>
<td>AGND</td>
</tr>
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<td>DGND</td>
<td>DGND</td>
<td></td>
<td></td>
<td>DGND</td>
<td>DGND</td>
</tr>
<tr>
<td>15</td>
<td>+12 V</td>
<td>-12 V</td>
<td></td>
<td></td>
<td>+12 V</td>
<td>-12 V</td>
</tr>
<tr>
<td>16</td>
<td>VFB_UP.0</td>
<td>VPT_UP.0</td>
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<td></td>
<td>VFB_UP.0</td>
<td>VFB_UP.0</td>
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<td></td>
<td>VFB_UP.1</td>
<td>VFB_UP.1</td>
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<tr>
<td>18</td>
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<td>VPT_DN.0</td>
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<td></td>
<td>VFB_DN.0</td>
<td>VFB_DN.0</td>
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<tr>
<td>19</td>
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<td>VFB_DN.1</td>
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<td>+15 V</td>
<td>+15 V</td>
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<td></td>
<td></td>
<td>AGND</td>
<td>AGND</td>
</tr>
</tbody>
</table>

Table A.5: Backplane assignments. Pin 1 is located at the top of the card cage. The pins are noted on schematics as "1 F" for pin 1-front, etc.
A.2.3 Test Setup

In addition to the custom electronics, several other pieces of equipment are required, including

- ±15 V power supplies, rated 0.6 A, for external analog electronics
- ±5 V power supply, rated 0.1 A, for external digital electronics
- ±4 V and -2.5 V power supplies, for $V_{dd}$ and $V_{ss}$, to the chip
- 600 kHz square-wave generator, TTL output, for timing clock ($f_m=100$ kHz)
- ammeter, for monitoring chip bias current
- one or more function generators for position reference inputs, $V_{ref}$'s
- computer interface for digital bitstream filtering and storage
Appendix B

HSPICE Input Files

Information in the appendices (and elsewhere in this thesis) will be accessible on the World Wide Web (WWW) through a hypertext viewer, such as Mosaic, by specifying the Universal Resource Locator (URL) for the Berkeley Sensor & Actuator Center home page, “http://nitride.eecs.berkeley.edu”. From that location, browse to find the link to my research information (look for “Gary Fedder”). Good luck!

B.1 CMOS Unity-Gain Buffer HSPICE File

Buffer with pmos current mirror load 7/27/94

* There are four different input arrangements:
* 1) DC/AC input - to determine gain, bandwidth and offset
  * (dc vtest -0.3 0.3 0.02)
  * (ac dec 10 10k 1G)
* 2) Square wave input - to determine risetime, offset and gain
  * (tran 1n 100n)
* 3) AC input with series cap. - to determine input capacitance
  * (ac dec 10 10k 1Meg)
* 4) Capacitor divider input - actual sensor operation conditions
  * (tran 1u 100u)
*

* differential-pair (buffer) output load capacitance (for #1,2,3 tests)
  * (use cshield for #4 test instead)
  .param cout=3p
  .param rout=100k
* source-follower output load capacitance
.param coutb=10p  
* shield capacitance  
.param cshield=3p  
* reference capacitance  
.param cref=45f  
* variable sense capacitance  
.param csense=200f  
* fixed sense capacitance  
.param csfixed=100f  
* fixed parasitic capacitance to ground  
.param cparasitic=10f

***************
* 1,2) uncomment for DC, AC, or Square wave input
vtest 3 0 dc 0 ac 0.1 pulse(-0.02 0.02 0 .1u .1u 5u 10u)
***************
* 3) uncomment for AC input with series capacitor 
*vtest 64 0 dc 0 ac 0.1
*ctest 64 3 10f
***************
* 4) uncomment for Capacitor Divider input
*rinput 63 3 1
*rshield 65 7 1
***************
*  
* Power supplies  
*  
vdd 20 0 dc 4.0
vss 10 0 dc -2.5
***************
*  
* Capacitor divider section (only connected for test #4 )  
*  
* balanced modulation voltages
vtest1a 60 0 dc 0 pulse(0 0.3 0 0.1u 0.1u 5u 10u)
vtest1b 61 0 dc 0 pulse(0 -0.3 5u 0.1u 0.1u 5u 10u)
etest1 30 0 vol=’v(60)+v(61)’
etest2 31 0 vol=’-v(30)’
*  
* capacitive divider  
cupper 30 63 cref
clower 63 32 csense
clowerfix 63 32 csfixed
cpar 63 0 cparasitic
cshld 65 63 cshield
*
* interconnect resistance to upper plate (can neglect)
rlower 31 32 100k
*
***************
* big resistors to provide dc path to ground for simulator
rdummy1 63 0 10000x
rdummy2 65 0 10000x
rdummy3 0 3 10000x
***************
*
* input diode
* (comment out to find buffer input capacitance w/o diode junction cap)
d1 0 3 diode1
***************
*
* Output load capacitance
cout1 7 0 cout
rout1 7 0 rout
coutb 9 0 coutb
***************
*
* Current reference
*
iref 0 2 dc 80u
m8a 2 2 10 10 mn_4um w=100u l=4u
+ AD=1000.0P PD=120.0U AS=1000.0P PS=120.0U
m8b 2 2 10 10 mn_4um w=100u l=4u
+ AD=1000.0P PD=120.0U AS=1000.0P PS=120.0U
***************
*
* Buffer
*
* Input diff pair
m1a 4 3 8 8 mn_4um w=100u l=4u
+ AD=700.0P PD=47.3U AS=1000.0P PS=120.0U
m1b 4 3 8 8 mn_4um w=100u l=4u
+ AD=700.0P PD=47.3U AS=1000.0P PS=120.0U
m2a 7 7 8 8 mn_4um w=100u l=4u
+ AD=700.0P PD=47.3U AS=1000.0P PS=120.0U
m2b 7 7 8 8 mn_4um w=100u l=4u
+ AD=700.0P PD=47.3U AS=1000.0P PS=120.0U
* Drain isolation
m3 6 5 4 4 mn_4um w=100u l=4u
+ AD=1000.0P PD=120.OU AS=700.0P PS=47.3U
m4 5 5 7 7 mn_4um w=100u l=4u
+ AD=1000.0P PD=120.OU AS=700.0P PS=47.3U

* Load transistors
m5 6 6 20 20 mp_8um w=100u l=8u
+ AD=1000.0P PD=120.OU AS=1000.0P PS=120.OU
m6 5 6 20 20 mp_8um w=100u l=8u
+ AD=1000.0P PD=120.OU AS=1000.0P PS=120.OU

* Diff pair current source
m7a 8 2 10 10 mn_4um w=100u l=4u
+ AD=1000.0P PD=120.OU AS=1000.0P PS=120.OU
m7b 8 2 10 10 mn_4um w=100u l=4u
+ AD=1000.0P PD=120.OU AS=1000.0P PS=120.OU

* Source follower buffer
m10a 20 7 9 9 mn_4um w=50u l=4u
+ AD=500.0P PD=22.0U AS=500.0P PS=70.0U
m10b 20 7 9 9 mn_4um w=50u l=4u
+ AD=500.0P PD=22.0U AS=500.0P PS=70.0U
m9a 9 2 10 10 mn_4um w=50u l=4u
+ AD=500.0P PD=22.0U AS=500.0P PS=70.0U
m9b 9 2 10 10 mn_4um w=50u l=4u
+ AD=500.0P PD=22.0U AS=500.0P PS=70.0U

******************************************************************************
* MOS Models are modified from the Orbit 2um models
* kp, vto, gamma, and lambda are from MICS cmos25-run data
******************************************************************************

.model diode1 d level=3 l=9e-6 w=15e-6 cj=5.3e-3 is=1 xw=1e-6

.model mn_4um nmos level=2 capop=0 acm=0
+ vto=0.56 kp=33u gamma=0.55 phi=0.6
+ lambda=0.043 rdc=10.0 rsc=10.0
+ ld=0.22 u xj=0.25u tox=500.0e-10 nsub=2.3e+16
+ uo=619.0 ucrit=2.6e+04 uexp=0.106
+ neff=1.000 delta=1.4 nfs=1.38e+12
+ rsh=4.0 pb=0.8
+ cj=4.06e-04 mj=0.443 cjsw=4.44e-10 mjsw=0.291
+ cgdo=2.5e-10 cgsc=2.5e-10 cgbo=2.5e-10
+ vmax=6.84e+4
+ nss=1.0e+12 tpg=1.0
*
.model mp_4um pmos level=2
+ vto=-0.56 kp=17u gamma=0.55 phi=0.6
+ lambda=0.046 rdc=100.0 rsc=100.0
+ ld=0.16u xj=0.25u tox=500.0e-10 nsub=0.79e+16
+ uo=257.0 ucrit=2.4e+04 uexp=0.270
+ neff=1.001 delta=0.0 nfs=1.1e+12
+ rsh=4.0 pb=0.71
+ cj=2.30e-04 mj=0.410 cjsw=2.20e-10 mjsw=0.1
+ cgdo=2.5e-10 cgso=2.5e-10 cgbo=2.5e-10
+ vmax=4.50e+4
+ nss=1.0e+12 tpg=-1.0
*
.model mp_8um pmos level=2
+ vto=-0.56 kp=17u gamma=0.55 phi=0.6
+ lambda=0.023 rdc=100.0 rsc=100.0
+ ld=0.16u xj=0.25u tox=500.0e-10 nsub=0.79e+16
+ uo=257.0 ucrit=2.4e+04 uexp=0.270
+ neff=1.001 delta=0.0 nfs=1.1e+12
+ rsh=4.0 pb=0.71
+ cj=2.30e-04 mj=0.410 cjsw=2.20e-10 mjsw=0.1
+ cgdo=2.5e-10 cgso=2.5e-10 cgbo=2.5e-10
+ vmax=4.50e+4
+ nss=1.0e+12 tpg=-1.0
*
.options acct chgtol=1e-16 post
.op

* 1a) uncomment for DC analysis
*.dc vtest -2.5 2.5 .05

* 1b,3,4) uncomment for AC analysis
.ac dec 10 10k 20meg sweep coutb lin 2 10f 10pf

* 2,4) uncomment for AC analysis
*.tran 0.2u 30u

.end
B.2 Testbed HSPICE File

Mechanical simulation of microactuator system with buffer 8/20/94

******************************************************************************
********** PARAMETERS ********************************************************
******************************************************************************
* All entered parameters are in mks units.
* Scale factors are used to scale up units used in internal calculations.

* step-generator position-reference input value (target sensor vpp)
 .param vref_z=56m

* initial conditions for displacement and rotation
 .param z_ic=-2n
 .param phi_ic=0.5u
 .param theta_ic=-0.3u

 .param z_scale=1e6
 .param phi_scale=1e6
 .param theta_scale=1e6
 .param cap_scale=1e-12
 .param cref=40.25f

****************************************************************************** material parameters **************************************************************************
* dimensions of plate: Lx, Ly, Lz
 .param lx=380e-6
 .param ly=360e-6
 .param lz=1.6e-6

* distance from center of plate to springs: Lkx, Lky
 .param lkx=113e-6
 .param lky=180e-6

* distance from center of plate to center of sensors: s_xc, s yc
* sensor electrode size: s_xw, s_yw
 .param s1 xc=60e-6
 .param s1 yc=60e-6
 .param s1 xw=100e-6
 .param s1 yw=100e-6

 .param s2 xc=-60e-6
 .param s2 yc=60e-6
 .param s2 xw=100e-6
 .param s2 yw=100e-6
.param s3_xc=-60e-6  
.param s3_yc=-60e-6  
.param s3_xw=100e-6  
.param s3_yw=100e-6  
.param s4_xc=60e-6  
.param s4_yc=-60e-6  
.param s4_xw=100e-6  
.param s4_yw=100e-6  

* distance from center of plate to center of lower actuators: ab_xc, ab_yc  
* sensor electrode size: ab_xw, ab_yw  
.param ab1_xc=150e-6  
.param ab1_yc=150e-6  
.param ab1_xw=52e-6  
.param ab1_yw=52e-6  
.param ab2_xc=-150e-6  
.param ab2_yc=150e-6  
.param ab2_xw=52e-6  
.param ab2_yw=52e-6  
.param ab3_xc=-150e-6  
.param ab3_yc=-150e-6  
.param ab3_xw=52e-6  
.param ab3_yw=52e-6  
.param ab4_xc=150e-6  
.param ab4_yc=-150e-6  
.param ab4_xw=52e-6  
.param ab4_yw=52e-6  

* distance from center of plate to center of upper actuators: at_xc, at_yc  
* sensor electrode size: at_xw, at_yw  
.param at1_xc=150e-6  
.param at1_yc=150e-6  
.param at1_xw=54e-6  
.param at1_yw=54e-6  
.param at2_xc=-150e-6  
.param at2_yc=150e-6  
.param at2_xw=54e-6  
.param at2_yw=54e-6
.param at3_xc=-150e-6
.param at3_yc=-150e-6
.param at3_xw=54e-6
.param at3_yw=54e-6

.param at4_xc=150e-6
.param at4_yc=-150e-6
.param at4_xw=54e-6
.param at4_yw=54e-6

* distance from poly1 to poly2 = z0
.param z0=2.2e-6

* distance from poly2 to poly3 = z0t
* air gap of upper actuator is negative by convention.
* This is compensated by setting bot_or_top=-1 in the ppc subckt.
.param z0t=-2.7e-6

* spring constant = k = spring
.param kz=0.25

* viscosity of air = 1.83e-5 Pa-s
.param viscosity='1.83e-5'

* etch-hole form factor for damping (zeta_z=12 in air)
.param bf_z='0.02'
.param bf_theta='0.02'
.param bf_phi='0.02'

* etch-hole form factor for capacitance
.param alpha_s='1.0'
.param alpha_l='1.0'
.param alpha_u='0.964'

* dielectric constant of air
.param ep='1.'

* Flexure resistance (ohms)
* about 22kohms in testbed suspension
.param r_flexure='22e3'

* Feedback voltage levels (no compensation)
.param v_up0='5.0'
.param v_dn0='5.0'

* Logic high and low voltages
.param vdd='2.5'
.param vss='2.5'

*******************************************************************************
*************** CALCULATIONS **************************************************
*******************************************************************************

********** IMPORTANT **********************
* All parameters associated with moments are scaled by *
* 1/Ly^2 for x-axis (theta) and 1/Lx^2 for y-axis (phi)*
*******************************************************************************

.param f_scale='cap_scale*z_scale*z_scale'
.param c_scale='z_scale/cap_scale'
.param x_scale='z_scale/phi_scale'
.param y_scale='z_scale/theta_scale'
.param mt_scale='theta_scale/z_scale/ly/ly'
.param mp_scale='phi_scale/z_scale/lx/lx'

* mass = m = bm
* density = 2330 kg/m^3
.param mass='2330*lx*ly*lz'

* squeeze film damping coefficient = c
* Ks = fitting factor for square plate = 0.425
* Use Lx as longer side of plate
* assume damping independent of position
.param damp='0.425*viscosity*lx*ly*ly/z0/z0/z0'

* scaled moment about x-axis or y-axis = J
.param moment='mass/12'

* scaled damping coefficient for moment about x-axis or y-axis = B
.param z_damp='bf_z*damp'
.param theta_damp='bf_theta*damp'
.param phi_damp='bf_phi*damp'

* torsional spring constant about x-axis = ktheta
.param ktheta='kz*lky*lky/ly/ly'

* torsional spring constant about y-axis = kphi
.param kphi='kz*lx*lx/1x/1x'

* gravitational force
.param fg='z_scale*9.8*mass'

* External forces for testing circuit
.param f_ext='0.0'
.param mphi_ext='0.0'
.param mtheta_ext='0.0'

*******************************************************
*********** MAIN CIRCUIT **********************
*******************************************************

* Sum of forces and moments
v_z_ext fz fat4_z f_ext
v_theta_ext mtheta m4_theta mtheta_ext
v_phi_ext mphi m4_phi mphi_ext

************************* mechanical system *********************
* 
* Mechanical subcircuit models a second-order system (mass-spring damper)
* subckt nodes: x1 <force node> <displacement node> mech
* input parameters: pm=mass, pb=damping factor, pk=spring constant
* 
* xz fz dz mech pm=mass pb=z_damp pk=kz pscale=z_scale
xtheta mtheta theta mech
+ pm=moment pb=theta_damp pk=theta_pscale=theta_scale
xphi mphi phi mech pm=moment pb=phi_damp pk=kphi pscale=phi_scale

************** sensor positions z1, z2, z3, z4 ***************
* 
* | y ~
* | |
* | |
* |
* | -------
* |
* | z2 z1 |
* |
* | |
* | theta rotation about x-axis
* | z3 z4 | phi rotation about y-axis
* |
* Use right-hand rule for rotation direction
in general: $z_i = z + L_y \theta + L_x \phi$

*Cs1 - output $v(31)$
$cs1_ref = 29$ $31 cref$
$x_{s1} 31 30 fs1_z ms1_theta ms1_phi 0$
+ $dz \theta \phi ppc xc=s1_xc yc=s1_yc zco=z0 xw=s1_xw yw=s1_yw$

*Cs2 - output $v(32)$
$cs2_ref = 29$ $32 cref$
$x_{s2} 32 30 fs2_z fs1_z ms2_theta ms1_theta ms2_phi ms1_phi$
+ $dz \theta \phi ppc xc=s2_xc yc=s2_yc zco=z0 xw=s2_xw yw=s2_yw$

*Cs3 - output $v(33)$
$cs3_ref = 29$ $33 cref$
$x_{s3} 33 30 fs3_z fs2_z ms3_theta ms2_theta ms3_phi ms2_phi$
+ $dz \theta \phi ppc xc=s3_xc yc=s3_yc zco=z0 xw=s3_xw yw=s3_yw$

*Cs4 - output $v(34)$
$cs4_ref = 29$ $34 cref$
$x_{s4} 34 30 fs4_z fs3_z ms4_theta ms3_theta ms4_phi ms3_phi$
+ $dz \theta \phi ppc xc=s4_xc yc=s4_yc zco=z0 xw=s4_xw yw=s4_yw$

*Parallel-Plate Actuators*

$x_{at1} 61 30 fat1_z fab1_z mat1_theta mat1_phi mab1_phi ms4_phi$
+ $dz \theta \phi ppc xc=at1_xc yc=at1_yc zco=z0t xw=at1_xw yw=at1_yw$
+ $bot_or_top=-1$

$x_{at2} 63 30 fat2_z fat1_z mat2_theta mat1_theta mat2_phi mat1_phi$
+ $dz \theta \phi ppc xc=at2_xc yc=at2_yc zco=z0t xw=at2_xw yw=at2_yw$
+ $bot_or_top=-1$

$x_{at3} 65 30 fat3_z fat2_z mat3_theta mat2_theta mat3_phi mat2_phi$
+ $dz \theta \phi ppc xc=at3_xc yc=at3_yc zco=z0t xw=at3_xw yw=at3_yw$
+ $bot_or_top=-1$

$x_{at4} 67 30 fat4_z fat3_z mat4_theta mat3_theta mat4_phi mat3_phi$
+ dz theta phi ppc xc=at4_xc yc=at4 yc zco=zt xw=at4_xw yw=at4_yw
+ bot_or_top=-1

*************** Timing Circuitry ***************
* Modulation voltages, modulation duty cycle will be small.
* Vm+ = v(29), Vm- = v(28)
* modulation frequency = 50 kHz
vmod1a 71 0 dc 0 pulse(0 0.3 0 .1u .1u 10u 20u)
vmod1b 72 0 dc 0 pulse(0 -.3 10u .1u .1u 10u 20u)
evmod1 29 0 vol='v(71)+v(72)'
evmod2 28 0 vol='v(29)'

* testbed suspension resistance
r_series 28 30 r_flexure
*
* Sample/Hold clocks
* vpp = v_sense(t=clk1)-v_sense(t=clk2)
* actuator output clocked out on clk3
vclk1 clk1 0 dc 0 pulse(0 vdd 2.5u .1u .1u 5u 20u)
vclk2 clk2 0 dc 0 pulse(0 vdd 12.5u .1u .1u 5u 20u)
vclk3 clk3 0 dc 0 pulse(0 vdd 0 .1u .1u 5u 20u)

********** Position-Reference Inputs **********
* Reference position inputs v(39),v(40),v(41),v(42)
vref1 39 0 dc 0 pulse(0 vref_z 200u .1u .1u 5m 10m)
vref2 40 0 dc 0 pulse(0 vref_z 200u .1u .1u 5m 10m)
vref3 41 0 dc 0 pulse(0 vref_z 200u .1u .1u 5m 10m)
vref4 42 0 dc 0 pulse(0 vref_z 200u .1u .1u 5m 10m)

********** Position-Sense Circuitry **********
* Node 61 produces a voltage pulse when z1 is negative, C is large,
* so use top actuators
* Node 62 produces a voltage pulse when z1 is positive, C is small,
* so use bottom actuators
* similar logic holds for the other quadrants
xsense1 31 39 61 62 clk1 clk2 clk3 sensor v_up=v_up0 v_dn=v_dn0
xsense2 32 40 63 64 clk1 clk2 clk3 sensor v_up=v_up0 v_dn=v_dn0
xsense3 33 41 65 66 clk1 clk2 clk3 sensor v_up=v_up0 v_dn=v_dn0
xsense4 34 42 67 68 clk1 clk2 clk3 sensor v_up=v_up0 v_dn=v_dn0

******************* SUBCKT's *******************
Sense ckt

.subckt sensor sense_in ref_in top bottom clk1 clk2 clk3
+ v_up=vdd v_dn=vdd
* Comparators (linear below 10^-15 V)
* Position strobed when Vm+ = -0.3 V, Vm- = 0.3 V
* so if v(1)>v(2), then the plate is below the reference
* and the top actuator is activated

* Unity-gain buffer
* nodes are: sense_in=buffer input, z_buf=buffer output
xbuffer z_buf sense_in buffer vos=6m
ez_in z_buffer 0 z_buf 0 1

* Sample signal
xsamp1 zsamp1 z_buffer clk1 sample
xsamp2 zsamp2 z_buffer clk2 sample

* Instrumentation amplifier
* Vpp = v(zsamp1) - v(samp2)
e_ampl v_pp 0 zsamp1 zsamp2 1

* position comparator
* positive z_hi means plate is above reference
xcomp_pos v_pp ref_in z_hi compare
xcomp_neg ref_in v_pp z_low compare

* latch signal on next sample cycle
xlatch top2 bot2 z_low z_hi clk3 latch

* activate either the top or bottom actuator
* output through second-order smoothing filter to help
* with convergence
e_a_top top3 0 vol='v_up*v(top2)/vdd'
e_a_bot bot3 0 vol='v_dn*v(bot2)/vdd'
xtop top3 top smooth
xbot bot3 bottom smooth
.ends sensor

S/H

.subckt sample out in phi_in
gs1 in out vcr pw1(1) phi_in 0 0.5v,100x 2.0v,1.0
csamp out 0 0.01u
.ic v(out) 0
.ends sample

******************** latch ********************
.subckt latch out_p out_m in_p in_m stb
xnand1 in_p stb 6 nand
xnand2 in_m stb 7 nand
xnand3 6 out_m1 out_p1 nand
xnand4 7 out_p1 out_m1 nand
*
* clean up digital output signals by sending through a comparator
vmids vmid 0 'vdd/2'
xdig_p out_p1 vmid out_p compare cmp_pl=0.025m cmp_pc=0.1n cmp_low=0
xdig_m vmid out_p1 out_m compare cmp_pl=0.025m cmp_pc=0.1n cmp_low=0
.ends latch

******************** comparator ********************
* .subckt compare in_p in_m out_p cmp_pl=0.25m cmp_pc=1n
  + cmp_hi=Vdd cmp_low=Vss
ez_less 1 0 pwl(1) in_p in_m -1u,cmp_low 1u,cmp_hi
rb in_p 0 10
rf in_p 1 1x
cb in_p 0 1f
xsmooth 1 out_p smooth pl=cmp_pl pc=cmp_pc
.ends compare

******************** nand gate ********************
.subckt nand 1 2 n_out
    e_nand n_out1 0 nand(2) 1 0 2 0
    + -2.5 2.5v
    + 0.0 2.5v
    + 0.25 2.4
    + 0.5 2.25
    + 2.0 0.25v
    + 2.25 0.1v
    + 2.5 0.0v
xnout n_out1 n_out smooth
.ends nand

******************** ppc ********************
.subckt ppc 1 2 fz2 fz1 mt2 mt1 mp2 mp1 z_in theta phi
  + xc=0 yc=0 zco=2 xw=1 yw=1 bot_or_top=1
******** fixed scale factors **************
* x_scale = z_scale/phi_scale
* y_scale = z_scale/theta_scale
* f_scale = z_scale*zscale*cap_scale
* c_scale = z_scale/cap_scale
* mt_scale = theta_scale/z_scale/lx/lx
* mp_scale = phi_scale/z_scale/ly/ly

* z_in, zc, and z force (fz) scaled by z_scale
* theta and theta moment (mt) scaled by theta_scale
* phi and phi moment (mp) scaled by phi_scale
* capacitance scaled by cap_scale

* x,y in mks units
* positive force pulls up, negative force pulls down

xcap 1 2 cap 0 tvc
* zc = z +/- Lx theta +/- Ly phi
* "Top" z position will actually be negative. This is compensated by
  * setting bot_or_top=-1 in ppc subckt.
ez zc 0 vol=
  + 'bot_or_top*(v(z_in)+zco*z_scale+yc*y_scale+v(theta)-xc*x_scale+v(phi))'
v_dz zc dzc 'bot_or_top*zco*z_scale'
r_dz dzc 0 ix
ec cap 0 vol='8.854e-12*c_scale*ep*xw*yw/v(zc)'
efz fz2 fz1
  + vol='-(v(cap)*f_scale*(v(1)-v(2))*(v(1)-v(2))/2)/v(zc)'
emt mt2 mt1 fz2 fz1 'yc*mt_scale'
emp mp2 mp1 fz1 fz2 'xc*mp_scale'
.ends

******** Time varying capacitor (tvc) subcircuit ********
* C is connected to nodes 1 and 2.
* C(t) = v(3,4)
.subckt tvc 1 2 3 4

* e1: generate non-linear voltage so, I = d/dt [C(v3-v4) * V]
e1 5 0 vol='v(3,4)*v(1,2)'
* c1: linear capacitance
c1 6 0 cap_scale
* v1: Ammeter to measure current into capacitor
v1 5 6 dc 0
* Drive the current through c1 back into the circuit
f1 1 2 v1 1
.ends tvc

****************************************************************************** smooth
******************************************************************************
.subckt smooth in out pl=0.1m pc=0.4n pr=1k
* second-order smoothing filter
* H(s) = 1/(LC s^2 + RC s + 1)
* damping factor = 0.5 R / sqrt(L/C) = 1
* w_m = 1/sqrt(LC) => 318 kHz (L=.25m, C=1n)
ef_in n1 0 in 0 1
r_in n1 n2 pr
l_in n2 n3 pl
c_in n3 0 pc
e1  out 0 n3 0 1
.ends

****************************************************************************** mech
******************************************************************************
.subckt mech f_in x_out pm=1 pb=1 pk=1 pscale=1
* f=v(f_in), z=v(x_out)
* f comes in scaled up by pscale (in micro Newtons)
* z comes out scaled up by pscale (in microns)
xin f_in force smooth
L1 force xr 'pscale*pm'
r1 xr xinit 'pscale*pb'
c1 xinit 0 '1./pk/pscale'
ez x_out1 0 vol='v(xinit)/pk'
route x_out1 0 1x
ez_clip x_out 0 pwl(1) x_out1 0 -2,-2 2,2
.ends mech

******************************************************************************

* include CMOS unity-gain buffer subcircuit
.include 'buffer.subckt'

****************************************************************************** MODELS
******************************************************************************

* .model diode d level=3 l=9e-6 w=15e-6 cj=5.3e-3 is=1 xw=1e-6
.model diode d

.model mn_4um nmos level=2 capop=0 acm=0
+ vto=0.56 kp=33u gamma=0.55 phi=0.6
+ lambda=0.043 rdc=10.0 rsc=10.0
+ ld=0.22u xj=0.25u tox=500.0e-10 nsub=2.3e+16
+ uo=619.0 ucrit=2.6e+04 uexp=0.106
+ neff=1.000 delta=1.4 nfs=1.38e+12
+ rsh=4.0 pb=0.8
+ cj=4.06e-04 mj=0.443 cjsw=4.44e-10 mjsw=0.291
+ cgdo=2.5e-10 cgso=2.5e-10 cgbo=2.5e-10
+ vmax=6.84e+4
+ nss=1.0e+12 tpg=1.0
*
.model mp_4um pmos level=2
+ vto=-0.56 kp=17u gamma=0.55 phi=0.6
+ lambda=0.046 rdc=100.0 rsc=100.0
+ ld=0.16u xj=0.25u tox=500.0e-10 nsub=0.79e+16
+ uo=257.0 ucrit=2.4e+04 uexp=0.270
+ neff=1.001 delta=0.0 nfs=1.1e+12
+ rsh=4.0 pb=0.71
+ cj=2.30e-04 mj=0.410 cjsw=2.20e-10 mjsw=0.1
+ cgdo=2.5e-10 cgso=2.5e-10 cgbo=2.5e-10
+ vmax=4.50e+4
+ nss=1.0e+12 tpg=-1.0
*
.model mp_8um pmos level=2
+ vto=-0.56 kp=17u gamma=0.55 phi=0.6
+ lambda=0.023 rdc=100.0 rsc=100.0
+ ld=0.16u xj=0.25u tox=500.0e-10 nsub=0.79e+16
+ uo=257.0 ucrit=2.4e+04 uexp=0.270
+ neff=1.001 delta=0.0 nfs=1.1e+12
+ rsh=4.0 pb=0.71
+ cj=2.30e-04 mj=0.410 cjsw=2.20e-10 mjsw=0.1
+ cgdo=2.5e-10 cgso=2.5e-10 cgbo=2.5e-10
+ vmax=4.50e+4
+ nss=1.0e+12 tpg=-1.0
*

************************************************************************************************************
************************************************************************************************************
************************************************************************************************************
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************************************************************************************************************
************************************************************************************************************

* .ic
+ v(dz)='z_ic*z_scale' v(xz.xinit)='z_ic*kz*z_scale'
+ v(phi)='phi_ic*phi_scale' v(xphi.xinit)='phi_ic*kphi*phi_scale'
+ v(theta)='theta_ic*theta_scale'
+ v(xtheta.xinit) = 'theta_ic*ktheta*theta_scale'
+ v(zz.xr) = 'z_ic*kz*z_scale'
+ v(xphi.xr) = 'phi_ic*kphi*phi_scale'
+ v(xtheta.xr) = 'theta_ic*ktheta*theta_scale'
+ v(xsense1.6) = vdd v(xsense1.7) = vdd
+ v(xsense2.6) = vdd v(xsense2.7) = vdd
+ v(xsense3.6) = vdd v(xsense3.7) = vdd
+ v(xsense4.6) = vdd v(xsense4.7) = vdd
+ v(61) = vdd v(62) = 0 v(63) = vdd v(64) = 0 v(65) = vdd v(66) = 0 v(67) = vdd v(68) = 0
+ v(70) = 0

.options acct
+ chgtol = 1e-16 absi = 1e-15 absv = 1e-9
+ dvdtt = 0 imax = 20 rmin = 1e-12
+ lvltim = 3 post
+ probe ingold = 1 co = 132

.tran 1u 1m uic

.print v(fz) v(mphi) v(mtheta) v(dz) v(phi) v(theta) v(30)
.print v(fab1_z) v(fab2_z) v(fab3_z) v(fab4_z)
+ v(fat1_z) v(fat2_z) v(fat3_z) v(fat4_z)
.print v(31) v(32) v(33) v(34) v(fsi1_z) v(fsi2_z) v(fsi3_z) v(fsi4_z)
.print v(x_s1.dzc) v(x_s2.dzc) v(x_s3.dzc) v(x_s4.dzc)
+ v(xsense1.v_pp) v(xsense2.v_pp) v(xsense3.v_pp) v(xsense4.v_pp)

.probe v(fz) v(mphi) v(mtheta)
.probe v(dz) v(phi) v(theta)
.probe v(fsi1_z) v(fsi2_z) v(fsi3_z) v(fsi4_z)
.probe v(fab1_z) v(fab2_z) v(fab3_z) v(fab4_z)
.probe v(fat1_z) v(fat2_z) v(fat3_z) v(fat4_z)
.probe v(x_s1.dzc) v(x_s2.dzc) v(x_s3.dzc) v(x_s4.dzc)
*.probe v(x_at1.dzc) v(x_at2.dzc) v(x_at3.dzc) v(x_at4.dzc)
*.probe v(x_ab1.dzc) v(x_ab2.dzc) v(x_ab3.dzc) v(x_ab4.dzc)
.probe v(30) v(31) v(32) v(33) v(34)
.probe v(61) v(63) v(65) v(67)
.probe v(xsense1.v_pp) v(xsense2.v_pp) v(xsense3.v_pp) v(xsense4.v_pp)
.end
Appendix C

MICS Fabrication Process

Information in the appendices (and elsewhere in this thesis) will be accessible on the World Wide Web (WWW) through a hypertext viewer, such as Mosaic, by specifying the Universal Resource Locator (URL) for the Berkeley Sensor & Actuator Center home page, “http://nitride.eecs.berkeley.edu”. From that location, browse to find the link to my research information (look for “Gary Fedder”). Good luck!

The following listing is the process flow for the Modular Integration of CMOS and Polysilicon Microstructures, called “MICS”. This flow reflects the status of the MICS process when the integrated-testbed system was fabricated, in the fall of 1993. Up-to-date information about MICS is available from the Berkeley Sensor & Actuator Center. Notes are included with the process outline to document the results from the integrated-testbed run. We have included dates with the flow to give an idea of the time it takes to finish a microstructure process; this run took a little over two months to complete.

MICS BACKEND PROCESS (3 SENSOR POLY)
Version 2.0
(08-27-93)

J. Bustillo, G. K. Fedder, C. T.-C. Nguyen, and R. T. Howe

1 or 2 um substrate gap, 2um thickness, In Situ Doped poly-Si

0.0-30.0 standard Baseline CMOS through and including Contact Etch
-----------------------------------------------
31.0 TiN/TiSi2 Formation - Wed Sept 22 1993
-----------------------------------------------

31.1 a) 20 sec 25/1 HF dip just before titanium metallization
          b) measure PSG oxide loss
31.2 Titanium Metallization: target = 350A
   CPA: pressure = 20 mTorr Ar, power = 2 kW,
   track speed = 60 cm/s
   Ti thickness on as200 = 200-285A (thinner than expected)
4-point probe on Ti monitor 1 (over bare Si): 37 ohm/sq
4-point probe on Ti monitor 2 (over oxide): 84 ohm/sq

31.3 RTA for TiN / TiSix Formation
   Heatpulse1: time = 30 sec, temp. = 600 C, flow = 2 slpm N2
   Wafer ends up silver, instead of usual golden color after anneal.
4-point probe on Ti monitor 1 (over bare Si): 14 ohm/sq

31.4 Self Aligned Ti Strip
   a) Soak wafers in 3:1 NH4OH:H2O2 for 12 min, agitated
   b) check for lack of continuity in field region
   c) add 5 min if field not clear

31.5 Check for field Ti shorts using I-V probe

31.6 RTA for TiSi2 and Rc reduction
   Heatpulse1: time = 30 sec, temp. 850 C, flow = 2 slpm N2
4-point probe on Ti monitor 1 (over bare Si): 5 ohm/sq

31.7 Titanium Nitride deposition: target = 650A
   CPA: p = 20 mTorr (Ar/N2=50/50), Pdc = 2 kW, speed = 30 cm/s
   TiN thickness measured with as200 = 200A
   (thinner than expected)
   inspect: some source contacts on cmos30-3 are gold/brown,
   whereas all other contacts are white/gold.
   No graininess.
4-point probe on Ti monitor 1 (over bare Si): 5 ohm/sq
4-point probe on TiN monitor 3 (over bare Si): 20 kohm/sq

31.8 TiN Anneal
   SVANNEAL: tylan14, 20min @ 600C in N2 (15 min ramp from 400C)
   2 hr ramp down to 375C
   inspect: no graininess, contacts are maize/gold
4-point probe on Ti monitor 1 (over bare Si): 5 ohm/sq

32.0 Tungsten Metallization: target = 5000-6000 A total

** option 1: (available in the Microlab and used for cmos30-2)
32.1 First tungsten deposition - Thu Sept 23 1993
CPA, 2.0kW, 20mT (Ar=100%), 16 cm/min

32.2 First tungsten stress relief anneal
RTA: 30sec @ 900C in Ar

32.3 Second tungsten deposition
CPA, 2.0kW, 20mT (Ar=100%), 16 cm/min

32.4 Second tungsten stress relief anneal
RTA: 30sec @ 900C in Ar
inspect: film quality is specular, no graininess in contacts.
4-point probe on Ti monitor 1 (over bare Si): 0.4 ohm/sq

** option 2: (preferred process due to reduced film stress)

CVD: hydrogen reduction process at Stanford CIM

32.1 Tungsten deposition
a) nucleation layer: SiH4 reduction (Tf=1000A)
b) bulk deposition: H2 reduction (Tf=5000A)

33.0 Metal Photo Mask: CMF (emulsion-cf)
a) Photo Module 1.0: thick g-line PR
b) align to POLY-CPG

34.0 Tungsten / Titanium Nitride Etch

34.1 Etch Module 1.0: Tungsten Etch

34.2 Etch inspect:
a) should see oxide color
b) test for lack of continuity in the field
c) check for stringers at gate poly vernier and TX gates

nanospec: field tox after W etch, in angstroms
T R B L C mean sigma

cmos30-2: 12202 11855 11930 12066 11590 -1 11929 +/- 231

34.3 PR strip: a) module 3.0 - no SP clean!
b) PRS-2000, 10 min, at 50C (needed)
c) acetone soak (if needed) (didn’t need)

35.0 Sintering and Test:
35.1 Acetone rinse for 30 min, DI rinse, blow dry (didn't do this)

35.2 SINTV: tylan14, 400 C for 20 min. in forming gas. (used SINTV instead of SINT400, because of higher forming gas flow. This may help inhibit tungsten oxidation while loading/unloading tube)

35.3 CMOS device testing of Vt's, and contacts (N+, P+, CPG)

36.0 Std. Tungsten clean: Acetone rinse for 30 min. + DI rinse in sink7. Blow dry with N2 gun. Also, clean NITCTRL1 and NITCTRL2 in sink6. (didn't do this, instead used:
mti: acetone strip program ran twice to clean wafers
sink8: DI rinse to 12 Mohm)

37.0 CMOS Passivation - Tue Sep 28 1993

37.1 LTO Deposition: tylan20, VDOLTOC, target = 3500-5000 A
Flows (sccm): SiH4 = 60, PH3 = 0, O2 = 90
Temp = 400 C, pressure = 300 mT
time = 25 min (review previous DR on wand)
Include NITCTRL1 and NITCTRL2 and a tox ctrl.
nanospec: passivation PSG thickness, in angstroms
T R B L C mean sigma
NITCTRL1: 4598 4697 4482 4448 4558 -> 4557 +/- 98
inspect: lots of ~1um hillocks have formed on tungsten

37.2 RTA LTO Densification
Heatpulse1: time = 30 sec, temp = 900 C, flow = 2.0 slpm Ar
nanospec: passivation PSG thickness, in angstroms
T R B L C mean sigma
NITCTRL1: 4476 4592 4343 4364 4444 -> 4444 +/- 99
nanospec: oxide thickness in field
cmos30-2: 16778 16448 16640 16766 16533 -> 16633 +/- 144

37.3 Low Stress Nitride Deposition:
tylan8, BSL0W.1, target=1750 A
Flows (sccm): DCS = 100, NH3 = 25, T = 835 C, P = 140 mT
time = 54 min (review previous DR on wand)
Include NITCTRL1 (not NITCTRL2) and thickness ctrls. (Si).
nanospec, prog2 R.I. =2.2: passivation nitride thickness
38.0 Inter CMOS-structure Contact Mask: SNT (chrome-df)
- Wed Sep 29 1993
  a) Photo Module: 1.0: thick g-line PR
  b) align to PLY-CPG

39.0 Nitride Passivation Etch - Thu Sep 30 1993
Etch Module 2.0: Nitride Etch
(had to use tegal instead of lam1, which was down)
tegal: 150mT, 200W, 80 sccm SF6, 1min 45sec etch
nanospec: oxide thickness in field left

40.0 Oxide Passivation Etch
a) Etch Module 4.0: Oxide Etch
b) check for continuity in CMOS gate poly
It took 2 min to etch.

41.0 PR strip: see module 1.0

42.0 uStructure Poly1 Deposition: target = 3000 A

42.1 Standard clean: a) sink6: SP clean, DI rinse
  b) 10 sec 10:1 HF dip, DI rinse
  (reduced dip time to avoid undercutting PSG)
  (used 15 sec 5:1 BHF dip instead)
  inspect: Exposed tungsten pads for contact testing
etched away in the pirahna.

42.2 Phosphorous-doped polysilicon deposition:
tylan16, DOPLY16A
  time = 1hr 50min (check DR on wand), temp.= 610 C +/- 6 C,
P = 375 mT, SiH4 = 100 sccm, PH3 = 1.0 sccm
Include etching controls: PLY1CTRL1, PLY1CTRL2
nanospec: SP1 polysilicon thickness

43.0 uStructure Poly1 Mask: SP1 (emulsion-cf) - Fri Oct 1 1993
a) Photo Module 2.0: standard i-line PR
(I used 2um g-line PR)
b) align to SNT layer

44.0 Poly1 Etch

Etch Module 3.0: Poly Etch
7sec SF6, 36sec C12 + 10sec overetch C12
nanospec, prog2 R.I.=2.2: nitride thickness left

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45.0 PR strip: see module 1.0
(include PSG1CTRL1 and PSG1CTRL2)

46.0 Sacrificial PSG Deposition: - Mon Oct 4 1993

46.1 Standard clean: a) sink6: SP clean, DI rinse

46.2 Sacrificial PSG Deposition: tylan20, VDOLTOC, target = 2 um
Flows (sccm): SiH4 = 60, PH3 = 10.3, O2 = 90,
time: 2 hrs (check DR on wand), p=300mT, T=450C
Include etching controls: PSG1CTRL1 (near load), PSG1CTRL3, and PSG2CTRL2 (near pump)
nanospec: sacrificial PSG1 thickness

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47.0 RTA for Sacrificial PSG Densification
Heatpulse1: time = 30 sec, temp = 900 C, flow = 2.0 slpm Ar
(also do PSG1CTRLs)
nanospec: densified sacrificial PSG1 thickness

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48.0 Dimple Photo Mask: SD1 (same as SD2) (chrome-df)
a) Photo Module 2.0: standard i-line PR
(used 1um g-line instead)
b) align to SP1 layer

49.0 Dimple Formation
Timed wet etch in 5:1 BHF. (Check E.R. with PSG TW)
2min 20sec, fresh 5:1 BHF
target dimple depth = 1.0um (or half the SACOX thickness)
inspect: Dimples present. Can’t measure since there’s
no process monitor. Color looks OK (not like poly).

50.0 PR strip: see module 1.0

51.0 uStructure Anchor Photo Mask: SG1 (chrome-df) - Tue Oct 5 1993
a) Photo Module 1.0: thick g-line PR
b) align to SP1 layer

52.0 Thick Oxide Etch
a) Etch Module 4.0: Oxide Etch
b) check for continuity in uStructural Poly1
   Etch took 3 min 30 sec
   inspect: contacts are white/green/rose, depending on wafer position, iv shows conduction between 250 to 1.5kohm

53.0 PR strip: see module 1.0

54.0 uStructure Poly2 Deposition: - Wed Oct 6 1993

54.1 Standard clean: a) sink6: SP clean, DI rinse
                         b) 10 sec 10:1 HF dip, DI rinse
                         (reduced dip time due to exposed PSG)

54.2 uStructure Poly2 Deposition -
   tylan16, D0PLY16A, target=2.0um,
   time = 12 hrs (check DR on wand), temp.= 610 C +/- 6 C,
   p= 375 mT, SiH4 = 100 sccm, PH3 = 1.0 sccm
   Include etching controls: PLY2CTRL1, PLY2CTRL2
   tylan16 was inadvertently acked at 9 hrs 18 min dep time
   I decided to pull wafers out at this time.
   nanospec: SP2 polysilicon thickness
   T R B L C mean sigma
   PLY2CTRL1: 16085 16445 16024 16052 16048 -> 16131 +/- 177

55.0 PSG Oxide Mask Deposition - target = 0.5 um
   tylan20, VD0LT0C
   Flows (sccm): SiH4 = 60, PH3 = 10.3, O2 = 90, p=300mT, T=450C
   time = 25 min (check DR on wand)
   Include etching controls: PSG2CTRL1 and PSG2CTRL2
   nanospec: PSG thickness (non-erodible mask for SP2 etch)
   T R B L C mean sigma
   PSG2CTRL1: 4681 4625 4384 4660 4564 -> 4583 +/- 120
56.0 RTA Polysilicon stress relief anneal  
   Heatpulse: time = 60 sec, temp = 900 C, flow = 2.0 slpm Ar  
   inspect: poly looks uniform, no bubbles

57.0 uStructure Poly2 Mask: SP2 (emulsion-cf)  
   a) Photo Module 2.0: standard i-line PR (must use i-line)  
   b) align to SP1 layer

58.0 Oxide Etch  
   Etch Module 4.0: Oxide Etch  
   59 sec to endpoint + 15 sec overetch  
   inspect: I was worried about the 1um lines, since  
   they looked eroded to 0.5um due to the illusion of PR  
   over the oxide mask. It turns out the lines  
   were fine. There was still PR over the larger  
   oxide areas so I went ahead with the lam4 etch on faith.

59.0 Structural Poly2 Etch - Thu Oct 7 1993  
   Etch Module 3.0: Poly Etch  
   7 sec SF6, 4 min Cl2 + 1 min 20 sec overetch  
   inspect: 1um lines look fine, poly stringers etched.  
   nanospec: sacrificial PSG1 thickness left  
   T C B L R mean sigma  
   PSG1CTRL1: 21579 21670 21307 21026 20897 -> 21296  
   PSG1CTRL3: 22051 22382 22347 21549 21683 -> 22002

60.0 uStructural Planarization - Fri Oct 8 1993

60.1 Standard clean: a) sink8: SP clean, DI rinse  
   b) sink6: SP clean, DI rinse

60.2 Planarization 1st Dielectric (PLAD1)  
   PSG Deposition: tylan20, VDOLT0C, target = 0.7um  
   Flows (sccm): SiH4 = 60, PH3 = 10.3, O2 = 90,  
   time = 39 min (check DR on wand), P=300mT, T=450C  
   include PSG1CTRL1 through PSG1CTRL3  
   nanospec: pre-SOG PSG thickness  
   T C B L R mean sigma  
   PLAD1CTRL1: 7352 7297 7219 7253 7072 -> 7239 +/- 106
60.3 Planarization 2nd Dielectric (PLAD2) - 10/08/93
SOG Application: Allied Signal Accuglass 512
warmed to ambient for 60min prior to use.
a) dehydration bake at 120C (approx 60min)
   a) 1st coat: spinner1, 3000 rpm, 15 sec
b) hot plate bakes: 1 min @ 90C, 1 min @ 150C, 1 min @ 250C
c) 2nd coat: spinner1, 3000 rpm, 15 sec
d) hot plate bakes: 1 min @ 90C, 1 min @ 150C, 1 min @ 250C

nanospec: SOG index of refraction (Nf) and thickness (Tf)

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60.4 SOG cure: tylan14, SVANNEAL, 60 min at 425C in N2
   (10' ramp up, 5' stab, 60' cure, 10' ramp dwm, 400C idle)
nanospec: SOG index of refraction (Nf) and thickness (Tf)

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<tr>
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<td>8423</td>
<td>8401</td>
<td>8446 -&gt; 8423 / 69</td>
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60.5 SOG Etch Back: Etch Module 5.0 - Mon Oct 11 1993

SOG Etch Back
Technics-C Plasma Etcher

| P (mT) | 260 (non-regulated) |
| RF (W)  | 100 |
| SF6 (sccm) | 13 (cf = 0.28) |
| He (sccm)  | 21 (cf = 1.46) |
| time (min) | 5 |

* Note: Due to the across-wafer nonuniformity of this system,
   rotate wafers 180 degrees after half the etch time.
nanospec: oxide/SOG thickness after etchback

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PSG loss during EB = 7239 - 4860 = 2379A  ER = 476 A/min
SOG loss during EB = 8367 - 2371 = 5996A  ER = 1199 A/min

61.0 Sacrificial PSG2 Deposition: target = 2 um - Thu Oct 14 1993

61.1 Standard clean: a) sink6: SP clean, DI rinse
61.2 Sacrificial PSG2 Deposition:
tylan20, VDOLT0C, target = 2 um
Flows (scm): SiH4 = 60, PH3 = 10.3, O2 = 90,
time = 2 hrs (check DR on wand), P=300mT, T=450C
Include etching controls: PSG3CTRL1 and PSG3CTRL2
inspect: all wafers look fine, some small 1um PSG "bubbles"
in field, probably there from before dep.
comb finger gaps look clear, can see PSG sidewalls

62.0 Sacrificial PSG2 Densification
Heatpulse1: time = 30 sec, temp = 900 C, flow = 2.0 slpm Ar
(also include PSG1CTRLs and PSG3CTRLs)
inspect: same bubbles in field, comb finger gaps are now dark
on all wafers. All wafers have brown streaks in field,
where the SOG still exists. The streaks are radial
out from the center, from the SOG spin. This brown
color did not show up until after the RTA.
Occasional trenches had long cracks in the SOG.
nanospec: densified sacrificial PSG2 thickness
T R B L C mean sigma
PSG3CTRL1: 20192 19983 19570 20214 19627 -> 19917 +/- 305
PSG1CTRL1: 50253 49833 48501 50356 48288 -> 49446 +/- 983
PSG1CTRL3: 50817 49603 48655 50987 48724 -> 49757 +/- 1111

63.0 Dimple Photo Mask: SD3 (chrome-df) - Mon Oct 18 1993
a) Photo Module 1.0: double thick g-line PR (2um-thick)
b) align to SP2 layer

64.0 Dimple Formation
Timed wet etch in 5:1 BHF. 2 min 20 sec (Check E.R. with PSG TW)
target dimple depth = 1.0um (or half the PSG2 thickness)
nanospec: sacrificial PSG2 thickness for dimples (after etch)
T R B L C mean sigma
PSG3CTRL1: 10899 11037 10937 11577 10256 -> 10941 +/- 470
so dimple depth is about 19917 - 10941 = 8976 A

64a.0 Back Side PSG etch (this is not a "standard" MICS process step)
a) Spin on 2um g-line PR, hardbake
b) 14 min, 5:1 BHF etch (until backside dewets in water)

65.0 PR strip: see module 1.0

66.0 uStructure Anchor Photo Mask: SG2 (chrome-df) - Tue Oct 19 1993
a) Photo Module 3.0: 4-times (4um) thickness g-line PR
b) align to SP2 layer

67.0 Thick Oxide Etch - PSG2
a) Etch Module 4.0: Oxide Etch
b) check for continuity in uStructural Poly2
etch time = 6 min 30 sec
rotate wafers 180 deg after each 1 min etch
inspect: after 5 min etch, most contacts are etched to
white, however, small SG2 contacts have extra SOG.
The SOG creates round contacts with residual oxide in
corners. After 6 min total etch, contacts on all but
side dies are clear and conducting on iv.
Check SP2-SP1 contacts at this time - they're ok.

68.0 PR strip: see module 1.0

69.0 uStructure Poly3 Deposition: - Wed Oct 20 1993

69.1 Standard clean: a) sink6: SP clean, DI rinse
b) 15 sec 10:1 HF dip, DI rinse

69.2 uStructure Poly3 Deposition -
tylan16, DOPLY16A, target=1.0um
time = 6 hrs (check DR on wand), temp. = 610 C +/- 6 C,
P = 375 mT, SiH4 = 100 sccm, PH3 = 1.0 sccm
Include etching controls: PLY3CTRL1, PLY3CTRL2
nanospec: second structural polysilicon thickness, PLY3
T R B L C mean sigma
PLY3CTRL1: 11799 12104 11664 11697 12049 -> 11863 +/- 202

70.0 PSG Oxide Mask Deposition - target = 0.5 um - Mon Nov 1 1993
tylan20, VD0LT0C
Flows (sccm): SiH4 = 60, PH3 = 10.3, O2 = 90, P=300mT, T=450C
time = 20 min (check DR on wand)
Include etching controls: PSG4CTRL1 and PSG4CTRL2
nanospec: PSG4 thickness (non-erodible mask for PLY3 etch)
T R B L C mean sigma
PSG4CTRL1: 3503 3522 3419 3471 3444 -> 3472 +/- 42

71.0 uStructure Poly3 Definition Mask: SP3 (emulsion-cf)
- Tue Nov 2 1993
a) Photo Module 3.0: 4X thickness g-line PR
(required because of poor planarization)
(used 3um-thick g-line PR instead)
b) align to SP2 layer

72.0 Oxide Etch
a) Etch Module 4.0: Oxide Etch
   45 sec to endpt + 15 sec overetch
b) 15 sec. 5:1 BHF dip in sink 8 to remove oxide stringers

73.0 Structural Poly3 Etch
a) Etch Module 3.0: Poly Etch
   7 sec SF6, 170 sec Cl2 to endpt (C), 120 sec overetch
b) Poly3 stringer removal - technics-c
   SF6 =13.0, He = 21.0, O2 = 0.0, power = 100 W
   etch time = 0.5 min., inspect, rotate wafers 180 deg.
   etch for additional time = 0.5 min. (if needed)
   (etch required because of poor planarization)
   inspect: the SF6 etch for stringer removal of cmos30-2
   was actually done after the SREL lithography step 77.1
   no poly3 stringers after 30 sec SF6 etch

74.0 PR strip: see module 2.0

75.0 RTA PSG Densification and Polysilicon stress relief anneal
   Heatpulse1: time = 30 sec, temp = 900 C, flow = 2.0 slpm Ar
   two RTA cycles, so total time is 60 sec

76.0 Back Side Etch (not done on cmos30-2)

76.1 PR spin, no exposure, hard bake: 60 min @ 120C

76.2 repeat 16.2

76.3 Etch back side of wafers as follows:
a) dip off oxide in BHF (PSG3 oxide mask)
b) wet etch poly-Si (structural poly3)
c) dip oxide off in BHF (sacrificial PSG2)
d) wet etch poly-Si (structural poly2)
e) dip oxide off in BHF (sacrificial PSG oxide)
f) wet etch poly-Si (ground-plane poly1)
g) etch nitride in Tegal
h) etch oxide off in BHF (oxide over W and over capacitor)
i) wet etch poly-Si (capacitor poly)
j) etch oxide in BHF (capacitor oxide)
k) wet etch poly-Si (CMOS gate poly)
1) final dip in BHF until back dewets

76.4 PR strip: see module 1.0

77.0 uStructure Release

77.1 SREL photolithography (optional, and done for cmos30-2)
   a) Photo Module 2.0: std g-line PR
   b) align to SP2

77.2 a) Wet etch: 10:1 BHF (sink8), or Mon Nov 8 1993
      concentrated (49%) HF (sink7) - if SREL not used.
      (agitate slowly, time: as required)
      For cmos30-2, we used 35 min, 5:1 BHF release in total
      darkness (covered with opaque bell jar) to inhibit
      electrochemical etching of polysilicon pads.
      b) DI rinse
      c) SP clean, 10min
      We did pirahna clean for 1hr.
      d) DI rinse

77.3 Dry: Fri Nov 12 1993
   a) methol soak
   b) supercritical CO2 drying

frontend:  S. Fang/K. Voros
backend:  J. Bustillo/G. Fedder/C. Nguyen

Backend MICS_2poly alignment strategy:

<table>
<thead>
<tr>
<th>mask</th>
<th>type</th>
<th>name</th>
<th>aligns to</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>METAL</td>
<td>emulsion-cf</td>
<td>CMF</td>
<td>POLY_CPG</td>
<td>2.0µm g-line</td>
</tr>
<tr>
<td>uS CONTACT</td>
<td>chrome-df</td>
<td>SNT</td>
<td>CPG</td>
<td>2.0µm g-line</td>
</tr>
<tr>
<td>uS POLY1</td>
<td>emulsion-cf</td>
<td>SP1</td>
<td>SNT</td>
<td>std i-line</td>
</tr>
<tr>
<td>DIMPLE</td>
<td>chrome-df</td>
<td>SD2/SD1</td>
<td>SP1</td>
<td>std i-line</td>
</tr>
<tr>
<td>uS ANCHOR</td>
<td>chrome-df</td>
<td>SG1</td>
<td>SP1</td>
<td>2.0µm g-line</td>
</tr>
<tr>
<td>uS POLY2</td>
<td>emulsion-cf</td>
<td>SP2</td>
<td>SP1</td>
<td>std i-line</td>
</tr>
<tr>
<td>DIMPLE2</td>
<td>chrome-df</td>
<td>SD3</td>
<td>SP2</td>
<td>2.0µm g-line</td>
</tr>
</tbody>
</table>
assuming 2.0um uStructural design rules, alignment should be within +/-1.0um a-w and +/-0.5um at ctr.

--------------------------------------------------

MICS Backend
Plasma/RIE Etch Modules
version 2.0

-----------------------------------------------

1.0 Tungsten Etch
-----------------------------------------------

Tegal 701 RIE

SF6 = 80 sccm
Pin = 200 Watts
p = 200 mT
T = 40 C (temperature set at chiller)

*Note: Set forward power using Bird meter.
Use matching network in manual mode.

SF6 etch will also clear underlying TiN over field.

-----------------------------------------------

2.0 Nitride Etch
-----------------------------------------------

Lam1 AutoEtch 490 Plasma Etch

step 2 step 4

<table>
<thead>
<tr>
<th></th>
<th>step 2</th>
<th>step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (mT)</td>
<td>375</td>
<td>300</td>
</tr>
<tr>
<td>RF (W)</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>gap (cm)</td>
<td>1.35</td>
<td>2.50</td>
</tr>
<tr>
<td>O2 (sccm)</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>He (sccm)</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>SF6 (sccm)</td>
<td>175</td>
<td>50</td>
</tr>
<tr>
<td>time endpt</td>
<td>10% 0/E</td>
<td></td>
</tr>
</tbody>
</table>
3.0 Polysilicon Etch

Lam4 Rainbow Plasma Etch
(standard recipe #400)

<table>
<thead>
<tr>
<th></th>
<th>step 5</th>
<th>step 7</th>
<th>step 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (mT)</td>
<td>400</td>
<td>425</td>
<td>425</td>
</tr>
<tr>
<td>RF (W)</td>
<td>200</td>
<td>275</td>
<td>275</td>
</tr>
<tr>
<td>gap (cm)</td>
<td>1.00</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Cl2 (sccm)</td>
<td>-</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>He (sccm)</td>
<td>-</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>SF6 (sccm)</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>time</td>
<td>7 sec</td>
<td>endpt</td>
<td>0/E</td>
</tr>
<tr>
<td>CH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>delay</td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>norm sec</td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>norm val</td>
<td></td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>trigger</td>
<td></td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>%</td>
<td></td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

* Note: HBr etch of structural poly will passivate sidewalls and may leave "grass" when thick poly is etched. Use the chlorinated etch process for SP layers.

4.0 Oxide Etch

Lam2 AutoEtch 590 Plasma Etch

<table>
<thead>
<tr>
<th></th>
<th>step 2</th>
<th>step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (Torr)</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>RF (W)</td>
<td>850</td>
<td>700</td>
</tr>
<tr>
<td>gap (cm)</td>
<td>0.38</td>
<td>0.40</td>
</tr>
<tr>
<td>He (sccm)</td>
<td>120</td>
<td>110</td>
</tr>
<tr>
<td>CHF3 (sccm)</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>CF4 (sccm)</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>time</td>
<td>endpt</td>
<td>0/E</td>
</tr>
</tbody>
</table>

* Note: Overetching SP masking oxide w/ step #4 can cause polymerization and subsequent micromasking of SP layer during the SP etch,
or difficulty making poly-poly contacts at SNT, SG1, or SG2. Any overetching should be done with an extension of step #2.

Suggest excluding the overetch step (#4) except for CMOS contacts (metal-silicon contacts not affected).

----------------------------------------------------------------------------------
MICS Backend
Photolithography Modules
----------------------------------------------------------------------------------

1.0 2X Thick g-line PR (CMF and SD1 layers)
----------------------------------------------------------------------------------

1 Dehydrate: VWR Oven for 30 min. @ 120 C
----------------------------------------------------------------------------------

2 HMDS vapor prime
----------------------------------------------------------------------------------

3 Spin g-line resist: KTI 820 (prog. 9),
   target PR = 1.8-2.0um
   30sec @ 1500rpm,
   soft bake: 60sec @ 120 C
----------------------------------------------------------------------------------

4 Expose: GCA2 6200-10X G-line wafer stepper
   or
   GCA1 6200-10X I-line wafer stepper
   4.1 Focus/Exposure Matrix
   4.2 calculate appropriate P/E for thicker PR
   4.3 align to appropriate layer
----------------------------------------------------------------------------------

5 Post exposure bake: 60sec @ 120 C (prog. 4)
----------------------------------------------------------------------------------

6 Develop in MTI-Omnichuck:
   Kodak 932 2:1, 60 seconds. (prog. 1)
----------------------------------------------------------------------------------

7 Develop Inspect (five sites)
----------------------------------------------------------------------------------

8 Descum in Technics-C: 02 plasma, 50 Watts, 1 minute.
----------------------------------------------------------------------------------

9 Hard bake in VWR oven: 60min @ 120 C convection
----------------------------------------------------------------------------------
2.0 Standard i-line PR (SNT, SP1, SG1, SP2, and SREL layers)

1. Dehydrate: VWR Oven for 30 min. @ 120 C

2. HMDS: Vapor prime

   25 sec @ 4600 RPM, softbake: 60 sec @ 90 C

4. Expose: GCA1 6200-10X I-line wafer stepper, align to appropriate layer

5. Post Exposure Bake on Eaton: 60 secs. @ 120 C

6. Develop in MTI-Omnichuck:
   Std. Olin-Hunt I-line (prog. 70)

7. Develop Inspect (five sites)

8. Descum in Technics-C: O2 plasma, 50 Watts, 1 minute.

9. Hard bake in VWR oven: 120 C, 60 min. convection

3.0 4X Thick g-line PR (SG2 and SP3 masks)

1. Dehydrate: VWR Oven for 30 min. @ 120 C

2. HMDS vapor prime

3. Spin g-line resist: KTI 820 (prog. 9),
   target PR = 1.8-2.0um
   30sec @ 1500rpm,
   soft bake: 60sec @ 120 C
   ** repeat to get 3.6-4.0 um **

4. Expose: GCA2 6200-10X G-line wafer stepper
   (larger depth of focus required)
4.1 Focus/Exposure Matrix
4.2 calculate appropriate F/E for thicker PR
4.3 align to appropriate layer

5 Post exposure bake: 60sec @ 120 C (prog. 4)

6 Develop in MTI-Omnichuck:
   Kodak 932 2:1, 60 seconds. (prog. 1)

7 Develop Inspect (five sites)

8 Descum in Technics-C: O2 plasma, 50 Watts, 1 minute.

9 Hard bake in VWR oven: 60min @ 120 C convection

=================================================================================

Standard PR Strip Modules
=================================================================================

1.0 PR strip: a) technics-c, 300W, 02, 10 min
               b) sink8: 10 min SP clean, DI rinse

2.0 PR strip: a) sink8: 10 min SP clean, DI rinse
               (used after SP2 or SP3 etch)

3.0 PR strip: a) technics-c, 300W, 02, 10 min - only!
               (used after tungsten etch)

=================================================================================