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NC STATE UNIVERSITY

Monolithic Copper Integrated Circuitry supporting Multi-layer Micro-Electro-Mechanical Systems

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1 *Perform Mechanical Characterization and Establish Design Guidelines for future CuMEMS Designers*

An important step in the design of MEMS devices within a new process is the accurate characterization of strain fields and inherent properties in the mechanical material. Differences between thermal expansion coefficients of stacked thin films are a primary source of stresses across the films. These associated strain fields can cause bending and buckling of the mechanical layers once the sacrificial oxides are removed. Another important property to characterize is the Young's modulus of the copper thin films. Used in calculating resonance frequencies for many MEMS devices, including mirror pistons, accurate determination of the Young's modulus for these films is required to calculate device characteristics such as switching speeds.

Measurement Techniques

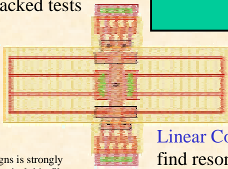
- Active --> Optical Blur, Micrometer Reticle
- Passive --> Monochromatic Interferometry

Upper-layer Metals become Mechanical

- Sacrificial etch --> "free" structures
- Replicated tests on each mechanical layer
- Intermediate lift-off --> stacked tests

Extracted Parameters

- Latent Stress *(ε)*
- Young's Modulus *(E)*
- Poisson's Ratio *(P)*
- Residual Strain



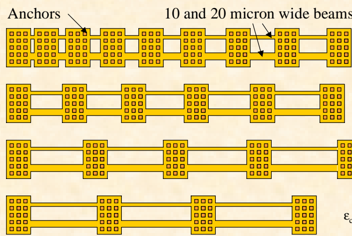
Linear Comb Actuators

find resonance --> *E*

The resonance frequency of many MEMS designs is strongly correlated to the Young's modulus of the mechanical thin film. For future MEMS design in copper, the Young's modulus of the films must be determined. The procedure chosen uses an electrostatic actuator known as a comb motor. An AC signal is supplied to the comb fingers and the shuttle is held at a ground potential. The electrostatic attractions of the shuttle to the comb fingers cause the shuttle to resonate with the AC signal. The drive frequency is swept and the resonance is detected under a light microscope and CCD camera.

Doubly-clamped Beams

critical length --> compressive strain fields in metal



$$\varepsilon_c = \frac{\pi^2 h^2}{3L^2}$$

Double clamped beams with identical cross sectional areas have a critical length, above which the beams begin to bend and buckle. The transition beyond this length is abrupt, therefore easily observed among an array of beams with identical cross sectional areas varying only in length. At that critical length, the associated compressive strain in the beam is given above. The beams vary in length from 5 to 200 microns, allowing the determination of strain fields between 0.132 and 8.225×10^{-5}.

Guckel rings are, likewise, used to determine any stress that is tensile.

Guckel Rings

- interferometric measurement of bending
- determination of tensile strain fields

Objective:

Enhance UMC Copper usefulness, and deliver to the design community a process suitable for monolithic implementation of complex microsystems (aka, MEMS) and complete systems-on-a-chip (SoC)

Copper-based Advantages:

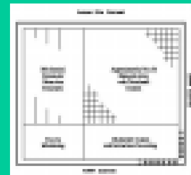
Unprecedented VLSI-MEMS seamless integration for microsystem array development in a standard process
(no lateral separation of definition areas, as in M^{3}S, iMEMS, or SmartMUMPs)

Simultaneous multi-level capability in both mechanics and wiring
(MEMS are typically either poly-Si w/ single metal, or Single laminated stack of Al-dielectric-Al)

Potential for smallest-ever electromechanical elements
(ala damascene planarity and low-stress vias)

CuMEMS

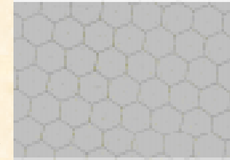
Three Pronged Approach:
Chip layout includes three main sections:



3 *Microsystem Demonstrator: Arrayable Smart Sensor/Actuator Elements*

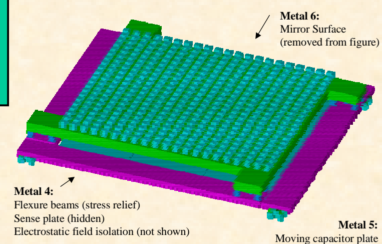
"Smart" Micromirrors (surface: Metal 6)

- Circuitry directly under each element
- CC-ramp capacitive position sense
- Compare & calibrate to master or ext. ref.
- D2A HV drive & Mechanical failure detect

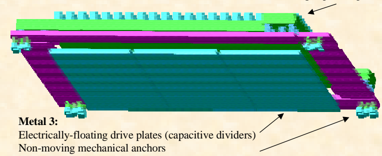


High Fill-factor Array

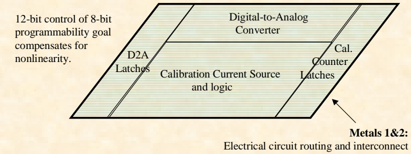
Element Stackup:



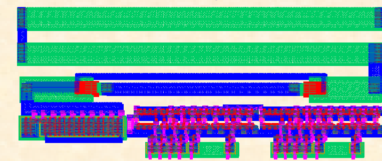
Electrostatic potential, driven across the air gap and a series stabilizing capacitor, acts to pull the mirror downward. Flexure beams provide a restoring force.



12-bit control of 8-bit programmability goal compensates for nonlinearity.



D2A Converter w/ 20V range & 12-bit resolution



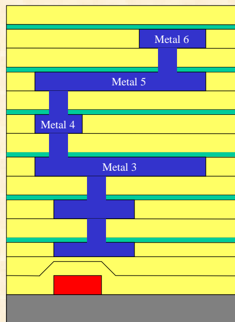
System Application

- Analog height (phase) + Binary tilt (amplitude)
- Precise free-space wavefront modulation
- Beam steering and adaptive optics

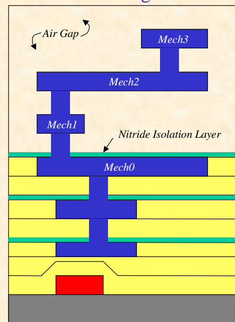
2 *Develop Post-processing Recipe for Controlled Release of Surface Micromachines*

Micromachining involves the release of material structures by selectively etching chosen sacrificial materials (dielectric and nitride) from what become the electromechanical layers (metal). As the number of released metal layers is increased, so too is the potential complexity of the resulting mechanical system. With only one (1) mechanical layer, designers limited to building deformable beams and membranes (just as in bulk micromachining). With two (2) mechanical layers, fixed hinges and axles can be created. Three (3) layers allows for free (horizontal or vertical) translation of those two-layer devices (e.g., for a crank-arm). And four (4) mechanical layers allows for translatable gears on shared axles.

As Delivered from UMC



After Multistage Release



Demonstrator Release Recipe for 3/3 (Mechanical/Non) Layer Tradeoff

Step #0 - Sample Preparation - Cleaning
Wash sample first with acetone, then with methanol.
Place on a hot plate to dry for 10 minutes.
Methanol will remove any residue left from the acetone rinse.

Step #1 - Remove the Nitride Cap (Etch stop: Oxide Cap)
[illegible] nitride removed with a timed wet etch using hot phosphoric acid (85%).

Step #2 - Remove Oxide Cap (Etch Stop: Nitride 6)
[illegible] silicon oxide removed with a timed wet etch using HF acid (49%)
73 seconds at room temperature.

Step #3 - Remove the Nitride 6 Layer (Etch Stop: SiO2 6)
1000A nitride removed with a timed wet etch using hot phosphoric acid (85%).

Step #4 - Remove the SiO2 6 Layer, *Releasing Metal 6 (Mech3)*
[illegible] silicon oxide removed with a timed wet etch using HF acid (49%)
312 seconds at room temperature. (Etch Stop: Nitride 5)

Step #5 - Remove the Nitride 5 Layer (Etch Stop: SiO2 5)
[illegible] nitride removed with a timed wet etch using hot phosphoric acid (85%).

Step #6 - Remove the SiO2 5 Layer, *Releasing Metal 5 (Mech2)*
[illegible] silicon oxide removed with a timed wet etch using HF acid (49%)
312 seconds at room temperature. (Etch Stop: Nitride 4)

Step #7 - Remove the Nitride 4 Layer (Etch Stop: SiO2 4)
[illegible] nitride removed with a timed wet etch using hot phosphoric acid (85%).

Step #8 - Remove the SiO2 4 Layer, *Releasing Metal 4 (Mech1)*
[illegible] silicon oxide removed with a timed wet etch using HF acid (49%)
174 seconds at room temperature. (Etch Stop: Nitride 3)

Process Monitor Structures *(not shown)*

- Under-etch (intersecting cavities)
- Over-etch and Material Selectivity
- Stiction (cantilever beams)

Variable-Depth Cu Release Recipe

- alternating materials act as etch stops
- tunable design tradeoff of layers
  mechanical complexity *vs.*
  non-mechanical wiring density

In comparison to common surface micromachined polysilicon, the electrodeposited Copper process has potential to provide greater design complexity, lower stress (and therefore lower drive voltages), and better VLSI integration.

Typical polySi-based MEMS post-release mirror flatness