Microfabrication of Heterogeneous, Optimized Compliant Mechanisms

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Fig. 1. Single-material Heatuator with selective doping on one arm (G.K. Ananthasuresh)
Compliant Mechanisms

- Monolithic micromachined structures
- Devices that deform flexibly to achieve useful work when actuated

Examples:
- Compliant overrunning clutches offer high torque and minimizes problems with assembly
- Micro-compliant pantographs can amplify force and motion at the micro scale

Fig. 2. Micro-compliant clutches (BYU)

Fig. 3. Micro-compliant pantographs (BYU)
Micro-electro-mechanical Systems (MEMS)

- Structures that have static or moveable parts with some dimensions on the micron scale
- Devices combining electrical and mechanical components
- Transducers: devices that converts input energy of one form into output energy of another

Question: What if MEMS are made to contain properties of compliant mechanisms?

Fig. 4. Electro-thermal linear micromotor using v-beams (J. Maloney – U.Maryland)
Electro-thermal-compliant (ETC) Actuators

- MEMS devices that are based on joule heating-induced thermal expansion
- With input of electrical power yields large forces and deflections
- Micro-mechanical structures that perform micro-manipulation and micro-positioning tasks

Fig. 5. Heatuator: electro-thermal in-plane actuation – composed of a single material (J. Maloney – U.Maryland)
Two-material ETC Mechanism

Fig. 6. Single material crimping mechanism acting as a micro-gripper embedded with ETC actuation (G.K. Ananthasuresh)

Fig. 7. (a) Basic model of two material topology optimized compliant mechanism, (b) simulation showing displacement
Flow Chart of Manufacturing Process for Two-material Compliant MEMS

MEMS: Actuators

Compliant Mechanisms and Electro-thermal Actuation

Designing Method

Need New Fabrication Process for Heterogeneous Device

Bulk Micro-machining

Electroplating

Release Structure with Wet Etching
Creating the Cavity With Bulk Micro-machining

- Silicon on Insulator wafer
- Deposition of nitride using LPCVD and then spin photoresist (positive)
- Transfer desired pattern onto the photoresist with chromium mask (ultra-violet light exposure)
- Plasma etching of silicon nitride layer
- Remove the photoresist
- Wet chemical etching of silicon with KOH solution
- Remove silicon nitride layer
- Electron beam evaporation of seed layer onto silicon

Fig. 8. Cavity created on SOI wafer with lithography, etching and e-beam techniques
Electroplating Theory

- Potential exists between cathode and ions in gold solution
- External voltage creates ion concentration gradient across diffusion region
- Reduction of SOI wafer at cathode with gold ions

Fig. 9. Electrochemical Cell

Fig. 10. Electroplating model
Electroplating Gold

Adjusting parameters for obtaining *high-resolution morphology*
- Current density
- Electroplated area
- Temperature
- Forced convective techniques

Solutions to Non-uniform Gold Deposits

1. Reduce the current density applied
2. Maximize the reaction kinetics of electroplating
   - Control electroplated area
   - Stir
   - Heat

Fig. 11
Morphology of Gold Deposits

Reason for electroplating uniform gold deposits: the **performance** of ETC devices depends on **electrical**, **mechanical**, and **thermal** boundary conditions.

Significance of **low current density**: smoother gold surface, uniform-size gold deposits → **better morphology**.
Optimal Electroplating Conditions

Lower current density works best:

1. produces less hydrogen bubbles
2. keeps the pH of the gold solution constant
3. maintains high current efficiency that is lost from the hydrogen production

- 2mA → yielded about 14 µm/hr plating rates of gold deposits
- Above 2mA current applications → yielded greater plating rates but wider ranges of deposition rates
- Below 2mA → not enough energy to drive chemical reaction

Current Density Vs. Deposition Rate

![Graph showing the relationship between current density (mA/cm²) and deposition rate (µm/hr). The theoretical and experimental data are represented by different lines. The graph indicates a positive correlation between current density and deposition rate.]
Wet Chemical Etching

- Back-side etching of silicon substrate with KOH and black wax

Results: ~15 hour etching at about 0.56 μm/min
A Novel Masking Method

- Melt black wax on glass
- Apply pressure to press silicon wafer into black wax
- Cover wafer with black wax except for the area of interest
- Immerse Glass substrate attached with silicon wafer into KOH solution
- Remove bubbles off etched surface (e.g. stirring)

Fig. 16. Masking with Black Wax
Future Work: Electro-thermal Actuation

- Complete microfabrication of compliant microactuator
- Electro-thermal-compliant microactuation by applying voltage
- Determine maximum actuator displacements and forces
- Analyze current and temperature distribution, and thermal properties (e.g. conduction, convection, and radiation) in the two-material structure

![Diagram](Fig. 16)

![Diagram](Fig. 17)

Heatuators
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