NICKEL-PLATED THERMAL ACTUATOR WITH ELECTROSTATIC LATCH

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Abstract: An innovative parallel gap actuator is developed and demonstrated based on a two-layer nickel plating process. It combines thermal actuation for large stroke movement with electrostatic actuation for the latch. Moreover, the electrostatic actuation is capable to hold this position with very low power requirements.

Keywords: thermal actuator, electroplating, latch

INTRODUCTION

This paper describes a unique new type of switch with a built-in electrical latching system. The chosen setup avoids the need for constant power drive of a thermal actuator [1-3], as well as the high voltage required for electrostatic actuation over large distances [4]. It relies on the fact that the electrostatic force for small gaps is inversely proportional to the separation distance, while this separation distance at the same time is dependent on the heat induced deflection. The operation principle is the following: the actuator is turned on by supplying current to an asymmetric beam, which starts to deflect due to the resistive Joule losses. A connected parallel plate capacitor is at the same time biased at a relatively low voltage, insufficient for pull-in. However, due to the Joule induced deflection, the pull-in criterion comes within reach, and the actuator is locked at a low voltage, even after switching off the heating current, i.e. it behaves as a zero power electrical latch.

OPERATION

The manufactured actuator is shown in operation in figure 1. Parts (A) and (B) form a well-known type of thermal actuator [1]. (C) is the two-plate capacitor, with one fixed plate (at the right), and one movable electrode, connected to the actuator beams A and B.

Figure 1. Actuator operation. Left: starting position, right: actuated position.

If a voltage is applied to contacts (D) and (E), the thermal actuators will move the movable plate of the capacitor towards the fixed plate. If the two plates are in close contact, the voltage over the capacitor can now create sufficient pull-in force to keep the plate in position due to electrostatic collapse, with thermal actuation turned off.

DESIGN

Several layouts are investigated, as shown in figure 2. The two main types are a 'folded' (1) and a 'linear' (2) actuator.

In operation, three forces can act upon the structure: thermal expansion force, spring force and electrostatic pull-in force.

Finite element simulations and subsequent experiments show that the thermal expansion force is high enough to allow the moving capacitor plate to travel the gap with the fixed capacitor plate.

Figure 2. Actuator layouts. Freestanding parts are in black, fixed parts in grey. Versions with the gap B between moving and fixed capacitor plates of 10, 20 and 40 μm in rest were made. The arm length A of the thermal actuator in the folded type was 1300 or 1700 μm . Thin freestanding parts have a width of 40 μm , thick parts a width of 150 μm . Both types were also manufactured on a $\frac{1}{2}$ scale.

The spring force is determined by finite element simulations. Table 1 shows the spring force on a fully collapsed actuator (moving and fixed capacitor plates touching). The electrostatic force must exceed this spring force to keep the actuator in the collapsed position.

Table 1. Spring force as a function of gap width and actuator arm length.

Gap width [μm]	Arm length [μm]	Spring force [N]
Folded actuator		
40	1300	0.016
20	1300	0.008
10	1300	0.004
40	1700	0.01
20	1700	0.005
10	1700	0.0024
Linear actuator		
40	1300	0.12
20	1300	0.06
10	1300	0.03

The finished actuators are coated with a 50 nm parylene dielectric layer. This prevents direct electrical contact between the moving and fixed capacitor plates. Parylene was chosen for its large dielectric strength, 275 V/μm, allowing a large voltage over a very thin layer. It can be deposited as a conformal coating on vertical sidewalls and other structures [5].

The electrostatic force between the capacitor plates is given by [6]:

$$F_c = \frac{\epsilon_0 \epsilon_r A V^2}{2d^2} \quad (1)$$

where A is the surface of the capacitor plates, V the voltage over the plates and d the distance between the plates. The relative permittivity is 3.15 for the parylene used. The thickness of the actuator is 50 μm. When the actuator is in collapse, with 100 nm of parylene dielectric between the plates, the formula yields $11 \times 10^{-5} \text{ N/V}^2$ for the folded type and $8 \times 10^{-5} \text{ N/V}^2$ for the linear type.

This means none of the folded actuator designs have to exceed the dielectric strength of parylene in order to overcome the spring force. For the linear type, actuators with a gap size of 40 μm would require a minimum voltage of 39 V, which exceeds the dielectric strength of a 100 nm parylene layer. These actuators are only included for testing purposes.

CONSTRUCTION

The actuators are deposited using a nickel electroplating process and a two-layer photo-definable polymer mold. This allows us to build freestanding structures. Figure 3 illustrates the different process steps.

Figure 3. Process flow. From left to right, top to bottom: 1) first patterned polymer layer on oxidized Si substrate, 2) Ti-Cu-Ti seed layer, 3) second patterned polymer layer, 4) Ni electroplating, 5) polymer and seed layer removal.

The 3" silicon substrates are oxidized at 1000 °C in a dry oxygen atmosphere for 1 hour. The oxidation is done to prevent the formation of Schottky-junctions between the metal actuators and the silicon substrate, which would result in unwanted side-effects (such as a parasitic junction capacitance).

The polymer used is EpoClad, an epoxy photoresist. This material has several advantages. It has good adhesion to both silicon oxide and the Ti in the seed layer. After spinning, it has less than 4% thickness variation over an entire 3" wafer. Lastly, it shows fewer tendencies to form microcracks than SU-8, a comparable material that is often used as a structural MEMS material or a mold for electroplating. The standard processing steps for EpoClad as advised by the manufacturer [7] are shown in table 2.

The relaxation step after spin coating is possible due to the less volatile solvent in EpoClad. It causes some reflow, resulting in a smoother top surface and no edge bead. This is especially important for the top polymer layer, since it has to cover an already patterned bottom layer, with a thickness of 20 μm. The top layer has a thickness of 50 μm. Spinning speeds are 4000 rpm for the bottom layer, and 2000 rpm for the top layer.

Table 2. EpoClad processing steps.

Processing step	Remarks
Substrate preparation	Oven, 200 °C for 30 min
Spin coating	60 sec, 2000 rpm for 50 μm
Relaxation	15 min
Prebake	50/90/120 °C for 5/5/10 min
Relaxation	30 min
Exposure	350-750 mJ/cm ²
Post exposure bake	50/90/110 °C for 5/5/10 min
Development	
Hardbake	120-140 °C for 60 min

Several adaptations had to be made to this standard process:

- Adhesion was found to be a problem with the oxidized substrates, with the EpoClad layers retracting from the wafer perimeter during prebake. This was solved by extending the 90 °C phase to 15 minutes and lowering the temperature of the 120 °C phase to 110 °C.
- Due to the lower temperature during prebake, the EpoClad layers showed a tendency for sticking to the photolithography masks. This was solved by extending the (now) 110 °C step during prebake from 10 to 150 min.
- The hardbake step was omitted completely, resulting in less crosslinking and subsequent easier mold removal. Hardbake is normally done to improve mechanical strength, reduce stress and remove microcracks, but these were not a problem in this application.

A sputtered Ti-Cu-Ti seed layer (20 nm Ti, 200 nm Cu, 20 nm Ti) was deposited before plating [8]. The Ti offers good adhesion to the EpoClad mold, the oxidized substrate and the Cu. The Cu adheres well to Ti and Ni, but not to the polymer, and forms a good electrical contact and conductor for the plating process. Ti and Cu are sputtered in the same run; therefore the Ti also serves to protect the Cu from oxidation.

Sputtering was done with a Balzers BAE370 RF magnetron sputtering device. The sputtering parameters were: 400 W, 20 seconds for Ti and 200 W, 2 minutes for Cu. Both were sputtered in an argon atmosphere of 2×10^{-3} mbar.

Figure 4 shows the use of this seed layer in more detail.

Figure 4. From left to right, top to bottom: 1) Cu layer sandwiched between two Ti layers for good adhesion to EpoClad polymer and oxidized silicon substrate, 2) upper Ti layer etched in HF to expose copper, 3) Ni plating on top of exposed Cu.

Immediately before plating, the exposed upper Ti layer is removed by a HF dip (10% HF solution for 30 seconds). The oxide layer that might have formed on the Cu is removed with an acetic acid dip (10% acetic acid solution for 30 seconds). This results in a clean starting surface for the Ni electroplating.

Nickel DC electroplating was chosen for the actuators. The plating bath used is a commercial Nikal PC-3 solution. Sodium lauryl sulfate and

saccharin are added to improve wetting and reduce residual stress, respectively. This bath is very stable and can be used multiple times without degradation or yield loss. The nickel electrode is placed behind a filter to prevent nickel particles contaminating the solution.

A plating current density of 40 mA/cm² is used, resulting in a total current of 80 mA with a plating voltage of less than 2 V. The observed plating speed is 20 µm/hour. Figure 5 shows the result of this plating process.

After plating, the mold is removed in several steps. First, the top layer of EpoClad and the upper Ti layer are removed with a plasma etch. Oxygen plasma is preferred, but a small amount of SF₆ will greatly increase the etch rate (100 W plasma power, 150 mTorr plasma pressure, 30 sccm O₂ flow and 4 sccm SF₆ flow). The Cu is removed with a FeCl₃ solution. The lower Ti layer and the bottom EpoClad layer are again removed in oxygen-SF₆ plasma. Underetching the freestanding structures this way takes approximately 3 hours.

Plasma etching was chosen for three reasons:

- No stiction problems as is the case with wet etch. The freestanding structures never come in contact with fluids.
- Efficient removal and high selectivity for EpoClad and Ti, leaving the Ni structures largely unaffected, even with large etching times.
- No high temperatures required that might cause further crosslinking in the bottom mold layer.

It was found that during seed layer sputtering, the substrate would heat up enough to cause some hardbaking in the bottom EpoClad layer. This causes a clear difference in etch rates for both layers.

Figure 5. Focused ion beam photograph of a finished actuator. Visible are parts of the capacitor plates (fixed on the left, moving on the right). Notice the well-defined sharp edges.

Finally, the now freestanding actuators are coated with a 50 nm parylene layer.

RESULTS

The finished actuators show a breakdown voltage of 20 – 30 V in collapse, indicating that the parylene is indeed deposited as a 50 nm layer on vertical sidewalls.

The thermal actuation over a distance of up to 40 μm requires ± 0.5 A of current, depending on the size and type of the actuator.

Electrostatic latching is achieved, but with higher voltages than predicted. It was 15 V for the folded type actuator, with a gap width of 20 μm and arm length of 1700 μm . According to calculations, it should have been ± 7 V. This is caused by the vertical sides of the capacitor plates not being completely flat. Since the electrostatic force is dependent on $1/d^2$, with d the distance between the capacitor plates, roughness and/or waviness can have an important influence. Additionally, the thermal actuation was found to induce plastic deformation in the actuators over time, increasing the gap width and the voltage needed to overcome the spring force.

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