A CMOS Micromachined Gripper Array with On-Chip Optical Detection

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Abstract—This paper presents the design, fabrication, and characterization of CMOS micromachined grippers with on-chip optical detection. The CMOS MEMS fabrication features a combination of metal wet etch and sacrificial polysilicon etch for structural release. The fabricated microstructure contains metal and dielectric layers, plus a polysilicon heater for electrothermal actuation. Optical detection is provided by the photo detectors placed beneath the gripping sites. Dynamic characterization of a 200 µm-long microgripper shows a measured thermal time constant of 53 µs. For an applied power of 6 mW, one arm of the gripper produces a 3.6-µm in-plane displacement and a 1.6-µm out-of-plane displacement. The corresponding maximum heater temperature is 220°C, while the temperature elevation at the tip is only 28°C. The measured sensitivity and dynamic range of the photo detector are 1.42 V/lux-sec and 48.5 dB, respectively.

I. INTRODUCTION

The development of miniaturized systems for manipulating biological samples in aqueous solutions is an important topic and challenge for bioMEMS research. Conventional biomanipulation tools such as optical tweezers, although powerful, may rely on bulky and expensive setups; besides, manipulation of multiple samples can be difficult for conventional tools and that is where MEMS can play an important role. Micromechanical grippers capable of being activated in aqueous solutions provide an option for biomanipulation. Developed microgrippers in prior work are driven based on the electrostatic force [1-2], thermomechanical effect [3-5], and piezoelectric actuation [6-7], etc. Some of them, such as the electrostatic-type grippers, cannot be operated in physiological solutions because of the compatibility issues in terms of the material and the actuation mechanism. It is highly desirable to incorporate sensing capability into microgrippers such that operation of multiple devices can be simultaneously monitored and even closed-loop controlled. There are few examples of microgrippers with integrated actuation and sensing elements [4-5]. Piezoresistive sensing is mostly employed because of its compatibility with operation in solutions. Other than piezoresistive sensing, optical detection is an option that can be considered for sensing of gripper’s operation. One rare example of this kind is a hybrid system consisting of an electro-discharge machined gripper with optical detection [8] intended for the application of assembling micro-components.

II. DEVICE FABRICATION

The TSMC 0.35 µm two-polysilicon four-metal (2P4M) CMOS process is used for device fabrication. The process flow in figure 2 shows the development of a released microstructure in cross-section. The key for making the microgripper as proposed relies on the use of the double polysilicon layers which are essentially intended for making large capacitors in integrated circuits. After completion of the CMOS foundry process, the passivation on top of the gripper area is removed while the passivation on top of bond pads remains. As shown in figure 2(b), the microgripper sidewalls are formed after the wet etch of those stacked metal layers using a mixed H₂SO₄/H₂O₂ etchant with the dielectric layers for etch protection. Then the microstructure is released by a sacrificial etch of polysilicon.
using the XeF₂ gas as shown in figure 2(c). The polysilicon used for the sacrificial etch is the poly-1 layer, which is below the poly-2 and separated by a thin layer of silicon dioxide. As shown in figure 2, the released microgripper have no exposed conductors such that it is capable of being actuated in solution; in addition, the silicon substrate is covered by dielectric layers as well after the sacrificial polysilicon etch, such that photo detectors can be placed beneath the gripping sites to provide optical feedback during biomanipulation. To remove the passivation remaining on bond pads, a reactive ion etch using the CHF₃/O₂ plasma is performed with a thin Teflon tape to cover the microgrippers at the chip center. The released microgrippers are shown in figure 3.

Figure 2. CMOS micromachining process.

Figure 3. SEM of the fabricated devices.

III. DESIGN

A. Microgripper

The top-view schematic of the electrothermally driven microgripper design in figure 4 shows that the polysilicon (poly-2) heater (44 µm long and 0.8 µm wide) is placed near the base of the microstructure. The cross-sectional view in figure 4 shows the materials that make up the actuated beam include aluminum (metal-1 and metal-2), polysilicon (poly-2), and dielectric layers. Thermal energy produced by the heater is quickly transferred to the overlaying metal layers through the tungsten vias. Since the thermal expansion coefficient of aluminum (~ 25 ppm/°C) is much larger than that of silicon dioxide (~ 0.5 ppm/°C), the actuated beam is expected to displace laterally toward the side containing pure silicon dioxide. Due to the asymmetrical distribution of materials as shown by the beam cross section, the beam can be electrothermally actuated in the out-of-plane direction as well due to the thermal mismatch between metal and dielectric layers. Practically, it is better to produce an upward, rather than a downward motion in the gripper to avoid contact friction with respect to the dielectric layer below. The key issue for design is to cautiously select the necessary metal layers to be placed in the actuated beam, although all four metal layers in the 2P4M CMOS process can be inserted. As aluminum has a much larger thermal expansion coefficient, the desired upward motion can be achieved by placing only the metal-1 and metal-2 without the top metal layers.

The heater and the metal layers are placed inside the actuated beam with a distance of 1.3 µm to the edge. These layers are protected against the attack of wet etch by a dielectric sidewall. However, this sidewall produces a counter bimorph effect against the desired motion. For enhancement of the desired thermomechanical effect, a dielectric portion wider than the sidewall is placed on the other side of the heater, producing an actuated beam width of 5 µm. The gripper is 200-µm long. Produced displacement by the actuated beam is amplified by the extended beam made of pure dielectric layers as shown in figure 4. The long dielectric beam of low thermal conductivity helps to keep a low temperature elevation at the tip during actuation, a
desired feature for biomanipulation. The silicon substrate is used as the common heat sink for all grippers by extending the metal-1 on top of the polysilicon heater into the anchor region and connecting it to the substrate using vias.

A complete electrothermomechanical analysis based on finite-element simulation is performed to obtain the displacement and temperature distribution of the microgripper at a given power. For setting of the thermal boundary condition, the structure includes an extended anchor area whose faraway side patch is assigned as the thermal ground at room temperature. Other than the heat conduction considered in simulation, heat convection has to be considered as well to produce a reasonable temperature distribution in the gripper. As the gripper suspends over the dielectric layer below with a small separation, it is reasonable to assume there is more convection happening at the bottom than through the top and sides of the gripper. The convection coefficient for the top and side patches is set at 25 W/m²°C as for the case of free convection in air. For a fixed coefficient value of 90000 W/m²°C at the bottom, the maximum heater temperature is about 220°C at about 6 mW, close to the measured data as will be shown later. The lateral gripper displacement by simulation is 1.1 µm at 6 mW. Note that the temperature change occurs mostly around the heater as the applied power increases, while the temperature at the tip remains almost unchanged in simulation.

B. Photo Detector

Photodiodes are placed beneath the gripping sites to provide optical feedback of the gripper operation. Two types of p-n junctions inherited in a typical CMOS process, n-well/p-substrate and n+/p-well junctions, are often adopted for realizing photodiodes. Our design adopts the n-well/p-substrate diode, which, in general, provides a better optical response than that of n+/p-well diode due to a wider and deeper depletion region. The disadvantages, however, could be a larger design area and a higher dark current.

The schematic of the detection circuit in figure 5 shows that the photodiode is first reset by the pulsed voltage applied to the M1 transistor, and then the established reverse bias across the photodiode induces the depletion region for sensing. The source voltage of the M1 transistor is pulled down when a photocurrent is produced, and the output signal is obtained when the M3 transistor is activated. The total area of the n-type active region is 65.5 µm², and the perimeter is 52 µm. The photo detector circuit can be simulated in HSpice with the photodiode being represented by a capacitance and a current source. The value of the capacitance is estimated at 49.7 fF by calculation.

IV. EXPERIMENT

The curves in figure 6 show the measured transient responses of the photo detector under luminous flux densities from 0 up to 200 lux at a reset period of 5 ms. The rate of voltage drop due to the dark current is 1.42 V/sec as calculated using the curve of zero lux in figure 6. The dynamic range, defined as the ratio of the maximum sensed signal at saturation over the voltage drop due to dark current, was obtained at 48.5 dB by measurement.

The microgripper displacement was measured by an optical profiler (ZoomSurf 3D, Fogale nanotech) at different heater voltages. The total resistance of the two heaters in series within the two actuated arms was measured simultaneously for calculation of the applied power. Measured values are 6.4 kΩ and 8.33 kΩ at 0 V and 10 V, respectively. The two actuated arms move toward each other as predicted by the finite-element simulation. Figure 7 depicts the measured in-plane and out-of-plane displacements of one actuated arm with respect to the heating power, with maximum values of 3.6 µm and 1.6 µm, respectively, at an applied power of 6 mW. Likewise, the out-of-plane motion is in the upward direction as predicted by simulation.
Temperature distribution of the actuated microgripper was obtained at different heating power by infrared measurement (Infrascope II, Quantum Focus Instruments). The maximum temperature during actuation occurs at where the heater is located. The curves plotted in figure 8 show the measured temperatures at the heater and the tip, respectively, with respect to the applied power. The maximum heater temperature is about 220°C under 6 mW. The curve of the heater temperature is quite linear with a slope of about 25°C/mW. The other curve in the figure shows that the temperature elevation at the tip is only 28°C under 6 mW, much less than that of the heater. The length of the dielectric beam can be extended to further reduce the temperature elevation at the tip.

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The dynamic response of the microgripper was measured by a MEMS motion analyzer. The measured dominant pole frequency is about 3000 Hz, which is equivalent to a thermal time constant of 53 μs.

V. DISCUSSION AND CONCLUSION

This work presents the first attempt on making integrated microgrippers with photo detectors in a conventional 2P4M CMOS process. The CMOS micromachining process features the use of the bottom polysilicon layer as the sacrificial material and the top polysilicon layer as the heater for electrothermal actuation. The high selectivity of the XeF₂ sacrificial etch provides the key to the success of the fabrication. Fabricated microgrippers and photo detectors have no exposed conductor in air, and therefore can be operated in aqueous solution for biomanipulation.

The measured photo detector response provides a resolution close to 8 bits, which is enough for simple binary detection of the gripping operation. The measured leakage current is about 100% larger than the value normally obtained using the same process. One of the reasons can be attributed to the many 90° corners in the non-optimized photodiode layout. The displacement can be further increased by reducing the original actuated beam width of 5 μm by half. The original design is rather conservative in having a 1.3-μm dielectric sidewall for wet etch protection, which consequently causes a wide dielectric portion to be included in the actuated beam in order to produce a larger bimorph effect than the counter effect produced by the sidewall. The temperature elevation at the tip is only 28°C for 6 mW, much less than that of the heater. The length of the dielectric beam can be extended to further reduce the temperature elevation at the tip.

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