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Capacitive flexible force sensor

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Abstract

We have realized a flexible force sensor, composed of four redundant capacitors, the operation of which is based on the measurement of a load-induced capacitance change. We use polyimide both as flexible substrate and as elastic dielectric between two levels of finger-shaped aluminum electrodes. In particular we have developed a technology for realization of polyimide micro-features with gentle slopes to facilitate subsequent metallization processes. Thereby, we could improve step coverage and electrical contacting between the two metallization levels, as well as the mechanical stability of the sensor. The smooth polyimide slopes were obtained by combining lithographic resist-reflow techniques with dry etching procedures. We have electrically characterized the capacitors using an impedance analyzer and obtained a typical force sensitivity of 1-2 fF/N.

Keywords: force sensor; capacitive sensor; flexible sensor ; lithography; polyimide; pattern transfer

1. Introduction

Polymeric microstructures with non-vertical sidewalls have been developed already for devices such as optical lenses [1], microcavities [2], or suspended bridges and cantilevers [3]. Most reported techniques apply to the three-dimensional structuring of photoresist (PR), and do less concern alternative resins such as polyimide (PI), which is commonly used as a dielectric interlayer in integrated circuits [4] or a flexible package material for sensors [5].

Polymeric substrates have shown great promise in flexible force sensors, which have found applications in tactile imagers and artificial skin concepts [6-7], plantar pressure measuring systems for humanoid robots [8] or human gait analysis [9]. The usual compliant film substrates and materials used for these sensors are polydimethylsiloxane (PDMS) [6], parylene-C [10], and PI [8]. Amongst reported polymer-based force and pressure sensors, the most common ones have a capacitive approach, due to numerous advantages when compared to resistive and piezoresistive systems [11].

Our motivation was to develop a batch-type process for PI-based capacitive flexible force sensors, compatible with standard clean room microfabrication. The longer term perspective of our work is to develop a full force measurement system to be applied under the plantar surface of the foot.

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In this paper, we propose two effective methods for the fabrication of angled profile edges in PI, which were exploited to manufacture a flexible capacitive force sensor. The gentle slopes facilitate subsequent metallization processes, electrical contacting between the two metallization levels, as well as the mechanical stability of the sensor. The smooth PI slopes are obtained by combining lithographic resist-reflow techniques [1, 3] with dry etching procedures. We also present the initial electrical characterization of our sensor.

2. Sensor structure and fabrication

Figure 1 illustrates a schematic diagram of the metal electrode parts of our sensor: two levels of finger-like microstructures, which maintain flexibility of the sensor, form four redundant capacitors (*C1-C4*) with common top electrode. Contact pads are designed on the lower metal layer, which is electrically connected to the top layer via a tapered pad. Consequently, mechanical stability of the sensor is maintained and wire bonding on the contact pads is possible, even when the top electrode moves with regard to the bottom electrode.

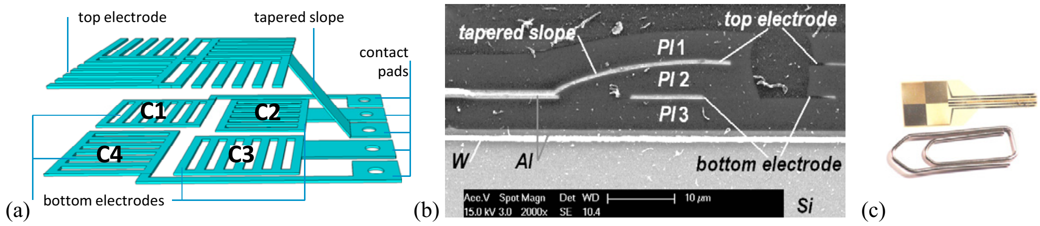

Fig. 1. (a) A conceptual view of the metallic electrode parts of the capacitive structure; (b) SEM cross-section micrograph of the finalized device; (c) flexible sensor released from the silicon support wafer.

The complete sensor is embedded in PI, except for openings kept on the contact pads. Each capacitor has an area of 5 x 5 mm^2, and the thickness of the insulation layer between top and bottom electrode is fixed at 5 μm. The cell deforms under normal force applied, decreasing the spacing between the electrodes and increasing the capacitance value.

The process flow of the sensor is shown in Figure 2. We start by sputtering a 500 nm conductive layer of tungsten, with sacrificial 1μm Al layer (needed for anodic dissolution of the finalized flexible structure from the silicon support), followed by spin-coating the 5 μm layer PI*1* (PI2611, HD Microsystems). The lower 500 nm thick aluminum electrode layer (Al*1*) is sputtered following an oxygen plasma surface activation step and a 50 nm film of Ti adhesive layer. The electrodes are patterned in a dry etch process with Cl_2/BCl_3 chemistry.

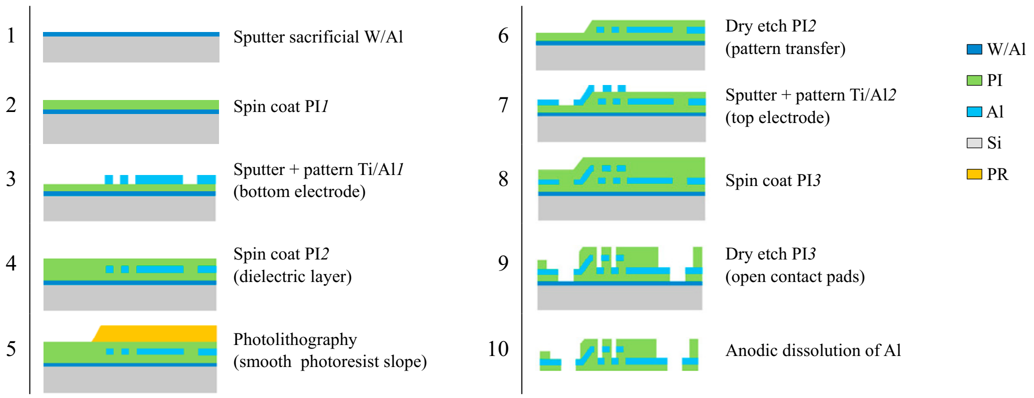

Fig. 2. Process flow for the fabrication of the capacitive sensor.

The 5 μm dielectric layer PI*2* is spin-coated and patterned in such a way, that smooth slopes in PI*2* are obtained. A photolithographic process is used to structure the PR in a tapered shape, followed by an anisotropic plasma etch. Two distinct PRs are tested: (i) AZ ECI 3027 (AZ Electronic Materials), a PR which after exposure and development exhibits oblique sidewall topography; (ii) AZ 9260 (AZ Electronic Materials), a PR with vertical sidewalls, which we melt after the development, on a hotplate at 130 °C for 90 seconds.

The 5 μm thick PR is structured over the layer of PI*2*. Next, the tapered PR pattern is transferred into the PI*2* by an anisotropic oxygen plasma etch. Because of the very poor selectivity of the PR mask with respect to the etched PI*2* layer, the profile of the PR is directly transmitted into the PI*2* substrate.

The tapered slope allows conformal metallization by a 50 nm Ti adhesion layer, followed by a 500 nm Al*2* top electrode layer, which is patterned in dry etch process. The process continues by spin-coating the 5 μm thick PI*3* layer, and deposition and structuring of an amorphous Si mask for defining the contact pad openings during a subsequent oxygen plasma dry etching step. Finally, the structures are released from the rigid Si wafer by anodic dissolution of the sacrificial Al [12].

3. Results

Figure 1(c) shows a sensor obtained after anodic dissolution of the Al layer from the silicon support. Figure 3 are Scanning Electron Microscopy (SEM) graphs showing the smooth PI*2* slope after the PR structuring / dry etching step and after sputtering layer Al*2*, for the two methods proposed. Figure 1(b) is a cross-section SEM graph of the finalized sensor stack.

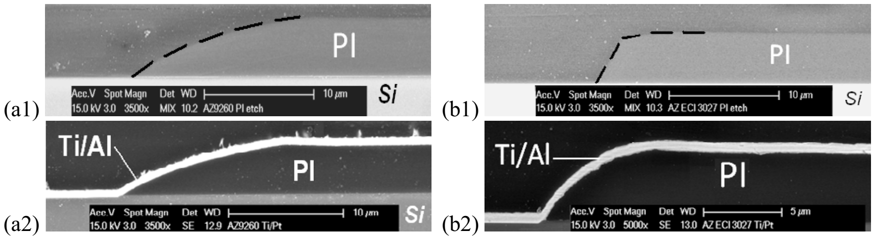

Fig. 3. SEM cross-section micrographs (1) after realization of the smooth slope in PI*2* and (2) after Al*2* metal coverage, for different PR used as an etch mask: (a) AZ ECI 3027, (b) AZ 9260.

For the connection to the measurement system the sensor was attached to a printed circuit board (PCB) with a gold bump bonding technique [13]. Figure 4(b1) shows the electrical characterization of the four unloaded capacitors (*Z1-Z4*) of a single sensor, as measured by an Agilent 4294A impedance analyzer. The initial capacitances were in the range of 110-130 pF, and the four curves are superimposed. We hereby could demonstrate the good performance and feasibility of our microfabrication process. Force sensing experiments were done with the measurement setup shown in Figure 4(a). A self-centering, self-gripping puller with a ball-bearing ended screw was used to compress the force sensor locked in between stiff polymethylmethacrylate (PMMA) blocks and the iLoad Pro Digital load cell (LoadStar Sensors, US) which was used to measure the applied force.

Figure 4(b2) shows the results of the measured capacitance versus applied force in the 0-3 kN range. Both sensor loading and unloading characteristics were obtained, revealing a mechanical hysteresis effect of the dielectric. We find a sensitivity of the sensor $\Delta C/\Delta F \sim$ 1-2 fF/N. From dedicated loading experiments in the lower force range, we find a limit of detection of 100 N.

4. Conclusion

In this paper we have successfully demonstrated a fabrication process of tapered slopes in polyimide, which we have exploited for the realization of capacitive flexible force sensors. Applying a normal force to the sensor revealed high strength and durability, as well as an acceptable limit of detection and sensitivity.

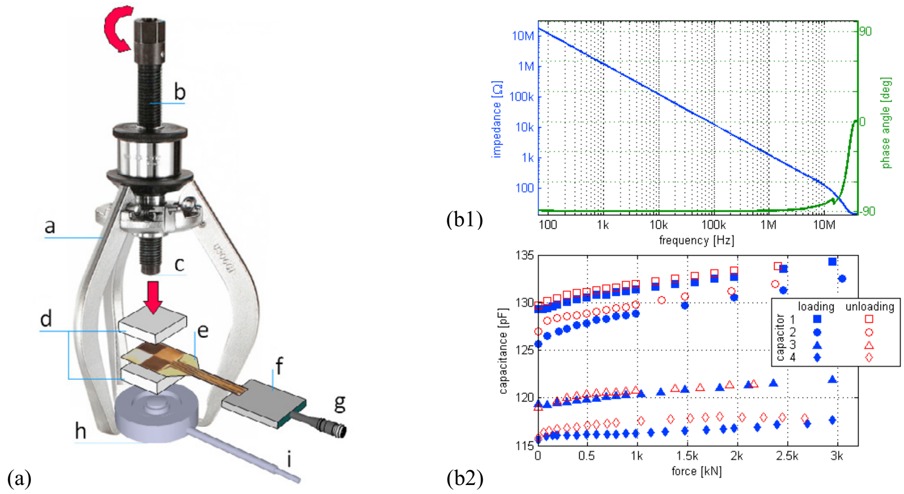

Fig. 4. (a) Experimental setup for testing the force sensor: (a) gripper; (b) screw; (c) bearing; (d) blocks; (e) flexible capacitive force sensor; (f) PCB; (g) connection to impedance analyzer; (h) load cell; (i) connection to a PC; (b1) Impedance and phase angle vs frequency characteristics of the four capacitors of one sensor, *Z1-Z4*; (b2) Measurement results: output capacitance at 2.7 kHz versus applied compressive load for four capacitors during a loading and unloading cycle.

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