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Fabrication, modeling and integration of a silicon technology force sensor in a piezoelectric micro-manipulator

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Abstract

A silicon technology sensor integrated in a micro-gripper is presented in this work. The force sensor consists of a monolithic silicon cantilever based structure. Forces applied on the cantilever are sensed by piezoresistive gauges in the clamping area and the resulting output voltage is measured by a Wheatstone bridge. Scaling of the proposed force sensor is done using analytical and numerical tools. The resulting force sensor enables the measurement of forces ranging from 1 to 600 mN with a resolution of 10 μN. Characterization of force sensors in the laboratory has confirmed the expected range of forces. The former sensor is next integrated in a piezoelectric micro-manipulator called micro-robot on chip (MOC). The aim of this integration is the measurement of handling forces during the manipulation of micro-samples in SEM and room conditions. Results from the characterization of silicon sensors show that a force range from 1 to 600 mN is measured. This range of forces can be adapted to the particular conditions of the MOC micro-manipulator.

Keywords: Force sensors; Micro-manipulator; Silicon technology; Piezoactuator; Precision engineering; Modeling; Micromanipulation; Micromachining

1. Introduction

Force sensors are currently used for many applications. One example is the manipulation of micro-samples in domains so diverse as micro-engineering, biotechnologies or material sciences for instance. There is a real necessity, in the above mentioned fields, to know the handling forces when micro-samples are manipulated in order to avoid their deterioration or damage. A force sensor permits to avoid this kind of problems, making the system more efficient for manipulation tasks. In addition, any control strategy applied to micromanipulation tasks needs information about the handling forces.

Works of Miyazaki [1,2] and Koyano and Sato [3] show results concerning the research on the interaction forces between the sample and the micro-manipulator. Micromanipulation forces are an important issue during the manipulation of the micro-samples. The success and performance of the micro-manipulator depend on the understanding of forces interaction at the micromanipulation scale. A recent work by Sun et al. [4] reports the implementation of a multiaxis capacitive force sensor in an electrostatic micro-actuator for micromanipulation and micro-assembly. Resolving forces are up to 490 μN with a resolution of 0.01 mN in x and 0.24 mN in y directions for a force up to 900 mN (see Sun [4,5]). Shen et al. [6] proposes an in situ PVDF piezoelectric force sensing for a force guided micro-assembly technology. Fung et al. [7] presents also a PVDF force sensing systems applied to micromanipulation and micro-assembly. All these works illustrate quite well the challenges of micro-manipulators having different performances in different domains.

This paper intends to show the potential of the Silicon technology of force sensors in a piezoelectric micro-manipulator, focusing on modeling, fabrication and characterization of a silicon sensor and its integration on a micro-manipulator based on the piezoelectric effect. Section 2 handles with the modeling, fabrication and characterization of the silicon sensor. Section 3 presents the micro-manipulator called micro-robot on chip (MOC). The integration of the silicon sensor on the MOC for sensing tasks is presented in Section 4 followed by conclusions in Section 5.

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2. Silicon force sensors

A silicon technology procedure is utilized for the fabrication of the proposed force sensors. One of the advantages of the silicon technology for sensing tasks is that it is well known. Sensors based on the electromechanical properties of silicon have been used for the last 30 years. In addition, performance of silicon sensors is very high [8]. Gauge factor (GF) for this kind of technology is 50 and the change rate of resistance $\Delta R/R$ is 0.01%. The GF for semiconductors n or p is much more important compared to other technologies such as metallic or serigraphy made gauges. Moreover, this technology is not expensive and is well known. Thus, the fabrication and implementation of a sensor based on silicon technology for micromanipulation tasks seems to be feasible and attractive.

The force sensor proposed in this work consists of a silicon cantilever beam with force sensing elements located closed to the clamping area. The piezoresistive circuit contains a set of piezoresistors in Wheatstone bridge configuration with additional compensation of temperature and offset voltage. Force sensors with different cantilever length (1–3 mm) and thickness (up to 100 μm) are fabricated to cover a wide range of gripping forces. The end of the cantilever beam is utilized in this work as an end-effector. Moreover, optional surface of the gripping area of the cantilever is envisaged to improve localization and handling of samples.

2.1. Fabrication of sensors

A modification of a double sided silicon micromachining process developed for manufacturing of piezoresistive AFM microprobes is utilized to fabricate the force sensors. The fabrication process is schematically illustrated in Fig. 1. A both side polished ⟨1 0 0⟩- oriented, n-type, 1–5 Ω cm silicon wafer undergoes an initial cleaning of 600 nm of thermal oxidation. Future gripping tip area is defined utilizing standard photolithography (Fig. 1a). Next, using anisotropic KOH etching, a set of silicon tips is fabricated (Fig. 1b). A piezoresistive circuit is fabricated at the support of the future cantilever during a standard complementary metal-oxide–semiconductor processing sequence. Boron and phosphorous diffusions create p^+-type and n^+-type regions, serving as connecting diffusion paths and contacts to the substrate (Fig. 1c). Then, the oxide mask is removed and wafers are oxidized to create clean and thin oxide required for piezoresistors. A set of piezoresistors in a Wheatstone bridge configuration are made through boron implantation and post-implantation annealing (Fig. 1d and e). The back side photolithography of the oxide layer followed by deep plasma etching is performed to create mounting cavities (Fig. 1f). Next, back side photolithography of the nitride layer with a corner compensated pattern and deep, anisotropic silicon wet etching in KOH solution is used to create a 15–20 μm thick membrane (Fig. 1g). The front side of the wafer is protected from etching with a nitride layer. In the next step, the front side photolithography followed by deep, anisotropic silicon wet etching in KOH solution is carried out to create depression for mounting pads (Fig. 1h and i). After deposition and photolithography of metal layer (Fig. 1j) the cantilever shape is defined in the membrane by the last photolithography step and dry plasma etching of silicon (Fig. 1k). In the last step the photoresist mask is removed and the force sensor is separated from the wafer (Fig. 1l).

An example of the resulting force sensor is shown in Fig. 2a. The set of 60 blunt tips on the cantilever surface are used to facilitate the gripping task of an object (see Fig. 2b). A deep cavity

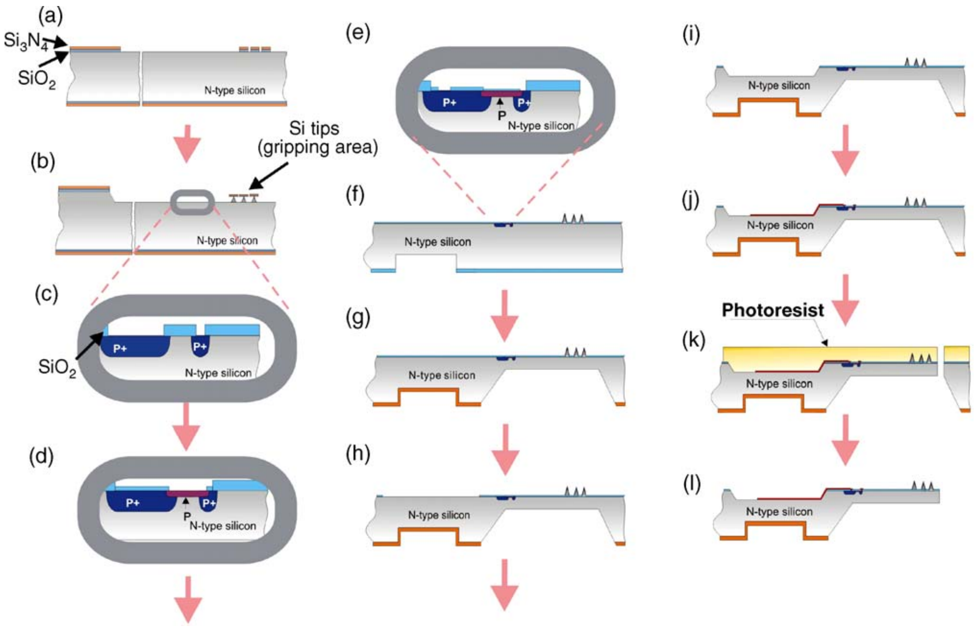

Fig. 1. The fabrication sequence (a) photolithography of Si tips in the gripping area, (b) KOH etching of silicon formation of tips, (c) phosphorous and boron diffusions formation of diffusion paths, (d) boron implantation and annealing—formation of piezoresistors, (e) photolithography of contacts, (f) photolithography of backside mounting cavities, (g) fabrication of silicon membrane (KOH etching), (h) photolithography of depression for contact pads, (i) fabrication of depression for contact pads (KOH etching), (j) deposition and photolithography of metal, (k) photolithography of cantilevers and (l) separation of devices.