A Sidewall Piezoresistive Force Sensor Used in a MEMS Gripper

Tao Chen[1], Liguo Chen[1], Lining Sun[1], Jiachou Wang[1], and Xinxin Li[2]

[1] State Key Laboratory of Robotics and System, Robotics Institute, Harbin Institute of Technology, Harbin 150080, China
{Tao Chen,cht22}@sina.com, {Liguo Chen,clg}@hit.edu.cn,
{Lining Sun,lnsun}@hit.edu.cn,
{Jiachou Wang,jiatao_wang}@163.com
[2] State Key Lab of Transducer Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China
{Xinxin Li,xxli}@mail.sim.ac.cn

Abstract. This work reports the design and development of a MEMS based, piezoresistive sensor for micro-force measurement. Surface and bulk micromachining technology is employed to fabricate the force sensor from single crystal silicon wafer (i.e., no silicon on insulator wafer is used). Boron diffusion process combined with deep reactive ionic etching (DRIE) technique is used to form the side direction force sensors. The force sensor is integrated in a four arms structure MEMS gripper to experimentally verify the performance of the sensor. The resolution of the force sensor is in the micronewton range and, therefore, provides feedback of the forces that dominate the micromanipulation processes. Testing results show that the sensitivity of the piezoresistive sensors is better than 72V/N and the resolution is better than 3μN. Experimental show that it can successfully provide force sensing and play a main role in preventing damage of microparts in micromanipulation and microassembly tasks.

Keywords: MEMS, Microgripper, Sidewall piezoresistive sensor.

1 Introduction

With the development of micromanipulation and microassembly and the miniaturization of the objects to manipulate, particularly efficient, reliable and precise handling strategie are required. Microobjects are hard to manipulate because their different behavior. In order to handle small objects effectively and efficiently under uncertain environment, feedback-sensor is critical in the process of manipulation, and they allow for the controllable actuation with a range and resolution of force and displacement matching the required size scale. Micromanipulation of those objects requires the use of miniaturized tools with end-effectors on the size-scale of the manipulated objects. So the integration of the force sensor in the manipulation tools is a difficult and key technique. MEMS technology allows for the fabrication of such devices that meet these requirements.

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Grippers or tools integrated with piezoresistive force sensors or semiconductor strain-guage sensors have been reported in recent years. Arai F [1] fabricated the micropyramids and the integrated piezoresistive force sensor on the micro end-effector to reduce and control the adhesive force in microgripping tasks. Hybrid gripper designs have been demonstrated in [2] having integrated piezoresisitve force sensors. In [3] a micro-gripper is designed and fabricated to manipulate the small object like a cell. On the gripper a piezoresistive sensor is integrated for sensing the gripping force. A prototype miniature robotic instrument consisting of a microfabricated microgripper, instrumented with semiconductor strain-gauges as force sensors is described in [4]. A magnetically actuated gripper with piezoelectric force sensing has been reported in [5], and an optical method for force measurement is presented in [6]. These designs provide a reasonable sensitivity and resolution, but complicated and expensive assembly processes are required to build the grippers. In [7], an electro-thermally actuated microgripper with integrated force sensor is presented. It is fabricated on the wafer level using a simple fabrication process. Unfortunately, the sensitivity is much lower compared to hybrid designs, making it impossible to measure the small forces dominating micromanipulation processes. The gripper proposed by Y.Sun [8] was actuated by electrostatic force and include a capacitive force sensor measuring the gripping force, while measuring the small capacity change is also a difficult work.

Piezoresistive sensing is mostly employed because of its compatibility with operation in solutions and the simple fabrication process. This paper presents a new design for piezoresistive force sensing integrated in a gripper to sensing the gripping force. This sensorized microgripper can be successfully used in microassembly system for force-controlled micro gripping.

2 Design of the Force Sensor

Now the most general semi-conductor pressure sensor is the PN junction type pressure sensor that made by distribution process. Main advantage of the piezoresistive sensor is the simple process, low cost. In this paper the vertical sidewall surface piezoresistor can be deep-reactive ionic etching (DRIE) form at the outboard surface of the both root of the testing cantilever.

Fig. 1(*a*) shows the configuration of this piezoresistive force sensor and the position in the MEMS gripper. This sensor has been designed to measuring rang from 5μN to 500μN. The end-effector of the gripper is a four arms structure. Two arms both sides are fixed as the force sensor cantilevers. The intermediate two arms are moveable which are actuated by electrostatic comb. It means that there are two tweezers in one gripper and the gripping force can be sensed. Two force sensor cantilevers are along <110> crystal orientation. The piezoresistors are located at the outboard surface of the both end of the cantilevers.

To pick up an object, the moveable arms are pushed to close with the fixed arms. This generates a gripping force that deflects the fixed arms shown in Fig. 1(*b*). This deflection is measured by the piezoresistor for force sensing on the end of the fixed cantilevers. The deflection of the arm is proportional to the gripping force and is independent of the size or the mechanical properties of the object which is gripped.

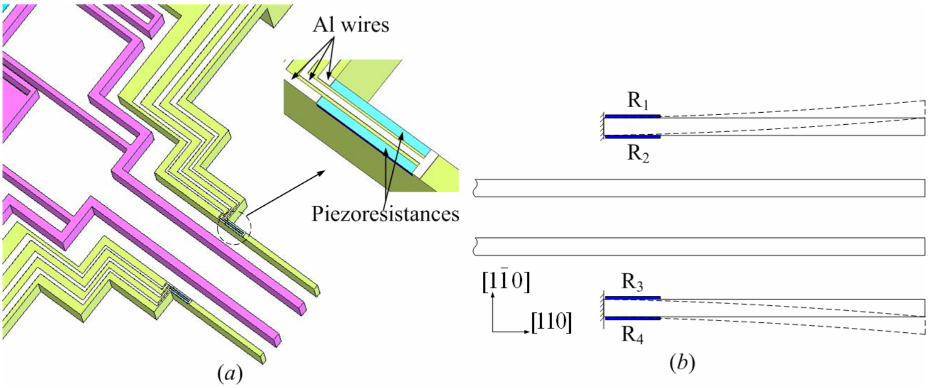


Fig. 1. Sketch of the force sensor

How to get the reasonable maximal stress is key point. It determines the measuring range and the resolution of the sensor. And the maximum stress of the cantilever must be lower than the yield strength. Based on the Material Mechanics and Finite Element Analyze, stress in the position A is maximal in Fig. 2:

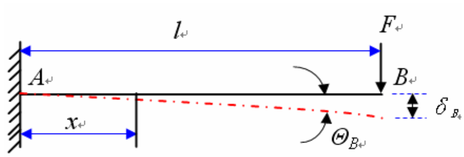


Fig. 2. Sketch of the deflection of the force sensor cantilever

Measuring band width of the sensor is limited by the resonance frequency of the cantilever. In general, the measuring band width is expected to less than half of the resonance frequency. Moreover, the cantilever with low resonance frequency is easily influenced by the environment. So the analyze of the frequency is necessary. The FEA results are shown in Table 1. The first-order is most important in the using of this sensor. And Modal analysis shows that it is 183524Hz which can satisfy the frequency influence completely in gripping relative to the frequency of the environment and the driven voltage.

Table 1. Modal analysis

Exponent number	1	2	3	4
Frequency(Hz)	183524	408075	1138982	2403305

The piezoresistive sensor uses the change of the electrical resistivity due to the strain variation according to the applied force. The resistance change is expressed as the summation of multiplication of the resistivity and the stress in the longitudinal and transverse direction. The resistance change due to the mechanical stress is given by [9]:

$$\Delta R / R = (\pi_l \sigma_l + \pi_t \sigma_t) . \tag{1}$$

Where $\Delta R / R$ is the relative change of resistance in a conventional piezoresistor due to the longitudinal stress, π_l and π_t are the longitudinal and the transverse piezoresistance coefficients, σ_l and σ_t are the longitudinal and the transverse stresses, respectively. The σ_t can be neglected in the bending cantilever so the equation (1) can be reduced to:

$$\Delta R / R = \pi_l \sigma_l . \tag{2}$$

The longitudinal piezoresistance coefficients are given by:

$$\pi_{l,110} = (\pi_{11} + \pi_{12} + \pi_{44}) / 2 . \tag{3}$$

Where π_{11}, π_{12}, π_{44} are three independent coefficients of the first order piezoresistive tensor. The values are given in Table 2. Relative to π_{44}, π_{11} and π_{12} can be neglected.

Table 2. Resistivity according to the Material Type

Type	π_{11}/(10^{-11}m^2/N)	π_{12}/(10^{-11}m^2/N)	π_{44}/(10^{-11}m^2/N)
P-type	+6.6	-1.1	+138.1

Two piezoresistors are placed and connected at the end of the beams so as to maximize the sensitivities to various components of force and moment. The piezoresistive effect of conventional single crystalline piezoresistors can be expressed as below:

$$S = \Delta R / R = (\int_0^l \frac{1}{2} \pi_{44} \sigma_l (x) dx) / l . \tag{4}$$

In the measuring system, two resistances form is designed in a Half Wheatstone bridge. The resistances of two sensing resistors change in opposite direction if a lateral force is applied. The bridge configuration of the resistors compensates for the signals caused by the deflection. When a lateral load is applied to the tip of the cantilever, the differential change of resistance occurs on two resistors R_{s1} and R_{s2}. The other piezoresistors R_1, R_2 are the compensation resistors.

When the piezoresistor value is changed byΔR, the lateral output signal is given by:

$$\Delta V = \Delta R \cdot V_{power} / 2R = \pi_{44} \sigma_{l,\max} V_{power} / 4 . \tag{5}$$

Where V_{power} is the supply voltage and R is the resistance of the non-stressed piezoresistor. The V-I characteristic curve of piezoresistor is shown in Fig. 3.

The main process of piezoresistor is boron ion implantation. Implantation is along z direction, and forms the resistance areas 100μm×4μm in x-y coordinate surface as shown in Fig. 4.

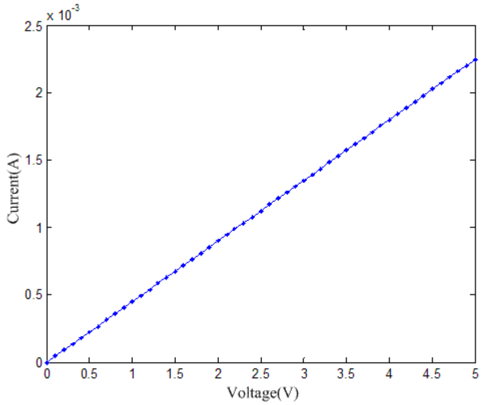
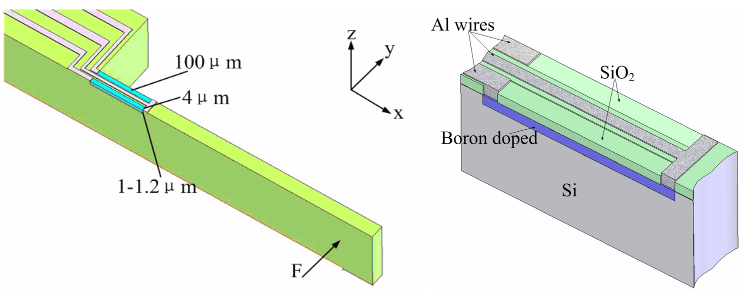


Fig. 3. V-I characteristic curve of piezoresistor

But in this paper, the force F is lateral direction along y direction and the bend of the cantilever is in x-y coordinate surface. Then the boron ion implantation is utilized to form the piezoresistor on y-z surface. 1μm -1.2μm depth PN junction is formed in this paper. Therefore the area of the piezoresistor to measure the gripping force F is about 100μm×(1μm -1.2μm), and depth is 4μm. Two piezoresistors are located at the bilateral root of the cantilever.



(*a*) (*b*)

Fig. 4. (*a*) The sketch of piezoresistor cantilever. (*b*) The close-up view of the piezoresistor. The Al wires and Si are electrically isolated by the previously formed SiO_2.

For the special structure of the sidewall piezoresistor, the shape is only designed to be rectangular. The value of the resistance can be given:

$$R = R_s L / W \cdot \tag{6}$$

Where R_s——sheet resistance;
L——length of the piezoresistor;
W——width of the piezoresistor

According to the standard process of the piezoresistor and the dimension of the testing cantilever, the sheet resistance is about 80Ω/□, width of the piezoresistor is 4μm. From the equation (6), the length of the piezoresistor can be given as 100μm. The dimensions of the sensor are 100μm×20μm×1.2μm.

The resolution of testing cantilever is limited by the four intrinsic noises in semiconductors, which include Johnson noise, shot noise, generation-recombination noise and Hooge noise. In all of which, frequency-independent Johnson noise and low-frequency Hooge noise are two dominant noise sources. The voltage noise power can be expressed as

$$V_n = \sqrt{\left(\alpha V_{power}^2 / N_p W t b_p\right) \ln\left(f_{\max} / f_{\min}\right) + 4 k_B T R\left(f_{\max} - f_{\min}\right)} \,. \tag{7}$$

Where α is parameter independent of dimensions, which dependent on anneal for implant resistors, N_p is the impurity concentration ($4.5\times10^{15}/cm^3$), W is the piezoresistor width and t is the piezoresistor thickness. k_B is the Boltzmann's constant, f_{max} and f_{min} are, respectively, the upper limit and the lower limit of the bandwidth and T is the temperature in Kelvin.

It is evident that the resolution is determined by more parameters, besides the dimensions of the testing cantilever, the parameters of the doped piezoresistors also play more important role in the displacement resolution.

3 Fabrication of the Force Sensors

Surface and bulk micromachining fabrication technology is used to fabricate micro-grippers from silicon wafers. The fabrication sequence is illustrated in Fig. 5.

a) The starting material is 4-inch, N-type, (100) orientation, 1-10Ωcm double polished silicon wafer with a thickness of 300μm.
b) 0.5μm thick thermal oxide layer is grown on both sides of the wafer which is used as the protection layer for the boron infusion. Photolithography is conducted on the front side of the wafer to pattern the piezoresistors, and then buffer HF acid etching SiO2 with photoresist as the etching mask. The piezoresistors are formed by boron diffusion process, and then drive-in process is done to send boron ions deeper into the silicon substrate.
c) The contact holes are patterned by photolithography and opened by wet etching in buffered HF solution.
d) 1 μm-thick aluminum wires and bonding pads are formed by vacuum evaporation, photolithography, and etching processes. The aluminum thin film is photoetched for interconnection, and stripped by plasma etching.
e) The testing cantilever structure and the vertical sidewall surface piezoresistors on the testing cantilever are patterned photoresist and SiO_2 as the etching mask.
f) DRIE is used to form the testing structure and the piezoresistors synchronously. In order to ensure the identical dimension of the each piezoresistor. the parameters of the DRIE should be controlled strictly.

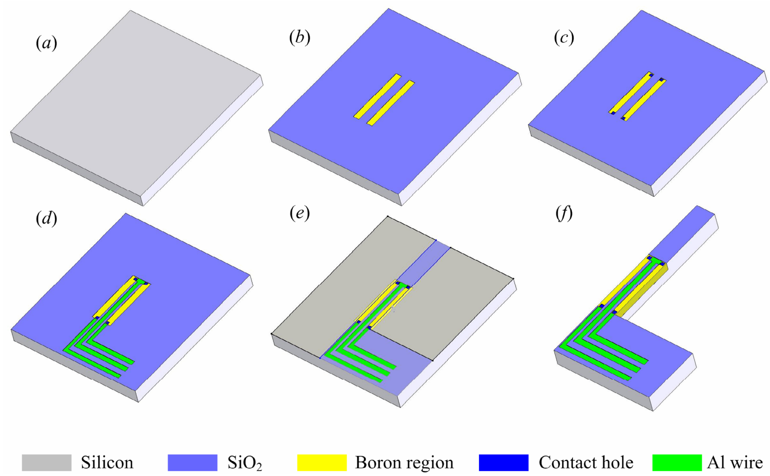
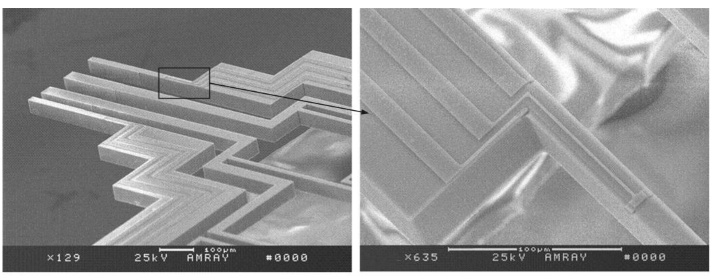


Fig. 5. Process flow schematic of piezoresistor fabrication. *(a)* The double polished N-type (100)-oriented silicon wafer; *(b)* the SiO_2 mask and boron ion implantation; *(c)* The contact holes etching; *(d)* The vacuum evaporation and stripping of aluminum lead; *(e)* Photoresist coating and patterning; *(f)* DRIE of the structure.

4 Testing and Discussion

Fig. 6 shows SEM images of the end effector of the gripper and the piezoresistor.



(*a*) (*b*)

Fig. 6. SEM images. *(a)* The end effector of the gripper. *(b)* The piezoresistor and the Al wires.

The microscope photographs of the local view of the piezoresistive cantilever are shown in Fig. 7.

For calibrating the piezorisistance sensor, an electronic scale and a precision voltage meter are used. The resolution of the piezoresistor sensor is 3μN given by the calibration. The relationship curve of the gripping force and the sensor voltage output is linear shown in Fig. 8. The sensitivity 72V/ N can be received from the curve. Considering the influence of the actual process, the dimensions of the cantilevers and the result of the doped piezoresistor are different with theoretical calculation. The sensitivity 72V/ N satisfies the request of the manipulation.

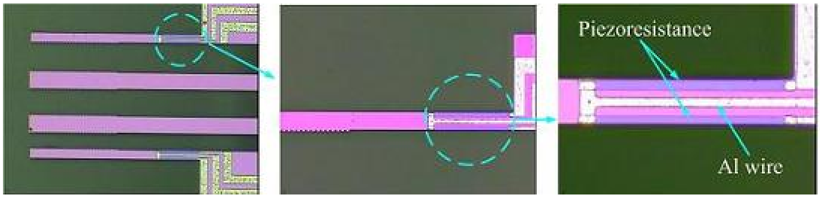


Fig. 7. The photographs of the local view of the piezoresistor cantilever

Table 2. Testing results

Force measuring range	Sensor Resolution	Breakdown voltage of Piezoresistor
5-500μN	3μN	32V

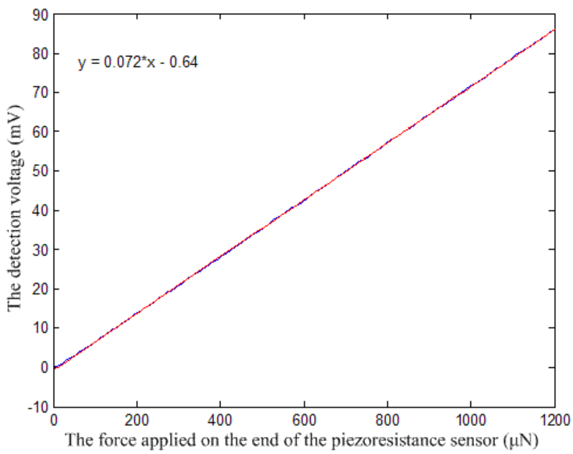


Fig. 8. The relationship of the force applied on the sensor and the detection voltage. The range from 0-400μN is commonly used in the manipulation.

The testing results of the force sensor are stated in Table 3.

An experiment of grasping polystyrene microsphere with different sizes is performed with the gripper shown in Fig. 9. Different voltages are applied during pick-and-release manipulations, and the signal output of the force sensor is shown in Fig. 10. By closing and opening the gripper arm, the signal has a step up and down. The voltage corresponds with the negative gripping force. The values of the voltages reflect different gripping force.

It is found that this fabrication technology and the microgripper configuration are reliable by experiment.

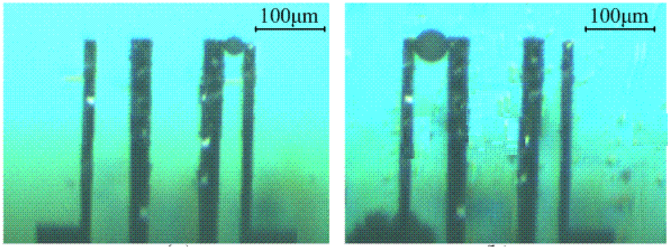


Fig. 9. Grasping the polystyrene microspheres in the gripper

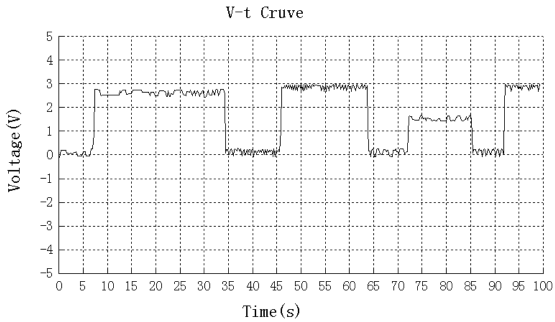


Fig. 10. The signal output of the force sensor. The step up means the picking operation and the step down means the placing operation. Different driving voltages generate the different amplitudes.

5 Conclusion

A novel vertical sidewall surface piezoresistor technique based on bulk-micromachining technologies is proposed in this paper. We combine Boron diffusion process with DRIE technique to form the side direction force sensors. The design and fabrication of the force sensor is presented based on the process and the characteristic of the MEMS gripper. The piezoresistors are integrated in the MEMS gripper ingeniously to measuring the gripping force. Which is High-yield low-cost fabrication technology, with the process, the piezoresistor of random dimension can be located on the vertical sidewall surface easily. Testing results verify the vertical sidewall surface piezoresistor technique, the sensitivity of the fabricated Piezoresistive sensors is better than 72V/N and the resolution is better than 3μN. Experimental show that it can successfully provide real-time force feedback with a high sensitivity sensing and play a main role in preventing damage of microparts in micromanipulation and microassembly tasks.

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