Piezoelectric Vibratory-Cantilever Force Sensors and Axial Sensitivity Analysis for Individual Triaxial Tactile Sensing

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Abstract—**Vibratory force sensors are fabricated using piezoelectric capacitors on microcantilever structures for triaxial sensitivity by the individual sensor element. The cantilevers have been formed into a 3-D curved shape by controlling residual stress combination of the multilayered structure. Triaxial tactile sensitivity of the cantilever sensor is analyzed under a tactile load application onto the surface of an elastomer in which the cantilever is embedded, mimicking human skin structure. The cantilever is converse-piezoelectrically excited by an external ac voltage and three resonant modes are developed to detect the applied load vector components by the single sensor element. Resonant frequency shifts of each mode are investigated upon load applications. The results show that the frequencies vary to the three axial tactile loads independently and they can be superposed with corresponding to the superposition of the load components. The applied load vectors are estimated by resonant frequencies of the single cantilever sensor with compensating nonlinearities of the sensor response. The estimated error is less than 1.1% to the full scale of the load ± 4 kPa.**

Index Terms—**Frequency shift, tactile sensor, triaxial sensitivity, vibratory cantilever.**

I. INTRODUCTION

MINIATURIZED tactile sensors have increasingly investigated for precise touch sensing on robots especially for nursing care applications against the recent rapid increase of the aged population. The human-caring robots need sophisticated multiaxial tactile sensitivity to not only pressure but also slippage to prevent the robots from damaging the touching object. Silicon-micromachined multiaxial tactile sensors have been developed using strain-gauge cantilevers embedded in an elastomer material mimicking human skin structure. They have sensitivity to stress along with normal and two orthogonal shear directions caused by applied tactile load on the elastomer surface, by using a combination of flat cantilevers [1], horizontal and vertical cantilevers [2], or slanted cantilevers [3]. Although the developed cantilever sensors measure a tactile vector by using three or four sensor elements, multiaxial sensitivity by a single sensor element is required for integration into a sensor array in a high density and for reduction of the number of wirings. Moreover, the tactile vector information might be distorted and measure errors would be caused if the components of the single vector are measured by the sensor elements located at different positions. One sensor element of the strain gauge-type sensors, however, can detect only one direction of the force vector due to the limitation of static measurement principle.

On the other hand, piezoelectric vibratory tactile sensors have been developed for position and distribution measurement of tactile objects [4], or for elasticity and viscosity measurement [5]. Using the dynamical measurement technique, one sensor element of vibratory force sensors has possibility to detect plural components of the force information through plural vibration frequencies or vibration modes. That is, they have potentiality to measure the vector components of the tactile information by individual sensor element [6].

The authors propose vibratory cantilever force sensors embedded in the elastomer material for three-dimensional vector tactile sensing by individual sensor element. The cantilevers have three-dimensionally curved shape and can respond to stress along with all directions. The vibration state changes by the external tactile load applied on the elastomer surface through the internal stress distribution change in the elastomer-cantilever system. The tactile load is consequently detected as a resonant frequency change in a resonant mode. The vibration of the three-dimensionally curved cantilever embedded in the elastomer should be investigated under a simulation to obtain the design method for optimal tactile sensing, while vibrating arms were characterized with active constrained layer damping [8] and optimum control of multi-arm robotic system was investigated in a simulation [9].

In this paper, a fabricated sensor device and its fabrication process are firstly introduced. Triaxial tactile load sensitivity by means of resonant frequency shift is then investigated theoretically by using finite element method on the cantilever sensor embedded in the elastomer. Three simple and basic vibration modes are selected in the analysis to easily illustrate the measurement principle with the vibratory cantilever. Finally the tactile load estimation from the resonant frequency shift is discussed.

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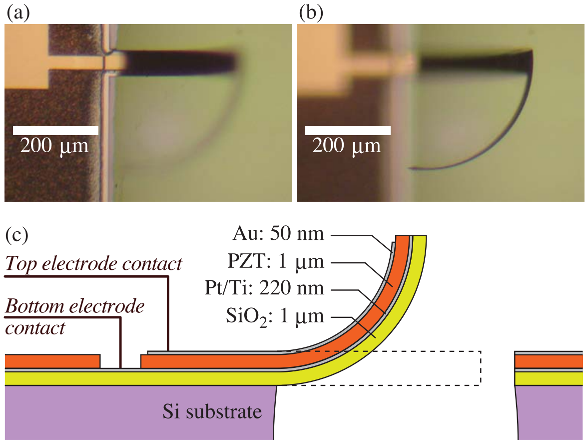

Fig. 1. Fabricated L-shape cantilever sensor element with 400 + 400-μm long by 50-μm wide. (a) Photograph focused on the substrate. (b) Photograph focused on the tip of the cantilever. (c) Schematic illustration of the cross section of the layered structure of the root part of the cantilever.

II. STRUCTURE AND FABRICATION OF SENSOR DEVICE

A. Structure of the Sensor Device

Figure 1 shows photographs of a fabricated cantilever sensor and a schematic illustration of the cross section of the layered structure of the cantilever. A lead-zirconate-titanate (PZT) capacitor is formed on an L-shape SiO_2 cantilever and underneath silicon is removed by deep etching from the backside. Combination of compressive stress by the SiO_2 layer and tensile stress by the PZT layer makes the whole structure into curved shape when the cantilever is released. The cantilever is patterned into L-shape on the substrate in 50 μm wide by 400 μm long each for the root part and the tip part. The both parts of the L-shape cantilever curl from the SiO_2 layer to the PZT layer and make up the three-dimensionally curved structure. Figure 1 (a) and (b) show the photograph focused on the substrate and that focused on the tip of the cantilever, respectively. These photographs indicate the double curled structure curves upward from the substrate and then to the right in 90° each. The curvature radius of the both part is 255 μm, which corresponds well to formerly designed value from the preliminary study for residual stress of the layers [7].

B. Fabrication Process of the Sensor Device

Figure 2 shows the fabrication process of the curved cantilever structure. Note that the substrate is put upside-down in steps (d), (e) and (g) in Fig. 2 due to the etching process from the backside of the substrate. The released cantilevers spontaneously stand up, and the fabrication process has been designed delicately to prevent the cantilevers from collapsing. (a) The start substrate is a silicon wafer oxidized thermally on the both sides up to 1 μm thick. (b) Bottom electrode of platinum and titanium thin films are deposited by using rf magnetron sputtering, piezoelectric PZT film is deposed by using conventional sol-gel method, and top electrode of gold thin film is deposited by using rf magnetron sputtering. (c) The gold thin film is patterned into the top electrode by using iodine and potassium iodide solution, the PZT film is patterned into the cantilever shape and for contact holes by using nitric acid and hydrofluoric acid, the platinum and titanium thin films are patterned into the cantilever shape by using ICP (inductively coupled plasma)-assisted sputter etching with argon plasma, and the SiO_2 layer is patterned into the cantilever shape by using BHF (buffered hydrofluoric acid). (d) The backside SiO_2 layer is patterned to make etching mask for the following silicon bulk etching. (e) The bulk silicon of the substrate underneath the cantilever patterns is etched from the backside vertically by using ICP-RIE (reactive ion etching) with conventional Bosch process, and the etching is stopped before the silicon is completely removed. The thickness of the remained silicon is around 10 μm. (f) The front side of the substrate is covered with photoresist to prevent the cantilevers from standing up during the following silicon etching. (g) The remained silicon is completely removed by using normal RIE with SF_6 plasma. Note that at this step the substrate does not need to be cooled and we can make a gap between the substrate and the wafer chuck of the etcher. The gap prevents the cantilevers from collapsing when they stand up partially from the substrate towards the wafer chuck. (h) The photoresist is removed by using normal RIE with oxygen plasma, and the cantilevers completely stand up to be freed from the photoresist.

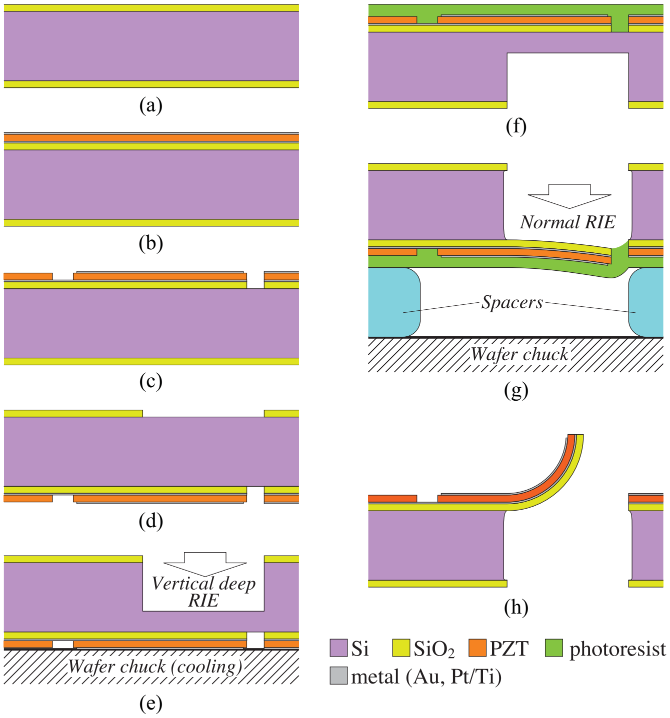

Fig. 2. Fabrication process of the curved piezoelectric cantilever sensor structure. The substrate is put upside-down in steps (d), (e), and (g) due to the etching processes from the backside.

III. TRIAXIAL SENSITIVITY ANALYSIS

Figure 3 illustrates the analytical model; the L-shape curved PZT/SiO_2-bilayer structure is embedded in PDMS (polydimethylsiloxane) elastomer. The cantilever is fixed at the root and the elastomer is fixed at the bottom. Tactile loads P_x, P_y and P_z are applied on the surface of the elastomer, and the cantilever is excited by 5 V ac applied on the PZT