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Sensors and Actuators A 139 (2007) 17–22
SENSORS AND ACTUATORS A PHYSICAL
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Low cost thin film based piezoresistive MEMS tactile sensor

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Received 31 July 2006; received in revised form 10 October 2006; accepted 19 October 2006
Available online 16 November 2006

Abstract

Most reported MEMS tactile sensors are fabricated by silicon micromachining process. Presently, the cost of the silicon-based MEMS fabrication is still relatively high, thus alternative process should be developed for low cost applications. In this work, we develop a low-cost non-silicon-based process for MEMS tactile sensor fabrication. The MEMS tactile sensor with a trampoline membrane structure has been fabricated by successive sputtering of Cr, Al, AlN, indium tin oxide (ITO), and Au layers through electroplated Ni micro-shadow masks over an 8 μm-thick photoresist sacrificial layer on a glass substrate. In addition, the sensitivity of the sensor has been optimized by controlling sputtering parameters including oxygen flow rate and film thickness of the ITO piezoresistive layer. The fabricated tactile sensor has been tested for displacement and force sensing by a Dektak surface profiler. The fabricated sensor is capable of small force sensing in μN ranges with good linear sensitivity of 0.2 mV/μN.
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Keywords: MEMS; Tactile sensor; Physical sensor; Thin film sensor

1. Introduction

MEMS tactile sensor is typically used to sense contact force regarding touch with objects for robotic end effectors. Other potential applications of this sensor include the sensing of organic tissue on a small scale at the end of catheter or on the fingers of an endoscopic-surgery telemanipulator. MEMS tactile sensors offer several advantages over conventional sensors, including compact size, high sensitivity, and multi-dimension functionality [1–11]. A wide variety of MEMS tactile sensors mostly based on silicon micromachining have been demonstrated [1–8]. Tactile sensors are generally classified based on sensing mechanisms. These include piezoreistive [1–5], capacitive [6–8], piezoelectric [9–11], and optical tactile sensors [12]. Among them, piezoresistive tactile sensor is widely used because of low cost fabrication process, good sensitivity, and simple electronic interface.

While the cost of the silicon based MEMS devices is still relatively high, alternative process should be developed for low cost applications. In this work, we develop a low-cost non-silicon-based process for MEMS tactile sensor fabrication by the combination of electroplating, standard photolithography, and physical vapor deposition.

2. Experimental

2.1. Device design and simulation

The MEMS tactile sensor structure as seen in Fig. 1 consists of a multi-layer AlN/Al/Cr square shuttle plate (200 μm × 200 μm) with four arms on which four piezoresistors are placed. In addition, contacts of each piezoresistor are coated with Cr/Au. The indium tin oxide (ITO) is a piezoresistive material. When an external force is applied, it changes electrical resistance due to induced strain. The gold layer is used as the electrode and bonding pad of the piezoresistor. The AlN layer is acted as an insulator providing isolation between the Cr/Al membrane and the piezoresistor. The Cr layer is used as an adhesive film and thick Al layer is used to increase flexibility and rigidity of the membrane structure.

When an object applies force on the membrane, the structure is deformed and strain is induced on the piezoresistor. For small deformation, the relationship between applied force and displacement is linear:

$$F = K_m d \quad (1)$$

where F is the applied force, d the membrane displacement, and K_m the equivalent spring stiffness constant of the membrane. The larger K_m will results in smaller displacement at a given applied force and the lower sensitivity of tactile sensor. K_m depends on

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doi:10.1016/j.sna.2006.10.037

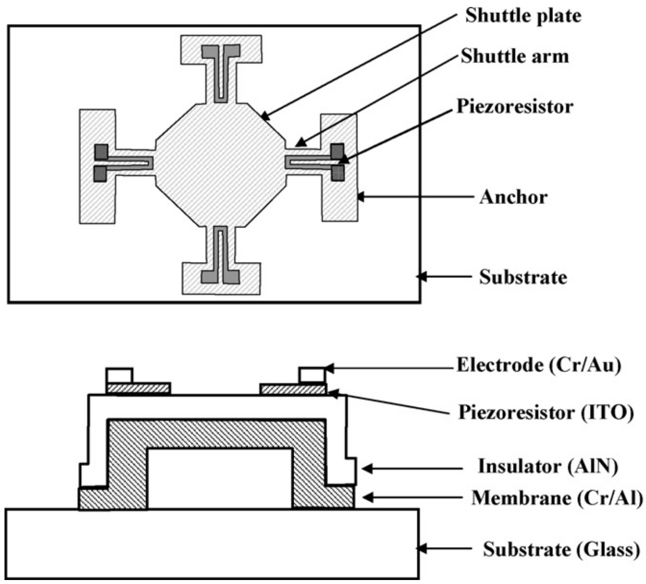

Fig. 1. Structure of MEMS tactile sensor.

the geometry and mechanic material property of the membrane. For circular thin membrane structure, K_m is given by [13]:

$$K_m = \frac{16\pi E}{3(1-\nu^2)}\left(\frac{h^3}{r^2}\right) \quad (2)$$

where E, ν, h, r are Young's modulus, Poisson's ratio, height, and radius of the membrane, respectively. The equation suggests that E and h should be decreased while r should be increased to increase the sensitivity of tactile sensor. In this work, the membrane is square and consists of multiple layers. The analytical form of spring stiffness for this relatively complex structure is not available. However, a square multi-layer membrane may be roughly estimated by a single layer circular membrane with composite material parameters. Thus, the spring stiffness equation of a circular membrane may be used for the first order design while the design refinement can be achieved by numerical simulation of the actual membrane structure.

The displacement and corresponding strain causes the peizoresistors to change their resistance, which can be measured by external electronic circuit. The resistance change of piezoresistor is given by

$$\frac{\Delta R}{R_0} = \mathrm{GF}\varepsilon_d \quad (3)$$

where R_0, GF, ε_d are the strain-free resistance, gauge factor, and strain of the piezoresistor, respectively. The large GF means the higher sensitivity for piezoresistor. GF depends on geometry and piezoresistive coefficients of the piezoresistive material. For single crystal piezoresitive materials, it can be determined from theory or experiment. While polycrystal and amorphous thin film materials, it is usually measured from experiment. Typical values for GF of common materials are widely varied between 5 and 1000.

The sensor was first designed by the above analytical approach to sense typical contact force in the range of 100 μN with a given membrane dimension of 200 μm × 200 μm and maximum vertical displacement of 8 μm. The membrane displacement can be approximated to be 0.64 μm from the Pythagorean triangle law. The required spring stiffness can then be calculated to be 156.5 N/m. Assuming the nominal average young modulus of 10 GPa and the average Poisson's ratio of 0.3, the suitable membrane thickness estimated by Eq. (2) is ∼2 μm. While the Gauge factor of sputtered ITO thin film is not yet known and will be measured experimentally in this work, it is assumed that GF is on the order of 100. From the first order design, it can be deduced that the total membrane thickness should be a few microns, which is in accordance with experimental capability.

For more accurate analysis, CoventorWare^{TM}, commercial MEMS simulation software, is then used to simulate the mechanical-piezoresistive behaviors of the device to determine the relationship between applied force, mechanical deflection, and piezoresistive current. In this simulation, two modules, MemsMech and MEMPZR, are successively used to simulate for mechanical and piezoresistive characteristics. From the actual layout and defined processes, three-dimension model is generated. In this structure, the thickness of Al/Cr shuttle plate, AlN insulation, ITO piezoresistor, Cr/Au electrode, and air-gap layers, are 1.5, 1, 0.5, 0.3, and 8 μm, respectively. The extruded brick mesh is applied to the solid model. The whole structure is meshed with lateral element size of 100 μm and vertical element size between 1 and 0.25 μm depending on the thickness of each layer. Material properties used in the simulation are obtained from standard table and related literature data.

The meshed structure has been simulated by MemsMech module for mechanical displacement, stress, and strain. The boundary conditions consist of fixed displacement at the four anchors and uniform applied force on the square shuttle plate with varying applied forces. The mechanical output from MemsMech is then input into MEMPZR module to simulate for piezoresistive current change as a function of applied force. The boundary conditions for MEMPZR is constant applied potential of 5 V at electrode contacts equally applied on all piezoresistors. The output 3D displacement and piezoresistive current density

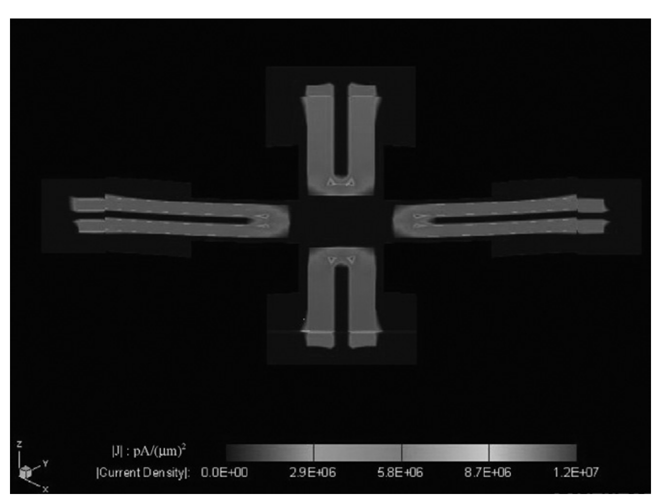

Fig. 2. Typical simulated piezoresistive current density distribution of MEMS tactile sensor.

distributions for an optimum design are shown in Fig. 2. From the figure, it can be seen that the current density is uniform with average value of $\sim 1 \times 10^7$ pA/(μm)^2 except those in the corners. The displacement of 8 μm is obtained at an applied force of 250 μN and the piezoresistive sensitivity of ∼76 mΩ/μN is found from the simulation. It can be seen that the simulated results is considerably different from the first order design. The simulated results should be more accurate than the first order calculation because standard material properties and detailed structure are used. The simulated displacement versus applied force is subsequently shown in Fig. 8 to compare with experimental data.

2.2. Device fabrication

The fabrication process as shown in Fig. 3 is started from patterning an 8 μm-thick photoresist sacrificial layer on a glass substrate by standard photolithography. Next, Cr, Al, and AlN layers are successively deposited by reactive dc magnetron sputtering through the first electroplated Ni micro-shadow mask with square shuttle patterns. Before sputtering, the substrate is cleaned by 100 W rf-plasma for 5 min. The sputtering is conducted in argon (Ar) gas at 3×10^{-3} mbar. For the first sputtered layer, the low plasma power of 100–150 W is used in order to minimize photoresist etching or removal by the plasma. For subsequent layers, higher plasma power of 200–250 W is then used. For AlN sputtering, nitrogen is mixed with Ar gas by the flow ratio of 4:1 (N_2:Ar) to perform reactive dc magnetron sputtering.

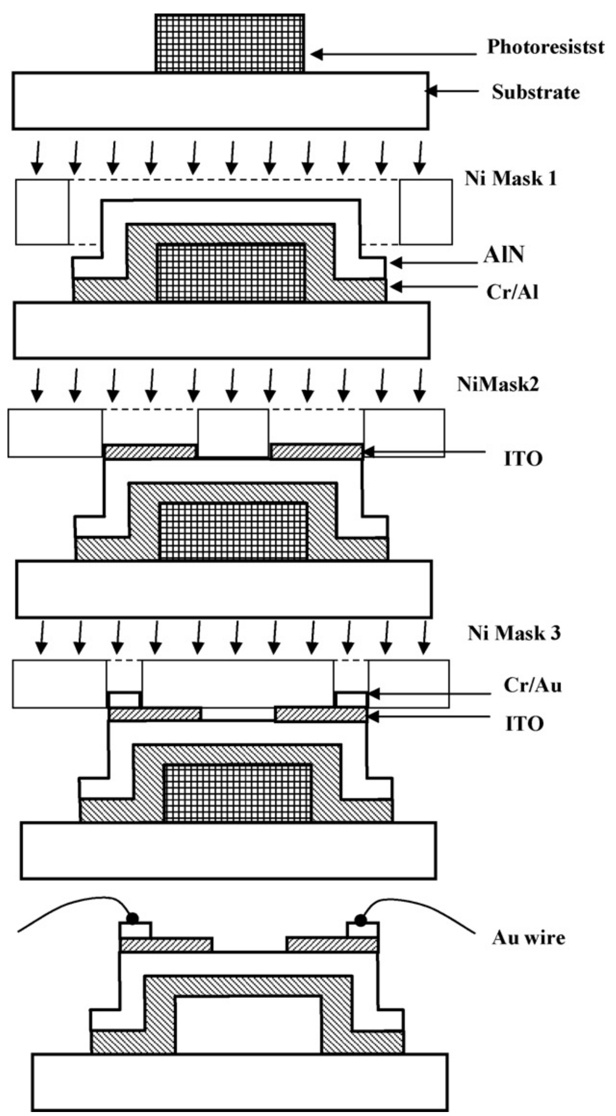

Fig. 3. The fabrication process of thin film based piezoresistive MEMS tactile sensor.

A indium tin oxide (ITO) layer is then reactively sputtered through the second micro-shadow mask with 100 μm u-shape resistor patterns. For the critical sensing layer, the ITO films are sputtered with different oxygen addition and film thickness in order to determine the condition for an optimum gauge factor of the piezoresistor. For gauge factor evaluation, the ITO film single line pattern was simultaneously deposited on a cantilever beam test structure Next, Cr and Au layers are successively deposited through the last micro-shadow contact mask. The sensor is then cut and gold wire bonded to a standard package. The photoresist sacrificial layer is finally released by dissolving in acetone and oxygen plasma. The oxygen plasma is done in the final etching stage in order to avoid sticking problem.

It can be seen that the sensor structure and fabrication process are relatively low cost when compared to silicon micromachined tactile sensors. The substrate is conventional glass slide which is much cheaper than silicon wafer and the structural layers are also made of low cost materials. In addition, the structure is made through near-room-temperature processes, including sputtering and electroplating of micro-shadow mask. Furthermore, only one photoresist step, which is sacrificial layer, is used, thus the cost of photolithography is minimized. It should be noted that the photolithography is also used to make micro-shadow masks but it is used only once before the sensor fabrication.

2.3. Tactile sensor testing

The sensor testing consist of two parts. First, the gauge factor of the ITO thin film is determined by measuring the resistance change of the test straight-line piezoresistor on cantilever beam structure with a controlled displacement using the Dektak probe station. The scanning electron micrograph (SEM) of an array of ITO coated cantilever beam test structure is shown in Fig. 4. The Si_3N_4/PolySi cantilever beam is 50 μm wide, 200 μm long, and 2 μm thick, suspended 2.5 μm above Si_3N_4/Si substrate. The thickness of ITO film on this cantilever beam is approximately 0.2 μm. The vertical displacement of cantilever beam is controlled to be between 0.5 and 1.5 μm for gauge factor measurement. The gauge factor is calculated from the ratio between resistance change and the known strain, which is computed from the controlled displacement. The average gauge factor is then determined from measurements with different controlled vertical displacement of the cantilever beam.

Next, the displacements of the tactile sensor under different applied forces are then measured by a Dektak surface profiler. The force-sensing experiment is conducted by the use of the surface profiler with static press at the center of the shuttle plate as shown in Fig. 5. A Wheatstone bridge circuit is used to measure

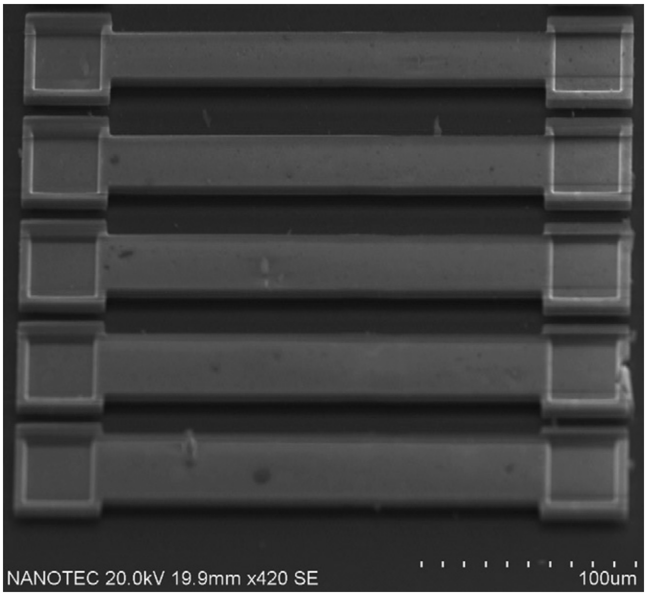

Fig. 4. SEM image of the cantilever beam test structure.

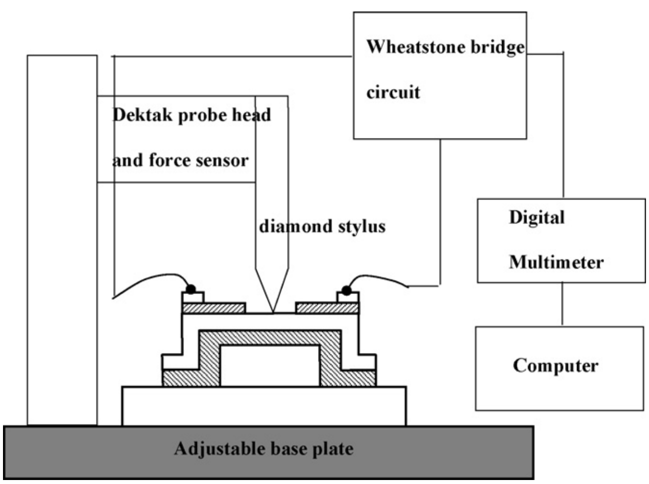

Fig. 5. The setup for force-sensing experiment.

the small change in the resistivity of piezoresistors and provides temperature compensation. The four piezoresistors are serially connected as one arm in the Wheatstone bridge circuit while the other three balancing resistors are ITO resistors on the glass substrate. The output voltage from the bridge circuit is continuously measured and recorded with multimeter. Labview computer system is used to acquire the data from the multimeter.

3. Experimental results

The physical structure of the fabricated sensor is examined by scanning electron microscope (SEM) as shown in Fig. 6. It demonstrates floating trampoline released membrane structure over a glass substrate with surrounding Wheatstone bridge resistors and electrodes. It can be seen that the membrane is slightly bowing downward, indicating tensile residual stress of the composite layer structure. The residual stress of the thin film structure is difficult to be predicted because it depends on several process parameters including deposition rate, power, source to target distance, layer interface, defects, etc. In this work, the process has not yet been optimized for minimum residual stress of this structure.

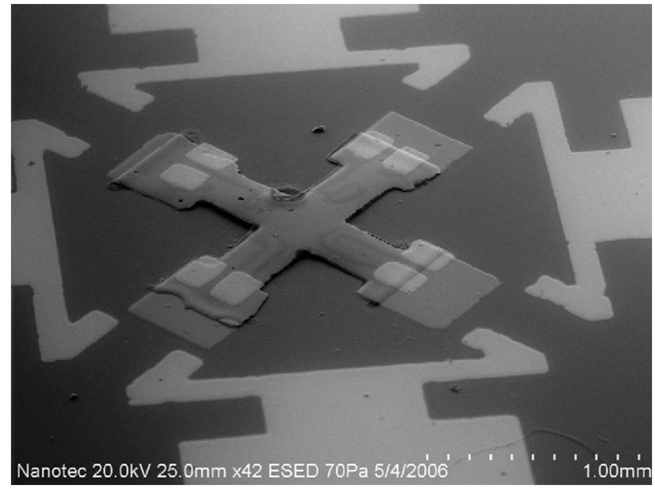

Fig. 6. SEM image of the fabricated tactile sensor.

The gauge factor of the ITO piezoresistive material on cantilever beam test structure is measured as a function of sputtering parameter including oxygen flow rate and film thickness to optimize the sensitivity of the sensor. The gauge factors versus oxygen flow rate for ITO sensing layer with different ITO thickness are shown in Fig. 7. The measurement errors due to the statistical variation of fabrication parameters, applied testing conditions, and electrical measurements are found to be within 20% of the average values. It can be seen that the gauge factor of ITO thin film decreases nonlinearly as the oxygen flow during sputtering process increases. A possible explanation of this behavior may be that the oxygen ion addition during sputtering reduces oxygen vacancies and increases the bandgap [14]. As a result, the electron density that can respond to bandgap change

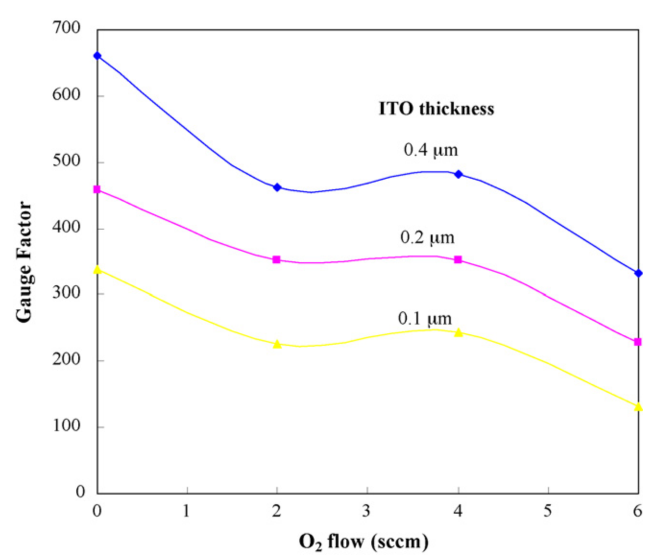

Fig. 7. Gauge factor vs. oxygen flow rate of the ITO piezoresistor with different thicknesses.

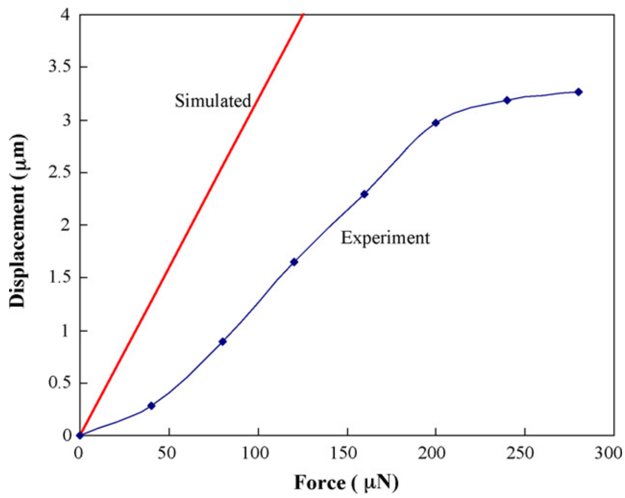

Fig. 8. Vertical displacement vs. applied force of the fabricated tactile sensor.

due to strain is reduced. In addition, the gauge factor is increased as the ITO film thickness increases from 0.1 to 0.4 μm. From our results, it can be seen that the 0.4 μm-thick ITO film with no oxygen flow provides an optimum piezoresistive gauge factor of ∼650.

The measured vertical displacement versus applied force characteristic of the tactile sensor along with simulation result are shown in Fig. 8. It demonstrates linear characteristic with applied force up to 200 μN and the displacement begins to slowly and nonlinearly increase as the applied force increase further. This unexpected nonlinear behavior may be resulted from the tensile residual stress in the structure. Comparing to the simulation result, the measured displacement is considerably different from the simulated one. The large discrepancy is mainly due to unknown residual stress, unknown exact mechanical parameters including Young's modulus, Poisson's ratio of the thin film, and other nonlinear effects. It is known that mechanical properties of the thin film can be significantly different from those of bulk materials and they are depending on various process parameters. In our future work, the mechanical parameters such as Young's modulus, residual stress, and dimensions of the structural layers will be accurately measured in order to improve the simulation model. The output voltage of Wheatstone bridge circuit versus applied force characteristics is shown in Fig. 9. It also shows approximately linear behavior over the applied force ranging from 0 and 200 μN. The sensitivity of the tactile sensor in the linear region is ∼0.1–0.2 mV/μN. The sensitivity of 0.2 mV/μN is considered good compared to some reported silicon micromachined tactile sensors [3]. When the applied force exceeds 200 μN, the output voltage begins to increase nonlinearly. This nonlinear output should be due to the nonlinear displacement characteristics.

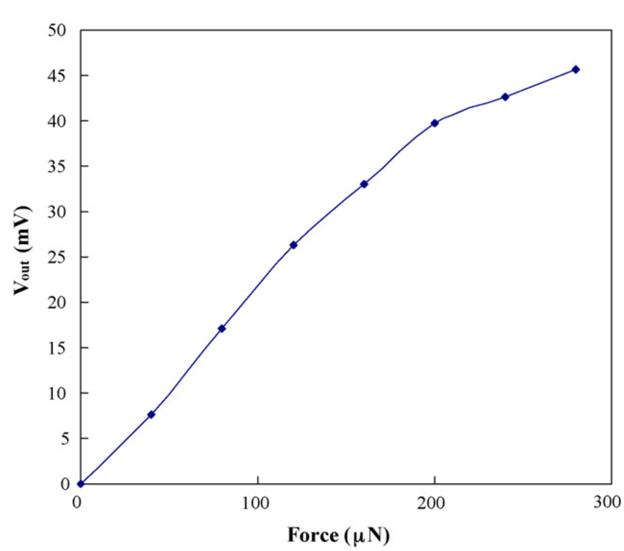

Fig. 9. Measured output voltage vs. applied force characteristic of the fabricated tactile sensor.

4. Conclusion

In conclusion, we have developed a low-cost non-silicon-based process for MEMS tactile sensor fabrication by the combination of standard photolithography and physical vapor deposition. The tactile sensor is designed and simulated by CoventorWareTM, commercial MEMS simulation software before the device fabrication. The sensor has been successfully fabricated and tested. In addition, the sensitivity of the sensor has been optimized by controlling sputtering parameters including oxygen flow rate and film thickness of the ITO piezoresistive layer. The fabricated sensor has demonstrated ability to sense small force in μN ranges with good sensitivity.

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Biographies

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