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Fabrication and Characteristics of Si Piezoresistive Micropressure Sensors for Tactile Imaging Devices

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This paper describes the characteristics of a Si piezoresistive micropressure sensor fabricated by using a three-electrode electrochemical etch-stop to reduce the pressure sensitivity variation, as well as its application to both force and load distributions for instruments or tactile imaging devices. The Si microdiaphragm thickness is precisely controlled by using a natural etch-stop in aqueous tetramethyl ammonium hydroxide (TMAH) : isopropyl alcohol (IPA) : pyrazine solutions. Using the electrochemical etch-stop technique, we have made 801 microdiaphragms on a 5-inch Si wafer with 20-μm-thick n-epi Si grown epitaxially on p-type substrates. The average thickness of the 801 microdiaphragms with sizes of 1.43 × 1.43 mm^2 has been measured to be 20.03 μm with a standard deviation of $\pm 0.26 \mu$m. The etch-stopped microdiaphragm surface is extremely flat without any noticeable taper or nonuniformity. The pressure sensitivity of the fabricated devices is 1.72 mV/(V.Kgf.cm^{-2}), and its variation is less than ±2.3 %. This result indicates that the electrochemical etch-stop technique in TMAH : IPA : pyrazine solutions is useful for the manufacture of the uniformly thick microdiaphragms needed for producing micro-electro-mechanical-systems (MEMS) on a wafer scale.

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I. INTRODUCTION

Rapid improvements over the last years in Si integrated circuits and micromachining technologies have allowed the development of various sensing instruments. A reliable, low-cost, and high-resolution tactile sensor that can be used in unfamiliar and harsh environments is particularly needed in the area of automation process and industrial robot control sensors [1]. Recently, methods of using tactile imaging devices to measure not only force but also force distribution have been based on solid-state pressure sensors utilizing an array of either piezoresistive or capacitive cells [2,3]. When making these devices, it is very important to develop a pressure sensor cell where the variation of the pressure sensitivity is extremely small over a large area.

The Si piezoresistive pressure sensor is currently one of the most widely used because of its high sensitivity, good linearity, lack of hysteresis, good stability over a wide dynamic range, and suitability for batch processing [4]. However, control of the pressure sensitivity has been difficult since it is inversely proportional to the square of the thickness of the diaphragm formed by anisotropic etching [5]. Especially in the case of a microdiaphragm thickness less than 10 μm, if there exists a significant irregularity or nonuniformity in the etched diaphragm surface, the stress distribution over the diaphragm will be disturbed. This causes significant variations in the pressure sensitivity, the offset voltage, and the dynamic range of the resulting pressure sensors. Therefore, accurate control of the diaphragm thickness with a uniformly etched surface is very important to the resolution of pressure sensors.

Widely used methods to control the microdiaphragm for achieving the desired thickness are the etched-time stop, the boron etch-stop [6], the Si-on-insulator (SOI) substrate [7], and the electrochemical etch-stop methods [8]. One disadvantage of the etched-time stop method is that the variation in the etch rate for certain etchants causes a large percentage thickness error in the etched Si region of the diaphragm or the beam. One disadvantage of the boron etch-stop method is that heavily boron-doped, single-crystal Si introduces a compressive stress into other structures; it is also not compatible with circuit-processing techniques. The SOI substrate method shows good etch-stop characteristics, but it is not practical because of the price of SOI wafers. Therefore, we focus on the electrochemical etch-stop method, which is based on the anodic passivation characteristics of Si with a reverse-bias pn junction, to provide good etch selectivity for p-type Si over n-type Si in an anisotropic wet etchant [9]. It has the advantages that it can easily

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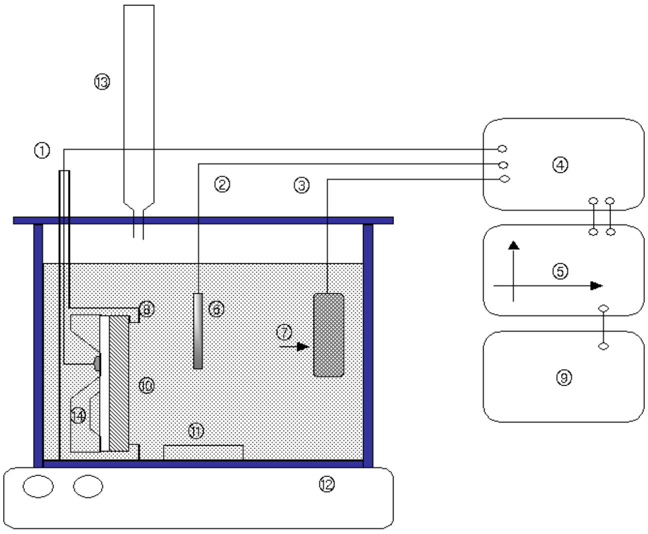

Fig. 1. Schematic diagram of the three-electrode electrochemical etch-stop for Si diaphragm formation. 1. Working electrode 2. Reference electrode 3. Counter electrode 4. Potentiostat 5. Plotter 6. Ag/AgCl 7. Pt mesh 8. Teflon holder 9. PC 10. Sample 11. Magnetic stir-bar 12. Hot plate 13. Reflux condenser.

control the impurity concentration in and the thickness of epitaxial layers.

In this paper, we describe the thickness reproducibility of 801 microdiaphragms made on a 5-inch Si wafer by using electrochemical etch-stop in aqueous TMAH : IPA : pyrazine solutions and the fabrication of Si piezoresistive pressure sensors. Experimental results obtained from sensitivity measurements and the sensitivity variation analysis are also discussed.

II. EXPERIMENTS

1. Diaphragm Formation

The starting materials consisted of <100>-oriented 5-inch Si wafers that had 20-μm-thick n-type Si grown epitaxially on p-type substrates. Both surfaces were covered with a 4000-Å-thick thermal oxide layer to protect them from the etchant. On the p-type substrate surface, 801 diaphragm patterns were formed by SiO_2 etching using a photolithographic technique. In the n-type Si layer, we implanted boron to form a contact, and the anodic contact area was also opened up to apply the anodic voltage.

The optimum anisotropic etch condition is TMAH (20 wt.%) : IPA (8.5 vol.%) : pyrazine (0.5 g/100 ml) solutions [10]. Under this condition, the etch rate is higher than that in TMAH : IPA solutions, and the surface quality is excellent [11]. The three-electrode electrochemical etch-stop was controlled using an EG & G 362 potentiostat. An Ag/AgCl-type electrode, whose working temperature extends up to 100 °C, was used as the reference electrode, and a Pt mesh, which supports high currents, was used as the counter electrode. All voltages presented in the paper refer to those of the Ag/AgCl electrode. Etching was performed in the dark using a tank equipped with a reflux condenser into which nitrogen was bubbled. A temperature of 80 °C was chosen for all experiments and was controlled to within ±1 °C during the process. The experimental setup used in this work is shown in Fig. 1. The I-V curves were obtained using an electrochemical etch-stop system with the voltage sweep rate set at 2 mV/s. The holder that prevented the solution from leaking out to the back of the wafer was made of Teflon and an O-ring.

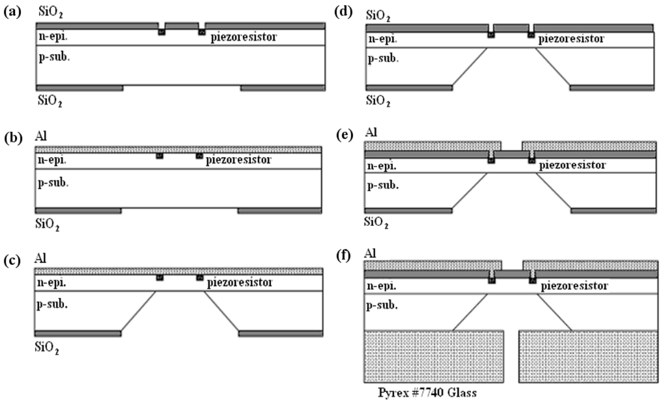

Fig. 2. Cross-sectional views illustrating the processing steps for Si piezoresistive micropressure sensor fabrication utilizing the electrochemical etch-stop. (a) Piezoresistor formation (b) Al deposition for WE (c) Diaphragm formation by using the electrochemical etch-stop (d) Contact open (e) Al Electrode formation (f) Glass bonding.

2. Pressure Sensor Fabrication

Si piezoresistive micropressure sensors were fabricated using a standard Si IC process, combined with an electrochemical etch-stop technique. A cross-section of each fabrication step is shown in Fig. 2. The starting material is an n/p epitaxial Si wafer, in which the 20-μm-thick n-type epitaxial layer corresponds to the diaphragm thickness of the pressure sensors. First, p-type piezoresistors were formed on the surface of the n-type epitaxial layer by boron-ion implantation, $\varphi = 3.5 \times 10^{14}$ cm^{-2}, E = 100 keV, followed by annealing at 1140 °C for 2 hr. Finally, p-type piezoresistors with a 3×10^{18} cm^{-3} surface impurity concentration were formed. Second, the Al electrode used as the working electrode during the electrochemical etch-stop was deposited on the surface of the Si substrate. Then, the diaphragms were formed using the electrochemical etch-stop method mentioned above. Third, the contact holes were opened to the SiO_2 layer of the piezoresistor's end terminals. An Al wiring pattern was formed to make a Wheatstone bridge circuit with

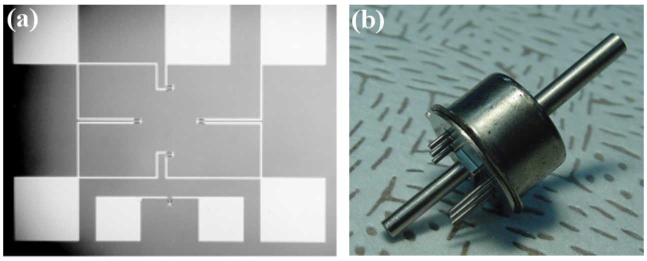

Fig. 3. (a) Top surface and (b) an assembled TO-5 package photograph of pressure sensors fabricated by using the electrochemical etch-stop.

Fig. 4. Photograph of microdiaphragms fabricated on a 5-inch Si wafer.

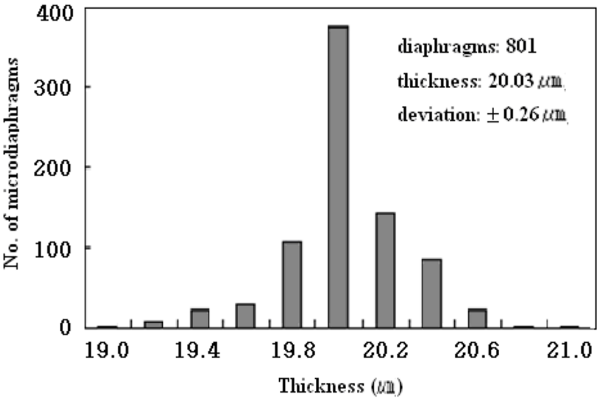

Fig. 5. Thickness distribution of 801 microdiaphragms fabricated on a 5-inch Si wafer by using the electrochemical etch-stop process in TMAH : IPA : pyrazine solutions.

four piezoresistors oriented in the (100) direction. Then, a 5000-Å-thick CVD SiO_2 layer was deposited on the surface as a passivation layer by using chemical-vapor deposition. Finally, the Si substrate on which the pressure sensor was formed was bonded to a Pyrex #7740 glass substrate, by applying a DC voltage of 1000 V at 450 °C by using a method of anodic bonding, to reduce the offset drift due to the mismatch in the thermal expansion coefficients. Then, the TO-5 packaged instructions were followed to complete the pressure sensor. Figs. 3(a) and (b) show the top surface and an assembled TO-5 package photograph of the Si piezoresistive pressure sensor fabricated by using electrochemical etch-stop method.

III. RESULTS AND DISCUSSION

For mass production, identical mechanical properties are required in all devices. Hence, the reproducibility of a uniform thickness in Si microdiaphragms is an important fabrication feature. In order to evaluate the reproducibility of the uniform thickness in Si microdiaphragms across a wafer, we fabricated 801 microdiaphragms on a 5-inch Si wafer having a 20-μm n-type Si epilayer grown on a p-type substrate, as shown in Fig. 4. After the electrochemical etch-stop process in TMAH : IPA : pyrazine solutions at a reverse bias of 0.8 V, the thickness of the microdiaphragms was evaluated by using scanning electron microscopy (SEM). Fig. 5 shows a histogram of the thickness variation of the Si microdiaphragms fabricated on a 5-inch Si wafer. Si microdiaphragms having a thickness of 20 ± 0.2 μm comprise 77.9 % of the total number of microdiaphragms on the 5-inch wafer. The average thickness of the 801 Si microdiaphragms is 20.03 ± 0.26 μm. This indicates that marked improvement was achieved in comparison with previous microdiaphragm fabrication methods [12]. In this work, the thicknesses of microdiaphragms in the central part of the Si wafer were slightly smaller than 20 μm, due to the electrical contacts. Because of the attachment of four-point electrodes on each of the corners of the Si wafer, the central part of the Si wafer was not passivated to sufficiently n-type Si at the p-n junction. The thicknesses of the microdiaphragms at the edge of the Si wafer were larger than 20 μm because of the etching holder. Since the hydrogen bubbles generated during etching were not eliminated completely, they gathered around the holder. If an additional point electrode were to be employed and the structure of the etching holder were to be modified, these problems could be solved. Moreover, this thickness distribution reflects the thickness variation of the epitaxial Si layer in the wafers used in these experiments, which is about 0.2 μm. Between different wafers, the thickness of the epitaxial layer could vary by more than 0.5 μm, yielding a large variation of the microdiaphragm thickness. Therefore, the reproducibility of uniformly thick Si microdiaphragms using the electrochemical etch-stop method is shown to be limited only by the reproducibility of a uniformly thick n-epilayer during the epitaxial layer growth process.

The sensitivity of a piezoresistive pressure sensor is known to be a function of the square of the ratio of diaphragm's side to the thickness. Therefore, the variation of the pressure sensitivity is proportional to the square of the diaphragm thickness variation. A special feature of Si piezoresistive pressure sensors fabricated by using an electrochemical etch-stop is the development of a high-resolution pressure sensor with invariant pressure sensitivity over a large area. To determine the varia-

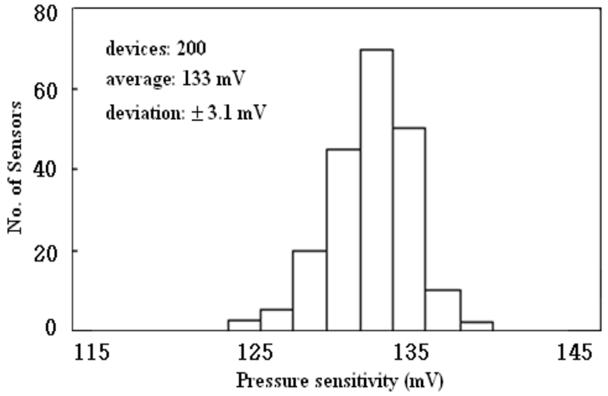

Fig. 6. Histogram of the pressure sensitivity variation of 200 pressure sensors from one wafer.

Table 1. Si piezoresistive pressure sensor specifications.

Chip size:	3.0 mm × 3.0 mm
Diaphragm dimensions:	1.43 mm × 1.43 mm × 20 μm
Piezoresistance:	4 × 2 kΩ
Pressure range:	0 – 2 kgf/cm^2
Pressure sensitivity:	1.72 mV/V.kgf/cm^2
Nonlinearity:	+0.16 % Full scale
Hysteresis:	+0.5 % Full scale
Pressure sensitivity variation:	±2.3 %
Temperature range:	25 – 100 °C
Dependence of sensitivity:	–0.3 % Full scale
Dependence of offset voltage:	+0.2 % Full scale

tion in the pressure sensitivity experimentally, we used a three-electrode electrochemical etch-stop to control the thickness of microdiaphragms for piezoresistive pressure sensors, and we measured their output characteristics at room temperature for a pressure range from 0 to 2 kg. Fig. 6 shows a histogram of the pressure sensitivity variation of the fabricated pressure sensors. The histogram includes 200 devices relative to the average value. The average pressure sensitivity was 133 mV, and the standard deviation of the measured pressure sensitivities was only ±2.3 %. This is an important improvement compared to previous fabrications of piezoresistive pressure sensors, where the microdiaphragms were fabricated by using the etching time, the V-groove, and the boron etch-stop techniques. Moreover, this variation is similar to that for the thickness of microdiaphragms formed on SOI substrates, in which the fabrication cost of the pressure sensors is high due to the SOI wafer [13]. Besides the thickness variation of the microdiaphragms, there are many factors that affect the pressure sensitivity's uniformity: for example, the alignment error between the piezoresistors and the microdiaphragm edge also cause sensitivity variations. Stress generated by the diaphragm deflection changes with distance from the diaphragm edge, and sensitivity is proportional to stress. The piezoresistive coefficient π_{44} changes with the impurity concentration in the piezoresistor [14]. Table 1 summarizes some specifications of the fabricated sensor. It is obvious that the fabrication cost of individual sensors can be reduced if their output characteristics are reproducible. Therefore, it is very important to fabricate a pressure sensor with constant output characteristics for mass production and for application to not only force but also load distribution instruments or tactile imaging devices through use of a full array of pressure sensors.

IV. CONCLUSION

In this work, high resolution Si piezoresistive pressure sensors were fabricated using a three-electrode electrochemical etch-stop technique during the formation of Si microdiaphragms, and the pressure sensors were evaluated. The developed electrochemical etch-stop was useful for the formation of microdiaphragms with flat and uniform thicknesses on a wafer. The most significant factor affecting the pressure sensitivity of Si diaphragm pressure sensors is the diaphragm thickness variation. In particular, the variation in pressure sensitivity could be reduced to within a standard deviation of ±2.3 % from wafer to wafer. Consequently, we demonstrated that the electrochemical etch-stop is an easy-to-handle, yet powerful, fabrication tool. Since almost any wafer can be etched, the process can be automated if the current is used as an automatic end-point detector, and there is no danger of overetching the microdiaphragms.

The results of microdiaphragm formation by using an electrochemical etch-stop presented in this work suggest a very promising technique for the development of high-resolution mechanical sensors with no variation in the pressure sensitivity. Furthermore, this technique seems to be especially attractive for applications to microsensors and microactuators using microdiaphragms.

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