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Application of silane-free atmospheric-plasma silicon deposition to MEMS devices

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ABSTRACT

We have developed a silane-free atmospheric-pressure plasma Si deposition process and investigated the properties of the deposited films by fabricating strain gauge type pressure sensors for the first time. The Si deposition process, which is known as plasma-enhanced chemical transport, utilizes the temperature difference between the solid Si source and the substrate in atmospheric hydrogen plasma. The Si films were deposited at a low temperature of 300 °C at 700 Torr. We have clarified that the Si films were composed of poly crystals by X-ray diffraction (XRD) patterns and Raman spectra. We fabricated strain gauges using the poly-Si films. The gauge factor of approximately 10 was achieved. The bridge voltage of the pressure sensor was found to be proportional to the pressure. The Si films are deemed appropriate for use as MEMS devices.

1. Introduction

While various materials have been used in MEMS products and have also been proposed for new applications, Si having variety of electrical and mechanical functions still takes important roles in MEMS devices. The mainstream of present Si deposition processes is plasma enhanced-CVD, which uses vacuum chambers and gases such as SiH_4. Devices are produced at lower costs through the use of larger substrates. Larger evacuation systems are required because it is necessary to use vacuum chambers that can accommodate the larger substrate sizes. Moreover, the cost of equipment for safety disposal is always necessary. Therefore with a view toward solving future cost issues of enlarging vacuum systems for large-scale MEMS devices and equipment for safety disposal, we anticipate the future development of innovative atmospheric Si deposition techniques.

Our target image of a method of continuous large-area deposition is shown in Fig. 1. In this image, we assume that Si can be deposited under atmospheric pressure without a vacuum chamber and SiH_4 gas. It is necessary to develop the technique of local ambient gas control with gas curtain to prevent the depositing area from the atmosphere and the hydrogen gas leak. To build such an innovative system, we have been developing the basic technology to utilize plasma-enhanced chemical transport for remote plasma deposition under atmospheric pressure. Plasma-enhanced chemical transport is a promising mechanism since it does not use toxic and expensive SiH_4 gas, but instead utilizes the temperature difference between the solid Si source and the substrate in hydrogen plasma. However it is necessary to achieve the stable and continual glow discharge under the atmospheric pressure by using the hydrogen gas which is hardly discharged. The principle of this plasma-enhanced chemical transport has long been reported [1,2]. Recently Si deposition using VHF band plasma has also been reported [3]. Because Si films can be deposited at low temperatures using this technique, reduced film stress can be expected. Moreover this deposition process can be applied to a variety range of substrates like flexible substrates [4]. But the characteristics of Si films deposited under atmospheric pressure, which are necessary in several applications, have not been reported previously. Therefore we prepared strain gauges type pressure sensors using our poly-Si film to examine the characteristics of Si [5].

In this paper, new data which is necessary for the MEMS device fabrication is added and we also report on the more detailed characteristics of the Si films and our evaluation of the pressure sensors.

2. Atmospheric plasma silicon deposition

2.1. Principle

Unlike plasma-CVD, this method is not deposition by decomposition of a material gas. Instead, using hydrogen plasma, this method involves deposition by transporting a raw material hydride

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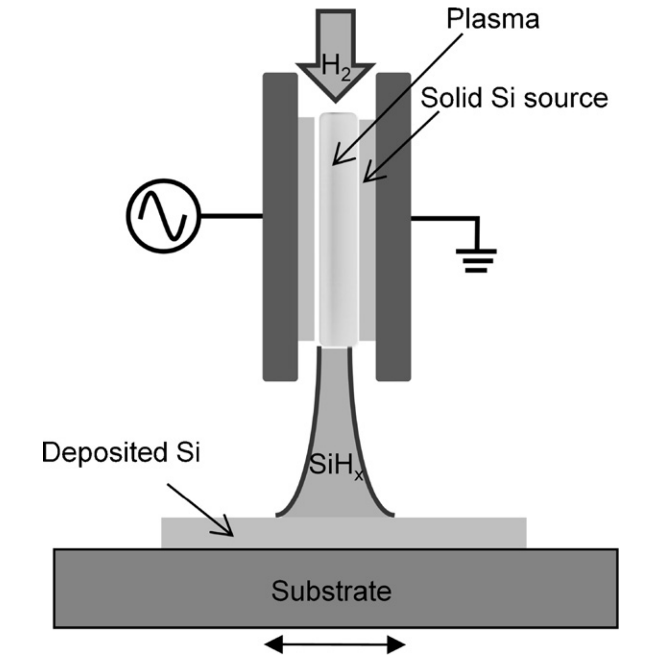

Fig. 1. Target image of a chamber-less Si deposition system using plasma-enhanced chemical transport.

to the substrate. As such, the film cannot be deposited without using hydrogen plasma. On the other hand, this technique can be applied to the material forming the hydride. For example, the use of carbon has also been reported [6].

The principle of this method for Si deposition is shown in Fig. 2. At low temperatures, Si etching proceeds at the surface of the solid Si source, as shown in the chemical equation (1). At high temperatures, Si deposition proceeds on the substrate surface, as shown in the chemical equation (2).

$$\mathrm{Si(solid)} + x\mathrm{H(gas)} \rightarrow \mathrm{SiH}_x\mathrm{(gas)} \quad (1)$$

$$\mathrm{SiH}_x\mathrm{(gas)} \rightarrow \mathrm{Si(solid)} + x\mathrm{H(gas)} \quad (2)$$

As a result, Si is transported to the substrate, using hydrogen plasma.

2.2. Deposition experiment

To fabricate the Si deposition system shown in Fig. 1, it is necessary to understand the basic characteristics. The simple system

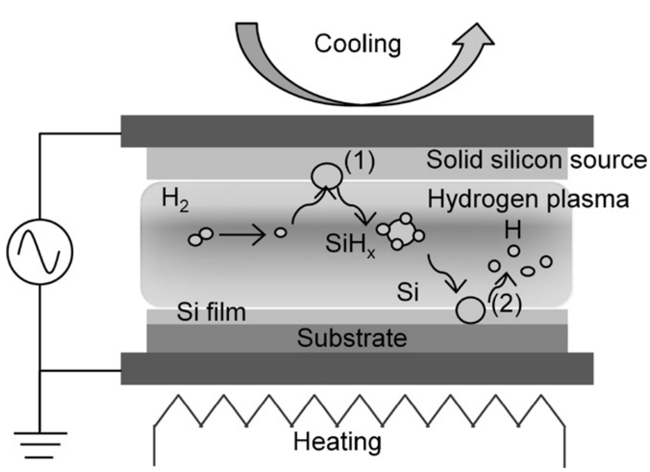

Fig. 2. Principle of plasma-enhanced chemical transport.

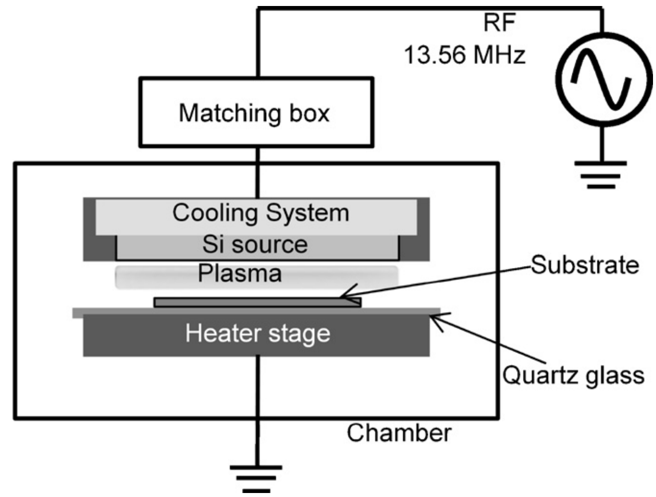

Fig. 3. Experimental setup using parallel plate electrodes.

used in our study and shown in Fig. 3 has parallel plate electrodes to which RF power is applied in a pressure-controlled chamber. The upper electrode is a solid Si source which is cooled by water, and the bottom one is a heated stage. A dielectric quartz glass is set up on the heater stage, because the atmospheric pressure plasma is generated by using the dielectric barrier discharge. Solid Si sources are transported to the substrate placed on the quartz glass using the plasma which is excited between the upper and lower electrodes. Compared with low-pressure plasma used in conventional plasma CVD methods, atmospheric-pressure plasma easily causes arc discharge and partial discharge in unexpected portions. To obtain a suitable glow-discharge for deposition, a potential difference between facing surfaces of the narrow place was prevented by the plating. The deposition conditions were as follows: f_{RF} = 13.56 MHz, P_{RF} = 18 W/cm^2, H_2/He = 6.25%, pressure = 700 Torr, temperature = 300 °C, gap = 4 mm. Fig. 4 shows a view of glow discharge.

2.3. Evaluation of the deposited Si film

Fig. 5 shows SEM images of the Si film deposited on a thermally oxidized Si wafer. The deposition time was 3 h. The surface was clearly grainy in appearance. The grain of about 800 nm was observed in the maximum on the surface. Therefore the surface roughness was measured using a stylus surface profiler. As a result, the Ra = 43.9 nm and RMS = 57.5 nm were measured. After depositing Si film on a thermally oxidized Si wafer, the opening area of 2 mm^2 was formed with 5 mm pitch by photoresist. Afterwards the Si film was etched with ICP-RIE and the distribution of the film thickness was measured as shown in Fig. 6. The average

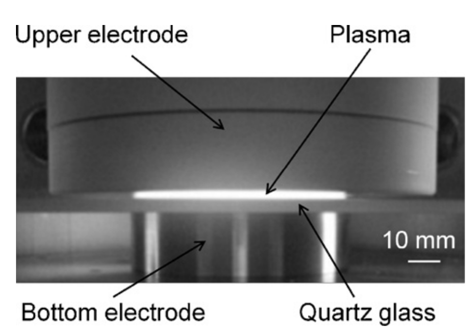

Fig. 4. Glow discharge at 700 Torr.