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Fabrication of Boron-Doped Polycrystalline Silicon Films for the Pressure Sensor Application

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압력센서용 Boron이 첨가된 다결정 Silicon 박막의 제조

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ABSTRACT

The boron-doped polycrystalline silicon films which can be used in pressure sensors were fabricated in a high-vacuum resistance heating evaporator. Poly-Si films were deposited on quartz substrates at various temperatures and the boron was doped to the silicon film in a diffusion furnace using BN wafer. The silicon films deposited at 500℃ was amorphous, began to show crystalline at 600℃, and became polycrystalline at 700℃. After doping boron at 900℃ for 10 minutes, the resistivity of the films was in the range of 0.1Ω·cm～1.5Ω·cm, the boron density was 9.4×10^{15}～$2.1\times10^{17}cm^{-3}$, and the grain size was 107Å～191Å.

요 약

저항가열식 고진공증착기를 이용하여 압력센서로 사용될 수 있는 boron이 첨가된 다결정 silicon 박막이 제조되었다. 다결정 silicon 박막은 여러온도에서 quartz 기판위에 증착되었으며, boron은 BN 웨이퍼를 사용하여 확산로에서 doping하였다. 500℃의 기판온도에서 증착된 silicon 박막은 비정질이었으며, 600℃에서 결정을 보이기 시작하였고, 700℃에서 다결정이 되었다. 900℃에서 10분동안 boron을 doping한 후, 박막의 비저항은 0.1Ωcm～1.5Ωcm의 범위에 있었으며, boron 밀도(농도)는 9.4×10^{15}～$2.1\times10^{17}cm^{-3}$이었고, 입자의 크기는 107Å～191Å이었다.

1. INTRODUCTION

Solid-state polycrystalline silicon (abbreviated as poly-Si henceforth) has recently become a focus of interest with respect to sensor applications[1-3]. Onuma and Kamimura [4] have demonstrated that pressure sensors with a good gauge factor can be manufactured by depositing the poly-Si thin-film on an insulating SiO_2 layer supported by a stainless steel substrate. Although there have been some pressure sensors developed based on poly-Si, its widespread application in pressure sensors is still in an early stage. Furthermore, most poly-Si pressure sensors have been developed on metallic substrates.

Previous studies[5-8] have shown temperature sensitivity, piezoresistivity, and electrical properties of the poly-Si thin-film. It has been reported that the piezoresistive properties of poly-Si are strongly affected by its microstructure such as grain size and orientation [4,8]. The grain size and orientation of a poly-Si film are strongly dependent upon a substrate material and deposition conditions such as deposition technique, deposition rate, and substrate temperature. Subsquent heat treatment of a deposited film can also affect the final microstructure and boron doping also causes the growth of crystallites with preferred orientation, and thus these have effects on piezoresistive properties of a poly-Si film.

The main objective of the present study is to fabricate poron-doped poly-Si films which can be used in pressure sensors. Poly-Si films were deposited on quartz substrates at various temperatures in a high-vacuum resistance heating(thermal) evaporator. The small amount of boron was doped to the silicon film by using hard BN wafer. The microstructure of a deposited film was controlled by both deposition rate and substrate temperature, and its crystallinity and grain size were examined from X-ray diffraction peaks. The electrical properties of the film were measured as functions of substrate temperature and deposition rate. The optimum deposition condition for the fabrication of poly-Si pressure sensors was investigated.

2. EXPERIMENTAL PROCEDURE

2.1. Deposition of Poly-Si Films

Quartz disks with 1.2 inch diameter and 0.025 inch thickness (Bond Optics Co.) were used as the substrate materials. All substrates were thoroughly cleaned by D. I. water and trichlorotrifluoethane(Freon TF solvent, Van Waters & Rogers Inc.) and mounted on a specially designed sample holder. The substrate heating element was made by Kanthal wire and small alumina tubes. The substrate temperature was accurately measured by R-type thermocouple inserted through channel of the sample holder. The sample holder also has provision of holding a mask in a precise position.

Two different types of shadow masks were used for the deposition of poly-Si films with desired patterns. One was designed to provide a straight line with 0.77 inch length and 0.14 inch width. The other was designed to provide a circle with 0.77 inch diameter for X-ray diffraction analyses.

Poly-Si films with approximately 2000 Å thickness were prepared with a high-vacuum resistance heating evaporator described as follows.

Under a pressure of less than 5×10^{-6} Torr, high purity silicon materials were evaporated on a quartz substrate. The Ta crucible holder and heating filament and the boron nitride crucible were used for evaporation of silicon. Two deposition rates (1.5Å/sec and 5.0Å/sec) were employed by controlling AC power. The thickness of the deposited film and deposition rates were controlled and monitored with a crystal oscillator(Inficon, Leybold-Heraeous Co.) installed in the high-vacuum evaporator.

As reported earlier, the microstructure of the deposited film was controlled by the substrate temperature in addition to the deposition rate. Accordingly, the silicon film was deposited at 500℃, 600℃, and 700℃, respectively to give a wide range of microstructure.

2.2. Boron Doping

The small amount of boron was doped to silicon film in the diffusion furnace shown in Fig. 1 in order to reduce the resistivity of the silicon film[9-11]. The boron nitride(BN)wafer (Owens-Illinois Inc.) with 0.04 inch thickness was used as a dopant source. A four-rail quartz boat shown in Fig. 1 was used as a sample holder. This boat can be moved by an attached quartz rod. The spacing between the silicon film and the dopant surface was kept constant. In order to remove any moisture absorbed on BN wafer, the wafers were kept at 900℃ for 12 hours in a purified argon atmosphere. The quartz boat was slowly inserted into the center of the diffusion furnace at 900℃ and maintained for 10 minutes in that furnace. At the end of diffusion experiment, the boat was withdrawn at a rate of 4 inch/min.

2.3. Characterization of the Film

The grain size and orientation of deposited silicon films were examined with a X-ray Diffractometer (Model D/Max IIB, Rigaku Co.) as functions of substrate temperature, deposition rate, and boron dopant concentration. Grain sizes were calculated from the half width of the X-ray diffraction peaks using Sherrer's formula[12]. The resistance of the silicon thin film was measured with a Semiconductor Parameter Analyzer(Model 4145A, Hewlett Packard Co.). The thickness of this film was again measured using a long scan profiler with

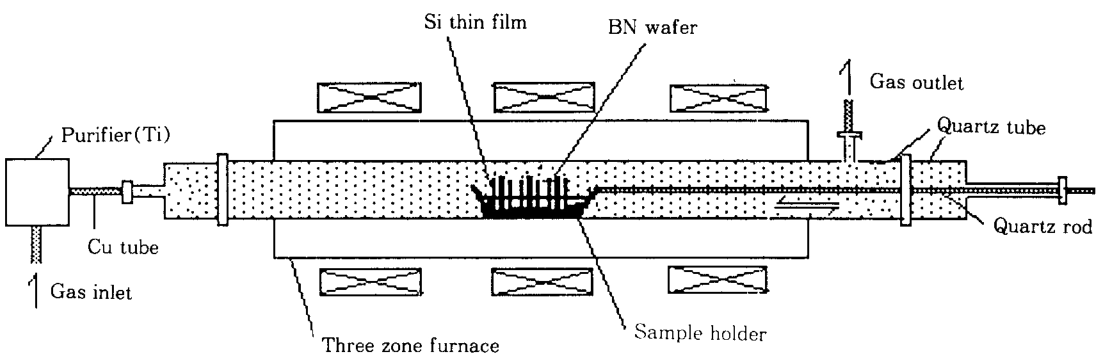

Fig. 1. Schematic diagram of the diffusion furnace for doping boron in the silicon film.

Table 1. The properties of silicon films

Substrate temp.(℃)	Deposition rate(Å/sec)	Boron dopant	Thickness (Å)	Grain size (Å)	Resistance (kΩ)	Resistivity (Ω·cm)	Boron density (1/cm³)
500	1.5	undoped	2190	non-crystalline	6×10^6	2.4×10^4	-
600	1.5	undoped	2196	non-crystalline	6×10^6	2.4×10^4	-
700	1.5	undoped	2285	109	6×10^6	2.5×10^4	-
500	1.5	doped	1960	112	424	1.51	9.4×10^{15}
600	1.5	doped	1980	134	98	0.35	4.9×10^{16}
700	1.5	doped	2136	224	124	0.48	3.4×10^{16}
500	5.0	undioped	2057	non-crystalline	6×10^6	2.2×10^4	-
600	5.0	undoped	2042	non-crystalline	4×10^6	1.5×10^4	-
700	5.0	undoped	2330	95	6×10^6	2.5×10^4	-
500	5.0	doped	1808	107	401	1.32	1.1×10^{16}
600	5.0	doped	1959	120	178	0.63	2.5×10^{16}
700	5.0	doped	2211	191	27	0.11	2.1×10^{17}

a resolution of 1Å(Model P-1, Tencor Instruments) in order to establish the exact thickness of thin films.

3. RESULTS AND DISCUSSION

3.1. Structure of the Film

The typical photograph for the poly-Si thin film prepared in this experiment is shown in Fig. 2. The results for thickness measurements of the films are shown in Table 1 and an example of them is shown in Fig. 3. Fig. 3(a) shows a thickness profile of point A through point B in Fig. 2(b). This sample was deposited with 1.5Å/sec at 600℃ and its average thickness was 2196Å. Fig. 3(b) shows that the surface of the film is very smooth with the average roughness of 12Å.

The physical and piezoresistive properties of poly-Si thin films have been reported to depend on substrate temperature, annealing temperature, and boron concentration [8, 13]. Accordingly, the results of X-ray diffraction analysis for the substrate temperature and boron doping effects of the silicon films deposited at a rate of 1.5Å/sec are shown in Fig. 4. As shown in Fig. 4, the silicon film deposited at 500℃ was completely amorphous, whereas that at 600℃ began to show crystalline nature. As the substrate temperature increased, the crystal

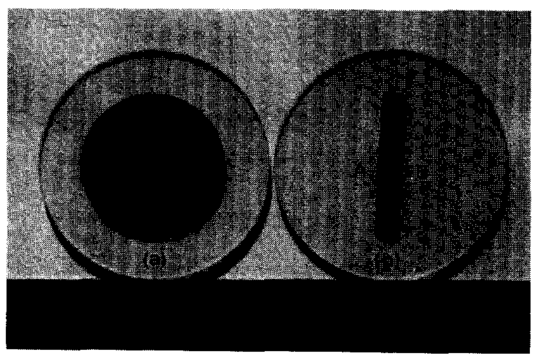

Fig. 2. Photograph of silicon thin film deposited on quartz substrate(top view).

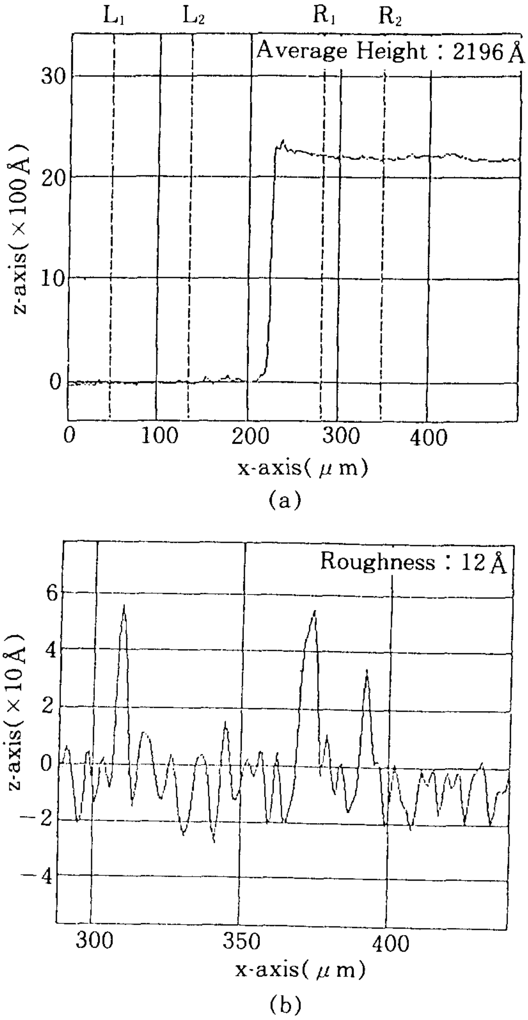

Fig. 3. The results of thickness and surface roughness measurements of silicon film using a long scan profiler.

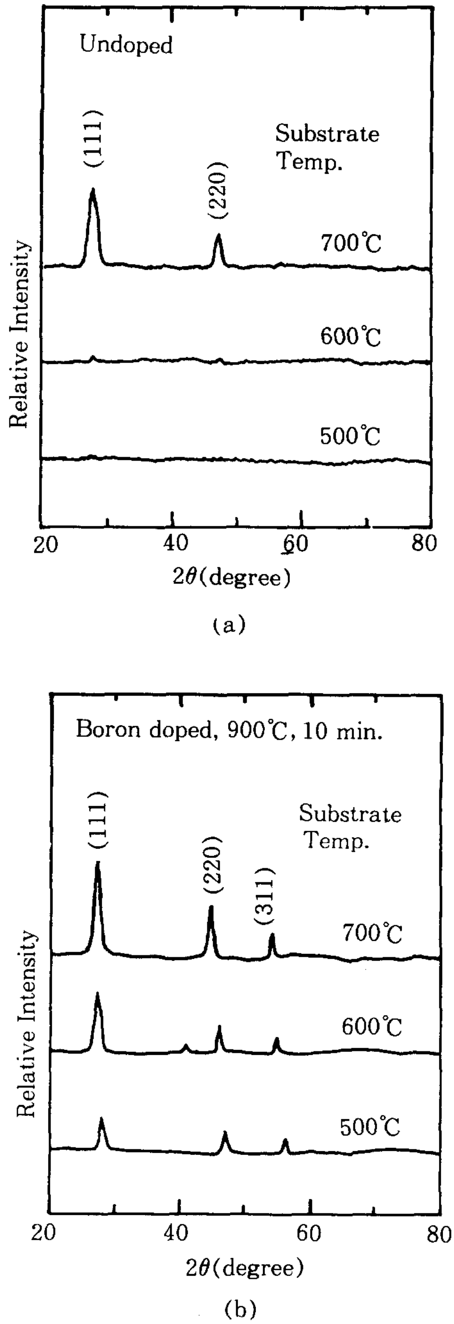

Fig. 4. X-ray diffraction patterns of the silicon films deposited on quartz substrates at a rate of 1.5 Å/sec; (a) undoped and (b) boron doped.

structure was improved and became polycrystalline. All of silicon films which boron was doped at 900℃ for 10 minutes show strong X-ray peaks, indicating crystalline nature of the films. Fig. 4(b) shows that the intensities of the diffraction peaks for the boron-doped silicon films increased with increasing the substrate temperature from 500℃ to 700℃. X-ray

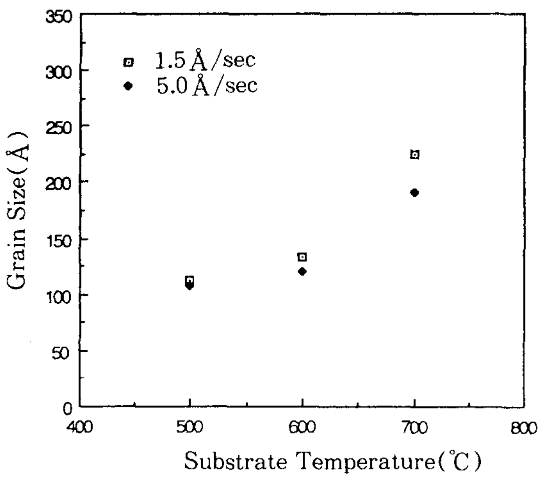

Fig. 5. Grain size versus substrate temperature for B-doped poly-Si films.

diffraction peaks of the silicon films deposited with 5.0Å/sec had patterns similar to those deposited with 1.5Å/sec.

The grain sizes of these films were calculated using Sherrer's formula [12] and the results are summarized in Table 1. Fig. 5 shows the grain size as a function of the substrate temperature for boron-doped poly-Si films. As shown in Fig. 5, the grain size of the films increased with increasing the substrate temperature. The grain size of the films deposited with a rate of 1.5Å/sec is greater than that of the films deposited with 5.0Å/sec. It is assumed that the reason is due to the difference of deposition time. In order to get the same thickness of the films with different deposition rates, the deposition time of the film deposited with 1.5Å/sec is longer than that for 5.0Å/sec. Consequently, the deposition time is longer, the annealing effect at substrate temperature is greater.

3.2. Electrical Properties of the Film

Table 1 also summarizes the electrical properties of the deposited films as functions of substrate temperature, deposition rate and boron dopant concentration. The results of resistance measurements are also shown as well as calculated resistivity and boron concentration. At this time, the boron concentration of boron-doped poly-Si films was earned by using the resistivity to dopant density conversion table[10]. Table 1 shows that boron was lightly doped compared to the silicon films doped by ion implantation [14]. Seto [13] reported that lightly boron-doped poly-Si film can be used as a pressure sensor with high gauge factor. After the boron was doped to silicon film at 900℃ for 10 minutes, the thickness of the films was generally reduced and the resistance was abruptly decreased by approximately 10^4 order (see Fig. 6). The decrease of resistivity for the boron-doped silicon film is due to the conductivity increase by boron doping[9-11].

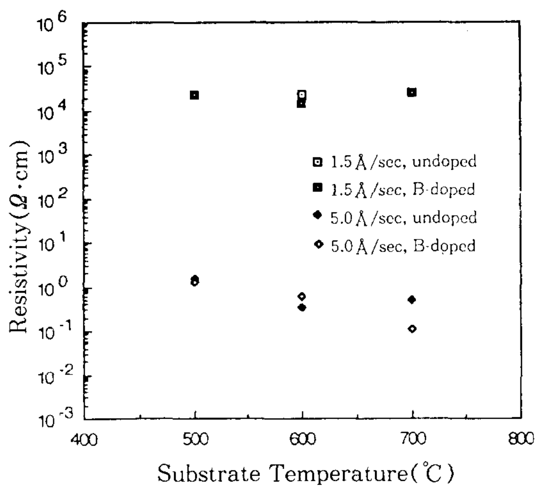

Fig. 6. Resistivity versus substrate temperature characteristics for silicon films.

4. SUMMARY

The basic study for a feasibility of using poly-Si thin films for pressure-sensor application was performed in this experiment. It was found that a good quality poly-Si film can be deposited on quartz substrates above 600℃ using the resistance heating evaporator. The crystallinity and resistance of the film were found to be a strong function of substrate temperature, deposition rate, and dopant concentration. The poly-Si film deposited at 700℃ and doped boron had the lowest resistivity($1.1\times10^{-1}\Omega cm$) and the highest boron density($2.1\times10^{17}cm^{-3}$). It is expected that further refinement of the deposition processes should yield the poly-Si thin films on quartz substrates that can be used for commercial pressure sensors.

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