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Fabrication of Heavily-Doped Polycrystalline Silicon Film Using a Laser-Doping Technique

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A structure composed of alternating layers of hydrogenated amorphous silicon (a-Si:H) film and either phosphorus or boron film was used to fabricate low-resistivity polycrystalline silicon (poly-Si) film at low temperature. This structure was formed by a radio-frequency glow discharge process at 230°C and then irradiated by a pulsed XeCl excimer laser at room temperature. Simultaneous crystallization and uniform diffusion of the dopant atoms was achieved. The 240 nm-thick boron-doped poly-Si film had a sheet resistivity of 23 Ω/□ ($\rho=5.5\times10^{-4}$ Ωcm).

§1. Introduction

Pulsed-excimer laser doping techniques which form shallow source and drain regions in metal-oxide semiconductor (MOS) transistors[1-3] have made it possible to reduce processing temperatures, since melting is rapid and heating of an entire substrate is unnecessary. Reduced processing temperatures will make it possible to reduce the device dimensions, and thereby increase the speed and packing density of MOS circuits.

In this paper we report the use of a structure composed of alternating layers of hydrogenated amorphous silicon (a-Si:H) film and either phosphorus or boron film to fabricate low-resistivity polycrystalline silicon (poly-Si) film at low temperatures. This structure is formed using a radio-frequency glow discharge (rf-GD) process and then irradiated by a pulsed XeCl excimer laser. Low-resistivity poly-Si films fabricated at low temperatures are suitable for use as electrodes and interconnecting materials in thin-film transistor circuits fabricated on glass substrates as well as in MOS circuits.

§2. Experimental

An a-Si:H film and a dopant film were deposited on a glass substrate by decomposing SiH_4, B_2H_6 and PH_3 by rf-GD. In this process, Ar was used to dilute SiH_4 to 10%, and both B_2H_6 and PH_3 to 1%. All gases were then introduced into a diode-type plasma reactor. The pressure, substrate temperature, and rf power were 200 mTorr, 230°C, and 5 W, respectively.

To study the doping behavior of boron and phosphorus, two types of structures were fabricated. The first was fabricated by depositing a single layer of a-Si:H (250 nm) on a glass substrate and subsequently depositing a single layer of dopant (dopant/a-Si:H). The deposition time for both dopant and a-Si:H film was 10 minutes. The thickness of the boron film was about 10 nm. However, the thickness of the phosphorus film was less than 2 nm, since the deposition rate for phosphorus was lower. The second was a 20-layer structure fabricated by repeatedly depositing alternating layers of an a-Si:H film and a dopant film of either boron or phosphorus. The thickness was 250 nm. The deposition time for each layer of both the a-Si:H and dopant film was 1 minute.

Both samples were then placed perpendicular to a laser beam in a laser-processing chamber and irradiated in He gas. The beam size was 5×8 mm^2 on the surface of the sample. The samples were not heated. A XeCl-excimer laser beam, with a pulse width of 30 ns pulsing 10 pps, was focused on and scanned across the surface using an optical scanning device mounted on an X-Y stage. The laser-energy density was controlled using density filters.

Using the results of our studies on the crystallization of a-Si:H by irradiation of excimer laser,[4] the laser-energy density was chosen to be 180 to 270 mJ/cm^2. Cross-sectional transmission electron microscopy (TEM) revealed that the a-Si:H film began to crystallize when the energy density reached 150 mJ/cm^2, and that only the top 130 nm of the film was crystallized by a laser pulse at 220 mJ/cm^2. When the laser irradiation is above 240 mJ/cm^2, explosive evaporation of hydrogen atoms can occur and damage the film. To overcome this problem, we used a two-step irradiation process in which the sample was first irradiated by 10 pulses at 170 mJ/cm^2 to release the hydrogen atoms, and then again irradiated by 10 pulses above 180 mJ/cm^2 to improve the crystallization.

From the observations, using a time-resolved reflectivity measurement system with an Ar-514.5 nm laser as the probe light, it was determined that crystallization had occurred through a melt-regrowth process. Figure 1 shows the change in the reflectivity of the hydrogen-released film during treatment by a laser pulse at 220 mJ/cm^2. The high-reflectivity phase, associated with surface melting, lasted 40 ns. Since the diffusion coefficient of boron and phosphorus in molten silicon is in the order of 10^{-4} cm^2/s,[5] which is much larger than that of 10^{-11} cm^2/s[6] in solid silicon, the dopant could easily diffuse into the molten silicon.

§3. Results and Discussion

Figure 2 shows the sheet resistivity (R_s) plotted against the laser energy for both samples when the dopant was phosphorus. Figure 3 shows the sheet resistivity plotted against the laser energy for both samples when the dopant was boron. In Fig. 2, when the laser energy was increased from 190 to 270 mJ/cm^2, R_s for the single-layer phosphorus/a-Si:H film and for the phosphorus/a-Si:H

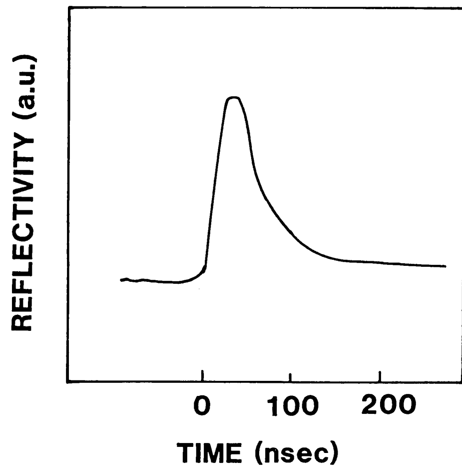

Fig. 1. Time-dependent reflectivity measured using an Ar-514.5 nm probe-laser beam during laser treatment with a 30 ns-pulsed XeCl excimer laser at 220 mJ/cm^2. Before the measurement, the a-Si:H film was subjected to laser irradiation with 10 pulses from a laser operating at 170 mJ/cm^2 in order to release the hydrogen atoms.

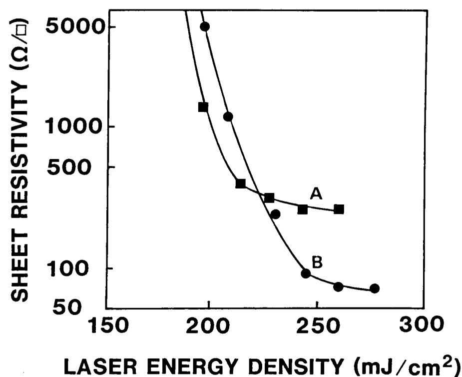

Fig. 2. The dependence of sheet resistivity on laser-energy density for single-layer phosphorus/a-Si:H films (A) and films with a 20-layer structure with alternating layers of a-Si:H and phosphorus(B), respectively.

film with a layered structure decreased to 300 Ω/□ and 70 Ω/□, respectively. In Fig. 3, when the laser energy was increased from 190 to 270 mJ/cm^2, R_s for the single-layer boron/a-Si:H film and for the boron/a-Si:H film with a layered structure decreased to 160 Ω/□ and 60 Ω/□, respectively. These figures show that a great amount of reduction in R_s occurs when the dopant of either phosphorus or boron is used with a multiple-layer structure, indicating that a large number of dopant atoms efficiently diffuses into the silicon. However, since only the top 130 nm region of the a-Si:H film was crystallized, as previously noted, the doped poly-Si film was formed near the surface region of the samples.

In order to fabricate a thick heavily doped poly-Si film, we repeated the deposition of multiple-layer structure and the irradiation with laser pulses as previously described. First, a 120 nm-thick doped poly-Si film was fabricated by depositing a 120 nm-thick 10-layer structure composed of alternating layers of a-Si:H and dopant films, followed by the irradiation of laser pulses. A second, 120 nm-thick film with a layered structure was then deposited on the doped poly-Si film, and irradiated. In this way, a 240 nm-thick heavily doped poly-Si film can be fabricated. Figure 4 shows that the R_s for heavily

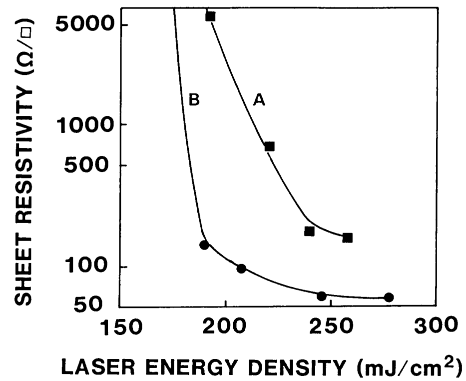

Fig. 3. The dependence of sheet resistivity on laser-energy density for single-layer boron/a-Si:H films (A) and films with a 20-layer structure with alternating layers of a-Si:H and boron (B), respectively.

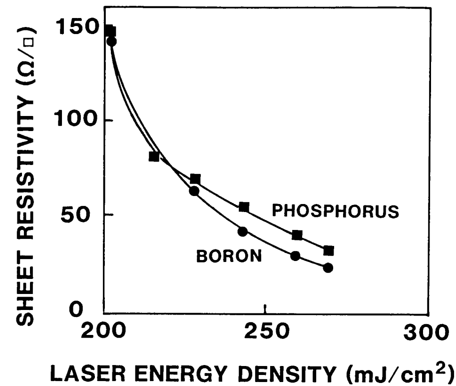

Fig. 4. The dependence of sheet resistivity on laser energy density for 240 nm-thick poly-Si films doped with either phosphrous or boron fabricated by repeating the fabrication and irradiation processes to obtain a second 120 nm-thick film on top of the first.

doped poly-Si films with either phosphorus or boron decreased to 33 Ω/□ and 23 Ω/□ when irradiated by 10 laser pulses at 270 mJ/cm^2, respectively. The resistivity for the phosphorus-doped poly-Si film and the boron-doped poly-Si film was then 7.9×10^{-4} Ω.cm and 5.5×10^{-4} Ω.cm, respectively. The resistivity of phosphorus-doped poly-Si film was comparable to that of a phosphorus-doped poly-Si film fabricated by a conventional chemical vapor deposition, followed by furnace annealing at 1200°C.[7] On the other hand, the process of the fabrication of the boron-doped poly-Si film, using the laser-doping technique previously described, provided much lower resistivity than the conventional process of chemical vapor deposition and subsequent furnace annealing.[8]

The Hall-effect measurement revealed that the phosphorus-doped poly-Si film with R_s of 33 Ω/□ had a carrier concentration of 3.8×10^{20} cm^{-3} and a Hall mobility of 21 cm^2/V.s, and that the boron-doped poly-Si film with R_s of 23 Ω/□ had a carrier concentration of 8.3×10^{20} cm^{-3} and a Hall mobility of 13 cm^2/V.s. The carrier concentration of the boron-doped poly-Si film exceeds the solid solubility limit of boron in crystalline silicon (6×10^{20} cm^{-3}),[6] indicating that the rapid melt and solidification process causes a large number of impurities to be incorporated into the substitutional sites of the silicon. Moreover, the Hall mobility of the heavily doped poly-Si films is much larger than that of the a-Si:H

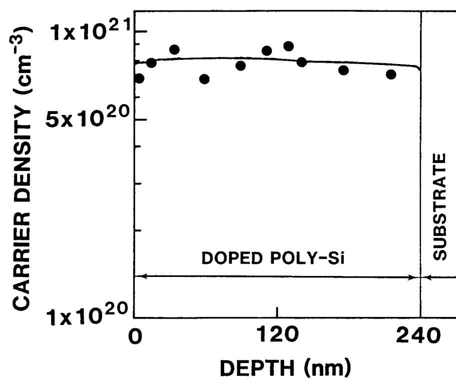

Fig. 5. The in-depth carrier profile for the 240 nm-thick boron-doped poly-Si film with a sheet resistivity of 27 Ω/□ fabricated by repeating the fabrication and irradiation processes.

film ($\leq 1\ cm^2/V.s$),[9] indicating that the a-Si:H is well crystallized.

Figure 5 shows the in-depth carrier concentration profile of the 240 nm-thick boron-doped poly-Si film with R_s of 27 Ω/□, obtained by the combination of etching step by step with CF_4 plasma, and the repetition of the Hall-effect measurement. Carrier concentration distributes uniformly at $8 \times 10^{20}\ cm^{-3}$ throughout the poly-Si film. This indicates that boron atoms diffuse uniformly from the multiple boron layers into the silicon layers.

§4. Summary

Heavily doped poly-Si film was successfully fabricated on a glass substrate at 230°C using a structure composed of alternating layers of hydrogenated amorphous silicon film and either phosphorus or boron film which were then melted using a laser-doping technique. The laser irradiation caused the a-Si:H to crystallize and the dopant to diffuse simultaneously. When the deposition of a 120 nm-thick multiple-layer structure and irradiation processes were repeated, it was possible to fabricate a 240 nm-thick heavily doped poly-Si film whose R_s was 33 Ω/□ when phosphorus was the dopant and 23 Ω/□ when boron was the dopant. Carrier concentration distributes uniformly at $8 \times 10^{20}\ cm^{-3}$ in 240 nm-thick boron-doped poly-Si films with R_s of 27 Ω/□.

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