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Characterization of pulsed laser crystallization of silicon thin film

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Abstract

Increases in the melt duration of silicon films were achieved by electrical current heating during and after pulsed excimer laser heating. When 50 nm thick amorphous silicon films formed on glass substrate were irradiated by 28-ns-pulsed excimer by applying 1.8 μs long pulsed-voltage at 100 V to the films, the silicon films were melted for the duration of the voltage pulse. The power threshold for heat energy for this long melting by the self-heating effect of the silicon films was 3.0×10^5 W/cm^2. The high electrical conductivity of the silicon film (2.9×10^{-2} S/cm) was found after regrowth of the silicon using a laser energy density of 360 mJ/cm^2 and a pulsed voltage of 150 V. The advantages of the long melt duration for large crystalline growth are discussed. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Joule heating; Thin film; Electrical conductivity; Long melting; Defect state

1. Introduction

Polycrystalline silicon films have been applied to many devices such as high-efficiency solar cells and thin-film transistors (TFTs) [1]. The importance of making polycrystalline silicon films at low cost has been demanded in recent years. To obtain high-quality polycrystalline silicon films, the grain boundaries and defects exert a profound influence on the device characteristics and degrade the carrier transportation. Many fabrication processing technologies for large-grained polycrystalline silicon films have been reported. There are, for example, rapid thermal annealing, laser

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annealing, electron beam annealing and graphite-stripe heating [2–4]. Laser annealing has many advantages for the formation of polycrystalline silicon films at a low temperature and causes good grain with low density of defect states. In order to fabricate crystalline silicon for photovoltaic devices, large crystalline grain growth is one of essential points. We, in this paper, investigated two methods to increase the melt duration for large grain growth. One is heating substrate, which reduces heat diffusion in melt-regrowth process at laser irradiation. The other one is self-current heating effect, which resulted from applying a pulsed voltage to the silicon films during and after laser irradiation. We report the melt-regrowth characteristics obtained by transient conductance measurements. We also discuss electrical conductivity of polycrystalline silicon films formed by present methods.

2. Experimental

Fig. 1 shows a schematic diagram of the experimental system. 50 nm thick amorphous silicon films were formed on quartz substrates by low-pressure chemical vapor deposition (LPCVD). Silicon islands with a width of 50 μm were defined. Al gap electrodes with a length of 250 μm were formed on silicon stripes. The samples were placed in a vacuum chamber, which was then evacuated by a turbo molecular pump to $1.5 \times 10^{-}4$ Pa. For investigation of substrate heating effect, the temperatures of substrates used were room temperature, 200°C and 250°C. A bias voltage of 10 V was applied to the Al gap electrodes for transient conductance measurement at the laser

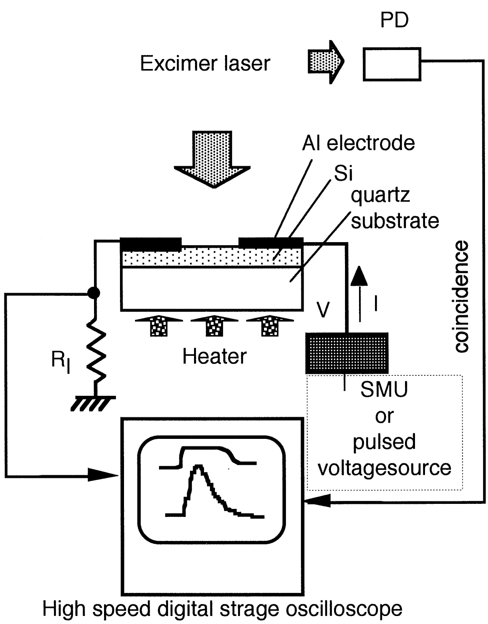

Fig. 1. Schematic diagram for transient conductance measurement.

irradiation. 28 ns pulsed 308 nm XeCl excimer laser was irradiated to the sample placed in the chamber. The incident laser energy density was varied using an equipment of optical attenuation. The laser beam area was 8.5 mm × 10 mm at the sample surface. Multiple laser irradiation was provided for the samples. Laser energy density was increased stepwise from 60 to 410 mJ/cm^2. Changes in the electrical conductance of the silicon films caused by laser irradiation were measured using a high-speed storage oscilloscope as changes in voltage of 50 Ω load resistance connected to silicon. The transient sheet conductance G was obtained using the equation

$$G = \frac{I}{V - (R_c + R_\ell)I} \times \frac{L}{W},$$

where I is transient current, V is bias voltage, R_c the resistance of the Al electrodes plus contact resistance of 195 Ω, R_ℓ the load resistance of 50 Ω and L/W the geometric factor 250/50 μm of the samples.

For investigation of current-induced joule heating effect, we used silicon films 50 nm thick doped with phosphorus atoms at $7.4 \times 10^{17}\,\mathrm{cm}^{-3}$ using the ion implantation method. Samples defined as strips with a width of 50 μm and a length of 250 μm with Al electrodes were placed in a vacuum chamber and connected with metal probes to Al electrodes to apply electrical voltages to the silicon films. A voltage source generating pulsed voltages with a pulse width of 3 μs was used to heat silicon films. The pulsed voltages were applied to the samples. In coincidence with voltage pulse, samples were irradiated with 28 ns pulsed XeCl excimer laser to melt silicon films partially during voltage application. Because of experimental system delay, laser pulses were shined to samples about 1.2 μs after the initiation of pulsed voltage application. Although silicon films have a high resistivity in solid phase at room temperature because of a low carrier density, the resistance of silicon markedly decreases when silicon is melted because liquid silicon has the metallic phase. Laser-induced melting during voltage application therefore causes a high joule heating per unit area induced by electrical current, I^2R_{Si}/S, where S is the area (width × length) of silicon films. The electrical current was measured as a voltage at a load resistance connected between sample and ground using a high-speed digital oscilloscope.

3. Results and discussion

Fig. 2 shows changes in electrical conductance per unit area of the silicon films with time when the laser energy density was 240 mJ/cm^2 at room temperature, 200°C and 250°C. High conductance associated with silicon melting appeared. It increased to 0.015 S/sq during laser irradiation. The fact that electrical conductivity of liquid silicon is 12 000 S/cm (0.06 S/sq) explains why the silicon films were partially melted in only the surface regions by the laser irradiation. After irradiation, the electrical conductance gradually reduced to zero owing to solidification of liquid silicon. Duration of electrical conductance detected gives the melt duration of silicon films. The melt duration was 90 ns for the initial temperature at room temperature. The melt

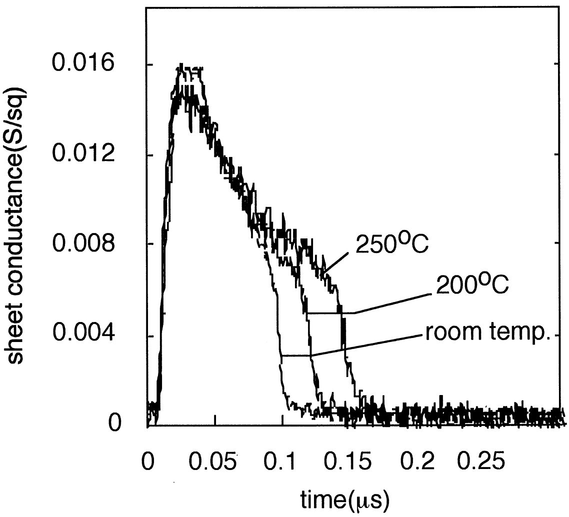

Fig. 2. Changes in electrical conductance caused by 28 ns XeCl excimer laser irradiation with a laser energy density of 240 mJ/cm^2 for 50 nm thick silicon films when the samples were heated to 200°C and 250°C as well as at room temperature.

duration was increased to 140 ns as the substrate temperature increased to 250°C. This means that high substrate temperature reduced diffusion of thermal energy generated in silicon films by laser irradiation.

Experiments of current-induced joule heating of silicon resulted in changes in the electrical conductance with time for laser irradiation with densities of 186 and 356 mJ/cm^2 as shown in Fig. 3. Pulsed voltage was applied at 100 V to the samples. A small electrical conductance of 0.013 S/sq was observed in the case of 186 mJ/cm^2 and its melt duration was about 100 ns, as shown in the left curve of Fig. 3. Silicon films were partially melted by laser irradiation and the small molten region gave the small electrical conductance. On the other hand, a very large electrical conductance was observed in the case of 356 mJ/cm^2 irradiation and its melt duration was 1.8 μs, as shown in the right curve of Fig. 3. This means that the long melt duration was achieved for silicon by a combination of laser irradiation with the high pulsed voltage application. The melt duration was almost same as the pulse duration of pulsed voltages. Laser irradiation at 356 mJ/cm^2 increased the electrical conductance to 0.018 S/sq at first. Joule heating with 3.1×10^5 W/cm^2 was then generated by electrical current caused by applying 100 V to the silicon islands. Melting of silicon films were induced by the current heating and melting continued after irradiation. The electrical conductance increased to 0.045 S/sq at maximum. It means that silicon was melted almost completely for a long time compared with simple laser-induced melting case. On the other hand, electrical conductance and joule heating were not sufficient to increase the melt duration for 186 mJ/cm^2 irradiation case. Fig. 4 shows melt duration as a function of laser energy density when pulsed voltages were applied to the samples

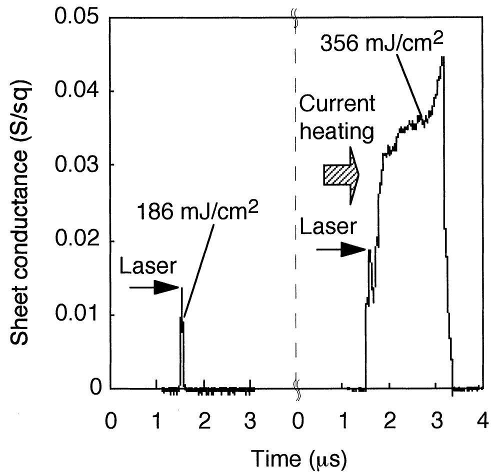

Fig. 3. Change in electrical sheet conductance as functions of time for laser irradiation with densities of 186 and 356 mJ/cm^2 during 100 V pulsed voltage application.

at laser irradiation. The melt duration with the pulsed voltage of 50 V increased slightly as the laser energy density increased. The melt duration with pulsed voltages 100 and 150 V also increased slightly when the laser energy density was low. The melt duration increased markedly to about 1.8 μs at 330 mJ/cm^2 irradiation for the 100 V voltage application case and at 225 mJ/cm^2 irradiation for the 150 V voltage application, respectively. The laser-induced melting reduced the resistance of silicon films. The resistance decreased as the laser energy density increased because of melting of deep regions of silicon films. A high initial resistance of silicon melted partially by laser heating at a low energy density needs a high voltage in order to cause a high enough joule heating intensity at $I^2R_{\mathrm{Si}}/S(=V_0^2R_{\mathrm{Si}}/\{R_{\mathrm{Si}}+R_\ell)^2S\})$ to melt silicon for a long time after laser irradiation. The results of Figs. 3 and 4 clearly give evidences of current-induced joule heating resulting in melting of silicon. The threshold intensity of the joule heating to cause a long and complete melting of silicon was obtained as 3.0×10^5 W/cm^2.

Fig. 5 shows the electrical conductivity as functions of pulsed voltages for silicon after a laser irradiation of 360 mJ/cm^2. The Al gap electrodes with a length of 2 μm were formed on silicon in order to obtain the electrical conductivity. The electrical conductivity of silicon increased from 2.5×10^{-6} (no voltage application) to 2.9×10^{-2} S/cm as pulsed voltage increased to 150 V, which was very large conductivity compared to that of the as-crystallized polycrystalline silicon by simple laser irradiation [5]. This result means that long melting duration caused large grain growth. There must be a region of small number of grain boundaries between the electrodes with the gap of 2 μm. These experimental results show that the joule heating induced by electrical current is effective to increase melt duration, which is an essential point to form large crystalline grains.

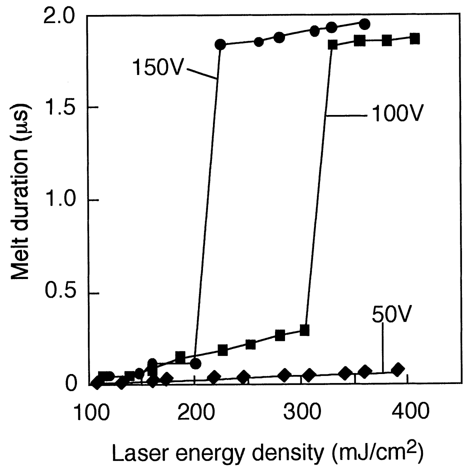

Fig. 4. Melt duration as functions of laser energy density during pulsed voltages of 50,100 and 150 V application.

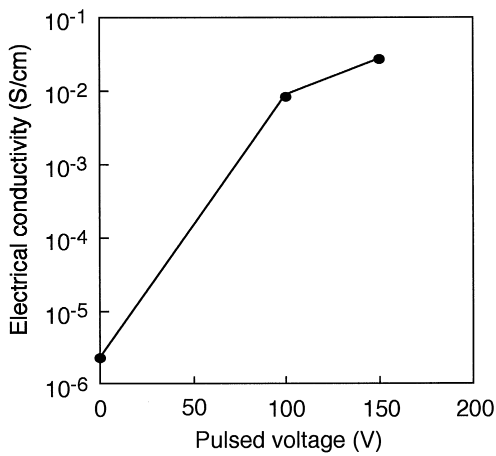

Fig. 5. Electrical conductivity as functions of pulsed voltages for laser energy density of 360 mJ/cm^2. The 2-μm-gap electrode was used for the electrical current measurements.

4. Conclusion

We investigated laser-induced melt-regrowth characteristics of 50 nm-silicon films for looking for conditions to achieve large crystalline grain growth by two heating methods. One is the substrate heating method to reduce heat diffusion induced by laser irradiation into glass substrates. Melt duration of the silicon films increased from 90 to 140 ns by substrate heating of 250°C at 240 mJ/cm^2 laser irradiation. The other method is the electrical current-induced joule heating of silicon. When 3 μs-pulsed voltage of 100 V was applied to the silicon films at melting initiation, the silicon films were melted for 1.8 μs in the case of 356 mJ/cm^2 laser irradiation. Current-induced joule heating in silicon at powers higher than 3.0×10^5 W/cm^2 effectively kept the liquid state for a long time against heat diffusion into substrate. The high electrical conductivity of the silicon film, 2.9×10^{-2} S/cm was observed after electrical current induced joule heating of 5.7×10^{17} cm^{-3} phosphorus-doped silicon films with a laser energy density of 360 mJ/cm^2 and a pulsed voltage of 150 V. This result means that polycrystalline silicon films with a large grain size were formed. Long melting will be an advantage for the formation of large crystalline grain silicon films.

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