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Crystallization of silicon thin films by current-induced joule heating

T. Sameshima*, K. Ozaki

Tokyo University of Agriculture and Technology, Tokyo 184-8588, Japan

Abstract

Electrical-current-induced joule heating was applied to the crystallization of silicon films formed on glass substrates. Electrical energy accumulated at a capacitance was applied to the silicon films. Coincident irradiation with 30-ns-pulsed laser melted films partially reduced their resistance. Complete melting of 42 μs and solidification duration of 28 μs were observed in the case of heating at a capacitance of 2 μF The analysis of electrical conductivity reveled a density of defect states of 1.3×10^{12} cm^{-2} at grain boundaries. The formation of 15-μm crystalline grains was observed. The preferential crystalline orientation was (110).

Keywords: Electrical-current-induced joule heating; Crystallization; Silicon films

1. Introduction

Polycrystalline silicon films have been applied to many devices such as thin film transistors (TFTs) and solar cells [1,2]. Many technologies have been reported for the formation of polycrystalline silicon films at low processing temperatures [1–3]. The pulsed laser crystallization method has an advantage for the formation high-quality polycrystalline silicon films because of rapid melting followed by solidification. It is important to fabricate large crystalline grains with a low density of defect states, especially for solar cell application. Several methods have been reported for the formation of large crystalline grains using the pulsed laser crystallization method [4]. We have also reported the possibility of crystallization of silicon films with electrical-current-induced joule heating [5].

In this paper, we report a crystallization method with pulsed-electrical current-induced heating of silicon films in order to fabricate large crystalline grains. We demonstrate that silicon thin films are melted for a long time and their melt duration is easily controlled by electrical current intensity. Electrical and optical properties of the crystalline film are presented. Large grain growth is demonstrated.

2. Experimental

Undoped 60-nm-thick amorphous silicon films were formed by low-pressure chemical vapor deposition (CVD) methods on quartz glass substrates. Some silicon films were doped with phosphorus atoms at 7.4×10^{17} cm^{-3} using the ion implantation method. Undoped and lightly doped silicon stripes with a width of 50 μm were defined. Al electrodes with a gap of 250 μm were formed on the silicon stripes. Samples were connected to metal probes to apply electrical voltages. The voltages were applied to the silicon stripes as well as the capacitance in parallel, as shown in the inset of Fig. 1. Simultaneous with voltage application, samples were irradiated by a 30-ns pulsed XeCl excimer laser to partially melt the silicon films. Although silicon films have high resistivity in the solid phase at room temperature because of a low carrier density, the resistance of

* Corresponding author. Tel.: +81-423-88-7109; fax: +81-423-88-7109.
E-mail address: tsamesim@cc.tuat.ac.jp (T. Sameshima).

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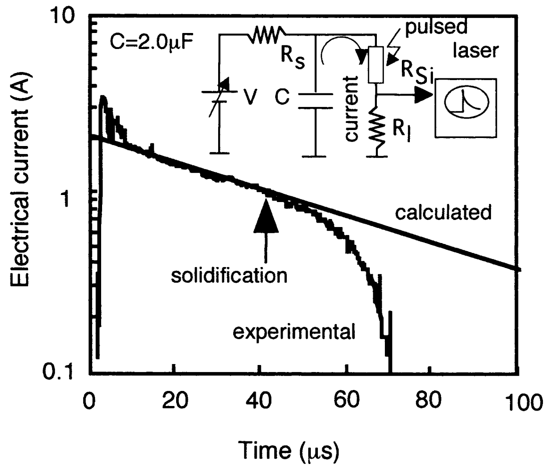

Fig. 1. Changes in the electrical current flowing in 60-nm-thick silicon stripes. The samples were heated by laser irradiation at 400 mJ cm^{-2} during application of a voltage at 130 V. Equivalent circuit is shown in the inset. Series resistance *R*, and load resistance *R*, were 1 KΩ and 5 Ω.

silicon markedly decreases when it is melted, because liquid silicon has a metallic phase. Laser-induced melting during voltage application therefore leads to a high joule heating per unit area induced by the electrical current, I^2R_{Si}/S, where S is the area (width × length) of silicon films.

3. Results and discussion

Fig. 1 shows changes in the electrical current flowing in the silicon films obtained experimentally with a capacitance of 2.0 μF as a function of time. High electrical current was observed by laser irradiation at 400 mJ cm^{-2} due to rapid melting of silicon films. The electrical current was still observed after the termination of the laser pulse due to the electrical-current-induced joule heating. Fig. 1 also shows the calculated change in the electrical current flowing in the silicon films with time constants $(R_{si}+R_l)C$ under the assumption that the silicon film was completely melted and had a constant and minimum resistance. Both experimental and calculated electrical currents decreased with time for a while, keeping the same current. This means that the resistance of silicon films did not change because the current-induced joule heating kept the silicon at the melted state. However, a rapid decrease in the electrical current was observed at the point indicated by arrows in Fig. 1 compared with the calculated current. This reduction of the electrical current means an increase in the resistance of the silicon films. It indicates the solidification initiation point. Fig. 2 shows the duration of complete melting and the solidification duration as a function of capacitance. The complete melting continued for 42 μs as the capacitance increased to 2 μF after 30-ns-pulsed laser irradiation. The solidification duration also increased to 28 μs. This means that the present current-induced joule heating makes it possible to control the melt duration and the solidification duration, which are important parameters in the crystallization of silicon films. We estimated the cooling rate with numerical analysis of heat diffusion into glass substrate under the condition of time-dependent joule heating [6]. The intensity of the electrical-current-induced joule heating at silicon films per unit volume was estimated from the electrical current measured at the load resistance. The cooling rate was calculated at the solidification initiation point under the assumption that silicon solidified at the melting point. The cooling rate at the solidification point markedly decreased from 6.5×10^8 K s^{-1} to 2×10^7 K s^{-1} as the capacitance increased from 0 to 2.0 μF. It is possible to control the cooling rate by the present current-induced-joule heating, and that the cooling rate was reduced accompanied by an increase in melt duration caused by heating for a long time using high capacitance.

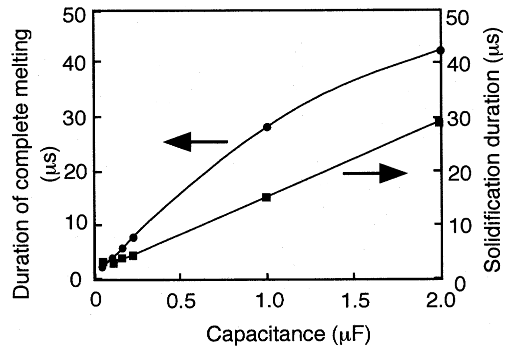

Fig. 2. Duration of complete melting and solidification as functions of capacitance.

Fig. 3a shows a photograph of the bright-field image at the edge region of silicon stripes crystallized by the present method at a capacitance of 0.22 μF. Crystalline grains approximately 3.5 μm long were formed from the edge. The width of the grains was rather narrow at

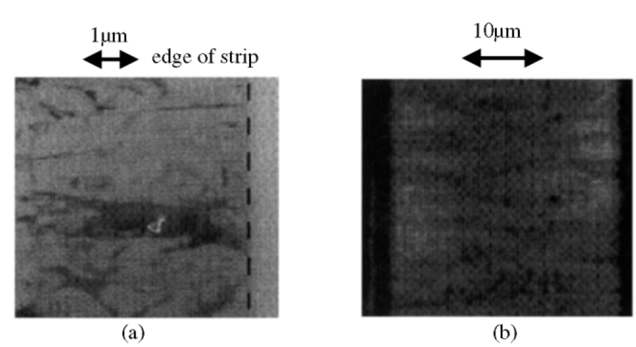

Fig. 3. Photographs of the bright field image at the edge region of silicon stripes crystallized by the electrical current-induced joule heating method with a capacitance of 0.22 μF (a) and of Secco etched films crystallized at 1.0 μF (b).

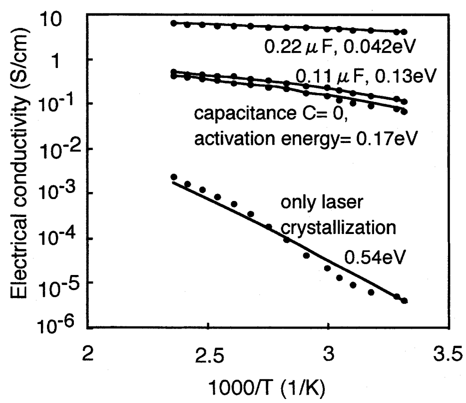

Fig. 4. Electrical conductivity measured (dotted curves) and calculated (solid curves) as a function of reciprocal absolute temperature for 7.4×10^{17} cm^{-3} phosphorus-doped silicon films crystallized at 0.11, 0.22 μF and zero capacitance as well as for simple laser crystallization at 400 mJ cm^{-2}. Inset presents image of Al electrodes with a narrow gap of 4 μm formed at the edge region of silicon strips after crystallization.

approximately 0.5 μm. Crystalline grains were formed close to each other and there is no marked disordered region among them. The preferential crystalline orientation direction to the substrate was (110). The distribution of preferential orientation was $\pm 1°$ among the crystalline grains. The large grain growth at the edge region indicates that crystallization initiated at the edge of the silicon stripes and proceeded inside because there were temperature gradient at the edge region due to high heat dissipation from the edges. Fig. 3b shows a photograph of the distribution of crystalline grains treated slightly by Secco etching in the case of crystallization with at a capacitance of 1.0 μF. Formation of crystalline grains approximately 15 μm long were observed. These results indicate the possibility of crystalline grain growth in the lateral direction using the present heating method and with a certain method for the formation of a temperature gradient.

Fig. 4 shows the electrical conductivity as a reciprocal function of absolute temperature for 7.4×10^{17} cm^{-3} phosphorus-doped silicon films crystallized by the electrical current-induced joule heating at capacitances of 0.11 and 0.22 μF and at zero capacitance, as well as for simple laser crystallization at 400 mJ cm^{-2}. For simple laser crystallization, the electrical conductivity was very low at room temperature. On the other hand, high electrical conductivity was observed for the electrical current-induced joule heating cases and the activation energy decreased, as shown in Fig. 4. We analyzed changes in the electrical conductivity of polycrystalline films using a statistical thermodynamical analysis program [7] involving a Gaussian-type defect state at a deep energy level at grain boundaries. The Fermi energy level is determined by the statistical thermodynamical conditions maintaining the charge neutrality among the densities of ionized dopant atoms, defect states charged negatively with electron carriers and free carriers. For crystallization at zero capacitance, the density of defect states per unit area was estimated to be 1.5×10^{12} cm^{-1}, which was much lower than that of 3.8×10^{12} cm^{-3} for silicon films formed by laser crystallization. The density of defect states further decreased to 1.3×10^{12} cm^{-2}. On the other hand, the calculation of temperature change in the electrical conductivity assuming no defect states showed good agreement with the experimental result for crystallization of 0.22 μF, as shown in Fig. 4. Single-domain crystalline regions were probably formed in the 4-μm-long electrodes.

4. Summary

We investigated electrical current-induced joule heating for crystallization of silicon films. Voltages and coincident irradiation with 30-ns-pulsed excimer laser at 400 mJ/cm^{-2} were applied to 60-nm-thick amorphous silicon films formed on glass substrates and capacitance connected in parallel. A large electrical current flowed in the silicon films and its joule heating melted silicon films completely for a long time. The joule heating from electrical energy accumulated at a capacitance of 2.0 μF caused a duration of complete melting and solidification duration of 42 and 28 μs, respectively. Heat flow analysis gave a cooling rate of 2×10^{7} K s^{-1}. Transmission electron microscopy revealed that crystalline grains were formed with the preferential orientation of (110); 15-μm-long crystalline grain growth was observed. The statistical thermodynamical analysis of the electrical conductivity indicated the density of the defect state at grain boundary plane was approximately 1.3×10^{12} cm^{-2} crystallization with a capacitance of 0.11 μF.

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References

[1] T. Sameshima, S. Usui, M. Sekiya, IEEE Electron Dev. Lett. 7 (1986) 276.
[2] Y. Chida, M. Kondo, A. Matsuda, J. Non-Cryst. Solids 198-200 (1996) 1121.
[3] K.H. Lee, J.K. Park, J. Jang, IEEE Trans. Electron Dev. 45 (1998) 2548.
[4] J.S. Im, H.J. Kim, Appl. Phys. Lett. 64 (1994) 2303.
[5] T. Sameshima, K. Ozaki, N. Andoh, Appl. Phys. A (in press).
[6] R.F. Wood, G.E. Giles, Phys. Rev. B 23 (1981) 2923.
[7] Y. Tsunoda, T. Sameshima, S. Higashi, Jpn. J. Appl. Phys 39 (2000) 1656.