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著者	Kitagawa Akio, Takeuchi Masaki, Futagi Sadaki, Kanai Syungo, Tubota Kazunori, Kizu Yasuhiro, Suzuki Masakuni
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High Speed Crystallization of a-Si by Lateral Sweep Annealing in Steep Temperature Gradient

Akio KITAGAWA[†], *Member*, Masaki TAKEUCHI[†], Sadaki FUTAGI[†],
Syungo KANAI[†], Kazunori TUBOTA[†], Yasuhiro KIZU[†], *Nonmembers*
and Masakuni SUZUKI[†], *Member*

SUMMARY The a-Si films deposited on quartz substrates were crystallized by lateral sweep annealing in steep temperature gradient using a gas burner. Random nucleation in amorphous region was effectively suppressed in the temperature gradient, so lateral solid phase epitaxial growth from crystallites generated at the initial stage of lateral sweep annealing spread over 100 μm. Their crystallographic orientations were mostly (100).

***key words:** SOI structure, crystallization, poly-Si film, gas flame annealing, solid phase epitaxy*

1. Introduction

Silicon on Insulator (SOI) structures are important in the fabrication of high speed microelectronic devices. Poly crystalline silicon (poly-Si) of good electronic properties is also required especially for the fabrication of thin film transistors in giant-microelectronics. For the improvement of electronic properties of poly-Si films, the enlargement of grain size and the reduction of defect states in grain boundaries are effective.

In any field, low temperature processes are desirable. As the solid phase crystallization of amorphous silicon (a-Si) occurs far below the melting temperature of Si, it is an attractive phenomenon to obtain single crystalline Si or poly-Si films(1).

In solid phase crystallization, grain growth or solid phase epitaxial (SPE) growth rate increases with increasing temperature(2), but the annealing of a-Si at high temperature is not suitable for obtaining large grains. In the crystallization processes of amorphous solids, there exists the induction time for nucleation, which decreases with increasing temperature(3),(4). Thus, the solid phase crystallization is usually performed at the temperature lower than 600°C to minimize the conflict between random nucleation and the crystal growth. However, lateral SPE growth in a simple furnace annealing is limited to several ten micron meter so far(5),(6).

Lateral SPE growth length from the seed crystal can not exceed $V_g(T) \times t_{ind}(T)$, where $V_g(T)$ is the lateral SPE growth rate at temperature T and $t_{ind}(T)$ is the induction time for nucleation in amorphous solids at T(4). To enhance lateral SPE growth length, large $V_g(T)$ and/or t_{ind} are desirable. In fact, SPE growth rate of those P-doped a-Si is enhanced and large area lateral SPE growth has been achieved in P-doped a-Si(5),(6).

Another way to achieve large area lateral SPE growth is to develop the annealing method taking into account two contradictory factors(7), that is, temperature dependences of the induction time for nucleation and SPE growth rate. The solid phase crystallization should be performed at high temperature to promote SPE growth, while amorphous regions should be kept at low temperature to suppress random nucleation. We have, thus, developed the lateral sweep annealing of a-Si films in a steep terperature gradient, where a tungsten halogen Lamp or a ribbon heater (KANTHAL A-1) was used(7),(8). Laser and electron beam are also available in lateral sweep annealing in the steep temperature gradient.

The gas flame heating has some advantages of cost and processing speed, because gas flames can produce efficiently higher temperature than 1000°C on the sample surface. In this paper, we have studied the solid phase crystallization of a-Si films by the lateral sweep annealing using gas flame heating.

2. Experimental

A lateral sweep annealing apparatus for solid phase crystallization consists of a cooling pad with a shielding plate, a moving stage and a gas heating system as shown in Fig. 1. In order to raise the temperature of gas flames oxygen-mixed gas (C-6:hydrogen and lower hydrocarbon gases, 5000 kcal/h) was used. Sample films on the moving stage traveled on the tilted stand at a constant speed. The traveling speed of the moving stage was fixed on a value between 1～10 mm/s. A cooling pad wetted by water kept amorphous regions at low temperature.

The a-Si films with thickness of 0.2～0.7 μm were deposited on 0.5 mm thick quartz substrates at 300°C by electron-beam evaporation in a vacuum of <5×

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[†] The authors are with the Faculty of Technology, Kanazawa University, Kanazawa-shi, 920 Japan

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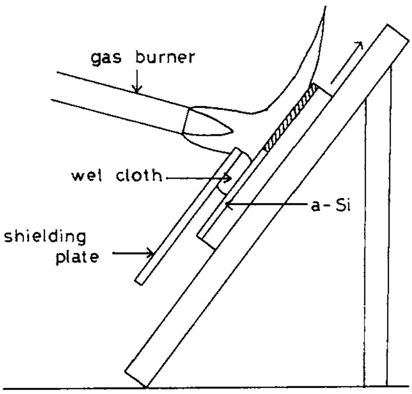

Fig. 1 Lateral sweep annealing apparatus using gas flame heating.

10^{-8} Torr, and then annealed at 400°C for 60 min without breaking vacuum to densify amorphous structures. The deposition source was p-type Si doped with boron, of which concentration was $2\times10^{16}\,\mathrm{cm}^{-3}$. The deposition rate of a-Si were 30 Å/min.

The temperature of the surface of sample films was estimated by measuring with a chromel/alumel thermo-couple attached on the quartz substrates. The distance between the nozzle of the gas burner and sample surfaces was set to 14 cm, at which the surface of the sample films was expected to be heated above 1000°C. The width of the sample films was limited to 5 mm to assure uniform heating.

Solid phase crystallization was investigated with transmission electron microscopy (TEM) and transmission electron diffraction (TED). Global observation by optical microscopy was performed for those samples etched in Wright etchant.

3. Results and Discussion

The temperature of the surface of sample films, which was measured with a chromel/alumel thermocouple attached on the quartz substrates, varied with traveling through gas flames, as shown in Fig. 2, where the traveling speed V was 1 mm/s. The temperature increased sharply and decreased slowly when passing through gas flames. From these results, the maximum temperature attained in the sample films was estimated to be about 1100°C, but the temperature gradient built in the sample films during lateral sweep annealing was not known because temperature measurements were performed without a cooling system to produce the temperature gradient.

Figures 3 (a) and (b) show TEM and TED pattern photographs for crystallized samples of the traveling speed of 1 mm/s and 4.3 mm/s, respectively. Grains of several micron meter were observed for the sample films processed at the traveling speed of 1 mm/s, while grains less than one micron meter were observed for the sample of the traveling speed of 4.3 mm/s. Although the crystallinity varied not only from sample to sample but from area to area even in one sample, TED patterns of crystallized samples were mostly (100) as shown in Figs. 4 (a) and (b). These results would be due to the predominance of the (100) growth rate in the SPE growth[(9)].

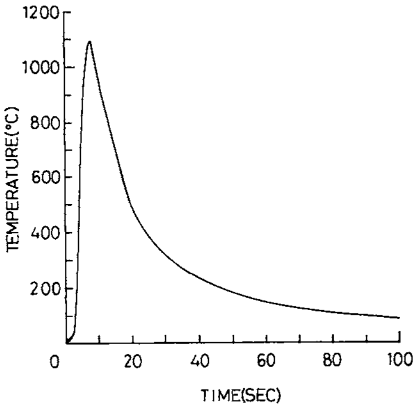

Fig. 2 Temperature variation along with the traveling through gas flames. Traveling speed is 1 mm/s.

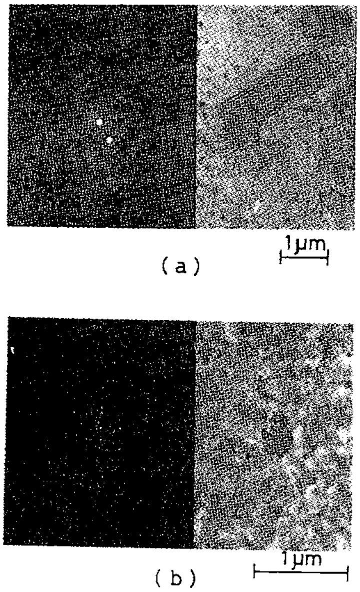

Fig. 3 TEM and TED patterns photographs of the Si films crystallized by lateral sweep annealing.
(a) Traveling Speed V = 1 mm/s. (b) V = 4.3 mm/s

Figures 4 (a) and (b) show Nomarski optical micrographs for the sample films etched in Wright

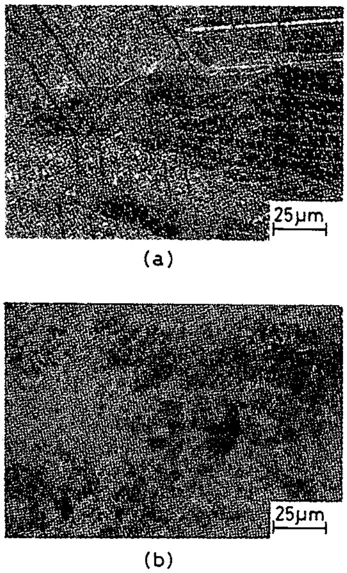

Fig. 4 Nomarski optical micrographs of two samples crystallized by lateral annealing and etched in Wright etchant. (a) was taken from the sample of V = 3.1 mm/s. (b) was taken on another sample of V = 1.6 mm/s.

etchant. They were taken on the samples of the traveling speed of 3.1 mm/s and 1.6 mm/s, respectively. A large lateral SPE growth area with subgrains spread over more than 100 μm as seen in Fig. 4 (a), while the grain size observed in Fig. 4 (b) were of the order of 10 μm.

These results indicate that the lateral SPE growth conditions were partly satisfied to and fro, in other words, those conditions were not satisfied over a whole range of sample films. Controllability of gas flames was insufficient and contact conditions between a cooling pad and sample surfaces were unsatisfactory during annealing.

The conditions of continuous SPE growth from the seed crystals are given(7),(8),

$$V < V_g(T) \qquad (1)$$

$$\int_0^L \exp[-Ea/kT]\,dx < \tau_0\, v, \qquad (2)$$

where V is the traveling speed of a-Si films in a steep temperature gradient, Ea is the activation energy for nucleation, τ_0 is the pre-exponential factor and L is the distance between the positions at $T = T_h$ and $T = T_l$.

In the present work, T_h and T_l are assumed to be 1100°C and 100°C respectively. Then, L is estimated to be less than 10 μm, so the average temperature gradient preventing random nucleation in amorphous regions must be steeper than 100°C/μm. Such a steep temperature gradient is so difficult to build up in the sample films, so Eq.(2) appeared not to be held. The SPE growth rate V_g at 1100°C is estimated to be 200 μm/s(1), which is so small compared to the traveling speed V, so Eq.(1) is also broken.

It is, however, certain from the experimental results that continuous SPE growth conditions were partly held in the present experimental set-up. The effective induction time for nucleation was calculated using the extrapolated values from low temperature regions, so we might have underestimated it. The temperature formed in the sample films during annealing might have also been underestimated, since the heat capacity of a thermo-couple was large compared to that of sample films. Then, continuous SPE growth conditions may be satisfied beyond our estimation.

Smooth surfaces were preserved after the lateral annealing by gas flames, but sometimes interference fringes due to surface undulation were observed in some areas under a microscope. Undulation occurs on the surface of molten Si over SiO_2, when the encapsulation layer is not thick enough(10), and a-Si films are reported to melt far below the melting temperature of Si under the condition of abrupt heating(11). Thus, grains seen in Fig. 4 (b) are likely to grow up in the molten region, since weak surface undulation was observed in Fig. 4 (b). Anyway, the temperature gradient built in the sample films and the temperature at the SPE growth front, which determines the traveling speed of sample films, are important factors.

4. Conclusion

It can be said that lateral annealing of a-Si films in a steep temperature gradient is suitable for the large grain growth, since random nucleation is effectively suppressed and the SPE growth from the seed crystals generated at the initial stage of annealing is promoted. Lateral solid phase epitaxial growth area spread over 100 μm.

Control of both temperature of gas flames and the contact conditions between the cooling pad and the surface of the sample was extremely important for SPE growth in the lateral sweep annealing. Single crystalline Si films over an entire substrate would be produced, if fluctuations of the traveling speed and the temperature during lateral annealing are minimized.

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