J-5-02 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp681-682

Characteristics of Rapidly Solid Phase Crystallized Amorphous Silicon Films Formed by Micro-Thermal-Plasma Jet Irradiation

Hoa Thi Khanh Nguyen[1], Hiroaki Hanafusa[1], Yuri Mizukawa[1], Shohei Hayashi[2], and Seiichiro Higashi[1]

[1] Hiroshima Univ.
Kagamiyama 1-3-1, Higashihiroshima, Hiroshima, 739-8530 Japan
Tel : +81-82-424-7655, E-mail : semicon@hiroshima-u.ac.jp
[2] Toray Research Center, Inc. Morphological Research Laboratory
3-7, Sanoyama 3-chrome, Otsu, Shiga, 520-8567 Japan

Abstract

This research investigated the characteristics of solid phase crystallized (SPC) of amorphous silicon (a-Si) films annealed by micro-thermal-plasma jet (μ-TPJ) at high temperature region. Nucleation temperature (T_c) increases from 985 to 1013°C when heating rate (R_h) increases from 4.45 x 10^5 to 8.86×10^5 K/s. The grain size is smaller than 60 nm and decreases when R_h increases. The theoretical results are fairly agreed with experimental results.

1. Introduction

Crystalline silicon thin-film transistors (c-Si TFTs) have attracted much attention because of their high field-effect mobility, high reliability, and ability to integrate complementary metal-oxide-semiconductor circuits [1]. In fabrication of c-Si TFTs, crystallization of a-Si is one of the key process technologies. One of the simple methods produce c-Si is making SPC-Si by annealing a-Si films. SPC mechanism at low temperature region has been investigated since the 70s of the last decade [2]. However, SPC kinetics at high temperature is still matter of research.

In this study, we investigate the mechanism of SPC at high temperature by annealing a-Si films using μ-TPJ irradiation. Using time-resolved reflectivity (TRR) method, T_c and crystalline volume fraction R_c can be extracted. High-resolution transmission electron microscopy (HRTEM) was used to investigate the grain size. A simple physical model is introduced to explain the phase transformation process from amorphous to crystalline in the microsecond regime.

2. Experimental

Experimental set-up is shown in Fig.1. It consists of a μ-TPJ to irradiate 150-nm-thick a-Si films and a high-speed camera (HSC) was set on the motion stage which moved linearly with sample in front of μ-TPJ with scanning speed (v) ranging from 350 to 800 mm/s. The He-Ne laser was introduced to objective lens of HSC and focused on the a-Si film. The transient reflectivity ($\mathcal{R}$) of Si films during μ-TPJ irradiation was collected by a photodiode connected with a fast oscilloscope through a bandpass filter.

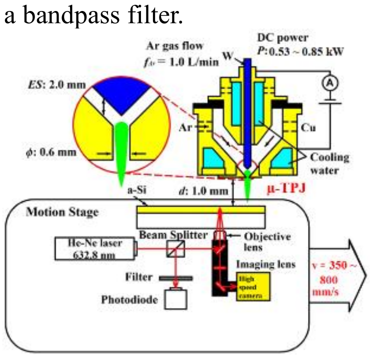

Fig.1. Experimental set-up

3. Results and discussion

Figure 2 shows a typical example of the transient $\mathcal{R}$ of 150-nm-thick a-Si film annealed by μ-TPJ under conditions of supplied power (P) as 0.61 kW, the distance between sample and anode (d) as 1.0 mm, argon gas flow rate (f_{Ar}) as 1.0 L/min, and v as 500 mm/s.

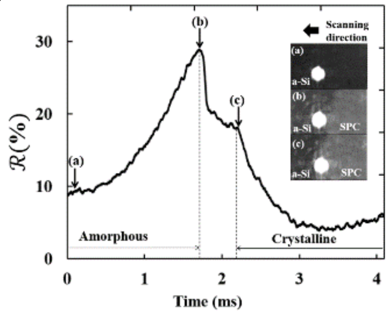

Fig.2. HSC snapshot and transient $\mathcal{R}$ of 150-nm-thick Si film during μ-TPJ irradiation under conditions of P = 0.61 kW, d = 1.0 mm, f_{Ar} = 1.0 L/min, and v = 500 mm/s.

The point (a), (b), and (c) correspond to point (a), (b), and (c) of HSC snapshots in the inset. As seen in the inset, the He-Ne laser spot is a bright spot. The transient $\mathcal{R}$ from (a) to (b) increases because of the increase in film temperature in amorphous phase. Nucleation occurs at (b) and phase transformation from amorphous to crystalline proceed until (c). The decrease in $\mathcal{R}$ from (b) to (c) is accounted as the change in R_c.

By obtaining the thermo-optic coefficient (TOC) of a-Si films, combining with the transient $\mathcal{R}$ as a function of time from Fig.2 (a) to (b), we can extract the dependence of a-Si film temperature on time as shown in Fig. 3. From this result, we can estimate the T_c to be 991 °C. The time for temperature increases from room temperature to T_c was 1.708 ms, and the average R_h was 5.66 x 10^5 K/s.

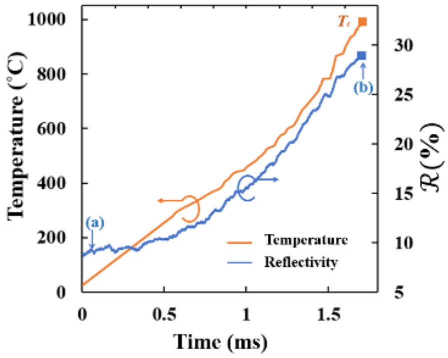

Fig.3. The transient variation of temperature and ℛ of a-Si film are extracted from Fig.2(a) to (b).

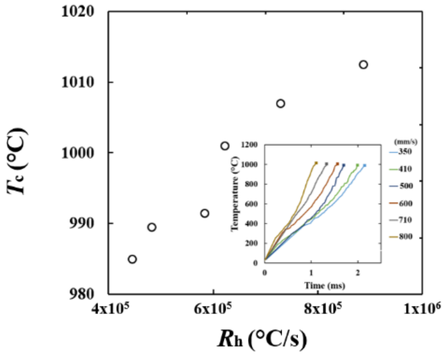

Fig.4. Dependence of T_c on R_h. The inset shows the transient variation of a-Si temperature measured under different v depends on heating time, ■ marks indicate the T_c.

The dependence of T_c on R_h are summarized in Fig. 4. The inset shows the transient variation of a-Si temperature measured under v from 350 to 800 mm/s. It is clearly seen that T_c increases from 985 to 1013 °C when R_h increases from 4.45×10^5 to 8.86×10^5 K/s. For our knowledge, this is the first experiment result reporting the temperature of nucleation in millisecond annealing.

The transient ℛ from Fig.2 (b) to (c) reflects the phase transformation of amorphous to crystalline. We consider the film as a homogeneous optical medium with an optical constant equal to a linear combination between amorphous and crystalline Si values [3]. Figure 5 shows examples of R_c as a function of time during phase transformation under v at 500 and 800 mm/s. The solid lines are experimental results, the dots are calculation results from our theoretical model which is presented in next part.

Figure 6 shows the HRTEM images of SPC films formed at v (a) of 500 mm/s, and (b) of 800 mm/s. When the v is 500 mm/s, rough estimation of grain size distribution is from 30 to 60 nm and when the v increases to 800 mm/s, most of the grains are smaller than 20 nm. It is clearly seen that the decrease of grain size is related to increasing of v.

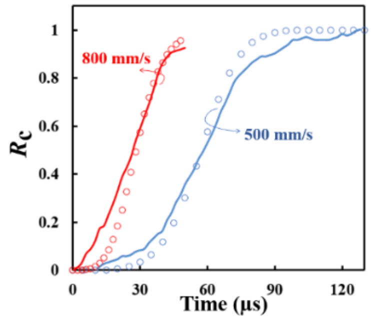

Fig. 5. Crystalline volume fraction as function of time during phase transformation when a-Si film was annealed by µ-TPJ under v as 500 mm/s (a), and 800 mm/s (b), respectively. The dotted line is calculation data of R_c based on the physical model.

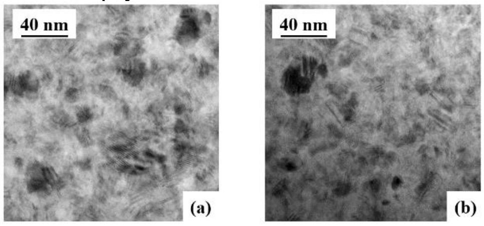

Fig. 6 HRTEM images of solid-phase crystallized a-Si films annealing by µ-TPJ at v of (a) 500 mm/s and (b) 800 mm/s, respectively.

We introduced a theoretical model to explain the mechanism of SPC at high temperature region based on classical nucleation theory. We assume that R_h does not change during the phase transformation process. The time for complete crystallization is divided into small fractions with step Δt. At the initial time, a-Si film reaches to nucleation temperature, no crystal inside the volume. Then, temperature linearly increases with slope R_h. After Δt µs, there are N_1 nuclei appearing inside the volume and grow up with velocity v_{g1}, and volume of a-Si reduces. In the next time step, N_2 nuclei additionally appear and grow with velocity v_{g2}. In addition, N_1 nuclei in previous time step continue to grow with the same velocity v_{g2}. The volume of a-Si keeps on reducing. This process will be continued until the crystal grains fill out the considering volume and no appearance of a-Si. From the theoretical calculation, the average grain size decreases with the increasing of R_h. This estimated r is fairly agreed with HRTEM results.

4. Conclusions

This work researched the mechanism of SPC-Si in high temperature region by using TRR method. The T_c increases from 985 to 1013 °C when R_h increase from 4.45×10^5 to 8.86×10^5 K/s. Theoretical results and experimental results show the best agreement.

References

[1] S. J. Park, Y. M. Ku, E. H. Kim, J. Jang, K. H. Kim, and C. O. Kim: J. Non-Cryst. Solids 352 (2006) 993

[2] R.B.Iverson, R.Reif, J. Appl. Phys. 62 (1978), 1875.

[3] G.L.Olson, J.A.Roth, Mater. Sci. Rep. 3 (1988), 11.