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# Two-dimensional Visualization of Temperature Distribution in Molten Region of a-Si Film during Atmospheric Pressure Thermal Plasma Jet Annealing

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## Abstract

**In this paper, we demonstrate two-dimensional visualization of temperature distribution in molten silicon region during atmospheric pressure thermal plasma jet annealing of amorphous silicon films on quartz. A non-contact temperature measurement and a high-speed camera observation have been conducted simultaneously. We succeeded in clarifying the temperature distribution and the degree of supercooling on the various crystallization or the molten silicon region.**

## 1. Introduction

When we produce thin film transistors (TFTs) with high field-effect mobility, we need to understand the melting and solidification of an amorphous silicon (a-Si) film on a glass substrate. Furthermore, the high-crystallinity polycrystalline silicon (poly-Si) film is needed. So, it is important to clarify the mechanism of silicon melting/solidification and grain growth for forming a poly-Si film with high crystallinity.

The other researchers have proposed their own techniques to measure the lattice temperature, time-resolved electrical-conductance and optical-reflectance, and so on [1,2]. We also have proposed our own technique directly to observe the phase transformation during atmospheric pressure thermal plasma jet (TPJ) annealing by using a high-speed camera (HSC) in real-time. We have found out various crystallizations, which are a solid-phase crystallization (SPC), a high-speed lateral crystallization (HSLC) and leading wave crystallization (LWC) [3–5]. Also, a non-contact temperature measurement using He-Ne laser [6] allows us to obtain the temperature distribution of sample surface. In this paper, we demonstrate to reveal the two-dimensional temperature distribution in molten silicon region by using the simultaneous measurement combined the non-contact temperature measurement and HSC observation in high-time resolution.

## 2. Experimental

The a-Si films of 100-nm-thick on 525-µm-thick quartz substrates were formed by plasma-enhanced chemical vapor deposition at 250 °C. These samples were dehydrogenated at 450 °C in $N_2$ ambient. Figure 1 shows the schematic illustration of experimental setup for a simultaneous measurement in real time to obtain the temperature distribution in molten Si region. This setup is consisted of two kinds of measurement systems. Temperature measurement setup had a He-Ne laser at 632.8 nm, a mirror for reflecting a laser beam, a beam splitter, an optical filter, and a condenser lens. The HSC observation setup had a high-speed camera (frame rate: 3000 fps, exposure time: 1 µs), a manual positioner and a light source. We simultaneously measured the transient reflectivity for obtaining temperature information of sample surface and observed the molten region in real time when the a-Si film on a quartz substrate were irradiated by TPJ.

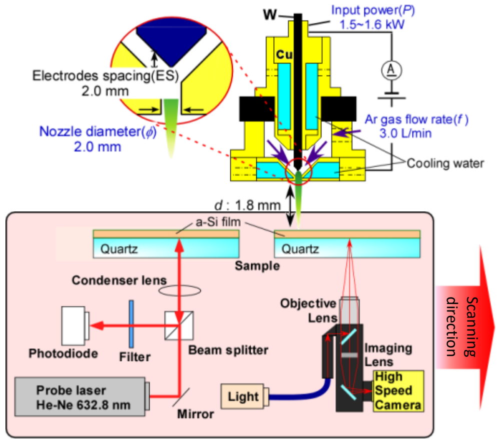


Fig. 1 Schematic illustration of the simultaneous measurement systems for obtaining the temperature distribution in molten silicon region.

## 3. Results and Discussion

We irradiated the a-Si film on quartz with TPJ three times. First irradiation was conducted at a scanning speed of 1350 mm/s, and the HSC image obtained in this condition is shown in Fig. 2(a). we can confirm SPC and LWC region as indicated in Fig. 2(a) inset. Then, the film was irradiated at 1320 mm/s, and we observed the formation of molten Si region as shown in Fig. 2(b) inset. Following the movement of molten Si, we observed the lateral crystal growth as seen in dendritic morphology. Then, the same sample was irradiated at 1350 mm/s again, and we confirmed the shrinkage of molten region as shown in Fig 2(c) inset. Next, we'll explain about the temperature analysis. Figure 3(a) shows the relative reflectivity of the quartz substrate with the a-Si film irradiated at 1350 mm/s corresponding to Fig. 2(a). The red line is the experimental result and the blue line is a simulation result, respectively. We fitted simulation by adjusting the parameters such as the TPJ profile and power transfer efficiency from TPJ to the sample surface to obtain the time-variation of surface temperature, as shown in Fig. 3(b). In this case, $T_{max}$ is 1553 K. Fig. 3(c) shows the relative reflectivity with 1350 mm/s (blue line, same one as (a)) and 1320 mm/s (red line, corresponding to Fig. 2(b)). We can confirm a rapid increase and decrease of reflectivity in 1320 mm/s case, which is attributed to the

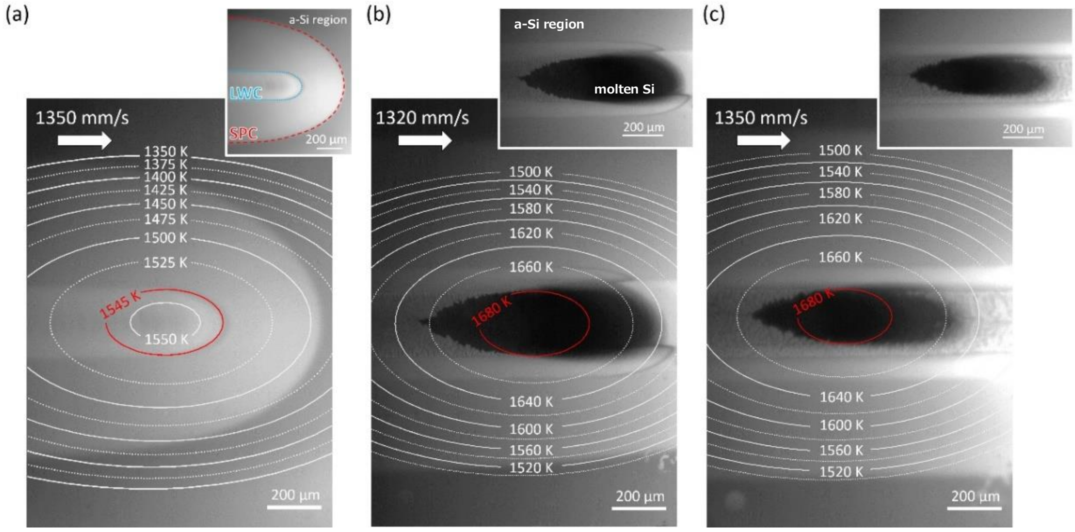


Fig. 2 Two-dimensional temperature distribution in the molten silicon region (a) during first irradiation on the a-Si films, (b) during second irradiation on the first crystallization and (c) during the third irradiation on the second crystallization (HSLC region). (intervals between dotted line and solid line: (a) 25 K, (b–c) 20 K) Inset images show the crystallization region and molten silicon region.

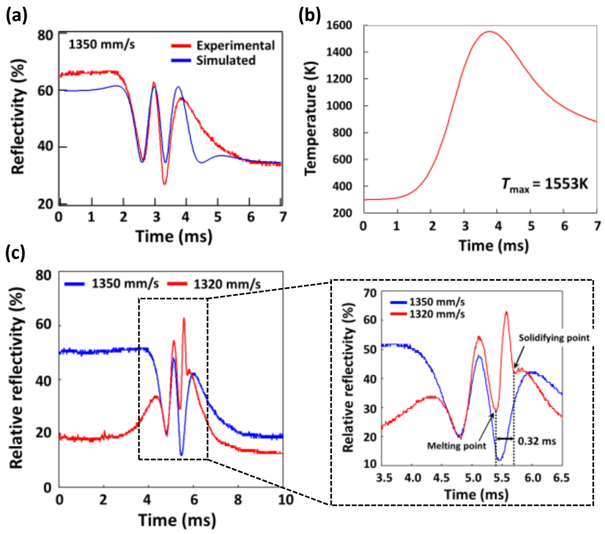


Fig. 3 (a) Relative reflectivity of the simulated result (blue line) and the experimental result (red line) during SPC crystallization. (b)Time-variation of temperature in Fig.2(a). (c) Relative reflectivity with the scanning speed of 1350 mm/s (blue line) and 1320 mm/s (red line) during TPJ irradiation.

melting of Si film. From this observation, we can determine the melting started from 5.4 ms and solidification was completed at 5.72 ms. Namely, the melt duration was 0.32 ms. We attempted to calibrate the melting point on a-Si film by obtaining the correct thermo-optic coefficient (TOC) of the quartz substrate and explore the analysis condition in order that the width of points at the intersection of temperature variation at 1650–1680 K and silicon melting time of 0.32 ms is the same. In these results, we obtained the TOC as $n_q = 1.457 + 1.27 \times 10^{-5} \times T + 0.7 \times 10^{-9} \times T^2$ (°C). From these analyses, we obtained the isotherm and visualized temperature distribution in molten silicon region, as shown in Fig. 2. The intervals between dotted and solid line in Fig. 2(a) is 25 K and that of Fig. 2(b–c) is 20 K. In Fig. 2(a), the width of LWC region in HSC image, which is 230 μm, and the 1545 K line (red line) of temperature distribution of which width is about 230 μm are fitted well. So, this indicates that the LWC started at 1545 K. From Fig. 2(b) and (c), it was clarified that the supercooling region appeared frontside and backside of molten silicon region. It should be noted that Si film melts at a temperature below the melting point (1680 K), which means the molten Si is in supercooling. We found the supercooling regions not only in the backside of TPJ movement, but also in the frontside of that. From Fig 2(b), the supercooling degree in frontside and backside of molten silicon region was approximately 40 K–45 K and 25 K, respectively. In the same way, the supercooling degree of that in Fig 2(c) was approximately 25 K–30 K and 15 K, respectively. It was revealed the difference of supercooling degree of frontside and backside molten region between Fig. 2(b) and (c) was about 15 K and 10 K, respectively. Also, the trimming images in Fig. 2(a–c) show crystallization region and molten silicon region in detail. In comparison with the trimming images in Fig. 2(b) and (c), it is obvious that the molten region in Fig. 2(c) is smaller than that of Fig. 2(b). It is hypothesis that the forward supercooling region occurred because the melting point in the amorphous region and micro-crystallized region is lower than that of crystallized region. From results of Fig. 2(b) and (c), we were able to prove its hypothesis is accurate.

## 4. Conclusions

In this paper, the two-dimensional visualization of a temperature distribution on the molten region allows us to reveal temperature field when the various crystallization was formed. So, it is expected that the proposed simultaneous measurement helps us to clarify the crystallization mechanism.

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