

# Phase Transformation of Amorphous Si Films in Millisecond Time Domain Induced by Thermal Plasma Jet Irradiation

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## 1. Introduction

The low temperature crystallization of amorphous Si (a-Si) films is a key for the fabrication of thin film transistors (TFTs) on glass substrates. So far, the crystallization techniques using an excimer laser to the film crystallization have been studied intensively [1]. However, due to the limit to the output power, the application of laser crystallization technique to large area processing leads to difficulties in reduction of the process cost. Recently, we have proposed the application of thermal plasma jet (TPJ) annealing [2] as an alternative crystallization technique and demonstrated its feasibility as obtained from good TFT performance such as the maximum field effect mobility of  $70 \text{ cm}^2/\text{Vs}$  and threshold voltage of 3.3 V [3]. In TPJ annealing of a-Si films, the phase transformation to crystalline occurs in the time domain of millisecond. However, the mechanism of rapid crystallization in this time domain has not been well understood yet.

In this work, we have applied *in-situ* monitoring technique of phase transformation and surface temperature of substrate using an optical probe technique. The relationship between the temperature and the duration of phase transformation will be discussed.

## 2. Experimental

The experimental set up for the crystallization of a-Si films by TPJ is schematically illustrated in Fig. 1. The W cathode and the water-cooled Cu anode separated 1 mm each other are connected to a power supply. Arc discharge was performed by supplying DC biases of 13.2 – 15.0 V and 120 - 160 A (power input ( $p$ ) = 1.72 – 2.11 kW) between the electrodes with an Ar gas flow ( $f$ ) of 7.0 to 9.8 L/min. The thermal plasma jet was formed by blowing out the arc plasma through a 4 mmφ nozzle. Hydrogenated amorphous Si films with a thickness of 40 nm were formed on quartz substrate from an inductively coupled plasma (ICP) of 50% SiH<sub>4</sub> diluted with H<sub>2</sub> at 250°C. The substrate was linearly moved by a motion stage in front of the plasma jet with scanning speed

ranging from 100 to 1500 mm/s. The distance between the plasma source and the substrate ( $d$ ) was set at 1.0 – 11.5 mm. To observe the phase transformation and analyze the surface temperature of quartz substrate during the TPJ annealing, the reflectivity of the a-Si film and quartz substrate was monitored simultaneously by irradiating them with a laser light (532nm) from the backside of the quartz substrate and detecting the reflected light intensity by a photo-diode through a band pass filter. Since the refractive index of Si in amorphous phase ( $n \sim 4.8$ ) is lower than that in crystalline phase ( $n \sim 4.1$ ), one can observe the phase transformation from the transient variation of Si film's reflectivity. The measurement of the reflectivity of the quartz substrate was used to analyze the temperature profile in quartz substrate. The laser light irradiated to the quartz substrate is multiply reflected at the top and back surfaces, thus the reflectivity of the substrate varies quite sensitively by their interference condition. By irradiating the substrate with TPJ, we can observe oscillating reflectivity due to the change of optical thickness of the substrate with temperature. By analyzing the oscillation, we can know the transient temperature profile in the substrate with the time resolution of millisecond. The details of this analysis are reported elsewhere [4].

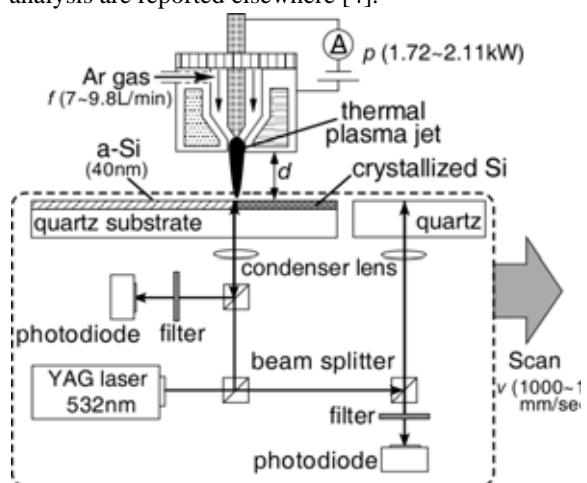
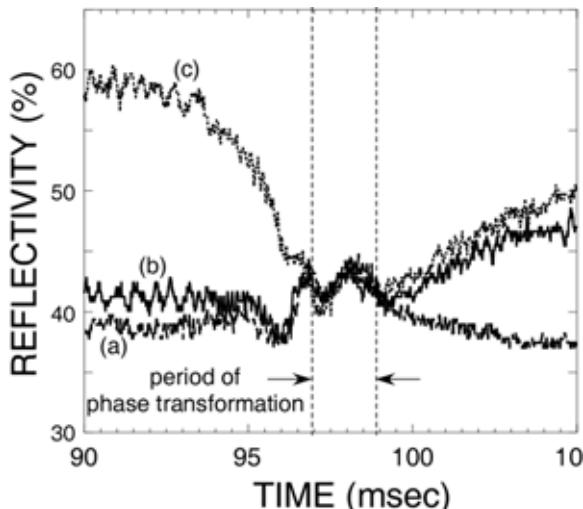


Fig.1 : Schematic diagram of plasma jet annealing of Si films and the optical set up for *in-situ* monitoring of the phase transformation and the

### 3. Results and Discussion

Figure 2 shows examples of transient reflectivity waveforms of a Si film measured during TPJ annealing with  $d$  of 1.5 mm and  $v$  of 1000mm/sec at  $p$  of (a) 1.71 kW where the Si film remains amorphous (b) 1.85 kW where a-Si film is transformed to crystalline and (C) 1.85 kW obtained from the crystallized film. The waveform (b) until 96.9 ms is almost the same as the waveform (a), and after 99.3 ms, it follows the waveform (c). The result indicates that the Si film is in amorphous phase until 96.9 ms and is transformed to crystalline phase by the time of 99.3ms. From this result, we can determine the duration of phase transformation to be 2.4ms. Based on this observation technique, the duration of phase transformation under different scan speeds was evaluated. When crystallizing the a-Si film at slower scan speed, the samples were annealed with larger  $d$ , so that the phase transformation was observed under similar  $p$  values.

Figure 3 (a) shows the temperature variations of Si films crystallized at different scan speeds, as obtained by analyzing the transient reflectivity from quartz substrate. The Si film annealed with the  $v$  of 1500 mm/sec, with the  $d$  of 1mm and the  $p$  of 1.95kW, the phase transformation was observed when the maximum temperature reached to 1230K and the duration of phase transformation was 1.1 ms. When the same experiment done at the  $v$  of 100mm/sec, with the  $d$  of 11.5 mm and the  $p$  of 1.89 kW, the duration of phase transformation increased more than 30 ms and the maximum temperature reduced to 1077 K. As understood from Fig. 3, the maximum temperature required for phase transformation increases with



**Fig.2** ; examples of transient reflectivity waveforms measured under constant  $v$  of 1000 mm/sec,  $d$  of 1.5 mm and different  $p$  of (a) 1.71 kW, (b) 1.85 kW and (c) 1.85 kW.

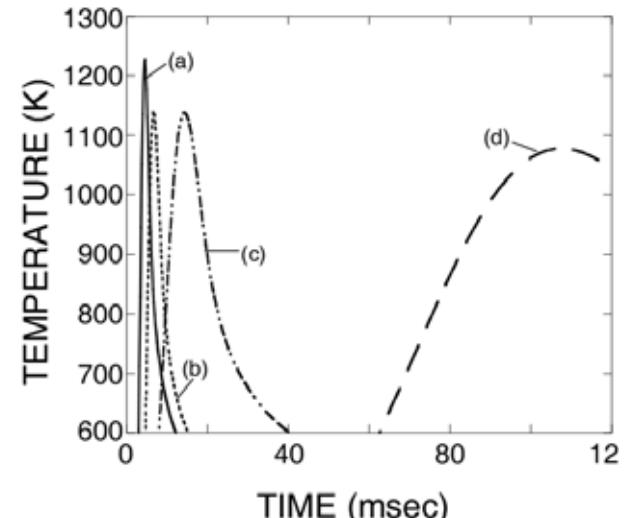
decreasing annealing duration. By reducing the duration of phase transformation from 44 to 1.1 ms, the temperature for crystallization increased from 1100 to 1230 K. This result is understood that a higher temperature is required to induce significant nucleation in the a-Si film within short period. Therefore, the crystallization of a-Si film in this time domain is nucleation-controlled phase transformation.

### 4. Conclusion

The duration and the temperature of phase transformation in TPJ annealed a-Si are investigated using *in-situ* monitoring technique. The temperature of crystallization increased with decreasing phase transformation duration. This result indicates that the crystallization in this time domain is strongly governed by the nucleation rate in the a-Si films.

### References

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- [2] H. Kaku, S. Higashi, H. Taniguchi, H. Murakami, and S. Miyazaki, Appl. Surf. Sci. 244, (2005), pp.8-11.
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**Fig.3** : Transient temperature of Si films crystallized different annealing conditions of (a)  $v$  of 1500 mm/sec,  $d$  of 1 mm and  $p$  of 1.98 kW (b)  $v$  of 1000 mm/sec,  $d$  of 1.5 mm and  $p$  of 1.85 kW (c)  $v$  of 500 mm/sec,  $d$  of 5 mm and  $p$  of 1.94 kW (d)  $v$  of 100 mm/sec,  $d$  of 11.5 mm and  $p$  of 1.89 kW

## Analysis of Si Thin Film Crystallization Induced in Milli-Seconds Range by Thermal Plasma Jet Irradiation

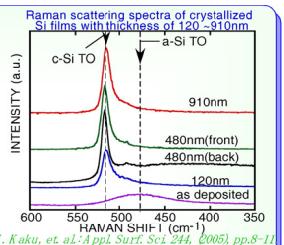
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### Background

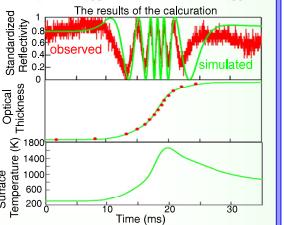
#### Plasma Jet Crystallization (PJC)

Succeed the crystallization of amorphous Si (a-Si)  
crystallize Si Films in the thickness even for the films as thick as  $\sim 1\mu\text{m}$   
not need dehydrogenation



#### Direct observation technique of transient temperature profile

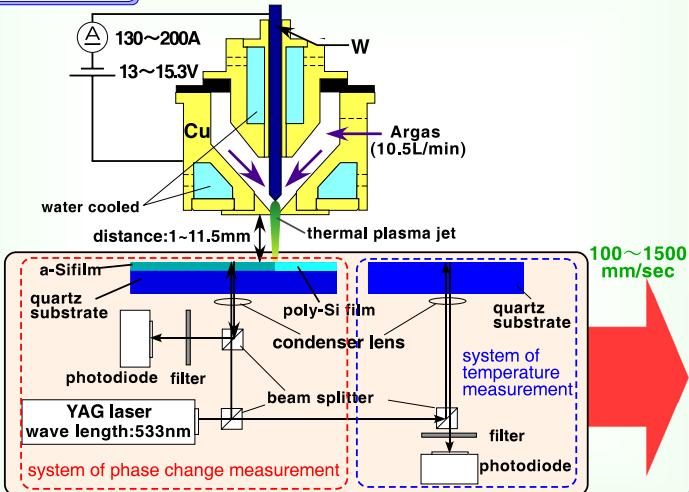
Calculate the observed reflectivity from the quartz substrate  
Investigate the transient temperature profile in milli-second domain



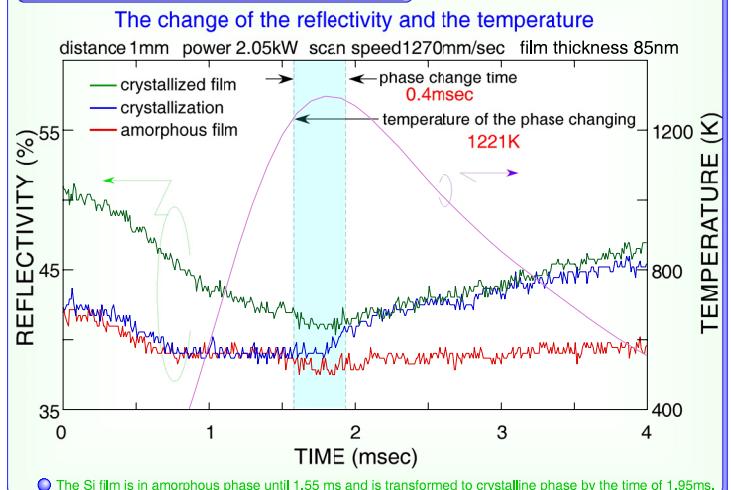
### Objective

Investigate the mechanism of the crystallization process in milli-second domain

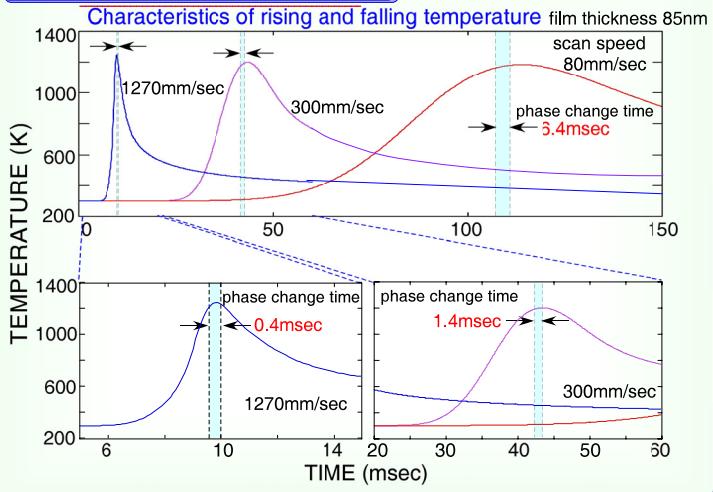
### Experimental System of real time observation



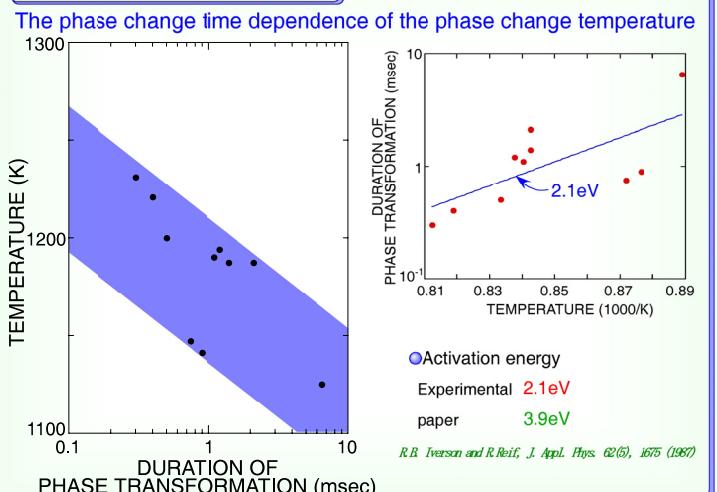
### Real time observation of the reflectivity



### Real time observation of the reflectivity

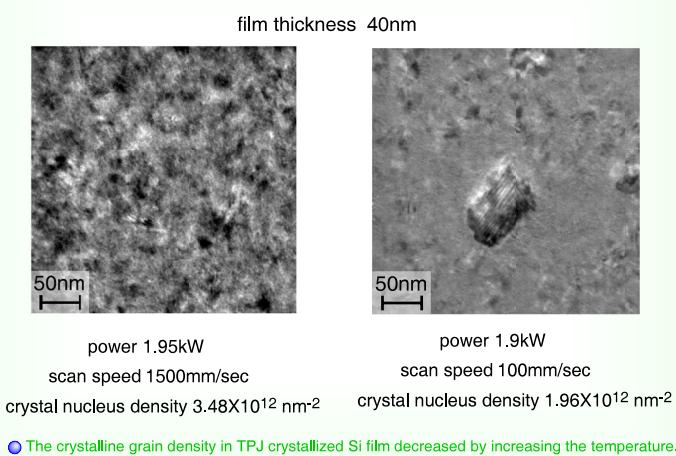


### Analysis of crystallization process

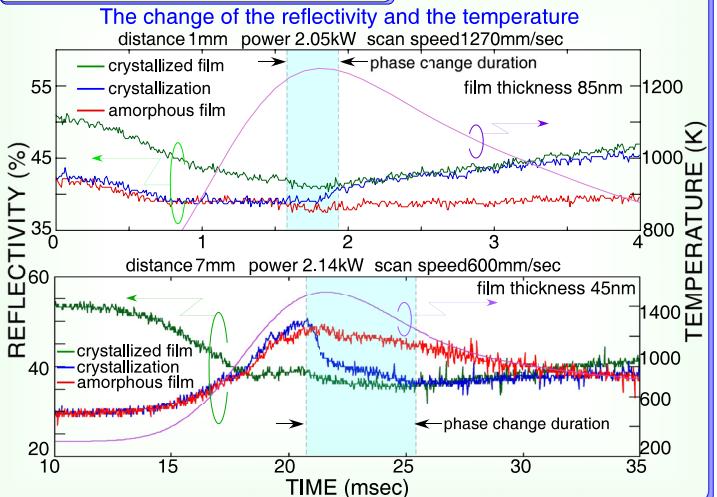


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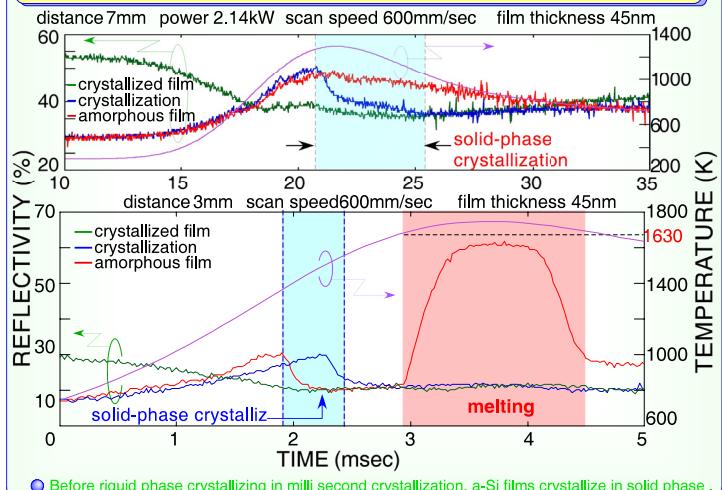
### TEM image



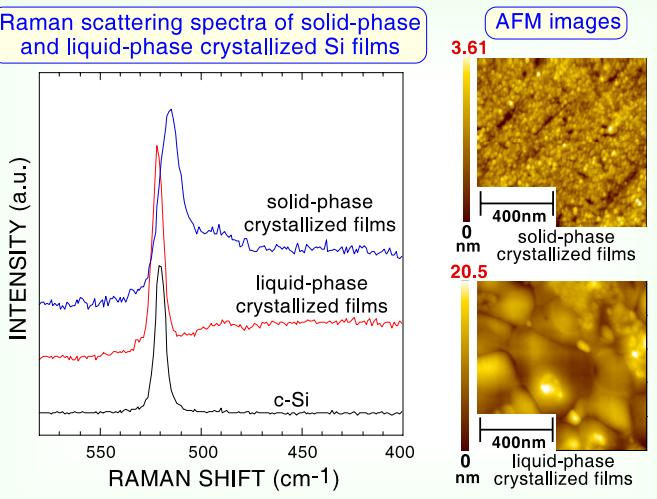
### Real time observation of the reflectivity



### Real time observation of the reflectivity at liquid-phase crystallization



### Raman scattering spectra of solid-phase and liquid-phase crystallized Si films



• The liquid-phase crystallization result in better crystallinity than the solid-phase crystallization

### Summary

- The process of crystallization in milli-second domain
- The phase change began at 1221 K in case of 0.4 ms phase change time  
The phase change began at 1125 K in case of 6.4 ms phase change time
- The temperature of crystallization increased with decreasing phase transformation duration.
- The activation energy of phase change was 2.1eV
- The crystalline grain density in TPJ crystallized Si film decreased by increasing the temperature.
- Before liquid phase crystallizing in milli second crystallization, a-Si films crystallize in solid phase .
- The liquid-phase crystallization result in better crystallinity than the solid-phase crystallization