Analysis of Transient Temperature Profile During Thermal Plasma Jet Annealing of Si Films on Quartz Substrate

T. Okada, S. Higashi, H. Kaku, N. Koba, H. Murakami and S. Miyazaki

Graduate School of Advanced Sciences of Matter, Hiroshima University
e-mail: semicon@hiroshima-u.ac.jp

1. Introduction

For the fabrication of polycrystalline Si (poly-Si) thin-film transistors (TFTs) with low temperature process, excimer laser annealing (ELA) has been widely used. However, due to the limit to the output power of the laser, the application of ELA to large area processing leads to difficulties for reduction in the process cost. As an alternative crystallization technique, we have proposed thermal plasma jet crystallization (PJC) [1]. One can generate a high power density thermal plasma jet by a DC arc discharge under atmospheric pressure. So far, we have succeeded the crystallization of amorphous Si (a-Si) films by PJC, and the crystallinity of the Si films is improved with increasing annealing duration and the power input to the plasma source. We have confirmed that the a-Si films are crystallized either in solid phase or liquid phase depending on the annealing condition [2]. Also we have demonstrated an application of PJC to TFT fabrication and obtained the maximum field effect mobility of 70 cm^2/(V·s) and the threshold voltage of 3.3 V [3]. Thus, the PJC technique is very promising for the low temperature process in the next generation. However, the crystallization mechanism in millisecond time domain is still a matter of research. For this purpose, we need to know the temperature change during the plasma jet annealing.

In this work, we have developed a direct observation technique of transient temperature profile. And, we have demonstrated that by combining an optical reflectivity measurement and numerical simulation analysis, the temperature profile can be accurately obtained with the time resolution of millisecond.

2. Experimental

The thermal plasma source used in the experiment is schematically shown in Fig. 1. The W cathode and the water-cooled Cu anode separated 1 mm each other was connected to a power supply. Arc discharge was performed by supplying DC biases of 14 to 15.5 V with the discharge current of 150 A between the electrodes under an Ar gas flow of 9.8 L/min. The thermal plasma jet was formed by blowing out the arc plasma through an orifice of 4 mm in diameter. The substrate was linearly moved by a motion stage in front of the plasma jet with scanning speed ranging from 500 to 1000 mm/s. The distance between the plasma source and the substrate was set at 2 to 3 mm. In order to measure the surface temperature change during annealing, the reflectivity of 600 nm-thick Si film was measured by irradiating the film with a He-Ne laser light (632.8 nm) from the backside of the quartz substrate and detecting the reflected light intensity by a photo-diode through a band pass filter as shown in Fig. 1. The transient reflectivity was measured by scanning the sample and the measurement system together on a motion stage. Considering a reported temperature dependence of the refractive index of Si, $n_{Si} = 3.98 + 4.7 \times 10^{-4} \times T(^\circ\mathrm{C})$ [4], one can expect that the reflectivity of Si film strongly affected by the interference condition inside the film, which results in oscillation in reflected light intensity with scanning the plasma jet on the sample surface.

3. Results and Discussion

The transient reflectivity waveform measured under annealing condition with the power input to the plasma source of 2.2 kW and scanning speed of 700 mm/s is shown in Fig. 2 (a) (solid line). Oscillation of reflectivity during the plasma jet irradiation was clearly observed and the number of oscillation increased with decreasing scanning speed. The observed increase in the number of oscillation with decreasing scan speed indicates an increase in the temperature of the film. However, the observed oscillation can not be well explained with a consideration of temperature dependence of Si refractive index only.

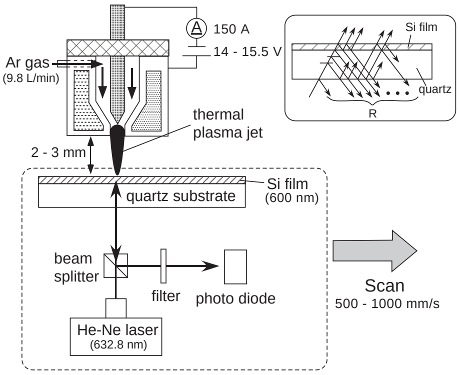

Figure 1: Schematic diagram of plasma jet annealing of Si films. Transient reflectivity was measured by irradiating the sample with a He-Ne laser (632.8 nm) from the backside of the substrate.

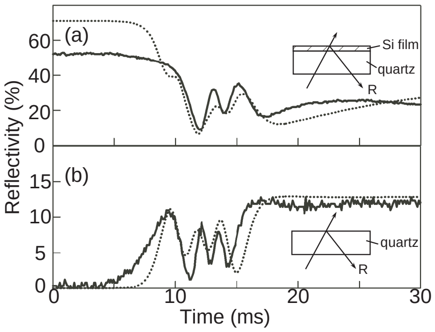

Figure 2: Measured transient reflectivity (solid lines) and simulated reflectivity (dotted lines) of (a) 600 nm-thick Si film on quartz and (b) quartz when the plasma jet was scanned with 700 mm/s.

So we confirmed the contribution of the change in the reflectivity of quartz substrate to the oscillation, where a quartz substrate without any Si film was annealed by plasma jet under the same condition. Quite similar oscillation cycles were observed as shown in Fig. 2 (b) (solid line). Thus, to characterize the measured oscillation in the reflectivity, the optical interference both in Si film and quartz substrate have to be taken into account.

In that regards, we performed numerical simulations on heat diffusion and optical interference. Two-dimensional heat diffusion was simulated based on an equation below.

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{S}{\rho c_p}, \qquad (1)$$

where x is the position along the plasma jet scanning direction, y is the depth from the surface, T is the temperature, λ, ρ and c_p are the thermal conductivity, the density and the specific heat of quartz substrate respectively, and S is the thermal incidence.The numerical calculation was performed by an explicit method with the boundary

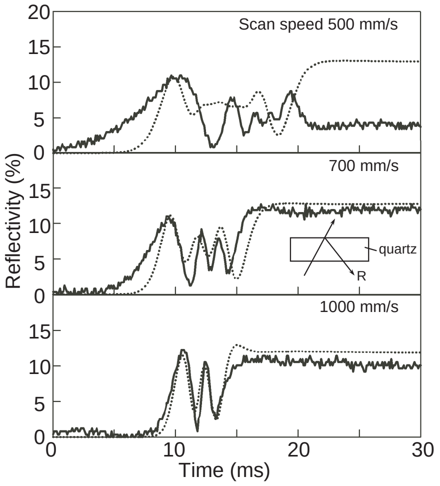

Figure 3: Measured transient reflectivity (solid lines) and simulated reflectivity (dotted lines) of quartz substrate under the same conditions in the plasma jet and scanning speed.

condition that the initial temperature was 300 K. It was assumed that the plasma jet has two-dimensional gaussian power profile with the width of W, and the effective power transfer efficiency from plasma to the substrate surface to be ε.

Then optical reflectivity simulation was performed based on the heat diffusion simulation considering the temperature dependence of refractive indices of Si film and quartz substrate ($n_q = 1.457 + 1.27 \times 10^{-5} \times T(^\circ\mathrm{C})$ [5]) and multiple reflection interference effect as schematically shown in the upper right of Fig. 1.

The experimental results in the case of Si film samples were fitted with the two fitting parameters of W and ε, and results are shown in Fig. 2 (a) (dotted line). Similarly, the waveforms obtained from quartz substrate are fitted as shown in Fig. 2 (b) (dotted line). Best fitting was obtained with the values of W=3.2 mm, and ε=60 %. These parameters also reproduced the waveforms in the cases of different scanning speeds (Fig. 3). As understood from the fitting results, the experimental waveforms have been reproduced very nicely by the simulation.

The experimental and simulation results agree well even in the cases of different scanning speeds and different sample structures. These results show that one can know the transient temperature profile very accurately by this analysis.

From the fitting results, we obtained the temperature profile and transient variation at the substrate surface with the power input of 2.2 kW and scanning speeds of 500, 700 and 1000 mm/s as shown in Figs. 4 and 5. By the plasma jet annealing, only the surface portion of the substrate is heated beyond 1000 K. Since the heat diffusion length in this time scale is about 100 μm, most part of the substrate stays relatively cool. The maximum surface temperature, maximum rate of heating and cooling are summarized in Table. 1. The maximum surface temperature increases from 1300 to 1560 K by reducing the scan speed from 1000 to 500 mm/s. The maximum rates of heating and cooling decrease from 340 to 197 and 147 to 81 K/ms, respectively.

4. Conclusions

By measuring the transient reflectivity and analyzing the oscillation, we have investigated the transient temperature profile during thermal plasma jet annealing. The reflectivity shows the oscillation during plasma jet annealing, which is originated from the change of refractive indices of Si film and quartz substrate with temperature and interference effect. From the results, the plasma jet have 3.0 to 3.4 mm diameter and 60 to 78 % of the effective power transfer efficiency to the substrate surface. The maximum heating rate and cooling rate are ranging between 197 to 340, 81 to 147 K/ms respectively, and the surface temperature increases from 1300 to 1560 K by decreasing the scan speed from 1000 to 500 mm/s with the power input to the plasma source 2.2 kW.

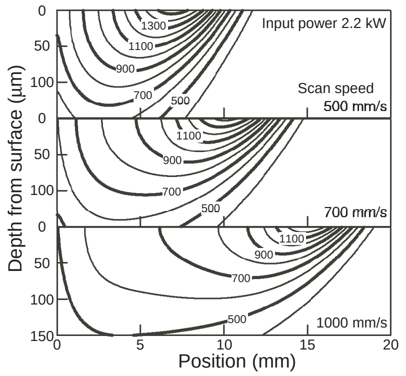

Figure 4: Two-dimensional temperature profile under different annealing conditions obtained by the analysis.

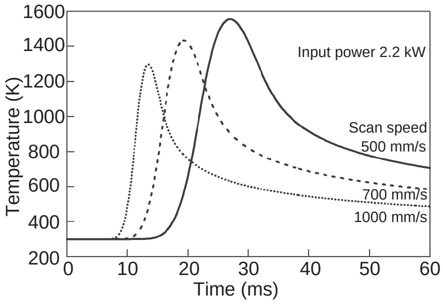

Figure 5: Temperature variation at the substrate surface under different annealing conditions.

Table 1: Characteristic temperatures obtained by the analysis.

Scan speed (mm/s)	500	700	1000
Maximum surface temperature (K)	1560	1430	1300
Maximum heating rate (K/ms)	206	244	340
Maximum cooling rate (K/ms)	85	103	147

Acknowledgments

A part of this work was supported by Mitutoyo Association for Science and Technology (MAST), and New Energy and Industrial Technology Development Organization (NEDO) of Japan.

References

[1] H. Kaku, S. Higashi, H. Taniguchi, H. Murakami and S. Miyazaki: Appl. Suf. Sci. **244**, (2005), pp. 8-11.

[2] S. Higashi, H. Kaku, H. Taniguchi, H. Murakami and S. Miyazaki: Int. Conf. Polycrystalline Semiconductors 2004 (Potsdam, Germany, September 5-10, 2004), in series Thin Solid Films **487**, (2005), pp. 122-125.

[3] S. Higashi, H. Kaku, H. Murakami, S. Miyazaki, H. Watakabe, N. Ando and T. Sameshima: Jpn. J. Appl. Phys. **44**, (2005), pp. L108-L110.

[4] K. Murakami, K. Takita and K. Masuda: Jpn. J. Appl. Phys. **20**, (1981), pp. L867-L870

[5] J. H. Wray, J. T. Neu: J. Opt. Soc. A. **59**, (1969), pp. 774-776.

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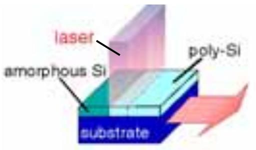
Motivation

Low temperature process

TFT
Solar Cell

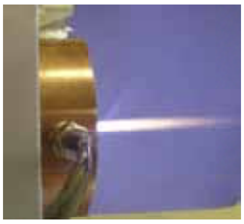
Excimer laser annealing (ELA)



- Limit to the output power of laser
- Difficulties for reduction in the process cost

Thermal Plasma Jet Crystallization (PJC)

- High power density
- Simple structure
- Atmospheric pressure processing



Thermal Plasma Jet

Previous work

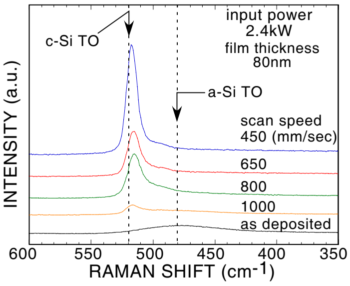
PJC

Succeed the crystallization
of amorphous Si (a-Si)

Application to TFT fabrication

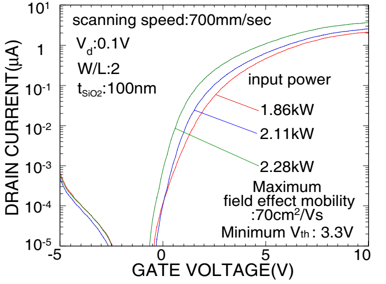
Maximum field effect mobility：70cm^2/Vs

Raman scattering spectra of Si films
before and after anneal



H.Kaku, et. al., Appl. Surf. sci. (2005)

Transfer characteristics of Poly-Si TFT



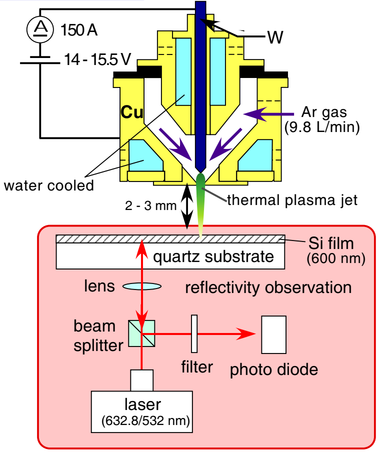
S.Higashi, et. al., JJAP 44(3), L108–L110 (2005)

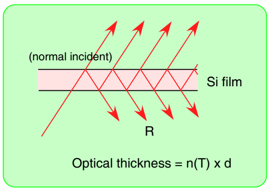
This work

To investigate the temperature variation
during the PJC

- Developed a direct observation technique of transient temperature profile.
- Investigate the transient temperature profile during thermal plasma jet annealing.

Experimental





Optical thickness = n(T) x d

Refractive index of Si

$n(T) = 3.98 + 4.7 \times 10^{-4} \times T(℃)$

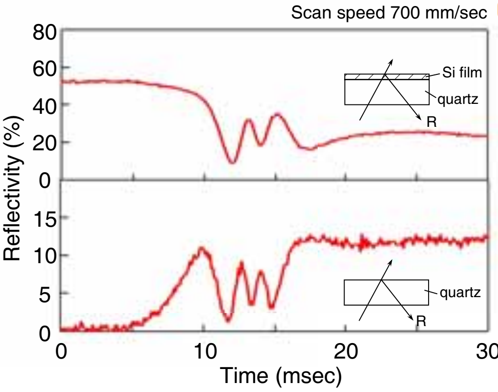
K. Murakami, et. al.,
JJAP 20(12), L867–L870 (1981)

Scan
500 - 1000 mm/sec

- Measuring the reflectivity, utilize refractive index of Si dependent on the film temperature.

Observed reflectivity

Input power : 2.2 kW



- Similar waveform is observed.

Refractive index of quartz

$$\frac{dn}{dT} = 1.27 \times 10^{-5}$$

J. H. Wray, et. al.,
J. Opt. Soc. A 59(6), L774–L776 (1969)

- To characterize the measured oscillation in the reflectivity, the optical interference both in Si film and quartz substrate have to be taken into account.

Simulation

Thermal simulation

Optical simulation

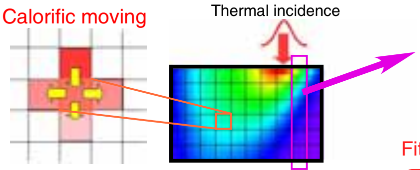
Two-dimensional heat diffusion in quartz substrate

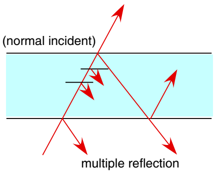
Determination of refractive index from temperature

Reflectivity variation

Equation of heat conduction

$$\frac{\delta T}{\delta t} = \frac{\lambda}{\rho c_p}\left(\frac{\delta^2 T}{\delta x^2} + \frac{\delta^2 T}{\delta y^2}\right) - \frac{S}{\rho c_p} - \alpha (T - T_0)$$





Boundary condition (The edges of substrate : Thermally insulated
Initial temperature : 300(K)

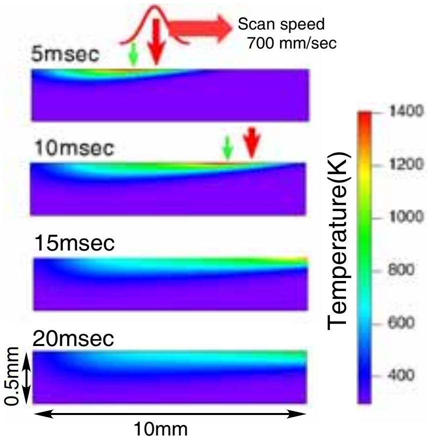
Considering temperature dependence of the specific heat and the thermal conductivity

Fitting parameter

Plasma diameter *W*
Efficiency of power transfer ε

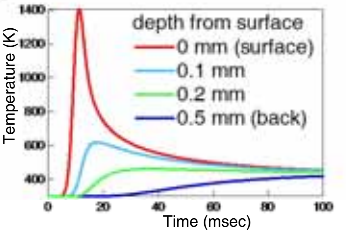
- By the 2-step simulation, we get the reflectivity variation.

Two-dimensional temperature profile



Input power : 2.2 kW
W : 2.3 mm
ε : 28 %

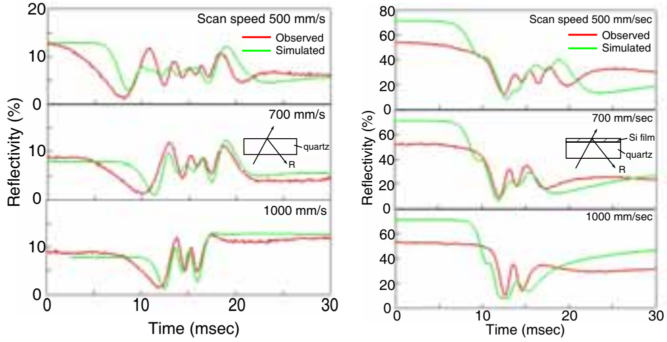
Transient temperature variation at different depth from substrate surface



- Only surface portion of the substrate is heated to a high temperature.

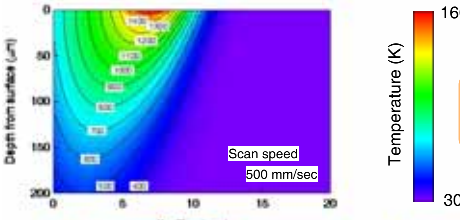
Simulated and observed reflectivity

Input power : 2.2 kW
W : 3.2 mm
ε : 60 %

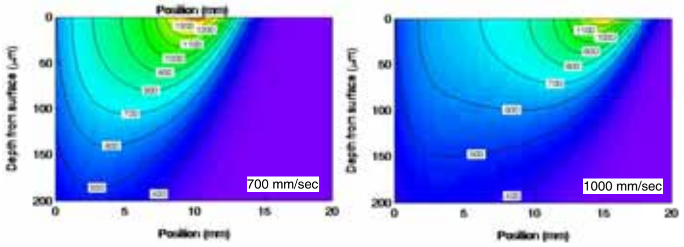


- Changing fitting parameter (plasma diameter, efficiency power transfer), fitted simulated waveform with observed waveform of 700 mm/sec.

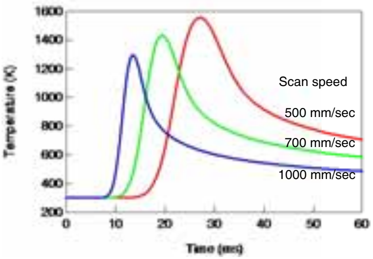
Two-dimensional temperature profile



Plasma diameter : 3.0 - 3.4 mm
Input power : 2.2 kW
Efficiency of power transfer : 60 - 78 %



Temperature variation at the substrate surface

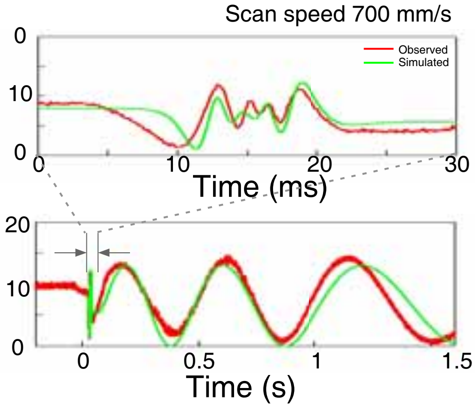


Plasma diameter : 3.0 - 3.4 mm
Input power : 2.2 kW
Efficiency of power transfer : 60 - 78 %

Scan speed	500 mm/sec	700 mm/sec	1000 mm/sec
Maximum surface temperature	1560 K	1430 K	1300 K
Maximum heating rate	197 K/msec	244 K/msec	340 K/msec
Maximum cooling rate	81 K/msec	103 K/msec	147 K/msec

- Results of simulation led to these temperature variations.

Long time observation

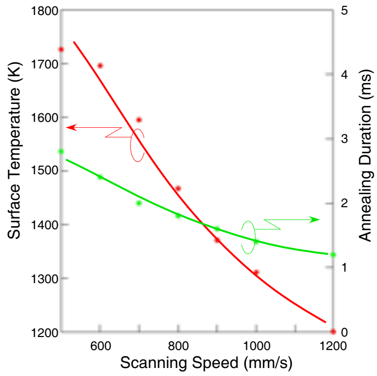


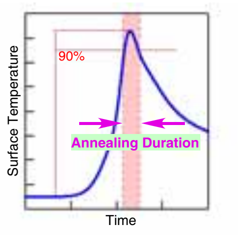
Input power : 2.2 kW
W : 3.4 mm
ε : 60 %
α : 80

Heat radiation factor α

- Considering to heat radiation, experimental waveforms also have been reproduced in long time domain.

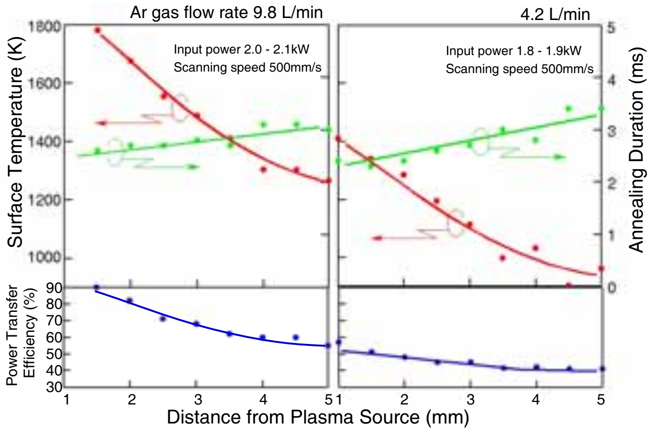
Surface temperature variation & annealing duration as a function of the scanning speed





- With decreasing scanning speed, increase the surface temperature and the annealing duration.

Surface temperature variation & annealing duration as a function of the distance from the plasma source



- By putting close to the plasma source, increase the surface temperature without change the annealing duration.

Conclusions

- By measuring the transient reflectivity and analyzing the oscillation, we have investigated the transient temperature profile during thermal plasma jet annealing.

- The reflectivity shows the oscillation during plasma jet annealing, which is originated from the change of refractive indices of Si film and quartz substrate with temperature and interference effect.

- The plasma jet have 3.0 to 3.4 mm diameter and 60 to 78 % of the effective power transfer efficiency to the substrate surface.

- Scanning speed leads to change both the maximum surface temperature and annealing duration, but the distance from plasma source leads to change only the maximum surface temperature.