Crystallization of Amorphous Si films on Glass Substrate Using Plasma Jet and Its Application to Thin Film Transistor Fabrication

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Abstract

Crystallization of a-Si films on glass substrate using plasma jet crystallization (PJC) technique and its application to thin film transistor fabrication have been studied. Amorphous Si (a-Si) films were crystallized by thermal plasma jet under conditions of input power to the plasma source of 1.6 to 2.6 kW and substrate scan speed of 170 to 1000 mm/s. The crystallinity of the films is improved by treating the film at higher input power for longer duration. Thin film transistors (TFTs) fabricated using the crystallized films show good electrical performance. With increasing input power from 1.86 to 2.29 kW in the crystallization, the average field effect mobility is increased from 42 to 61 $cm^2V^{-1}s^{-1}$ and threshold voltage is decreased from 4.0 to 3.4 V. These results indicate that the PJC technique is a very promising low temperature process technology.

Introduction

For the fabrication of thin-film transistors (TFTs) on glass substrate, 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. Therefore, the development of a crystallization technique replacing the laser with high power and a simple equipment structure has been strongly required. In this work, we focused on thermal plasma jet because high power density of several tens of kw/cm^2 is achieved at atmospheric pressure with a simple equipment structure. We have demonstrated the feasibility of this technique for the crystallization of Si films on the glass substrate and its application to TFT fabrication.

Experimental

A thermal plasma source was developed as shown in Fig. 1 and the inset of Fig.2. The W cathode and the water-cooled Cu anode separated 2 mm each other are connected to a power supply. Arc discharge was performed by supplying DC biases of 13 to 15.3 V and 130 to 200 A between the electrodes with an Ar gas flow of 3 to 8 L/min. The thermal plasma jet was formed by blowing out the arc plasma through a 4 mmϕ nozzle. Amorphous Si (a-Si) films were formed on quartz substrate from an inductively coupled plasma (ICP) of 50% SiH_4 diluted with H_2 at 150 °C. The substrate was linearly moved by a motion stage in front of the plasma jet with scanning speed ranging from 170 to 1000 mm/s. The distance between the plasma source and the substrate was set at 2 mm.

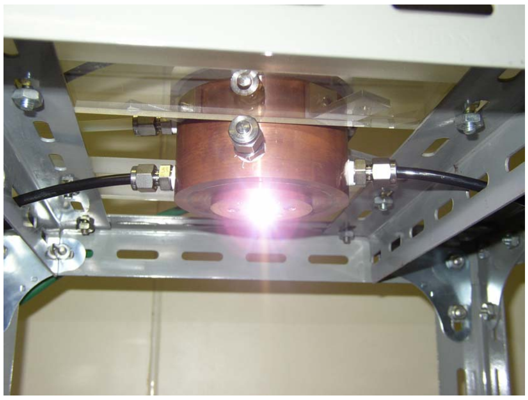

Fig. 1. Photograph of plasma jet generated by a DC arc discharge under atmospheric pressure.

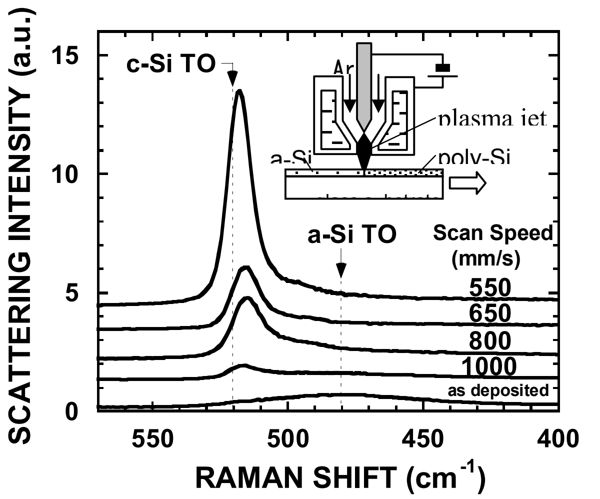

Fig. 2. Schematic diagram of thermal plasma jet annealing of Si films on glass (inset) and Raman scattering spectra of 80 nm thick Si films annealed by thermal plasma jet.

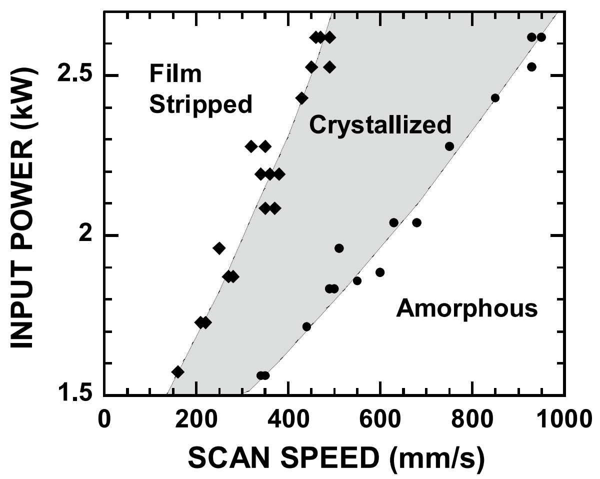

Fig. 3. Conditions of input power to the plasma source and scanning speed for the crystallization of a-Si films.

Results and Discussion

Raman spectra obtained from 80 nm-thick Si films before and after anneal at different scanning speeds under a constant input power to the plasma source of ~ 2.4 kW are shown in Fig. 2. By reducing the scanning speed below 1000 mm/s, a sharp peak due to crystalline Si TO phonons appears in the range from 515 to 518 cm^{-1}. This confirms that Si films are crystallized by the thermal plasma jet. With decreasing scanning speed from 1000 to 550 mm/s, the full width at half maximum (FWHM) and the peak position are reduced from 19 to 10 cm^{-1} and increased from 515 to 518 cm^{-1}, respectively. Figure 3 shows the crystallization conditions of the input power to the plasma source and the scanning speed. When increasing the input power, a-Si films are crystallized at higher scanning speed and the process window becomes lager. However, the film stripping was facilitated with a decrease in the scanning speed down to a certain value. It has been clarified that PJC occurs either in solid phase or liquid phase depending on the condition [1].

In order to demonstrate an application of this technique to electronic device, n-channel TFTs are fabricated using 20-nm-thick Si films crystallized by thermal plasma jet with input power of 1.86 to 2.29 kW and scanning speed of 700 mm/s [2,3]. The fabricated TFTs had good performance as seen in transfer and output characteristics shown in Fig. 4 (a) and (b), respectively. The on-current increased as the input power to the plasma source during the crystallization is increased from 1.86 to 2.29 kW as shown in Fig. 4 (b). The average field effect mobility and threshold voltage of the TFTs extracted from the transfer characteristic increased

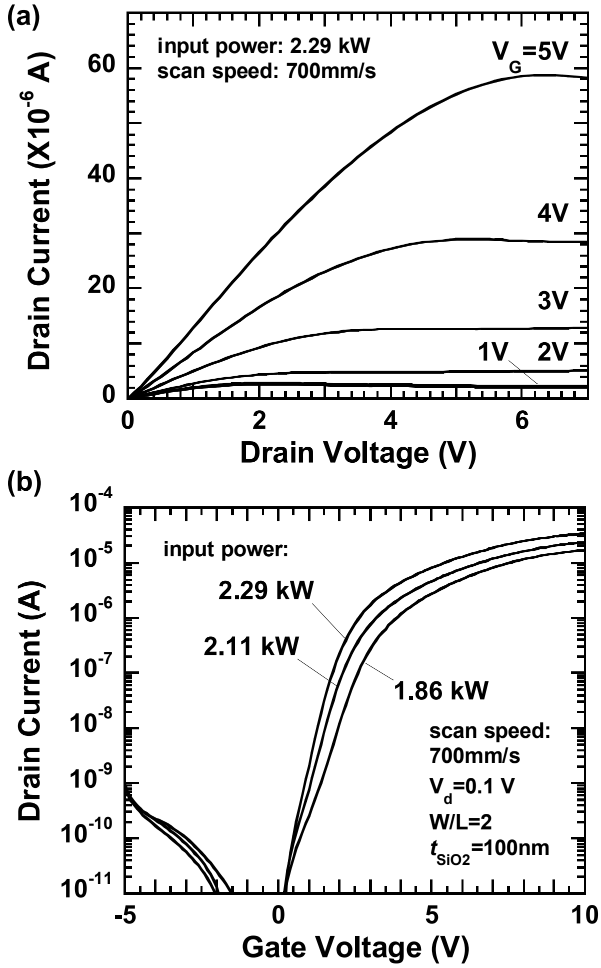

Fig. 4. Output (a) and Transfer (b) characteristics of TFTs fabricated with PJC Si films.

from 42 to 61 $cm^2V^{-1}s^{-1}$ and decreased from 4.0 to 3.4 V with increasing input power from 1.86 to 2.29 kW, respectively. These results well agree with an improvement of crystallinity by the increase in the input power to the plasma source. These results strongly suggest that PJC is a very promising technology for the large area electronic device fabrication in the next generation.

Reference

[1] S. Higashi, H. Kaku, H. Taniguchi, H. Murakami and S. Miyazaki, *Int. Conf. Polycrystalline Semiconductors 2004 (Potsdam, Germany, September 5-10, 2004)*, in series submitted to Thin Solid Films.

[2] S. Higashi, H. Kaku, H. Murakami, S. Miyazaki, M. Asami, H. Watakabe, N. Ando and T. Sameshima: *Proc. Int. Workshop on Active-Matrix Liquid-Crystal Displays, (Tokyo Japan, August 25-27, 2004)* pp. 179-180.

[3] S. Higashi, H. Kaku, H. Murakami, S. Miyazaki, H. Watakabe, N. Ando and T. Sameshima, submitted to Jpn. J. Appl. Phys..

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Background and Motivation

- **Issues of Excimer Laser Annealing (ELA)**
  > Low Power (~300 W)
  > High Cost
  1. Complicated mechanical structures
     high initial price, frequent adjustments required
  2. Running consumption
     medium gases, laser tube exhaustion

An Alternative Crystallization Technique is strongly required

About "Thermal Plasma"

- **Local Thermal Equillibrium (LTE) Plasma**
  $T_e \sim T_i \sim T_n$ ("hot" plasma)
  High density
- **Features as a Heat Source**
  > Simple structure and high power
  > Atmospheric pressure discharge
  > Heat transfer by plasma jet

Possible candidate for a heat source to crystallize Si films on glass substrate

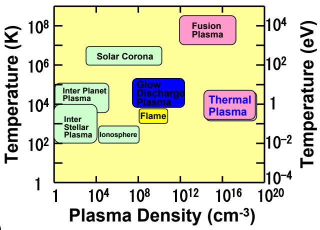


Fig. 1. Mapping of various plasmas based on the density and the temperature.

Plasma Source and Plasma Jet Formation

- **DC arc discharge plasma source**

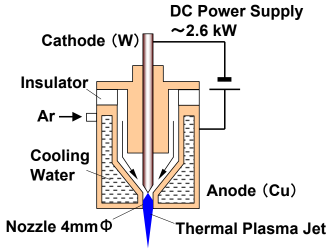


Fig. 2. Schematic diagram of thermal plasma source.

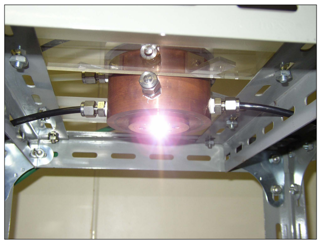


Fig. 3. Photograph of thermal plasma jet generated by atmospheric pressure discharge.

Optical Emission Spectroscopy

- **Strong emission lines from Ar atoms are observed**

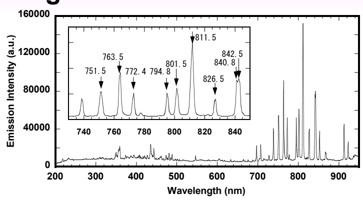


Fig. 4. Optical emission spectrum of thermal plasma jet.
Most of the significant lines are identified to be emission from Ar atoms as indicated in the inset. From the Boltzmann's plot of the Ar lines, the temperature of the plasma was roughly estimated to be 8,300K.

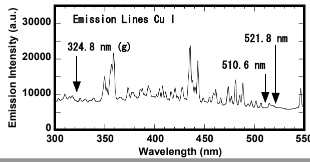


Fig. 5. Identification of emission lines from Cu in thermal plasma jet.
No emission lines from Cu was observed in the optical emission spectrum of thermal plasma jet.

Crystallization of a-Si Films on Glass by Thermal Plasma Jet

- **Experimental Setup**

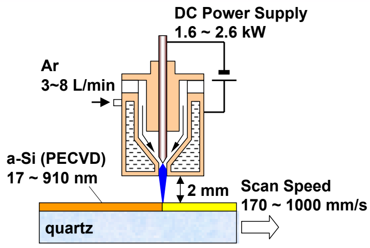


Fig. 6. Schematic diagram of experimental setup for annealing of a-Si film by thermal plasma jet.

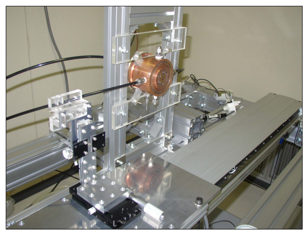


Fig. 7. Photograph of experimental setup.

Raman Scattering Spectra of Si films Before and After the Annealing

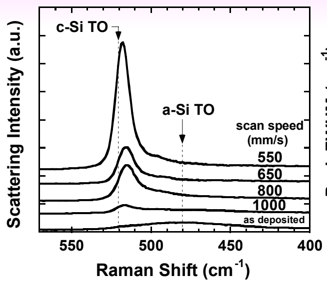


Fig. 8. Raman scattering spectra of Si films before and after the annealing.
80nm-thick a-Si films are crystallized by the thermal plasma jet.

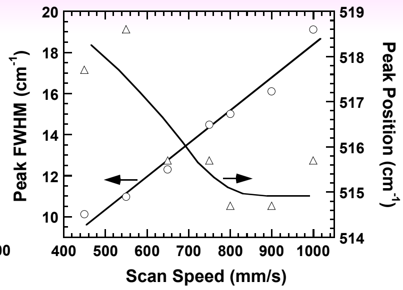


Fig. 9. Width (FWHM) and position of crystalline Si TO phonon peak as functions of scan speed.
Crystalline quality is improved by annealing the Si film at higher temperature for longer duration.

Surface Morphology of Crystallized Film

- AFM Image of Crystallized Film

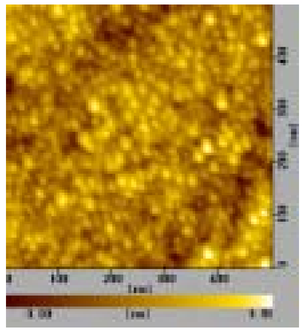


Fig. 10. AFM image of a Si film crystallized by thermal plasma jet.
(t_{Si}: 20 nm、input power : 2.57 kW、scan speed : 600 mm/s、Ar flow rate : 10.5 l/min)
roughness: 3.5 nm (RMS: 0.53 nm)
grain size : 20～30 nm

Crystallization Condition for a-Si Film

- Crystallization Condition of Input Power to the Plasma Source and Scan Speed

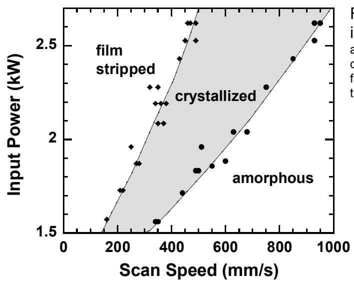


Fig. 11. Crystallization condition of input power and scan speed.
a-Si film is crystallized over a wide annealing condition. No de-hydrogenation is required. the film stripping was facilitated with a decrease in the scanning speed down to a certain value

Crystallization of Thin and Thick a-Si Film

- a-Si Films With the Thickness Ranging From 17 ~910 nm Are Successfully Crystallized

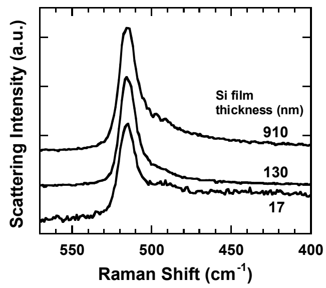


Fig. 12. Raman scattering spectra of crystallized Si films with the thickness ranging from 17 ~ 910 nm.
The broad peaks in lower wave number regime seen in 17 nm film is the signal from quartz substrate. Both thin and thick a-Si films have been crystallized. This is because the thermal diffusion length of this annealing technique is much larger than the film thickness.

Crystalline Quality of Si Films At the Top and the Bottom Interface

- UV Reflectivity Spectra Obtained From Top and Backside of the Substrate

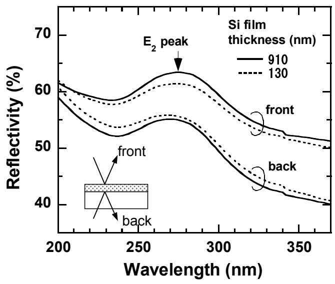
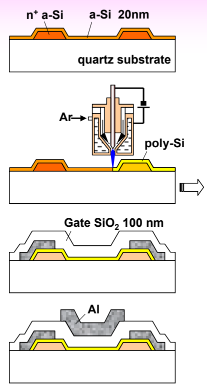


Fig. 13. UV reflectivity spectra of crystallized Si films obtained from top and backside of the substrate. Spectra obtained from 130 and 910 nm thick films are compared.
Clear E_2 peak are observed from both samples. The Si film is completely crystallized to the bottom interface independent of film thickness.

Thin-Film Transistor Fabrication



- a-Si Deposition
  - > S/D n+ a-Si (PECVD)
  - > Channel a-Si deposition(PECVD)
- Crystallization
  - > Thermal Plasma Jet
  - 2.3kW 700mm/s
  - > Excimer Laser Annealing (ELA) :Reference
- Channel Isolation
  - > Dry Etching (SF_6)
- Source/Drain Electrode Formation
  - > Thermal Evaporation Al
- Gate SiO_2 Formation
  - > SiO Evaporation in Oxygen Radical
- Gate Electrode Formation
  - > SiO Evaporation in Oxygen Radical
- Defect Reduction
  - > High-Pressure H_2O Vapor Anneal

TFT Performance

- **Transfer and Output Characteristics of the TFT**

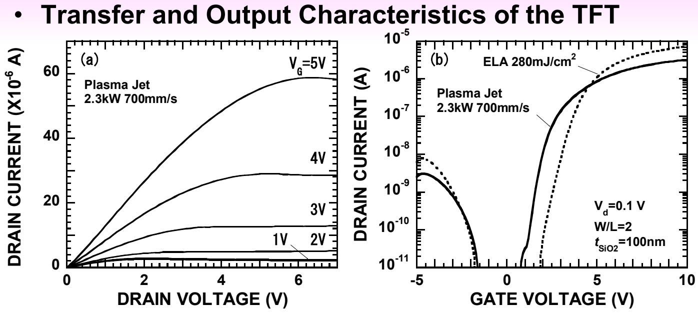


Fig. 14. Output (a) and transfer (b) characteristics of TFT fabricated by thermal plasma crystallization technique. For comparison, ELA TFT is also fabricated on the same substrate.

Summary of TFT Fabrication Results

- **Maximum process temperature** : 260℃
- **TFT parameters**

  t_{Si} : 20 nm t_{SiO2} : 100 nm

  W/L : 2
- **TFT performances**

	Thermal Plasma Jet	ELA
μ_{FE} ($cm^2V^{-1}s^{-1}$)	**62**	**160**
V_{th} (V)	**3.4**	**4.3**
I_{ON} / I_{OFF}	**>10^6**	**>10^6**

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Conclusions

- A novel crystallization technique of Si films on glass substrate using thermal plasma jet have been developed.
- a-Si film is crystallized with the input power and the scan speed of 1.6 ~ 2.6 kW and 170 to 1000 mm/s, respectively.
- a-Si films with the thickness ranging from 17 ~ 910 nm are crystallized.
- TFTs fabricated with the thermal plasma jet crystallized Si film showed good performance with the field effect mobility of 62 $cm^2V^{-1}s^{-1}$ and threshold voltage of 3.4 V.

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