Ultrarapid Thermal Annealing Induced by DC Arc Discharge Plasma Jet Irradiation

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1. Introduction

Ultrarapid thermal annealing (URTA) under non thermal equilibrium is one of the key process technologies for the fabrication of large area electronic devices such as thin-film transistors (TFTs) and solar cells. By localizing the heat to the substrate surface, amorphous Si (a-Si) films are crystallized without serious thermal damage to the substrates, which allow the use of low heat-resistant substrates such as glass and plastic. In addition, URTA technique is a key process technology in ULSI fabrication because precise control of dopant diffusion in shallow junction is required in nano-scaled MOSFETs.

Recently, we have developed a millisecond annealing technique using thermal plasma jet (TPJ) [1]. This is an atmospheric pressure process utilizing DC arc discharge thermal plasma, which can generate high temperature gas flow with simple equipment. Because thermal plasma has a high density in the order of 10^{18} cm^{-3} with a temperature higher than 10000 K, the electrical power introduced to the plasma is strongly concentrated at the nozzle. The TPJ transfers the power to the substrate surface. In this research, the temporal variation in substrate surface temperature induced by TPJ irradiation is investigated using a noncontact temperature measurement technique [2,3]. The application of TPJ URTA technique to the crystallization of a-Si films is also studied. The electrical characteristics of TFTs fabricated with the URTA technique are demonstrated.

2. Experimental

TPJ is generated by an atmospheric pressure DC arc discharge under Ar gas flow, and blowing out the arc plasma through an orifice of 3 to 4 mm in diameter. URTA of a-Si films on quartz substrate was performed by linearly moving the samples on a motion stage in front of TPJ. Annealing temperature was controlled by varying the power input to plasma source (p), Ar gas flow rate (f), the distance between the plasma source and the substrate (plasma-substrate gap) (d) and the substrate scanning speed (v).

In order to measure the temperature profile generated in the quartz substrate during the TPJ irradiation, transient reflectivity was measured by irradiating the substrate with a laser light (λ = 633 or 532 nm) from the backside and detecting the reflected light intensity with a photodiode through a band pass filter. The details of the temperature measurement are described in Refs. [2] and [3].

3. Results and Discussion

On the basis of the measurement technique, one can obtain the transient temperature profile at arbitrary depth with the time resolution of millisecond as shown in Fig. 1. In the case of this example, the maximum surface temperature ($T_{\max}$) reached ~1640 K. Since the characteristic heat diffusion length in millisecond is in the order of several 10 μm, the temperature at positions deeper than 50 μm is much lower compared to that of the surface, which indicates the TPJ heats only the substrate surface. The accuracy of the measurement has been

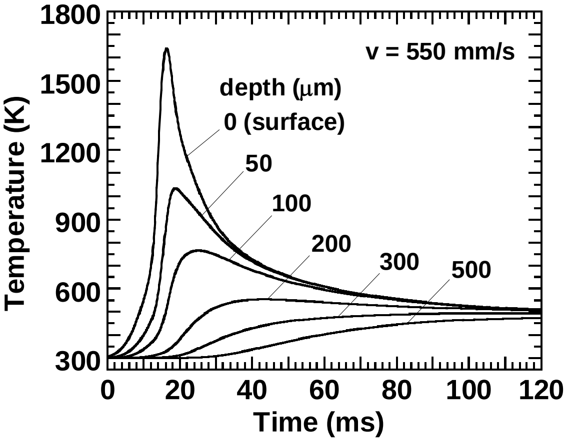

Fig. 1. Transient temperature profiles generated in quartz substrate during TPJ URTA.

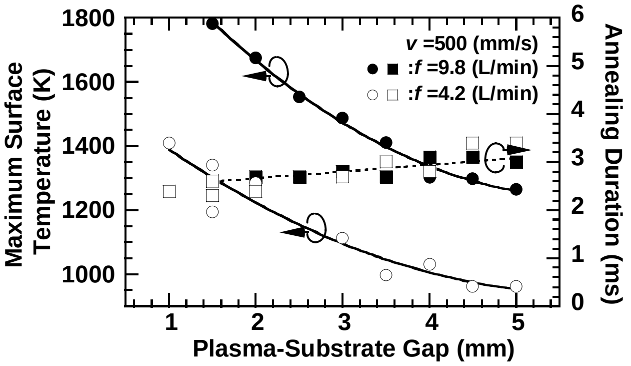

Fig. 2. Maximum surface temperature ($T_{\max}$) and annealing duration (t_a) obtained from noncontact temperature measurement technique.

evaluated in terms of errors in fitting and absolute temperatures [4]. So far, the error is less than 30 K at measurement temperature of ~1670 K. The $T_{\max}$ and annealing duration (t_a) as functions of d under a constant v = 500 mm/s and different f are shown in Fig. 2 [3,4]. $T_{\max}$ can be controlled in the range of ~960 to ~1780 K with almost constant t_a of ~3 ms. The characteristic values of the URTA such as $T_{\max}$, t_a, maximum heating rate (R_h) and cooling rate (R_c) are summarized in Table I.

Table. I. Characteristic values of TPJ URTA with different plasma-substrate gap d.

d (mm)	1.5	3.0	5.0
$T_{\max}$ (K)	1781	1488	1266
t_a (ms)	2.6	2.8	3.0
R_h (x10^5 K/s)	3.87	2.93	2.23
R_c (x10^5 K/s)	1.47	1.00	0.69

TPJ annealing technique has been applied to the crystallization of a-Si films [1,5]. Raman scattering spectra of 80-nm-thick Si films before and after TPJ annealing at different v values under a constant p of 2.40 kW, an f of 7.0 L/min and a d of 2.0 mm are shown in Fig. 3. After the TPJ URTA of a-Si films, clear peaks associated with crystalline Si TO phonons are observed. This confirms that the a-Si films are crystallized within millisecond. By reducing v from 1000 to 550 mm/s, the FWHM and position of the TO phonon peak are reduced from 19 to 11 cm^{-1} and increased from 515 to 518 cm^{-1}, respectively. A-Si films are crystallized in solid phase, and a higher temperature and a longer annealing duration have improved in crystallinity. It has been confirmed that the a-Si films are crystallized either by solid phase crystallization (SPC) or melting and resolidification depending on URTA condition [7].

For the evaluation of the electrical characteristics of TPJ crystallized Si films, TFTs were fabricated and the transfer characteristics are shown in Fig. 4 [7]. The field-effect mobility (μ_{fe}) and threshold voltage (V_{th}) of the TFTs increases from 42 to 61 $cm^2 \cdot V^{-1} \cdot s^{-1}$ and decreases from 4.0 to 3.4 V, respectively, with increasing p from 1.86 to 2.29 kW. These results indicate that the TPJ URTA technique is applicable to the fabrication of semiconductor devices, which means it is a very promising technique for the future URTA processing.

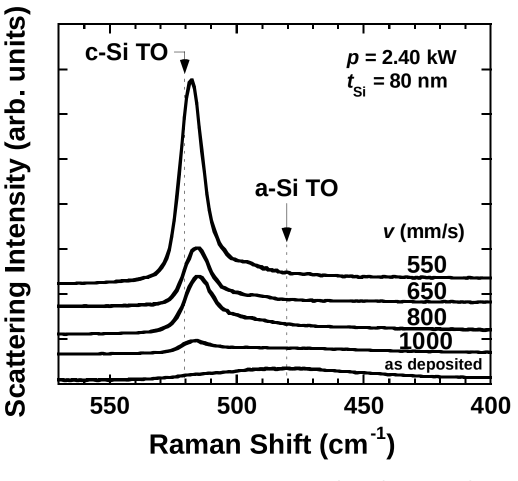

Fig. 3. Raman scattering spectra of Si films before and after TPJ irradiation under different scan speed v.

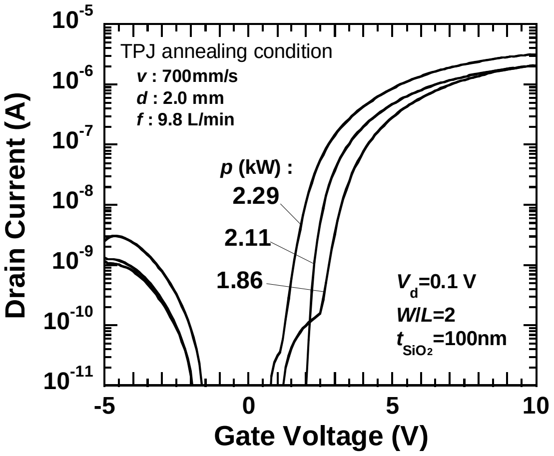

Fig. 4. Transfer characteristics of TFTs fabricated by TPJ crystallized Si films.

4. Conclusions

URTA in millisecond time domain induced by TPJ irradiation is investigated. Substrate surface temperature during URTA is measured by a noncontact technique. $T_{\max}$ is controlled from ~960 to ~1780 K with typical t_a of ~3 ms. A-Si films are crystallized by TPJ URTA and it is demonstrated that TPJ URTA is applicable to TFT fabrication as demonstrated with a high μ_{fe} of 61 $cm^2 \cdot V^{-1} \cdot s^{-1}$ and a low V_{th} of 3.4 V, respectively.

Acknowledgements

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