Extended Abstracts of the 2007 International Conference on Solid State Devices and Materials, Tsukuba, 2007, pp. 376-377

P-1-27L

In-situ Measurement of Temperature Variation in Si Wafer During Millisecond Rapid Thermal Annealing Induced by Thermal Plasma Jet Irradiation

Hirokazu Furukawa, Seiichiro Higashi, Tatsuya Okada, Hirotaka Kaku,
Hideki Murakami and Seiichi Miyazaki

Department of Semiconductor Electronics and Integration Science,
Graduate School of Advanced Sciences of Matter, Hiroshima University
1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8530, Japan
Phone: +81-82-424-7648 Fax: +81-82-422-7038 E-mail: semicon@hiroshima-u.ac.jp

1. Introduction

For the formation of ultra-shallow junction, development of millisecond rapid thermal processing such as flash lamp annealing (FLA) [1] and laser spike annealing (LSA) [2] is the key technological issue. Substitutional doping of impurities to Si lattice with a concentration beyond equilibrium soluble limit has to be achieved without significant diffusion of dopant atoms. Accordingly, precise control of heating and cooling rates in millisecond or even shorter rapid thermal annealing (RTA) is indispensable. However, there is no practical way that allows us to measure Si wafer temperature with such a high time resolution.

In our previous work, we have developed a non-contact temperature measurement technique applicable to millisecond RTA of quartz substrate induced by thermal plasma jet (TPJ) irradiation [3, 4]. During the RTA, a periodic oscillation is observed in transient reflectivity of quartz substrate, which is originated from change in optical thickness due to heat diffusion. By analyzing the oscillation, temperature profile is obtained with millisecond time resolution. In this work, we have applied the principle to Si wafer by introducing an infrared laser light as the probe light. Experimental results on the *in-situ* measurement of transient temperature evolution in millisecond RTA are demonstrated.

2. Experimental

Millisecond RTA was performed by irradiating 0.7-mm-thick n-type Si (100) wafer with TPJ. 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 from each other were connected to a power supply. Arc discharge was generated by supplying DC power (p) of 2.0 kW, where the DC voltage was 13.3 V with a constant discharge current of 150A, between the electrodes under an Ar gas flow rate of (f) 9.8 L/min. The TPJ 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 TPJ with scanning speed (v) ranging from 500 to 2000 mm/s. The distance between the plasma source and the substrate (d) was set at 0.6 mm. For the measurement of temperature profile in the Si wafer during the TPJ annealing, an optical probe as illustrated in Fig. 1 was used. The transient reflectivity was measured by irradiating the Si substrate with an infrared laser (λ= 1310 nm) from the backside of the substrate and detecting the reflected light intensity by a photodiode.

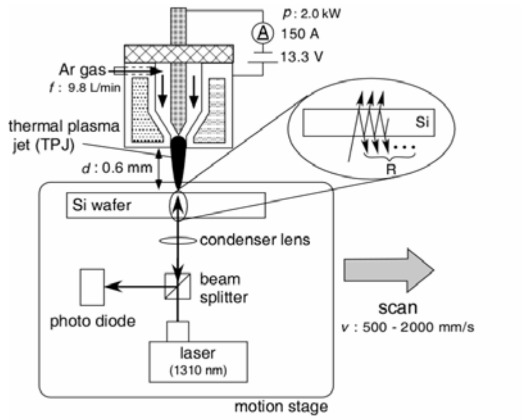

Fig.1. Schematic diagram of thermal plasma jet (TPJ) annealing of Si wafer. The transient reflectivity was measured by irradiating the sample with an infrared laser (λ= 1310 nm) from the backside of the substrate.

The optics and the substrate was set on a motion stage, and moved together.

3. Results and discussion

The observed transient reflectivity waveform under different v is shown by solid lines in Fig. 2. The oscillation in reflectivity during the TPJ irradiation was clearly observed, and the number of oscillations increased with decreasing v. The oscillation in the transient reflectivity is due to the interference of the incident light multiply reflected between the top and bottom surface of the substrate as schematically shown in the inset of Fig. 1. Since the refractive index of Si (n_{Si}) changes with temperature, the optical thickness of Si substrate during the annealing changes in accordance with heat diffusion and this induces the oscillation. By simulating the change in optical thickness based on heat diffusion and optical interference, we can reproduce the observed reflectivity very nicely as shown by dotted lines in Fig. 2. Here, we use the reported thermal conductivity [5], and the temperature dependence of refractive index $n_{Si} = 3.5039 + 1.7737 \times 10^{-4} \times T$ (°C) was obtained from *ex-situ* measurement using same optics. The spatial profile of TPJ was deconvoluted by two Gaussians with typical width of 2.5 ~ 3.5mm and 4.8 ~ 5.3 mm, respectively. These values roughly agree with the observed TPJ profiles. In the transient reflectivity, we notice the amplitude modulation. This was well reproduced by

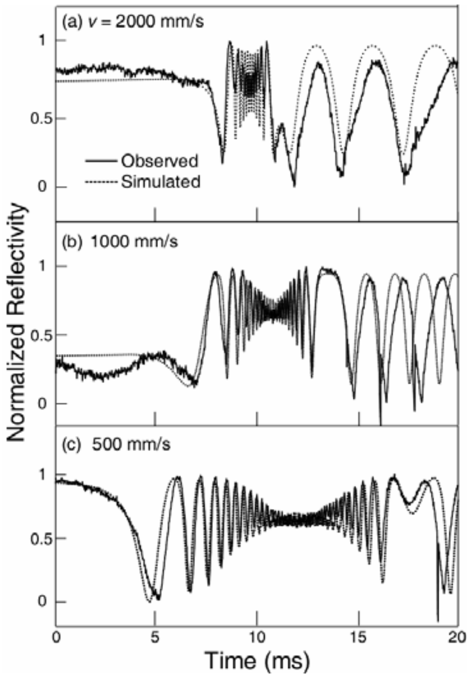

Fig. 2. Measured (solid line) and simulated (dotted line) transient reflectivity under different scan speeds *v*.

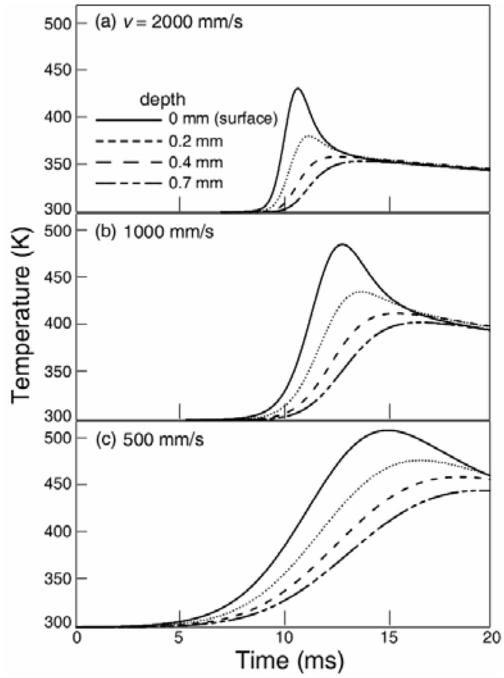

Fig. 3. Measured transient temperature variations corresponding to (a) – (c) in Fig. 2. Temperatures at different depths in Si wafer are shown.

considering the lateral heat diffusion within the probe laser spot of 0.08 mm in diameter. As a result, we obtained the temperature distribution in Si wafer with millisecond time resolution as shown in Fig. 3. Figures 3 (a) to 3 (c) show transient temperature variation at different depths in the substrate under RTA conditions of (a) v = 2000 mm/s, (b) v = 1000 mm/s and (c) v = 500 mm/s, respectively. From these result, we obtained the maximum surface temperature (T_{max}), annealing duration (t_a), maximum heating rate (R_h) and cooling rate (R_c) as summarized in Table. 1. T_{max} and R_h as functions of v are plotted in Fig. 4. These results show that the transient temperature profile and temperature distribution of Si substrate are obtained very accurately by this newly developed technique.

Table. 1. Characteristic values of the TPJ annealing performed under different scan speeds *v*.

v (mm/s)	500	1000	2000
T_{max} (K)	510	487	432
t_a (ms)	8.2	3.08	1.52
R_h (×10^5 K/s)	0.36	0.81	1.30
R_c (×10^5 K/s)	0.12	0.32	0.59

4. Conclusions

Using the analysis of transient changes in optical reflectivity of Si substrate, the temperature during TPJ process is measured with millisecond time resolution. In the analysis, we can well reproduce the observed waveforms with double-Gaussian shapes of TPJ profile and considering the spatial distribution. From the analysis of transient changes in optical reflectivity of Si substrates exposed to the TPJ, T_{max} increased from 432 to 510 K and R_h decreased from 1.30 × 10^5 to 0.36 × 10^5 K/s with decreasing v from 2000 to 500 mm/s. Present temperature measurement technique is a very powerful method for the further development of millisecond and even shorter RTA process.

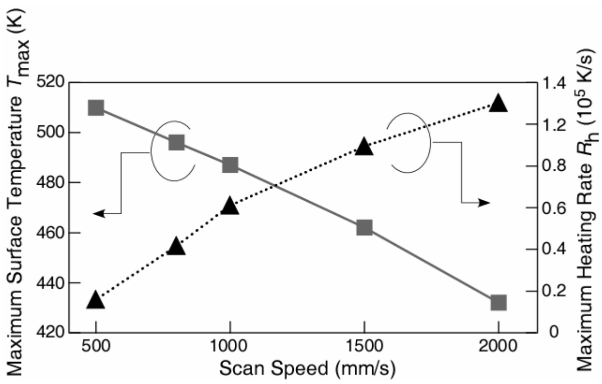

Fig. 4. T_{max} and R_h as function scan speeds *v*.

Acknowledgements

A part of this work was supported by New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for scientific research of priority area (B) of Japan. The authors would like to acknowledge Professor S. Yokoyama and Dr. Y. Tanushi of Research Center for Nanodevices and Systems, Hiroshima University for their experimental cooperation.

References

[1] T. Ito, et al., Jpn. J. Appl. Phys. **41** (2002) 2394.
[2] A. Shima, et al., Jpn. J. Appl. Phys. **45** (2006) 5708.
[3] T. Okada, et al., Jpn . J. Appl. Phys. **45** (2006) 4355.
[4] T. Okada, et al., Thin Solid Films, **515** (2007) 4897.
[5] H. R. Shanks, et al., Phys. Rev. **130** (1963) 1743.