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Time-resolved observation of surface temperature distribution of Silicon irradiated by nanosecond laser pulse using a nanosecond imaging technique

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Abstract

In nanosecond pulsed laser processing techniques such as laser annealing and laser doping, the surface temperature of the laser-irradiated area and surrounding area changes on a nanosecond scale, which affecting the processing results. Laser energy and pulse width are especially important parameters in the surface microprocessing of semiconductor materials because they dramatically affect the surface temperature. Therefore, surface temperature measurement with nanosecond time resolution is very effective monitoring technique in order to optimize the laser processing conditions. We have developed an in-situ, non-contact, nanosecond time-resolved and micro-scale spatial resolution temperature measurement system by using a nanosecond gated camera and two-color temperature measurement method. In this study, we estimated nanosecond two-dimensional and time-resolved surface temperature of Si wafer irradiated by nanosecond excimer laser pulse using the measurement system.

Keywords: two-color temperature method; surface temperature measurement; nanosecond time-resolved imaging;

1. Introduction

In recent years, lasers have been used in various fields, such as cutting, welding, microfabrication, and annealing, owing to their improved performance. Nanosecond pulsed lasers are used in Si and SiC semiconductor processing. In the area irradiated by a nanosecond pulsed laser, the temperature changes rapidly on the nanosecond scale, which affects the properties of the processed material. Therefore, controlling the surface temperature during laser irradiation is necessary to stabilize the processing quality. In addition, quality control methods are investigated in the manufacturing field, and methods to control the quality in real-time are required. Thus, an in-situ non-contact temperature measurement method with nanosecond-time responses and a microscale spatial resolution is required to determine the temperature distribution.

Temperature changes during laser irradiation can be estimated by irradiating a probe laser onto a pulsed-laser-irradiated area and measuring the reflectivity. In addition, two-dimensional (2D) measurements of the temperature distribution in a laser-irradiated area using a camera with a microsecond time resolution has been reported. We focused on nanosecond pulsed laser processing and suggest that real-time and highly accurate laser and quality control can be achieved by analyzing the surface temperature of the laser-irradiated area in two dimensions with a nanosecond time resolution.

In this paper, we propose a temperature measurement method, based on a two-color temperature method with an ICCD camera at a nanosecond gate speed, with both nanosecond time and spatial resolutions. The two-color temperature method is based on Planck's law [5] and calculates the temperature from the ratio of thermal radiation intensities at two different wavelengths, even for objects with unknown emissivities. We constructed an optical system to observe thermal radiation without plasma emission or reflected light, which are measurement noises. Using this system, nanosecond-time-resolved and 2D surface temperatures were measured to determine the effect of pulse width when a Si wafer was irradiated by a KrF excimer laser (commonly used in annealing). The surface conditions of the irradiated area were determined by probe-laser irradiation and reflectance measurements. We assess the feasibility of evaluating the sample conditions based on temperature.

2. Experimental Setup

The laser irradiation system for nanosecond-time-resolved 2D temperature distribution measurements is shown in Fig. 1. Nondoped Si wafers were used as targets, which were irradiated by a KrF excimer laser (wavelength, λ = 248 nm). The laser was operated as in the single-pulse mode with a pulse width of 24 or 82 ns and laser fluence of 1.0 J/cm2. An aperture was used to set the laser irradiation area at the target surface to 400 µm x 400 µm. An ICCD camera with a minimum gate time of 2 ns was used for the 2D temperature measurements. Further, 750 and 850 nm bandpass filters with a full width at half maximum of 25 nm were placed in front of the ICCD camera to measure the intensity of the thermal radiation. The oscillation signal from the KrF excimer laser was used as the gate trigger for the ICCD camera. The time variation in the thermal radiation intensity was measured by setting a delay time for the gate operation. A probe laser (λ = 634.7 nm) was irradiated onto the laser-irradiated area, and the reflectivity was measured. The light reflected from the probe laser was detected by a photodetector with a rise time of 2.3 ns, and the signal was measured with an oscilloscope. A bandpass filter was placed in front of the photodetector to prevent exposure to stray light. An ultraviolet-cut filter was used to remove light reflected from the laser.

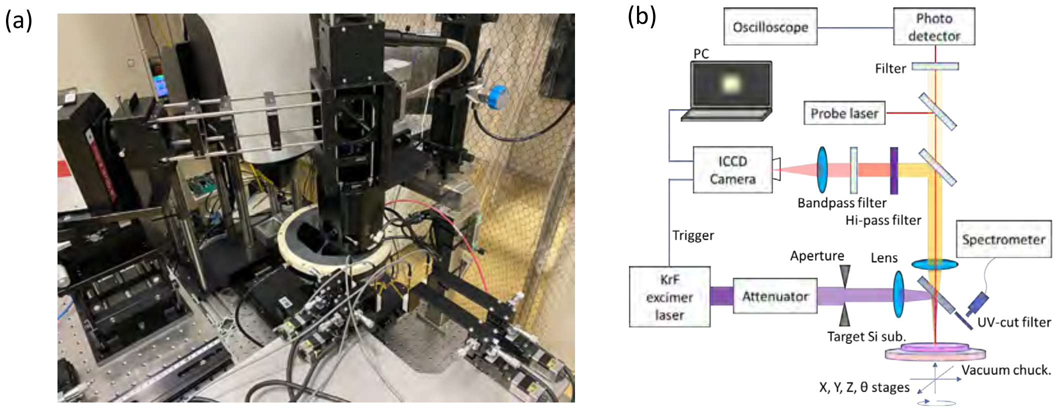

Fig. 1. (a) Experimental setup without shading cover; (b) Schematic of the experimental setup

3. Results and discussion

3.1. Temperature Measurement

Fig. 2 shows the time variation of the thermal radiation intensity at 750 and 850 nm with a pulse width and laser fluence of 24 ns and 1.0 J/cm2, respectively. The color bar indicates the magnitude of the intensity, and the red dotted line represents the irradiated area. The lower-left image shows the start time of the camera gate opening from the laser irradiation. At both the wavelengths, the intensity of the thermal radiation changes over time.

Fig. 3 shows the time variation of the 2D temperature distribution obtained using the two-color temperature method. The color of the image represents the temperature, shown on a scale of 1500–4000 K. The lower limit of temperature detection is approximately 1500 K because of the limited grayscale of the ICCD camera used in this study. The temperatures are averaged over the irradiated areas. The temperature increases to 1700 K after 10 ns of laser irradiation; the highest temperature of 2100 K is observed after 20 ns of irradiation, and then, the temperature decreases to 1500 K at 70 ns.

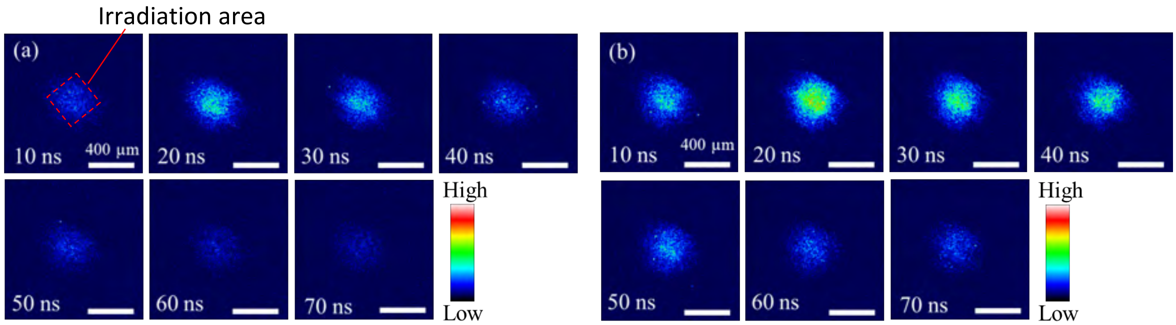

Fig. 2 Time variation of the thermal radiation intensity at (a) 750 nm and (b) 850 nm with a pulse width of 24 ns and fluence of 1.0 J/cm^2.

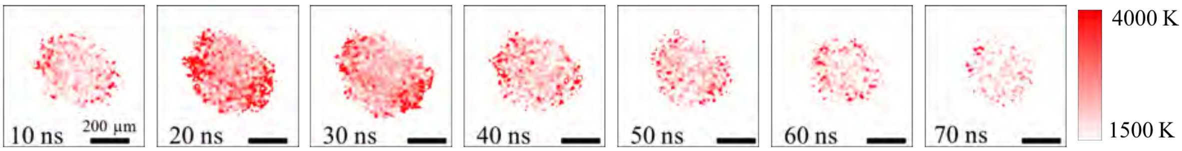

Fig. 3 Time variation of the 2D temperature distribution at a pulse width of 24 ns and fluence of 1.0 J/cm^2.

Fig. 4 shows the time variation of the thermal radiation intensity at 750 and 850 nm with a pulse width of 82 ns and laser fluence of 1.0 J/cm2. The temperature increases to 1700 K after 10 ns of laser irradiation, reaches the maximum value of 1500 K at 20 ns, remains at approximately 1900 K from 60 to 80 ns, and then decreases to 1500 K over 160 ns.

For the same fluence, a longer pulse width results in a lower energy density per hour and lower maximum temperature, and the high-temperature state time above 1500 K increases with the pulse width. The temperature measurements were performed at different pulse widths.

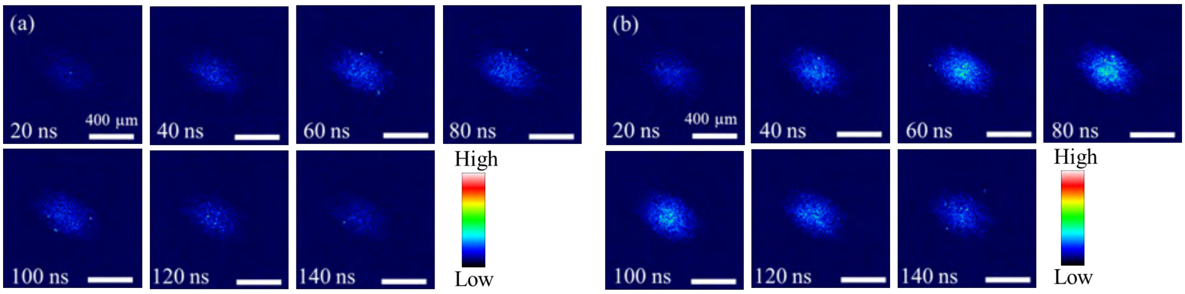

Fig. 4 Time variation of the thermal radiation intensity at (a) 750 nm and (b) 850 nm with a pulse width of 82 ns and fluence of 1.0 J/cm^2.

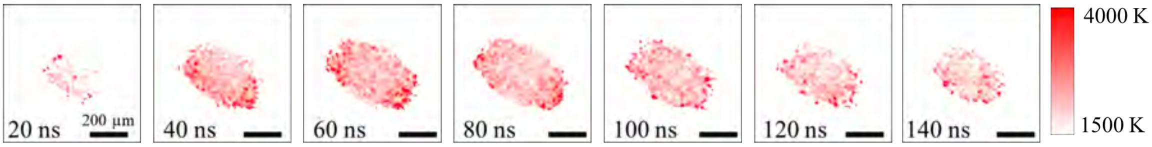

Fig. 5 Time variation of the 2D temperature distribution at pulse width of 82 ns and fluence of 1.0 J/cm^2.

3.2. Material-condition evaluation

Fig. 6 shows the average temperature variation of the 2D temperature distribution and reflectance variation of the probe laser. The position at 0 ns corresponds to the start of the laser oscillation. From -50 ns to 0 ns, the nonradiated Si surface exhibits a reflectivity of approximately 31 %, which is consistent with that of solid Si reported in previous studies. When the probe laser is turned off, no signal is detected by the photodetector even after laser irradiation. This observation confirms that the reflection intensity measurement does not include stray light or plasma-emission components.

Fig. 6 shows that the reflectivity of the probe laser increases at a temperature of 1685 K, which is the melting point of Si, and reaches its maximum value after approximately 20 ns of irradiation. According to previous reports, the reflectivity of Si rapidly increases upon melting. Subsequently, the reflectance decreases with the decreasing temperature. During solidification, a low surface roughness is observed, and the corresponding reflectivity is lower than that observed before the laser irradiation; similar results are obtained for each pulse width.

For each pulse width, the Si surface exhibits a 2D temperature distribution. Therefore, we successfully measured the surface temperature distribution in two dimensions, with a high temporal resolution, based on the pulse width during laser irradiation.

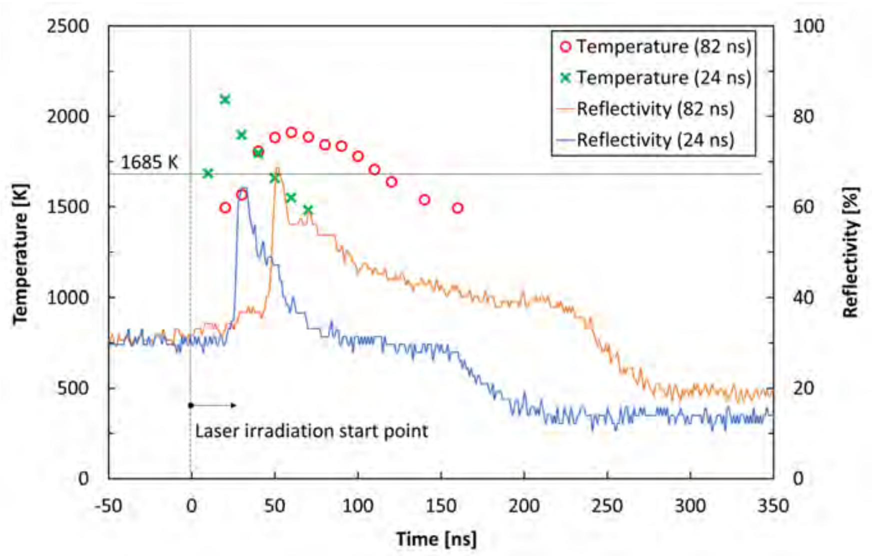

Fig. 6 Time variation of the average temperature (plot) and, reflectivity (solid line) at a fluence of 1.0 J/cm^2.

4. Conclusions

We constructed a laser irradiation system using a KrF excimer laser and obtained 2D temperature distributions from the thermal radiation intensity captured by an ICCD camera, with a nanosecond gate speed, using a two-color temperature method. The results confirmed that the temperature distribution on the Si surface during nanosecond pulse laser irradiation was obtained with a nanosecond time resolution. By irradiating the wafer by lasers of different pulse widths (24 and 82 ns), we confirmed that the temperature variation depended on the pulse width; thus, the response of the measurement was sufficient. For the same fluence, changing the pulse width changed the energy density per hour, and a difference in the maximum temperature was confirmed. This implies that our system can be used to control the temperature and quality of a target by adjusting the pulse width. Further, it is possible to control the temperature and quality of the target by changing the fluence (not described herein).

Furthermore, it was confirmed that the average temperature at the center of the laser-irradiated area coincided with the change in the reflectance of the probe laser. Thus, we can infer the state of the target from the temperature distribution, and this process is useful in annealing materials that are difficult to recrystallize in a molten state.

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