Oxygen precipitates in Czochralski Silicon (Cz-Si) wafers effectively act as getter sites for heavy metal impurities in semiconductor devices, and they also increase the mechanical strength of the wafer by precipitation hardening. Both these roles are important for stable device manufacturing, but oxygen precipitates are also responsible for decreasing the mechanical strength of the wafers if their size and density are not appropriately controlled. In addition, when oxygen precipitates remain in the device formation region, they can result in failure due to current leakage. For this reason, oxygen precipitation must sometimes be suppressed depending on the kind, structure, and process conditions of a semiconductor device. In particular, because of current advances in device structures such as scaling and three-dimensional chip integration, precise control of oxygen precipitation will become more significant as the stress induced in Si wafers during device fabrication becomes increasingly crucial. Therefore, an effective method that can be used for either promoting or suppressing oxygen precipitation in Cz-Si crystals is needed.

Many studies have been performed on methods for achieving such precise control of oxygen precipitation. However, maintaining the stability of the growing crystal both in the pulling and radial directions still remains difficult. Thus, both local and widespread nonuniformity often exists in the grown crystal. To address this very important problem, we have proposed rapid thermal oxidation (RTO) at ultrahigh temperature (ultrahigh-temperature RTO). Our results obviously demonstrated that the oxygen precipitate nuclei generated during the crystal growth were dissipated entirely, and dense oxygen precipitate nuclei were formed uniformly in the radial direction during RTO at temperatures over 1350 °C. We believed that the newly formed oxygen precipitates in the wafers that had been subjected to ultrahigh-temperature RTO were closely related to preserved vacancies. In particular, each oxygen precipitate nucleus is thought to consist of an oxygen-vacancy complex (for example, O₂V). The oxygen precipitate nucleus formation to yield either uniformly distributed precipitates or completely suppressed precipitation. Our results indicate the flexible and precise control of oxygen precipitation nucleus using ultrahigh-temperature RTO technique is beneficial for device fabrication.

The suppression of oxygen precipitation in Czochralski silicon (Cz-Si) using the ultrahigh-temperature rapid thermal oxidation (ultrahigh-temperature RTO) technique was investigated by infrared (IR) tomography. The oxygen precipitate nucleus generated during crystal growth were completely dissolved, and the formation of new nuclei due to ultrahigh-temperature RTO was also restrained by controlled slowing of the cooling rate. The ultrahigh-temperature RTO technique is demonstrated to effectively control the oxygen precipitate nucleus formation to yield either uniformly distributed precipitates or completely suppressed precipitation. In this paper, we demonstrate in detail such suppression of oxygen precipitation in Cz-Si wafers subjected to ultrahigh-temperature RTO.

Several 300-mm-diameter nitrogen-doped Cz-Si (100) wafers were cut from single Cz-Si crystals. The oxygen concentration (according to the old American Society for Testing and Materials (ASTM) standards), nitrogen concentration, and resistivity of the boron-doped wafers were 2.4–1.30 × 10¹⁸ cm⁻³, 1.9–2.1 × 10¹⁴ cm⁻³, and 26.4–27.1 Ω cm, respectively. The reason we chose high oxygen concentration range Cz-Si wafers in recent device fabrication is for better understanding of oxygen precipitation behavior. A commercially available RTP unit was used at 1375 °C for 15 s to anneal the wafers in a pure O₂ atmosphere in order to introduce point defects. The cooling rates to 600 °C were 5 °C/s and 120 °C/s. After RTP, these wafers were annealed at 780 °C for 3 h followed by 1000 °C for 16 h (two-step annealing) in a pure O₂ atmosphere using a commercially available vertical batch furnace to grow the oxygen precipitate.

The density of oxygen precipitates at wafer depths of 7–380 μm was evaluated by IR tomography (Raytex MO-441). The detection limits for size and density were 25 nm and 1 × 10¹⁴ cm⁻³, respectively.

The relation between the RTO conditions and the radial distribution of oxygen precipitates in the wafers is shown in Fig. 1. Typical IR tomography images of these samples are also shown in Fig. 2. The oxygen precipitate density in the sample produced without RTO treatment decreased at approximately 110–145 mm from the wafer center, as shown in Fig. 1. This corresponds to OSF normally stands for Oxide-induced Stacking Fault ring (so called OSF ring) that originated from large silicon oxide precipitate nucleation during the crystal pulling. Generally, a vacancy-rich region exists inside the OSF ring. This nonuniformity of the oxygen precipitate size is assumed to be caused by the OSF ring, because the vacancy concentration in the OSF ring area is lower than that in other vacancy-rich areas.

It should be noted that no oxygen precipitation was observed along the radial direction of the wafer subjected to ultrahigh-temperature RTO with a cooling rate of 5 °C/s, as shown in Fig. 1. The density was obviously below the detection limit at all measurement points. This is again clearly demonstrated in Fig. 2. Therefore, the oxygen precipitates that already existed in the wafer before RTO (formed during crystal growth) must have been completely dissolved during the ultrahigh-
The calculated depth profile of \( C_{\text{v}} - C_{\text{i}} \) obtained after RTO with cooling rates 5\(^{\circ}\)C/s and 120\(^{\circ}\)C/s.

Figure 2. Typical IR tomography images. The uppermost and the lowermost of each IR tomography image correspond to the wafer surface and 380 \( \mu \)m deep from surface, respectively. The scale bar is the same for all images.

Figure 1. Relation between RTO conditions and distribution of oxygen precipitates along the radial direction in Si wafers.

Furthermore, it was confirmed that oxygen precipitates can form with cooling rates as low as 25 \( ^{\circ}\)C/s in our previous study.\(^{11}\) In contrast, ultrahigh-temperature RTO with a cooling rate 5 \( ^{\circ}\)C/s led to a calculated \( C_{\text{v}} - C_{\text{i}} \) value lower than the critical value throughout the bulk, as shown in Fig. 3. Although vacancies are slightly more abundant than interstitial Si (\( C_{\text{v}} - C_{\text{i}} > 0 \)) in the Si wafer, they are thought to be insufficient to form \( \text{O}_2\text{V} \) during the ultrahigh-temperature RTO. Decreasing the cooling rate from 120 \( ^{\circ}\)C/s to 5 \( ^{\circ}\)C/s clearly decreases \( C_{\text{v}} - C_{\text{i}} \) greatly, which qualitatively agrees with the experimental observation. Thus, the formation of oxygen precipitate nuclei was effectively suppressed by lowering the vacancy concentration by reducing the cooling rate in ultrahigh-temperature RTO.

We demonstrated that reducing the cooling rate in ultrahigh-temperature RTO suppresses oxygen precipitation in Cz-Si wafers with diameters of 300 mm. Ultrahigh-temperature RTO with a cooling rate 5 \( ^{\circ}\)C/s provided a wafer with no oxygen precipitates even though it had a relatively high oxygen concentration. This is thought to be due to the greatly reduced vacancy concentration in the wafer. Thus, our results clearly demonstrate that ultrahigh-temperature RTO can effectively control the oxygen precipitation, not only leading to the formation of uniform oxygen precipitates at high cooling rates but also suppressing oxygen precipitation completely in vacancy-rich Cz-Si wafer at low cooling rates, so that the fundamental heterogeneity of crystals caused by intrinsic point defects and the related growth of defects are removed.

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