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Characterization of recrystallized depth and dopant distribution in laser recovery of grinding damage in single-crystal silicon

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ABSTRACT

A nanosecond pulsed Nd:YAG laser was irradiated on a boron-doped single-crystal silicon wafer with a diamond grinding finish to recover the grinding-induced subsurface damage. In order to visualize and measure the depth of the laser melted/recrystallized layer, small-angle beveled polishing was performed in pure water followed by KOH etching. It enabled the direct observation of the recrystallized region using a differential interference microscope and the measurement of its depth using a white light interferometer. Crystallinity analysis of the recrystallized region was carried out by using laser micro-Raman spectroscopy, and the dopant concentration profile was characterized by using radio frequency glow discharge optical emission spectrometry (rf-GD-OES). The results showed that the crystallinity and boron distribution in the recrystallized region changed after laser recovery. The dopant concentration becomes higher at the boundary of the recrystallized region and the bulk. This study demonstrates the possibility of boron concentration control by using suitable laser parameters.

1. Introduction

Silicon is widely used in semiconductor industry. Currently, silicon wafers with a diameter of 300 mm are used mainly for the production of various electronics products. Usually, silicon substrates are produced by slicing, lapping, grinding and chemo-mechanical polishing (CMP) processes. Such mechanical machining processes cause subsurface damages, such as amorphous layers, dislocations, and microcracks, in silicon wafers [1–3]. Conventional grinding causes the formation of subsurface damage up to a depth of 2 – 5 µm [4]. By using electrical in-process dressing (ELID) grinding with extremely fine abrasive grains, the depth of damaged layer can be reduced to 0.4 – 1.3 µm [5]. However, it is extremely difficult to completely eliminate the subsurface damage layer through mechanical approaches which require physical contact.

As an alternative, Yan et al. successfully recovered subsurface damage generated by diamond machining in single-crystal silicon wafers, using laser recovery [6–8]. Laser recovery technology must be distinguished from laser annealing. Laser annealing can be used to rearrange impurities from strongly disordered material which is induced by ion beam, and produce poly-crystalline material from amorphous material. On the other hand, laser recovery technology can be used to selectively melt and recrystallize the machining-damaged subsurface layers including amorphous layers, dislocations, and microcracks, and reproduce a single-crystalline structure identical to that of the bulk. Furthermore, laser recovery technology can produce a low surface roughness in comparison to conventional grinding. Thus, laser recovery technology is expected to be more suitable as post-grinding process than the current chemical polishing. However, in order to apply the laser recovery technology to the processing of silicon wafers with various depths of subsurface damage, it is important to investigate and establish the laser recoverable depth, i.e., the depth of laser-induced silicon melting and recrystallization.

The depth of laser-affected layers in amorphous silicon can be measured by cross-sectional observation of the sample, as done in laser annealing. Since laser irradiation changes the surface structure from amorphous to poly-crystalline state, a clear boundary can be distinguished between the recrystallized layer and the amorphous bulk [9–11]. In laser recovery, however, it is difficult to directly observe the recovered layer in single-crystal silicon because there is no identifiable boundary between the recovered layer and the bulk when observation is performed with a scanning electron microscope (SEM) or a transmission electron microscope (TEM). Simulation has also been used to estimate the laser-induced recrystallized depth [6,12–14], but to date, there has been no experimental method to validate the simulated results.

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In order to make this recovery boundary visible, the use of small-angle beveled polishing and etching is proposed. By polishing at a small-angle to the top surface, the recrystallized region can be extended in the depth direction. Therefore, the small-angle beveled polishing process reveals greater details of the recrystallized depth profile and its crystallinity than a standard cross-sectional polishing process (polished at 90° to the top surface). It is known that in laser irradiation, the melting and recrystallizing process cause dopant movement in the irradiated region, and the dopant concentration becomes maximum at the maximum melt depth [15–19]. This dopant distribution gives rise to a different etching rate between the high dope concentration region and low concentration region [20]. Thus, through etching, a boundary of the recrystallized region is thought to appear on the beveled polished surface. From this boundary, it may be possible to measure the recrystallized depth.

The purpose of this study is to characterize the recrystallized depth and dopant distribution in laser recovery of grinding damage in single-crystal silicon. This will be realized by using a new visualization method based on small-angle beveled polishing and subsequent chemical etching. The success of the proposed method will contribute greatly to the visualization and clarification of the laser recovery mechanism and the optimization of other laser melting processes of single-crystal silicon.

2. Methods

The laser recovery mechanism of a ground silicon surface is shown in Fig. 1. Generally, grinding will induce subsurface damages in silicon, such as amorphous layers, dislocations, and microcracks (Fig. 1a). After a laser pulse is irradiated on the surface, a top-down melted layer will be generated and it becomes thicker and thicker when laser irradiation continues, reaching the defect-free bulk region (Fig. 1b-c). After laser irradiation, bottom-up epitaxial growth begins from the defect-free bulk which acts as a seed crystal (Fig. 1d-e) [6–8]. In this way, a defect-free single-crystalline structure is obtained in the laser-irradiated region (Fig. 1f).

To visualize the laser melted/recrystallized layer of a ground silicon sample, small-angle beveled polishing is proposed. A frosted silica glass pad was used as the polisher, without using abrasive grains. The beveled angle is set to less than 1° in order to enlarge the observation area of the laser-recrystallized region which is extremely thin, down to the submicron level. A schematic diagram of visualization mechanism of the recrystallized region is shown in Fig. 2. The recrystallized region boundary on beveled polished surface is not visible before etching (Fig. 2a). After etching with a KOH solution, the recrystallized region on the beveled polished surface becomes visible due to an elevated boundary between the bulk and the recrystallized region (Fig. 2b). Fig. 2c-e present the cross-section taken along the black dotted line in Fig. 2a-b, and these figures indicate the mechanism of elevated boundary generation. The top surface is flattened by polishing, and the laser-recrystallized region has a boron concentration gradient. The center of the laser-irradiated region has lower dopant concentration than the outer region. During KOH etching (Fig. 2d), the etching rate of the high concentration region is lower than that of the low concentration region [20]. As a consequence, an elevated boundary is generated on the polished surface as shown in Fig. 2e, which is identifiable by microscopic observation.

3. Experimental procedures

Boron-doped P^{++} single-crystal silicon (1 0 0) wafers machined by precision grinding using diamond abrasive grains (Average grain size

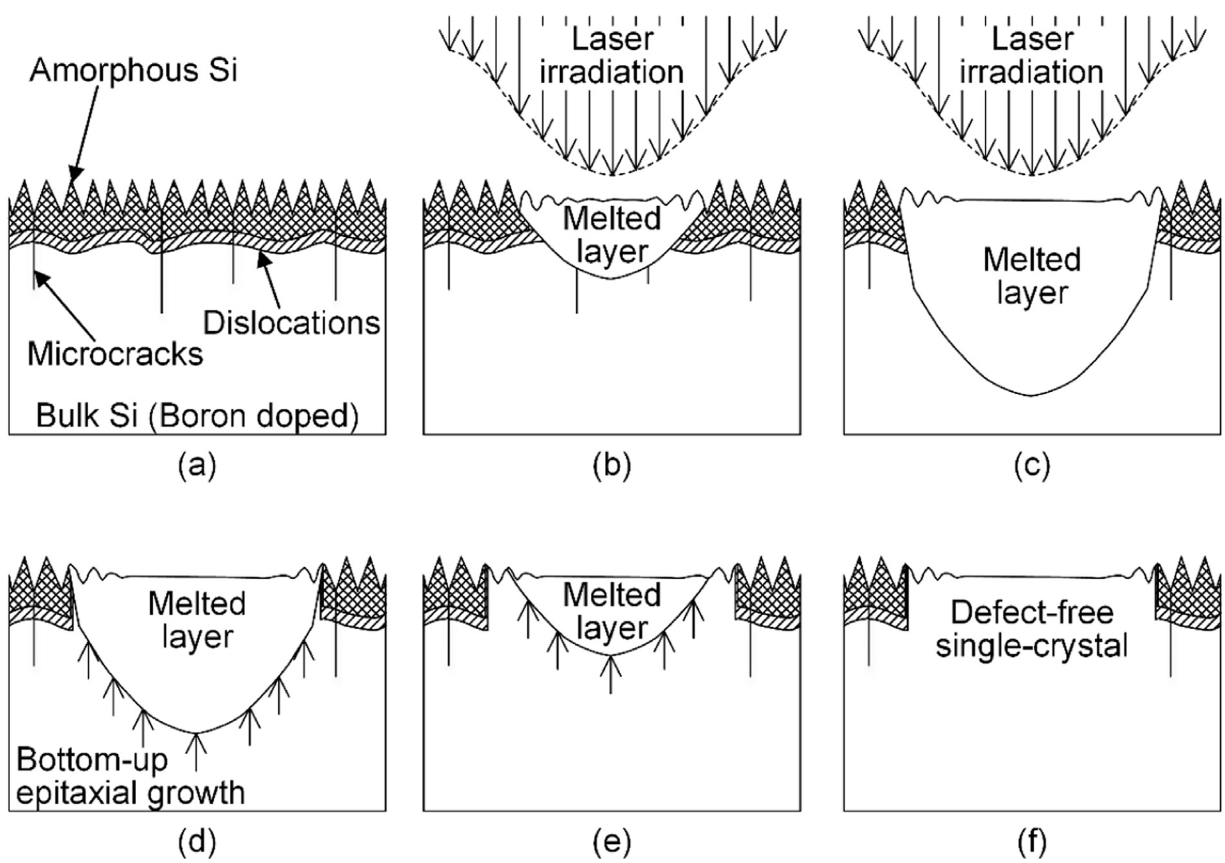

Fig. 1. Schematic diagram of laser recovery mechanism for a ground silicon surface: (a) silicon wafer with subsurface damage, (b) start of laser irradiation, (c) formation of top-down melted layer, (d) after laser irradiation, (e) bottom-up epitaxial growth from the defect-free bulk, and (f) a defect-free single-crystalline structure in the laser-irradiated region.