Silicon layer transfer using plasma hydrogenation

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In this work, we demonstrate a novel approach for the transfer of Si layers onto handle wafers, induced by plasma hydrogenation. In the conventional ion-cut process, hydrogen ion implantation is used to initiate layer delamination at a desired depth, which leads to ion damage in the transferred layer. In this study, we investigated the use of plasma hydrogenation to achieve high-quality layer transfer. To place hydrogen atoms introduced during plasma hydrogenation at a specific depth, a uniform trapping layer for H atoms must be prepared in the substrate before hydrogenation. The hydrogenated Si wafer was then bonded to another Si wafer coated with a thermal oxide, followed by thermal annealing to induce Si layer transfer. Cross-section transmission electron microscopy showed that the transferred Si layer was relatively free of lattice damage. The H trapping during plasma hydrogenation, and the subsequent layer delamination mechanism, are discussed. These results show direct evidence of the feasibility of using plasma hydrogenation to transfer relatively defect-free Si layers. © 2005 American Institute of Physics. [DOI: 10.1063/1.2048811]

The ion-cut process is currently being used to produce silicon-on-insulator (SOI) wafers.$^1$ While ion-implanted hydrogen can be readily annealed out of Si at temperatures between 500 and 600 °C,$^2$ the high concentrations of radiation damage present in the transferred layer are often difficult to remove, even after high temperature annealing at ∼1000 °C. This residual damage has a deleterious effect on electrical properties in the transferred layers, especially for thin Si layers with thicknesses of ∼5–100 nm. As the ion energy is reduced to decrease the cut depth, the fraction of the layer that is damaged and contains hydrogen becomes more significant.

Preliminary work, including our results, suggested that it is possible to use plasma hydrogenation instead of H ion implantation to induce surface blistering.$^{3,4}$ Defects and/or disruptions in the Si lattice provide dangling bonds for hydrogen attachment, and appear necessary for nucleating H2-gas bubbles which subsequently lead to layer delamination. Therefore, if defect structures could be preengineered into the substrate, the introduction of hydrogen by any means would lead to the conditions necessary for layer delamination. Plasma hydrogenation, coupled with defect engineering, appears to be a promising method for hydrogen-induced layer transfer. While preliminary experimental results of layer splitting due to plasma hydrogenation have been reported,$^{3,4}$ there has been little or no direct evidence reported for successful layer transfer based on this novel approach. In this work, we report the complete sequence of steps for fabricating a SOI structure, using plasma hydrogenation combined with conventional wafer bonding technology.

Figure 1 shows a sketch of the proposed approach to achieve Si layer transfer. In this study, boron implantation was used as an illustrative means to create H-trapping centers inside the Si wafers. Boron atoms are known to have large affinities for hydrogen, thus attracting H atoms in the Si lattice.$^7,8$ It should be pointed out that trapping centers, not involving any ion implantation, are also possible, such as strain and impurities.

Our process started with $p$-type 1−35 Ω cm (111) Si wafers. A dose of $5 \times 10^{15}$ cm$^{-2}$ B$^+$ was implanted into the Si substrates at 170 keV, followed by boron activation at 900 °C in N$_2$ for 20 min. Plasma hydrogenation was conducted at 280 °C in a plasma immersion ion implantor (PIII) with a radio frequency (RF) plasma source for 10 min.$^9,10$ These conditions were selected to introduce sufficient hydrogen atoms into the substrates, but without causing surface blistering to arise directly after plasma hydrogenation. After Ar plasma activation of the sample surface, the hydrogenated sample was bonded to a Si handle wafer with an oxide top layer. Finally, the bonded structure was thermally annealed at 400 °C to induce Si layer splitting and transfer. Cross-section transmission electron microscopy (X-TEM), Ruther-

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ford backscattering spectrometry (RBS) in both the random and channeling modes, and elastic recoil detection (ERD) were used to characterize our samples.

Figure 2(a) shows a typical cross-section transmission electron micrograph of the resulting SOI structure. It is evident that a thin Si layer of ~380 nm thickness has been successfully transferred onto the handle wafer, thus providing direct experimental evidence of layer transfer induced by hydrogenation. The bulk of the top Si layer of the final SOI structure was relatively free of damage. There were defects located near the surface region of the as-transferred sample, related to the boron implantation and subsequent activation processes. This defective surface region can be removed by subsequent surface treatments. For comparison, an XTEM micrograph from a hydrogenated sample after 80-keV 5 × 10^{15} \text{ cm}^{-2} boron implantation and activation is shown in Fig. 2(b) (after Ref. 6). It should be pointed out that this sample already formed H-induced cracks and showed surface blistering directly after a sufficient hydrogenation at 350 °C for 1.5 h.

The hydrogen distribution in the final SOI sample was examined by ERD (not shown here). Within the detection limits of ERD, no noticeable H was seen in the bulk of the transferred Si layer, other than a surface H concentration peak. Figure 3 shows RBS channeling results from the final SOI sample. The average value of the channeling minimum yield ($\chi_{\text{min}}$) in the entire as-transferred Si layer was ~8%, and could be further improved after annealing. These results indicate the capability of the plasma hydrogenation process for fabrication of high-quality Si transferred layers, with implanted B damage as trapping centers.

Our previous studies showed that for B-implanted Si followed by activation, H-induced cracks were located at a specific depth, $R_p$, which was located ~210 nm below the surface, as shown in Fig. 2(b). This depth was shallower than the boron projected range, $R_p$, which was ~260 nm, given by the stopping and range of ions in matter (SRIM) simulation.\(^1\) The ratio of $R_p/R_p$ was ~0.8. However, for the hydrogenated samples without boron activation, cracks formed from the near-surface region extending into the substrate;\(^6\) therefore, a specific value of $R_p/R_p$ was not well defined. In the present study, the ratio of the transferred Si layer thickness ($R_t$, ~380 nm) to the projected range of the 170-keV boron implant (~500 nm, given by the SRIM simulation), $R_p/R_p$, was again a specific value of ~0.8. Therefore, in order to obtain a uniform transfer layer of specific thickness, activation of the implanted sample is preferred.

The trapping of H during plasma hydrogenation is a crucial issue that determines the final transferred layer thickness. In our case of utilizing implantation defects as H trapping sites, the distribution of the postactivation implantation damage is directly related to the H trapping location and the crack depth. High-temperature activation after implanting a dose of $5 \times 10^{15} \text{ cm}^{-2}$ B into the Si wafer caused the formation of a very defective band within the substrate, but rendered the rest of the wafer relatively defect free.\(^6\) The projected range, $R_p$, was located at approximately the middle of the defective band, as shown in Fig. 2(b). During hydrogenation, the incoming H atoms diffuse relatively rapidly into the substrate until they become trapped at the beginning of the defective region. Diffusion into the defective region is retarded due to trap-limited diffusion in a region with a high density of traps. Eventually, the hydrogen concentration

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**FIG. 1.** Schematic drawings of the novel layer transfer approach: (a) Introduce H trapping sites (such as defects, strain, impurities, etc.) at a well-defined depth into a silicon wafer; (b) plasma hydrogenate the sample enabling H entrapment at the specific depth; (c) clean and activate the wafer surfaces and then bond the hydrogenated silicon wafer to a handle wafer with an oxide top layer; and (d) anneal the bonded pair to induce layer splitting and transfer.

**FIG. 2.** Cross-section transmission electron micrographs obtained from (a) final SOI sample fabricated by plasma hydrogenation combined with wafer bonding in the present work; (b) $5 \times 10^{15} \text{ cm}^{-2}$ dose of boron preimplanted and activated sample after hydrogenation for 1.5 h at 350 °C (after Ref. 6). Bright-field images, with the 220 Bragg condition satisfied.

**FIG. 3.** RBS random and channeling spectrum from the final SOI sample. RBS analyses were performed using a 2.0-MeV He analyzing beam. The detector was located 167° away from the direction of the incident beam.
builds up at the damage band and ultimately leads to the formation of H-related defects such as H platelets.\textsuperscript{7}

The development of these H platelets will result in H microbubbles which in turn lead to H-induced microcracks in the substrate. Previous work showed that ion-implantation-induced radiation damage increased the fracture toughness of the implanted silicon, suppressing material brittle fracture in the heavily implanted region where plastic flow was preferred.\textsuperscript{12,13} Accordingly, the location of H-induced microcracks in the high-dose H-implanted Si substrate was in a region deeper than the damage peak, which contained less damage but sufficient H concentration.\textsuperscript{14} In our case, H-induced cracks will be more difficult to form within the heavily damaged region due to a high fracture toughness. The beginning edge of this defective region acts somewhat as a boundary between materials with a different fracture toughness. Sufficiently high H concentration is also present around this boundary. Thus this depth becomes a preferential location for cracking. Consistent with this idea is the fact that the transferred layer thickness in Fig. 2(a) is similar to the crack depth shown in Fig. 2(b), which occurs just above the edge of defective region, and not at other locations. Most of the boron implantation damage was annealed out of the near-surface region after the boron activation, resulting in a transferred layer with relatively high-crystalline quality. The defective band created by coalescence of implant damage near the projected range was beneath the H-induced cracking depth, and was therefore not transferred onto the handle wafer.

In summary, we have demonstrated the feasibility of using plasma hydrogenation of Si wafers for layer transfer to form SOI structures. Boron ion implantation was used as an illustrative example to create H trapping sites within a Si substrate. A uniform Si layer, relatively free of defects, was successfully transferred onto a handle wafer, and thus a SOI structure was obtained. The H trapping during hydrogenation was related to the boron-implant-induced damage distribution. H-induced cracks occurred at the depth where there was sufficient hydrogen concentration, and the material fractured relatively easily with comparison to other regions. Trapping centers unrelated to ion damage are currently under investigation in our laboratories.

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