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The role of implantation damage in the production of silicon-on-insulator films by co-implantation of He^+ and H^+

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THE ROLE OF IMPLANTATION DAMAGE IN THE PRODUCTION OF
SILICON-ON-INSULATOR FILMS
BY CO-IMPLANTATION OF He^+ AND H^+

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ABSTRACT

Recent work has demonstrated that the process of silicon thin-film separation by hydrogen implantation, as well as the more basic phenomenon of surface blistering, can occur at a much lower total dose when H and He are co-implanted than when H is implanted alone (1). Building on that work, this paper investigates the role of implantation damage in this process by separating the contributions of gas pressure from those of damage. Three different experiments using co-implantation were designed. In the first of these experiments, H and He implants were spatially separated thereby separating the damage from each implant. The second experiment involved co-implantation of H and He at a temperature of 77 K to retain a larger amount of damage for the same gas dose. In the third experiment, Li was co-implanted with H, to create additional damage without introducing additional gas. These experiments together show that increasing the implantation damage itself hampers the formation of surface blisters, and that the increased efficiency observed for He co-implantation with H is due to the supplementary source of gas provided by the He (1).

INTRODUCTION

There is great deal of interest in a new process that uses H implantation to produce thin silicon-on-insulator (SOI) films (2). In this process, a surface layer of a silicon wafer, implanted with H^+ , is sheared and transferred onto an oxidized wafer after the two wafers are bonded together and annealed (2). Since the remaining sheared wafer can be re-polished and used again, this process has the potential to produce SOI wafers more economically than competing processes such as high-dose oxygen implantation or bonded-etchback, in which two silicon wafers are consumed to make one SOI wafer.

This process of H-induced thin-film separation was originally based on the observation that implantation of high-dose H leads to blistering and flaking on the surfaces of metals and semiconductors (3). Bonding to a support wafer confines the fracture in the implanted wafer to a plane parallel to the bonded interface, so that a continuous fracture surface is created rather than isolated blisters.

To understand both the thin-film process and the surface blistering induced by H implantation, Weldon, *et. al*, performed a series of studies in which both the chemical and physical-mechanical effects of the implanted H in silicon were investigated [4]. Those authors found that H-passivated microvoids or platelets are formed as a result of implantation, and that H₂ gas trapped in these microvoids provides the physical pressure necessary to produce the observed surface blistering and flaking. They also demonstrated that blistering and the thin-film separation process are due to the same mechanism, except that in the case of film separation the bonded wafer provides a mechanical restoring force that drives the microvoids to grow laterally and intersect to form continuously separated surfaces. Other authors have also concluded that the same process controls both the observed blistering and the thin-film separation because they have the same activation energy (5).

In our previous work (1), we have demonstrated that the total implantation dose needed for surface blistering or thin-film separation can be reduced by greater than 70% using H and He co-implantation. Since ion implantation is known to produce damage in silicon, it is also important to understand the role of the implantation damage in the co-implantation process. In this work, we investigate the impact of the crystalline damage induced by implantation on the surface blistering phenomenon, and thus the thin-film separation process. We have separated the damage induced by He, the co-implanted ion, from the physical effects of the He gas in the following ways. In one set of experiments, He was implanted deeper than H, separating the damage from the He implant from the location of the H implant. The surface blistering did not change when the H and He implants were spatially separated, indicating that the damage induced by the He implant played little role in improving the efficiency of the formation of surface blisters. Experiments were also performed in which H and He were co-implanted at a low temperature (77K) to produce more crystalline damage for a constant gas content. In this case, the surface blistering was suppressed relative to room-temperature implantation. Co-implantation of Li, instead of He, was also performed to add implantation damage without adding gas. We found that when Li was implanted with a large dose of H, that alone would produce surface blistering, the surface blistering was suppressed.

EXPERIMENT

All studies were performed on Czochralski (CZ) Si(100) substrates. H, He, and Li ions were implanted with energies and doses ranging from 30 to 130 keV and from $1 \times 10^{16}/\text{cm}^2$ to $1 \times 10^{17}/\text{cm}^2$, respectively. The H and He doses were chosen from previous work (1) and TRIM simulations were used to determine the dose of Li in order to match the number of displacement collisions to that of the He co-implants. Implants were performed using a Varian Extrion implanter with a 90° magnetic mass analyzer. Implanted samples were subjected to rapid thermal annealing (RTA) at 750°C for 20 s in flowing Ar. The surfaces of annealed samples were imaged using an optical microscope with Nomarski contrast capability. In this work, we take the observation of blistering to be an indication that layer transfer would occur under the same conditions in a bonded-wafer configuration. Defect profiles were determined by ion-channeling measurements using a 2 MeV He^+ beam from a 2.5 MV van de Graaff accelerator. Cross-sectional transmission electron microscopy (XTEM) was also performed on implanted and annealed samples. XTEM samples were prepared by mechanical thinning and Ar^+ ion-beam milling at 77K. Extended defects were imaged using the weakly excited 220 and 400 reflections. Secondary ion mass spectrometry (SIMS) was used to profile He in implanted and annealed samples using a 8 keV O_2^+ sputter beam.

RESULTS

A. Spatial Separation of H and He profiles.

In previous work, we have shown that the surface blistering and flaking that result from a high-dose H ($6 \times 10^{16}/\text{cm}^2$) implant into silicon after an RTA at 750°C for 20 s is also observed after RTA of a much lower dose of H ($1 \times 10^{16}/\text{cm}^2$) if the H is co-implanted with a low dose of He ($7.5 \times 10^{15}/\text{cm}^2$) such that the profiles coincide in depth. These same doses do not result in surface blistering for either single-species implant. When the energies were 30 keV for H and 33 keV for He, the profiles overlapped at a depth of 0.4 μm and blisters and craters with diameters in the range of 2-5 μm and depths of 0.4 μm were observed after annealing.

According to the above results, the addition of a He implant assisted the blistering process when implanted at the same depth as H. However, in that experiment, both the He and its associated damage coincided with the H. To separate the location of the He-induced damage from the H, 30 keV H ions were implanted with 130 keV He ions at doses of $3 \times 10^{16}/\text{cm}^2$ and $1 \times 10^{16}/\text{cm}^2$ respectively, and annealed at 750°C for 20s. Figure

Ia is an optical micrograph showing the surface blistering that result from these implant and annealing conditions. For comparison, the results for the same doses of H and He with energies of 30 keV and 33 keV are shown on Fig. Ib. Comparison of Figs. Ia and Ib shows that separating the implant profiles had no significant effect on the surface blistering. Since the blistering remained essentially unchanged as a result of placing the He damage deeper than the H damage, we can conclude that the effects of the damage induced by the He did not play a significant role in enhancing the formation of the surface blisters at lower doses. Another sample was similarly implanted with $3 \times 10^{16}/\text{cm}^2$ of 30 keV H and $1 \times 10^{16}/\text{cm}^2$ of 30 keV He, then annealed in vacuum at 450°C for 15 min. Experience has shown that this anneal is just below the threshold for blister formation. SIMS profiles of this sample before and after the 450°C anneal are shown in Fig. II, where the arrow indicates the depth of the H implant. The as-implanted SIMS depth profile shows that the He distribution is initially very broad and located deeper than the H profile. Upon annealing, the He is observed to be located in a narrow region near the depth of the H implant. Therefore, it is simply the presence of the He gas in the H-rich region that leads to the formation of surface blisters, and thus makes the thin-film separation process more efficient.

B. Cryogenic Implantation.

It is well known that the amount of retained implant damage is larger at lower implant temperatures. Therefore, we performed another set of experiments in which the same 30 keV 3×10^{16} H/ cm^2 and 33 keV 1×10^{16} He/ cm^2 were co-implanted into silicon at 77K. In this way, we increased the amount of implant damage for a fixed gas content. Figure III is an optical micrograph of the 77K implant after RTA at 750°C for 20s. Figure III illustrates that the low implant temperature suppressed the surface blistering previously observed in Fig. Ib. Ion channeling (Fig. IV) confirmed that implantation at 77K created a much larger amount of damage to the silicon lattice than did room-temperature implantation. These experiments demonstrate that increasing the amount of implant damage for a fixed H and He gas content is detrimental to the formation of the surface blisters.

C. Co-implantation with Li^+ .

Implant damage was also introduced by co-implantation of Li instead of He. A dose of $8 \times 10^{15}/\text{cm}^2$ of 50-keV Li was co-implanted with $1 \times 10^{17}/\text{cm}^2$ of 30-keV H. The dose of the Li implant was chosen to match the damage induced by a $1 \times 10^{16}/\text{cm}^2$ He implant, as calculated by TRIM. TRIM simulations of the displacement distributions for

the He and Li implants are compared in Fig. V. Figure VIa is an optical micrograph of the surface of a silicon substrate following co-implantation of Li with H and RTA. Figure VIa can be compared to Fig. VIb, which shows the corresponding result for the $1 \times 10^{17}/\text{cm}^2$ H implant without a Li co-implant. Co-implantation with Li clearly suppresses the formation of the characteristic surface blisters. Ion channeling (Fig. VII) shows that the Li^+ implant induced much more damage than the He implant. These experiments demonstrate that increasing the amount of damage for a fixed amount of H gas hampers the formation of blisters, similar to the above case of cryogenic H and He co-implantation.

CONCLUSIONS

The role of implant damage in the thin-film separation process that uses co-implantation of H and He was investigated by separating the contributions of gas pressure and implantation damage. The presence of He in the region of the H implant was shown to make the process of surface blistering more efficient. When the amount of damage was increased for a fixed gas content, either by reducing the implantation temperature or by adding a Li co-implant, the formation of surface blisters was suppressed. These experiments, as well as previous work, suggest that the essential role of H is to chemically interact with implantation damage to create a high density of microvoids, which are plate-like cracks whose internal surfaces are likely to be H-passivated (4). The presence of H is expected to aid the crack formation process by reducing the surface free-energy density of the new internal surface area produced during crack growth. While H is efficient at forming the required high density of microvoids due to its propensity to passivate dangling bonds in silicon, we argued that the same chemical interaction hampers segregation of excess H into the voids and formation of H_2 gas for two reasons. First, all of the broken bonds created by energetic collisions during the implantation can compete for the available H and many of these may not be associated with microvoids. Furthermore, H diffusion in Si is known to be severely limited by defect traps (6), (7). Consequently, when H is implanted alone, a larger dose of H is necessary to produce the excess H_2 gas pressure needed for surface blistering. However, He is not as readily trapped by dangling bonds and can more easily diffuse into the microvoids, providing the force that drives crack growth leading to exfoliation.

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Figure 1. Optical micrograph of the surface of Si(100) implanted with
a) $30 \text{ keV } 3 \times 10^{16} \text{ H/cm}^2 + 130 \text{ keV } 1 \times 10^{16} \text{ He/cm}^2$ and b) $30 \text{ keV } 3 \times 10^{16} \text{ H/cm}^2 + 33 \text{ keV } 1 \times 10^{16} \text{ He/cm}^2$ and annealed at $750^\circ\text{C}/20 \text{ s}$.

Figure 2. SIMS concentration profile vs depth for $30 \text{ keV } 3 \times 10^{16} \text{ H/cm}^2 + 130 \text{ keV } 1 \times 10^{16} \text{ He/cm}^2$ annealed at $450^\circ\text{C} / 15 \text{ min}$.

10 microns

Figure III. Optical micrograph of the surface of Si(100) implanted with $30 \text{ keV } 3 \times 10^{16} \text{ H/cm}^2 + 30 \text{ keV } 1 \times 10^{16} \text{ He/cm}^2$ at 77 K and annealed at $750^\circ\text{C}/20\text{s}$.

Figure IV. Channeling spectrum of Si(100) co-implanted with $30 \text{ keV H } 3 \times 10^{16}/\text{cm}^2$ and $33 \text{ keV He } 1 \times 10^{16}/\text{cm}^2$ at a) 77 K and b) RT

Figure V. TRIM simulation of damage induced in silicon by a 33 keV $1 \times 10^{16}/\text{cm}^2$ He^+ implant and by a 50 keV $8 \times 10^{15}/\text{cm}^2$ Li^+ implant.

Figure VI. Optical micrograph of the surface of Si(100) implanted with 30 keV $1 \times 10^{17} \text{H}/\text{cm}^2$ + 50 keV $8 \times 10^{15} \text{Li}/\text{cm}^2$ and b) 30 keV $1 \times 10^{17} \text{H}/\text{cm}^2$ and annealed at $750^\circ\text{C}/20\text{s}$.

Figure VII. Channeling spectrum of Si(100) implanted with 1) 33 keV He $1 \times 10^{16}/\text{cm}^2$ and 2) 50 keV Li $8 \times 10^{15}/\text{cm}^2$. A Random spectrum is included for reference

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