Transient enhanced diffusion without {311} defects in low energy B^+-implanted silicon

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Low energy and low dose B^+-implanted Si has been studied using transmission electron microscopy (TEM) and secondary ion mass spectrometry (SIMS). Czochralski-grown (100) Si wafers were implanted with 4 keV B^+ to a dose of $1\times10^{14}/cm^2$. Subsequently, anneals were performed between 700 and 800 °C for times between 15 s and 8 h in an ambient atmosphere of N_2. SIMS results show transient enhanced diffusion (TED) of the boron that saturates in less than 15 min for all annealing temperatures studied. TED results in an increase in the junction depth by at least 60 nm at a $1\times10^{16}/cm^3$ concentration. TEM studies show that, even for the shortest times before TED is observed, {311} defects are not detected. These results imply that there may be more than one source of interstitials for TED. © *1995 American Institute of Physics*.

As microelectronic device dimensions decrease, the need to produce ultrashallow (<60 nm deep) junctions becomes essential. Ion implantation with low energy (<10 keV) B^+ is seen as one of the most promising techniques for producing shallow p^+ contacts. The limiting factor in the depth of the junctions produced by low energy B^+ implants into crystalline substrates is random channeling during the implant and transient enhanced diffusion (TED) during subsequent annealing. Transient enhanced diffusion arises from implantation-induced point defects and can result in diffusivities several thousand times greater than the normal diffusivity but only for a very short period of time (e.g., a few minutes at 800 °C).[1,2] After implantation and annealing, a typical B profile consists of an inactive peak region that is relatively immobile and a tail region that is electrically active and diffuses very rapidly.[1–3] There is a great interest in understanding both regions from the standpoint of accurate process modeling. This letter focuses on our effort to better understand the diffusion in the tail region. Michel *et al.*[2] reported a displacement of 150–200 nm in the tail region of a 60 keV, 2×10^{14} ions/cm^2 B^+implant after a 35 min 800 °C anneal. The corresponding calculated diffusion length for intrinsic B diffusion is only 3 nm for this annealing condition. Others have reported similar results.[4] In order to understand the correlation of TED with defects arising from annealing following B^+ damage, a number of studies have been conducted on the defect formation processes.[5–10] These studies have indicated that TED of B^+-implanted Si occurs by the pairing of B with Si self-interstitials.[11] Recently, Eaglesham *et al.*[10] and Stolk *et al.*[8] have suggested that TED occurs by the emission of Si self-interstitials from {311} defect dissolution. The {311} defects are extrinsic defects that have a {311} habit plane and are elongated in the ⟨110⟩ directions. These defects provide a low energy configuration for accommodating excess interstitials. The dissolution of these defects occurs under the same time and temperature conditions as TED. Thus, for Si^+ implants into Si containing B-doped spikes, the {311} defects are believed to be the source of the excess interstitials during TED. In this letter we report that when the energy of a B^+ implant decreases below 10 keV, TED is observed without the formation or dissolution of {311} defects.

All samples were prepared from 150 mm diam, (100), *n*-type (phosphorus), 8–20 Ω cm, Czochralski-grown Si wafers. The samples were implanted with $^{11}B^+$ at 4 keV to a dose of 1×10^{14} ions/cm^2. The implants were performed with the beam stationary and the wafers spinning; thus, the beam divergence is small. The tilt-twist angles were 5°/0°. The beam current was 0.69 mA. During ion implantation, the samples were kept at about room temperature using water cooling. Subsequent anneals were performed at 700 °C for 2 min, 15 min, 4 h, or 8 h; 750 °C for 3 min, 13 min, 30 min, or 2 h; 800 °C for 15 s, 15 min, 1 h, or 2 h, all in N_2 ambient, using fast pushes and pulls. These conditions were chosen based on the TED saturation times as reported by Michel[12] and the {311} defect dissolution rate as reported by Stolk *et al.*[8] Plan-view TEM samples were prepared using jet-etching procedures and examined under weak beam dark field using the $\mathbf{g}_{220}$ beam. SIMS was performed in an ion microscope using an O_2^+ primary beam with a 5 keV net impact energy and positive secondary ion detection. Oxygen flooding of the surface was used to minimize near-surface transient effects. The primary beam current of ~200–300 nA was focused and rastered over a 250 μm×250 μm area. The $^{11}B^+$ secondary ions were extracted from a circular area of 60 μm diam. A relative sensitivity factor (RSF) for boron with respect to silicon was determined by equating the depth integral of the depth profile of the as-implanted sample to the nominal dose. This RSF was used to establish the concentration scale for all profiles, with an estimated uncertainty of ±25%. The depth scale for each profile was established by measuring the final crater depth with a stylus profilometer, and assuming that the erosion rate was constant during the

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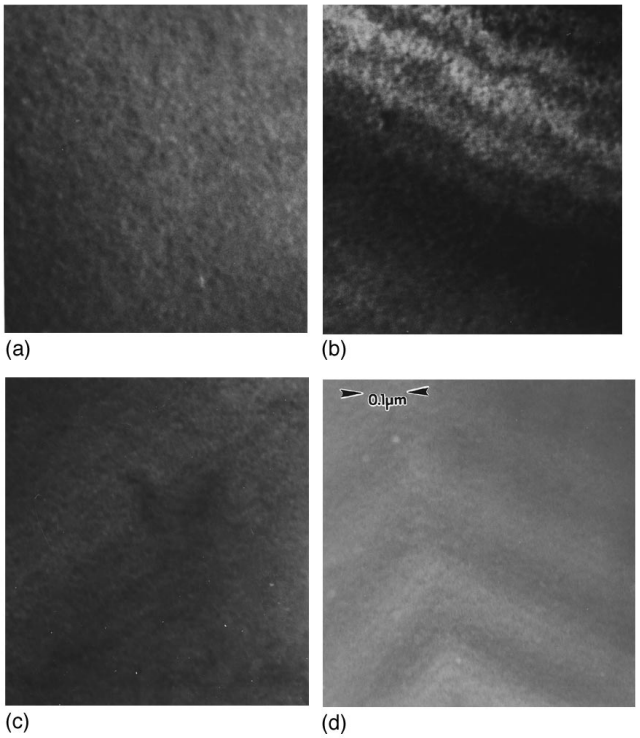

FIG. 1. The plan-view TEM micrographs of B^+-implanted Si samples annealed at 700 °C for (a) 2 min and (b) 8 h, and at 800 °C for (c) 15 s and (d) 1 h.

profile. The estimated depth-scale uncertainty is ±5%.

Figure 1 shows the plan-view TEM micrographs for samples annealed at 700 °C for 2 min or 8 h, and at 800 °C for 15 s or 1 h. No {311} defects or extended defects were ever observed to form after annealing this 4 keV, 1×10^{14} ions/cm^2 B^+ implant. Figure 2 shows the B^+ profiles from SIMS of B in the as-implanted sample and samples annealed at 700 °C for 2 min, 15 min, 4 h, or 8 h, respectively. It is seen that TED saturates between 2 and 15 min at 700 °C. The total displacement induced by TED at 700 °C was about 60 nm at 1×10^{16} atoms/cm^3. TED at 750 °C was observed to saturate between 3 and 13 min. Figure 3 shows the boron profiles obtained from SIMS after annealing at 800 °C for 15

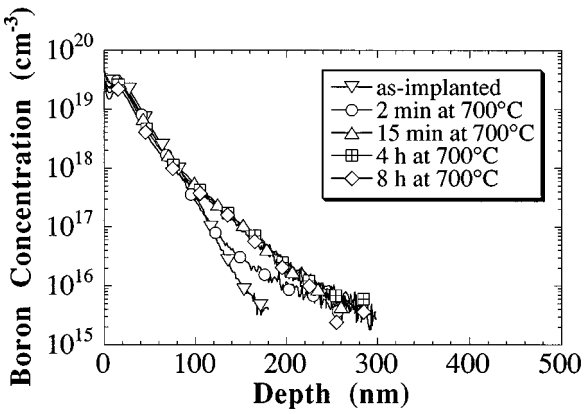

FIG. 2. The B profiles of as-implanted and annealed samples from SIMS. The B^+ implant was at 4 keV to a dose of 1×10^{14}/cm^2. The anneals were at 700 °C for 2 min, 15 min, 4 h, and 8 h, respectively.

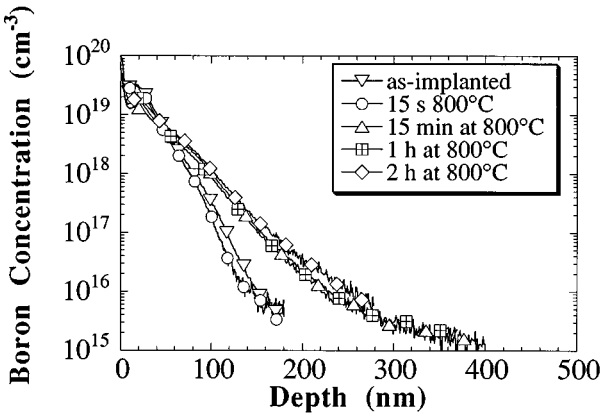

FIG. 3. The B profiles of as-implanted and annealed samples from SIMS. The B^+ implant was at 4 keV to a dose of 1×10^{14}/cm^2. The anneals were at 800 °C for 15 s, 15 min, 1 h, and 2 h, respectively.

s, 15 min, 1 h, or 2 h. Considering the depth-scale uncertainties, there is no statistically significant difference in the profiles between the as-implanted and the 15 s anneal conditions. The profile for the 1 h anneal was the same as for the 15 min anneal. Thus, for a B^+ implant at 4 keV and 1×10^{14} ions/cm^2, TED saturation occurs between 15 s and 15 min at 800 °C. The 15 min anneal shows that the transient enhanced diffusion has resulted in a displacement of about 90 nm at a concentration of 1×10^{16} atoms/cm^3 relative to the as-implanted profile. TED occurs below 5×10^{18} atoms/cm^3, which is consistent with the observations of Cowern *et al.*[1] and Michel *et al.*[2]

The lack of {311} defect formation is not unexpected. Eaglesham[13] has found that the threshold dose for {311} defect formation in samples of Si^+-implanted Si at 40 keV is as low as 5×10^{12}/cm^2. He also noted a strong decrease in {311} stability with decreasing implant energy. Liu[14] has found the threshold dose for {311} formation from B^+ implants to be considerably higher than for comparable Si^+ implants. Her results showed that, for a 40 keV B^+ implant, the threshold dose for {311} defect formation was ~1×10^{14}/cm^2. She also observed an increase in the {311} defect formation threshold dose with decreasing energy. The increase in the threshold dose is probably due to the combination of two factors. First, as the energy of the implant decreases, surface recombination may decrease the number of interstitials available for {311} defect formation. Second, the distribution of the damage in the ion tracks also appears to be important. For example, the 15 keV B^+ implant has the same projected range as a 40 keV Si^+ implant, yet the threshold dose for {311} defect formation is significantly higher for the B^+ implant (~1×10^{14}/cm^2) than for the Si^+ implant (~5×10^{13}/cm^2). In-progress molecular dynamic simulations of recombination in ion tracks may help to explain this effect. Thus, the decrease in mass and in implant energy in this experiment relative to previous studies has resulted in a set of implant conditions in which {311} defects do not form. These results, of course, do not rule out the possibility that submicroscopic interstitial clusters formed after implantation and annealing.

Several authors have tried to extract an effective activa-

tion energy for TED by plotting the time to saturate TED as a function of 1/T. Michel[12] reported an activation energy for saturation of TED of 4.7 eV for a 60 keV, $2\times10^{14}/cm^2$ B^+ implant. Packan[15] also studied TED by implanting B^+ into float-zone Si samples at 160 keV to a dose of $7\times10^{11}/cm^2$, annealing the samples, implanting Si^+ at 200 keV to a dose of $5\times10^{13}/cm^2$ or $1\times10^{14}/cm^2$, and finally measuring TED of the B upon annealing the Si^+ implant. His data yield an activation energy of 3.7 eV for the $1\times10^{14}/cm^2$ Si^+ dose and 3.1 eV for the $5\times10^{13}/cm^2$ dose. Previous results such as those of Liu[16] indicate that {311} defects probably formed for the conditions used by both Michel[12] and Packan.[15] Since TED is believed to occur by the pairing of B with Si self-interstitials,[11] the activation energy represents a complex process that could depend on a number of variables including the intrinsic boron diffusivity, the interstitial/boron binding energy, the trapping of interstitials by impurities, the energy for release of interstitials by {311} defects, and the recombination process of interstitials both in the bulk and at the surface. Since many of these factors could be different in these experiments, variations in the effective activation energy are not unexpected. It is unusual that the saturation time for TED is relatively temperature independent in these low energy B^+ implant experiments. These results, although incomplete, possibly imply a smaller effective activation energy for TED when {311} defects are absent. Although no extended {311} defects were observed, we cannot rule out the possibility of submicroscopic Si-interstitial cluster formation. The dissolution of such clusters may have a low activation energy for release and thus reduce the effective activation energy for TED.

In conclusion, low energy, low dose B^+-implanted Si has been studied using TEM and SIMS. It is shown that, for a 4 keV and $1\times10^{14}/cm^2$ B^+ implant in Si, significant transient enhanced diffusion occurs for times less than 15 min between 700 and 800 °C, despite the TEM evidence that {311} defects did not form. These results imply there may be more than one source of interstitials for TED.

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