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Surface metal contamination on silicon wafers after hydrogen plasma immersion ion implantation

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Abstract

Hydrogen plasma immersion ion implantation (PIII) in conjunction with ion-cut has been successfully utilized to fabricate silicon-on-insulator (SOI) wafers. In order for PIII to be accepted by the semiconductor industry as a commercial process, surface metal contamination that can affect device yield and properties must be minimized. Total-reflection X-ray fluorescence (TXRF) analysis of hydrogen PIII silicon wafers reveals surface iron contamination to be greater than 10^{12} atoms/cm^2. Even though ions bombard all surfaces in a PIII chamber and the sample stage is made of stainless steel, the small sputtering yield by hydrogen cannot fully account for the surface iron on the wafer. Further studies reveal that the sputtering contribution of ionized atmospheric species in the residual vacuum is significant. To minimize metal contamination in hydrogen PIII, the gas lines must be designed and sealed properly as outside air can easily leak into vacuum chamber due to the negative pressure inside the gas line. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Silicon-on-insulator; Plasma immersion ion implantation; Contamination

Silicon-on-insulator (SOI) is the preferred substrate to fabricate deep sub-micrometer low power, low voltage microelectronic devices [1,2]. Because of the significant throughput advantage, plasma immersion ion implantation (PIII) may one day supplant conventional beam-line ion implantation in the preparation of thin SOI wafers for fully-depleted MOS devices. Oxygen PIII has been shown to be a viable technique to synthesize separation by implantation of oxygen (SIMOX) wafers and hydrogen or helium PIII coupled with ion-cut has produced bonded SOI materials [3–7]. In comparison with SIMOX, the PIII/ion-cut technology is particularly promising as the buried oxide layer thickness is independent of the implantation energy that is typically limited to below 100 kV [8–10].

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Even though the PIII/ion-cut technique has been demonstrated, acceptance by the semiconductor industry requires the resulting SOI wafers to be as uniform [11] and clean as those prepared by the conventional beam-line ion implantation technique. In this work, we investigate the amount of surface metal contamination on silicon wafers after hydrogen PIII. The interior of the stainless steel PIII chamber is typically shielded by an aluminum liner and should not contribute any iron contamination. The sample stage in a PIII instrument is typically made of stainless steel because it is easy to engineer when sample heating (for SIMOX) and sample cooling (for hydrogen PII and ion-cut) must be implemented. Although ions from the plasma impact all exposed surfaces biased negatively, very little sputtering of the sample stage is expected by hydrogen due to its light mass. However, our results indicate substantial surface metal contamination that cannot be explained by hydrogen alone, and further investigation reveals that the metal contamination stems from sputtering of the sample stage by atmospheric elements in the vacuum chamber.

Hydrogen implantation was performed in our PIII system that has been described in details elsewhere [12]. A p-silicon wafer 100 or 150 mm in diameter was put on top of a stainless steel platen 150 mm in diameter and 60 mm thick mounted in the center of the vacuum chamber. Before hydrogen gas was introduced into the vacuum chamber, the chamber was pumped down to a base pressure of 4×10^{-7} Torr. After the gas pressure stabilized at 0.4 mTorr, the hydrogen plasma was ignited by the RF (radio frequency) source mounted on top of the chamber. The RF power was 800 W. Hydrogen PIII was conducted at -20 kV. The pulse width was 30 μs and frequency was 100 Hz. The low frequency kept the wafer below 100°C during PIII to avoid uncontrolled blistering. The implantation dose determined by secondary ion mass spectrometry (SIMS) analysis was 6×10^{16} atoms/cm^2. The implantation time was 1 h due to the low duty cycle.

The implanted wafer was analyzed by total-reflection X-ray fluorescence (TXRF) and SIMS. TXRF has a typical sampling depth of 5–10 nm from the surface while SIMS is used to reveal the iron distribution and concentration deeper than 10 nm. The iron levels detected by TXRF and SIMS from our 100 and 150 mm wafers are listed in Table 1. The Fe content determined by TXRF is more than ten times higher than that calculated by SIMS. It implies that most of the iron is transferred to the wafer via a deposition mechanism. Sub-surface iron originates from ion mixing and implantation of ionized Fe species in the plasma.

As the interior of the vacuum chamber is surrounded by an aluminum liner, the only exposed stainless steel part is the sample stage. In PIII, since the entire sample stage is biased at the same voltage as the silicon wafer, it is conceivable that Fe can be sputtered by ions impacting the sample stage and subsequently deposited or implanted into the silicon wafer. The fact that the larger wafer (150 mm) shows lower surface Fe (Table 1) illustrates quite clearly that it originates from the sample stage. The sample stage platen has a diameter of 150 mm. A 100 mm silicon wafer only partially covers the top of the platen and Fe can be sputtered off from an adjacent exposed area in addition to the side of the stage. On the other hand, a 150 mm silicon wafer covers the platen entirely and only the side of the stage can release Fe into the plasma. However, it is difficult to envision that such a high surface Fe level (over 10^{13} atoms/cm^2 for the 100 mm silicon wafer) can be attributed to hydrogen alone because the sputtering yield of hydrogen is quite low. There must be another contribution to introduce that much Fe into the plasma.

To investigate the possible cause, SIMS analysis was used to profile N and O in the as-implanted

Table 1
Iron contamination on 100 and 150 mm silicon wafers determined by TXRF (surface to 10 nm) and SIMS (10 nm and deeper)

Wafer size (mm)	Iron dose by TXRF (<10 nm) (10^{11} cm^{-2})	Iron dose by SIMS (>10 nm) (10^{11} cm^{-2})
100	126	7.8
150	72	5.4

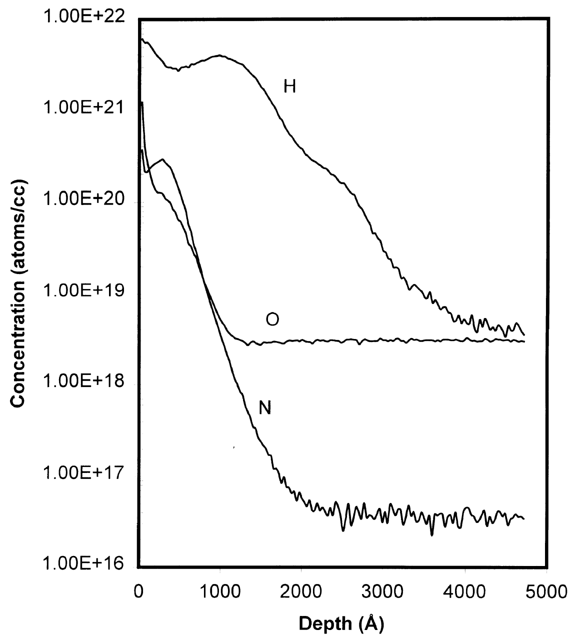

Fig. 1. SIMS depth profiles of H, O and N in the as-implanted silicon wafer. The projected ranges of oxygen and nitrogen are in line with 10 keV, O^+ and N^+ implantation predicted to be about 28 nm for N and 25 nm for O by TRIM95.

sample and the results are shown in Fig. 1. The calculated H, O, and N doses are 5.9×10^{16}, 1.2×10^{15} and 1.3×10^{15} atoms/cm^2, respectively. In terms of percentage, the relative concentration of oxygen and nitrogen to hydrogen is only about 2%, but N and O are much heavier than hydrogen and cause substantially more sputtering of the stage than hydrogen. Table 2 compares the relative number of iron atoms sputtered by H, O and N. The sputtering yields by H, O and N are estimated using TRIM95. In our process, the dominant ion species are H_3^+, O_2^+ and N_2^+, respectively [10]. The net implantation voltages are thus 6.7 kV for hydrogen, 10 kV for oxygen, and 10 kV for nitrogen. Our simulation results show that the sputtering rate of either oxygen or nitrogen is a hundred times higher than that of hydrogen. That is, while a hydrogen ion bombarding the stage creates 3.8×10^{-3} iron atom, 0.02 atom of oxygen or nitrogen ion will sputter off 2.2×10^{-2} and 1.8×10^{-2} iron atom, respectively. Hence, it is obvious that most of the iron contamination on the silicon wafers is sputtered by oxygen and nitrogen in the residual vacuum, not by hydrogen. Our calculation shows that sputtering due to hydrogen only accounts for 10% of the total contamination, and the amount of the sputtered iron that can subsequently erode the sample stage to introduce more contamination is orders of magnitude lower than those of the atmospheric species.

Although the purity of the hydrogen gas used in our experiment is 99.999% and the equipment is pumped down to 4×10^{-7} Torr before implantation, atmospheric elements such as oxygen and nitrogen can exist in small quantities in the plasma. These gases can arise from outgassing of the chamber wall if the pumping time is too short and more likely from leaks in the system. When the silicon wafer is loaded into the chamber, the whole chamber is exposed to the air. The chamber wall absorbs oxygen and nitrogen molecules that are later released gradually into the vacuum during pumping. Moreover, after the plasma is ignited, secondary electrons emitted from the silicon wafer and sample stage bombard the chamber wall and raise the temperature, thereby releasing more trapped O and N. Therefore, outgassing can be serious if the pumping time is too short or when there is moisture in the venting gas. The second and major source of C and O is leaks in the

Table 2
Number of iron atoms sputtered by 6.7 keV hydrogen, 10 keV oxygen and 10 keV nitrogen calculated by TRIM95. The total doses are determined experimentally by SIMS

	H	O	N
Total dose (cm^{-2})	5.9×10^{16}	1.2×10^{15}	1.3×10^{15}
Relative dose	1	0.02	0.02
Sputtering yield	3.8×10^{-3}	1.1	0.91
Relative number of sputtered atoms	3.8×10^{-3}	2.2×10^{-2}	1.8×10^{-2}

chamber and gas line. The hydrogen pressure during PIII is 0.4 mTorr. The gas line after the mass flow controller is at a lower pressure than the outside (atmospheric pressure). Air can leak into the gas line quite easily and ionized by the RF source. Unlike a conventional ion implanter, a PIII reactor does not have a mass filtration system. All ions existing in the plasma are accelerated across the sheath into the wafer and sample stage during implantation.

To allay the surface iron contamination on the implanted wafer, the most intuitive means is to use a sample stage made of silicon. However, engineering is very difficult because sample cooling must be incorporated on the sample stage for commercial PIII/ion-cut process. An alternative is to cover the stage by a quartz shroud, but a quartz covering around the sample stage has been shown to induce deleterious focusing effects affecting implant uniformity [13]. The more practical and easier way is to reduce the amount of oxygen and nitrogen in the chamber by incorporating a sample load lock and carefully designing an air tight hydrogen induction system.

In summary, surface metal contamination arising from sputtering of the stainless steel sample stage by oxygen and nitrogen in the residual vacuum is observed on hydrogen PIII silicon wafers. In order to produce SOI materials with less defects, efforts must be made to minimize the concentration of atmospheric species in the chamber.

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