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Inner surface ion implantation using deflecting electric field

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Abstract

Because of its non line-of-sight nature, researchers have recently focused on plasma immersion ion implantation (PIII) to enhance the properties of inner surfaces of industrial components to combat wear and corrosion. However, theoretical simulation has shown a relatively dim prospect because of the limitation on impact energy and retained dose. In this paper, we describe a procedure to improve the efficiency of inner surface implantation by using a symmetrical experimental setup and deflecting electric field. Improvements of 43% and 71% are observed for the implantation depth and retained dose, respectively. Since a large portion of the ions implanted into the interior surface originate from outside of the bore, a longer pulse-width will be more beneficial. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Plasma immersion ion implantation; Inner surface modification

Plasma immersion ion implantation (PIII) has no line-of-sight restriction and emulates conventional beam-line ion implantation when dealing with non-planar targets [1,2]. In particular, it has spurred a lot of interests on interior surface treatment [3–7]. Unfortunately, inner surface implantation is hampered by the difficulty to achieve the full implantation energy. It has been calculated that the maximum energy can reach only 36.8% of the applied potential [3–5]. It has also been pointed out that for inner surface implantation, the plasma density in the bore decays from the edge towards the center, and the use of a metal anode to draw primary electrons into the bore to ionize the working gas has been suggested [6]. Zeng et al. proposed to use a coaxial auxiliary electrode to improve the ion impact energy [7]. Further studies have shown that the ion impact energy in the bore can be improved, but the ion density decays to zero very rapidly [8]. Hence, the solution is to use extremely fast pulse modulators but instrument complexity and costs are consequently higher.

Until now, the investigation on inner surface implantation has mainly concentrated on theory or simulation. Recently, Malik et al. [9] used a grounded coaxial electrode to deposit TiN_x and diamond like carbon thin films onto the interior of a hollow cylindrical sample. However, it remains to be proven that this technique can emulate conventional coating methods. On the other hand, high

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energy PIII in which ions are implanted into the specimen to change the surface properties has more unique applications. In this paper, we present our data on inner surface PIII while employing a deflecting electric field. Our experimental results show that both the impact energy and retained dose are improved substantially when compared to the case without a deflecting electric field.

A stainless steel hollow bore 200 mm in length and 100 mm in diameter was implanted in our experiments. The wall thickness was 1.5 mm, and 3 mm × 3 mm stainless steel sheet samples were affixed on the inner and outer surfaces of the bore 50 mm away from the rim to monitor the implant dose and energy. The more convenient way of placing the target vertically on the sample stage will not work properly for inner surface implantation due to the non-uniform electric field around the sample stage. Moreover, as the bottom of the cylindrical bore sample is in touch with the sample stage, outside ions can only replenish from the top thereby exacerbating dose non-uniformity along the bore interior. In order to minimize the influence of the sample stage and achieve uniform implantation, we placed the hollow bore horizontally in the vacuum chamber of our multi-purpose PIII instrument [10]. To keep it away from the sample stage, the bore was elevated by means of a 260 mm long aluminum rod connected to the sample stage on one end and the bore on the other end. A 6 mm-diameter metal electrode was placed along the axis of the bore in order to set up a deflecting electric field inside the bore. The electrode was connected to the chamber wall on both ends for support and thus had the same ground potential as the wall. A schematic of the setup is shown in Fig. 1. The chamber was pumped down to a base pressure of 9.1×10^{-4} Pa. Nitrogen plasma was generated in the chamber using a filament source. The bore was biased to a pulsed voltage of −15 kV. The pulsing frequency was 200 Hz, and the pulse width was 15 μs. A similar bore was implanted using the same parameters but without the coaxial electrode.

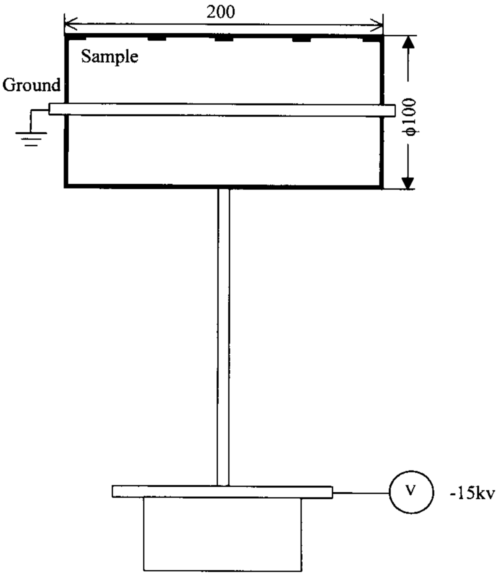
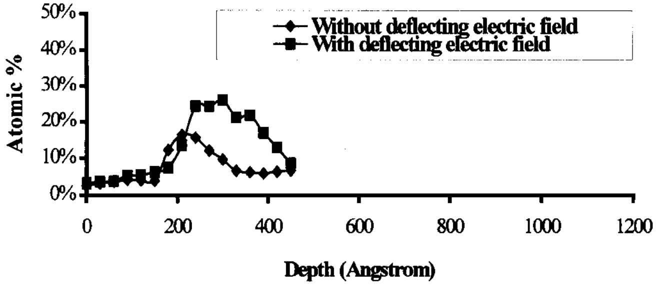
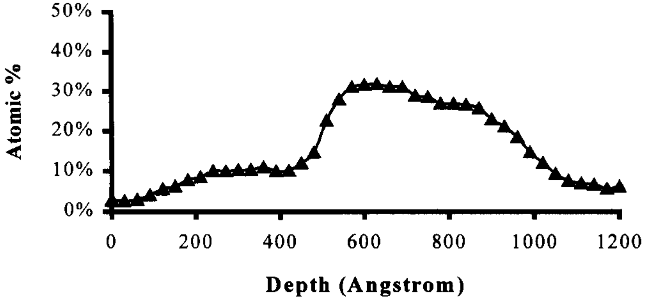


Fig. 1. Schematic of experimental setup.

After implantation, the stainless steel sheets were taken out and Auger electron spectroscopy (AES) was performed to measure the nitrogen depth distribution. Fig. 2(a) compares the AES depth profiles of nitrogen in the samples implanted with and without the deflecting electric field. Fig. 2(b) shows the depth distribution on the outer surface of the bore for comparison. The results are summarized in Fig. 3 that compares the projected range (i.e. implantation energy) and Fig. 4 which displays the total retained ion dose (area under the curves in Fig. 2) of the three samples. Our results indicate that both the impact energy and retained dose are improved in the presence of the deflecting electric field, but the retained dose and impact energy are lower than those achieved on the outer surface of the bore, even though all areas have been implanted simultaneously. The peak of the nitrogen depth profile implanted without the deflection electric field is at 210 Å or 33% of that of the outer surface, whereas the peak of the sample implanted with the deflection electric field is increased to 300 Å or 48% of the outer surface. Comparing the influence of the deflection electric field, the implant depth into the inner surface is improved by 43%. The retained dose of the inner surface without the deflection electric field is only 1.6×10^{16} atom/cm^2 or 19% of that of the outer surface, and the retained dose with the deflecting electric field is 2.7×10^{16} atom/cm^2 or 32% of that



(a)



(b)

Fig. 2. Nitrogen depth profiles determined by Auger electron spectroscopy: (a) the interior surface with and without a deflecting electric field and (b) the exterior surface of the bore.

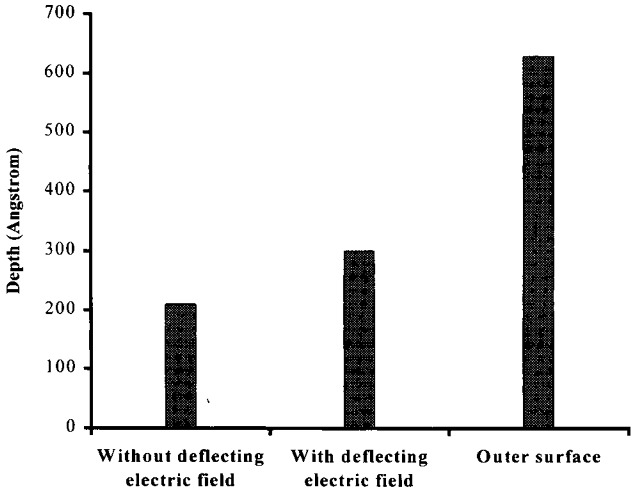


Fig. 3. Comparison of the peak position of the three samples shown in Fig. 2.

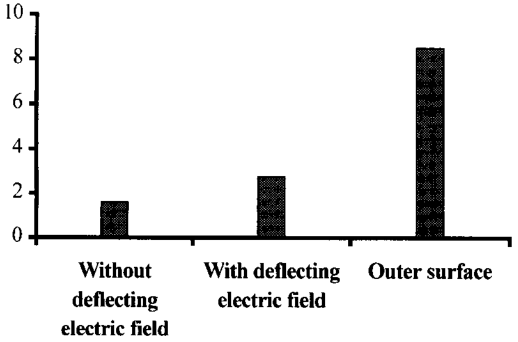


Fig. 4. Retained dose (× 10^{16} atoms/cm^2) of the samples shown in Fig. 2.

of the outer surface. The retained dose is improved by 71% with the deflecting electric field.

The improvement can be visualized and explained in Fig. 5. The plasma is assumed to be collisionless and cold, and the edge effect of the electric field is neglected. Our calculation shows that the ions in the bore will be exhausted or depleted within 3 μs after the pulse has been applied. Since the pulse duration used in this investigation is 15 μs, many implanted ions originate from outside of the bore. An ion going into the bore has velocity components parallel and orthogonal to the axes of the bore. The two velocity components will interact with the applied electric field in the bore to decide where or whether the ion will impact the inner wall or drift out from the other end (i.e., unimplanted). In the presence of a deflecting electric field, there is a very strong radial electric field even after the ion density in the bore has decayed to zero. Ions entering the bore subsequently from the outside will be accelerated toward the wall as illustrated in Fig. 5(a). Only when the axial velocity component is very large or when the bore is very short that the ion will escape from the other end

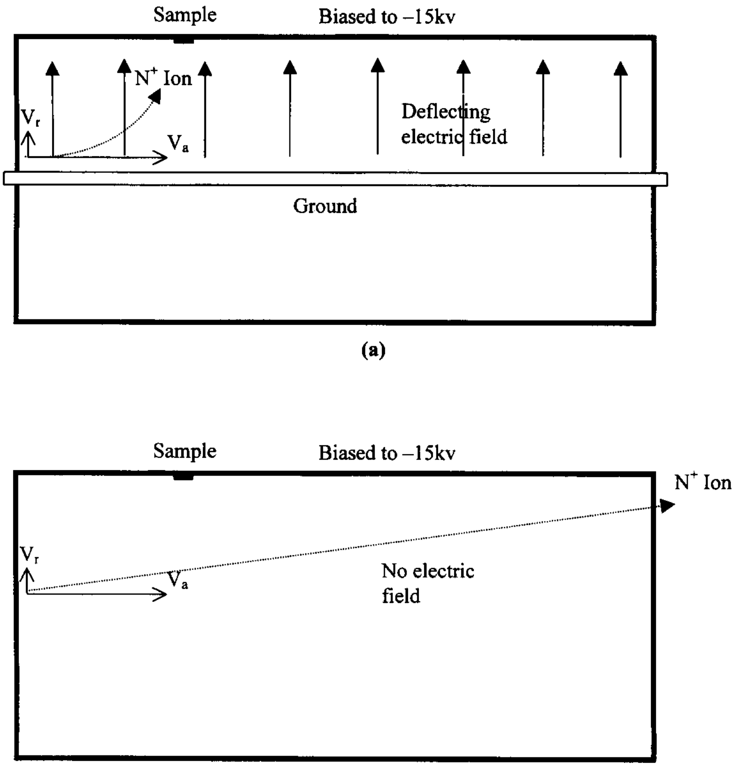


Fig. 5. Schematic showing the effects of the deflecting electric field on inner surface implantation.

of the bore (Fig. 5(b)). The pulse duration in this investigation is very long compared with the time scale to exhaust the ions within the bore. Hence, during most of the implantation time, ions implanted to the interior area come from a region outside the bore. The presence of the deflection electric field causes a change in the ion trajectory, accelerates the ions toward the interior wall, and yields higher implantation energy as shown in Fig. 3. The higher impact energy and more normal incident angle (relative to the wall surface) give rise to the higher retained dose shown in Fig. 4. The improved implantation conditions will bring about better modification effects on the interior surface. Without the deflection electric field, ions existing in the bore before the pulse is applied will still get implanted, albeit with a lower impact energy. However, after they are exhausted, few additional ions will be implanted as ions entering through the bore hole from the outside will receive no added radial acceleration. Therefore, unless they possess a high intrinsic radial velocity component upon entrance, they will likely pass through the bore without impacting the interior wall. Comparison of the retained dose for the cases with and without the deflecting electric field suggests that a significant portion of the implanted ions come from the region outside of the bore. A longer pulse is thus expected to yield better results, even though the demand on the modulator and electronics is more stringent.

We have confirmed experimentally that the deflecting electric field created by a grounded coaxial electrode gives rise to better impact energy and retained dose. The impact energy of the inner surface is improved by 43%, and the retained dose is increased by 71% when compared to the case without the deflecting electric field. However, to put things in perspective, although the improvement is significant, the implantation energy and dose are still worse that those accomplished on the exterior surface. Our results also suggest that a large portion of the ions implanted to the interior region originates from outside the bore, and a longer pulse width will thus be more beneficial. This observation has not been predicted by theories.

Acknowledgements

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