Spatial Potential Distribution around Trench Target during Plasma Immersion Ion Implantation

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Plasma ion implantation, an alternative to conventional beam-line ion implantation, is a sheath-acceleration ion bombardment technique and the initial sheath is crucial to the process efficacy and surface properties. The initial spatial potential distribution in the plasma sheath around a trench-shaped target is simulated using a two-dimensional model in this work. The results demonstrate that the sheath structure depends very much on the trench width. The potential drop in the trench may be quite small and the sheath expands outward if the width is small. This leads to a smaller incident ion dose into the sidewalls of the trench. In contrast, the initial potential distribution in the central region is quite similar to that without a trench if the trench width is larger than twice the ion-matrix sheath thickness for an infinite plane. Consequently, a higher ion dose into the sidewalls is possible.

KEY WORDS: Plasma ion implantation, Trench target, Potential distribution

1. Introduction

Ion implantation is an effective tool to optimize the surface properties of materials. Conventional ion implantation is a line-of-sight process in which ions are extracted from an ion source using an ion extraction system, accelerated as a collimated beam by a high voltage, and eventually impinge into the sample. If the specimen is non-planar, sample manipulation or beam scanning is needed to implant all the sides. This adds complexity and costs in many cases. An alternative technique, namely plasma immersion ion implantation (PIII) and proposed late in 1980 s, is relatively effective compared to the traditional beam-line technique[1]. Its other advantages are high throughput and capability to treat objects possessing an irregular shape without complex manipulation. PIII has hitherto been used to increase the corrosion and wear resistances of metals as well as to enhance the biocompatibility of biomedical materials[2,3]. In microelectronics, silicon-on-insulator (SOI) fabrication using the PIII/ion-cut technique has also been reported[4]. While there are inherent differences, PIII does not deviate extensively from conventional ion implantation. In PIII, the plasma sheath becomes a part of the ion extraction system, and so the dimensions of the samples have a considerable influence on the ion implantation dynamics. The plasma sheath evolves around the sample when a negative potential relative to the chamber wall is applied to the sample. The ions in the sheath are accelerated by the potential drop across the sheath and bombard the surfaces of the sample. Therefore, the configuration of the plasma sheath and spatial potential around the target are very important in determining the final processing results. In this work, the initial plasma sheath and potential distribution around a sample possessing a trench geometry is modeled and calculated using a two-dimensional simulation due to its huge influence on the processes[5]. The trench-shaped target represents a typical industrial component possessing cavities or hole, e.g., bear ring, gear, cylinder, etc.[6]

2. Sheath Model

Figure 1 depicts the schematic of the simulation of a trench target. A zero rise-time of the applied pulse is assumed and the plasma density is also assumed to be uniform before each voltage pulse is applied to the target. The potential configuration around the trench is given by the solution of Poisson’s equation:

$$\nabla^2 \phi = \frac{-e}{\varepsilon_0} (n_i - n_e)$$  \hspace{1cm} (1)

where $\phi$ is the potential applied to the sample, $e$ is the unit charge, $\varepsilon_0$ is the free-space permittivity, $n_i$ is the ion density, and $n_e$ is the electron density. Here, we assume that the electrons are in thermal equilibrium, so that the influence of the spatial potential on the electron density can be described by the Boltzmann relation:

$$n_e = n_0 \exp \left( \frac{e\phi}{K T_e} \right)$$  \hspace{1cm} (2)

where $n_0$ is the plasma density, $K T_e$ is the electron temperature. Consequently, in rectangular coordinates Eq.(1) becomes

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = \frac{-e n_0}{\varepsilon_0} \left[ 1 - \exp \left( \frac{e \phi}{K T_e} \right) \right]$$  \hspace{1cm} (3)

for simplicity and generality, the target dimension is normalized to the planar ion-matrix sheath width:

$$S_0 = \left( 2 \varepsilon_0 e / e n_0 \right)$$  \hspace{1cm} (4)

and the potential is normalized to the target potential $\phi_0$, so that the dimensionless potential is $\psi = \phi / \phi_0$. Due to symmetry, only one half of the target needs to be considered during the simulation processes as shown in Fig.1.

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Fig.1 Schematic of the simulation arrangement and region
Fig. 2 Sheath configuration for different trench widths: (a) \( L=0.5\ S_0 \), (b) \( L=2.0\ S_0 \), (c) \( L=4.0\ S_0 \)

Fig. 3 Potential profile along the central line for \( L=1.0\ S_0 \)

3. Results and Discussion

The sheath configuration and potential distribution are shown in Fig.2 for different trench widths. For a big trench width (e.g., \( L=4.0\ S_0 \)), the plasma sheath is conformed to the target shape except in the vicinity of the corners. Near the corners, the equivalent potential lines are smooth and round while the lines parallel to the target surfaces far away from the corners as indicated by the potential distribution near the surface without the trench (opposite side). In the trench, the flat potential line becomes shorter due to the sidewall effect. The sheath configuration evidently varies with the trench size. With decreasing trench width, the equivalent potential lines become curved and the sheath expands outwards. For the case of \( L=0.25\ S_0 \), the whole sheath is nearly symmetrical on both upper and lower surfaces and the effects of trench are very small as if the trench did not exist.

The potential profile along the central line for \( L=1.0\ S_0 \) is depicted in Fig.3. The potential distributions on the opposite sides are substantially different. On the surface without the trench (back side), the potential rapidly decreases from the target surface (\( \gamma=1 \)) to the sheath edge (\( \gamma=0 \)), which is similar to that of a planar ion-matrix sheath. In contrast, the potential changes gradually in the trench and there exists an inflection point near one half the trench height. Consequently, the potential drop in the trench is smaller. That is to say, the ions in the trench receive smaller energies before bombarding the central surface. For example, the ions near \( L_V=2.5 \) (middle of sidewall) receive at most 25% of the applied potential if they fly along the central line. With decreasing trench width, the position of the inflection point moves upwards and the potential distribution also changes as shown in Fig.4. Interestingly, when the trench width is less than 0.5 \( S_0 \), the potential drop within the trench is very small along the central line. For instance, for \( L=0.25\ S_0 \), the potential drop along the central line within the trench becomes relatively small, i.e. \( \gamma\approx0.1 \), and the remaining 90% potential drop occurs outside the trench. In comparison, the potential drop happens in the trench and changes slightly if the trench width is larger than 2 \( S_0 \). The variations of the sheath for different trench widths indicate the influence of the sidewalls. If the trench width is large, the interaction between the plasma sheaths from opposite sidewalls is small and the sheath from the bottom of trench approaches as if it was a planar sample without the trench, particularly for larger trench width. For example, the central potential distribution is almost symmetrical on both zones of the target of \( L=4.0\ S_0 \). On the other hand, if the trench width is small, the composite effect of the sheaths propagating from the two sidewalls and bottom surface moves the sheath outwards. It should be noted that the potential distribution near the surface without the trench (back side) is slightly affected by the trench dimension as shown in Fig.4. The sheath thickness along the central line is trench-width dependent as shown in Fig.5. If the trench width is larger, the sheath resembles that near the surface without the trench and there is hardly any change with increasing widths. If the trench width is smaller, the sheath thickness increases and approaches a steady-state value that is equal to the sum of the trench height and sheath thickness near the surface without the trench.

The horizontal potential distribution is similar to that along the central line. Figure 6 displays the potential within the trench at a height of \( L_V=2.5 \). It can be observed that a small trench width also results in a smaller horizontal potential drop in addition to small potential drop along the central line. This means that ion acceleration within the trench is
In contrast, if the trench is narrow, lower implantation into the sidewalls results since the equivalent potential line is almost orthogonal to the sidewalls, that is, the electric field line almost parallels to the sidewalls.

4. Conclusion

The initial plasma sheath and potential distribution around a trench-shaped target are simulated using a two-dimensional model. The potential structure depends very much on the trench width. There exists a potential point of inflection along the central line that is responsible for the effects of the potential applied to sidewalls. If the trench width is relatively small, the potential drop within the trench is insignificant leading to outward expansion of the plasma sheath and the sidewalls will receive less incident ion dose due to the glancing incidence of the implanted ions. Hence, it is critical to optimize the processing parameters in order to achieve effective implantation in practical applications.

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