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External magnetic field effect on the sheath dynamics and implantation profiles in the vicinity of a long step shaped target in plasma immersion ion implantation

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ABSTRACT

This work investigates the sheath dynamics and implantation profiles during the plasma immersion ion implantation (PIII) process on a long step shaped target in the presence of a DC magnetic field with the different inclination angles. The fluid model is used to demonstrate the time evolution of the sheath parameters and the influence of the magnetic field on these parameters. The results of the numerical solution of the equations show that, the magnetic field inclination angle strongly affects the ion-implanted dose in the different faces of the step shaped target. According to the results, the vertical sidewall of the target is only implanted when the magnetic field inclination angle is *30*°. Whereas, at the magnetic field inclination angles of *70*° and *80*° the horizontal parts of the target can be implanted selectively. Furthermore, the implantation profiles can be well explained using the ions energy and incident angle.

1. Introduction

Plasma based ion implantation has developed as an advanced technique for the materials surface modification [1–3]. It has attracted considerable research interests due to its superior performance such as non-line-of-sight operation and complex sample manipulation compared with the conventional methods [2,4,5]. In this method, the work piece is immersed in the plasma and a high negative pulse voltage is applied to the sample. As a result, the ions accelerate toward the sample through the plasma sheath [6].

Some high voltage sheath models, including matrix sheath and Child law sheath are proposed to describe the ion dynamics during the plasma ion implantation process [5–8]. Besides the analytical methods, the numerical techniques try to give more details about different structures and more complicated experimental conditions. In the planar structures, the energy distribution of the striking ions, the implantation profile, and the magnetic field effect on the implantation parameters have been extensively investigated by different authors [9–14]. Simulation of the non-planar structures has recently received more attention due to their practical importance [15–22]. Donally and Wolterson have simulated the sheath structure near the square and wedge-shaped edges for the stationary ion matrix sheath [23]. After that, Sheridan [18] and Hong [24] have presented their simulation results about the expanding plasma sheath around the convex corner of a square target. They obtained time evolution of the plasma sheath around the target and showed the non-uniformity of the incident ion dose near the corners which arises from the target geometry.

In this paper, we present a numerical solution for the fluid equations to obtain the sheath dynamics around a long step shaped target in the presence of a DC magnetic field. It can be considered as a part of cogged devices like gears. We simulate the plasma sheath around a cog from the middle of a top land to the middle of the next bottom land. Generally, the improvement of implantation uniformity, implantation in the inaccessible parts of the target and reduction of the shadowing effects are considered as the critical issues in the plasma ion implantation process. In this regard, we investigate the magnetic field effect on the implantation profiles in different faces of the target. In this study, the plasma fluid model has been used to give an appropriate description of the ion implantation on the vertical and horizontal walls of the step shaped target in the presence of an external magnetic field. We focus on the sheath characteristics in different conditions of the DC magnetic

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field. The implantation profiles are studied and the energy and incident angle of the ions on the target surface are employed to explain the results.

2. Theory

We present the fluid model to study the plasma sheath dynamics and ion implantation on a long step shaped target. This target can be regarded as a part of a cog in the industrial machines. Because of the symmetry, the problem can be reduced to a two dimensional problem in the x–y plane. A rectangular domain, from the middle of a top land to the middle of the next bottom land, is considered as the simulation region. A schematic diagram of the simulation region has been shown in Fig. 1. It is defined over the rectangular area which is bounded by the dashed lines, X and Y axis and includes a rectangular tip surrounded by plasma. According to the diagram, the rectangular cross section of the target and the external magnetic field are placed at the x–y plane and the magnetic field makes an angle of θ with respect to the x-axis.

Four basic equations, the Boltzmann distribution for the electrons density, the continuity and momentum transfer equations for ions and the Poisson equation, are used to analyze the sheath dynamics during the ion implantation process. The Boltzmann equation for the electron density is

$$n_e = n_0 \exp\left(e\varphi/k_B T_e\right) \tag{1}$$

where n_e and n_0 are the electron density in the plasma sheath and at the sheath edge (plasma-sheath interface), respectively, e is the fundamental electric charge, φ is the electric potential, k_B is the Boltzmann constant and T_e is the electron temperature. Furthermore, it is assumed that the plasma sheath is collisionless and the ions are cold. According to these assumptions, the equations of the ion continuity, ion momentum transfer and Poisson equation can be respectively written as follow:

$$\partial_t n_i + \nabla\cdot(n_i \boldsymbol{u_i}) = 0, \tag{2}$$

$$n_i M_i(\partial_t + \boldsymbol{u_i}\cdot\nabla)\boldsymbol{u_i} - q_i n_i(\boldsymbol{E} + \boldsymbol{u_i}\times\boldsymbol{B}) = 0, \tag{3}$$

$$\nabla^2\varphi = -e(n_i - n_e)/\varepsilon_0, \tag{4}$$

where n_i and $\boldsymbol{u_i}$ are the ion density and velocity, respectively, M_i is the ion mass, $q_i = e$ is the ion electric charge, $\boldsymbol{E} = -\nabla\varphi$ and $\boldsymbol{B}$ are the electric and magnetic fields, respectively and ε_0 is the free space permittivity.

Because of the symmetry condition of the problem, all of the physical parameters are assumed to change only along the x and y directions. Therefore, $\nabla \rightarrow \partial_x \boldsymbol{i} + \partial_y \boldsymbol{j}$ and Equations (2)–(4) will be transformed to

$$\partial_t n_i + \partial_x(n_i\, u_x) + \partial_y(n_i\, u_y) = 0, \tag{5}$$

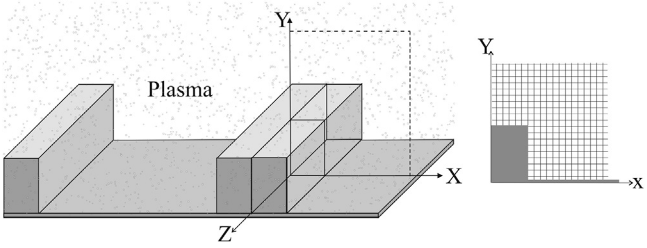

Fig. 1. Schematic diagram of the simulation region.

$$\partial_t u_x + (u_x\partial_x + u_y\partial_y)u_x + (e/M_i)\partial_x\phi + eB_0 u_z \sin\theta/M_i = 0, \tag{6}$$

$$\partial_t u_y + (u_x\partial_x + u_y\partial_y)u_y + (e/M_i)\partial_y\phi - eB_0 u_z \cos\theta/M_i = 0, \tag{7}$$

$$\partial_t u_z + (u_x\partial_x + u_y\partial_y)u_z - eB_0(u_x \sin\theta - u_y\cos\theta)/M_i = 0, \tag{8}$$

$$\partial_x^2\varphi + \partial_y^2\varphi = e(n_e - n_i)/\varepsilon_0 \tag{9}$$

For the sake of simplicity, these equations are normalized using some dimensionless parameters. The normalized form of the governing Equations (1) and (5)–(9) will be

$$N_e = \exp(\eta), \tag{10}$$

$$\partial_\tau N_i + \partial_X(N_i U_X) + \partial_Y(N_i U_Y) = 0, \tag{11}$$

$$\partial_\tau U_X + (U_X\partial_X + U_Y\partial_Y)U_X + \partial_X\eta + \rho U_Z \sin\ \theta = 0, \tag{12}$$

$$\partial_\tau U_Y + (U_X\partial_X + U_Y\partial_Y)U_Y + \partial_Y\eta - \rho U_Z \cos\theta = 0, \tag{13}$$

$$\partial_\tau U_Z + (U_X\partial_X + U_Y\partial_Y)U_Z - \rho(U_X \sin\theta - U_Y\cos\theta) = 0, \tag{14}$$

$$\partial_X^2\eta + \partial_Y^2\eta = N_e - N_i, \tag{15}$$

in which, the normalized parameters are

$$\tau = t\omega_{pi},\ \eta = e\varphi/k_B T_e,\ N_i = n_i/n_o,\ N_e = n_e/n_o,\ X = x/\lambda_{\rm De},\ Y = y/\lambda_{\rm De},\ U_X = u_x/C_s,\ U_Y = u_y/C_s,$$

$U_Z = u_z/C_s$, $\rho = \omega_c/\omega_{\rm pi}$ and $\lambda_{\rm De} = \sqrt{\varepsilon_o k_B T_e/e^2 n_o}$ is the Debye length, $C_s = \sqrt{k_B T_e/M_i}$ is the ion acoustic velocity, $\omega_{pi} = \sqrt{n_0 e^2/M_i\varepsilon_o}$ is the ion plasma frequency and $\omega_c = eB_0/M_i$ is the ion gyro frequency. In order to solve the nonlinear Poisson equation, we used an iterative linearization technique [25]. To initiate the plasma ion implantation process, a negative high voltage pulse in the form of

$$V(t) = V_p[1 - exp\,(-2.5t/t_r)] \tag{16}$$

is applied to the target at $t = 0$. The rise time (t_r) and the amplitude (V_p) of the high voltage pulse [in Equation (16)] are assumed to be 30 ns and −30 kV, respectively. The helium plasma with the plasma density of 10^{14} m^{-3} is used as the process medium. The constant electron temperature is assumed to be 1.3 eV and magnitude of the magnetic field is 1T. The dimensions of the simulation region and the target cross section are $(50 \times 300)\lambda_{\rm De}$ and $(5 \times 15)\lambda_{\rm De}$, respectively. In this simulation, the equations system are numerically solved using the finite difference method [26].

The initial and boundary conditions on the simulation area are specified as follow:

At time $\tau = 0$, no potential is applied on the work piece ($\eta = 0$). Ions in the plasma are still at rest ($\boldsymbol{U_i} = 0$) and $N_i = 1$ because of the quasi neutrality of the plasma at the initial time ($n_{i0} = n_0$). Obviously, the ions density and velocity on the target ($Y = 0$ and rectangle bounded by $0 \le X \le 5$ and $0 \le Y \le 15$), are considered to be zero ($N_i = 0$ and $\boldsymbol{U_i} = 0$).

As the boundary condition, on the right side of the simulation area ($X = 50$), Neumann boundary condition is imposed ($\partial_x = 0$). On the left boundary, over the rectangular tip ($X = 0$ and $Y > 15$) the Neumann boundary condition is applied ($\partial_x = 0$). On the target ($Y = 0$ and rectangle bounded by $0 \le X \le 5$ and $0 \le Y \le 15$), the ions density and velocity are zero ($N_i = 0$ and $\boldsymbol{U_i} = 0$) and potential varies