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Effects of strong magnetic field on plasma immersion ion implantation of dielectric substrates

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ABSTRACT

In this paper the effects of a strong magnetic field on plasma immersion ion implantation (PHI) of dielectric substrates were investigated. A plasma fluid model and finite difference schemes were used to simulate a one-dimensional system of plasma immersion ion implantation. The effect of secondary electron emission from the electrode on PHI was also taken into consideration. It was found that the magnitude and direction of the magnetic field have slight effects on sheath thickness but have considerable effects on current densities in the y and z directions which are perpendicular to the direction of the electric field (the x direction). The simulations showed that the current densities in the y and z directions increased significantly with increasing magnitude of the magnetic field at a given fixed angle, the reason being attributed to the rotational force exerted on the ions by the magnetic field. With a fixed magnetic field, increasing the angle of the magnetic field, θ, with respect to the electric field produced a continuous increase in current density in the y direction from zero to its maximum at $\theta = 90°$ but the current density in the z direction could be described as saddle-shaped being zero at both ends.

1. Introduction

Plasma immersion ion implantation (PIII) is an established and cost-effective method that has been found to have important effects on the surface-related properties of materials [1–3]. These effects have made possible several areas of applications to both researchers and industry such as in microelectronics and semiconductor industry, metallurgical processes and recently surface treatment of insulating materials [4–7]. PHI creates a thin surface layer of modified material, resulting in increased hardness, fatigue life, and corrosion resistance; reduced wear and sliding friction and modified electrical and optical properties [2,4]. In PHI the target is immersed in weakly ionized plasma and biased repetitively to a negative high voltage. When the voltage pulse is applied, almost instantaneously (on a time scale of ω_{pe}) electrons are repelled to uncover a region of uniform ion density called the "matrix sheath", while ions respond much slower (on a time scale of ω_{pi}) [3]. When a high voltage pulse is applied to the electrode a strong electric field directs ions onto the target surface with enough energy to penetrate the atomic structure of the target and come to rest many atomic layers below the surface. In order to maintain the ion flux, the sheath edge propagates into plasma at about ion acoustic speed to uncover more ions until the end of the voltage pulse [1,8]. Since the main ion acceleration is concentrated in plasma sheath, understanding the sheath structure can help to better understanding of ion properties in sheath reign and thereby to better understanding of PIII operation itself. Currently a good understanding of the basic PIII mechanism exists both experimentally and theoretically and many aspects of it have been investigated [2]. Plasma fluid model and particle-in-cell (PIC) simulations usually are used to numerically evaluate various features of PIII [8–12].

Introducing a magnetic field in a PIII system affects charged particles motion and will make PHI operation more complex. Until recently little research has been reported concerning the influence of an external magnetic field on PIII dynamics. Keidar and coworkers [13] performed an experiment to investigate how the sheath thickness in PIII alters in the presence of a transverse magnetic field. They found that the steady-state sheath thickness increases with increasing the magnetic field strength. Secondary electron emission (SEE) has always been a matter of issue in the PIII process and its effect should be included in calculations when the SEE coefficient is large [13–15]. Tan and coworkers [16,17] have exploited a transverse magnetic field to suppress secondary electrons and the associated generation of X-rays. Although strong magnetic fields are rarely feasible in laboratory experiments, their approximate effect on PHI can easily be estimated by numerical computations. Davoudabadi and Mashayek [18] have investigated the effect of strong magnetic field on the sheath and found that the presence of magnetic field induces fluctuations in ion density.

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In the present work, using plasma fluid equations in one dimension and finite difference methods, we focus simultaneously on effects of secondary electron emission of a dielectric layer on the cathode and a strong uniform DC magnetic field on PIII parameters. The calculations have shown that sheath thickness slightly decreases with increasing magnetic field while current densities in the y and z directions can increase considerably.

2. Model description

We assume a low-pressure collisionless plasma with density n_0 in which an oblique uniform magnetic field is placed in the x–z plane and makes an angle 6 with the negative x direction. The metal electrode is covered by a dielectric layer and connected to a pulsed high voltage system Fig. 1.

The magnetic force exerted on charged particles in the systems considered here is considerably weaker than the electric force since in PHI the strength of electric field is very intense and even a relatively large magnetic field cannot distort the distribution of electrons very much. So, we suppose that the fast motion of electrons in the fluid regime can be averaged to lead to the Boltzman distribution. Also, on account of the relative magnitude of the negative high voltage we can neglect the thermal motion of ions. Thus, the one-dimensional plasma fluid equations with convenient normalization of parameters are:

$$\frac{\partial^2\varphi}{\partial x^2} = -(n_i - n_e) \text{ (Poisson's equation)} \tag{1}$$

$$n_e = \exp(\varphi) \text{ (Boltzman equation)} \tag{2}$$

$$\frac{\partial u_x}{\partial t} + u_x\frac{\partial u_x}{\partial x} = \left(-\frac{\partial\varphi}{\partial x} + u_y\alpha\sin\theta\right) \times \text{(equation of motion of ions in } x \text{ direction)} \tag{3}$$

$$\frac{\partial u_y}{\partial t} + u_x\frac{\partial u_x}{\partial x} = -(u_x\alpha\sin\theta + u_y\alpha\sin\theta) \times \text{(equation of motion of ions in } y \text{ direction)} \tag{4}$$

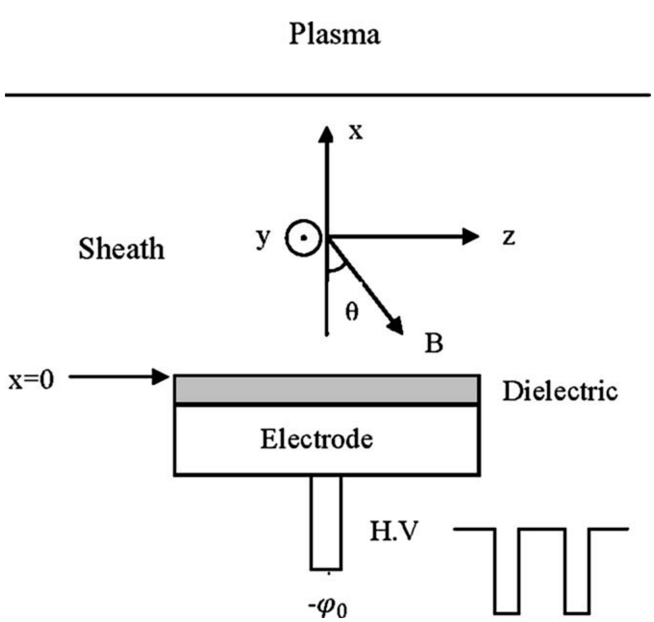

Fig. 1. Configuration of magnetic field in a PIII system.

$$\frac{\partial u_z}{\partial t} + u_x\frac{\partial u_z}{\partial x} = u_y\alpha\cos\theta \times \text{(equation of motion of ions in } z \text{ direction)} \tag{5}$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial(n_i u_i)}{\partial x} = 0 \text{ (equation of continuity for ions)} \tag{6}$$

where u_x, u_y, u_z are the ion drift velocities in the x, y, z directions respectively normalized to Bohm velocity ($u_B = \sqrt{\kappa T_e/m_i}$), x is the distance from the dielectric surface normalized to Debye length ($\lambda_D = \sqrt{\varepsilon_0\kappa T_e/e^2 n_0}$), $n_i(x, t)$ and $n_e(x, t)$ are the ion and electron densities normalized to uniform density n_0, t is time normalized to ω_{pi}^{-1}, ω_{pi}, and ω_{pe} are the ion and electron plasma frequencies ($\omega_{pi} = \sqrt{e^2 n_0/\varepsilon_0 m_i}$), $\varphi(x,t)$ is the electric potential inside the sheath normalized to $(\kappa T_e/e)$, $\alpha = B_0\sqrt{\varepsilon_0/m_i n_0}$, m_i is the ion mass and ε_0 is the permittivity of free space.

Finite difference schemes were used in order to solve equations (1)–(6). We used Taylor's expansion in order to linearize the Poisson's equation [9,19].

$$e^{\varphi} = e^{\psi}e^{(\varphi-\psi)} \cong e^{\psi}(1 + \varphi - \psi). \tag{7}$$

Substituting this transform into Eq. (1) we have

$$\frac{\partial^2\varphi}{\partial x^2} - e^{\psi}\varphi = -\left(n_i - e^{\psi} + \psi e^{\psi}\right), \tag{8}$$

where ψ is the potential of the preceding time and φ is the potential of present time. Given an initial value of ψ, we obtain the new value φ from the solution of two-point boundary value problem of Eq. (8). Then taking φ as a new initial value for the next step, we solve Poisson's equation again. This process is iterated until it converges.

In order to solve equations above they should be subjected to appropriate initial and boundary conditions. Before the inception of the voltage pulse we suppose that we have uniform quasi-neutral plasma with motionless ions. We also assume that in the plasma-sheath boundary we have quasi-neutrality condition *i.e.* the potential drops down to zero and ions enter into the plasma with the Bohm velocity. During the voltage on time, because of implanted positive ions, the dielectric surface charges up and its potential varies in time. Furthermore, dielectric substrate itself will cause a reduction in the applied voltage on the dielectric surface. Thus, for boundary conditions we can write $(\varphi(x|_{sh}, t) = 0, u_x(x|_{sh}, t) = \varphi(0, t) = \varphi_s(t))$. Where, $\varphi_s(t)$ is the instantaneous surface potential and should somehow be determined. Using Gauss' law, Emmert derived a relation for the voltage at the dielectric–plasma interface in terms of instantaneous sheath

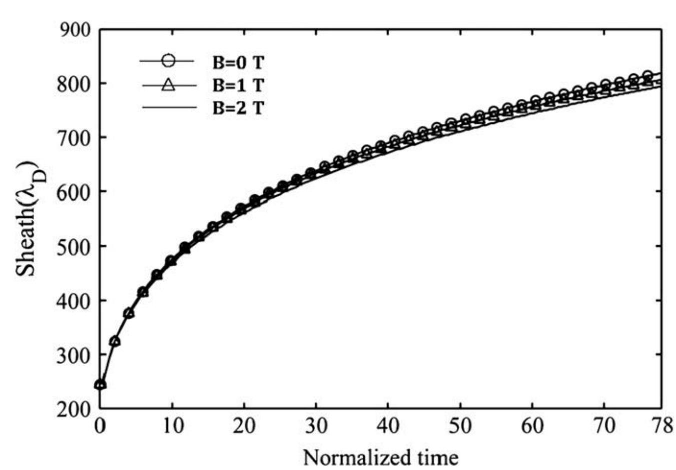

Fig. 2. Sheath variation versus time in different magnetic fields at $\theta = 30°$.