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Effect of target bias on magnetic field enhanced plasma immersion ion implantation

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Abstract

Recent studies have demonstrated that sheath dynamics in plasma immersion ion implantation (PIII) is significantly affected by an external magnetic field, especially in the case when the magnetic field is parallel to the workpiece surface or intersects it at small angles. In this work we report the results from two-dimensional, particle-in-cell (PIC) computer simulations of magnetic field enhanced plasma immersion implantation system at different bias voltages. The simulations begin with initial low-density nitrogen plasma, which extends with uniform density through a grounded cylindrical chamber. Negative bias voltage is applied to a cylindrical target located on the axis of the vacuum chamber. An axial magnetic field is created by a solenoid installed inside the target holder. A set of simulations at a fixed magnetic field of 0.0025 T at the target surface is performed. Secondary electron emission from the target subjected to ion bombardment is also included. It is found that the plasma density around the cylindrical target increases because of intense background gas ionization by the electrons drifting in the crossed $E \times B$ fields. Suppression of the sheath expansion and increase of the implantation current density in front of the high-density plasma region are observed. The effect of target bias on the sheath dynamics and implantation current of the magnetic field enhanced PIII is discussed.

Keywords: PIII; Computer simulation; Magnetic field; Sheath

1. Introduction

Plasma Immersion Ion Implantation (PIII) is a fast and efficient surface modification technique specially developed for treatment of complex shaped three-dimensional objects [1]. In the PIII process, a workpiece to be treated is immersed in plasma generated in a vacuum chamber. The plasma usually consists of a weakly ionized discharge created by gaseous precursor admitted into the vacuum vessel. When the target is pulsed at a high voltage with negative polarity, electrons in the plasma are driven away leaving behind a region of positive ions known as the ion matrix sheath.

On the time scale of the inverse ion plasma frequency the resulting electric field in the sheath accelerates the ions to high energy toward the substrate. As the sheath conformably surrounds the target, all workpiece surfaces are implanted at the same time and at normal incidence. To maintain the ion flux during the negative high-voltage pulse, the charge balance drives the sheath-plasma edge further way, exposing new ions that are accelerated across the sheath and implanted into the sample. Eventually, at high bias voltage and relatively low plasma density the growing sheath may deplete the plasma, terminating the PIII process when the sheath expands all way to the chamber wall. On the other hand, at higher plasma density the system evolves towards a steady-state Child law sheath [2].

Since the main ion acceleration occurs in the sheath, sheath behavior is extremely important in PIII related processes. As predicted by a 1D theory the sheath thickness is governed by the target voltage and the plasma density [3]. However, for a real 3D case, when the plasma density is non uniform the sheath dynamics can be quite complicated. The matrix sheath and its time evolution determine the implantation current and its distribution along the sample. The characteristics of dynamic sheath expansion during the PIII process are very important for optimum PIII design and process control. For example, to ensure a conformal implantation it is important to maintain

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sufficiently small sheath thickness compared with the work-piece characteristic size [4]. In many cases, this is hardly accomplished due to power supply limitations.

One alternative approach to control the sheath thickness relies on the use of a transverse magnetic field. Recent experiments [5] have demonstrated that the sheath thickness is altered by the application of a transverse magnetic field. PIII systems with crossed $E\times B$ fields, as in a cylindrical magnetron, were investigated in the range of low bias voltages [6] and a significant enhancement of the implantation current was observed. These experimental results suggest that a transverse magnetic field intensifies the PIII process.

In this paper we report results of two-dimensional computer simulations of plasma immersion ion implantation with an oblique magnetic field whose field lines enclose the substrate crossing it at the edges. A magnetic field with this configuration is produced by a small solenoid inserted into the substrate holder. The target is immersed in low-density nitrogen plasma with concentration of 0.5×10^{-9} cm^{-3}. By applying a high negative voltage to the substrate, a system of crossed radial electric field and axial magnetic field is created, providing circular electron drift motion in the azimuthal direction. Electrons are efficiently confined in this crossed $E\times B$ system and as a result of the intense electron impact ionization of the background gas a region of high-density plasma is created around the target [5]. Since the sheath thickness depends on the plasma density, which in the presence of magnetic field is no longer uniform, the sheath-plasma edge does not envelop conformably the target. With **B**, the dynamics of the transient sheath as well as its space configuration are determined by the local plasma density, which in turn depends on the electron confinement in crossed $E\times B$ fields. So in the case of magnetic field enhanced PIII, both the magnetic field and the target voltage control the sheath dynamics in the PIII process and correspondingly determine the implantation dose and the ion current distribution. The two-dimensional computer simulation reported in this article provides further insights in the effect of bias voltage on the PIII process at fixed magnetic field strength of 0.0025 T.

2. Simulation

The PIII process depends on the acceleration of ions across the high-voltage plasma sheath that develops around the workpiece. The evolution and the spatial configuration of the sheath are strongly affected by the shape of the substrate and plasma density. In this paper we report the results from a two-dimensional computer simulation in r–z cylindrical coordinates of a magnetic field enhanced PIII system. The simulation has been carried out using the computer code KARAT [7]. It employs the particle-in-cell (PIC) algorithm for calculation of charged particle motion in an electromagnetic field and the Monte Carlo method for collisions of electrons and neutrals in plasma. The layout of the PIII system geometry simulated with KARAT is shown in Fig. 1. The dimensions of the vacuum chamber (13-cm radius, 38-cm length) have been chosen closely to those of experimental PIII system operated at LAP/INPE and described elsewhere [8]. The vacuum chamber wall is grounded, while an insulated sample holder terminating with a 3.0-cm-diam, 9-cm-length target is located on the chamber axis. The magnetic field around the target is created by a small solenoid placed inside the sample holder. The magnetic field strength was controlled by the solenoid current and in the present set of simulations was kept constant. The magnetic field line configuration is depicted in Fig. 1. The main component of the magnetic vector is parallel to the target surface and its value at the surface is 0.0025 T. The simulation begins with the simulation volume filled with low-density nitrogen plasma (N_2^+ ions) with number density of 0.5×10^{-9} cm^{-3} and electron temperature $T_e=1$ eV and high-voltage pulse off. The particles that hit the conductive walls are absorbed. A background nitrogen gas precursor with concentration of 10^{14} cm^{-3} is admitted to the vacuum chamber and the probabilistic Monte Carlo algorithm is employed to simulate the ionization process. The neutral gas is composed of ground state nitrogen molecules at room temperature uniformly distributed throughout the chamber. Only electron impact ionization and excitation from the ground state are included as inelastic electron-neutral collisions. Simply one type of ionic species (N_2^+) is considered. A negative high-voltage pulse with pulse rise time of 0.2 μs and flat top amplitude in the 2.5 kV to 25.0 kV range is applied to the target immersed in the initial uniform plasma. The actual mass ratios of the nitrogen ions are employed. Secondary electron emission from the target as a result of the ion bombardment is included in the simulation. The secondary emission coefficient from a metal surface depends on the ion velocity. Since in this set of simulations we varied the target voltage the secondary electron yield γ (the number of secondary electrons released per implanted ion) is not constant. To determine the secondary emission coefficient at given bias voltage we used the empirical relation $\gamma=\gamma_0\sqrt{V(kV)/20}$ where γ_0 is the electron yield at 20 kV tabulated in [9] for diverse target materials. Stainless steel is used as target material for calculating the secondary electron yield. In our numerical calculations square cell with size $\Delta z=2$ mm and $\Delta r=1$ mm and a time step of 2.0 ps

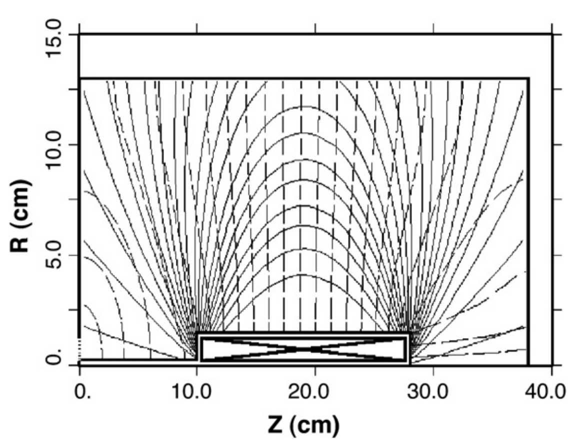

Fig. 1. Layout of the simulation geometry and the spatial configurations of the electric and magnetic fields in a magnetic field enhanced PIII system. Dashed and solid lines represent the electric and magnetic field lines, respectively.