# A model of plasma source ion implantation for inner surface modification



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RAPID COMMUNICATION

# A model of plasma source ion implantation for inner surface modification

**Mu Sun, P Zhu and S Z Yang**

Institute of Physics, Chinese Academy of Sciences, Beijing 100080, People's Republic of China

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**Abstract.** A model has been developed that describes the propagation of the transient sheath which forms inside a cylindrical target immersed in a plasma for inner surface implantation. Following this model, a differential equation and its integrated solution are obtained for the sheath-edge position as a function of time. This result can be used to predict the final sheath extent during each pulse for inner surface implantation of a cylindrical target.

## 1. Introduction

Plasma source ion implantation (PSII) is a new non-line-of-sight technique for surface modification of a wide range of materials for industrial applications [1–4]. However, the present PSII method is only suitable for implantation of the outer surface or exposed areas of a target. Because of a very low plasma density and there being no electric field inside a cylindrical target when a pulse of high negative voltage is applied to the target, inner surface implantation of such a target is quite limited or even impossible.

We recently developed a new PSII method applied to the inner surface implantation of targets and succeeded in demonstrating it experimentally. In our new PSII device, a co-axial metal anode connected to the vacuum chamber wall is set up inside a cylindrical target. This metal anode can help draw primary electrons into the cylindrical target to ionize the working gas so that the plasma density and uniformity inside the target are considerably increased. At the same time a uniform electric field can be formed between the inner surface of the target and the metal anode when a negative high-voltage pulse is applied to the target, which results in a plasma sheath propagating from the inner surface of the target to the centre when the target is immersed in a plasma, thus making inner surface implantation possible.

For ion implantation to be effective the dose of ions implanted in the target must lie within a certain range, which is determined by the extent of propagation of the transient sheath. So an understanding of the sheath dynamics related to this case is important.

In this paper we will present a model of the transient sheath applied to PSII for inner surface implantation of a cylindrical target and then derive a differential equation for the sheath-edge position as a function of time, which is integrated numerically. Finally, this result will be compared with that calculated by Scheuer *et al* [5] for outer surface implantation of a cylindrical target.

## 2. The model of the transient sheath

In this case a cylindrical target is placed directly inside a plasma source chamber and a co-axial metal anode is fixed inside the target. When a large negative high-voltage pulse is applied to this target on a time scale of the inverse electron plasma frequency $\omega_{pe}^{-1}$, electrons near the target inner surface are expelled from this region and ion motion is negligible so that an ion matrix sheath is formed (see figure 1). Next, on a slower time scale of the inverse ion plasma frequency $\omega_{pi}^{-1}$, ions are accelerated towards the inner surface of the target as they fall through the ion matrix sheath. Finally, on a still longer time scale, the decreasing ion density inside the sheath region causes a corresponding decrease in the electron density and the sheath edge expands towards the centre at the ion acoustic velocity. Here, we follow the model of Lieberman [6] in assuming that the expanding sheath obeys the Child–Langmuir law at each instant of the propagation. At the same time we also follow the assumption of zero-ion drift prior to interaction with the sheath edge presented by Scheuer *et al* [5] because the sheath propagation is still fast in this case.

## 3. Calculation of sheath propagation

According to the above model, we will derive an expression of the sheath-edge position as a function of time for inner surface implantation of a cylindrical target. In this case,

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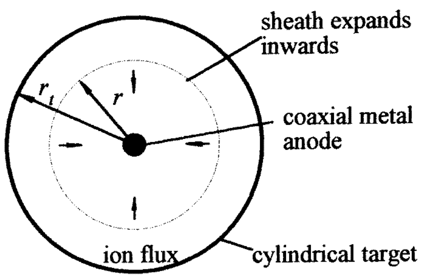


**Figure 1.** The sheath model for inner surface implantation of a cylindrical target.

the Child–Langmuir law for space-charge-limited emission [7] is

$$j = \frac{4\varepsilon_0}{9}\left(\frac{2e}{M}\right)^{1/2}\frac{\nu^{3/2}}{rr_t(\beta)^2} \qquad (1)$$

where $j$ is the current density crossing the sheath edge, $e$ is the charge of the ion, $M$ is the mass of the ion, $\nu$ is the absolute value of the potential applied to the target, $r$ is the radius of the sheath edge, $r_t$ is the inner radius of the target and $\beta = f(r/r_t)$ [7]. The current supplied to this space-charge-limited sheath is also assumed to result only from the ions uncovered by the expanding sheath,

$$j = ne\frac{\mathrm{d}(r_t - r)}{\mathrm{d}t} = -ne\frac{\mathrm{d}r}{\mathrm{d}t} \qquad (2)$$

where the negative sign means that the sheath expands inwards. By equating equations (1) and (2), a differential equation for sheath-edge position as a function of time is obtained,

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -\frac{4\varepsilon_0}{9n}\left(\frac{2}{eM}\right)^{1/2}\frac{\nu^{3/2}}{rr_t(\beta)^2}. \qquad (3)$$

To simplify the above equation it can be normalized as

$$\frac{\mathrm{d}R}{\mathrm{d}\theta} = \frac{-1}{R\beta^2(R)} = \frac{-1}{f(R)} \qquad (4)$$

where

$$\theta \equiv \frac{4\sqrt{2}}{9}A^{3/2}\omega_{pi}t \qquad R \equiv \frac{r}{r_t} \qquad A \equiv \frac{e\nu\lambda_D^2}{kT_e r_t^2}.$$

To obtain the extent of sheath propagation during one pulse for a particular inner surface implantation, one must integrate equation (4) from initial conditions until the pulse is stopped,

$$\int_{R_{init}}^{R_f} -f(R)\,\mathrm{d}R = \int_0^{\theta_f}\mathrm{d}\theta = \theta_f. \qquad (5)$$

Since $\beta$ is not a simple analytic function, we integrate this equation numerically with a quadrature spline interpolation method from the initial conditions $\theta_{init} = 0$, $R_{init} = 0.9$, up to $R = 0.01$. These boundary values are selected on the basis of those which will result from most actual applications. The solution of this integration is shown in figure 2.

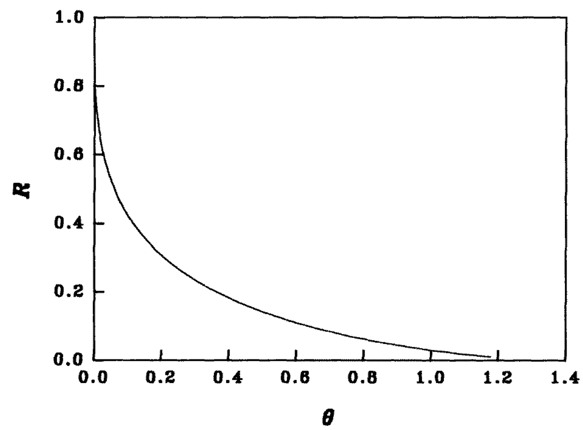


**Figure 2.** The ratio ($R$) of sheath-edge radius to target inner radius as a function of normalized time ($\theta$) for inner surface implantation of a cylindrical target.

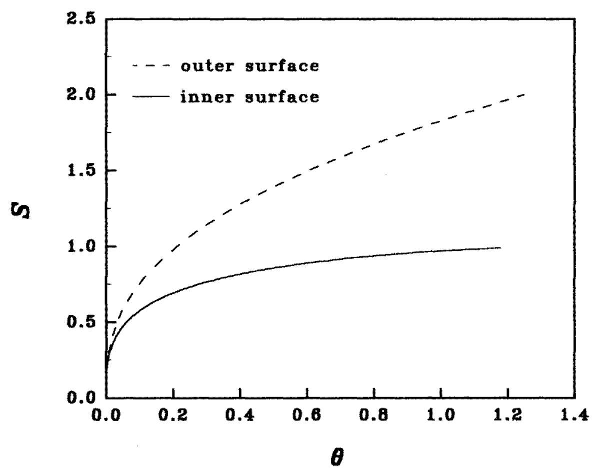


**Figure 3.** A comparison of sheath thickness increase during outer surface and inner surface implantation under the same conditions.

Equation (5) can also be broken up as

$$\int_{R_{init}}^{R_0} -f(R)\,\mathrm{d}R - \int_{R_0}^{R_f} f(R)\,\mathrm{d}R = \theta_f$$

where $R_0 \equiv r_0/r_t$, $r_0$ is the ion matrix sheath radius. Based on Conrad's formula [8] $R_0$ can be approximated as

$$R_0^2 \cong [(2A)^{1/2} + 1][(3A)^{1/3} + \tfrac{1}{2}]. \qquad (6)$$

Defining

$$\int_{R_{init}}^{R_0} -f(R)\,\mathrm{d}R \equiv \theta_0$$

we have

$$\int_{R_0}^{R_f} -f(R)\,\mathrm{d}R = \theta_f - \theta_0 = \Delta\theta$$

where

$$\Delta\theta \equiv \frac{4\sqrt{2}}{9}A^{3/2}\omega_{pi}t_{pulse} \qquad (7)$$

and $t_{pulse}$ is the total pulse length. Thereupon,

$$\int_{R_{init}}^{R_f} -f(R)\,\mathrm{d}R = \int_0^{\theta_f} \mathrm{d}\theta = \theta_f = \theta_0 + \Delta\theta.$$

Following the above equations, one can first determine the ion matrix sheath extent $R_0$ from equation (6) and $\Delta\theta$ from equation (7) for given plasma conditions. From $R_0$ one then obtains the corresponding $\theta_0$ from figure 2. Adding $\theta_0$ and $\Delta\theta$ gives $\theta_f$. The final sheath extent $R_f$ corresponding to $\theta_f$ is then obtained from figure 2.

If we let

$$S = 1 - R = (r_t - r)/r_t = s/r_t$$

where $s$ is the sheath thickness, then from figure 2 we obtain the corresponding $S$–$\theta$ curve in figure 3. For comparison we would like to plot the $S$–$\theta$ curve for outer surface implantation of a cylindrical target using the same procedure as in figure 3, together with the above curve. Note that $S = R - 1 = (r - r_t)/r_t = s/r_t$ for outer surface implantation. From figure 3 it is found that, under the same conditions, the sheath thickness increases faster and keeps enlarging for outer surface implantation, whereas it more slowly and gradually reaches a maximum for inner surface implantation.

## 4. Summary

In this paper we have presented a model of the transient sheath which forms inside the cylindrical target for inner surface implantation. Following this model we have derived and solved an expression for the sheath-edge position as a function of time for inner surface implantation. Compared with that for outer surface implantation under the same conditions, the sheath propagation is slower and gradually reaches a maximum for inner surface implantation.

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