Effects of Ion Temperature on Collisional DC Sheath in Plasma Ion Implantation

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The collision frequency should definitely be taken into account in high pressure discharges. In this work by using forth order of Rung Kuta method, and two-fluid model, temperature dependence of the characteristics of a collisional DC plasma sheath, such as electric field, electric potential, ion and electron number density, and ion velocity, has been studied. It will be shown in the constant cathode electric potential, the more the ion temperature, the low the thickness of sheath.

Keywords: Ion temperature, DC plasma sheath, collisional plasma, two-fluid model

1. Introduction

Ion implantation has been shown to be an effective technique in modifying many mechanical [1, 2], electrical and optical properties [3, 4] of materials. The most efficient method for ion implantation [5] is plasma source ion implantation (PSII). Nowadays PSII is used for the surface modification of materials such as metals, semiconductors, ceramics, and polymers [6]. In this method, the workpiece (target) is immersed in plasma and biased to repetitively high negative voltages. An ion sheath builds up around the workpiece and the plasma ions are accelerated in the sheath potential difference, and are implanted in the workpiece.

Ion implantation, whether by conventional ion beams or PSII techniques, the amount of modification in the properties of implanted targets, depends strongly on the implanted dose and depth of penetration. Measurement and control of implantation dose and penetration depth are therefore critical issue in the design of ion implantation systems. It has been reported as an example showing effect of the ion dose on mechanical properties of materials in Ref. 5. It has been known that the ion dose is related to ion density, and the penetration depth is related to the ion energy in the sheath. Many models have been developed to study and describe the different characteristics and aspects of a plasma sheath, and their results are often consistent with the experimental results [7-11].

Recently it has been shown that ion temperature, strongly affects on the sheath parameters (such as ion energy and density). G. C. Das *et al.* [12] deduced a Sagdeev potential by a collisionless two-fluid model and derived an ion temperature dependent Bohm criterion. Effect of ion temperature on RF plasma sheath was described by M. Lei *et al.* [13]. Moreover, G. C. Das *et al.* and B. Alterkop [14] studied the DC plasma sheath formation in thermal plasma, but the boundary condition for a collisional thermal plasma sheath was not studied yet.

In this paper in a sequel to the earlier works by M. Lei. *et al.*, the characteristics of the DC plasma sheath are obtained numerically by solving sheath nonlinear equations in a two-fluid model. This model is involved in ion-neutral collisions, in addition the effect of the ion pressure (temperature). To understand the main physical features determining the stationary sheath, we restrict the analysis to the charged boundary layer, omitting processes in the plasma body and presheath.

The study is organized follows. After the introduction, in Sec. 2, the nonlinear equations in a simple plasma sheath model are formulated. In Sec. 3, numerical results and the corresponding discussions are presented showing the role of warm ions in the formation of the sheath. Section 4 gives a brief summary and the conclusion.

2. Basic Equations and Sheath Formulation

Here an unmagnetized and collisional plasma with finite ion temperature is considered to examine the electrostatic sheath. If a planar target with a large negative potential is immersed in this plasma, a planar (one-dimensional) sheath is formed around it. We choose the position of the plasma-sheath interface to be at $x = 0$. In the $x < 0$ region, there is a neutral plasma with $\phi = 0$. The plasma consists of electrons and singly charged ions, which are considered as fluids. In the $x > 0$ region, there is a non-neutral sheath. In the steady state ($\partial/\partial t = 0$), for a source-free sheath, the ion fluid equations are,

$$\frac{d}{dx}(n_i v_{ix}) = 0 \qquad (1)$$

$$M n_i v_{ix} \frac{dv_{ix}}{dx} = -e n_i \frac{d\phi}{dx} - \frac{dP_i}{dx} - M n_i \gamma_i v_{ix} \qquad (2)$$

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with the ion equation state

$$P_i = KT_i n_i \qquad (3)$$

The electrons are in thermal equilibrium due to its high mobility, given their density we find

$$n_e = n_0 exp(\frac{e\phi}{KT_e}) \qquad (4)$$

finally using the Poisson's equation that relates the electron and ion density to the electric potential, we can close these equations

$$\frac{d^2\phi}{dx^2} = -\frac{e}{\epsilon_0}(n_i - n_e) \qquad (5)$$

where v_{ix} is the x component of ion velocity, n_i and n_e are the ion and electron density, respectively, M is the ion mass, ϕ is the electrostatic potential (with $E = -\nabla\phi$ as electric field), γ_i is the ion-neutral collision frequency, P_i is the ion pressure, K is the constant of Boltzmann, T_i and T_e are the ion and electron temperatures, respectively, in Kelvin, and n_0 is the ion and electron density in the bulk of plasma. We assume that the ion-neutral collision makes indirectly the ions as an isothermal fluid.

If these four equations are rewritten in some normalized dimensionless variables, we will have

$$N_i U = Ma \qquad (6)$$

$$N_e = exp(-\eta) \qquad (7)$$

$$\frac{d^2\eta}{d\xi^2} = N_i - N_e \qquad (8)$$

$$\frac{dU}{d\xi} = \frac{U}{U^2 - T}(\frac{d\eta}{d\xi} - \nu U) \qquad (9)$$

where the normalized dimensionless variables are

$$N_i = \frac{n_i}{n_0}, \qquad N_e = \frac{n_e}{n_0}, \qquad c_s = \sqrt{\frac{KT_e}{M}},$$

$$\xi = \frac{x}{\lambda_D}, \qquad U = \frac{v_{ix}}{c_s}, \quad \lambda_D = \sqrt{\frac{\epsilon_0 KT_e}{n_0 e^2}},$$

$$\eta = -\frac{e\phi}{KT_e}, \qquad \nu = \frac{\gamma_i \lambda_D}{c_s}, \qquad T = \frac{T_i}{T_e},$$

In these definitions, c_s is ion acoustic velocity, $Ma = U_0/c_s$ is the ion Mach number, λ_D is the electron Debye length, ξ is distance from the plasma-sheath boundary normalized by λ_D. ν is also a dimensionless constant frequency of collision, ranging from zero to one in laboratory's plasmas. The boundary conditions are

$$\eta(0) = 0\,, \ \acute{\eta}(0) = 0.1\,, \ U(0) = Ma\,,$$
$$N_i(0) = N_e(0) = 1\,, \qquad (10)$$

at the plasma-sheath interface.

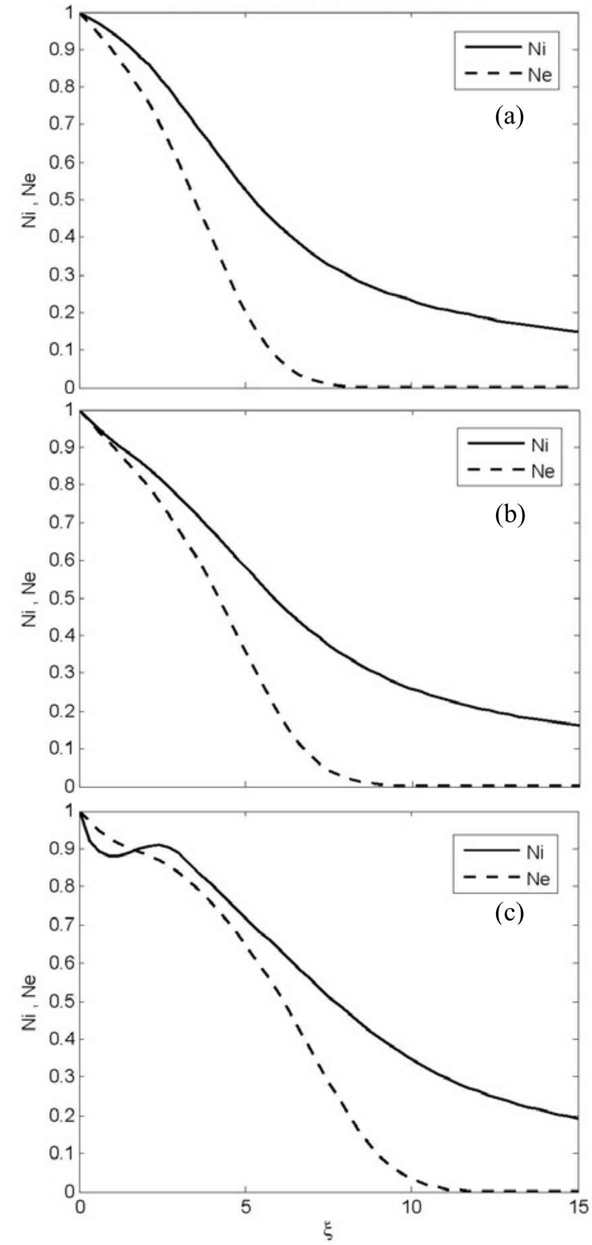

Fig. 1. The normalized ions and electrons densities versus ξ, for $Ma = 1$ and $\nu = 0.04$. However, in figure (a) $T = 0$, figure (b) $T = 0.3$, and figure (c) $T = 0.6$.

3. Computational Results and Discussion

Equations (6-9), with boundary conditions (10) are solved, and Computational results are discussed in the following.

3.1. Ion Temperature Effect on Bohm Sheath

The normalized densities of ions and electrons, as functions of normalized distance from plasma-sheath interface (sheath edge), are shown in Fig. 1. In these calculations the following constants: ion Mach number $Ma = 1$, ion-neutral collision frequency $\nu = 0.04$, and the temperature ratio $T = 0\,, 0.3\,, 0.6$ are used. According to equation (9), the more the ion temperature, the more the force on the ion toward the sheath (so,

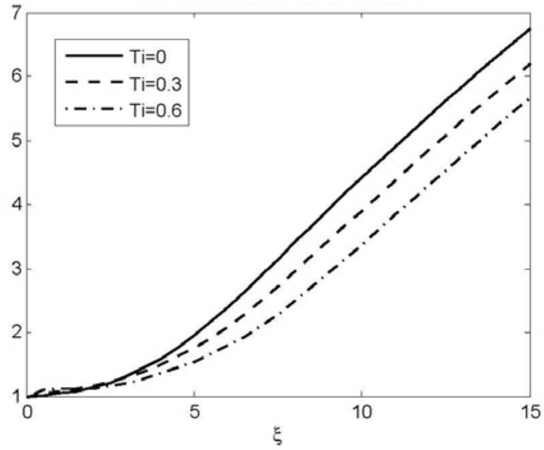

Fig. 2. The normalized ion velocity U as a function of normalized distance from boundary ξ, for $Ma = 1$, $T_e = 1$ eV, and $\nu = 0.06$.

decreasing the ion density), and for the ion temperatures greater than a minimum value, the sheath criteria is not satisfied more. In the basis of this idea, ion temperature increases the Bohm velocity criterion in agreement with the conclusion of some previous work [12]. This issue is shown apparently in the figures 1.(a) 1.(b) 1.(c) where the ion temperature is fixed at 0, 0.3 and 0.6 eV, respectively. It is shown that, by increasing the ion temperature, the sheath criterion is not satisfied. In Fig. 1.(c) up to x=2, the ion density is less than electron density. Indeed in the sheath region, if $n_i > n_e$ (or $d^2\phi/dx^2 < 0$) the sheath criteria is satisfied. Of course, by increasing the ion collision frequency, the sheath criterion is satisfied at $T_i = 0.6$ eV too. In the following of the paper, the normalized collision frequency has increased to 0.06 in order to satisfy the Bohm criteria.

3.2. Ion Temperature Effect on Ion Velocity

The normalized ion velocity is shown in Fig. 2 as a function of normalized distance from plasma-sheath interface for three ion temperatures. The initial velocity

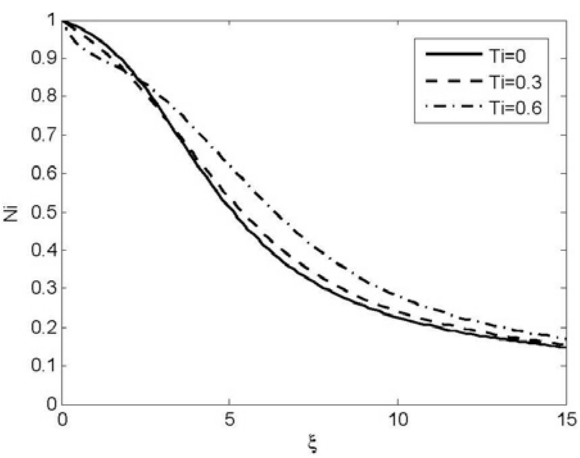

Fig. 3. The normalized ion density distribution in sheath region. The parameters are the same as in Fig. 2.

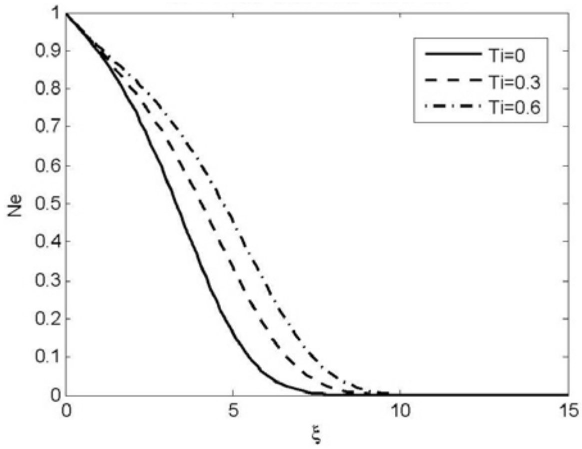

Fig. 4. The normalized electron density distribution in the sheath region. Parameters are the same as in Fig. 2.

of these three ions, at ion mach number is the same. Based on Eq. (9) at first the ion with greater temperature has a greater acceleration, and its velocity overtakes to the other velocities. But with increasing of ion velocity, the resultant force of electric field and collision on ion with greater temperature decreases and its velocity relative to the velocity of other ions decreases gradually. The Fig. 2 is divided to two parts. In the first part, the ion with higher temperature has a bit higher velocity, but in the second part it is vice versa, i.e. the ion with higher temperature have a lower velocity. This duality originates of initial velocity selection. If the initial velocity for each ion temperature is selected properly, we will find that in the all of the sheath region points, the ion velocity goes down with increasing of ion temperature. This issue is shown clearly in Fig. 2.

3.3. Ion Temperature Effect on Particle Density

In the sheath region, the ion density increases as ion temperature improves, as shown in Fig. 3. Since the ion density is inversely proportional to the ion velocity in a steady state, and as mentioned above, the high the ion temperature, the low the ion velocity, it can be concluded that the ion density must go up with rising the ion temperature. Increasing ion density leads to increase in electron density as shown in Fig. 4. The variation of both N_e and N_i with ϕ is shown in Fig. 5. The electron density goes down exponentially with increasing electric potential in the sheath, according to the Boltzmann relation. The ion density decreases too, since the ion accelerates with increasing of sheath potential, and then its velocity increases. But this figure shows that with rising ion temperature and electric potential, the ion density goes down. On the other hand, Fig. 5 explains with rising the ion temperature, the charge separation reduces, and it has a direct effect on the sheath width. Indeed reducing the charge separation means to reduce the sheath width. These conclusions are in agreement with some previous work [12].

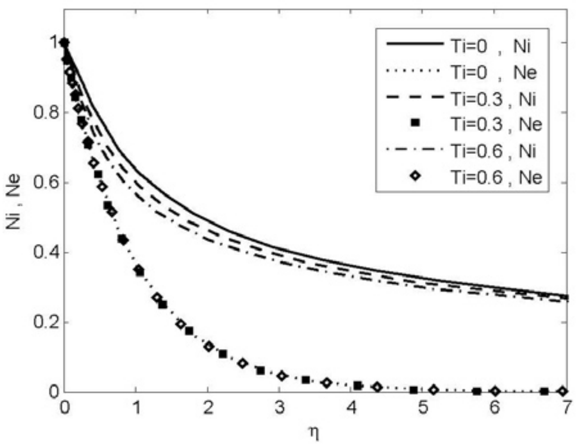

Fig. 5. The normalized electron and ion density in sheath region as a function of normalized electric potential in different ion temperatures. Parameters are the same as in Fig. 2.

3.4. Ion Temperature Effect on Sheath Thickness

The sheath potential variation is shown in Fig. 6 for various ion temperatures. It is shown that, increasing the ion temperature causes to decrease the sheath potential. It is clear that, as the sheath potential reduces, the sheath thickness must increase. Indeed, if the cathode electric potential is maintained in a constant value, the more the ion temperature, the more the thickness of sheath.

4. Summary and Conclusion

Here a general description of a simple plasma model with warm ionic species was presented in which the lighter electrons are described by Boltzmann relation, while the heavier positive ions are in the dynamical system under the fluid approximation. Based on the model, the ion and electron density were calculated and it is found that the densities vary according to the Bohm criterion and the ion temperature plays an important role in the formation of plasma sheath. As the ion temperature increases, the ion density slowly goes down, while electron density falls exponentially. It has been shown that, due to the thermal effect, the sheath width increases. This may have different applications, where different sheath thicknesses are desired for different purposes. It is found that increasing the ion (plasma) temperature, causes to decrease the kinetic energy of ions. Hence, less and less ions hit the cathode surface.

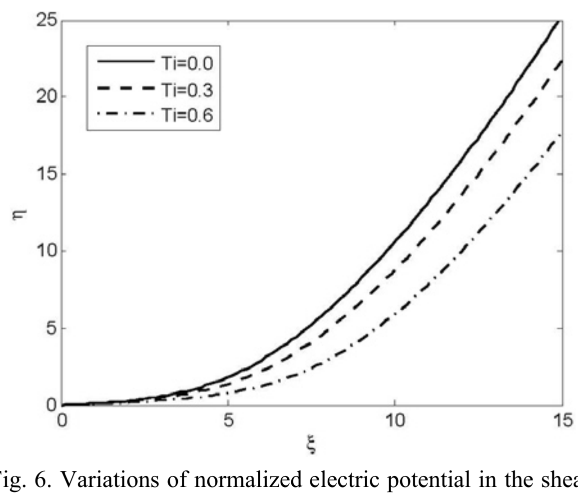

Fig. 6. Variations of normalized electric potential in the sheath as a function of normalized distance from boundary. Parameters are the same as in Fig. 2.

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