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Effects of Ion Temperature on Collisionless and Collisional RF Sheath*

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Abstract A numerical two-fluid simulation of the non-ionized radio frequency (rf) sheath model, has been carried out. This model is "global" and thus applicable to the sheath, pre-sheath and plasma regions, In the model all variables in the ion force balance equation, including the electrical force, ion pressure and neutral particle friction, are considered. The model is solved through a finite difference scheme and sheath characteristics are obtained. The effects of the ion temperature on both the collisionless and collisional sheath characteristics are discussed. Then it is concluded that 1) the model is in a good agreement with Bohm Theorem; 2) the ion temperature has significant effects on the rf sheath characteristics. The effects are far more significant on a collisional rf sheath than on a collisionless sheath.

Keywords: plasma sheath, radio-frequency, collisions in plasmas

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1 Introduction

Low temperature plasmas have now been applied extensively in the microelectronics industry. For many instances, the plasmas are generated by electron cyclotron resonance sources [1], capacitive or inductive sources [2], or helicon sources [3], and the wafers to be etched are placed on an electrode usually controlled by a separate, capacitively coupled rf bias power supply. In these systems the quality of the wafers is individually determined by the rf sheath of the electrode. Consequently to control the quality of the etched wafers it is necessary to have a full understanding of the rf sheath. However, to study the sheath theoretically, one has to consider the effects of the rf frequency ω, the ion plasma frequency $f_{\rm pi}$, neutral particle collision γ and ion temperature $T_{\rm i}$. For a low pressure plasma, an assumption of a collisionless sheath is applied and practicable based on the fact that the boundary of the collisionless sheath can be defined whereas the ion velocity equals to the Bohm velocity. Many experiments and theoretical investigations [4~20] have been performed to study the collisionless rf sheath. Accurate models have been developed to describe the rf-sheath for arbitrary frequency [19,20].

It should be pointed out that these collisionless models are applicable only for very low pressure plasmas with a collision frequency much less than the ion plasma frequency. Recently discharging in higher or even the atmospheric pressure has become more and more realizable [21,22]. Under such a pressure the collision frequency should definitely be taken into account. A great deal of work has been conducted for the collisional rf sheath [23~25], mainly focused on a discharging electrode sheath. These works were often based on a model that the current is sinusoidal for an rf sheath, a full circuit system is then solved. In comparison with ω and $f_{\rm pi}$, the collision frequency due to that the ion temperature effect is relatively ignorable. However recent work [29,30] demonstrated that the ion temperature effect was significant in the sheath. DAS et al [29] derived a Sagdeev potential and then a Bohm criterion for two-fluid plasmas. FERNANDEZ PALOP et al [30] established a three-fluid model based on the Bohm criterion. Both papers showed that the ion temperature had a significant effect on sheath characteristics, e.g., a high ion temperature lowered the ion density and narrowed the sheath width.

In the present study the main goal is to study the effect of ion temperature on collisional rf sheath. For collisionless and collisional plasma sheaths generated by an electrode powered by a separate, capacitively coupled rf bias and also considering the effect of the ion pressure, we establish a simple but practical model. Since Bohm criterion is not suitable for a collisional sheath [21,22] we handle a global region ranging from the electrode to plasma region. The "plasma region boundary" $x = d_{\rm s}$ is taken distant enough from the electrode not affecting the sheath characteristics. The velocity near the boundary is defined as an average value $u_{d_{\rm s}} =< u_{\rm x} >$. The "electrode boundary" is at $x = 0$.

The characteristics of the sheath are then obtained numerically by solving the two-fluid model between the two boundaries and the effect of the ion temperature on both the collisionless and collisional rf sheath are discussed. The basic model is described in Section 2.

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The numerical solutions and discussions are presented in Section 3. A short summary is given in Section 4.

2 Basic sheath equations

We consider a non-ionized thermal collisional or collisionless rf sheath with the continuity

$$\frac{\partial n_{\rm i}}{\partial t}+\frac{\partial(n_{\rm i}u_{\rm i})}{\partial x}=0, \tag{1}$$

and force balance

$$\frac{\partial u_{\rm i}}{\partial t}+u_{\rm i}\frac{\partial u_{\rm i}}{\partial x}=-\frac{e}{m_{\rm i}}\frac{\partial V}{\partial x}-\nabla P-\gamma u_{\rm i}, \tag{2}$$

As well as the equation of state

$$P=n_{\rm i}k_{\rm B}T_{\rm i}, \tag{3}$$

for the ion density $n_{\rm i}(x,t)$ and velocity $u_{\rm i}(x,t)$ with $m_{\rm i}$ the ion mass, $-e$ the electronic charge, $V(x,t)$ the sheath potential, P the ion pressure, $k_{\rm B}$ Boltzmann constant and $T_{\rm i}$ the ion temperature. Since the rf frequency is much less than the electron plasma frequency $\omega << \omega_{\rm pe}$, the electrons respond instantly to the field and therefore are assumed in a Boltzmann equilibrium

$$n_{\rm e}(x,t)=n_0{\rm exp}\Big[\frac{eV(x,t)}{k_{\rm B}T_{\rm e}}\Big], \tag{4}$$

where n_0 is the electron density at the plasma-sheath boundary and $T_{\rm e}$ is the electron temperature.

Together with the Poisson equation

$$\frac{\partial^2 V}{\partial x^2}=-\frac{e}{\varepsilon_0}(n_{\rm i}-n_{\rm e}), \tag{5}$$

where ε_0 is the vacuum permittivity, Eqs. (1) $\sim$ (5) make a complete set of equations for the solutions of the rf sheath.

We solve Eqs. (1) $\sim$ (5) in a region from the electrode to plasma, including the sheath, pre-sheath and the plasma. At the plasma boundary $x=d_{\rm s}$, the velocity of the ions entering the sheath is taken to be the ions' average thermal velocity in x-direction

$$u_{d_{\rm s}}=\frac{1}{4}\bar{u}=\frac{1}{4}\Big(\frac{8k_{\rm B}T_{\rm i}}{\pi m_{\rm i}}\Big)^{1/2}, \tag{5}$$

where $\bar{u}$ is the average thermal velocity and the densities of electrons and ions satisfy the quasi-neutrality condition, then the electric potential is zero. At the electrode wall $x=x_{\rm wall}=0$ a harmonic potential form is assumed

$$V(t)=V_{\rm dc}+V_{\rm rf}\cos\omega t, \tag{6}$$

where $V_{\rm rf}$ is the amplitude of the rf voltage and $V_{\rm dc}$ is the direct current (DC) part of the bias voltage. The ion density and the velocity can then be extrapolated.

The model can now be solved under the boundary conditions in steady state with parameters $T_{\rm e}$ = 1.0 eV, the plasma density $n_0=10^{12}$ cm^{-3}, ion plasma

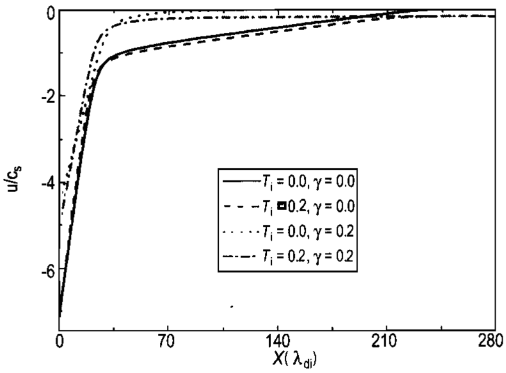

Fig.1 Time average of the ion velocity distribution in regions from the sheath to the plasma in an entire rf period for different cases with $n_0=10^{12}$ cm^{-3}, $T_{\rm e}$ = 1.0 eV and $f_{\rm rf}=13.56\times10^6$ Hz. Ion temperature and collision frequency are in eV and $f_{\rm pi}$ respectively

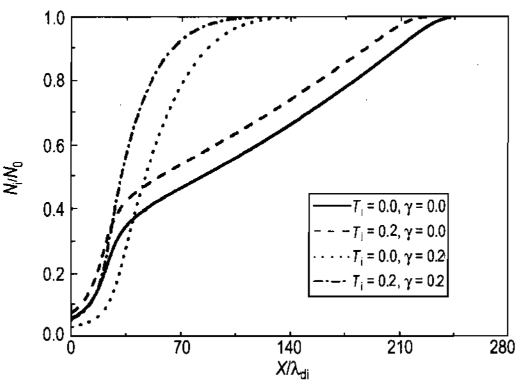

Fig.2 Time average of the ion density distribution in regions from the sheath to the plasma in an entire rf period for different cases, with the same parameters as in Fig. 1

frequency for the $f_{\rm rf}=33.24\times10^6$ Hz as well as $V_{\rm dc}=-29$ and $V_{\rm rf}=-21$ as in experiments of M. A. SOBOLEWSKI et al [12].

3 Numerical solutions and discussion

Using the above model the equations are solved by a second-order finite difference scheme in space and a first-order finite difference scheme in time. The simulation is started from preset initial conditions of a DC sheath. It can then be converged as the sheath enters a steady state. Thus the characteristics of the sheath and the pre-sheath are obtained. Some of them are discussed below.

3.1 Bohm theorem and collision

The collisionless sheath in the model is in a very good agreement with the Bohm Theorem, i.e., the collisionless sheath is conformed to the Bohm criterion. The regions from the plasma to the electrode are divided into the sheath region and the pre-sheath region distinctively. Shown in Figs. 1 $\sim$ 4, the ion velocity, ion

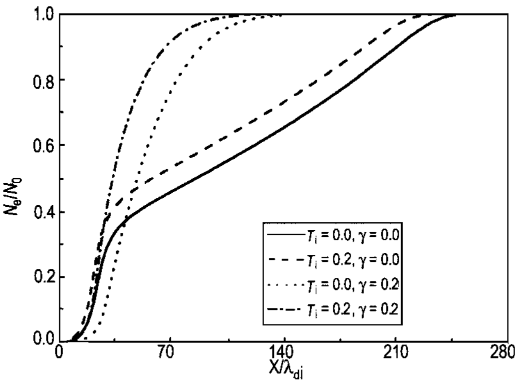

Fig.3 Time average of the electron density distribution in region from the sheath to the plasma in an entire rf period for different cases, with the same parameters as in Fig. 1

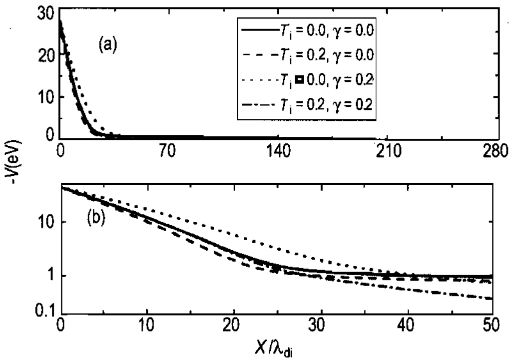

Fig.4 Time average of the magnitude of the sheath potential distribution in regions from the sheath to the plasma in an entire rf period for different cases with the same parameters as in Fig. 1. In the upper Panel (a) the potential in a full range from the plasma to the electrode is in linear scale and in Panel (b) the potential in the sheath region ($0 < L < 50\lambda_{\rm di}$) is in profit scale

density, electron density and potential distributions all have the distinguishable sheath and pre-sheath. For a collisionless sheath then , no matter how high the ion temperature is, the ion in the pre-sheath is always accelerated to the level of the Bohm velocity ($C_{\rm s}$) when it arrives at the sheath region. The pre-sheath region is much wider than the sheath region. Because the ion density is inversely proportional to the ion velocity, from Eq. (1) in a steady state, the ion density in the pre-sheath region decreases lineally. Also since the electrons respond to the ion's motion instantly the electron density and the ion density in the pre-sheath are almost equal to each other so that the potential in the pre-sheath is very low ($V_{\rm pre-sheag} \leq 1.0$ eV). In a collisional sheath, however, the Bohm criterion is not valid, seen clearly in the figures. Since the collision effect cannot be neglected in this case, the ion velocity is reduced by the collision, although there is still an interface distinguishing the sheath and the pre-sheath. The ion in the pre-sheath then cannot be accelerated linearly. Thus the velocity in the collisional pre-sheath is less than that in the collisionless one. Moreover, the colli-

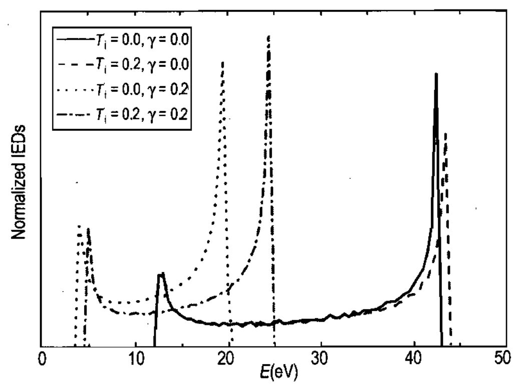

Fig.5 The ion kinetic energy distribution in an entire rf period for different cases with the same parameters as in Fig. 1

sional ion velocity at the sheath boundary (the interface) is less than the Bohm velocity as shown in Fig. 1. The ion density in the pre-sheath region, as shown in Fig. 5, decreases nonlinearly and is larger than that in the collisionless pre-sheath region. All these results are in agreements with the fact that the Bohm theorem is for a collisionless plasma sheath. The potential in the collisional pre-sheath is found very low too.

3.2 Effect of ion temperature

The ion temperature affects the rf sheath characteristics in terms of decreasing the sheath thickness, increasing the ion and electron density and shifting the ion energy distribution (IED) towards the high energy regime. The effects are found much more significant on the collisional sheath than on the collisionless one. In the sheath region, the ion density increases due to the finite ion temperature, as shown in Fig. 2. This does not coincide with the conclusion of some previous work [29] due to the the Bohm criterion applied there with a uniform ion entering velocity $u_{\rm i}\big|_{\rm sheath\ boundary} = u_0$ and thus a uniform ion entering flux($n_{\rm i}u_{\rm i}$). In the present "global" model the Bohm criterion is not applied to the collisional sheath. The ion flux in the global simulation depends on the ion temperature. The flux of ions with a finite temperature is shown larger than that with a zero temperature. Since the ion flux is conserved in a sheath without ionization the ion density with a finite temperature should then to be larger than that with a zero temperature. The increase in ion density leads to an increase in electron density as shown in Fig. 3. It then results in an increase of the sheath potential due to the Boltzmann electron approximation. As seen clearly in Fig. 4, the magnitude of the sheath potential ($-V$) at its boundary (the interface) is reduced due to the finite ion temperature. Since the temporal average of the electrode bias potential is fixed, as shown in Fig. 4, the thickness of the sheath decreases. Another significant effect of the ion temperature is on IED. It is easily understood that the ions with a finite temperature have a higher energy than that with a zero temperature as

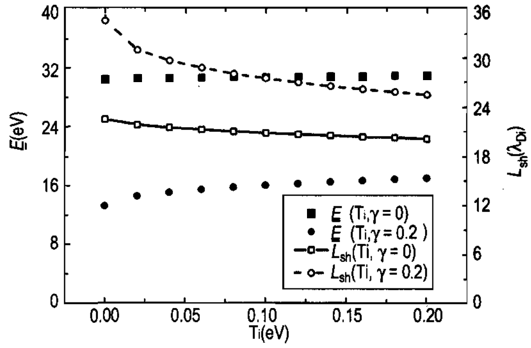

Fig.6 The ion impact energy and the sheath length as functions of the ion temperature in an entire rf period for different cases with the same parameters as in Fig. 1

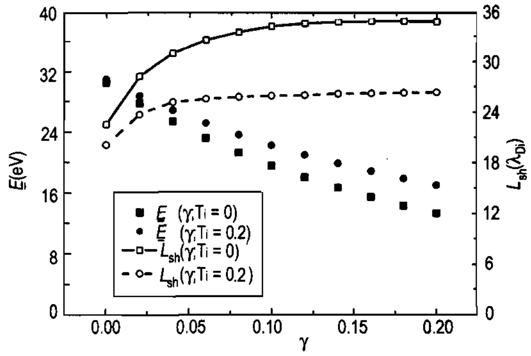

Fig.7 The ion impact energy and the sheath length as functions of the collision frequency in an entire rf period for different cases with the same parameters as in Fig.1

they arrive at the electrode, as shown in Fig. 5. The IED with a higher ion temperature then shifts towards the higher energy regime.

In comparison with the collisionless rf sheath case, the effect of ion temperature on a collisional sheath is much more significant. To a collisionless sheath, the ions with different temperatures are accelerated linearly in the pre-sheath region to almost the same velocity, the Bohm velocity, at the sheath boundary. However the ions in the collisional case are not accelerated uniformly due to the ion-neutral collision. The velocity of ions with a finite temperature at the interface is greater than that of a zero temperature. Then ions with a finite temperature, entering the sheath region with a velocity higher than that of the zero temperature case, have much higher energy than the latter, as shown in Fig. 1. Thus the effect of ion temperature on ion velocity in a collisional sheath is greater than that in a collisionless sheath. Consequently the other effects of ion temperature on the characteristics are significant correspondingly. It is shown that both the ion and electron densities are much higher, shown in Figs. 2 and 3, and the sheath is much thinner, shown in Fig. 4. The IED shifts towards the high energy regime, shown in Fig. 5. These effects are more significant than those in a collisionless sheath.

In order to study the effect of both ion temperature and neutral collisionality in detail, the average ion impact energy $\underline{E}$ and the sheath length L_{sh} as functions of ion temperature and collisionality are calculated. The impact energy $\underline{E}$ represents a temporally averaged energy for ions arriving at the electrode. The sheath length is defined as the distance from the electrode to the sheath-presheath interface of the ion density distribution. It is shown in Fig. 6 that in the collisionless case the ion impact energy is almost insensitive to the ion temperature, though the sheath length decreases as the ion temperature increases. In the collisional case, however, the ion impact energy increases with the ion temperature while the sheath length decreases much dramatically than in the collisionless case.

3.3 Effect of collision on ion impact energy and sheath length

In this sub-section, the effects of collision on the ion impact energy $\underline{E}$ and the sheath length are discussed. The effect of collision on the impact energy has been discussed previously [24,25]. But the effect of collision on the sheath length has not been studied. Fig. 7 demonstrates the ion impact energy $\underline{E}$ and the sheath length Lsh as functions of the collision frequency under different ion temperatures. It is found that the ion impact energy decreases and the sheath length increases as the collision frequency increases regardless whether the temperature is zero or finite, an effect similar to that of the ion temperature as explained above.

4 Summary

A "global" fluid model of sheathes in both collisional and collisionless cases, is developed to study the spatio-temporal characteristics of the sheath. The model is valid "globally" for the plasma, pre-sheath and sheath for arbitrary rf frequencies. The effects of ion temperature on the characteristics of both the pre-sheath and the sheath are discussed. The conclusions are 1) the characteristics in the case of the collisionless sheath agrees well with the Bohm criterion; 2) ion temperature can significantly affect the rf sheath characteristics and the effect is more significant on the collisional sheath rather than on the collisionless sheath.

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