Study of stochastic heating in single frequency capacitive discharges

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Abstract

Capacitive discharges have two types of electron heating mechanisms, one is ohmic heating due to electron-neutral collisions and the other is stochastic heating at the edge of bulk plasma due to momentum transfer from the high voltage moving sheath. Stochastic heating in single and dual frequency capacitive discharges is very important in low pressure industrial plasmas. In this work we investigate the stochastic heating and its dependence on various parameters in single frequency capacitive discharges. Particle-in-cell(PIC) simulation techniques are used to investigate the stochastic electron heating. The self-consistent mobile- ion simulation results for stochastic heating are in good agreement with the analytical hard wall model and Kaganovich model for a wide range of **H**. Here we are interested in the lower and upper critical limits of **H** outside which it disagrees with the results of the analytical model. The second key issue of investigation is the evolution of stochastic heating for a broad range of applied radio frequency.

Introduction

Low pressure capacitive discharges are very important in many applications like semiconductor industry, flat panel display, thin film etching and deposition, because of low cost and robust uniformity over large area. In such type of discharges ohmic heating and stochastic heating are the principle mechanism of electron heating. Ohmic heating occur in the bulk plasma due to electron-neutral collisions . The sheath voltage is generally much higher than electron temperature T_e so potential of sheath is generally impenetrable for electrons moving from bulk to sheath. Electrons moving from the bulk side interact with highly oscillating electron sheath edge and momentum transfer occur which generates stochastic heating at sheath edge. Electrons can escape to electrode only when the sheath is fully collapsed. At low pressure, stochastic heating is the dominating process. Stochastic heating in low pressure capacitively discharges has been also investigated experimentally[1] and also by various models[2, 4, 5, 6]. Models based on 'hard wall' approximation were proposed by Godyak and further developed by Lieberman, where the electrons move towards the sheath and interact elastically with the sheath edge and bounce-back. Due to the sheath expension and contraction the electrons are either heated or cooled[7].

Because of significant phase randomization in the bulk plasma, there is net energy gain by electrons. Lieberman[2] derived an analytical expression for stochastic heating in collisionless rf sheath driven by sinusoidal current using the hard wall model, but neglected the bulk motion. Later Kaganovich[6] used a two step ion density model to study the effects of induced electric fields on heating by a modified hard wall model that considers the bulk motion. Surendra and Turner[5, 4] introduced the idea that the compression and decompression of the electron cloud near the sheath vicinity is responsible for the stochastic heating.

In this paper we have investigated stochastic heating in a single frequency capacitive discharge using Particle in cell simulation technique. Simulations have been done for a wide range of current amplitude (i.e **H**) at a single frequency ($\omega_{rf} = 2\pi \times 27.12MHz$) and for a range of frequencies at fix current current amplitude (i.e **H**).

PIC Simulation

We have used the S.U.Sh.I particle-in-cell(PIC)[3] code for the simulation of rf capacitive discharges. This self consistent PIC code can be used at low pressure/pressure = 0 to determine the dependence of stochastic heating on various discharge parameters.We have used Argon(Ar) gas in device of size $\sim$ 0.04 - 0.12 m and the driving frequency is $\omega_{rf} = 2\pi \times 27.12MHz$. The electron and ion temperature is $k_B T_e \sim 2.5$ eV and $k_B T_i \sim 0.03$ eV respectively. Pressure is assumed zero($P = 0$) for all set of simulations. The cell width Δx was chosen to resolve the electron debye length λ_D and time step Δt was chosen to resolve the electron plasma frequency ω_{pe}. The average number of particles per cell $\equiv N_p/N_c \geq 200$, where N_p and N_c are the number of particles and spatial cells, respectively.

In our model we have assumed the existance of plasma without rf current.Due to the lower mass and high mobility of electrons, a sheath will be created at electrode. We have used 'Nachmann-Than' criterion to find sheath edge. According to this criterion, the sheath edge is located at the point where the change in electron density is maximum for a small change in potential. The sheath edge was detected by this criterion and calculated average heating for this case ($J_{rf} = 0$) and take this as a reference point. And then we have passed different values of rf current and calculate the stochastic heating.

So the stochastic heating in our simulation upto the sheath edge is given by following formula:

$$\bar{S}_{simulation} = \int_0^{X_{SheathEdge}} \langle J.E \rangle \, dx \tag{1}$$

In above equation '0' is the point on electrode. Density has been kept constant throughout our simulation so as we increase current, the sheath width increases.

Analytic calculation

Lieberman[2] derived an analytical solution for a collisionless rf sheath driven by sinusoidal current $J(t) = J_{rf} \sin \omega t$. He calculated the stochastic heating $\bar{S}_{stocL}$ by using the hard wall model, but overestimated the actual heating by neglecting the bulk motion i.e

$$\bar{S}_{stocL} = \frac{3\pi}{32} H m_e \bar{v_e} n_{sm} u_b^2 \quad (2)$$

Here, $\bar{v_e} = [8k_B T_e/\pi m_e]^{1/2}$ is the mean electron thermal velocity, n_{sm} is the ion sheath density at the ion sheath-plasma boundary and $u_b = J_{rf}/(e n_{sm})$ is the amplitude of the bulk electron oscillation velocity $v_b(t) = u_b \sin \omega t$. We can define **H** as

$$H = \frac{J_{rf}^2}{\pi k_B \varepsilon_0 T_e \omega^2 n_{sm}} \quad (3)$$

so increasing J_{rf} means increasing **H**.

In brief we can write that the ion density at the wall is given by

$$n_w = n_{sh}(\pi) = \frac{n_{sm}}{1 + 3\pi H/4} \quad (4)$$

We can get the quadratic equation in **H** by substituting equation(3) in equation(2) and solution of this quadratic equation is

$$H = -\frac{2}{3\pi} + \frac{2}{3\pi}\sqrt{1 + \frac{3J_{rf}^2}{k_B \varepsilon_0 T_e \omega^2 n_w}} \quad (5)$$

Since we know the n_w from our PIC data so we can calculate **H** by equation(4) and then calculate n_{sm} by equation(3) and finally $\bar{S}_{stochastic}$ by equation(1). Kaganovich[6] used a two step ion density model to study the effects of induced electric fields on heating. He calculated $\bar{S}_{stochastic}$ by a modified hard wall model that consider the bulk motion so that electrons can see an effective sheath velocity of $v_{sh} - u_b$ and hence a velocity kick of $2(v_{sh} - u_b)$ on interaction with the moving electron sheath edge. So

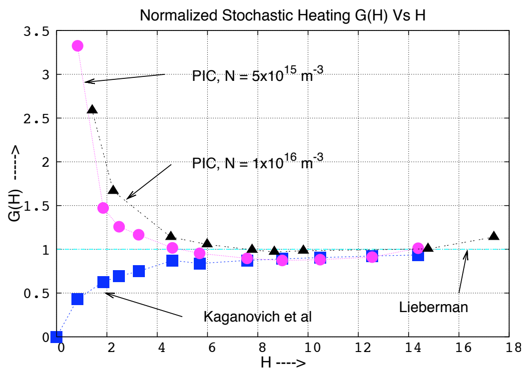

Figure 1: Normalized stochastic heating G(H) for two different set of densities.

$$\bar{S}_{stochasticK} = \left[\frac{H}{H + 1.1}\right] \bar{S}_{stochasticL} \quad (6)$$

Results and discussion

We have studied the normalized stochastic heating $G(H) = \bar{S}_{stoc}/\bar{S}_{stocL}$ for a wide range of $H \sim 0.833 - 15$ for two different set of densities i.e $5\times10^{15}m^{-3}$ and $1\times10^{16}m^{-3}$. Our results fairly agree with hard wall and Kaganovich [6] results in the range of **H** from 4.5 to 15. Below $H = 4$ our results deviate from both models. It shows that hard wall model underestimates the stochastic heating below $H = 4$.(Fig.1). In our simulation the discharge is not stable after $H = 15$ for density $5\times10^{15}m^{-3}$, and $H = 18$ for density $1\times10^{16}m^{-3}$.

Kawamura[8] el al also studied stochastic heating in the range of $H = 1.7 - 5.7$ with PDP1 code and their results fairly agree with Kaganovich model in this range of **H**.

The second important point we have investigated is study of stochastic heating for broad range of applied rf frequency at constant value of $H = 7$ at density $5\times10^{15}m^{-3}$. As we can see in (Fig.2) that normalized stochastic heating $\bar{S}_{stochastic}/\bar{S}_L$ is almost constant in the range of $\omega rf/\omega_{pe} \sim 0.0023 - 0.009$.

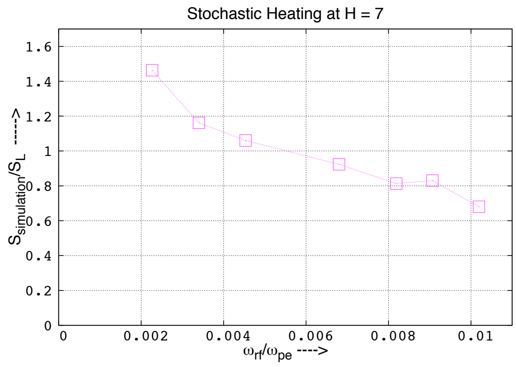

Figure 2: Normalized stochastic heating Vs normalized $\omega_{rf}(n = 5\times10^{15}m^{-3})$.

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References

[1] V. A. Godyak and R. B. Piejak, Phys. Rev. Lett. **65**, 996 (1990).

[2] Michael A. Lieberman, IEEE Transactions on Plasma Science **16**, 6 (1988).

[3] G. Gozadinos, M.M. Turner and D. Vender, Phys. Rev. Lett. **87**, 135004 (2001).

[4] M. M. Turner, Phys. Rev. Lett. **75**, 1312 (1995).

[5] M. Surendra and D. B. Graves, IEEE Trans. Plasma Sci. **19**, 144 (1991).

[6] I. D. Kaganovich, Phys. Rev. Lett. **89**, 265006 (2002).

[7] E. Fermi, **75**, 1169 (1949)

[8] E. Kawamura,M.A. Lieberman and A.J. Lichtenberg, Phys. Plasmas **13**, 053506 (2006).