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Properties of low-pressure electronegative plasmas contaminated with dust particles

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The model for low-pressure dust-contaminated plasmas is presented. Using the model the spatial profiles of the electron, positive and negative ion densities, the electron temperature, and the dust charge distribution are obtained for different dust densities and sizes, input powers, and neutral gas pressures.

A one-dimensional (1D) parallel-plate discharge geometry is considered. We assume that the discharge is bounded at $x = \pm L/2$ by metal (or dielectric) surfaces and symmetrical with respect to midplane $x=0$. The discharge is in a quasistationary state, and the electric field sustaining the plasma is uniform in x - direction. Basing on data from typical silane-based discharges with the highest number densities of singly charged SiH_3 ions, it is assumed that the electrons, SiH_3^+ positive ions, SiH_3^- negative ions, and the dusty particles are the main species in the silane plasma with nano-sized dusty particles. The density distribution of the nanoparticles is chosen to fit that typically observed in the dusty particle growth experiments [1]. Since the dusty particles have much larger mass than the other charged and neutral particles, they are treated as immobile point masses. For all the charged particles the energy distribution functions are assumed to be Maxwellian. The ions and neutrals kept to be at the room temperature (300 K).

We assume the plasma is in a quasineutral state, and positive and negative currents in the plasma balance each other

$$n_i - n_e - n_- + \Sigma_k n_d^k Z_d^k = 0\,, \qquad \Gamma_i = \Gamma_e + \Gamma_- \tag{1}$$

where n_α and Γ_α are density and flux of the species $\alpha = e, i$ and -, corresponding to electrons, positive and negative ions, respectively, n_d^k is the density of the dusty particles having the charge $Z_d^k = ke$ (with e the elementary charge and k an integer). The total dust density n_d $(= \Sigma_k n_d^k)$ is assumed to be fixed. The particle balance equation for the electrons/ions is

$$\partial_x \Gamma_\alpha = \beta_\alpha , \quad (2)$$

where $\beta_e = \nu^i n_e - \nu_{att} n_e - \sum_k \nu_{ed}^k n_d^k$, $\beta_i = \nu^i n_e - K_{rec} n_i n_- - \sum_k \nu_{id}^k n_d^k$, and $\beta_- = \nu_{att} n_e - K_{rec} n_i n_- - \sum_k \nu_{-d}^k n_d^k$, ν^i and ν_{att} are ionization and attachment rates, respectively, K_{rec} is the positive-negative ion recombination coefficient, and $\nu_{\alpha d}^k$ is the frequency with which species α attach to a powder particle of charge Z_d^k. The rates in the orbit motion limited (OML) probe theory approximation are: $\nu_{ed,id}^k = n_{e,i} \pi a_d^2 u_{e,i} \exp[-q_{e,i} Z_d^k / a_d \varepsilon_{e,i}]$ for $q_{e,i} Z_d^k \geq 0$ and $\nu_{ed,id}^k = n_{e,i} \pi a_d^2 u_{e,i} [1 - q_{e,i} Z_d^k / a_d \varepsilon_{e,i}]$ at $q_{e,i} Z_d^k < 0$, where $u_e = (8T_e / \pi m_e)^{1/2}$, $\varepsilon_e = T_e$, and $q_{e,i} = \mp e$ is the electron and ion charge, respectively. $\varepsilon_i = m_i u_i^2 / 2$, $u_i = (\upsilon_i^2 + 8T_i / \pi m_i)^{1/2}$ with $\upsilon_i = \Gamma_i / n_i$, a_d is the dusty particle radius.

The recursive relation for the charge distribution function F_k is [2]: $F_{k+1} = F_k \nu_{id}^k / \nu_{ed}^{k+1}$ with $\Sigma_k F_k = 1$. Thus, the density n_d^k of dusty particles having charge Z_d^k is $F_k n_d$. The power balance in the electronegative plasma is given by [3]:

$$\partial_x q_e \approx -n_e J_e + S_{ext} , \quad (3)$$

where q_e is the heat flux density [3], and J_e is the collision integral of the electrons, S_{ext} is the Joule heating term. At the numerical study it is assumed that rf power absorption P_{in} per unit area ($P_{in} = \int_{-L/2}^{L/2} S_{ext} dx$) is fixed.

Using the model the influence of the dusty particles and the external discharge parameters (neutral gas pressure p_0 and input power P_{in}) on the electron/ion densities, electron temperature, as well as the dusty particle charge distribution was investigated. Dependences of n_i, n_- , $|n_d < Z_d >|$ (where $< Z_d >$ is average dust charge) and n_e at $x=0$ on total nano-particle density n_d are presented in Fig. 1(a). It is assumed here that the density n_d is uniform for $x \leq 1$ cm and linearly decreases to zero at x=1. 5 cm. n_i profiles for different dust densities are shown in Fig. 1(b). One can see that an increase of n_d is accompanied by a drop of electron density and by increase of the ion density. The variations of the charged particle densities can be attributed to the effect of the nanoparticles on the electron temperature and on the diffusion of positive ions. The electron temperature grows with n_d : T_{eff} = 1.49, 1.62, and 1.72 eV for the dust densities $10^8, 5\times10^8$, and 10^9 cm^{-3}, respectively.

The temperature grows to sustain ionization in the discharge at increase of the electron loss (on dust particles) with n_d. As expected, the decrease of electron density with increase of dust density is accompanied by a decrease of the average negative charge on the dust grains [see Fig.1(c)].

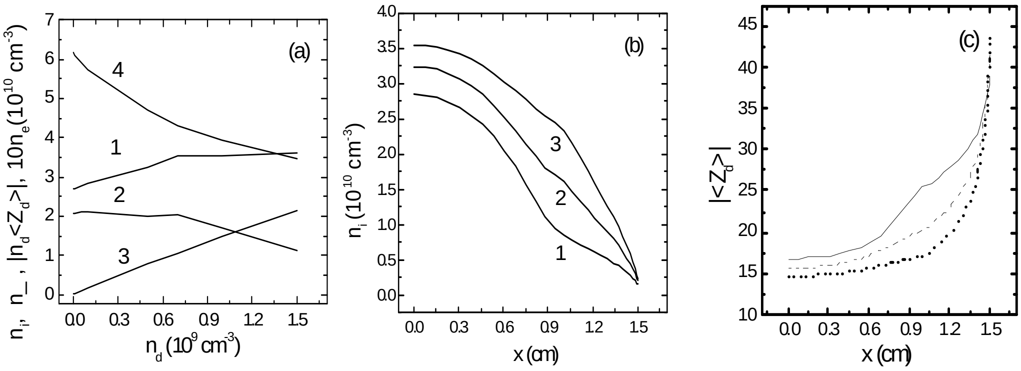

Fig. 1 Positive (1) and negative (2) ion densities, | $n_d Z_d$ | (3) and $10n_e$ (4) at x=0 in a 100 mTorr discharge sustained plasma slab 3 cm in thickness at a nanoparticle radius a_d =10 nm and an input power P_{in}=0.12 W/cm^2 in dependence of dust particle density (a). Profiles of positive ion density (b) and average dust charge(c) at the same conditions as in Fig.1 (a). The curves 1, 2, and 3 for n_i in Fig. 1(b), and solid, dashed, and dotted lines in Fig. 1(c) for | < Z_d > | correspond to n_d = 10^8 cm^{-3}, 5×10^8 cm^{-3}, and 10^9 cm^{-3}, respectively.

Particle size variation also significantly affects the plasma parameters. In Fig. 2 the density profiles of the electrons (a) and ions (b) are shown for different dust radii: 5, 7, and 10 nm.

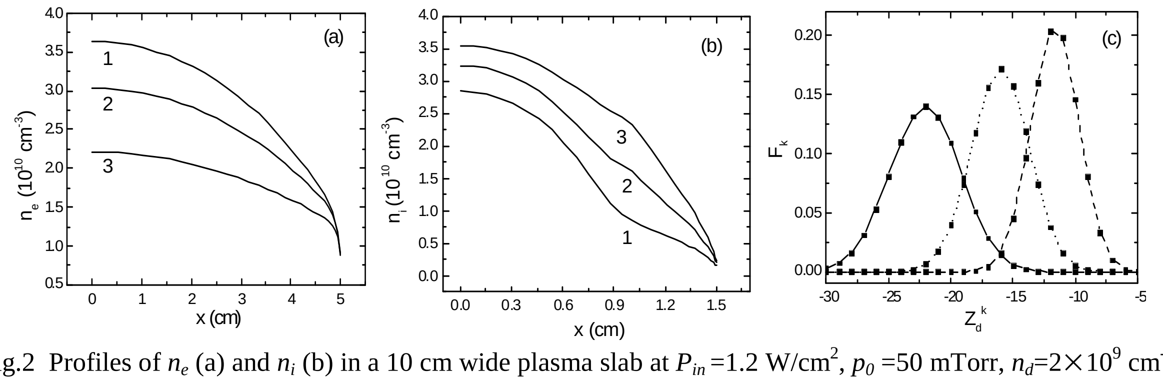

Fig.2 Profiles of n_e (a) and n_i (b) in a 10 cm wide plasma slab at P_{in} =1.2 W/cm^2, p_0 =50 mTorr, n_d=2$\times$10^9 cm^{-3} for different nanoparticle radii: (1) 5 nm, (2) 7 nm, and (3) 10 nm. The dashed, dotted and solid lines in Fig.2(c) for F_k (at x=0.52 cm) correspond to a_d = 5, 7, and 10 nm, respectively.

From Figs. 2(a) and 2(b), one can see that the electron density decreases as the powder size increases, while the positive ion density increases slightly and its profile becomes flatter in the central region of the plasma. Due to increase of electron loss on dusty particle, the electron temperature grows with a_d : T_e is 1.53, 1.64, and 1.83 eV for powder radii of 5, 7, and 10 nm respectively. An increase of the electron temperature also leads to increase of the collision integral J_e in (3), and for constant P_{in} it has to be accompanied by a decrease of the electron density. As the grain surface area increases, the average dust charge increases [Fig.

2(c)]. This then leads to increase of n_i at the shoulders of its profile. The ion density increases to provide the plasma quasineutrality (1). For the plasma parameters considered, the negative ion density is practically independent on the powder size.

Discharge properties also strongly depend on input power and neutral gas pressure. An increase of power is accompanied by a rise of the positive and negative ion densities, the electron density, and the charge accumulated on the dusty particles. For L = 10 cm, n_d = 2×10^9 cm^{-3}, a_d = 10 nm and p_0 = 100 mTorr the electron temperature at the discharge midplane $x=0$ is 1.83, 1.63 and 1.6 eV for P_{in} = 0.3, 2.4 and 4.8 W/cm^2, respectively. Enhancement of T_e with power drop is in our opinion due to additional electron loss to the nano-particles. As in a dust-free plasma the electron temperature decreases with pressure (e.g., T_e at $x=0$ is 1.57, 1.69 and 1.83 eV for pressures of 200, 100 and 50 mTorr, respectively. Here P_{in} =1.2 W/cm^2, L = 10 cm, n_d = 2×10^9 cm^{-3}, and a_d = 10 nm).

Results of this study show that the properties of silane plasmas with dusty particles can be controlled by varying the dust density and size, neutral gas pressure, and input power. In particular, the electron temperature in the silane plasma can be raised by decreasing p_0 and P_{in}, as well as increasing the dust size and density. The SiH_3^- anion density (here assumed to be the powder precursor) can be lowering by increasing the dust density and decreasing input power.

Control of the SiH_3^- density and electron temperature is important for managing the quality of silicon nano-structured films at PCVD technologies. In particular, by managing the density of SiH_3^- powder precursors in silane plasmas [1], one can enhance/suppress the initial protoparticle nucleation process leading to nano-particle growth in a silane discharge, and as a result control the properties of PECVD-fabricated silicon nano-structured films. From Figs. 1 (b) and 2 (b, it is seen that the spatial uniformity of the ion density can also be effectively controlled by varying the density and size of the dust particles.

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