IC/96/79

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A KINETIC MODEL FOR LOW PRESSURE GLOW DISCHARGES IN THE PRESENCE OF DUST PARTICLES[1]

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ABSTRACT

A kinetic model for electrons in dusty plasmas is developed. The Boltzmann and the dust charging balance equations are solved self-consistently. The dependence of the dust particle surface potential on plasma parameters and the effects of particulate contamination on electron energy distribution are investigated for direct-current argon glow discharges. It is shown that the dust particle surface potential obtained from this model is higher than that obtained for a Maxwellian electron distribution, and that the higher energy portion of the electron distribution is reduced in the presence of dust particles. Electron-dust collection and electron-atom inelastic collision are the main electron energy loss processes, and the electron energy loss due to electron-dust elastic collision is negligibly small for 10^{-16}V cm^2 $< E/N <$ 10^{-15} V cm^2 under the discharge conditions considered in this work, where E is the externally applied electric field and N is the argon atom density.

MIRAMARE – TRIESTE
May 1996

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1 Introduction

The successful application of direct-current, radio-frequency and microwave discharges in such important fields as plasma chemistry, thin-film deposition, plasma etching, laser excitation, etc., has caused a growing interest in the physics of these types of discharges. The electron energy distribution function, excitation and ionization rates, and transport parameters have been studied intensively because of their importance in understanding the basic physical properties of these discharges. However, glow discharges are usually analyzed as being pristine plasma, although the relevant devices such as plasma processing reactors, lasers and ion accelerators are routinely contaminated with dusty particles. These particles, with size varying from 10s of nm to 10s of μm, have been observed by many authors [1-6]. They result from sputtering of electrode and wall surfaces, gas phase nucleation, and polymerization. All of these observations further confirm that the particles are negatively charged. McCaughey and Kushner [7,8] developed a model of hybrid simulation using both Monte Carlo (MC) and molecular dynamics (MD) methods to study the effect of such particulate contamination on the electron energy distribution, and transport coefficients. They found that particulate contamination can shift the electron energy distribution to lower energies, thereby reducing electron impact rate coefficients, particularly ionization.

Here, we develop a kinetic model of dusty plasmas by solving the Boltzmann equation including the interaction between electron with dusty particle, and the dust charging balance equation self-consistently. It is a fast and efficient model which allows one to study dusty plasmas over wide parameter ranges. The dust potential as a function of plasma parameters, and the dominant effect of the particulate contamination in dusty argon plasma on the electron kinetic properties, is studied with this model.

2 Description of the model

2.1 Dust shielding potential and charging balance equation

We consider spherical dust particles, all of the same size, embedded in a discharge plasma. A Debye-Huckel potential (using a linearized Debye length) is taken as the potential profile in the shielding volume around the particle. The Debye-Huckel potential is given by

$$\phi(r) = \phi_s \frac{a}{r} \exp[-(r-a)/\lambda_L], \tag{1}$$

with the linearized Debye length [9]

$$\frac{1}{\lambda_L} = \sqrt{\frac{e^2 n}{\epsilon_0}\left(\frac{1}{kT_e} + \frac{1}{2E_0}\right)}, \tag{2}$$

where ϕ_s is the potential at the surface of the particle, a is the radius of the dust particle, n is the bulk plasma density, and E_0 is an average ion energy. The semianalytic theory of Daugherty et al. [9] is well approximated by a Debye-Huckel potential using a linearized Debye length except at large dust radius.

The electron current on a dust particle can be described by [10]

$$I_e = \pi a^2 n_e \int_{-e\phi_s}^{\infty} \left(1 + \frac{e\phi_s}{u}\right)\sqrt{\frac{2u}{m_e}} f(u)\sqrt{u}du, \tag{3}$$

where n_e is the bulk electron density, u is the electron kinetic energy, and $f(u)$ is the electron energy distribution. The ion current on a dust particle, the so-called orbital motion limited current [11], is

$$I_i = \pi a^2 n_i \sqrt{\frac{2E_0}{m_i}}\left(1 - \frac{e\phi_s}{E_0}\right), \tag{4}$$

where n_i is the bulk ion density. The potential ϕ_s on the surface of the dust particle is now determined by requiring a balance between the electron and ion surface currents. The particle potential can be obtained by solving

$$1 = \frac{n_e}{n_i}\sqrt{\frac{m_i}{2E_0}} \frac{1}{(1 - e\phi_s/E_0)} \int_{-e\phi_s}^{\infty} \left(1 + \frac{e\phi_s}{u}\right)\sqrt{\frac{2u}{m_e}} f(u)\sqrt{u}du, \tag{5}$$

where the ratio n_e/n_i is related to ϕ_s through

$$\frac{n_e}{n_i} = 1 + \frac{n_d}{n_i}\phi_s \frac{a}{e} 4\pi\epsilon_0, \tag{6}$$

because $n_e - n_d Q/e = n_i$ and $Q/4\pi\epsilon_0 a = \phi_s$, where n_d is the density of dust particles, and Q is the charge of a dust particle.

2.2 Electron kinetic equations

The situation to be considered here is that of a stationary gas discharge contaminated by dusty particles. The plasma is maintained by a uniform direct-current electric field. We assume that:

(i) The anisotropy of the electron energy distribution remains low so that the distribution function can be well represented by a two-term expansion in spherical harmonics.

(ii)The electron fluxes in configuration and velocity spaces resulting from the diffusion gradients and the space-charge field are small, and can be neglected.

(iii)Superelastic collisions and excitation of electron-atom from low-lying to higher-lying excited states are neglected.

In the framework of the preceding assumptions, standard procedures yield the following equation obeyed by the isotropic part of the electron distribution f

$$\frac{2eE^2}{3m_e}\frac{d}{du}[\frac{u^{3/2}}{\nu(u)}\frac{df(u)}{du}] = S_{ea}(f) + S_{ed}(f). \tag{7}$$

The term on the left–hand side of Eq.(7) describe heating by the electric field. The right–hand side contains both the electron-atom and the electron-dust collisions. E is the externally applied electric field, and ν is the total collision frequency. $u = m_e v^2/2e$ is the electron kinetic energy.

The electron-atom collision term has several ingredients. One begins with

$$S_{ea}^e(f) = -\frac{d}{du}[\frac{2m_e}{m_i}u^{3/2}\nu_{ea}^e(u)f(u)], \tag{8}$$

the contribution from elastic collision; ν_{ea}^e is the electron-atom elastic collision frequency. The inelastic processes can be decomposed into two main parts; the collision-induced atomic excitations are represented by

$$S_{ea}^{ex}(f) = \sum_k[\nu_{ea}^k(u)f(u)u^{1/2} - \nu_{ea}^k(u+V_k)f(u+V_k)(u+V_k)^{1/2}], \tag{9}$$

where ν_{ea}^k is the collision frequency of the kth inelastic process with a threshold energy V_k. An ionizing collision results in an extra electron. Assuming that the available energy is equal (the orginal and the newly generated), the collision ionization term is written as [12]

$$S_{ea}^i(f) = \nu_{ea}^i(u)f(u)u^{1/2} - 4\nu_{ea}^i(2u+V_i)f(2u+V_i)(2u+V_i)^{1/2}, \tag{10}$$

where only one main ionization process with the frequency ν_{ea}^i and the threshold energy $V_i = 15.76$ eV is considered.

The electron-dust interaction includes the scattering of the electrons from the Coulomb-like potential around the dust, and the electron loss caused by absorption into the dust particle. The entire electron-dust collision term is modeled by

$$S_{ed}(f) = -\frac{d}{du}[\frac{2m_e}{m_d}u^{3/2}\nu_{ed}^e(u)f(u)] + \nu_{ed}^c(u)f(u)u^{1/2}, \tag{11}$$

where ν_{ed}^e and ν_{ed}^c are respectively the momentum transfer, and the electron absorption frequency of the electron-dust system. The normalization for the distribution function is

$$\int_0^\infty f(u)u^{1/2}du = 1. \tag{12}$$

The electron power balance equation is obtained by multiplying both sides of Eq.(7) by the electron energy u and then integrating over the whole energy range as Ferreira and Loureiro did [13]. This yields

$$\frac{1}{2}\frac{eE^2}{m_e\bar{\nu}} = \frac{2m_e}{m_i} < u\nu_{ea}^e > + \sum_k V_k\bar{\nu}_{ea}^k + \frac{2m_e}{m_d} < u\nu_{ed}^e > + < u\nu_{ed}^c >, \tag{13}$$

where

$$\frac{1}{\bar{\nu}} = -\frac{2}{3}\int_0^\infty \frac{1}{\nu}u^{3/2}\frac{df}{du}du, \tag{14}$$

and

$$\bar{\nu}_{ea}^k = \int_{V_k}^\infty \nu_{ea}^k f(u)\sqrt{u}du. \tag{15}$$

The symbol <> denotes the energy-averaged value. The term on the left–hand side of Eq.(13) represents the average power input from the field. The first and second terms on the right represent respectively the power losses due to electron-atom elastic collisions, and due to inelastic processes including ionization. The third and last terms represent the electron-dust elastic collision, and energy losses due to electron collection on the dust particles.

Considering $\lambda_e \gg \lambda_L$ (λ_e is the electron mean free path), we assume that there are neither inelastic collisions, nor energy loss in elastic collisions in the shielding volume around the dust particle. The externally applied field is two order of magnitude smaller than the average field induced by the dust charge in the shielding volume around the dust particle. In other words, the electrons move solely in a shielding Coulomb field of dust described in equation (1). With these approximations, following the same procedure as Tsendin [14], we derive the equation for the isotropic part of electron distribution valid in the shielding volume around the dust ($\varepsilon = u - e\phi$)

$$\frac{1}{r^2}\frac{\partial}{\partial r}[r^2 u^{1/2} D(\varepsilon, r)\frac{\partial f(\varepsilon, r)}{\partial r}] = 0, \tag{16}$$

where

$$u^{1/2} D(\varepsilon, r) = \frac{2e}{3m}\frac{u^{3/2}}{\nu(u)}. \tag{17}$$

Equation (16) describes the electron diffusion motion in the plane (r, ε). Integrating Eq. (16) yields

$$r^2 \frac{\partial f(\varepsilon, r)}{\partial r} = \frac{C(\varepsilon)}{vD(\varepsilon, r)}. \tag{18}$$

Let us now suppose that vD is finite at $v = 0$. Then, the requirements of regularity for $f(\varepsilon, r)$ and $\partial f(\varepsilon, r)/\partial r$ at $\varepsilon = -e\phi(r)$, lead to the conclusion that $C(\varepsilon)$ is zero. Thus, $\partial f(\varepsilon, r)/\partial r = 0$, and

$$f(\varepsilon, r) = f_0(\varepsilon), \tag{19}$$

where $f_0(\varepsilon)$ is an arbitrary function of ε. In the present case, we can determine the formation of $f_0(\varepsilon)$ by supposing that $f_0(\varepsilon)$ is identical with $f(u)$ calculated from equation (7) when $\phi(r)$ approaches zero. The electron distribution in the kinetic energy domain at a given position of the shielding volume is obtained from the relation

$$f(u, r) = f_0(\varepsilon = u - e\phi(r)). \tag{20}$$

2.3 Collisional sections

We will use the following models proposed by Ferreira and co-workers [13] for the electron-atom momentum transfer cross section σ_{ea}^{e}

$$\sigma_{ea}^{e} = \begin{cases} \alpha_1 u/V_x & \text{for } u \leq V_x \\ \alpha_1 (u/V_x)^{-1/2} & \text{for } u \geq V_x, \end{cases} \tag{21}$$

and for the total excitation cross section σ_{ea}^{ex}

$$\sigma_{ea}^{ex} = \alpha_2 (\frac{u}{V_x})^{-1/2} (\frac{u}{V_x} - 1) \text{ for } u \geq V_x, \tag{22}$$

with $\alpha_1 = 1.59 \times 10^{-15}$ cm^2 and $\alpha_2 = 1.56 \times 10^{-16}$ cm^2. The value $V_x = 11.55$ eV is the first excitation threshold of the argon atom. The calculations in [13] have demonstrated these electron cross section data used by them (and in this paper) are quite legitimate. We also use ionization cross section given by Rapp and Englander-Golden [15].

Considering the electron-dust interaction potential (1), one can deduce the electron-dust momentum transfer cross section

$$\sigma_{ed}^{m}(u) = \pi a^2 (\frac{-e\phi_s}{u})^2 e^{2a/\lambda_L} \ln \Lambda, \tag{23}$$

and

$$\ln \Lambda \simeq \ln[\frac{\lambda_L T_e}{a(-e\phi_s)}], \tag{24}$$

where T_e is the electron temperature in eV. Expression (23) is basically in agreement with the simulation results of Choi and Kushner [16]. The electron-dust collection cross section is

$$\sigma_{ed}^{c}(u) = \begin{cases} \pi a^2 (1 + e\phi_s/u) & \text{for } u \geq -e\phi_s \\ 0 & \text{for } u < -e\phi_s. \end{cases} \tag{25}$$

Equation (25) clearly shows that only sufficiently fast electrons can be collected by the dust particles.

3 Results and discussion

The normalized electron energy distribution and the dust surface potential, in an Ar discharge plasma contaminated by dust particles, are self-consistantly calculated by numerically solving the electron kinetic equation (7) and the dust charge balance equation

(5). The electron energy distribution in the shielding volume around a particle is calculated from equation (20). The ionization rate coefficient $C_i = < \nu_{ea}^i > /N$ and the electron temperature $T_e = \frac{2}{3} < u >$ are calculated from the electron energy distribution. The fractional power transfers (electron energy loss divided by the total power input from the field) for various collisional processes are abtained from Eq. (13). Here, the gas pressure is 0.1 Torr, and the temperature is 300 K. This means a gas density of $N = 3.22 \times 10^{15}$ cm^{-3}. The average ion energy is $E_0 = 0.06$ eV. The mass ratio of electron to dust is $m_e/m_d = 3.4 \times 10^{-6}$. The main results of the present calculation are represented in the following figures.

The calculated electron energy distribution for the dust-free, and the dusty plasma are shown in Fig. 1. The input parameters are $E/N = 1.5 \times 10^{-16}$ Vcm^2 (the ratio of the electric field to gas density), $n_d = 3.0 \times 10^6$ cm^{-3}, and $n_i = 3.0 \times 10^{10}$ cm^{-3}. The calculation yields $T_e = 3.60$ eV for the dust-free plasma, and $T_e = 2.31$ eV and $\phi_s = -5.65$ V for the dusty plasma. Comparing with the electron energy distribution for the dust-free plasma, we can find that the electron energy distribution for the dusty plasma decreases obviously when electron energy exceeds 5.65 eV and has a peak near the zero energy. The electrons collected by dust cause a reduction in the high-energy portion of the electron energy distribution. An increase of the total collision frequency in the very low energy region due to the momentum transfer electron-dust collision (see Eq. (23)) causes a decrease of the energy input from the field (see the left side of Eq. (7)), and an increase of the low energy electrons. In Fig.2, we show the calculated electron energy distribution at different radii for $E/N = 4.0 \times 10^{-16}$ Vcm^2. The calculation leads to $T_e = 3.38$ eV and $\phi_s = -6.93$ V if the dust particles have a radius $a = 0.5\mu$m, and to $T_e = 2.08$ eV and $\phi_s = -4.96$ V for $a = 1.0\mu$m. The increase of the dust radius reduces considerably the high energy portion of the distribution because of the enhancement of the electron absorption or collection section (see Eq. (25)). The calculated electron energy distributions in the shielding volume around a particle, and also in the bulk plasma far from a particle are displayed in Fig.3. The electron energy distribution in the vicinity of the particle is more dramatically shifted to lower energies, which results from the negative potential in the shielding volume. Because the spatial scale of the bulk plasma is much larger compared to λ_L, the shielding volume surrounding individual particles can be ignored in calculating the macroscopic paremeters.

The calculated dust surface potentials in the dusty plasma, for two values of the bulk plasma density, $n_i = 3.0\times10^{10}$ cm^{-3} and 1.2×10^{11} cm^{-3} are plotted as a function of E/N in Fig.4. The dust potential becomes more negative with increasing E/N since the random flux of high energy electrons increases. In high E/N region, the variation of the dust potential is slow because of the electron energy loss through the electron-atom inelastic collision. As the plasma density increases, the calculated dust potential moves towards higher negative values since the electron flux, available to the dust particle, increases. In Fig.5, where the dust potentials are plotted as a function of the electron temperature, we compare the results obtained from the electron energy distribution calculated in this paper with those from a Maxwellian distribution. The dust potential calculated from the present model is higher than that obtained from a Maxwellian distribution.

The calculated ionization rate coefficients for the dust-free, and the dusty plasma as a function of E/N are shown in Fig.6. The depopulation of the high energy portion of the electron energy distribution in the dusty plasma results in a corresponding decrease in the ionization rate coefficient. Increasing the dust density naturally makes the ionization rate coefficient lower. The electron temperatureshould also go down in the presence of dust. Fig.7, where we flot the calculated electron temperatures for the dust-free and the dusty plasma respectively as a function of E/N, illustrates this. The difference between electron temperatures in the dust-free, and the dusty plasma becomes large in the low E/N region. The high dust surface potential in the low E/N region (see Fig. 4) implies a greater number of electrons collected by the dust.

The fractional electron energy losses by the various collision processes are shown in Fig.8. It is evident that electron collection by the dust provides the main electron-energy loss mechanism in the range $10^{-16} < E/N < 4 \times 10^{-15}$ Vcm^2. As E/N increases, the energy loss due to the electron-dust collection decreases, and the electron-atom inelastic collision becomes the biggest energy loss process when $E/N > 4.0 \times 10^{-16}$ Vcm^2; the inelastic collision frequency is strongly enhanced with the increase of the high energy electrons. The energy loss caused by the electron-dust elastic collisions can be neglected in the region of E/N relevant to this study.

4 Conclusions

The particle surface potentials and the effects of particulate contamination on electron energy distribution and electron transport parameters, in a direct-current argon glow discharge, have been investigated by solving self-consistently the Boltzmann equation and the charging balance equation of dust. As E/N or T_e increases, the dust potential becomes more negative. The dust potential calculated by the present model is higher than that calculated by an assumed Maxwellian distribution of electrons. The dominant influence of particulate contamination is to reduce the high energy content of the electron energy distribution, thereby reducing both the effective electron temperature, and the electron ionization rate coefficients. The electron collection by the dust is found to be the main energy loss process for the electrons in the range $10^{-16} < E/N < 4.0 \times 10^{-15}$ Vcm^2. For higher E/N, the energy loss due to the electron-dust collection decreases, and the electron-atom inelastic collisions become the dominant energy loss mechanism when $E/N > 4.0 \times 10^{-16}$ Vcm^2.

Acknowledgements

One of authors (De-Zhen Wang) would like to thank the International Centre for Theoretical Physics, Trieste and the Department of Theoretical Physics, University of Trieste, for hospitality. This work was supported by the China-Italy Culture Exchange Program, and by the Natural Science Foundation of China.

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Figure captions

1. Electron energy distributions for dust-free and dusty plasma. The conditions are $E/N = 1.5 \times 10^{-16}$ Vcm^2, $n_i = 3.0 \times 10^{10}$ cm^{-3}, $a = 0.5\mu$m, and $n_d = 3.0 \times 10^6$ cm^{-3}.

2. Electron energy distributions for dusty plasma with particle radius 0.5μm and 1.0μm respectively. The other conditions are $E/N = 4.0 \times 10^{-16}$ Vcm^2, $n_i = 3.0 \times 10^{10}$ cm^{-3}, and $n_d = 3.0 \times 10^6$ cm^{-3}.

3. Electron energy distributions in the shielding volume around a particle at $r = 1.0\mu$m (A), $r = 4.0\mu$m (B) and in the bulk plasma far from a particle (C). The other conditions are $E/N = 4.0 \times 10^{-16}$ Vcm^2, $n_i = 3.0 \times 10^{10}$ cm^{-3}, $a = 0.5\mu$m, and $n_d = 3.0 \times 10^6$ cm^{-3}.

4. Calculated dust surface potentials for the bulk plasma density $n_i = 3.0 \times 10^{10}$cm^{-3} (A) and $n_i = 1.2 \times 10^{11}$ cm^{-3} (B) as a function of E/N. The other conditions are $a = 0.5\mu$m and $n_d = 3.0 \times 10^6$ cm^{-3}.

5. Calculated dust surface potentials for the present calculated electron energy distribution (A) and Maxwellian distribution (B) as a function of T_e. The conditions are $n_i = 3.0 \times 10^{10}$ cm^{-3}, $a = 0.5\mu$m, and $n_d = 3.0 \times 10^6$ cm^{-3}.

6. Calculated ionization rate coefficients for the cases $n_d = 0$ (A), $n_d = 6.0 \times 10^5$ cm^{-3} (B) and $n_d = 3.0 \times 10^6$ cm^{-3} (C) as a function of E/N. The other conditions are $n_i = 3.0 \times 10^{10}$ cm^{-3} and $a = 1.0\mu$m.

7. Calculated electron temperatures for the dust-free (A) and dusty (B) plasma as a function of E/N. The conditions are $n_i = 3.0 \times 10^{10}$ cm^{-3}, $a = 0.5\mu$m, and $n_d = 3.0 \times 10^6$ cm^{-3}.

8. Fractional electron energy losses as a function of E/N for electron-atom inelastic collision (A), electron-dust collection (B), electron-atom elastic collision (C), and electron-dust elastic collision (D). The conditions are $n_i = 3.0 \times 10^{10}$ cm^{-3}, $a = 0.5\mu$m, and $n_d = 3.0 \times 10^6$ cm^{-3}.

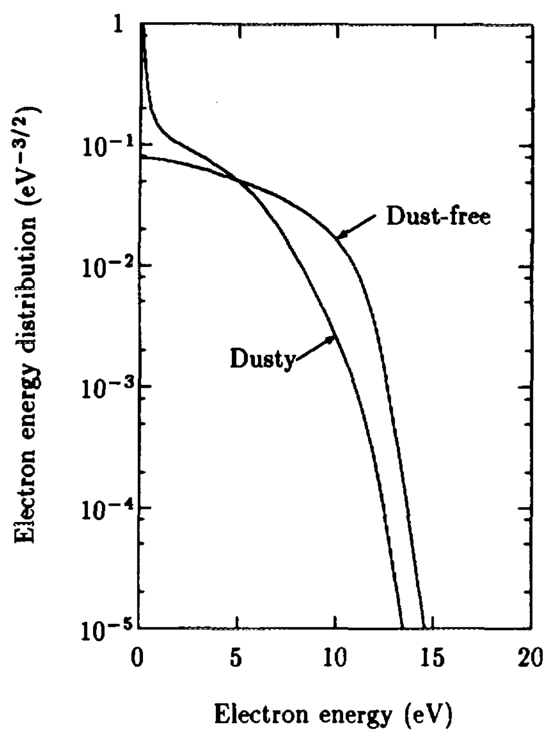


Figure 1.

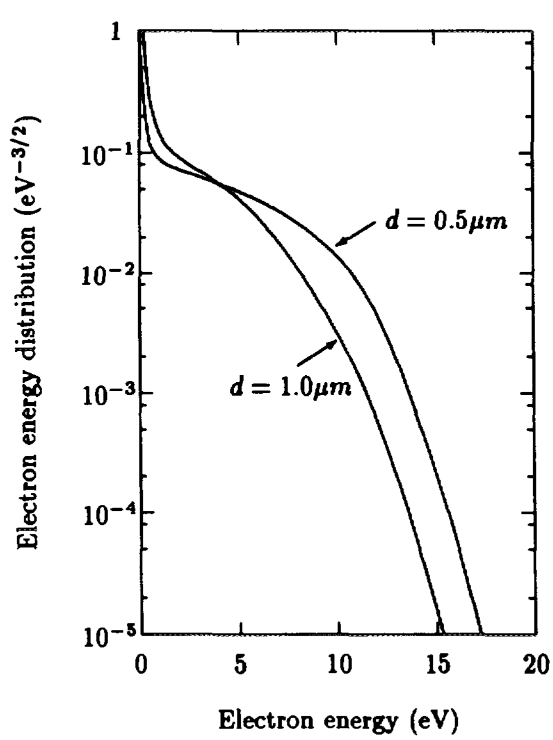
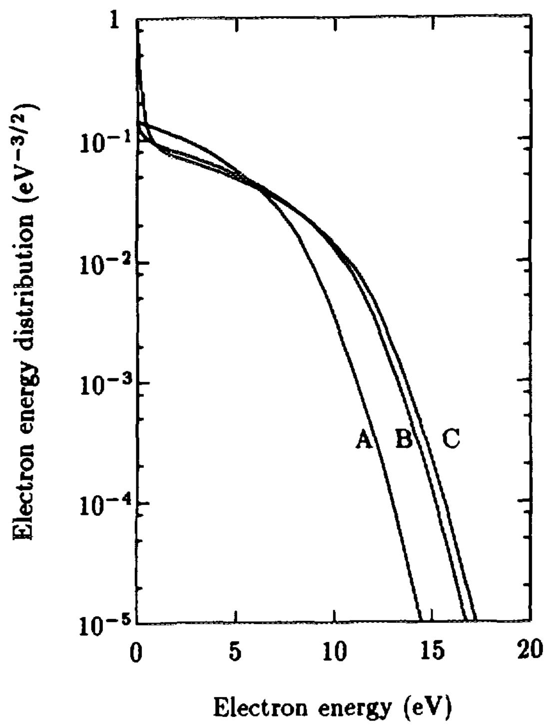


Figure 2.



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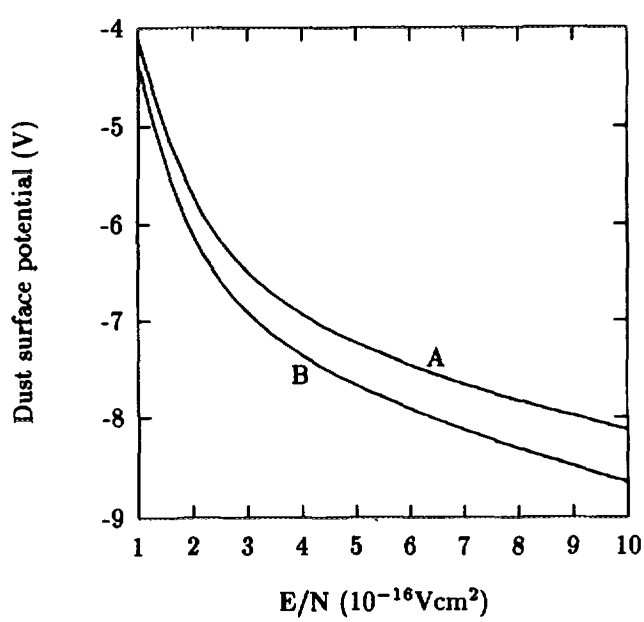

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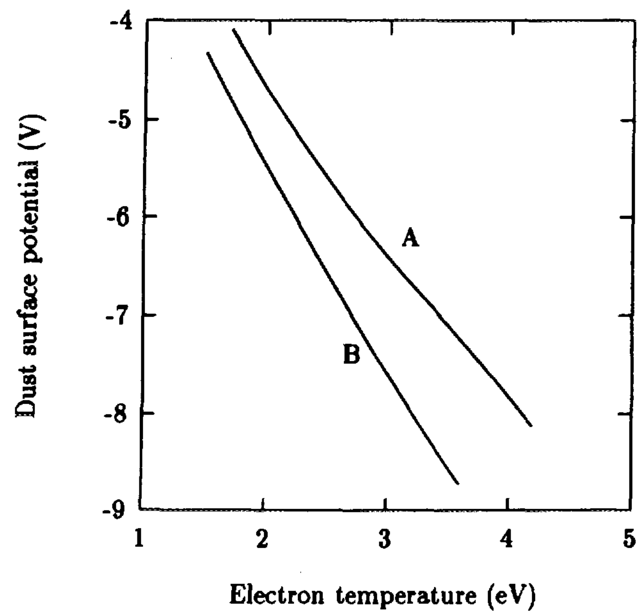

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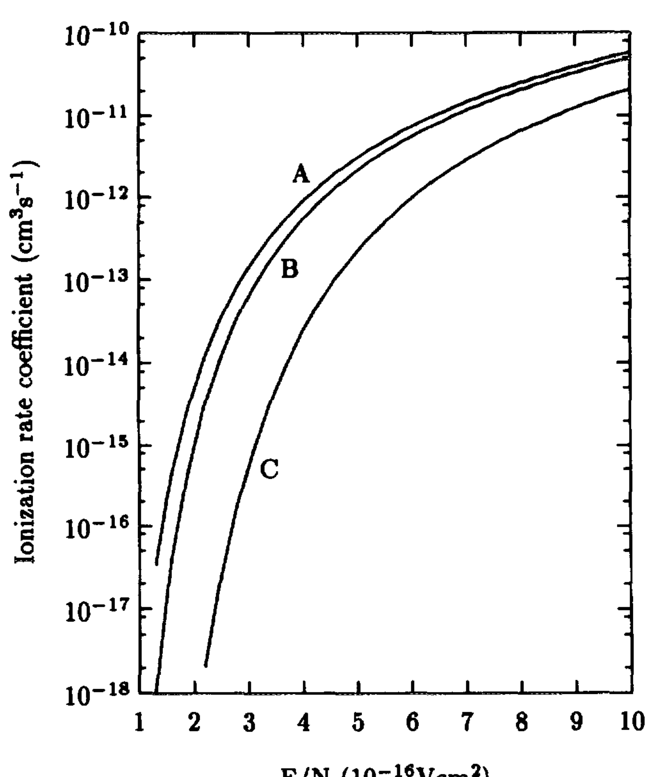

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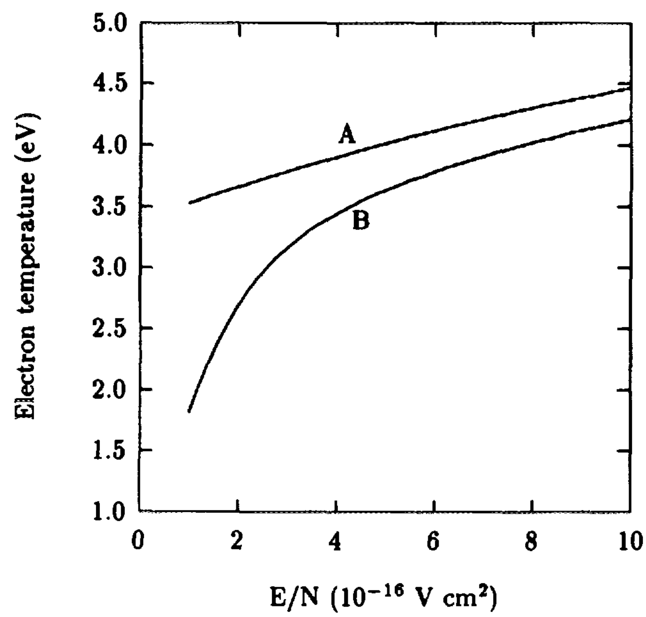

Figure 7.

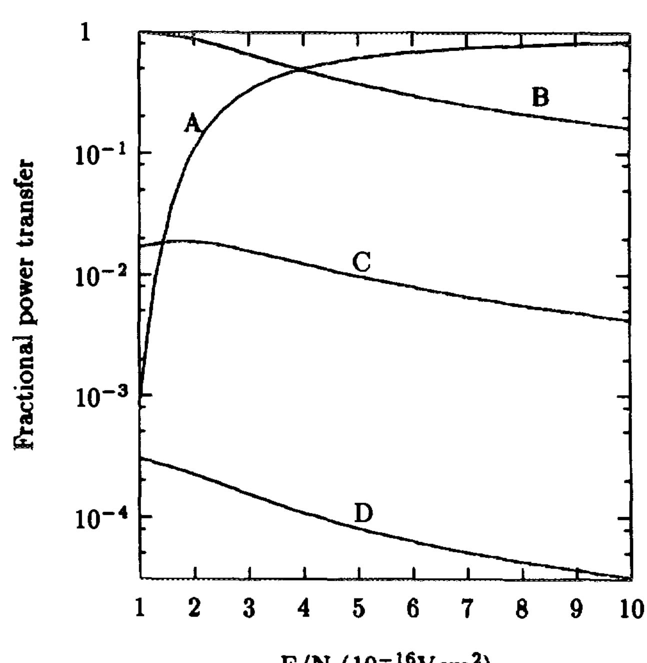

Figure 8.