Properties of electron swarms in gases in the upstream region of an electron source z

H Sugawara, Y Sakai and H Tagashira

Department of Electrical Engineering, Hokkaido University, Sapporo 060 Japan

Abstract. **Exponential spatial growth of electron swarms in gases under steady-state Townsend conditions may be observed not only in the downstream region of an electron source but also in the upstream region due to backward diãusion. Relations among swarm parameters in the upstream region were deduced and found to have peculiar characteristics. For example, the sign of the average electron velocity v_d for steady-state Townsend conditions depends on whether the gas is electro-positive or electro-negative. This property is conårmed quantitatively by calculating the electron energy distribution using a propagator method modiåed for analysis in the upstream region. As an example of the eãect of backward diãusion, the decay in the electron number density in front of the anode in a steady-state Townsend experiment between parallel plane electrodes was studied. The decay is caused by the missing electrons absorbed at the anode. The energy distribution of the missing electrons has a non-equilibrium relaxation region and the equilibrium region lies towards the cathode direction. The number density of the missing electrons showed an exponential spatial dependence in the equilibrium region. The relative gradient of the decrease agreed well with the relative density gradient ã obtained in the upstream region. It was also found that the electron energy distribution in the decaying region tends to that in the upstream equilibrium region.**

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1. Introduction

A steady-state electron swarm is formed by continuously supplying initial electrons from a point source in gases in the presence of an electric åeld. As shown in ågure 1, three regions can be deåned relative to the source location; the near-source region, the downstream region (DSR) and the upstream region (USR). The near-source region is a region of non-equilibrium relaxation. The DSR and USR are regions in equilibrium.

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Here, we define downstream as being the direction in which an electron would move in the presence of an electric field, E, in a collisionless environment. The USR is simply the opposite direction. In the DSR, as the distance from the source increases, the electron number density exponentially increases by ionization or decreases by attachment. This is the well-known steady-state Townsend (SST) condition. The assumption of an exponentially growing electron number density with distance from the source is the basis for analysis of electron swarms to obtain the effective ionization coefficient α.

Because of collisions, electrons can be found not only in the DSR but also in the USR as has been demonstrated for example by a Monte Carlo simulation (MCS) (Braglia and Lowke, 1979). Here, we define backward diffusion as being the mechanism by which electrons penetrate the USR. Although most of the literature has dealt with the DSR, a number of investigators have addressed electron behaviour in the USR.

Tagashira (1985, 1991) suggested that the two solutions for α, obtained by solving the continuity equation assuming exponentially varying electron number densities in space, correspond to the coefficients of the relative density gradient in the USR and DSR. Standish (1989) solved a kinetic equation for the steady-state spatial distributions of charged particles using eigenfunctions for particle transport. His analysis showed the exponential spatial dependence of the electron density in both the USR and DSR. The conclusion that the two solutions for α are the real roots of the zeroth-order dispersion relation for electron transport and that they correspond to the USR and DSR was obtained by Standish (1989), Kondo and Tagashira (1990) and Robson (1991).

Chantry (1982) investigated the decay in the electron number density in front of an absorbing anode in terms of backward-diffusing electrons. It is shown in the present paper that the behaviour of backward-diffusing vacancies, namely missing electrons due to the absorption, may be equivalent to that of electron swarms in the USR.

Knowing the characteristics of backward-diffusing electron swarms may permit one to extend the treatment of the properties of electron swarms. Therefore, in order to develop the theory of electron swarms further, analyses for backward-diffusing electrons in the USR as well as those for the DSR are important.

Characteristics of the electron energy distribution and relations among the electron swarm parameters in the USR are discussed in section 2. In order to confirm the relations, the electron energy distribution in the USR is calculated in section 3 under a uniform electric field using a previously developed propagator method (PM) (Sugawara et al 1994) but implemented here for the USR. A discussion of results is given in section 4. The problem of the decay in the electron number density in front of the anode of parallel plane electrodes is an example of application of the principle and technique investigated in the present paper. This problem is treated in section 5, where a comparison is made between results by the PM and a MCS to prove the validity of application of the present PM to the problem.

2. Relations among swarm parameters

2.1. The relative density gradient coefficient

The continuity equation for electrons under SST conditions may be described using SST swarm parameters (Thomas 1969, Tagashira et al 1977, Blevin and Fletcher 1984). Following Blevin and Fletcher (1984), when an exponential solution $n_e(x) = n_0 \exp(\alpha x)$ for the electron number density at position x is assumed for an electron source located at x = 0, the continuity equation is described using the effective ionization frequency R_{is}, the drift velocity W_s and the diffusion coefficient D_s for SST conditions as

$$R_{is} n_e(x) - W_s \frac{\partial}{\partial x} n_e(x) + D_s \frac{\partial^2}{\partial x^2} n_e(x) = 0. \qquad (1)$$

These SST parameters were defined by rearranging all the higher order parameters for the time-of-flight (TOF) experiment. Since the spatial growth is assumed to be exponential, we may replace the operator $\partial/\partial x$ with α to give

$$R_{is} n_0 - \alpha W_s n_0 + \alpha^2 D_s n_0 = 0. \qquad (2)$$

Two solutions for α are obtained as follows.

$$\alpha = \frac{W_s \mp \sqrt{W_s^2 - 4 R_{is} D_s}}{2 D_s} \qquad (3)$$

Tagashira (1985) inferred that these solutions correspond respectively to the USR (x < 0) and the DSR (x > 0). For the DSR, the negative sign is adopted for α so that α becomes zero when R_{is} tends to zero.

In contrast, αx in the USR should always have a negative value so that the electron number density always decays in the upstream direction irrespective of the sign of R_{is}. In this case, α simply represents the relative gradient of the electron number density.

As shown by Standish (1989), Kondo and Tagashira (1990) and Robson (1991), there are two different eigenvalues for the values of α to represent exponential growth in the USR and DSR. The equilibrium electron energy distributions for the USR and DSR should be different from each other since they are determined by different eigenvalues or relative density gradients. Therefore, the electron energy distributions are different and swarm parameters such as W_s, D_s and R_{is} should have different values for the USR and DSR, although the formulations to deduce them from the energy distributions should be identical for both USR and DSR (Tagashira et al , 1977, section 3.3; Blevin and Fletcher, 1984, section 3(b)).

Hereafter, the primed swarm parameters indicate those obtained from the energy distribution in the USR while the unprimed ones indicate those of the DSR as follows.

$$\alpha = \frac{W_s - \sqrt{W_s^2 - 4 R_{is} D_s}}{2 D_s} \qquad \text{for the downstream region} \qquad (4)$$

$$\tilde{a}^0 = \frac{W_s^0 + \sqrt{W_s^{02} + 4R_{is}^0 D_s^0}}{2D_s^0} \qquad \text{for the upstream region} \tag{5}$$

It is important to note that the reason for using different values of the drift velocity, diffusion coefficient and ionization frequency in the USR and DSR comes from the fact that the SST swarm parameters are dependent on the electron concentration gradient and are quite different from the concentration-gradient-independent TOF parameters (Tagashira et al 1977) in this respect.

2.2. Drift velocity

If an exponential distribution, $n_0 \exp(\tilde{a}^0 x)$, is assumed for the electrons in the USR (Standish, 1989), then the total number of electrons, $N_e(x^0)$, on the upstream side of $x = x^0 (< 0)$ has a finite value and can be written as

$$N_e(x^0) = \int_{-1}^{x^0} n_0 \exp(\tilde{a}^0 x)dx = \frac{n_0}{\tilde{a}^0} \exp(\tilde{a}^0 x^0). \tag{6}$$

Since $N_e(x^0)$ is constant under a steady state, the electron generation per unit time $R_{is}^0 N_e(x^0)$ in this region must be equal to the electron outflow across $x = x^0$ towards the DSR per unit time. Equating the outflow, which is the flux denoted as $n_0 \exp(\tilde{a}^0 x^0) v_d^0$, to the generation rate, one obtains

$$R_{is}^0 \frac{n_0}{\tilde{a}^0} \exp(\tilde{a}^0 x^0) = n_0 \exp(\tilde{a}^0 x^0) v_d^0. \tag{7}$$

Here, v_d^0 is the SST average velocity (= flux/density, Robson, 1991), which is identical to the diffusion-modified drift velocity ($= W_s^0 - \tilde{a}^0 D_s^0$, Tagashira et al , 1977) under SST conditions. This velocity represents the average of the velocity component parallel to E for SST conditions. Equation (7) can be simplified to

$$R_{is}^0 = v_d^0 \tilde{a}^0 \tag{8}$$

which is similar to $R_{is} = v_d \tilde{a}$ in the DSR. An equivalent discussion may be made by using a differential form of the continuity equation of electrons for SST.

Since $v_d > 0$ is always satisfied in the DSR, the same sign is shared by R_{is} and $\tilde{a}$. The relative gradient, $\tilde{a}$, of $n_e(x) = n_0 \exp(\tilde{a}x)$ directly represents electron multiplication by ionization ($R_{is} > 0$) or decay by electron attachment ($R_{is} < 0$). On the other hand, since $\tilde{a}^0$ in the USR always has a positive value, R_{is}^0 and v_d^0 should share the same sign. Therefore, the sign of average velocity v_d^0, as well as that of R_{is}^0, indicates whether the gas is effectively electropositive or electronegative.

In the special case that the number of electrons is conserved, or the gain of electrons by ionization exactly balances the loss by attachment, v_d^0 becomes zero since $R_{is}^0 = 0$. Under this condition, the relation $W_s^0 = \tilde{a}^0 D_s^0$, deduced from equation (2), represents a balance between drift by the electric field and backward diffusion as a result of the density gradient.

3. Calculation of the electron energy distribution

In the preceding section, it was shown that the relation among swarm parameters in the USR is exactly analogous to that in the DSR. Next, the validity of equations (5) and (8) is demonstrated by a simulation using a propagator method which was previously used by the authors for analysis in the DSR but is modiåed here for analysis in the USR.

3.1. Numerical method for the upstream region

A numerical technique based on a propagator method (Sugawara et al 1994) for the calculation of equilibrium energy distribution in the DSR under SST conditions was modiåed for the USR. In the propagator method, the electron energy distribution $F(è; í)$ is represented as a function of the electron energy è and the angle í between E and the direction of electron motion. Phase space $(è; í)$ is devided into many small cells for every Å è and Å í. For every time step, electron propagation among the cells is calculated using operators called propagators, which represent the acceleration due to E and scattering by collisions with gas molecules.

In the implementation of the previous PM, the assumption of exponential spatial growth in the DSR enabled us to obtain equilibrium solutions for $F(è; í)$ in a thin slab normal to the electron çow without considering the spatial relaxation process. The PM is now applied for analyses in the USR, since the formulation of the continuity equation in the USR is analogous to that for the DSR.

Using a similar technique to the previous PM, the quantity $\exp(ã^0 Åx)$ is obtained from the following conservation equation by describing the variation of the number of electrons in a thin slab with a thickness Åx;

$$n_b \mathbf{f}\exp(ã^0 Åx)\ \ddot{\mathbf{A}}\ 1\mathbf{g} + n_f \mathbf{f}\exp(\ddot{\mathbf{A}} ã^0 Åx)\ \ddot{\mathbf{A}}\ 1\mathbf{g} + (n_i\ \ddot{\mathbf{A}}\ n_a) = 0: \qquad (9)$$

Here, n_f, n_b, n_i and n_a are the changes of the number of electrons in a time step corresponding to respectively forward and backward outçows, ionization and attachment. Equation (9) has two solutions;

$$\exp(ã^0 Åx) = \frac{(n_f + n_b\ \ddot{\mathbf{A}}\ n_i + n_a)\ \ddot{\mathbf{U}}\ \sqrt{(n_f + n_b\ \ddot{\mathbf{A}}\ n_i + n_a)^2\ \ddot{\mathbf{A}}\ 4n_f n_b}}{2n_b}: \qquad (10)$$

The sign of the solution is chosen in the same way as discussed in section 2.1; the positive sign is adopted for $ã^0$, since it always has a positive value in the USR. Note that the choice of the negative sign was shown to be valid for determining the electron energy distributions and swarm parameters in the DSR in the previous PM (Sugawara et al 1994).

Here, using a Taylor expansion as $\exp(-\alpha' \Delta x) \simeq 1 - \alpha' \Delta x$, equation (10) becomes

$$\alpha' = \frac{1}{\Delta x}\left[\frac{(n_f - n_b + n_i - n_a) + \sqrt{(n_f - n_b + n_i - n_a)^2 - 4n_f(n_i - n_a)}}{2n_f}\right]. \quad (11)$$

The exact value of α' should be obtained when Δx tends to zero. Although Δx in practical calculations has a non-zero value, Δx is set to be as small as possible in the calculation.

The calculation is started using an appropriate choice of the initial distribution of $F(\varepsilon, \mu)$ and is repeated until the distribution reaches equilibrium. In the USR, some of the electrons must have sufficiently high energies that they can diffuse backwards against E. Therefore, a high enough maximum energy ε_{max} and appropriate values for $F(\varepsilon_{max}, \mu)$ were chosen for calculation of $F(\varepsilon, \mu)$. To confirm the validity of the solutions, an energy balance (Thomas 1969 equation (9)) was performed to demonstrate the drift equiliblium here in the USR.

3.2. Gases and electric fields

Three classes of gases were chosen to confirm equation (8); argon as an electro-positive gas (case 1, $R^0_{is} > 0$), a ramp model gas in which ionization and attachment do not occur (case 2, $R^0_{is} = 0$), and sulphur hexafluoride as an electronegative gas (case 3, $R^0_{is} < 0$). The sets of cross sections used in the present work are based on those of Suzuki et al (1990), Mason and Newell (1987) and Sakai et al (1972) for argon, Reid (1979) for the ramp model gas and Itoh et al (1993) for sulphur hexafluoride.

The values of the reduced electric field are chosen to be E/N = 1410, 283 and 141 Td for cases 1, 2 and 3 respectively. For case 1, a high E/N is chosen so that R^0_{is} is large enough to give a significant value of v^0_d. On the other hand, a low E/N is chosen for case 3 so that R^0_{is} is a large negative quantity. These are chosen to emphasize the ionization in case 1 and attachment in case 3. The number density of gas molecules, N, is assumed to be 3.53×10^{16} cm^{-3} (1 Torr at 0°C).

4. Results and discussion

4.1. The electron energy distribution

$F_0(\varepsilon)$, the isotropic part of $F(\varepsilon, \mu)$, $F_1(\varepsilon)$, an anisotropic part, and all other terms of the Legendre expansion can be obtained from the exact solution $F(\varepsilon, \mu)$ calculated here by the PM. $F_0(\varepsilon)$ and $F_1(\varepsilon)$ are shown in figure 2. There are two important differences between the electron energy distributions in the USR and the DSR. In contrast to those in the DSR, the electron energies in the USR are in general lower and on the average the high-energy electrons move backwards.

Electrons diãuse backwards into the USR because of the large gradient in the electron number density. In this case, only high-energy electrons can diãuse backwards since diãusion against E results in rapid energy loss. Some electrons lose part of their energy by collisions during their stay in $x < x^0$, where x^0 is a location in the USR. When they eventually lose enough energy, they drift towards the DSR unless they are lost in the USR by attachment. If super-elastic collisions are neglected, then those electrons that have undergone backward diãusion will necessarily have a lower energy at x^0 than those that have not undergone backward diãusion. Therefore, $F_1(è)$ will be positive for low energy electrons as shown in ågures 2(a) and (c). In the electronegative gas, the number of electrons decreases by attachment as they diãuse backwards. As a result, $F_1(è)$ is negative for all è for the conditions in ågure 2(e).

As expected, a shift in $F_0(è)$ towards higher energies with increasing E=N was observed even in the USR. This is similar to what occurs in the DSR. A high E=N prevents low energy electrons from diãusing backwards. The total number of electrons penetrating into the USR, as denoted in equation (6), decreases since $ã^0$ increases with increasing E=N. An exponential spatial distribution at a high E=N is formed by backward diãusion of electrons with commensurately larger energies.

4.2. Electron swarm parameters

The trends in the energy distribution presented in ågure 2 signiåcantly aãect the swarm parameters. The mean energy $ê$, the eãective ionization frequency R^0_{is}, the relative gradient of the electron number density $ã^0$, the quantity $R^0_{is}=ã^0$ and the drift velocity v^0_d in the USR are listed in table 1 together with those in the DSR under the same E=N for comparison. A comparison between v^0_d and $R^0_{is}=ã^0$ conårms equation (8). Here, v^0_d is given as $\frac{1}{3}\int_0^1 V_1 \sqrt{è}F_1(è)dè$ where V_1 is the speed of an electron with the energy of 1 eV. The values of $R^0_{is}=ã^0$ and v^0_d are found to agree well with each other to within a fraction of a percent.

Table 1. List of swarm parameters.

gas	region	E=N	$ê$	R^0_{is}	$ã^0$	$R^0_{is}=ã^0$	v^0_d
			R_{is}	$ã$	$R_{is}=ã$	v_d	
		(Td)	(eV)	($ñs^{Ä1}$)	($cm^{Ä1}$)	(cm/ñs)	(cm/ñs)
Ar	upstream	1410	5.37	17.3	138	0.126	0.125
(case (1))	downstream	1410	15.7	590	10.1	58.2	57.9
ramp model gas	upstream	283	0.54	0.0	270	0.0	-0.004
(case (2))	downstream	283	2.13	0.0	0.0	| *	13.3
SF_6	upstream	141	2.71	-112	33.6	-3.33	-3.30
(case (3))	downstream	141	5.62	-30.1	-2.4	12.3	12.3

* undeåned since $ã = 0$

Typically, an electron swarm under SST conditions can be regarded as the integral of an isolated swarm with respect to time at a fixed position (Sakai et al , 1977). In section 2.2, the fact that $v_d^0 = 0$ when $R_{is}^0 = 0$ is explained using a macroscopic approach. This conclusion can also be attained with a microscopic approach, that is by looking at the behaviour of an individual electron. Following Sakai et al (1977), the contribution of an individual electron to the drift velocity v_d^0 is the electron velocity component parallel to E weighted by its residence time in a small interval in space with a thickness Δx. If there is no production and loss of electrons, an electron that passes across Δx in the USR must return across Δx towards the DSR, hence the number of crossings by an individual electron across Δx is necessarily even. Since the residence time is inversely proportional to the velocity component parallel to E and the velocity changes sign with each crossing, the net contribution to the drift velocity is zero. In contrast, the number of crossings is odd in the DSR. The difference in the parity of the number of crossings in the two regions is the key difference between the drift velocities for the USR and DSR.

5. A practical example of backward diffusion

5.1. The influence of absorbing anode

A practical example of backward diffusion in the USR, as previously discussed, is seen in an SST experiment between parallel plane electrodes. The decay in the electron number density in front of an absorbing anode may be regarded as the appearence of vacancies due to the absorption of electrons at the anode. Here, we define the vacancy as being missing electrons.

Chantry (1982) discussed the effect of an absorbing anode on the SST electron swarm using a concept of complementarity. The complementarity theorem of Chantry (1982) is as follows. If a plane which is perpendicular to E is placed in the region where the electron swarm is in equilibrium, electrons near the plane are a mixture of those electrons that are diffusing forwards and those that are diffusing backwards across the plane. When we regard the plane as an absorbing anode, swarm parameters on the upstream side near the plane would vary spatially corresponding to the contribution of backward-diffusing electrons to the energy distribution, since these electrons would be lost by absorption.

If those electrons absorbed at the anode could move freely as if they were in the presence of the electric field even after absorption, then they could diffuse backwards and fill the vacancy. Here, the energy distribution of backward-diffusing electrons $F_v(\varepsilon, x)$ necessary to fill the vacancies is defined as

$$F_v(\varepsilon, x) = F_{d:eq}(\varepsilon) - F_a(\varepsilon, x) \tag{12}$$

where $F_{d:eq}(\varepsilon)$ and $F_a(\varepsilon, x)$ are the electron energy distributions at positions in the

equilibrium region in the DSR and vicinity of the anode respectively as shown in figure 3.

5.2. Monte Carlo simulation

To test the concept of backward diffusion of vacancies as defined by equation (12), a Monte Carlo simulation (MCS) was performed to obtain $F_v(\varepsilon, x)$. It is assumed that the initial electrons are supplied at a plane source and they drift and diffuse downstream. Those electrons which arrive at the position of an imaginary anode are labelled to indicate that they are absorbed. They are then allowed to continue propagating under the influence of the electric field. The electrons that return across the anode are sampled yielding $F_v(\varepsilon, x)$ of electrons which diffuse backwards from the anode. In this case, the anode becomes equivalent to a source; the region in front of the anode becomes the USR; the region `inside' the anode becomes the DSR.

As a benchmark case, a simulation was performed for a ramp model gas. The initial electrons were given a uniform energy distribution between 0 and 10 eV. The distance from the electron source to the anode was 5 mm. This distance is long enough for the electrons to reach equilibrium under the same conditions as those given in section 3.2.

The results from the MCS are shown in figures 4 and 5. In figure 4, the energy distributions of the vacancies, $F_v(\varepsilon, x)$, are presented as a function of the distance from the anode. An important feature to note is that the shape of $F_v(\varepsilon, x)$ converges to $F_{u:eq}(\varepsilon)$, where $F_{u:eq}(\varepsilon)$ is the equilibrium electron energy distribution in the USR. In the region in figure 5, where the gradient of the logarithm of the electron number density agrees with α' in table 1, the shape of $F_v(\varepsilon, x)$ in figure 4 is essentially the same as $F_{u:eq}(\varepsilon)$. This shows that the backward-diffusing electrons from the anode also undergo processes of relaxation and exponential decay essentially similar to the behaviour of the backward-diffusing electrons in the USR.

Because of the large value of α', there is a steep decay in the number density of backward-diffusing electrons adjacent to the anode. The resulting low number density of these electrons at increasing distances from the anode ($< \mathbf{\Delta} 0.05$ cm) results in the statistical fluctuations observed in figure 5.

6. Conclusions

The properties of electron swarms in gases in the upstream region of the electron source, formed by backward diffusion of electrons against the electric field, are studied under steady-state Townsend conditions.

Relations among electron swarm parameters for the upstream region are deduced under the assumption of exponential spatial growth. It is shown that the sign of the electron drift velocity v_d is positive when the gas is electropositive, and v_d is negative when the gas is electronegative. v_d is zero where there is no ionization or attachment.

These characteristics are confirmed by calculating the electron energy distribution using a previously developed propagator method (Sugawara et al 1994) but modified here for analyses in the upstream region.

A steady-state electron swarm between parallel plane electrodes is simulated using a Monte Carlo method to show that the decay in the electron number density in front of the absorbing anode is due to vacancies created by electrons absorbed at the anode. The exponential decay in the electron number density with distance was also confirmed by the Monte Carlo simulation. The electron energy distribution when the decay reaches equilibrium and becomes exponential is demonstrated to be the equilibrium electron energy distribution in the USR.

The equilibrium behaviour of these electrons is shown to be essentially the same as that in the upstream region. The agreement between the electron energy distributions calculated by the propagator methods and the Monte Carlo simulation validates the use of the present propagator method to predict electron swarm behaviour in the upstream region.

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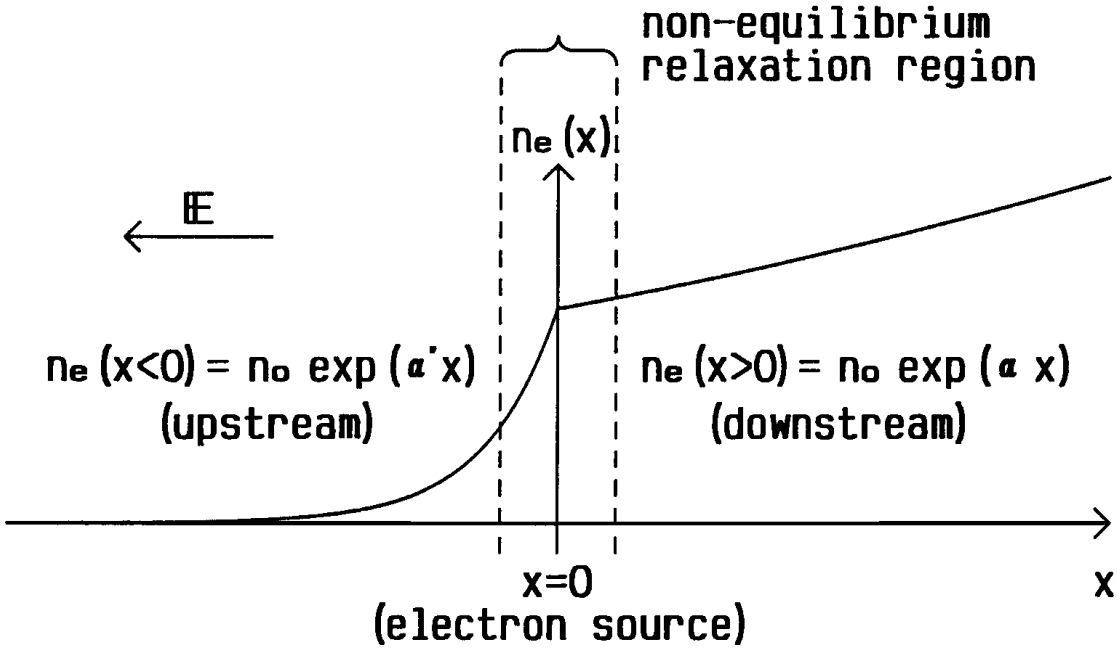


Figure 1. The model of steady-state electron flow on each side of the electron source.

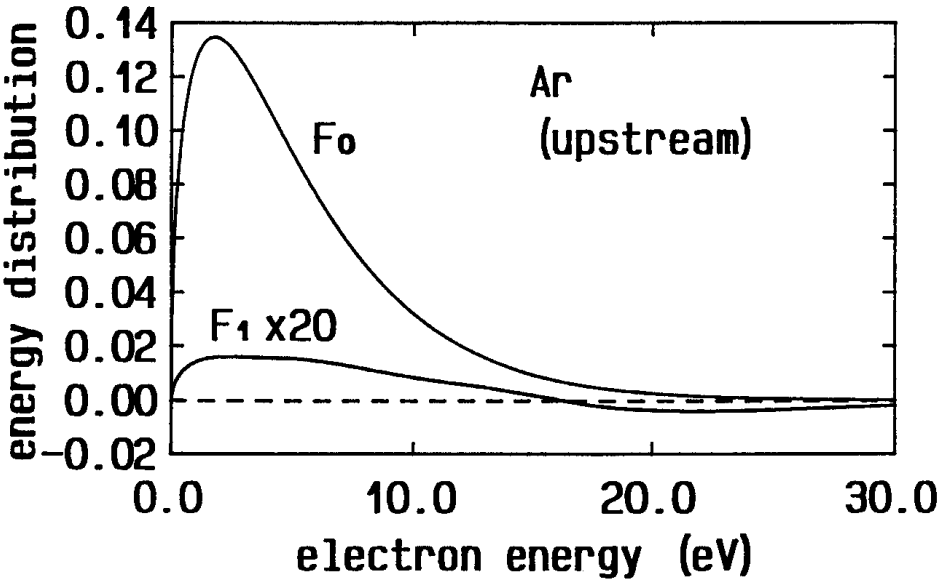


Figure 2(a)

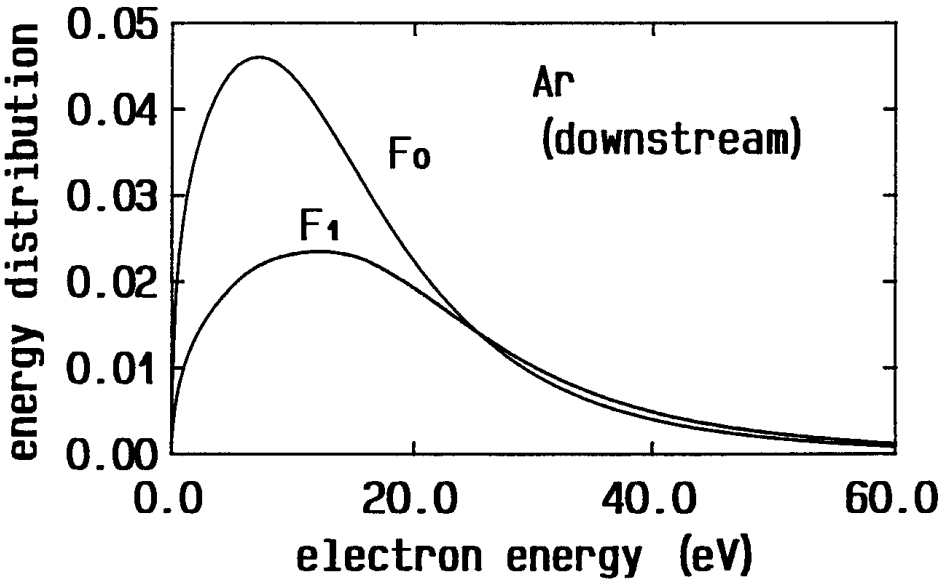
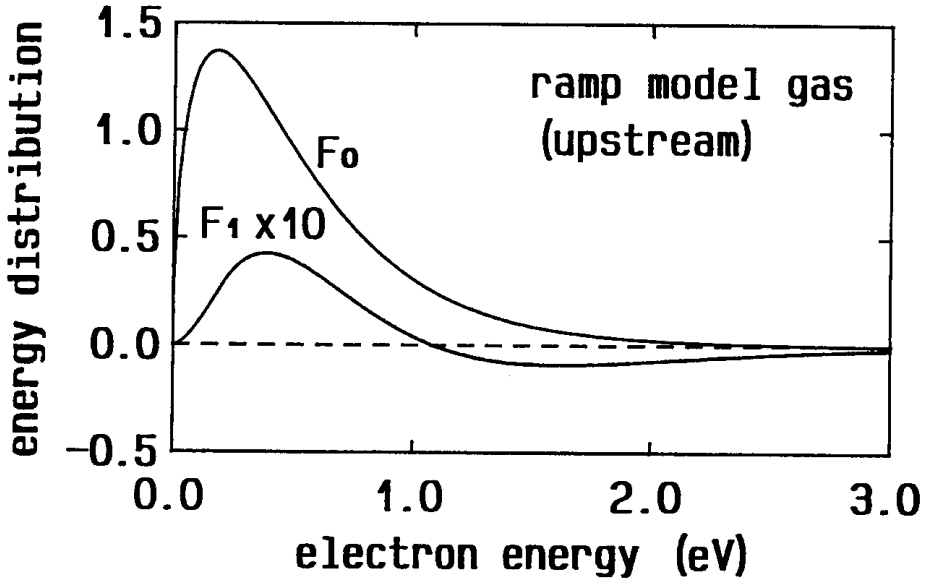


Figure 2(b)

Figure 2. Electron energy distributions calculated using a propagator technique: (a) and (b), argon at E/N = 1410 Td; (c) and (d), ramp model gas at E/N = 283 Td; (e) and (f), sulphur hexafluoride at E/N = 141 Td. Figures (a), (c) and (e) are for the upstream region, while figures (b), (d) and (f) are for the downstream region.



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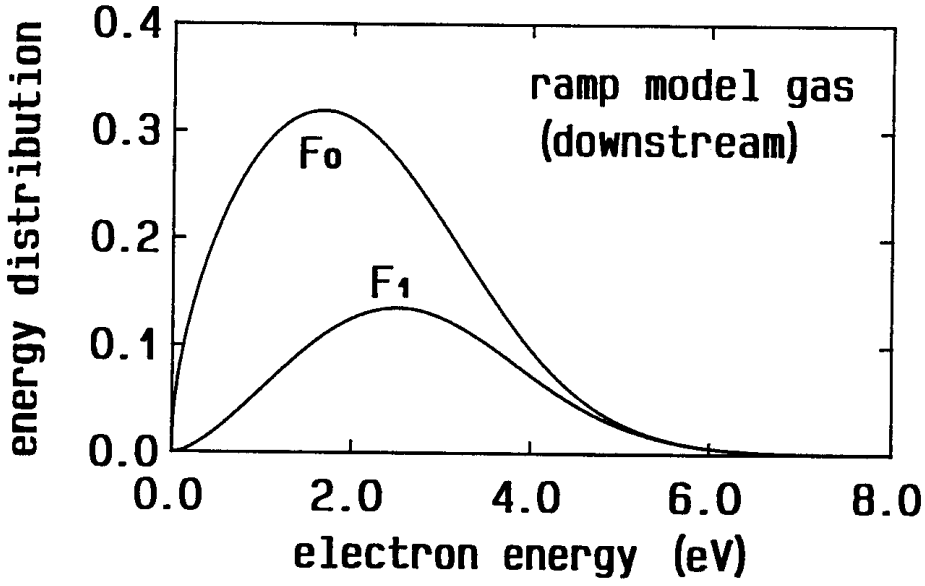

Figure 2(d)

Figure 2. Electron energy distributions calculated using a propagator technique: (a) and (b), argon at E/N = 1410 Td; (c) and (d), ramp model gas at E/N = 283 Td; (e) and (f), sulphur hexafluoride at E/N = 141 Td. Figures (a), (c) and (e) are for the upstream region, while figures (b), (d) and (f) are for the downstream region.

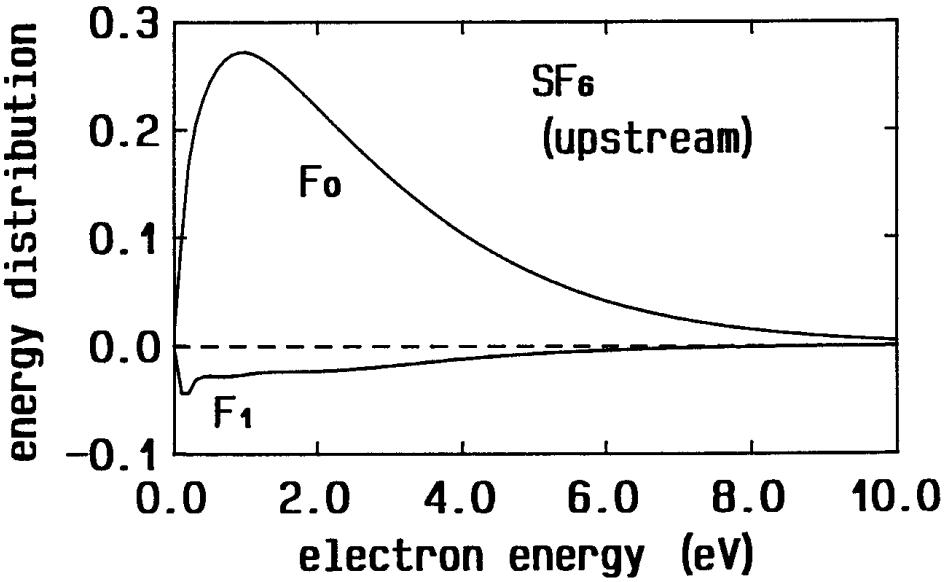

Figure 2(e)

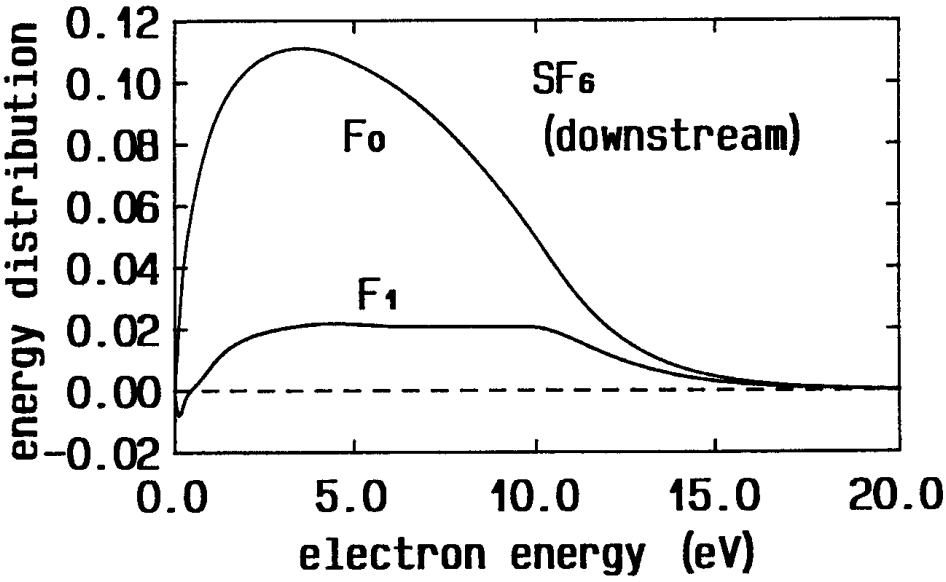

Figure 2(f)

Figure 2. Electron energy distributions calculated using a propagator technique: (a) and (b), argon at E/N = 1410 Td; (c) and (d), ramp model gas at E/N = 283 Td; (e) and (f), sulphur hexafluoride at E/N = 141 Td. Figures (a), (c) and (e) are for the upstream region, while figures (b), (d) and (f) are for the downstream region.

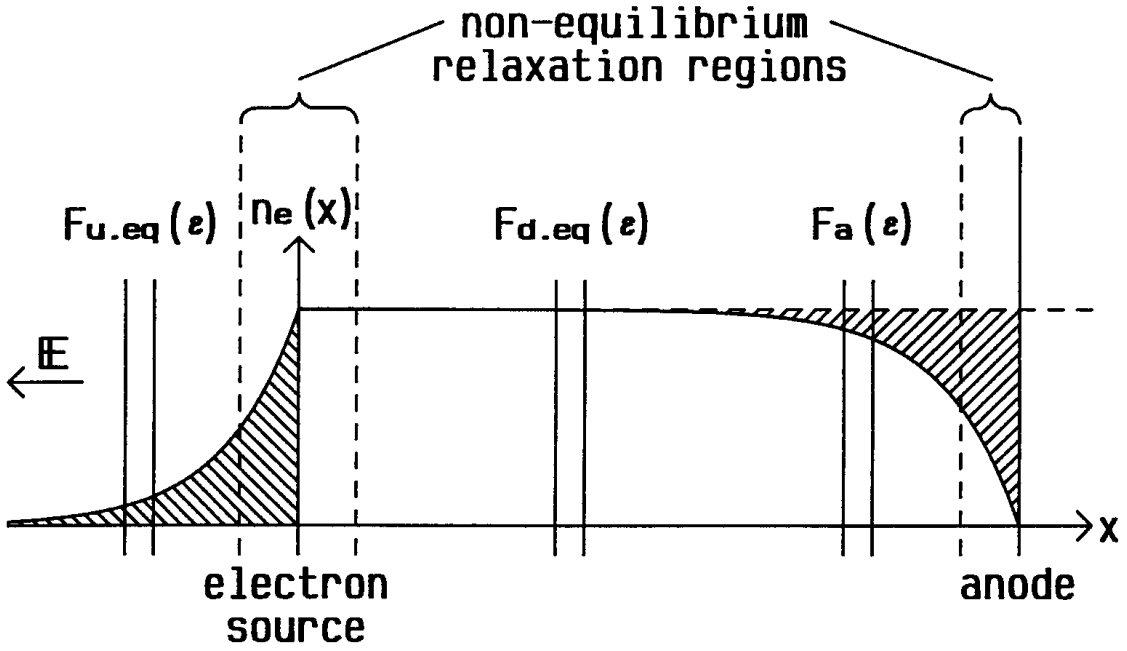

Figure 3. The model of a steady-state electron swarm in front of the anode. $F_{u.eq}(\varepsilon)$, $F_{d.eq}(\varepsilon)$ and $F_a(\varepsilon)$ represent the equilibrium electron energy distributions in the upstream and downstream regions and that under the influence of an absorbing anode respectively. The hatched part in front of the anode, given as $F_v(\varepsilon,x) = F_{d.eq}(\varepsilon) - F_a(\varepsilon,x)$, describes the distribution of missing electrons due to absorption.

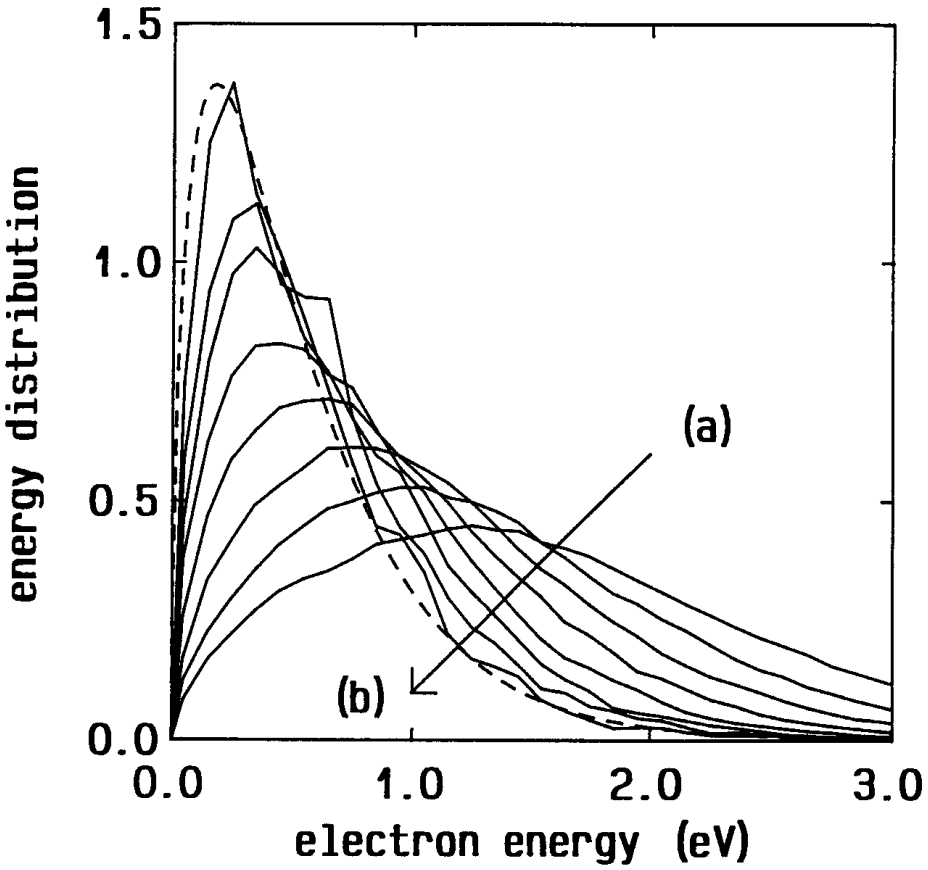

Figure 4. The energy distribution of backward-diffusing electrons in a ramp model gas obtained by a Monte Carlo simulation at E/N = 283 Td as a function of distance from the anode. The electron energy distributions are presented for every 0.004 cm from (a) −0.002 cm to (b) −0.030 cm. The electrons are assumed to move even after arrival at the anode. The distribution tends to the equilibrium solution indicated by the broken line, which is obtained by the present propagator method.

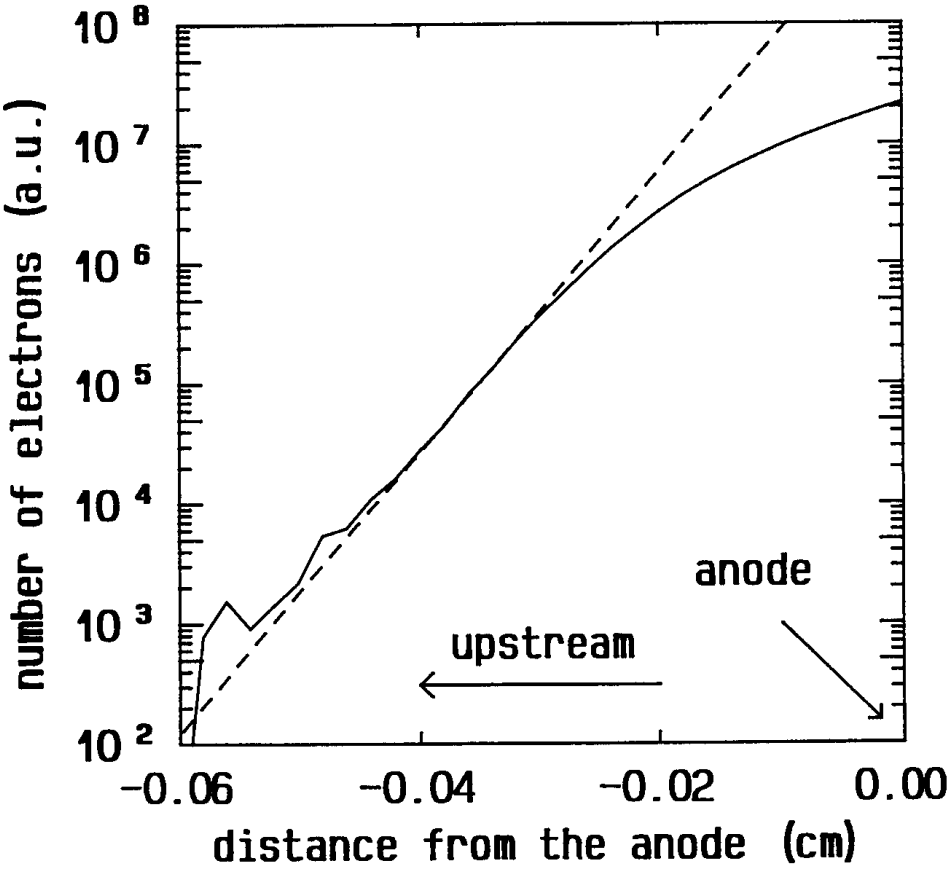

Figure 5. The number density of backward-diffusing electrons in a ramp model gas as a function of the distance from the absorbing anode under a steady-state Townsend condition obtained by a Monte Carlo simulation at E/N = 283 Td. Each electron is sampled just after its arrival at the anode. The broken line represents the relative density gradient, α', from table 1 obtained by the present propagator method. The deviation from linearity towards the cathode is due to the low electron number density.