Properties of electron swarms in CF_3I

H. Hasegawa,[1] H. Date,[2,a)] M. Shimozuma,[3] and H. Itoh[4]
[1]*Tomakomai National College of Technology, Tomakomai 059-1275, Japan*
[2]*Faculty of Health Sciences, Hokkaido University, Sapporo 060-0812, Japan*
[3]*Hokkaido Institute of Technology, Sapporo 006-8585, Japan*
[4]*Muroran Institute of Technology, Muroran 050-8585, Japan*

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We report the electron swarm parameters, the drift velocity, and the ionization coefficients in CF_3I gas for relatively wide ranges of reduced electric fields (E/N). The drift velocity is measured based on the arrival-time spectra of electrons for $E/N=200-3000$ Td, and the first and second ionization coefficients are determined by the steady-state Townsend method for $E/N=400-5000$ Td. The results are compared with those of CF_4 to show that CF_3I has a high reactivity for electron attachment in a low E/N region resulting in a much higher limiting E/N value (440 Td) than that of CF_4. © *2009 American Institute of Physics*. [doi:10.1063/1.3224197]

In the manufacturing process of semiconductor devices, fluorine compounds (C_xF_x) have been utilized as dry etching gases.[1] In particular, CF_4 has been widely used.[2] However, these specified chlorofluorocarbons are currently the target for reduction to prevent ozone depletion and global warming. Thus, a substitute gas CF_3I was created, which possesses low values for ozone depletion and global warming potentials.[3,4]

In this article, we present the experimental results for the electron swarm parameters in CF_3I, obtained by the arrival-time spectra (ATS) method using the double-shutter drift tube and the steady-state Townsend (SST) method. In the ATS method, we have measured the drift velocity W_m (the mean arrival-time drift velocity) for the reduced electric field at E/N from 200 to 3000 Td, while the first and second ionization coefficients (α and γ) have been determined in the SST method at E/N from 400 to 5000 Td. Although electron collision data for CF_3I have been examined in detail by Christophorou and Olthoff,[4] the experimental swarm parameters for CF_3I have not been reported in the literature. Therefore, we have made a comparison of the results with those of CF_4. As to the electron transport properties in CF_4, several studies have been presented. For example, Naidu and Prasad,[5] Shimozuma *et al.*,[6] Hunter *et al.*,[7] and Nakamura and Tomisawa[8] have obtained the swarm parameters in CF_4 experimentally, while Itoh *et al.* (1993)[9] have determined them computationally by the Boltzmann equation analysis. Furthermore, Christophorou and co-workers[1,2] have assessed and integrated several investigations including some of those above.

The experimental techniques used in the present study are based on two methods: the ATS method and the SST method. These are described briefly here. To measure the drift velocity W_m, we have employed the ATS method.[10] W_m is determined from the distribution of arrival-time of electrons at fixed locations, which is a coefficient of the specific transport equation given by the interchange in space and time in the conventional continuity equation as follows:

$$\frac{\partial n}{\partial z} = \alpha^{(0)} n - \alpha^{(1)} \frac{\partial n}{\partial t} + \alpha^{(2)} \frac{\partial^2 n}{\partial t^2} - \alpha^{(3)} \frac{\partial^3 n}{\partial t^3} + \cdots, \tag{1}$$

where

$$\alpha^{(0)} = \frac{1}{N(z)} \frac{dN(z)}{dz} = \bar{\alpha}, \tag{2}$$

$$\alpha^{(1)} = \frac{d\langle t \rangle}{dz} = \frac{1}{W_m}, \tag{3}$$

$$N(z) = \int_0^\infty n(z,t) dt. \tag{4}$$

Here, $n(z,t)$ is the electron number density at a position z and time t, $\bar{\alpha}$ is the effective ionization coefficient, and $\langle t \rangle$ represents the average of the arrival-time of electrons at every location. The coefficients in the right-hand side of Eq. (1) are the parameters describing the behavior of the ATS at the spatial location of the electrode capturing arrival electrons. The experiment is conducted using a double-shutter drift tube, where arriving electrons are collected by the electrode with shutter 2 at a certain distance from the cathode (with shutter 1 releasing initial electrons). The experimental apparatus and procedure for this method are the same as those described by Hasegawa *et al.*[11] The value W_m is determined by the derivative of the mean arrival-time $\langle t \rangle$ with respect to the drift distance as in Eq. (3). On the other hand, to determine the effective ionization coefficient $\bar{\alpha}$, the SST method has been used. The experimental apparatus and procedure are basically the same as those by Hasegawa *et al.*[12] Since the theoretical equation for the current growth for the SST experiment is represented by

$$I = I_0 \frac{\frac{\alpha}{\alpha-\eta}\exp[(\alpha-\eta)d] - \frac{\eta}{\alpha-\eta}}{1 - \gamma_T \frac{\alpha}{\alpha-\eta}\{\exp[(\alpha-\eta)d] - 1\}}, \tag{5}$$

we can deduce the first ionization coefficient α and the electron attachment coefficient η by fitting this equation to the experimental current growth curve. Here, I_0 is the initial current value and γ_T is the secondary coefficient. If the second-

a)Author to whom correspondence should be addressed. Electronic mail: date@hs.hokudai.ac.jp. Tel.: +81-11-706-3423. FAX: +81-11-706-4916.

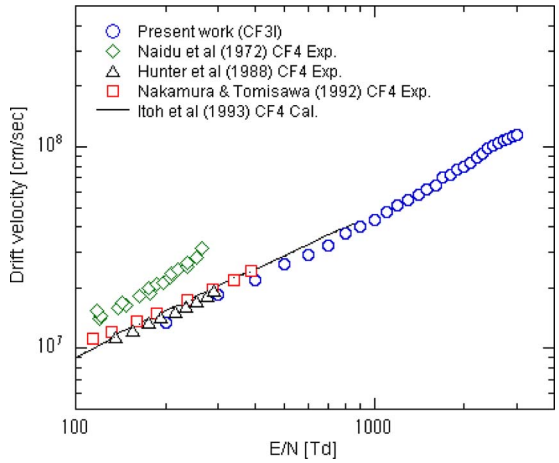

FIG. 1. (Color online) Comparison of the drift velocity. The point in the present work represents the mean arrival-time drift velocity W_m. In the figure legend, Exp. denotes the experimental result and Cal. the calculated result.

ary effect appears significantly, the attachment process can be regarded as negligible (i.e., $\eta \cong 0$). Then, Eq. (5) is reduced to

$$I = I_0 \frac{\exp(\alpha d)}{1 - \gamma_T[\exp(\alpha d) - 1]}. \tag{6}$$

In the fitting procedure of each equation to the experimental result, the linearized least-square-method was employed.

The purity of CF_3I gas sample used is above 99.99% (Tosoh F-Tech, Inc.).[13] The reduced electric fields (E/N) applied for the ATS experiment was E/N=200–3000 Td and the gas pressure was 0.1–1.0 Torr at 0 °C-reduced temperature, while E/N=400–5000 Td and the gas pressure 0.2–4 Torr for the SST experiment. The drift length between the cathode and the double-shutter to collect electrons in the ATS experiment was 10–40 mm, and the gap length of the electrodes in the SST experiment (using the Harrison type electrodes) was 2–15 mm.

Figure 1 shows the drift velocity in comparison with the reported data for CF_4. The present W_m values for CF_3I at E/N below 1000 Td are generally 10%–20% smaller than the drift velocity for CF_4 by the other investigations, except for the drift velocity by Naidu and Prasad,[5] which lies at notably higher values than the others.

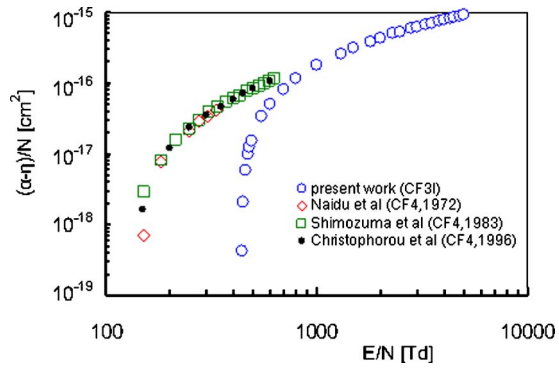

FIG. 2. (Color online) Comparison of the effective first ionization coefficient, $\bar{\alpha}/N=(\alpha-\eta)/N$. The data by Christophorou *et al.* (Ref. 2) (CF_4) are recommended values.

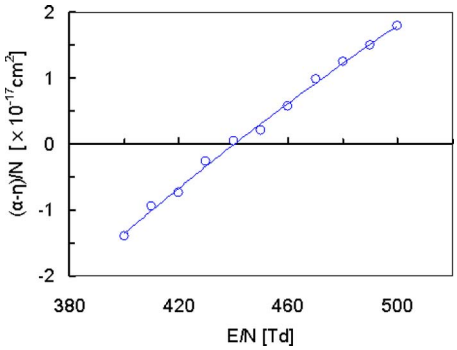

FIG. 3. (Color online) The effective first ionization coefficient, $\bar{\alpha}/N=(\alpha-\eta)/N$, in a low E/N region.

The effective first ionization coefficient (per gas density N) is shown in Fig. 2. Although the values of the coefficient for CF_3I are much lower than those for CF_4 at E/N below 1000 Td, they exhibit an inclination to approach to the value for CF_4 as E/N increases. For the low E/N region, the coefficient is specifically plotted in Fig. 3. The limiting E/N (for $\alpha-\eta=0$) is found to be about 440 Td, which is much greater than 140 Td for CF_4.[6] This suggests that the CF_3I molecule has a high reactivity for electron attachment. In fact, the attachment cross section of CF_3I has been estimated to be very large (particularly for electron energy below 1 eV).[4] It should be noted that the limiting E/N found here is also superior to that of SF_6 (355 Td).[14] Figure 4 shows the total secondary ionization coefficient γ_T, which was measurable at E/N's above 2000 Td.

The experiment in this study has been performed based on the assumption that energy distribution of electrons is in the equilibrium state (i.e., the hydrodynamic regime) that remains unchanged with a negligibly small effect of field distortion in the various gap lengths. In order to confirm the validity of the present experiment at the high E/N region in terms of the equilibrium, we attempted to draw the current growth by the Gosseries plot.[15] This plot represents the relationship between the reciprocal Y_d of the current at an electrode separation d and the reciprocal current measured at $d+\Delta d$ as

$$Y_d = Y_{d+\Delta d} \exp(\alpha \Delta d) + \frac{\gamma_T}{I_0}[\exp(\alpha \Delta d) - 1], \tag{7}$$

which is derived from Eq. (6). A plot of Y_d against $Y_{d+\Delta d}$ is linear only if both α and γ_T are spatially independent and the initial current I_0 is constant. Figure 5 shows the Gosseries plots for E/N=4000 and 5000 Td. As is shown in the figure, the linearity is very good for the both cases, and this implies

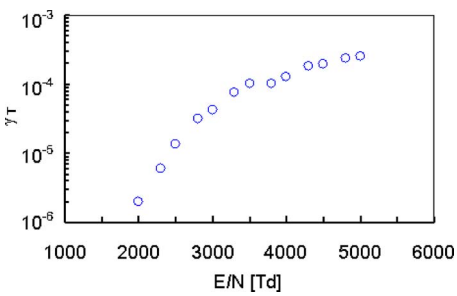

FIG. 4. (Color online) The secondary ionization coefficient as a function of E/N.

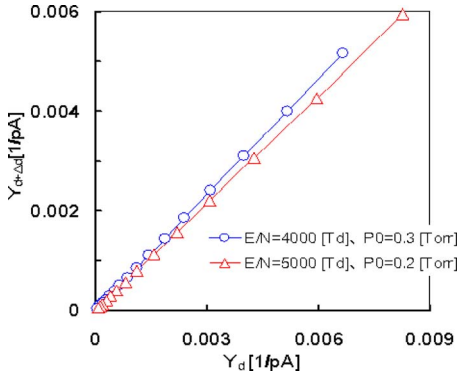

FIG. 5. (Color online) The Gosseries plots for the SST experiment with CF_3I at E/N=4000 and 5000 Td. Here, P_0 (pressure at 0 °C) is 0.3 Torr and Δd is 0.03 cm at E/N=4000 Td, and 0.2 Torr and 0.05 cm at E/N =5000 Td.

that the experiments have been carried out under the equilibrium state for every gap length configured.

In conclusion, as the electron swarm parameters in CF_3I gas, we have determined the drift velocity (W_m) by using a double-shutter drift tube for E/N from 200 to 3000 Td, and the first and second ionization coefficients (α and γ) by the SST method from E/N=400 to 5000 Td. The results were compared with those of CF_4. The comparison showed that the parameters differ largely in low E/N region while they have a tendency to coincide with each other at high E/N above 1000 Td. The limiting E/N value was about 440 Td, and the secondary ionization coefficient ranged from 10^{-6} to 10^{-4} orders for E/N from 2000 to 5000 Td with a monotonic increase. These results suggest that CF_3I can be used not only as a dry etching gas in semiconductor fabrications but also as an effective insulation gas between high voltage gaps. For the latter application, further investigations are necessary regarding disintegrations of CF_3I through the discharges and the chemical stabilities.

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