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Electron drift velocity in SF_6 in strong electric fields determined from rf breakdown curves

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Abstract
This paper presents measurements of the electron drift velocity V_{dr} in SF_6 gas for high reduced electric fields (E/N = 330–5655 Td (1 Td = 10^{-17} V cm^2)). The drift velocities were obtained using the method of Lisovskiy and Yegorenkov (1998 *J. Phys. D: Appl. Phys.* **31** 3349) based on the determination of the pressure and voltage of the turning points of rf capacitive discharge breakdown curves for a range of electrode spacings. The V_{dr} values thus obtained were in good agreement with those calculated from the cross-sections of Phelps and Van Brunt (1988 *J. Appl. Phys.* **64** 4269) using the BOLSIG code. The validity of the Lisovskiy–Yegorenkov method is discussed and we show that it is applicable over the entire E/N range where rf discharge ignition at breakdown occurs for rf frequencies of 13.56 MHz or above.

1. Introduction

Sulfur hexafluoride (SF_6) is a man-made gas with excellent dielectric properties and is widely used as an insulating gas in various electric devices [1, 2]. Mixtures of SF_6 with oxygen are employed for plasma etching semiconductor materials [3, 4] and for plasma cleaning of technological chambers [5]. It is also used in rare gas-halide excimer lasers, AWACS radar domes, x-ray machines, airplane tires, etc. [6]. Therefore, considerable attention has been devoted to studying the physical properties of this gas.

The drift velocity V_{dr} of electrons moving in an electric field is one of the most important characteristics of an ionized gas. It describes the electrical conductivity of a weakly ionized gas (the current carried by positive ions can be neglected due to their small drift velocity). The electron cloud in an ionized gas moves with a broad velocity spectrum, but the drift velocity describes the average movement of the electrons under the influence of an electric field. The electron drift velocity is a key transport coefficient and is required for fluid modelling of technological discharge plasmas, gas-filled counters of ionizing radiation, the Earth's atmosphere, etc.

Several methods have been developed to determine the electron drift velocity, including the pulsed Townsend method [7–9], the time-of-flight method [10–12], monitoring of the velocity of the optical emission of the moving electron cloud [13] and the shutter method [7, 14, 15]. However, as a rule, these methods can only be used for relatively low reduced electric fields (E/N lower than about 1000 Td). At high E/N the average energy of electrons is high; therefore, the efficiency of shutters is lower. For accurate V_{dr} measurements one may observe single avalanches but at higher E/N the probability of secondary avalanches increases. Therefore, conventional methods can only be applied at $\mu = \gamma \times (e^{\alpha L} - 1) \ll 1$, where γ is the ion induced secondary electron emission coefficient, α is the first Townsend coefficient, L is the inter-electrode

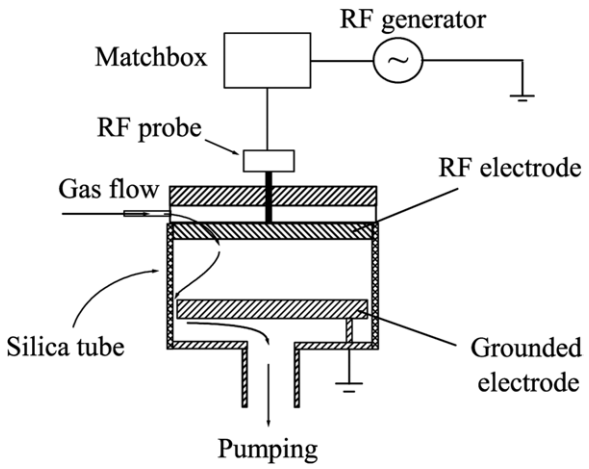

Figure 1. Schematic of our experimental set-up.

spacing. However, Lisovskiy and Yegorenkov [16, 17] have proposed a method based on analysing rf breakdown curves, which allows V_{dr} to be determined in stronger electric fields. Recently Petrovic *et al* [18] have criticized this method; we will address these criticisms in the final section of this paper.

In this paper we have used the Lisovskiy–Yegorenkov method to determine the electron drift velocity in SF_6. Measurements were made in the range $E/N = 330$–5655 Td. With the help of the 'Bolsig' numerical code and published cross-sections [19] we have calculated the electron transport parameters in SF_6 in the range $E/p = 1$–$5000\,\mathrm{V\,cm^{-1}\,Torr^{-1}}$, and the drift velocity values obtained from our experiment agree well with the calculated values.

2. Experimental

The ignition of rf capacitive discharges in SF_6 was studied over the pressure range $p \approx 0.02$–4 Torr. A large number of rf breakdown curves were recorded at the frequency $f = 13.56$ MHz, but some experiments were also performed at the frequency $f = 27.12$ MHz. The distance between the flat circular aluminium electrodes (143 mm in diameter) was varied over the range $L = 5$–25 mm. The rf voltage (amplitude $U_{rf} < 1500$ V) was fed to one of the electrodes, while the other was grounded. The electrodes were located inside a fused silica tube with an inner diameter of 145 mm (see figure 1). The gas was supplied through small orifices in the powered electrode. The orifices in the rf electrode served only for gas supply into the inter-electrode gap, the diameter of each orifice being 0.5 mm. Such narrow orifices would not let electrons perform long path breakdown. Gas was pumped out via a narrow gap between the grounded electrode and the wall of the fused silica tube. The gap width was also equal to 0.5 mm.

The gas flow was fixed with a mass flow controller to 5 sccm, and the pressure regulated by throttling the outlet to the pump. The rf voltage was measured with an rf probe (Advanced Energy Z'SCAN). Gas pressure was measured with a capacitive manometer (MKS Instruments), attached near the grounded electrode (between this electrode and the vacuum pump). For pressure gauging we attached the second capacitive manometer directly to the gap between the electrodes (chamber design permitted us to do so). We knew exactly what was the gas pressure in the inter-electrode gap over the whole gas pressure range studied.

By 'breakdown voltage' we mean the maximum rf voltage that can be applied across the electrodes without discharge ignition. The addition of even a small fraction of a volt leads to gas breakdown, the rf voltage drop across the electrodes decreases abruptly, a glow appears within the gap, a conductance current flows in the discharge circuit and the phase shift angle between rf current and voltage becomes less than $\pi/2$. All these changes, which appear simultaneously, are reliable indications of the gas breakdown and they are easily observed. The rf voltage was varied (before the breakdown) in steps of $\Delta U_{rf} \approx 0.3$ V (because the generator had stepwise control). The gas pressure was monitored with capacitive manometers with a smallest step of $\Delta p \approx 0.001$ Torr. The inter-electrode distance was measured with an accuracy of $\Delta L \approx 0.01$ mm. The rates of increase in the pressure (while measuring to the left of rf breakdown curve minimum in the multi-valued region) and in the rf voltage (right-hand branch) were very small. For example, after increasing the rf voltage by a minimum step $\Delta U_{rf} \approx 0.3$ V we waited several seconds for a possible breakdown and, if not, made the following step ΔU_{rf}.

The residence time for atoms and molecules in our chamber within all the range of gas pressure studied was less than 1 min, as the gas was renewed continuously. The time between successive breakdowns in our chamber was not less than 5 min; therefore, the excited atoms and molecules after previous breakdown were swept out of the chamber and did not affect the next breakdown. Consequently, no 'memory effect' [20] influenced the discharge ignition in our experiment.

We used the technique proposed by Levitskii [21] to measure the breakdown curves of the rf discharge. Near to, and to the high-pressure side of the minimum in the breakdown curve the SF_6 pressure was fixed before slowly increasing the rf voltage until gas breakdown occurs. To the low pressure side of the minimum the curve may be multi-valued, i.e. the curve turns back to higher pressures, and breakdown can occur at two different values of the rf voltage. Therefore, in this range we first decreased the SF_6 pressure, then fixed the rf voltage value and only then increased the SF_6 pressure slowly until discharge ignition occurred. At the moment of discharge ignition the rf voltage shows a sharp decrease, and a glow appears between the electrodes serving as the indicator of the onset of gas breakdown. The uncertainty in the measured breakdown voltages did not exceed 1–2 V over the whole U_{rf} range under study.

2.1. Determination of the electron drift velocity from rf breakdown curves and the data for SF_6

Breakdown curves for the rf capacitive discharges can be divided into three regions: the drift-diffusion region, the Paschen region and the multipactor region [16]. In this method we are interested in the drift-diffusion region. In the drift-diffusion region the charged particles are principally created

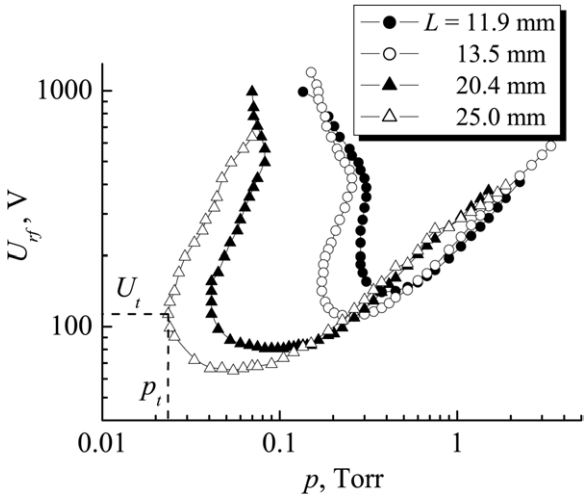

Figure 2. Rf breakdown voltage U_{rf} against SF_6 pressure p for various inter-electrode gap values, $f = 13.56$ MHz.

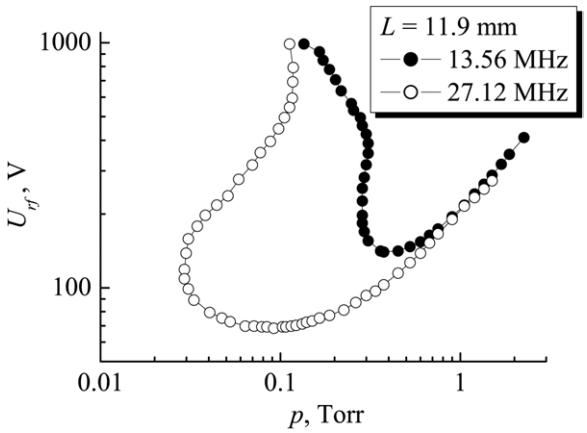

Figure 3. Rf breakdown voltage U_{rf} against SF_6 pressure for $f = 13.56$ MHz, and $f = 27.12$ MHz, $L = 11.9$ mm.

by the ionization of gas molecules via electron impact, and lost by the drift motion of electrons in the rf electric field, diffusion to the electrodes and discharge chamber walls, and attachment of free electrons to gas molecules (if a discharge is ignited in a electronegative gas). Electron-induced secondary electron emission from the electrode surface may play an auxiliary role. The drift-diffusion region is dominant for large inter-electrode gaps and sufficiently high frequencies f of rf field (see figures 2 and 3), but becomes weakly expressed with narrow gaps (less than 1 cm) and frequencies below 10 MHz. It is this branch that is of principal importance for us because the method we employ for determining V_{dr} is based on recording the coordinates (rf voltage U_t and gas pressure p_t) of the turning point of this branch. The mechanisms of generation and loss of charged particles for the other (Paschen and multipactor) regions are discussed elsewhere [16].

Let us briefly describe the Lisovskiy–Yegorenkov [16, 22, 23] method for determining the electron drift velocity from rf breakdown curves. The equation of motion of the centre of the electron swarm in a uniform rf electric field $E_{rf} \sin \omega t$ is given by

$$m\frac{d\vec{V}}{dt} = -e\vec{E}_{rf}\sin\omega t - m\vec{V}\nu_{me}, \tag{1}$$

where $\vec{V}$ is the electron velocity, e and m are the electron charge and mass, respectively, E_{rf} is the rf field amplitude, ν_{me} is the momentum transfer frequency of collisions between electrons and gas molecules (the quantity ν_{me} is assumed to be constant), $\omega = 2\pi f$ is the angular frequency of the rf field. Integrating this expression gives the following expressions for the velocity $\vec{V}$ and displacement $\vec{r}$ of electrons:

$$\vec{V} = \frac{e\vec{E}_{rf}}{m\sqrt{\omega^2 + \nu_{me}^2}} \cdot \cos(\omega t + \phi), \tag{2}$$

$$\vec{r} = \frac{e\vec{E}_{rf}}{m\omega\sqrt{\omega^2 + \nu_{me}^2}} \cdot \sin(\omega t + \phi), \tag{3}$$

where $\phi = \arctan(\nu_{me}/\omega)$. These equations were obtained earlier, e.g. in [24]. The amplitude, A, of the electron displacement in an rf electric field is given by

$$A = \frac{eE_{rf}}{m\omega\sqrt{\omega^2 + \nu_{me}^2}} = \frac{V_{dr}}{\omega}, \tag{4}$$

where the maximum instantaneous drift velocity of electrons, V_{dr}, is given by

$$V_{dr} = \frac{eE_{rf}}{m\sqrt{\omega^2 + \nu_{me}^2}}. \tag{5}$$

If $U_{rf} = U_{rf}(p)$ is the amplitude of the rf voltage at breakdown, a turning point occurs when $dU_{rf}(p)/dp \to \infty$. At the turning point of the breakdown curve (corresponding to $p = p_t$ and $U_{rf} = U_t$) the amplitude of the electron displacement is equal to half of the gap width L between the electrodes [22]:

$$A = \frac{V_{dr}}{\omega} = \frac{L}{2}. \tag{6}$$

Hence the electron drift velocity V_{dr} at the turning point of the rf breakdown curve is equal to

$$V_{dr} = \frac{\omega \cdot L}{2} = L\pi f. \tag{7}$$

It follows from equation (7) that the value of the electron drift velocity at the turning point of the breakdown curve depends only on the values of the inter-electrode gap and the frequency of the rf field. At the same time it is independent of the gas species. However, the corresponding value of E/N (or E/p) at this point will be different for each gas.

The coordinates of the turning point permit us to determine the reduced field, E/p (or E/N), corresponding to this electron drift velocity. For example, from figure 2 we determine the coordinates of the turning point of the rf breakdown curve for the gap of 2.5 cm: $p_t = 0.024$ Torr and $U_t = 113.1$ V. Then we find that $E/p = U_t/(L \times p_t) = 1885\,\mathrm{V\,cm^{-1}\,Torr^{-1}}$, $E/N = 5655$ Td and $V_{dr} = 2.5 \times \pi \times 13.56 \times 10^6 = 1.06 \times 10^8\,\mathrm{cm\,s^{-1}}$. In order to obtain a set of V_{dr} values over a wide range of E/N, rf breakdown curves must be recorded at various values of the inter-electrode gap L.

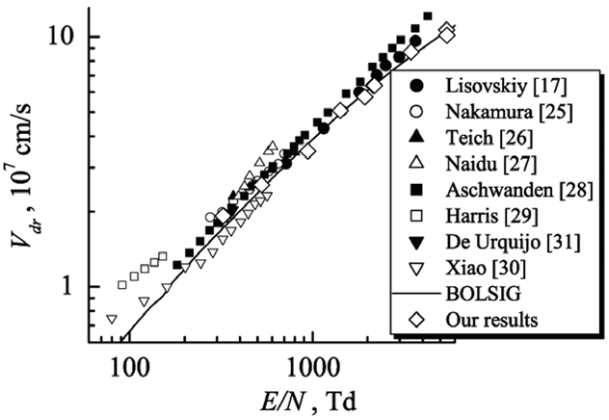

Figure 4. Electron drift velocity in SF_6 against E/N.

We may also vary the rf field frequency f with L fixed. The rf breakdown curves for $L \geqslant 11.9$ mm and $f = 13.56$ MHz, as well as for $f = 27.12$ MHz (presented in figures 2 and 3), show a diffusion-drift branch with multi-valued dependence of the rf breakdown voltage on gas pressure, so we may use them for determining the electron drift velocity values from the location of the turning points.

The values of the electron drift velocity determined from our measured breakdown curves are presented in figure 4. There have been a number of previous measurements of the electron drift velocity in SF_6 [17, 25–31]. Our data are in good agreement with the data of other authors within the range $E/N = 300$–600 Td. Christophorou and Olthoff [6] have reviewed the previous work, and state that only Lisovskiy and Yegorenkov [17] and Aschwanden [28] have report values for reduced electric fields above 1000 Td. Christophorou and Olthoff suggest 'recommended data' at high reduced field, obtained by fitting a line through the data of Aschwanden, due to the better agreement of these data with the other measurements at lower reduced field. In this paper we report our measurements of rf breakdown curves for SF_6 at a variety of electrode spacings, from which we have determined the electron drift velocity within the range $E/N = 300$–5655 Td. At $E/N \approx 300$ Td our results practically coincide with those of Aschwanden and other workers. However, our values are lower than those of Aschwanden for higher reduced fields. At $E/N = 3000$ Td we found values 20% lower, and with further increase in E/N this discrepancy increases.

We also calculated values of the electron drift velocity from the experimental cross-sections of Phelps and Van Brunt [19] for elastic and inelastic collisions between electrons and SF_6 molecules, using the BOLSIG code (www.siglo-kinema.com/bolsig.htm). The BOLSIG code allows numerical solution of the Boltzmann equation for electrons in weakly ionized gases and in steady-state, uniform fields. Figure 4 shows that our electron drift velocity values are in good agreement with the calculated values over the entire range of E/N. In contrast, the values of Aschwanden are higher, particularly at high reduced field. The previous measurements of Lisovskiy and Yegorenkov [17] (using the same method as here) are close to the present measurements and the calculated values. For strong reduced fields the values reported by Lisovskiy and Yegorenkov are slightly higher, but this could be attributed to lower gas purity in the older measurements.

As the values of the electron drift velocity obtained here are in good agreement with the results of other authors at low E/N and are also in good agreement with values calculated from collision cross-sections at high E/N, we consider that they are more reliable than those of Aschwanden [28]. This should be confirmed by further calculations and measurements (using other techniques) in the high reduced field region.

2.2. Validity of the determination of electron drift velocity from rf breakdown curves

Now let us consider the validity of the Lisovskiy–Yegorenkov method to determine the electron drift velocity. This method is based on the assumption that, when a sinusoidal rf electric field is applied, the electron drift velocity $V_{dr}(t)$ also oscillates sinusoidally, with an amplitude given by equation (4). It should be noted that at high rf frequencies there can be a phase shift between the field and the drift velocity, but this does not affect the measurement. The method is simple and gives good agreement with the data obtained by other techniques and numerical calculations (see, e.g., [16, 17, 22, 23, 32, 33]). The Lisovskiy–Yegorenkov method is accessible to many researchers. As far as we know, few installations exist for accurate V_{dr} determination. However, the number of rf discharge chambers at universities and research centres of companies can be counted in hundreds, if not thousands. The Lisovskiy–Yegorenkov method enables one to determine V_{dr} *in situ* within the E/N range and in the gas (or their mixtures) which are of interest to researchers.

We also remark that the spread of V_{dr} values determined with Lisovskiy–Yegorenkov method does not exceed that obtained with other methods. Figure 4 demonstrates that at $E/N \approx 500$ Td the measured V_{dr} values lie within the range from 3.12×10^7 cm s^{-1} [27] to 2.21×10^7 cm s^{-1} [30]. Our result $V_{dr} = 2.56 \times 10^7$ cm s^{-1} at this E/N value is within the V_{dr} spread presented in above papers.

However, in a recent paper Petrovic *et al* [18] have questioned the validity of this method. They point out that, under some conditions, $V_{dr}(t)$ can deviate significantly from simple sinusoidal behaviour. This is notably the case in gases that exhibit negative differential conductivity (NDC), such as CH_4 [34–36] or CF_4 [37, 38]. For these gases the electron drift velocity passes though a maximum, $V_{dr} = V_{max}$ at a reduced field $(E/N)_{max}$, drops to a minimum $V_{dr} = V_{min}$, then increases again monotonically for high E/N values. The NDC effect occurs for reduced electric fields such that the average electron energy is slightly higher than the energy where the cross section for an inelastic process (such as vibrational excitation) passes through a maximum; for example, in CH_4 the maximum in electron drift velocity occurs at $E/N \approx 4$ Td, passing through a minimum at $E/N \approx 30$ Td before rising again. Bzenic *et al* [34] calculated the temporal dependence of $V_{dr}(t)$ in CH_4 for rf frequencies of 100 kHz, 1 MHz, 10 MHz and 100 MHz for $E/N = 50$ Td (a little bit to the left of the minimum in V_{dr}). They found that for

the lower frequencies (100 kHz and 1 MHz) the $V_{dr}(t)$ has a complex, non-sinusoidal shape, because the drift velocity corresponds to the instantaneous rf electric field, and the non-linear dependence of V_{dr} on E/N. At the higher frequency of 10 MHz $V_{dr}(t)$ becomes almost sinusoidal (with a small contribution of higher harmonics) and approaches a pure sine form at 100 MHz.

Petrovic *et al* [18] assert that this non-sinusoidal behaviour of $V_{dr}(t)$ compromises the Lisovskiy–Yegorenkov method. Let us outline a number of arguments supporting this method:

(1) Although at high frequencies the phase of the drift velocity can shift considerably relative to the phase of the applied voltage, this has no importance for the Lisovskiy–Yegorenkov method, for which only the amplitude of the motion is of consequence.

(2) The rf breakdown inevitably occurs for high values of E/N far from the region where NDC occurs (if it occurs for the molecule in question). For example, for CF_4 [17] the V_{dr} values were determined for $E/N \geqslant 600$ Td, whereas NDC is only observed between 20 and 80 Td for this molecule.

(3) The rf excitation frequency used here (and elsewhere [16, 17, 22, 23, 32, 33]) is 13.56 MHz and above, where the effects of NDC on the $V_{dr}(t)$ waveform are small, whatever the value of E/N. It has been shown that in Ar gas at 13.56 MHz [39] the deviations from simple sinusoidal behaviour are less than 3%.

(4) In Monte Carlo simulations, as well as in multi-term Boltzmann equation calculations, the results are often presented for fixed values of the reduced frequency ω/N, and not for the frequency ω and density N of gas molecules separately [40–46]. The temporal profile $V_{dr}(t)$ of the electron drift velocity is determined only by the reduced frequency ω/N. For example, the $V_{dr}(t)$ profiles at 1 Torr pressure and 100 MHz frequency and at 0.1 Torr and 10 MHz are the same (keeping the reduced field value E/N unchanged) [43]. It follows from White *et al* [42] that even in a gas with NDC and with E/N in the NDC range the $V_{dr}(t)$ profile becomes harmonic for reduced frequencies above $\omega/N \approx 10^{-15} - 10^{-14}$ rad m^3 s^{-1}. For the smallest inter-electrode gap of $L = 11.9$ mm in figure 2 at the turning point on the rf breakdown curve we have $\omega/N = 8 \times 10^{-15}$ rad m^3 s^{-1}, so that under conditions of our experiments the $V_{dr}(t)$ profile must be harmonic even in a gas with NDC.

(5) Monte Carlo simulations in various gases [34, 45, 46] demonstrate that increasing E/N does not lead to the deterioration in the sine pattern of the $V_{dr}(t)$ profile and in the presence of NDC $V_{dr}(t)$ quickly becomes harmonic at higher E/N values.

(6) Now let us consider which gas pressures correspond to high and low E/N, when we determine the electron drift velocity. According to formula (7), at the turning point we have $V_{dr} = L \times \pi \times f$, i.e. at a low frequency and narrow gaps L we get moderate V_{dr} values relating to low E/N. In order to determine V_{dr} for high E/N values one needs to record rf breakdown curves for large gaps and/or high frequencies. It is clear from figure 2 that rf breakdown curves shift to lower gas pressure values with increasing L. In other words as L increases the reduced frequency ω/N must also increase, reaching the value $\omega/N \approx 10^{-13}$ rad m^3 s^{-1} for $L = 25$ mm in figure 2. At such a high ω/N value the $V_{dr}(t)$ profile must be sinusoidal, as is supported by the calculated data of a number of papers [34, 41, 42].

Obviously, the two-term approximation, which is used in BOLSIG, will give results that deviate from those obtained from more complete Monte Carlo simulations and multi-term Boltzmann analyses at very high E/N. This problem was studied in detail by White *et al* [47], who concludes that two-term theory may be applied when high accuracy ($\geqslant$10%) is not required, e.g. in modelling of plasma processes. However, when very high accuracy ($\sim$0.1%) is required the two-term theory becomes inapplicable and one has to employ a multi-term code or Monte Carlo simulation. Itoh *et al* [48] show that the value of the electron drift velocity in SF_6 in a strong electric field ($E/N = 3000$ Td), obtained using a three-term approximation, exceeds the value obtained with a two-term approximation by only 10%. The present results are lower than previous measurements [17] by approximately the same value. Under the same conditions the results of Aschwanden [28] exceed our data by approximately 30%, i.e. the discrepancy in experimental data is three times more than the possible discrepancy due to the application of the multi-term approximation instead of the two-term one. A later paper by Itoh *et al* [49] using the six-term approximation gives results close to ours. Our data are also in good agreement with data given by Teich and Sangi [26], which also run considerably below the data of Aschwanden.

As has been shown in a number of papers (see, e.g. [50] and the references cited therein), the temporal behaviour of the electron drift velocity and the electron energy distribution function (EEDF), for electrons subjected to an alternating electric field with the angular frequency ω, is determined by the characteristic rates of energy relaxation $\nu_e(\varepsilon)$ and of momentum transfer $\nu_{me}(\varepsilon)$:

$$\nu_e(\varepsilon) = \frac{2m}{M} \cdot \nu_m(\varepsilon) + \sum_j \nu_j(\varepsilon), \tag{8}$$

$$\nu_{me}(\varepsilon) = \nu_m(\varepsilon) + \sum_j \nu_j(\varepsilon), \tag{9}$$

where $\nu_m(\varepsilon)$ is the collision rate for the elastic momentum transfer, $\nu_j(\varepsilon)$ is the rate for inelastic excitation of the jth state, M is the gas molecule mass, ε is the electron energy. Three possible cases can be considered. (i) The electric field frequency is negligibly small compared with the rate of energy relaxation, $\omega \ll \nu_e \ll \nu_{me}$. In this case the EEDF has time to follow the electric field changes, and it is similar to EEDF in a dc field of amplitude equal to the instantaneous electric field $E_{rf}(t)$. Therefore the EEDF temporal modulation is large. (ii) At higher frequency ω, when $\nu_e \approx \omega \ll \nu_{me}$, the EEDF temporal modulation is considerably decreased. (iii) At $\nu_e \ll \omega \approx \nu_{me}$ the temporal modulation is small, and the

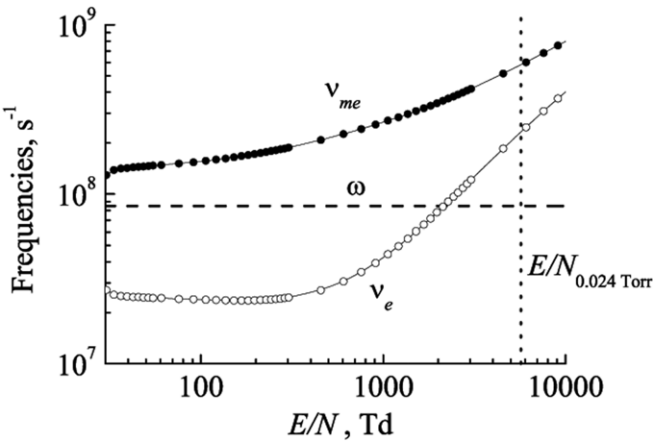

Figure 5. Relaxation rates of energy ν_e and momentum transfer ν_{me} against E/N at SF_6 pressure of $p = 0.024$ Torr ($E/N_{0.024\,Torr}$ means the reduced electric field, corresponding to the turning point on the rf breakdown curve for $L = 25$ mm in figure 2; ω is the circular frequency for 13.56 MHz).

EEDF in the alternating electric field is similar to that in a dc field of amplitude equal to the effective field E_{eff}

$$E_{eff} = \frac{E_0}{\sqrt{2}} \cdot \frac{1}{\sqrt{1 + (\omega/\nu_{me})^2}}. \qquad (10)$$

Therefore, when $\omega \ll \nu_{me}$ the anisotropic part of EEDF follows the rf electric field instantaneously. At each moment the oscillation velocity of electrons V coincides with the electric drift velocity in the dc field, equalling the instantaneous rf field [24]. Obviously the Lisovskiy–Yegorenkov method is applicable when the condition $\omega \ll \nu_{me}$ holds. In order to check the applicability of this inequality we used the Bolsig code to calculate the rates of elastic and inelastic collisions between electrons and gas molecules. From the collision rates we determined the rates of energy relaxation ν_e and momentum transfer ν_{me}. At pressures above 1 Torr the collision rates are high, and conventionally $\omega \ll \nu_e \ll \nu_{me}$. Therefore, let us clarify the relations between ω, ν_e and ν_{me} at the lowest SF_6 pressure. In figure 2 the turning point for $L = 25$ mm is located at $p = 0.024$ Torr. In figure 5 we see the dependences of ν_e and ν_{me} on reduced electric field E/N as well as the angular frequency $\omega = 2 \times \pi \times 13.56 \times 10^6 = 8.5 \times 10^7$ s^{-1}. We observe from figure 5 that at $E/N = 5655$ Td (just at this E/N value the rf breakdown curve for $L = 25$ mm has the turning point from which the drift electron velocity value $V_{dr} = 1.06 \times 10^8$ cm s^{-1} was determined) even at such low gas pressure the momentum transfer relaxation rate is sufficiently high for us to consider that the electron drift velocity has time to tune to the rf instantaneous field. Therefore, the maximum drift velocity V_{dr} in the maximum instantaneous electric field E_{rf} is equal to the electron drift velocity in the dc field E, which is equal to the maximum rf field $E = E_{rf}$. Therefore in figure 4 the rf electric field amplitude E_{rf} can be replaced by a dc field of equal amplitude.

To conclude, the Lisovskiy–Yegorenkov method for V_{dr} determination from rf breakdown curves is valid within the total E/N range where it generally can be applied (at least at frequencies $f \geqslant 13.56$ MHz).

3. Conclusions

This paper presents measured rf breakdown curves in SF_6. From the coordinates of the turning points in the drift-diffusion region of these curves the electron drift velocity was determined in SF_6 for reduced electric fields in the range $321 \leqslant E/N \leqslant 5655$ Td. The values obtained agree well with those calculated from published collision cross-sections. The validity of this method for electron drift velocity measurement was investigated and we conclude that it is valid within the total range of the reduced electric field E/N, where the ignition of the rf capacitive discharges is possible for excitation frequencies at or above 13.56 MHz.

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