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Extinction of RF capacitive low-pressure discharges

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Abstract. – Breakdown and extinction curves have been measured for RF capacitive low-pressure discharges in nitrogen and hydrogen at a frequency of 13.56 MHz and discharge gaps between 6 and 25 mm. In particular, the low-pressure, high-voltage region of the extinction curves is reported for the first time. The shape of the extinction curves was found to be similar to that of the breakdown curves. At sufficiently large gaps ($L > 10$ mm) the RF extinction voltage was found to be multi-valued in the low-pressure region, as is observed for the breakdown voltage. In this region, extinction can occur when the voltage is increased because the width of the two sheaths occupies the whole discharge space.

Radio frequency (RF) capacitive discharges in low-pressure gases are widely used for etching and modifying the surface of various materials, depositing oxide, nitride and other films, cleaning technological chambers, plasma chemical synthesis, sterilizing medical tools etc. The breakdown and extinction curves, which describe the range of pressure and RF voltage values where the RF discharge may exist, and therefore where technological processes may be performed, are fundamental characteristics of an RF discharge. Whereas RF breakdown has been quite widely studied, the literature concerning RF plasma extinction is more sparse.

Let us review briefly the results of studying the extinction of the RF discharge obtained by other authors. Hulburt [1] registered the minimum voltages for sustaining the RF discharge in hydrogen, oxygen and air for the frequency values of 0.86 MHz and 5.3 MHz, as well as for 60 Hz and DC discharges in the gas pressure range of 1–5 Torr and the values of the gap between flat disc electrodes up to 30 mm. Kirchner [2] measured extinction curves of the RF discharge in neon, air, oxygen and hydrogen for the frequency of 35 MHz in a tube with flat inner electrodes. Townsend and Nethercot [3] measured extinction curves in tubes of 3.1 cm diameter with inner and outer electrodes in the form of sleeves, which fitted tightly into or onto the tubes. They presented the results for the 0.005–1 Torr pressure range in nitrogen for several gap values at 7.5 MHz. Thomson [4] suggested a simple model of the RF discharge giving a qualitative description of the extinction curves [2]. Rohde [5] measured the extinction curves of the RF

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discharge in air, oxygen, hydrogen, helium, neon and argon in the range of wavelengths 2.16–9.8 m for the gaps between flat electrodes of 19 and 38 mm, as well as the dependence of the discharge extinction voltage in air on frequency in the range of 0.1–150 MHz. Llewellyn Jones *et al.* registered the extinction curves in air, hydrogen [6] and helium [7] in concentric cylinders at frequencies between 3.5 and 70 MHz. Pateyuk [8] presented the extinction curves of the RF discharge in neon, argon and hydrogen for various gaps between the glass-covered nickel electrodes and the RF frequencies of 57–500 MHz. Francis [9] summarized briefly the main results on RF discharge extinction in tubes of different geometry. Kakuta *et al.* measured the dependence of the extinction voltage of the RF discharge on frequency with a fixed value of gas pressure in argon, helium, hydrogen [10] and SF_6 [11]. The authors of [12] obtained the extinction curve of the RF discharge in argon for the gap of 23 mm between plane parallel electrodes and the frequency of 13.56 MHz. The authors of report [13] measured the extinction curves of the RF discharge in the mixtures of xenon with neon in the frequency range of 40 kHz–3 MHz and the gap of 3 cm between flat electrodes.

In all previous studies the extinction curves were measured only from the high-pressure side down to the voltage minimum (or only a little beyond); the behaviour of the extinction curves at lower pressure and higher RF voltage was not investigated. This paper presents measurements of the breakdown and extinction curves of 13.56 MHz RF discharges in hydrogen and nitrogen over broad ranges of gas pressure and applied RF voltages. At sufficiently large electrode gaps ($L > 10$–15 mm) in molecular gases the extinction voltage is multi-valued at low gas pressure. We have modelled the extinction curve in this multi-valued region using a fluid plasma simulation package.

Our experiments were performed over the pressure range $p \approx 0.01$–20 Torr between plane parallel electrodes of 143 mm in diameter in a fused silica discharge tube of inner diameter 145 mm, and for three different gap values ($L = 6$, 15 and 25 mm). One of the electrodes was supplied with an RF voltage with an amplitude of $U_{rf} \leq 1200$ V from an RF generator operating at 13.56 MHz, and the other one was grounded. At each pressure we determined the value (or values) of the breakdown voltage, $U_b(p)$, and the extinction voltage, $U_e(p)$.

Previous studies have found extinction curves are U-shaped with a single voltage minimum. At the high-pressure side $U_e \propto p$ and at the low-pressure side $U_e \propto 1/p$. However, we found that the extinction curves are more complicated, and in fact have a similar form to that of the breakdown curves. As is known [14], RF discharge breakdown curves can be described in terms of different branches, starting with a diffusion-drift branch at higher pressures (which can contain a region where the breakdown voltage is multi-valued), passing through the Paschen branch at intermediate pressures and followed by the multipactor regime at the lowest pressure. The extinction curves we observed had the same form.

Figure 1 shows the breakdown and extinction curves for hydrogen. The breakdown curve for a 6 mm gap shows a diffusion-drift branch at $p > 5$ Torr and $U_{rf} < 380$ V, containing the multivalued region. The extinction curve for this gap contains (at $U_{rf} < 300$ V) a branch of similar shape but its multivalued region is expressed very weakly. A similar branch of the extinction curve corresponds to the Paschen branch of the breakdown curve ($U_{rf} > 380$ V). For larger inter-electrode gaps the drift-diffusion branch of the breakdown curves is much wider and occupies the whole parameter space studied here. In this case the multi-valued region can be clearly seen in both the breakdown and extinction curves. For example, with $L = 25$ mm, $p = 0.1$ Torr and an RF voltage of 100 V, an RF discharge can be extinguished (at fixed pressure) either by decreasing the RF voltage to 42 V, or by increasing it to 170 V. As the RF voltage is increased, the discharge becomes unstable before extinction: it contracts to a filament which, depending on the gas composition, may either pulsate (contracting and expanding radially), or move chaotically over the surface of the electrodes.

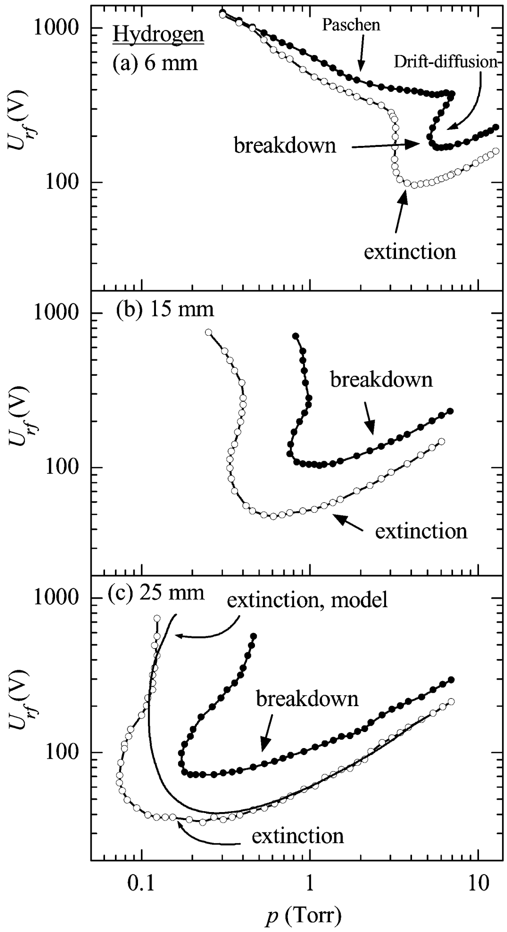

Fig. 1

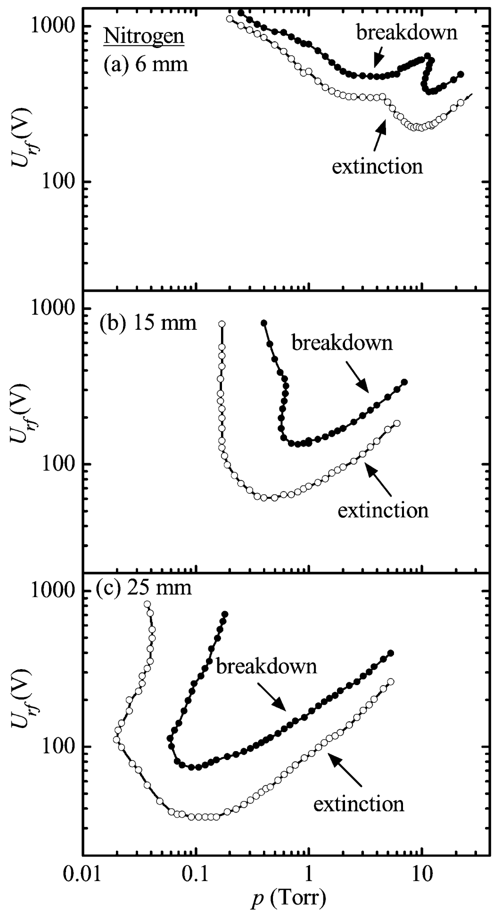

Fig. 2

Fig. 1 – Breakdown curves and extinction curves of RF discharges in hydrogen for inter-electrode gaps of $L = 6$, 15 and 25 mm. The solid line shows the results of the simulation for extinction with a gap of 25 mm.

Fig. 2 – Breakdown curves and extinction curves of RF discharges in nitrogen for inter-electrode gaps of $L = 6$, 15 and 25 mm.

Figure 2 shows breakdown and extinction curves for nitrogen, which are qualitatively similar. The breakdown curve for $L = 6$ mm exhibits two minima (for the Paschen and diffusion-drift branches), the second minimum being also observed on the extinction curve. As is the case for hydrogen, the extinction curves are similar to those for breakdown, but are shifted to lower pressures and RF voltages. The multivalued region of the extinction curves is usually less distinct (occurring over a narrower range of pressure) than is the case with breakdown curves. The extinction curves for nitrogen possess a multi-valued region only for the largest gap studied (25 mm).

Using the fluid plasma simulation code Siglo-RF (Kinema Research & Software), we have computed the extinction curves for an RF discharge in hydrogen with $L = 25$ mm. For a given

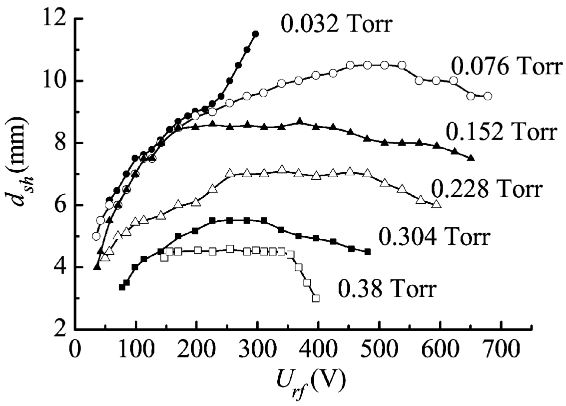

Fig. 3 – Observed sheath thickness against RF voltage for RF discharges in nitrogen at different pressures with a 25 mm gap.

gas pressure, we set the initial plasma density, $n_e \geq 10^8\,\mathrm{cm}^{-3}$, and then sought the smallest value of the RF voltage across the electrodes at which the average electron density at the discharge gap centre is constant in time (as a rule, the plasma density was of the order of $n_e \approx 10^7$–$10^8\,\mathrm{cm}^{-3}$). When the RF voltage was decreased slightly below this value the plasma density was seen to drop rapidly to zero. At low gas pressures it was also possible to find a maximum value of the RF voltage at which the RF discharge can be maintained, and above which the plasma density decreases quickly and the discharge is extinguished.

The computation results are presented in fig. 1. Above 5 Torr the computation results practically coincide with the observed extinction curve. At lower pressure the computed curve is above the experimental one (*i.e.* it predicts extinction at higher voltages and pressures). However, at low pressures a multi-valued region is clearly seen. The difference between the computational and experimental results is probably due to the absence of ion-induced secondary electron emission from the surface of the electrodes in the model. In reality, secondary electron emission from electrodes is known to play an important role in discharge maintenance at low pressure [12].

Figure 3 shows the observed sheath thickness d_{sh} as a function of the RF voltage for the discharge in nitrogen and $L = 25\,\mathrm{mm}$. At the pressure of 0.032 Torr, the sheath thickness increases rapidly with the RF voltage. When the sheath thickness approaches approximately 11.5 mm (almost half of the inter-electrode gap) a further increase in the RF voltage leads to the overlapping of two sheaths and the discharge is extinguished. This means that the discharge is extinguished when there is no free space for the quasineutral plasma or, in other words, when the plasma width becomes insufficient to generate as many charged particles as are lost to the electrodes. At higher pressures (to the right of the multivalued region of the extinction curve), the sheath thickness first increases with increasing RF voltage, and then decreases at large U_{rf}, and the discharge is not extinguished.

The following expression for the sheath thickness and current densities can be obtained from Raizer *et al.* [15]:

$$d_{sh} \propto \sqrt{\frac{U_{rf}}{n}}\,, \qquad (1)$$

where n is the plasma density. Equation (1) shows that the sheath thickness variation is determined by the fastest growing quantity, either the RF voltage across the electrodes or the plasma density at the sheath boundary. For example, for nitrogen at a pressure of $p = 0.38$ Torr in the weak-current (or "alpha") regime of the discharge, the plasma density is proportional to the RF voltage, therefore the sheath thickness remains constant up to $U_{rf} \approx 350$ V (fig. 3). At higher RF voltages, the discharge enters a strong-current ("gamma") regime, electron avalanches occur in the near-electrode sheaths causing a rapid increase of the plasma density at the sheath boundaries, and, as a result, the sheath thickness decreases with increasing RF voltage.

At lower gas pressures the plasma density is lower, due to the lower rate of ionising collisions, and the sheaths are wider. Again, the sheath thickness first increases with increasing RF voltage. However, the point at which the sheath width saturates and then starts to decrease occurs at increasingly higher voltages as the pressure is lowered; the transition to a high-current regime occurs later and is less marked. In the multi-valued region of the extinction curves (see the curve at 0.032 mTorr in fig. 3), the thickness of sheaths approaches one-half of the inter-electrode gap at high RF power before the sheath thickness saturates, so that the sheaths overlap and the RF discharge is extinguished (at $U_{rf} \approx 300$ V in this case).

This paper presents measurements of breakdown and extinction curves for RF capacitive low-pressure discharges in hydrogen and nitrogen. The shape of the extinction curves is similar to that of breakdown curves for the same gas species and gap values. The extinction curves may possess two minima (corresponding to the minima of the Paschen and diffusion-drift branches of the breakdown curves). For large gaps, $L > 10$ mm, a multi-valued region is observed at low pressure. The increase of the sheath thickness with RF voltage (at sufficient low gas pressure) may be the reason for this. When the sheaths overlap, the RF discharge becomes unstable and extinguishes. The results of a fluid simulation agree with the observed data.

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